Neutrino cross-sections at IceCube

outline

1. Neutrinos at IceCube
2. Neutrino cross section results
3. Neutrino event generators
4. Conclusion

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Teppei Katori for the IceCube collaboration
King's College London
NuSTEC-Board meeting,
December 12, 2019

1. Neutrinos at IceCube

2. Neutrino cross-section results

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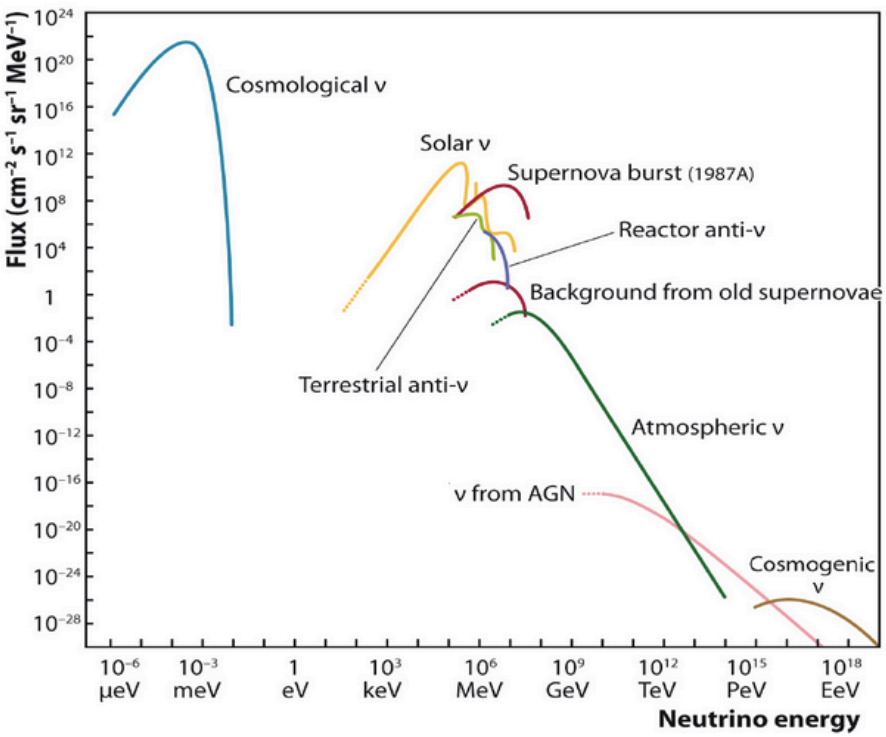
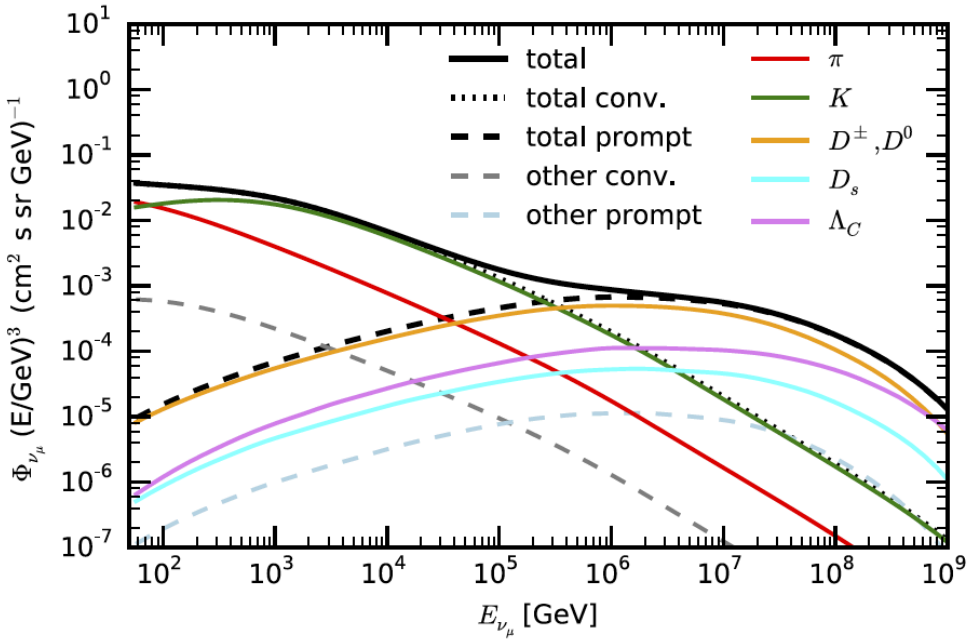
Fedynitch et al, EPJ Web of Conferences 99, 08001 (2015)

1. Neutrinos at IceCube

Atmospheric neutrinos

- Conventional, from π&K-decays, ~$E^{-3.7}$, dominant from ~100 MeV to ~20 TeV
- Prompt (not identified), from D-decays, ~E^{-3}





Fedynitch et al, EPJ Web of Conferences 99, 08001 (2015)
Austin Schneider (ICRC2019), ArXiv:1907.11266

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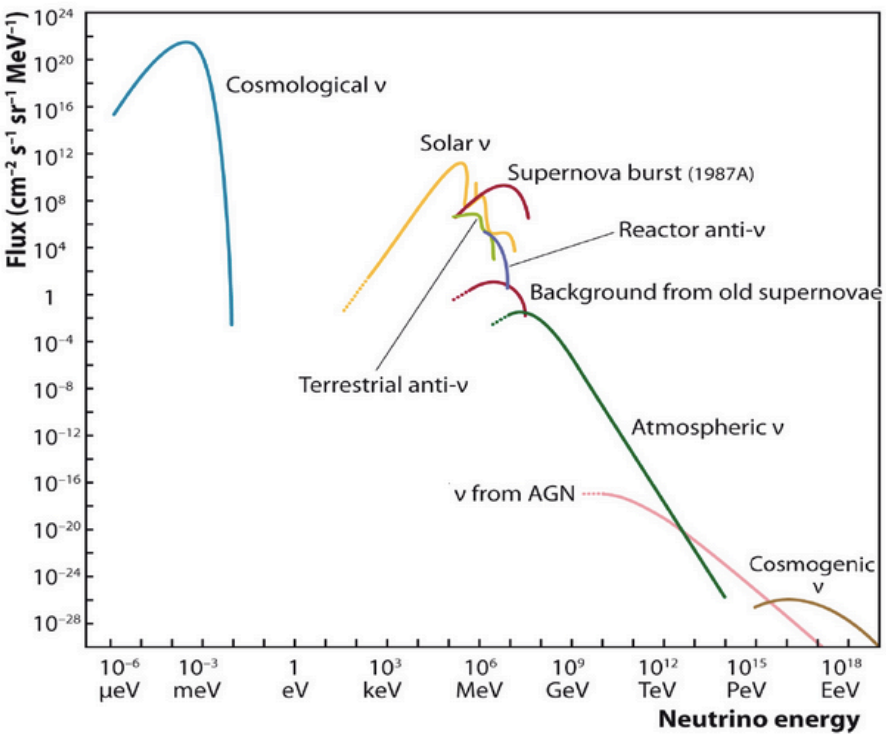
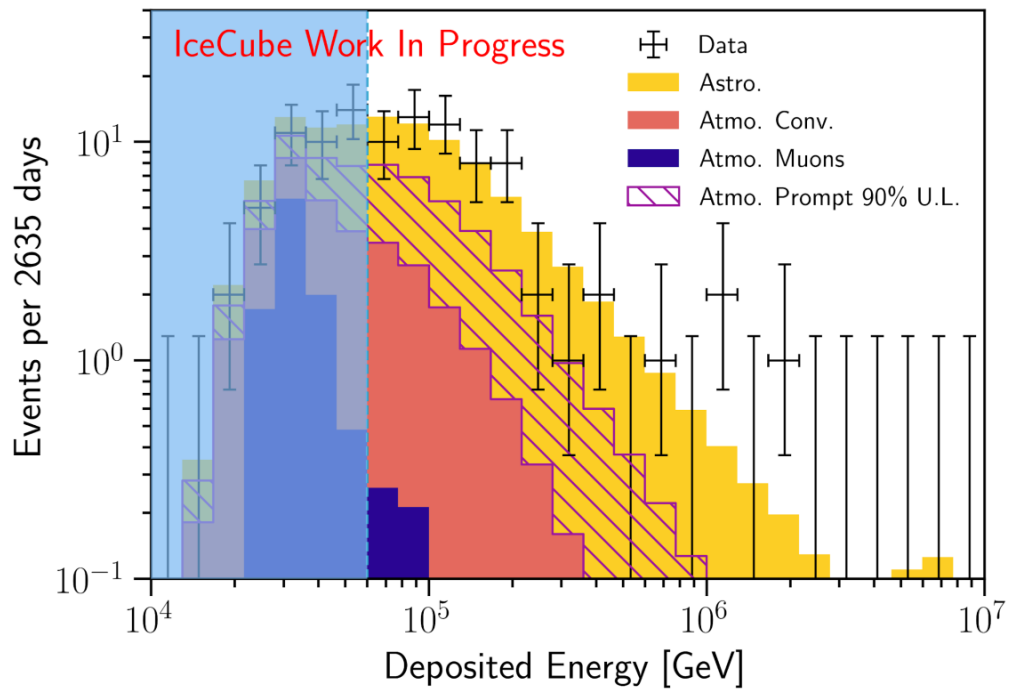
Astrophysical neutrinos

- Low-energy neutrinos (not identified), ~20 MeV, observed as increase of background rate
- High-energy neutrinos, from ~60 TeV to few PeV, (60 TeV ~ 6,000PE)





Austin Schneider (ICRC2019), ArXiv:1907.11266
Juliana Stachurska (ICRC2019), ArXiv:1908.05506

1. Neutrinos at IceCube

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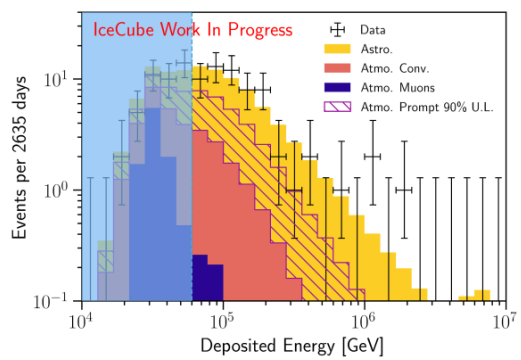
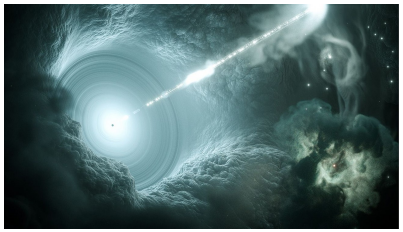
Astrophysical high-energy neutrinos

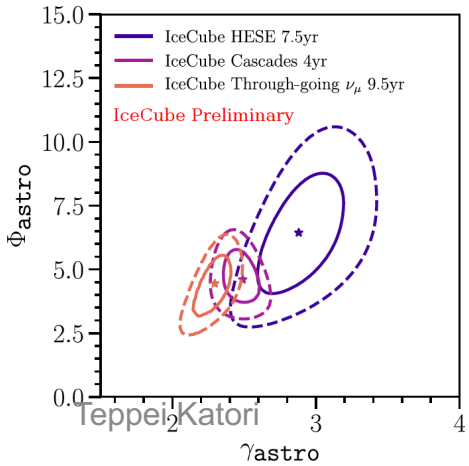
- ~60 events in 7.5-yr data
- Unlikely atmospheric neutrinos
- Sources are unknown (diffuse)
- Confusion in spectrum index
- Production flavours unknown

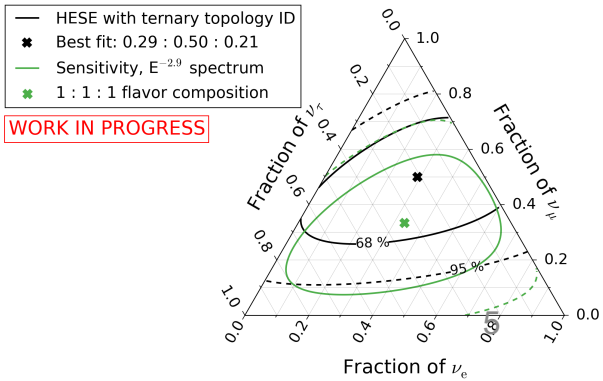


Blazar Neutrino
- IC170922A from TXS 0506+056



IceCube, Science361(2018)147
IceCube et al,(2018)eaat1378





1. Neutrinos at IceCube

2. Neutrino cross-section results

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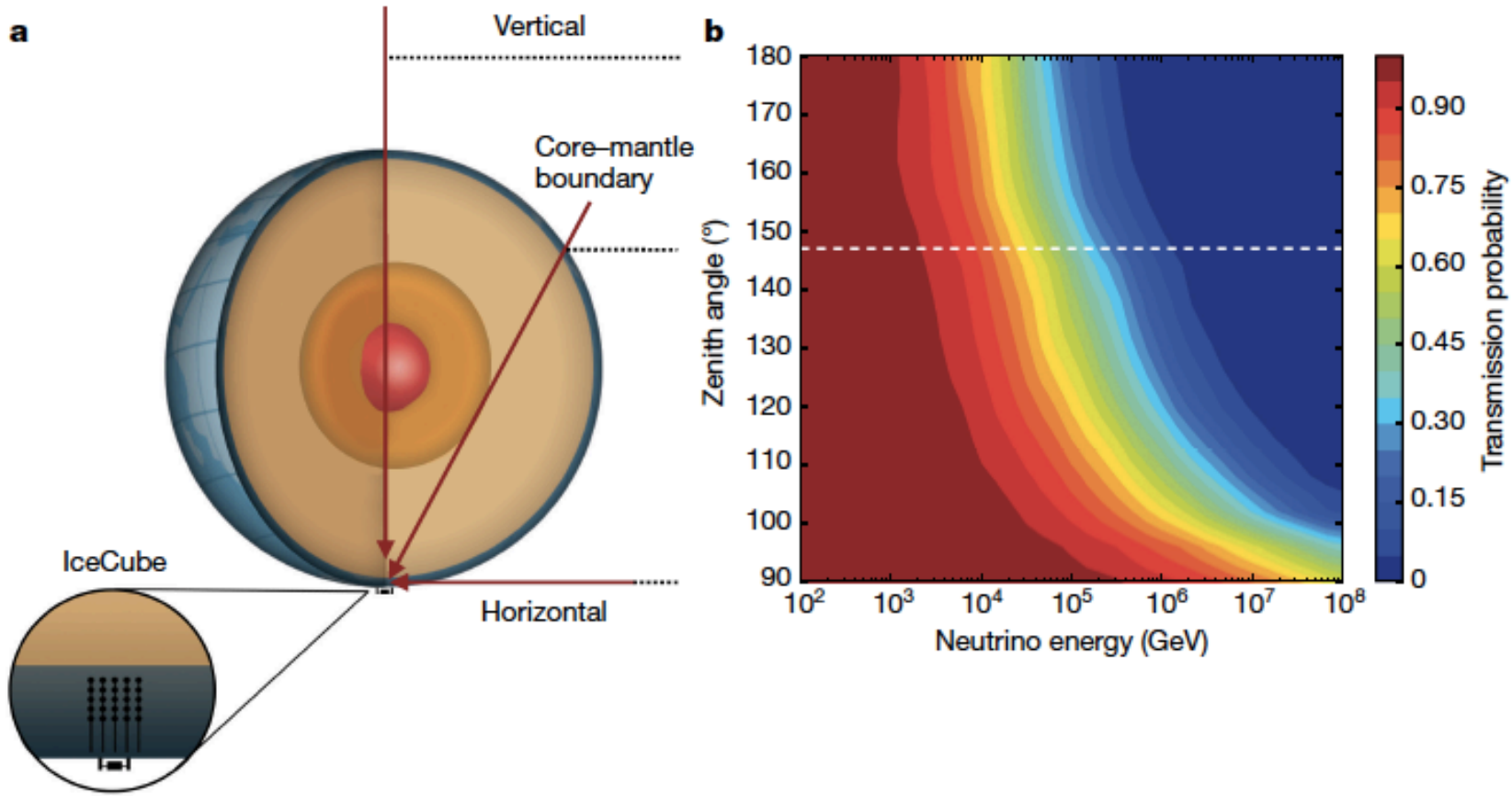
2. High-energy neutrino cross section measurement

cross section | efficiency | flux | target

Event rate $N = \Phi \times \sigma \times T \times \varepsilon$

Earth absorption for neutrino cross-section measurement
- high-energy neutrinos have high cross-sections with Earth material.
- Assuming astrophysical neutrino flux, and the Earth model, cross section is extracted from event rate.



IceCube, Nature551(2017)596
Bustamante and Connolly, PRL122(2019)041101

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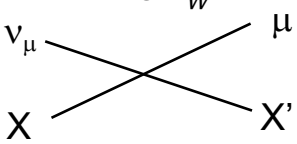
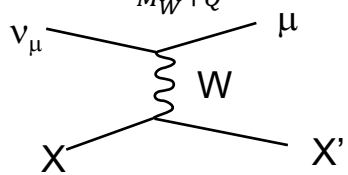
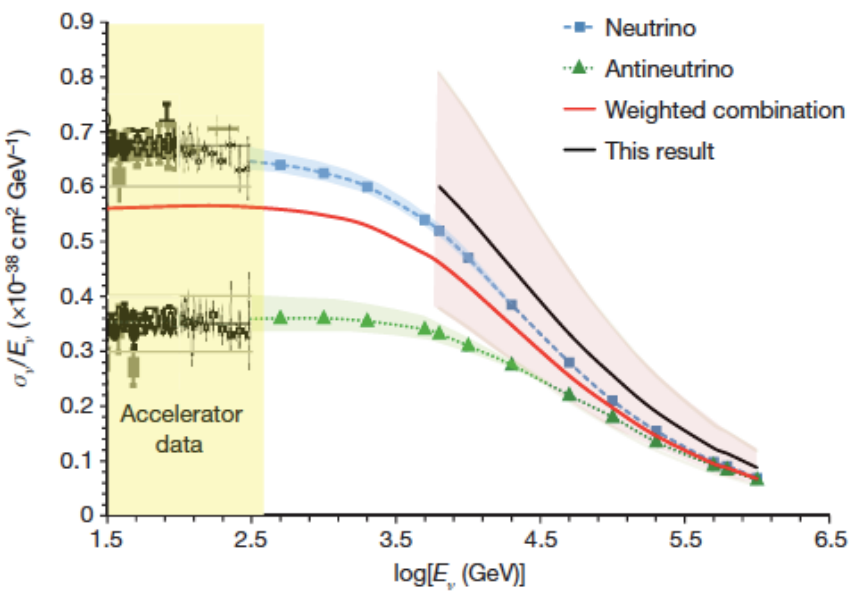
- first time Q^2 suppression is observed

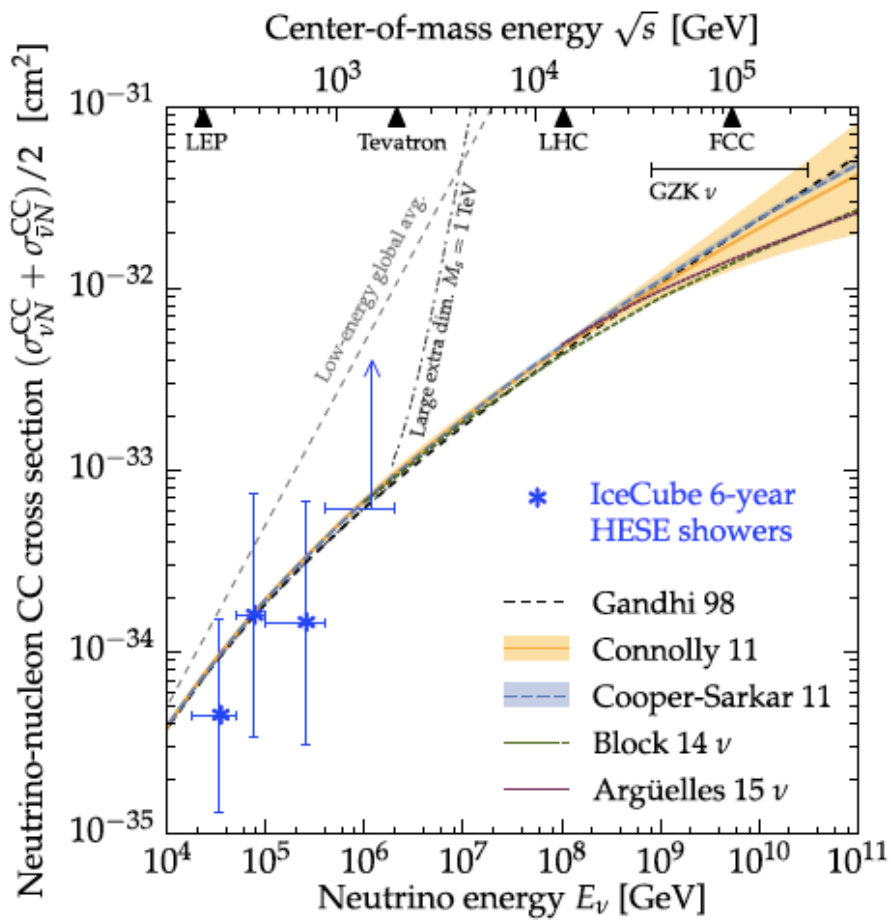
$$\sim G_F = \frac{\sqrt{2}g^2}{8M_W^2}$$



$$\sim \frac{1}{M_W^2+Q^2}$$







IceCube, Nature551(2017)596
Bustamante and Connolly, PRL122(2019)041101, Tianlu Yuan (ICRC2019), ArXiv:1908.07027

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flux | target

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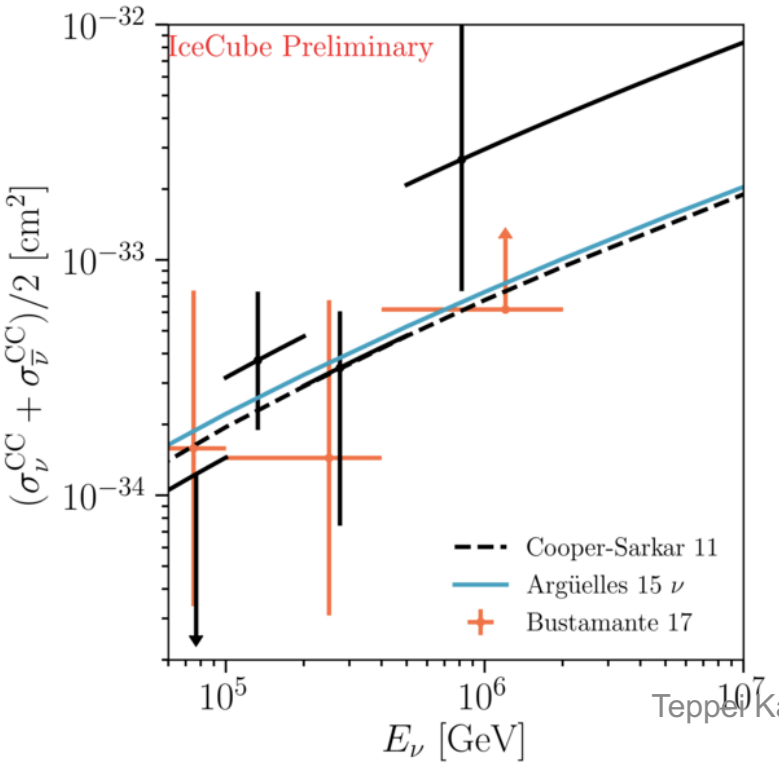
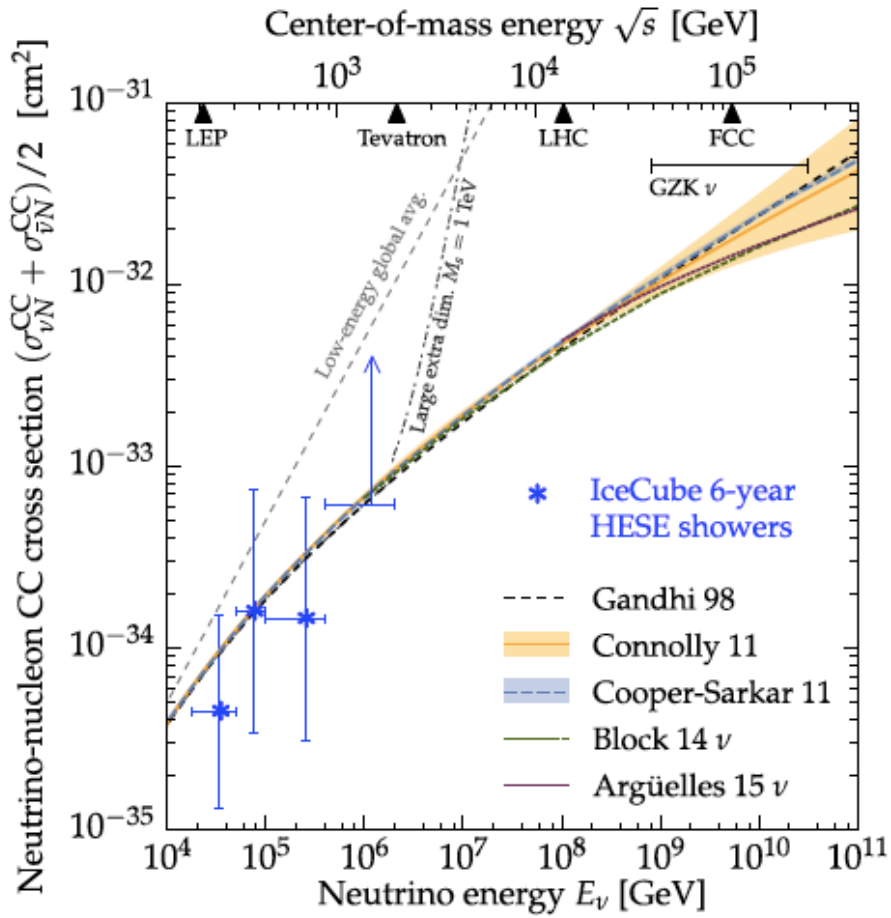
- first time Q^2 suppression is observed

Cross section measurement 2019

- The cross section is consistent with CSMS model



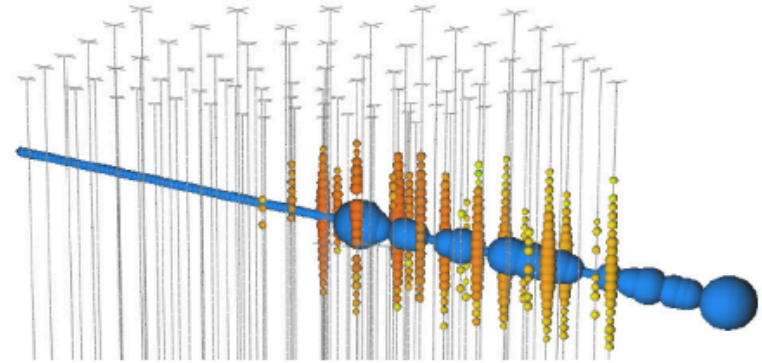


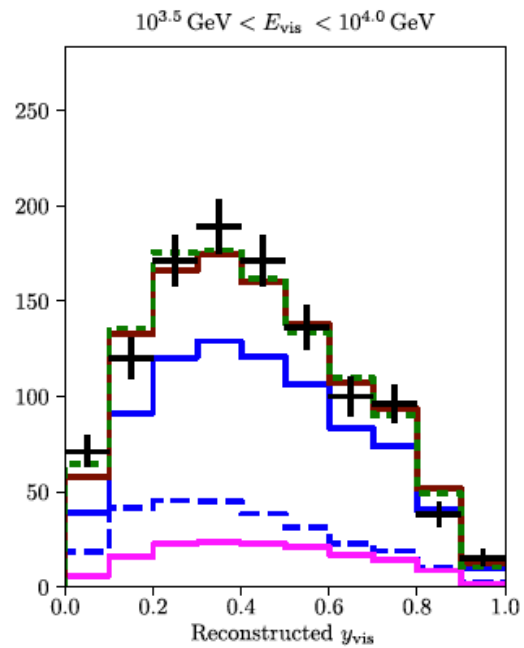
2. High-energy neutrino inelasticity measurement

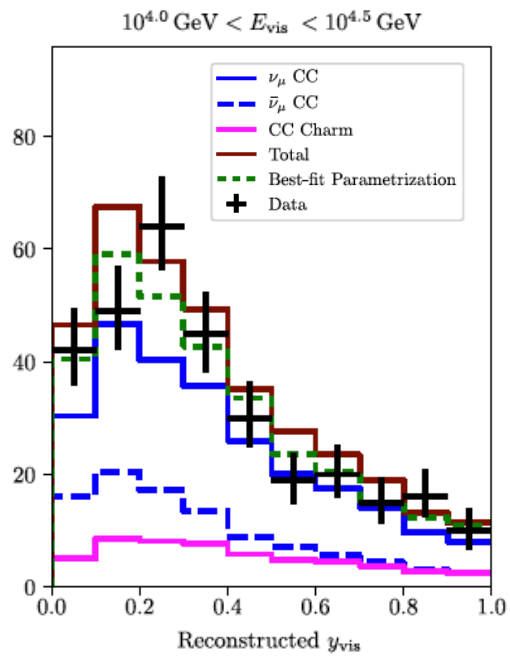
cross section | efficiency | flux | target

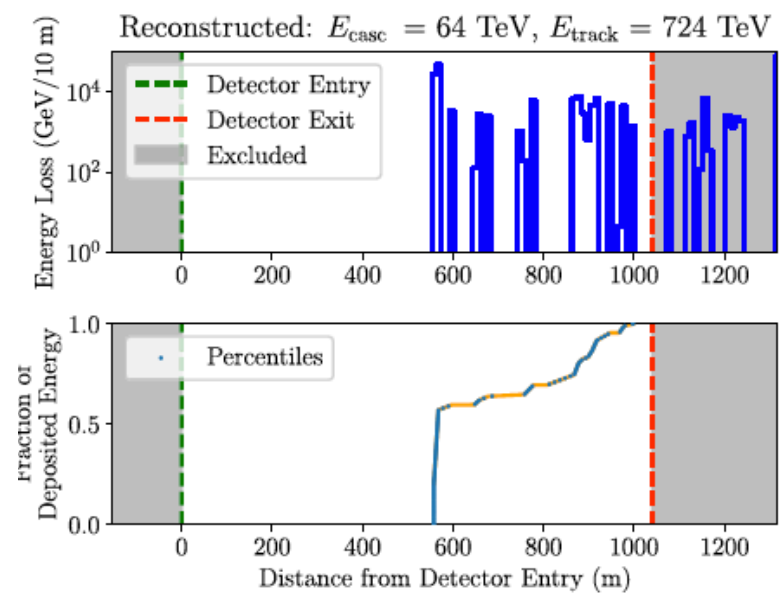
Event rate $N = \Phi \times \sigma \times T \times \varepsilon$

Visible inelasticity y_{vis} reconstruction
- E_{casc}: hadronic shower
- E_{track}: muon track
- $y_{vis} = E_{casc} / (E_{casc} + E_{track})$
- Low E inelasticity is important for $\nu/\bar{\nu}$ separation (NMO measurement)









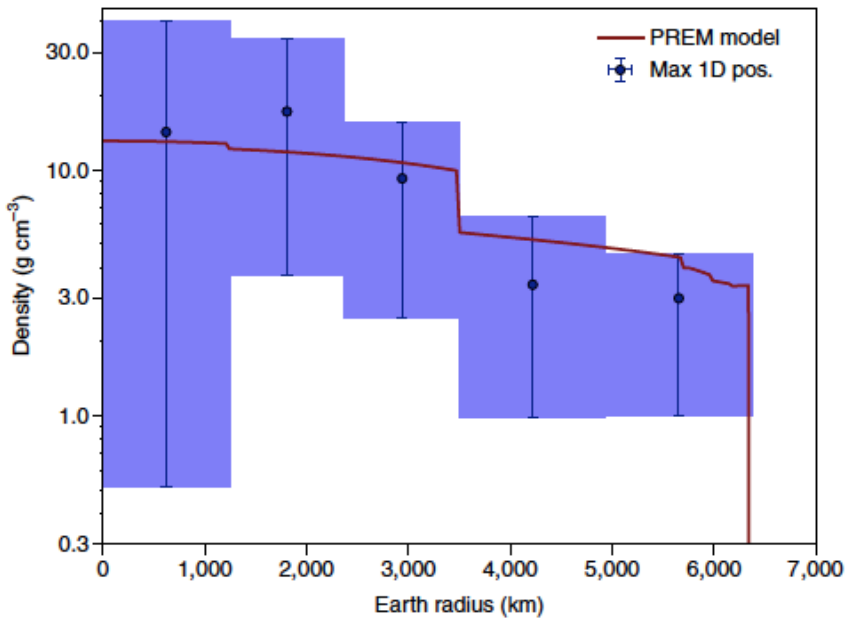
Dziewonski, Anderson (PREM), Phys. Earth Planet.Inter.25,(1981)297
Donini, Palomares-Ruiz, Salvado, Nature Physics 15(2019)37

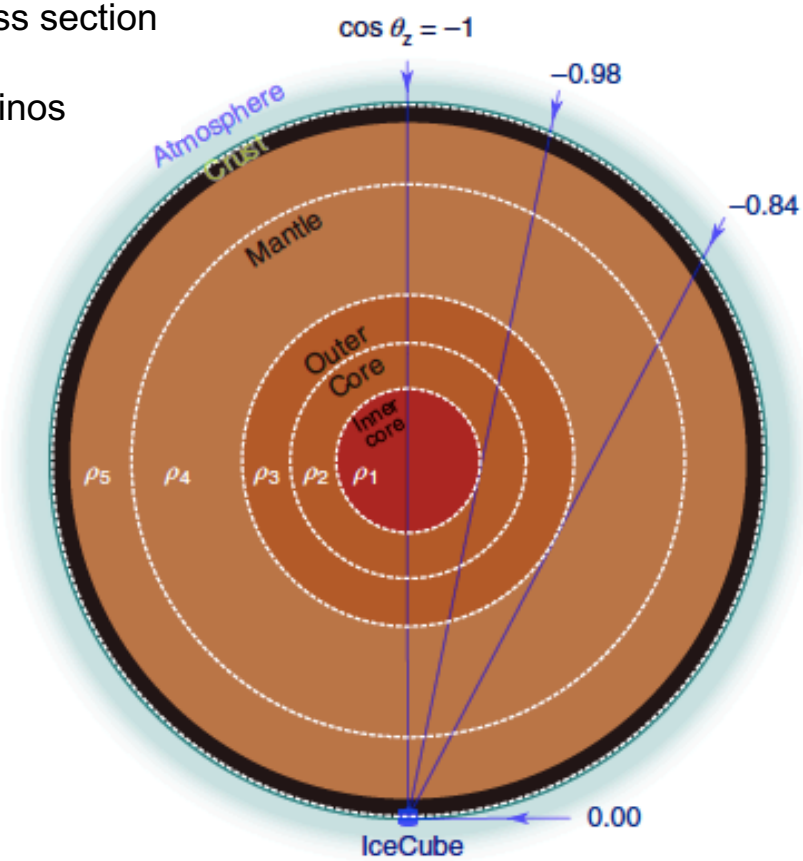
2. Earth tomography

cross section | efficiency
flux | target

Event rate $N = \Phi \times \sigma \times T \times \varepsilon$

Earth absorption for Earth density measurement
- PREM (Preliminary reference Earth model)
- Standard earth density model used by T2K, NOvA, etc
- Earth density profile is extracted by assuming flux and cross section
- Cross section, CSS model
- Measure Earth moment of inertia and Earth mass by neutrinos



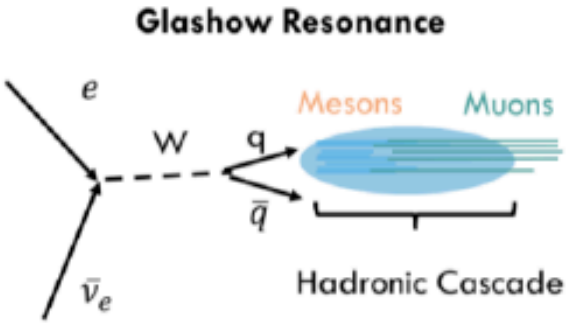


Taboada, Neutrino 2018, Lu Lu (ICRC2017), arXiv:1710.01191

IceCube preliminary

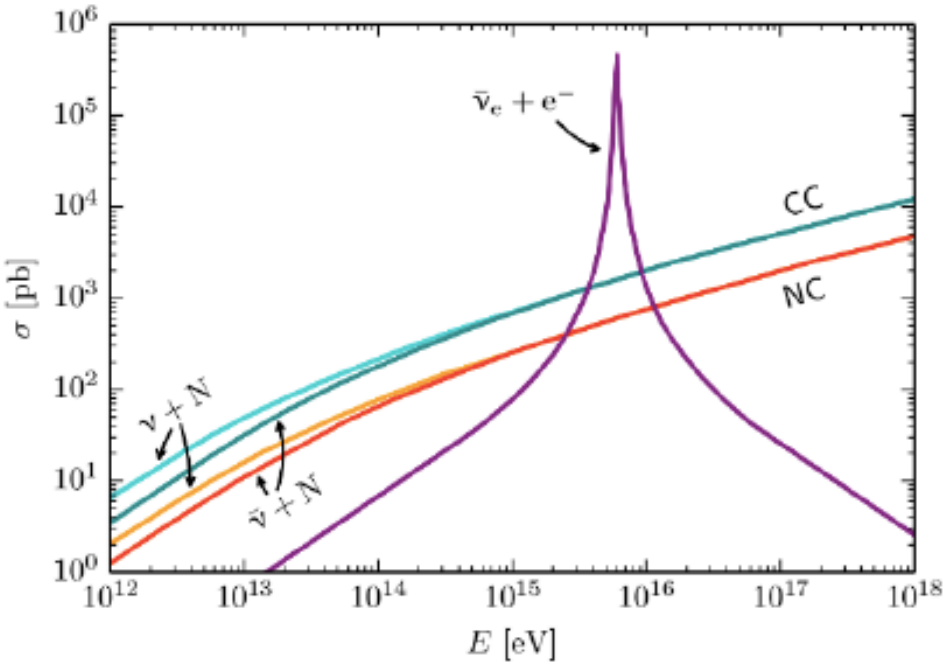
2. Glashow resonance

A 5.9 PeV event in IceCube

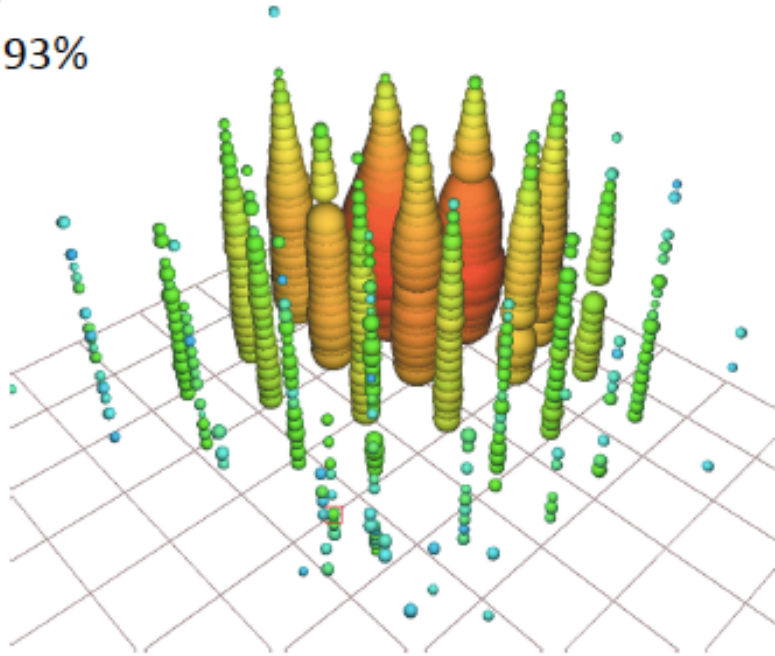


Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

On-shell production of W with rest electron target



Work in progress



Event identified in a partially-contained PeV search (PEPE)

Deposited energy: 5.9±0.18 PeV (stat only)

ICRC 2017 arXiv:1710.01191

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IceCube, PRD99(2019)032007
Ribordy and Smirnov, PRD87(2013)113007

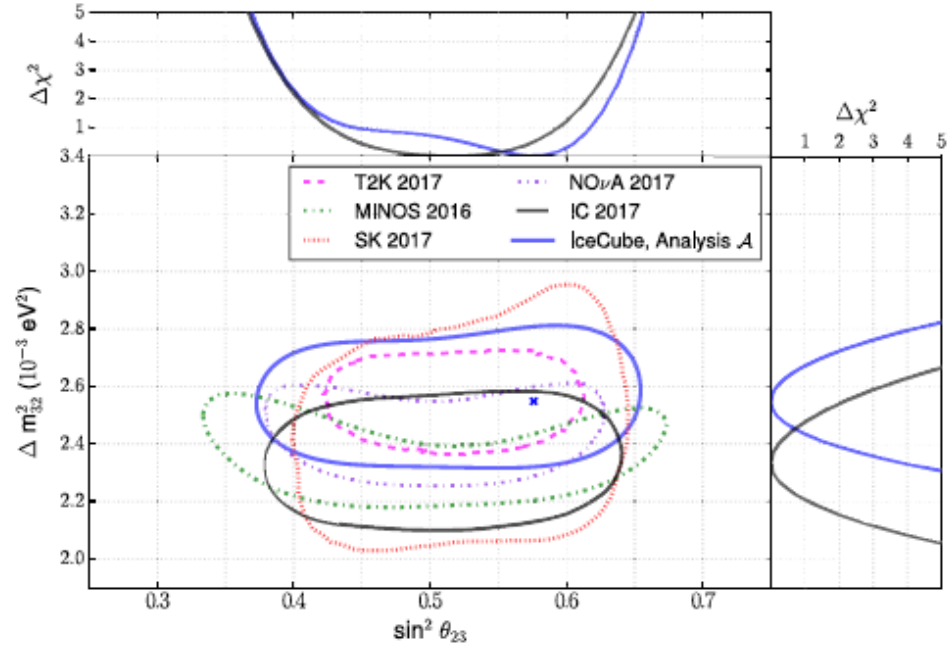
3. Neutrino interaction models

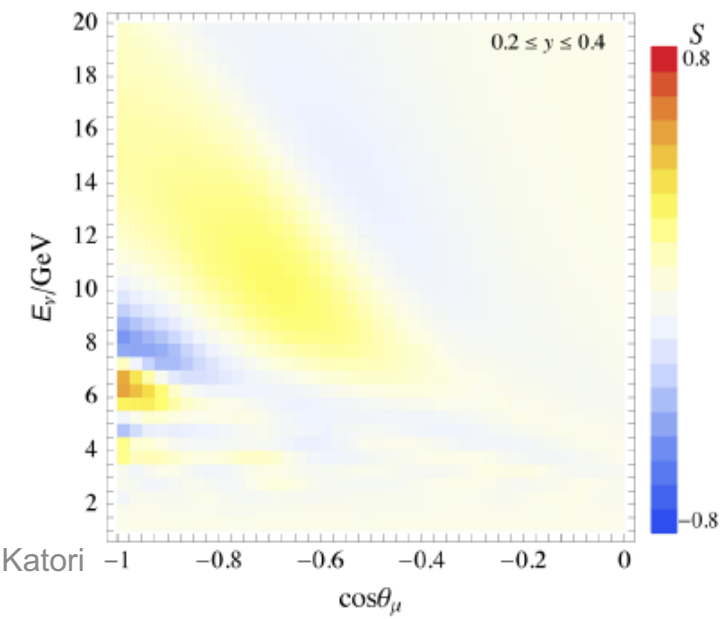
Low energy neutrino interaction model, GENIE

- GENIE v2.8.6
- Used for oscillation analysis (<100 GeV)
- M_A^{QE} and M_A^{RES} are nuxsec systematics
- NMO measurement may need more error (y-measurement → hadron errors)

e.g.) IceCube τ-appearance analysis

Parameter	Prior	Analysis $\mathcal{A}$ (CC + NC)	Analysis $\mathcal{A}$ Best fit (CC)
Neutrino flux and cross section:			
ν_e/ν_μ Ratio	1.0 ± 0.05	1.03	1.03
ν_e Up/Hor. Flux ratio (σ)	0.0 ± 1.0	−0.19	−0.18
$\nu/\bar{\nu}$ Ratio (σ)	0.0 ± 1.0	−0.42	−0.33
$\Delta\gamma_\nu$ (Spectral index)	0.0 ± 0.1	0.03	0.03
Effective Livetime (years)	···	2.21	2.24
M_A^{CCQE} (Quasielastic) (GeV)	$0.99^{+0.248}_{-0.149}$	1.05	1.05
M_A^{res} (Resonance) (GeV)	1.12 ± 0.22	1.00	0.99
NC Normalization	1.0 ± 0.2	1.05	1.06
Oscillation:			
θ_{13} (°)	8.5 ± 0.21	···	···
θ_{23} (°)	···	49.8	50.2
Δm^2_{32} (10^{-3} eV^2)	···	2.53	2.56
Detector:			
Optical Eff., Overall (%)	100 ± 10	98.4	98.4
Optical Eff., Lateral (σ)	0.0 ± 1.0	0.49	0.48
Optical Eff., Head-on (a.u.)	···	−0.63	−0.64
Local ice model	···	···	···
Bulk ice, scattering (%)	100.0 ± 10	103.0	102.8
Bulk ice, absorption (%)	100.0 ± 10	101.5	101.7
Atmospheric muons:			
Atm. μ fraction (%)	···	8.1	8.0
$\Delta\gamma_\mu$ (μ Spectral index, σ)	0.0 ± 1.0	0.15	0.15
Coincident $\nu + \mu$ fraction	$0.0 + 0.1$	0.01	0.01
Measurement:			
ν_τ Normalization	···	0.73	0.57





Cooper-Sarkar, Metsch, Sarkar, JHEP08(2011)042
PDF4LHC, ArXiv:1101.0536

3. Neutrino interaction models

High energy neutrino cross section - CSMS model

- Standard in HE-ν astrophysics community
- NLO DIS, HERAPDF1.5
- PDF4LHC for PDF error calculation
- Isoscalar approximation

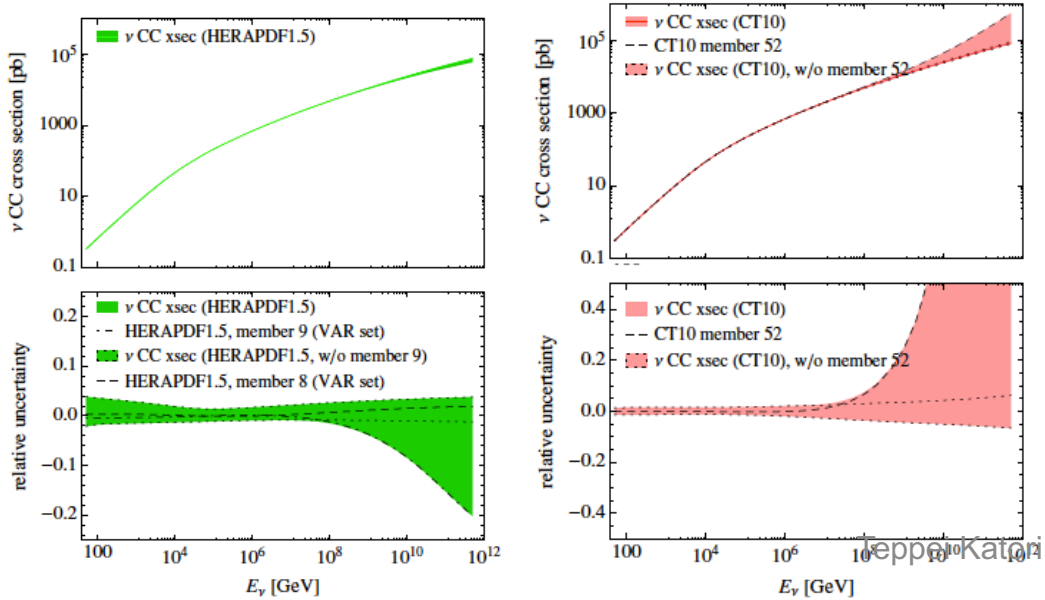
Beyond CSMS model

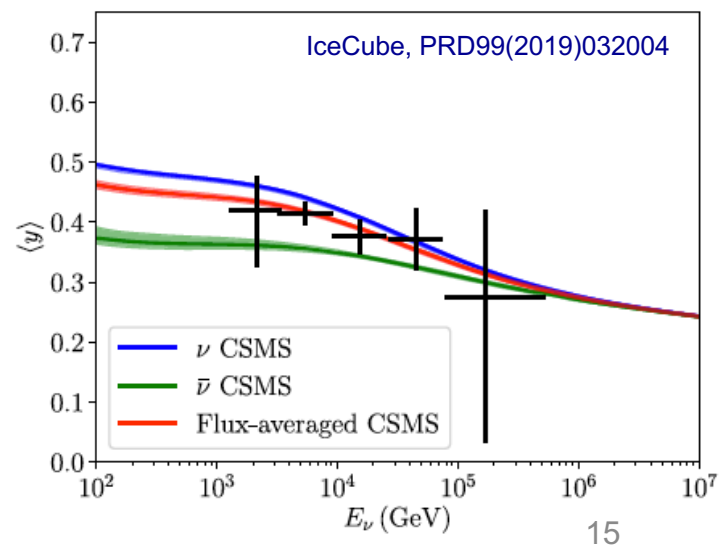
- Nuclear shadowing (EPPS16 nPDF)
- Non-isoscalar target

etc

E_ν[GeV]	σ_{CC}[pb]	up	down (w/o mem. 9)	down (w/ mem. 9)	σ_{NC}[pb]	up	down (w/o mem. 9)	down (w/ mem. 9)
50	0.32	4.1 %	-2.3 %	-2.4 %	0.10	3.8 %	-1.9 %	-2.0 %
100	0.65	3.8 %	-2.0 %	-2.0 %	0.20	3.5 %	-1.8 %	-1.8 %
200	1.3	3.5 %	-1.8 %	-1.9 %	0.41	3.2 %	-1.6 %	-1.7 %
500	3.2	3.2 %	-1.7 %	-1.8 %	1.0	2.9 %	-1.5 %	-1.5 %
1000	6.2	3.0 %	-1.6 %	-1.7 %	2.0	2.7 %	-1.4 %	-1.5 %
2000	12.	2.7 %	-1.6 %	-1.6 %	3.8	2.4 %	-1.3 %	-1.4 %
5000	27.	2.3 %	-1.5 %	-1.5 %	8.6	2.1 %	-1.3 %	-1.3 %
10000	47.	2.0 %	-1.4 %	-1.4 %	15.	1.8 %	-1.2 %	-1.2 %
20000	77.	1.8 %	-1.3 %	-1.4 %	26.	1.6 %	-1.1 %	-1.1 %
50000	140.	1.5 %	-1.2 %	-1.2 %	49.	1.3 %	-1.0 %	-1.1 %
100000	210.	1.4 %	-1.2 %	-1.2 %	75.	1.2 %	-1.0 %	-1.0 %
200000	310.	1.5 %	-1.1 %	-1.1 %	110.	1.2 %	-0.9 %	-0.9 %
500000	490.	1.6 %	-1.0 %	-1.0 %	180.	1.3 %	-0.8 %	-0.8 %
1×10^6	690.	1.7 %	-0.9 %	-0.9 %	260.	1.4 %	-0.8 %	-0.8 %
2×10^6	950.	1.9 %	-0.9 %	-0.9 %	360.	1.6 %	-0.8 %	-0.8 %
5×10^6	1400.	2.0 %	-0.9 %	-0.9 %	540.	1.8 %	-0.8 %	-0.8 %
1×10^7	1900.	2.2 %	-0.9 %	-0.9 %	730.	2.0 %	-0.8 %	-0.8 %
2×10^7	2600.	2.3 %	-0.9 %	-1.0 %	980.	2.2 %	-0.8 %	-0.9 %
5×10^7	3700.	2.5 %	-0.9 %	-1.2 %	1400.	2.4 %	-0.9 %	-1.1 %
1×10^8	4800.	2.7 %	-0.9 %	-1.5 %	1900.	2.6 %	-0.9 %	-1.3 %
2×10^8	6200.	2.8 %	-1.0 %	-2.0 %	2400.	2.7 %	-1.0 %	-1.8 %
5×10^8	8700.	3.0 %	-1.1 %	-3.0 %	3400.	2.9 %	-1.0 %	-2.6 %
1×10^9	11000.	3.1 %	-1.2 %	-3.9 %	4400.	3.0 %	-1.1 %	-3.4 %
2×10^9	14000.	3.3 %	-1.2 %	-5.0 %	5600.	3.2 %	-1.2 %	-4.4 %
5×10^9	19000.	3.4 %	-1.4 %	-6.8 %	7600.	3.4 %	-1.3 %	-6.1 %
1×10^{10}	24000.	3.6 %	-1.5 %	-8.5 %	9600.	3.5 %	-1.4 %	-7.6 %
2×10^{10}	30000.	3.7 %	-1.6 %	-10.3 %	12000.	3.6 %	-1.5 %	-9.3 %
5×10^{10}	39000.	3.8 %	-1.7 %	-13.1 %	16000.	3.8 %	-1.7 %	-11.8 %
1×10^{11}	48000.	4.0 %	-1.8 %	-15.2 %	20000.	3.9 %	-1.8 %	-13.9 %
2×10^{11}	59000.	4.1 %	-1.9 %	-17.5 %	24000.	4.0 %	-1.9 %	-16.1 %
5×10^{11}	75000.	4.2 %	-2.0 %	-20.3 %	31000.	4.2 %	-2.0 %	-18.8 %

Table 1. Neutrino CC and NC cross-sections on isoscalar targets, along with their uncertainties, in the perturbative DGLAP formalism at NLO, using HERAPDF1.5 (both with and without member 9).



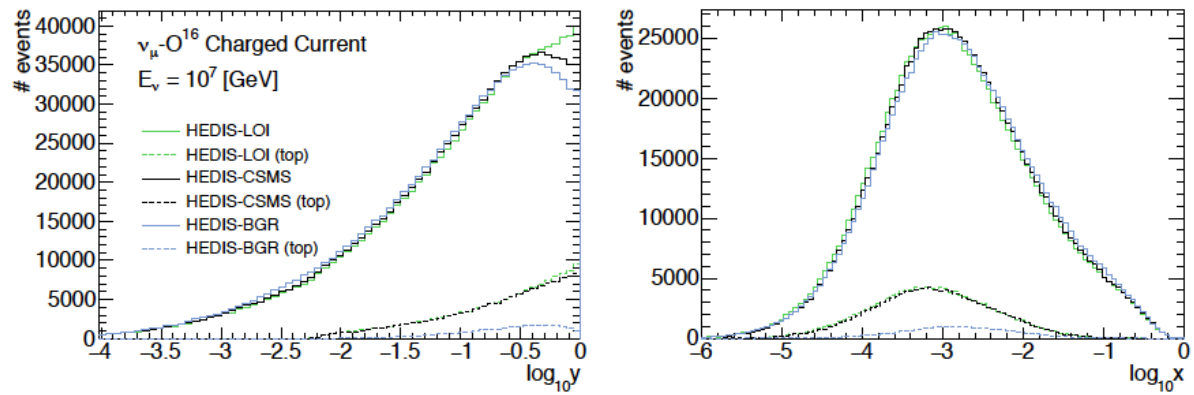


Alfonso Garcia (ICRC2019), ArXiv:1908.10077
Shivesh Mandalia (NuInt15), ArXiv:1602.00083, PhD Thesis (Queen Mary 2019)

3. GENIE high-energy extension

GENIE-HEDIS (KM3NeT)

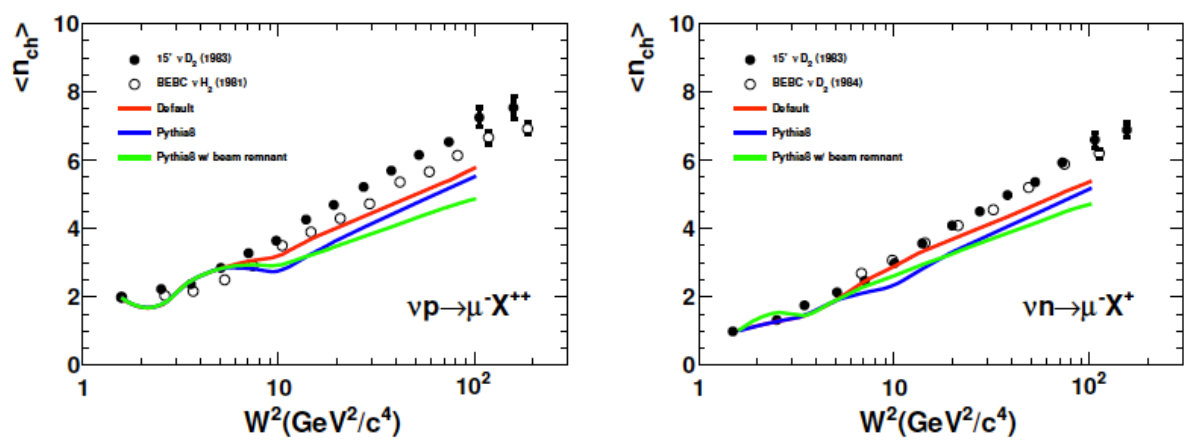
- NLO DIS, HERAPDF1.5
- ν-nucleon interaction (of course)
- valid $1<Q^2$ (GeV)$<10^9$, $10^{-6}<x<1$
- suitable for Eν>100 GeV



GENIE-PYTHIA8 (IceCube)

- PYTHIA6 is obsolete (not maintained, Fortran 77)
- New features for GENIE: beam remnant and underlying events, radiation correction
- PYTHIA choose quark+diquark (and more)
- Multiplicity prediction gets worse (PYTHIA8 is tuned LHC)

New DIS and hadronization model may be available for new version of GENIE



Conclusion

IceCube has a rich program using atmospheric neutrinos and astrophysical neutrinos

Conventional atmospheric neutrinos (E<20 TeV)
- For mainly oscillation physics (standard, tau-appearance, NSI, sterile, etc)
- GENIE

High-energy astrophysical neutrinos (60 TeV<E)
- For astrophysics, new physics search, etc
- CSMS model

Future: high-energy extension of GENIE?
- NLO DIS model (>100 GeV)
- PYTHIA8
- These are ready and can be used in the next version of GENIE

(no compatibility with low-energy models)

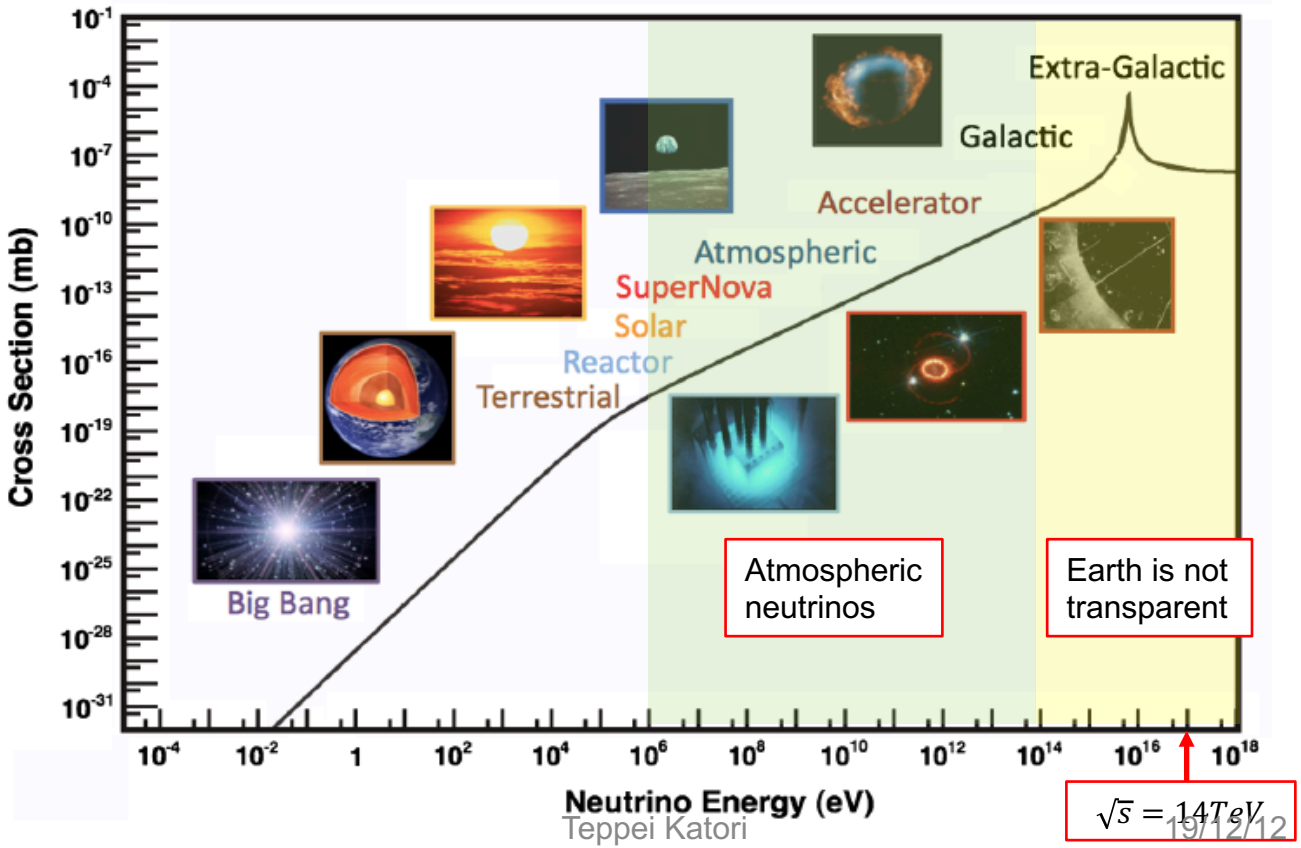
Thank you for your attention!

Formaggio and Zeller, Rev.Mod.Phys.,84 (2012) 1307

1. Atmospheric neutrinos, natural laboratories of new physics

Atmospheric neutrinos cover ~100MeV - 20 TeV (conventional) coming from all direction (diffuse). However, direction is related to the propagation distance.

→ They are the highest energy particles (~20 TeV) with the longest baseline (12700km) propagating the highest density material (~13g/cm^3) on Earth.



1. Atmospheric neutrinos, natural laboratories of new physics