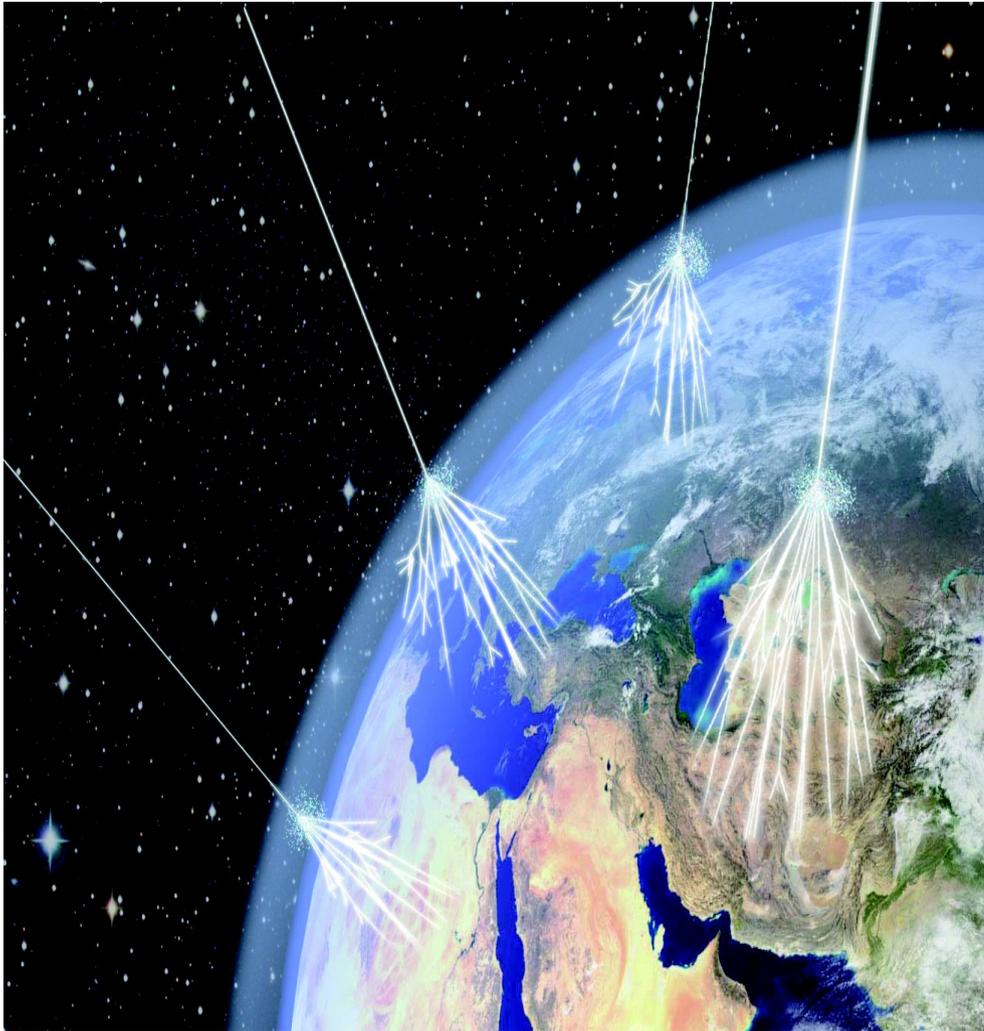


XIV International Workshop on Hadron Physics

18 – 23 March 2018
Florianópolis, SC, Brazil



Implications of hadronic interactions in the Cosmic Ray and Neutrino Physics

Victor P. Gonçalves

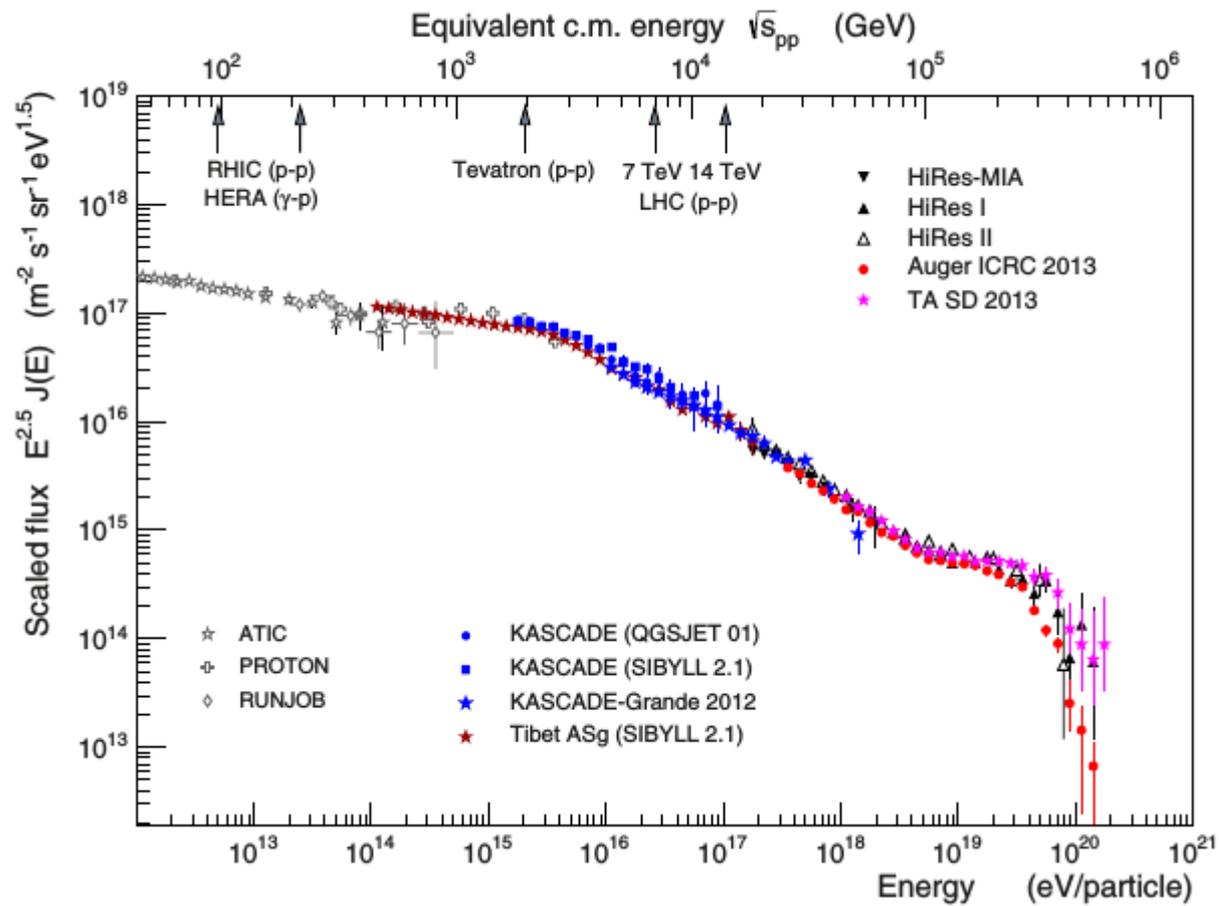
High and Medium Energy Group

Physics and Mathematics
Institute

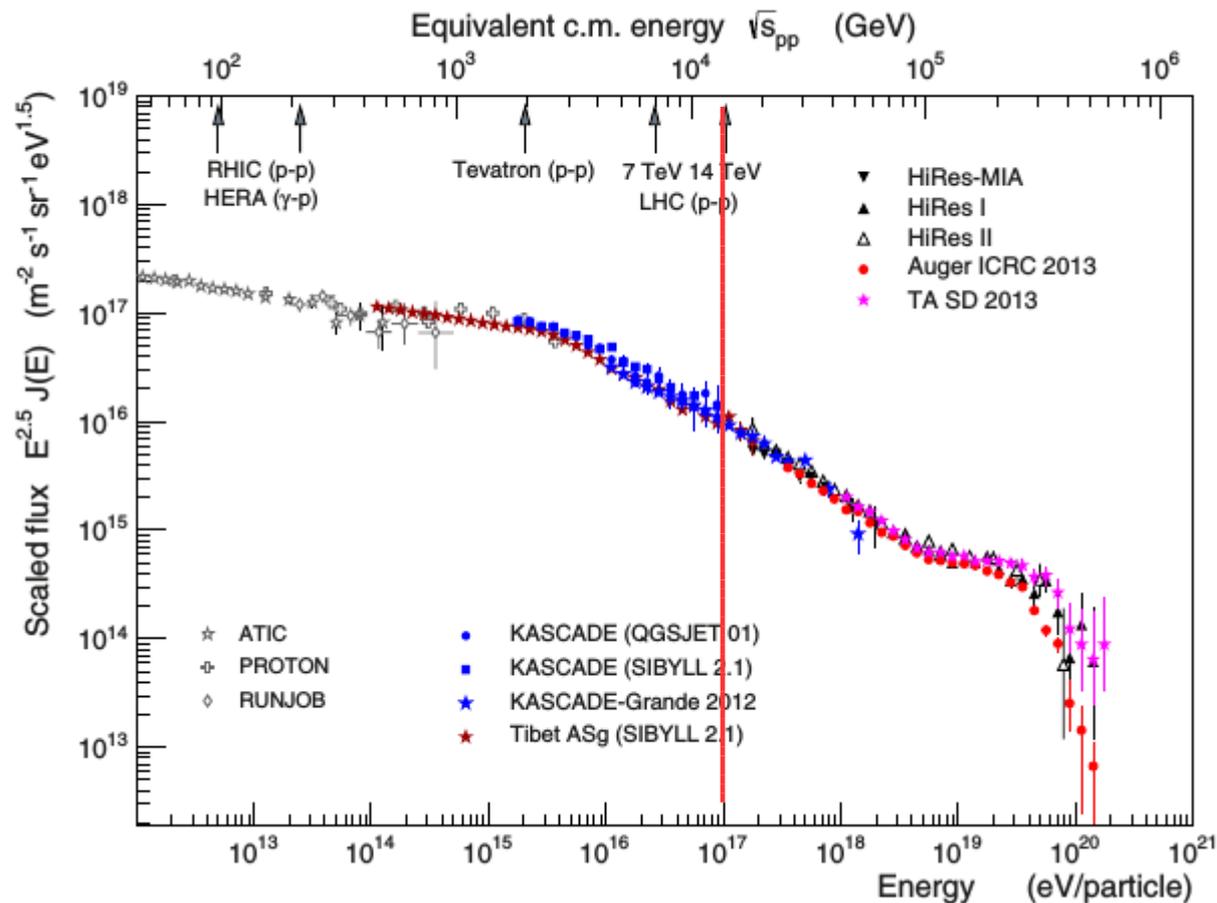
Federal University of Pelotas
(UFPEL)

Pelotas – RS – Brazil

Motivation

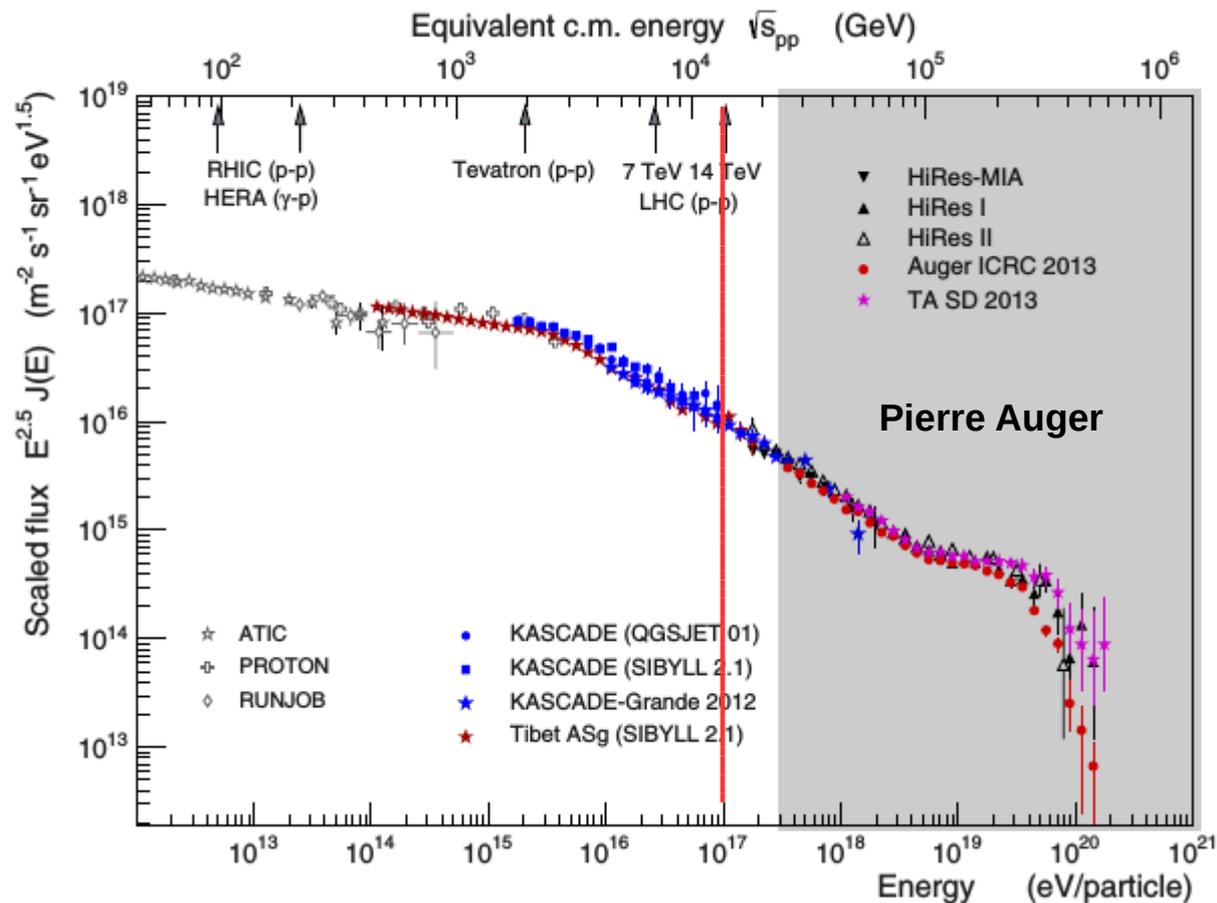


Motivation



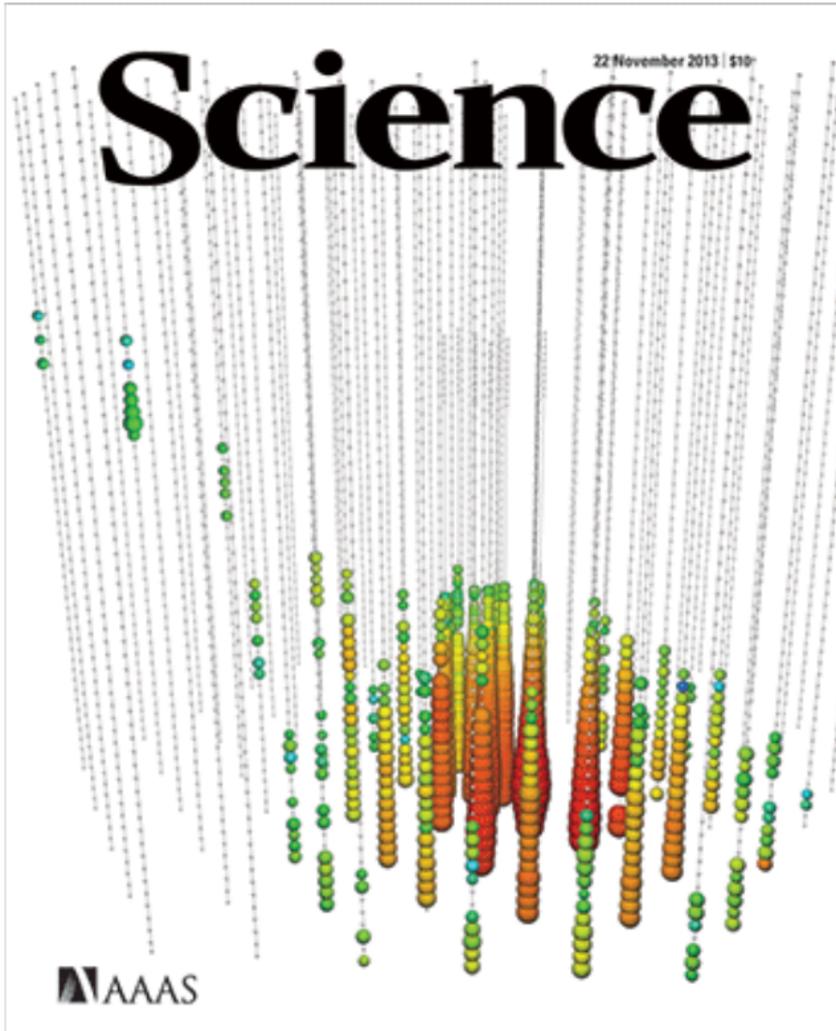
Cosmic Ray interactions probe the strong interactions in an energy range beyond the LHC.

Motivation



The description of the Auger data should take into account of new channels of particle production associated to processes with cross sections that increase with the energy (e.g. Heavy Quark production).

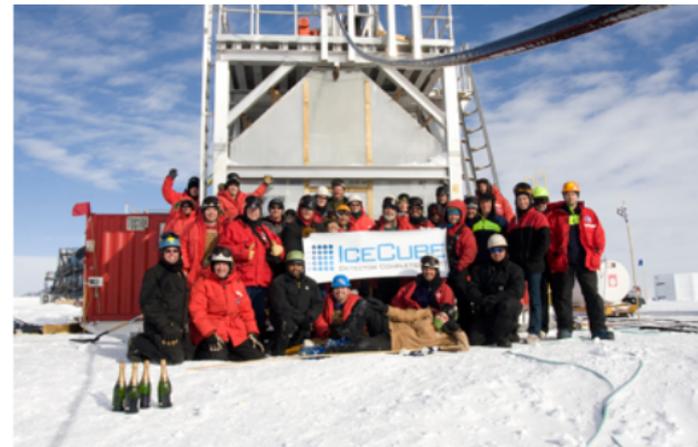
Motivation



Cosmic neutrinos named Physics World 2013 Breakthrough of the Year

Dec 13, 2013 [8 comments](#)

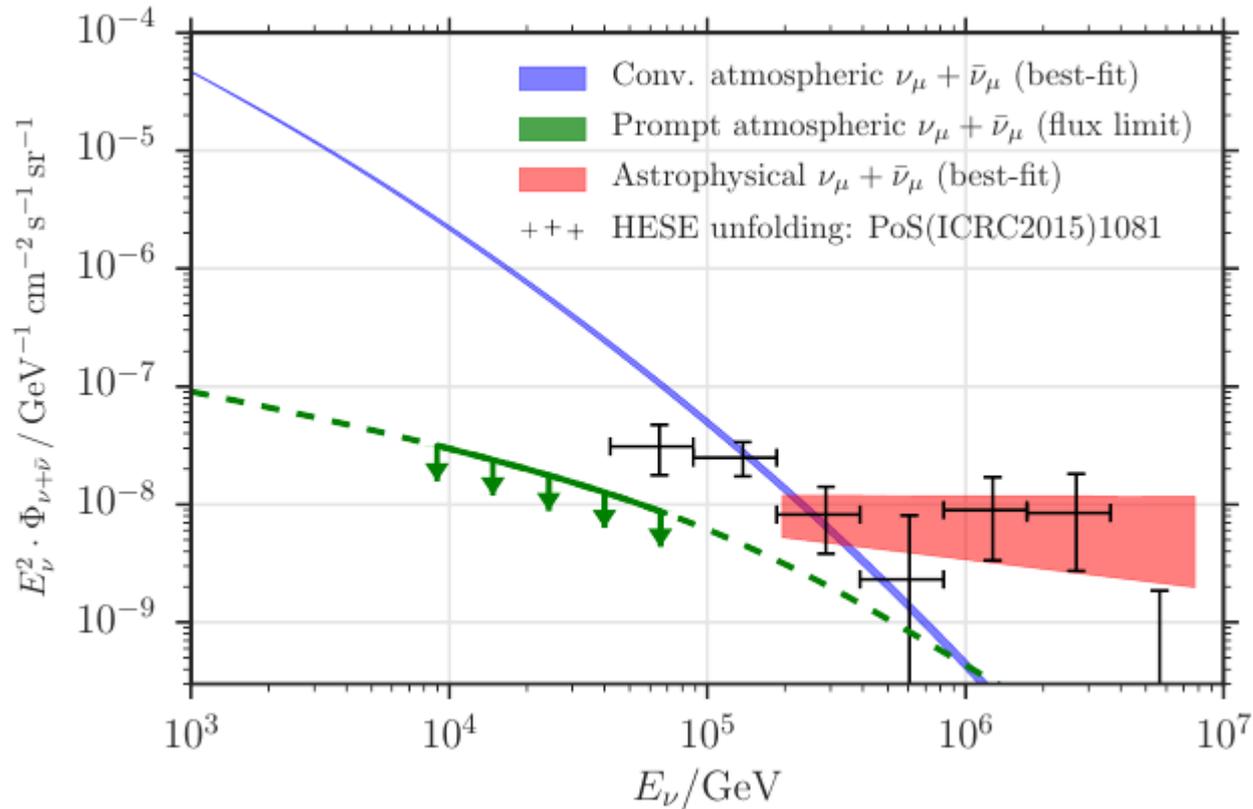
The *Physics World* award for the 2013 Breakthrough of the Year goes to "the [IceCube South Pole Neutrino Observatory](#) for making the first observations of high-energy cosmic neutrinos". Nine other achievements are highly commended and cover topics ranging from nuclear physics to nanotechnology



[Celebrating the completion of IceCube at the South Pole](#)

Motivation

IceCube 6 - year data:

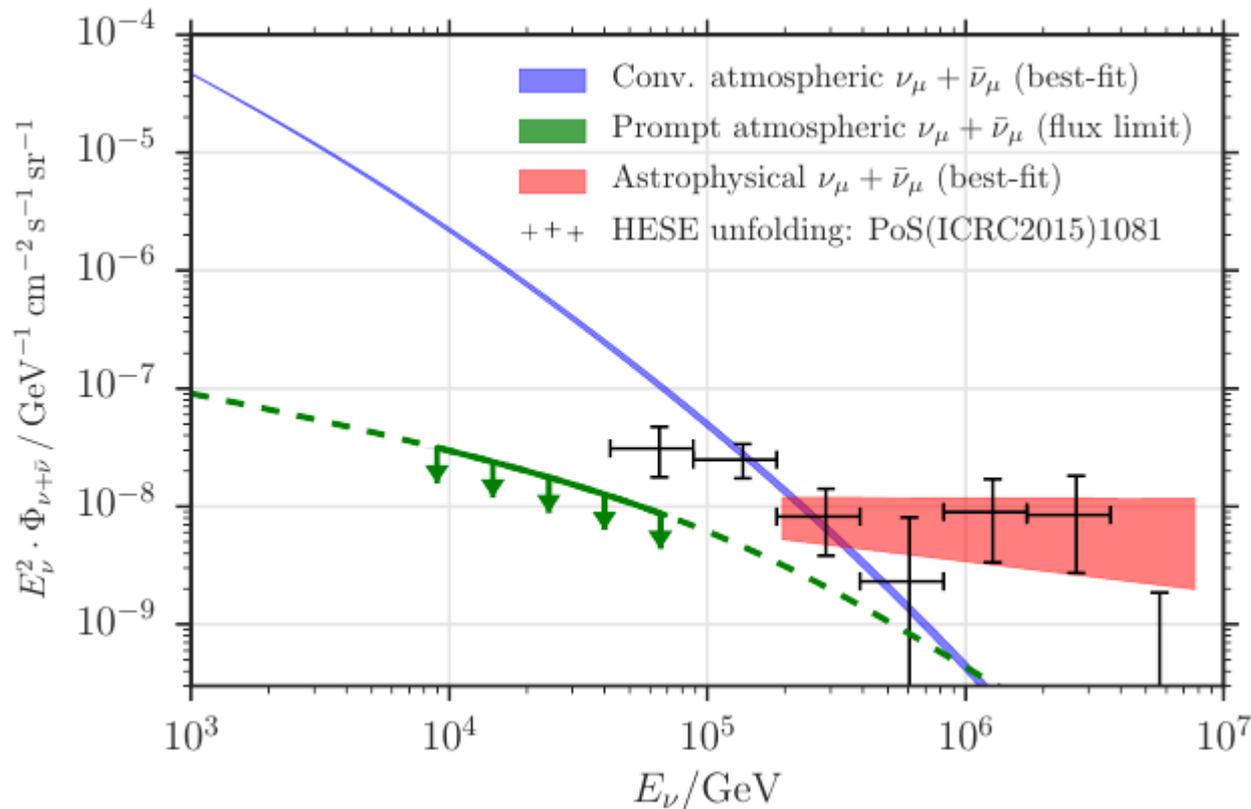


Main background for astrophysical neutrinos:

Flux of atmospheric (conventional + prompt) neutrinos

Motivation

IceCube 6 - year data:



Main background for astrophysical neutrinos:

Flux of atmospheric (conventional + prompt) neutrinos

The prompt contribution at given neutrino energy is determined by the heavy quark production in CR - Air collisions at energies that are a factor of 100 - 1000 larger.

Heavy quark production

- Heavy quark production provides a benchmark process for the study of perturbative QCD (pQCD).
- A quark is heavy if: $m_q \gg \Lambda_{QCD} \approx 250 \text{ MeV}$

$$m_q \gg \Lambda_{QCD} \Rightarrow \alpha_s(m_q^2) \propto \ln^{-1} \left(\frac{m_q^2}{\Lambda_{QCD}^2} \right) \ll 1$$

Perturbation theory (pQCD) is applicable !

charm: $m_c \approx 1.5 \text{ GeV} \Rightarrow \alpha_s(m_c^2) \approx 0.34$

bottom: $m_b \approx 4.5 \text{ GeV} \Rightarrow \alpha_s(m_b^2) \approx 0.22$

top: $m_t \approx 175 \text{ GeV} \Rightarrow \alpha_s(m_t^2) \approx 0.11$

Heavy quark production in ultra high energy cosmic ray interactions

VPG, D. R. Gratieri, *Astroparticle Physics* 61 (2015) 41

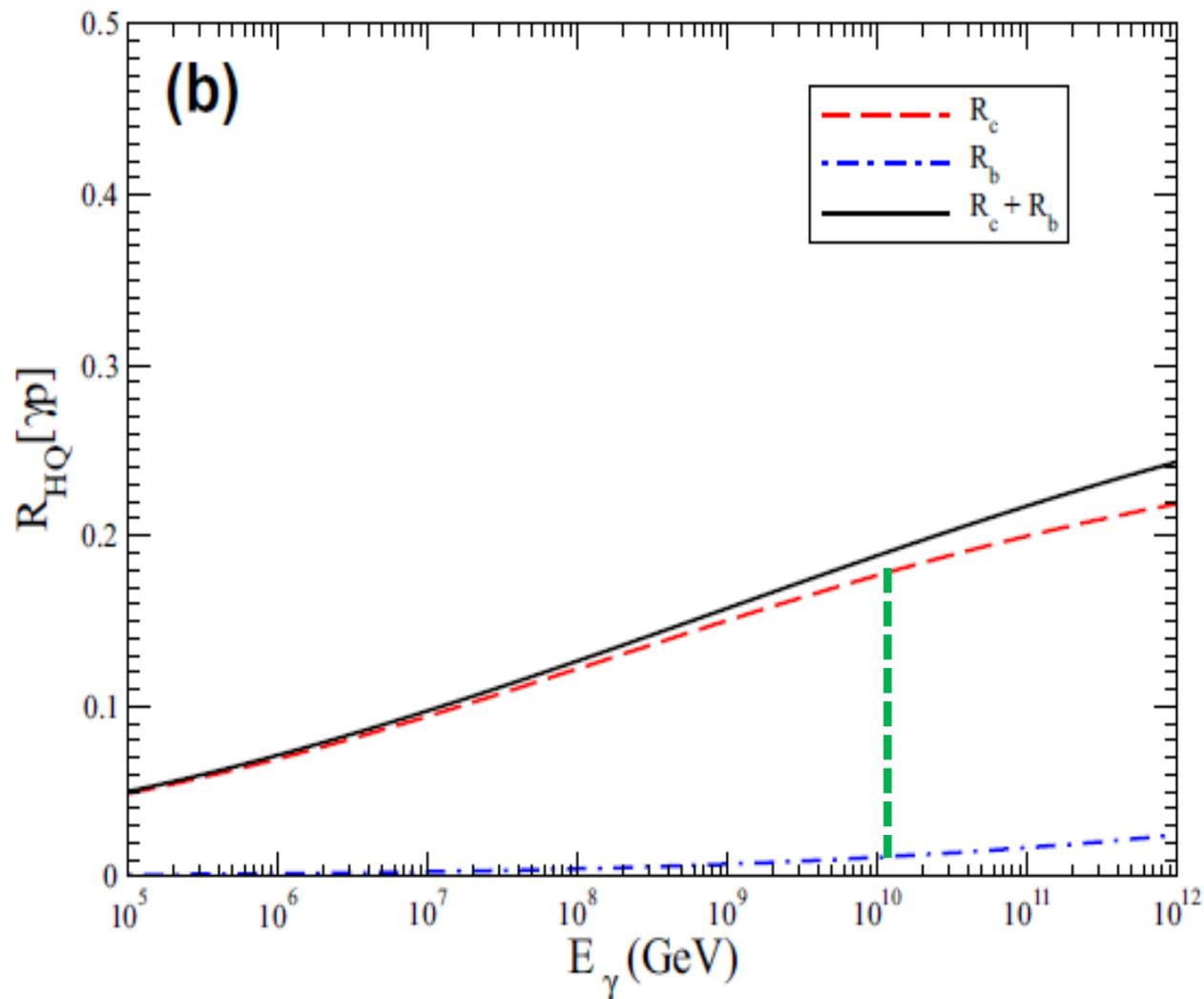
Heavy quark production in ultra high energy cosmic ray interactions (*)

- In order to estimate the heavy quark contribution for the total cross sections at ultra high energy cosmic ray energies interactions, in what follows we present our predictions for the ratio:

$$R_{HQ}[ip] = \frac{\sigma_{HQ}^{ip}}{\sigma_{tot}^{ip}}$$

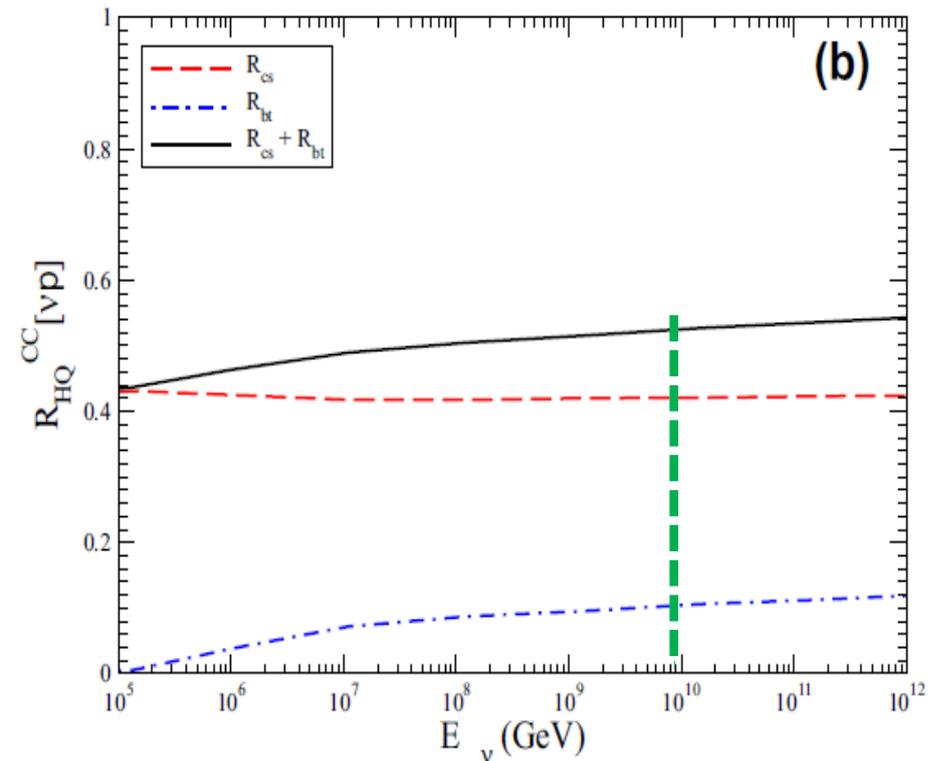
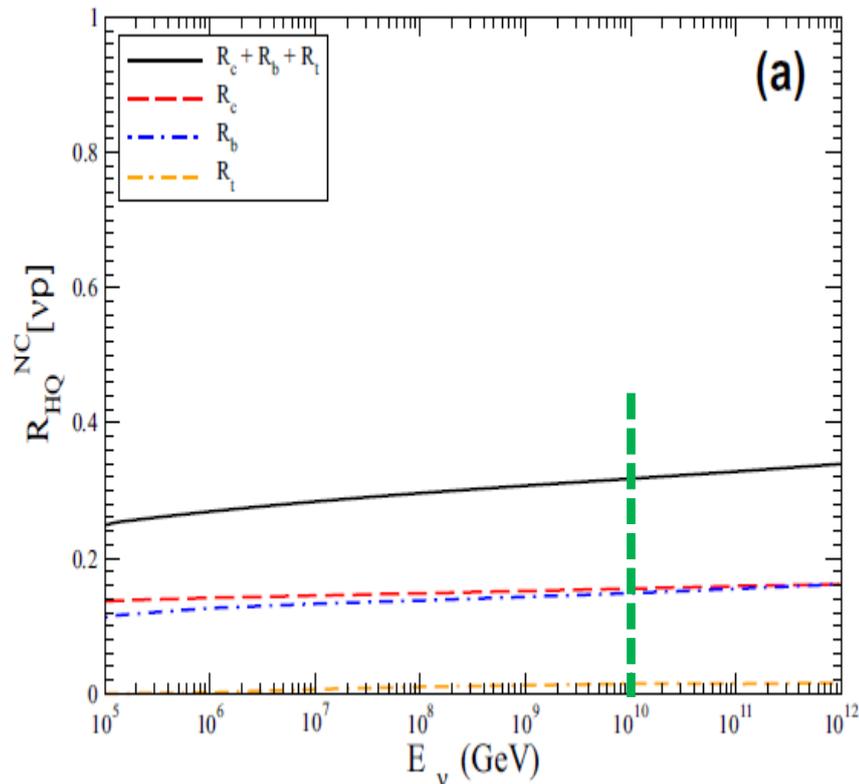
where "i" characterizes the primary cosmic ray, which can be a **photon**, **neutrino** or a **proton**.

Heavy quark production in photon - hadron interactions at ultra high energies



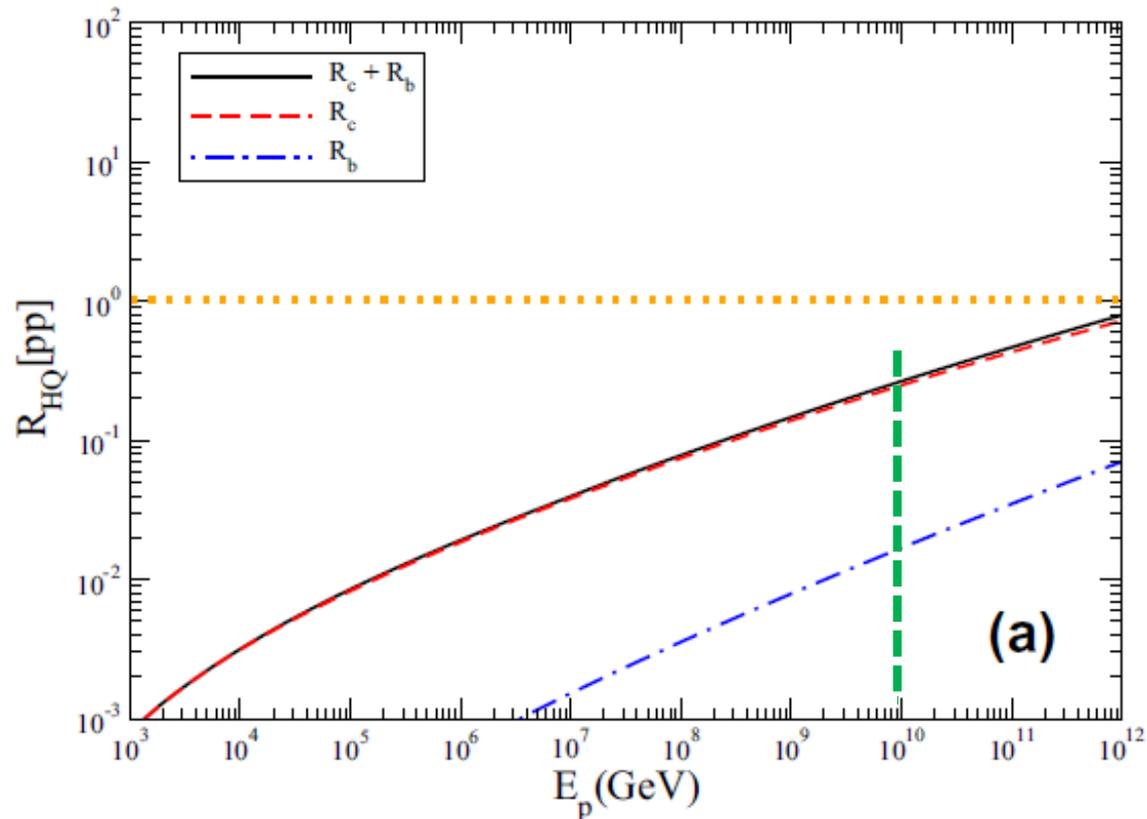
The total heavy quark contribution increases with the photon energy and becomes larger than 20 % at high energies.

Heavy quark production in neutrino - hadron interactions at ultra high energies



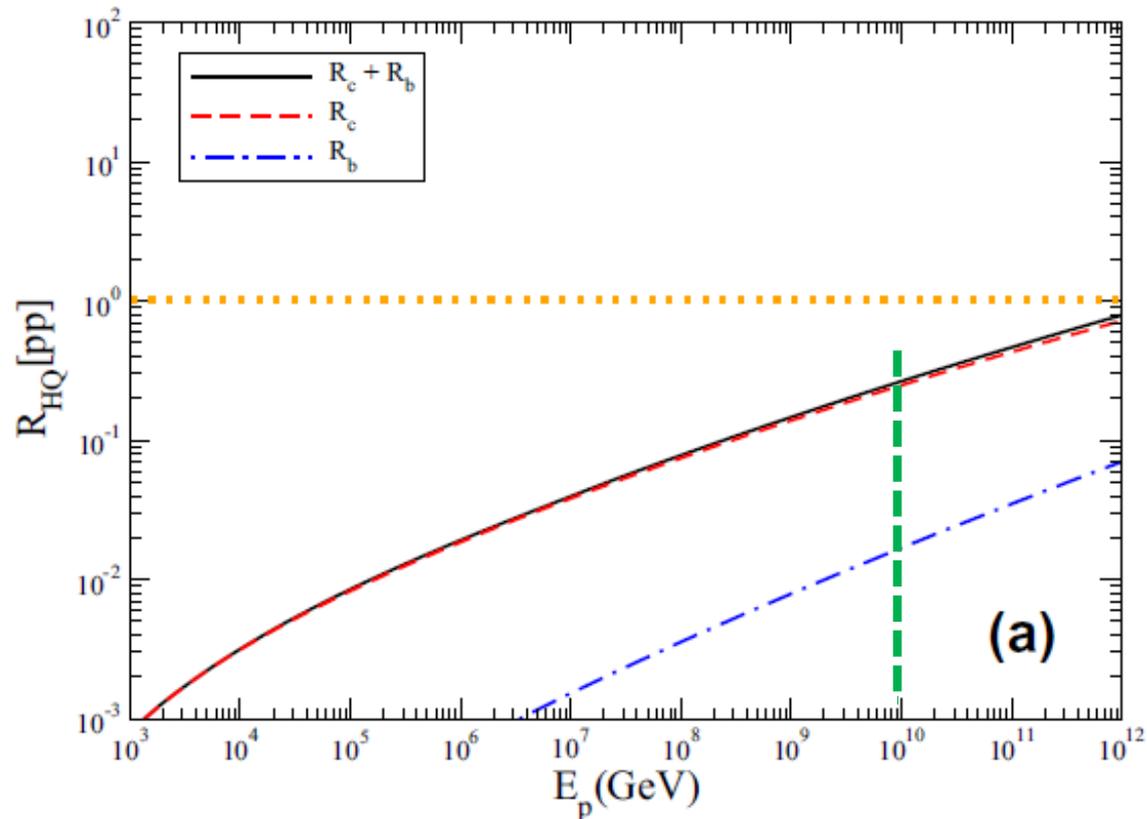
The total heavy quark contribution increases with the neutrino energy and becomes larger than 30 (50) % in neutral (charged) current interactions at high energies.

Heavy quark production in hadron - hadron interactions at ultra high energies



The total heavy quark contribution increases with the proton energy and becomes larger than 30 % at high energies.

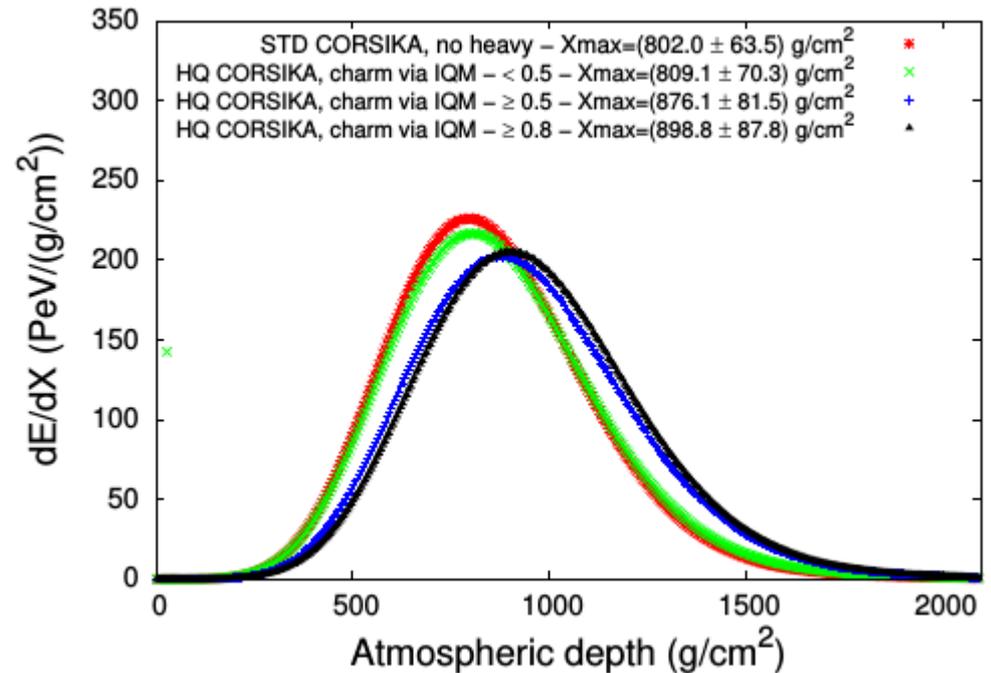
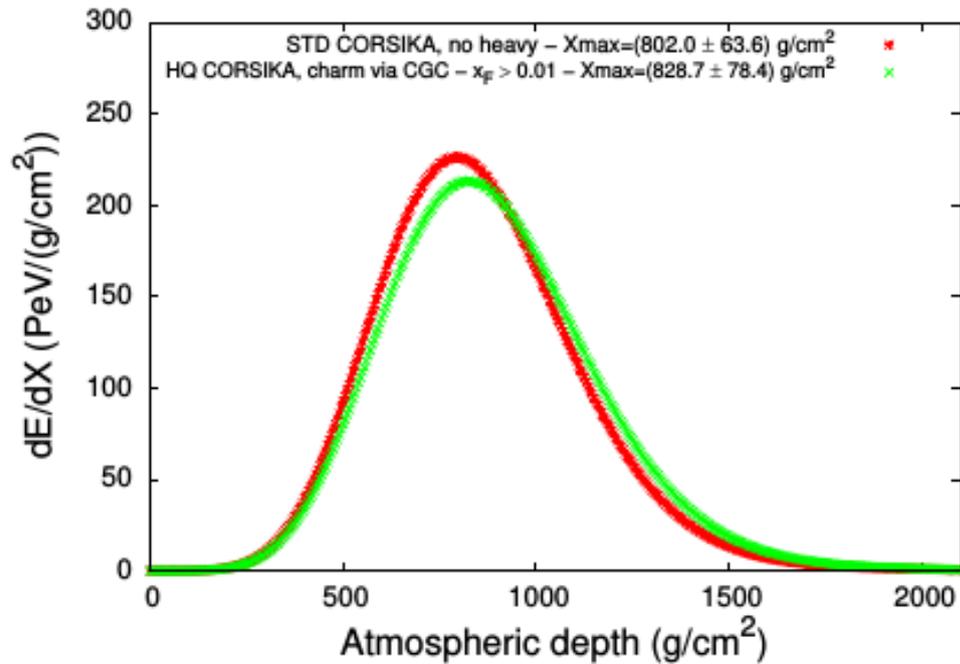
Heavy quark production in hadron - hadron interactions at ultra high energies



Main conclusion: The contribution of the heavy quark contribution cannot be disregarded in the description of the air showers at high energies.

Theoretical expectation: The presence of heavy particles in the shower should to modify the characteristics of the air showers and the magnitude of the flux of neutrinos and muons, generated when they decay.

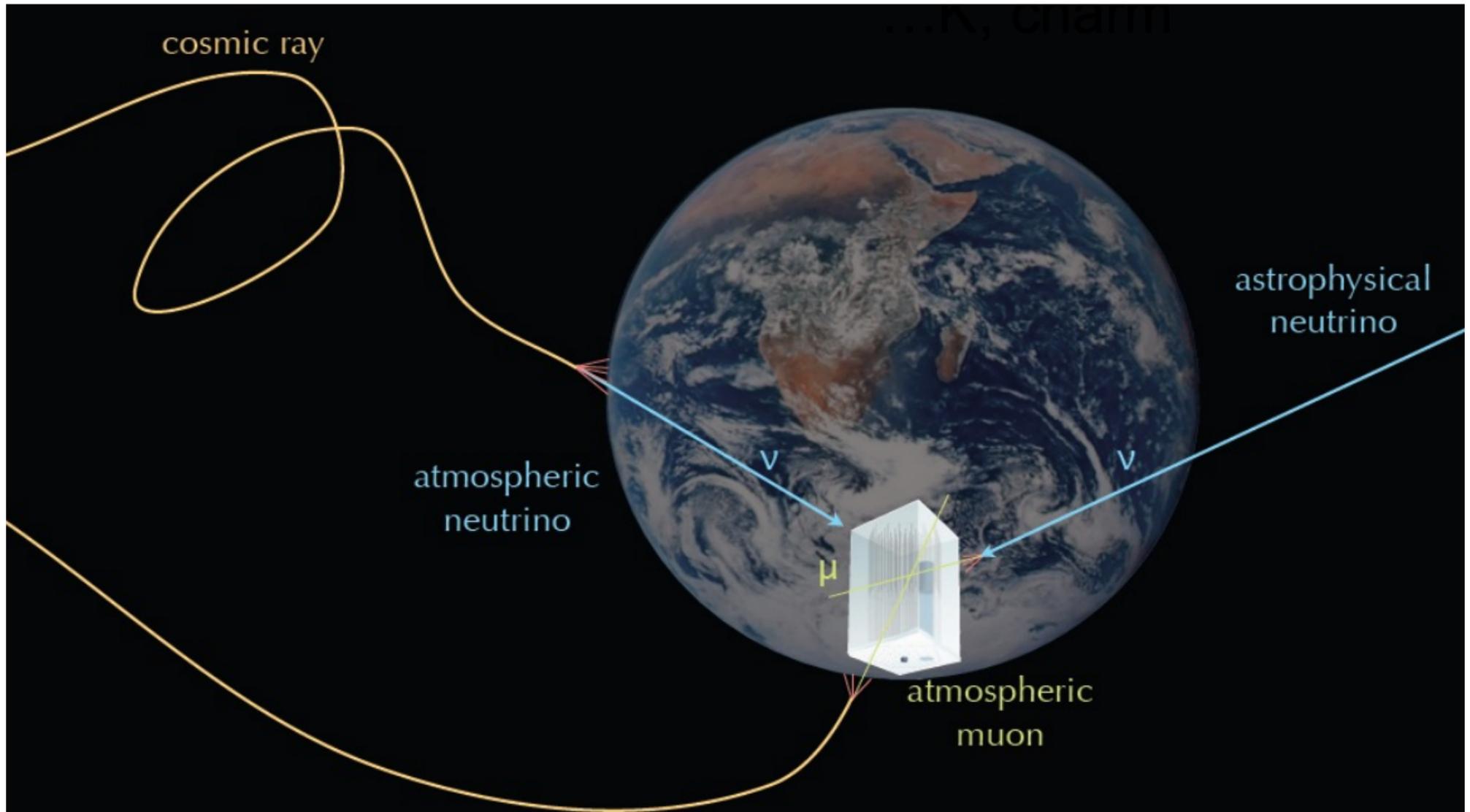
Impact of the heavy quark production on Extensive Air Showers



Mapping the dominant regions of the phase space associated with the $c\bar{c}$ production relevant for the atmospheric neutrino flux

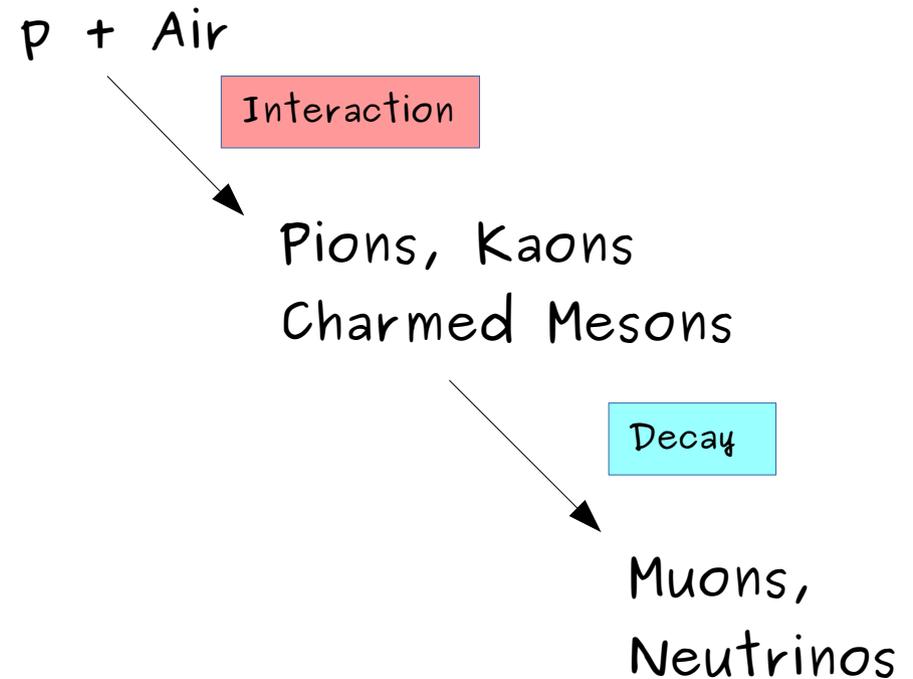
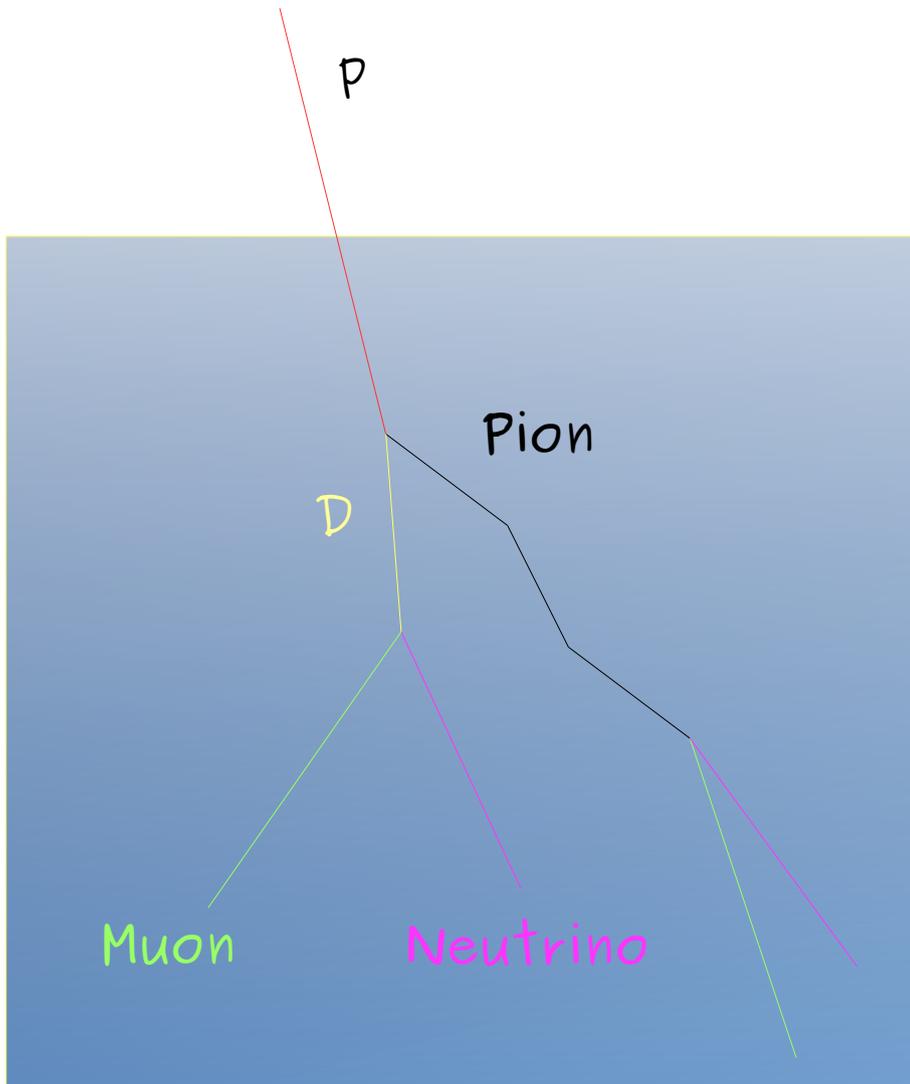
VPG, R. Maciula, R. Pasechnik, A. Szczurek, PRD 96 (2017) 094026

Neutrinos at IceCube



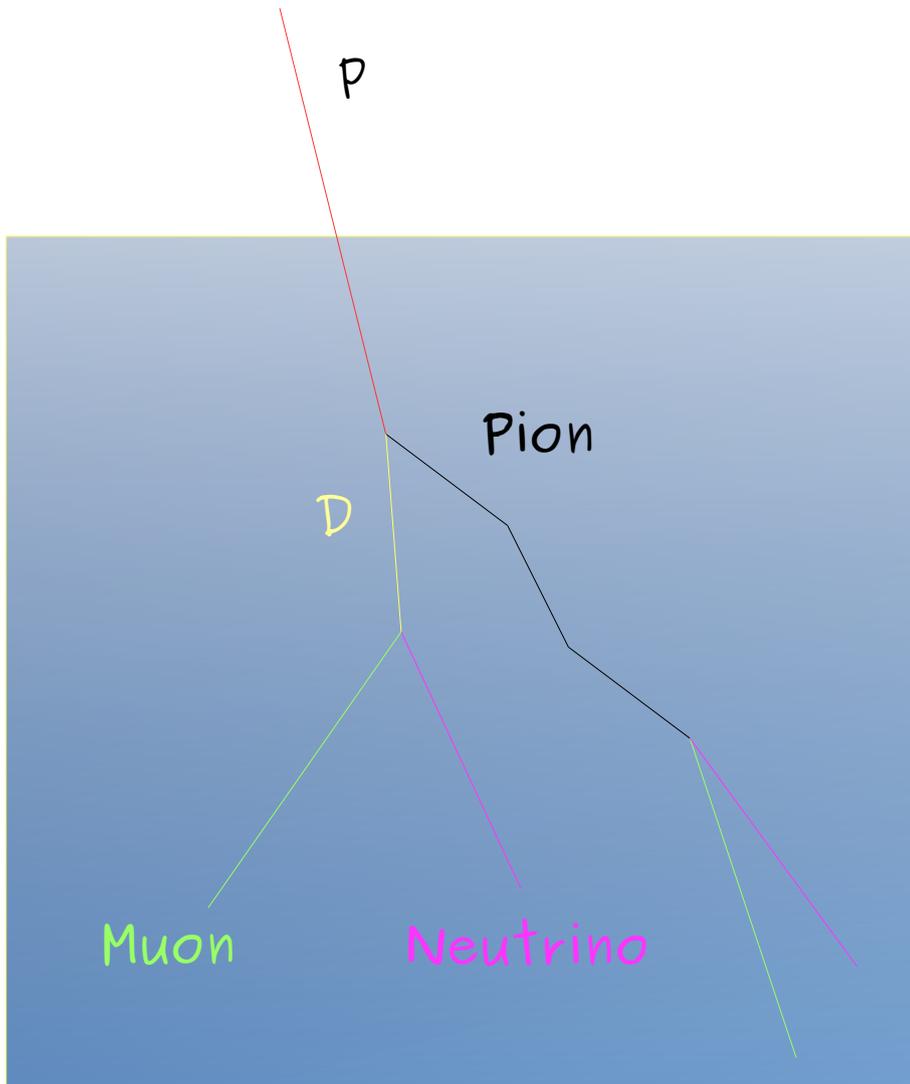
Atmospheric Neutrinos

Neutrinos in atmosphere originate from the interactions of cosmic rays with nuclei ($\langle A \rangle = 14.5$).



Atmospheric Neutrinos

Neutrinos in atmosphere originate from the interactions of cosmic rays with nuclei ($\langle A \rangle = 14.5$).



$p + \text{Air}$

Interaction

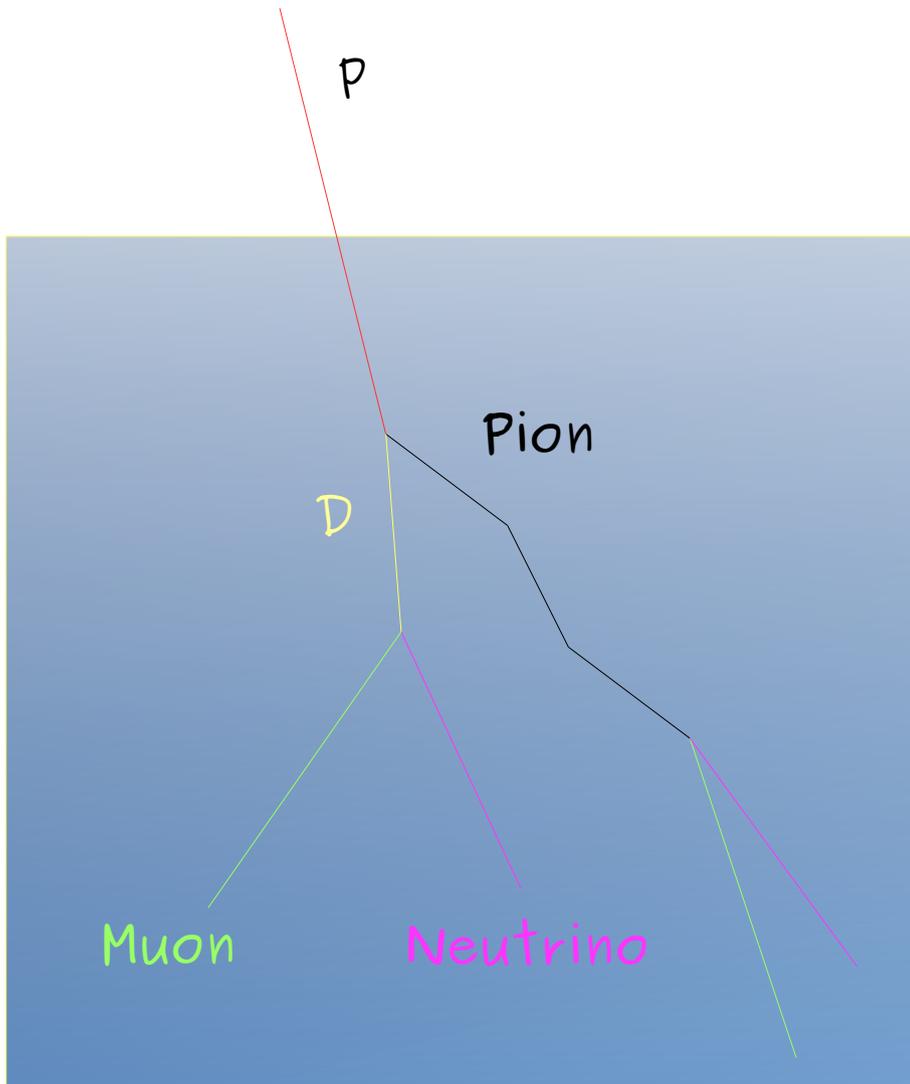
Pions, Kaons
Charmed Mesons

Decay

Conventional
Neutrinos

Atmospheric Neutrinos

Neutrinos in atmosphere originate from the interactions of cosmic rays with nuclei ($\langle A \rangle = 14.5$).



$p + \text{Air}$

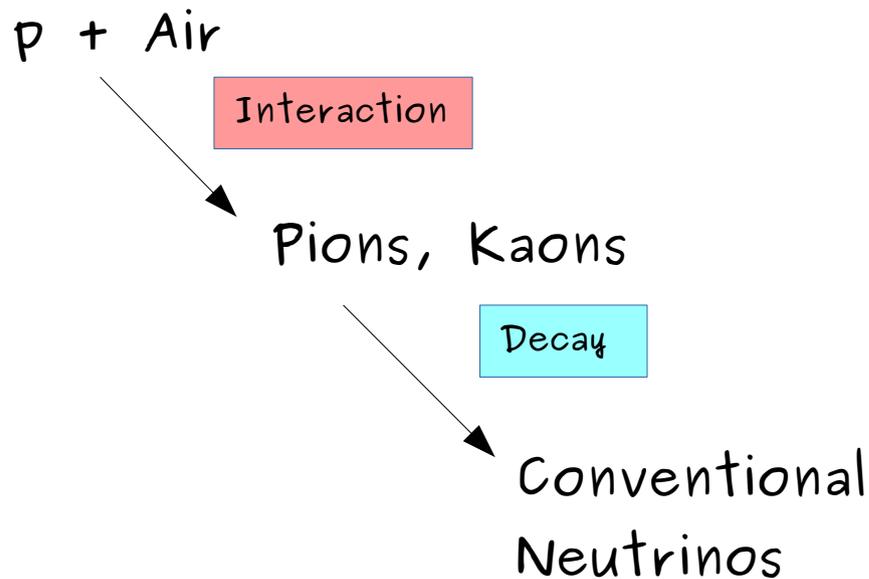
Interaction

Pions, Kaons
Charmed Mesons

Decay

Prompt
Neutrinos

Atmospheric Neutrinos: Conventional contribution



Light Mesons:

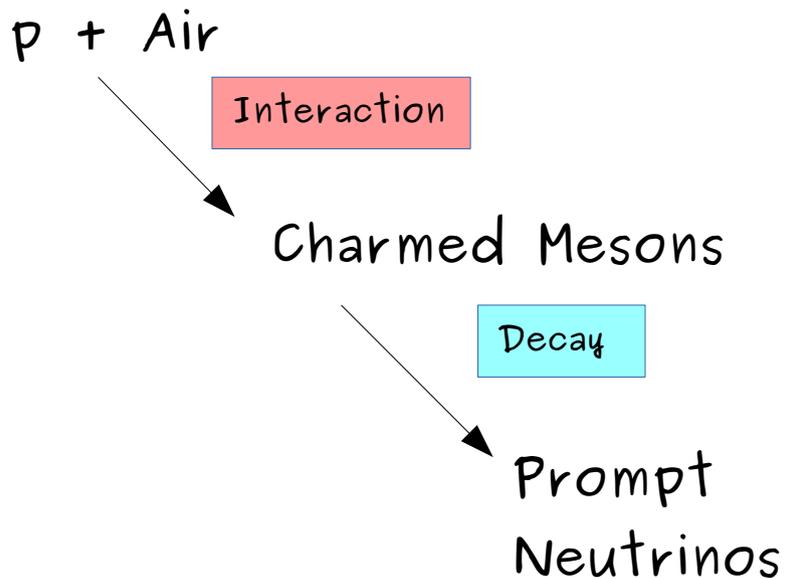
Mean lifetime: $\tau \sim 10^{-8} \text{ s}$

- Interaction occurs before decay and the mesons lose energy during the propagation.

- The neutrino flux has a steeply falling energy behaviour in comparison to the initial nucleon flux.

$$\Phi_\nu \sim E_\nu^{-3.7}$$

Atmospheric Neutrinos: Prompt contribution



Charmed Mesons:

Mean lifetime: $\tau \sim 10^{-12}$ s

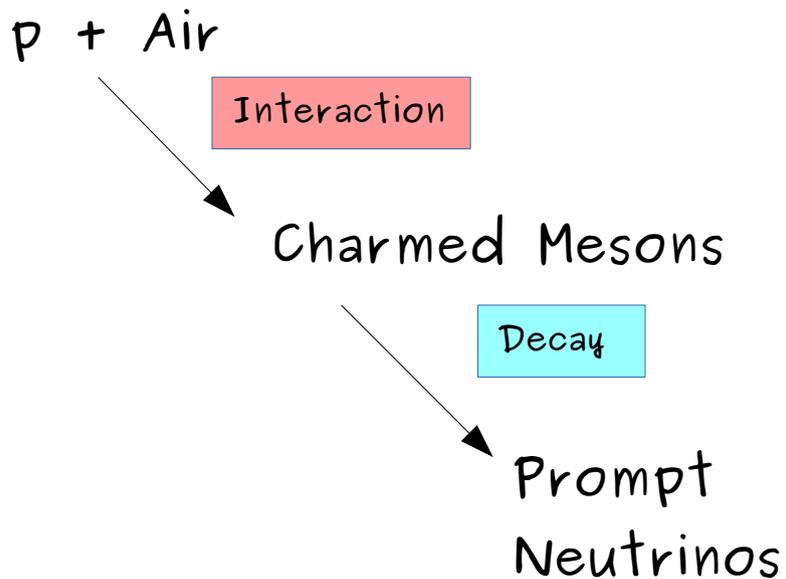
- Decay occurs before interaction and the mesons transfer its energy for the neutrinos.

- The prompt neutrino flux has a flatter energy behaviour in comparison to the conventional flux.

$$\Phi_\nu \sim E_\nu^{-2.7}$$

spectrum of primary CR and an isotropic zenith distribution.

Atmospheric Neutrinos: Prompt contribution



Charmed Mesons:

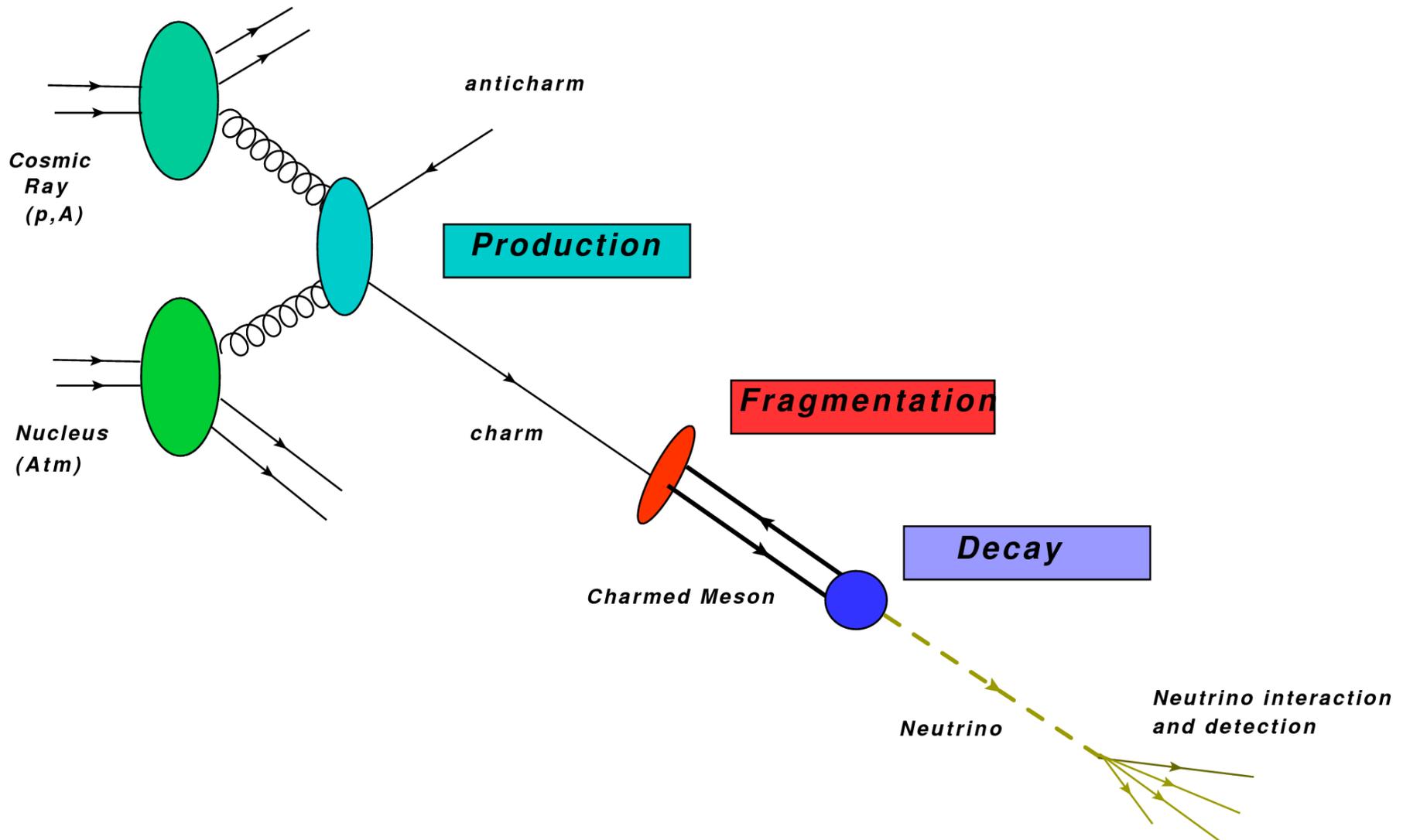
Mean lifetime: $\tau \sim 10^{-12} \text{ s}$

- Decay occurs before interaction and the mesons transfer its energy for the neutrinos.

- The prompt neutrino flux has a flatter energy behaviour in comparison to the conventional flux.

The prompt neutrino flux is expected to be the dominant contribution at high neutrino energies!

Atmospheric Neutrinos: Prompt contribution



Atmospheric Neutrinos:

Development of the air showers

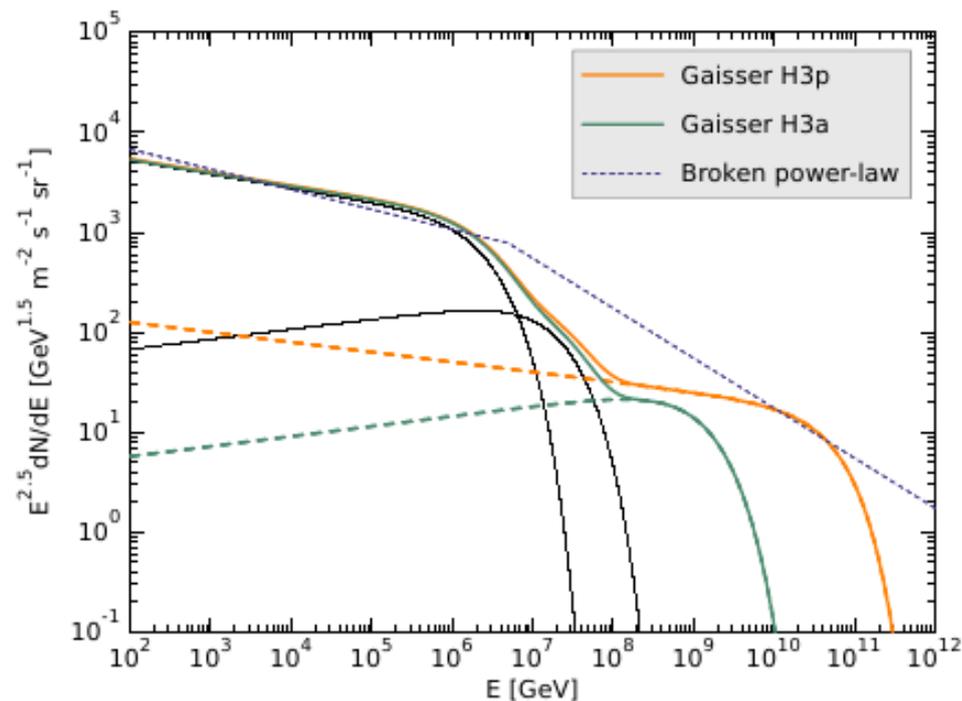
- In order to estimate the prompt neutrino flux we have to take into account the development of the air shower in the atmosphere, considering the production and decay of the different particles present in the shower.
- The cascade equations can be solved numerically or semi-analytically via the Z-moment method.
- Main inputs:
 - 1.) Initial nucleon flux
 - 2.) Feynman distribution for the charm production

$$Z_{pc}(E) = \int_0^1 \frac{dx_F \phi_p(E/x_F)}{x_F \phi_p(E)} \frac{1}{\sigma_{pA}(E)} \frac{d\sigma_{pA \rightarrow \text{charm}}(E/x_F)}{dx_F}$$

$$x_F \approx E_c/E_p = x_1 - x_2$$

$$x_2 \approx M_{Q\bar{Q}}^2/x_1 s \rightarrow 0 \quad \text{at } s \gg M_{Q\bar{Q}}^2$$

Initial Cosmic Ray flux

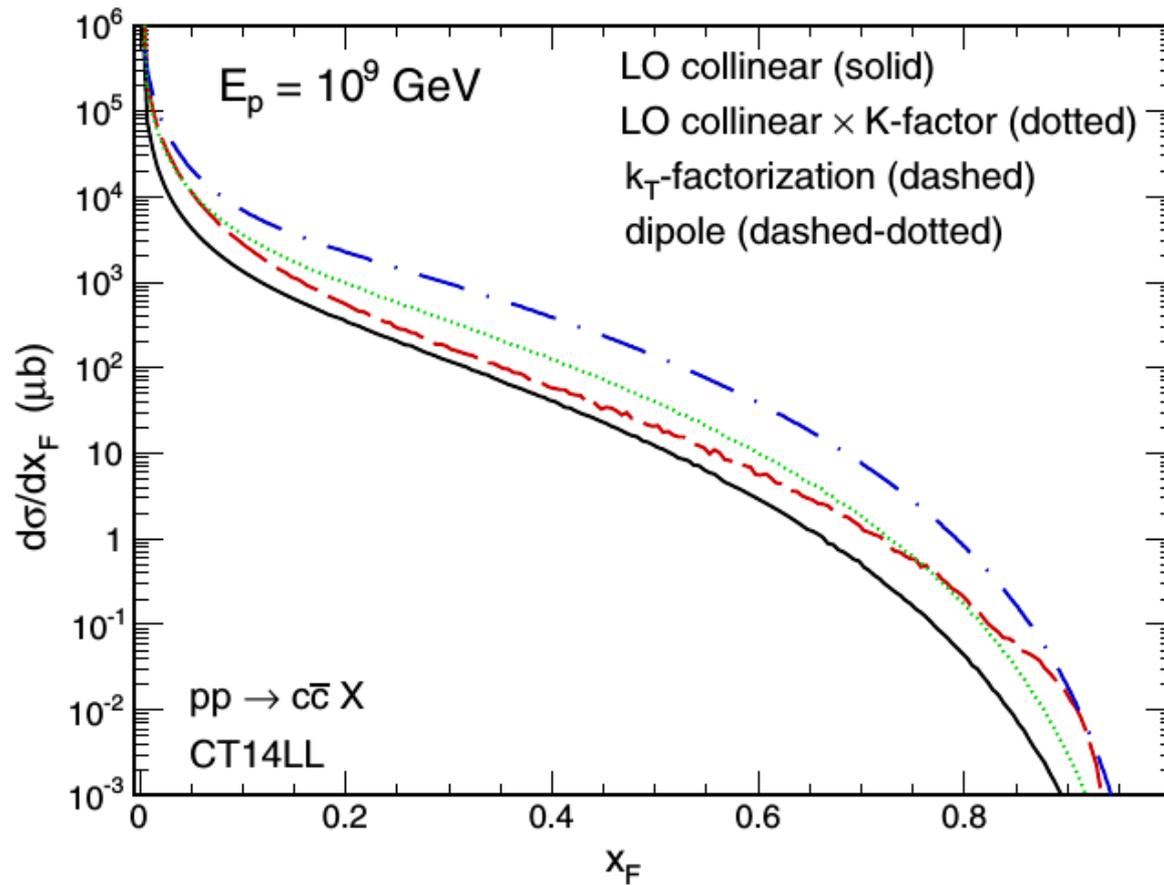


$$\phi_p^0(E) = \begin{cases} 1.7 E^{-2.7} & \text{for } E < 5 \cdot 10^6 \text{ GeV} \\ 174 E^{-3} & \text{for } E > 5 \cdot 10^6 \text{ GeV}, \end{cases}$$

- Useful approach: Broken power - law spectrum
- More recent approaches: Assume three different populations and five nuclei groups

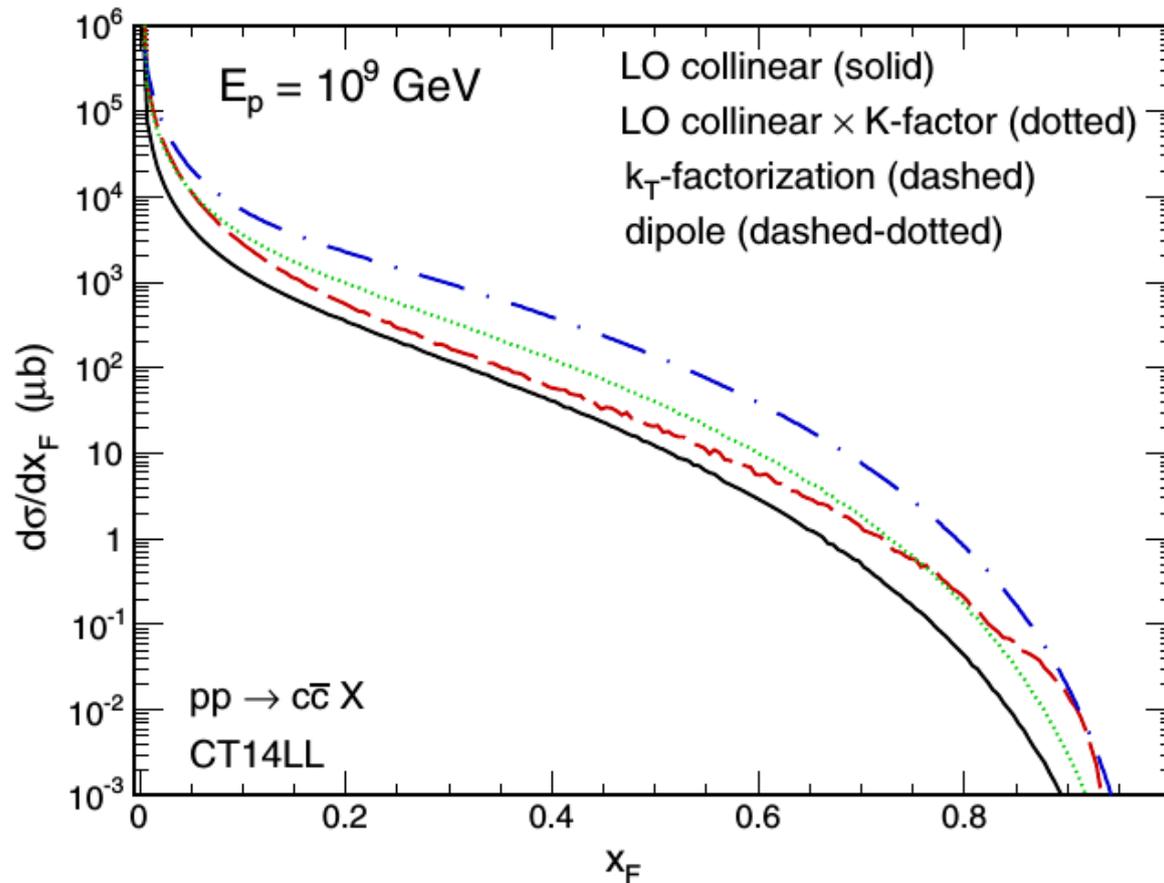
Large uncertainty connected with the limited knowledge of the extremely high - energy cosmic ray composition.

Feynman distribution for the charm production



strongly dependent on the approach used to estimate the heavy quark production at high energies.

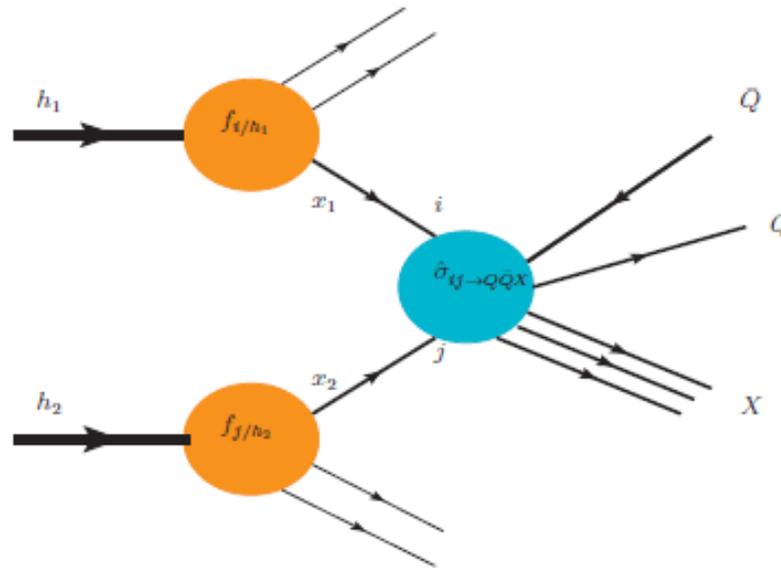
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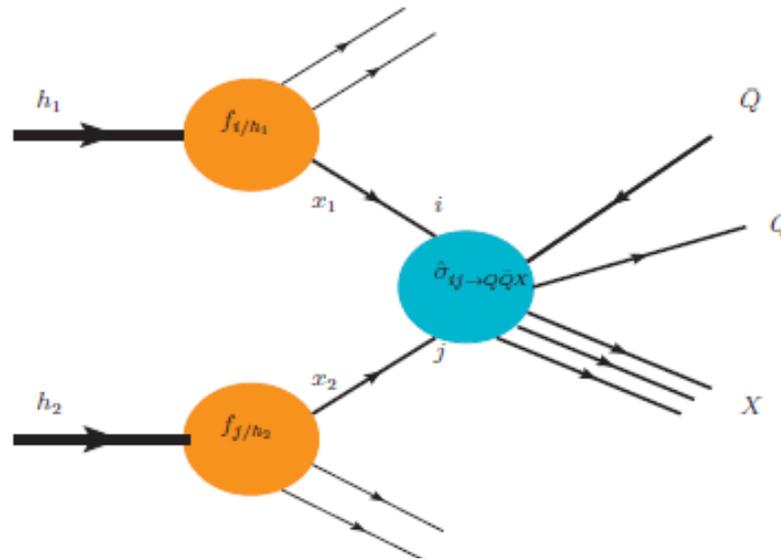
In what follows we will assume the standard collinear approach.

Heavy quark production: Collinear factorization approach



- In the collinear factorization approach the cross sections involving hadrons are given, at all orders, by the convolution of intrinsically non-perturbative (but universal) quantities - the parton densities - with perturbative calculable hard matrix elements, which are process dependent;
- Incoming partons are on - mass shell, carrying only longitudinal momentum. Their transverse momenta are neglected in the QCD matrix elements.

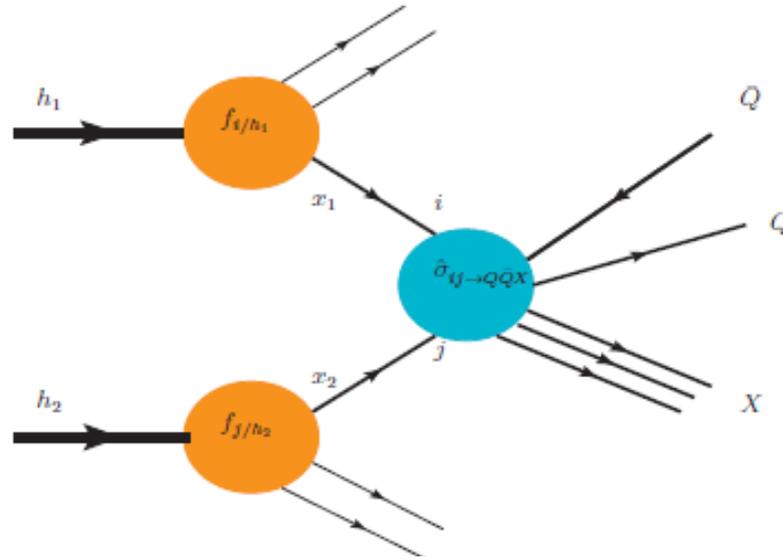
Heavy quark production: Collinear factorization approach



- The cross sections is factorized in a very simple way:

$$\sigma_{h_1 h_2 \rightarrow Q\bar{Q}X} = \sum_{i,j} \int dx_1 dx_2 f_{i/h_1}(x_1, \mu_F^2) f_{j/h_2}(x_2, \mu_F^2) \hat{\sigma}_{ij \rightarrow Q\bar{Q}X}(p_1; p_2; m_Q^2; \alpha_s(\mu_R^2); \mu_F^2; \mu_R^2)$$

Heavy quark production: Collinear factorization approach



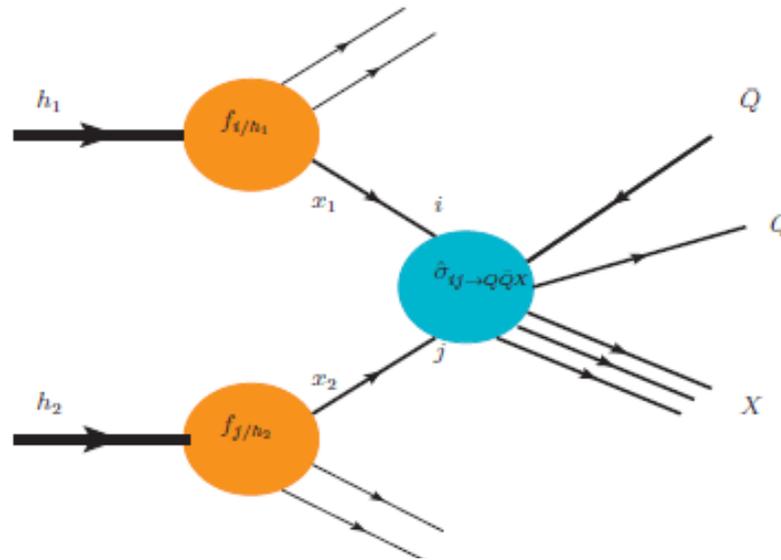
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Partonic Cross Sections



Heavy quark production: Collinear factorization approach



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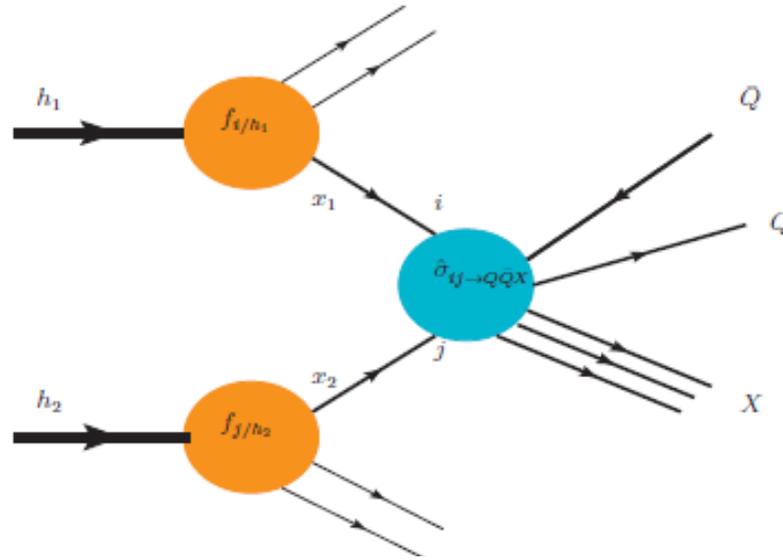
Partonic Cross Sections



$$\hat{\sigma} = \alpha_S^k \left(\underset{\uparrow}{\hat{\sigma}^{(0)}} + \frac{\alpha_S}{\pi} \underset{\uparrow}{\hat{\sigma}^{(1)}} + \left(\frac{\alpha_S}{\pi}\right)^2 \underset{\uparrow}{\hat{\sigma}^{(2)}} + \dots \right)$$

LO
NLO
NNLO

Heavy quark production: Collinear factorization approach



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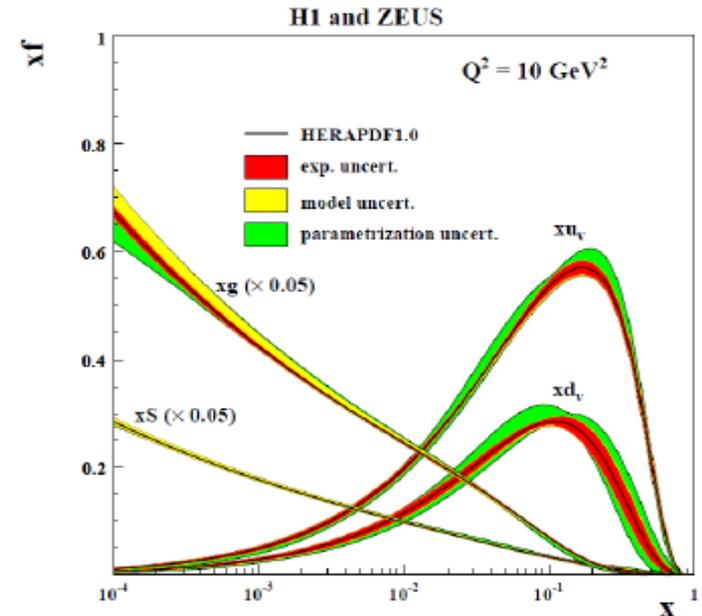
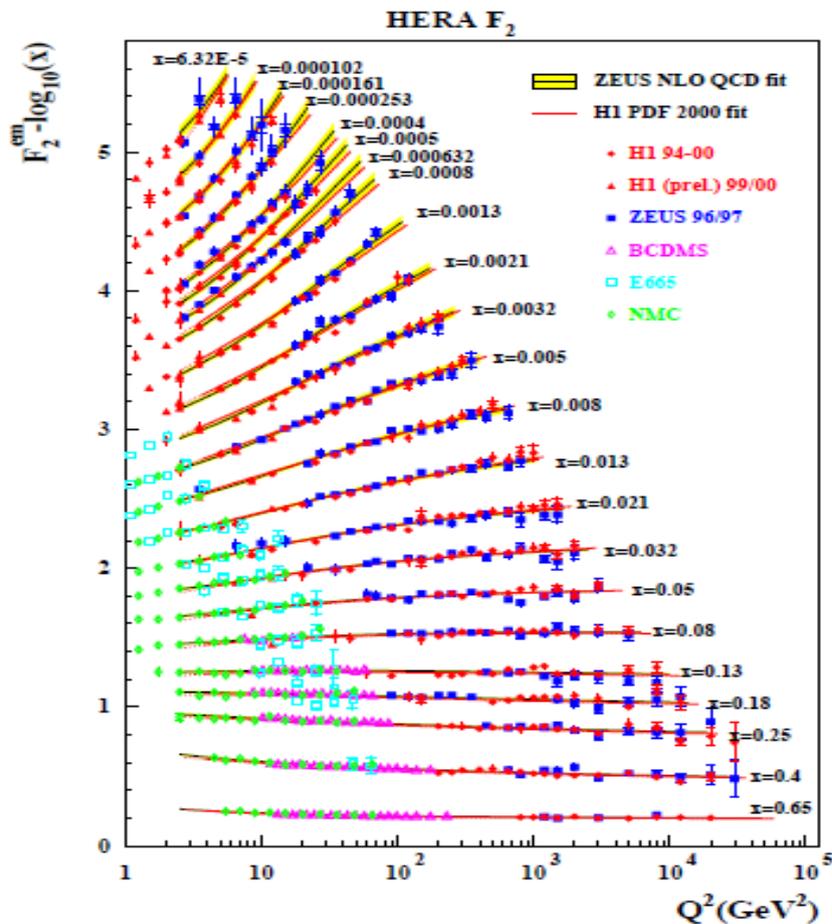
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Parton Distribution Functions



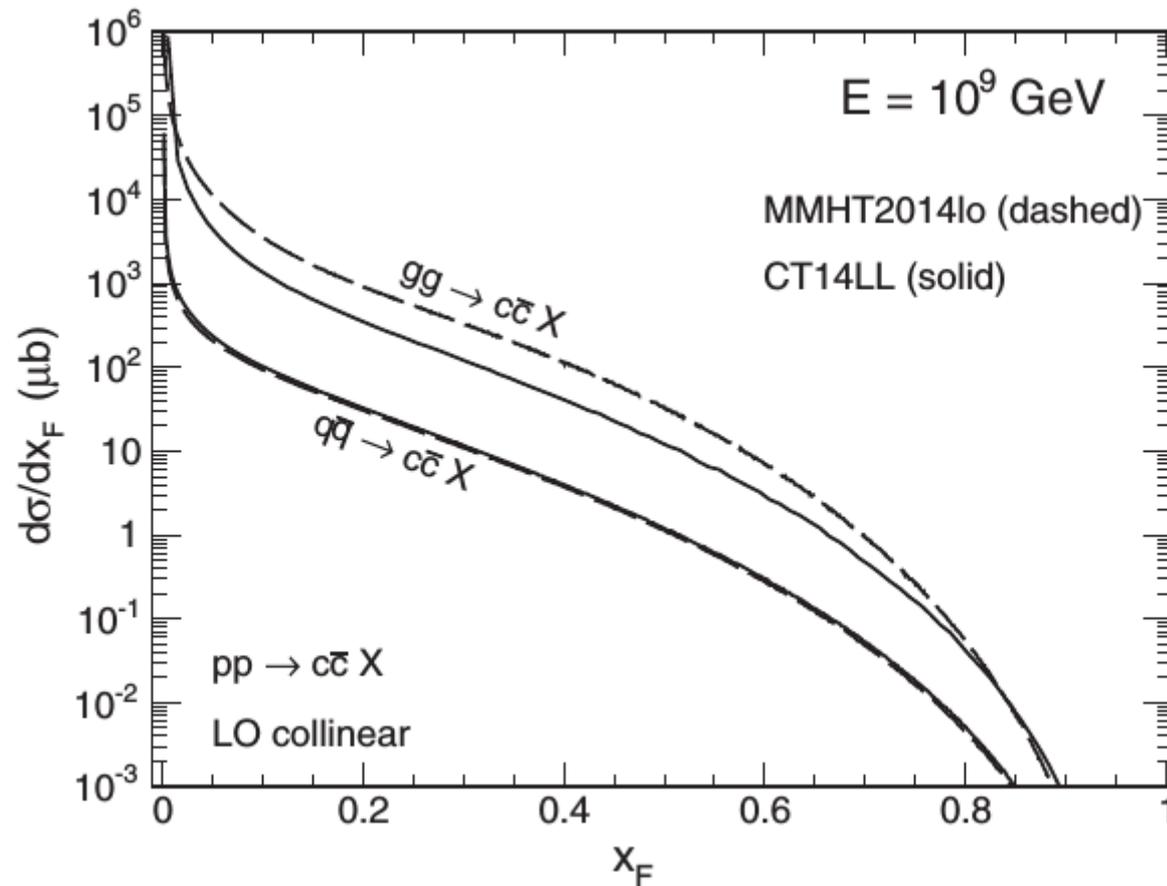
Parton distributions

Proton structure determined by the HERA measurements in electron - proton collisions in a large kinematical range.



- Gluon dominates the proton structure at high energies (low momentum fractions x).
- Gluon distribution poorly known at small- x .

Collinear factorization approach: Feynman distribution



- The distribution is dominated by gluon - gluon interactions;
- strongly dependent of the parametrization used to describe the gluon distribution.

Mapping the dominant regions of the phase space

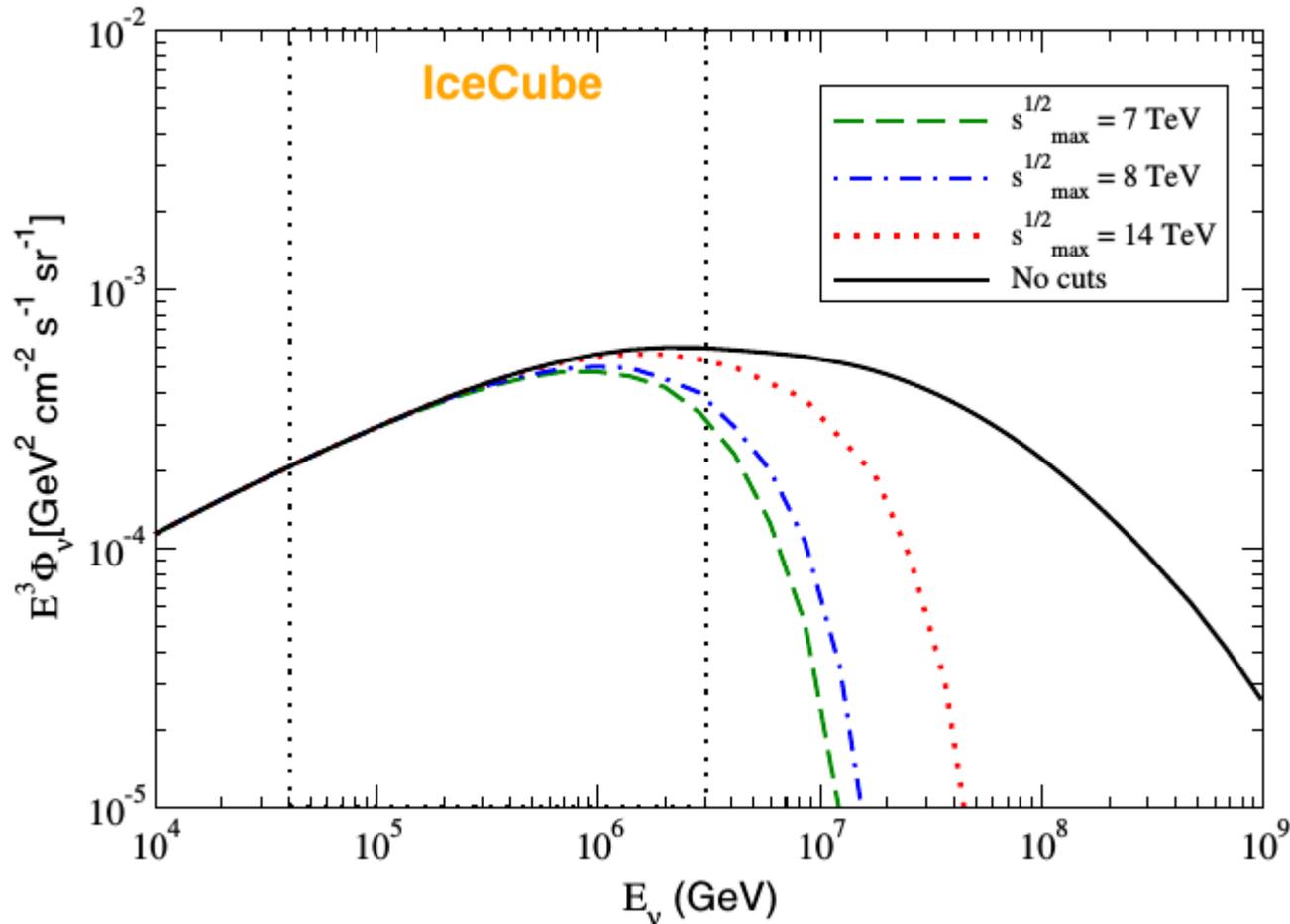
In what follows we will present our results for the prompt neutrino flux obtained assuming different cutoffs in the calculation of the charm Z -moment:

$$Z_{pc}(E) = \int_0^1 \frac{dx_F}{x_F} \frac{\phi_p(E/x_F)}{\phi_p(E)} \frac{1}{\sigma_{pA}(E)} \frac{d\sigma_{pA \rightarrow \text{charm}}(E/x_F)}{dx_F}$$

In particular, we estimate the Z -momentum assuming:

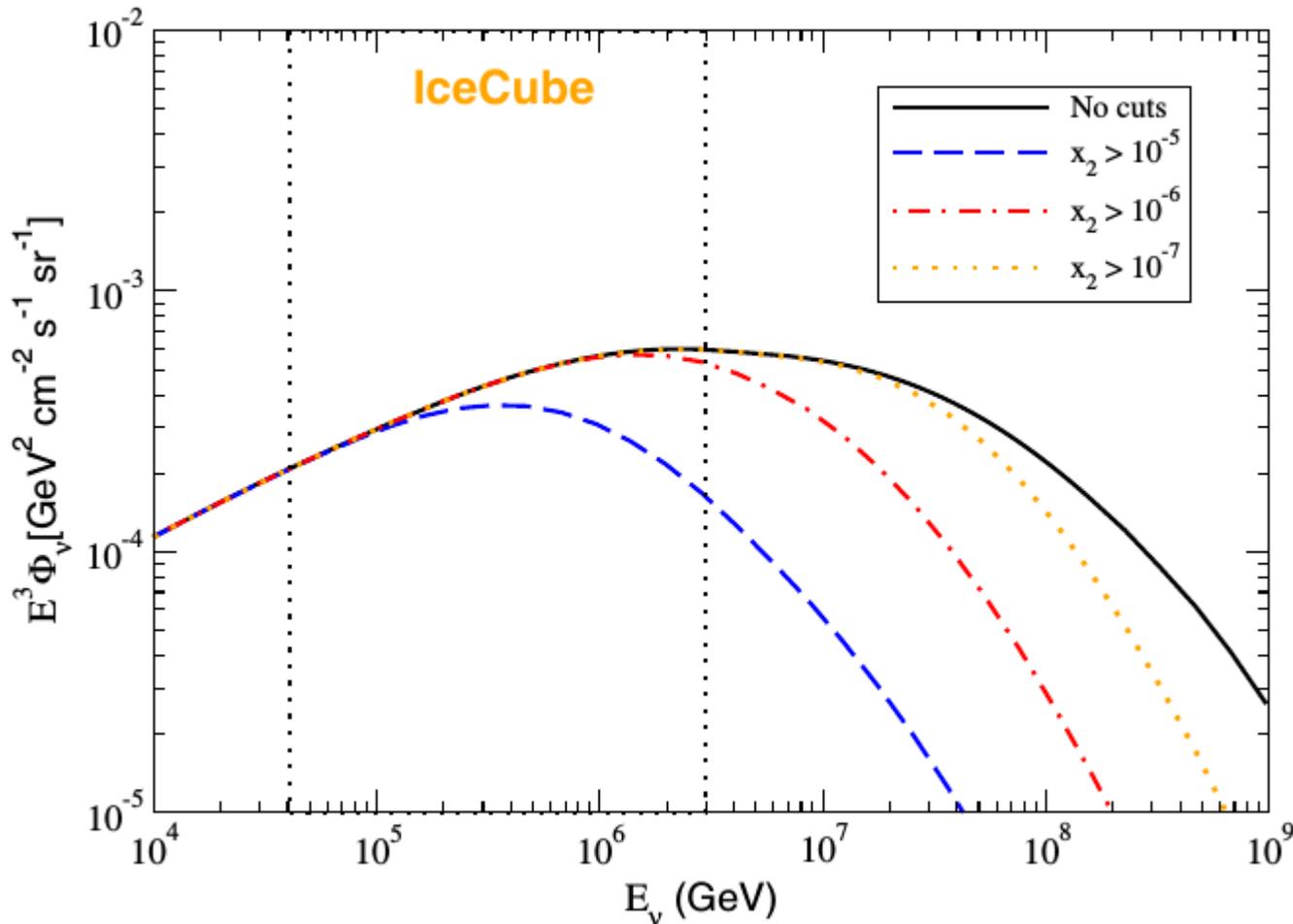
- 1.) a maximum value for the center of mass energy present in the proton - proton scattering;
- 2.) a minimum value for the momentum fraction of the target;
- 3.) a maximum value for the upper limit of integration in the Feynman x variable.

Mapping the typical values of center - of - mass energies



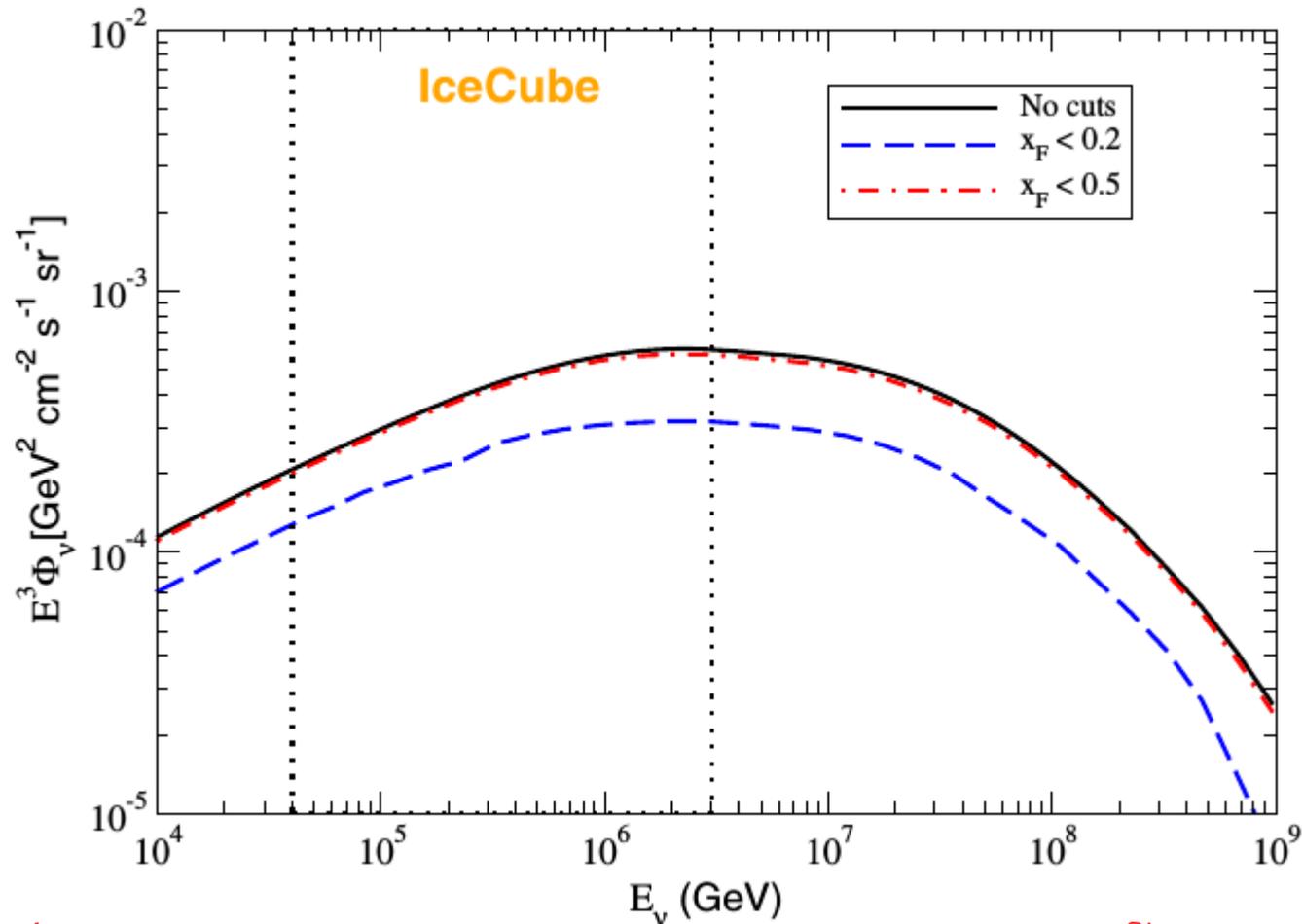
The production of neutrinos with energy larger than 10^7 GeV is sensitive to the c.m. energies larger than ones at the LHC.

Mapping the typical values of the target momentum fraction



The production of neutrinos with energy larger than 10^5 GeV is sensitive to the longitudinal momentum fractions of the projectile in the range $x < 10^{-5}$. This region is poorly constrained by the current collider data.

Mapping the typical values of Feynman x variable



The dominant contribution to the neutrino flux comes from x_F in the region $0.2 < x_F < 0.5$, which is associated to the charm production at very forward rapidities (beyond LHCb).

Summary

- ✓ The contribution of the heavy quark production at ultra high cosmic ray interactions is non-negligible and should be taken into account in a reliable description of the extensive air showers.
- ✓ In order to predict the prompt neutrino flux for typical neutrino energies at the IceCube Observatory and future neutrino telescopes, we should extrapolate the behavior of the heavy quark cross sections and energy distributions beyond the range accessible experimentally by current collider measurements.
- ✓ In order to address production of high-energy neutrinos ($E_\nu > 10^7$ GeV), one needs to know the charm production cross section for energies larger than those available at the LHC, as well as the parton/gluon distributions for the longitudinal momentum fractions in the region $10^{-8} < x < 10^{-5}$. Since this region of x is not available at the collider measurements at the moment, the predictions in the collinear factorization approach cannot very reliable.
- ✓ New dynamical effects and/or contributions can be important to describe the prompt neutrino flux.

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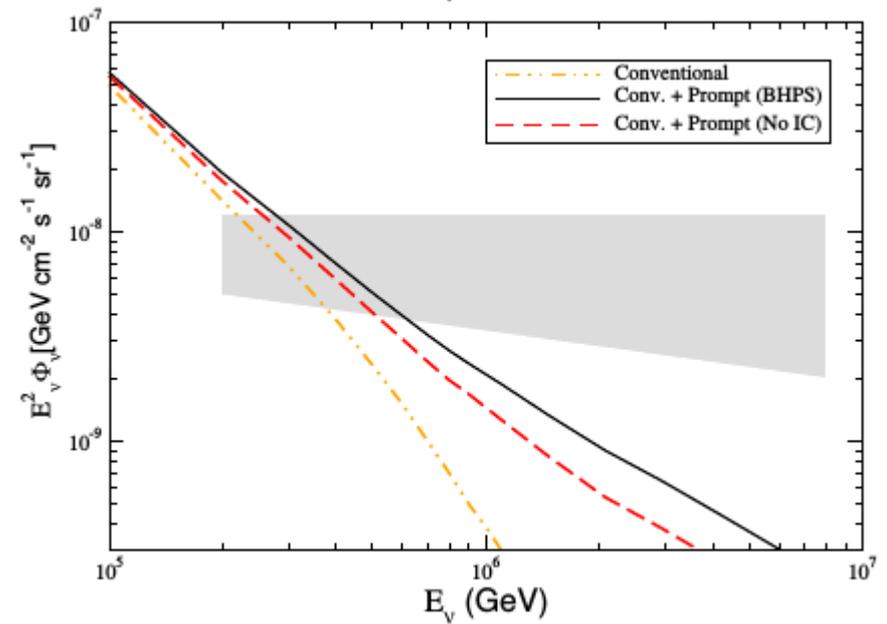
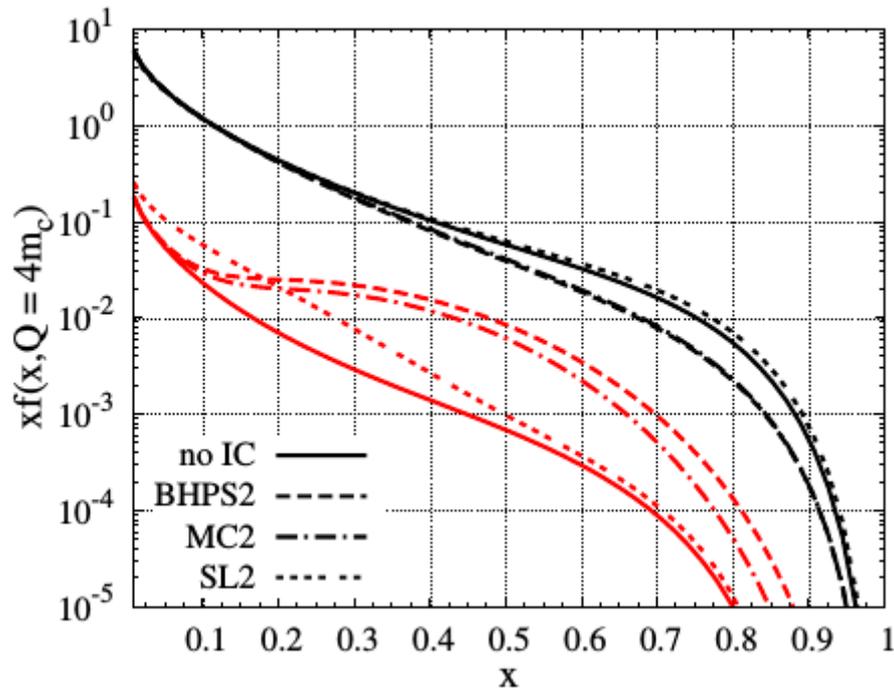
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Recent result:

ArXiv:1803.01728

On the intrinsic charm contribution to the prompt atmospheric neutrino flux

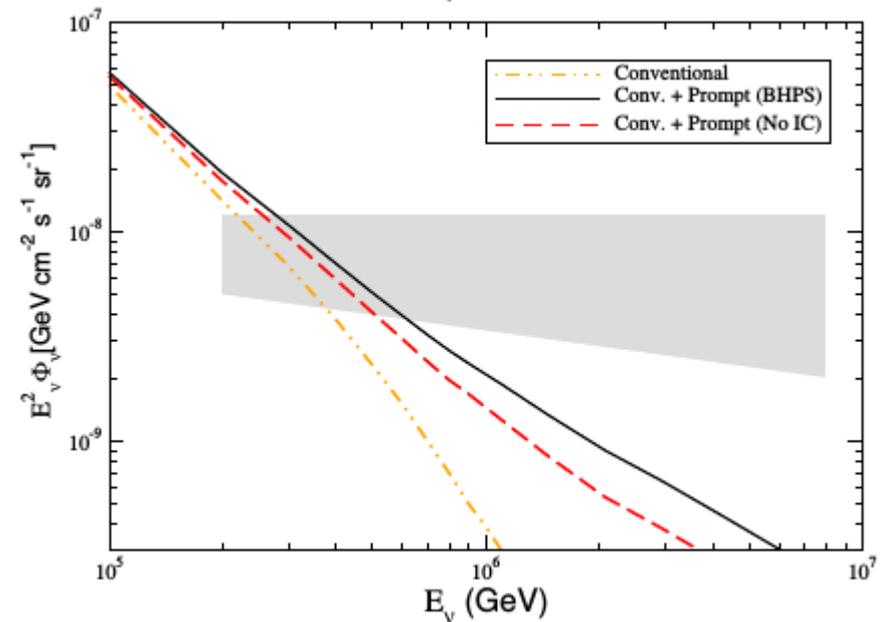
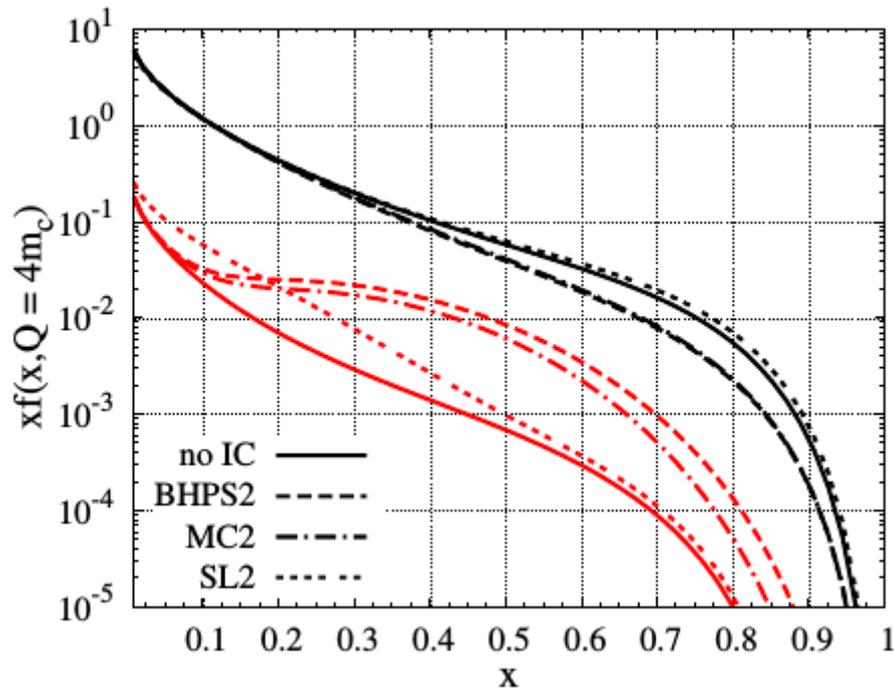
A.V. Giannini[‡], V.P. Gonçalves[§] and F.S. Navarra[‡]



Recent result: ArXiv:1803.01728

On the intrinsic charm contribution to the prompt atmospheric neutrino flux

A.V. Giannini[‡], V.P. Gonçalves[§] and F.S. Navarra[‡]



Thank you for your attention!

Extras

Parton distribution functions

- The linear DGLAP equations describe the evolution of the parton distribution functions in the hard scale $\mu^2 = Q^2$.
Resum Q^2 logs: $\sum_n [\alpha_s \ln(Q^2/Q_0^2)]^n$;

Quark sector:
$$\frac{\partial q_f(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} \left[q_f(y, Q^2) P_{qq} \left(\frac{x}{y} \right) + g(y, Q^2) P_{qg} \left(\frac{x}{y} \right) \right].$$

$$\frac{\partial}{\partial \ln Q^2} (q_f(x, Q^2)) = \underbrace{q_f(y, Q^2) \text{ (quark)} \rightarrow q_f(x, Q^2) \text{ (quark)} + \text{gluon loop}}_{P_{qq} \left(\frac{x}{y} \right)} + \underbrace{g(y, Q^2) \text{ (gluon)} \rightarrow q_f(x, Q^2) \text{ (quark)}}_{P_{qg} \left(\frac{x}{y} \right)}$$

Gluon sector:
$$\frac{\partial g(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} \int_x^1 \frac{dy}{y} \left[\sum_f q_f(y, Q^2) P_{gq} \left(\frac{x}{y} \right) + g(y, Q^2) P_{gg} \left(\frac{x}{y} \right) \right]$$

$$\frac{\partial}{\partial \ln Q^2} (g(x, Q^2)) = \sum_f \underbrace{q_f(y, Q^2) \text{ (quark)} \rightarrow g(x, Q^2) \text{ (gluon)}}_{P_{gq} \left(\frac{x}{y} \right)} + \underbrace{g(y, Q^2) \text{ (gluon)} \rightarrow g(x, Q^2) \text{ (gluon)}}_{P_{gg} \left(\frac{x}{y} \right)}$$

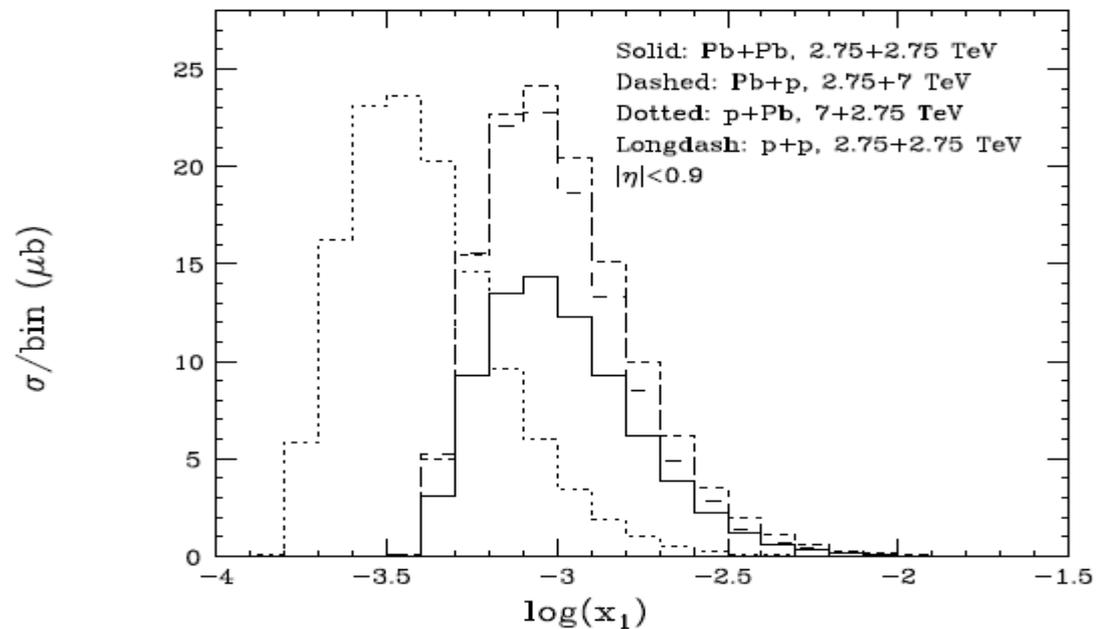
Splitting functions:
$$P_{ab}(\alpha_s, z) = \frac{\alpha_s}{2\pi} P_{ab}^{(0)}(z) + \left(\frac{\alpha_s}{2\pi} \right)^2 P_{ab}^{(1)}(z) + \left(\frac{\alpha_s}{2\pi} \right)^3 P_{ab}^{(2)}(z) + \dots$$

↑ LO (1974)
 ↑ NLO (1980)
 ↑ NNLO (2004: Moch et al.)

Charm production at the LHC

- Typical values of x for charm production at the LHC
- pp collisions at $\sqrt{s} = 5.5$ TeV

Central rapidity

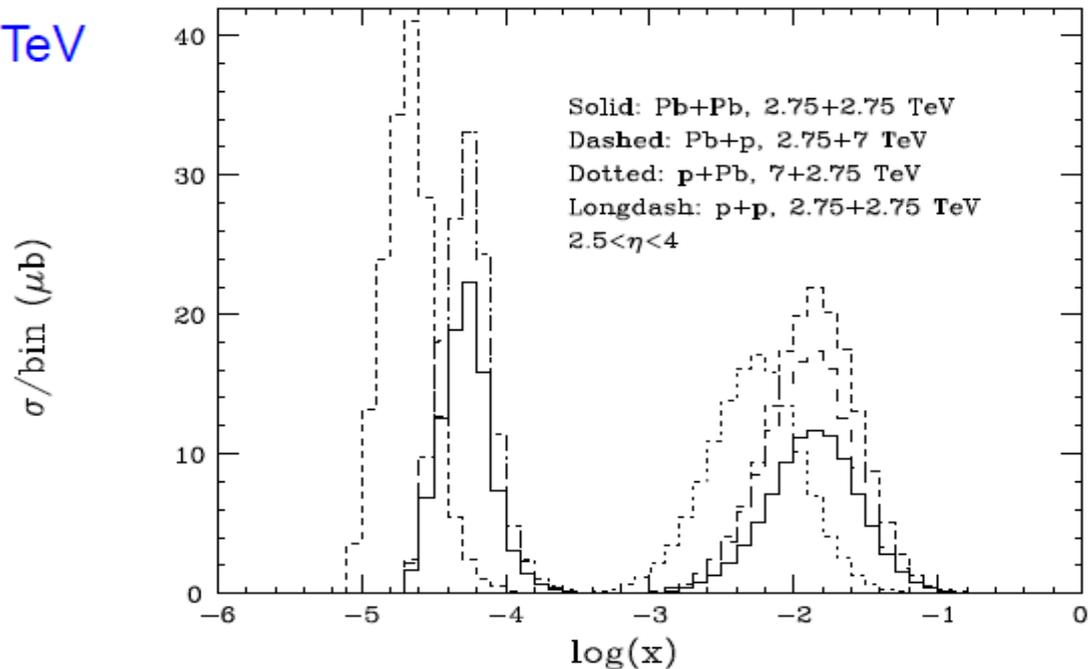


Charm production at the LHC

● Typical values of x for charm production at the LHC

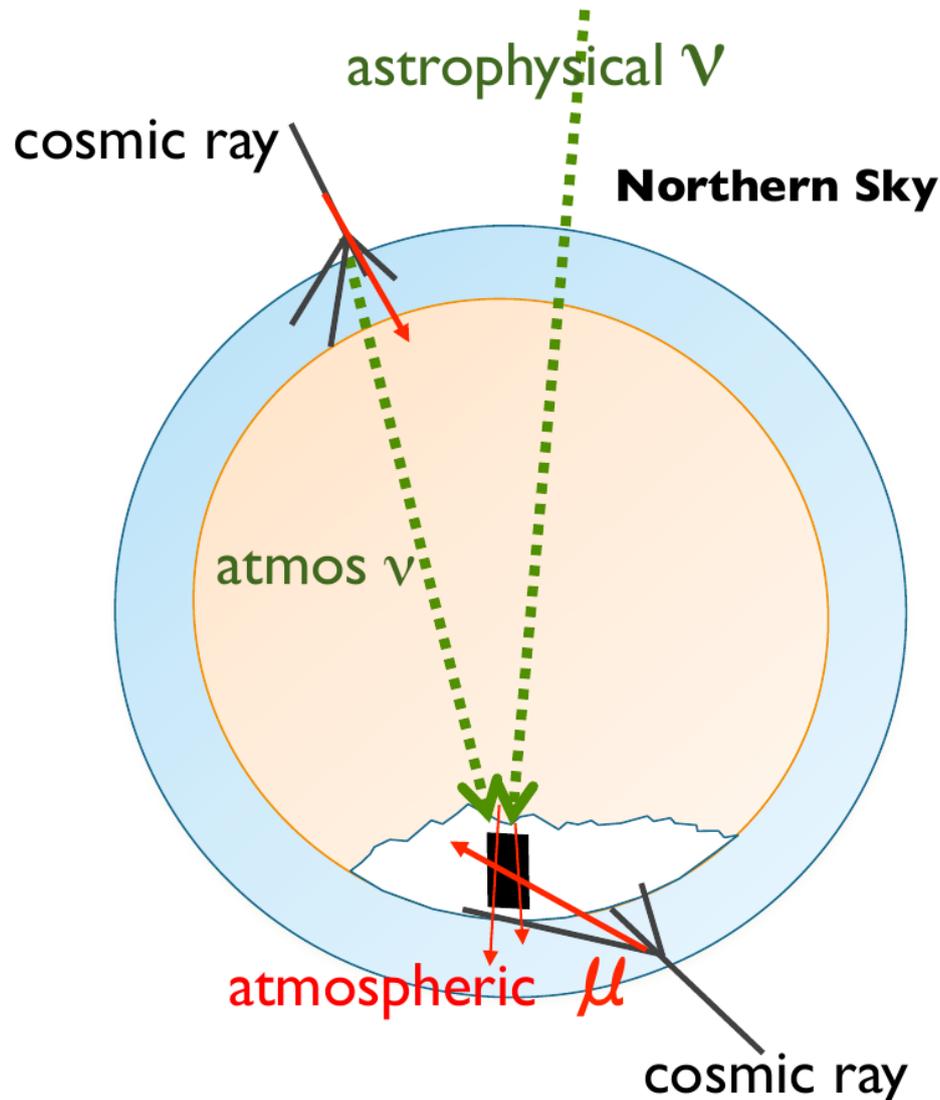
● pp collisions at $\sqrt{s} = 5.5$ TeV

Forward rapidity



● Very small values of x reached in one of the projectiles

Atmospheric neutrinos

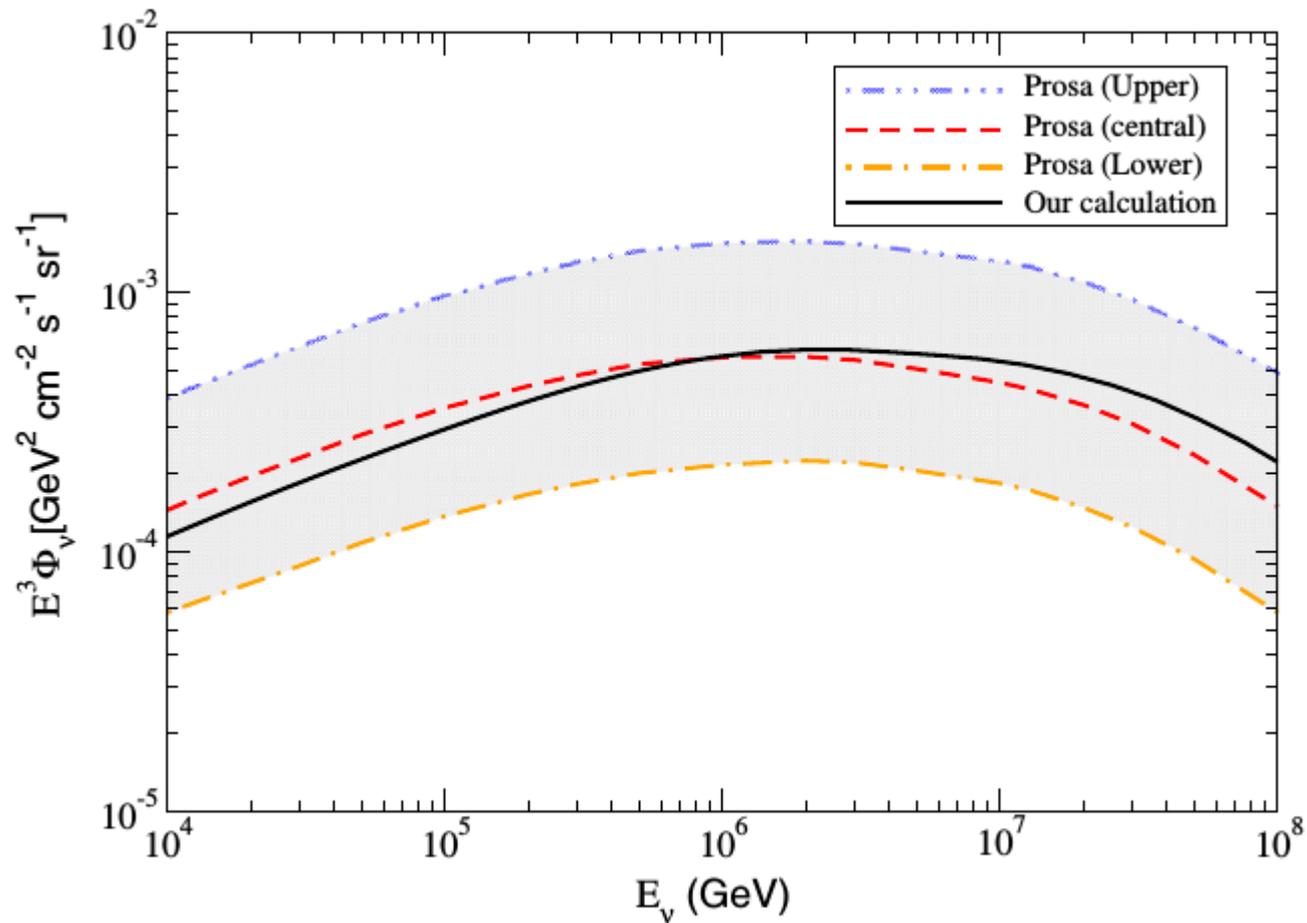


Cosmic-ray muons:
~3000 / second!

Atmospheric neutrinos:
~1 / 10 minutes

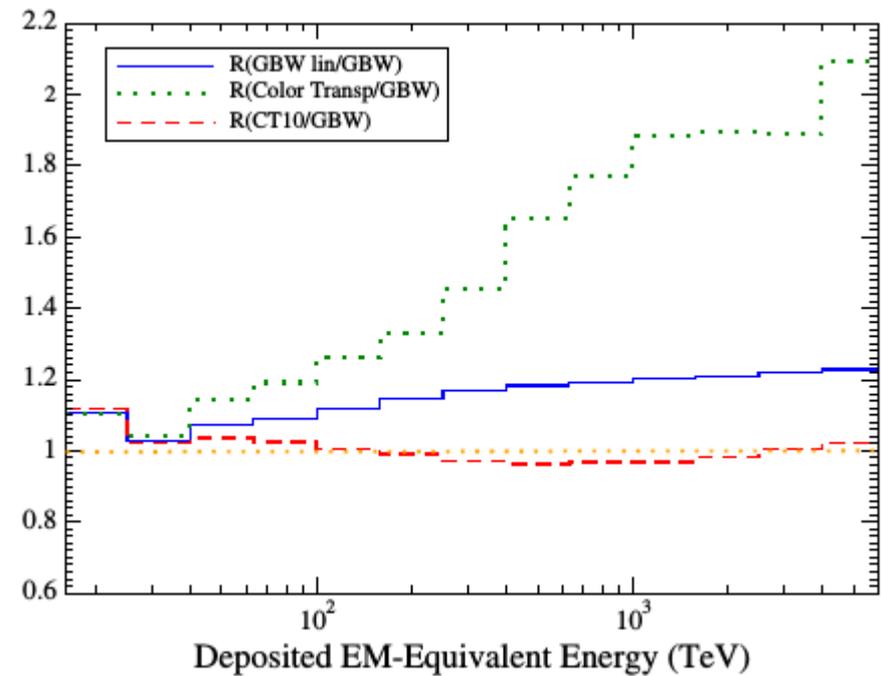
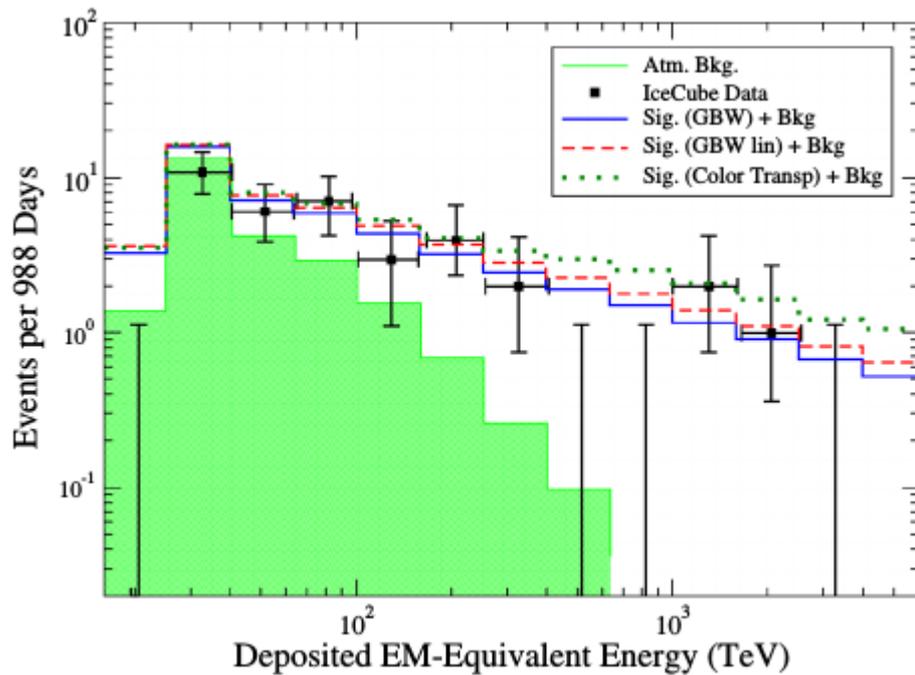
Astrophysical neutrinos: ???

Comparison with PROSA results (*)



(*) PROSA Collaboration: Garzelli et al., JHEP 05 (2017) 004

Non-linear effects at IceCube (*)



(*) VPG, D. R. Gratieri, PRD90 (2014) 057502