seasonal variations of atmospheric leptons as a probe for charm production
• particle production in extensive air showers
• heavy quark production and window to astrophysical signal
• correlation with Earth’s atmospheric temperature
• probing heavy quark component with seasonal variations
particle production in the atmosphere


Development of cosmic-ray air showers

\[ N_{CR} + N_{air} \rightarrow X + \pi + K + D + \Lambda + \ldots \]

Paolo Desiati
particle production in the atmosphere
hadronic interactions

- CR showers dominated by **soft component with small** $p_T$ *(non-perturbative QCD)*

- **hard component with high** $p_T$ with heavy quarks *(pQCD)*

- **phenomenological** descriptions of hadronic interactions with minijet production for hard component

- **models** to describe soft/hard interactions in forward region & extrapolated to high energy

**interaction models** from accelerators, **extrapolated** to forward region at high energy
particle production in the atmosphere

Ahn et al., ICRC 2013

Pierog, Engel

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particle production in the atmosphere
atmospheric leptons

\[ \phi_{\nu}(E_{\nu}) = \phi_{N}(E_{\nu}) \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu} \cos \theta E_{\nu}/\epsilon_{\pi}} + \frac{A_{K\nu}}{1 + B_{K\nu} \cos \theta E_{\nu}/\epsilon_{K}} \right\} \]

\[ A_{i\nu} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}} \quad (Z_{NN} = Z_{pp} + Z_{pn}) \]

\[ Z_{NN}(E) = \int_{E}^{\infty} dE' \frac{\phi_{N}(E')}{\phi_{N}(E)} \frac{\lambda_{N}(E')}{\lambda_{N}(E)} \frac{dn_{\pi^{\pm}}(E', E)}{dE} \]

\[ \epsilon_{i} = \frac{kT}{M g} \frac{m_i c^2}{ct_i} \quad i = \pi, K, charm, \ldots \]

meson’s characteristic energy

<table>
<thead>
<tr>
<th>Particle ((\alpha))</th>
<th>(\pi^{\pm})</th>
<th>(K^{\pm})</th>
<th>(K_{L}^{0})</th>
<th>Charm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\epsilon_{\alpha}) (GeV)</td>
<td>115</td>
<td>850</td>
<td>205</td>
<td>(\sim 3 \times 10^{7})</td>
</tr>
</tbody>
</table>

Paolo Desiati
heavy quark production and astrophysics

- LHC data show agreement of observations within FONLL (wide range of $\eta$) - pQCD

- intrinsic charm production: asymmetry in $c\bar{c}$ baryon production (SELEX 2002)

- $p \to \Lambda_c^+ + \bar{D}^0$ of order 1% $(m_s/m_c)^2$ compared to associated production $p \to \Lambda K^+$

- inclusive D-meson spectrum dominated by intrinsic charm at high pseudo-rapidity & $p_T$
  (Lykasov+ 2012; @LHC: Bednyakov+ 2013)

- non-perturbative QCD
heavy quark production and astrophysics

- effect of charm production models
- effect of primary cosmic ray spectrum

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**Intrinsic Charm**

Gaisser, arXiv:1303.1431

**pQCD**

Sibyll 2.2 - Fedynitch 2014

---

**pQCD**

GST 3-gen

GST 4-gen

H3a

poly-gonato

TIG

ERS '08
heavy quark production and astrophysics

observed through-going up-ward $\nu_\mu + \bar{\nu}_\mu$

observed starting all-direction all-flavor

\[ E^\omega \Phi(E_\nu)\text{[GeV]} \times \text{cm}^{-2} \times \text{s}^{-1} \times \text{sr}^{-1} \]

90% CL

IceCube Preliminary

\[ \text{Events per 988 Days} \]

charm contribution


Aartsen et al. Science 342 (2013) 1242856

Aartsen et al. arXiv:1405.5303

\[ \text{Deposited EM-Equivalent Energy in Detector (TeV)} \]

\[ \rightarrow \text{can neutrino telescopes measure neutrinos from charm?} \]

astrophysical neutrinos?
temperature seasonal variations

IceCube Preliminary

μ multiplicity - ICRC 2013

νμ

ICRC 2013

Tilav et al., ICRC 2009
PD et al., ICRC 2011
temperature seasonal variations

- muon production spectrum $P_\mu(E_i, \theta, X)$
- effective temperature

\[
T_{\text{eff}}(E_i, \theta) = \frac{\int dE_i \int dX \epsilon(E_i, \theta) P_\mu(E_i, \theta, X) T(\theta, X)}{\int dE_i \int dX \epsilon(E_i, \theta) P_\mu(E_i, \theta, X)}
\]

- temperature dependency of atmosphere density $\rightarrow$ meson critical energy

temperature data from NASA AIRS instrument on board the Aqua satellite
temperature seasonal variations

- temperature coefficient

\[ \alpha^t_{T}(\theta) = T \cdot \frac{\partial}{\partial T} \int dE_i \phi_i(E_i, \theta) \epsilon(E_i, \theta) \]

\[ \phi(E_i, \theta) = \int_{0}^{\infty} \mathcal{P}_\mu(E_i, \theta) \, dX \]

- temperature correlation of lepton intensity

\[ \frac{\Delta I_i}{\langle I_i \rangle} = \alpha^t_T \frac{\Delta T_{eff}}{\langle T_{eff} \rangle} \]

\[ \frac{\Delta R_i}{\langle R_i \rangle} = \alpha^e_T \frac{\Delta T_{eff}}{\langle T_{eff} \rangle} \]

\[ \alpha^e_T = 0.860 \pm 0.002(stat.) \pm 0.010(syst.) \]

temperature data from NASA AIRS instrument on board the Aqua satellite

PD et al., ICRC 2011
temperature seasonal variations

$K/\pi$ ratio

$$\phi_{\mu}(E_{\mu}, \theta) = \phi_{N}(E_{\mu}) \times \left( \frac{1}{1 + B_{\pi\mu} \cos \theta \times E_{\mu}/\epsilon_{\pi}} + \frac{A_{K\mu}/A_{\pi\mu}}{1 + B_{K\mu} \cos \theta \times E_{\mu}/\epsilon_{K}} \right), \quad \gamma \approx 1.7$$

$A_{K\mu}/A_{\pi\mu} = \left( \frac{BR_{K\mu}}{BR_{\pi\mu}} \right) \left( \frac{Z_{K\mu}}{Z_{\pi,\mu}} \right) \left( \frac{Z_{N\pi}}{Z_{N\pi}} \right)$

**Kaon/pion ratio**

$$R(K/\pi) = \frac{Z_{N\pi}}{Z_{N\pi}}$$

- **Data**
- **Theory**
- **Data Theory**

**Graph:**
- **$\alpha_T^{exp}$**
- **$\alpha_T^{th}$**

**Legend:**
- **NA49 (Pb+Pb)**
- **E735 (p+p)**
- **STAR (Au+Au, K'/p')**
- **STAR (Au+Au, K/p')**
- **MINOS (p+A**) atm
- **IceCube Preliminary (p+A**) atm

**ICRC, Beijing 2011**
temperature seasonal variations
charm component

- temperature correlation increases as meson interaction probability increases with energy
- measurable effect as relative importance of prompt component increases

charm contribution from RQPM model (Bugaev et al. 1998)

PD, Gaisser 2010
Paolo Desiati

temperature seasonal variations
charm component

PD, Gaisser 2010

![Graph showing temperature coefficient vs. \( E_{\nu, \mu} \) (GeV)](image)

<table>
<thead>
<tr>
<th>( E_{\nu, \mu\text{min}} ) (TeV)</th>
<th>no charm</th>
<th>RQPM charm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1 ( 90^\circ - 120^\circ )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>all</td>
<td>0.54</td>
<td>0.52</td>
</tr>
<tr>
<td>3</td>
<td>0.70</td>
<td>0.62</td>
</tr>
<tr>
<td>30</td>
<td>0.94</td>
<td>0.72</td>
</tr>
</tbody>
</table>

![Table showing correlation coefficients for muons with \( \theta \leq 30^\circ \)](image)

TABLE I: Correlation coefficients for muons with \( \theta \leq 30^\circ \) for three levels of charm (energy in TeV; rate in Hz/km²).

PD, Gaisser 2010

IC40×2

<table>
<thead>
<tr>
<th>( E_{\nu, \mu\text{min}} ) (TeV)</th>
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<th>RQPM charm</th>
</tr>
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<tr>
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<td>0.52</td>
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<tr>
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<td>0.70</td>
<td>0.62</td>
</tr>
<tr>
<td>30</td>
<td>0.94</td>
<td>0.72</td>
</tr>
</tbody>
</table>

![Observational zones](image)

~ 60% of events

~ 10% of events

“Antarctic weather”
Temperature seasonal variations
charm component

Muon multiplicity modifies temperature correlation (ICRC 2013)

Need to evaluate the energy of individual muons in the bundle

→ Single muons

2 × 10^8 µ/day → 220-430 µ/day

\( \alpha_T^{th} \) decreases 10-30% for \( E_\mu > 100 \text{ TeV} \)

10 years of HE muon data
temperature seasonal variations
charm component

- $100 \text{ v/day} \rightarrow 2-3 \text{ v/day}$
- $\alpha_T^{th}$ decreases 20% for $E_\nu > 30 \text{ TeV}$
- long time to accumulate enough statistics

**IC40 \times 2 \rightarrow IC86 \sim 4.8 \times IC40**

<table>
<thead>
<tr>
<th>$E_\nu,_{\min}(\text{TeV})$</th>
<th>no charm</th>
<th>RQPM charm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>$\alpha$</td>
<td>Events/yr</td>
</tr>
<tr>
<td>all</td>
<td>0.54</td>
<td>38400</td>
</tr>
<tr>
<td>3</td>
<td>0.70</td>
<td>14160</td>
</tr>
<tr>
<td>30</td>
<td>0.94</td>
<td>840</td>
</tr>
</tbody>
</table>

astrophysical neutrinos do not correlate with atmospheric temperature

neutrinos produced in larger portion of Earth’s atmosphere

small event statistics
conclusions

- single / low multiplicity muons useful tool to probe charm production in the atmosphere

  - in association to lower stratospheric temperature variations in Antarctica

  - measuring laterally separated muons @ high energy (Soldin’s talk)

  - measuring spectrum of single/low multiplicity (horizontal) muons

- hadronic models for heavy quark production & μ/ν correlation

- charm production described with pQCD: intrinsic charm & forward physics
backup slides
particle production in the atmosphere
atmospheric leptons

observed through-going $\nu_\mu + \bar{\nu}_\mu$

interaction models
cosmic ray composition
experimental uncertainties

Fedynitch, Becker Tjus, PD 2012

$\Phi_\nu (E/GeV)^{3.0} \text{ (cm}^2 \text{ s sr GeV)}^{-1}$

$E_\nu / \text{GeV}$

IceCube IC40, 2010
Amanda II, 2010

Paolo Desiati
observed starting all-direction **all-flavor**

→ can neutrino telescope measure neutrinos from charm ?

Aartsen et al. Science 342 (2013) 1242856
Aartsen et al. arXiv:1405.5303
heavy quark production and astrophysics

- effect of charm production models
- effect of primary cosmic ray spectrum

![Graph showing intrinsic charm and pQCD](image)
heavy quark production and astrophysics

transverse momentum $p_T$ vs pseudo-rapidity

data in available range of $\eta$ agrees with models extrapolaion to full phase space (FONLL)
due to large quark mass, **perturbative QCD** can be used (hard component). However

- significant charm production observed at $\sqrt{s} = 20$ GeV

- asymmetry in charm / anti-charm baryons (Selex Coll. 2002) → **intrinsic production**

$|p\rangle = \alpha|uud\rangle + \beta|uudcc\rangle + \ldots$ : the **c-pair** produced in projectile fragmentation can recombine with valence quarks and with sea-quarks to **produce charmed hadrons**.

$p \rightarrow \Lambda_c^+ + \bar{D}^0 \sim \text{order } (m_s/m_c)^2 (~1\%)$ compared to $p \rightarrow \Lambda K^+$

- inclusive D-meson spectrum dominated by intrinsic charm at high pseudo-rapidity & $p_T$ Lykasov+ 2012

- steep cosmic ray spectrum might **enhance the effect of intrinsic production** of charm
temperature seasonal variations

MACRO

Ambrosio et al. 1997
temperature seasonal variations

![Graph showing changes in ΔR_R/R and ΔT_eff/T_eff over time.](image)

**AMANDA**

Bouchta et al. 1999
temperature seasonal variations

AMANDA  Wissing, 2004

sudden stratospheric warming

Tilav et al., ICRC 2009
temperature seasonal variations

LVD
Selvi et al. 2009
Agafanova et al. 2011
temperature seasonal variations

MINOS

de Jong, Grashorn et al. 2009
Adamson et al. 2010
temperature seasonal variations

Borexino

Adamson et al. 2010
**temperature seasonal variations**

<table>
<thead>
<tr>
<th>Year</th>
<th>μ rate (SMT8)</th>
<th>CR shower rate (STA3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>500 Hz</td>
<td>13 Hz</td>
</tr>
<tr>
<td>2008</td>
<td>1100 Hz</td>
<td>15 Hz</td>
</tr>
<tr>
<td>2009</td>
<td>1700 Hz</td>
<td>25 Hz</td>
</tr>
<tr>
<td>2010</td>
<td>2000 Hz</td>
<td>30 Hz</td>
</tr>
<tr>
<td>2011+</td>
<td>2200 Hz</td>
<td>35 Hz</td>
</tr>
</tbody>
</table>

---

**Observed InIce SMT Rate (Run Duration > 1 hour)**

[Graph showing rate variations over time with labels for IC22, IC40, IC59, IC79, IC86_1, and IC86_2.]
temperature seasonal variations

effective temperature

\[
T_{\text{eff}}(\theta) = \frac{\int dE_\nu \int dX A_{\text{eff}}(E_\nu, \theta) P(E_\nu, \theta, X) T(\theta, X)}{\int dE_\nu \int dX A_{\text{eff}}(E_\nu, \theta) P(E_\nu, \theta, X)}
\]

seasonal variations decrease with prompt component
History

- Cornell
  P.H. Barret et al., Refs. Mod. Phys. 24 133 (1952)

- MACRO

- AMANDA

- LVD
  M. Selvi, Proc. 31st ICRC (2009)

- IceCube

- MINOS

- LVD

- Borexino
  G. Bellini et al., arXiv:1202.6403
temperature seasonal variations

\[ \phi_\mu(E_\mu, \theta) = \phi_N(E_\mu) \times \left( \frac{1}{1 + B_{\pi\mu} \cos\theta^* \frac{E_\mu}{\epsilon_\pi}} + \frac{A_{K\mu}/A_{\pi\mu}}{1 + B_{K\mu} \cos\theta^* \frac{E_\mu}{\epsilon_K}} \right) \]

\[ A_{K\mu}/A_{\pi\mu} = \left( \frac{BR_{K\mu}}{BR_{\pi\mu}} \right) \left( \frac{Z_{K\mu}}{Z_{\pi\mu}} \right) \left( \frac{Z_{N K}}{Z_{N \pi}} \right) \]

\[ R(K/\pi) = \frac{Z_{N K}}{Z_{N \pi}} \]

\[ \epsilon_{\pi, K} = \frac{kT}{M g} \frac{m_{\pi, K} c^2}{c \tau_{\pi, K}} \]

\[ Z_{N \pi^\pm}(E) = \int_E^\infty dE' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{d n_{\pi^\pm}(E', E)}{dE} \]

kaon/pion ratio

spectrum weighted moment of the cross section for a nucleon N to produce a secondary meson from a target nucleus in the atmosphere

critical energy regulates competition between meson interaction & decay

\[ \phi_\mu(E_\mu, \theta) = \int_0^\infty P_\mu(E_\mu, \theta, X) \, dX \quad \text{Muon Flux} \]
temperature seasonal variations
charm component

PD, Gaisser 2010
Fedynitch, Becker Tjus, PD 2012
temperature seasonal variations
charm component

PD, Gaisser 2010

TABLE I: Correlation coefficients for muons with \( \theta \leq 30^\circ \) for three levels of charm (energy in TeV; rate in Hz/km²).

<table>
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<tr>
<th>( E_{\mu,min} ) (TeV)</th>
<th>no charm</th>
<th>RQPM charm</th>
<th>ERS charm</th>
<th>int. charm</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>Rate</td>
<td>( \alpha )</td>
<td>Rate</td>
<td>( \alpha )</td>
</tr>
<tr>
<td>0.5</td>
<td>0.83</td>
<td>2050</td>
<td>0.82</td>
<td>2070</td>
</tr>
<tr>
<td>10</td>
<td>0.98</td>
<td>1.26</td>
<td>0.89</td>
<td>1.40</td>
</tr>
<tr>
<td>100</td>
<td>1.00</td>
<td>0.0025</td>
<td>0.53</td>
<td>0.0049</td>
</tr>
</tbody>
</table>

TABLE II: Correlation coefficients with and without charm for neutrinos in three zones of the atmosphere (see text).