Low x and ultrahigh energy neutrino physics

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Outline

- Motivation: low x and ultrahigh energy neutrino astronomy
- Calculation of atmospheric prompt neutrino fluxes
- Comparison with IceCube observations

Based on work in collaboration with

Atri Bhattacharya, Rikard Enberg, Mary Hall Reno, Ina Sarcevic

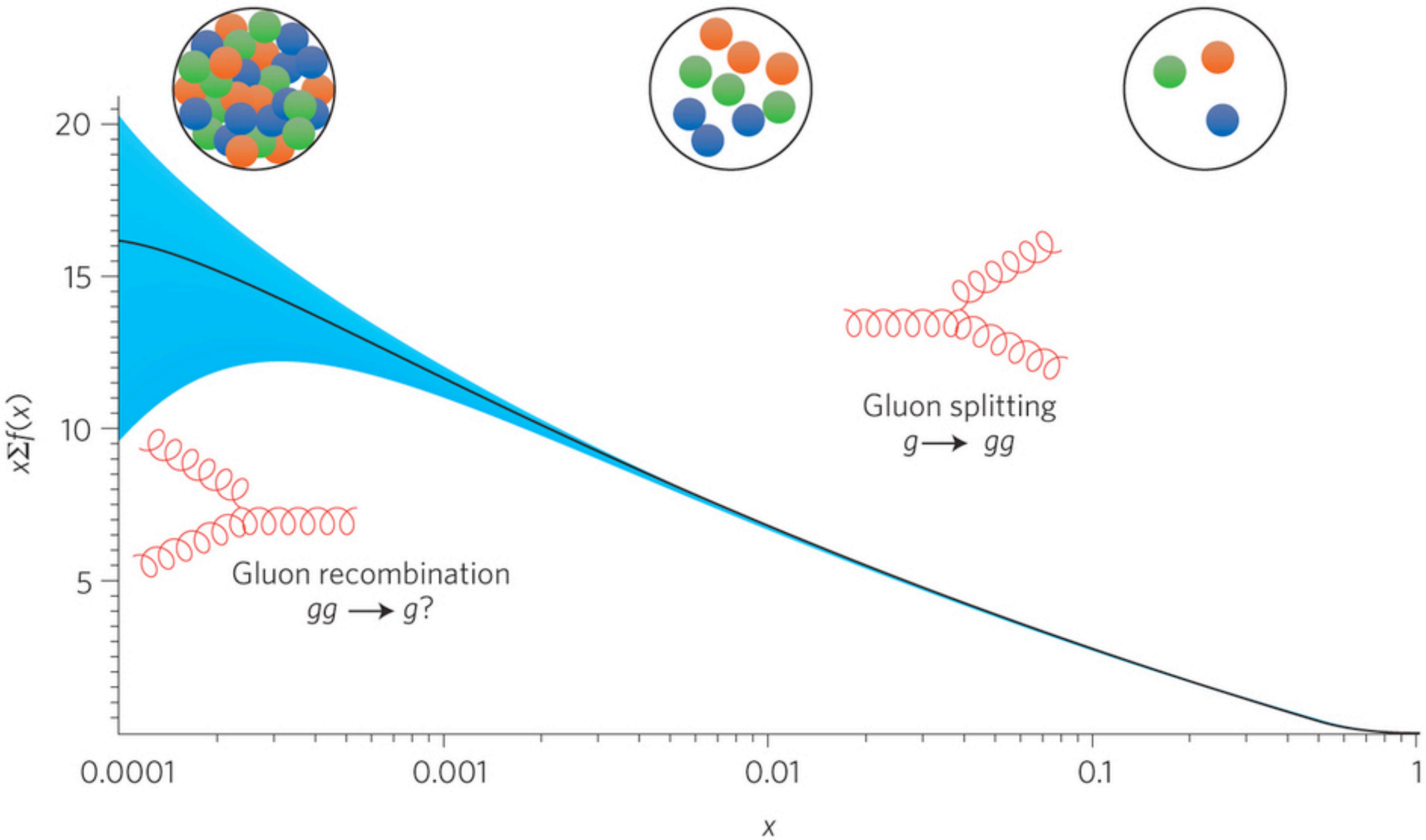
arXiv:1502:01076

Why small x is interesting?

Important lesson from HERA :

Observation of strong growth of the proton structure function at small x.
It is driven by the growth of the gluon density.

sum of parton densities



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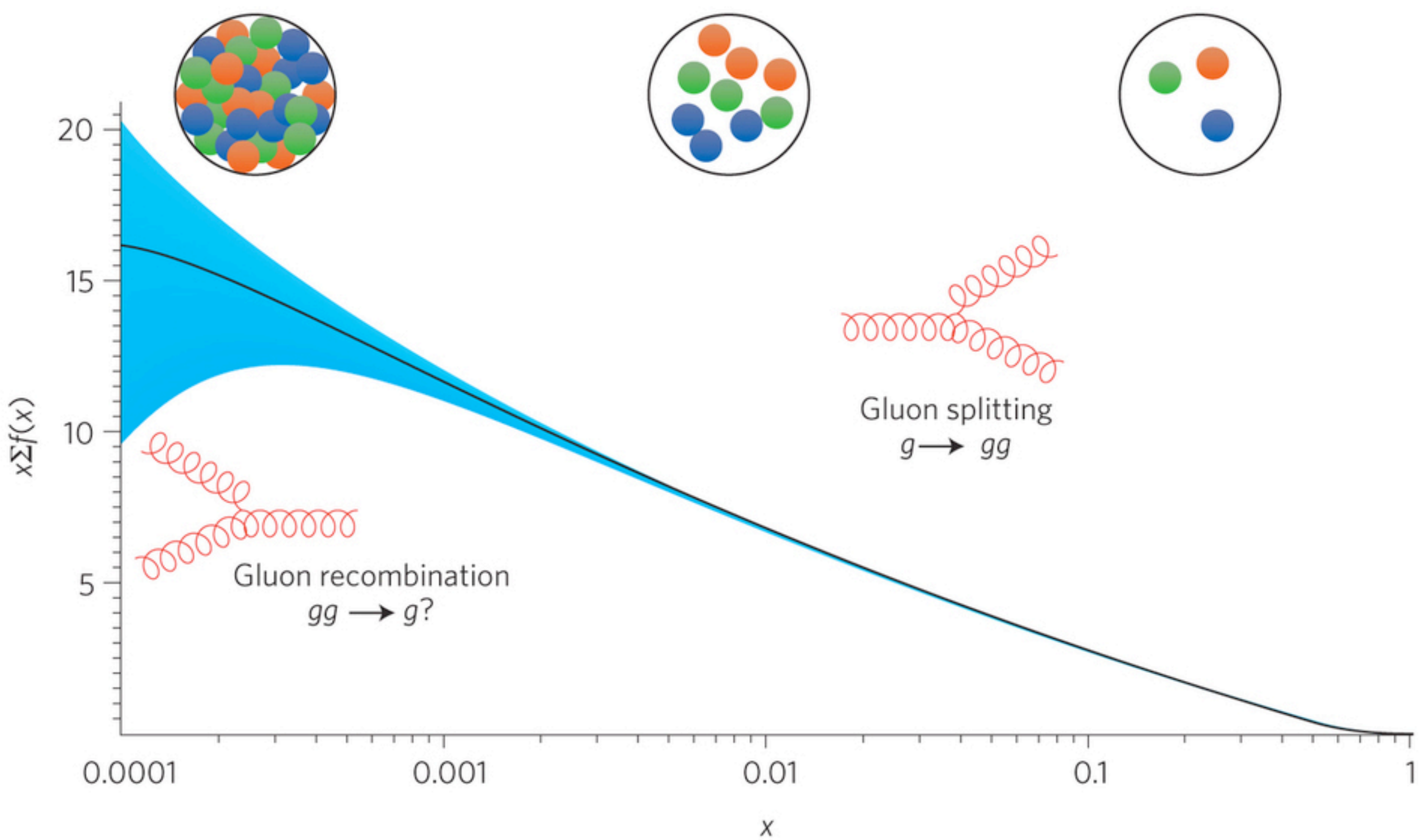

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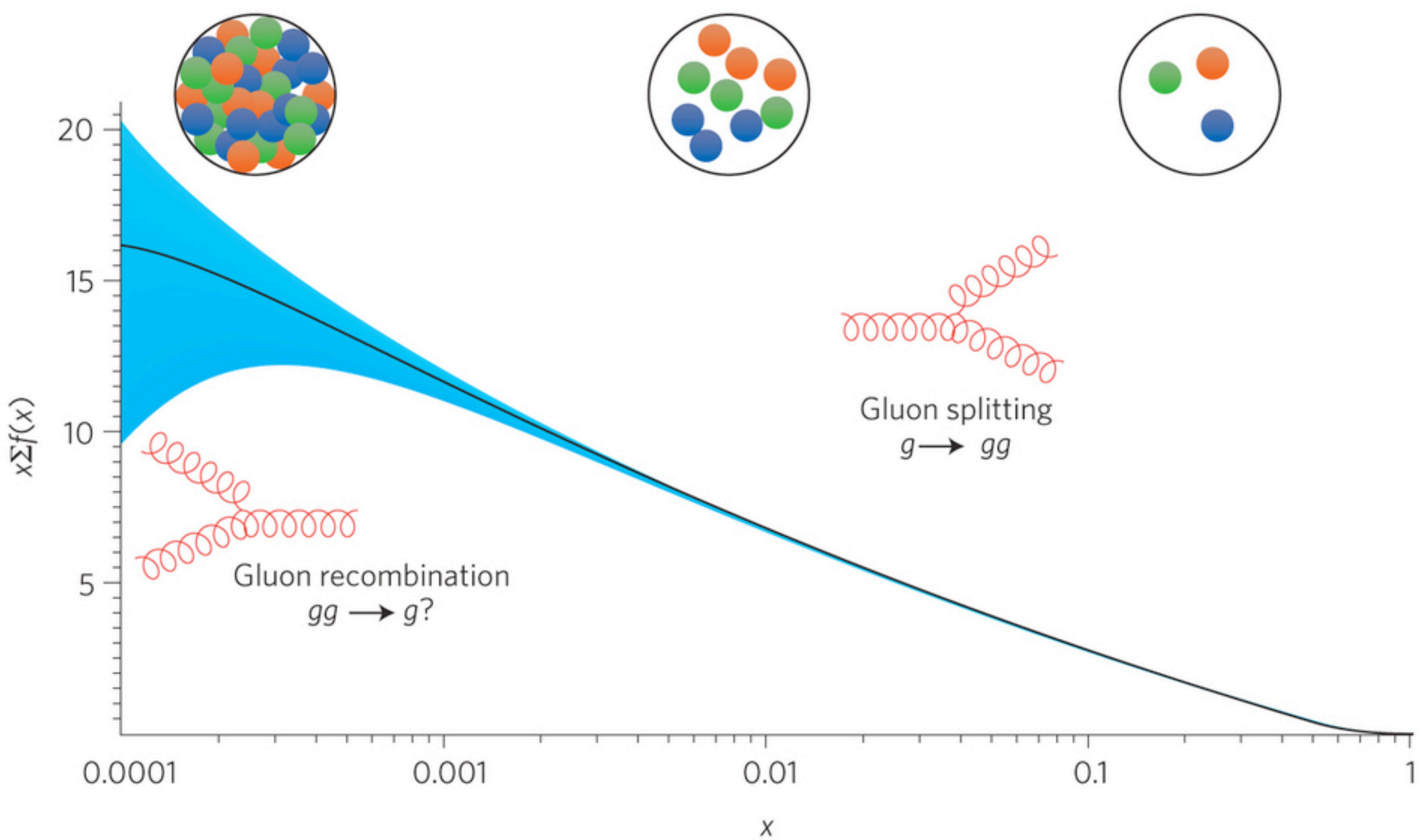

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- Further increase in the energy could lead to the importance of the recombination effects. Unitarity of the scattering amplitude.

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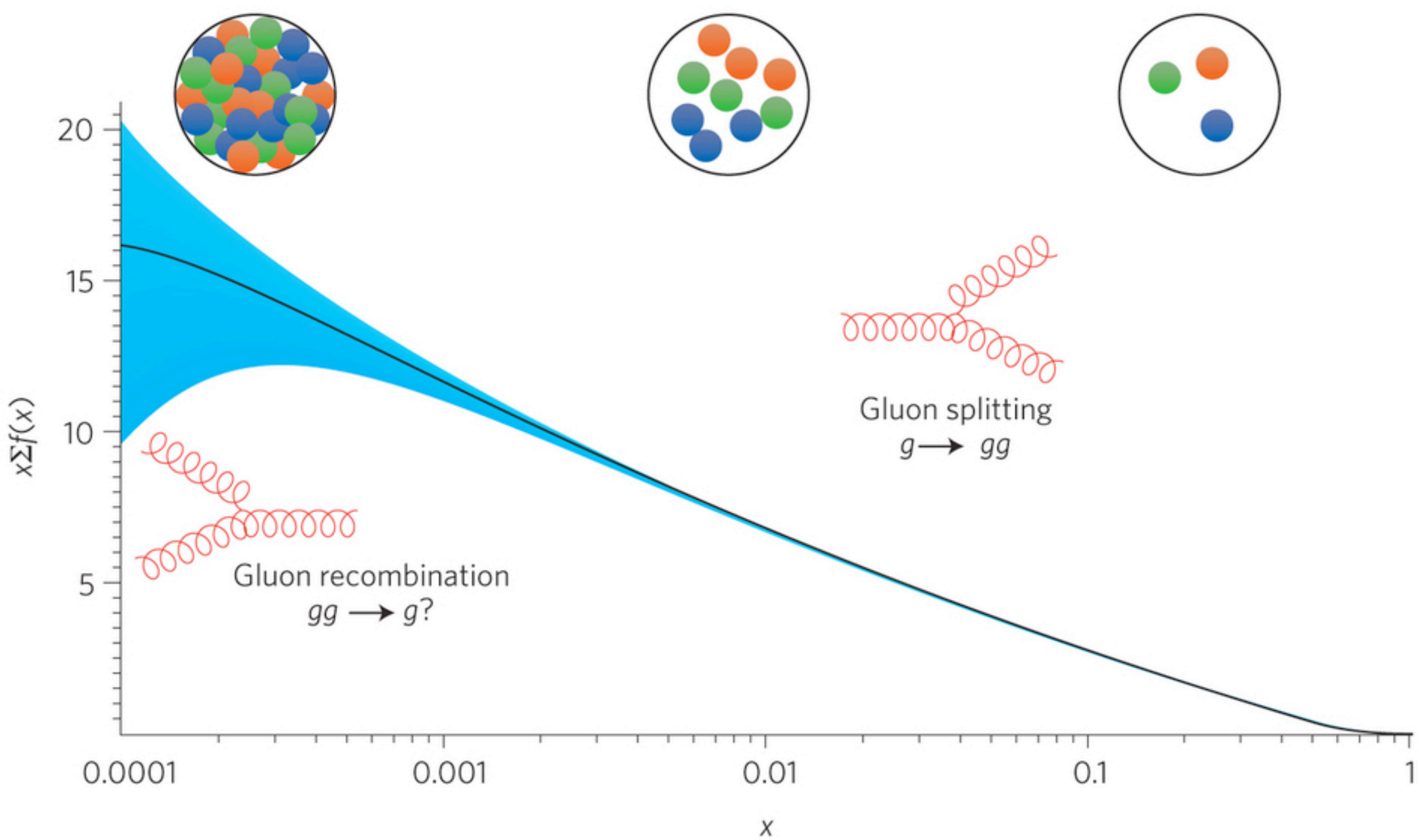
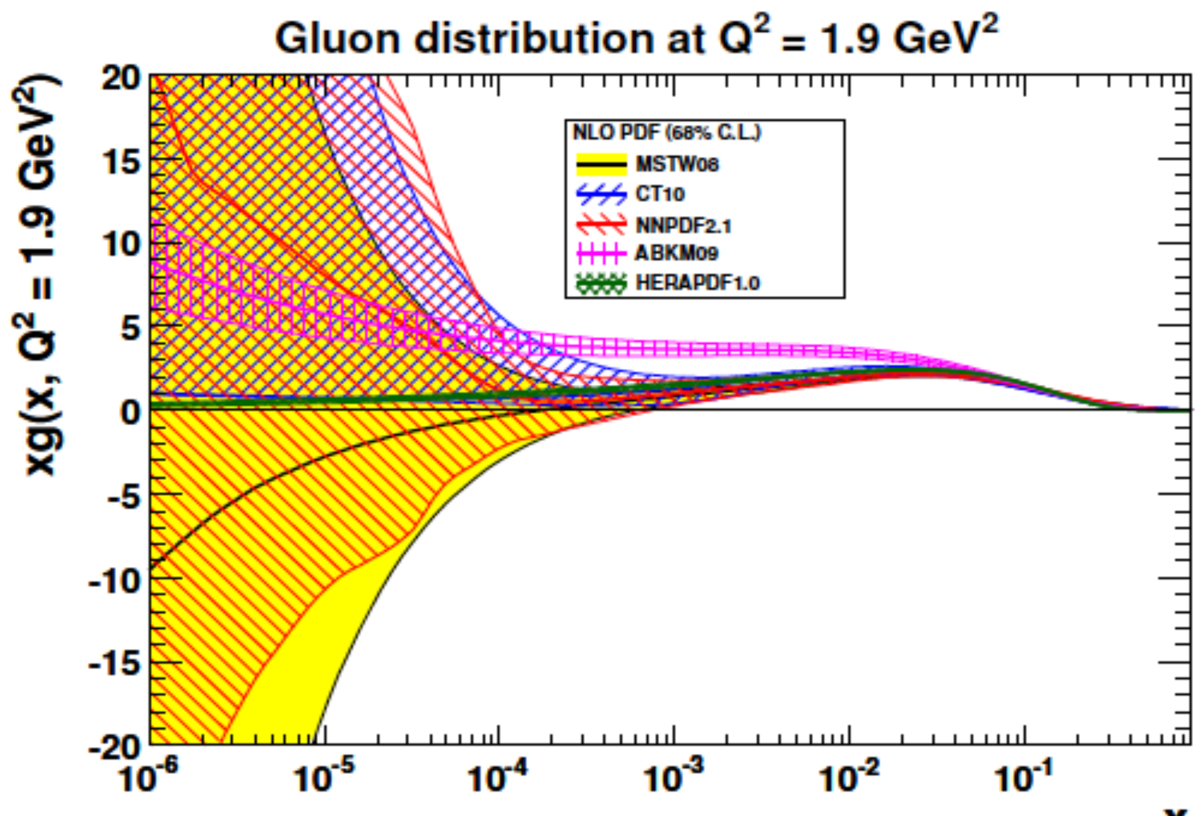
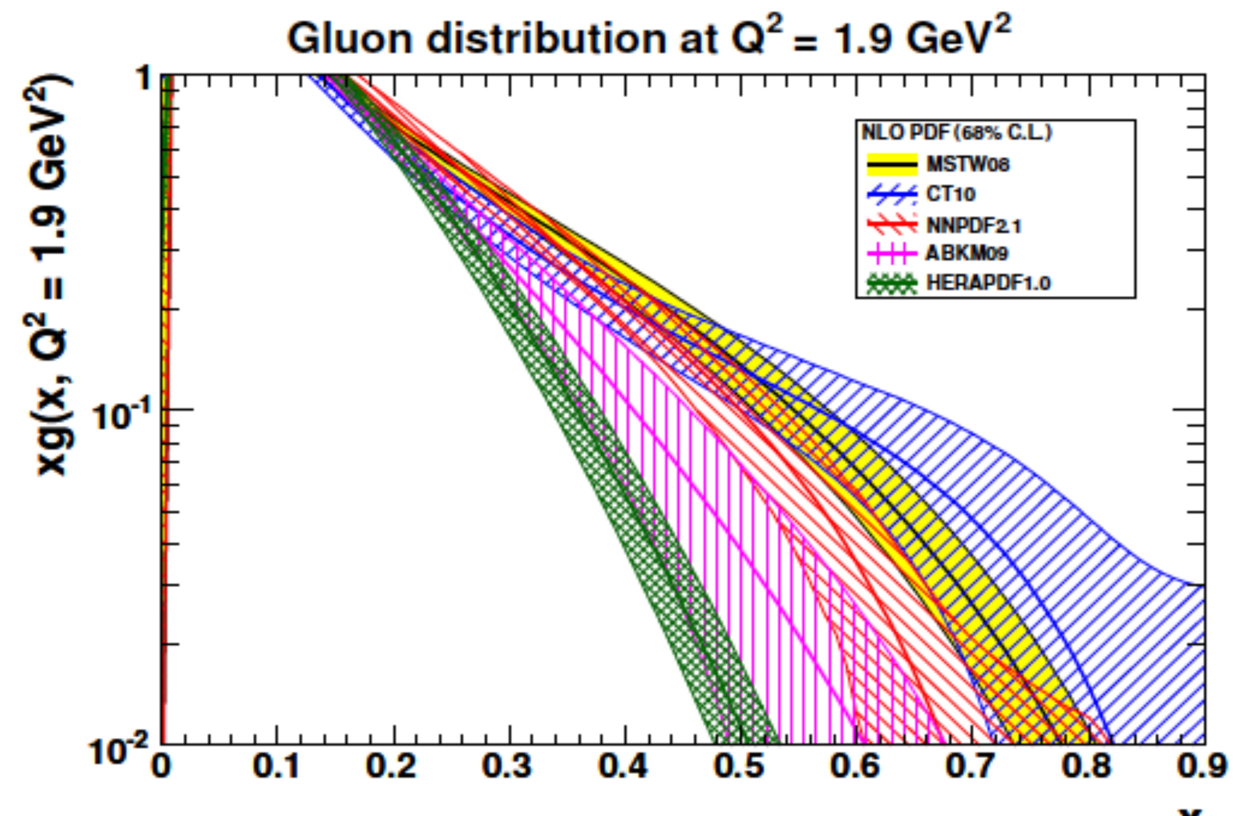


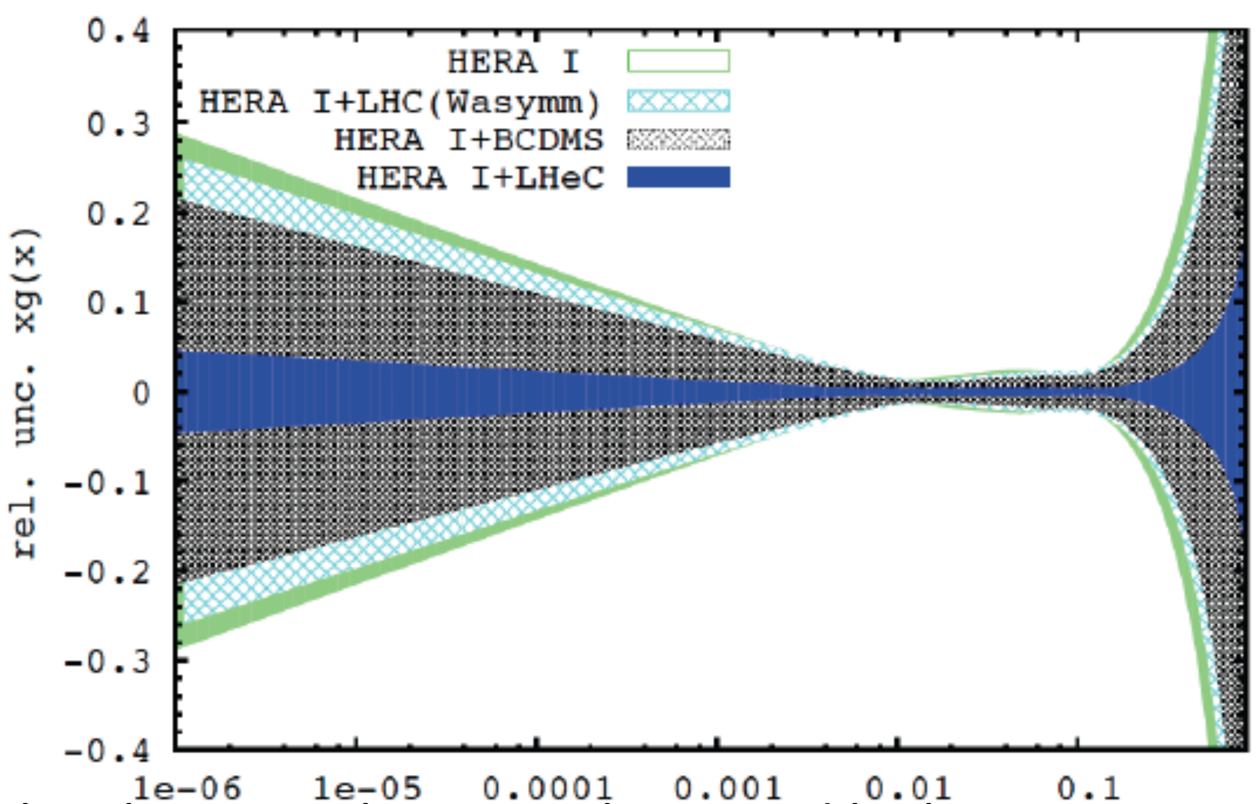
- Parton evolution needs to be modified to include potentially very large logs, resummation of log(1/x)
- Further increase in the energy could lead to the importance of the recombination effects. Unitarity of the scattering amplitude.
- Modification of parton evolution by including non-linear or saturation effects in the parton density.

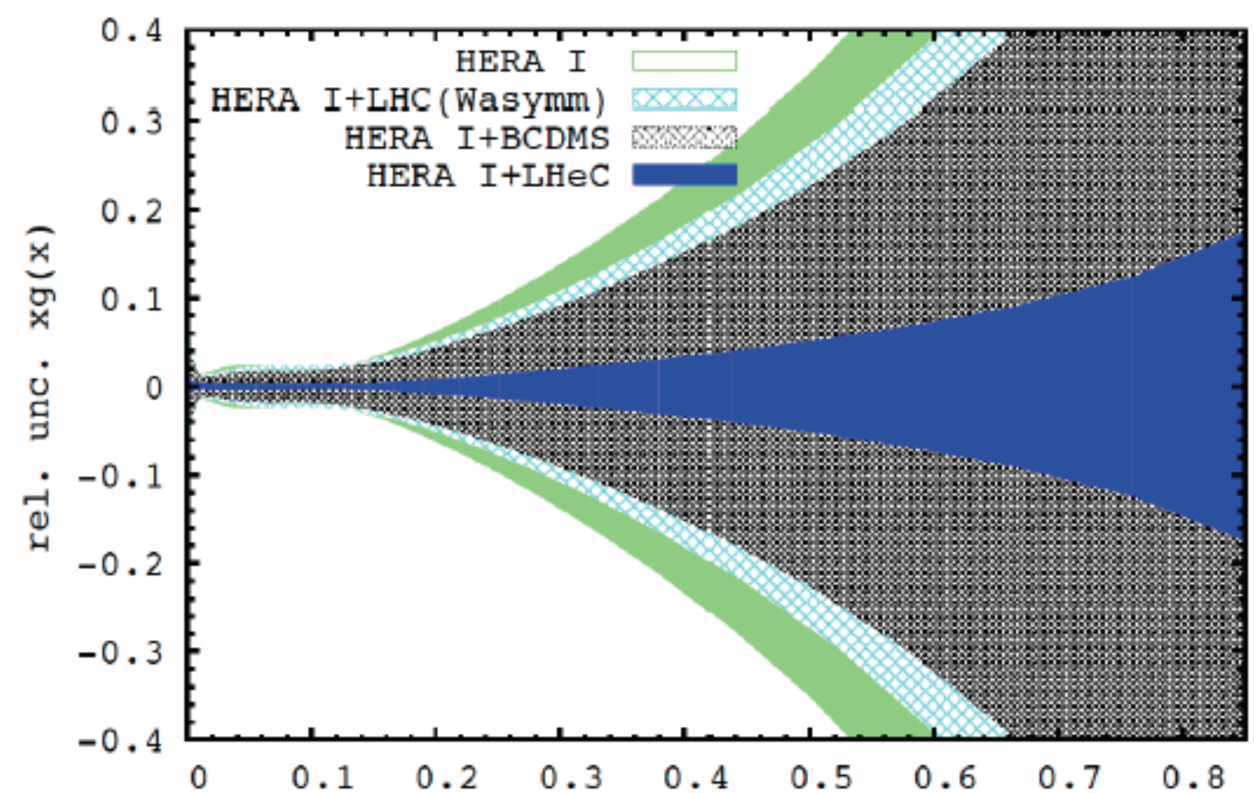
Mapping the Gluon Distribution





QCD fit analysis (default: NC,CC, LHeC only, following HERAPDF) with full experimental errors





The gluon is unknown at low x and high x – QCD: non-linear evolution, resummation. BSM: hi M – HL-LHC!

Neutrino astronomy

- Universe not transparent to extragalactic photons with energy > 10 TeV
- Weakly interacting: neutrinos can travel large distances without distortion

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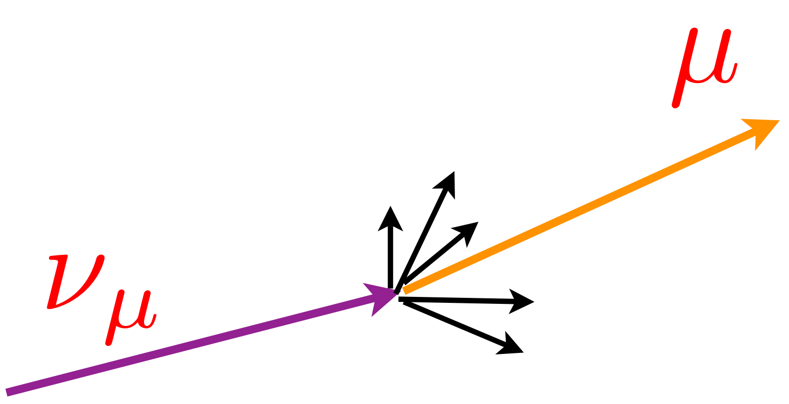
Angular distortion

$$\delta\phi \simeq \frac{0.7^o}{(E_\nu/{\rm TeV})^{0.7}}$$

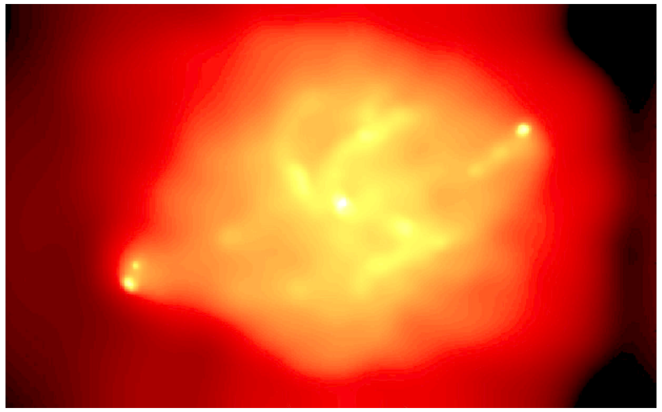


Sources of high energy neutrinos

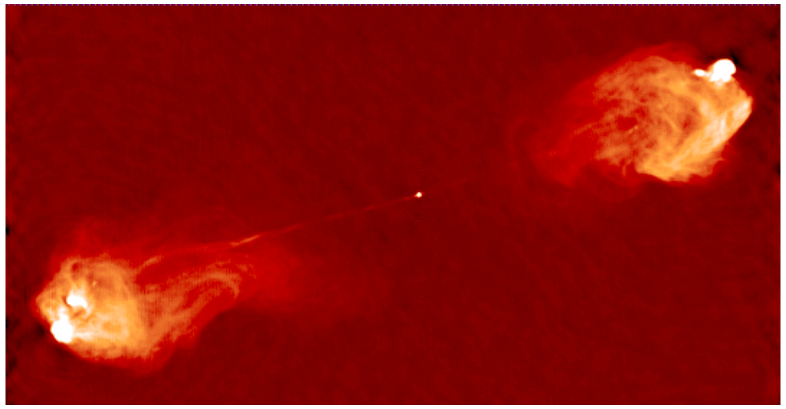
- Atmospheric: interactions of cosmic rays with nuclei in the atmosphere.
- Interactions of cosmic rays with gas, for example around supernova remnants. Interaction with microwave background (GZK neutrinos).
- Production at some source: Active Galactic Nuclei, Gamma Ray bursts.
- More exotic scenarios: WIMP annihilation (in the center of Sun or Earth), decays of metastable relic particles,...

Example AGN Cygnus A:

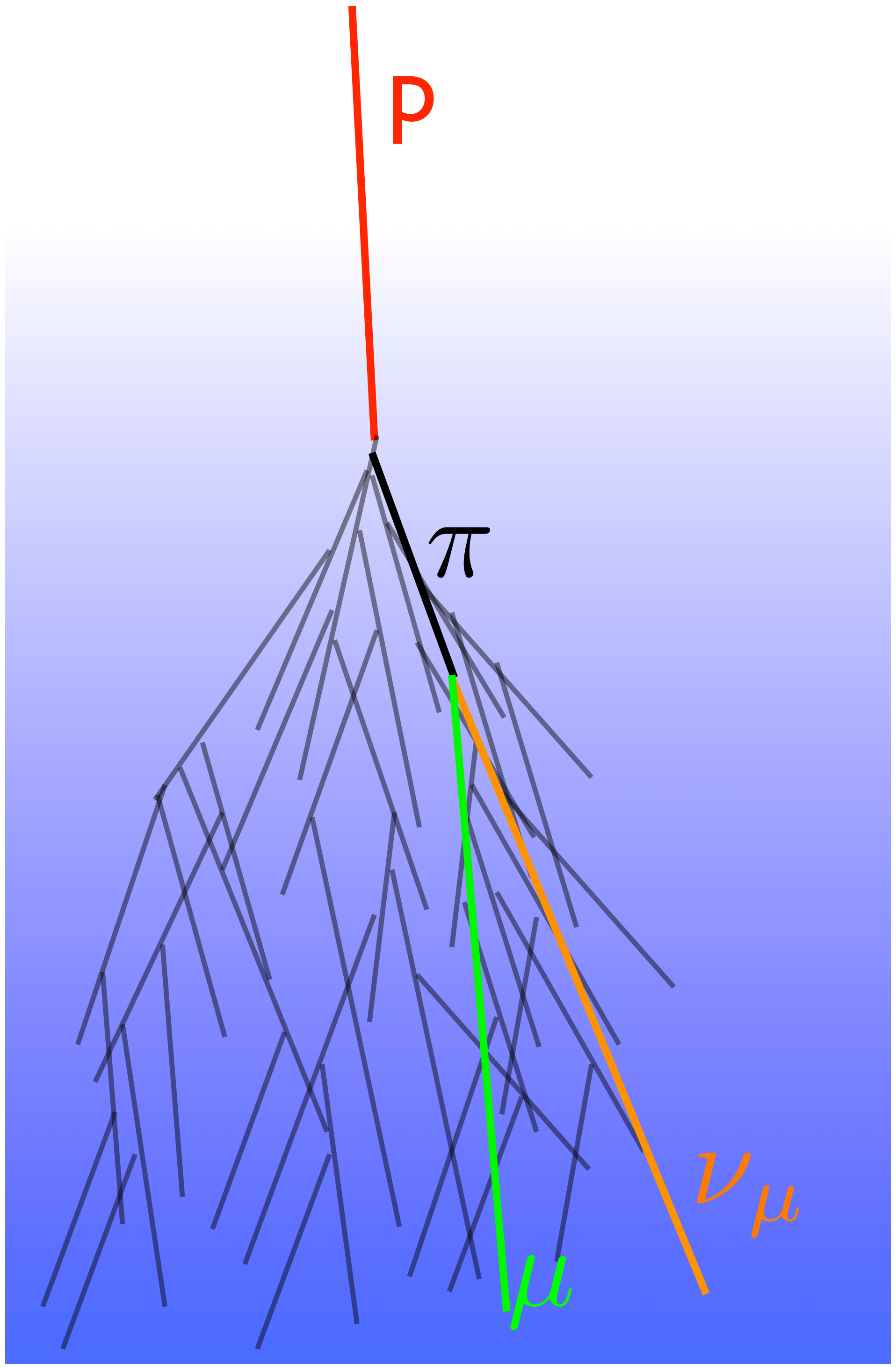
X ray



Radio image



Atmospheric neutrinos



Background to extraterrestrial neutrinos

Neutrinos in the atmosphere originate from the interactions of cosmic rays (etc. protons) with nuclei.

$p + \mathrm{Air}$

↓ *interaction*

π, K, D, B

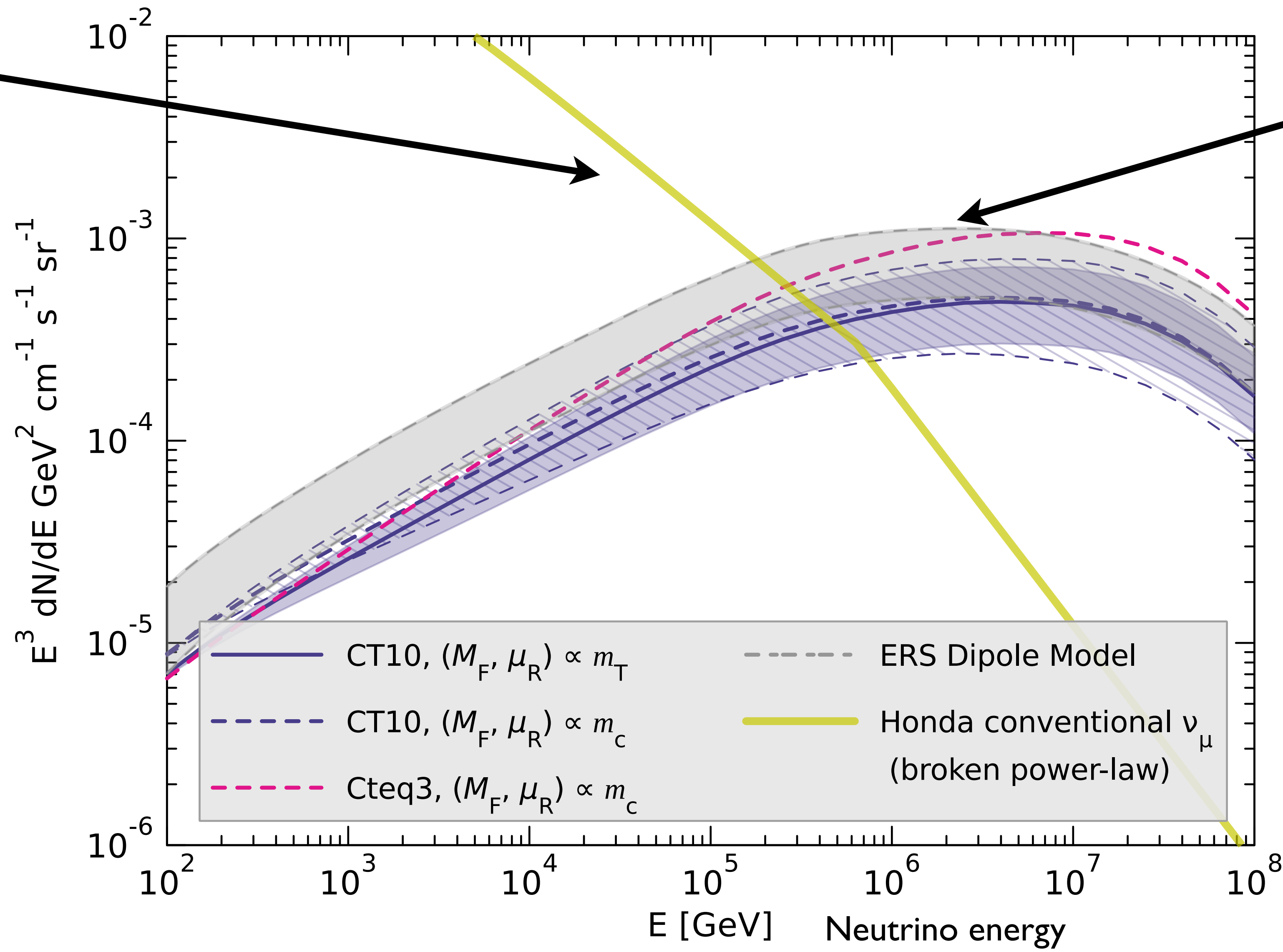
↓ *decay*

μ, ν_μ

Prompt vs conventional flux

conventional: decay of long lived pions and kaons: loose energy.
Soft spectrum.

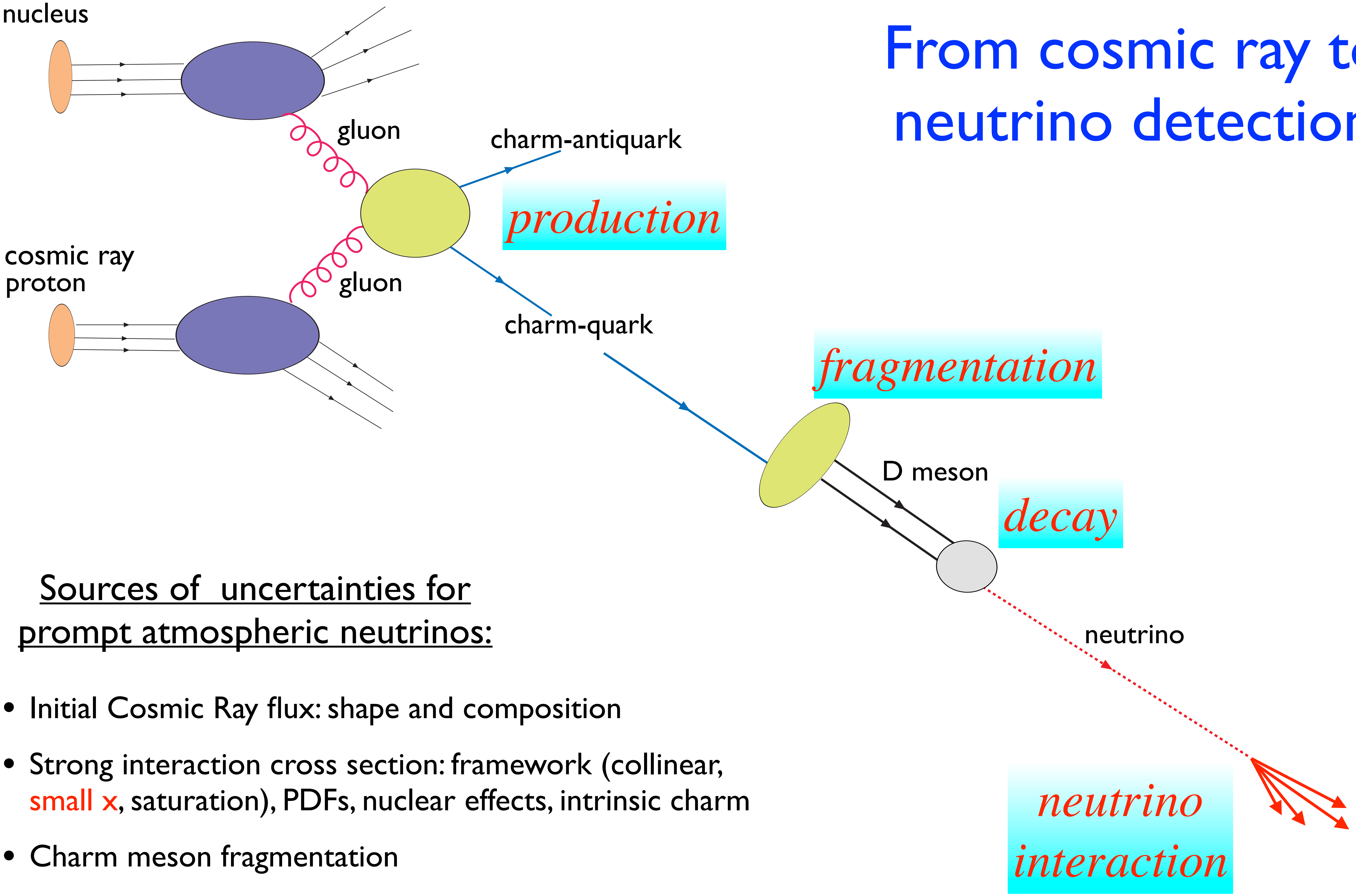
High energy atmospheric neutrino flux as a function of energy



prompt: decay of short lived charmed mesons: do not loose energy.
Hard spectrum.

Conventional flux: constrained by the low energy neutrino data.
Prompt flux: poorly known, large uncertainties.
Essential to evaluate as it can dominate the background for searches for extraterrestrial high energy neutrinos.

From cosmic ray to neutrino detection

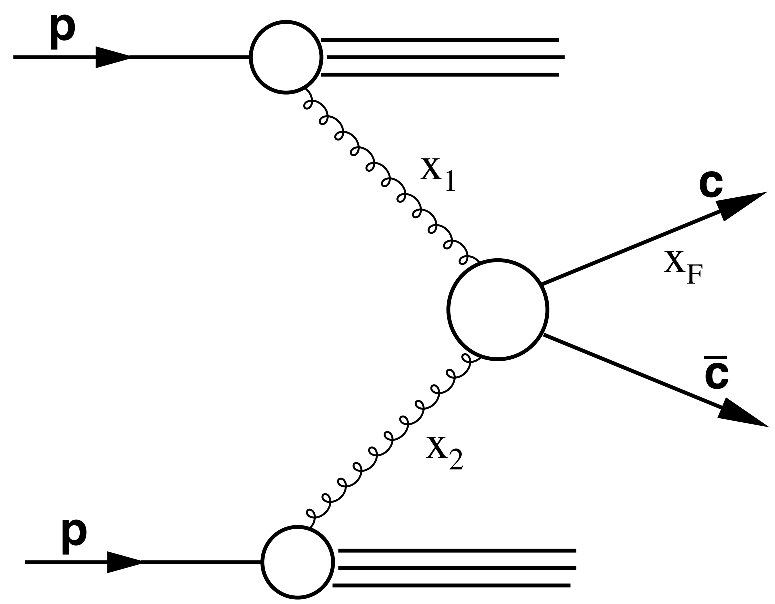


<u>Sources of uncertainties for prompt atmospheric neutrinos:</u>

- Initial Cosmic Ray flux: shape and composition
- Strong interaction cross section: framework (collinear, small x, saturation), PDFs, nuclear effects, intrinsic charm
- Charm meson fragmentation
- Decay
- Interaction cross section of neutrino (small x)

Forward charm production

Diagram for charm production in proton-proton collisions



In the collinear factorization:

$$\frac{d\sigma^{pp\to c+X}}{dx_F} = \int dx_1\, dx_2\, dz\; g(x_1,\mu_F^2)\, \frac{d\sigma_{gg\to c\bar{c}}}{dz}\, g(x_2,\mu_F^2)\,\delta(zx_1 - x_F)$$

where $z=(m_c^2-\hat{t})/s$ and $g(x,\mu_F^2)$ is the gluon density in the proton.

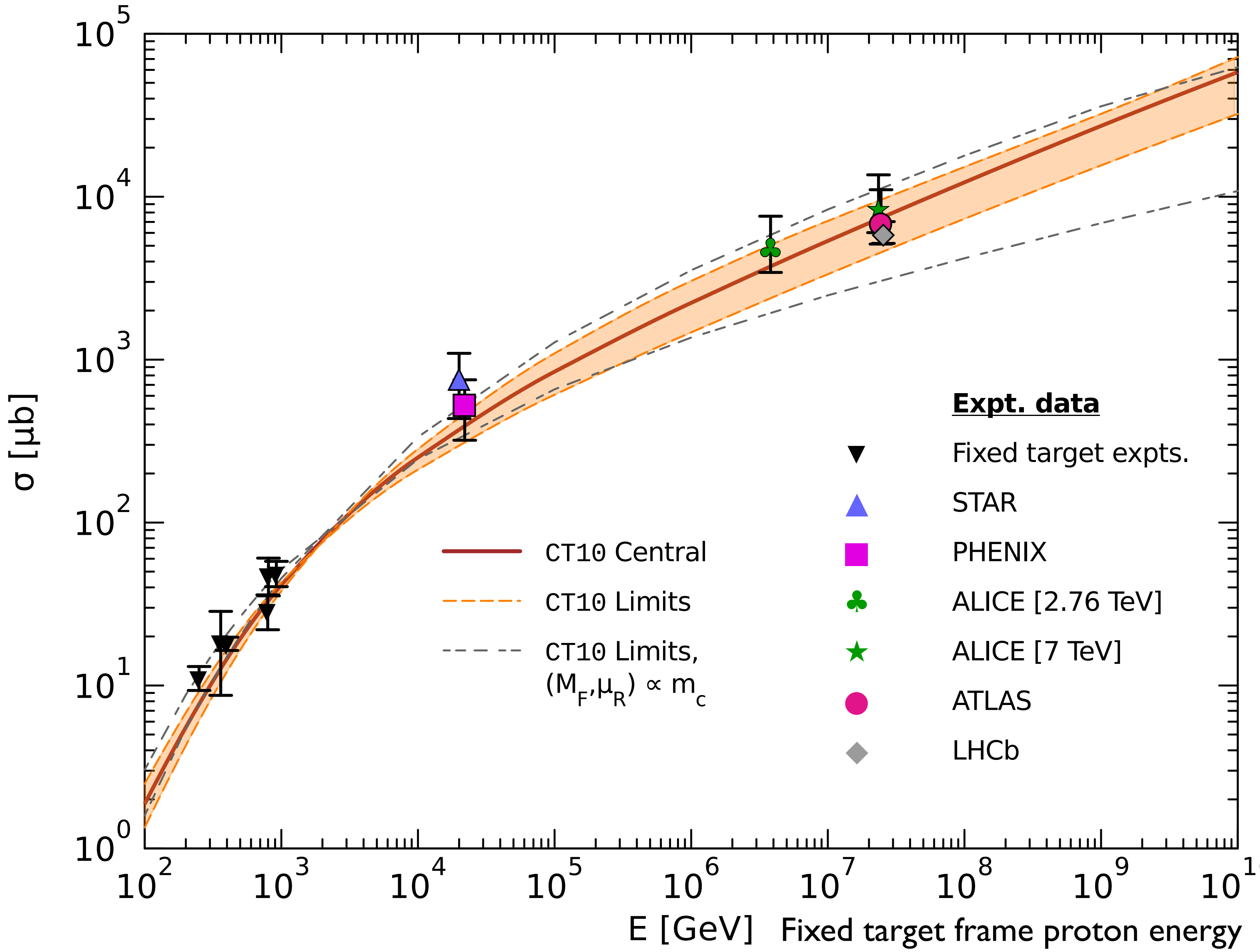
$x_F \simeq 0.2$ and $x_2 \simeq M_{c\bar{c}}^2/x_F s$

At very high energies $s \gg M_{c\bar{c}}^2$, x_2 is very small $x_2 \ll 1$

$x_2 \simeq 10^{-4} - 10^{-9}$ and small scales

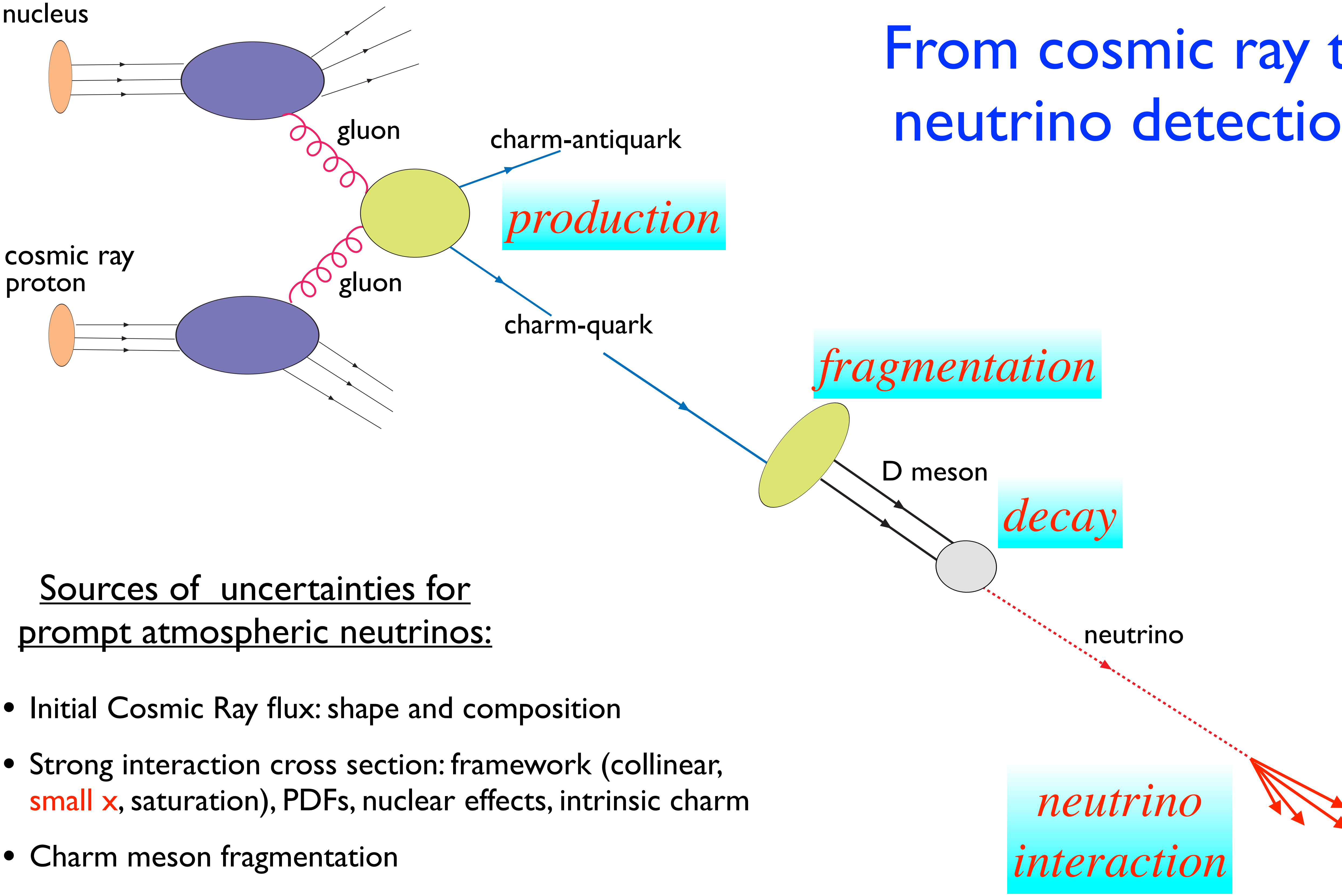
Charm production cross section

- Using NLO code by Cacciari,Frixione,Greco,Nason.
- Default set is CT10 Central.
- Charm quark mass $m_c = 1.27\ \mathrm{GeV}$
- Variation of factorization and renormalization scales with respect to $m_T^2 = m_c^2 + p_T^2$
- Comparison with RHIC and LHC data. Data are extrapolated with NLO QCD from measurements in the limited phase space region.



- Warning: need to extrapolate CT10 pdf down to very low x.
- PDF uncertainties not included in this plot.
- Based on collinear factorization, need to compare with kT factorization and dipole models with saturation.

From cosmic ray to neutrino detection



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UHE neutrino-proton cross sections

Neutrino DIS CC cross section
$$\frac{d^2\sigma^{CC}}{dxdy} = \frac{2G_F^2 M_N E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \cdot \left[xq(x,Q^2) + x\bar{q}(x,Q^2)(1-y)^2\right]$$

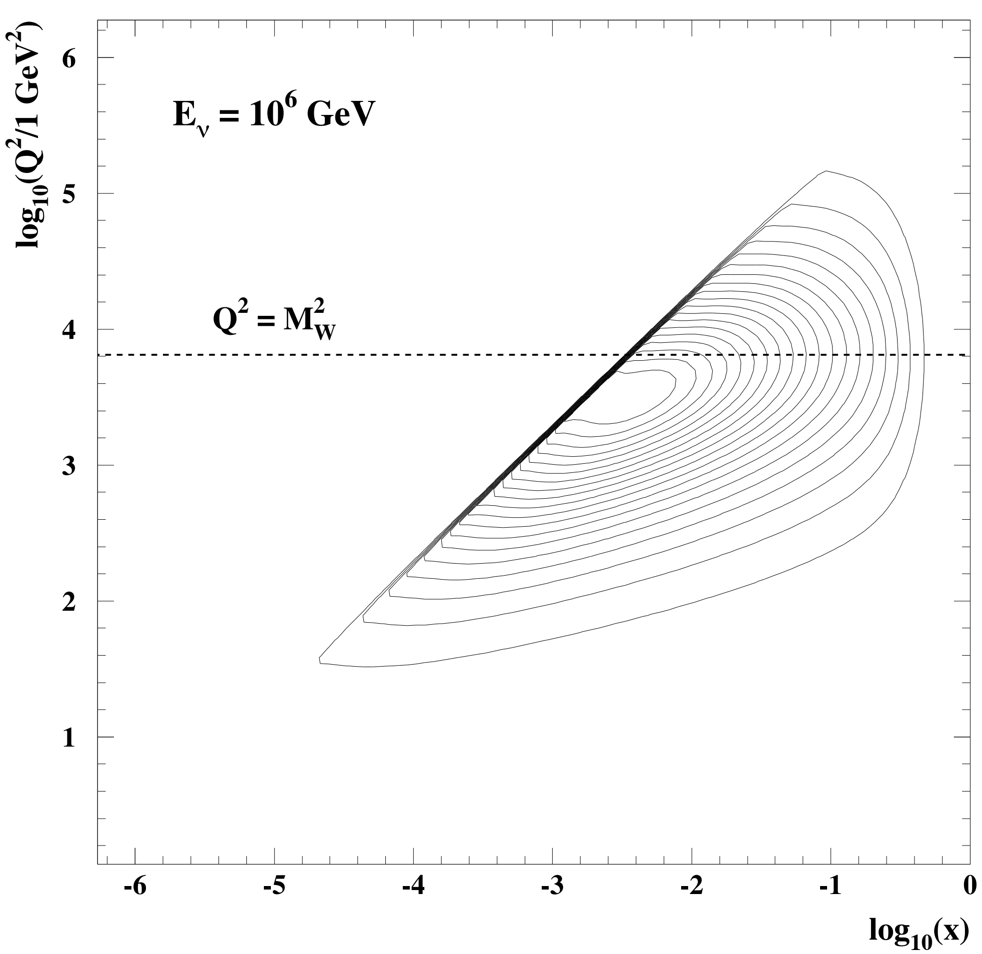
Since $xq(x,Q^2) \sim x^{-\lambda}$ this implies that

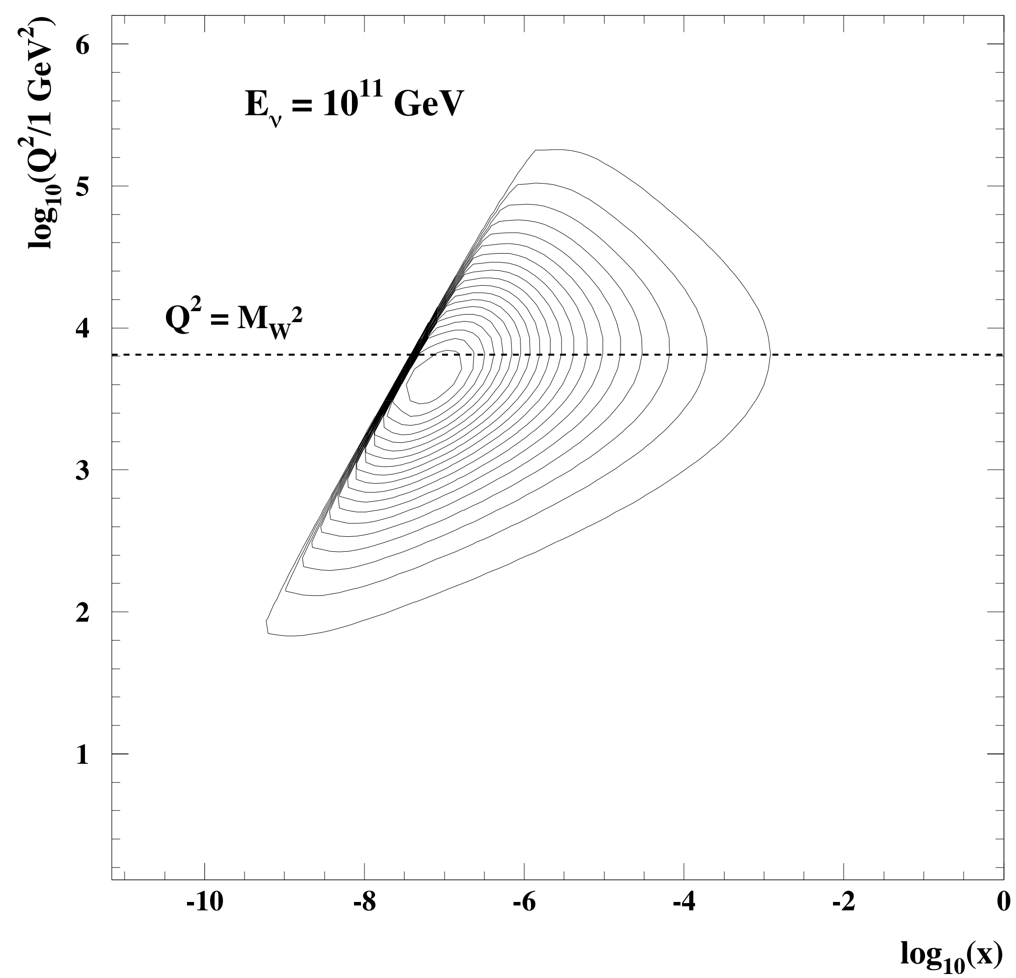
$$\sigma(E_\nu) = \int dxdy \frac{d^2\sigma^{CC}}{dxdy} \sim E_\nu^\lambda$$

Need extrapolations of parton densities to very small x

UHE neutrino cross sections important for IceCube

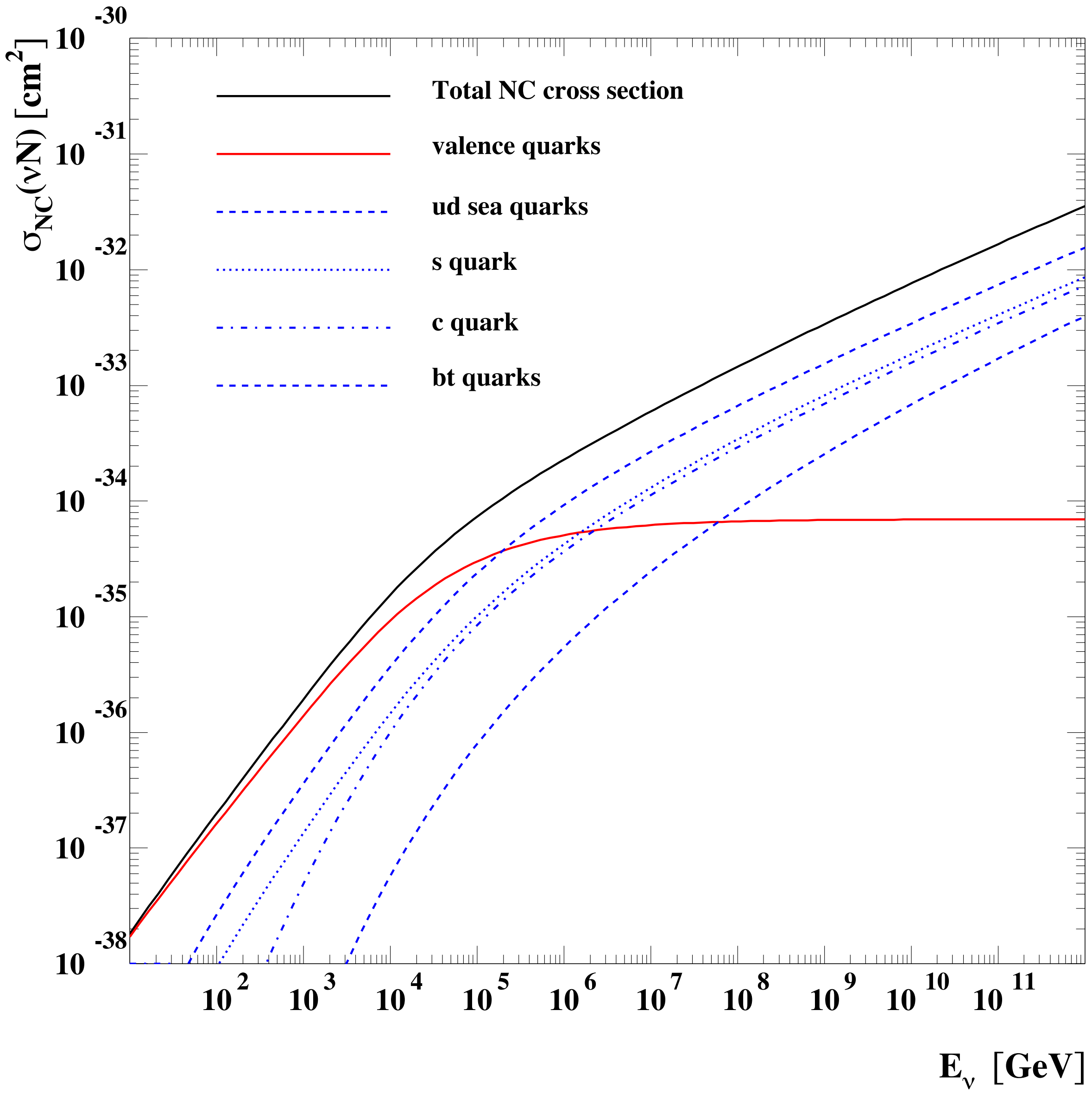
Contribution to the cross section in Q and x plane:

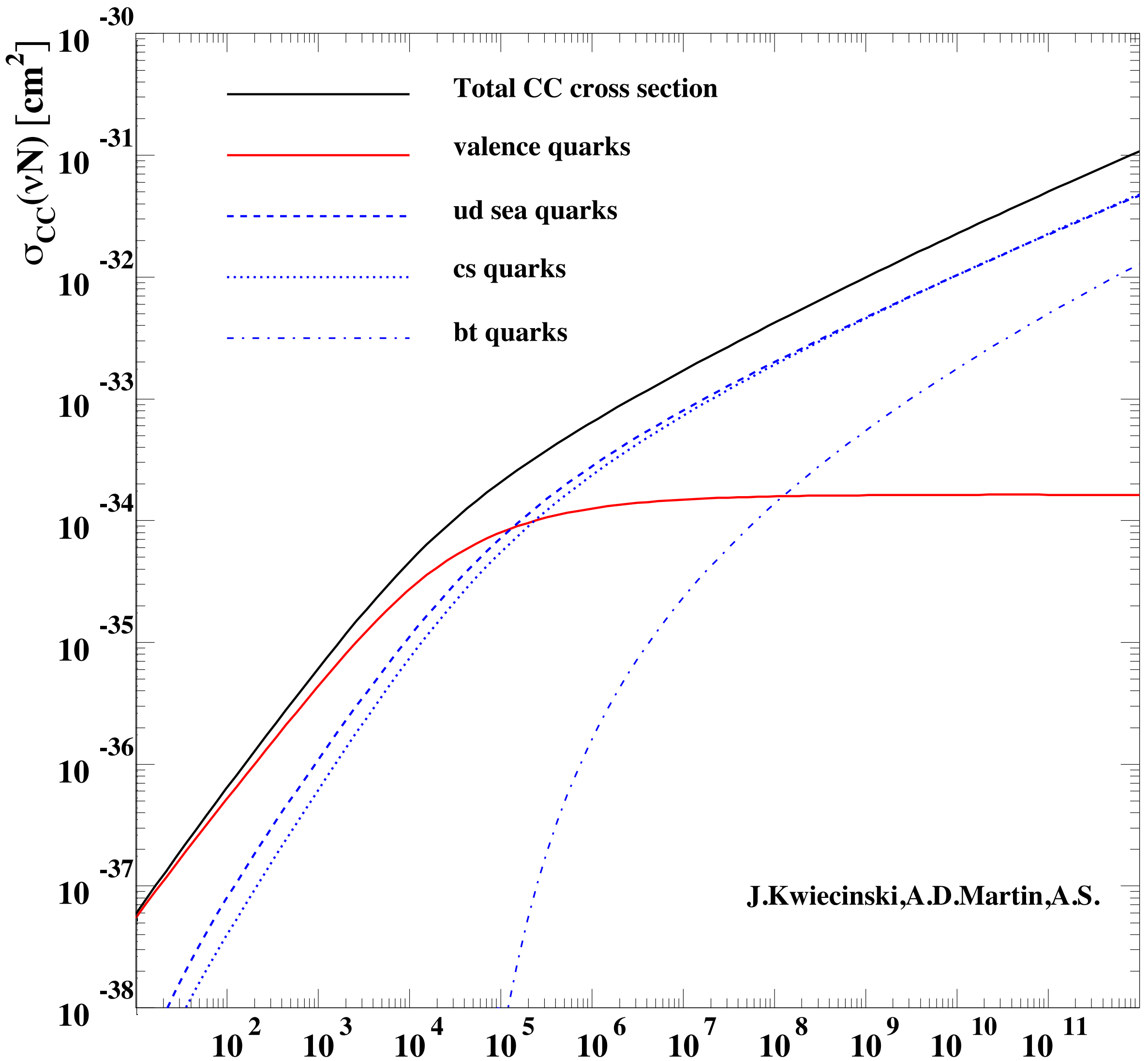




Neutrino cross sections

Calculation of the neutrino cross section using the unified BFKL/DGLAP evolution (includes resummation effects at low x).





Behavior at high energies controlled dynamically by the resummed evolution equation, rather than the parametrized extrapolation.

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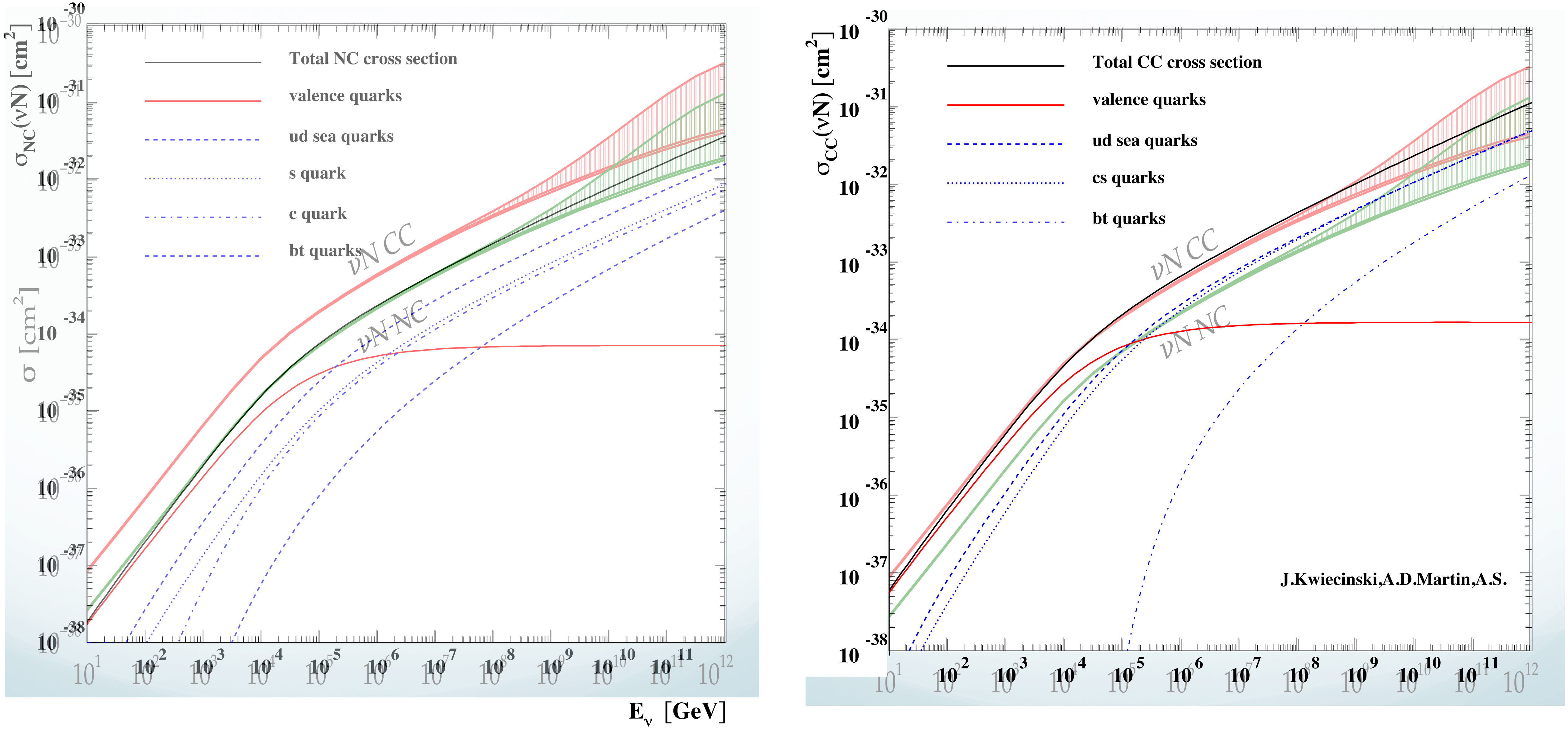


Comparison with latest estimates, I. Sarcevic et al.

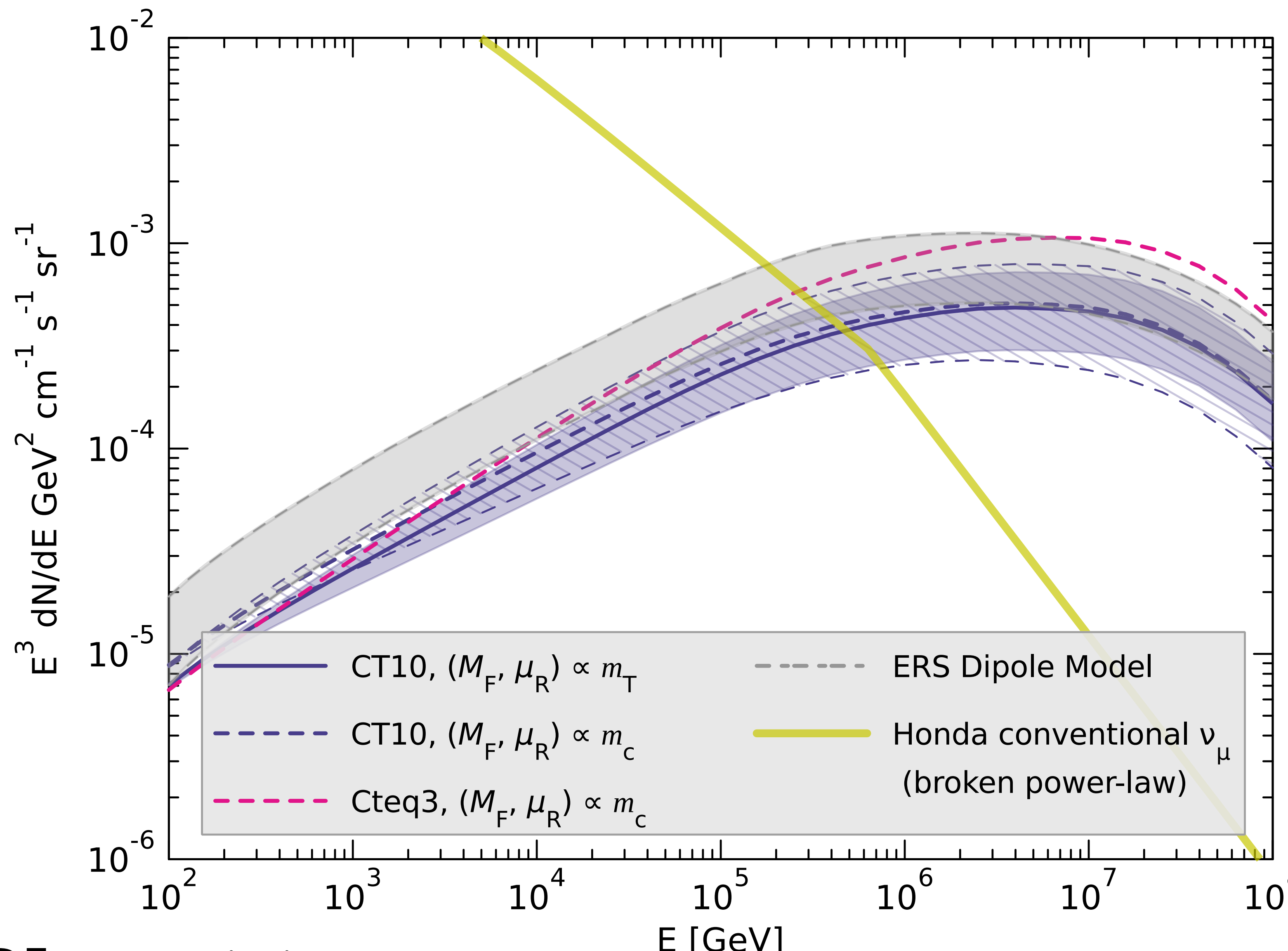
BFKL/DGLAP unified calculation still works well, within the uncertainty bounds for DGLAP

LHC data do not provide (so far) additional strong constraints on PDFs(relevant for this process)

LHeC/FCC-eh can provide important input for the cross section evaluation.

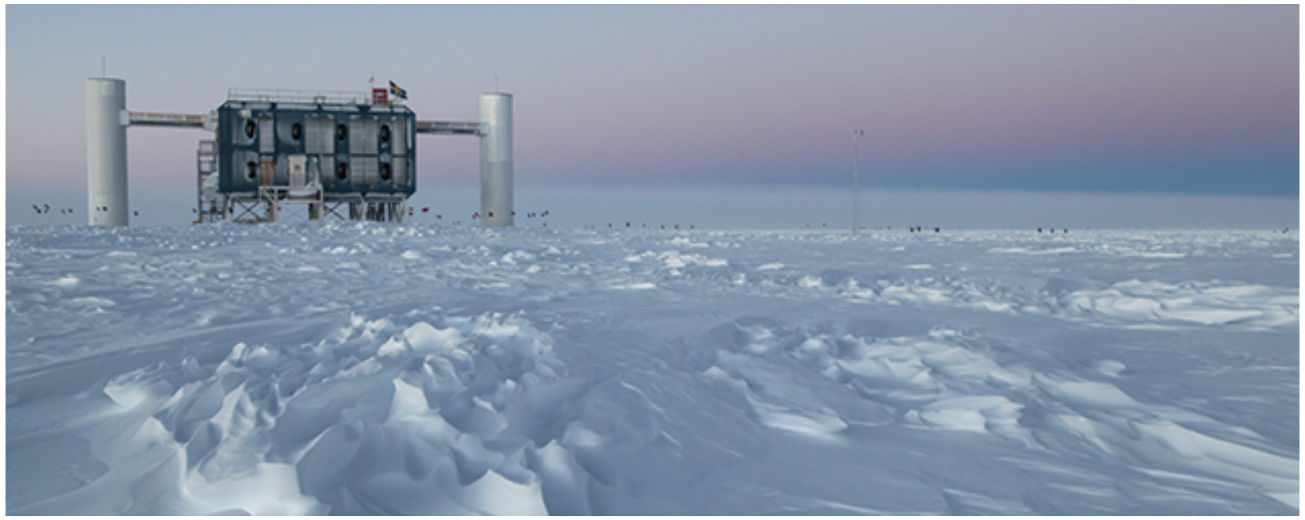
Neutrino fluxes: comparison collinear vs saturation

Flux of $\nu_\mu + \bar{\nu}_\mu$

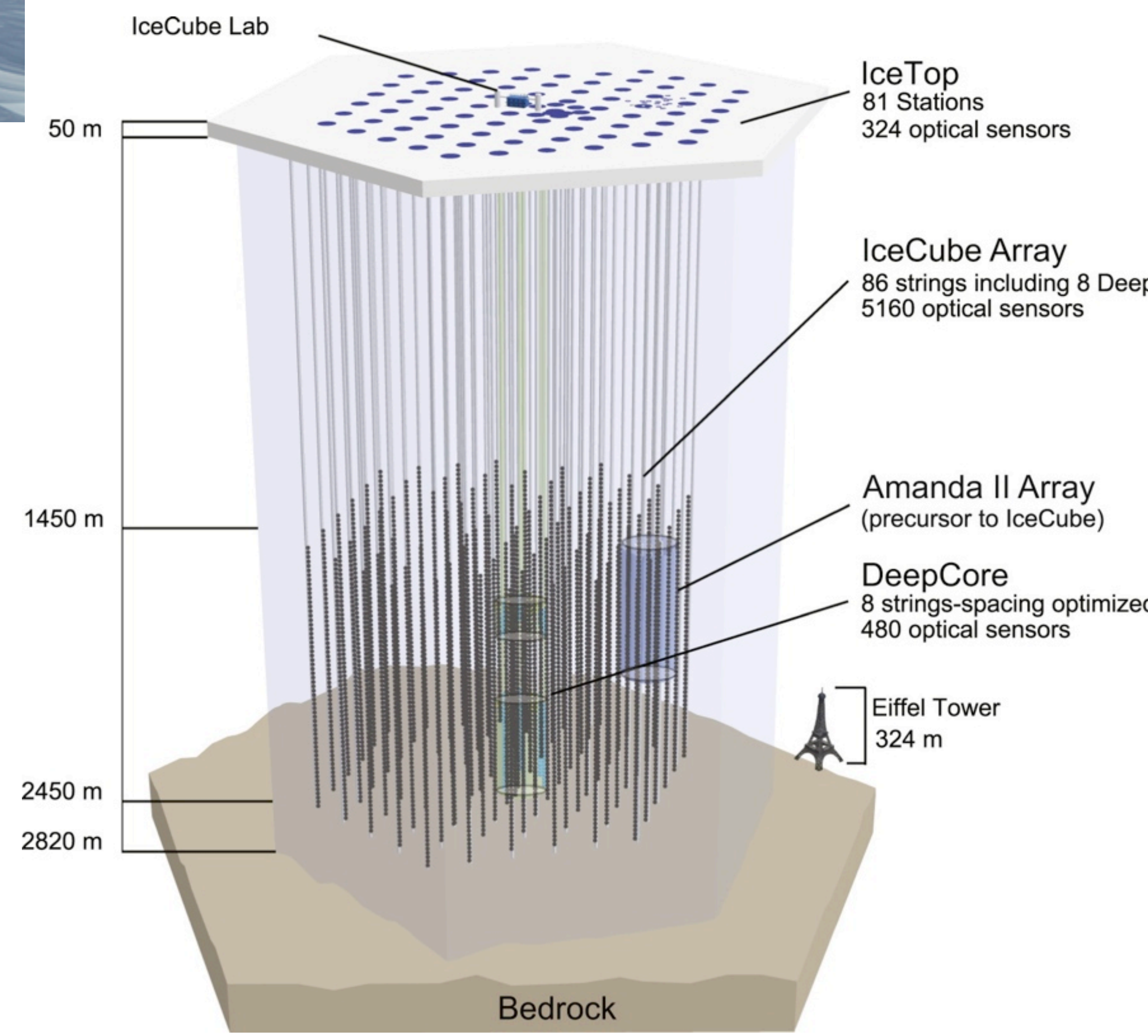


- Calculation does not include the PDF uncertainties.
- A bit of surprise: assuming the same initial cosmic ray flux NLO collinear calculation is lower than the calculation based on a dipole model with saturation…
- Different large x pdfs in the calculations. Should one move to NLO dipole model here as well?
- Gluon from CT10 is valence - like for low scales.
- LHeC/FCC-eh would provide an important constraint on the gluon in this context.

IceCube

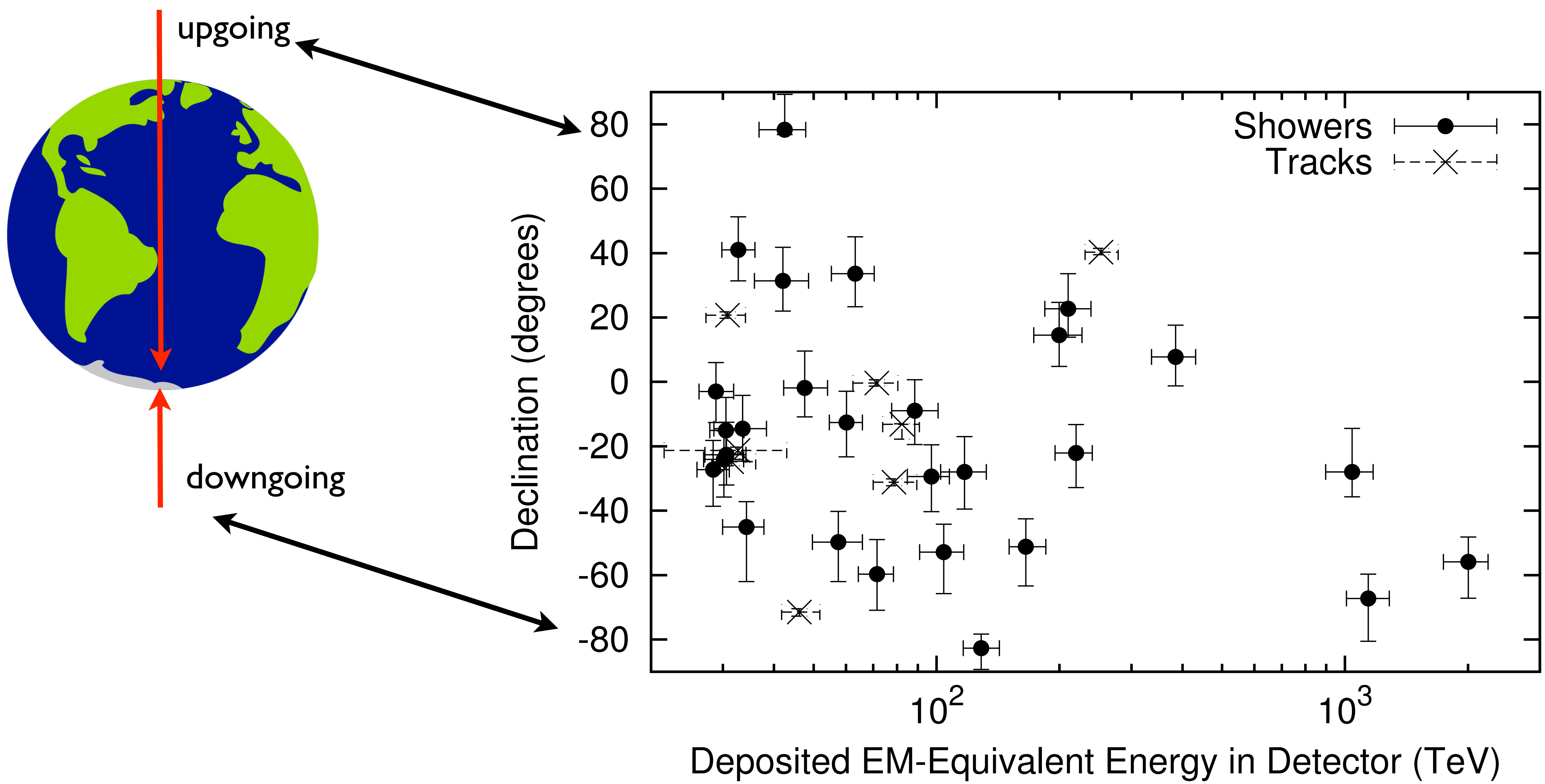


- UHE neutrinos measured in IceCube Antarctic detector
- Neutrinos detected using Cherenkov light produced by charged particles after neutrinos interact
- Sensitivity to high energy >100 GeV neutrinos (>10 GeV with Deep Core)



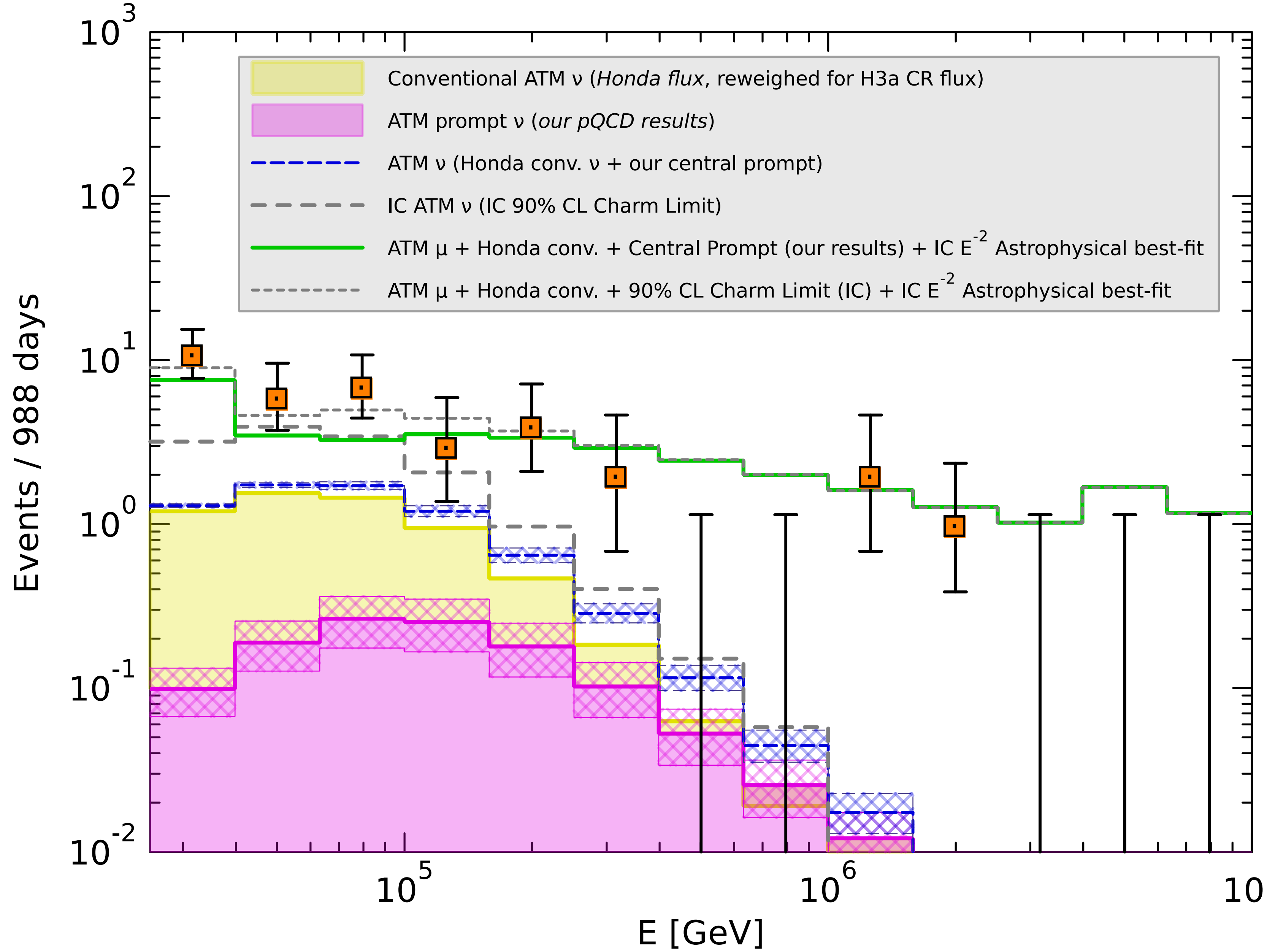
IceCube results

988 day sample, 37 events observed (after selection with entering muon veto) with energies between 30-2000 TeV



Comparison of prompt flux with IceCube results

- IceCube results point to the hard spectrum of neutrinos.
- Experimental data are well above the atmospheric background, implying that the origin of IceCube is likely extraterrestrial (also incoming muon veto by IC).
- NLO calculation from charm gives reduced background (with respect to earlier calculations).
- Small x uncertainties in the evaluation of both the background production and interaction cross sections.



Summary and outlook

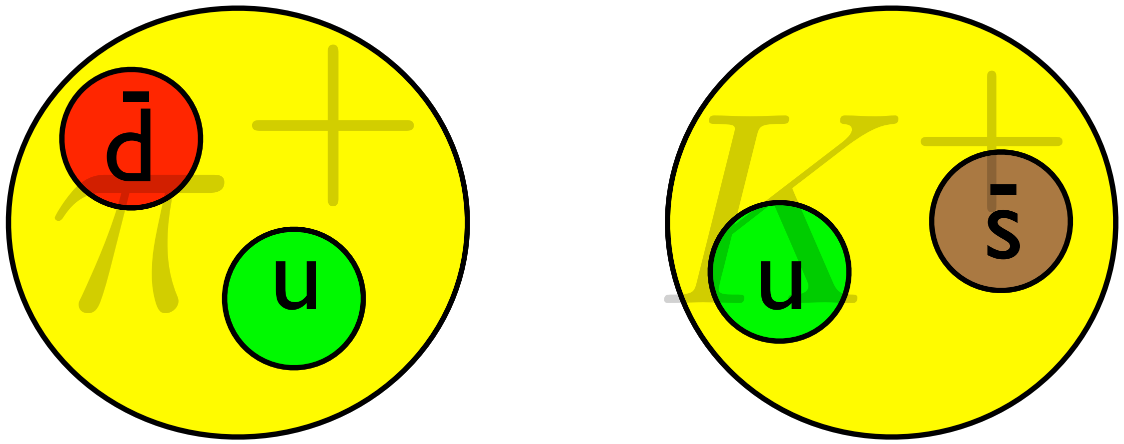
- Precise low x gluon density important for the UHE neutrino physics. LHeC/FCC-eh constraints can significantly reduce the uncertainties.
- Small x gluon comes into play when evaluating the UHE neutrino DIS interaction cross section and for the production of the atmospheric neutrinos.
- Calculation of the prompt neutrino flux using NLO and new PDFs, matched to LHC and RHIC data.
- Prompt component is rather small. The IC data are significantly above, new calculation will change the evaluation of the significance of the astrophysical signal for IC. However, not all uncertainties are taken into account.
- Work in progress: nuclear pdfs, small x calculations including saturation, resummation; intrinsic charm. Estimate of LHeC, FCC-eh impact on the uncertainties of PDFs onto the calculation.

backup

Atmospheric neutrinos

- *Conventional*: decays of lighter mesons

$\pi^{\pm}, K^{\pm}$



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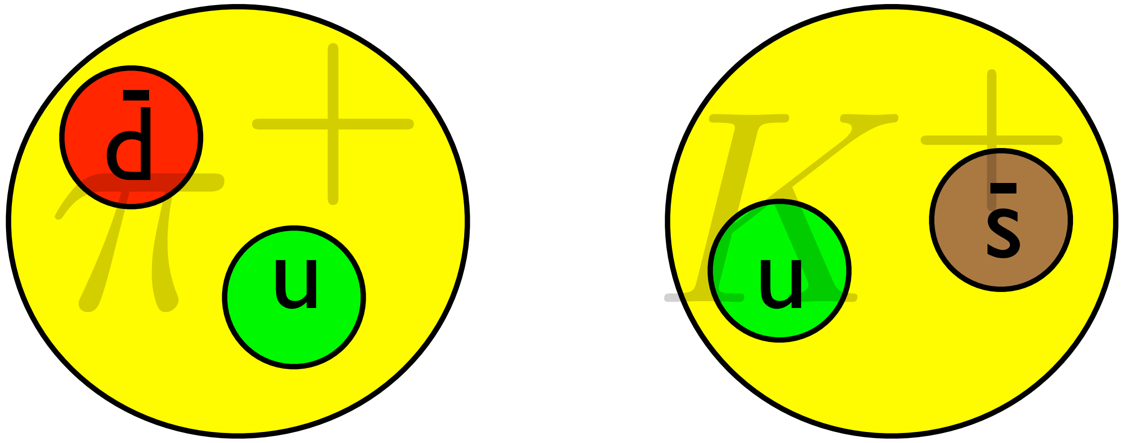

Mean lifetime: $\tau \sim 10^{-8}\ s$

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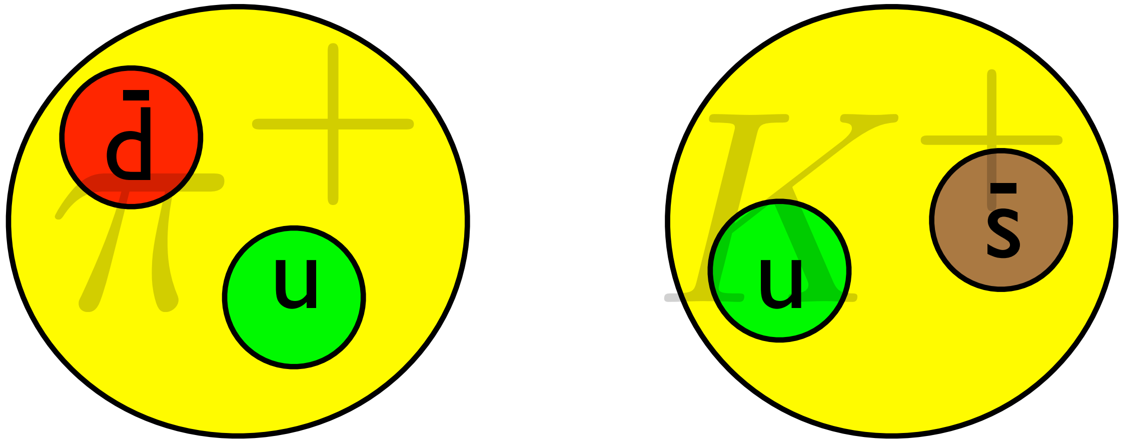

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$$\mathcal{L}_{\rm int} < \mathcal{L}_{\rm dec}$$

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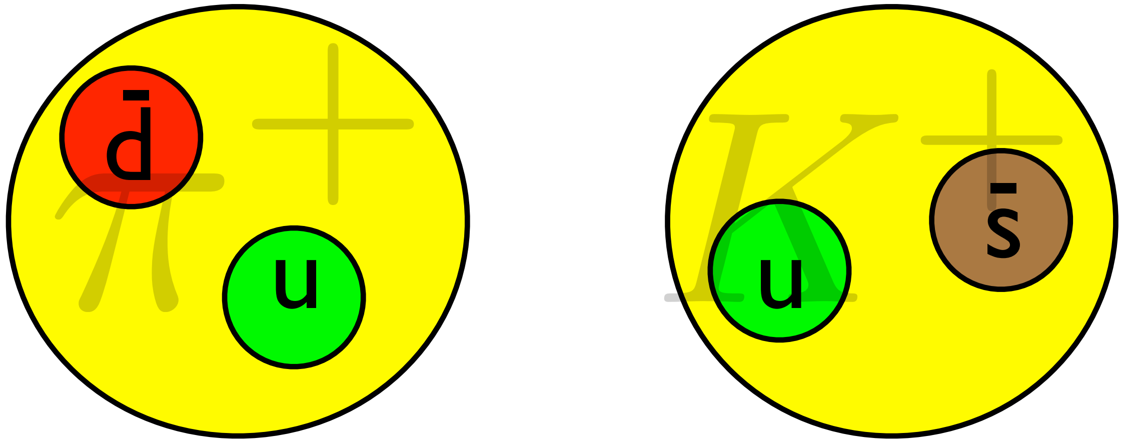

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Mesons loose energy

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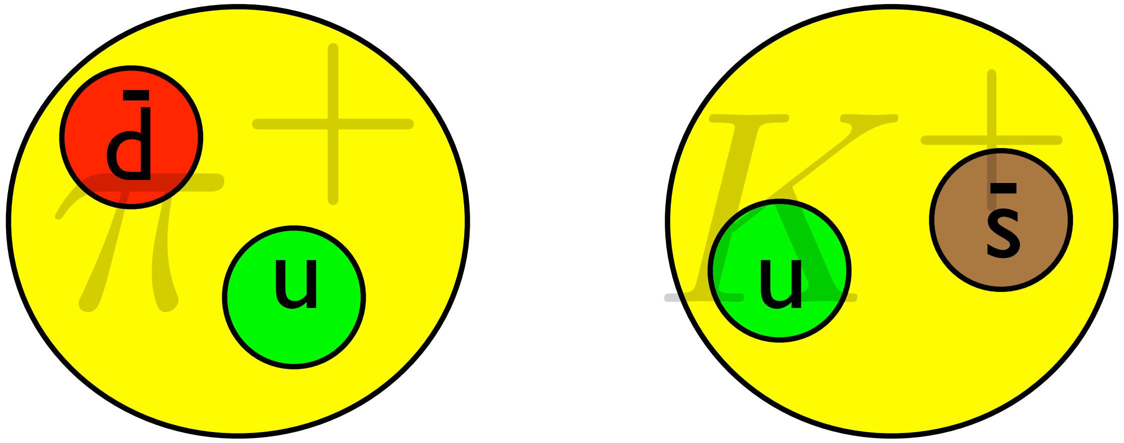

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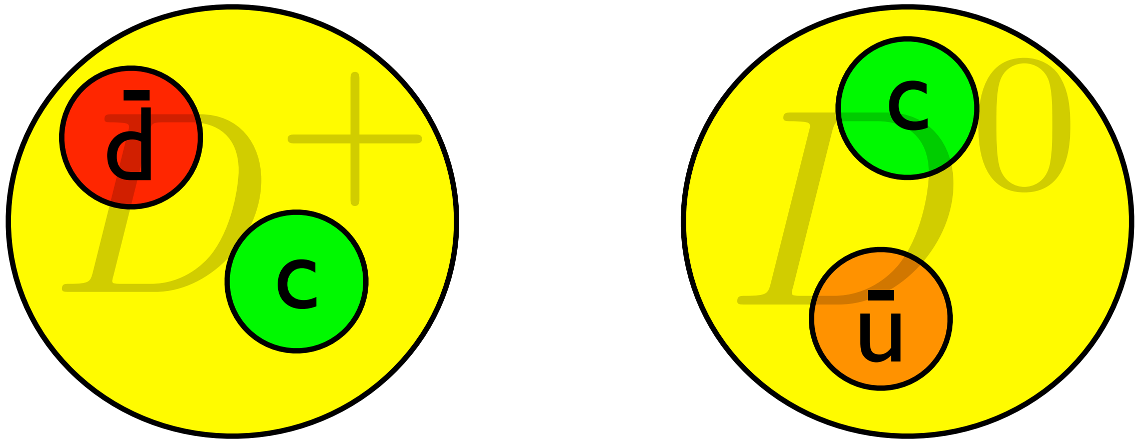
Mesons loose energy → Steeply falling flux of neutrinos $\Phi_\nu \sim E_\nu^{-3.7}$

Prompt neutrinos

- *Prompt*: decays of heavier, charmed or bottom mesons

$D^{\pm}, D^0, D_s$

baryon Λ_c



Prompt neutrinos

- *Prompt*: decays of heavier, charmed or bottom mesons

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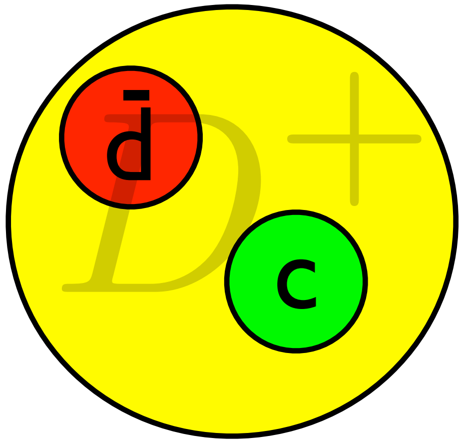
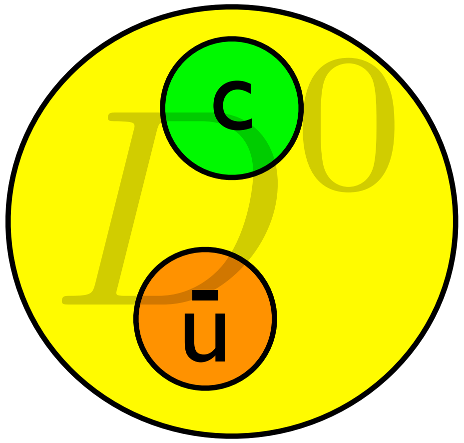
baryon Λ_c





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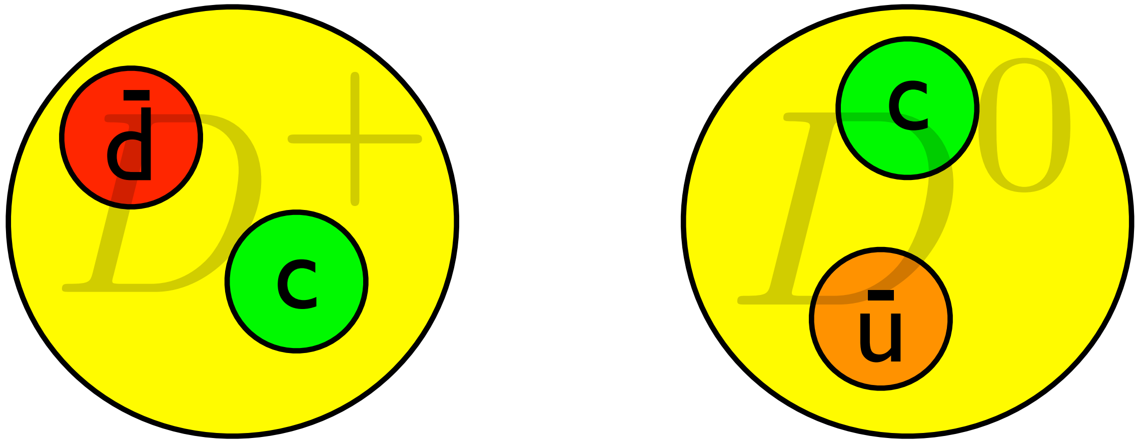

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Short lifetime: decay, no interaction

$$\mathcal{L}_{\rm int} > \mathcal{L}_{\rm dec}$$

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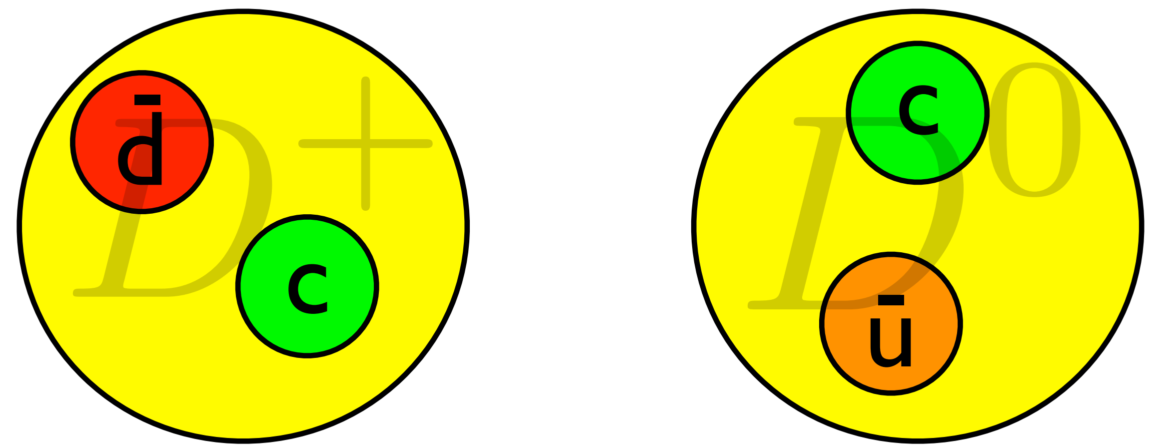

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Short lifetime: decay, no interaction

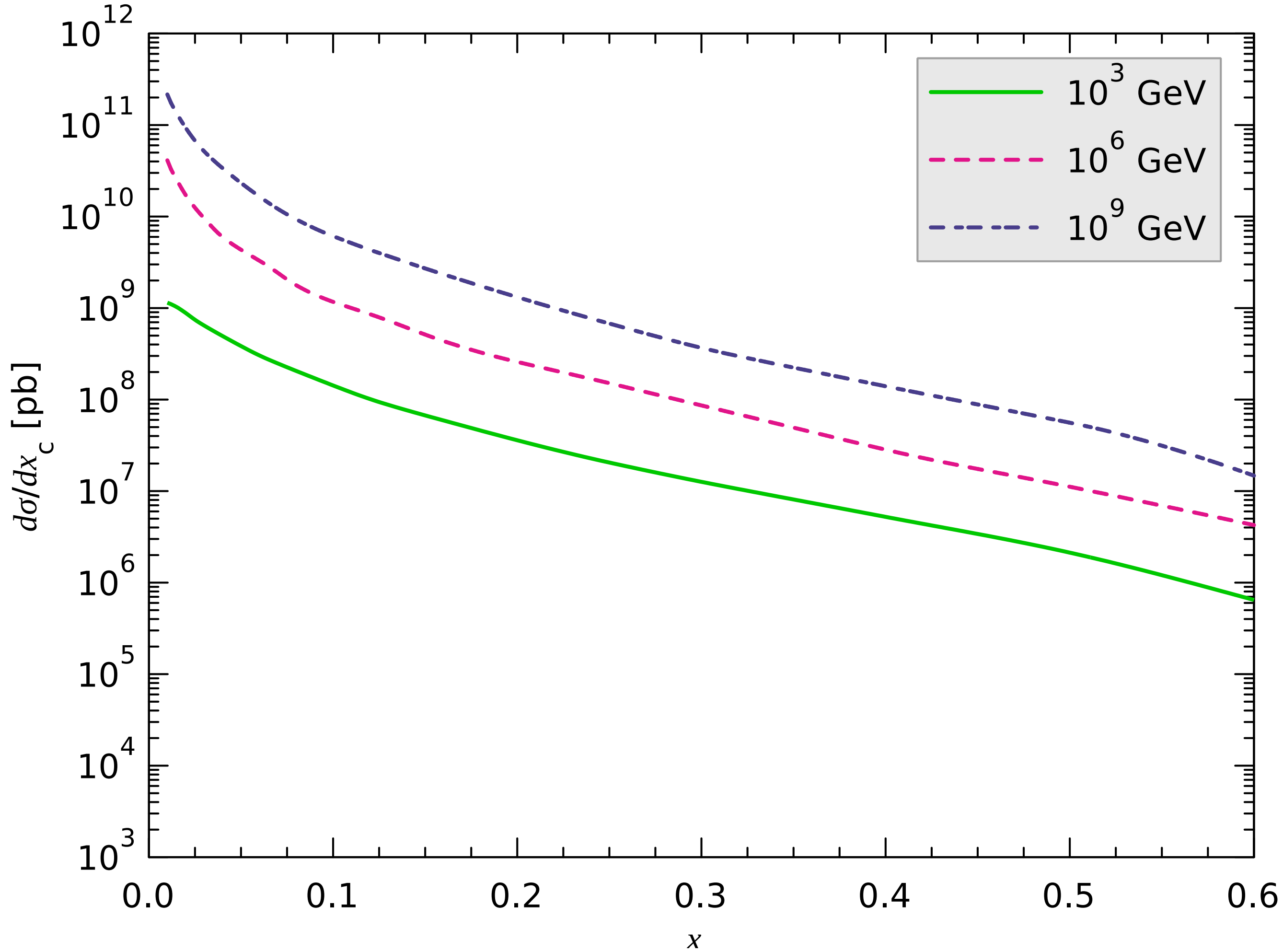
$$\mathcal{L}_{\rm int} > \mathcal{L}_{\rm dec}$$

Flat flux, more energy transferred to neutrino

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

Differential charm cross section

Differential charm cross section in proton-nucleon collision as a function of the fraction of the incident beam energy carried by the charm quark.



$$x_c = \frac{E_c}{E_p}$$

Differential charmed hadron cross section as a function of the energy:

$$\frac{d\sigma}{dE_h} = \sum_k \int \frac{d\sigma}{dE_k}(AB \to kX) D_k^h \left(\frac{E_h}{E_k} \right) \frac{dE_k}{E_k}$$

Using Kniehl, Kramer fragmentation functions.

IceCube results

Two classes of events:

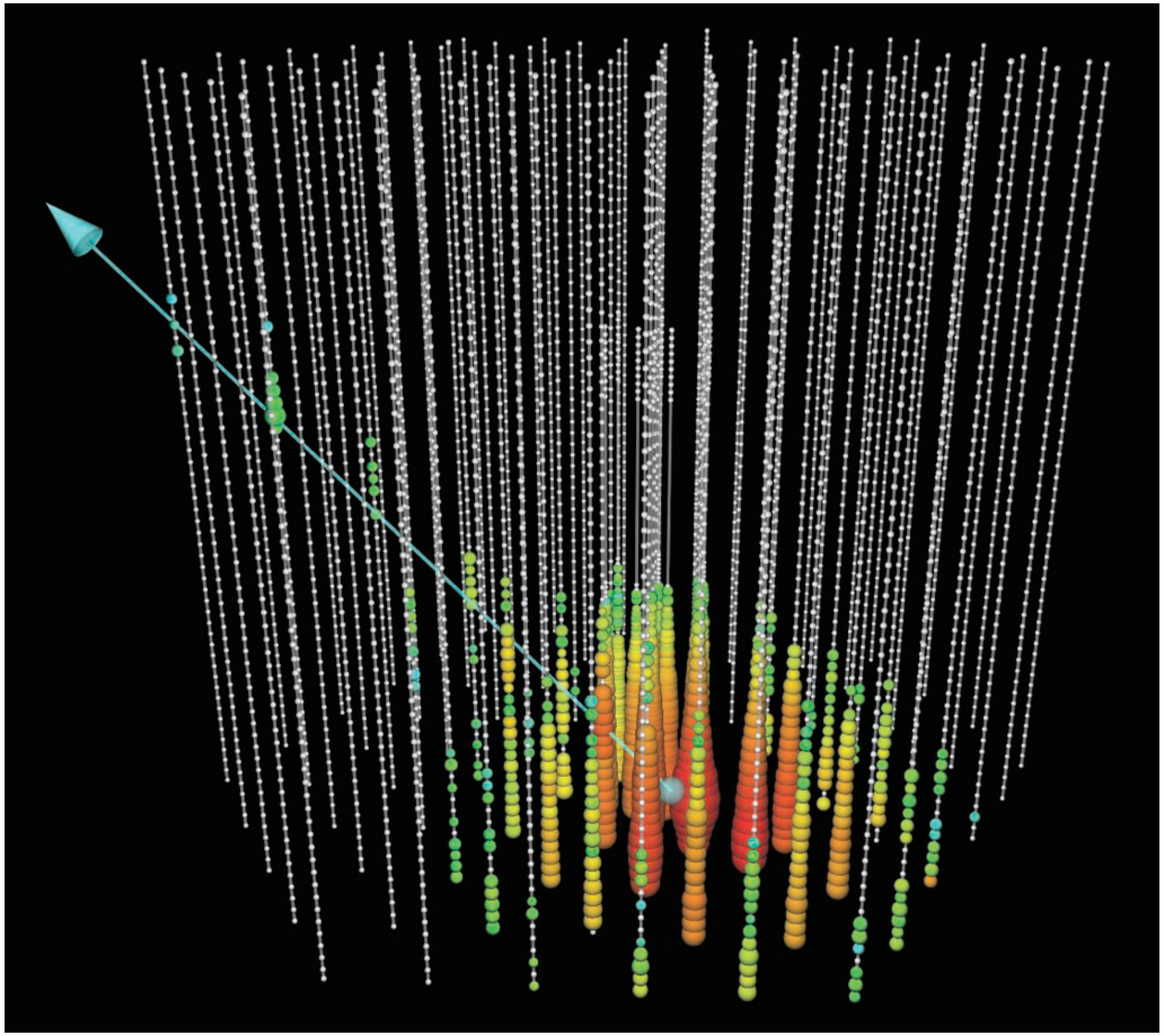
Showers: from secondary charged leptons and hadron dissociation

Tracks: events accompanied by an energetic muon (CC events with incoming ν_μ)

Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

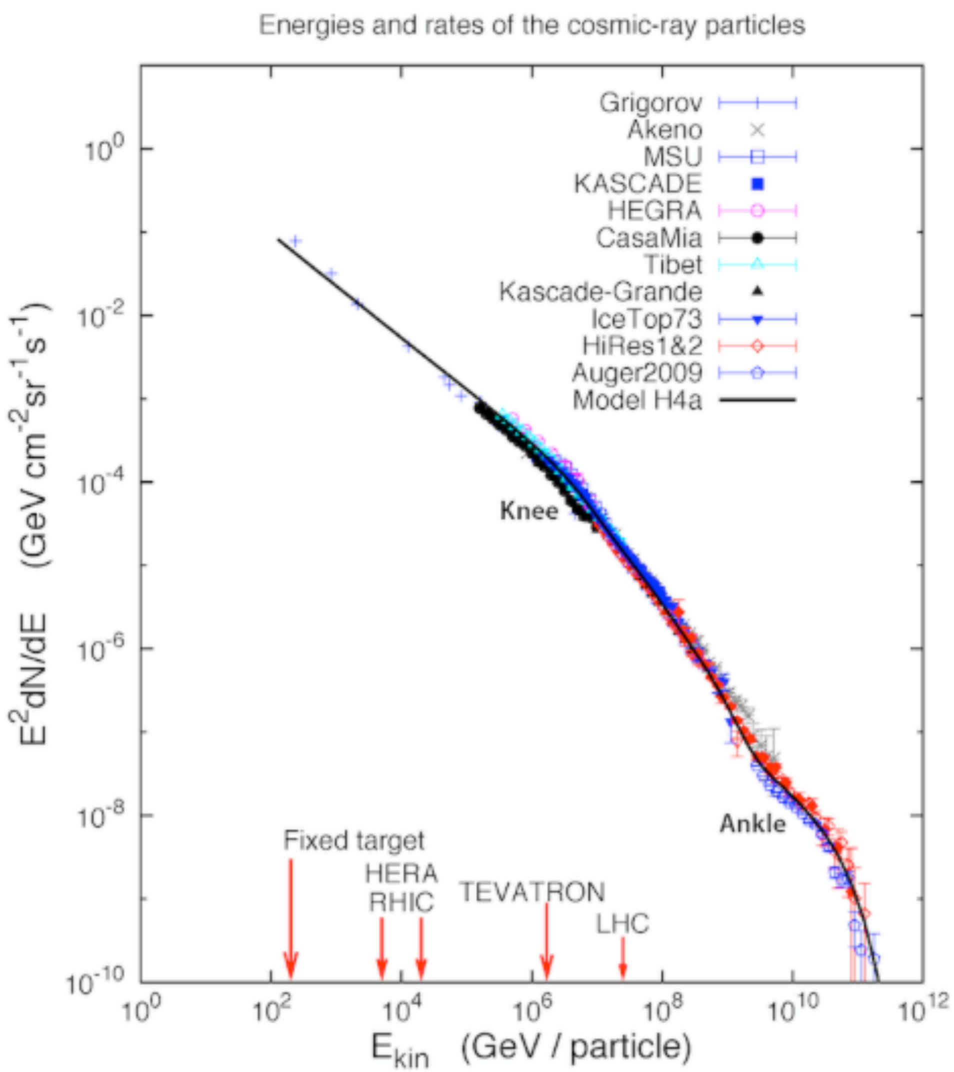
SCIENCE VOL 342 22 NOVEMBER 2013



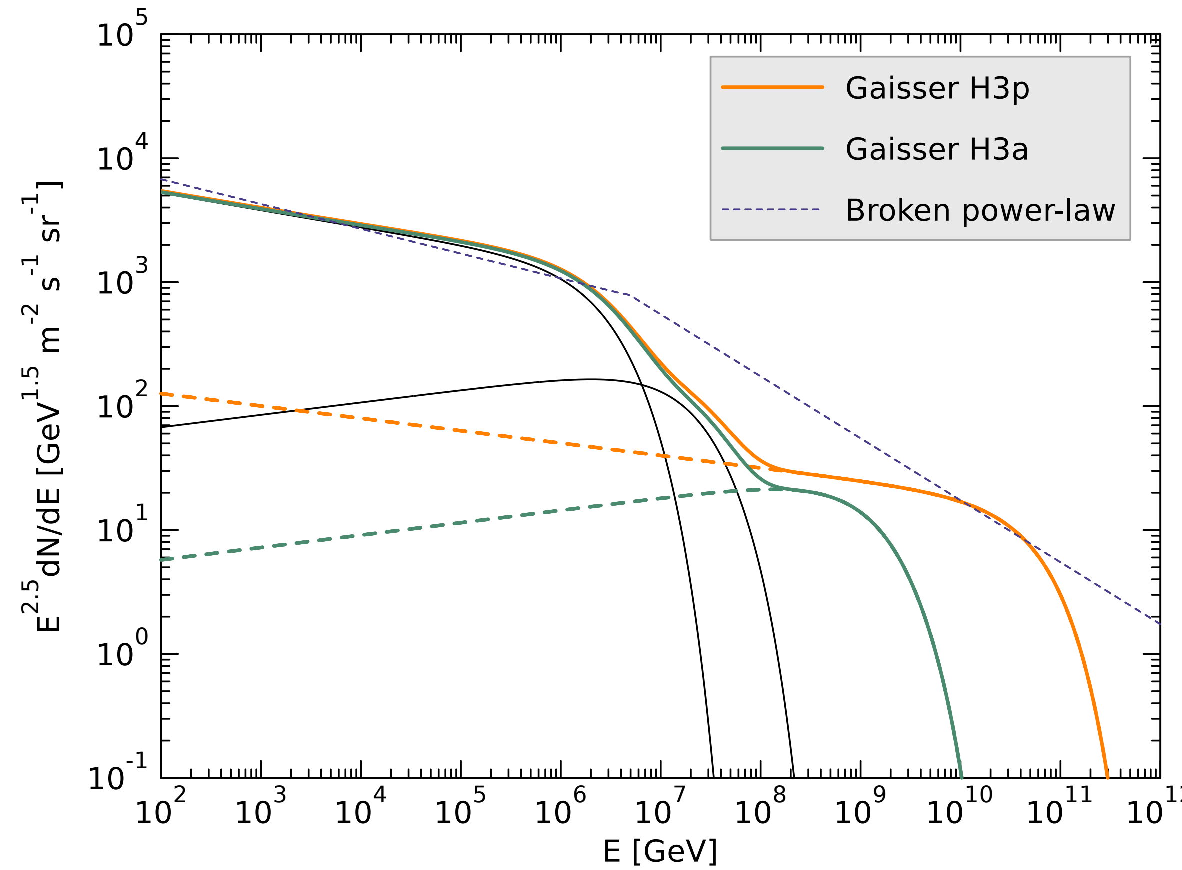
A 250 TeV neutrino interaction in IceCube. At the neutrino interaction point (bottom), a large particle shower is visible, with a muon produced in the interaction leaving up and to the left. The direction of the muon indicates the direction of the original neutrino.

Cosmic ray flux

Important ingredient: initial cosmic ray flux.



Parametrization by Gaisser with three populations:



energy per nucleon

Simple power law used for comparison:

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