Probing Small-x QCD with Cosmic Neutrinos

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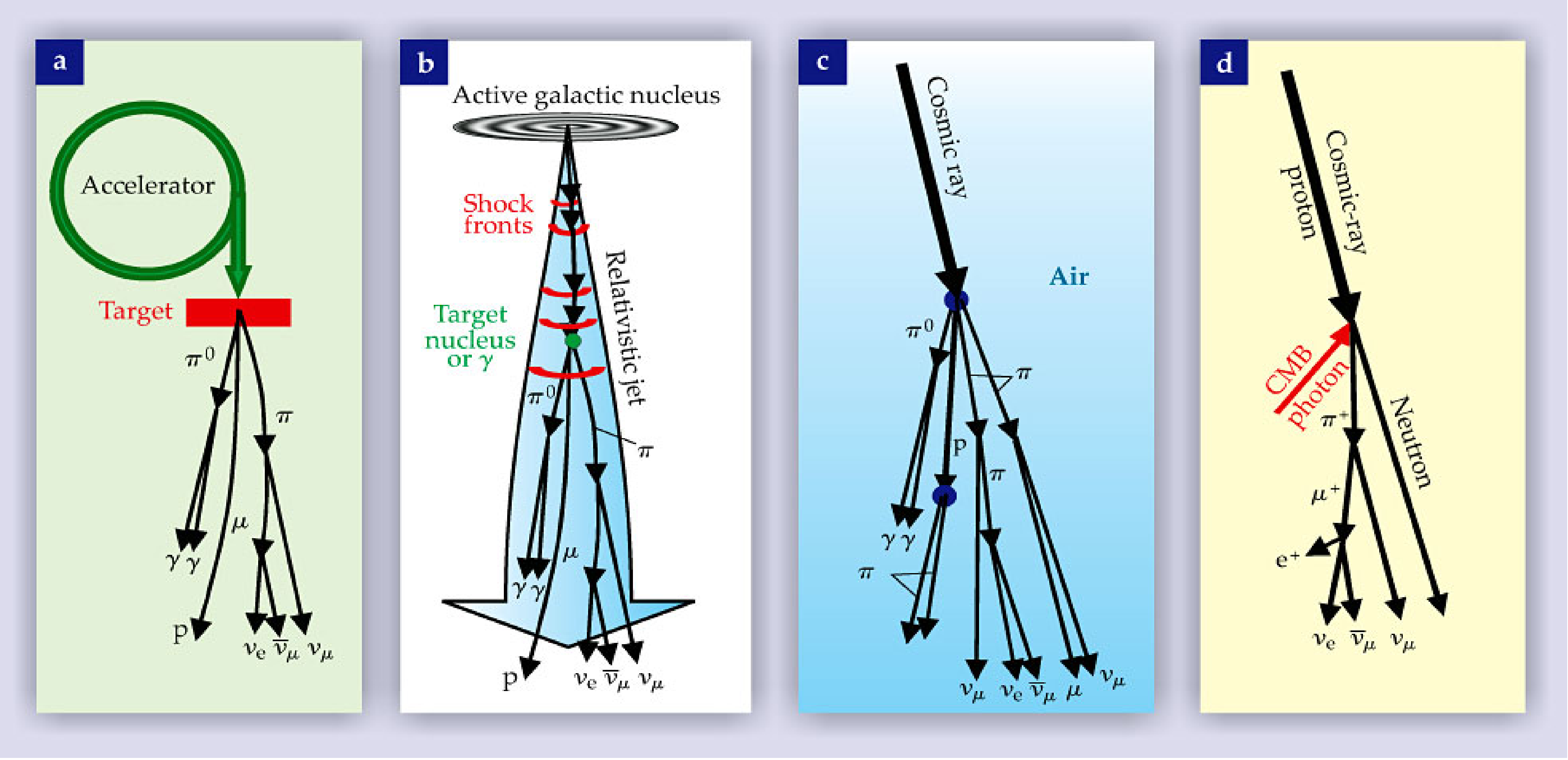
Cosmic accelerators

- Particles (electrons, protons, etc) are accelerated to high energies via Fermi shock acceleration
- High energy protons collide with ambient protons and photons
- Hadronic production of pions, kaons and D-mesons which decay into neutrinos

Cosmic Accelerators



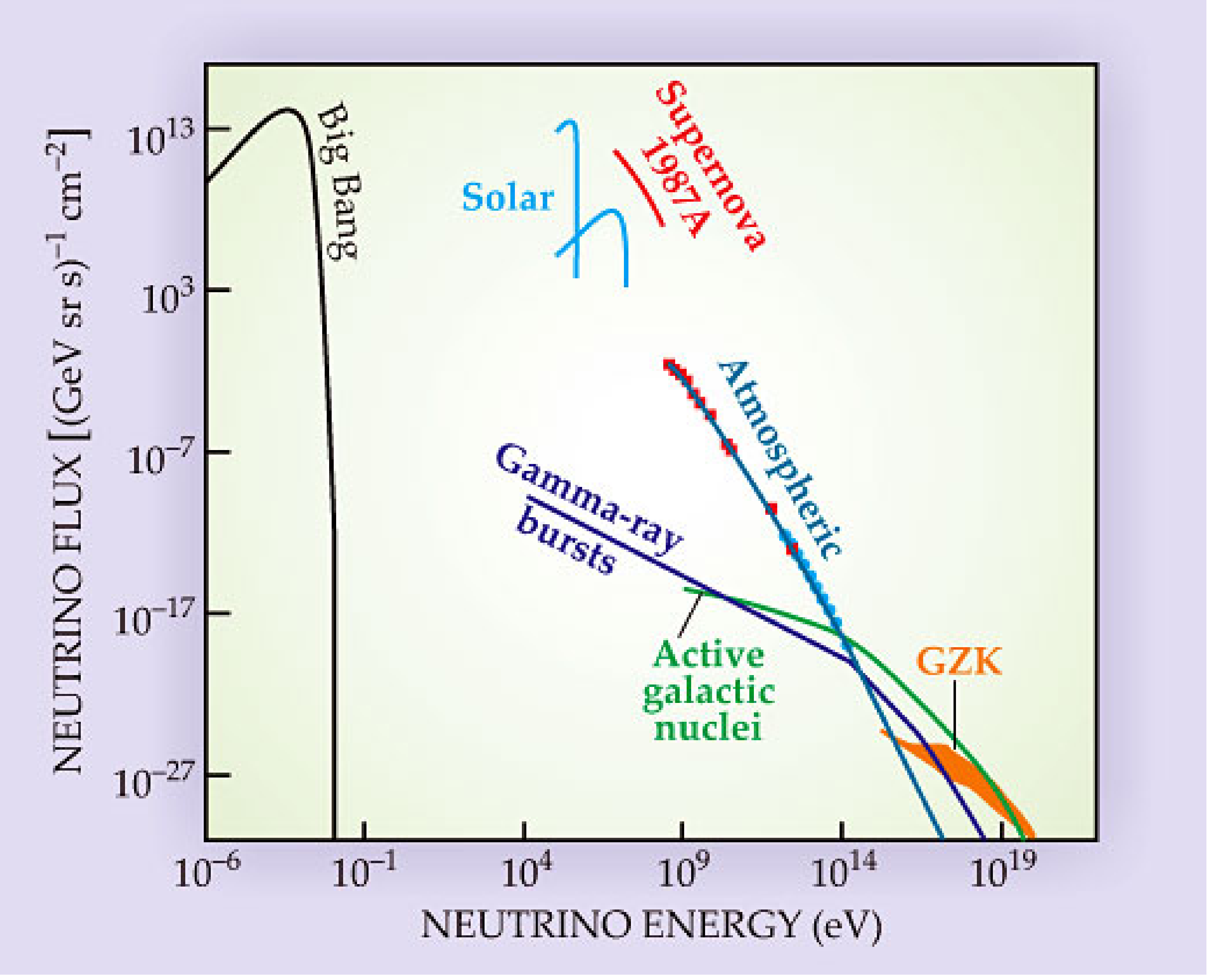
Physics Today 2009

Cosmic Neutrinos

- Solar Neutrinos (MeV energies)
- SN 1987A (MeV energies)
- Atmospheric Neutrinos (GeV to TeV energies)
- Extragalactic Neutrinos (AGN, GRB, cosmogenic; GeV to EeV energies)

  Cosmogenic Neutrinos (from interaction of cosmic rays with the microwave background radiation, guaranteed source of UHE neutrinos)

Neutrino fluxes



Neutrino Fluxes at Earth

Enberg, Reno and Sarcevic, Phys. Rev. D79(2009)

- Cosmic neutrino flux is obtained by solving the evolution equations for nucleon, meson and neutrino fluxes:

$$\frac{d\phi_N}{dX} = -\frac{\phi_N}{\lambda_N} - \frac{\phi_N}{\lambda_{rad}} + S(Np \to NY)$$

$$\frac{d\phi_M}{dX} = -\frac{\phi_M}{\lambda^{dec}} - \frac{\phi_M}{\lambda^{had}} - \frac{\phi_M}{\lambda^{rad}} + S(Mp \to MY)$$

$$\frac{d\phi_l}{dX} = \sum_M S(M \to \nu)$$

where $\lambda^{had}_{N,M}$ is the interaction length ($\lambda_N=1/(n_p\sigma_{pp})$) , $\lambda^{dec}=\gamma c\tau_M$ is the decay length

S(k -> j) is the regeneration function for k=p,$\pi^{\pm}$,K$^{\pm}$,D$^{\pm}$,D^{0},

$$S(k\to j)=\int_E^\infty \frac{\phi_k(E_k)}{\lambda_k(E_k)}\frac{dn(k\to j;E_k,E_j)}{dE_j}dE_k$$

dn(k ->j;E_k,E_j)/dE_j is the $\pi^{\pm}$,K$^{\pm}$,D$^{\pm}$,D^{0} **production** or decay distribution :

$$\frac{dn(k\to j;E_k,E_j)}{dE_j}=\frac{1}{\sigma_{kA}(E_k)}\frac{d\sigma(kp\to jY,E_k,E_j)}{dE_j}$$

$$\frac{dn(k\to j;E_k,E_j)}{dE_k}=\frac{1}{\Gamma_k}\frac{d\Gamma(kj\to jY,E_j)}{dE_j}$$

Charm Production and Cross Sections using pQCD and PDFs

$$\frac{d\sigma}{dx_F} = \int \frac{dM^2_{c\bar{c}}}{(x_1 + x_2)s} \sigma_{gg\to c\bar{c}}(\hat{s}) G(x_1, \mu^2) G(x_2, \mu^2)$$

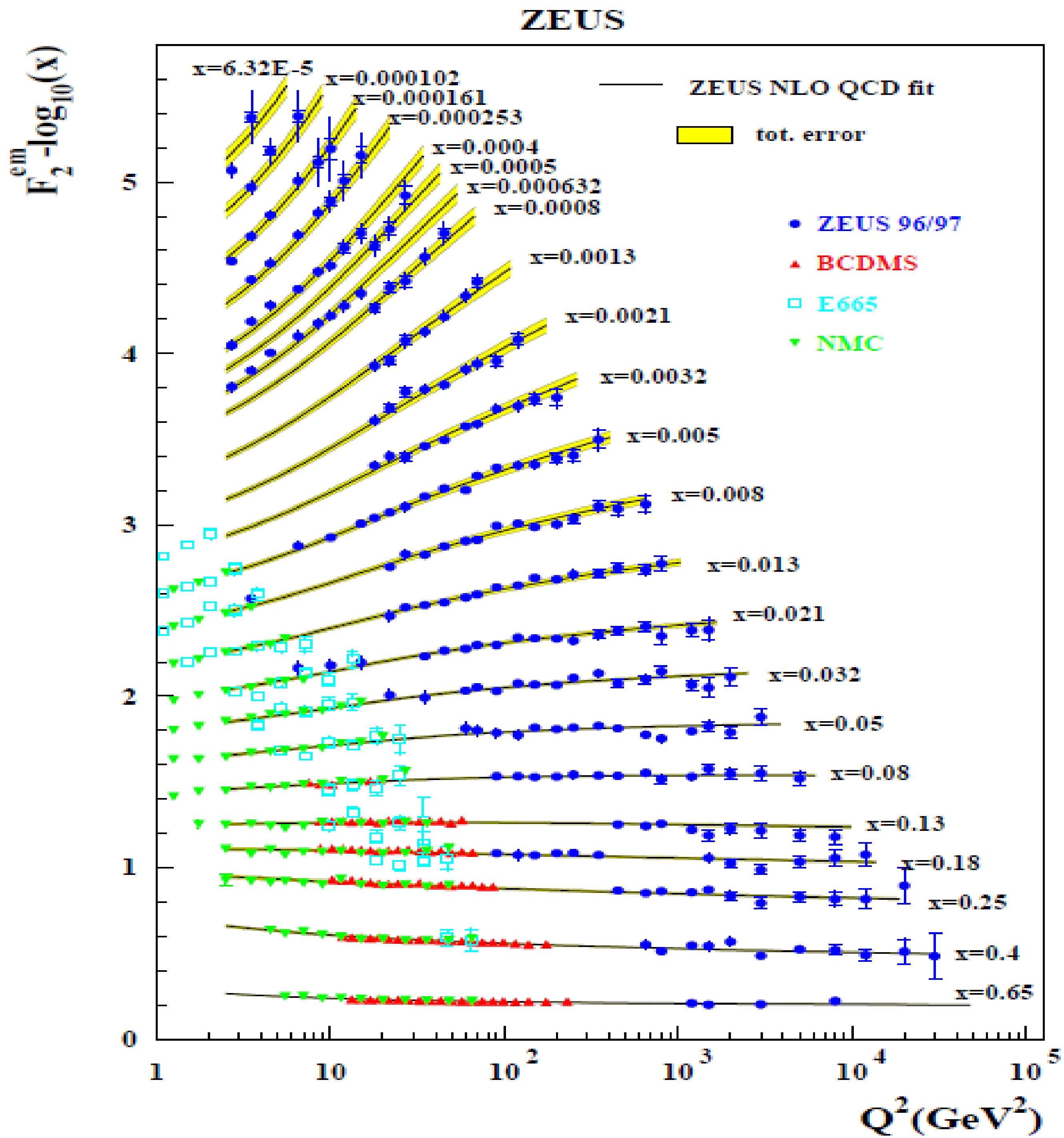
The total charm cross section in pQCD is given by:

$$\sigma(pp \to c\bar{c}X) = \int dx_1 dx_2 G(x_1, \mu^2) G(x_2, \mu^2) \hat{\sigma}_{gg\to c\bar{c}}(x_1 x_2 s)$$

where

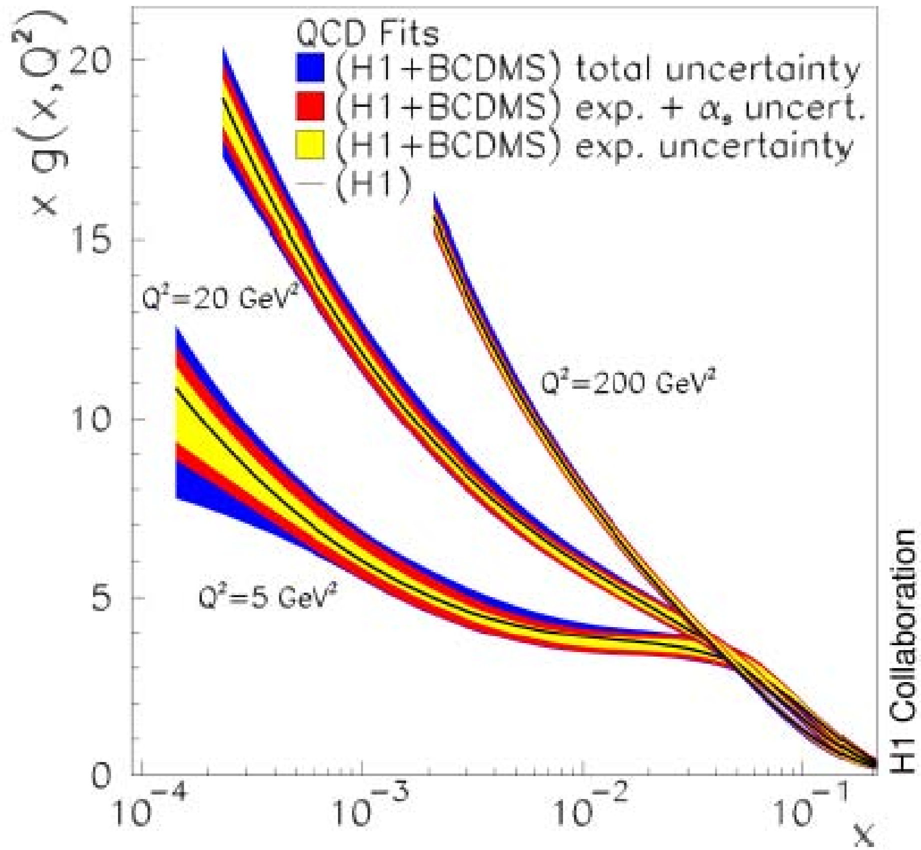
$$x_{1,2} \sim m_c / 2 m_p E_\nu$$

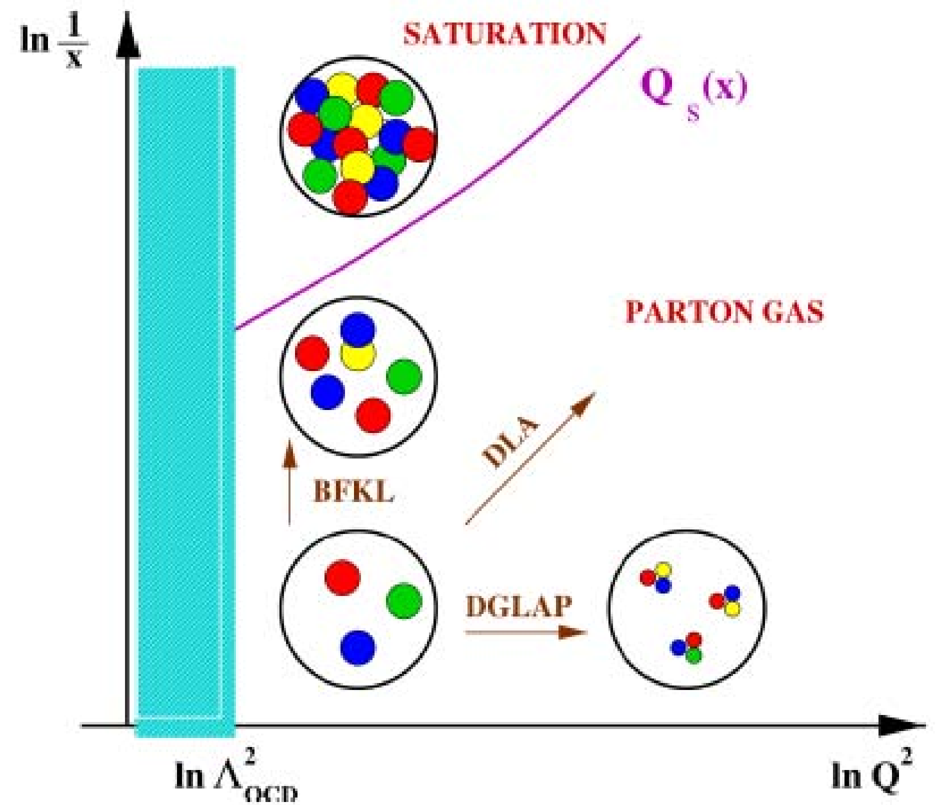
For high energies we need gluon PDF for small x, and low Q^2



ZEUS
F_2^{em}-$\log_{10}(x)$
$Q^2(GeV^2)$
ZEUS NLO QCD fit
tot. error
ZEUS 96/97
BCDMS
E665
NMC
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65

The problem of small x

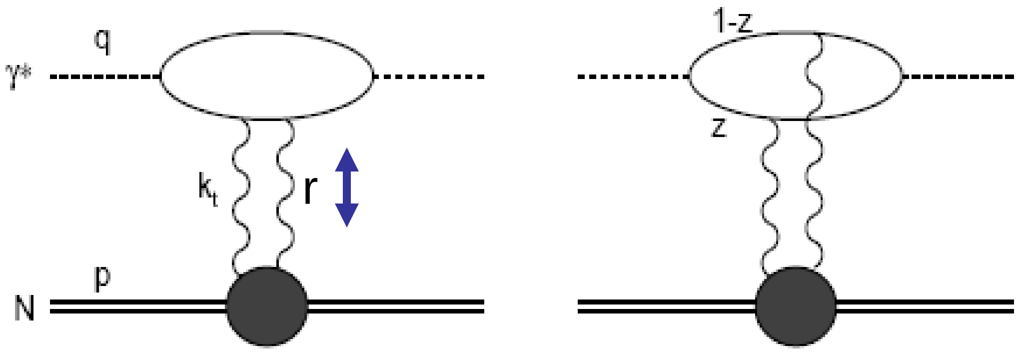




Gluon distribution grows rapidly as $x \rightarrow 0$: gluons start overlapping

and may start recombining: saturation of cross section

Charm Production: dipole approach



$$\gamma^\star \to q\bar{q}$$

$$q\bar{q}N \to X$$

heavy quarks:

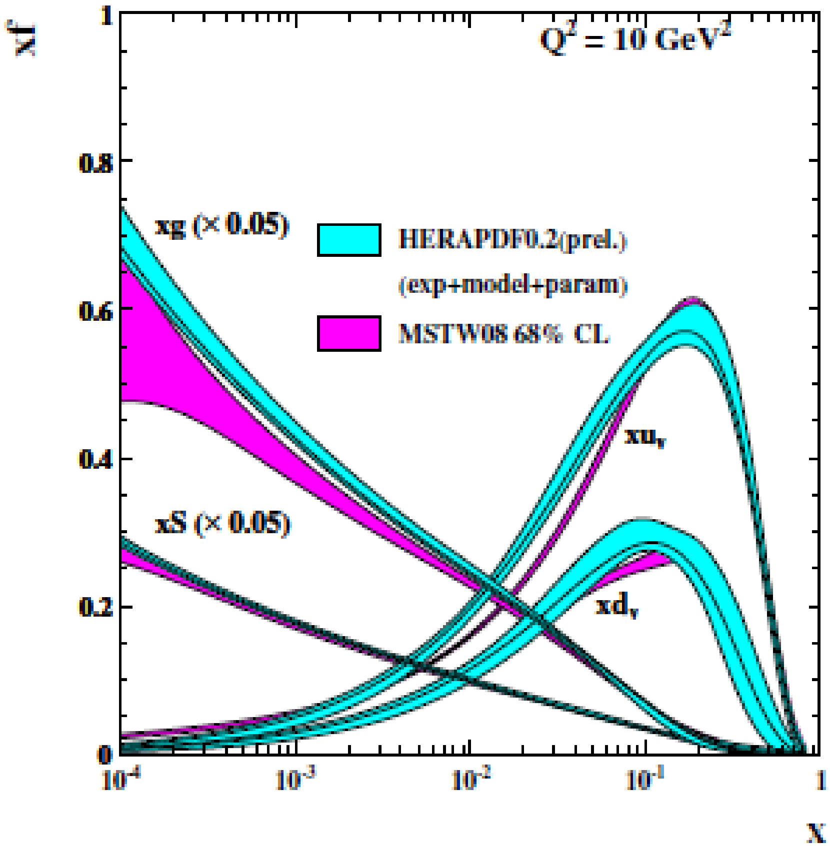
$$\gamma^\star \to c\bar{c}$$

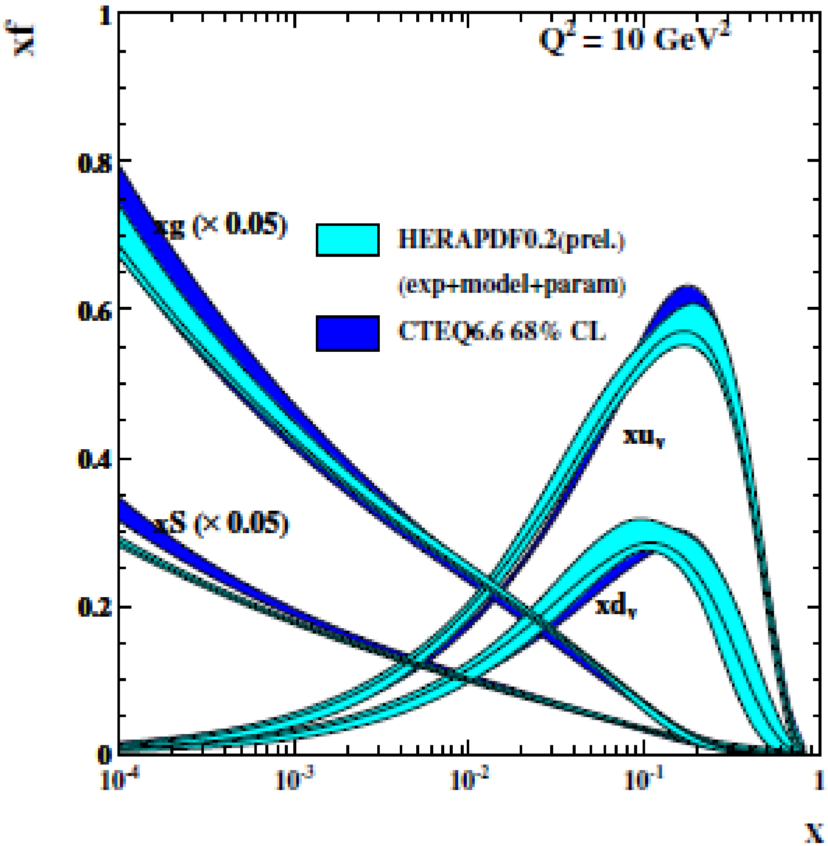
$$c\bar{c}N \to c\bar{c}X$$

$$\sigma_T(\gamma^\star N) = \int_0^1 dz \int d^2\mathbf{r} |\Psi_T(z,\mathbf{r},Q^2)|^2 \sigma_{dN}(x,\mathbf{r})$$

- **Dipole model fits small x data HERA data (Stasto, et al., PRL 86 (2001))**
- **Improved QCD motivated form – Balitsky-Kovchegov (BK) evolution modified for gluon -> charm anticharm pair**

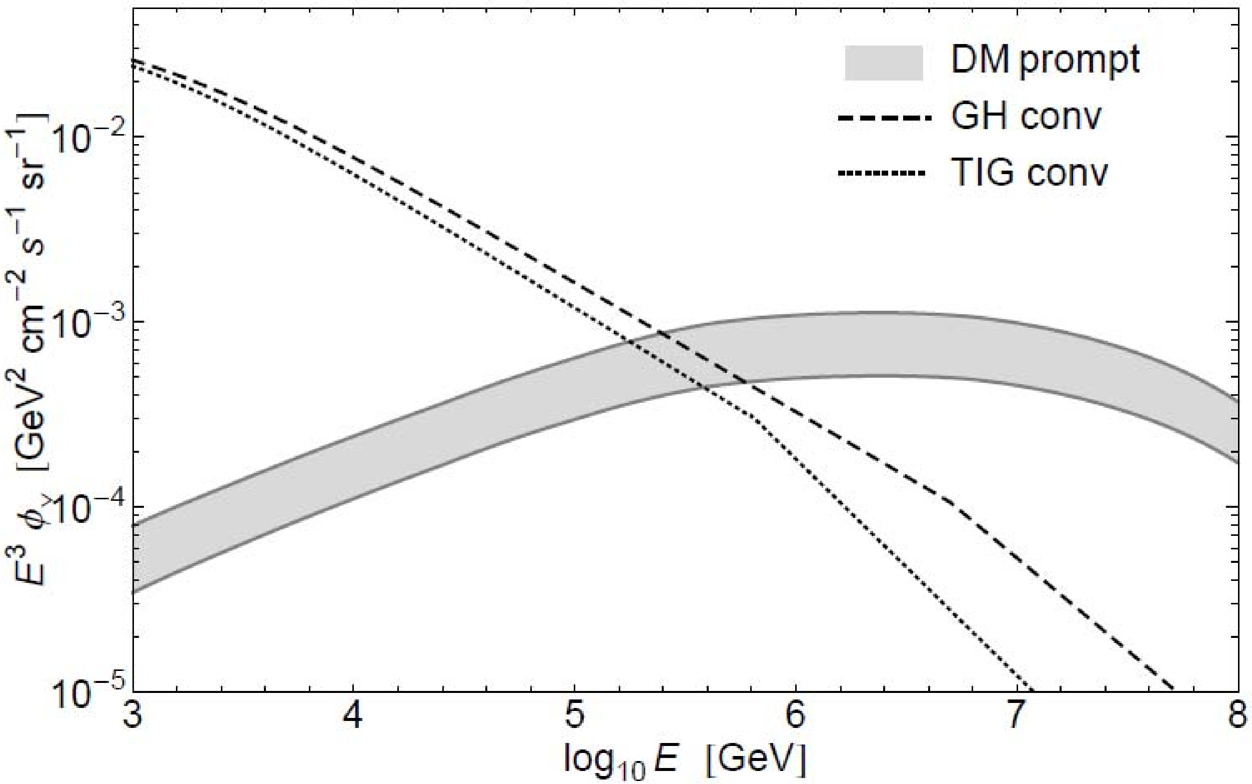
HERA PDF comparison with MRSTW and CTEQ





Raicevic (H1 and ZEUS), Nucl. Phys. B198 (2010)

Prompt Atmospheric Neutrino Flux



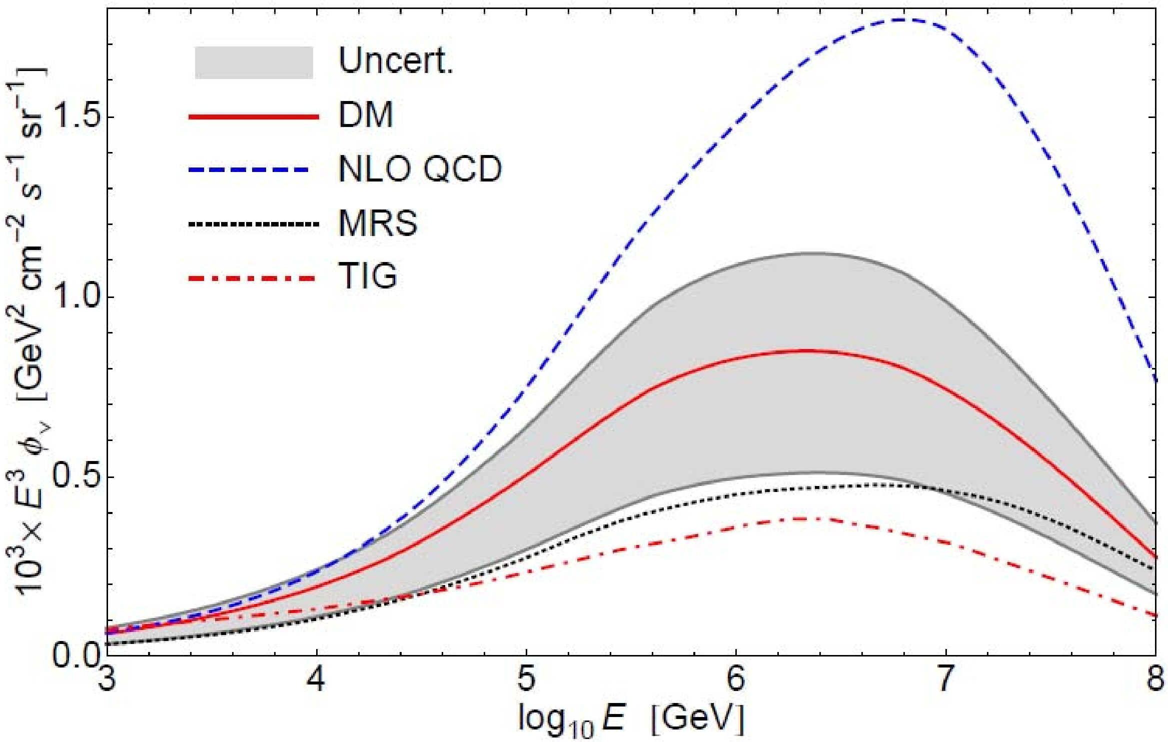
DM=dipole model

GH=Gaisser-Honda

TIG=Thunman et al. (PDF + pythia, small x extrapolation)

Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Prompt ATM Neutrino Flux



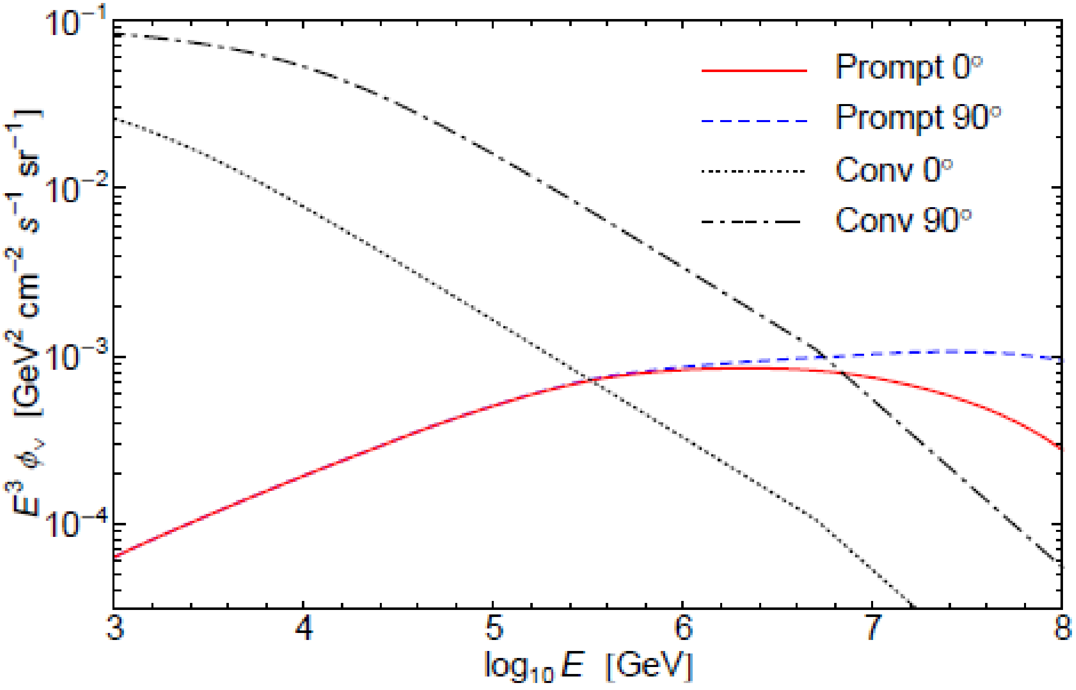
Range of predictions:

DM=our dipole model

MRS=Martin, Roberts, Stasto, Acta Phys. Polon. B34 (2003), uses a simpler form for dipole model cross section.

Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Atmospheric neutrinos-angular dependence



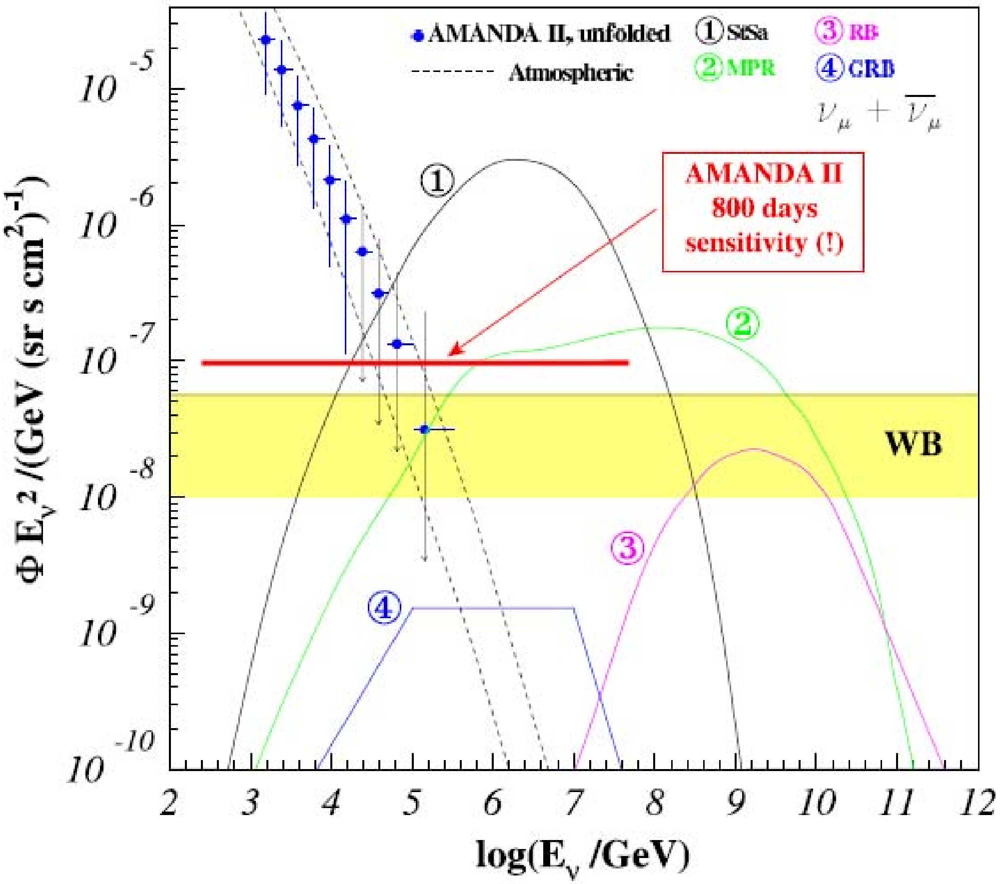
Muon neutrino plus antineutrino flux, from our dipole model "prompt" calculation.

Conventional flux from Gaisser-Honda.

Enberg, Reno, Sarcevic, Phys. Rev. D 78 (2008) 043005

Measurement of ATM Neutrino Flux

Icecube will be able to get more data at high energies



Halzen, Eur. Phys. J C46 (2006) 669

Neutrino Detection

- Detection of neutrinos depends on their interactions, i.e. cross section

- Muon neutrinos interacting with "matter",i.e. nucleons, producing muons

- Muons are "charged", so they leave charged tracks in the neutrino detector

- The event rate for “downward” muons from neutrino interactions

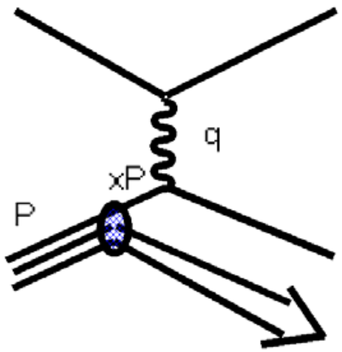
$$R = V \int dE_\nu \sigma_{cc}(E_\nu) F_\nu(E_\nu)$$

- The event rate for “upward” muons from neutrino interactions

$$R = N_A A \int dE_\nu \sigma_{cc} R_\mu S(E_\nu) F(E_\nu)$$

where F_ν (E_ν) is neutrino flux at the source, $S(E_\nu)$ is neutrino attenuation and R_μ is muon range

Ultrahigh energy neutrino-nucleon scattering



Medium energy, $\sigma \sim G_F^2 s \simeq 2.8 \cdot 10^{-39}\ \mathrm{cm}^2 \cdot s/\mathrm{GeV}^2$

High energy: $Q^2 \to M_W^2$

$$x_{\min} = M_W^2/2m_N E_\nu$$

$$\frac{d^2\sigma}{dx\,dy} = \frac{2G_F^2 M E_\nu}{\pi}\left(\frac{M_W^2}{Q^2+M_W^2}\right)^2 \left[xq(x,Q) + x\bar{q}(x,Q)(1-y)^2\right]$$

W boson propagator

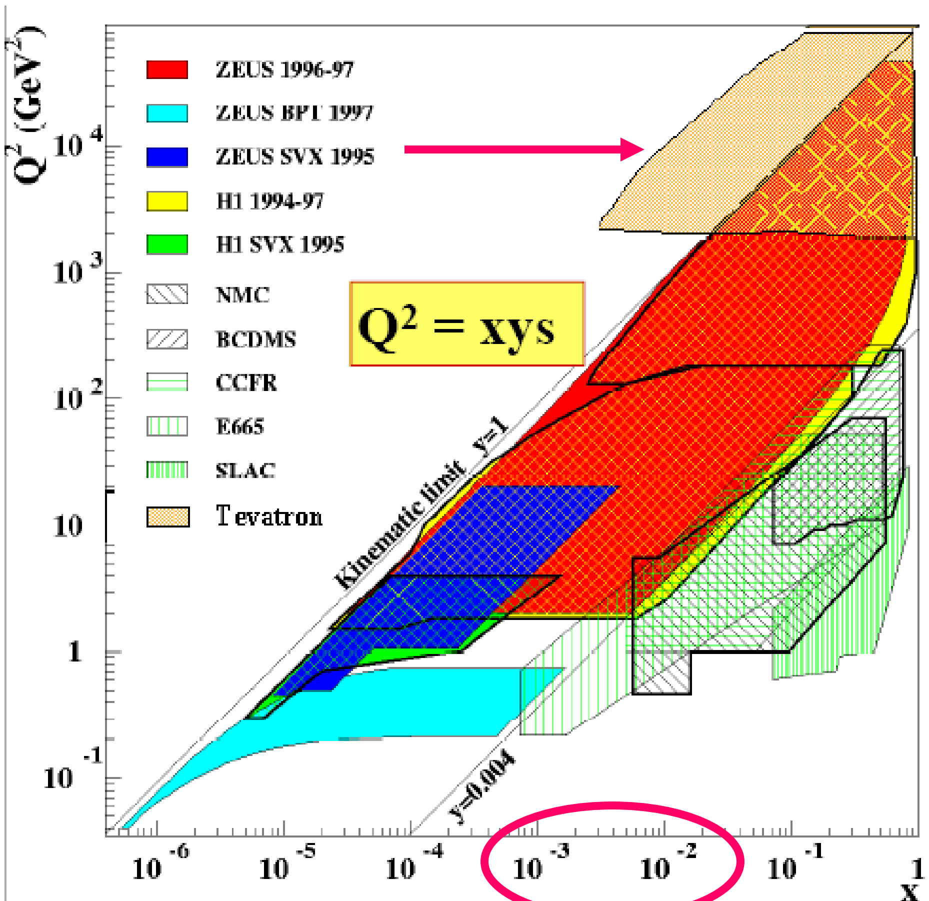
Quark distribution functions

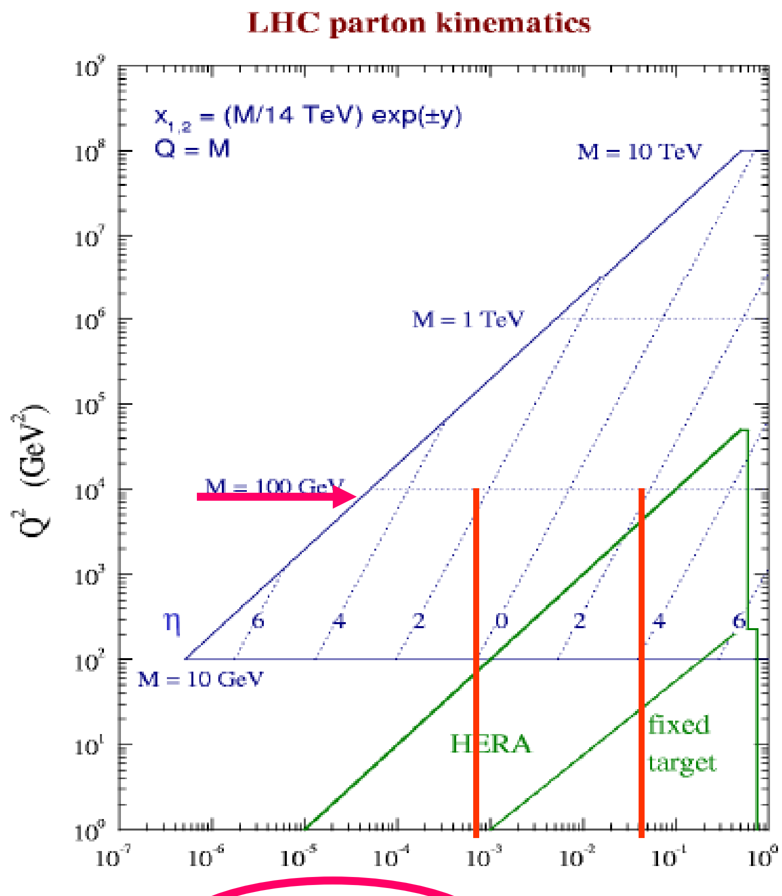
For $E_\nu > 10^8$ GeV, $x_{min} < 10^{-5}$, we need parton distributions at small x and $Q \sim M_W$

Gandhi, Reno, Quigg and Sarcevic, PRD 58 (1998); Astropart. Phys. 5 (1996)

Structure functions (to get PDFs)

LHC up to $s \sim 10^9\ \mathrm{GeV}^2$

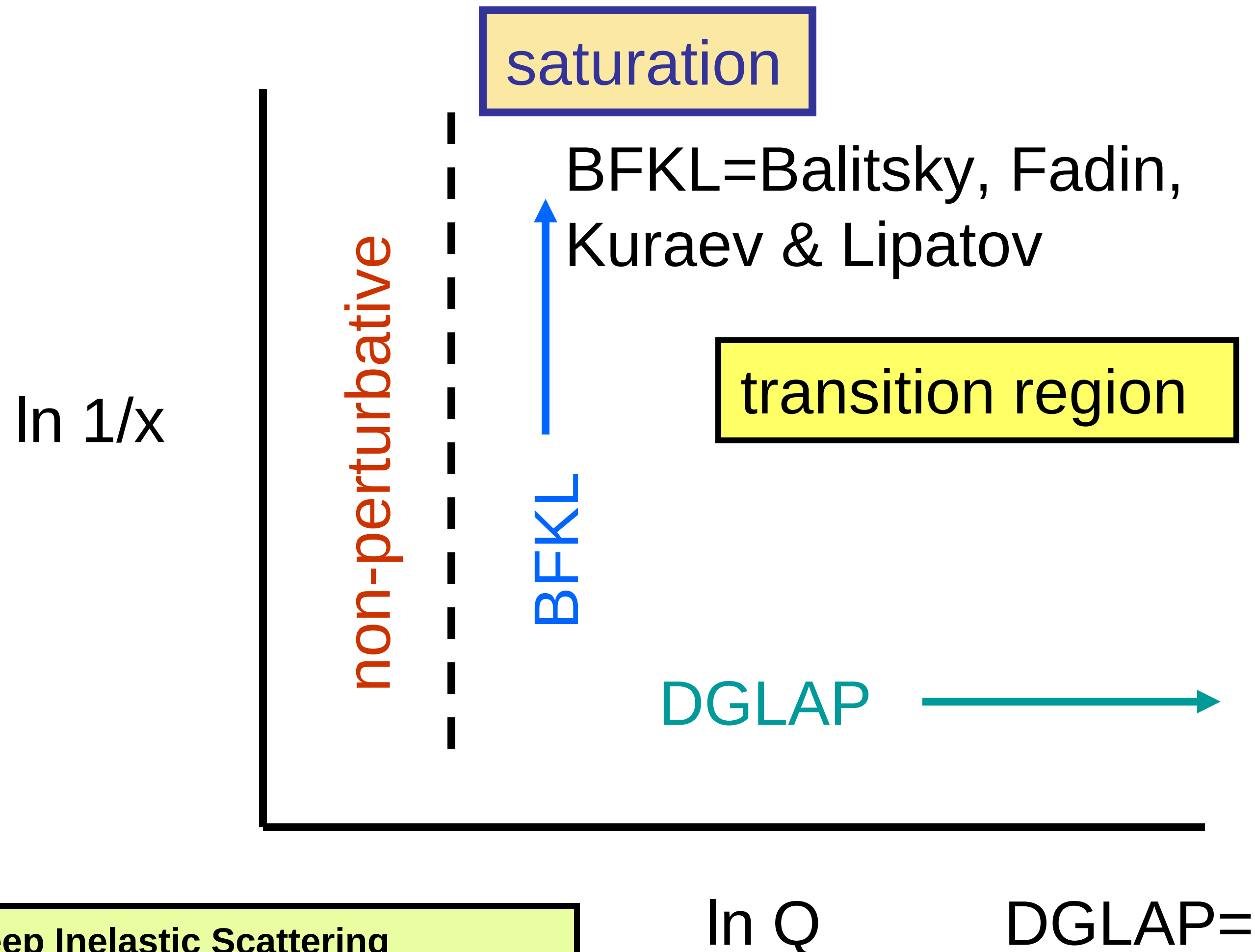




$10^{-5} - 10^{-4}$

From B. Foster’s 2002 Frascati Talk

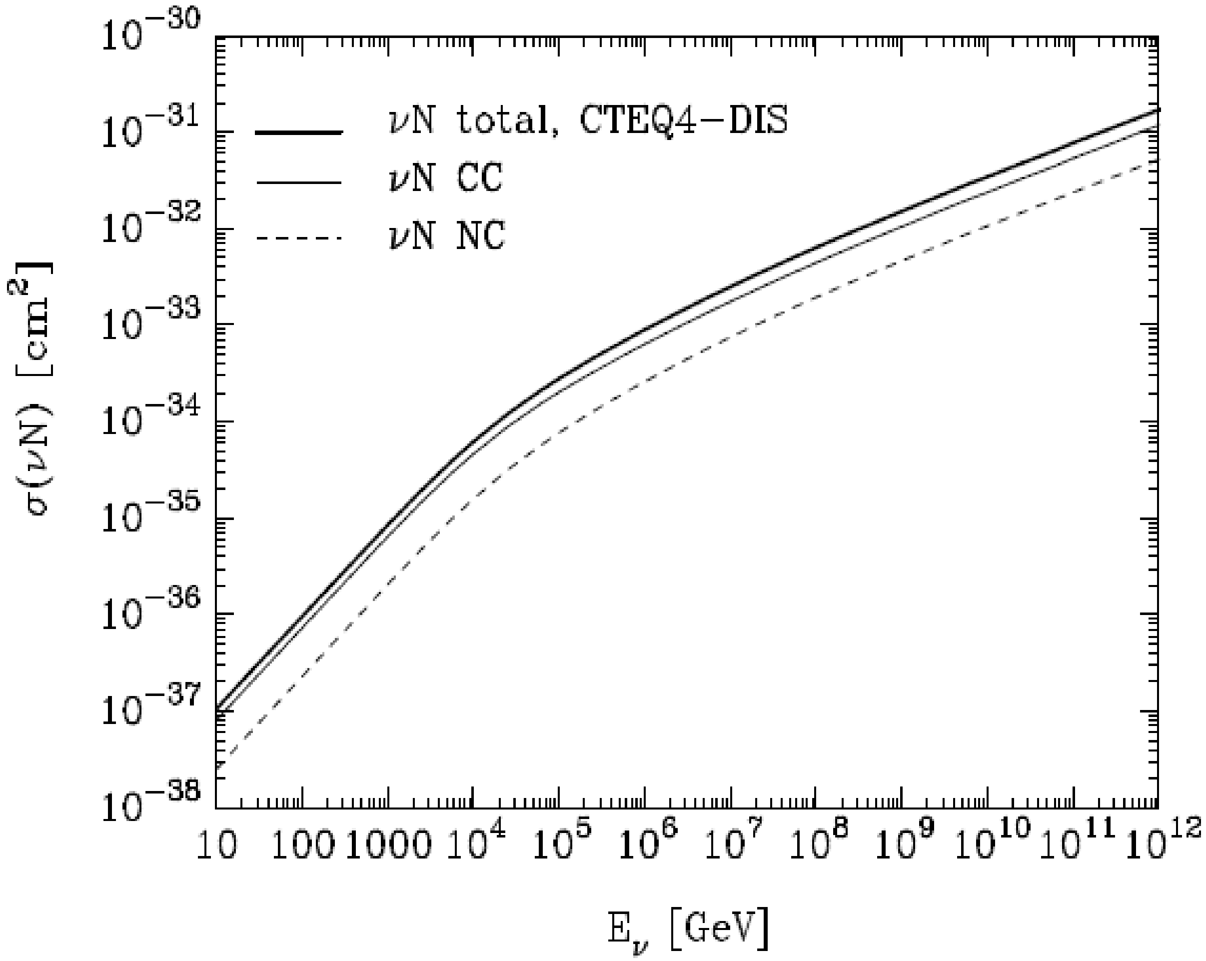
Theory Issues: how to extrapolate?



DGLAP=Dokshitzer,
Gribov, Lipatov, Altarelli
& Parisi

Deep Inelastic Scattering
Devenish & Cooper-Sarkar,
Oxford (2004)

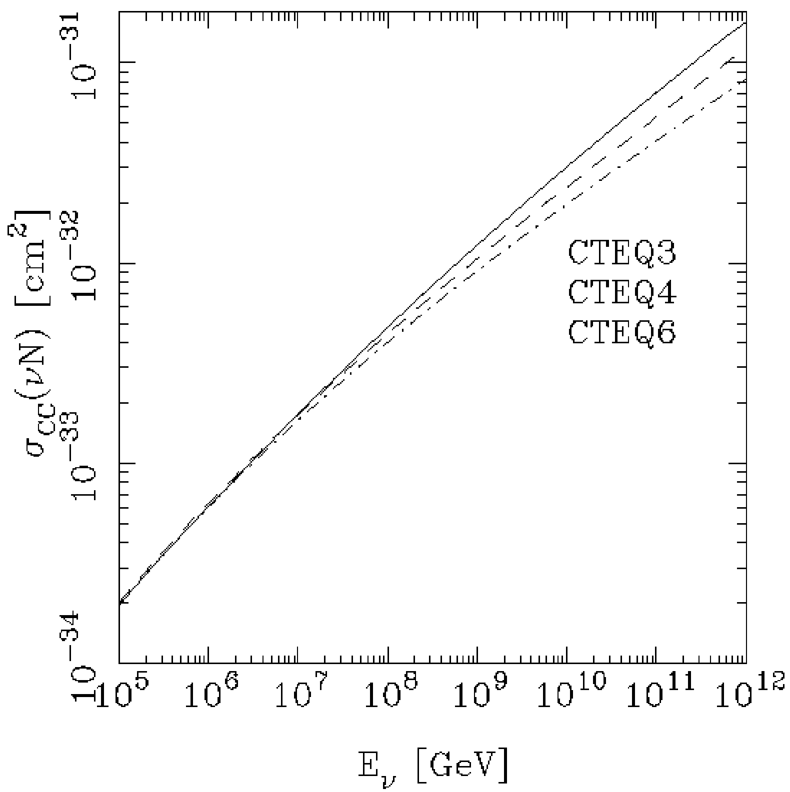
Neutrino Cross Sections

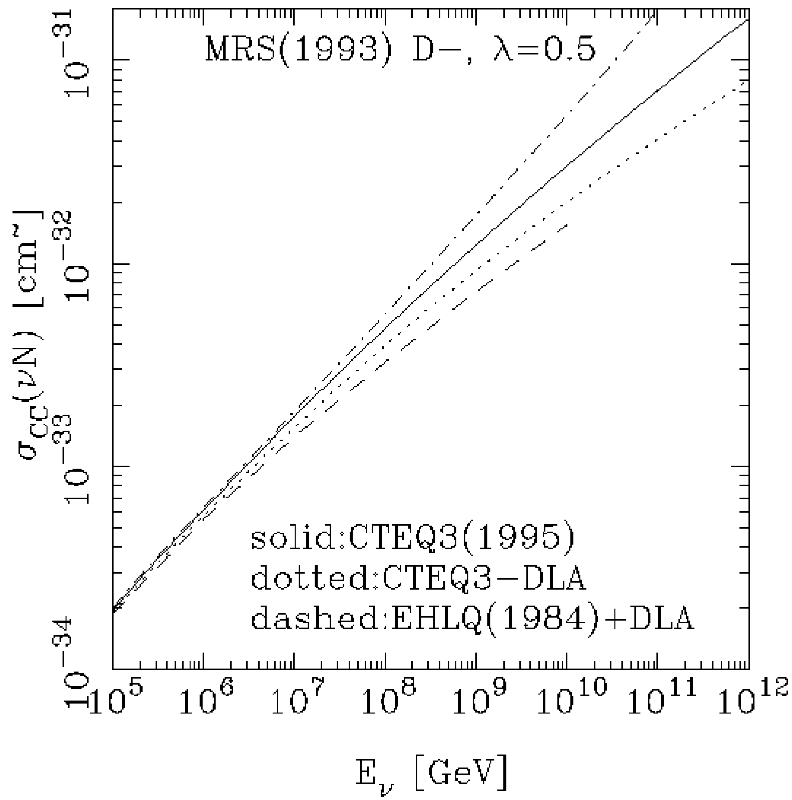


R. Gandhi, C. Quigg, M.H. Reno and I.S., PRD58 (1998)

At high energy σ (ν N) sensitive to small-x QCD

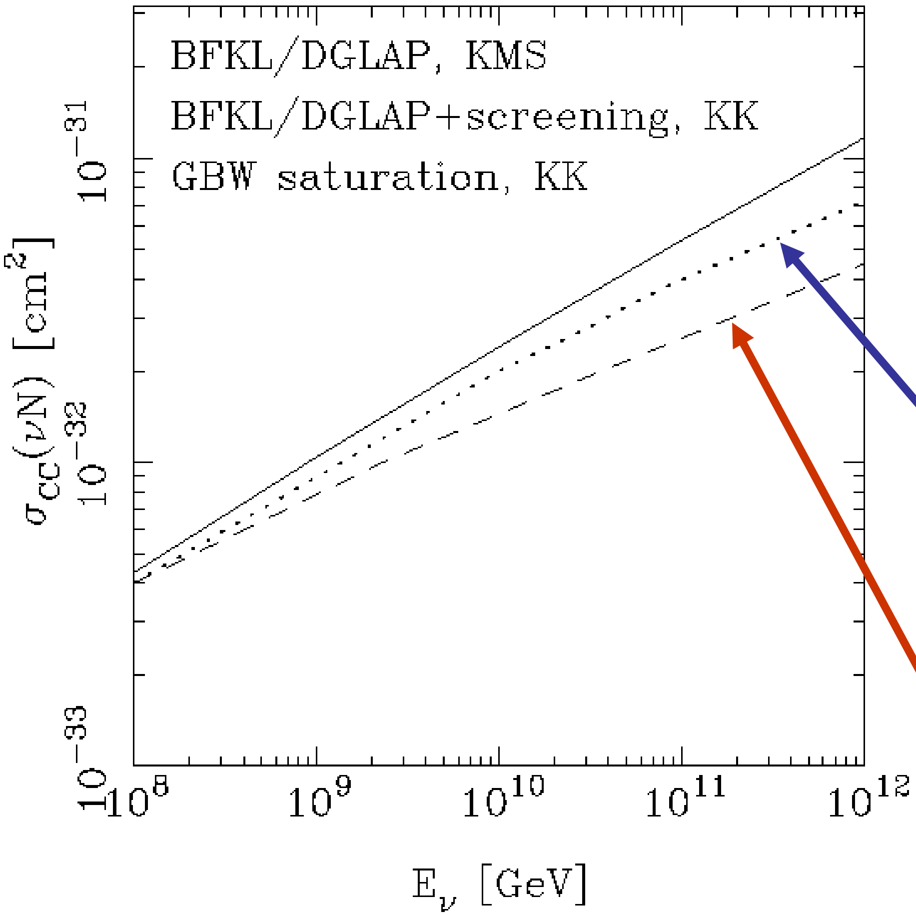
Small x extrapolations





Gandhi, Reno, Quigg and Sarcevic, PRD 58 (1998), Astropart. Phys. 5 (1996)

CC Cross Sections

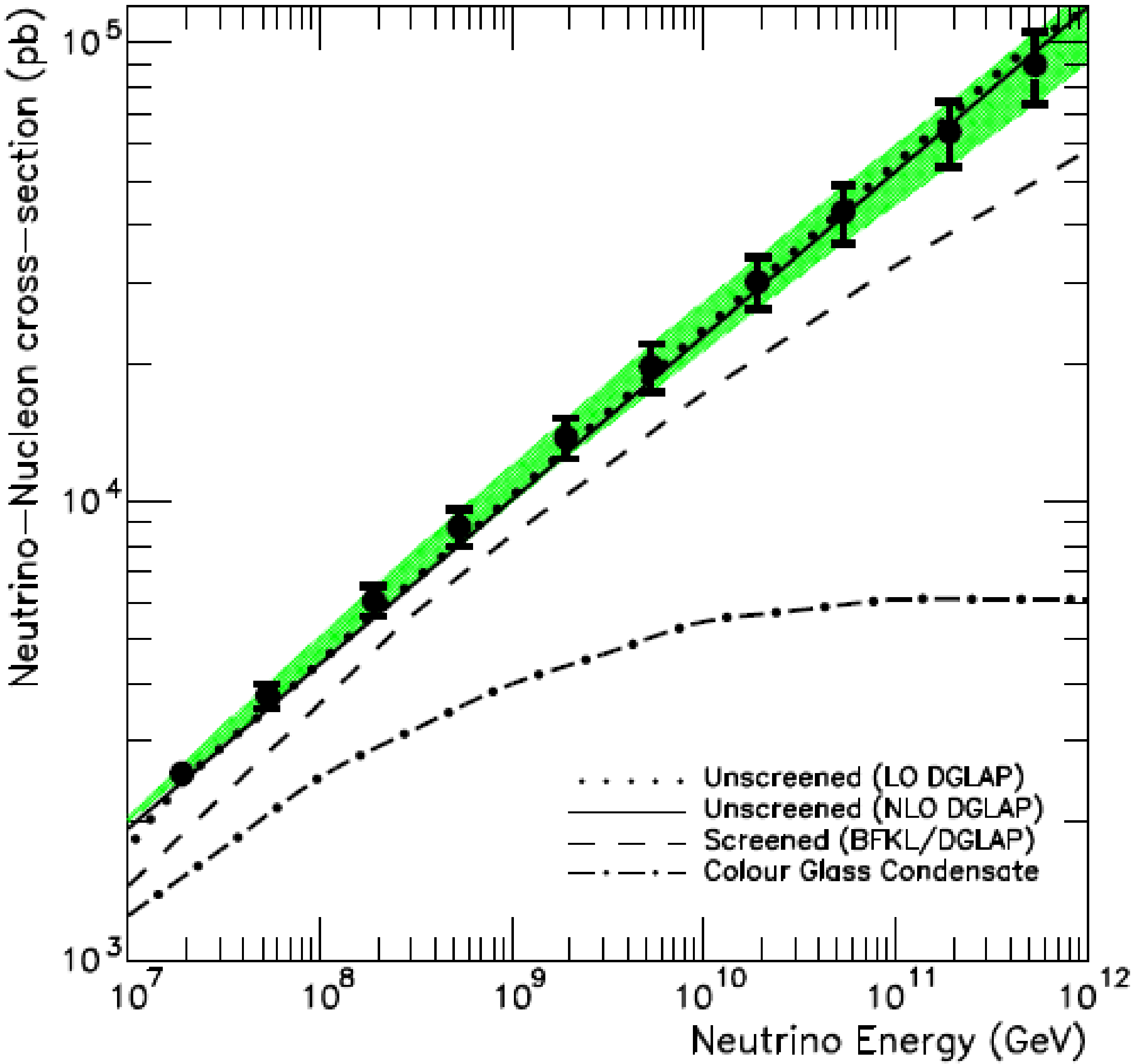


KMS: Kwiecinski, Martin & Stasto, PRD56(1997)3991;

KK: Kutak & Kwiecinski, EPJ,C29(2003)521

more realistic screening, incl. QCD evolution

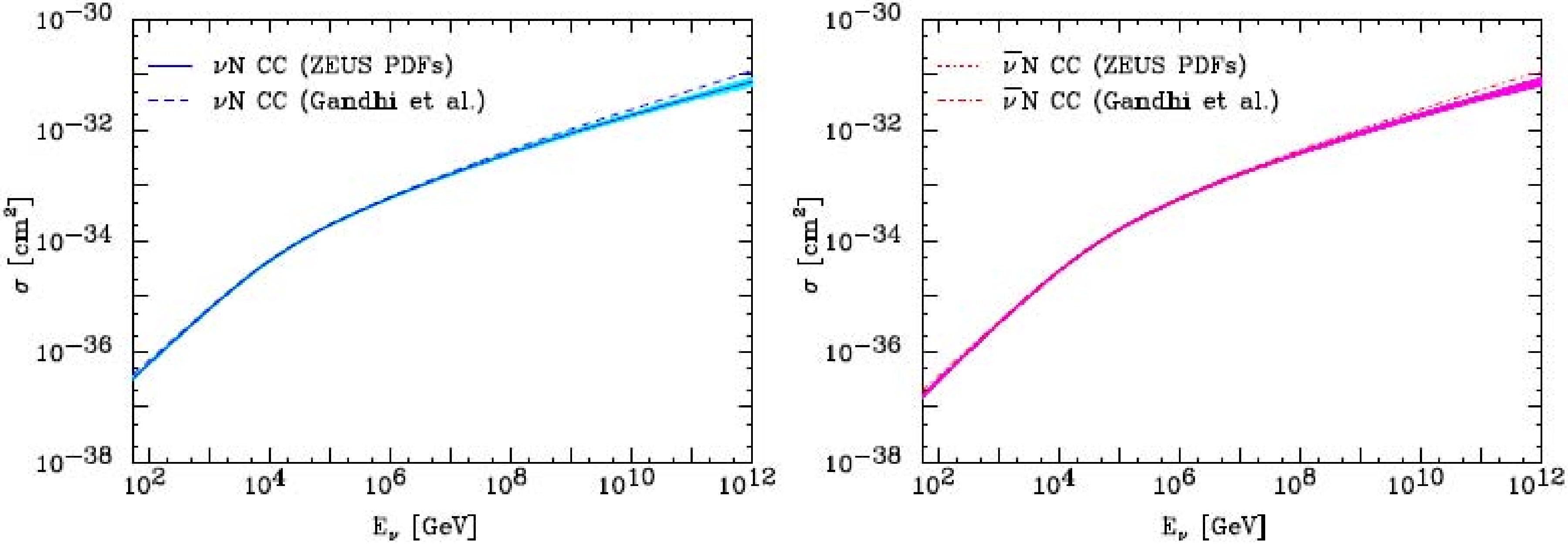
Golec-Biernat & Wusthoff model (1999), color dipole interactions for screening.



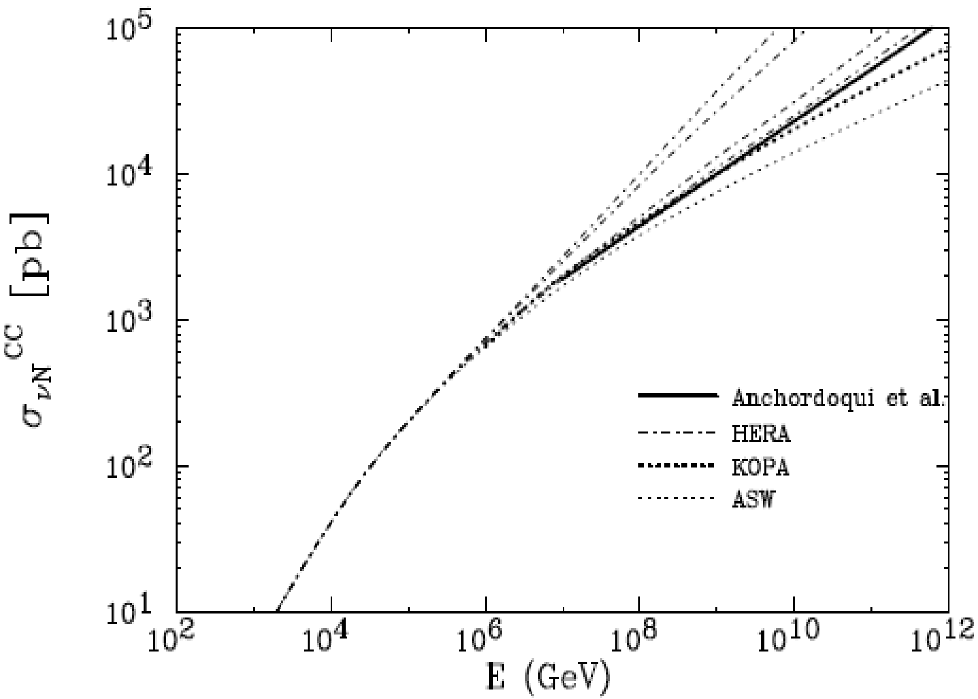
KK

Henley & Jalilian-Marian
PRD73 (2006) 094004

Anchordoqui, Cooper-Sarkar, Hooper & Sarkar,
Phys. Rev. D 74 (2006) 043008



Cooper-Sarkar & Sarkar, JHEP 0801 (2008), new analysis of HERA data incl. heavy flavor, lower cross section at UHE (closer to CTEQ6 results)



HERA: extrapolations with λ=0.5,0.4,0.38

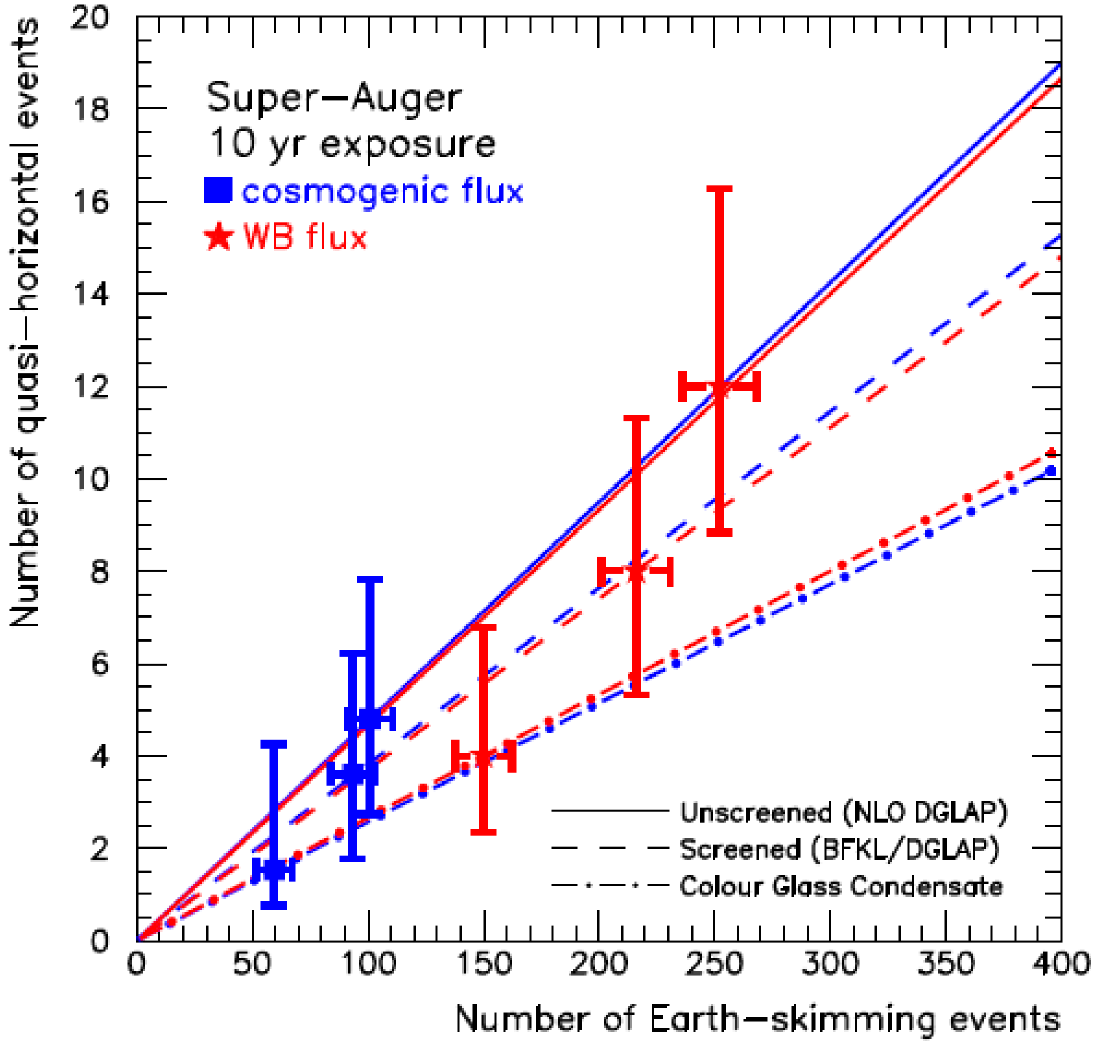
KOPA: DLA, Kotikov & Parente

ASW: saturation effects, Armesto, Salgado & Wiedeman

Armesto, Merino, Parente & Zas, PR D 77 (2008)

Anchordoqui, Cooper-Sarkar, Hooper & Sarkar, Phys. Rev. D 74 (2006)

Determining UHE Neutrino Cross Sections



Anchordoqui et al., PR D76 (2007)

$$\mathcal{N}_{\rm QH} \propto \int {\rm d}E_{\rm sh}\ \sigma_{\nu N}(E_\nu)\ A_{\rm QH}(E_{\rm sh},\theta_{\rm z})\ \phi^{\nu}(E_\nu)$$

Conclusions

- Charm contribution to neutrino production is important at high energies.
- Measurement of atmospheric neutrinos at high energies can provide information about small-x (small Q^2) parton distributions.
- Neutrino detection depends on neutrino cross section which relies on small-x extrapolations of parton distributions (large Q^2) well beyond the experimental measurements
- Cosmic neutrinos can be used as probes of small-x QCD

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"