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# Neutrino-Nucleon Cross Sections at High Energies

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# Motivation

- Center of mass of UHE neutrino interactions with nuclei exceed LHC energies $\sqrt{s}=\sqrt{(2M_N E_\nu)}$, $E_\nu=10^{18}$eV $\rightarrow\sqrt{s}=45$ TeV
- SM predictions of νN cross section at high energies rely on measurements of quark, anti-quark number densities at low x (parton momentum fraction)
  - $E_\nu>10^{17}$ eV $\rightarrow$ $x\lesssim10^{-5}$
  - HERA measures $x\gtrsim10^{-4}-10^{-5}$
- UHE neutrino experiments provide unique opportunity to measure νN cross sections at energies not accessible by human made accelerators
- High cross sections could be indication of new physics

# Outline

- Cross Section calculation with MSTW PDF's
- Measuring cross sections with an antenna array
- Projected limits on models with extra dimensions
- Summary

# MSTW Parton Distribution Functions

- 2008 marked 20th anniversary of publication of first MRS PDF distributions- first global NLO analysis
- Latest update: “MSTW 2008”: A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, “Parton distributions for the LHC,” arXiv:0901.0002v3 (2009)
  - Incorporated improvements in precision, kinematic range of recent measurements
  - Improved by theoretical developments, making global analyses more reliable
  - Timely in view of start of LHC
- Uncertainties are propagated from experimental errors on fitted data points, using diverse data sets
- There are N=20 free parameters describing the PDF’s. This parameter space is spanned by N orthogonal eigenvectors and eigenvalues, with independent uncertainties.

# νN Cross Section Calculation

$$\sigma_{CC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 \left[q + (1-y)^2 \bar{q}\right] \left(\frac{M_W^2}{Q^2 + M_W^2}\right)^2 dy\, dx$$

$$\sigma_{NC}(E_\nu) = \frac{2G_F^2 M_N E_\nu}{\pi} \int_0^1 \int_0^1 \left[q^0 + (1-y)^2 \bar{q^0}\right] \left(\frac{M_Z^2}{Q^2 + M_Z^2}\right)^2 dy\, dx$$

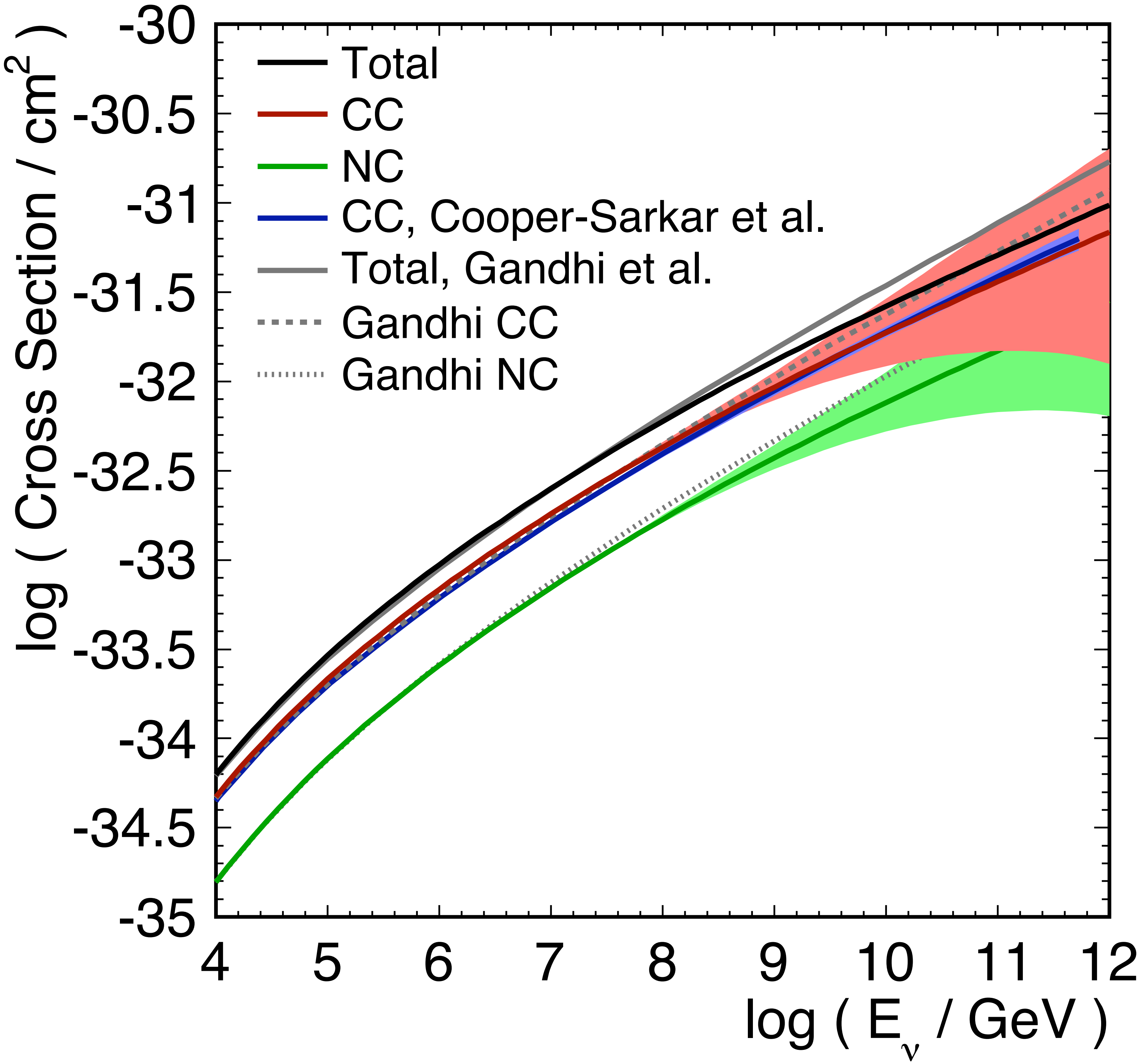
$$q = \frac{d+u}{2} + s + b \qquad \bar{q} = \frac{\bar{d}+\bar{u}}{2} + c + t$$

$$q^0 = \frac{u+d}{2}\left(L_u^2 + L_d^2\right) + \frac{\bar{u}+\bar{d}}{2}\left(R_u^2 + R_d^2\right) + (s+b)\left(L_d^2 + R_d^2\right) + (c+t)\left(L_u^2 + R_u^2\right)$$

$$\bar{q^0} = \frac{u+d}{2}\left(R_u^2 + R_d^2\right) + \frac{\bar{u}+\bar{d}}{2}\left(L_u^2 + L_d^2\right) + (s+b)\left(L_d^2 + R_d^2\right) + (c+t)\left(L_u^2 + R_u^2\right)$$

$$L_u = 1 - \frac{4}{3}x_W \qquad L_d = -1 + \frac{2}{3}x_W \qquad R_u = -\frac{4}{3}x_W \qquad R_d = \frac{2}{3}x_W$$

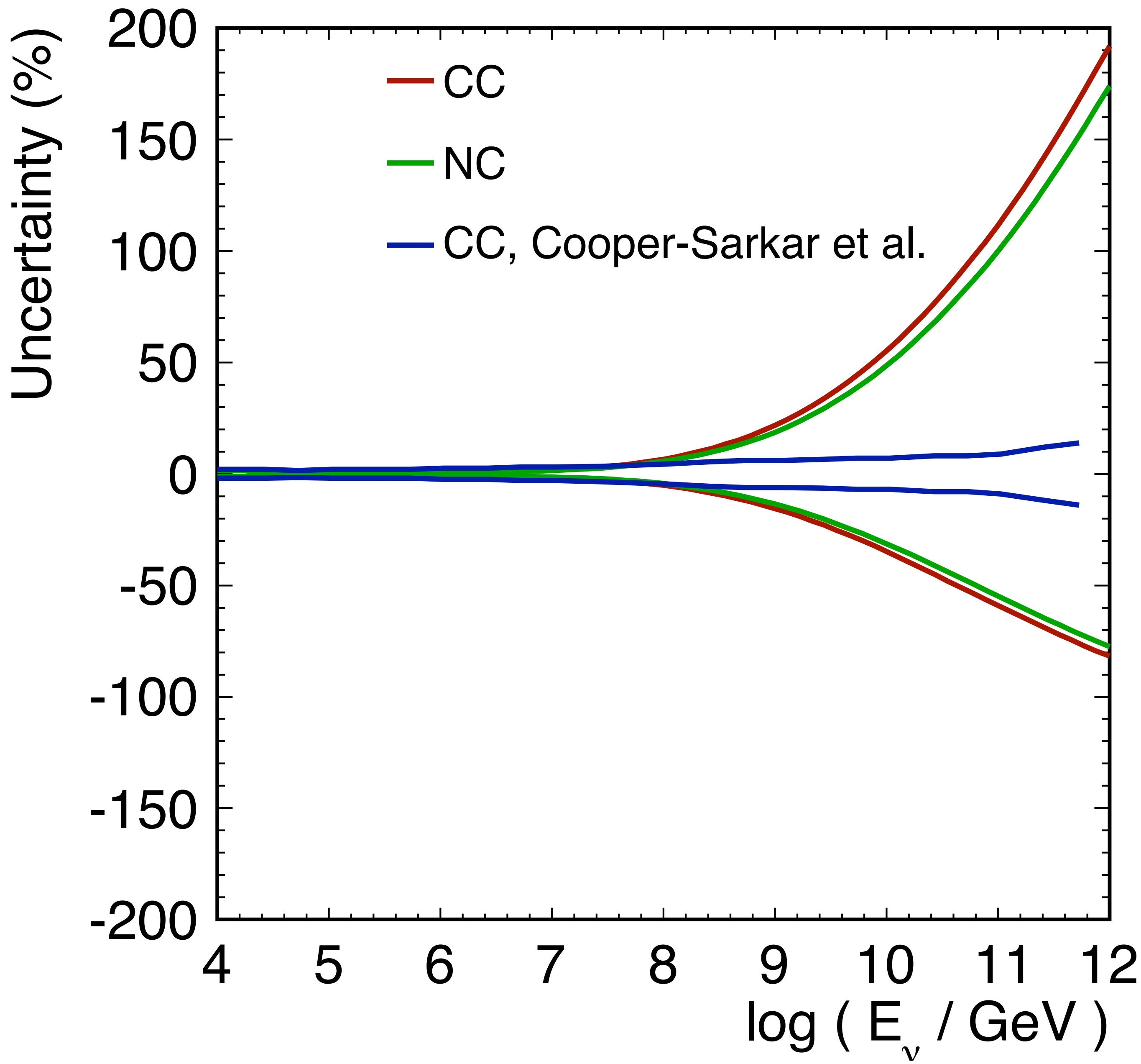
# νN Cross Sections




R. Gandhi et al., arXiv:hep-ph/9807264v1
Cooper-Sarkar et al., arXiv:0710.5303v2

# Uncertainties

- Dramatic difference between Cooper-Sarkar Sarkar (CSS) and this calculation due to different parameterization of the gluon structure function g(x)
- Weaker x dependence on g(x) by CSS does not allow for large uncertainty beyond experimental sensitivity




- CSS fit to just HERA data rather than a global fit (MSTW)

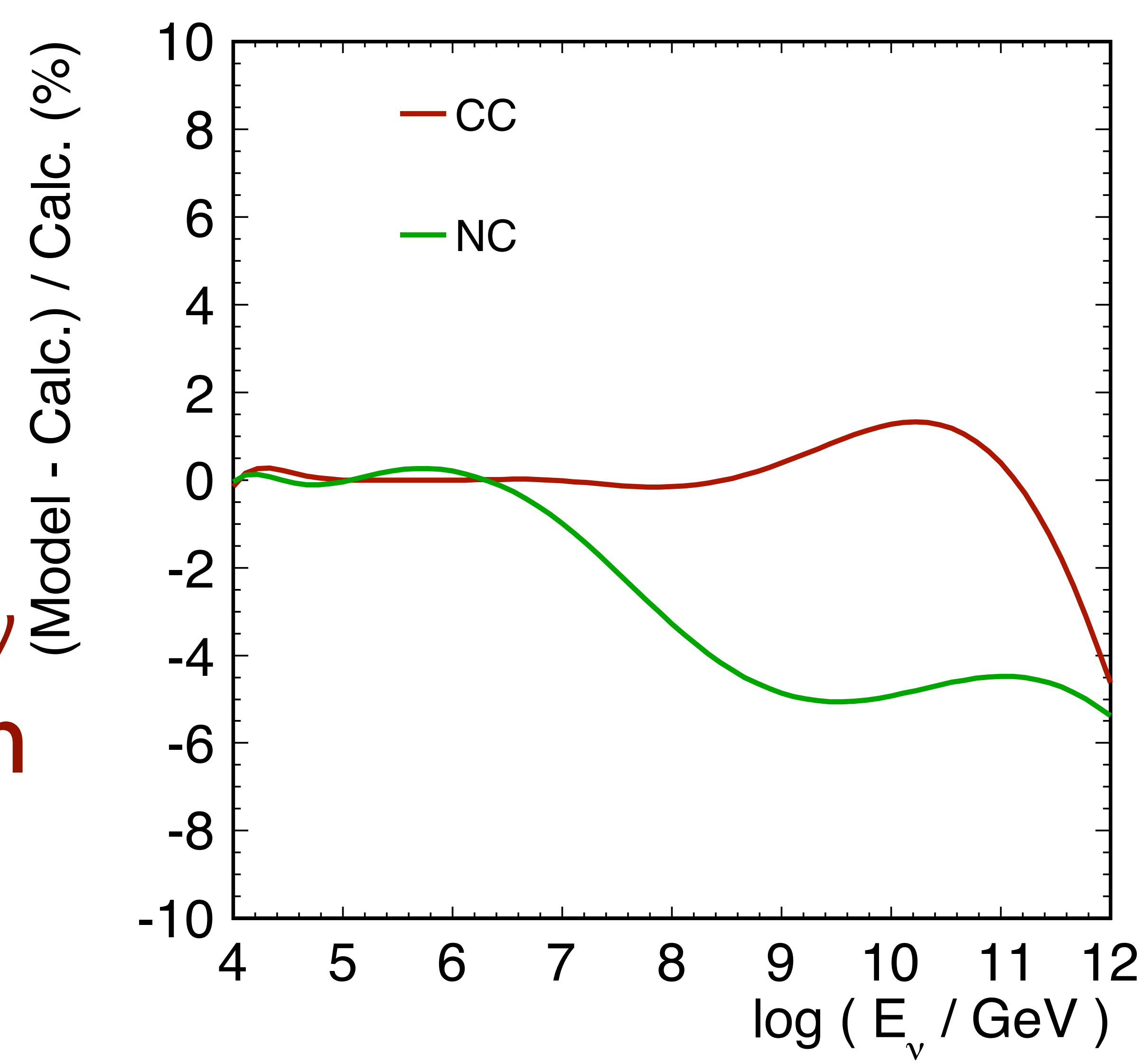
Gandhi: uncertainties factor 2±1

# Parameterisations

$$\sigma_{CC,NC} = C_1 + C_2 \cdot \log(E - C_0) + C_3 \cdot \log^2(E - C_0) + C_4 \cdot \log^3(E - C_0) + C_5 / \log(E - C_0) + C_6 \cdot (E - C_0)$$

| | $C_0$ | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ |
|---|---|---|---|---|---|---|---|
| CC | -1.03 | -10.5 | -4.67 | -0.98 | 1.46 | -20.2 | -1.46 |
| NC | -1.90 | -11.7 | -4.21 | -1.03 | 0.64 | -25.7 | -0.26 |

- Both NC and CC cross sections as a function of log $E_\nu$ can be parameterized as a sum of powers of logs plus a linear term
- Could be useful for simulators



# Correlations across energies

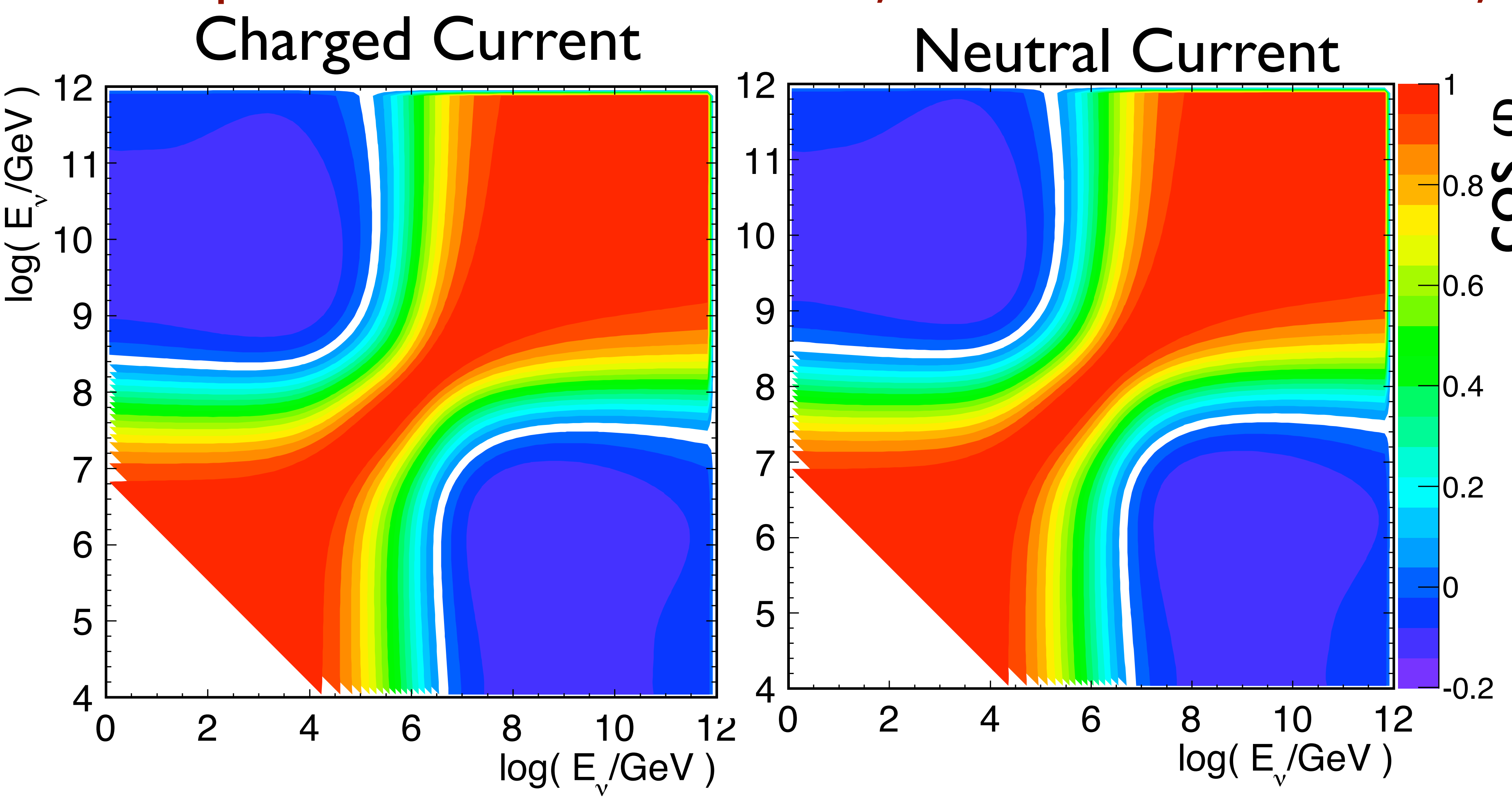
## From CTEQ6 paper arXiv:0802.0007v3

$$\cos\varphi = \frac{\vec{\Delta}X \cdot \vec{\Delta}Y}{\Delta X \Delta Y} = \frac{1}{4\Delta X \Delta Y}\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)\left(Y_i^{(+)} - Y_i^{(-)}\right)$$

$$\Delta X = \left|\vec{\Delta}X\right| = \frac{1}{2}\sqrt{\sum_{i=1}^{N}\left(X_i^{(+)} - X_i^{(-)}\right)}$$

Sum is over eigenvectors

cos φ=1: max. correlation, -1: anti-correlated, 0: no correlation



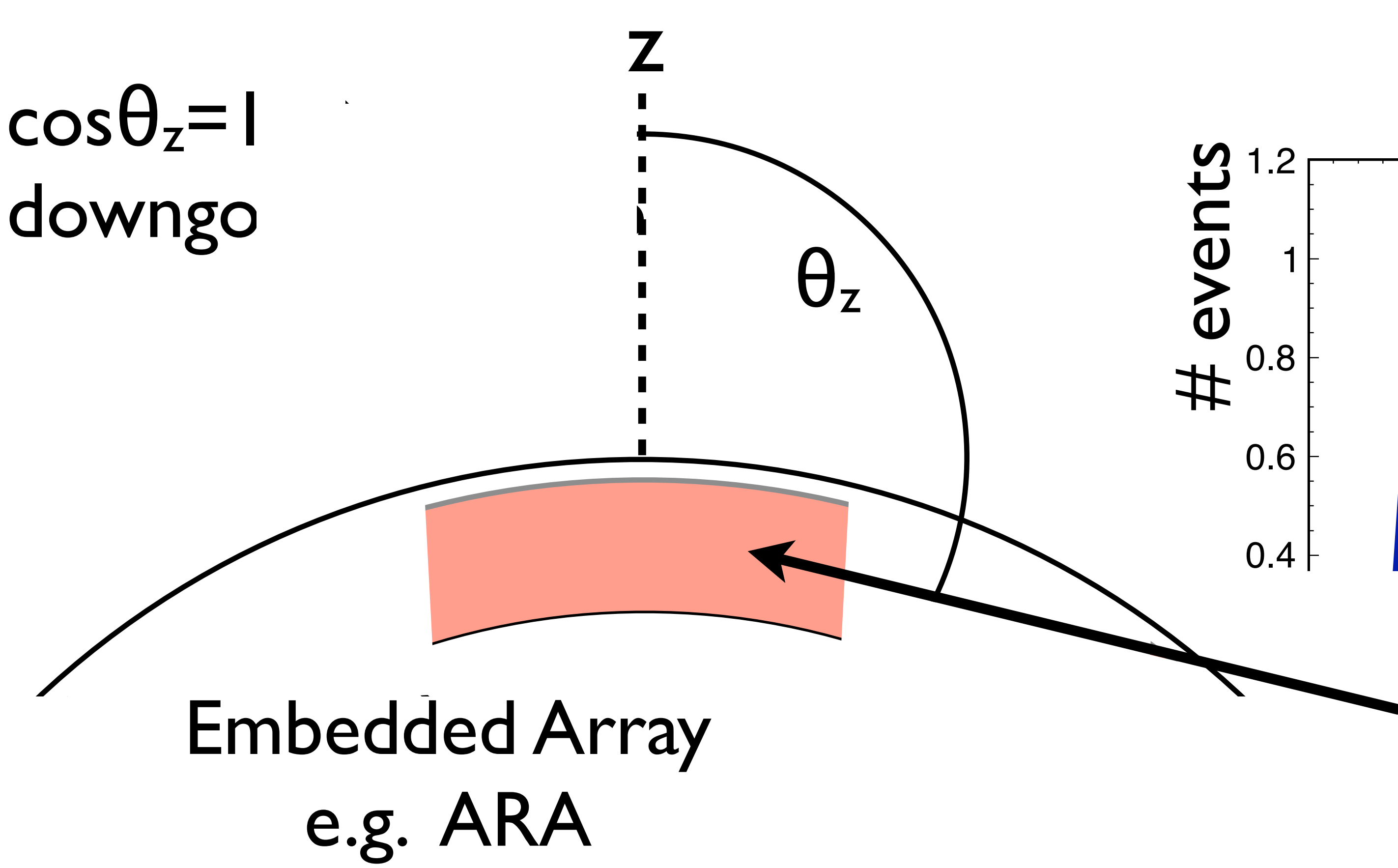

- Crossover @$10^6$:
  - Sum rules
  - HERA constraints
  - low: valence, high:sea

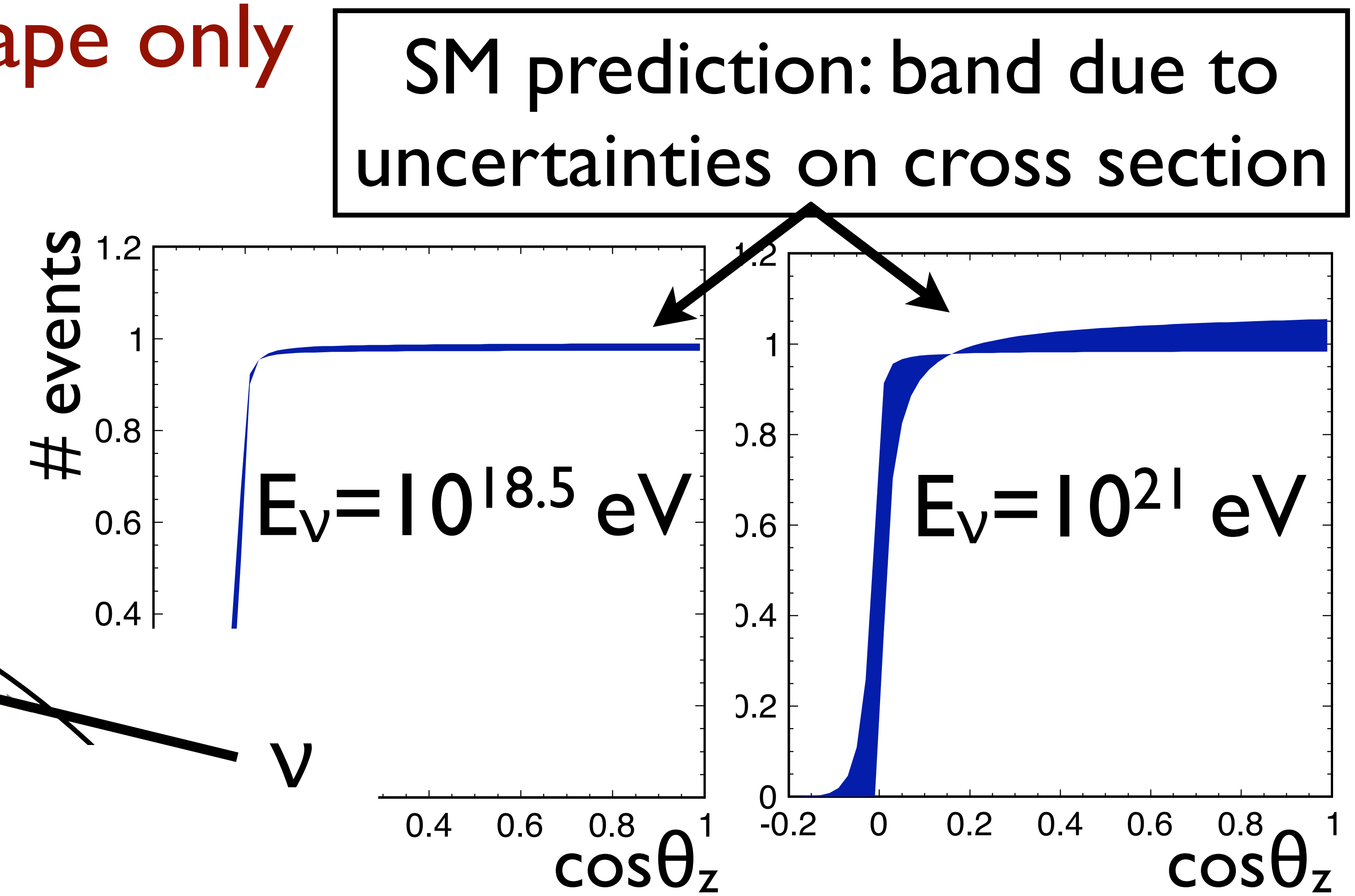
# Cross Section Measurement in a Radio Array

- For any earth based detector, incident neutrinos subject to absorption in earth

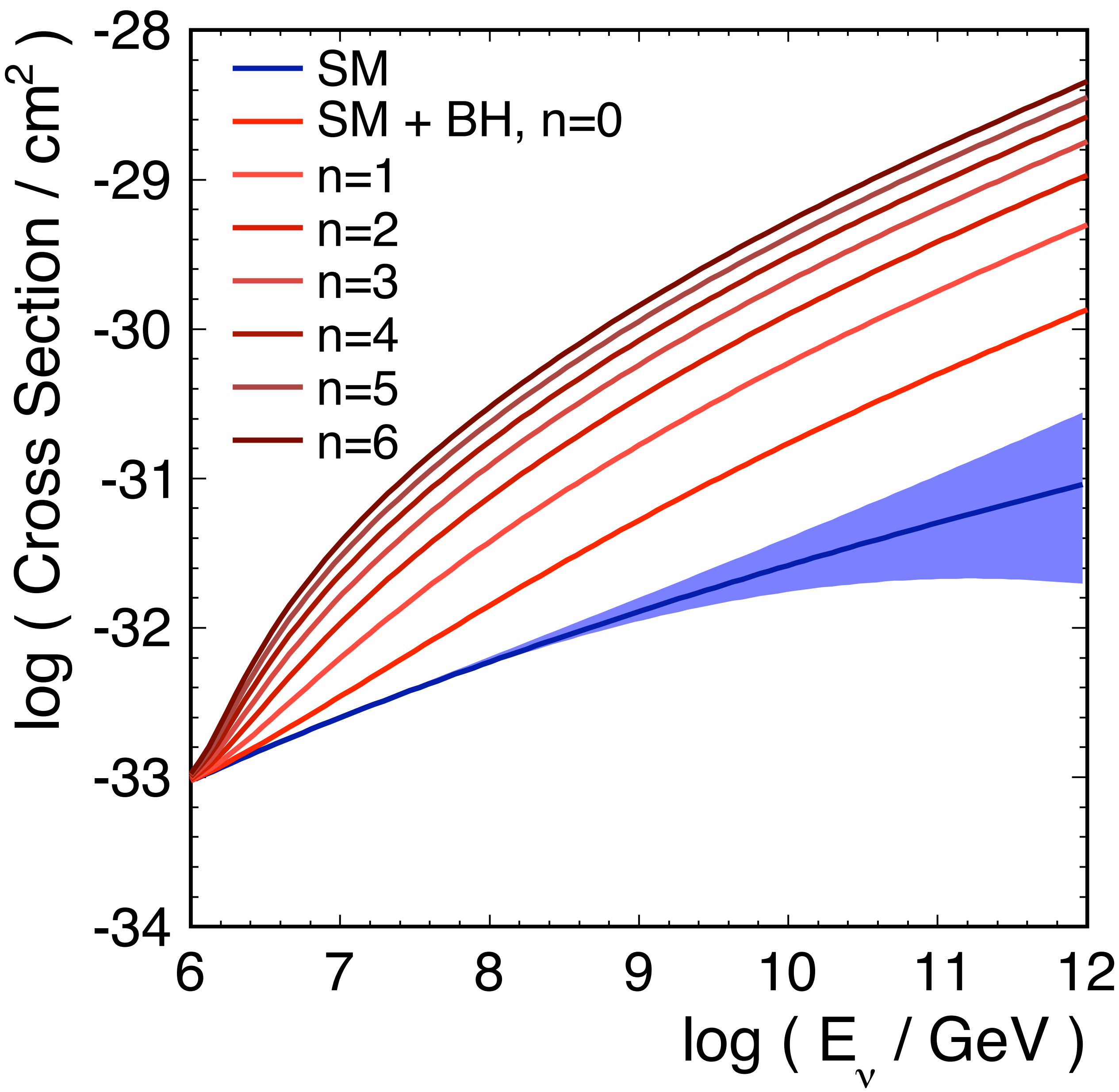
$$\frac{dn}{d\cos\theta_z} = A \cdot \exp - \left( \frac{\sqrt{(R^2 - 2Rd)\cos^2\theta_z + 2Rd} - R\cos\theta_z}{L} \right)$$

  n = # events, $\theta_z$ = zenith angle, R = earth radius, d = depth, L(E) = interaction length
- Cross section determines theta dependence
- Measurement based on shape only

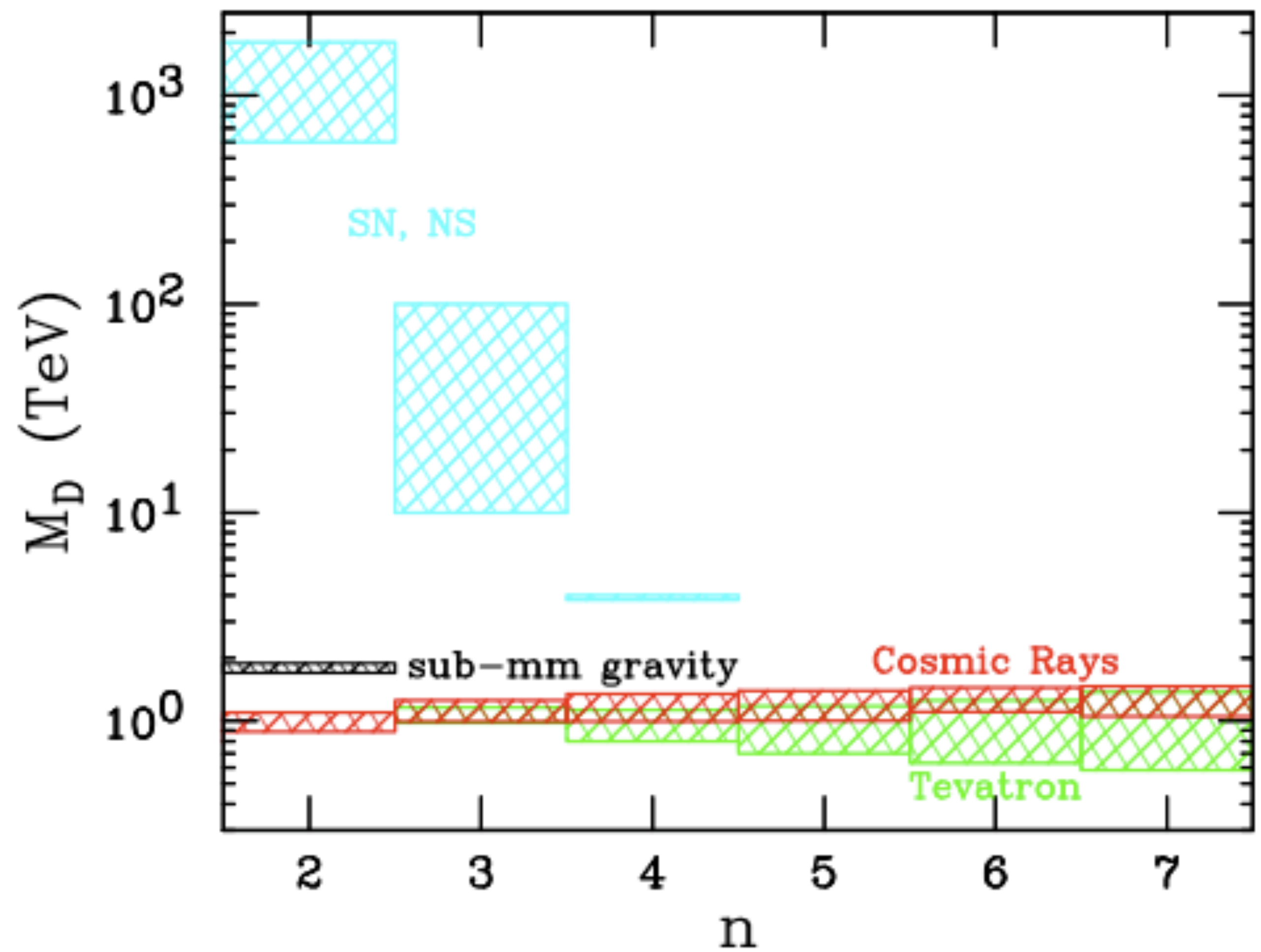


# Models with Extra Dimensions




BH models from Alvarez-Muniz et al., Phys.Rev.D65:124015,2002




Feng et al., arXiv:hep-ph/0109106v2

- $M_D$ = Fundamental Planck scale, n = # extra dimensions
- Minimum black hole mass $M_{BH}^{min} = x_{min} M_D$
- In this talk we consider $x_{min}=1$, $M_D=1$ TeV

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# Technique

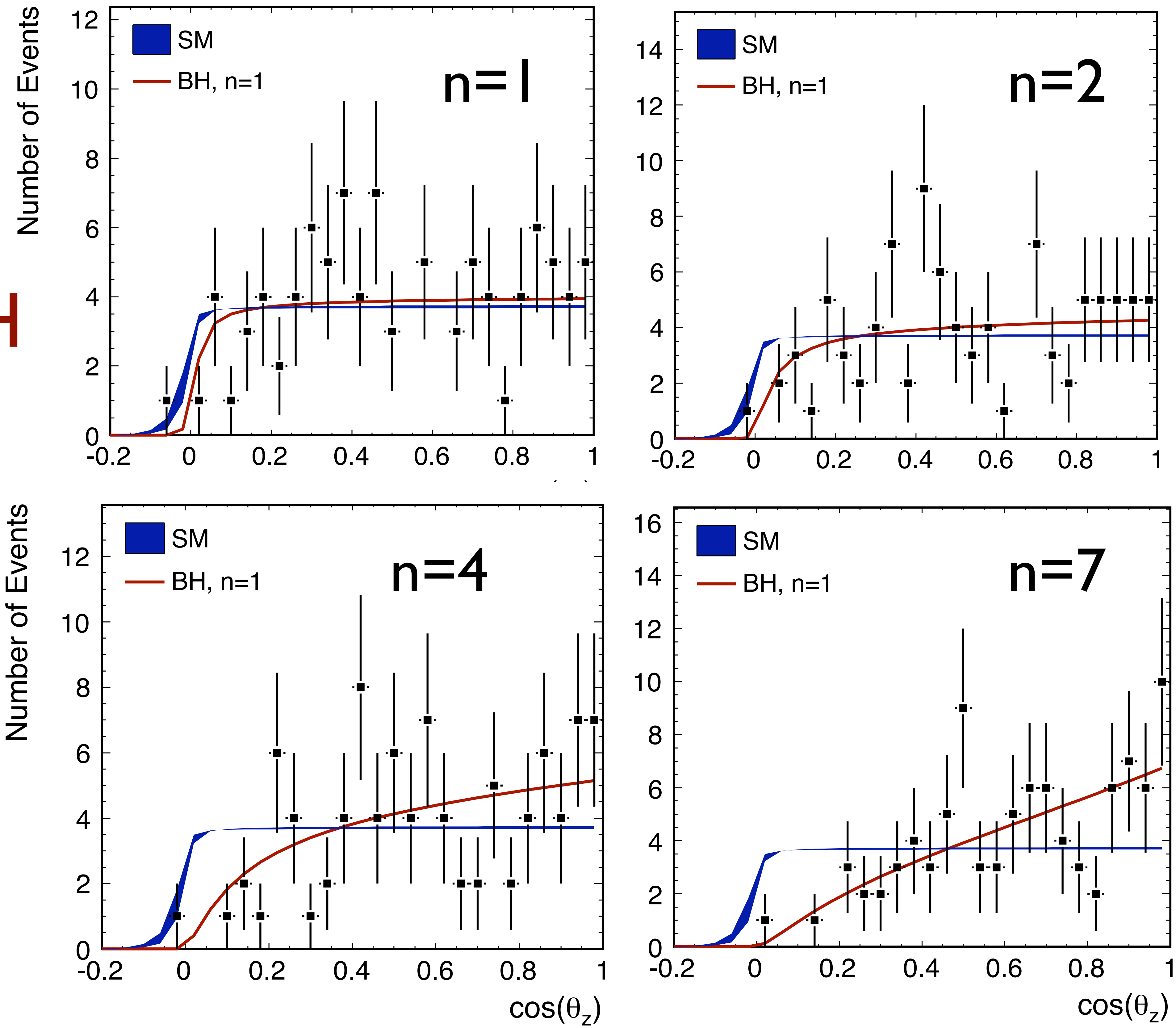
- Want to test sensitivity of an embedded array (ARA) to BH models with n extra dimension, depending on x events expected
- For a given n and x, generate a set of pseudoexperiments (500)
- Generate neutrino energies $E_i$ and zenith angles $\theta_{z,i}$
  - GZK spectrum convoluted with ARA effective area
- Smear energies and zenith angles according to their resolutions to get $E'_i$ and $\theta_{z,i}'$
- Get $\sigma_{SM}(E')$ and $\sigma_{BH,n}(E') \rightarrow L'_{SM}$, $L'_{BH,n}$
- Functions dn/cos $\theta_z(L'_{SM})$, dn/cos $\theta_z(L'_{BH})$ predict the theta distributions for each hypothesis
- Normalize each function to unit area, add to cumulative theta distribution for each hypothesis
- Calculate likelihoods by comparing cumulative theta distribution to generated distribution of $\theta_z$'s for the pseudoexperiment

# Caveats

- Here only use νN cross sections (not anti-νN)
- Only consider models where $x_{min}$=1, $M_D$=1 TeV
- Assume uniform experimental sensitivity vs. $\theta_z$ (this can be corrected for)
- Use unique interaction depth=250 m instead of accounting for different depth for each event

# Theta Distributions

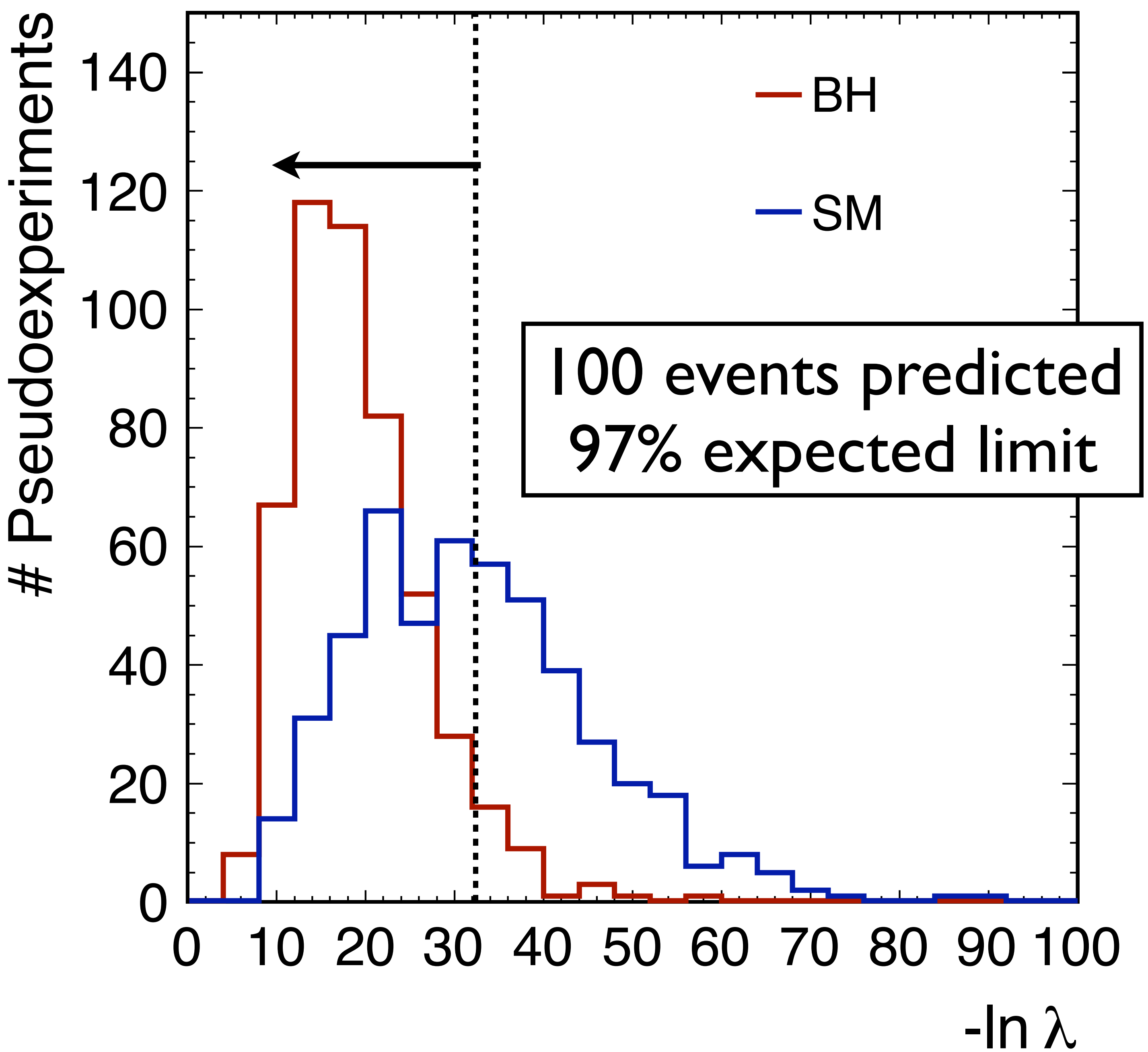
- Pseudo-experiments: 100 events expected, BH =true model
- $\Delta\theta_z=5°$
- $\Delta(\log E_\nu)=0.4$
- n: # extra dimensions
- $x_{min}=1$
- $M_D=1$ TeV



# Likelihoods

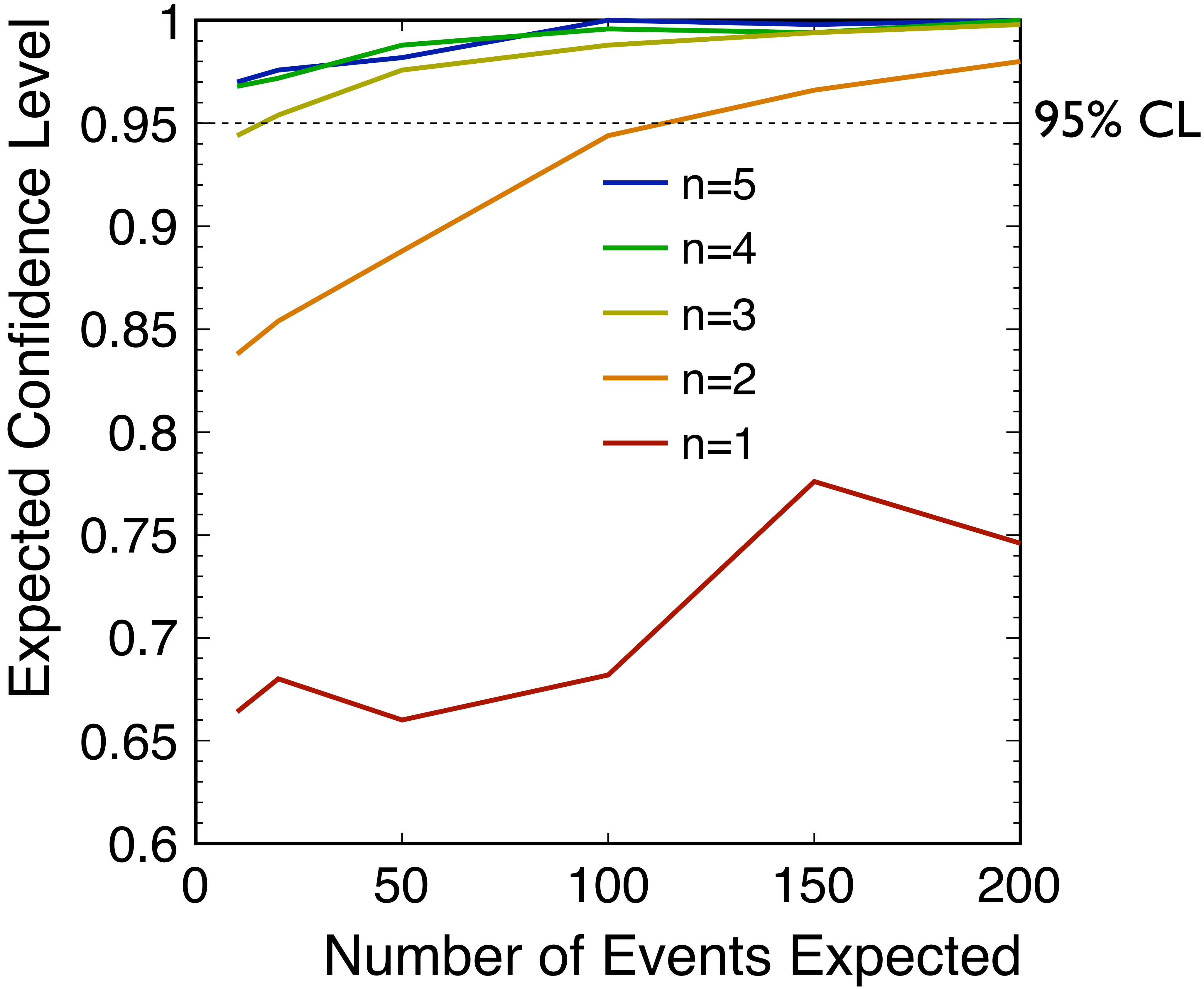
$$-2\ln\lambda = 2\sum_{i=1}^{N}\left[\nu_i - n_i + n_i \ln\frac{n_i}{\nu_i}\right]$$

(PDG Eq. 32.12 )




- Log likelihood ln $\lambda$
- Sum over N bins
- $\nu_i$=predicted
- $n_i$=measured
- Generate likelihoods
  - $\nu_i$ predictions always from BH model
  - $n_i$ values from pseudoexperiments assuming SM or BH truth
- CL limit is integral of $\lambda_{BH}$ from 0 to $<-\ln \lambda_{SM}>$

# Expected Limits



# Conclusions

- We have performed a new calculation of CC and NC νN cross sections from MSTW 2008 PDF's and uncertainties on cross sections due to PDF's based on global fits
- We have parameterized cross sections for ease of use in simulations
- UHE neutrino experiments provide unique opportunity to measure νN cross sections at energies not accessible by LHC
- For an experiment with ~100 measured neutrinos, can exclude models with $n=2$, $x_{min}=1$, $M_D=1$
- Models with $n>2$ can be excluded with much fewer events

**Now all we need are some UHE neutrinos!**

# Backup Slides

# Difference in CSS vs. MSTW uncertainties

**For the experts:** "The uncertainties are small since they parameterise the gluon at small x with just a single power, i.e. $g(x) \propto x^{\delta}$. This means the gluon uncertainty can only grow slowly as a function of ln(1/x) even after the data has run out, rather than the rapid expansion for MSTW which uses two powers" **Robert Thorne**

# The crossover at $10^6$ GeV

**For the experts:** "From sum rules in the PDFs there is a crossing point where changes in PDFs become anticorrelated, i.e. for any change the PDFs all tend to increase below this x and increase above this x. For high scales this is somewhere just below 0.01. It also happens to be the x where there is a very large amount of accuarte HERA data also tending to fix the PDFs. I think the 10^6 corresponds roughly to this. It is also the point at which for lower energies the valence quarks are dominating but for higher it is the sea quarks which are gluon driven." **Robert Thorne**

# Slope at $\cos\theta_z = 0$