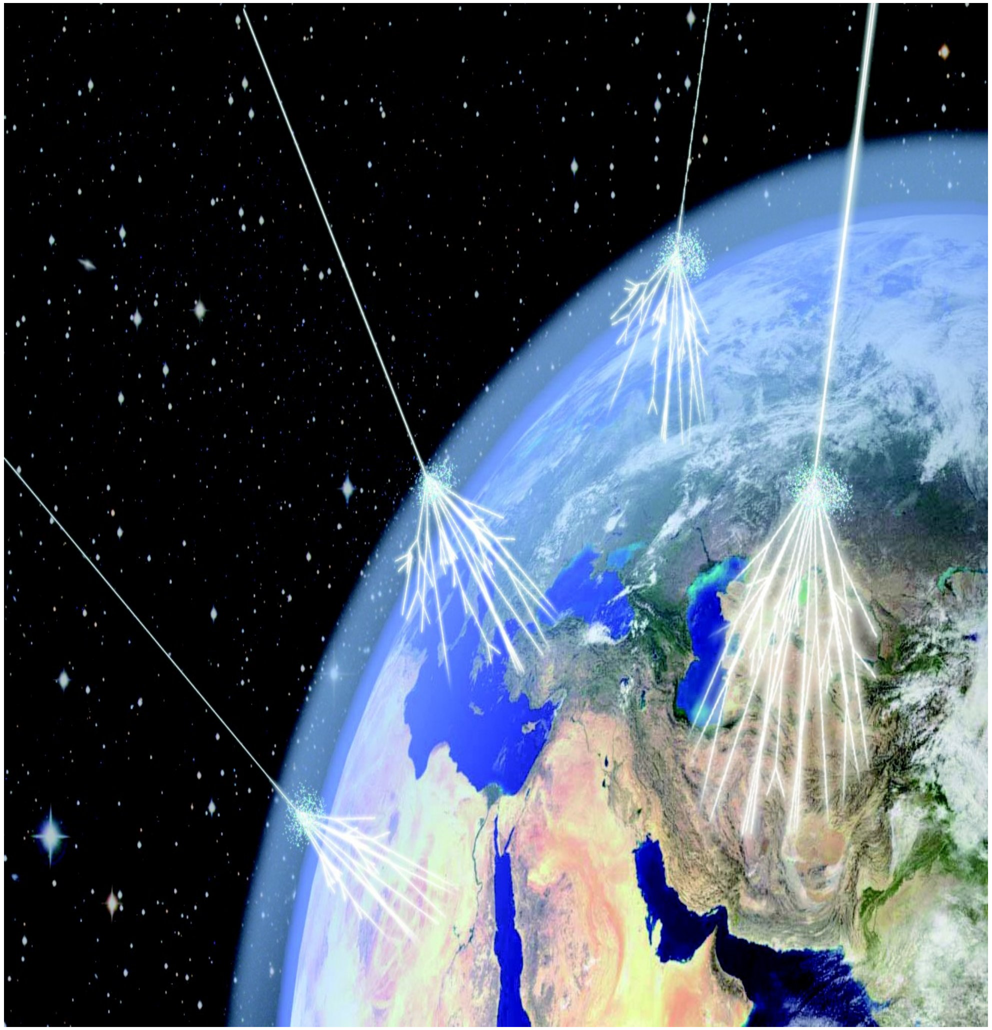
Institute of Physics of the Czech Academy of Sciences

20 February 2019
Prague, Czech Republic



Heavy quark production at Ultrahigh Cosmic Ray Energies and its Implications in Neutrino Physics

Victor P. Gonçalves

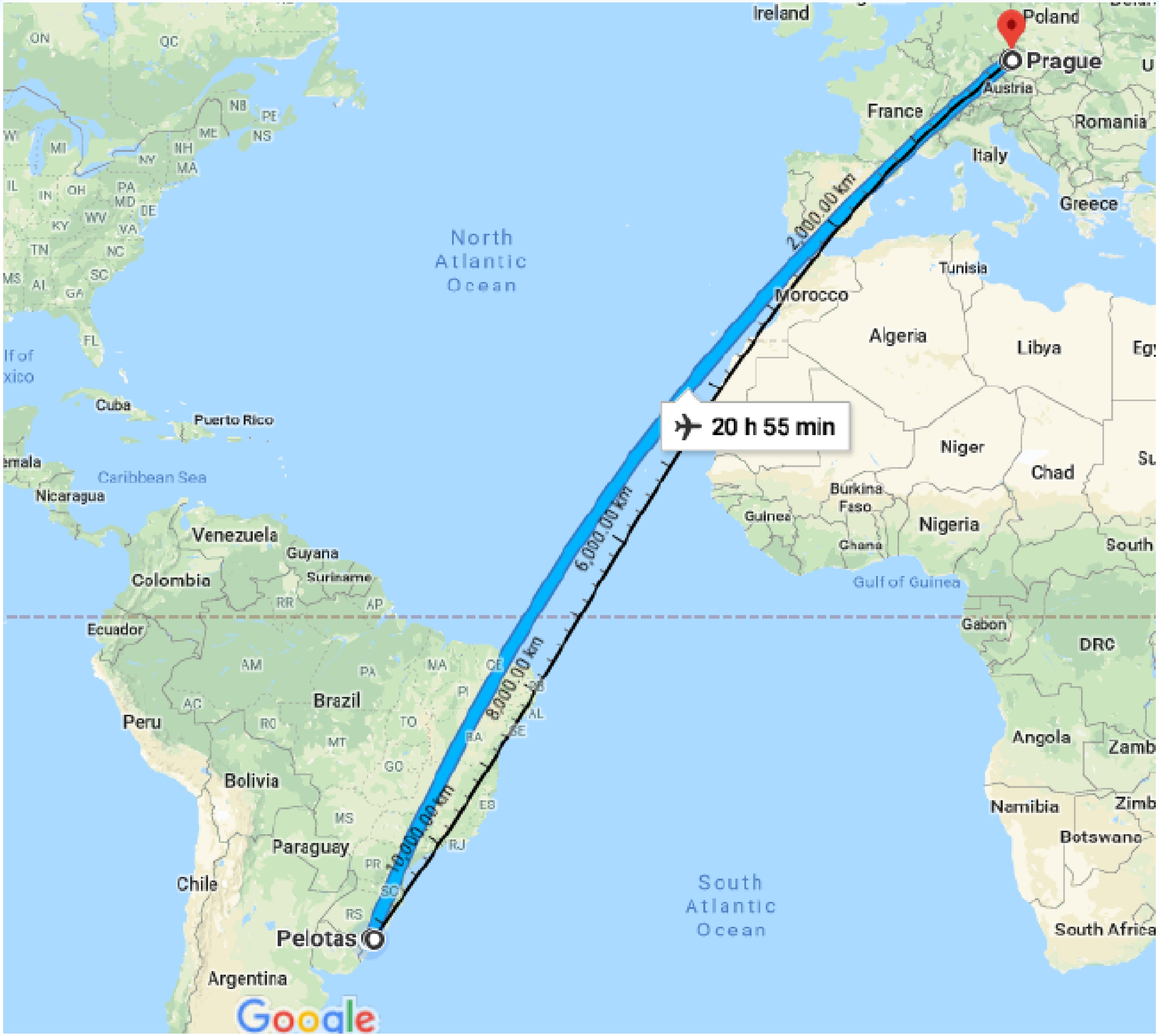
High and Medium Energy Group

Physics ans Mathematics Institute

Federal University of Pelotas (UFPel)

Pelotas - RS - Brazil

Where is Pelotas?



Pelotas

- Founded in 1777
- Current Population: 327 778
- Economy: Based on Agriculture (Rice, soy, corn, ...)
- Typical food: Churrasco

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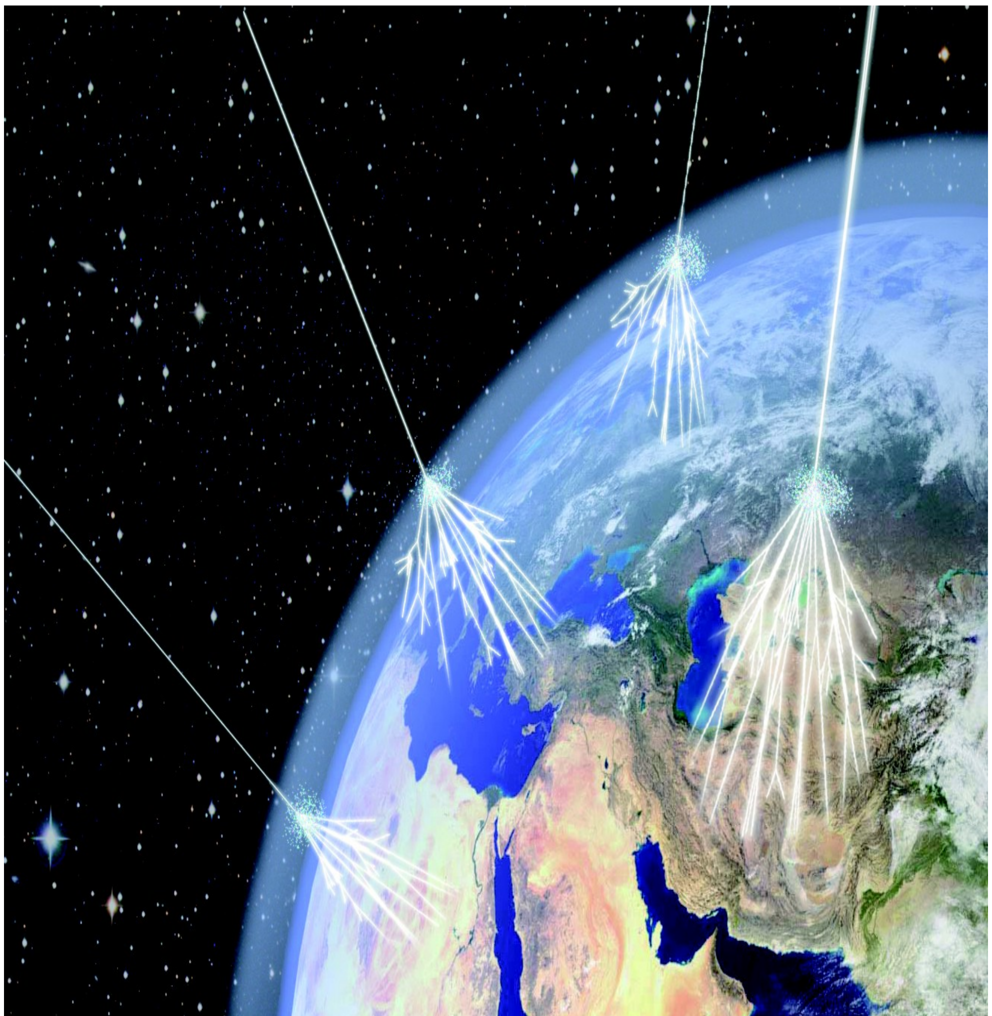

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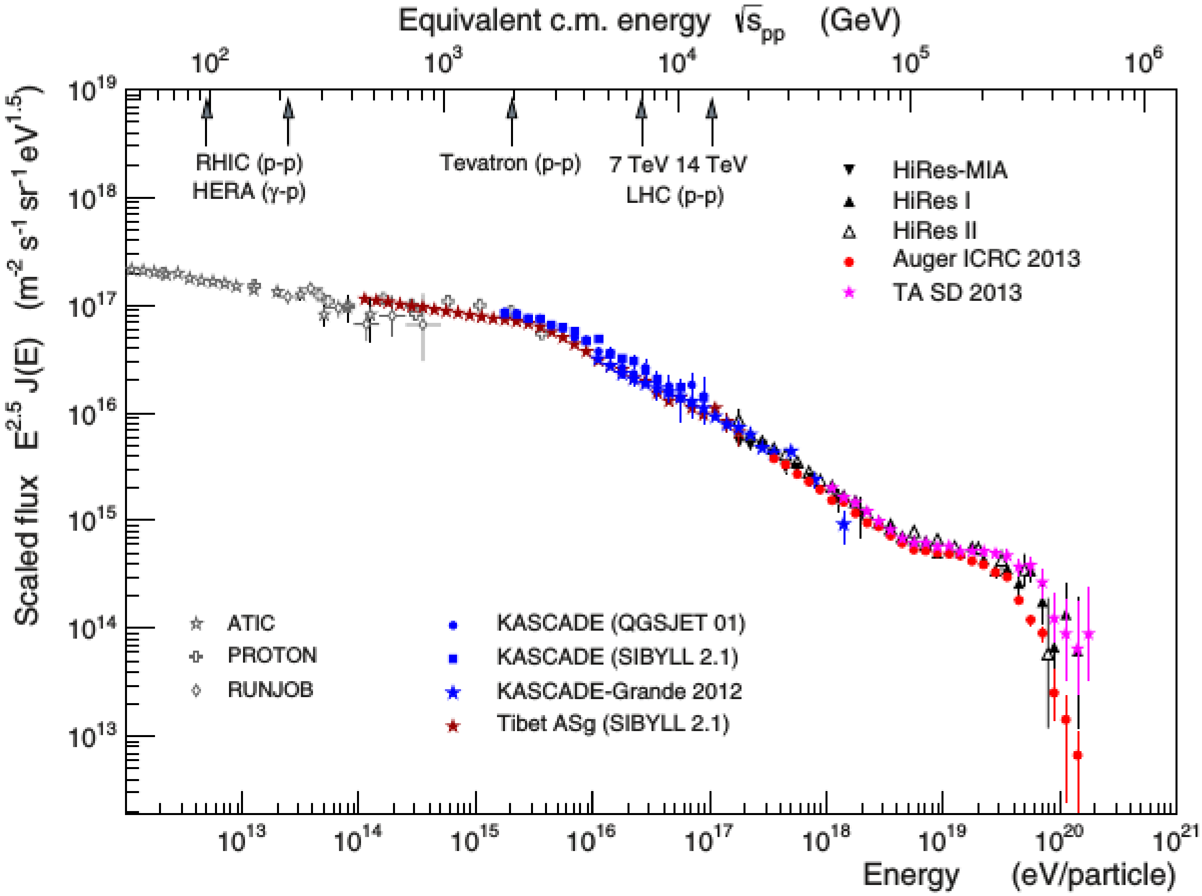
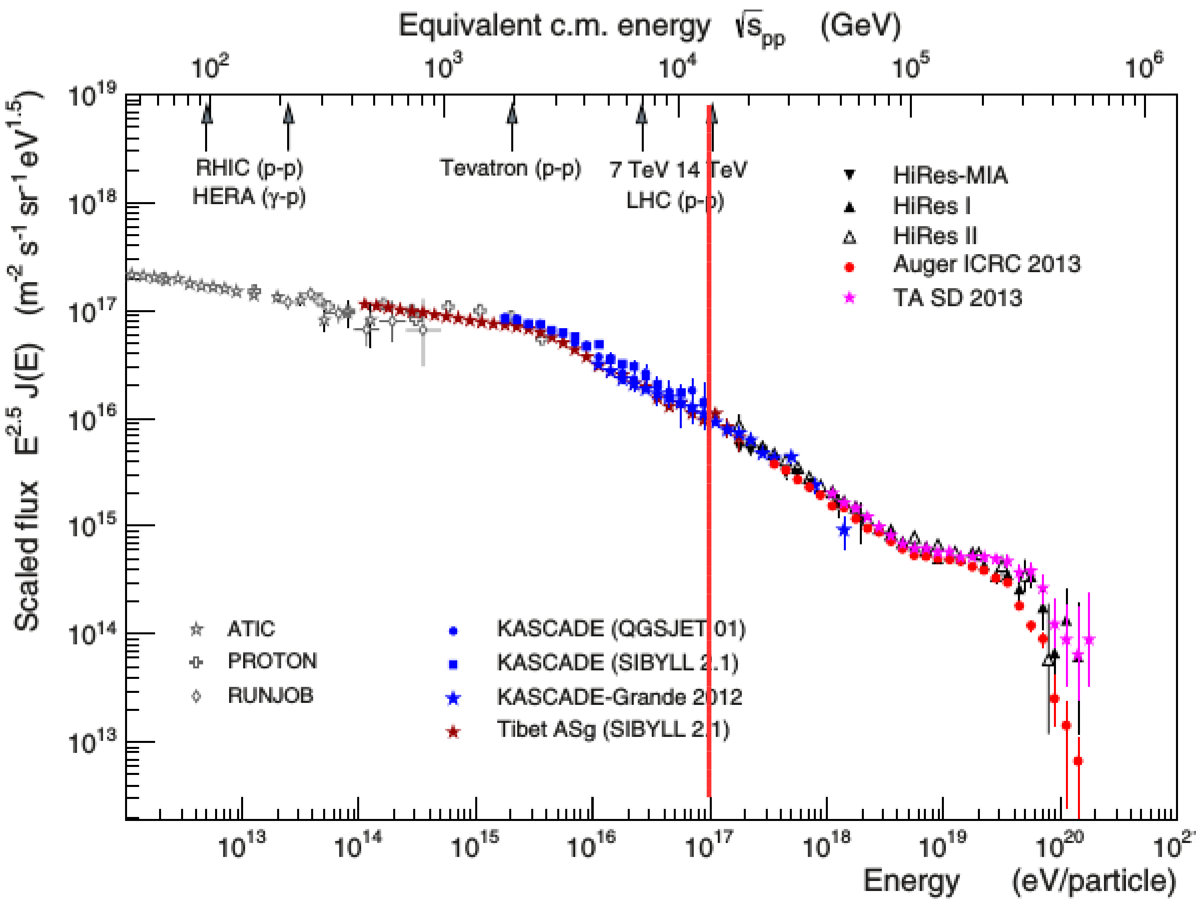
Motivation



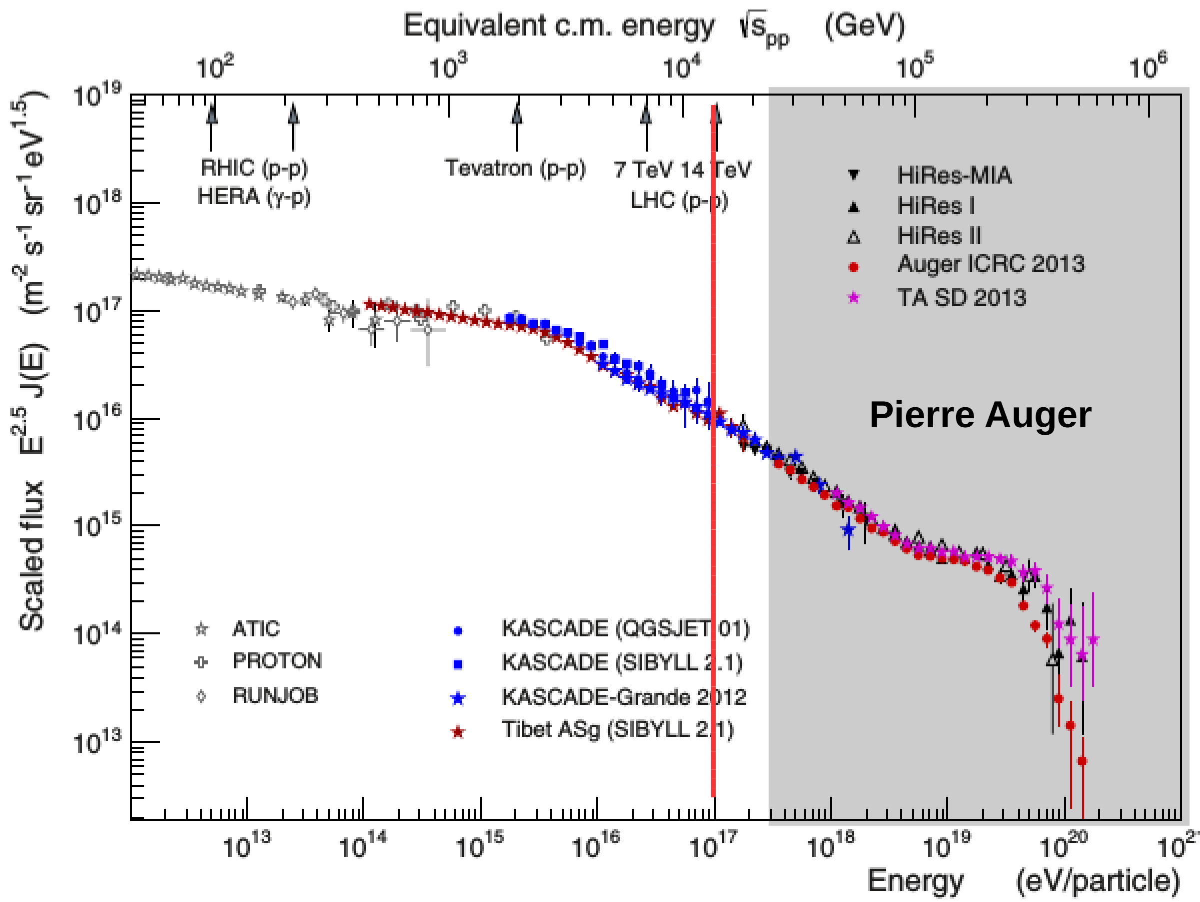
Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
10^19
10^18
10^17
10^16
10^15
10^14
10^13
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

Motivation



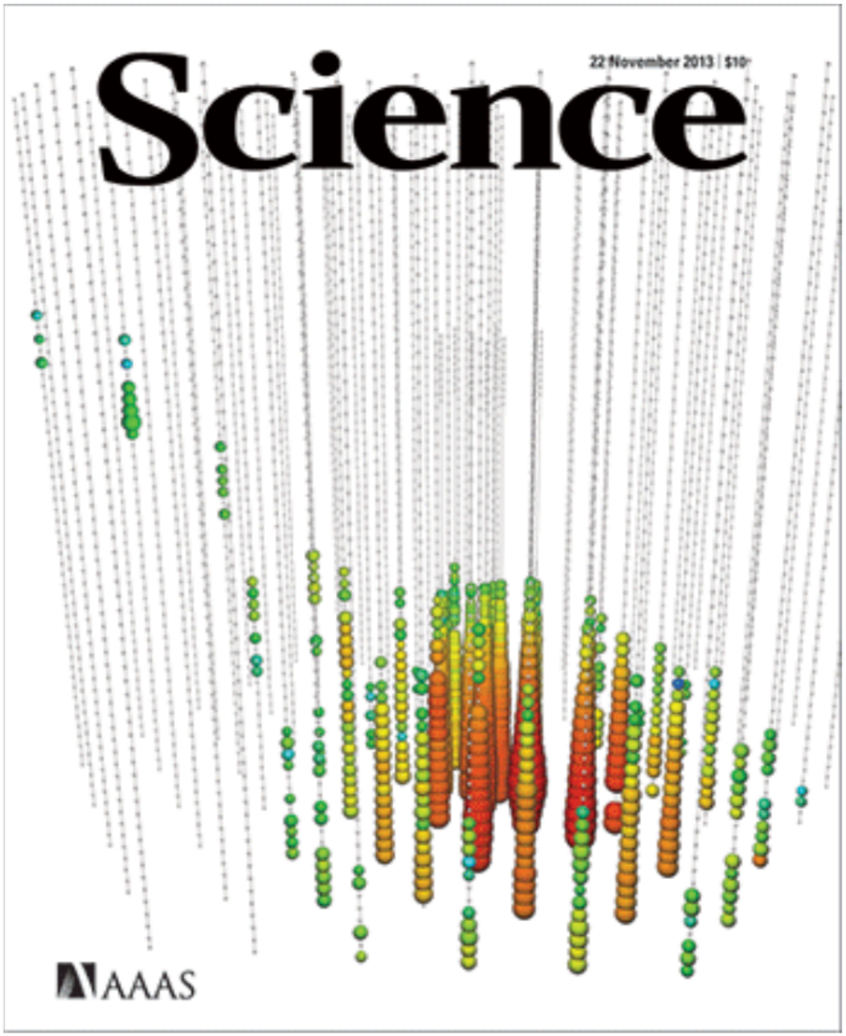
Cosmic Ray interactions probe the strong interactions in an energy range beyond the LHC.

Motivation



The description of the Auger data should to 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

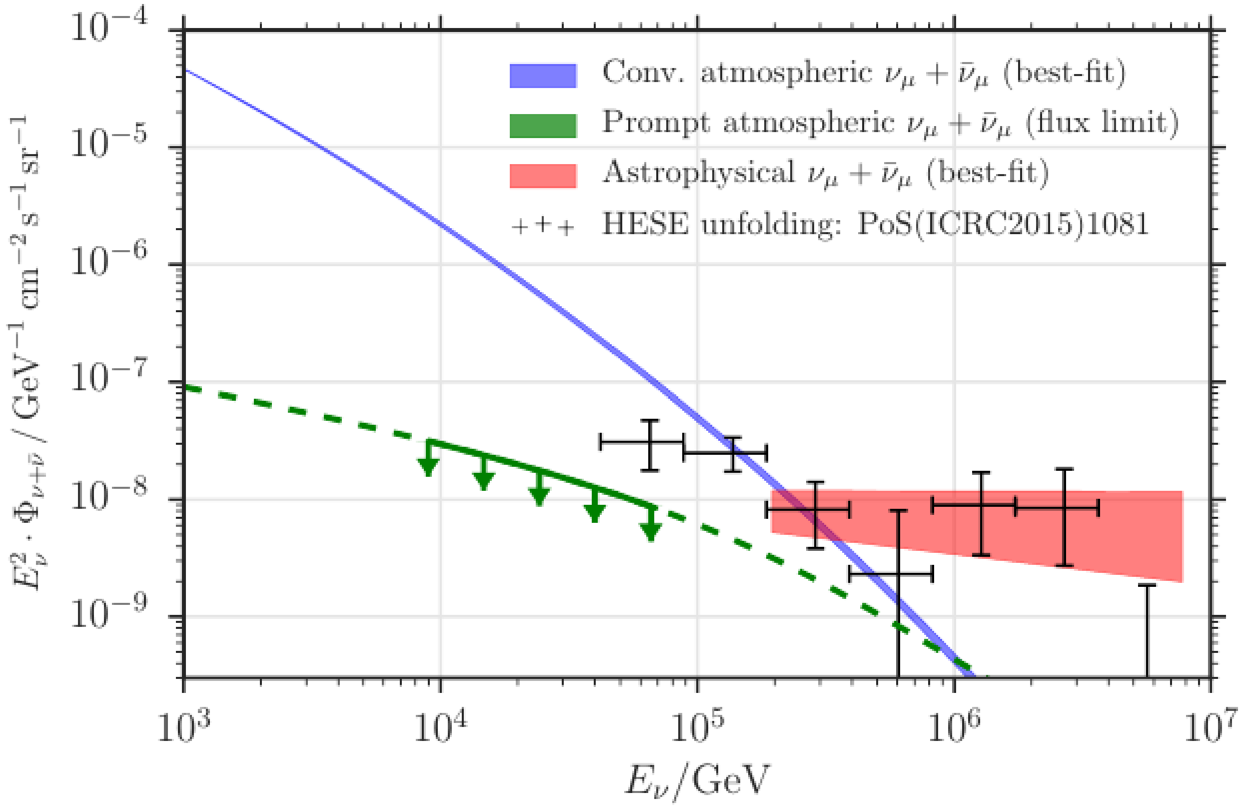
Dec 13, 2013 8 comments

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:

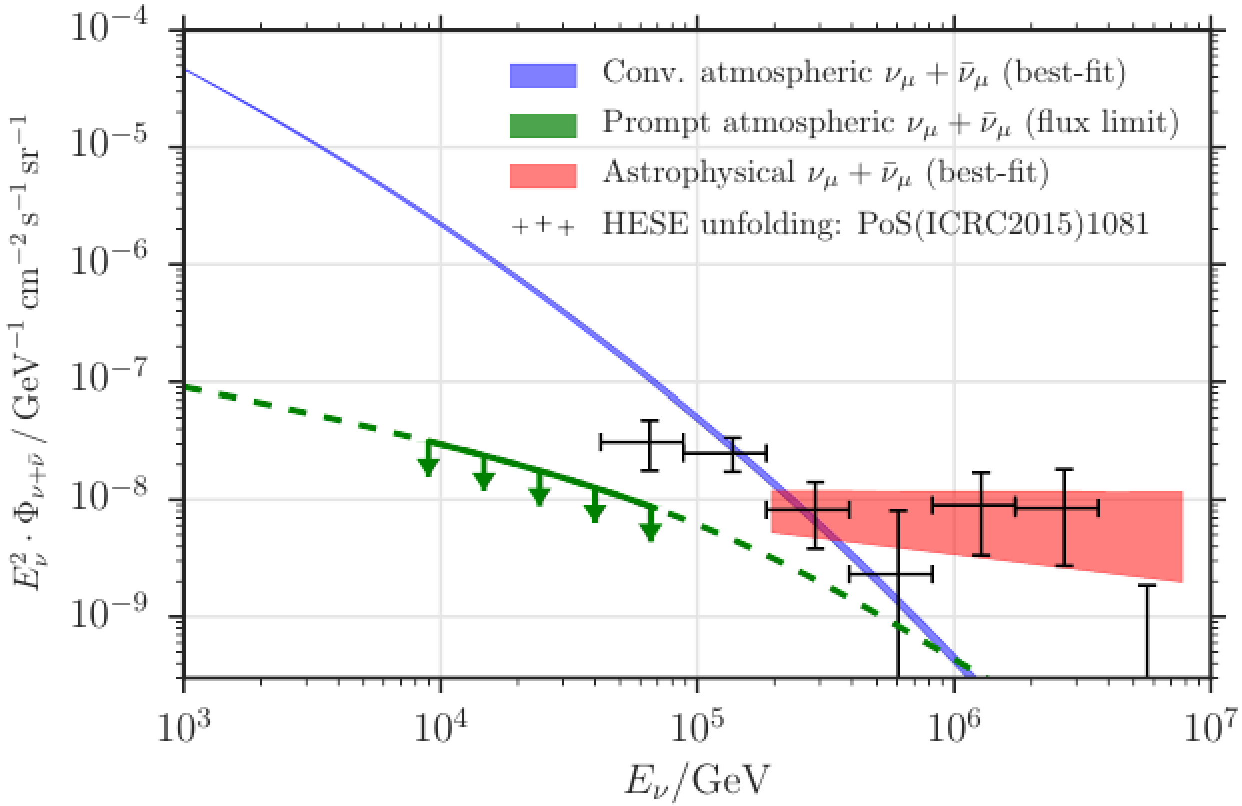


Main background for astrophysical neutrinos:

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

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

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

Heavy quark production in ultra high energy cosmic ray interactions

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

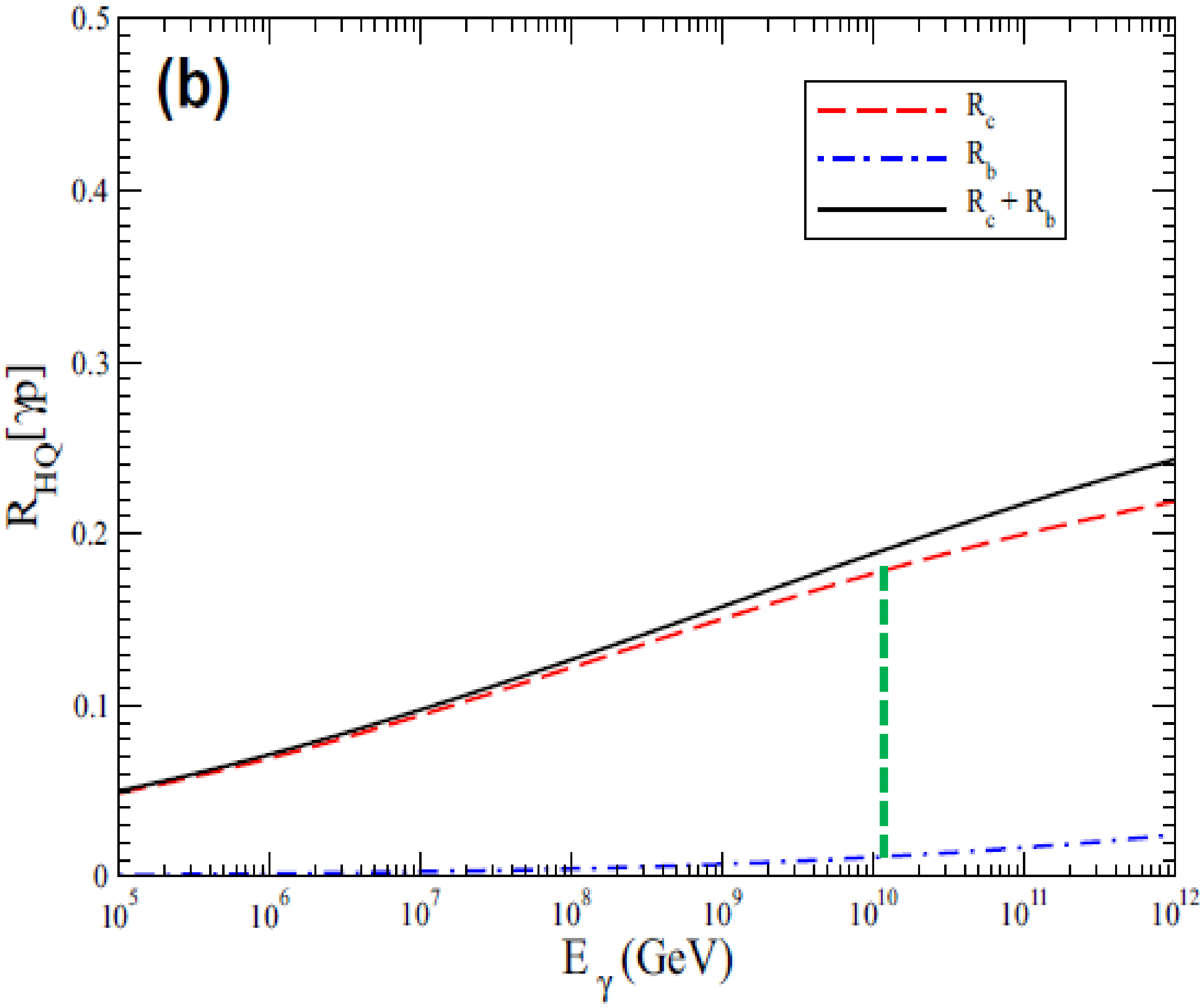
- In order to estimate the heavy quark contribution for the total cross sections at ultra high energy cosmic ray energies interactions, in what follows we present our predictions for the ratio:

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

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

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

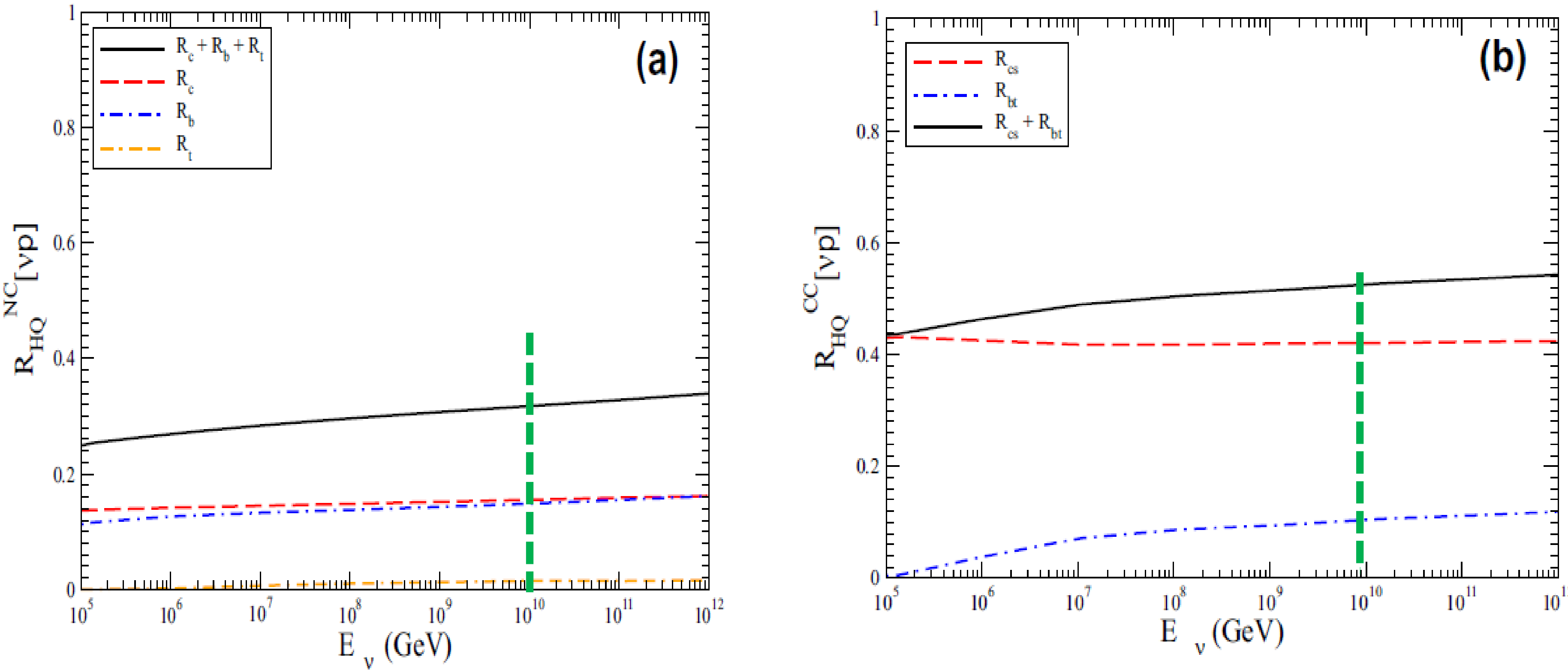
Heavy quark production in photon - hadron interactions at ultra high energies



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

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

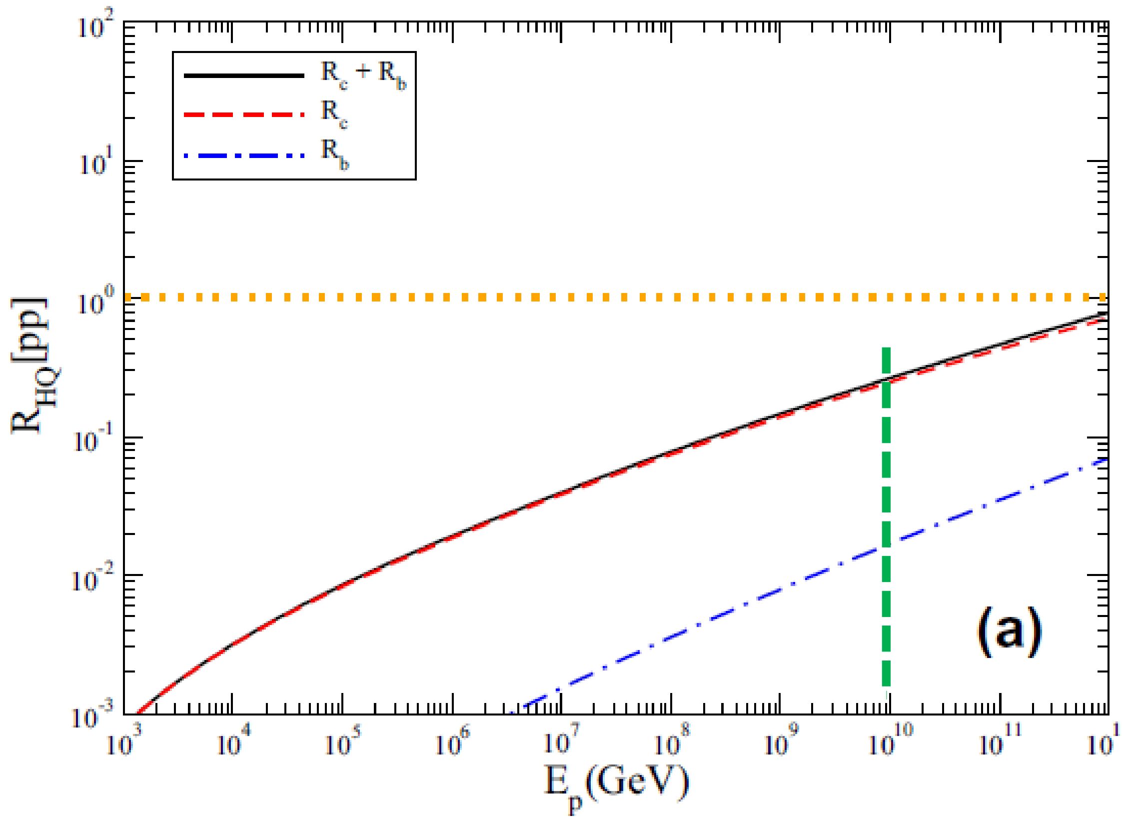
Heavy quark production in neutrino - hadron interactions at ultra high energies



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

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

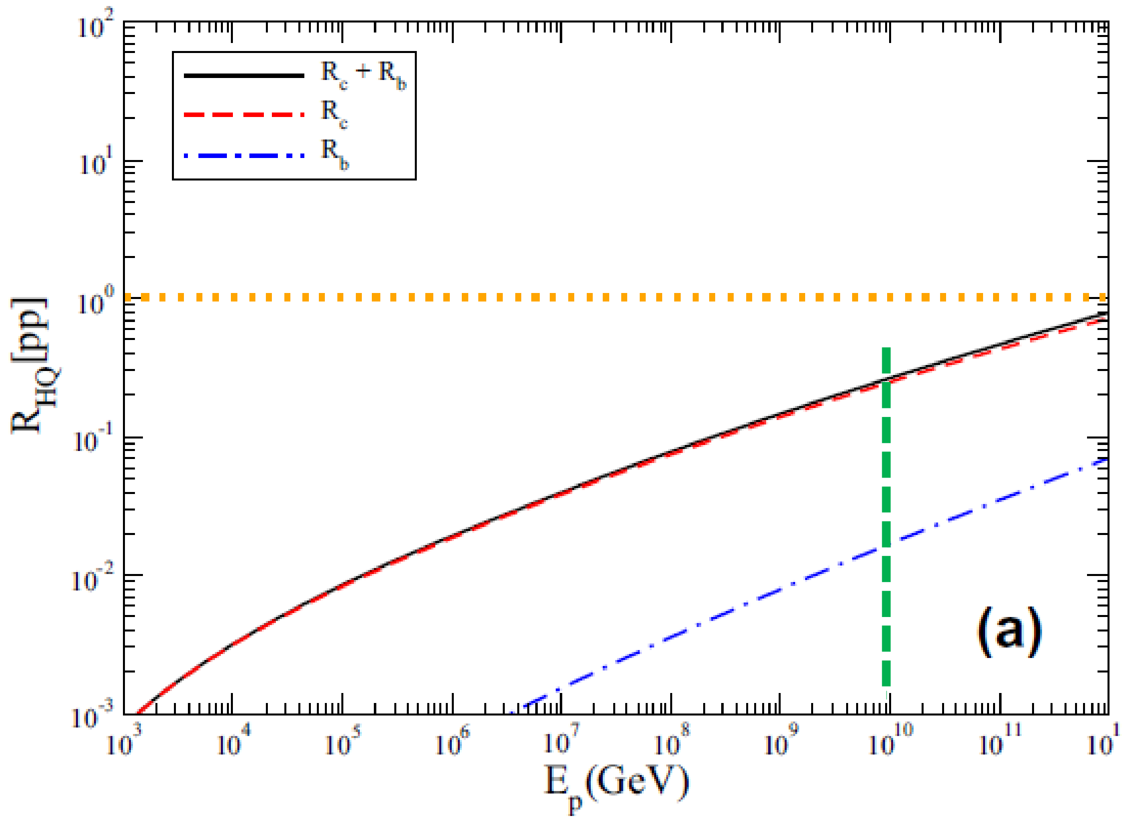
Heavy quark production in hadron - hadron interactions at ultra high energies



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

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

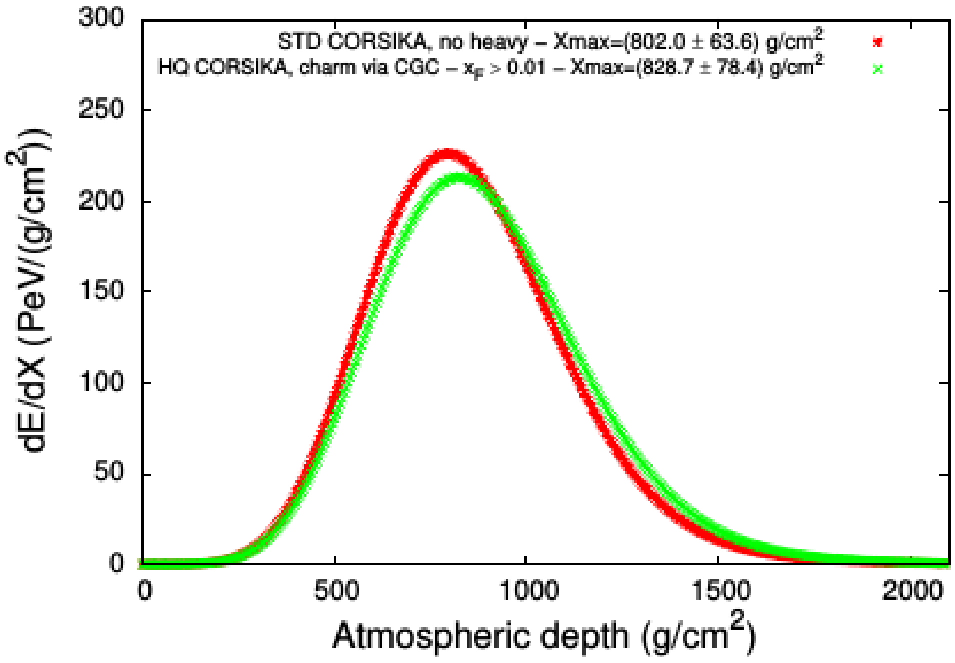
Heavy quark production in hadron - hadron interactions at ultra high energies

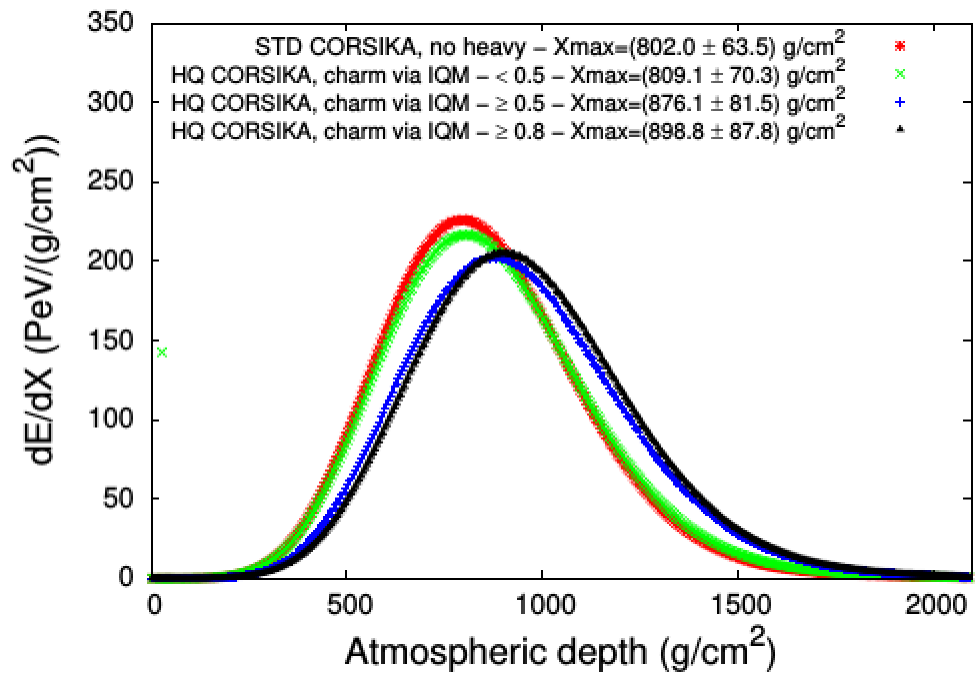


Main conclusion: The contribution of the heavy quark contribution cannot be disregarded in the description of the air showers at high energies.

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

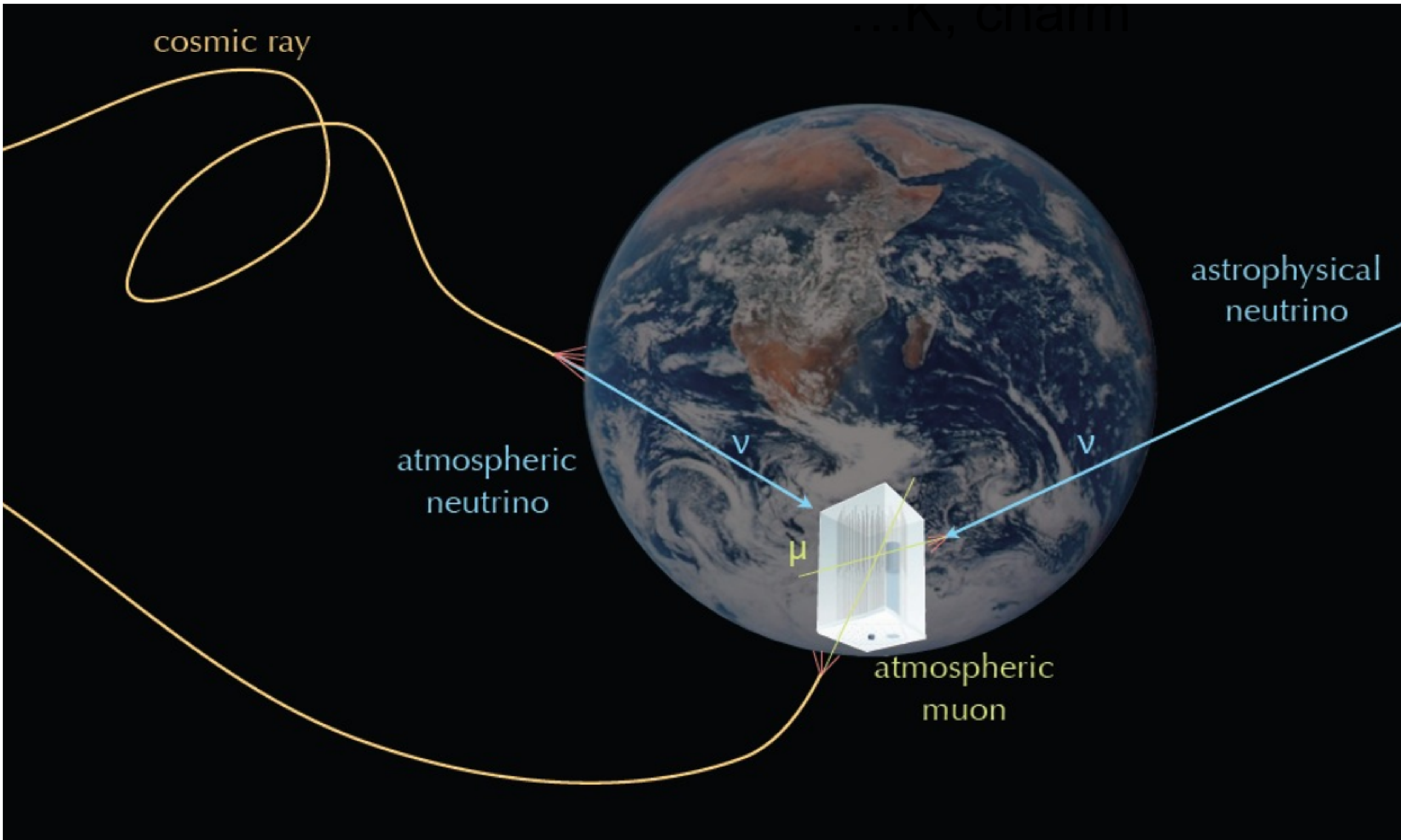




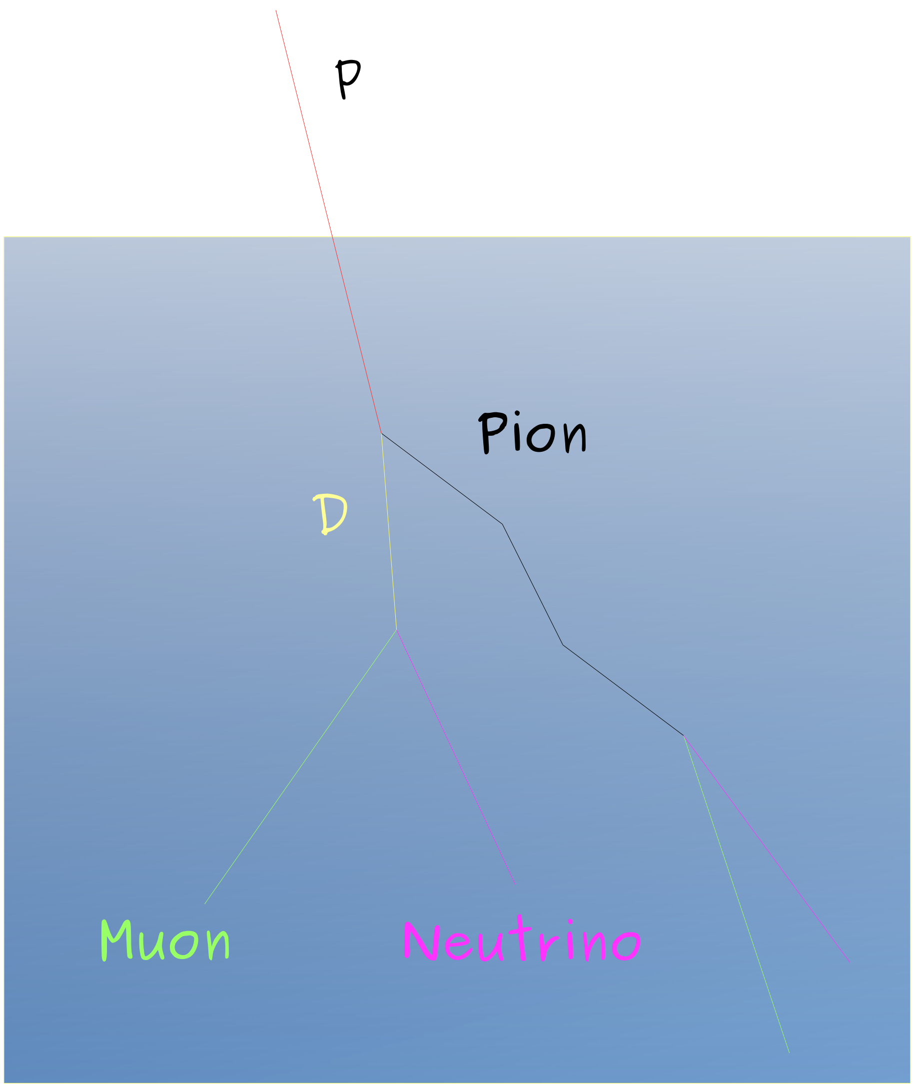
VPG, M. Muller, paper in preparation

Impact of the heavy quark production in the atmospheric neutrino flux

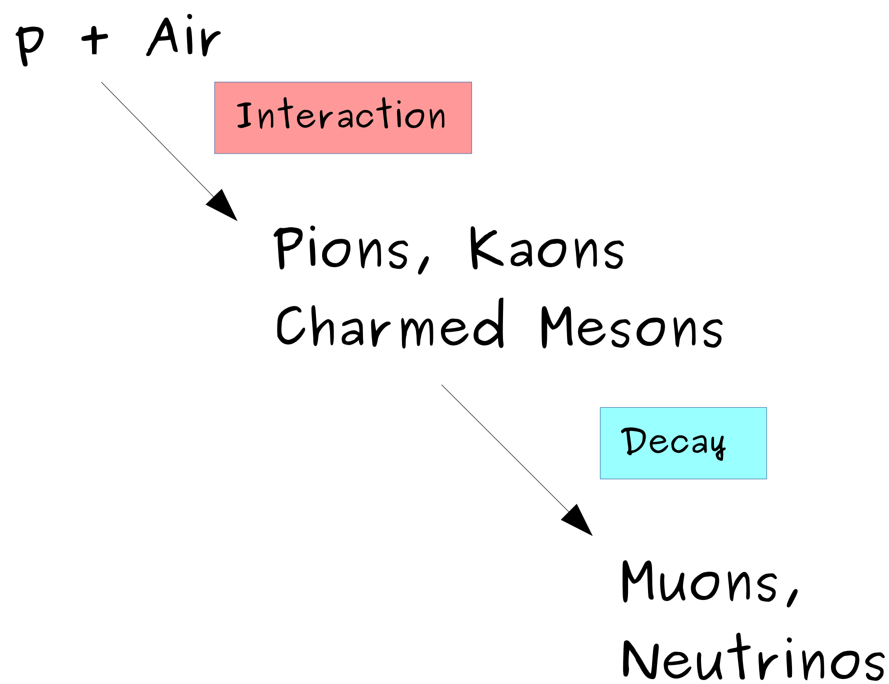
Neutrinos at IceCube



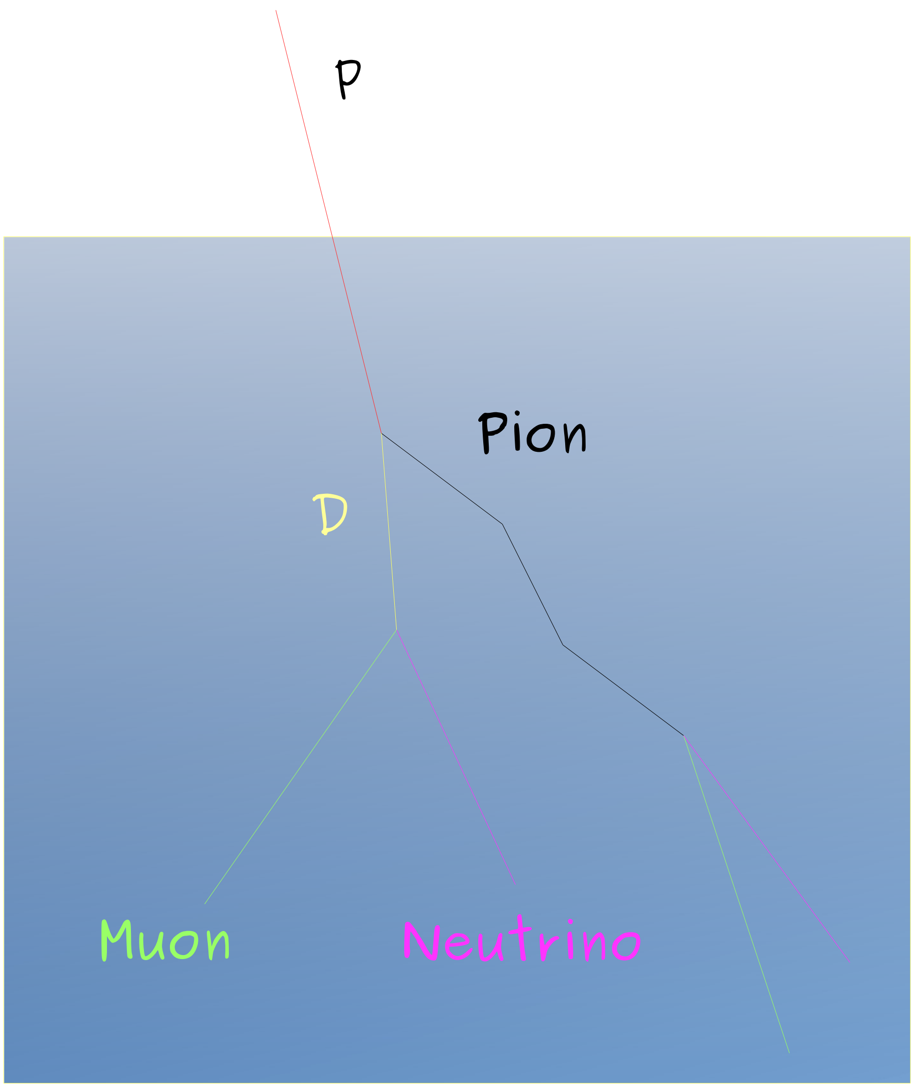
Atmospheric Neutrinos



Neutrinos in atmosphere originate from the interactions of cosmic rays with nuclei (<A> = 14.5).



Atmospheric Neutrinos



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

p + Air

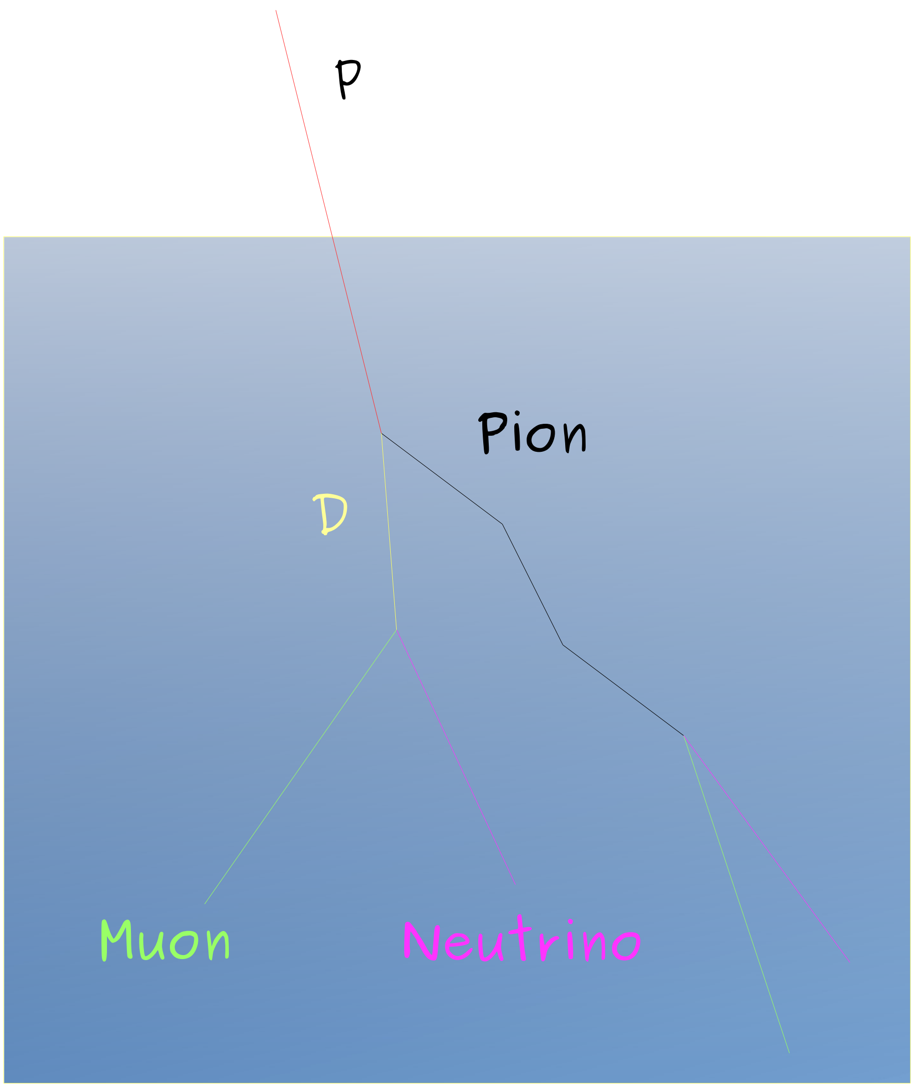
↓ Interaction

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 + Air

→ Interaction →

Pions, Kaons

Charmed Mesons

→ Decay →

Prompt Neutrinos

Atmospheric Neutrinos:
Conventional contribution

p + Air

↓ Interaction

Pions, Kaons

↓ Decay

Conventional Neutrinos

Light Mesons:

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

- Interaction occurs before decay and the mesons loose 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

p + Air

→ Interaction →

Charmed Mesons

→ Decay →

Prompt Neutrinos

Charmed Mesons:

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

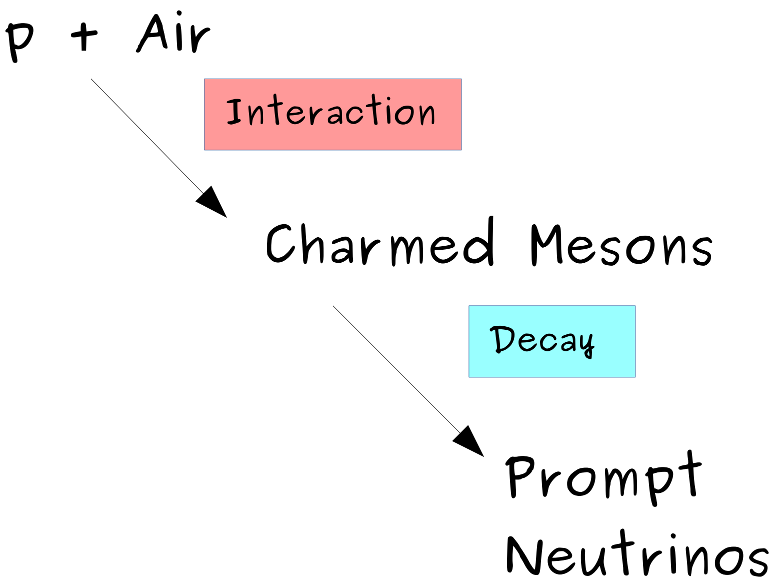
- Decay occurs before interaction and the mesons transfer its energy for the neutrinos.

- 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:

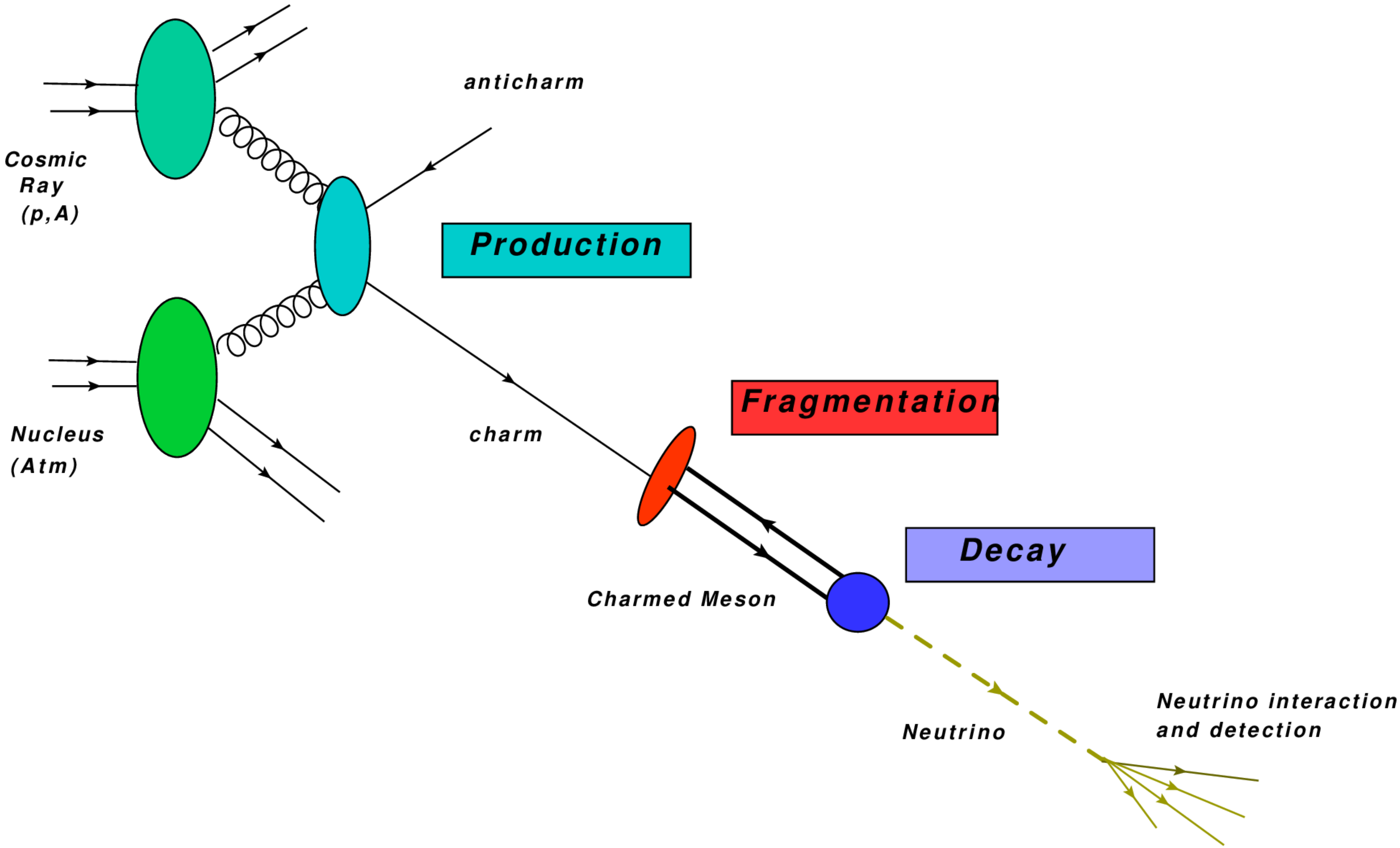
Mean lifetime: $\tau \sim 10^{-12}\ s$

- 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.

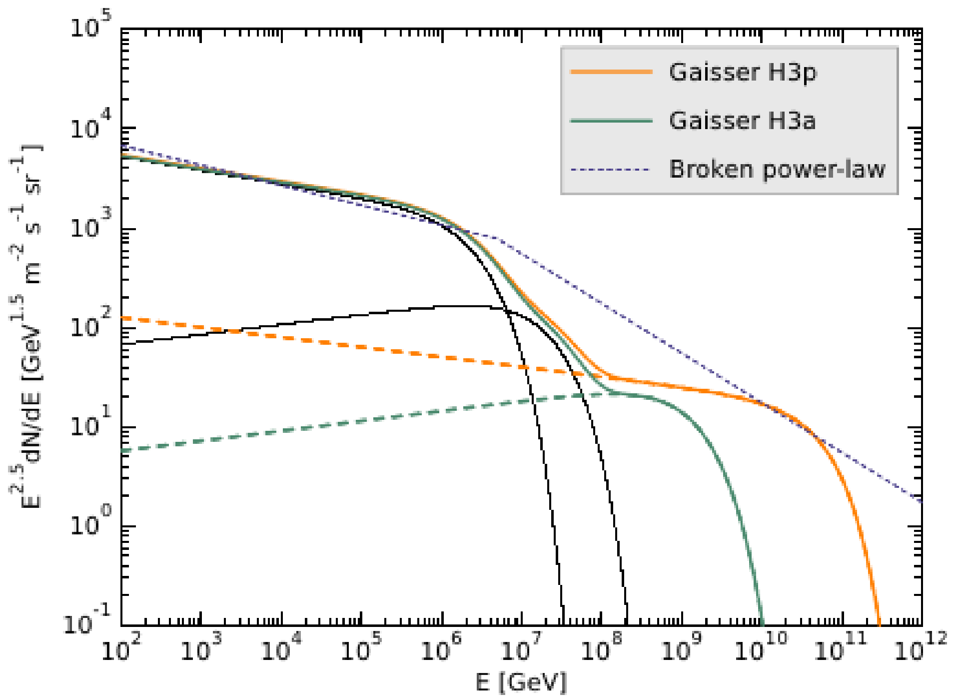
- The cascade equations can be solved numerically or semi-analytically via the Z- moment method.

- Main inputs:
  1.) Initial nucleon flux
  2.) Feynman distribution for the charm production

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

$x_F \approx E_c/E_p = x_1 - x_2$ $\quad$ $x_2 \approx M^2_{Q\bar{Q}}/x_1 s \to 0$ at $s \gg M^2_{Q\bar{Q}}$

Initial Cosmic Ray flux

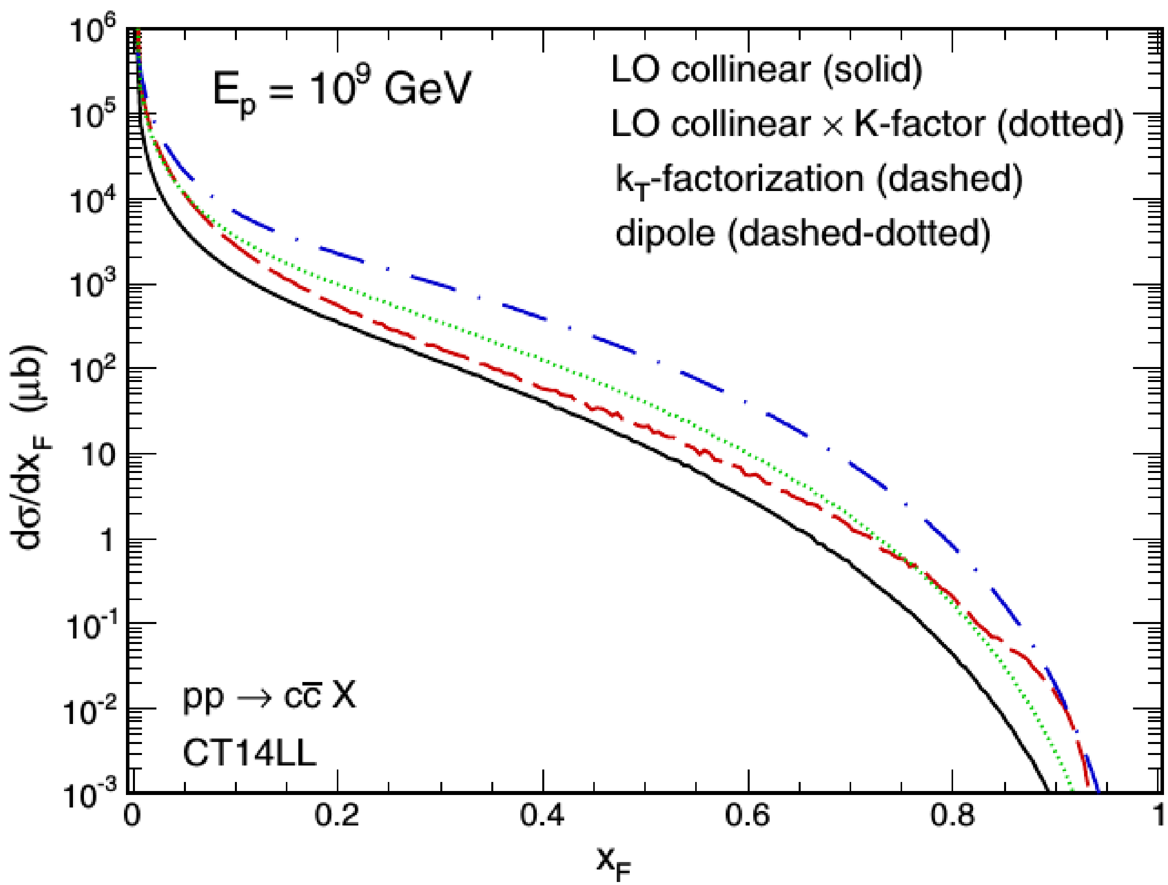


$$\phi_p^0(E) = \begin{cases} 1.7\,E^{-2.7} & \text{for } E < 5 \cdot 10^6 \text{ GeV} \\ 174\,E^{-3} & \text{for } E > 5 \cdot 10^6 \text{ GeV}, \end{cases}$$

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

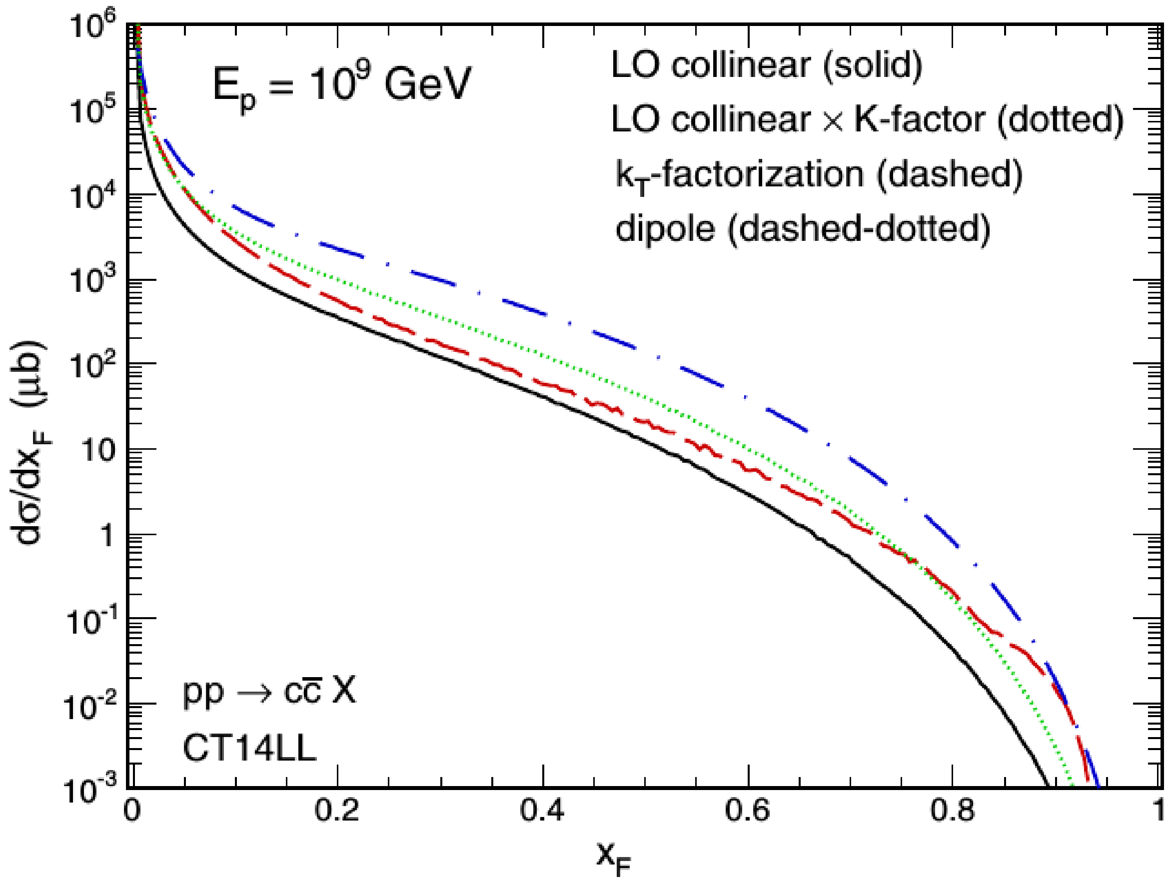
Large uncertainty connected with the limited knowledge of the extremely high - energy cosmic ray composition.

Feynman distribution for the charm production



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

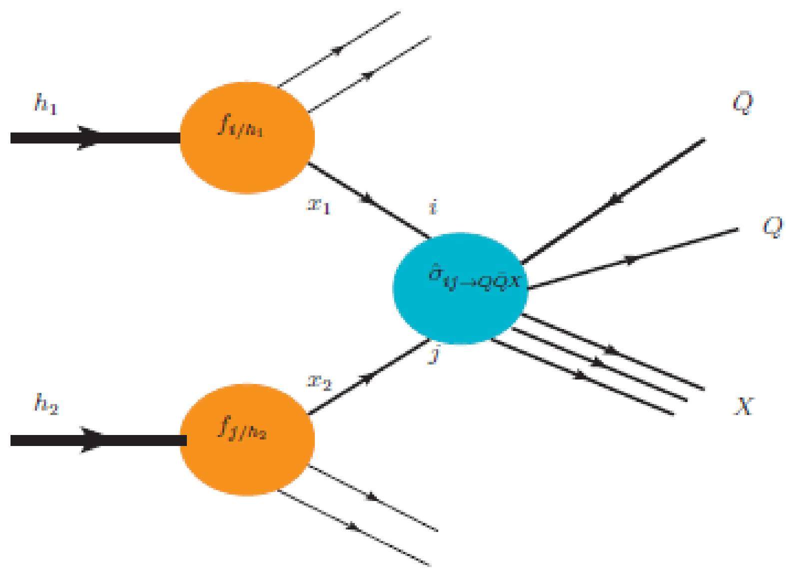
Feynman distribution for the charm production



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

In what follows we will assume the standard collinear approach.

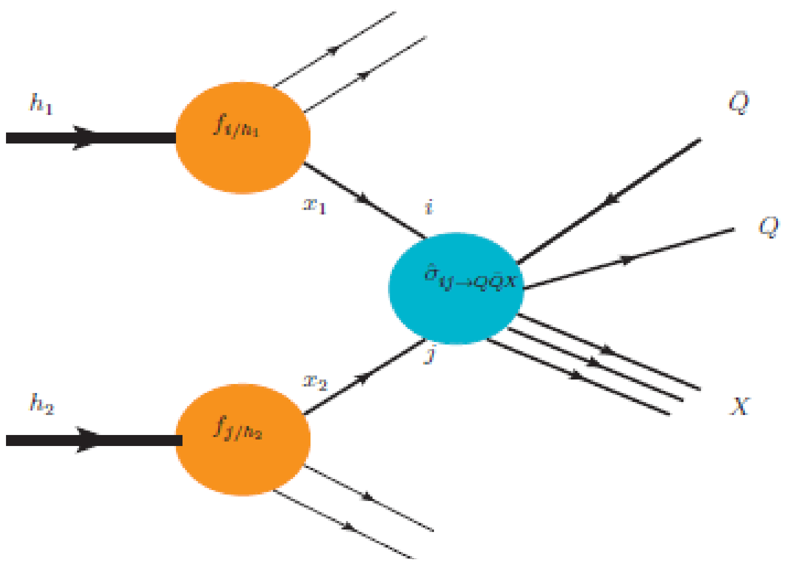
Heavy quark production: Collinear factorization approach



- 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.

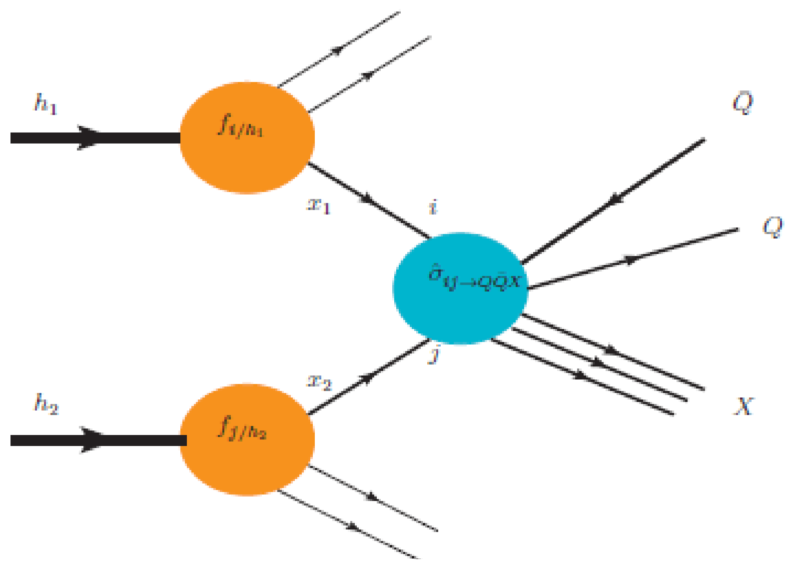
Heavy quark production: Collinear factorization approach



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

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

Heavy quark production: Collinear factorization approach



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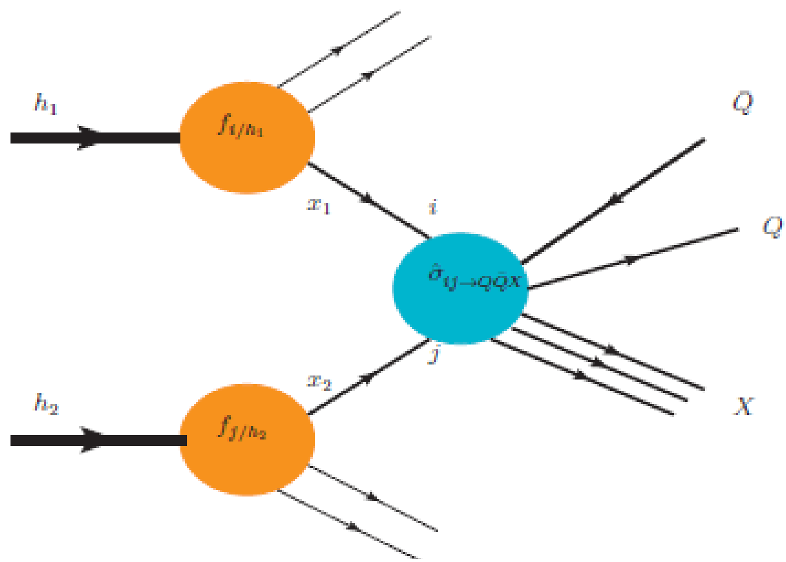
Partonic Cross Sections

Heavy quark production: Collinear factorization approach



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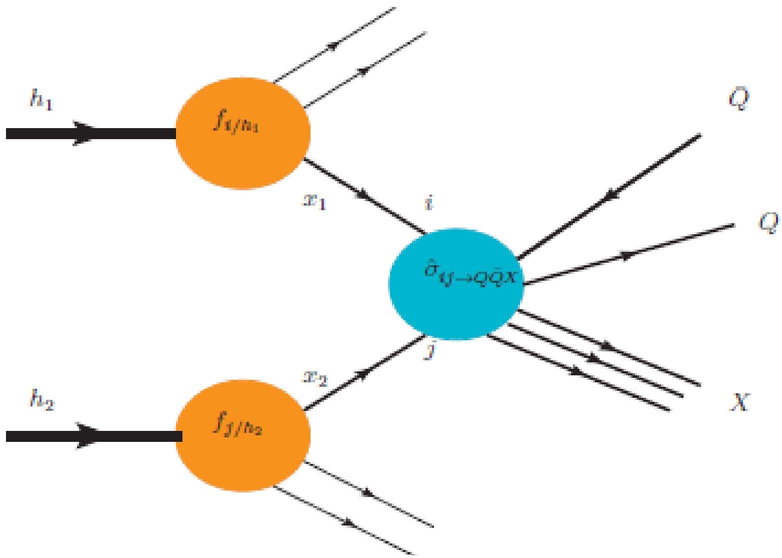
Partonic Cross Sections

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

LO NLO NNLO

Heavy quark production: Collinear factorization approach



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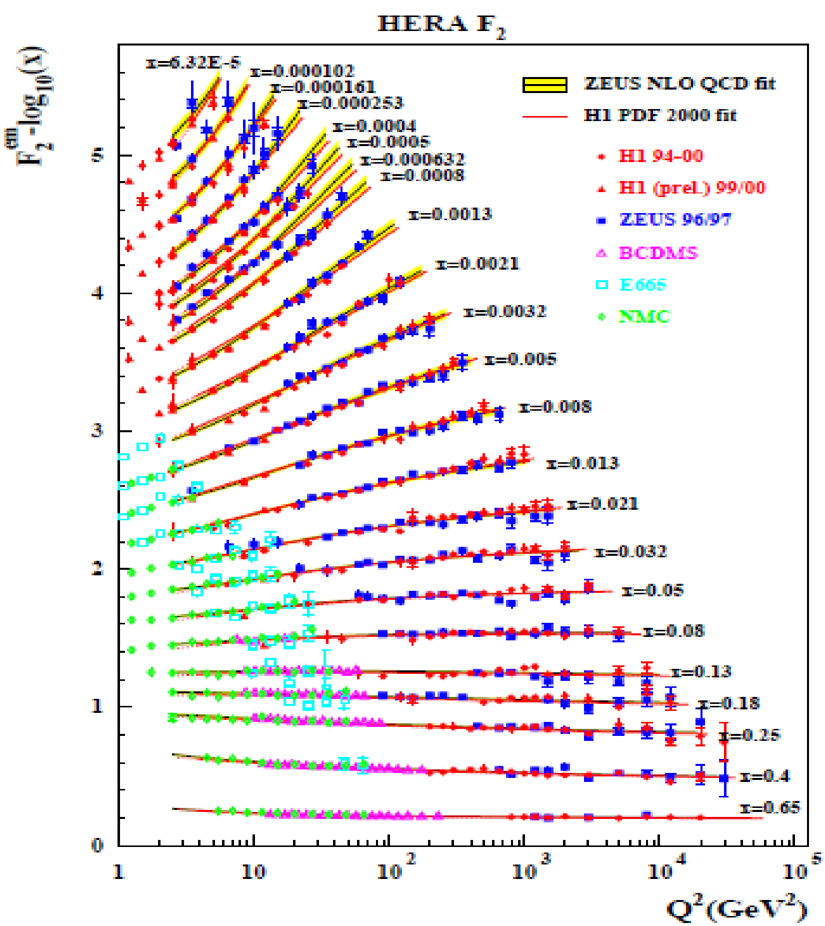
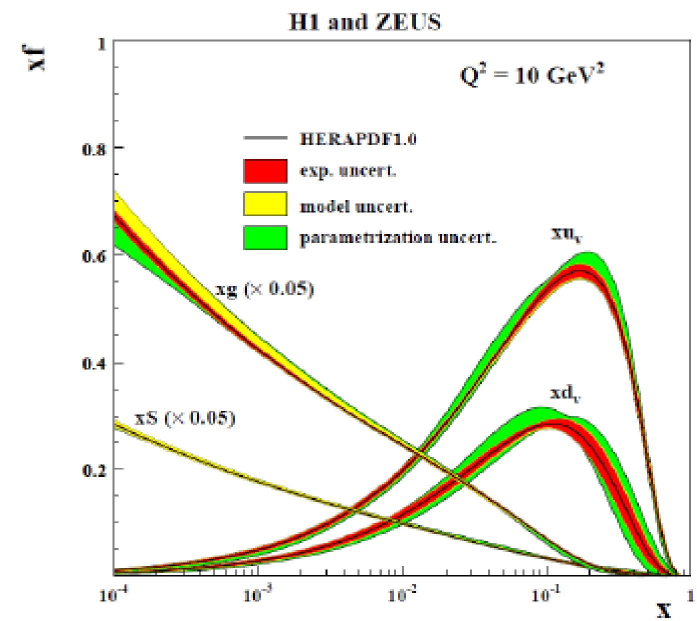
Parton Distribution Functions

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.

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:

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

In particular, we estimate the Z-momentum assuming:

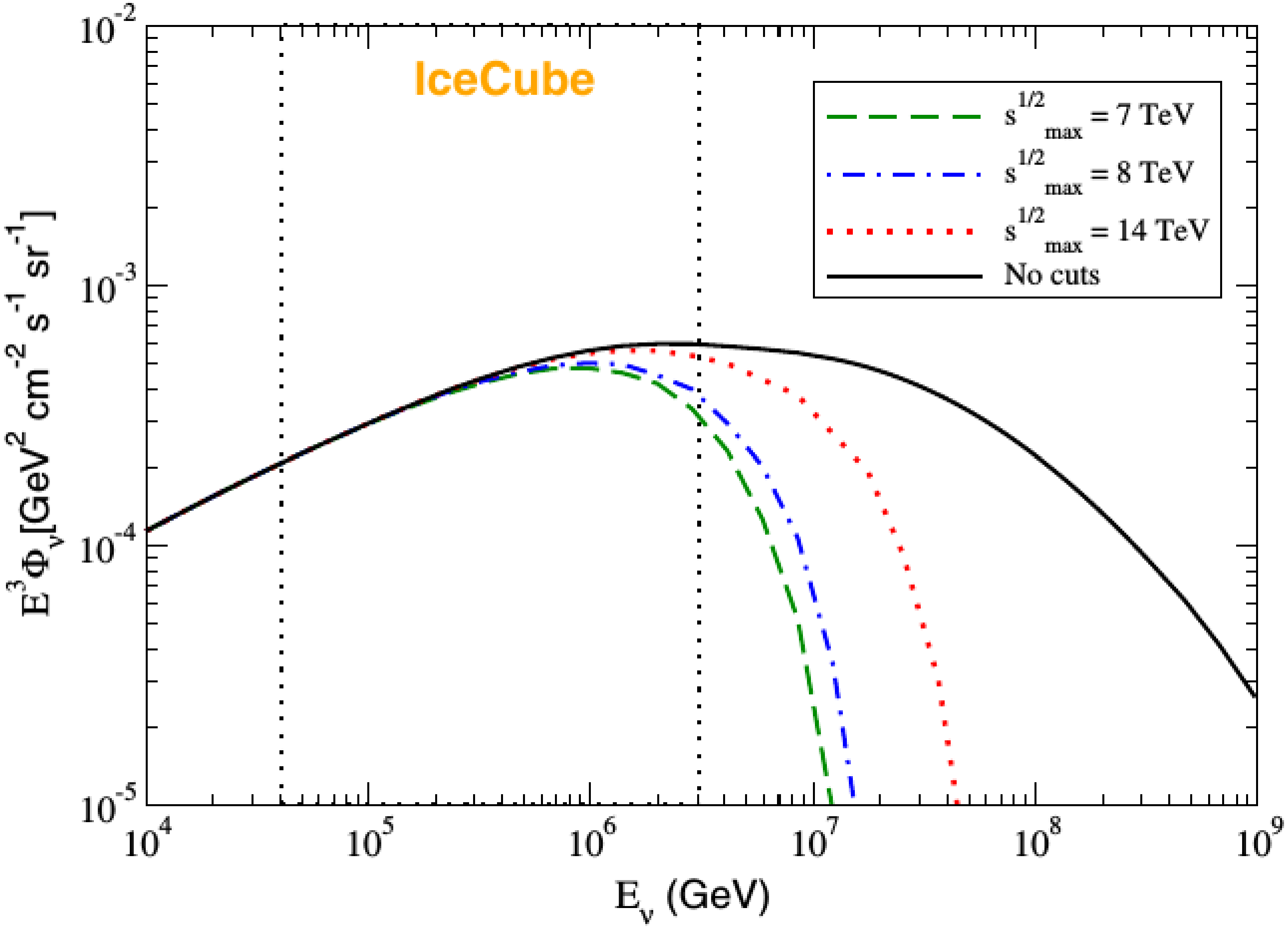
1.) a maximum value for the center of mass energy present in the proton - proton scattering;

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.

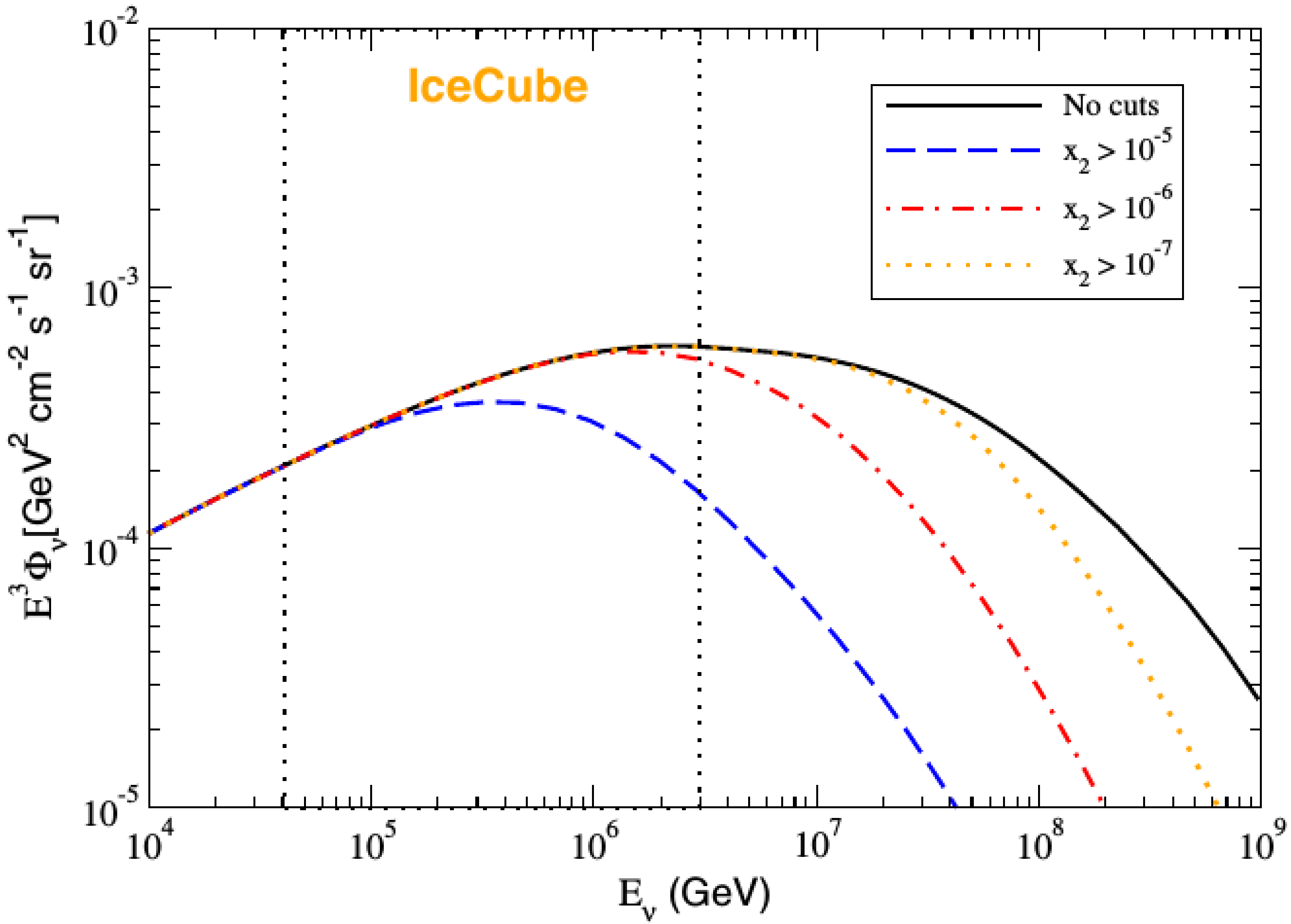
VPG, R. Maciula, R. Pasechnik, A. Szczurek, PRD 96 (2017) 094026

Mapping the typical values of center - of - mass energies



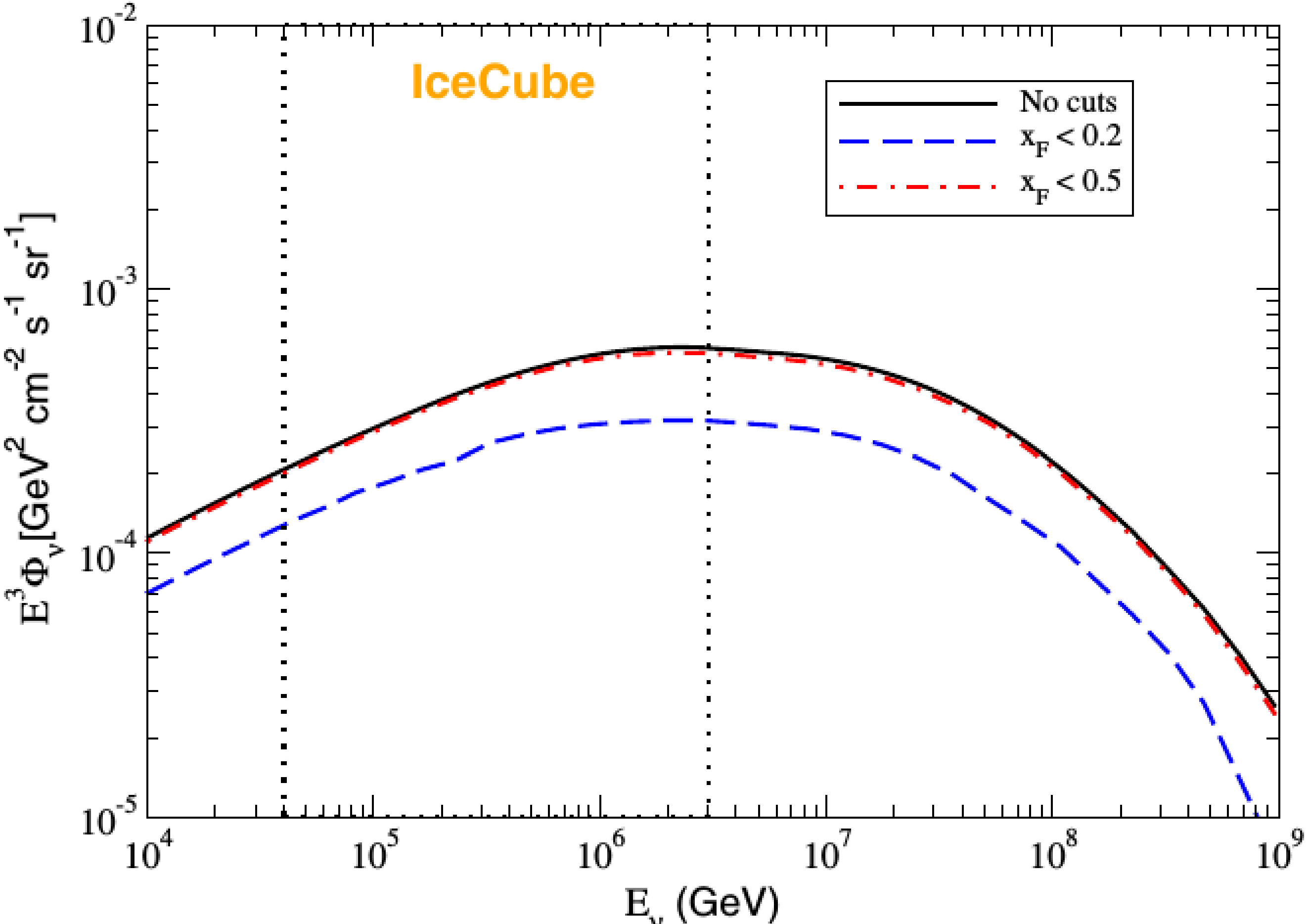
The production of neutrinos with energy larger than 10^7 GeV is sensitive to the c.m. energies larger than ones at the LHC.

Mapping the typical values of the target momentum fraction



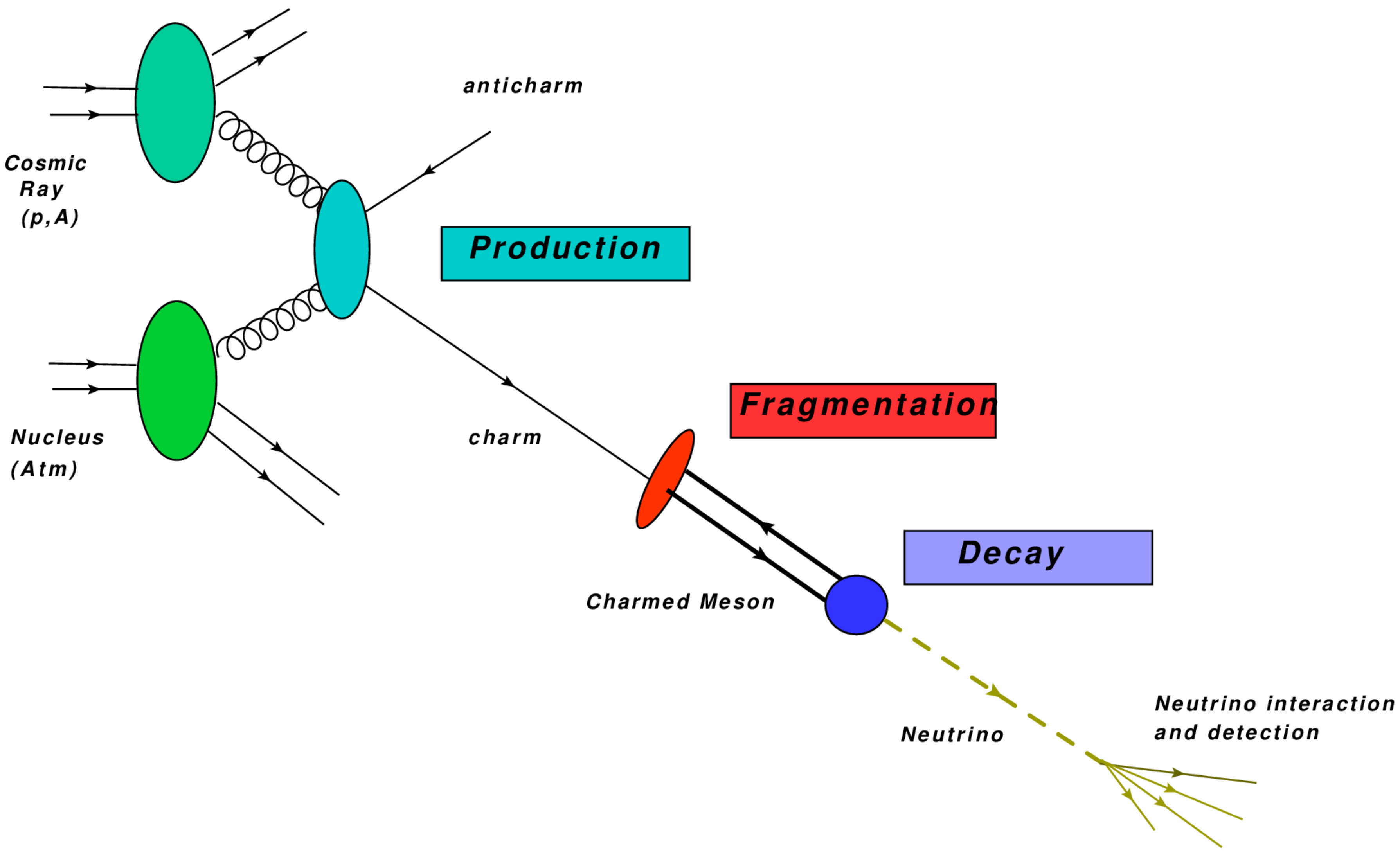
The production of neutrinos with energy larger than 10^5 GeV is sensitive to the longitudinal momentum fractions of the projectile in the range $x < 10^{-5}$. This region is poorly constrained by the current collider data.

Mapping the typical values of Feynman x variable

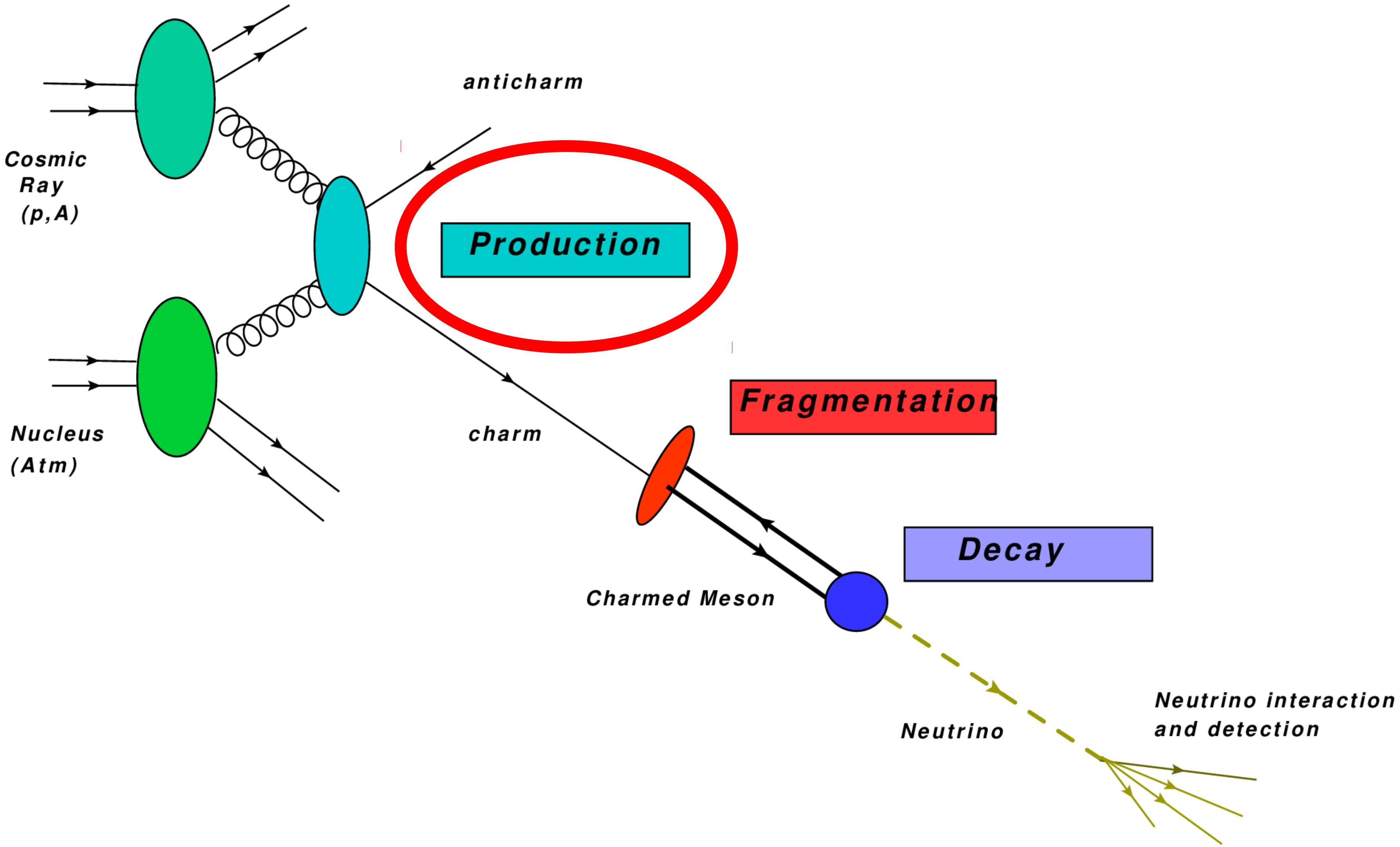


The dominant contribution to the neutrino flux comes from x_F in the region $0.2 < x_F < 0.5$, which is associated to the charm production at very forward rapidities (beyond LHCb).

Atmospheric Neutrinos:
Prompt contribution



Atmospheric Neutrinos:
Prompt contribution



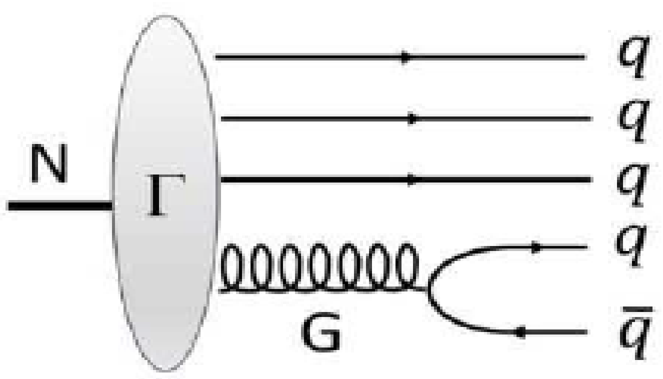
Intrinsic heavy quark

The wavefunction of a hadron in QCD can be represented as a superposition of Fock state fluctuations:

$$|N\rangle = \alpha_0 |n_V\rangle + \alpha_1 |n_V g\rangle + \alpha_2 |n_V Q\bar{Q}\rangle + \ldots$$

The extra gluons and quark pairs in the higher Fock states arise from QCD interactions.

→ Contributions which are due a single gluon splitting such as g → c cbar are extrinsic to the bound state nature of the hadron. Generated on a short time scale associated with large transverse momentum.



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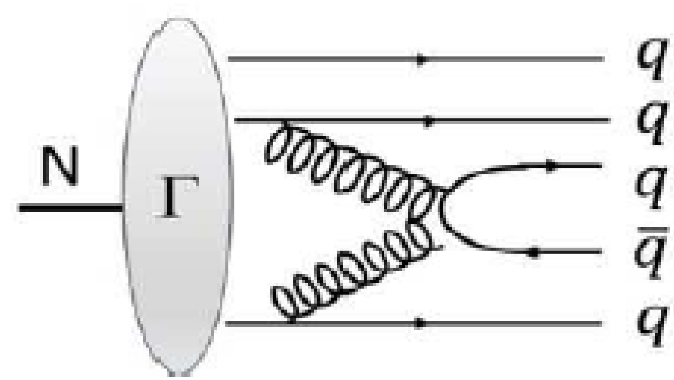
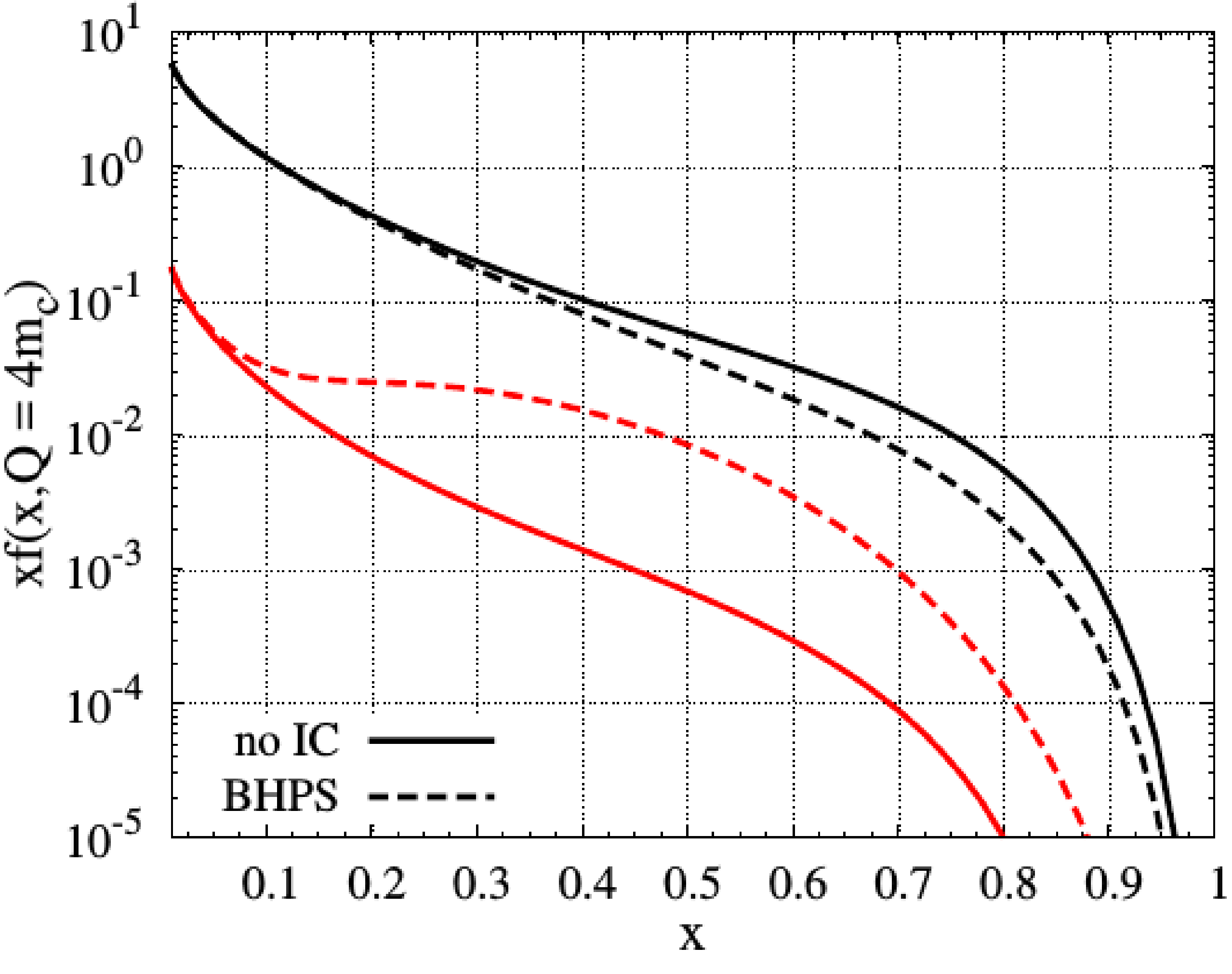
The extra gluons and quark pairs in the higher Fock states arise from QCD interactions.

→ In contrast, heavy quark pairs multiply connected to the valence quarks cannot be attributed to the gluon structure, and are intrinsic to the hadron's wavefunction (*). Exist over a time scale which is independent of any probe transverse momentum.

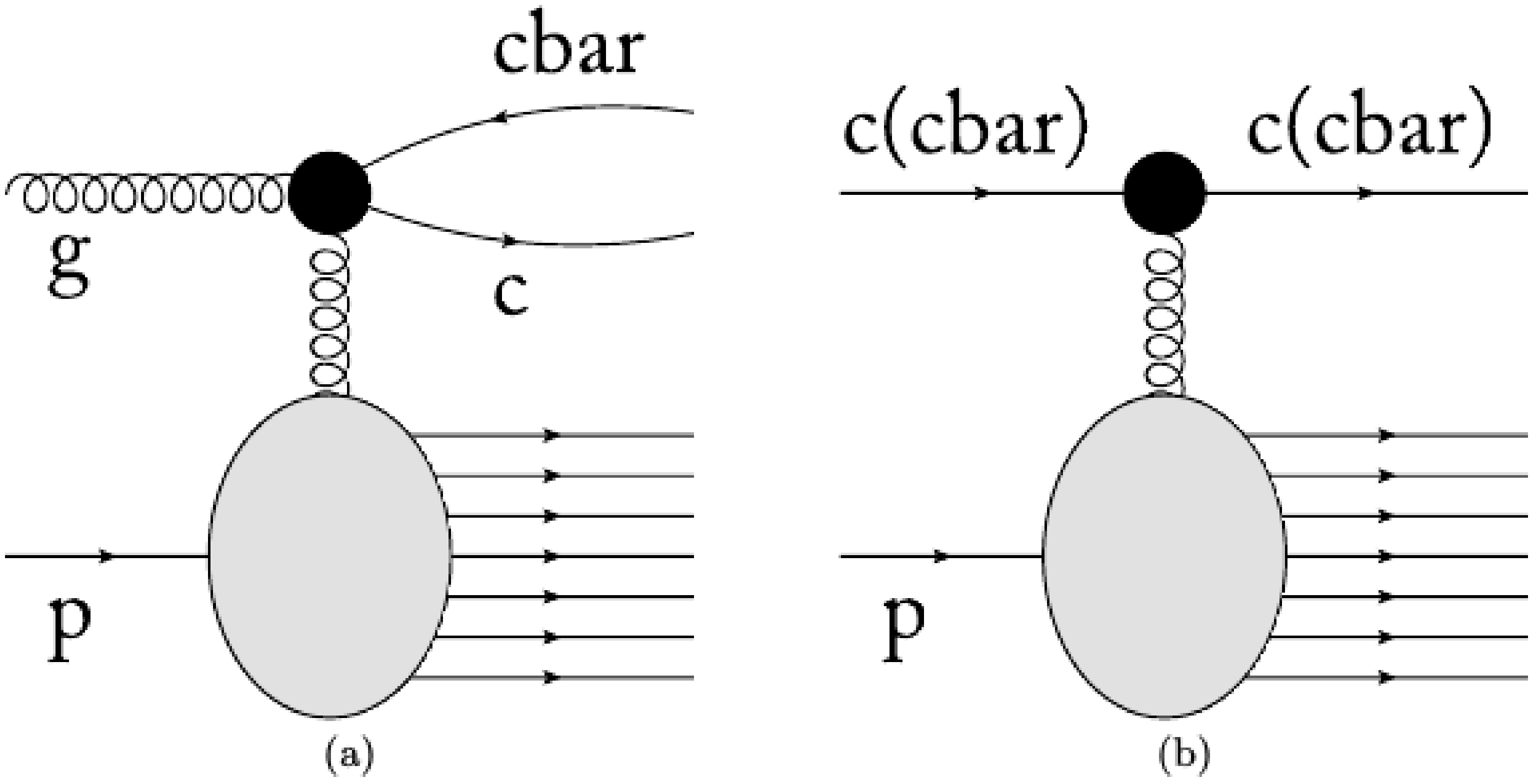


(*) Brodsky, Hoyer, Peterson, Sakai, PLB93 (1980) 451

Intrinsic heavy quark

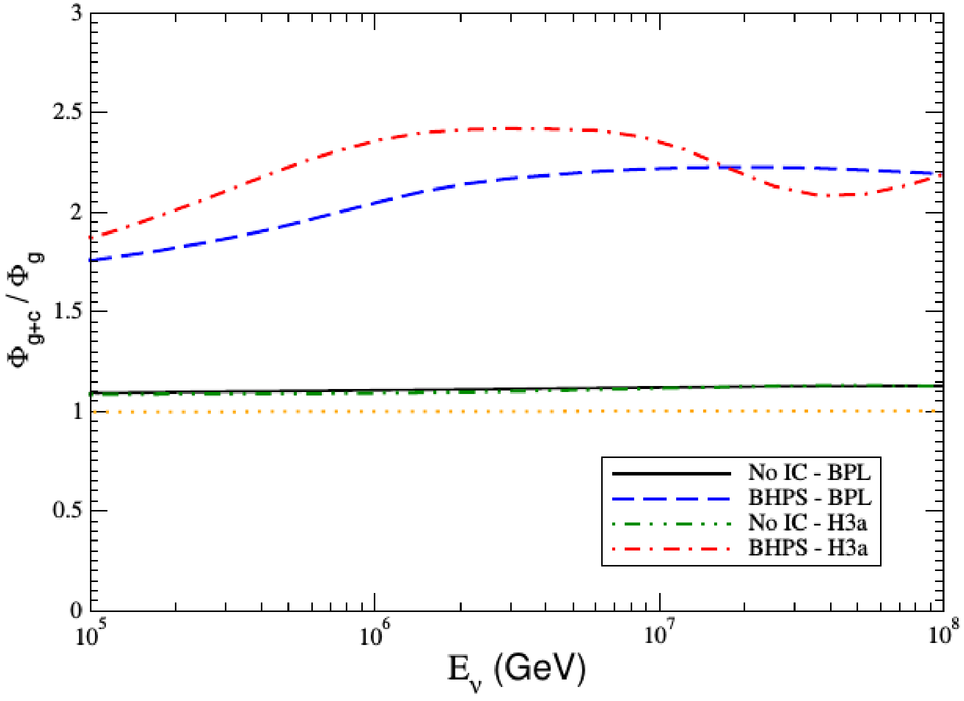


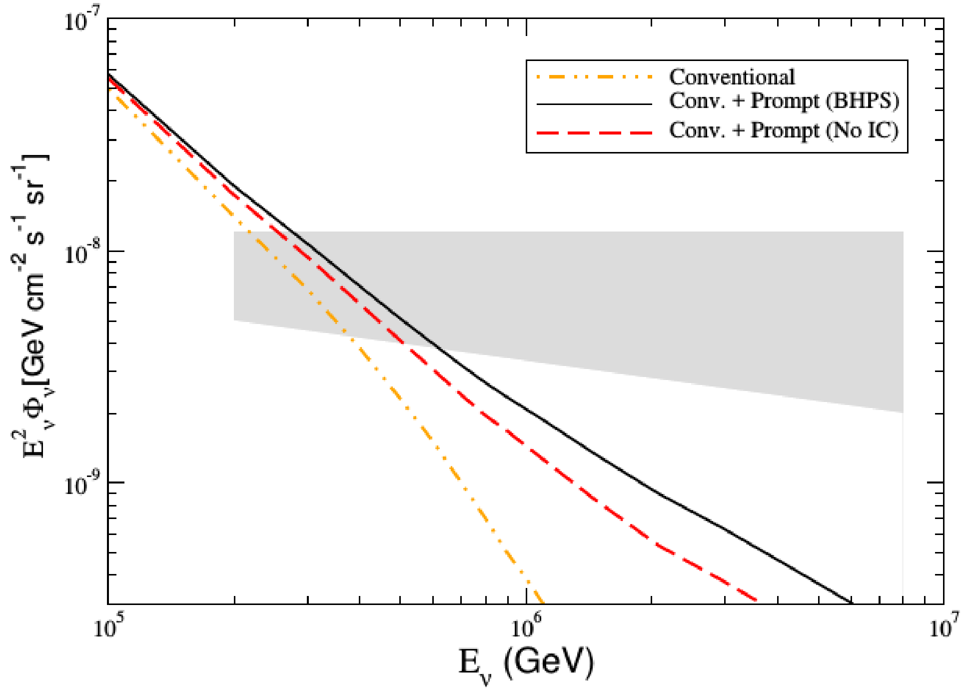
Intrinsic charm contribution to the prompt atmospheric neutrino flux



A.V. Giannini, VPG, F. S. Navarra, PRD 98 (2018) 014012

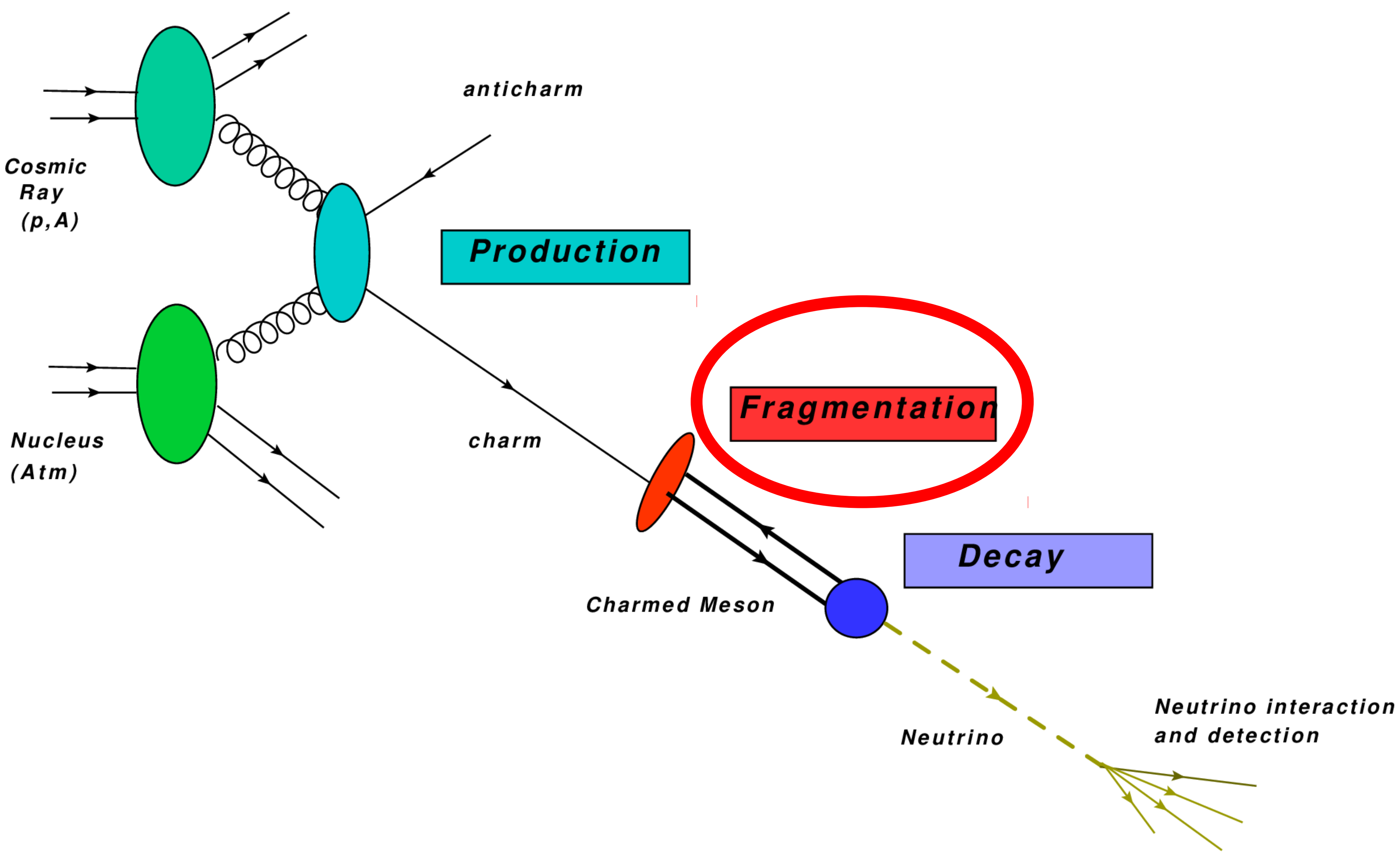
Intrinsic charm contribution to the prompt atmospheric neutrino flux





A.V. Giannini, VPG, F. S. Navarra, PRD 98 (2018) 014012

Atmospheric Neutrinos:
Prompt contribution



Heavy meson production

At large transverse momentum the hadronization is described by the fragmentation process.

Dominant process for Ds production:

gg → c cbar → c (sbar s) cbar → (c sbar) (s cbar) -> Ds+ Ds−

→ Predicts that #Ds+ = #Ds−

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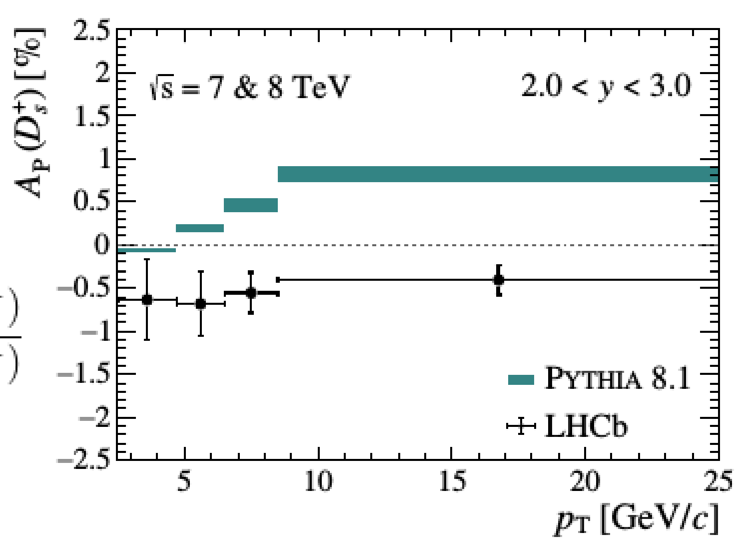
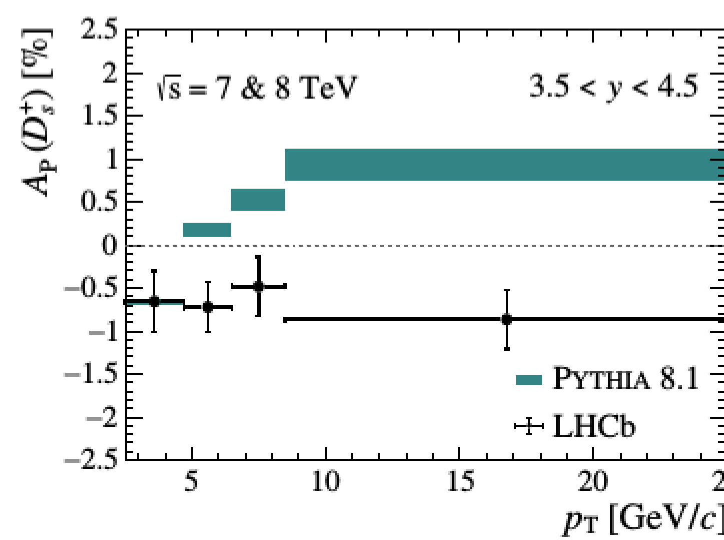
LHCb results:

$$A_{\mathrm{P}}(D_s^+) = \frac{\sigma(D_s^+) - \sigma(D_s^-)}{\sigma(D_s^+) + \sigma(D_s^-)}$$





Heavy meson production

From $D_s^\pm$ production asymmetry at the LHC to prompt ν_τ at IceCube

Victor P. Goncalves[*]
Instituto de Física e Matemática, Universidade Federal de Pelotas (UFPel), Caixa Postal 354, CEP 96010-900, Pelotas, RS, Brazil

Rafał Maciuła[†] and Antoni Szczurek[‡§]
Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, PL-31-342 Kraków, Poland

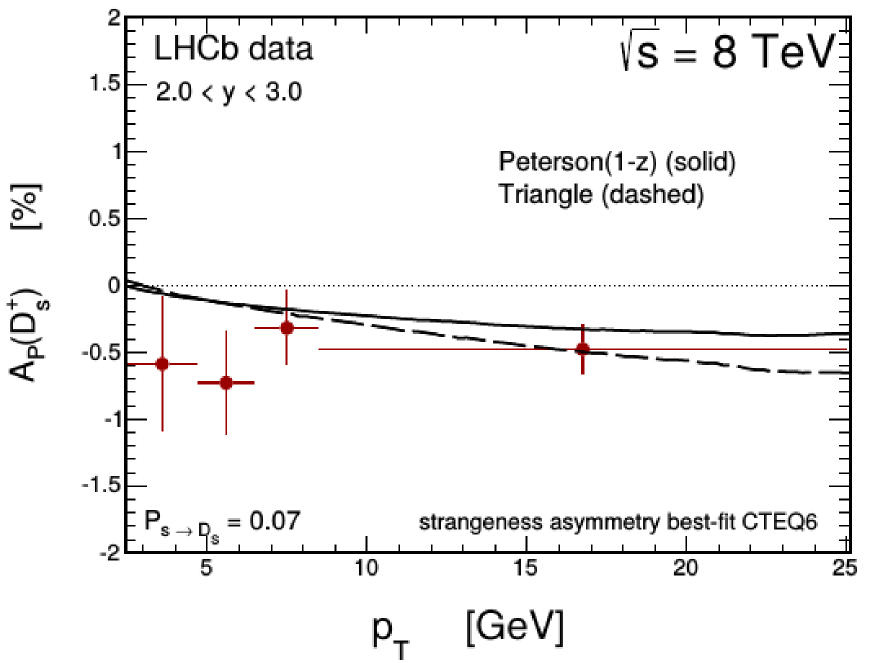
Our proposal: Take into account the contribution of the subleading fragmentation processes associated to the channels:

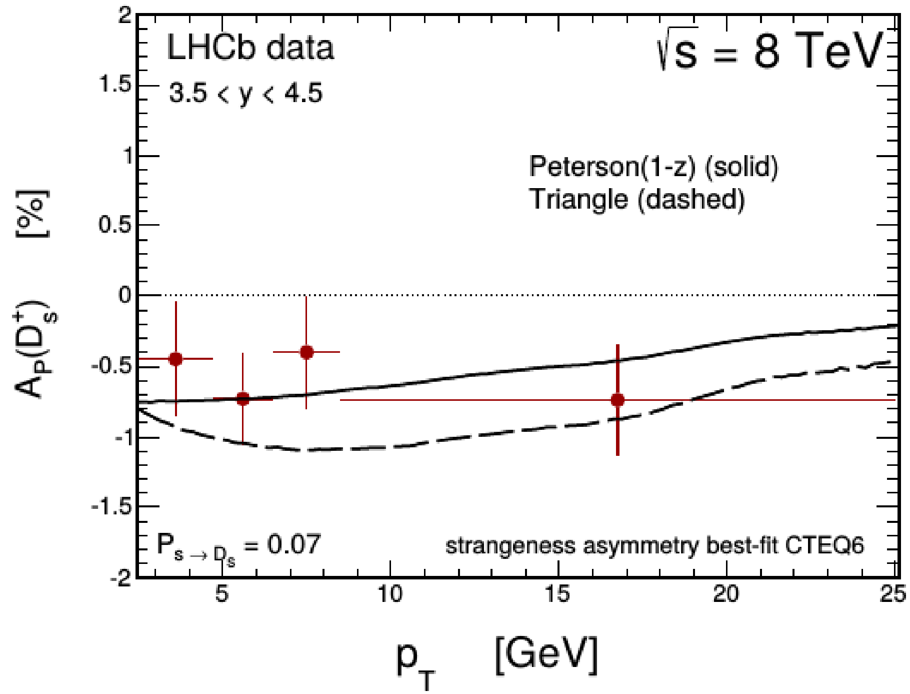
g s → g s → Ds−   and   g sbar → g sbar → Ds+

And that strange sea is asymmetric (s ≠ sbar) as described by the global analysis by the CTEQ Collaboration.

VPG, R Maciula, A. Szczurek, arXiv: 1809.05424

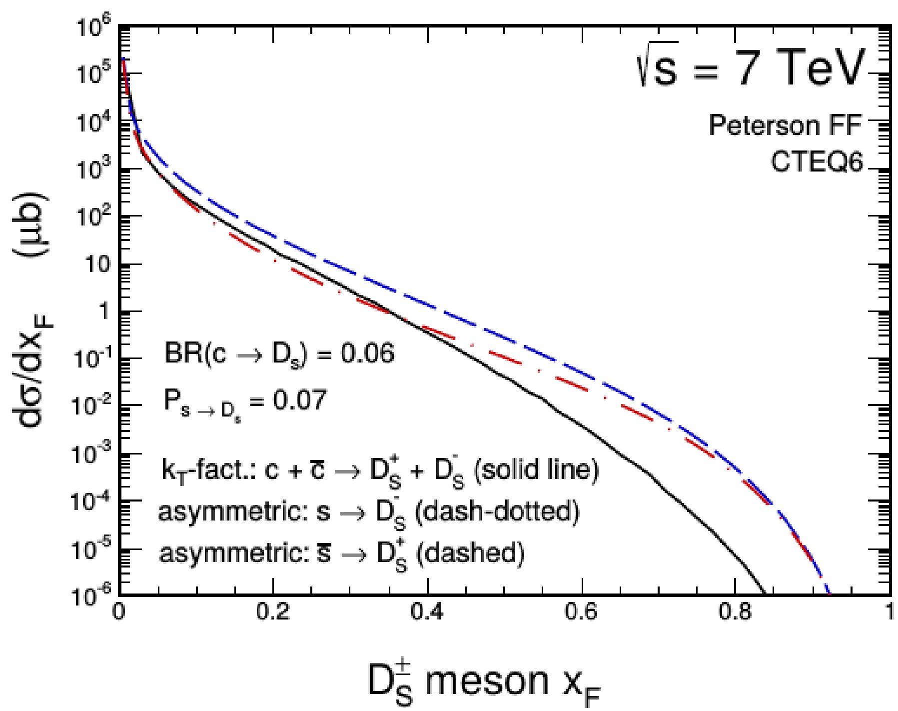
Heavy meson production

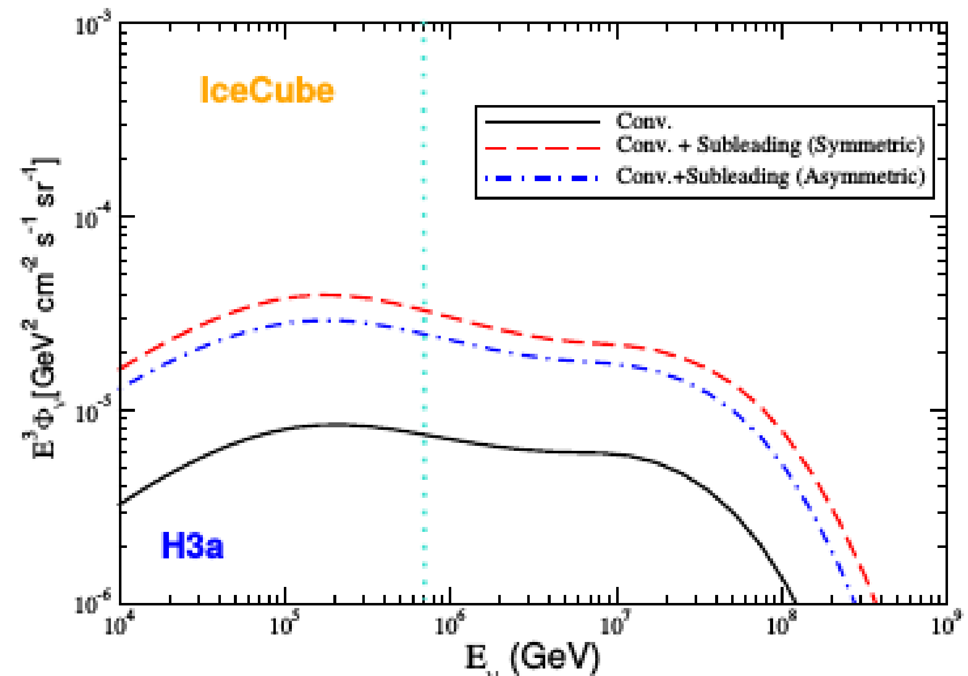




VPG, R Maciula, A. Szczurek, arXiv: 1809.05424

Impact on the prompt tau neutrino flux





Decay channels: $\begin{cases} D_s \to \nu_\tau \\ D_s \to \tau \to \nu_\tau \end{cases}$

VPG, R Maciula, A. Szczurek, arXiv: 1809.05424

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.
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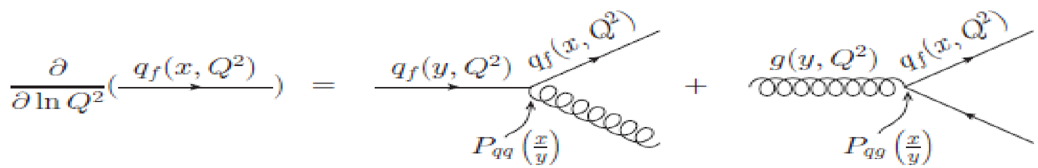
Thank you for your attention!

Extras

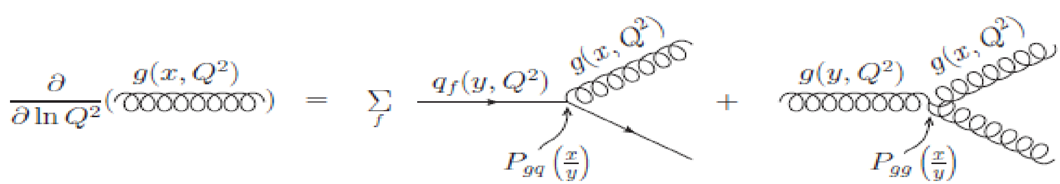
Parton distribution functions

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



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



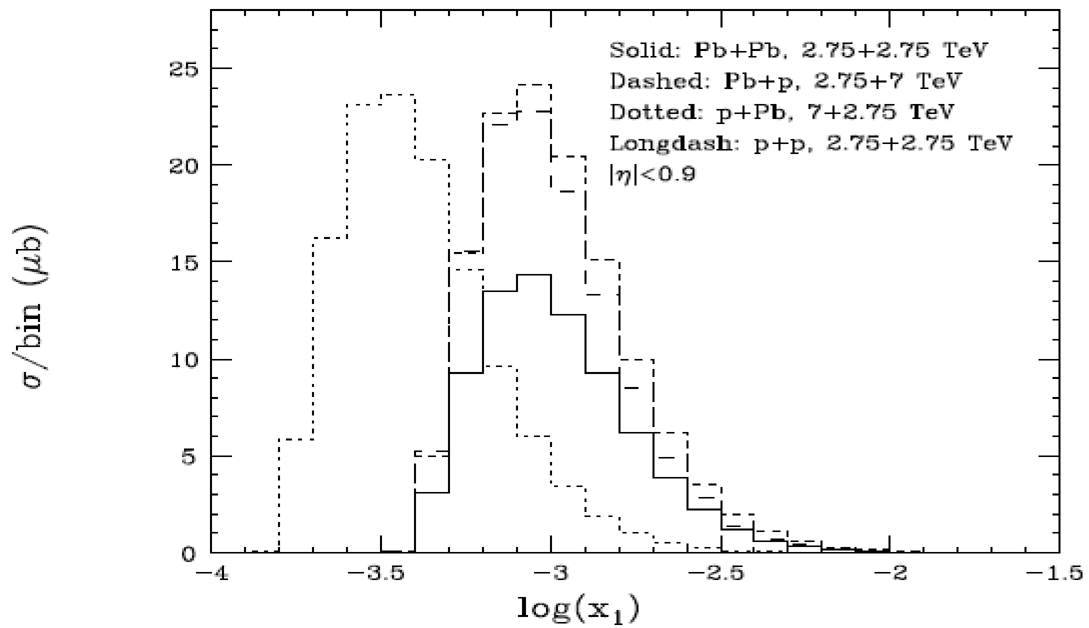
  - **Splitting functions:** $$P_{ab}(\alpha_S, z) = \frac{\alpha_S}{2\pi}P_{ab}^{(0)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^2 P_{ab}^{(1)}(z) + \left(\frac{\alpha_S}{2\pi}\right)^3 P_{ab}^{(2)}(z) + ...$$

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

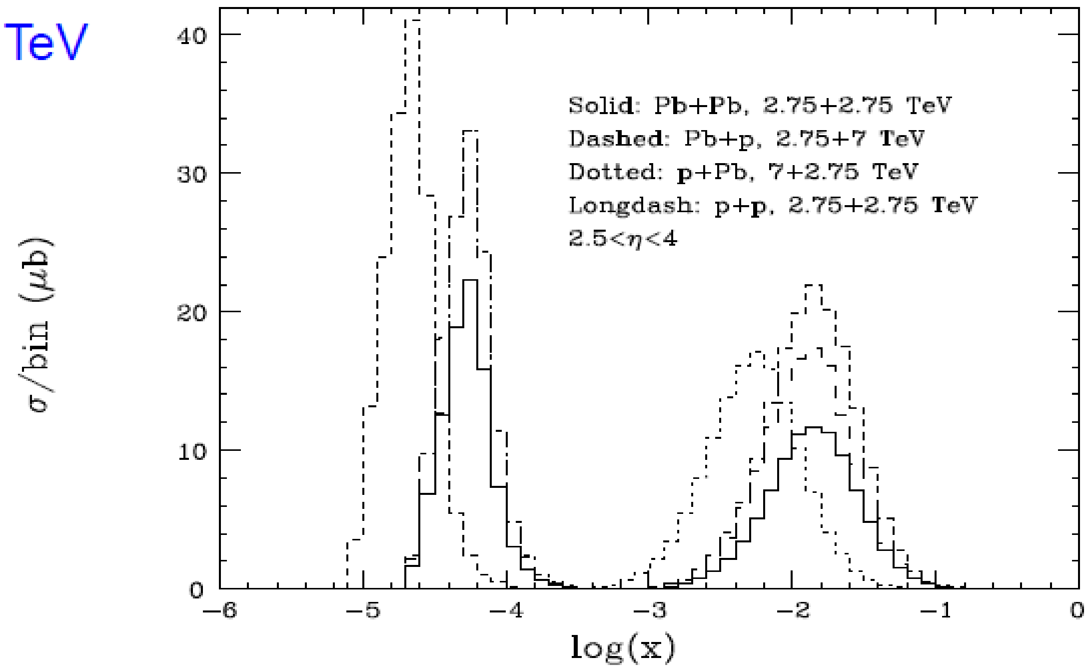


Charm production at the LHC

- Typical values of x for charm production at the LHC

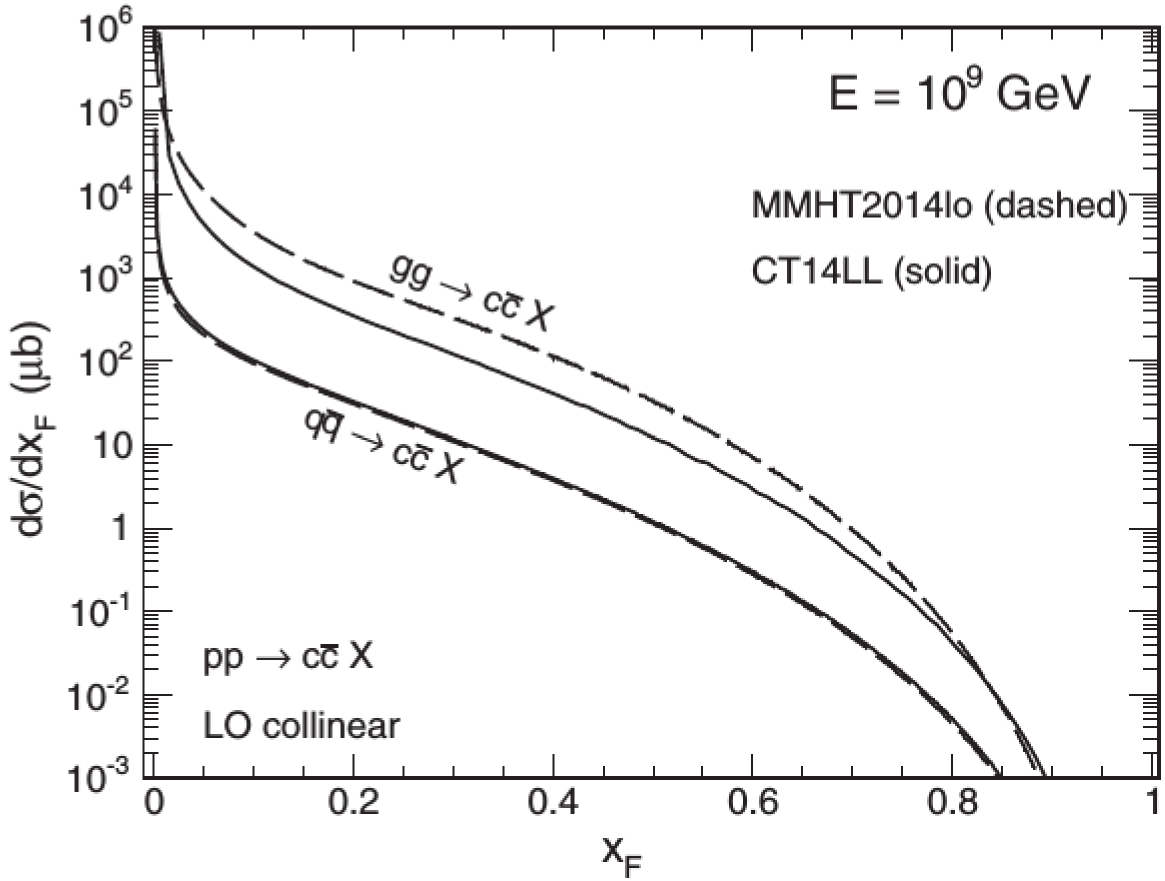
- pp collisions at $\sqrt{s} = 5.5$ TeV

Forward rapidity



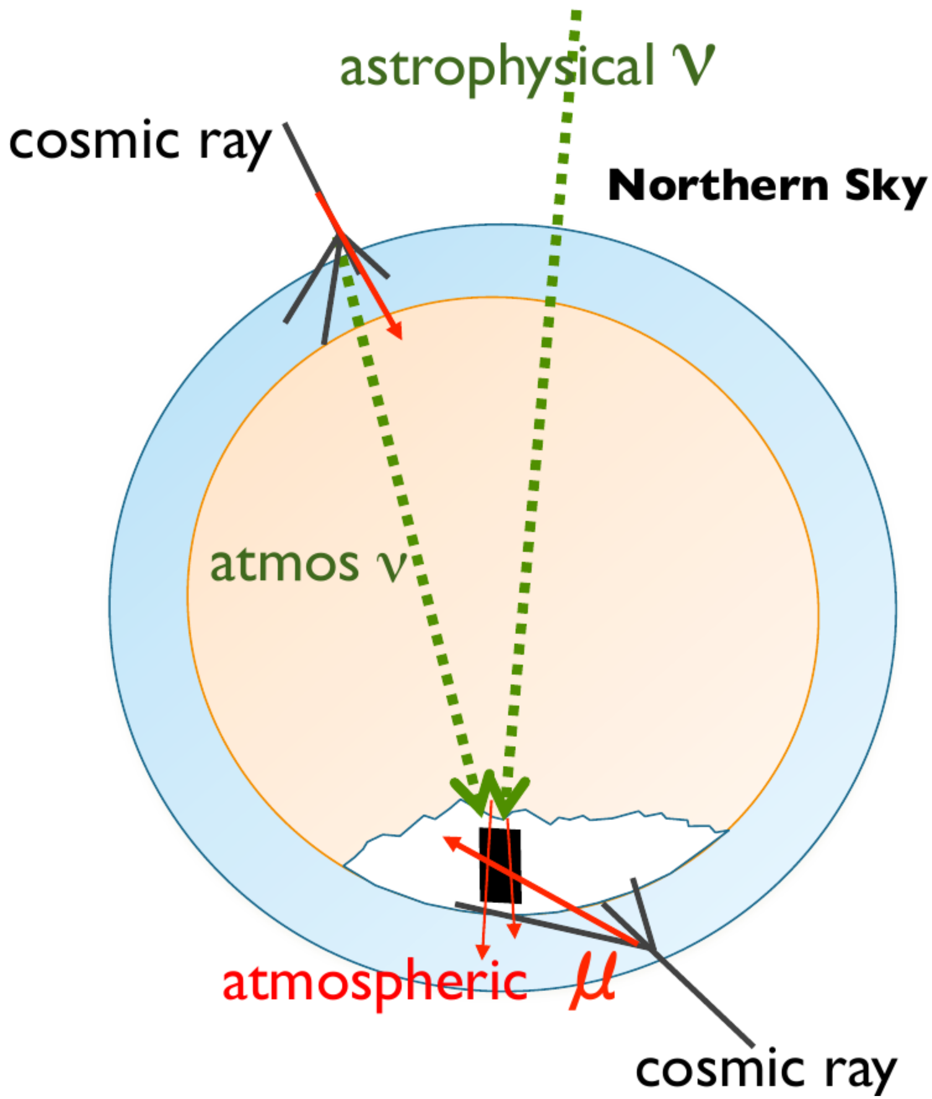
- Very small values of x reached in one of the projectiles

Collinear factorization approach: Feynman distribution



- The distribution is dominated by gluon - gluon interactions;
- Prediction depends on the parametrization used to describe the gluon distribution.

Atmospheric neutrinos

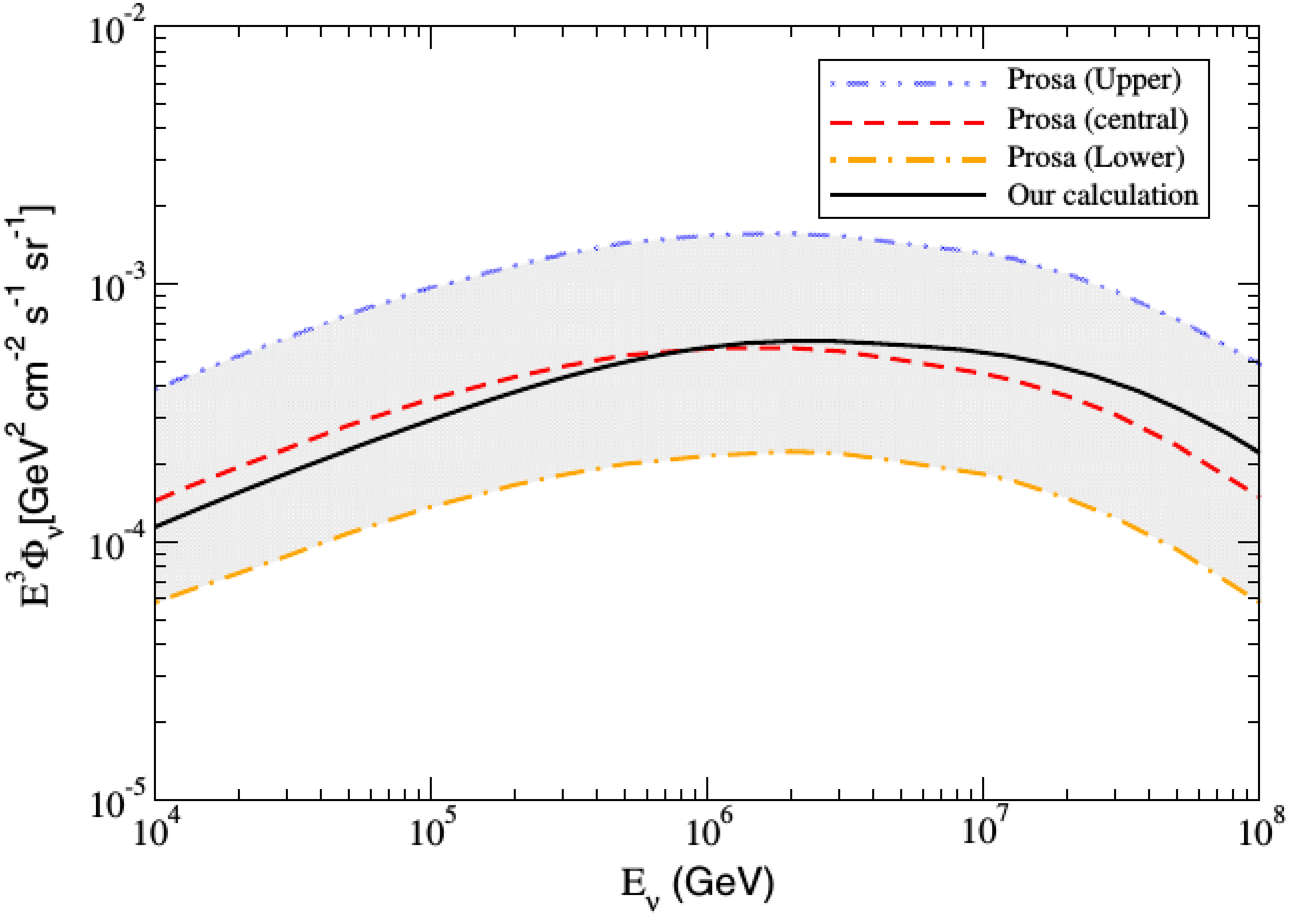


Cosmic-ray muons:
~3000 / second!

Atmospheric neutrinos:
~1 / 10 minutes

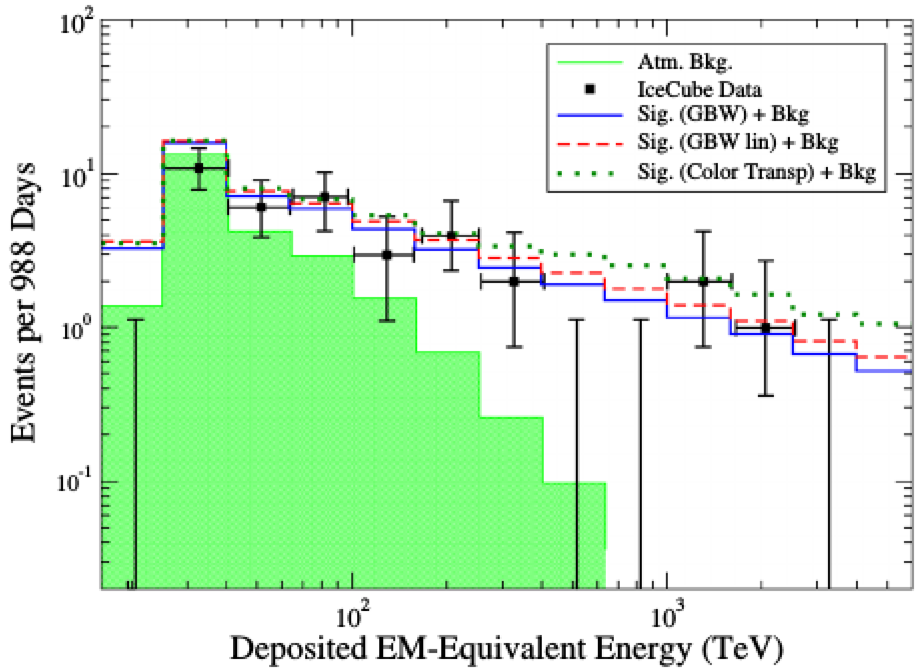
Astrophysical neutrinos: ???

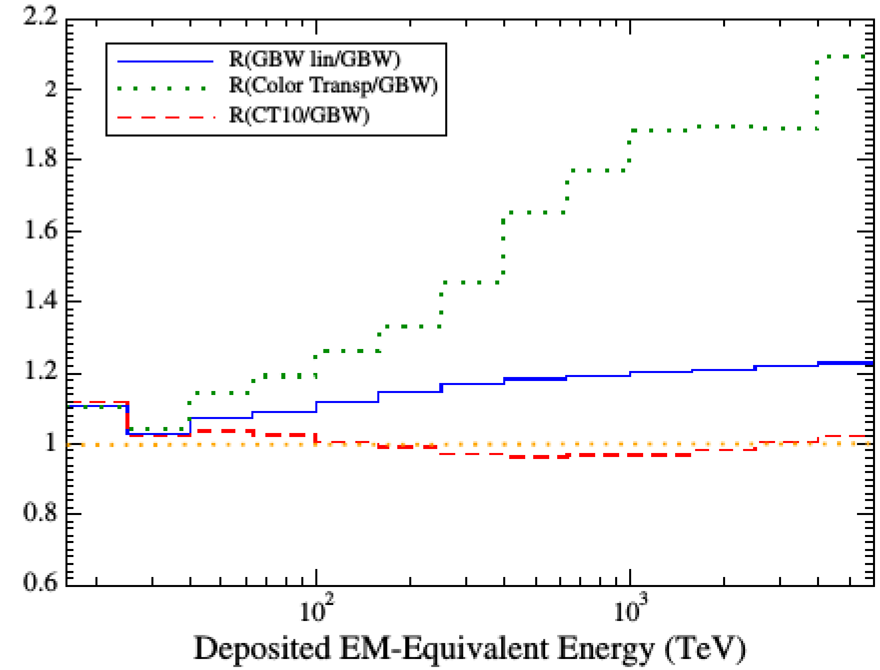
Comparison with PROSA results (*)



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

Non-linear effects at IceCube (*)





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