Constraints on atmospheric charmed-meson production from IceCube

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IceCube's detection of ultra-high energy neutrino events heralds the beginning of neutrino astronomy. At very-high energies (100 TeV - 1 PeV), the dominant background to the astrophysical signal is the flux of prompt neutrinos, coming from the semi-leptonic decay of charmed mesons produced by cosmic ray collisions in the atmosphere

Outline

- Introduction
- IceCube detector and detection principle
- Astrophysical Neutrinos
- Flux of prompt neutrinos as a background to the astrophysical neutrinos
- Summary

Introduction

Astrophysical Neutrinos

To first order, the energy spectrum of **astrophysical neutrinos** follows that of the cosmic rays at their acceleration sites.
If **Fermi shock acceleration** is the responsible mechanism,
a power law spectrum $E^{-\gamma}$ with $\gamma \simeq 2$ is expected [1]

The majority of the astrophysical neutrinos are expected to come from the decay of pions created in cosmic-ray interactions, therefore $\nu_e : \nu_\mu : \nu_\tau = 1:2:0$ flavor composition **at the production site** is predicted.
Due to **long-baseline neutrino oscillations,** the flavor composition at Earth should be in approximation equal to $\nu_e : \nu_\mu : \nu_\tau = 1:1:1$

Background

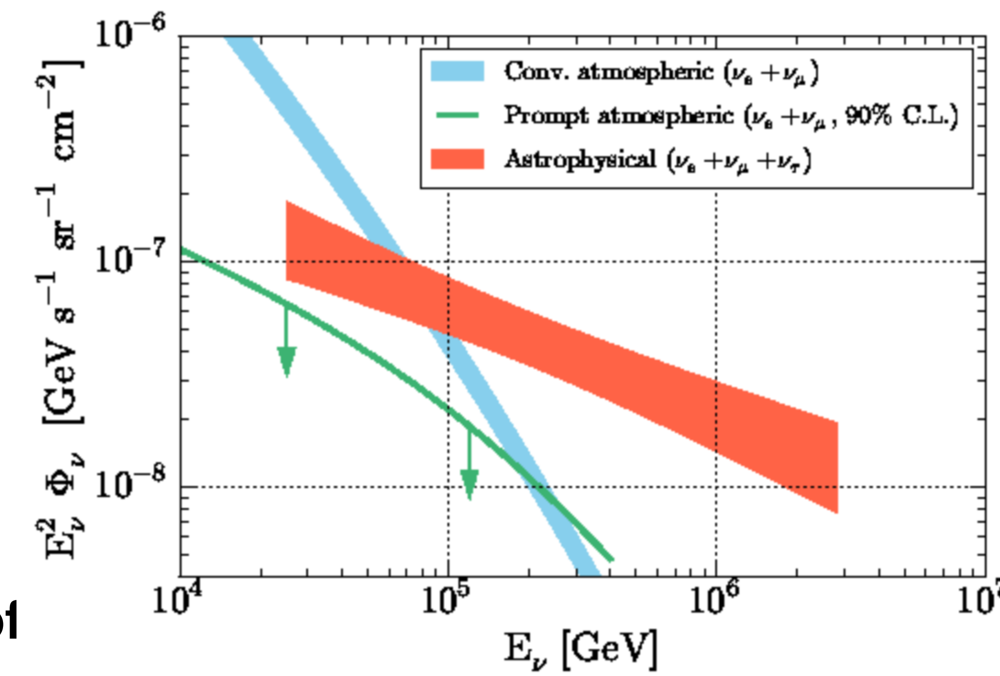
All relevant backgrounds to astrophysical neutrinos are created in cosmic ray-induced air showers in the atmosphere of the Earth

1) **Conventional atmospheric neutrinos** - from the decays of kaons and charged pions. These particles are likely to interact with air molecules before they decay, the resulting neutrino flux differs from the original cosmic ray flux -> **the energy spectrum is steeper** (approximately $E^{-3.7}$) and the **flux is higher near the horizon**

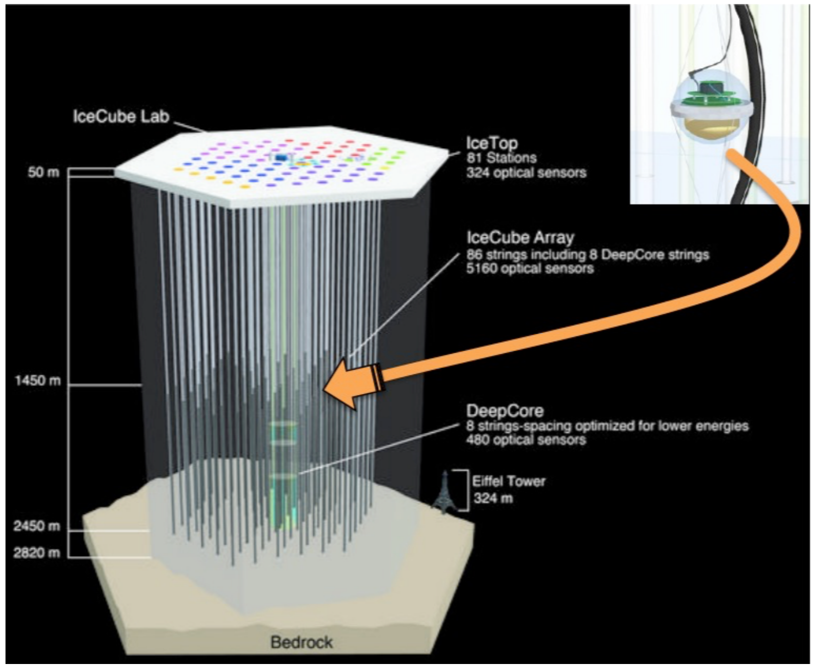
2) **Prompt neutrino flux** - from from the decays of heavy, short-lived hadrons containing a charm or bottom quark. This flux is predicted to follow that of the cosmic rays more closely, with an **energy spectrum of approximately $E^{-2.7}$ and an isotropic zenith angle distribution**

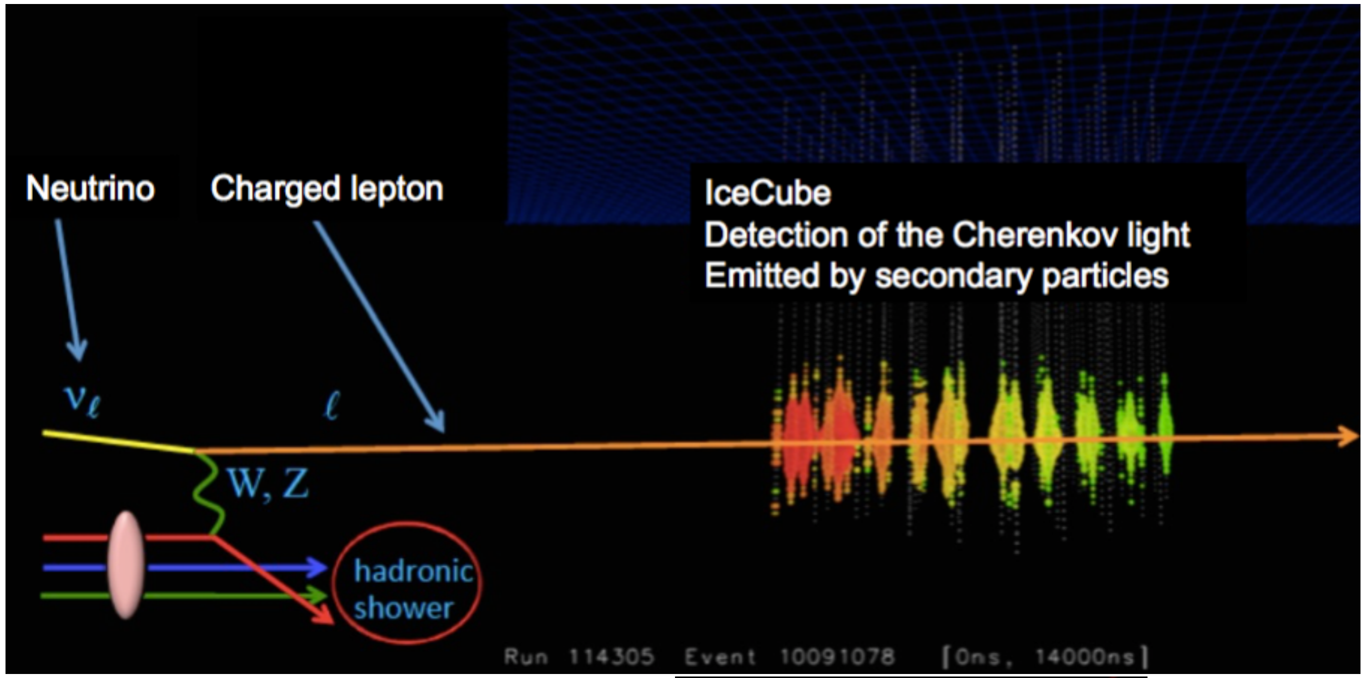
3) **Atmospheric muons** constitute the most abundant background. They reach the detector from ~above the horizon.

$$\frac{d\phi}{dE} \propto E^{-3.7} \qquad \frac{d\phi}{dE} \propto E^{-2.7} \qquad \frac{d\phi}{dE} \propto E^{-2}$$



IceCube detector & Detection principle





The characteristic pattern (topology) of the Cherenkov light provides information about the energy, direction, and flavor of the parent neutrino

1) Track-like events

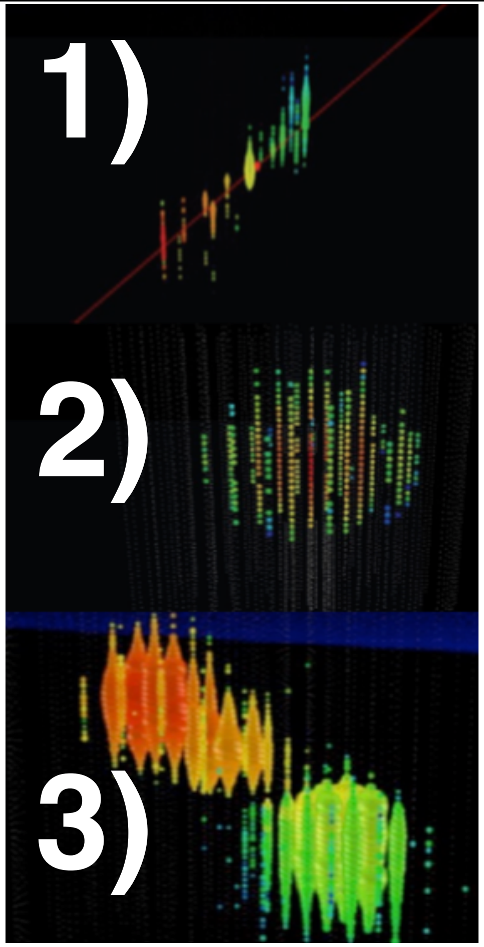
good angular resolution, limited energy resolution when not fully contained in the detector volume; source - νμ CC interactions

2) Cascade-like event

good energy resolution, limited angular resolution; source - νe, νμ, ντ NC + νe, ντ CC interactions

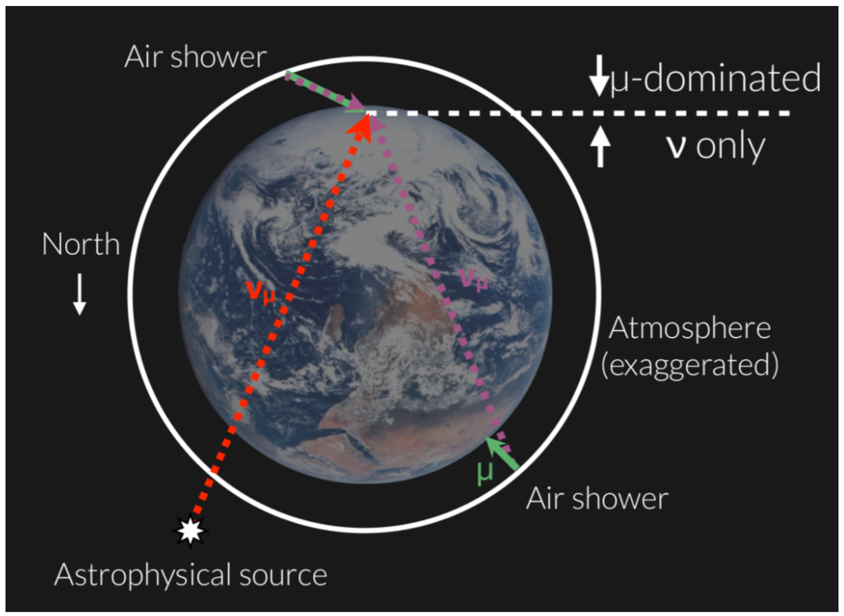
3) Composite events

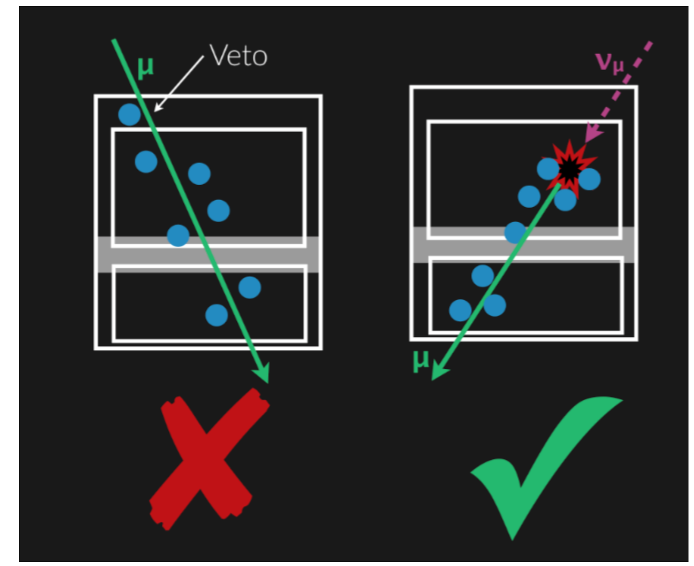
mixture of track-like and cascade-like events or multiple cascade events; high-energy ντ CC as a possible source

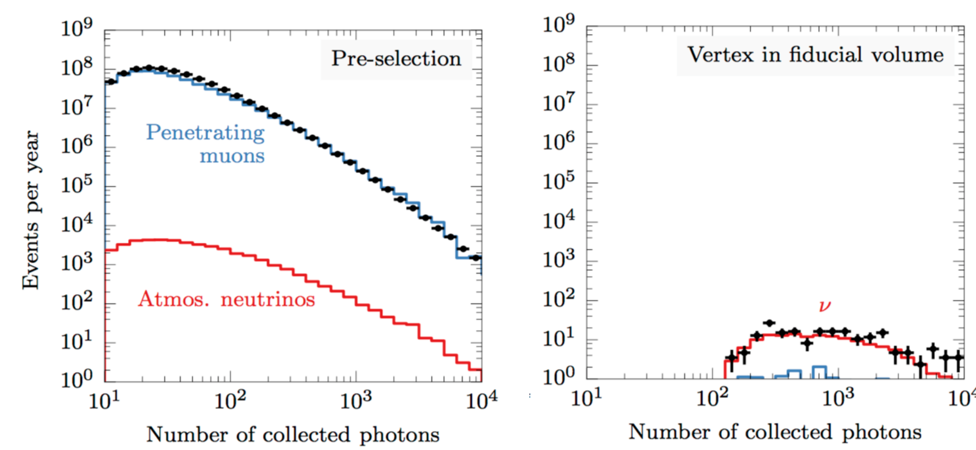


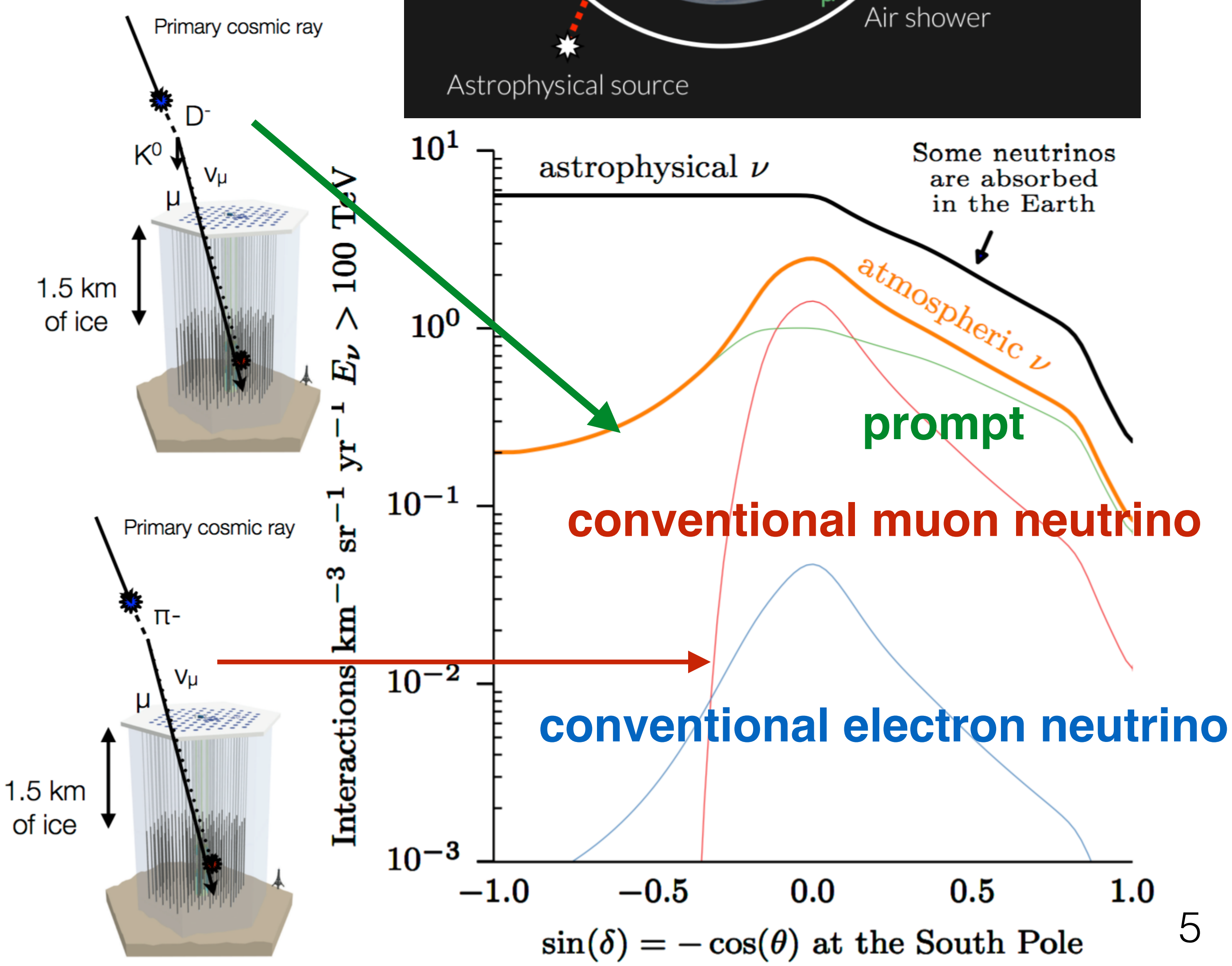
Detection methods.

Neutrino absorption in the Earth , self-veto, and detector veto



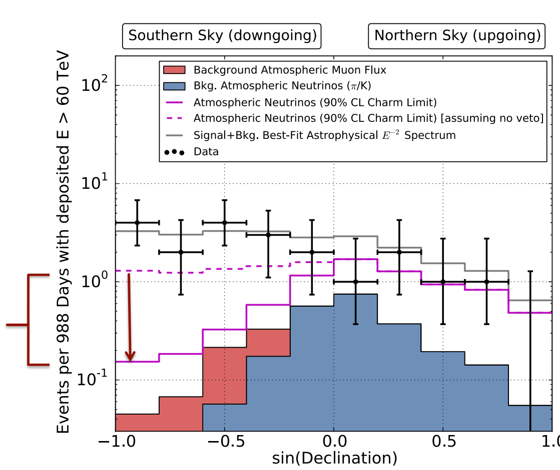






Angular distribution (E> 60 TeV)

Atmospheric ν veto

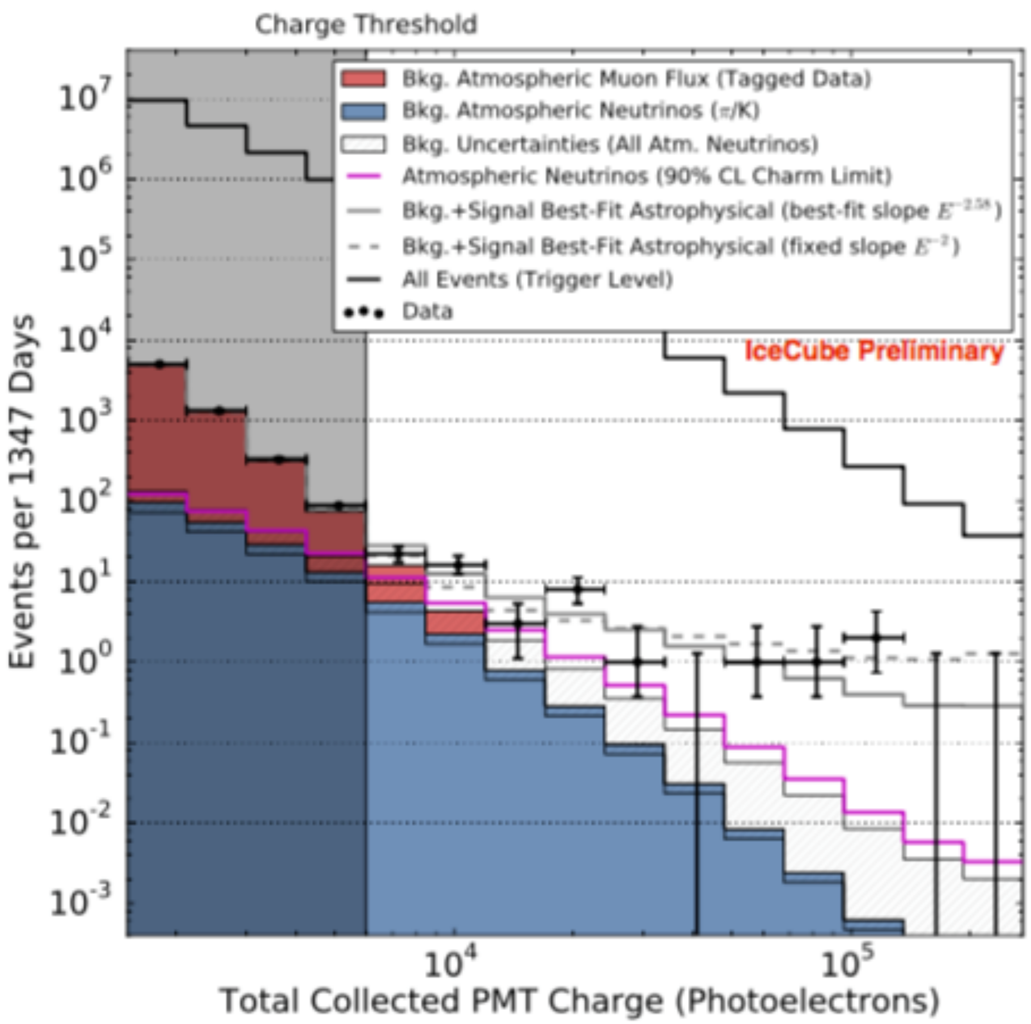


Select E > 60 TeV to get above atmospheric μ background.
Note shape of prompt atmospheric ν background.

Astrophysical Neutrinos

High Energy Starting Events

High energy cosmic neutrinos with deposited energies between 30 and ~2000 TeV and arrival directions consistent with isotropy



54 events between 60 TeV and 2.1 PeV
39 cascades
13 tracks
2 “background”

consistent with expectations for equal fluxes of all three neutrino flavors

Background Expectations:
Atmospheric muons: 12.6 +- 5.1 (from data)
Atmospheric neutrinos: 9.0 $^{+8.0}_{-2.2}$

power law spectrum $E^{-\gamma}$

“Soft”: $\gamma \approx 2.6$

A purely atmospheric origin of the observed events can be rejected with a significance of **5.7σ**

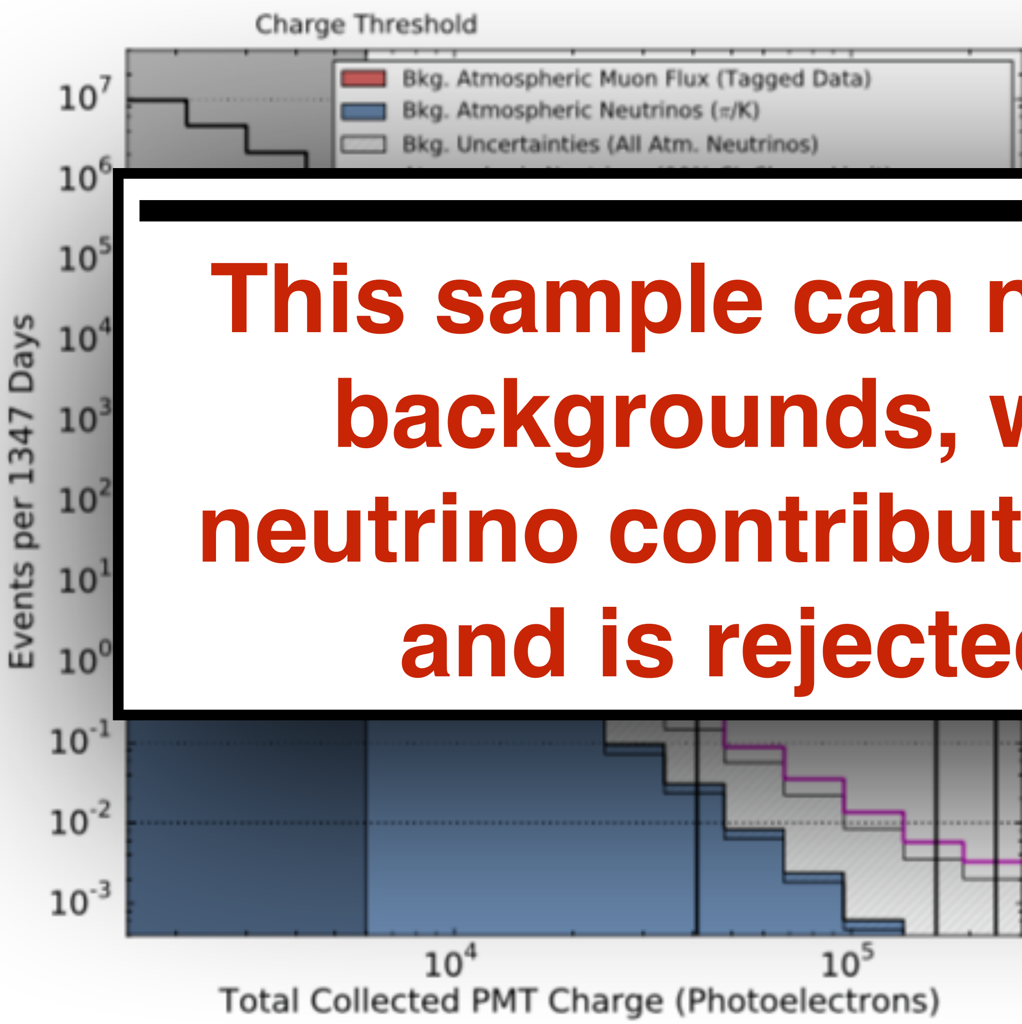
Observation of Astrophysical Neutrinos in Four Years of IceCube Data

“4-year” 2015 ICRC proceedings. arXiv:1510:05223
“3-year” PRL 113 (2014) 101101
“2-year” Science 342 (2013) 6161

Astrophysical Neutrinos

High Energy Starting Events

High energy cosmic neutrinos from the Southern sky with deposited energies between 30 and ~2000 TeV and arrival directions consistent with isotropy



54 events between 60 TeV and 2.1 PeV.

ors

atm ν (π, K + prompt):

$9.0^{+8.0}_{-2.2}$

power law spectrum $E^{-\gamma}$

“Soft”: $\gamma \approx 2.6$

This sample can not be explained by atmospheric backgrounds, which would require a prompt neutrino contribution 7 times larger than expected and is rejected with a significance of 5.7σ

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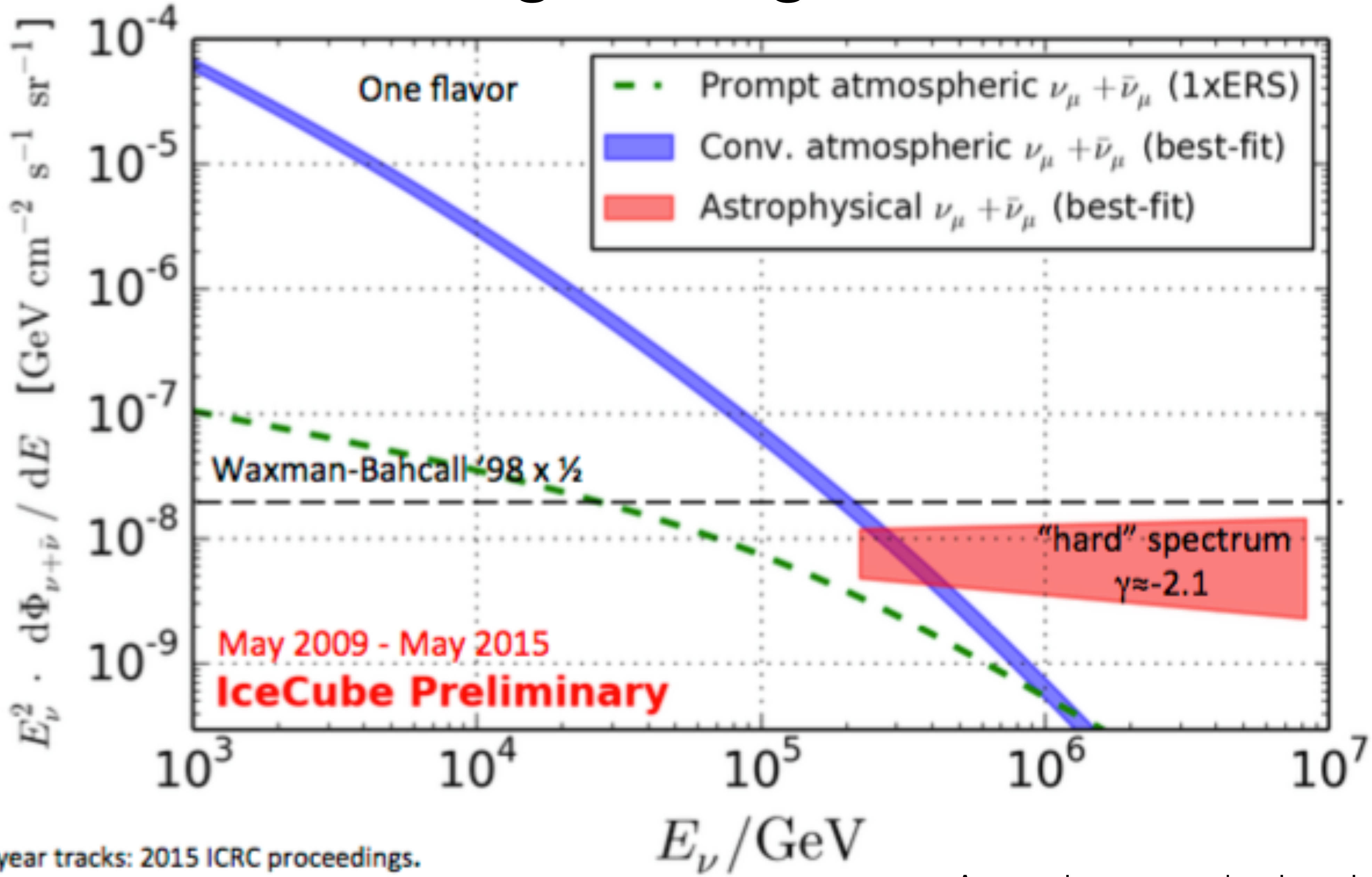
A purely atmospheric origin of the observed events can be
rejected with a significance of **5.7σ**

Astrophysical Neutrinos

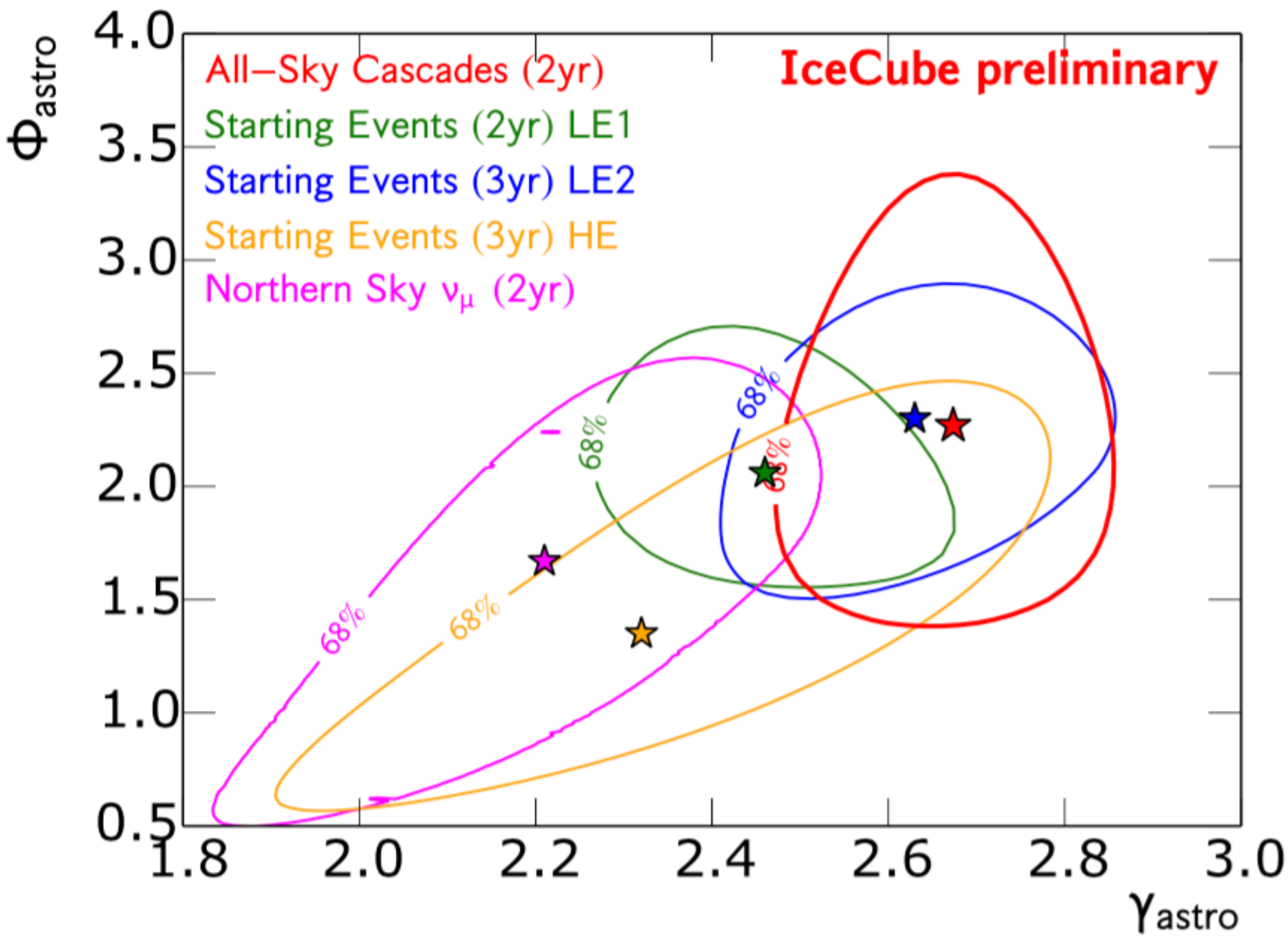
Though-Going Tracks



6-year tracks: 2015 ICRC proceedings.
arXiv:1510:05223

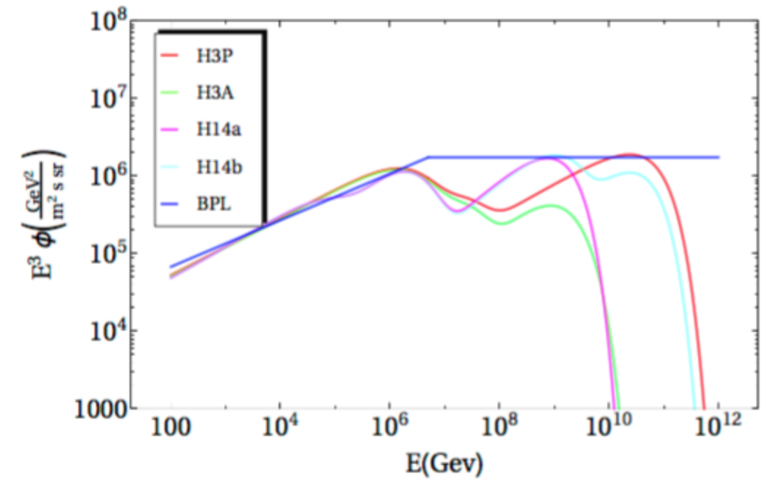
A purely atmospheric origin of the observed events can be rejected with a significance of **4.3σ**

Atmospheric Neutrinos: Spectral Index

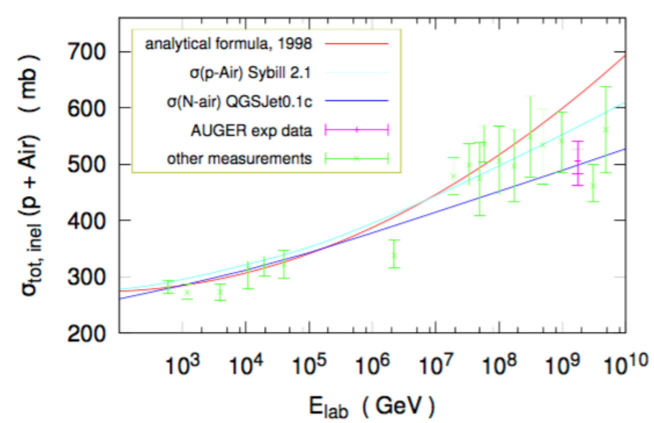


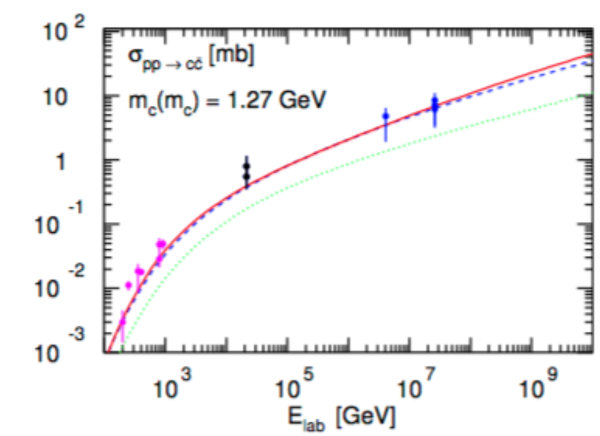
Estimation of prompt neutrino flux

- **<u>What do we need to know to estimate prompt neutrino flux?</u>**
  - **<u>Cosmic ray flux</u>**
  - **<u>Propagation of high energy particles and their decay products through the atmosphere</u>**
    - Cascade equations / full Monte Carlo
      - Proton-air inelastic cross section
      - Charm production cross-section
      - Charm fragmentation into hadrons (non-perturbative)
      - (σ (pA->D + X) ≈ <A> σ (pp->D + X)); D is generic charmed meson; is nuclear shadowing negligible?



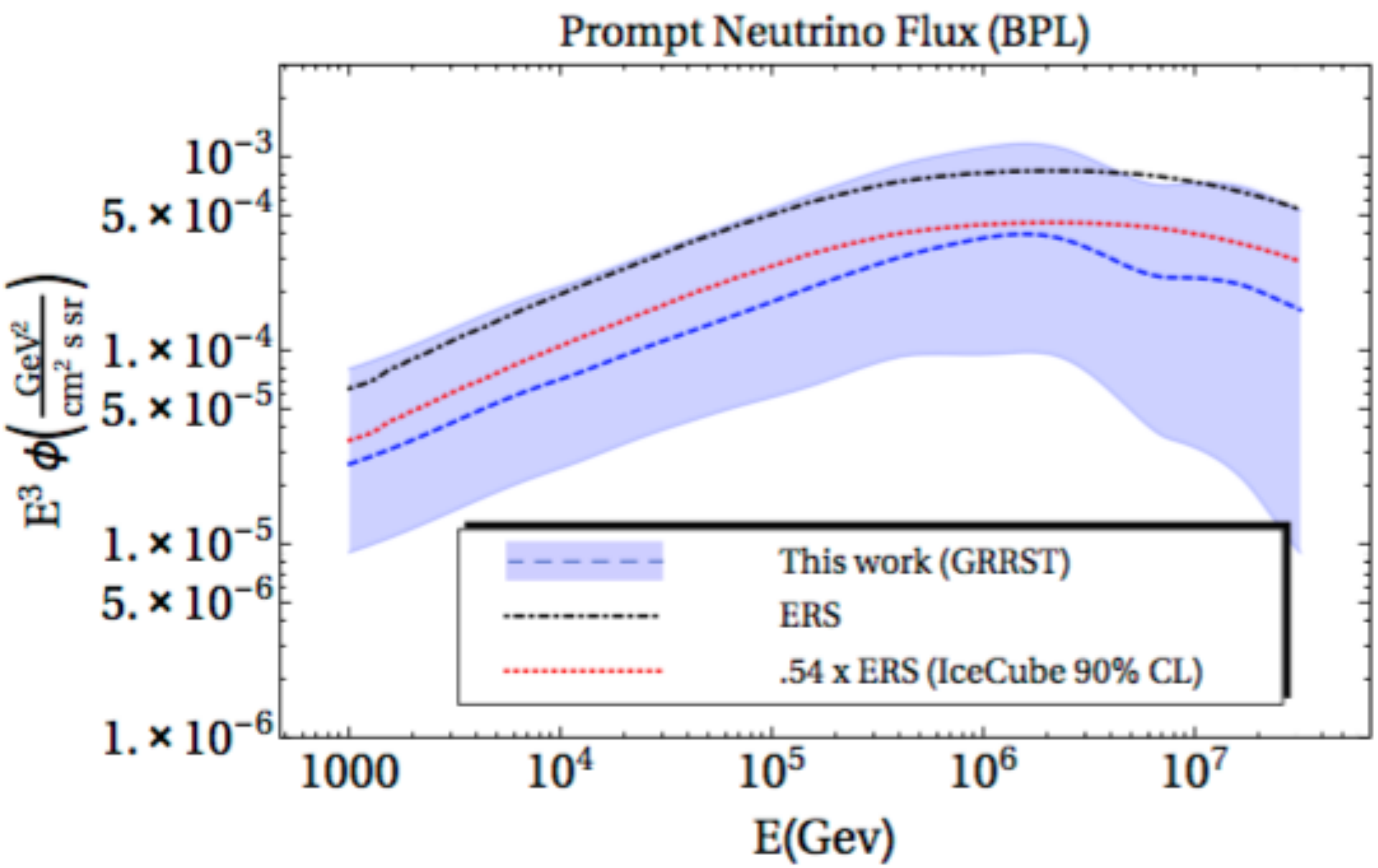
Essential component of any calculation of the prompt neutrino flux is the parameterization of <u>the incoming cosmic ray flux</u>, which is rather uncertain at the relevant high energies





Important Systematics:
Variation of the charm quark pole mass
Renormalization and factorization scales
PDF uncertainties

Influence of systematic errors on estimated prompt neutrino flux



ERS - includes parton saturation effects in the QCD production cross section of charm quarks (see arXiv:0806.0418 [hep-ph] for more details);
The ERS prompt flux calculation is commonly used as a standard benchmark background.

Central value of the ERS calculation is in tension with the 90% CL upper limit labeled '0.54×ERS'

The error band includes all relevant sources of theoretical uncertainties:
from PDFs (68% CL),
missing higher orders,
and the charm mass

arXiv: 1511.06346v3

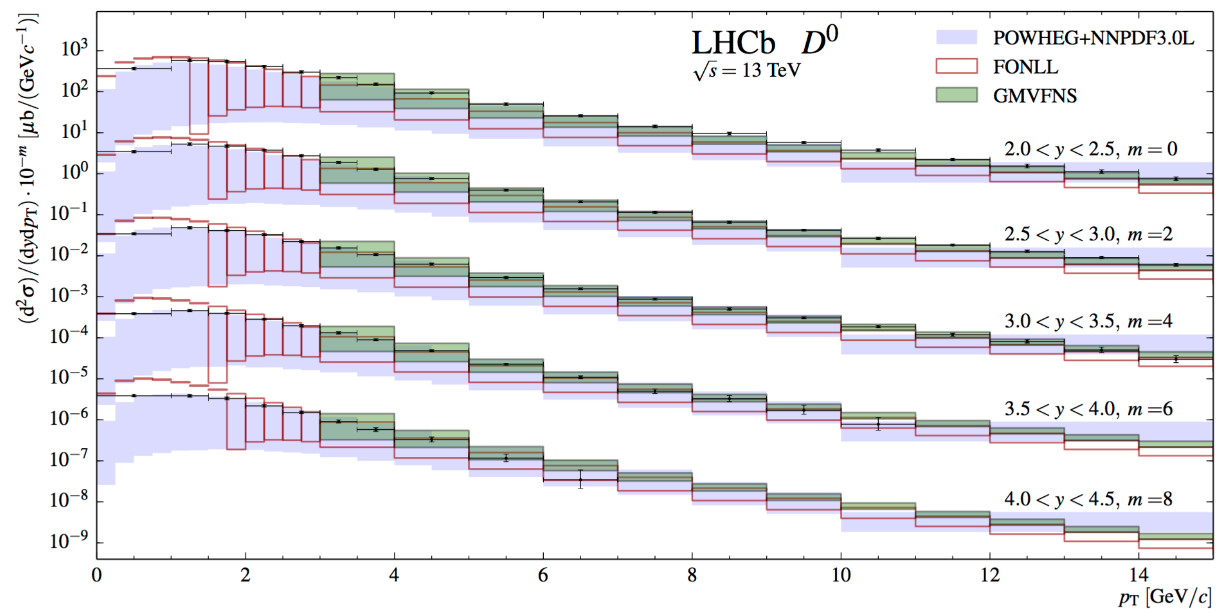
Validation of charm hadroproduction using LHC data

- **Charm production** in **p**roton **p**roton collisions at a centre-of-mass energy of **sqrt(s)=13TeV** (before 7TeV) has been measured

- The **shapes of differential cross sections for D^0, D^+, D^{*+}, D^+_S in agreement with NLO** (the predicted central values generally lie below the data but within the uncertainty)

- **<u>Limitation:</u> Modern collider experiments have no coverage in the very large rapidity region.**

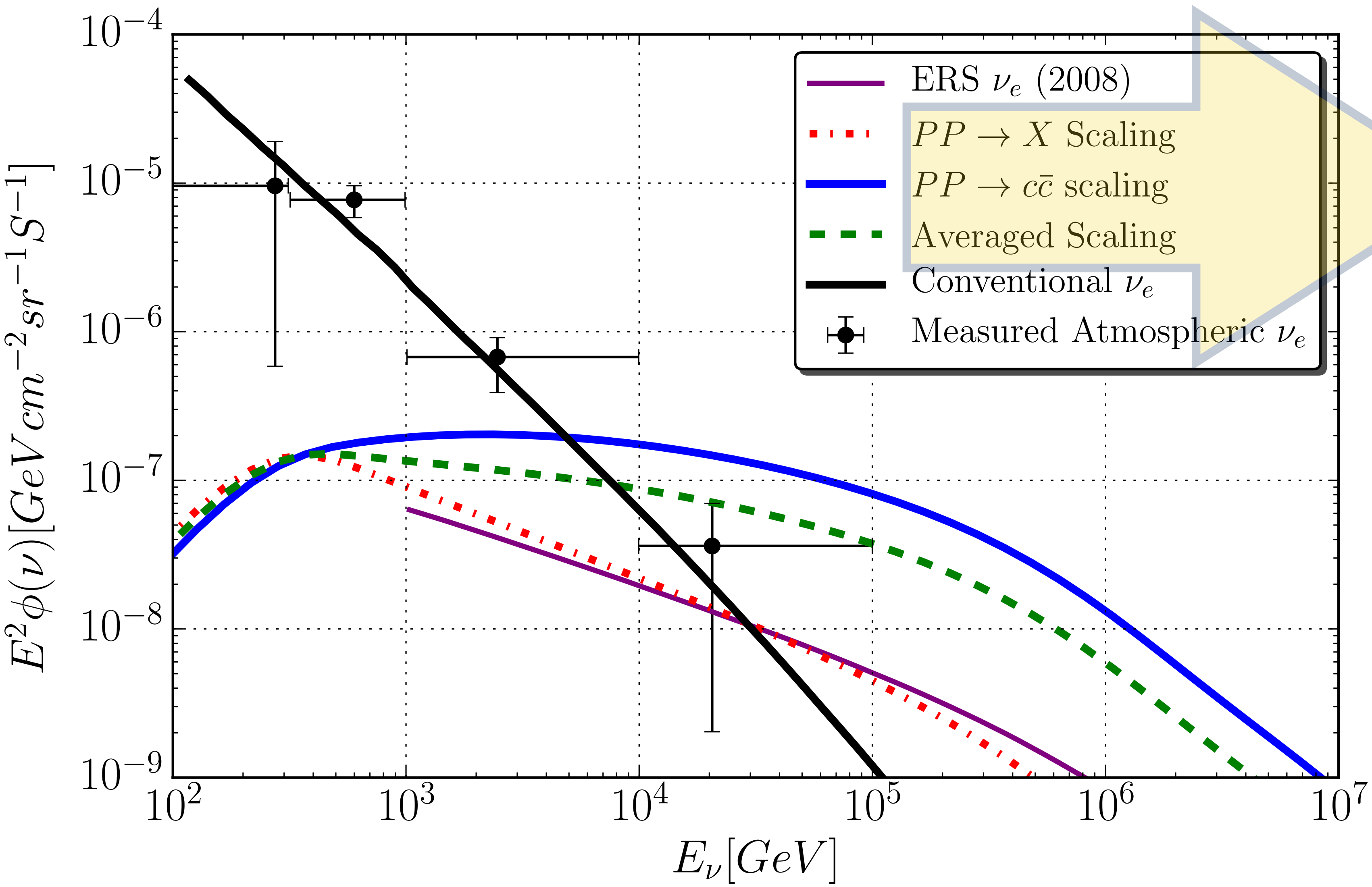
<u>Example</u>



Measurement and predictions for absolute prompt D^0 cross section, The boxes indicate the ±1σ uncertainty band on the theory predictions.

pQCD can calculate the pp -> cc cross section (see slide 9),
but that charm also has to fragment into hadrons.
<u>This fragmentation process is always non-perturbative</u>

Physics in the forward region

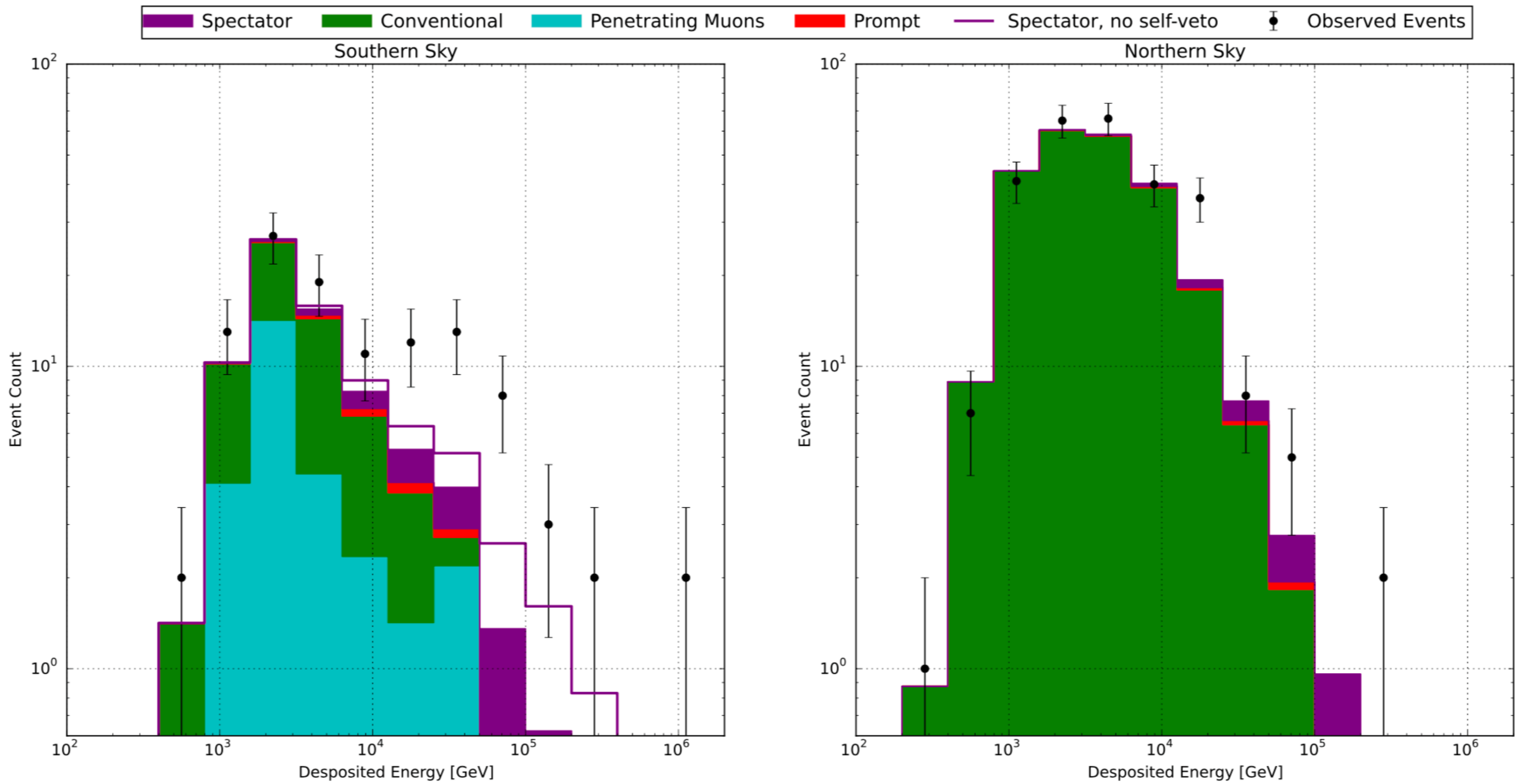


Different forward physics assumed

Flux of neutrinos from forward charm production may dominate the central component.
It may therefore also represent a significant contribution to the TeV atmospheric neutrino flux.

arxiv.org/abs/1601.03044

Physics in the forward region

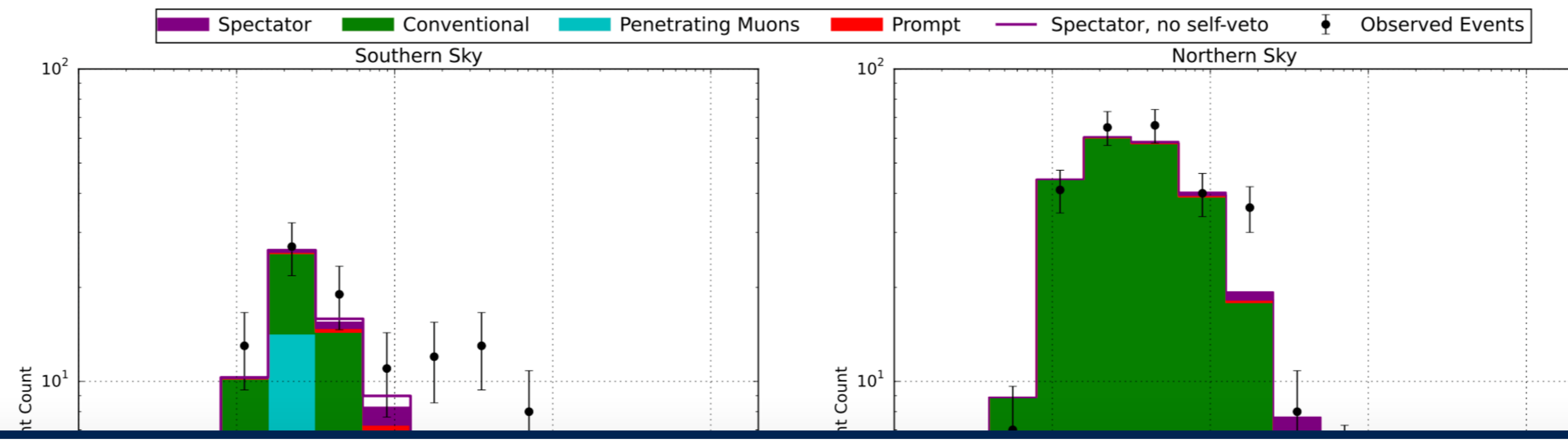


The expected number of events in both the southern (left) and northern (right) sky for two years in IceCube

Spectator - associated production of charm

arxiv.org/abs/1601.03044

Physics in the forward region



In the northern sky, the **maximal flux from the forward charm neutrino leaves little room** for an additional cosmic neutrino flux without exceeding the observed events.

<u>maximal</u> forward prompt neutrino flux cannot explain the high-energy events observed in IceCube

arxiv.org/abs/1601.03044

Summary

- At very-high energies (100 TeV - 1 PeV), the **dominant background to the astrophysical signal is the flux of prompt neutrinos**, coming from the semi-leptonic decay of charmed mesons produced by cosmic ray collisions in the atmosphere

- **Proper calculation of the prompt flux is complex and depends on many theoretical aspects** briefly shown and discussed in this presentation

- **The hadroproduction data can be used to increase our knowledge** and constrain theoretical predictions. However colliders have their limitations.

- Hypothesis of the non-zero intrinsic (or valence-like) heavy quark component of the proton distribution functions has not yet been confirmed or rejected but **maximal flux from the forward charm neutrino leaves little room for the additional intrinsic charm** (see slide 14)

Backup slides