High energy neutrino cross-sections

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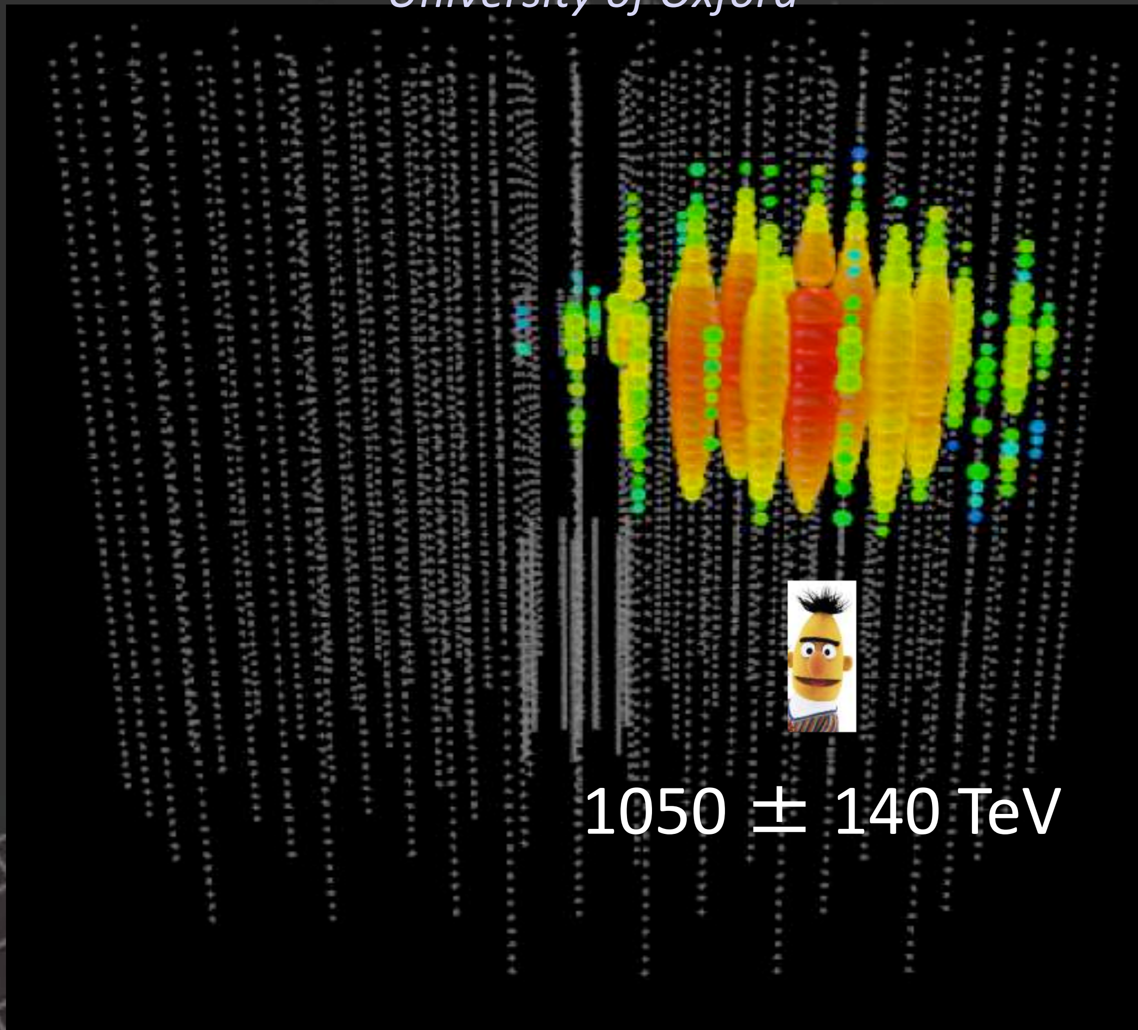
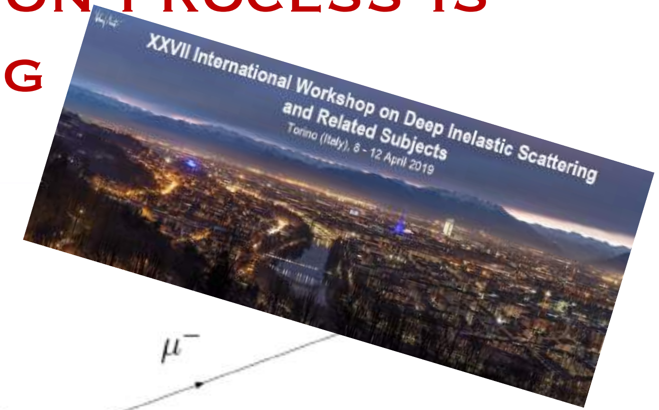


XVIII International Workshop on Neutrino Telescopes, Venice, 18-22 March 2019

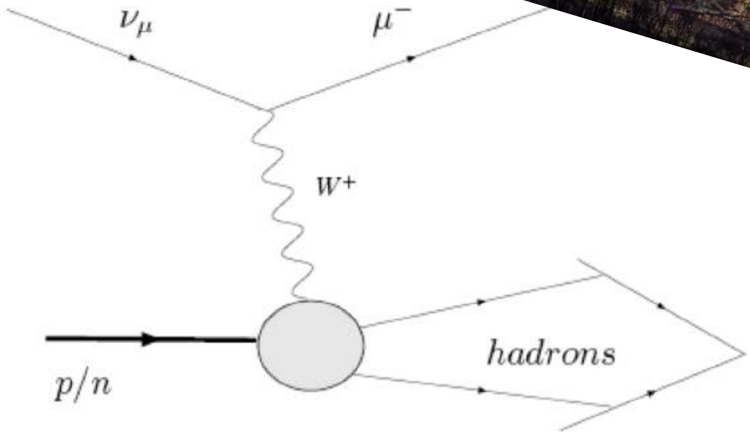
Above a few GeV the dominant interaction process is ν-N deep inelastic scattering



$$\frac{\partial^2 \sigma^{CC,NC}_{\nu,\bar{\nu}}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi} \left(\frac{M_i^2}{Q^2 + M_i^2} \right)$$

$Q^2 \uparrow \Rightarrow$ propagator $\downarrow$

$$\left[\frac{1 + (1-y)^2}{2} F_2^{CC,NC}(x, Q^2) - \frac{y^2}{2} F_L^{CC,NC}(x, Q^2) \pm y \left(1 - \frac{y}{2}\right) x F_3^{CC,NC}(x, Q^2)\right]$$



$Q^2 \uparrow \Rightarrow$ parton distribution functions $\uparrow$

$$F_i(x, Q^2) = \sum_{a=g,q} \int_x^1 \frac{\mathrm{d}z}{z} C_{i,a}\left(\frac{x}{z}, Q^2\right) f_a(z, Q^2)$$

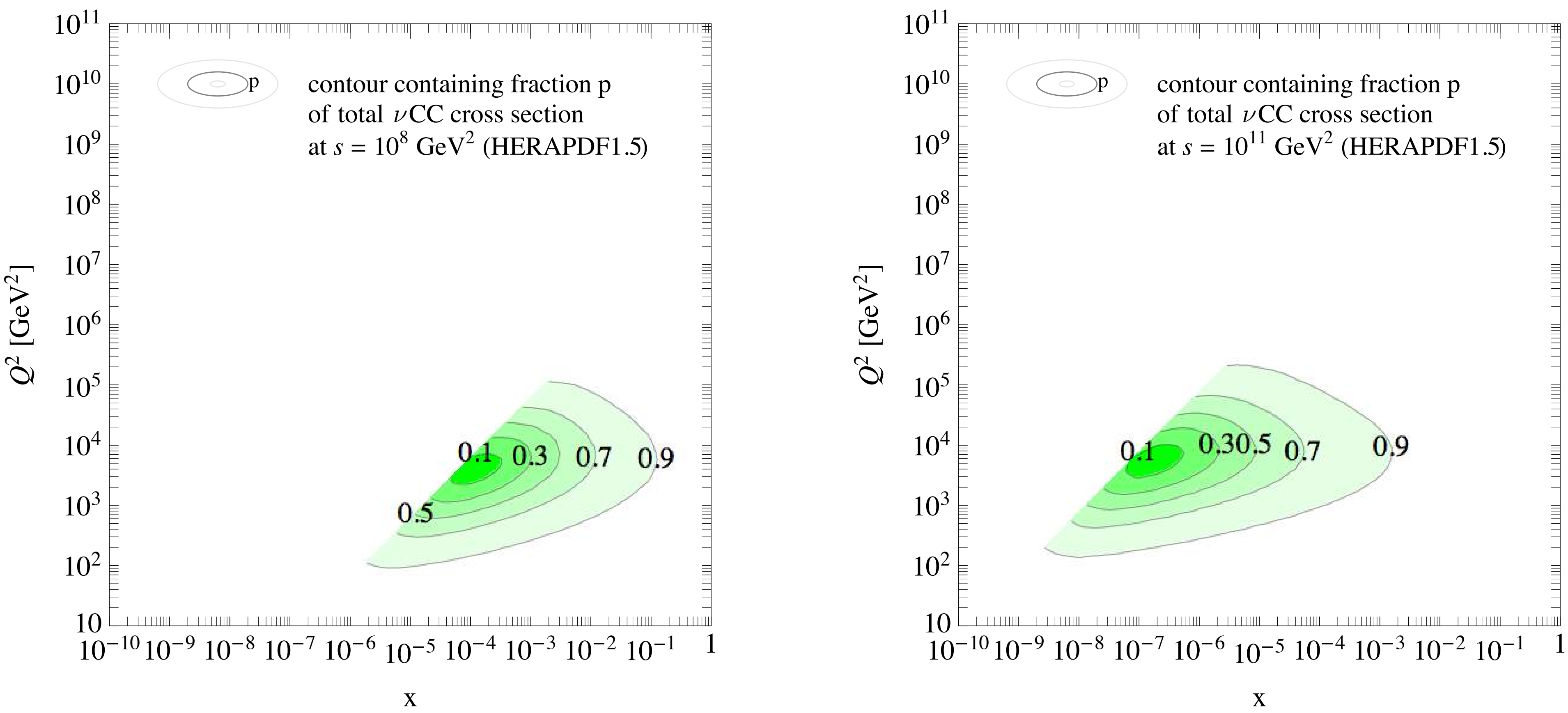
Most of the contribution to DIS cross-section comes from: $Q^2 \sim M_W^2$ and $x \sim \frac{M_W^2}{M_N E_\nu}$

$$\text{At leading order (LO)}: F_L = 0, \quad F_2 = x(u_v + d_v + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c}),$$

$$xF_3 = x(u_v + d_v + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_v + d_v + 2s + 2b - 2\bar{c})$$

Can calculate numerically at Next-to-Leading-Order (NLO) … *no* significant further change at NNLO

As the neutrino energy increases, *low* values of Bjorken-*x* are being probed

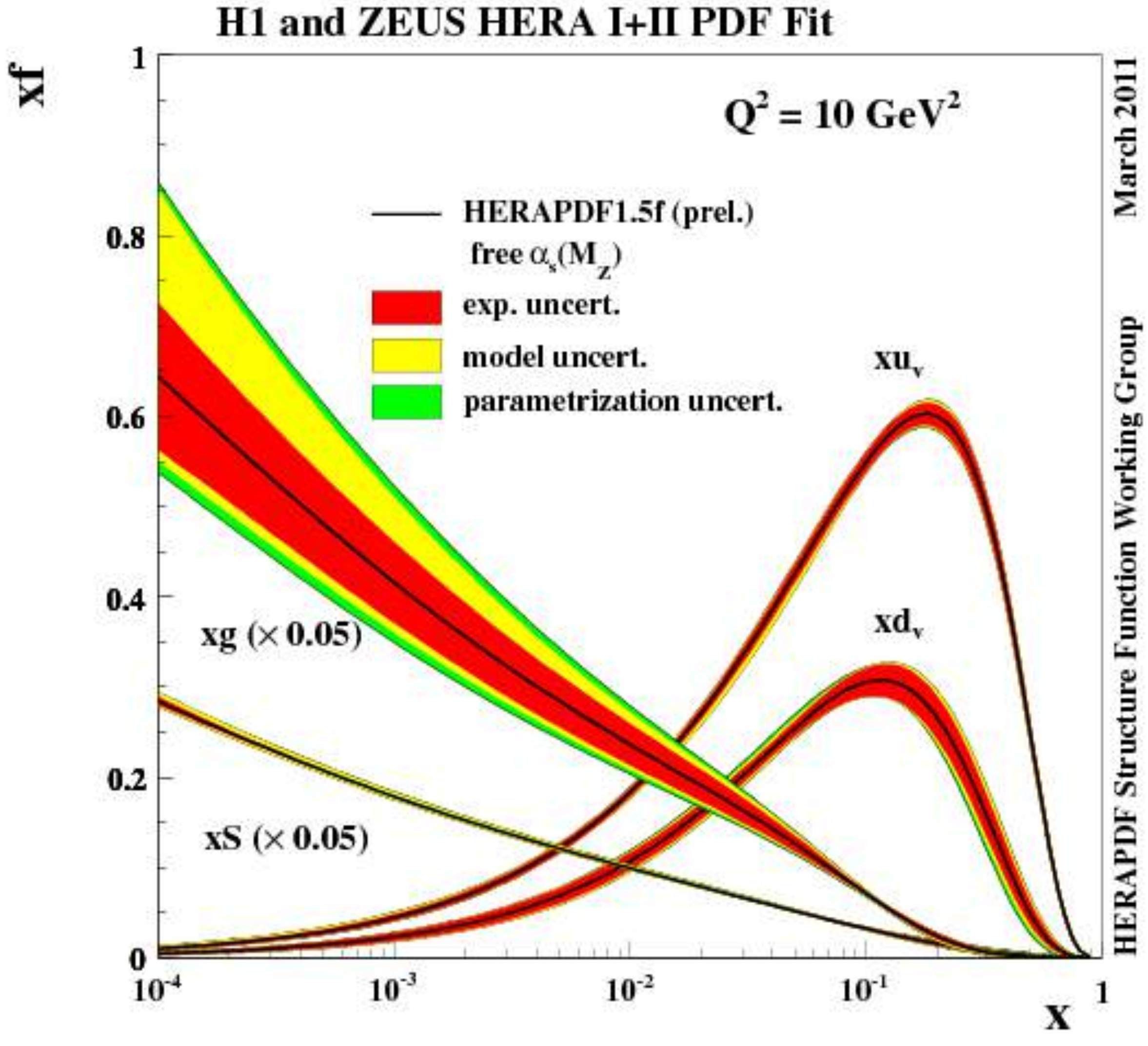


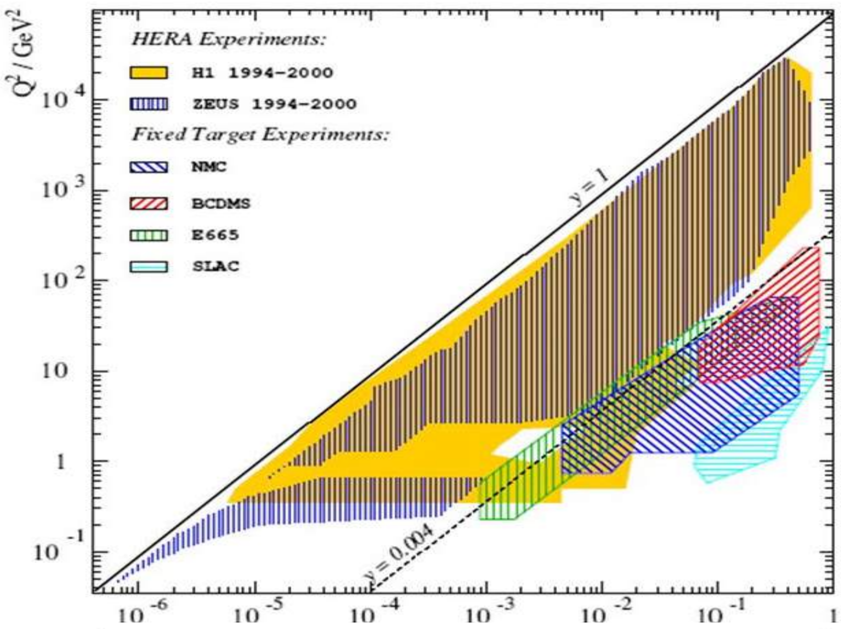
Mertsch, Cooper-Sarkar & Sarkar, JHEP 08:042,2011

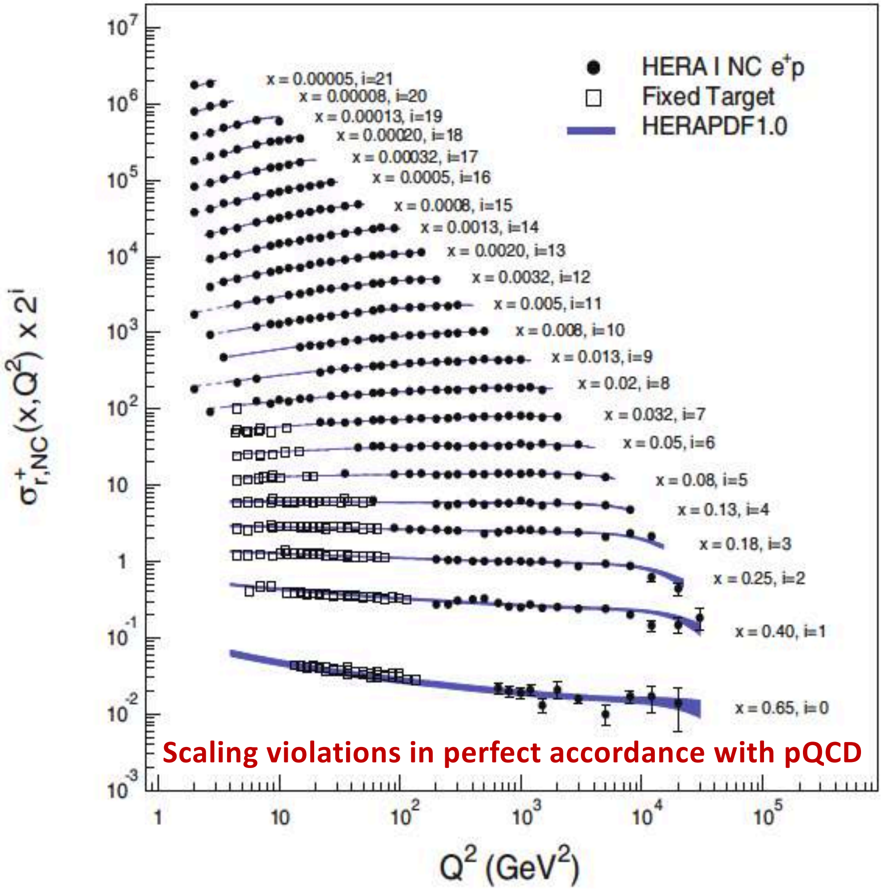
So to determine the DIS cross-section accurately it is essential to have measurements of PDFs down to as *low x* as is possible … for E_ν higher than $\sim 10^3$ TeV we have to evolve these further (using the DGLAP formalism)

(**Warning**: Off-the-shelf PDFs, e.g. on http://lhapdf.hepforge.org, often 'freeze' below some low value of Bjorken-*x* (i.e. values are set to *zero*), so care must be taken at very high E_ν to avoid errors!)

The H1 & ZEUS experiments at HERA were the first to measure DIS at high Q^2 and low Bjorken-x … an unexpected finding was the very *steep* rise of the **gluon PDF** at low x which has significance for high energy neutrino interactions





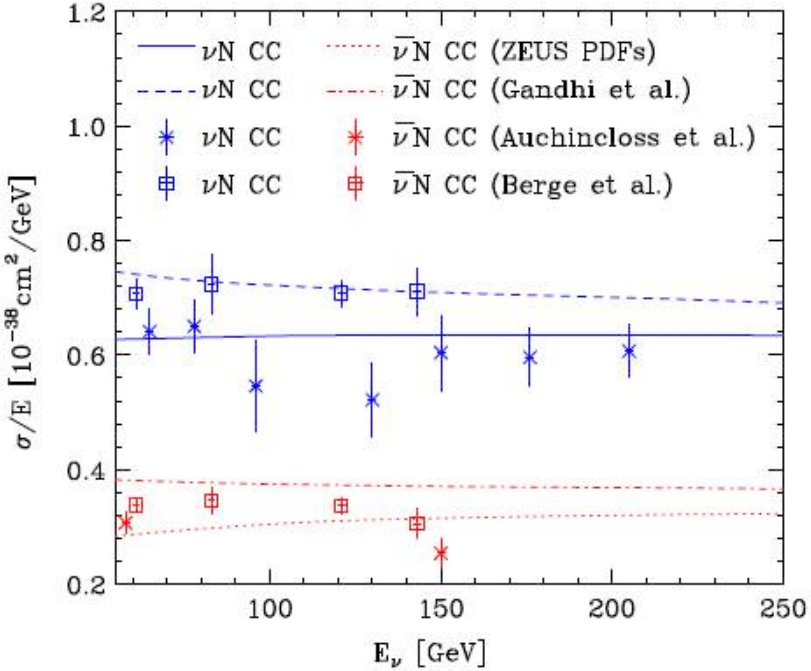


The cross-section using modern PDFs is up to ~40% *below* the previous ‘standard’ calculation of Gandhi *et al* (1998)

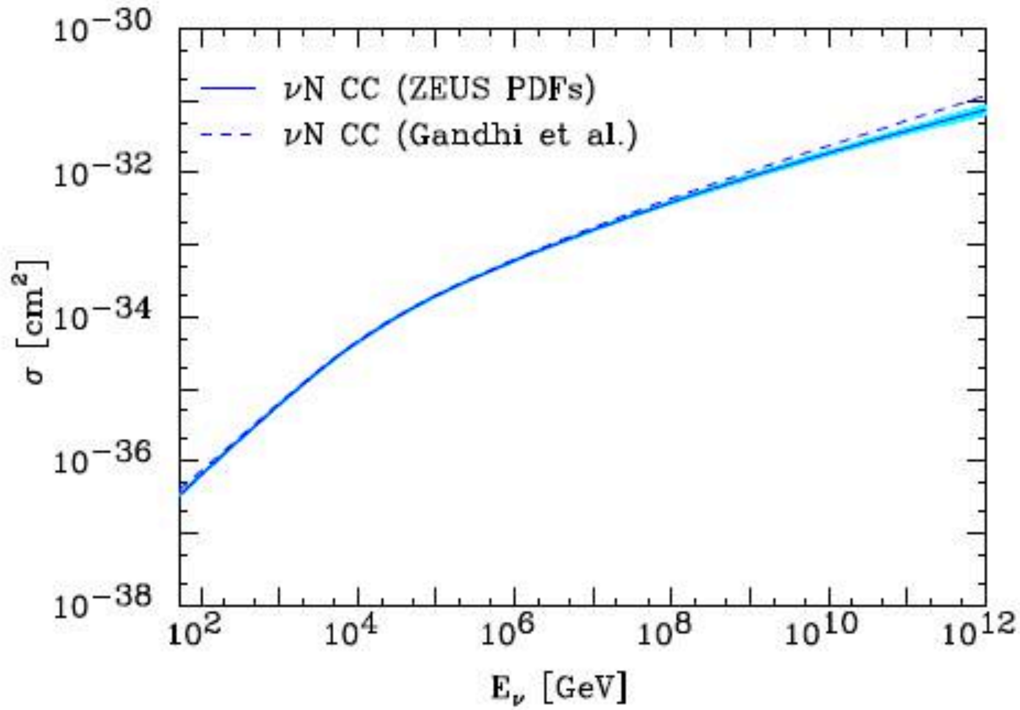
We also quantified the *uncertainty* to be < 5-10% even at the highest energies … in the framework of pQCD

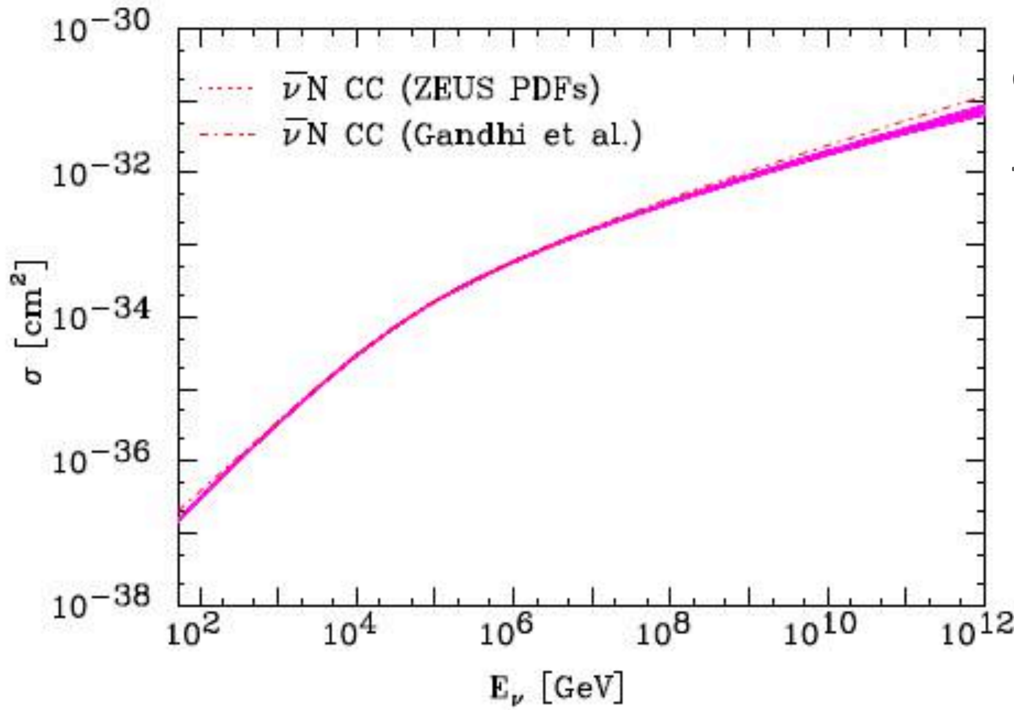
At very high energies where very low-x is being probed, recombination/saturation effects may reduce the cross-section by a factor of up to ~2 …
However DGLAP evolution appears to fit well *all* experimental data – so no imperative for this yet! (although fit does improve with BFKL resummation)

Agrees with low energy (>10 GeV) data



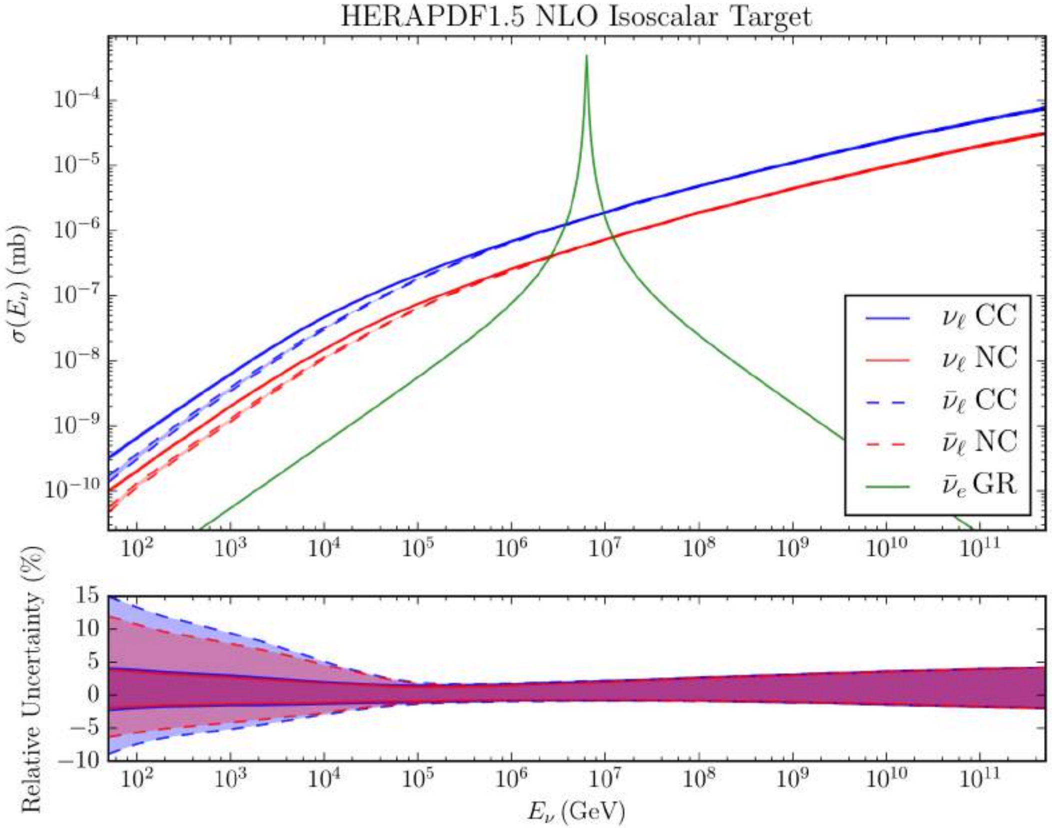
Cooper-Sarkar & Sarkar, JHEP **01**:075,2008



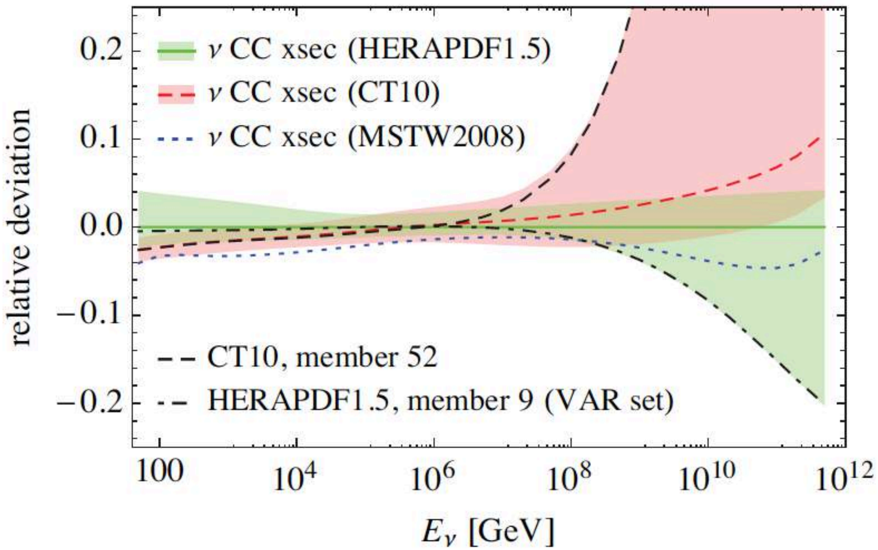


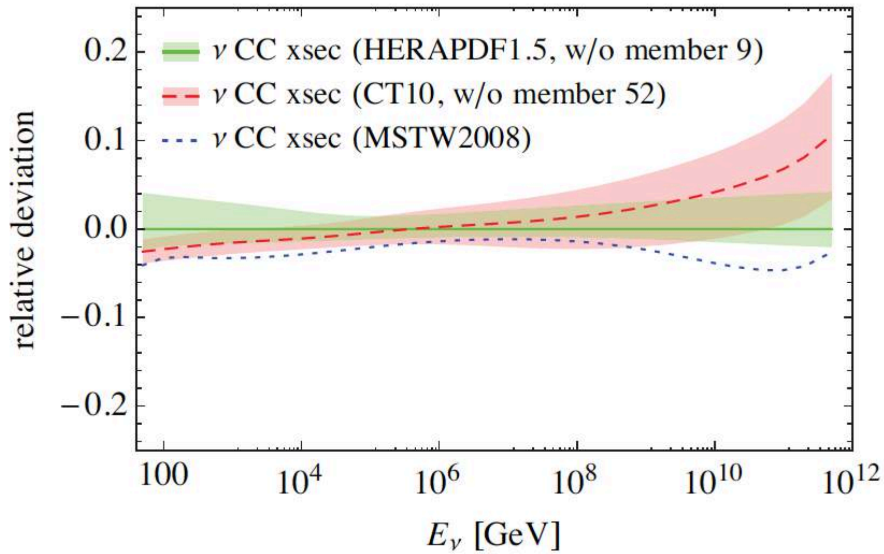
After the full HERA data release we updated the *ν-N* cross-section @ NLO using HERAPDF1.5, including the effect of heavy quarks on the DGLAP evolution
… the full code is implemented in:

https://dispred.hepforge.org/



This is the cross-section implemented in NuGen and other event generators



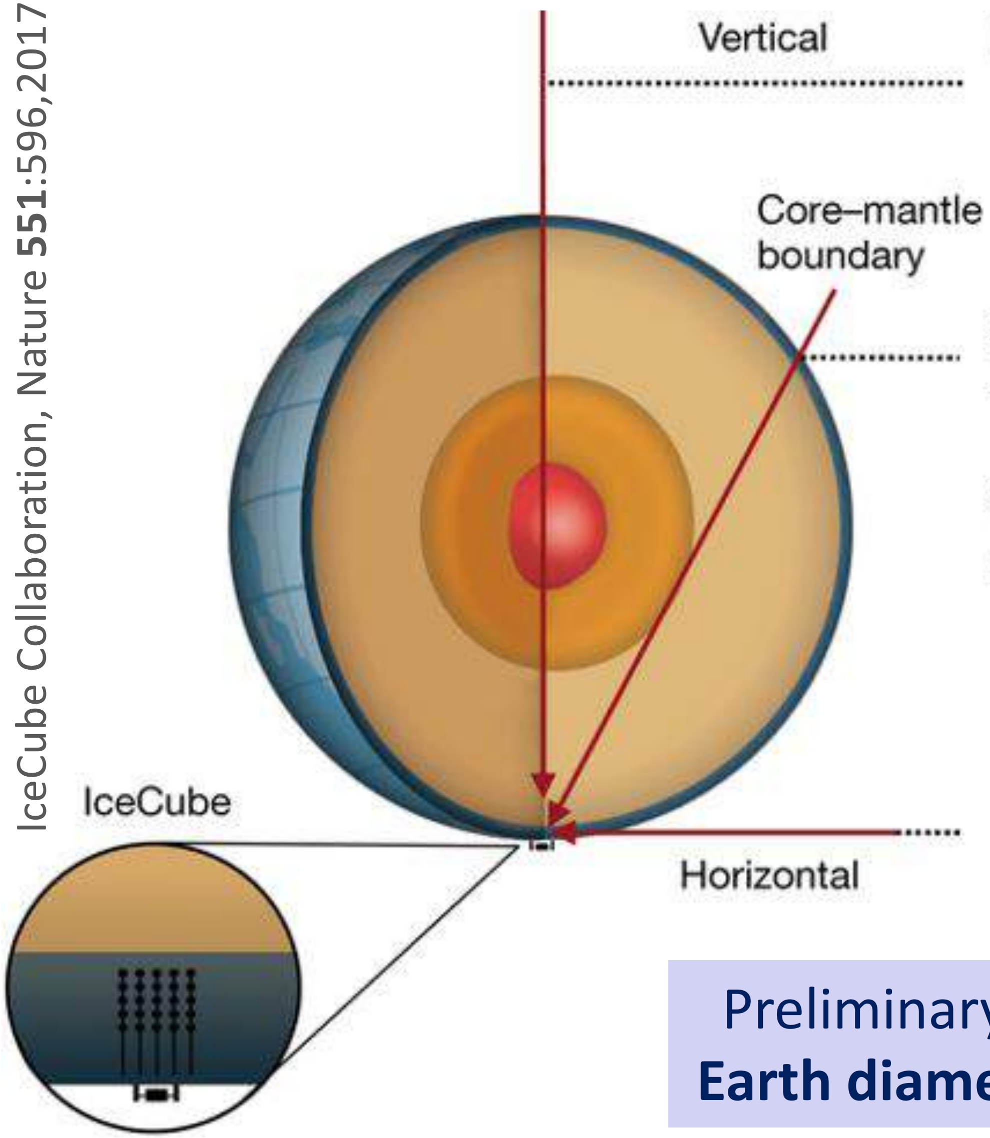


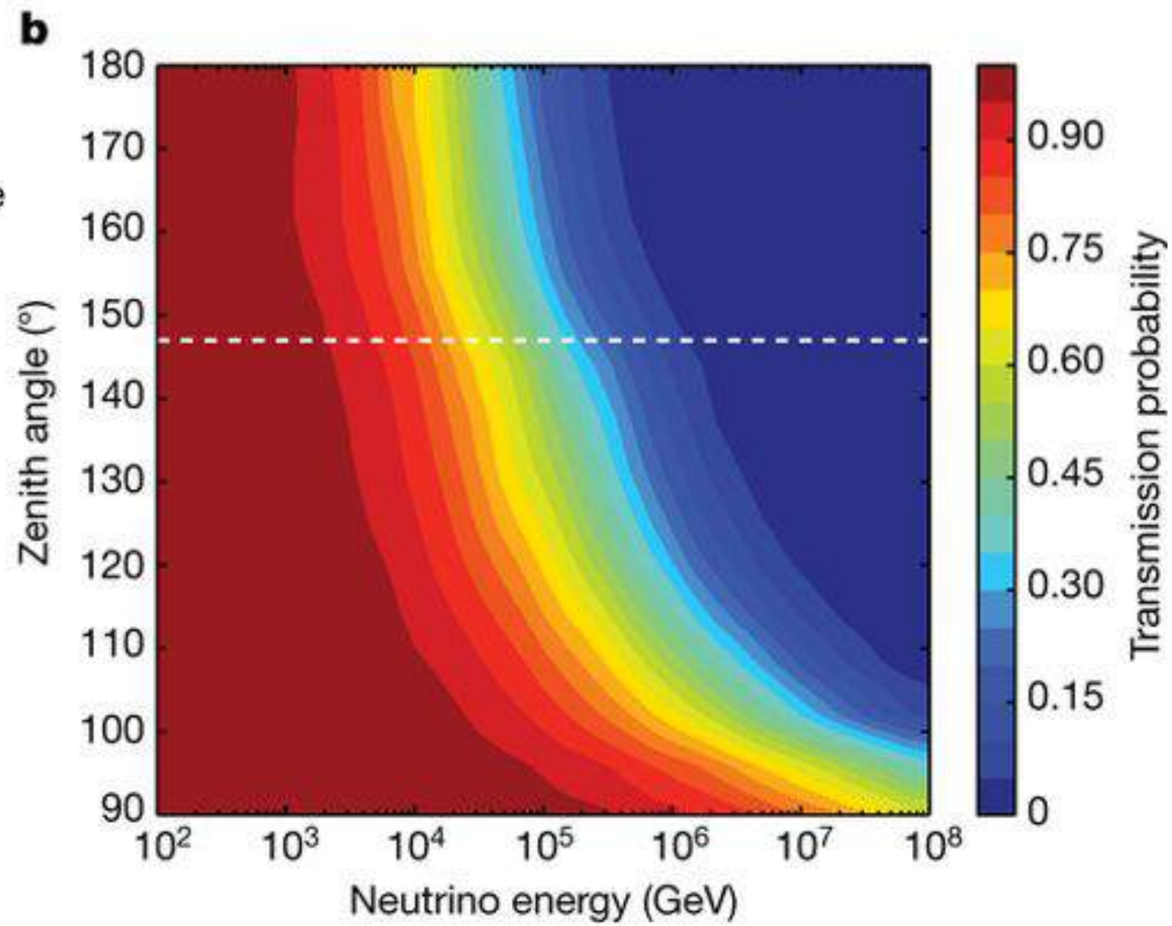
Mertsch, Cooper-Sarkar, Sarkar, JHEP **08**:042,2011 ⇒ **CSMS** 2011

We find *good* agreement between different PDF sets after rejecting unphysical members which would have yielded *negative* values for the structure function F_L (or violated the Froissart bound)

THE ν-N CROSS-SECTION PREDICTION CAN BE TESTED BY EXAMINING THE ZENITH ANGLE DEPENDENCE OF AN *ISOTROPIC* ν FLUX VIEWED THROUGH THE EARTH

IceCube Collaboration, Nature **551**:596,2017

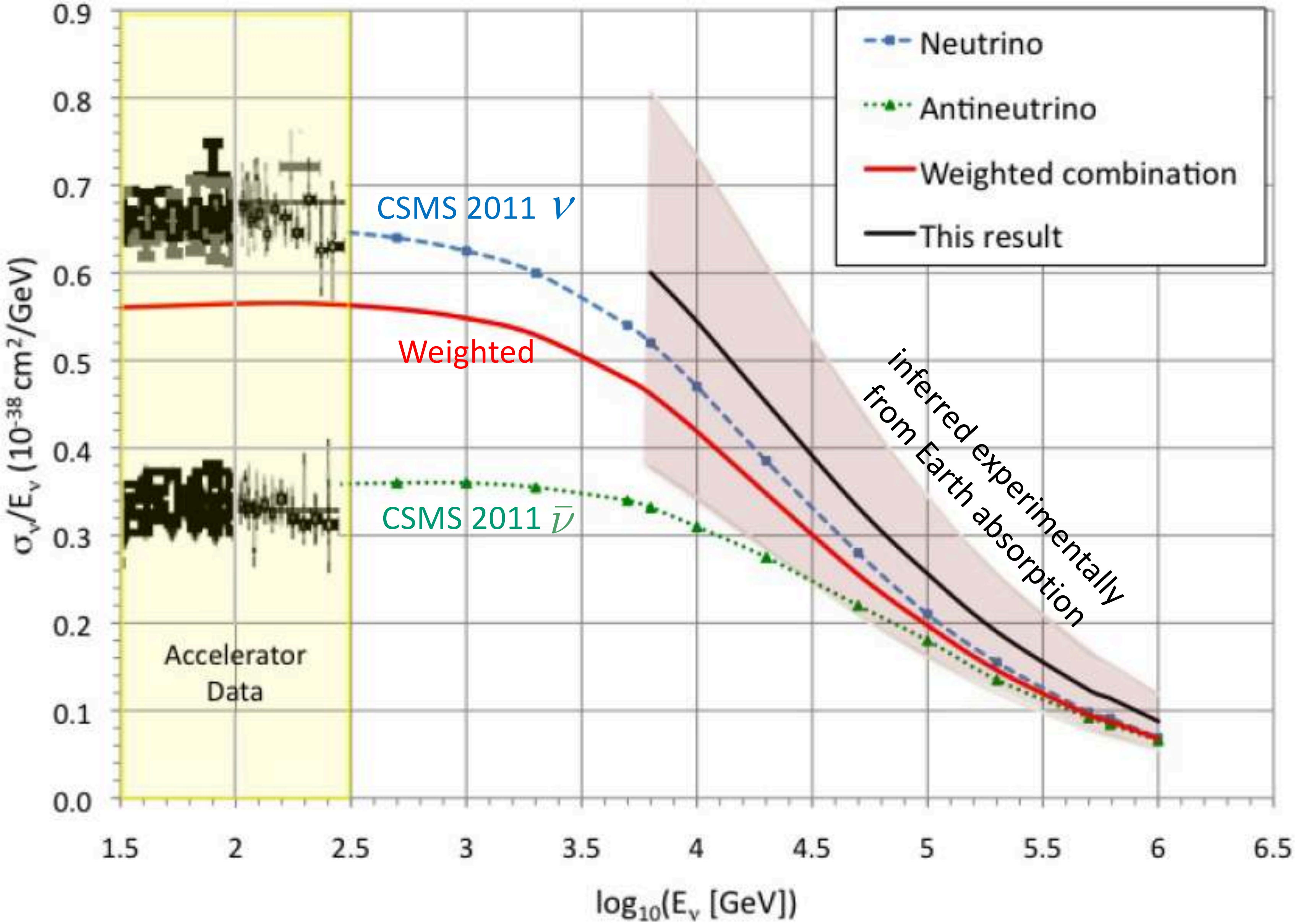




Preliminary Reference Earth Model (PREM), 1981
Earth diameter ⇒ interaction length at E_ν ~ 40 TeV

NB: The flux of atmospheric neutrinos (which dominate up to ~10^5 GeV) is isotropic … also a good approximation for the extragalactic flux … galactic component is <18%

No evidence of deviation from SM up to ~980 TeV

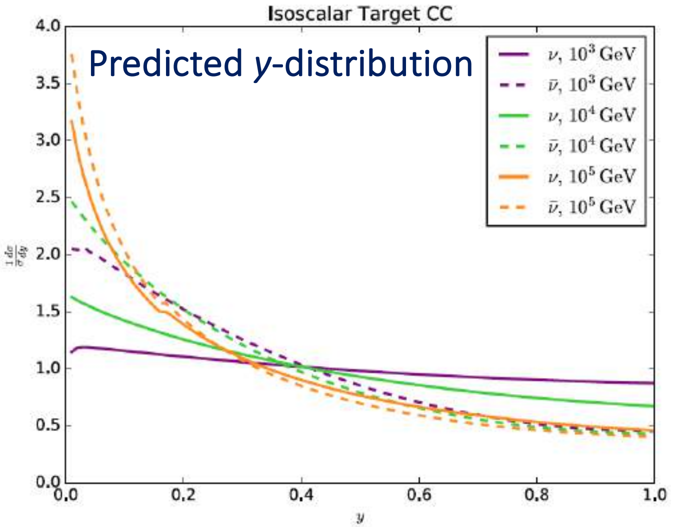


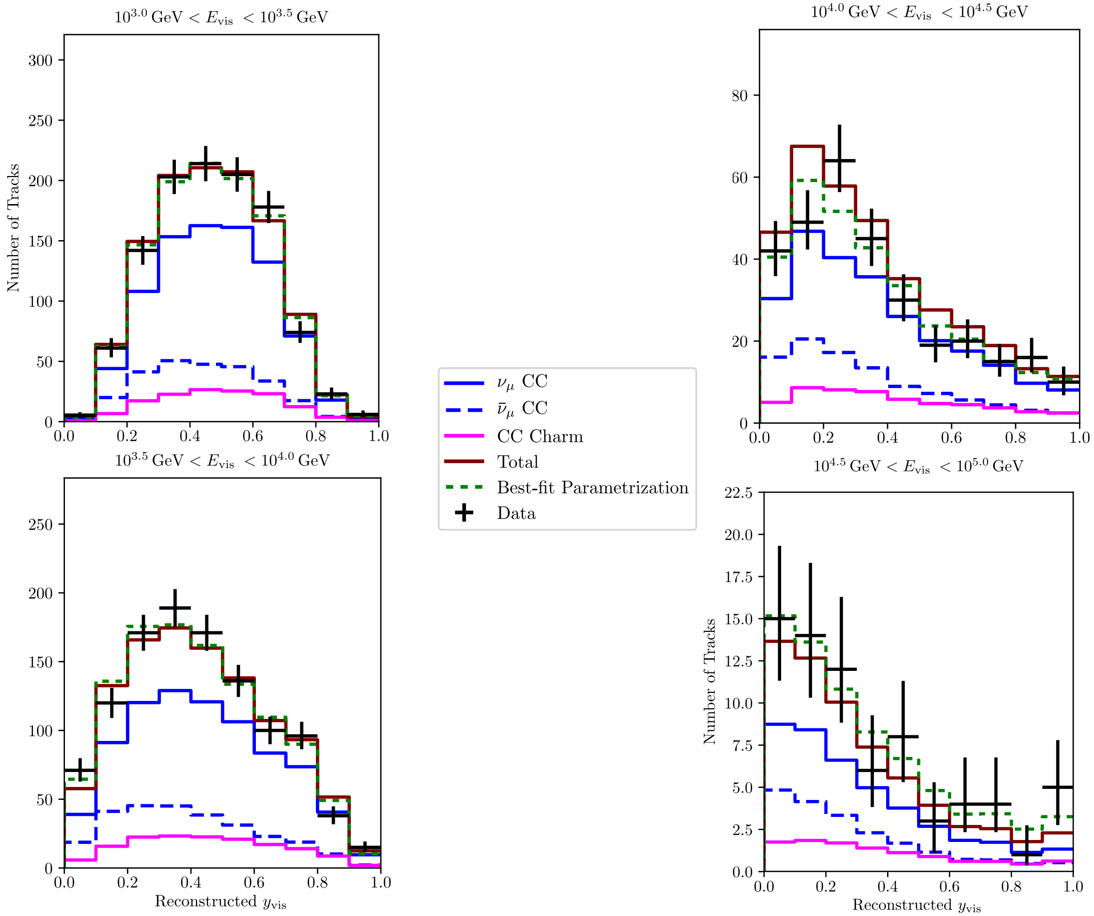
IceCube Collaboration, Nature **551**:596,2017

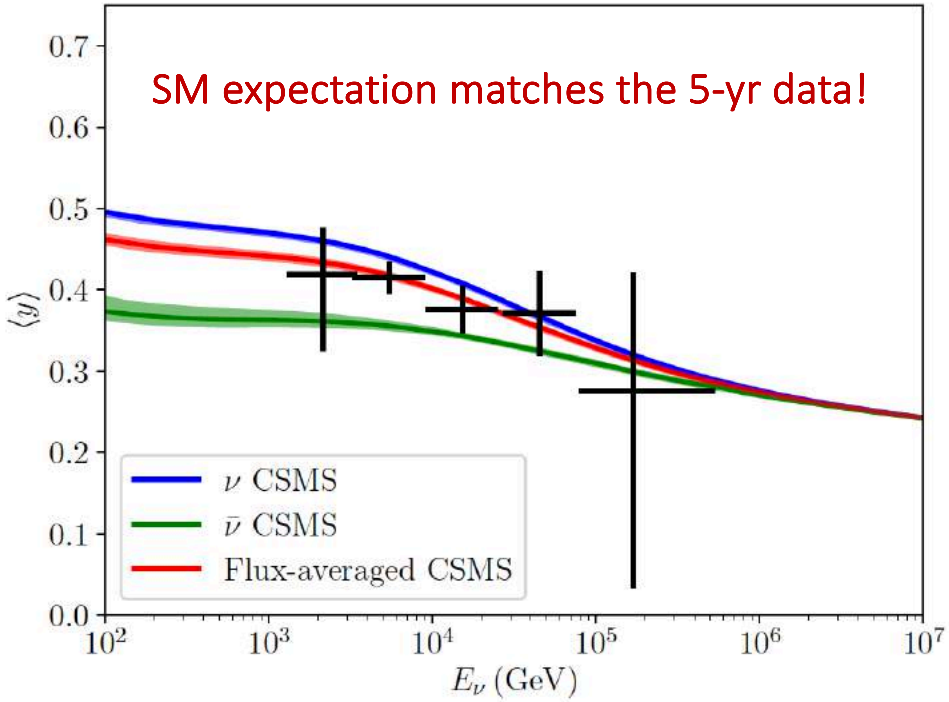
Powerful probe of new physics beyond the SM (e.g. leptoquarks, new dimensions)

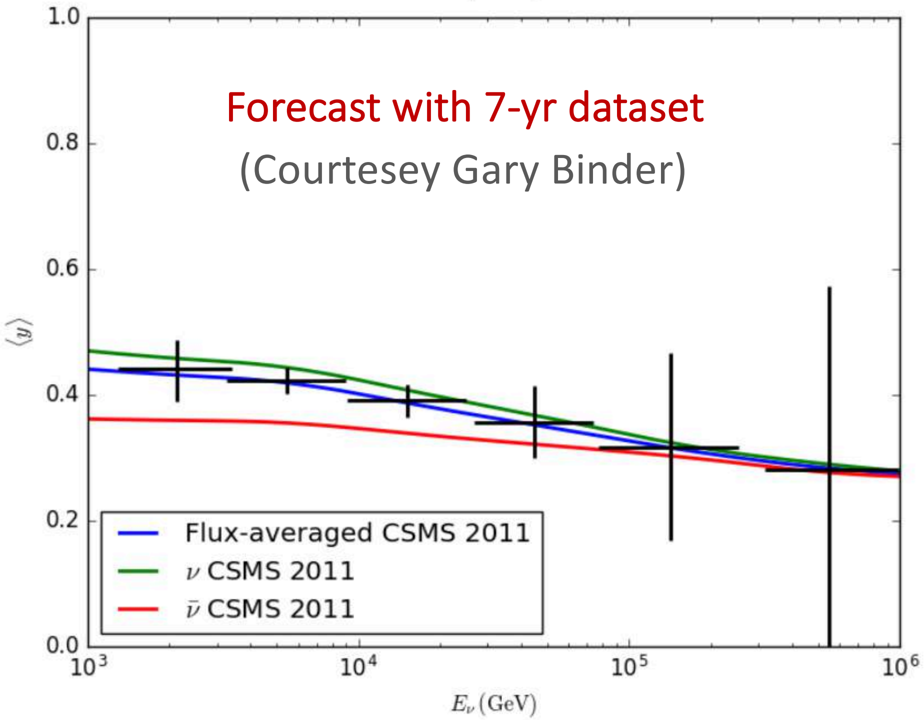
should be able to probe up to ~10^{10} GeV using cosmogenic ν - with **IceCube-Gen2**

Another test of new physics is the inelasticity distribution ..





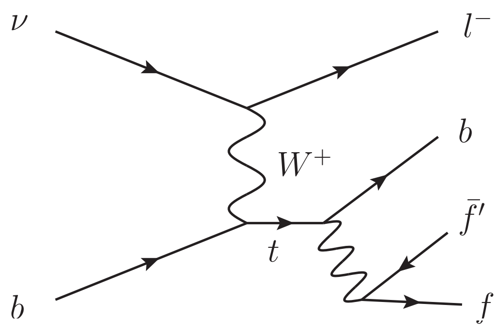


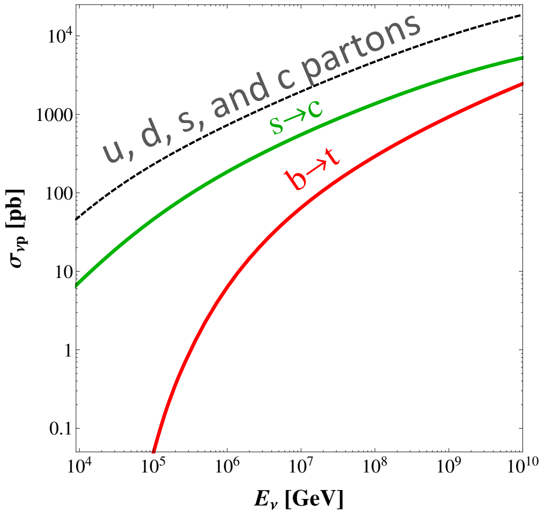


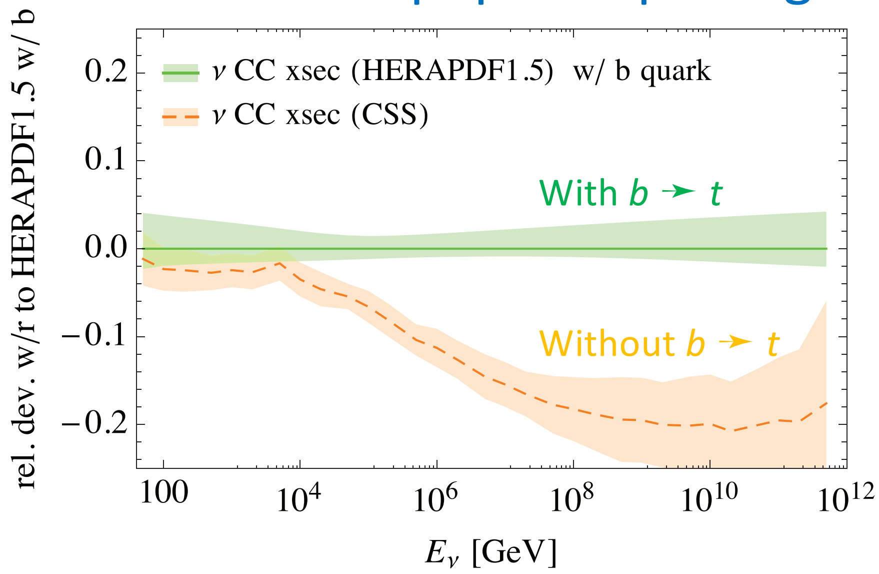
IceCube collaboration., Phys.Rev.D**99**:032004,2019

* Heavy quark mass effects on DGLAP evolution: bottom to top quark splitting

Barger *et al*, PR D95:093002,2017





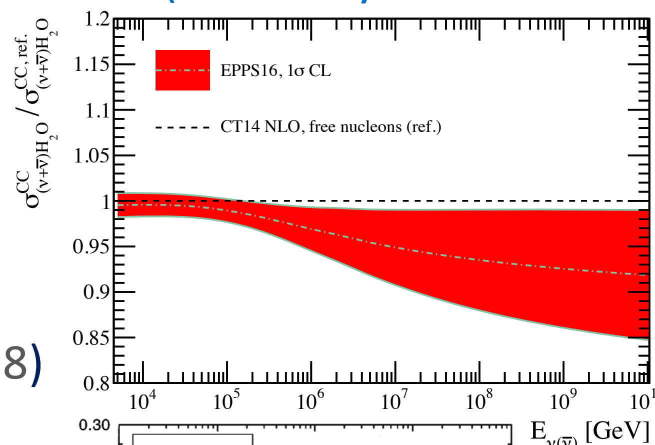


CSMS, JHEP **08**:042,2011

However the exact way the *b* ➛ *t* contribution turns on is under discussion (⇒ ~5% syst. uncertainty)

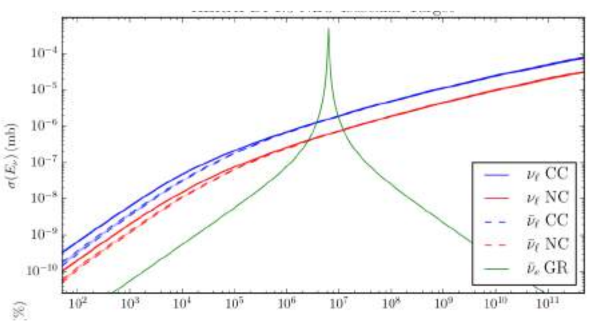
* Nuclear binding effects ('shadowing'):

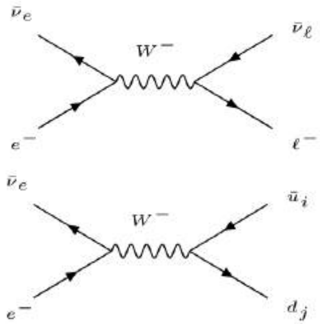
There is *no* experimental evidence for shadowing but it can depress the cross-section by ~5-10% at high energies according to some theoretical estimates (although uncertainties are large)

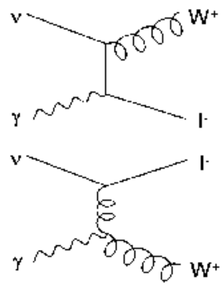


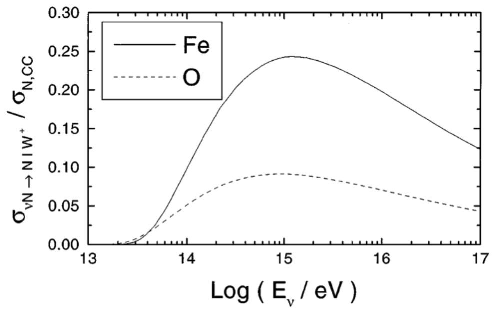
Bertone *et al*, JHEP **20**:217,2019

* Other contributions: E.g. Glashow resonance, νγ (Seckel 1998)

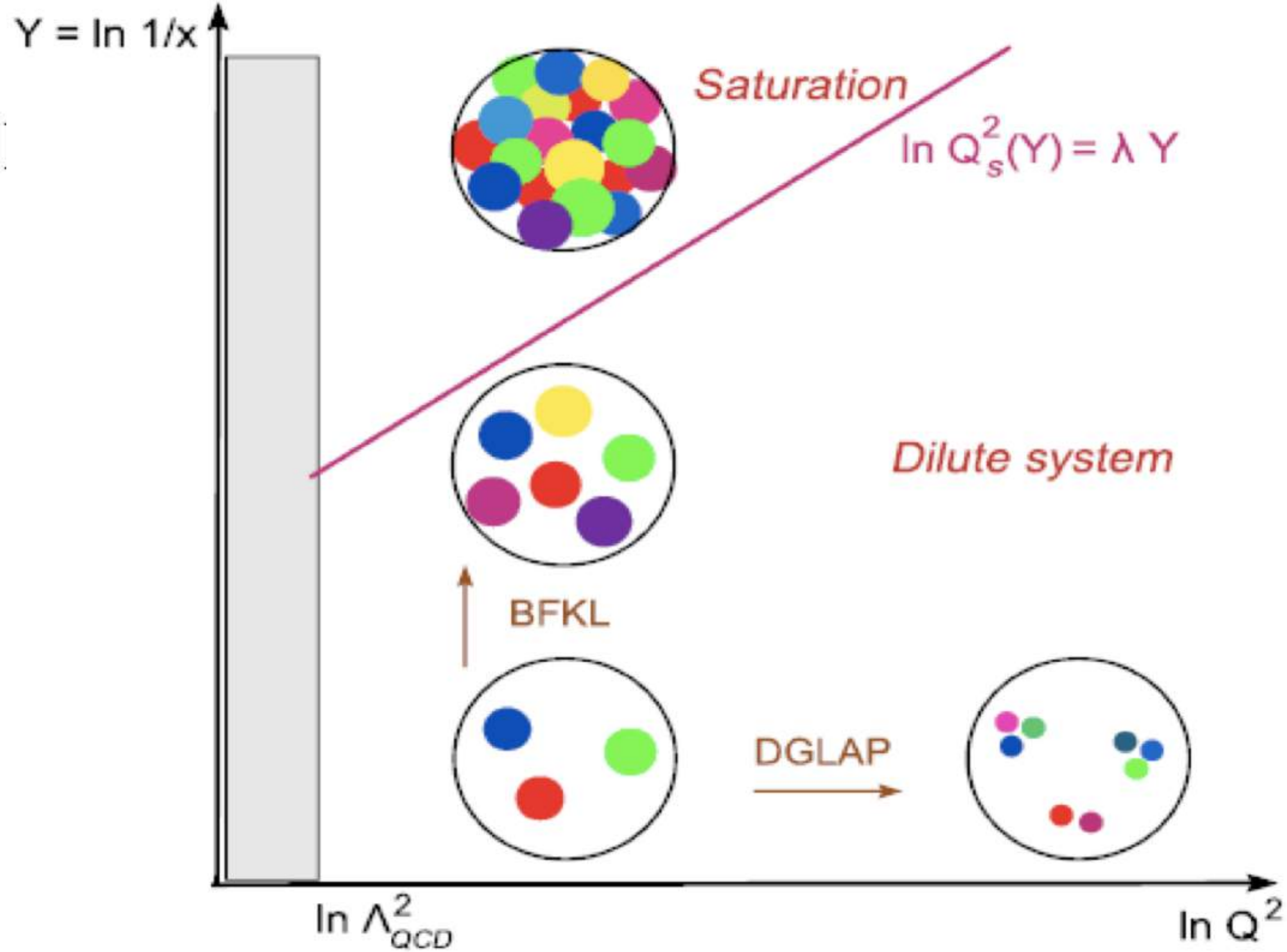








As the gluon density rises at low *x*, non-perturbative effects *must* become important … a new phase of QCD - Colour Glass Condensate - has been postulated to exist (and has support from RHIC and ALICE data)



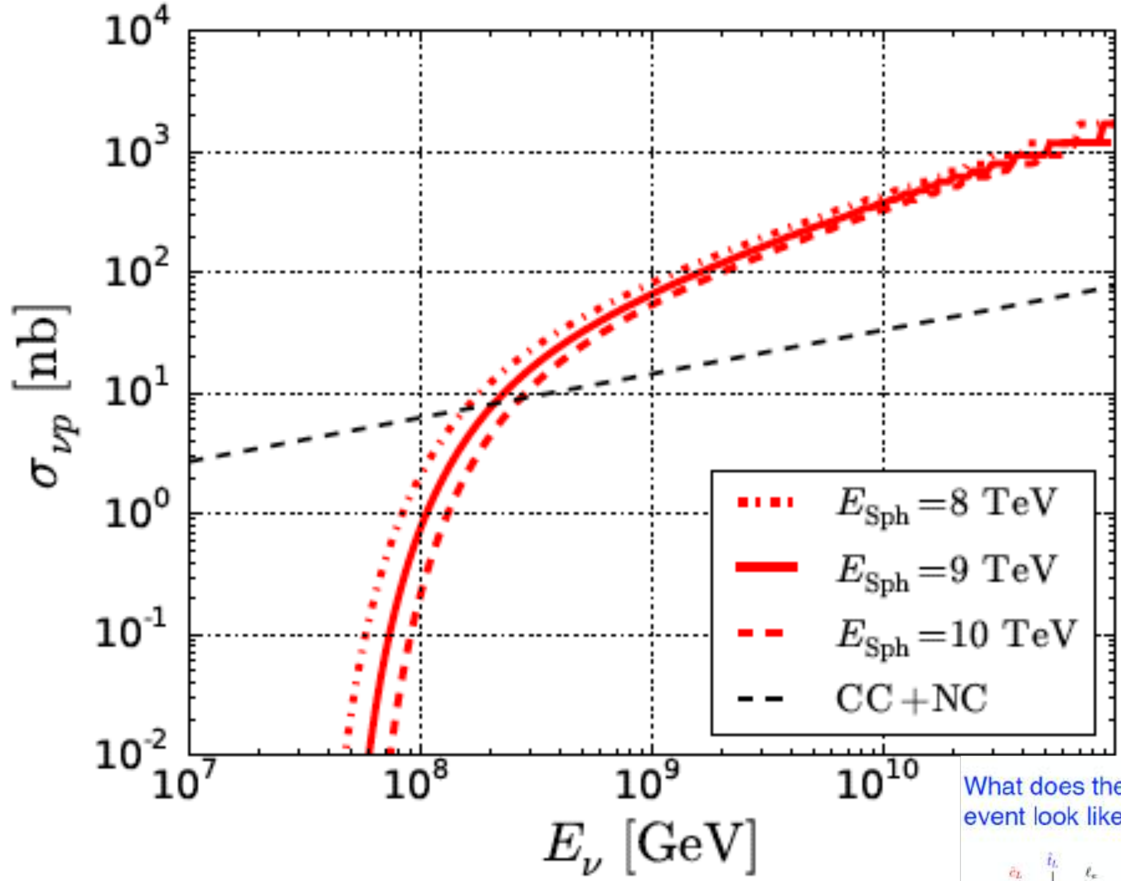
This would strongly suppress the ν-N #-secn below its (unscreened) SM value … can we test this experimentally with UHE cosmic neutrinos?

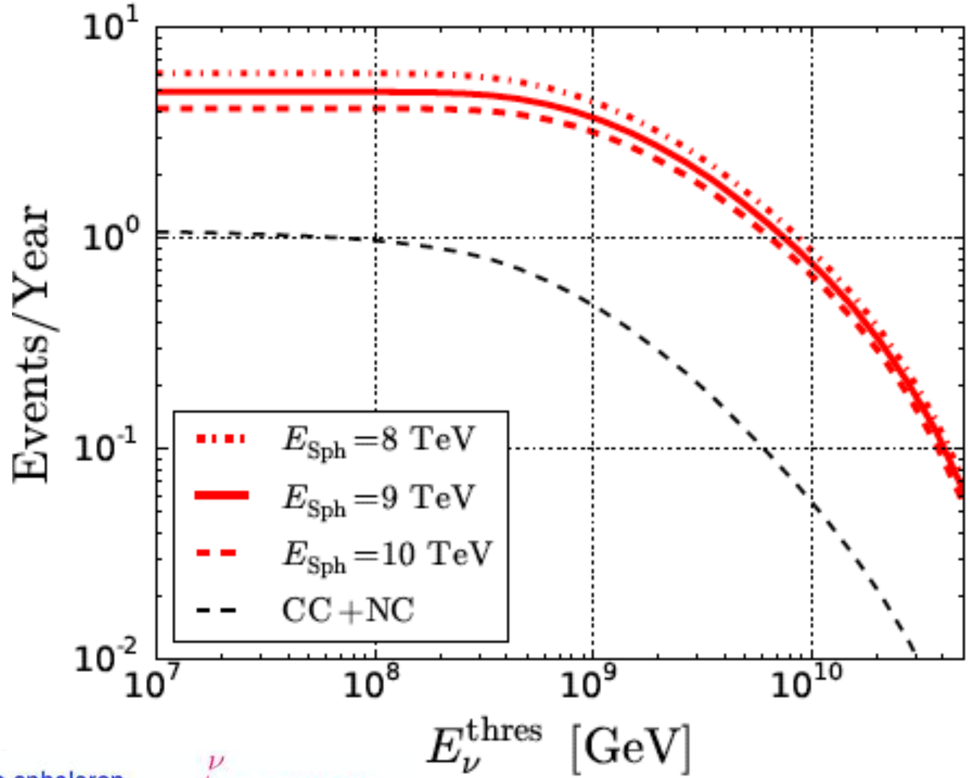
… or the ν-N cross-section may be much *higher* than in the SM

Non-perturbative transitions between degenerate *SU*(2) vacuua (with different *B*+*L* #) are *exponentially* suppressed below the "sphaleron" mass: $\sim M_W/\alpha_W \sim$ 9 TeV (update by Tye & Wong, PRD **92**:045005,2015) … *large* cross-sections are predicted for *ν-N* scattering at higher cms energies

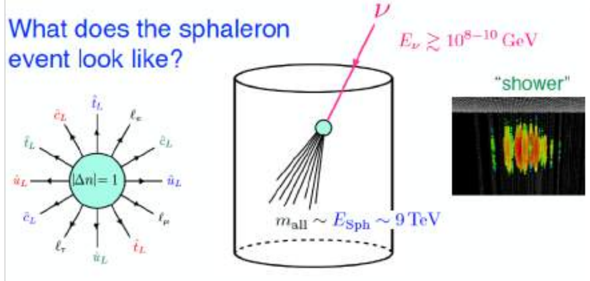
$$E_\nu \geq E^2_{\rm sph}/2xm_N \simeq 4 \times 10^7/x \sim 10^{9-11}\ \text{GeV}$$

Han & Hooper, PLB **582**:21,2004





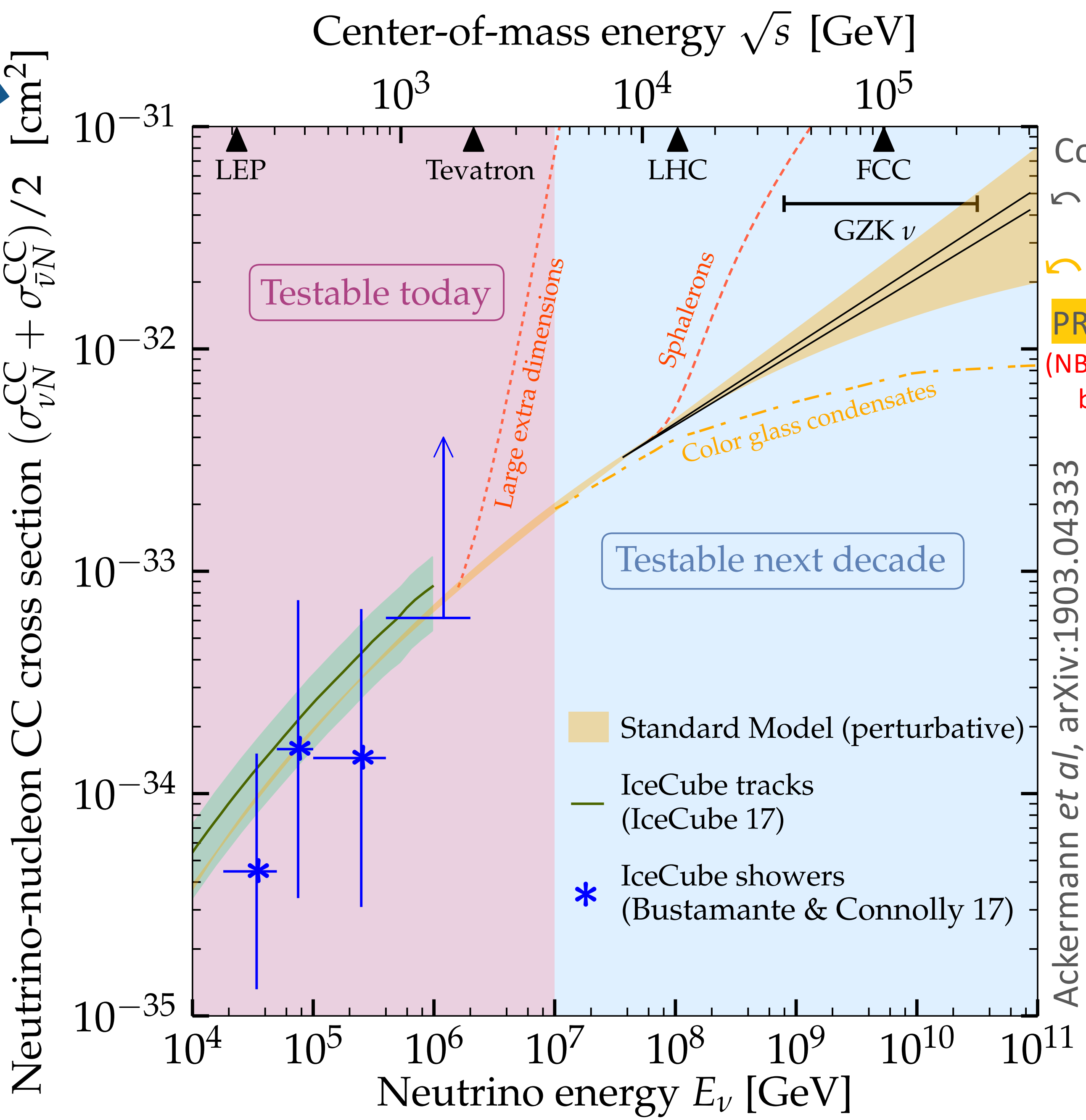
Ellis, Sakurai & Spannowsky, JHEP **05**:085,2016



IceCube has sensitivity to electroweak sphalerons comparable to LHC!

Astro2020 Science White Paper

Fundamental Physics with High-Energy Cosmic Neutrinos



Cooper-Sarkar *et al*, JHEP **08**:042,2011

Connolly *et al*, PRD**83**:113009,2011

(NB: errors overestimated because of including *unphysical* PDFs)

Ackermann *et al*, arXiv:1903.04333

The *perturbative* QCD prediction is in fact accurate to ±~5% (PDF uncertainties) even at GZK energies … so new physics (whether non-pert. SM *or* BSM) would be easy to identify *if* we can detect GZK νs

SUMMARY

- Neutrino telescopes have already measured the νDIS cross-section up to cms energies ~10 times higher than are attainable at the LHC … finding *no* deviation from the SM

- This sets constraints on new physics that can increase the cross-section e.g. new TeV-scale dimensions, leptoquarks (… admittedly these have been ruled out already in Run II)

- There may be new *non*-perturbative processes *in* the SM which can affect the νDIS cross-section at still higher energies, e.g. 'electroweak sphalerons' and 'QCD colour glass condensate' - to probe this will require studying the highest energy (GZK) cosmic neutrinos at $\sim 10^{10}$ GeV

To probe the energy frontier we *must* think BIG (Gen2, KM3NeT, …)