Prompt atmospheric muons:
recycling the neutrino-telescopes waste

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work with
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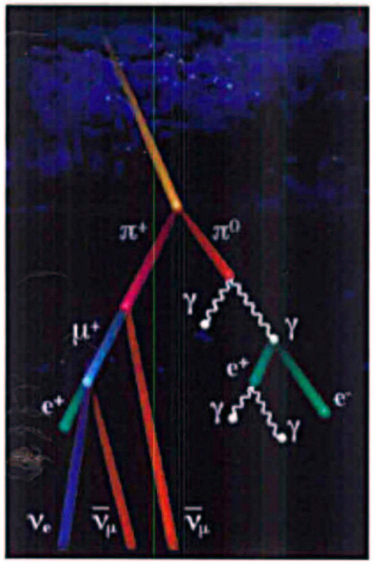
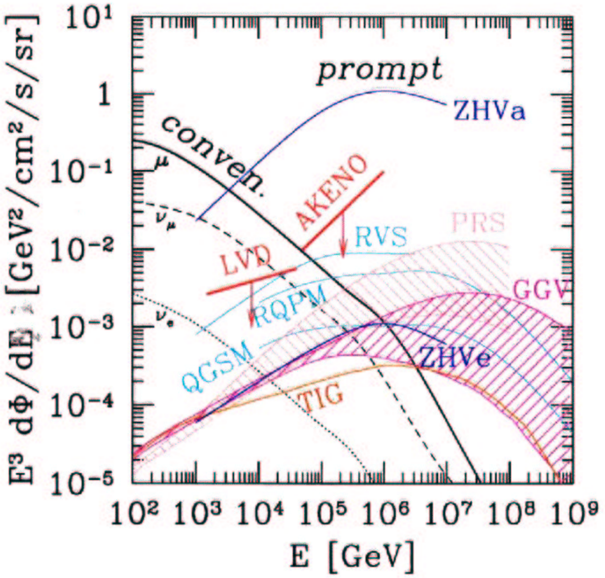
- I mean down-going muons!
- We could measure the small-x gluon density for $x < 10^{-5}$ with $E_\mu > 10^5 \mathrm{GeV}$
- We could measure the flux of prompt atmospheric neutrinos, which dominate the uncertainty in the atmospheric background to diffuse astrophysical neutrinos at E > TeV.

Cosmic-ray air showers



At E<TeV μ and ν fluxes are dominated by conventional sources, mostly π and κ mesons. With increasing energy these mesons interact in the atmosphere before decaying, and the contribution of the small fraction of short lived particles becomes dominant. Prompt μ and ν arise from the semi-leptonic decay of charmed particles.

Vertical atmospheric muon fluxes (from GGV 2003)



Conventional: μ, ν Lipari (E< 10^6 GeV) and TIG. Prompt: extreme charm production (ZHV), empirical (RVS), quark-gluon string and recombination quark-parton (QGSM, RQPM); perturbative QCD (PRS, GGV, TIG) models.

LIPARI: P. Lipari, Astropart. Phys. **1** (1993) 195.

ZHV: E. Zas, F. Halzen and R. A. Vazquez, Astropart. Phys. **1**, 297 (1993).

RVS: O. G. Ryazhskaya, L. V. Volkova and O. Saavedra, in *Topics in Astroparticle and Underground Physics (TAUP)*, Assergi, Italy, 2001, Nucl. Phys. Proc. Suppl. **110** (2002) 531.

QGSM and RQPM:E. V. Bugaev, V. A. Naumov, S. I. Sinegovsky and E. S. Zaslavskaya, Nuovo Cim. C **12**, 41 (1989).

TIG: M. Thunman, G. Ingelman, and P. Gondolo, *Astropart. Phys.* **5**, 309 (1996).

PRS: L. Pasquali, M. H. Reno, and I. Sarcevic, *Phys. Rev. D* **59**, 034020 (1999).

GGV: G. Gelmini, P. Gondolo, and G. Varieschi, *Phys. Rev. D* **61**, 036005 (2000); *Phys. Rev. D* **61**, 056011 (2000), *Phys. Rev. D* **63**, 036006 (2001); *Phys. Rev. D* **67**, 017301 (2003).

Estimates of prompt fluxes differ by 2 orders of magnitude!

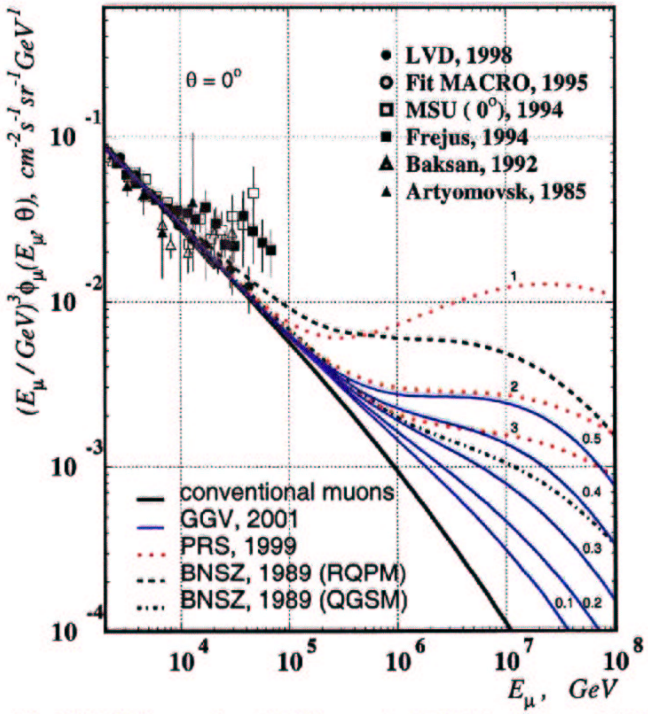
- Experimental searches for promt muons are inconclusive (large systematic errors)

- Theoretical predictions depend on charm production and decay model: before NLO calculation and new charm data in the last 10 years, **pQCD was thought to be inadequate to describe charm production**, so non-perturbative models were used to study atmospheric fluxes (such as QGSM, quark-gluon string model based on Regge asymptotics, and RQPM, the recombination quark -parton model, based on an intrinsic charm component in the nucleon)

- Today, **pQCD predictions and experiments are known to be compatible** so unconventional sources are not needed.

- However, the data are at $E_{lab} \sim 200$ GeV, while we need 10^3 to 10^8 GeV.

Experimental searches for prompt μ are inconclusive:



A. Misaki, T.S. Sinegovskaya, S.I. Sinegovsky, N. Takahashi; hep-ph/0302183
Vertical sea-level muon flux data and predictions. The lower solid line shows the flux conventional muons. Other curves show the total muon flux, the sum of prompt and conventional mouns.

pQCD describes well experimental data (GGV1, 1999)

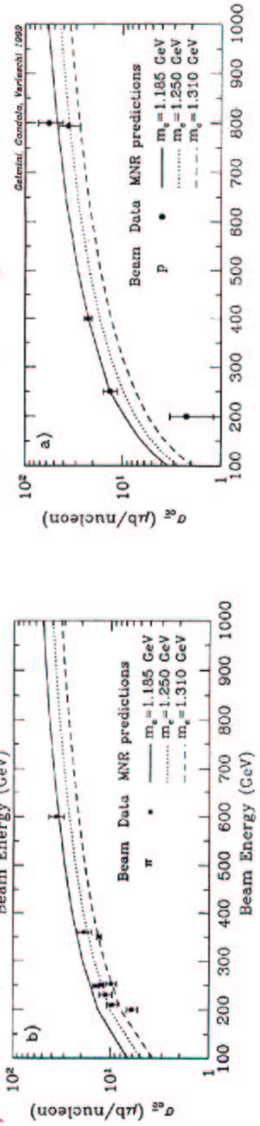


Figure 1:

MNR predictions for different m_c

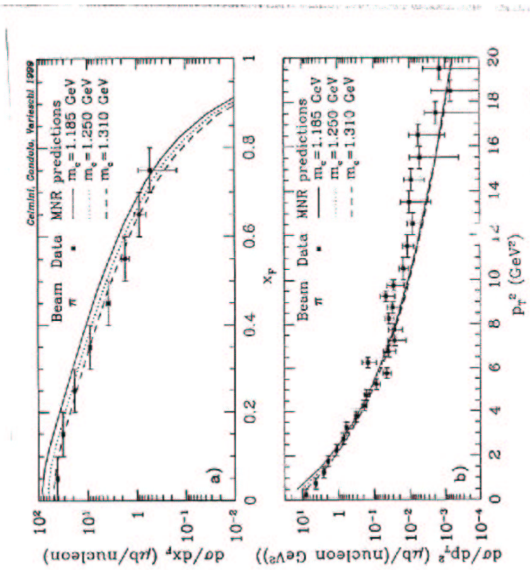


Figure 3:

WA92 data

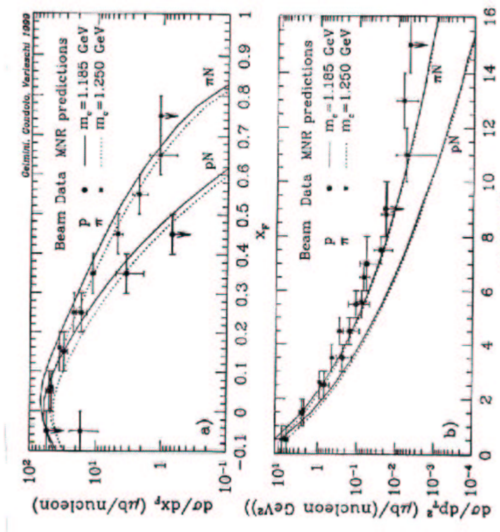


Figure 2:

E769 data

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Calculations of atmospheric fluxes based on pQCD

- First study performed by Thunman, Ingelman and Gondolo (TIG) in 1996: LO charm production cross section computed by PYTHIA multiplied by a constant K factor of 2 to bring it in line with the NLO values, and supplemented by parton shower evolution and hadronization according to the Lund model.
- Pasquali, Reno, and Sarcevic (PRS) in 1998 used NLO pQCD calculations as contained in the Mangano, Nason and Ridolfi (MNR) computer program to fit the K factor and approximate analytic solutions to the cascade equations in the atmosphere (also introduced by TIG),
- Gelmini, P. Gondolo, G. Varieschi (GGV) in 1999 to 2001 used NLO pQCD calculation of charm production, as implemented in the MNR program calibrated at low energies, followed by a full simulation of particle cascades in the

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atmosphere generated with PYTHIA routines (the same programs currently used to compare pQCD predictions with experimantal data in accelerator experiments).

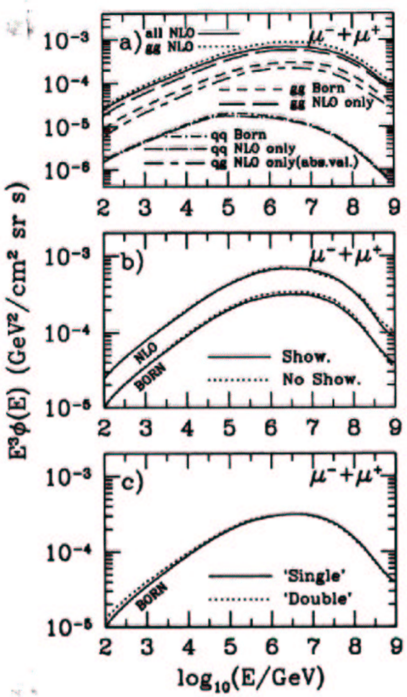
- All these calculations used the same model for the atmosphere and primary cosmic ray flux (following TIG)

$$\phi_N(E,0)\left[\frac{\text{nucleons}}{\text{cm}^2\ \text{s sr GeV }/\text{A}}\right] = \phi_0 E^{-\gamma-1} =$$

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

$\gamma =$ 1.7 and 2 respectively

Prompt Muons and neutrinos: NLO vs LO (GGV1)



Parton contributions: gluons dominate - PYTHIA options (showering, hadronization, interactions and decays: at most 10% in results. Single- vs double-diff. cross sections: negligible

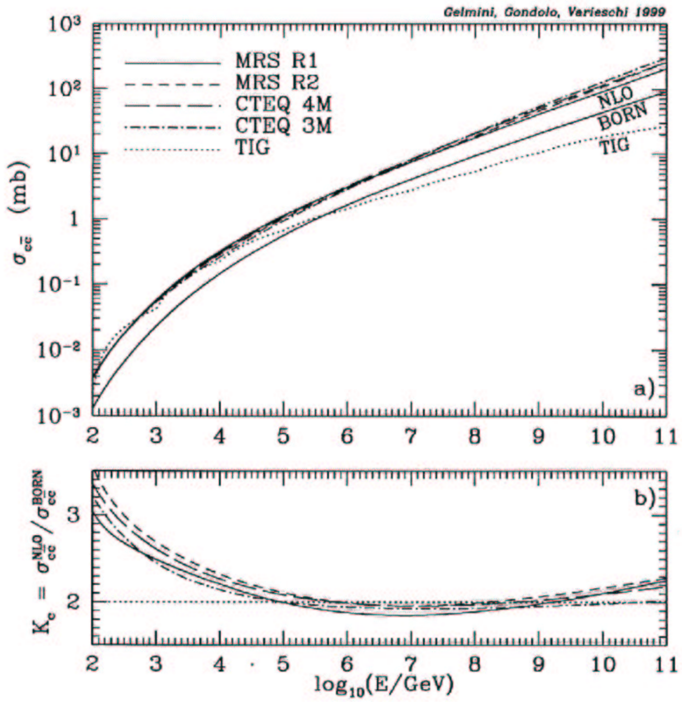


Figure 4:

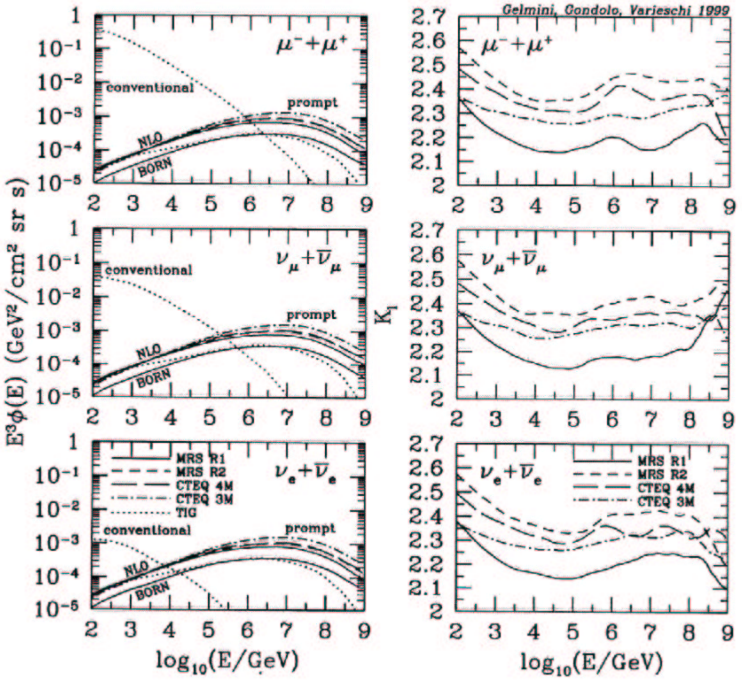


Figure 5:

Why gluons dominate

- Due to steep CR incoming flux only the most energetic c produced count, those comimg from the interaction of projectile partons carrying a large fraction x_1 of the incoming nucleon momentum: $x_1 \simeq O(10^{-1})$.

- Typical partonic center of mass energies are close to the $c\bar{c}$ threshold: $\sqrt{\hat{s}} \simeq 2m_c \simeq 2$ GeV, (since the differential $c\bar{c}$ production cross section decreases with increasing $\hat{s}$).

- The total center of mass energy squared is

  $$s = 2m_N E$$

  ($m_N \simeq 1$ GeV is the nucleon mass, and E is the energy per nucleon of the incoming cosmic ray).

- Calling x_2 the momentum fraction of the target parton in the nucleus of the atmosphere, we have

  $$x_1 x_2 = \hat{s}/s = 4m_c^2/(2m_N E) \simeq \text{GeV}/E$$

- Hence

  $$x_2 \simeq O(\text{GeV}/0.1\,E) \simeq O(\text{GeV}/E_l),$$

  where $E_l \simeq E_c \simeq 0.1E$ is the dominant muon or neutrino energy and for $x < 0.1$ the gluon PDF dominates over all others.

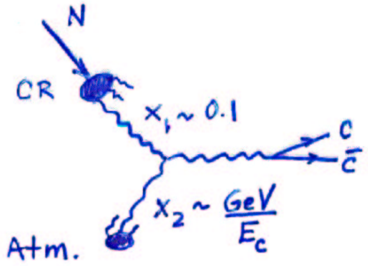
- Thus for $E_l > 10^5$ GeV we need the gluon PDF at $x < 10^{-5}$ where it has not been measured.

- **For $x \ll 1$, the gluon-PDF goes as**

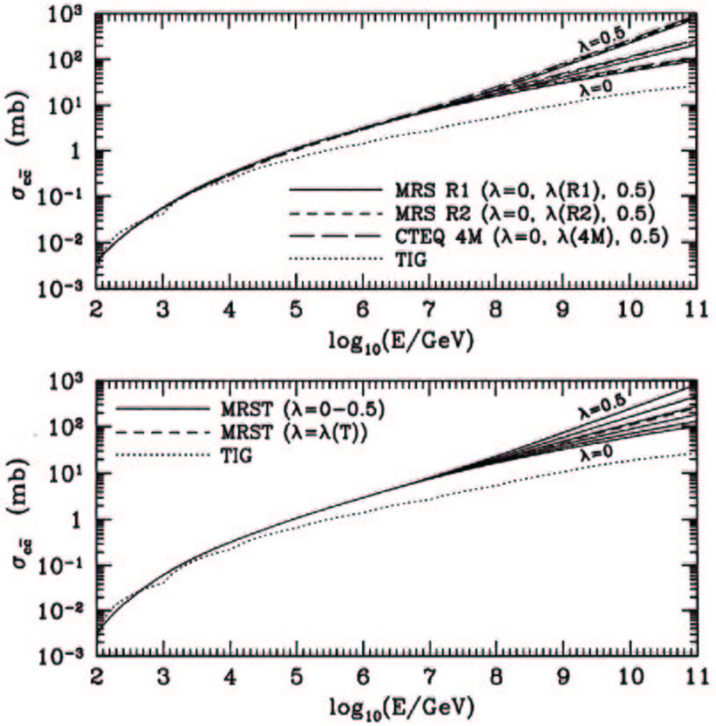
$$\mathbf{xg(x) \simeq x^{-\lambda}} \qquad (1)$$

with λ in the range 0 - 0.5

Extrapolations based on Regge analysis usually propose $\lambda \simeq 0.08$ while evolution equations used to resum large logarithms, such as the BFKL (Balitsky, Fadin, Kuraev, Lipatov) find $\lambda \simeq 0.5$.



Charm production cross section



TIG small: PYTHIA takes $\lambda = 0.08$ for $x < 10^{-4}$!

Concerns

- Possible saturation, unitarity and shadowing effects at $x < 10^{-5}$ are not included in the PDf's we used.

  Could only be important for atmospheric partons (thus not affected by CR composition). Shadowing could reduce the gloun PDF by as much as 30% and change the value of λ

- Unitarity of cross section $\sigma_{c\bar{c}} > \sigma_{pp} \sim 200$ mb,

  because $\sigma_{c\bar{c}}$ includes multiplicity.

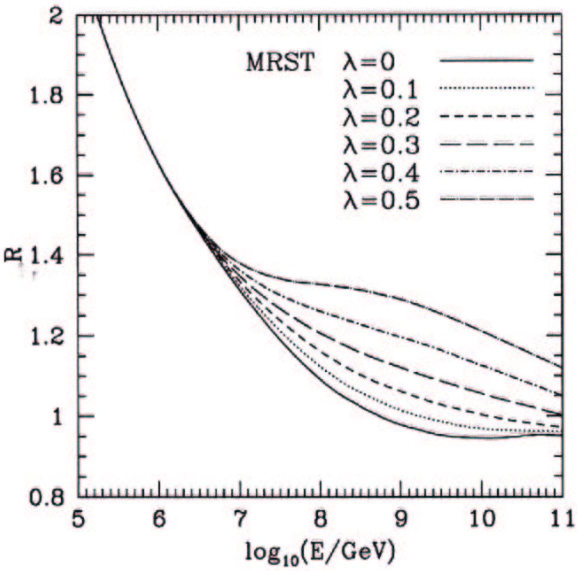
- $\log(p_T/m_c)$

  $p_T \sim m_c$ (no forward cut in acceptance), while at accelerators $p_T >> m_c$.

- $\log(\sqrt{s}/m_c)$ ["log(1/x)"]

  subdominant at NLO for $E_{\nu} < 10^9$ GeV, for all λ or up to highest energy considered, 10^{11} GeV, for $\lambda > 0.2$.

$\log(\sqrt{s}/m_c)$ ["log(1/x)"] subdominant at NLO



$$R = \frac{\sigma_{NLO} - \sigma_{LO}}{\sigma_{LO}\alpha_s \ln(s/m_c^2)/\pi}$$

If R is constant, σ_{NLO} is dominated by the ln terms and if R decreases, it is not (But higher orders...?)

E= "beam" energy

Calibration procedure

Besides the choice of the PDF set, our procedure has the freedom to choose reasonable values of the three parameters m_c, μ_F, and μ_R so as to fit the experimental data (both the total and differential cross sections at 250 GeV, without additional normalization factors)

Standard choice i.e. for MRST:

$$\mu_F = 2m_T, \quad \mu_R = m_T, \quad m_c = 1.250 \text{ GeV}$$

We explored the changes induced in cross sections and fluxes at high energies by different choices of parameters (for each m_c, μ_F, found best μ_R) which fulfil our calibration requirements.

The level of Promt Fluxes

- depend on $\lambda =$ (factor of 10) ←

  $\lambda = 0$ to 0.1

- depend on CR flux (factor of 5)

  (due to change of composition at the knee)

- depend on μ_F (factor of 10) ←

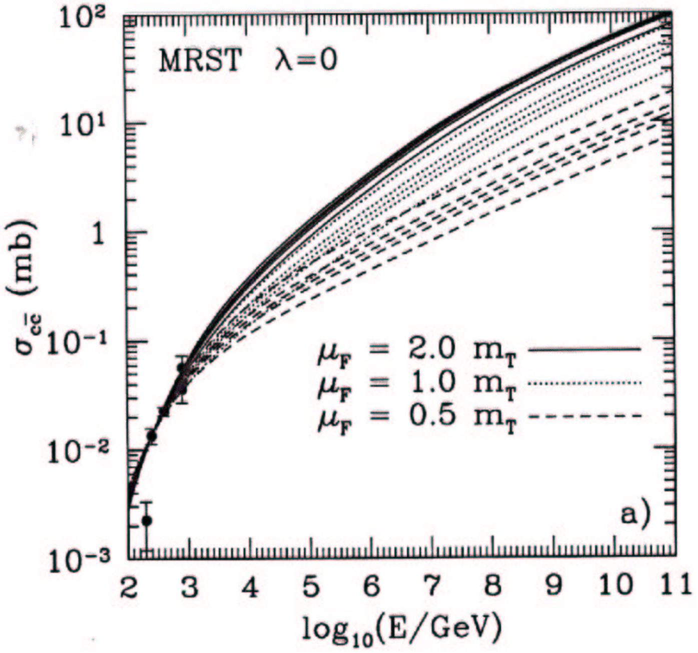
  $\mu_F = m_T/2, m_T, 2m_T$, $m_T = \sqrt{p_T^2 + m_c^2}$ is the transverse mass.

- depend on m_c (factor of 2)

  $m_c = 1.1$ GeV to 1.4 GeV

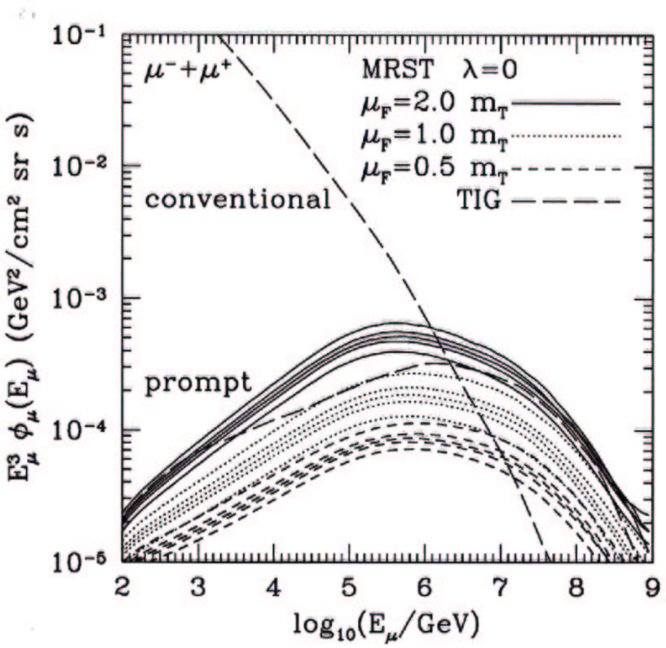
- depend on the PFD set (30 %)

Normalization of $\sigma_{c\bar{c}}$



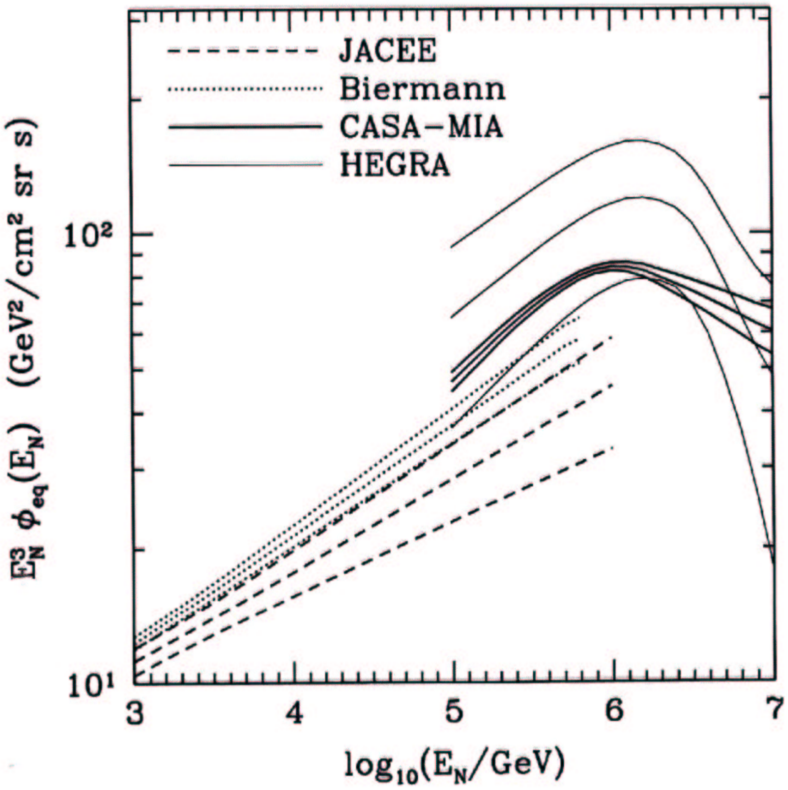
Within each μ_F band σ increases with m_c.

ϕ_μ depends on m_c and μ_F

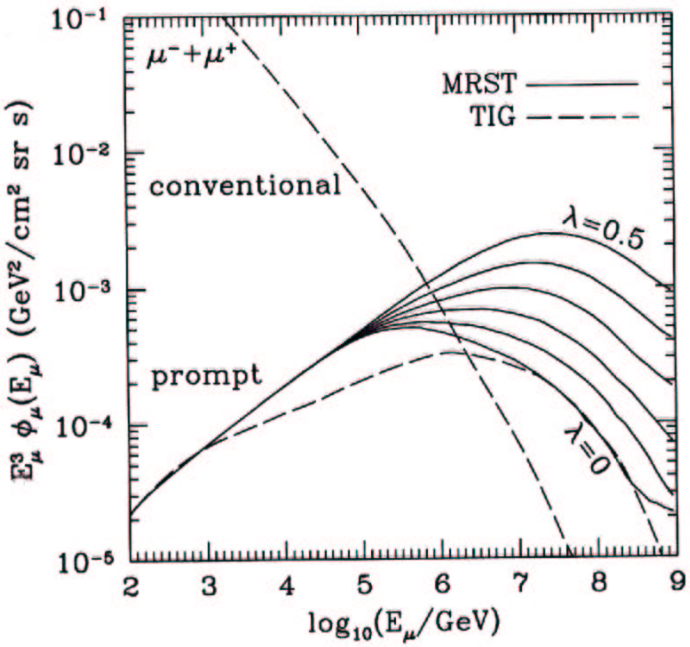


Within each μ_F band σ increases with m_c.

Equivalent nucleon spectrum

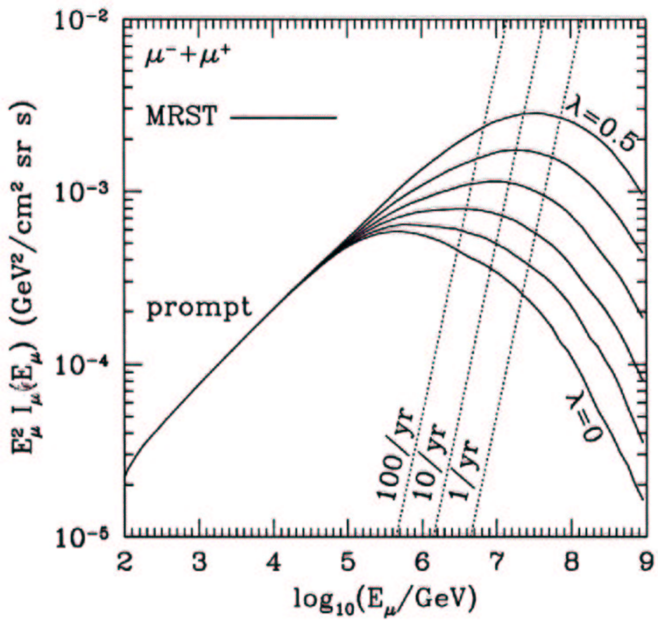


Vertical prompt ϕ_μ dependence on λ



Standard choice of other parameters.

Vertical prompt ϕ_μ dependence on λ



Number of particles traversing a $km^3 2\pi$ sr detector per year.

Proposal: measure the "prompt" muon spectral index $\alpha_\mu(E_\mu)$ using down-going muons

$$\phi_\mu(E_\mu) \propto E_\mu^{-\alpha_\mu(E_\mu)}$$

The "prompt" muon spectral index $\alpha_\mu(E_\mu)$

- is linear in λ !!

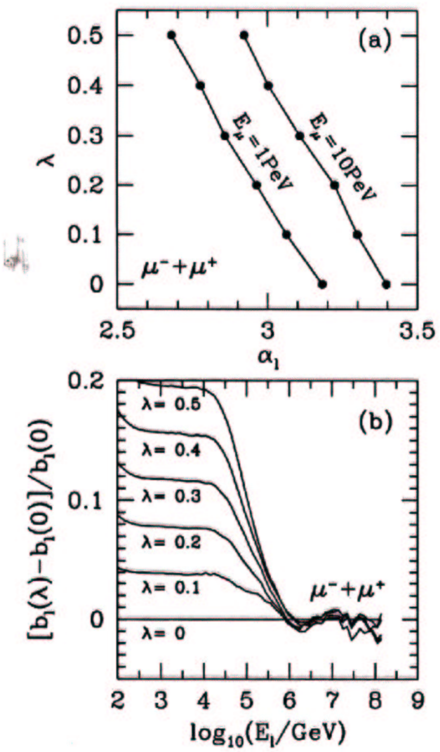
  small non-linearities ($\Delta\alpha_\mu \simeq 0.03$)

- is linear in γ ($\Delta\gamma \simeq 0.05_{stat} + 0.1_{syst}$)!?

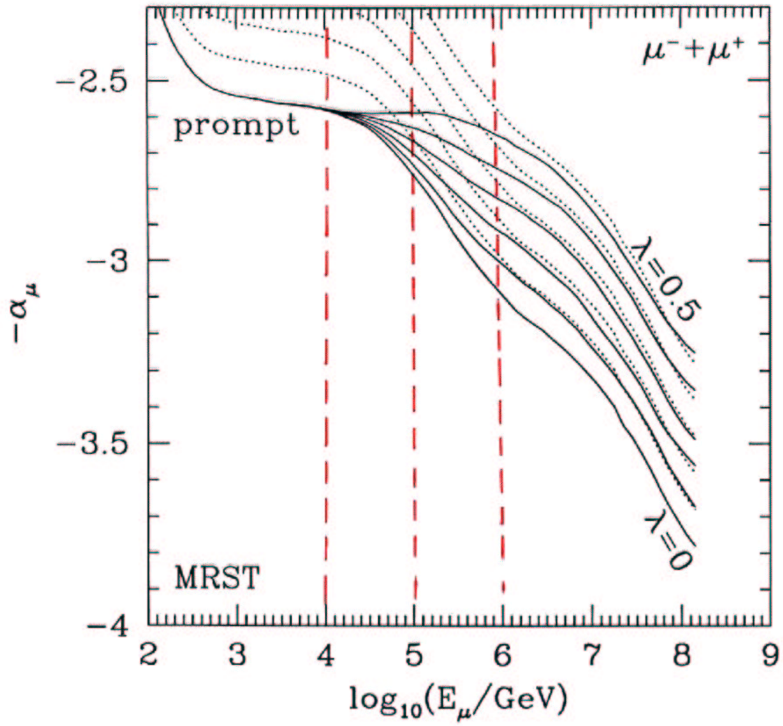
  small non-linearities ($\Delta\alpha_\mu \simeq 0.02$)

- depends on μ_F ($\Delta\alpha_\mu \simeq 0.06$)
- depends on m_c($\Delta\alpha_\mu \simeq 0.02$)
- depend on the PFD set($\Delta\alpha_\mu \simeq 0.01$)

$\alpha_\mu(E_\mu)$ is linear in λ : $\alpha_\mu = -\lambda + b$



Use the slope and not the flux itself :

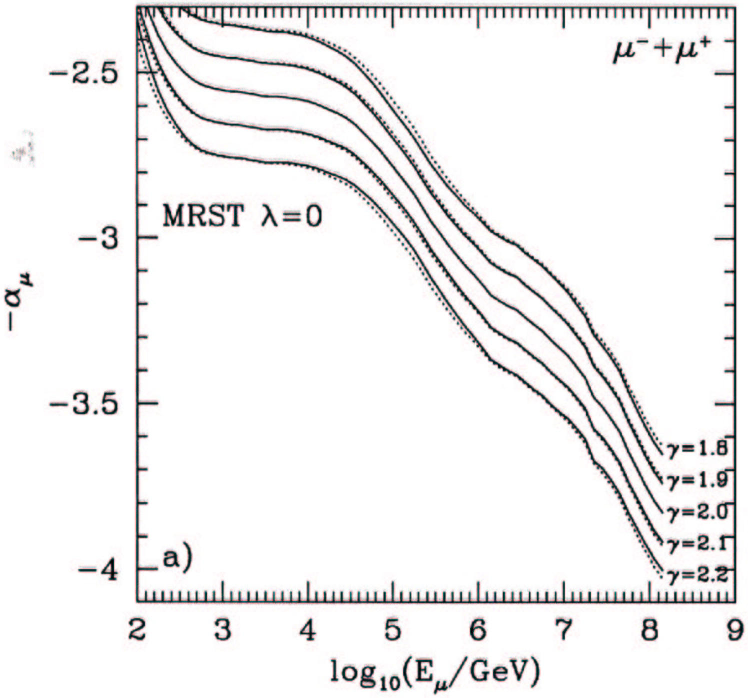


——— actual slope computed

------ $-\alpha_\mu = -\alpha_\mu(\lambda_g = 0) + \lambda_{gluon}$

This shows that above $E_\mu \gtrsim 10^6$ GeV the slope α_μ is linear in λ (the extrapolated gluon PDF $g(x) \simeq x^{-\lambda-1}$)

$\alpha_\mu(E_\mu)$ **is linear in** γ : $\alpha_\mu = -\lambda + b = -\lambda + \gamma + \bar{b}$

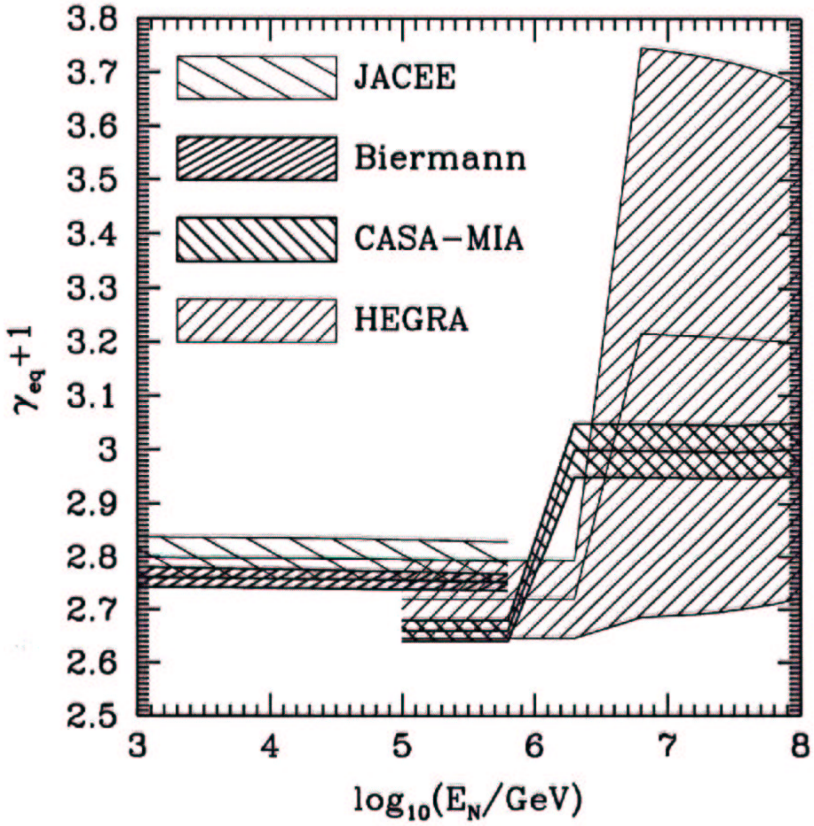


——— actual slope computed

------ $-\alpha_\mu = -\alpha_\mu(\gamma = 2) - \gamma$

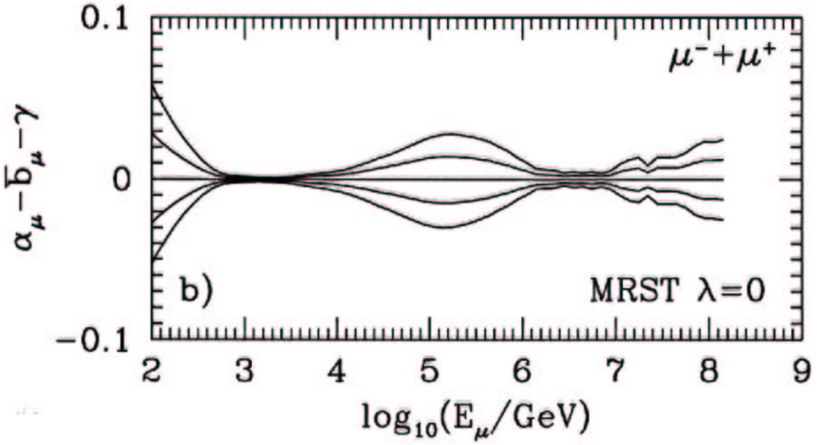
Equivalent spectral index

$\Delta\gamma \simeq 0.05_{stat} + 0.1_{syst}$

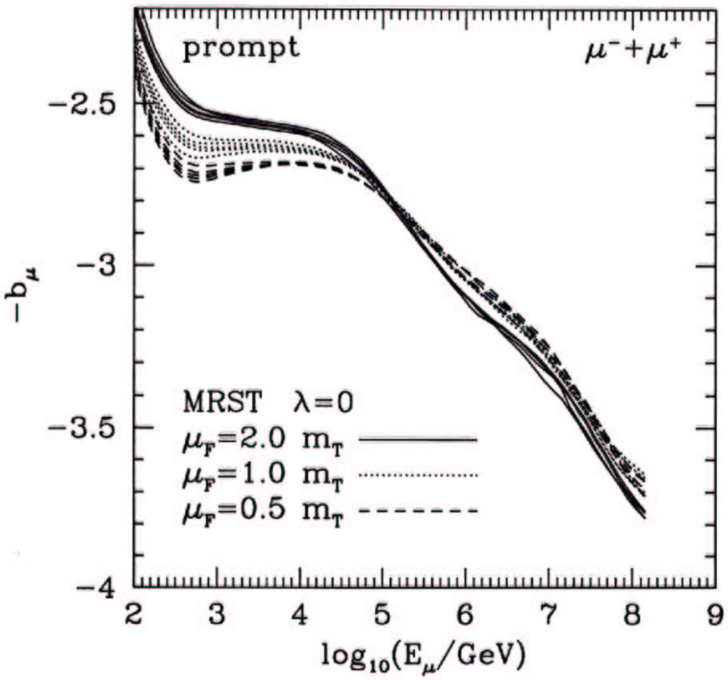


$\alpha_\mu(E_\mu)$ is linear in γ : $\alpha_\mu(\gamma) = -\lambda + \gamma + \bar{b}(\gamma = 0)$

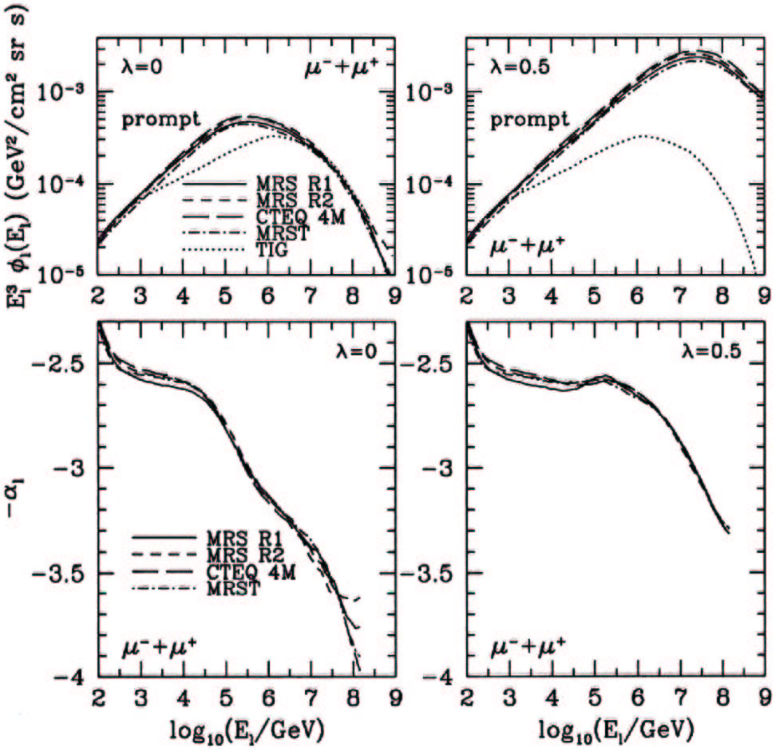
with small differences



α_μ depends on μ_f and m_c



α_μ depends on the PDF set



Theoretical errors

$\lambda = -\alpha_\mu + \gamma + \bar{b}$

- uncertainty in γ : $\Delta\lambda = 0.1_{syst}, 0.05_{stat}$
- dependence on μ_F: $\Delta\lambda = 0.06$
- non linearities in λ: $\Delta\lambda = 0.03$
- non linearities in γ: $\Delta\lambda = 0.02$
- dependence on m_c: $\Delta\lambda = 0.02$
- dependence on PDF set : $\Delta\lambda = 0.01$
- Total: $\Delta\lambda = 0.29$ (lin) or $\Delta\lambda = 0.13$ (quad)

Proposal: measure the slope λ of the gluon PDF at $x < 10^{-5}$ by measuring the slope of "prompt" down-going muons in neutrino telescopes at $E_\mu \simeq x^{-1}$ GeV (for which there is NO astrophysical "backgound")

- NOT the flux itself: uncertainties factor of 10!
- May reach $x \simeq 10^{-7}$ (for $E_\mu \simeq 10$ PeV: 50 ev. if $\lambda = 0.5$, 10 ev. if $\lambda = 0$). But best done between 100 TeV (where promt μ dominate) and 1 PeV , i.e. $x \simeq 10^{-4}$ to $x \simeq 10^{-6}$.
- ERROR: Theoretical from c-production model $(\Delta\lambda)_{charm} < 0.10$, from uncertainties in CR composition, $(\Delta\lambda)_{comp} < 0.15$ so TOTAL is $\Delta\lambda \sim 0.2$.
- Present data reach $x \simeq 10^{-5}$ (and LHC will not do better). This may be the only way to get to smaller x with the forseable experiments.

How small x?

- **HERA**

$$x < Q^2/s \sim 10^{-5}$$

$(\sqrt{s} \sim 300$ GeV, $\quad Q^2 \sim 1$ GeV$^2)$

- **LHC**

Smaller x obtained with the smaller mass and larger rapidity y,

$$x \sim m_b e^{-y}/\sqrt{s} \sim 10^{-4}$$

$(\sqrt{s} \sim 14$ TeV, $\quad y < 0.9)$

or slightly lower with c-tagging.

The uncertainty in the level of promtp neutrinos will limit the search for astrophysical neutrinos:

Atmospheric ν's and μ's are the most important source of background for present and future high-energy neutrino telescopes,

Atm. μ's reach the detector only from above (their range in Earth is only a few km); they are only down-going Atm. ν' instead reach the detector from all directions. Hence they are an irreducible background for diffuse astrophysical neutrino fluxes.

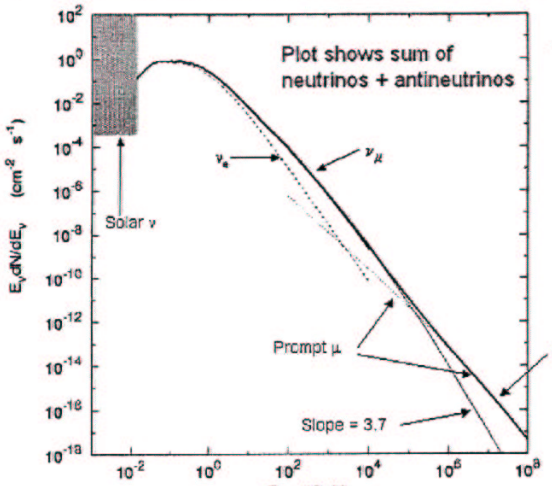
Uncertainty in conv. atm. ν' and μ's is 30% at present, 10% soon (see Gaisser), and at $\sim$ 1 TeV, the contribution of prompt neutrinos (with the LVD bound) could be as high as 10% of the con. ν flux!

Between 1 TeV and 100 TeV, prompt ν's become the biggest source of uncertainty in the atmospheric neutrino flux (at $E <<$ where they become dominant.)

Predictions differ by 2 orders of magnitude: need to measure the flux

Motivation

Global view of atmospheric ν spectrum



Uncertainty in level of charm a potential problem for finding diffuse neutrinos

May 26, 2002 Thomas K. Gaisser

Motivation

Summary (high energy)

- Kaon decays dominate atmospheric ν_μ, ν_e above 100 GeV
- Well-understood atmospheric ν_μ, ν_e useful for calibration of neutrino telescopes
- Uncertainty in level of prompt neutrinos (from charm decay) will limit search for diffuse astrophysical neutrinos

May 26, 2002 Thomas K. Gaisser

How to measure the prompt atmospheric neutrino flux?

Measure the flux of prompt ν (using reconstructed cascades).

Hooper, Nunokawa, Peres and Zukanovich Funchal *Phys. Rev. D* **67**, 013001 (2003): studied how to do it with showers induced by down-going neutrinos (asuming the energy of the parent neutrino can be reconstructed).

Problem: contamination with an astrophysical signal!

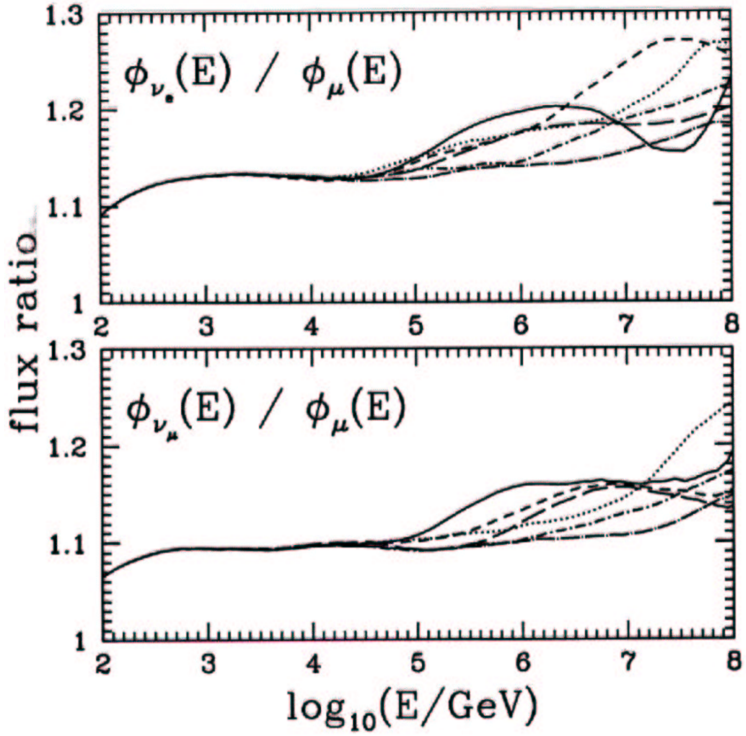
Measuring the prompt atmospheric neutrino flux with down-going muons in neutrino telescopes

Gelmini-Gondolo-Varieschi, Sept. 2002, *Phys. Rev. D* **67**, 017301 (2003).

- Due to the charmed particle decay kinematics and the same branching ratios for the semi-leptonic decays into $e\nu_e$ and $\mu\nu_\mu$, the prompt e and μ neutrino fluxes and the prompt μ flux are essentially the same (within 10%) at sea level Thus, result is independent of the c production model.

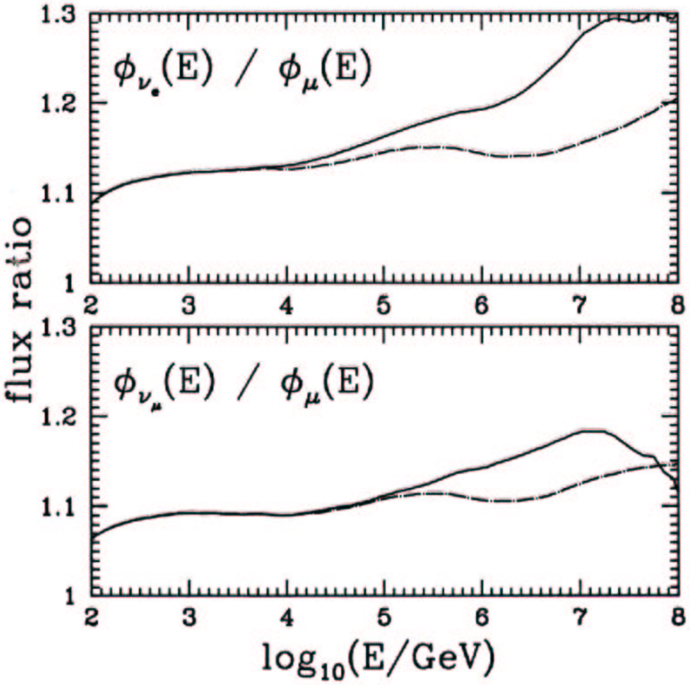
- Prompt down-going μ are very abundant: at 1 TeV the flux of down-going μ at sea level is about 10^7 of the up-coming μ (induced by ν_μ). At a slant depth of about 3 km w.e. the μ flux is only a fraction 0.4–0.6 of the sea level flux which means about 10^9 $\mu/km^2/$ yr/s, and about 10% of those are promtp (so need to record 1 out of 10^5 down-going μ to separate them)

Ratio of promp ν over prompt μ fluxes



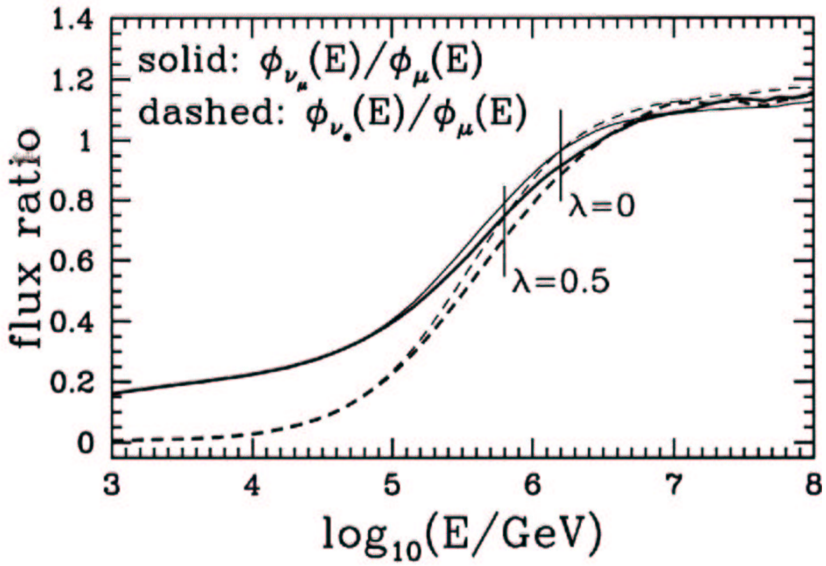
MRST PDF with $\lambda = 0$ (solid line), 0.1 (dotted), 0.2 (short-dashed), 0.3 (long-dashed), 0.4 (short-dashed dotted), and 0.5 (long-dashed dotted).

Ratio of promp ν over propmt μ fluxes



CTEQ 4M PDF and $\lambda = 0$ and 0.5.

Ratio of total ν over μ fluxes



Vertical marks denote the crossing energy from conventional to prompt muons.

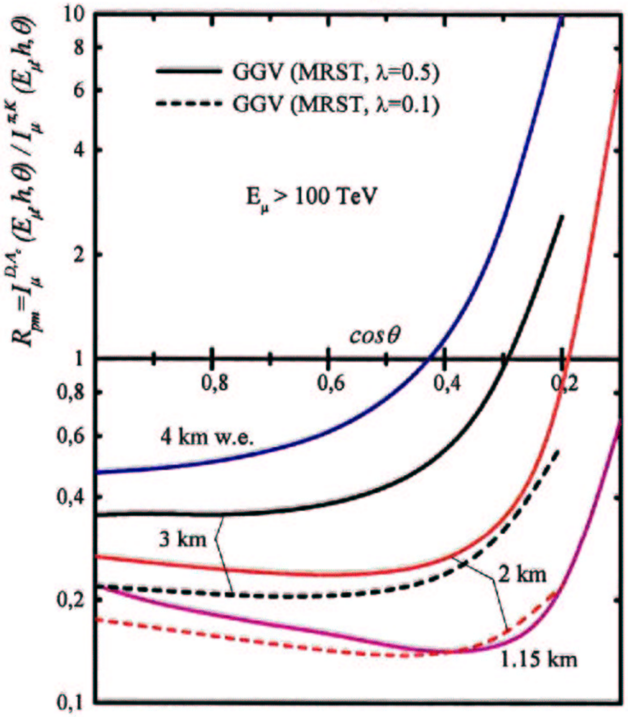
We need to separate the prompt μ from the conventional ones.

Bugaev *et al.*, (1998) and Sinegovskaya and Sinegovsky, (2001), studied three ways:

1. the different zenith angle dependence of the prompt and conv. fluxes;
2. the different depth dependence at a given zenith angle;
3. different spectral shape at a given depth and zenith angle.

1. Zenith-angle distribution at depths h

$h = 1.15$ km (Baikal)
$= 2, 3$ km (AMANDA)
$= 4$ km (NESTOR)

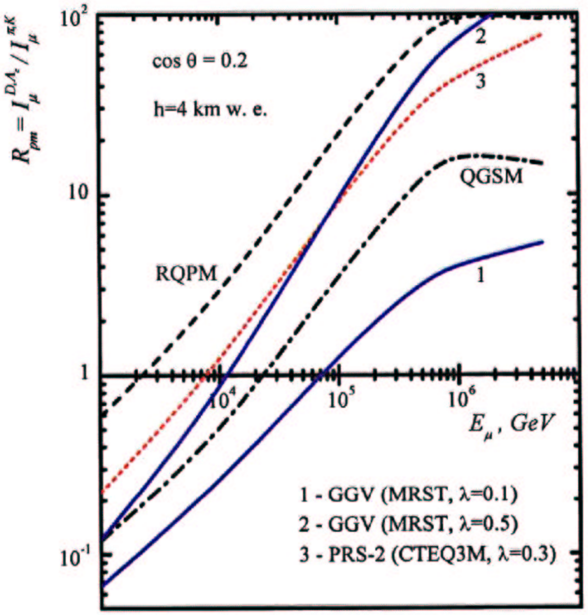


For $h \lesssim 3$ km w.e. • R_{pm} is near isotropic to ~ 60°

• $\cos\theta_{\text{"crossover"}}\big|_{\lambda=0.5} \simeq 0.3$, $\cos\theta_c\big|_{\lambda=0.1} \simeq 0.1$

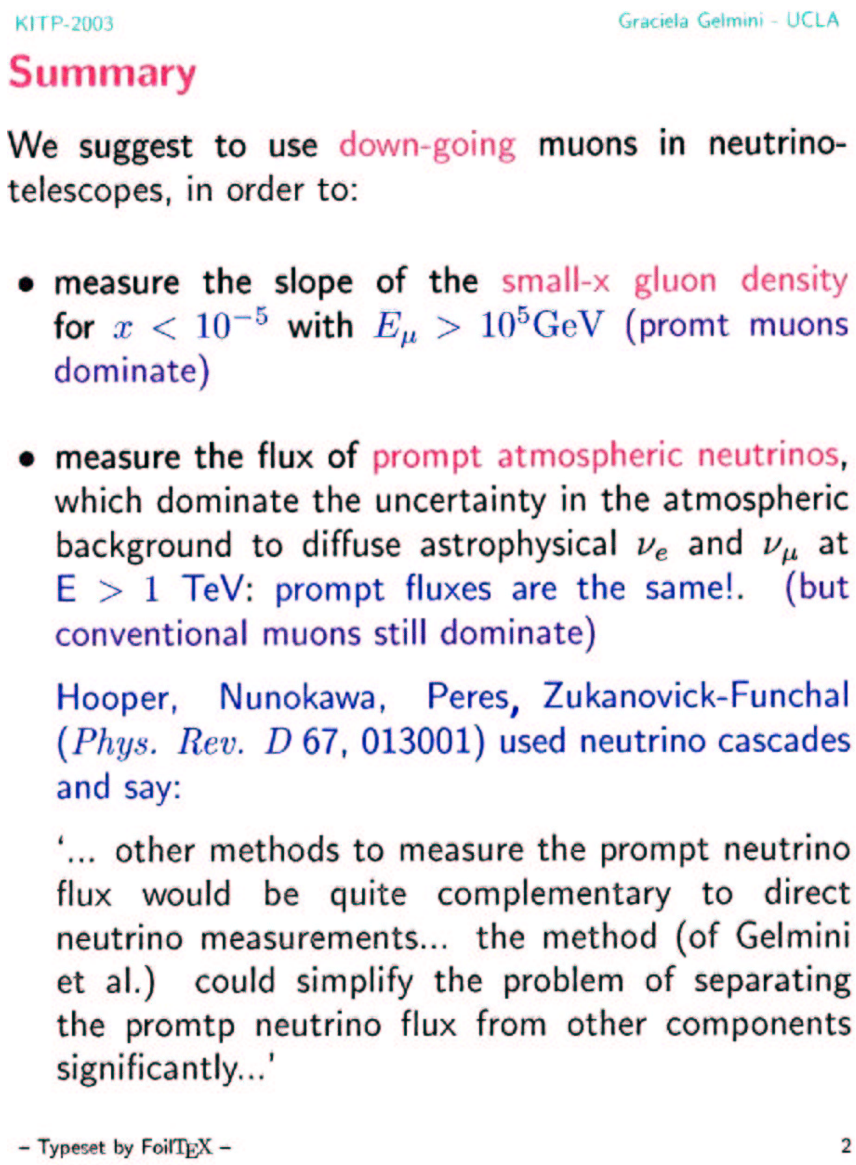
[1] A. Misaki, T.S. Sinegovskaya, S.I. Sinegovsky and N. Takahashi; hep-ph/0302183 .

3. different spectral shape at fixed h and θ



Ratio of integrated μ fluxes: prompt/conv.

[1] A. Misaki, T.S. Sinegovskaya, S.I. Sinegovsky and N. Takahashi; hep-ph/0302183 .



Summary

We suggest to use down-going muons in neutrino-telescopes, in order to:

- measure the slope of the small-x gluon density for $x < 10^{-5}$ with $E_\mu > 10^5 \mathrm{GeV}$ (promt muons dominate)

- measure the flux of prompt atmospheric neutrinos, which dominate the uncertainty in the atmospheric background to diffuse astrophysical ν_e and ν_μ at E $>$ 1 TeV: prompt fluxes are the same!. (but conventional muons still dominate)

  Hooper, Nunokawa, Peres, Zukanovick-Funchal (*Phys. Rev. D* 67, 013001) used neutrino cascades and say:

  '... other methods to measure the prompt neutrino flux would be quite complementary to direct neutrino measurements... the method (of Gelmini et al.) could simplify the problem of separating the promtp neutrino flux from other components significantly...'