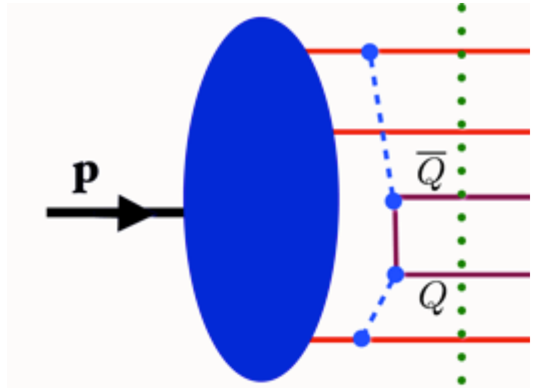



# IC at IC: IceCube can probe the intrinsic charm of the proton

Ranjan Laha

Kavli Institute for Particle Astrophysics and Cosmology (KIPAC)
Stanford University
SLAC National Accelerator Laboratory

in collaboration with Stanley J Brodsky

arXiv 1607.08240

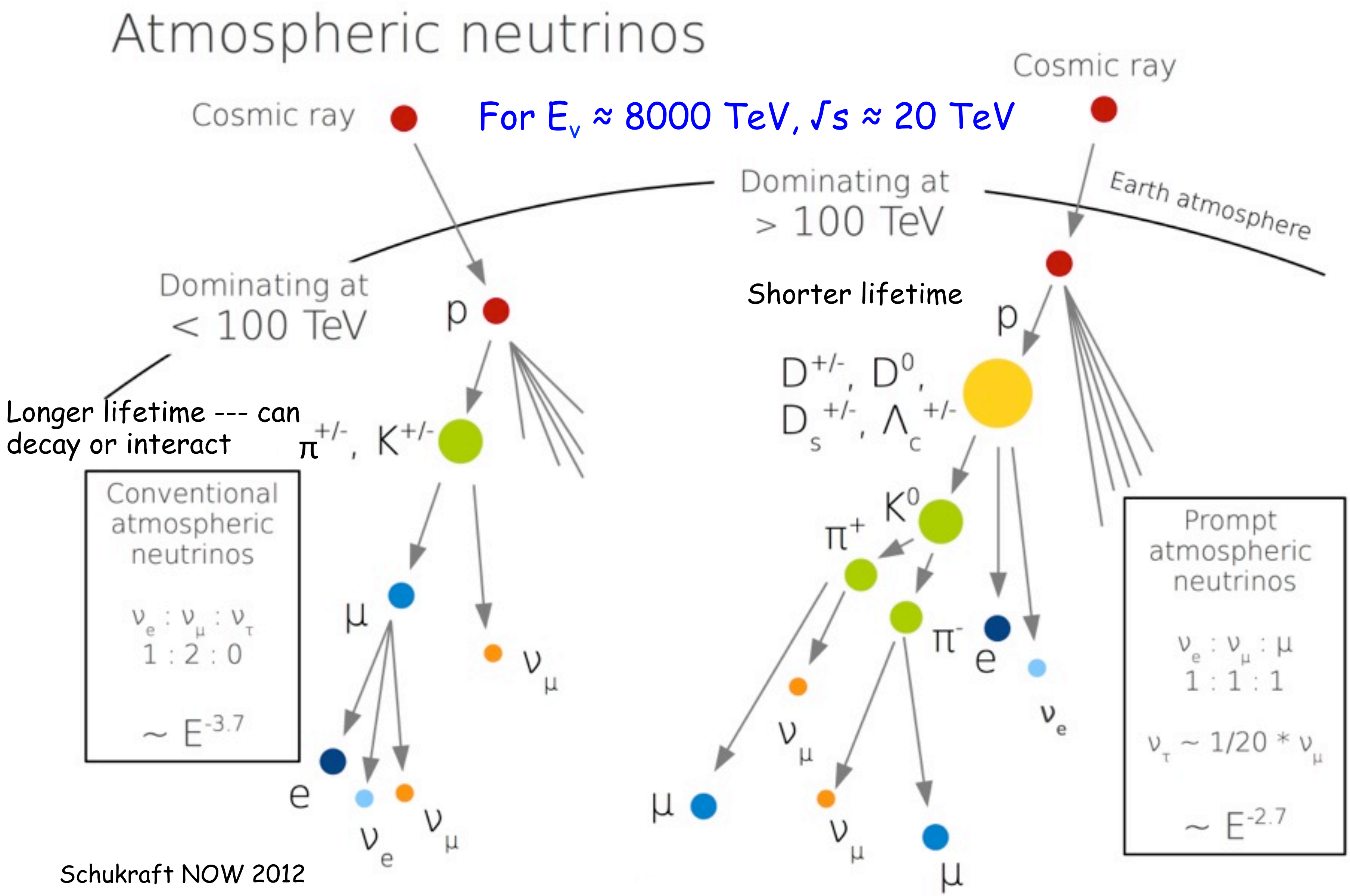
# Contents

- Atmospheric neutrinos and IceCube
- Prompt atmospheric neutrinos
- Intrinsic charm contribution to prompt atmospheric neutrinos

# Atmospheric neutrinos and IceCube

Neutrinos $\equiv$ neutrinos + antineutrinos

# Atmospheric neutrinos



# IceCube neutrino telescope

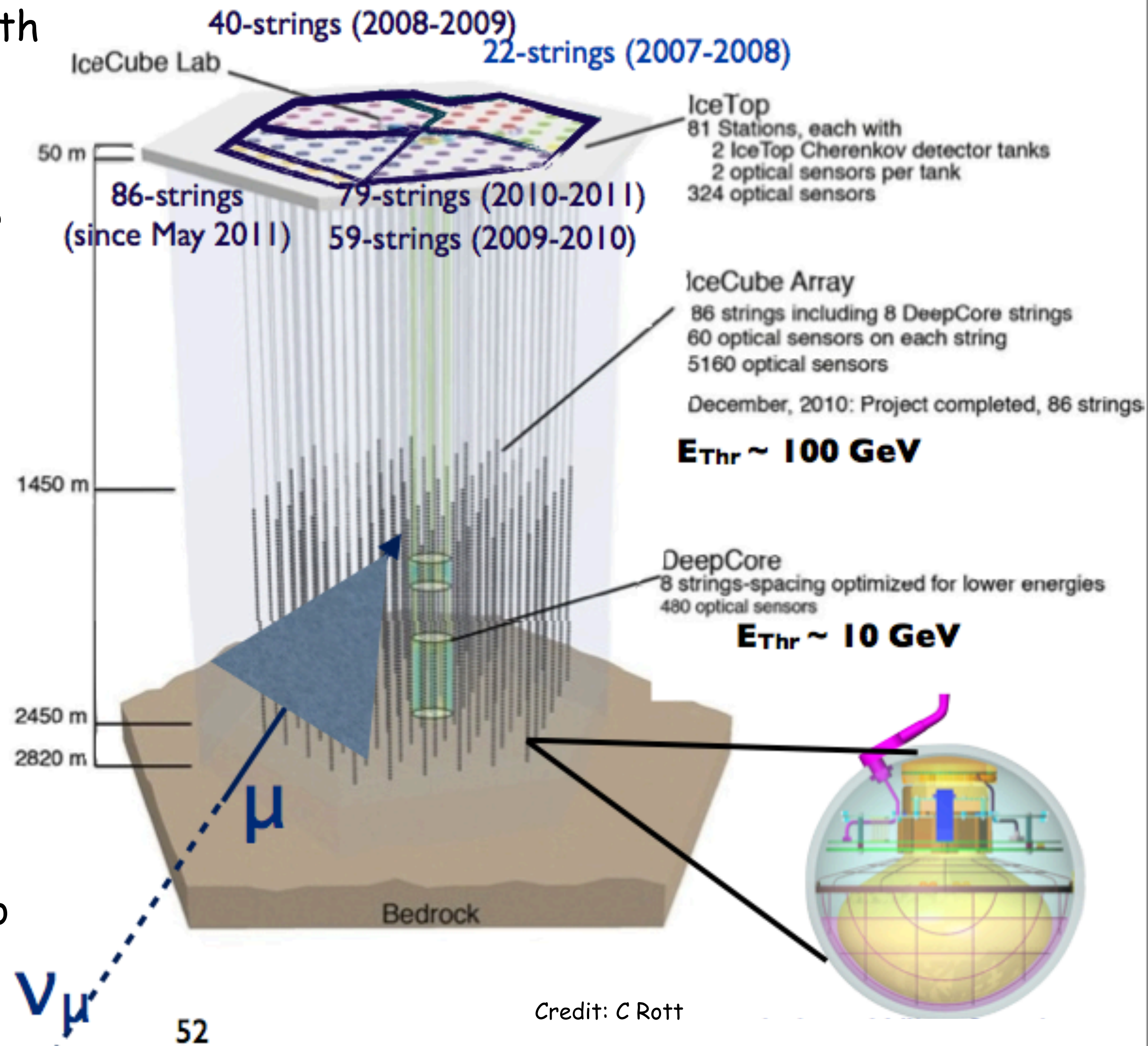
Gigaton effective volume neutrino detector at South Pole

5160 Digital Optical Modules distributed over 86 strings

Completed in Dec 2010; data in full configuration from May 2011

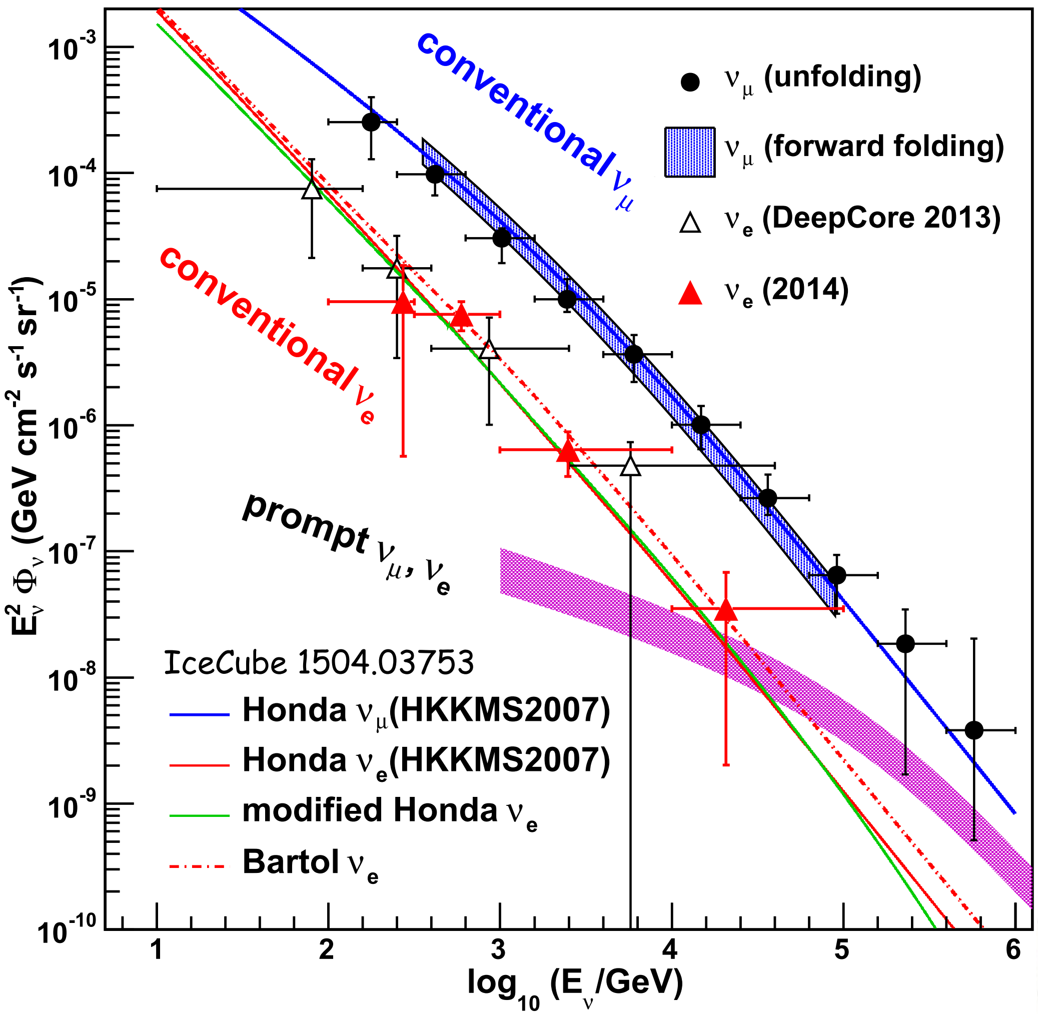
Data acquired during construction phase is analyzed

Neutrino detected through Cherenkov light emission from charged particles produced due to neutrino CC/NC interactions




Credit: C Rott

# Conventional atmospheric neutrinos




$$\mathrm{CR} + \mathrm{air} \rightarrow \pi^{\pm}, K^{\pm} \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$$

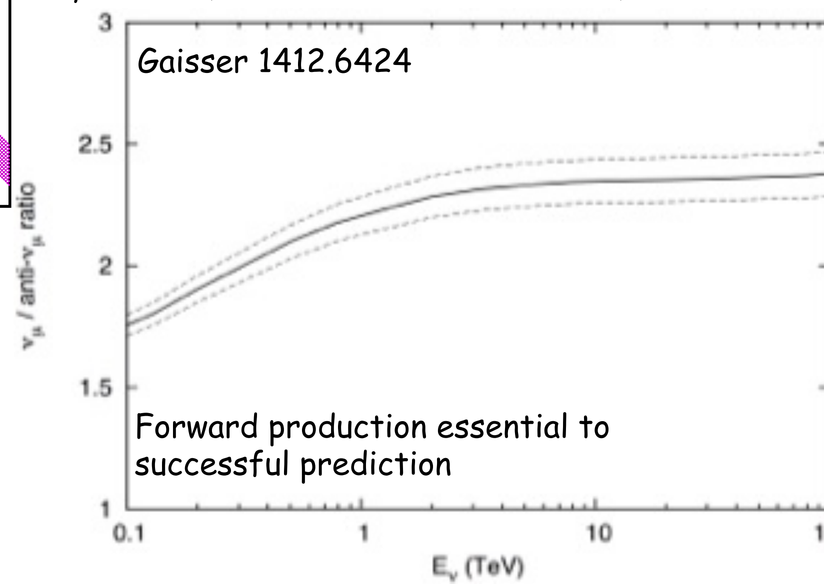
Very important measurement --- neutrino oscillation discovery

2015

The flux is lower in the vertical region, compared to the horizontal region

Negligible amount of $\nu_\tau + \bar{\nu}_\tau$

$$\nu_\mu : \nu_e (+ \mathrm{anti-particles}) \approx 2:1$$




Lower energy measurements also exist by Frejus, AMANDA, Super-Kamiokande.
Measurements at similar energy by ANTARES

# Prompt atmospheric neutrinos

# Prompt atmospheric neutrinos

- Production of charmed hadrons in the atmosphere

$$\mathrm{CR} + \mathrm{air} \rightarrow D^{\pm}, D^{0}, \bar{D}^{0}, D_s^{\pm}, \Lambda_c^{\pm}, \ldots$$

$$\text{charmed hadrons} \rightarrow \ell^{\pm}, \nu_\ell, \bar{\nu}_\ell, \ldots$$

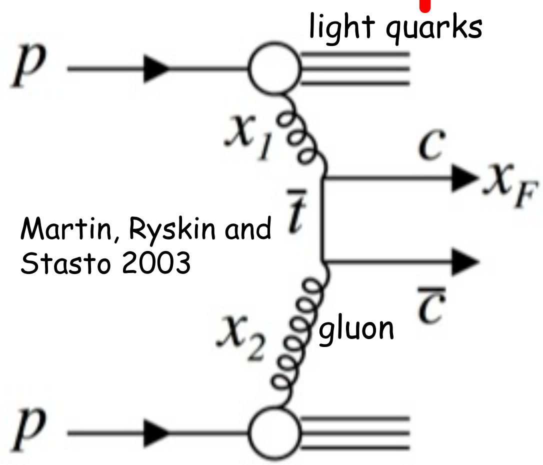
$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 0.1$ and $\nu : \bar{\nu} = 1 : 1$

"prompt" = the charmed hadrons decay faster compared to $\pi/K$

Isotropic flux till $10^7$ GeV

Prompt atmospheric neutrino flux shape ≈ cosmic ray flux shape

# Prompt atmospheric neutrinos




Martin, Ryskin and Stasto 2003

$$p + p \rightarrow c + \bar{c} + X$$

Most calculations are performed in perturbative QCD

Significant uncertainties due to

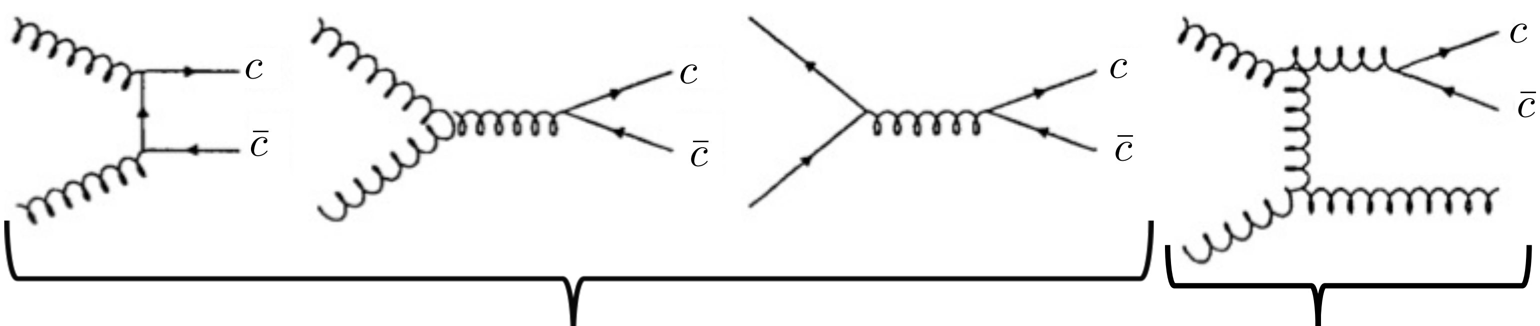
(i) Charm mass,

(ii) Factorization and renormalization scale, and

(iii) choice of the parton distribution function

Bhattacharya etal., 1502.01076

Additional uncertainty due to the cosmic ray input spectrum




Thunman, Ingelman and Gondolo 1996

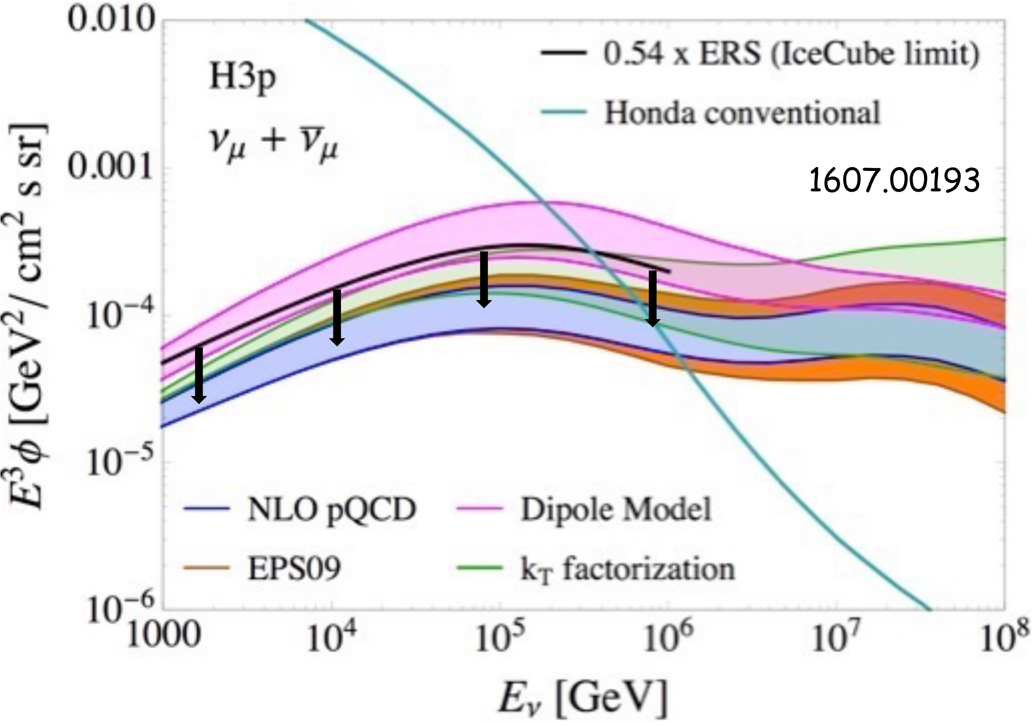
leading order

an important next-to-leading order

Sensitive to QCD mechanisms in regions beyond the reach of LHC

At high s, the interaction is very sensitive to the gluon distribution ($x \sim 10^{-8} - 10^{-4}$)

# Flux predictions from pQCD



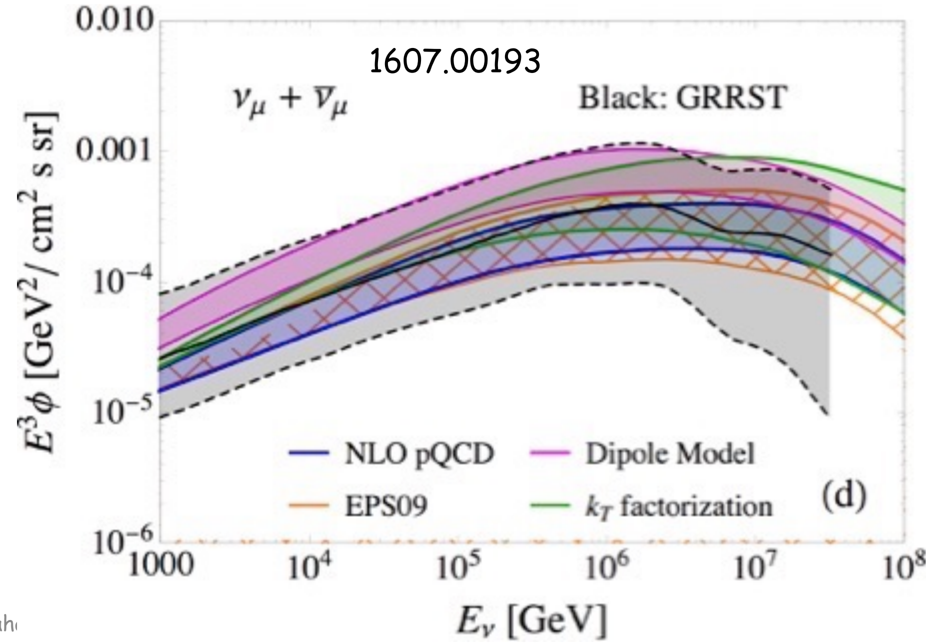

Various approaches in pQCD

Large uncertainty

Calculations by various groups in recent times: 1502.010776, 1507.01570, 1511.06346, 1607.00193, 1611.03815

The central values of various approaches largely agree

Present IceCube upper limits can constrain some of these approaches --- unique constraints on pQCD parameter space



# Intrinsic charm contribution to the prompt atmospheric neutrinos

arXiv 1607.08240

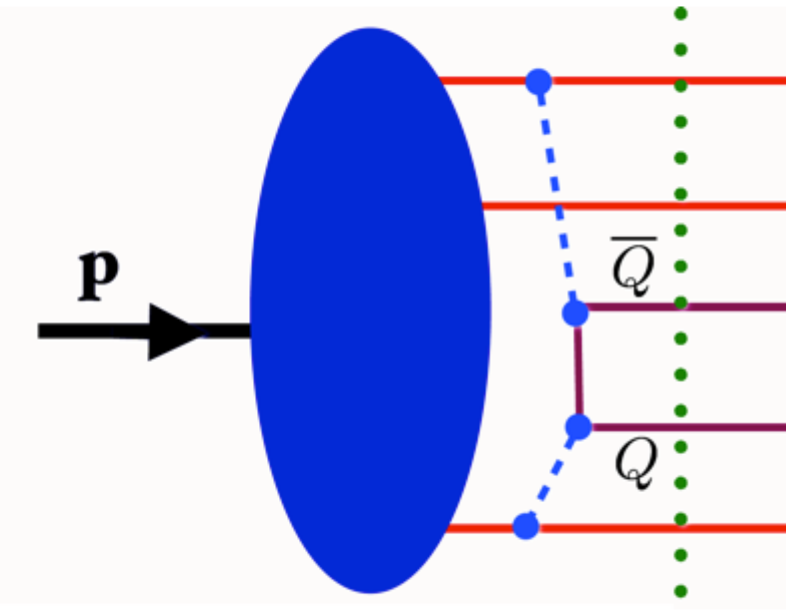
# Intrinsic charm

Brodsky, Hoyer, Peterson, and Sakai 1980

- A rigorous prediction of QCD
- Non-perturbative component
- Flattish $d\sigma/dx_F$ observed at SELEX, ISR
- Dominates at high $x_F$

See talks in this meeting by Gardner, Signori, Ilten, Dulat, Hobbs, and Sato

$$|p\rangle = A\,|uud\rangle + B\,|uudc\bar{c}\rangle + \ldots$$




Brodsky etal., 1504.06287

Quantum fluctuation of the proton

Probability for the proton to contain an intrinsic charm and anti-charm quark is related to $|B|^2$

During an interaction, the u, d and c quark can combine to form a $\Lambda_c$

There are a number of fixed-target experiments like SMOG at LHCb and AFTER@LHC which aim to confirm or constrain the intrinsic charm of the proton

The normalization constant B has to be deduced from experiments

# Intrinsic charm contribution

- The measurement of prompt atmospheric neutrinos is a forward measurement $\Rightarrow$ intrinsic charm can play an important role

$$x_F \approx E_c/E$$

$E_c$ = outgoing charm quark energy

$E$ = incident proton energy

- Intrinsic charm uses the incident proton energy more efficiently. It can play an important role since the cosmic rays have a steeply falling spectrum

- Nuclear dependence (~ $A^{0.7}$) is important since the atmospheric target is mostly nitrogen

# Cascade equations for protons, charm hadron and leptons

Atmospheric column depth; Equivalent all-proton flux; Nucleon attenuation length

$$\frac{d\phi_p(E,X)}{dX} = -\frac{\phi_p(E,X)}{\lambda_p(E)} + Z_{pp}(E)\frac{\phi_p(E,X)}{\lambda_p(E)}$$

Charm hadron flux; atmospheric density; Charm hadron decay length; Charm hadron attenuation length

$$\frac{d\phi_m(E,X)}{dX} = -\frac{\phi_m(E,X)}{\rho(X)\,\delta_m(E)} - \frac{\phi_m(E,X)}{\lambda_m(E)} + Z_{mm}(E)\frac{\phi_m(E,X)}{\lambda_m(E)} + Z_{pm}(E)\frac{\phi_p(E,X)}{\lambda_p(E)}$$

Lepton flux

$$\frac{d\phi_\ell(E,X)}{dX} = \sum_m Z_{m\ell}(E)\frac{\phi_m(E,X)}{\rho(X)\,\delta_m(E)}$$

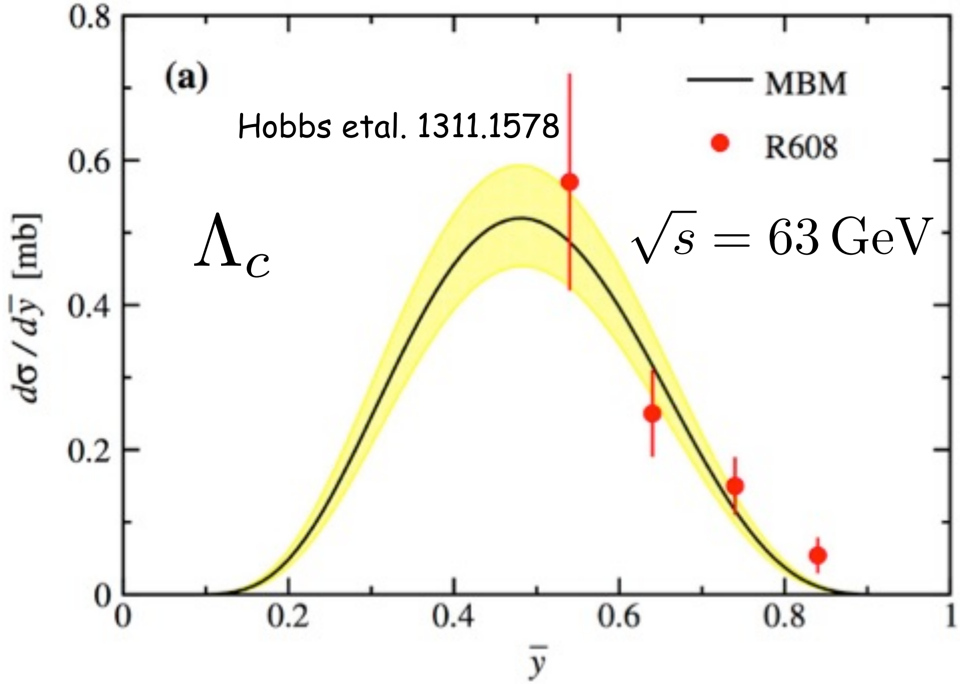
Cross-section weighted moment

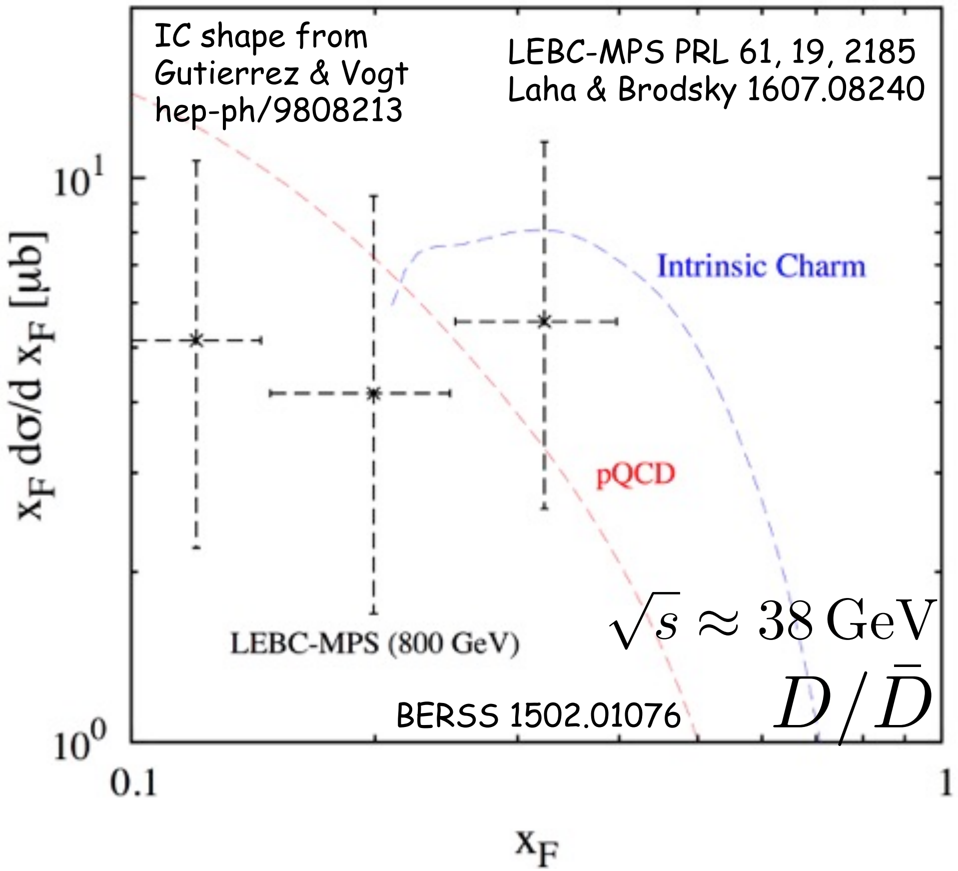
$$Z_{kj}(E) = \int_0^1 \frac{dx_E}{x_E}\frac{\phi_k\left(\frac{E}{x_E},0\right)}{\phi_k(E,0)}\frac{\lambda_k(E)}{\lambda_k\left(\frac{E}{x_E}\right)}\frac{dn_{kj}}{dx_E}(E/x_E)$$

$$\frac{dn}{dx_E} \equiv \frac{1}{\sigma}\frac{d\sigma}{dx_E}$$

$$x_E = \frac{E_{\rm hadron}}{E_{\rm beam}}$$

# Intrinsic charm cross section normalisation



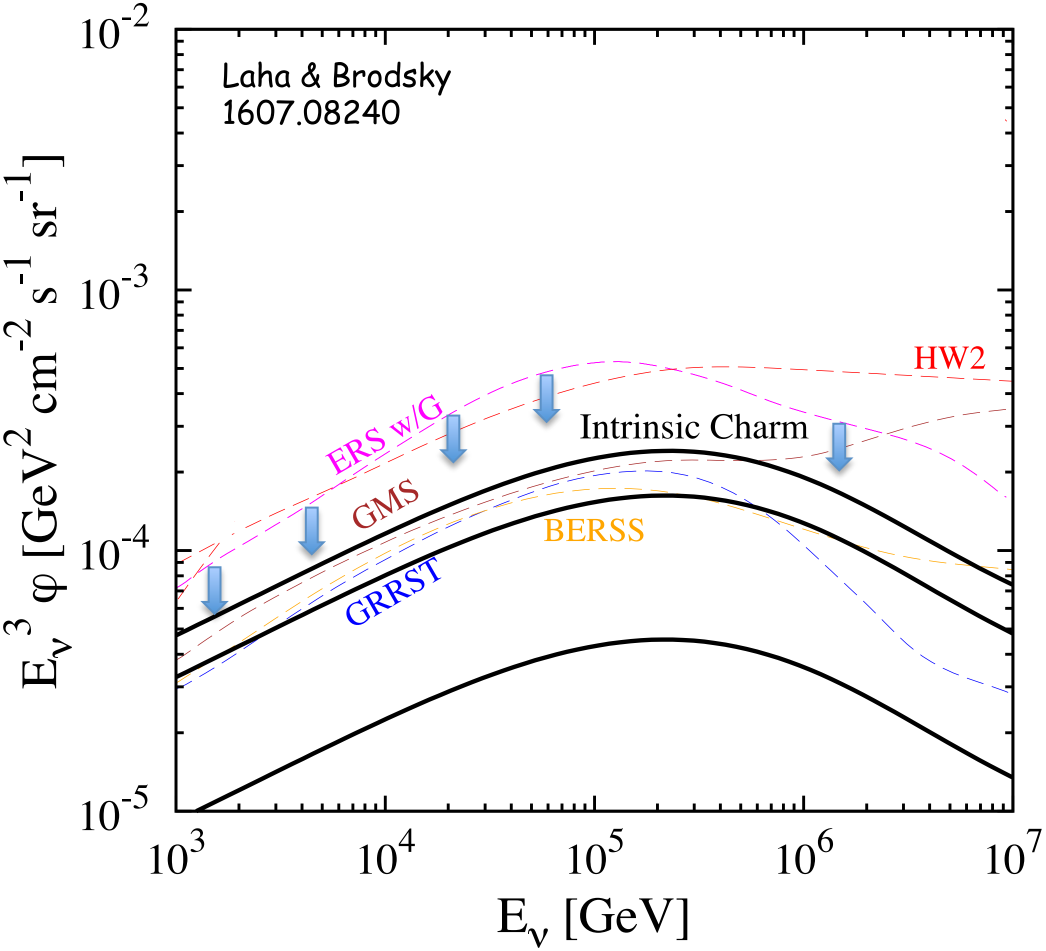




- Substantial uncertainty of pQCD $\Rightarrow$ challenging to find intrinsic charm

- We assume the best-fit pQCD cross section and then use LEBC-MPS data to normalize the D cross sections

- ISR cross section by itself produces too large atmospheric prompt neutrino flux

# Prompt atmospheric flux due to intrinsic charm




Depending on the normalization, the contribution due to intrinsic charm can be as large as that due to perturbative QCD.

The important charm hadrons that contribute towards this flux are

$$D^0, \bar{D}^0, D^\pm, D_s^\pm, \Lambda_c$$

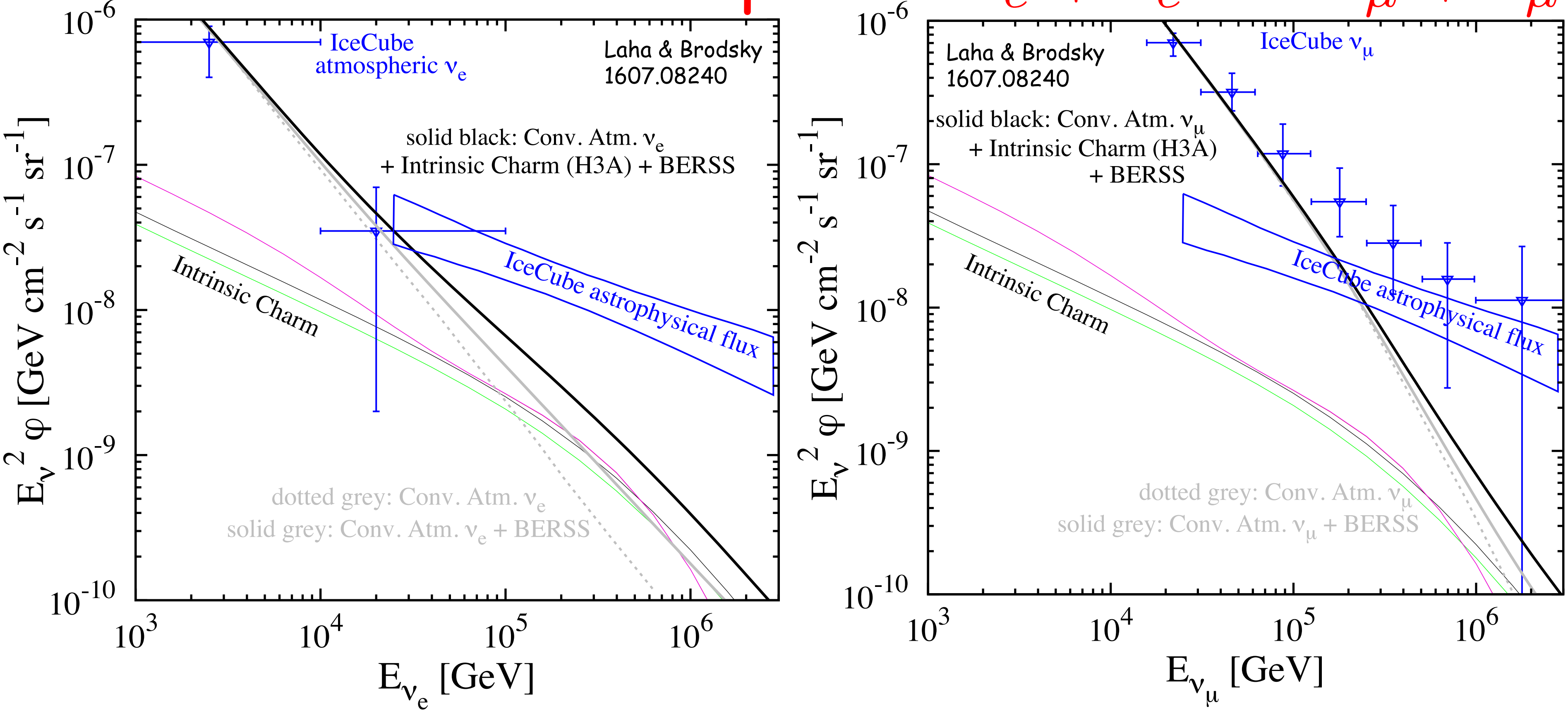
The neutrino flavor ratio is

$$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 0.1$$

This is an additional contribution to the prompt atmospheric flux

IceCube upper limits (near ERS w/G flux) are very close to the contribution due to intrinsic charm

# Contribution to atmospheric $\nu_e + \bar{\nu}_e$ and $\nu_\mu + \bar{\nu}_\mu$



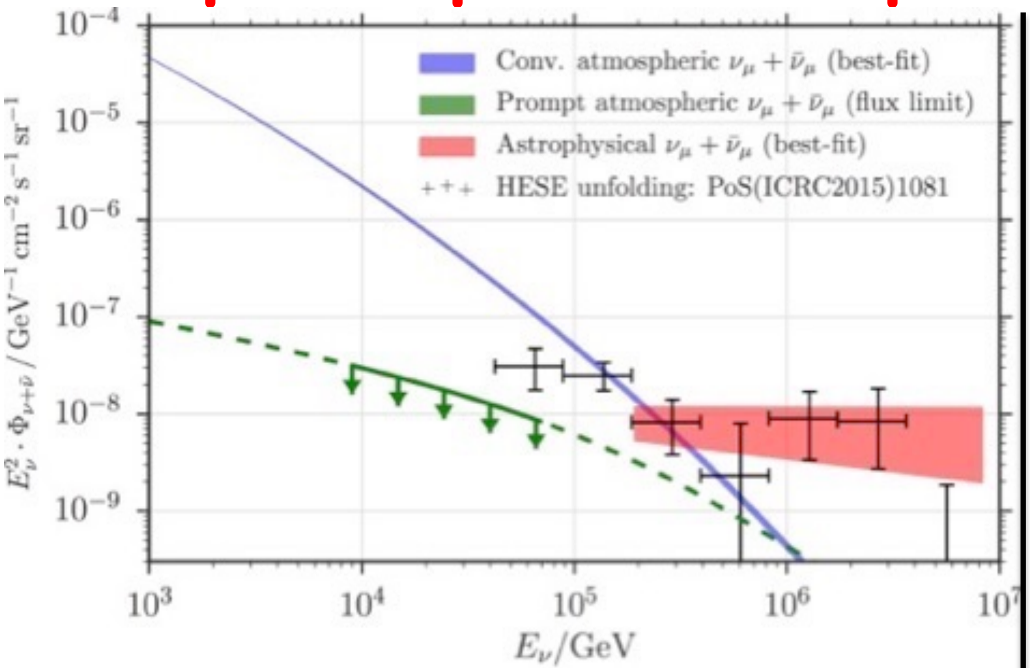

Conventional atmospheric $\nu_e + \bar{\nu}_e$ flux is lower but the statistics are poor

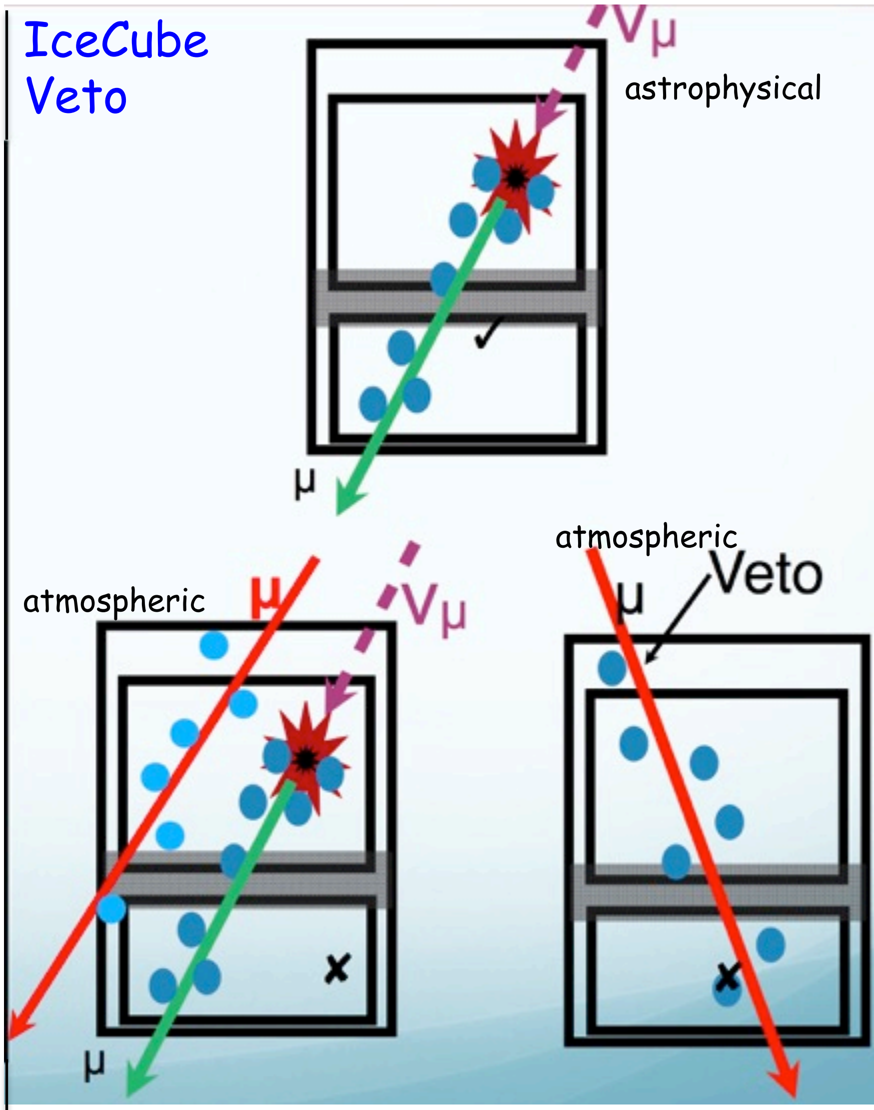
Conventional atmospheric $\nu_\mu + \bar{\nu}_\mu$ flux is higher but the statistics are larger

Present IceCube upper limits on atmospheric prompt neutrinos already constrain models of pQCD

Future limits on atmospheric prompt neutrinos will get stronger

# Astrophysical neutrinos v/s prompt atmospheric neutrinos




https://www.cppm.in2p3.fr/~brunner/2015/Labex-LAM-January/Talk_IceCube_Antares.pdf

## Difference in spectrum

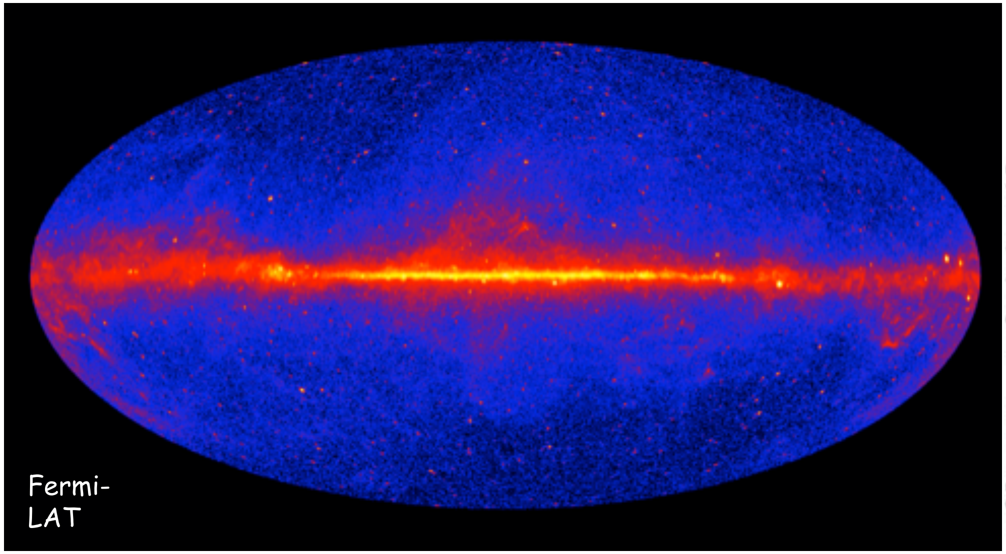
Astrophysical neutrinos have a harder spectrum compared to prompt atmospheric neutrinos

Conventional atmospheric $\nu_e$ spectrum is lower $\Rightarrow$ might be easier to search in that channel

# Conclusions

- High $x_F$ physics important for astroparticle experiments (see for e.g., 1601.03044, 1605.01409, 1701.08451)
- Prompt atmospheric neutrinos are an important signal for IceCube
- Intrinsic charm can have important contribution to the prompt atmospheric neutrinos
- IceCube can constrain the intrinsic charm of the proton

# Puzzling questions about the high energy astrophysical universe



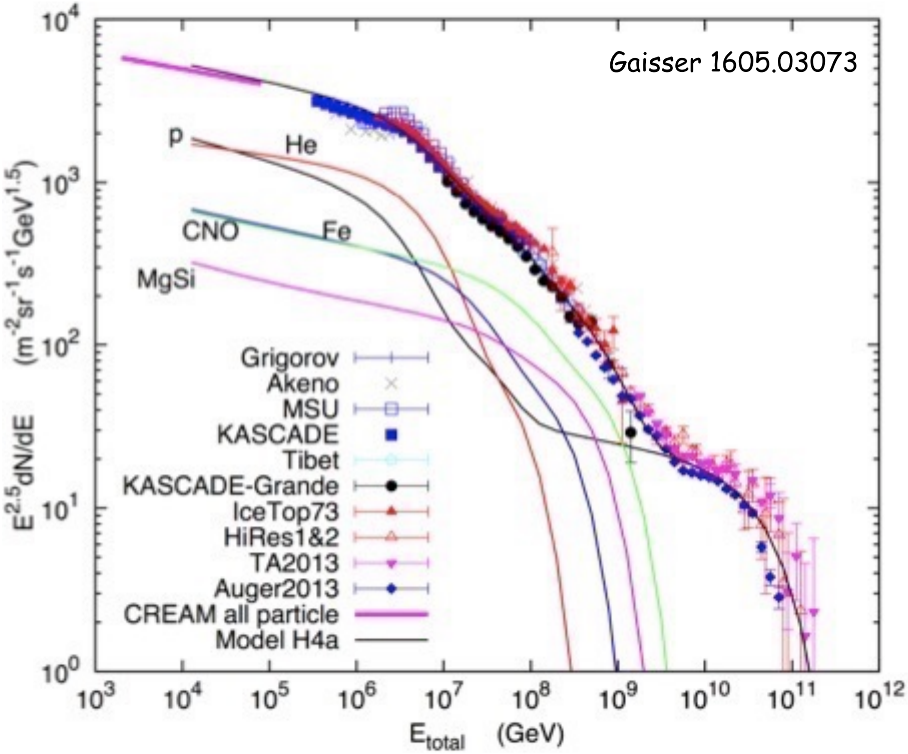

Gamma-ray sky: what process produces them?

Leptonic: $e^- + \gamma \rightarrow e^- + \gamma$

Hadronic: $p + p \rightarrow \pi^0 \rightarrow \gamma + \gamma$

$$p + p \rightarrow \pi/K + ... \rightarrow \nu/\bar{\nu}$$

The key difference are the neutrinos




Cosmic rays observed over a huge energy range

Neutrinos are inevitably produced in cosmic ray interactions

# Neutrinos as cosmic messengers

+ No deflection from source

+ Can escape from very dense sources

+ No interaction on the way from source to detector

+ Complementary to gamma-rays

.....

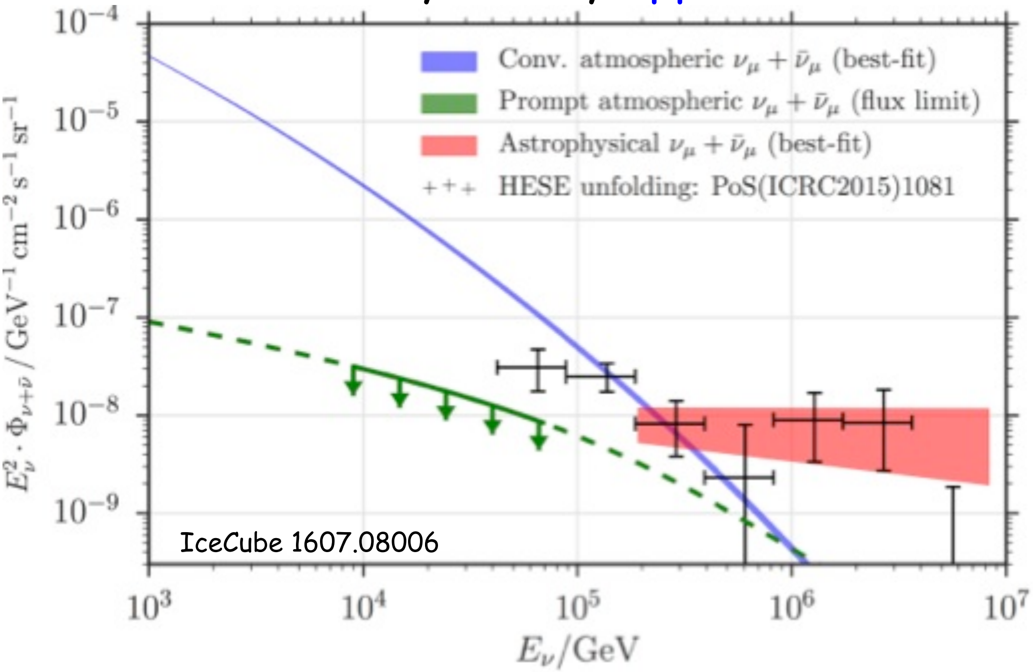
- Large detectors required

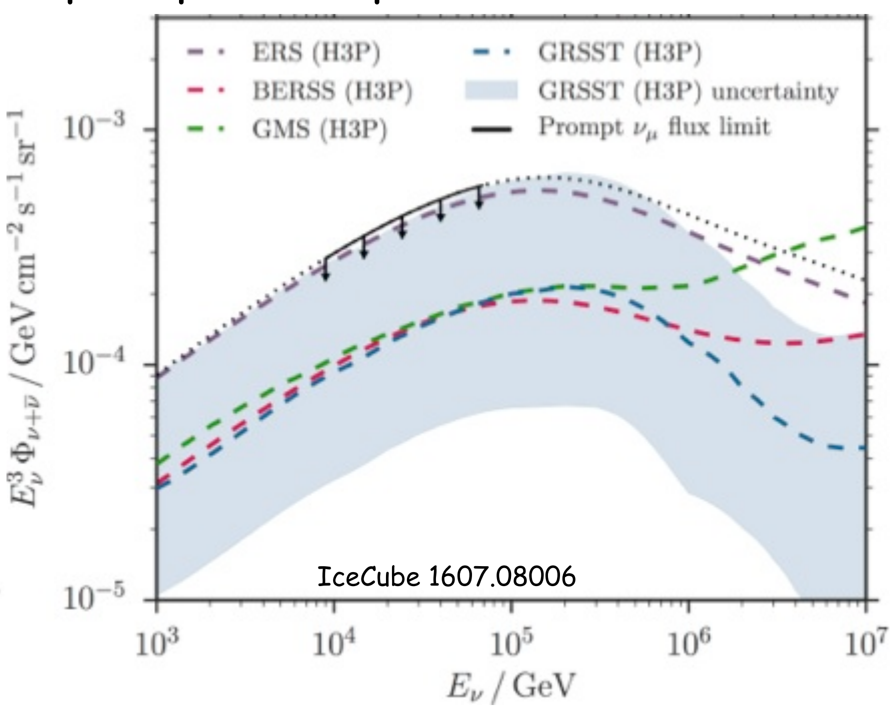
- Very long time required to collect signal

.....

# Prompt atmospheric neutrinos

No detection yet, only upper limits exist on prompt atmospheric neutrinos




Upper limits are at the upper end of present perturbative QCD predictions

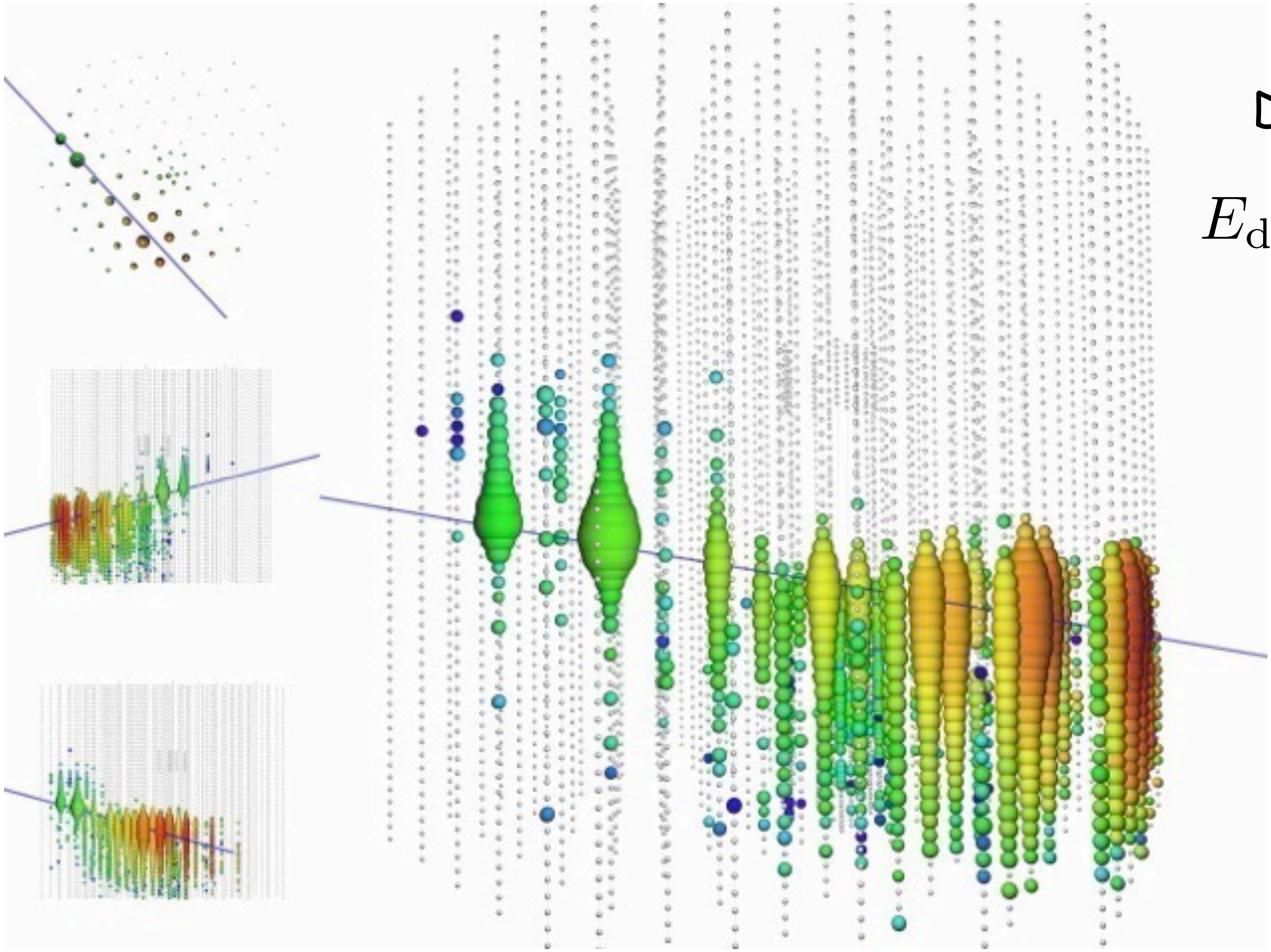
Already constrains mechanisms which predict a higher prompt atmospheric fluxes

The lower and higher energy neutrino spectrum dominated by conventional atmospheric neutrinos and astrophysical neutrinos respectively

Limits on the prompt atmospheric neutrinos depend on astrophysical neutrino flux modeling

# IceCube neutrino telescope

# Most energetic astrophysical neutrino event ever!!!



Deposited energy

$$E_{\rm dep} = 2.6 \pm 0.3\,{\rm PeV}$$

Where does it come from?

Does not correspond to any TeV source

Equatorial coordinates:
dec 11.42° RA 110.63°

IceCube 1607.08006

What is the energy of the parent neutrino?

Kistler & Laha 1605.08781

If $\nu_\mu$ produces this track, the neutrino energy is ~ 10 PeV

If $\nu_\tau$ produces this track, the neutrino energy is ~ 100 PeV

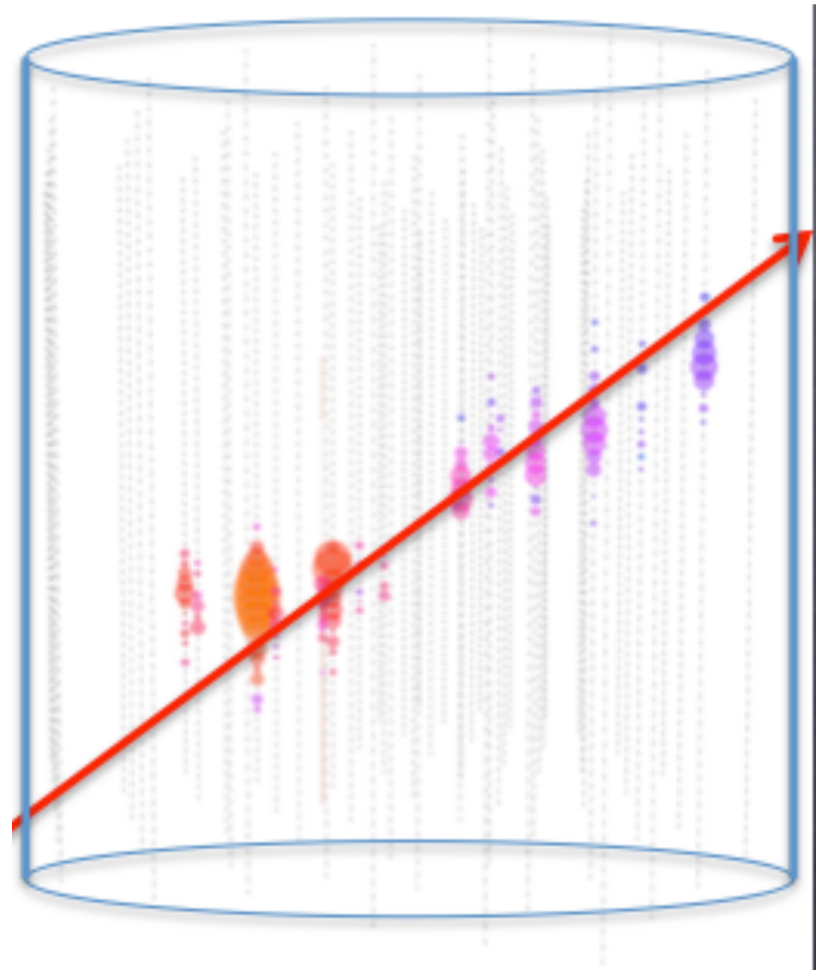
# Muon Tracks

Caused by muons produced in CC interaction of $\nu_\mu/\overline{\nu}_\mu$

+ Long range implies larger effective volume

+ Better Angular resolution ~ 1°

− Higher atmospheric neutrino backgrounds



$$\left.\frac{dN_\mu}{dE_\mu}\right|_{\rm tracks} = \frac{N_A\ \rho\ T\ A_{\rm det}}{\rho(\alpha+\beta E_\mu)} \times \int_{E_\mu}^{\infty} dE_\nu \frac{d\Phi_\nu}{dE_\nu}\sigma_{\rm CC}(E_\nu)e^{-\frac{L}{\lambda}}$$

# Cascades

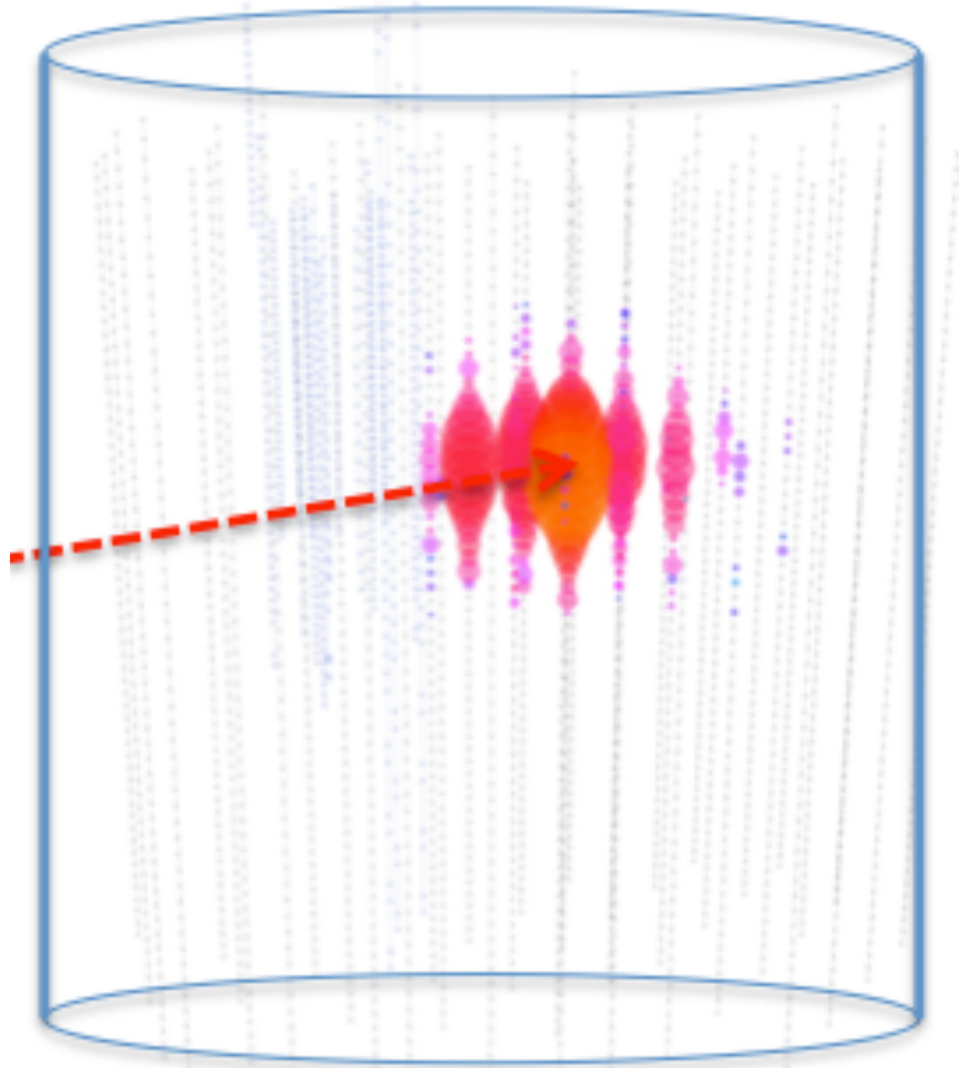
Caused by CC interactions of $\nu_e/\nu_\tau$ and their antiparticles and NC interactions of neutrinos of all flavors

+ Calorimetric

+ Lower atmospheric neutrino background

− Smaller effective volume

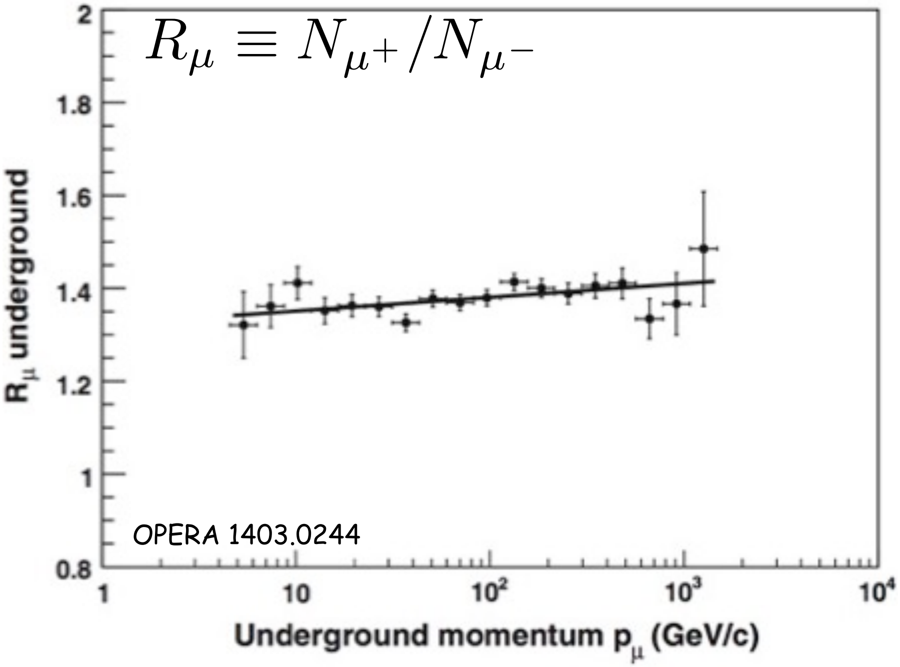
− Poor angular resolution ~ 50°

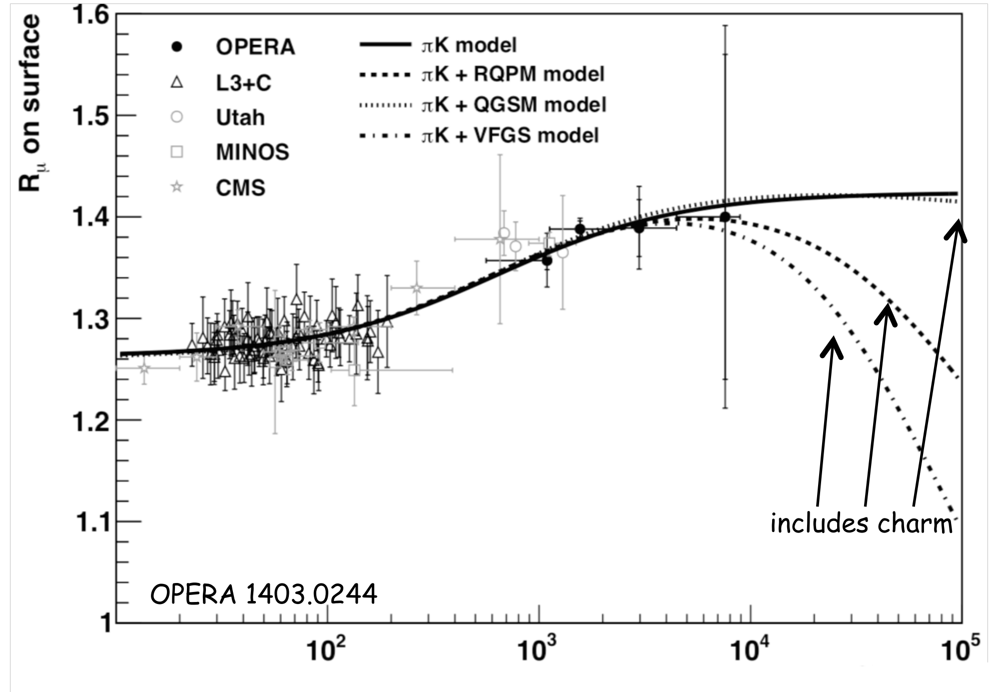


$$\left.\frac{dN_\nu}{dE_\nu}\right|_{\rm casc} = N_A\ T\ V_{\rm casc} \times \left(\sigma_{\rm CC}(E_\nu)\frac{d\Phi_{\nu_{e,\tau}}}{dE_\nu} + \sigma_{\rm NC}(E_\nu)\frac{d\Phi_{\nu_{e,\mu,\tau}}}{dE_\nu}\right)$$

# Atmospheric muon charge ratio and high $x_F$ physics

# Atmospheric muon charge ratio




$$\mathrm{CR} + \mathrm{air} \to \pi^\pm/K^\pm ... \to \mu^\pm\, \nu_\mu/\bar{\nu}_\mu$$

Muon energy at the surface $\longrightarrow$ $\varepsilon_\mu \cos\theta^*$ (GeV)

Zenith angle at the muon production point

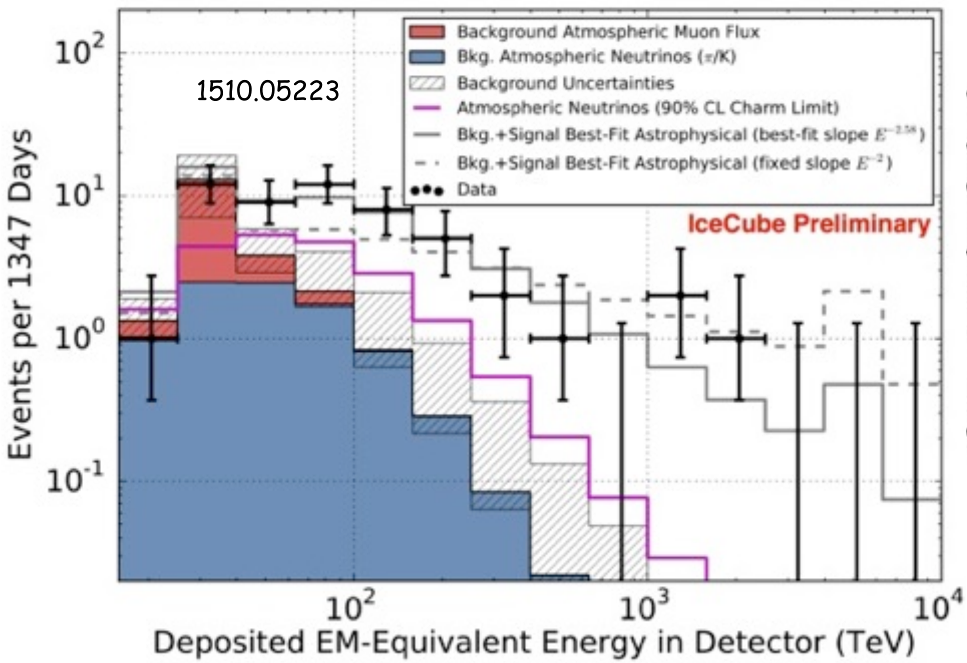
Sensitive probe of cosmic ray physics and hadronic interactions

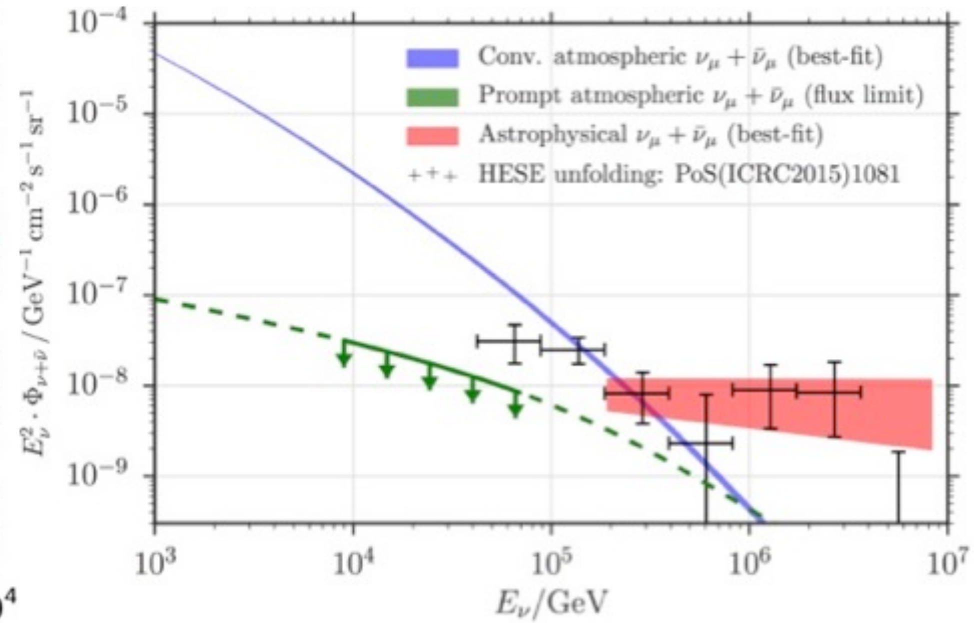
Plateau implies asymptotic kaon contribution $\Rightarrow$ validity of Feynman scaling up to primary energies/ nucleon around 200 TeV

Associated production of $\Lambda K^+$ important; no analogue for $K^-$; constrains the cross section in the high $x_F$ region ( difficult to probe via laboratory experiments ) Gaisser 1111.6675

Interplay of high $x_F$ physics and astroparticle experiments

# IceCube data




Diffuse spectrum of neutrinos

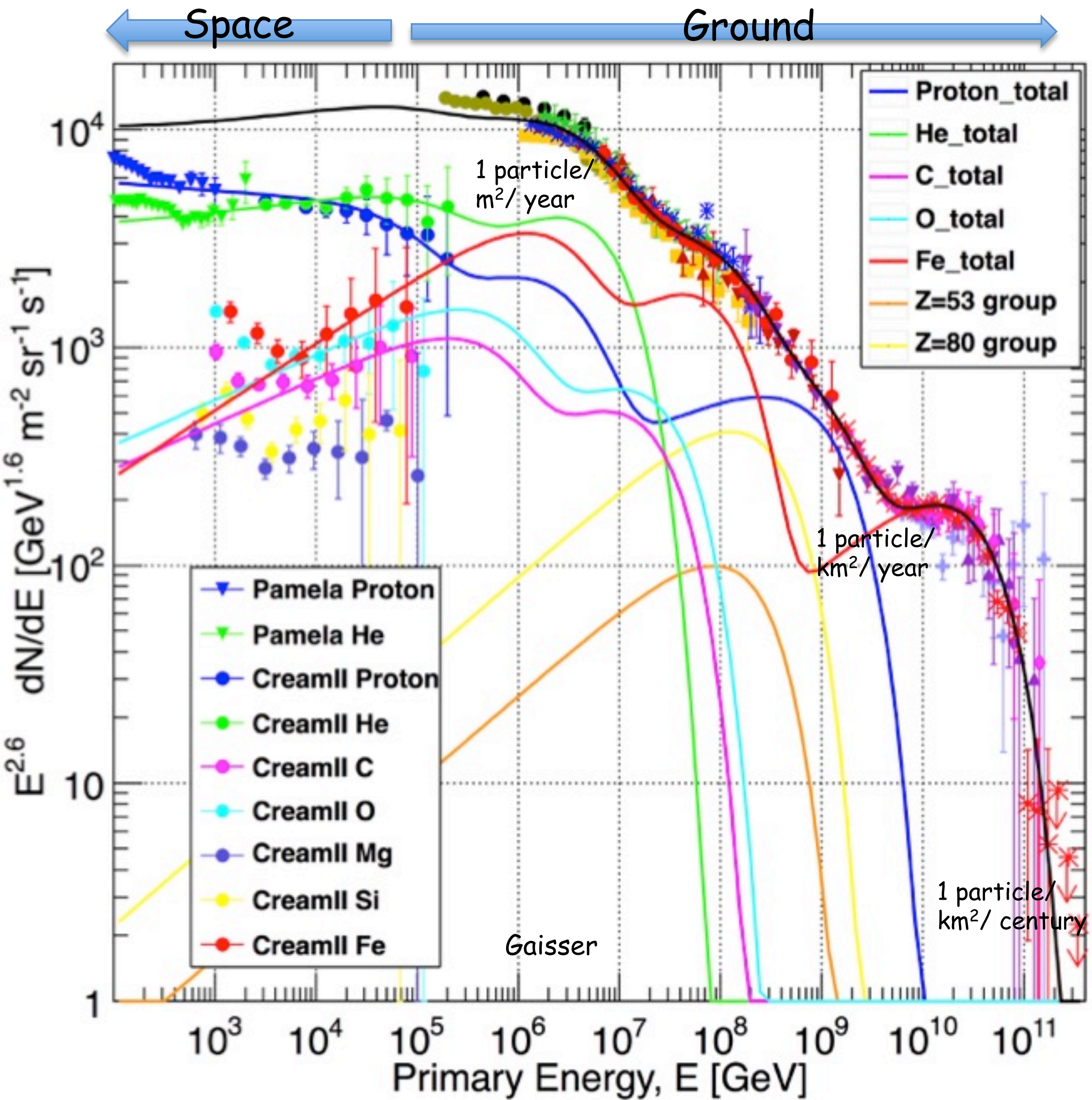
Time-independent

Clear evidence of the astrophysical nature of these neutrinos

None of them point to a specific source

# Cosmic rays

# Observed spectrum of cosmic rays



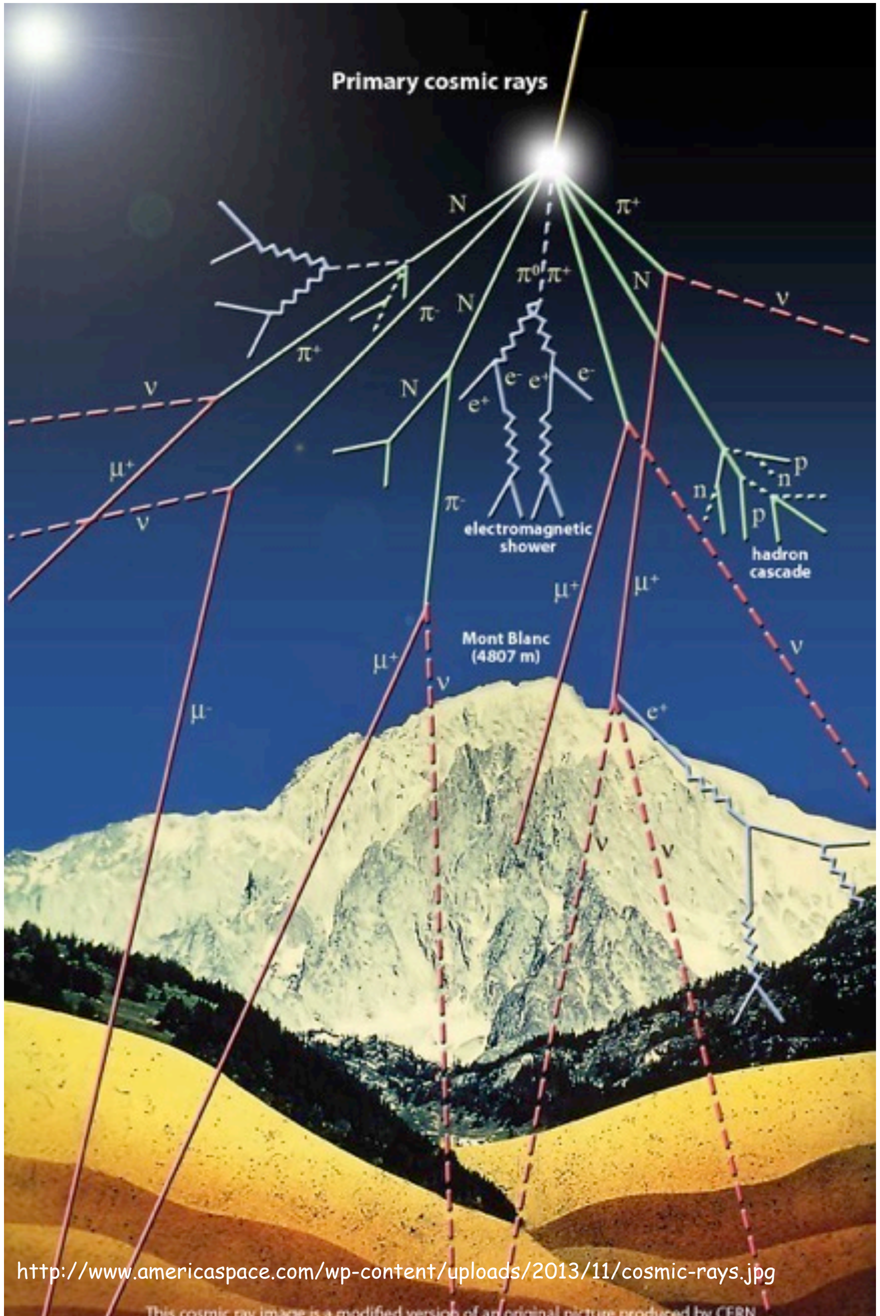

Spectrum of nuclei observed over many orders of magnitude in energy and flux

Observed via direct measurements (balloon/ space observatory) and air shower arrays

Tremendous amount of data to understand the acceleration mechanism

Knowledge of QCD needed to understand the interaction of cosmic rays with the atmosphere

# Cosmic ray interactions in the atmosphere




Cosmic ray interaction in the atmosphere is a fixed target experiment

Detailed knowledge of QCD required to understand the rates of various interaction products

Sensitive to QCD parameter space which is difficult to access in the laboratory

For e.g., for $E_\nu \approx 8000$ TeV, $\sqrt{s} \approx 20$ TeV

High energy pp interactions sensitive to gluon density in the small x ($\approx 10^{-8}$ – $10^{-4}$) region

Due to the flattish $d\sigma/dx_F$, intrinsic charm uses the incoming proton energy quite efficiently $\Rightarrow$ important since cosmic ray spectrum is falling