# Physics of Neutrino Interactions around 1-10 GeV

Teppei Katori
Queen Mary University of London
Modelling Neutrino-Nucleus Interactions, ECT*, Trento, Italy, July 9, 2018

**outline**

1. **IceCube neutrino observatory**
2. **IceCube low energy physics**
3. **DIS-hadronization systematic errors**
4. **DIS quark-hadron duality error**
5. **DIS differential cross section error**
6. **DIS A-scaling error**
7. **DIS PDF error**
8. **Low-W hadronization error**
9. **High-W hadronization error**
10. **Conclusions**

Subscribe “NuSTEC News”
E-mail to listserv@fnal.gov, Leave the subject line blank, Type "subscribe nustec-news firstname lastname"
(or just send e-mail to me, katori@FNAL.GOV)
like “@nuxsec” on Facebook page, use hashtag #nuxsec

# Physics of Neutrino Interactions around ~~1~~ 2-10 GeV

Teppei Katori
Queen Mary University of London
Modelling Neutrino-Nucleus Interactions, ECT*, Trento, Italy, July 9, 2018

**outline**

# IceCube-170922A & TXS 0506+056

**TITLE: GCN CIRCULAR**
**NUMBER: 21916**
**SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event**
DATE: 17
FROM: E

Claudio Ko
report on

On 22 Sep
probability
Extremely
normal on

**Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.**

ATel #10791; *Yo*
*Ko*

*Creden*

Subjects: Gamma

Referred to by AT
10844, 10845, 108

Tweet | Rec

We searched for
neutrino event e
10787) with all-sk
ray Space Telesco
and also included
located inside the

**First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A**

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
*on 4 Oct 2017; 17:17 UT*
*Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)*

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet | Recommend 448

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of

**Work on-going**

September 22, 2017: a neutrino alert issued by IceCube
Fermi and MAGIC identify a spatially coincident flaring blazar (TXS 0506+056)
Very active multi-messenger follow-up from radio to γ-rays

Taboada (Georgia Tech), Neutrino 2018

SHOP ICECUBE
OFFICAL SHOP OF THE ICECUBE NEUTRINO OBSERVATORY

https://charge.wisc.edu/icecube/wipac_store.aspx

**IceCube IC170922 t-shirt (Crew-Neck)**
$18.00
The front side features an image of "IC170922" and the IceCube logo on the back
Heathered navy, crewneck, rinspun cotton/polyester, Available in unisex sizes S-2XL. Runs small.

Support IceCube

**1. IceCube neutrino observatory**

2. IceCube low energy physics

3. DIS-Hadronization systematic errors

4. DIS quark-hadron duality error

5. DIS differential cross section error

6. DIS A-scaling error

7. DIS PDF error

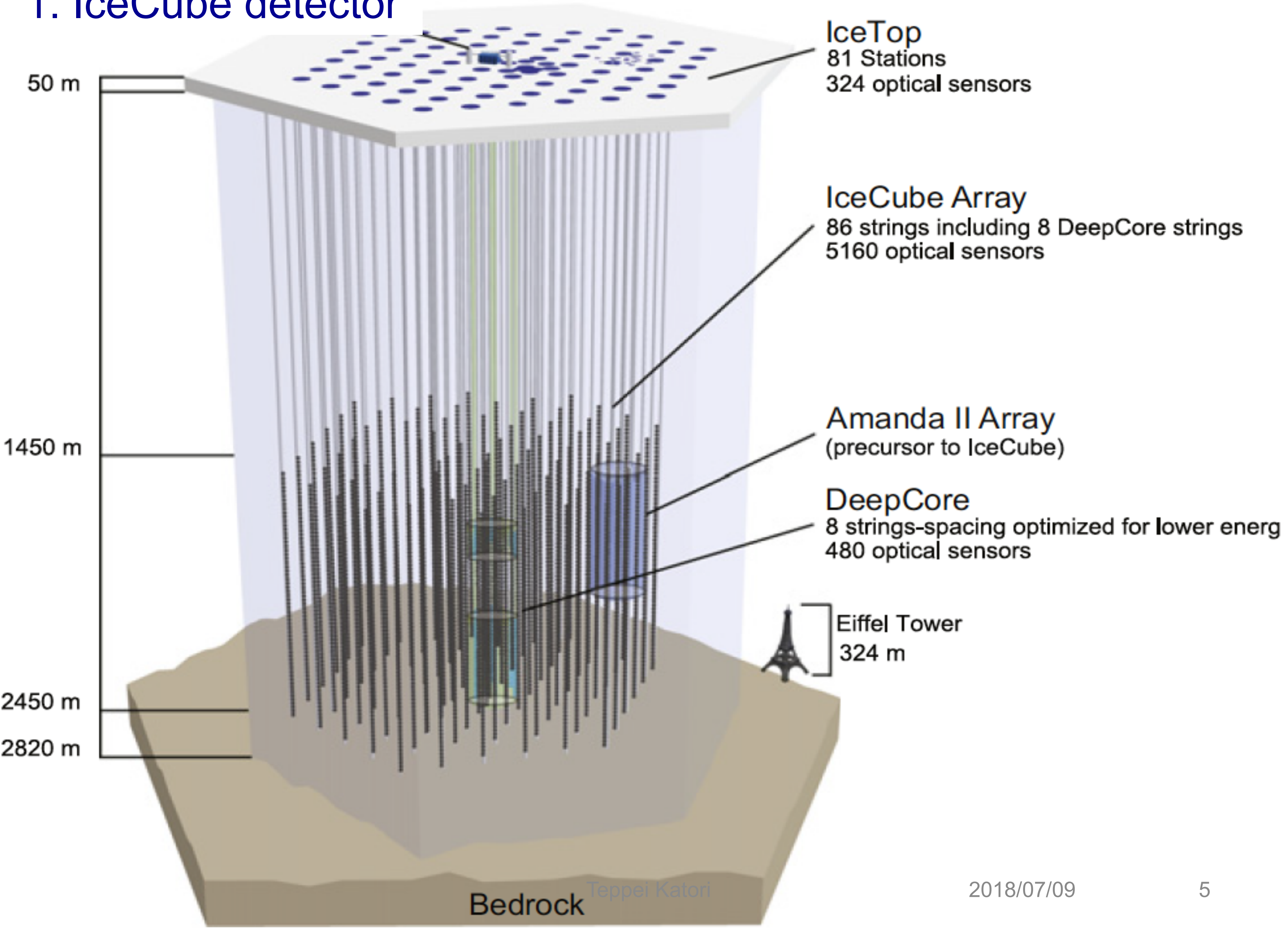
8. Low-W hadronization error

9. High-W hadronization error

10. Conclusions

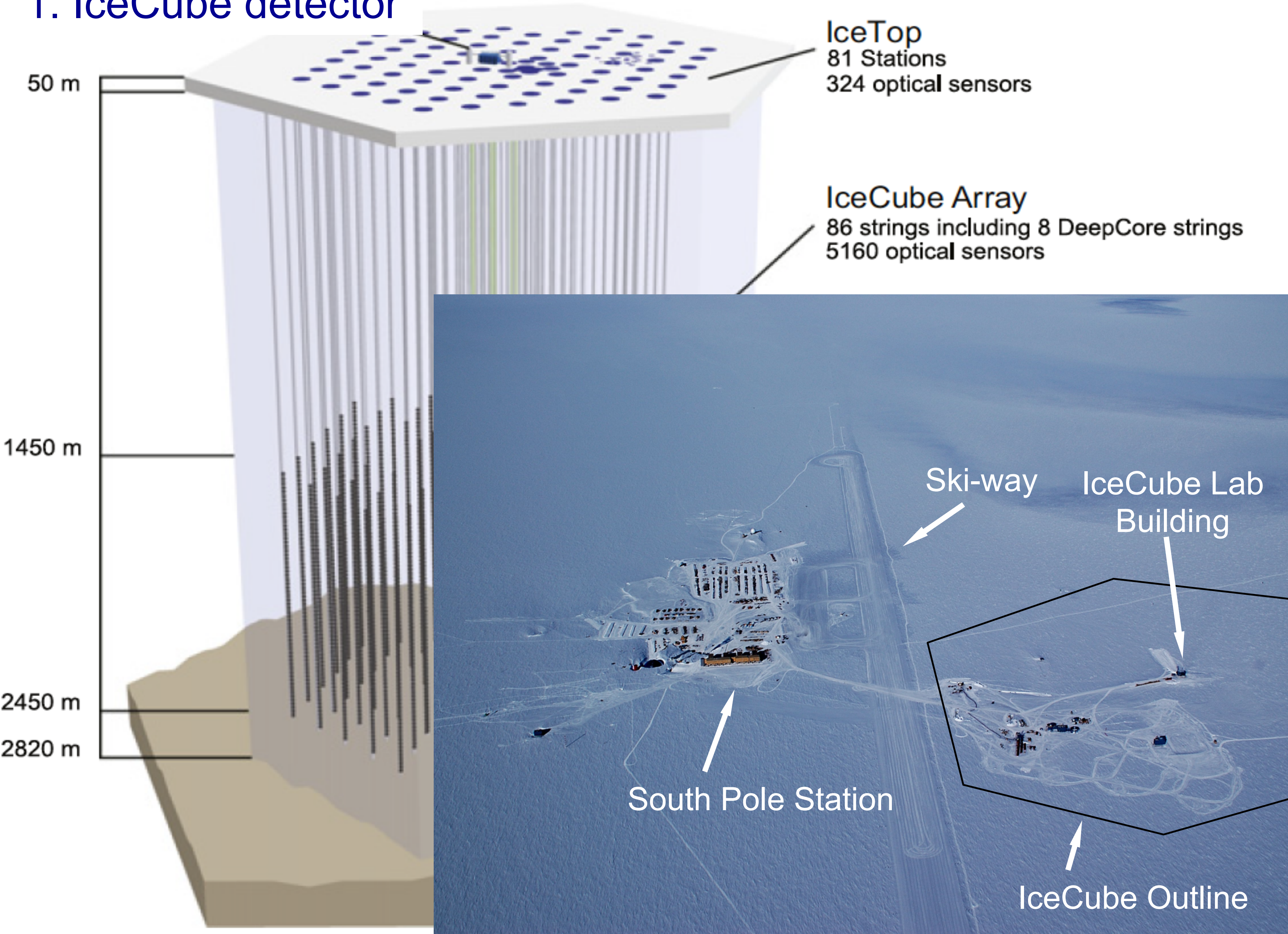
# 1. IceCube detector

IceCube, JINST12(2016)P03012



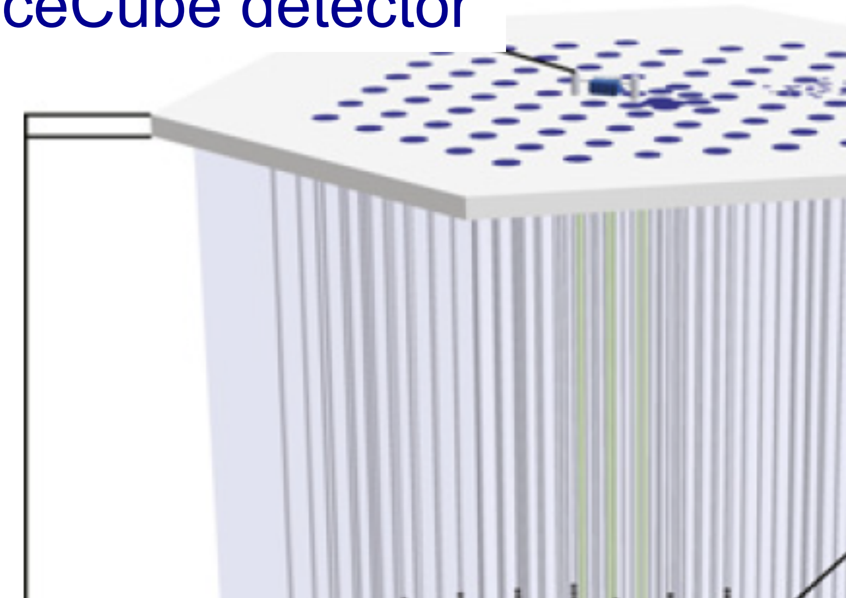
# 1. IceCube detector

IceCube, JINST12(2016)P03012

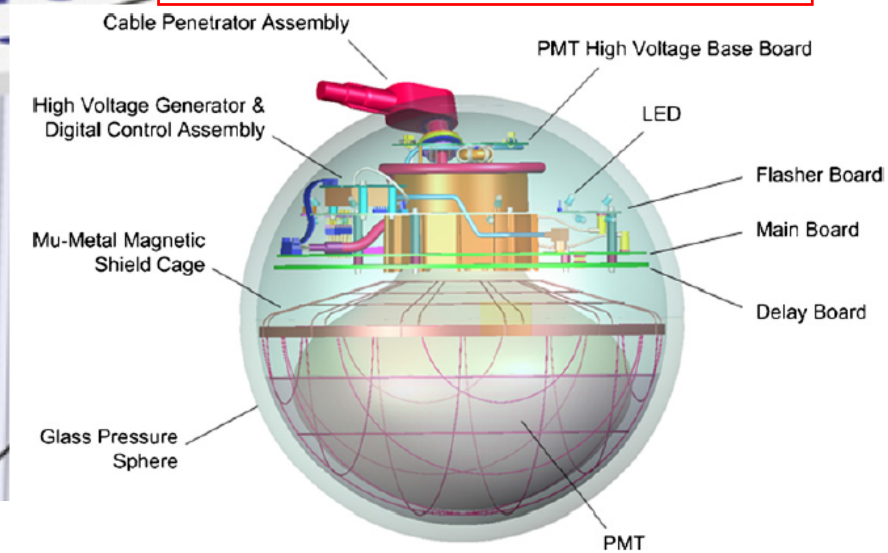


# 1. IceCube detector

IceCube, JINST12(2016)P03012



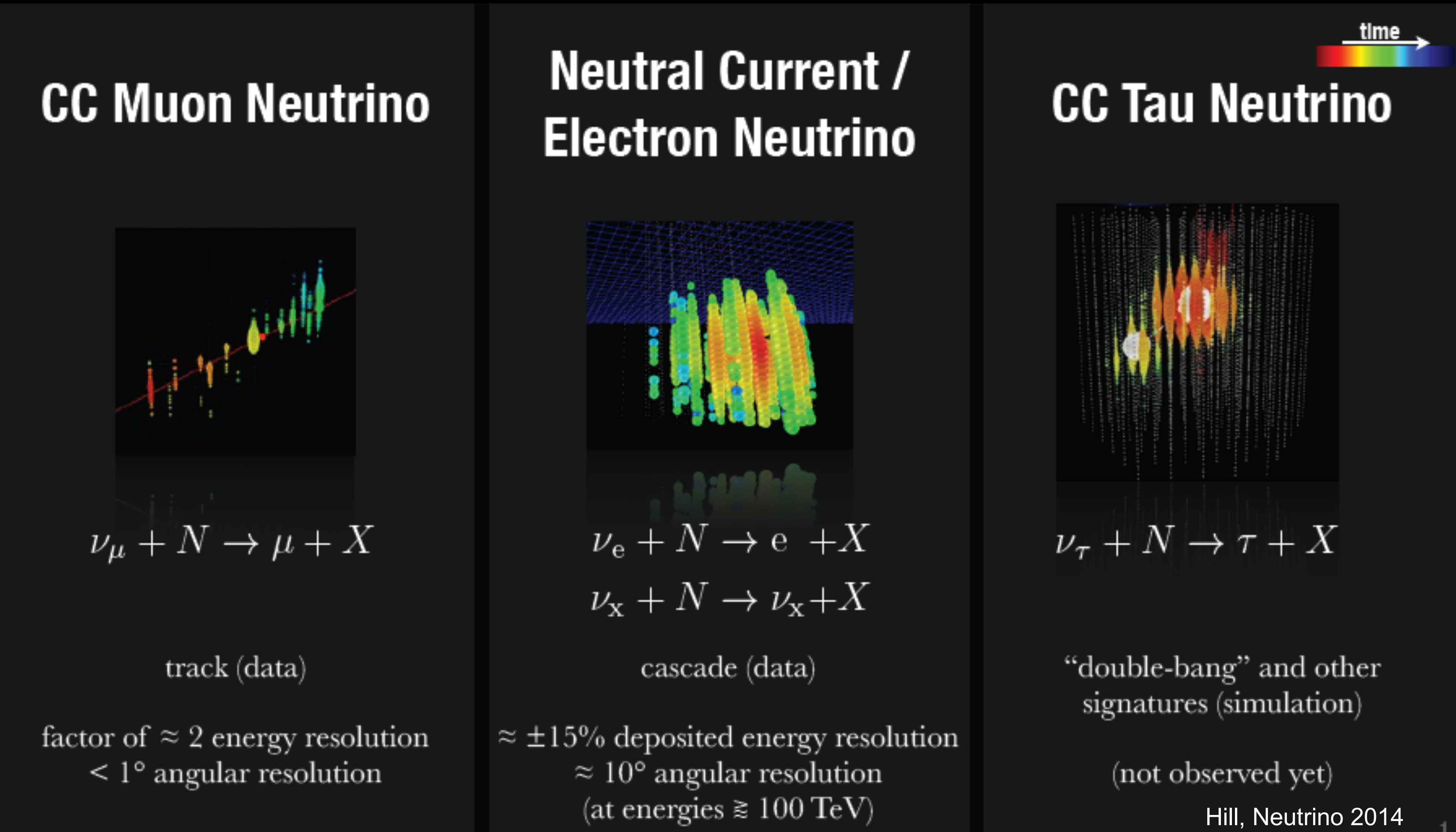

digital optical module (DOM)




optical sensor deployment

# 1. IceCube detector

Topology
- Track = muon (~$\nu_\mu$CC)
- Shower (cascade) = electron, tau, hadrons (~, $\nu_e$CC, $\nu_\tau$CC, NC)




Hill, Neutrino 2014

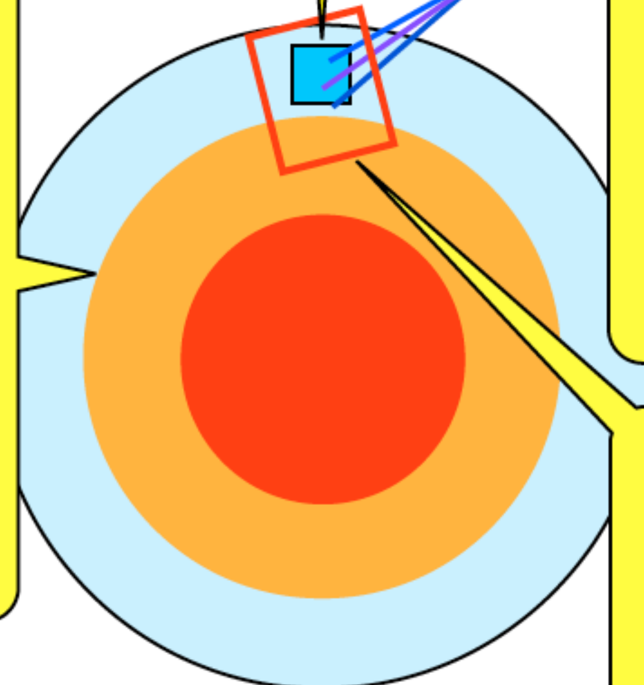
# 1. IceCube physics overview

Few MeV (supernova neutrinos) to
PeV (VHE astrophysical neutrinos)

## Why NuGen III ?

I want to use
Genie at detector!

I want to compare effect of In-Earth propagation with various EarthModel or neutrino cross section, while keeping near-detector simulation unchanged!



I want to use CORSIKA as neutrino source and want to simulate muon - neutrino coincidence events!

I need only near-detector simulation because I use my own (oscillation) calculation for in Earth propagation !

Well... yes, I can implement them,
but future NuGen maintainers will cry... :(
(NuGen is complicated enough already!)

Hoshina, 2013

# 1. IceCube physics overview

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

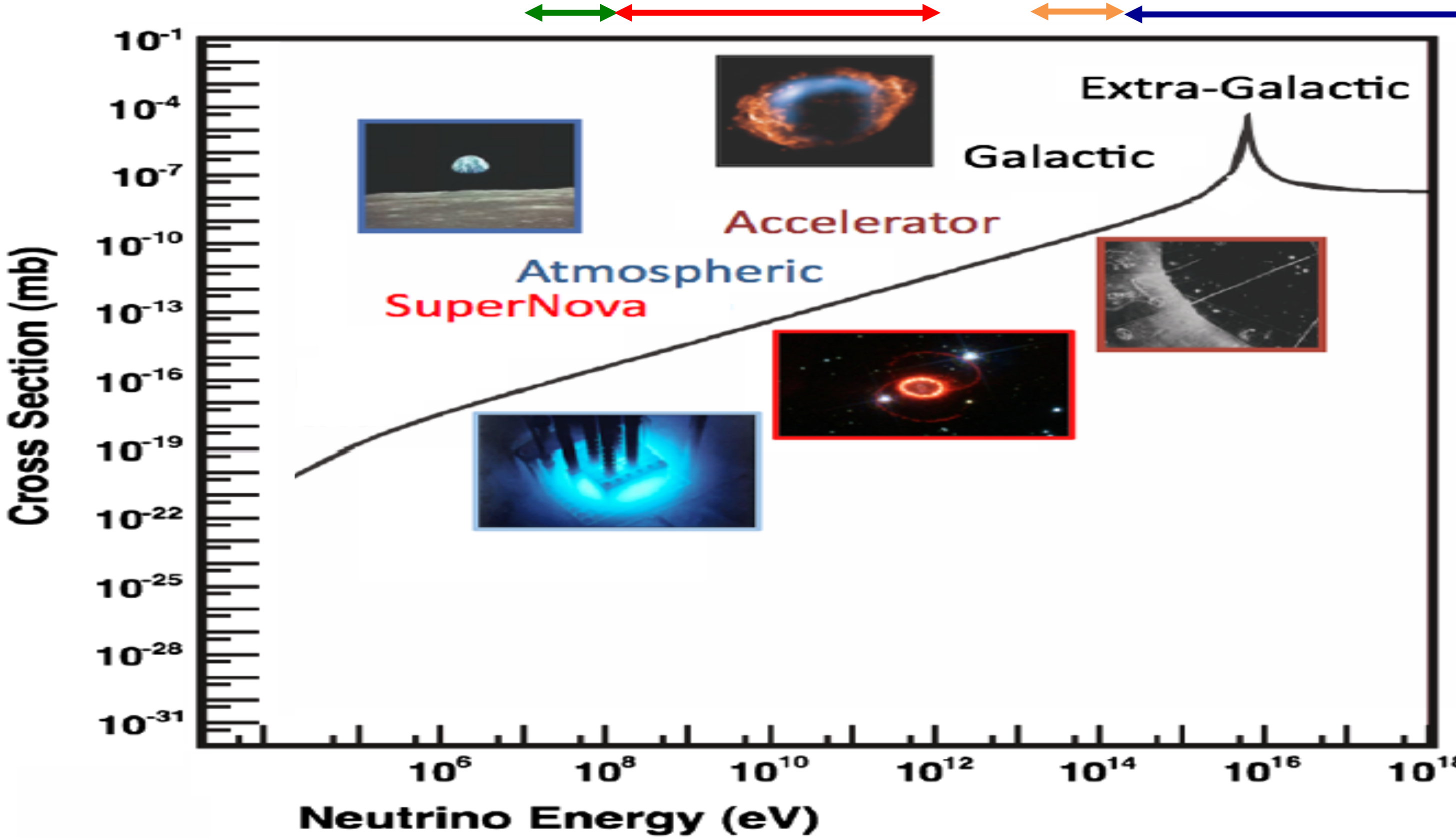
Bermuda triangle of IceCube
- 300 GeV - 10 TeV
- Too high for ionization, too low for stochastic energy reconstruction

**GENIE region**
- 100 MeV -300 GeV
- Conventional atmospheric neutrinos ($\pi$, K decay)
- Oscillation physics

**Confusion region**
- 10 TeV – 100 TeV
- Prompt atmospheric neutrinos (charm)
- Earth absorption starts
- Astrophysical neutrinos kicks in
- NNLO PDF and weak boson propagator suppression ($Q^2 >> M_W^2$), interplay with LHC

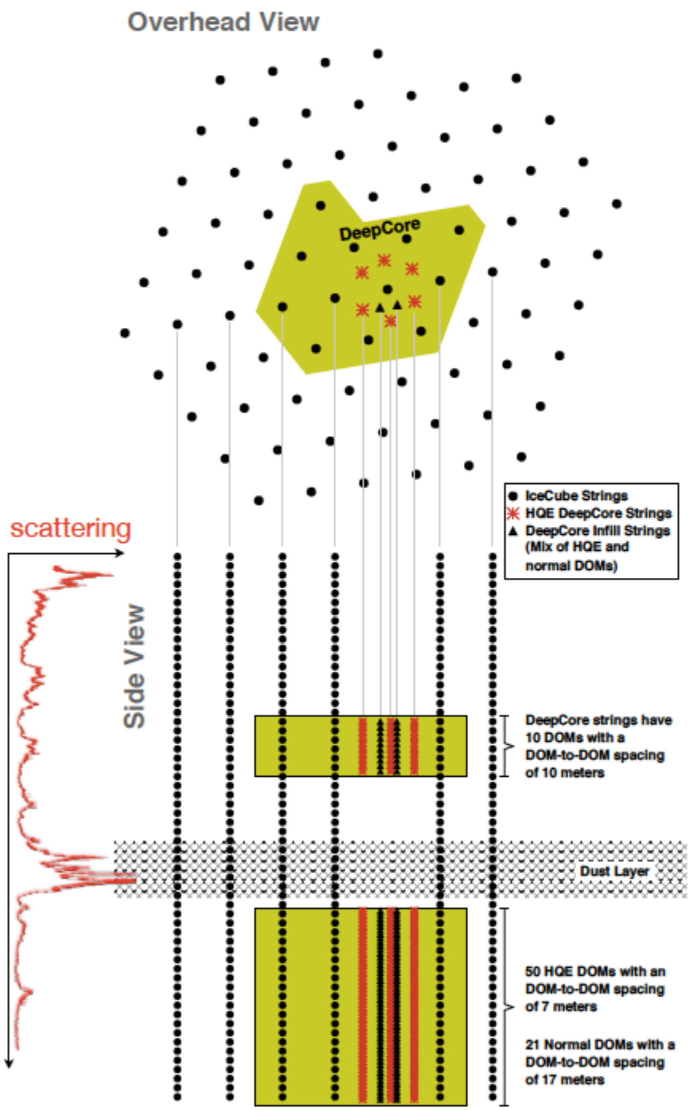
**Noise-like event**
- 10-100 MeV
- DSNB flux
- nuclear physics may be important

**Neutrino Astronomy Frontier**
- >100 TeV
- Astrophysical neutrinos
- BSM physics



1. IceCube neutrino observatory
2. **IceCube low energy physics**
3. DIS-Hadronization systematic errors
4. DIS quark-hadron duality error
5. DIS differential cross section error
6. DIS A-scaling error
7. DIS PDF error
8. Low-W hadronization error
9. High-W hadronization error
10. Conclusions

# 2. DeepCore



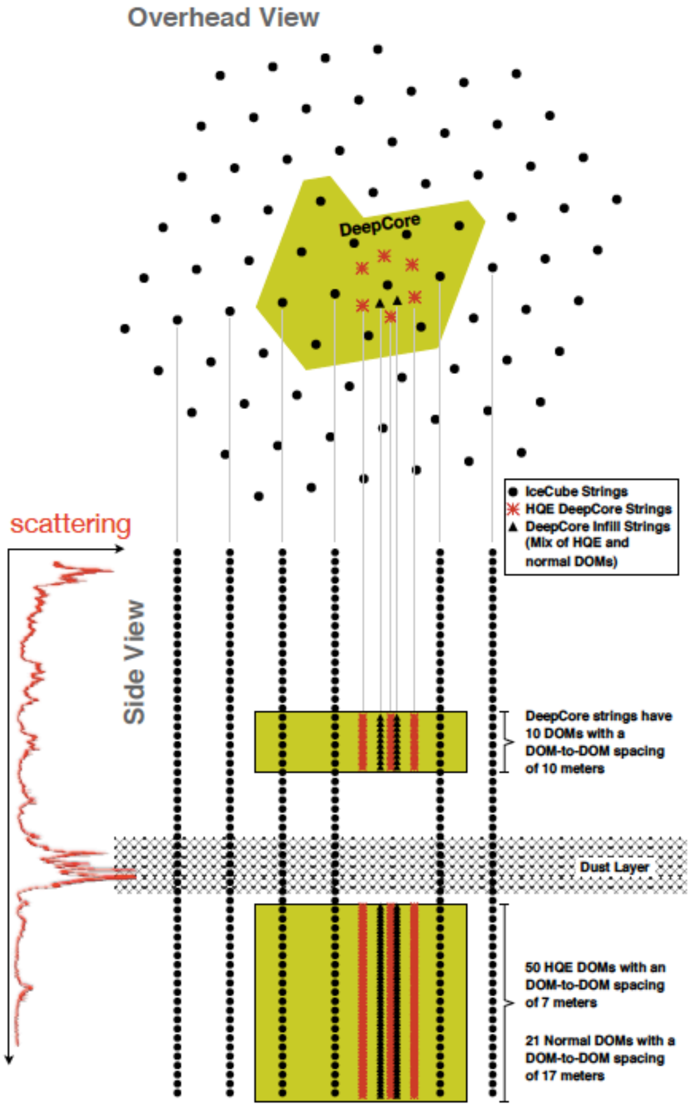

IceCube: 78 string, 125m string separation, 17m vertical DOM separation.

DeepCore: 8 new strings, ~75m separations, with 7m vertical DOM separation.

DeepCore is designed for low energy physics (<300 GeV). It can also push the threshold as low as 6 GeV, but this depends location of vertex and direction of events.

| 20 GeV | Track | Cascade |
|---|---|---|
| $\Delta E$ | 24% | 29% |
| $\Delta\theta$ | 10$^o$ | 16$^o$ |

# 2. DeepCore

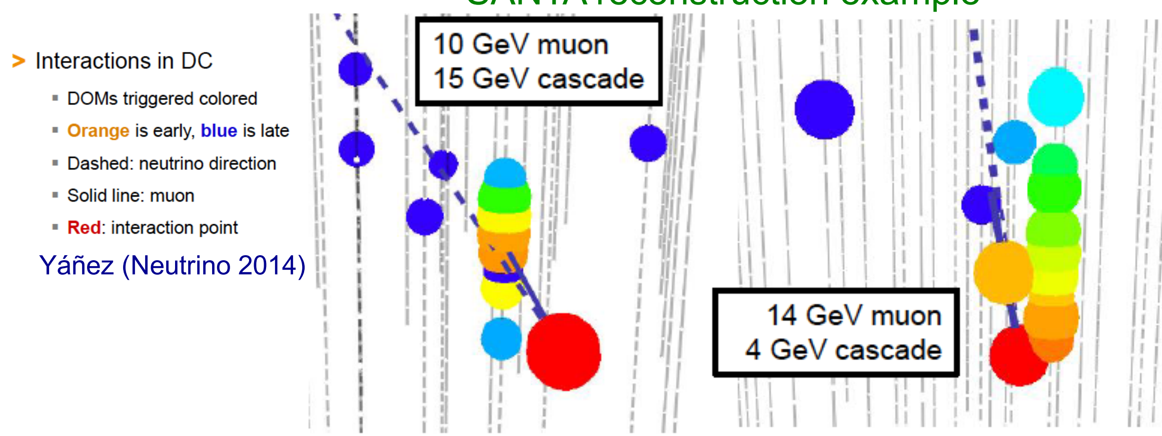



Information is very sparse for low energy neutrino reconstruction in IceCube

SANTA (2014 oscillation result)
- Simple algorithm based on Cherenkov profile
- less model dependent, only works for high angle events

Multinest (2017 oscillation result)
- High-level algorithm based on photon table
- highly model dependent (?)

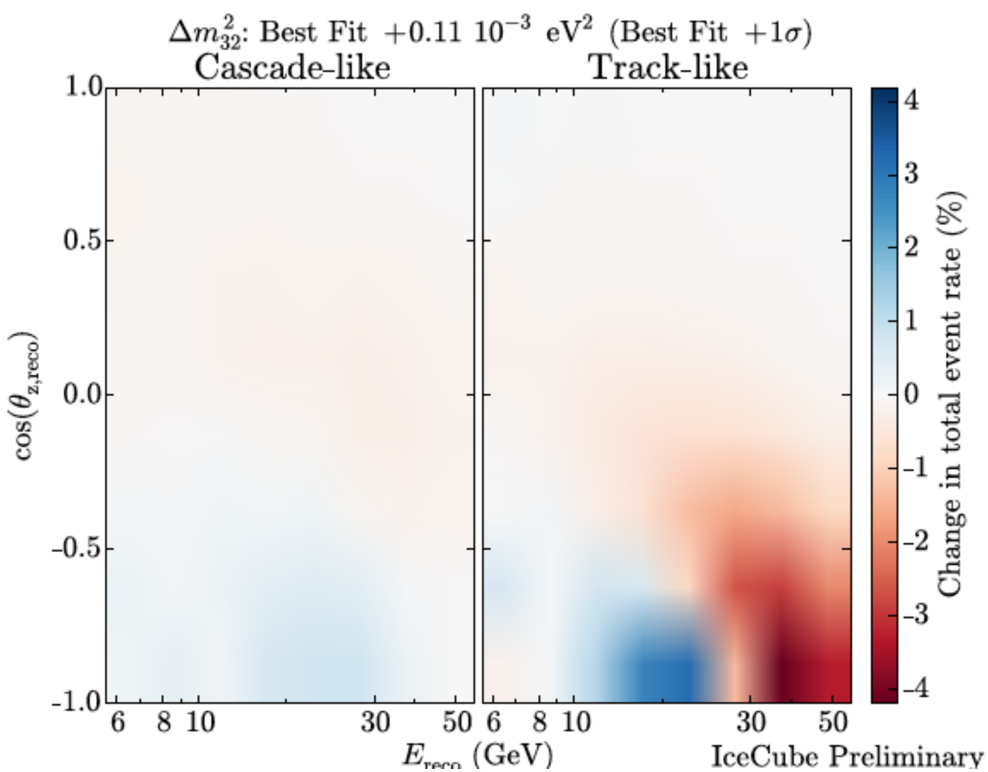
SANTA reconstruction example

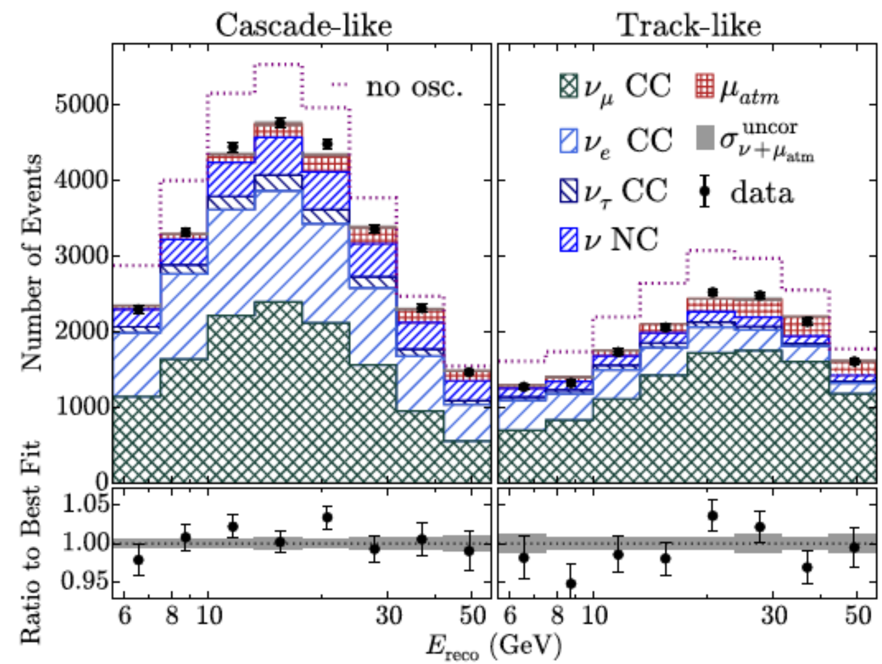



| 20 GeV | Track | Cascade |
|---|---|---|
| ΔE | 24% | 29% |
| Δθ | 10° | 16° |

# 2. DeepCore oscillation analysis

Oscillation fit is dominated around ~30 GeV neutrinos
- majority of events, > 10 GeV
- event peak around 15 -25 GeV




| 20 GeV | Track | Cascade |
|---|---|---|
| ΔE | 24% | 29% |
| Δθ | 10° | 16° |

# 2. DeepCore oscillation analysis

Oscillation fit is dominated around ~30 GeV neutrinos
- majority of events, > 10 GeV
- event peak around 15 -25 GeV

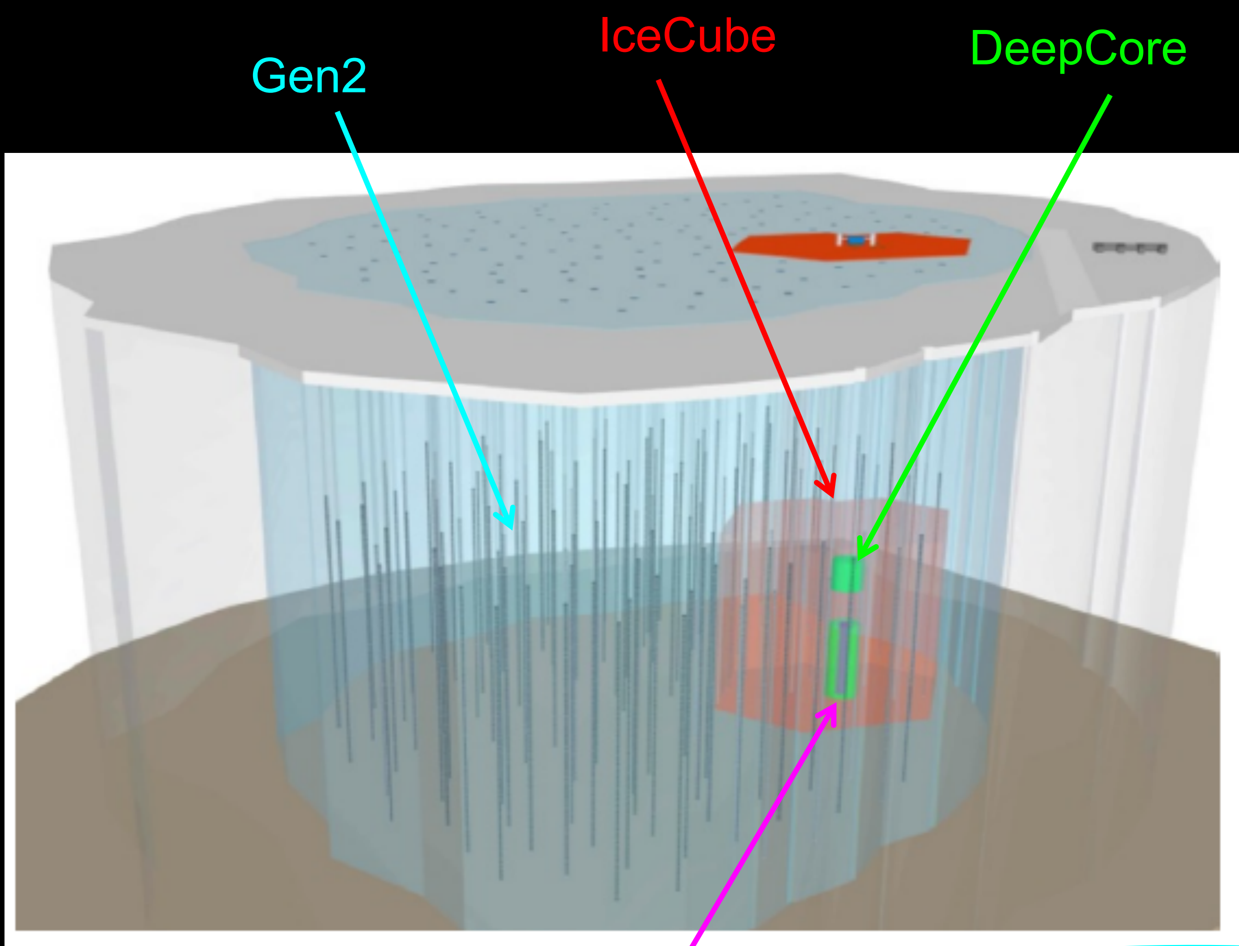
Systematic errors are mostly flux and detectors.

Future PINGU experiment (>2 GeV) will be sensitive to neutrino interaction systematics.

From here, I will discuss neutrino interaction systematics of future 2-10 GeV experiments (NOvA, DUNE, HyperK, PINGU, ORCA, INO, etc)

| Parameters | Priors | Best fit NO | Best fit IO |
|---|---|---|---|
| Flux and cross-section parameters | | | |
| Neutrino event rate [% of nominal] | No prior | 85 | 85 |
| $\Delta\gamma$ (spectral index) | $0.00 \pm 0.10$ | −0.02 | −0.02 |
| $M_A$ (resonance) [GeV] | $1.12 \pm 0.22$ | 0.92 | 0.93 |
| $\nu_e + \bar{\nu}_e$ relative normalization [%] | $100 \pm 20$ | 125 | 125 |
| NC relative normalization [%] | $100 \pm 20$ | 106 | 106 |
| Hadronic flux, energy dependent [$\sigma$] | $0.00 \pm 1.00$ | −0.56 | −0.59 |
| Hadronic flux, zenith dependent [$\sigma$] | $0.00 \pm 1.00$ | −0.55 | −0.57 |
| Detector parameters | | | |
| Overall optical efficiency [%] | $100 \pm 10$ | 102 | 102 |
| Relative optical efficiency, lateral [$\sigma$] | $0.0 \pm 1.0$ | 0.2 | 0.2 |
| Relative optical efficiency, head-on [a.u.] | No prior | −0.72 | −0.66 |
| Background | | | |
| Atm. $\mu$ contamination [% of sample] | No prior | 5.5 | 5.6 |

# 2. IceCube-Gen2 and PINGU




Bigger IceCube and denser DeepCore can push their physics

High Energy Extension
Larger string separations to cover larger area

PINGU
Smaller string separation to achieve lower energy threshold for neutrino mass hierarchy measurement

PINGU $E_{th}$ ~2 GeV (6 GeV for MSW oscillation max for mass hierarchy

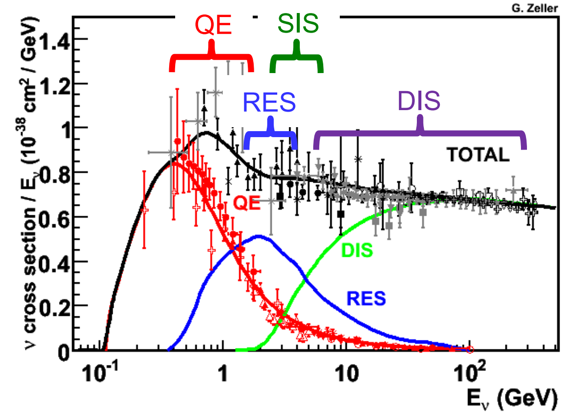
# 2. PINGU

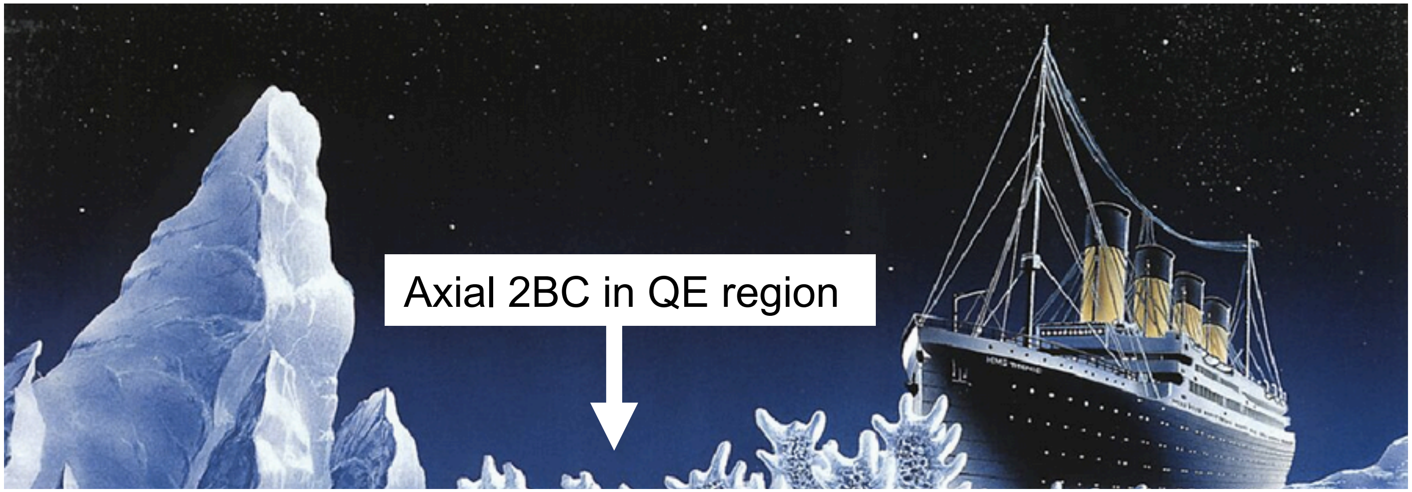
Oscillation fit is dominated around ~30 GeV neutrinos
- majority of events, > 10 GeV
- event peak around 15 -25 GeV

1. IceCube neutrino observatory
2. IceCube low energy physics
3. **DIS-Hadronization systematic errors**
4. DIS quark-hadron duality error
5. DIS differential cross section error
6. DIS A-scaling error
7. DIS PDF error
8. Low-W hadronization error
9. High-W hadronization error
10. Conclusions

# 3. Beyond QE peak

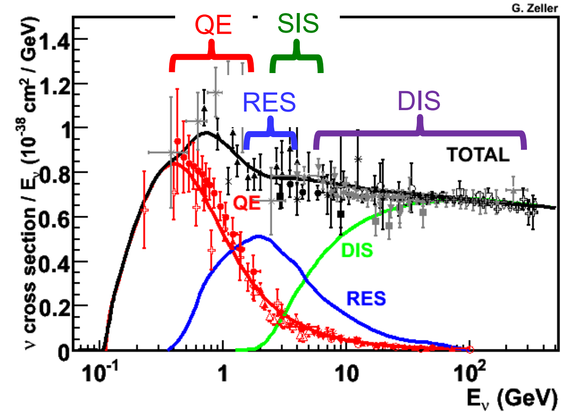
Axial 2-body current in QE region may be a tip of the iceberg…

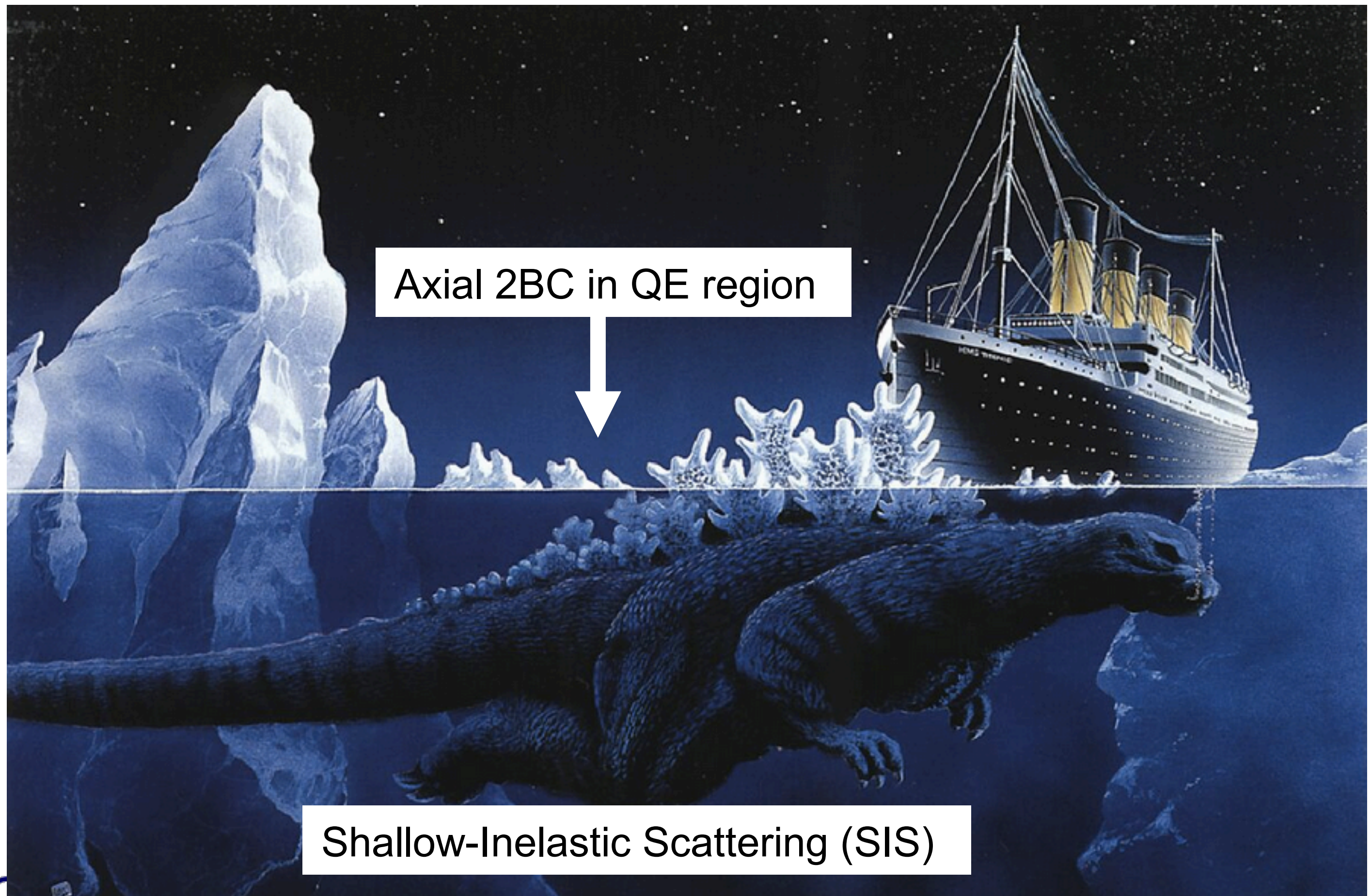


# 3. Beyond QE peak

Axial 2-body current in QE region may be a tip of the iceberg…, or maybe a tip of gozilla!



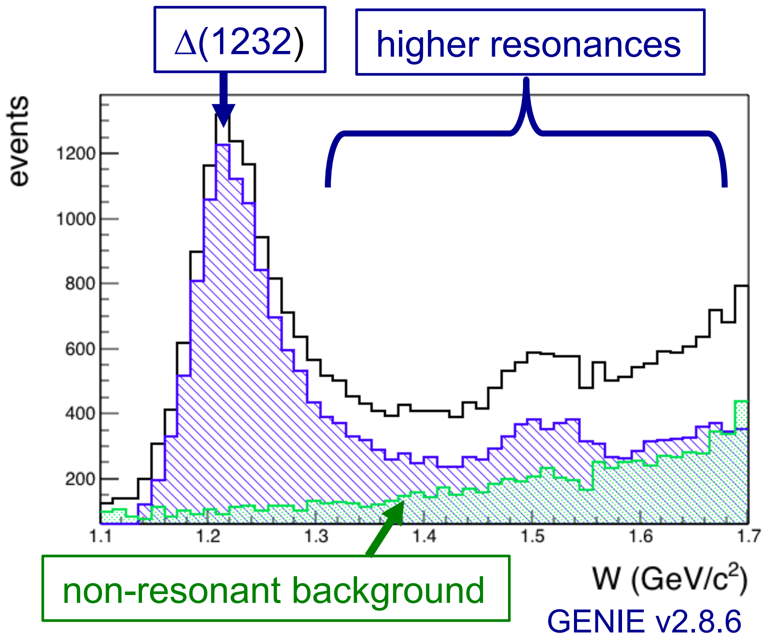



traditionally called "transition" region

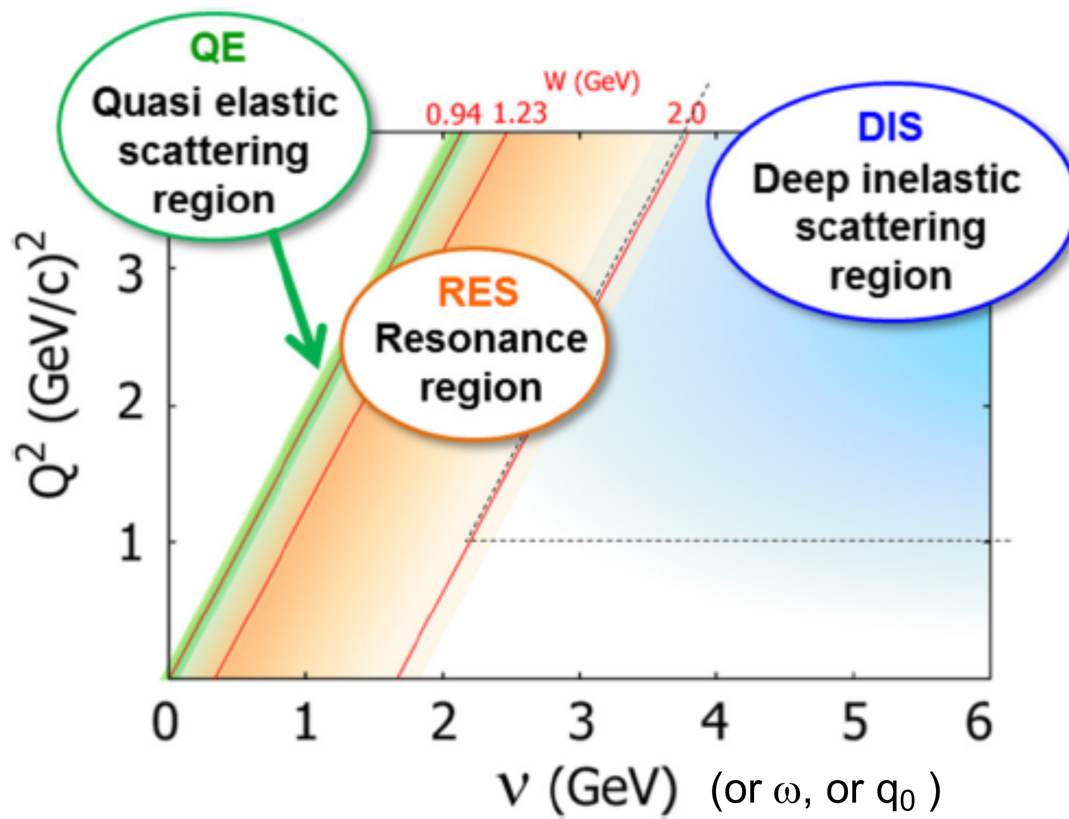
# 3. Sallow Inelastic Scattering (SIS) physics

Basic ingredients
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS

my talk




Rep. Prog. Phys. **80** (2017) 056301



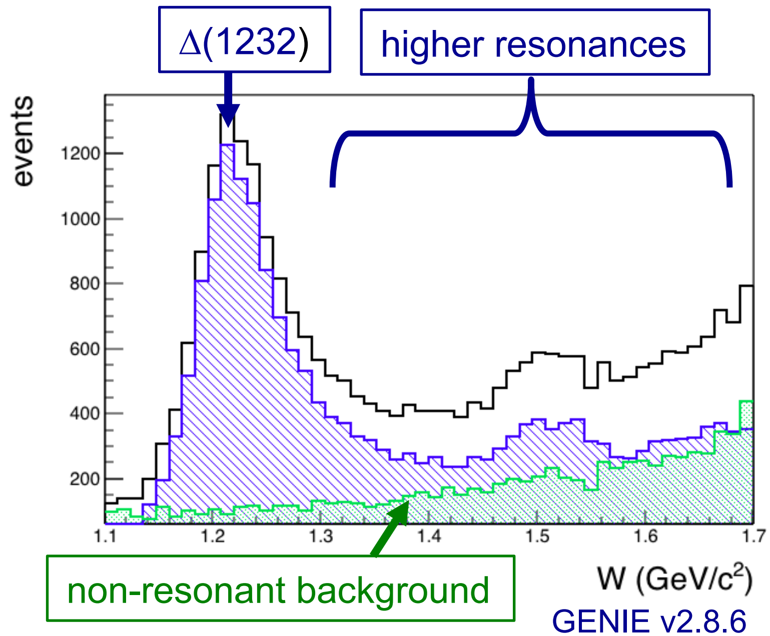
traditionally called “transition” region

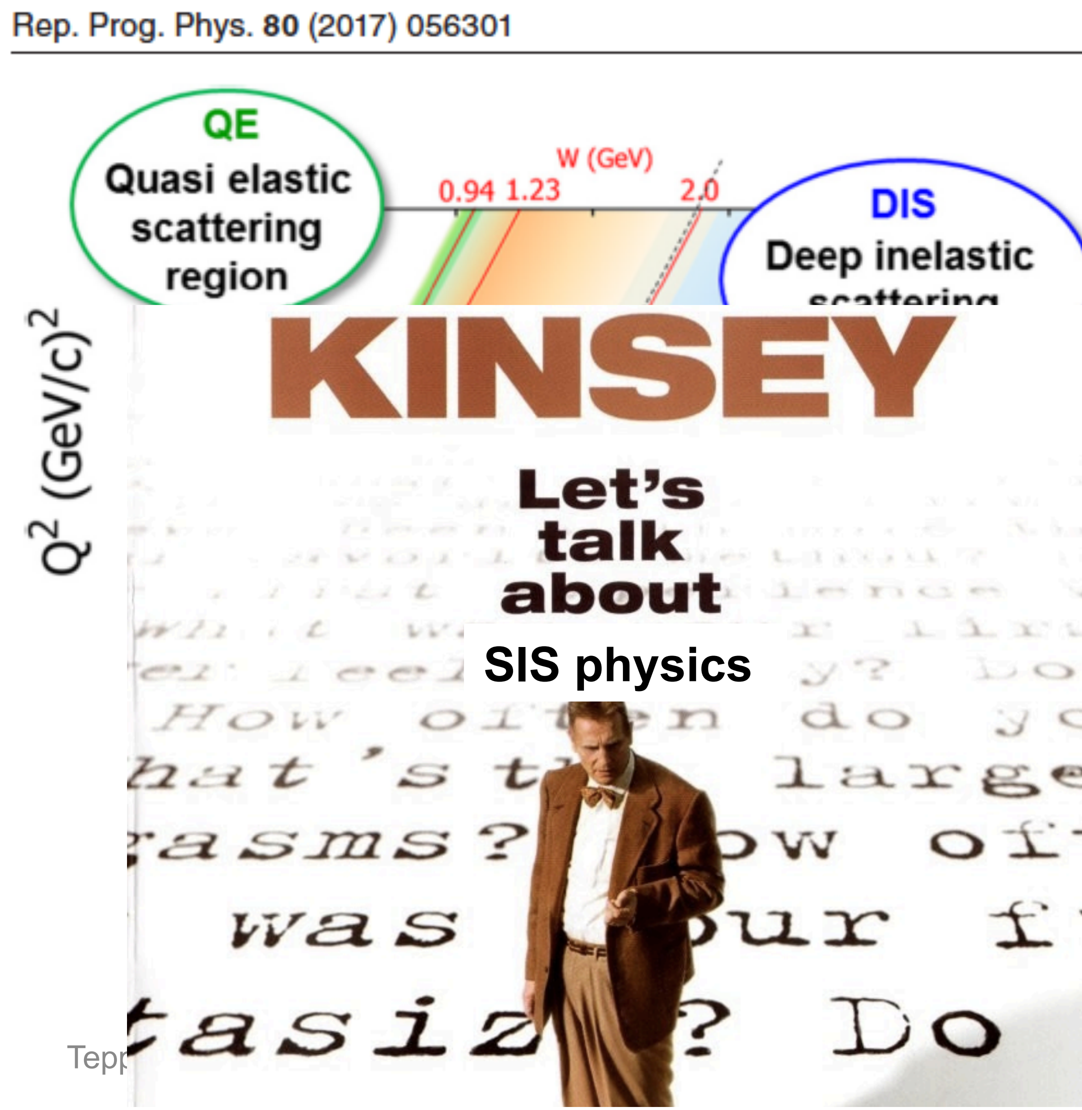
# 3. Sallow Inelastic Scattering (SIS) physics

Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS

my talk




Queen Mary
University of London

# 3. Sallow Inelastic Scattering (SIS) physics, summary

## Basic ingredients

1. $\Delta$(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS

} my talk (items 4 and 5)

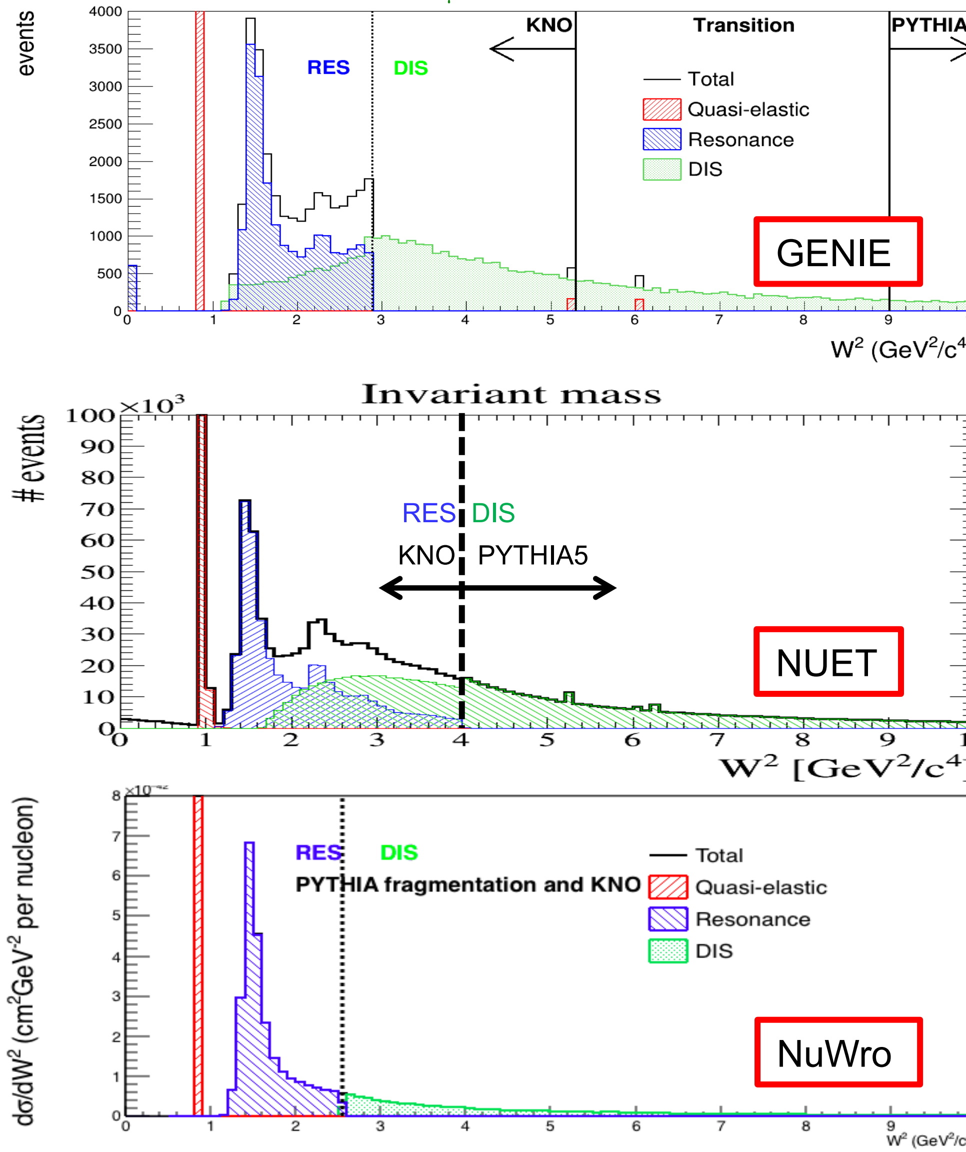
Generators show large disagreement for SIS models, also none of them look right

This talk will discuss potential errors of DIS and hadronization at 2-10 GeV region.

Most of studies are done by Shivesh (PhD student) and master students

**SIS is the home of Frankenstein models!**

Neutrino interaction generator comparison
(atmospheric $\nu_\mu$-$H_2O$ CC interaction)



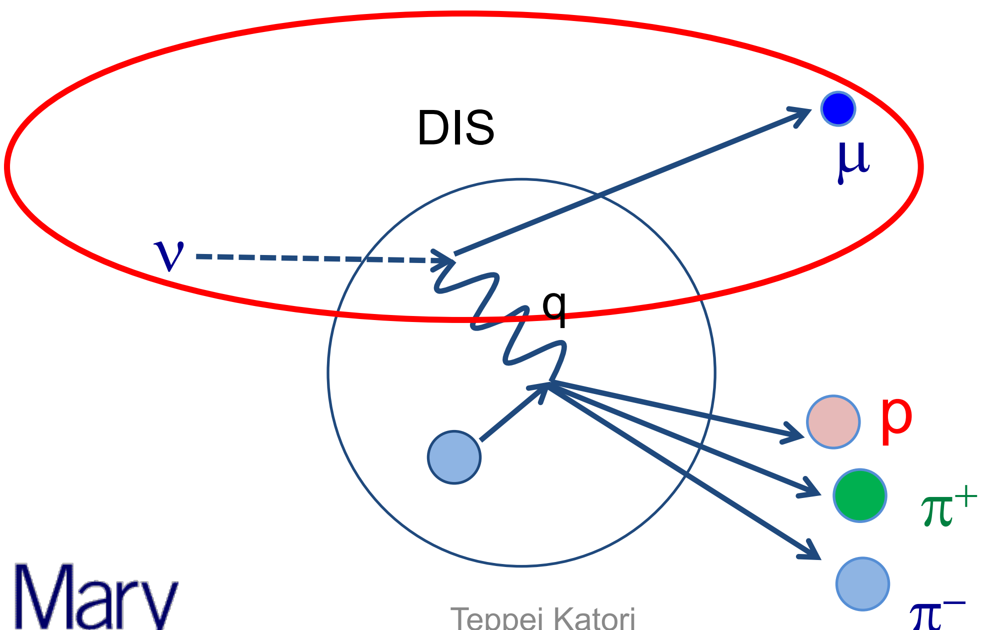

Queen Mary
University of London

Tep

# 3. Neutrino cross section overview

Deep Inelastic Scattering (DIS)

- a process to scatter a charged lepton by an incident lepton with given energy
- DIS differential cross section is function of x and y
- DIS total cross section is function of $E\nu$, integrated in x and y



# 3. Neutrino cross section overview

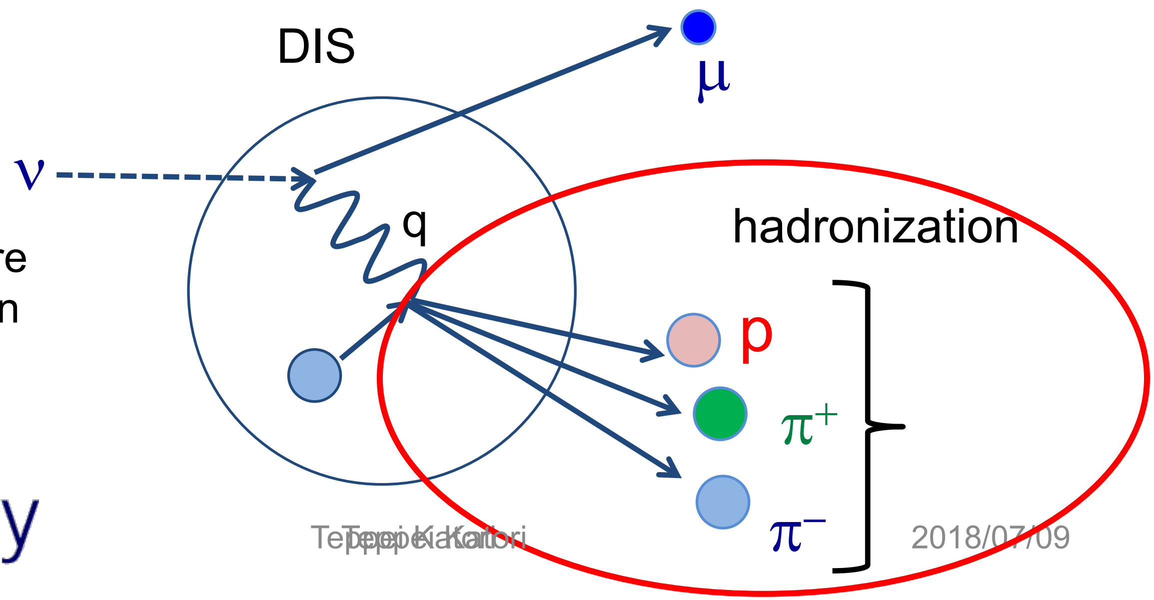
Deep Inelastic Scattering (DIS)

- a process to scatter a charged lepton by an incident lepton with given energy
- DIS differential cross section is function of x and y
- DIS total cross section is function of E$\nu$, integrated in x and y

Hadronization

- Hadronization is a process to generate hadrons from given $Q^2$ and W
- number of hadrons (multiplicity) and hadrons kinematics are computed.

DIS and Hadronization are modelled independently in simulation




Queen Mary University of London

# 3. Neutrino cross section overview

## Deep Inelastic Scattering (DIS)

- a process to scatter a charged lepton by an incident lepton with given energy
- DIS differential cross section is function of x and y
- DIS total cross section is function of Eν, integrated in x and y

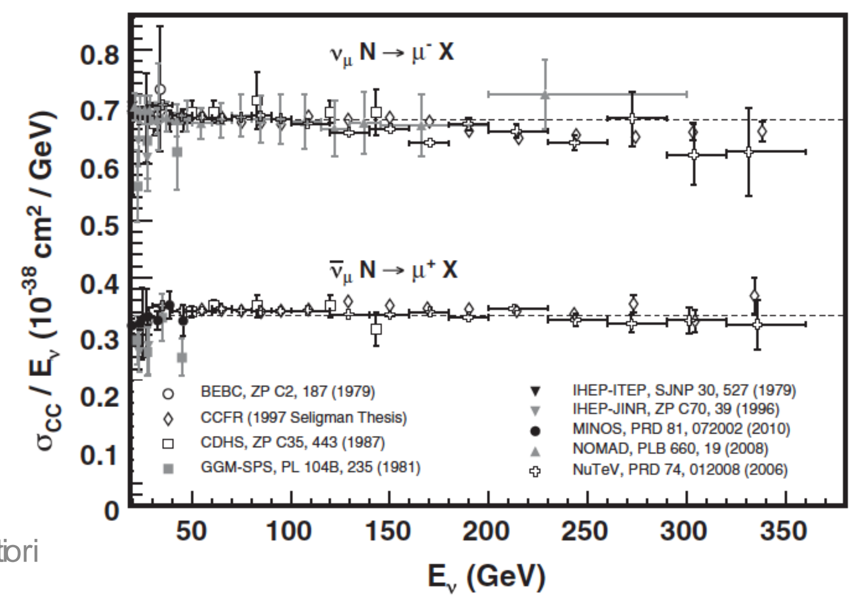
## Hadronization

- Hadronization is a process to generate hadrons from given $Q^2$ and W
- number of hadrons (multiplicity) and hadrons kinematics are computed.

- $\sigma(\nu)/E = 0.677 \pm 0.014 \times 10^{-38}$ ($cm^2$/GeV)

## DIS total cross section error ~ 2%?

- This is the error of CCDIS total cross section at 30 to 200 GeV
- Most of our analyses need errors of differential cross section error



# 3. DIS-hadronization error check list

- Goal is to make event weight with function of Ev, x, y, etc, for IceCube oscillation program
- All errors are expected to be unimportant for DeepCore oscillation analysis (?)

| DIS or Hadronization | type of error | approach | size |
|---|---|---|---|
| DIS | quark-hadron duality | play with Bodek-Yang parameters (by eyes) | ??? |
| DIS | differential xs | NuTeV-GENIE comparison (bottom-up) | ??? |
| DIS | A-scaling | MINERvA-GENIE (bottom-up) | ??? |
| DIS | PDF | From nuclear PDF, CT10? nCTEQ? (top-down) | ??? |
| Hadronization | low W averaged charged hadron multiplicity | play with KNO parameters (by eyes) | ??? |
| Hadronization | high W averaged charged hadron multiplicity | bubble chamber-PYTHIA comparison (bottom-up) | ??? |

1. IceCube neutrino observatory

2. IceCube low energy physics

3. DIS-Hadronization systematic errors

**4. DIS quark-hadron duality error**

5. DIS differential cross section error

6. DIS A-scaling error

7. DIS PDF error

8. Low-W hadronization error

9. High-W hadronization error

10. Conclusions

Bodek and Yang, AIP.Conf.Proc.670(2003)110,Nucl.Phys.B(Proc.Suppl.)139(2005)11

# 4. Bodek-Yang correction for low $Q^2$ DIS

GRV98 is a PDF designed for low Q2 region. Bodek-Yang correction makes GRV98 to work even lower Q2, or “duality” region by adding higher twist effect

- A: high order twist correction
- B: quark transverse momentum
- Cvu1, Cvu2: valence u-quark PDF correction
- Cvd1, Cvd2: valence d-quark PDF correction
- Cs1u, Cs1d: sea u- and d-quark PDF correction
- x0, x1, x2: d(x)/u(x) correction

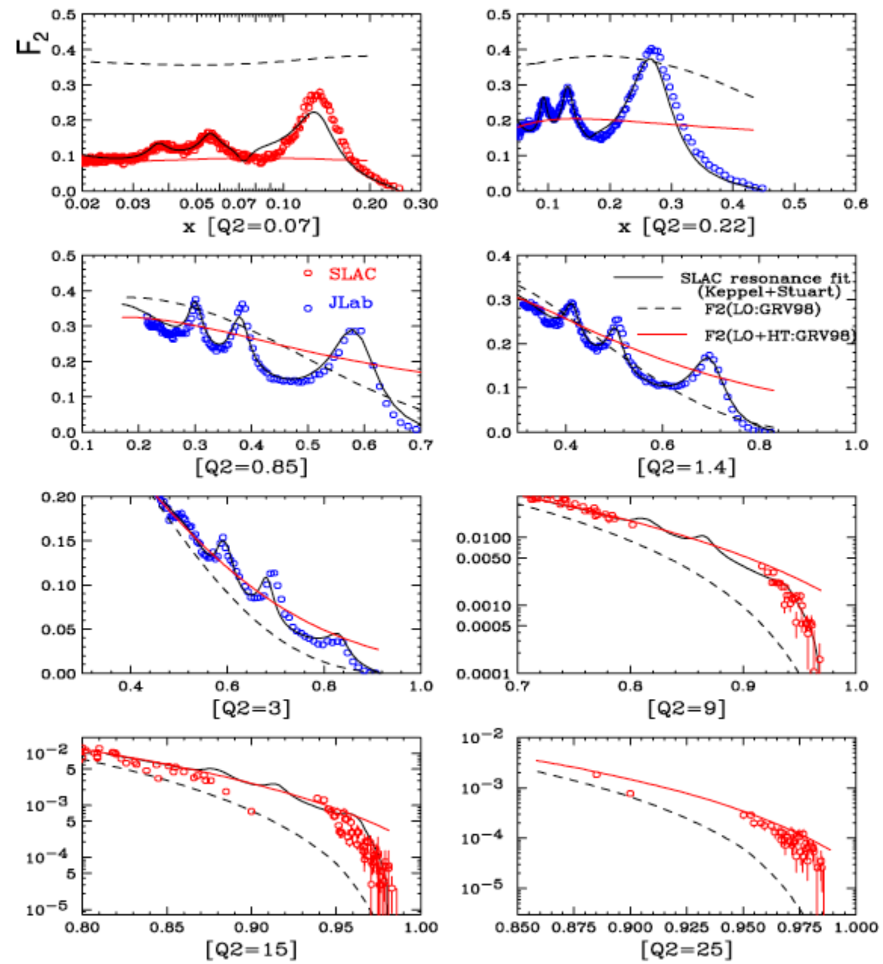
Nachtmann variable

$$\xi \rightarrow \xi_\omega = \frac{2x\left(1+\frac{M_f^2+B}{Q^2}\right)}{\left(1+\sqrt{1+\frac{4x^2M^2}{Q^2}}\right)+\frac{2Ax}{Q^2}}$$

$$K_{valence}(Q^2) = [1-G_D^2(Q^2)]\cdot\left(\frac{Q^2+C_{v2}}{Q^2+C_{v1}}\right)$$

$$K_{sea}(Q^2) = \frac{Q^2}{Q^2+C_{s1}}$$

Proton F2 function GRV98-BY correction vs. data




PINGU LoI variations

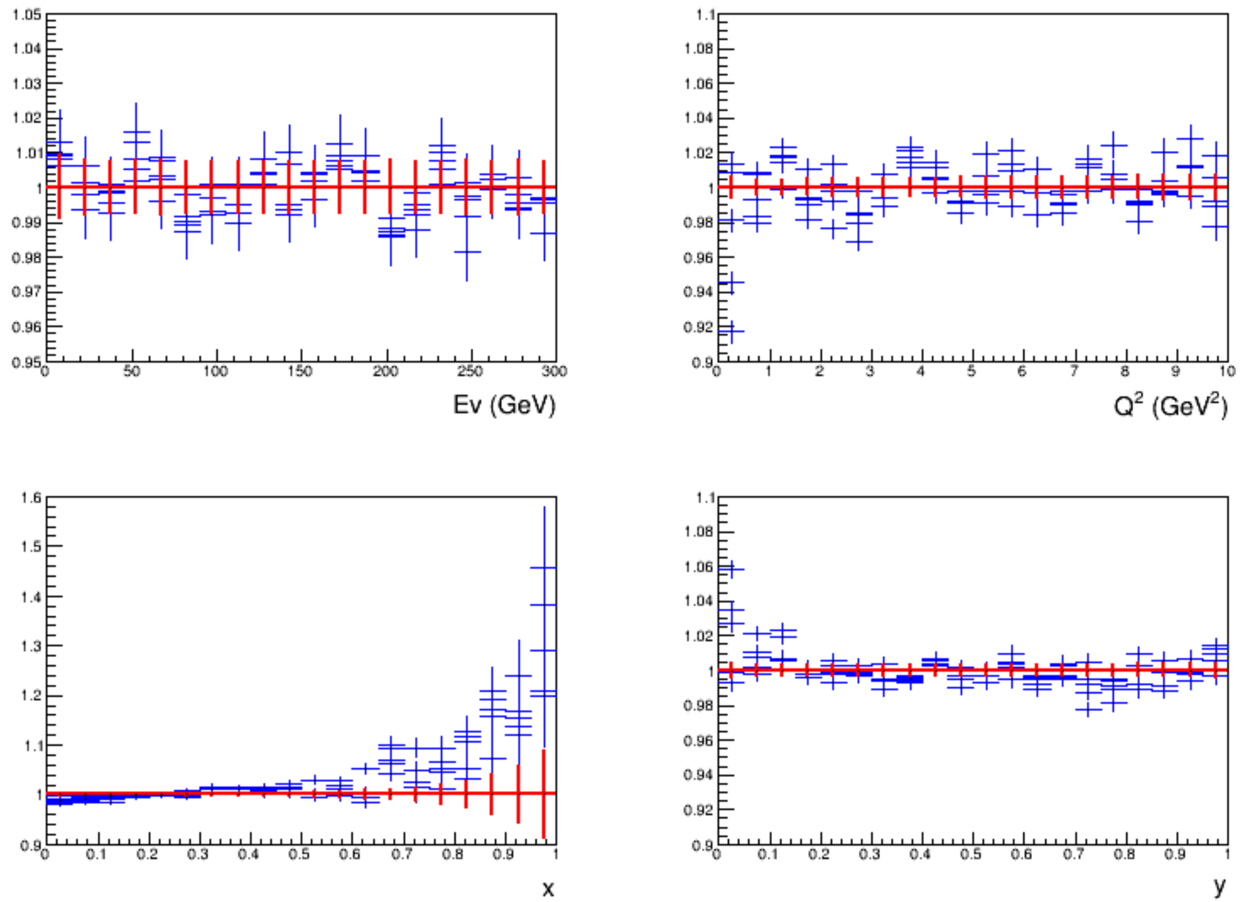
| Name | nominal value | uncertainty (%) |
|---|---|---|
| $M_A^{CCQE}$ | 0.99 | −15, +25 |
| $M_A^{RES}$ | 1.120 | ±20 |
| $A_{HT}^{BY}$ | 0.538 | ±25 |
| $B_{HT}^{BY}$ | 0.305 | ±25 |
| $C_{V1u}^{BY}$ | 0.291 | ±30 |
| $C_{V2u}^{BY}$ | 0.189 | ±30 |

# 4. Systematic errors of Bodek-Yang correction parameters

BY parameter variation make small variations in Ev. Q2, x, y.
- Ev: <2% variation in all region
- Q2: ~8% variation at Q2=0.5 GeV2
- x: ~50% variation at x~1
- y: ~6% variation at y~0

Errors of parameters are quoted without any correlations.

Variations can be large by assuming correlations on these parameters.




Queen Mary
University of London

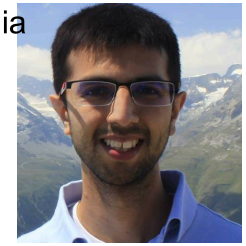
# 4. DIS quark-hadron duality error, summary

Lack of correlations between BY parameters make impossible to estimate meaningful error
→ First of all, we need to update Bodek-Yang correction with a modern PDF.

| DIS or Hadronization | type of error | approach | size |
|---|---|---|---|
| DIS | quark-hadron duality | play with Bodek-Yang parameters (by eyes) | maybe large? |
| DIS | differential xs | NuTeV-GENIE comparison (bottom-up) | ???? |
| DIS | A-scaling | MINERvA-GENIE (bottom-up) | ???? |
| DIS | PDF | From nuclear PDF, CT10? nCTEQ? (top-down) | ???? |
| Hadronization | low W averaged charged hadron multiplicity | play with KNO parameters (by eyes) | ???? |
| Hadronization | high W averaged charged hadron multiplicity | bubble chamber-PYTHIA comparison (bottom-up) | ???? |

1. IceCube neutrino observatory
2. IceCube low energy physics
3. DIS-Hadronization systematic errors
4. DIS quark-hadron duality error
5. **DIS differential cross section error**
6. DIS A-scaling error
7. DIS PDF error
8. Low-W hadronization error
9. High-W hadronization error
10. Conclusions

Shivesh Mandalia
(Queen Mary)

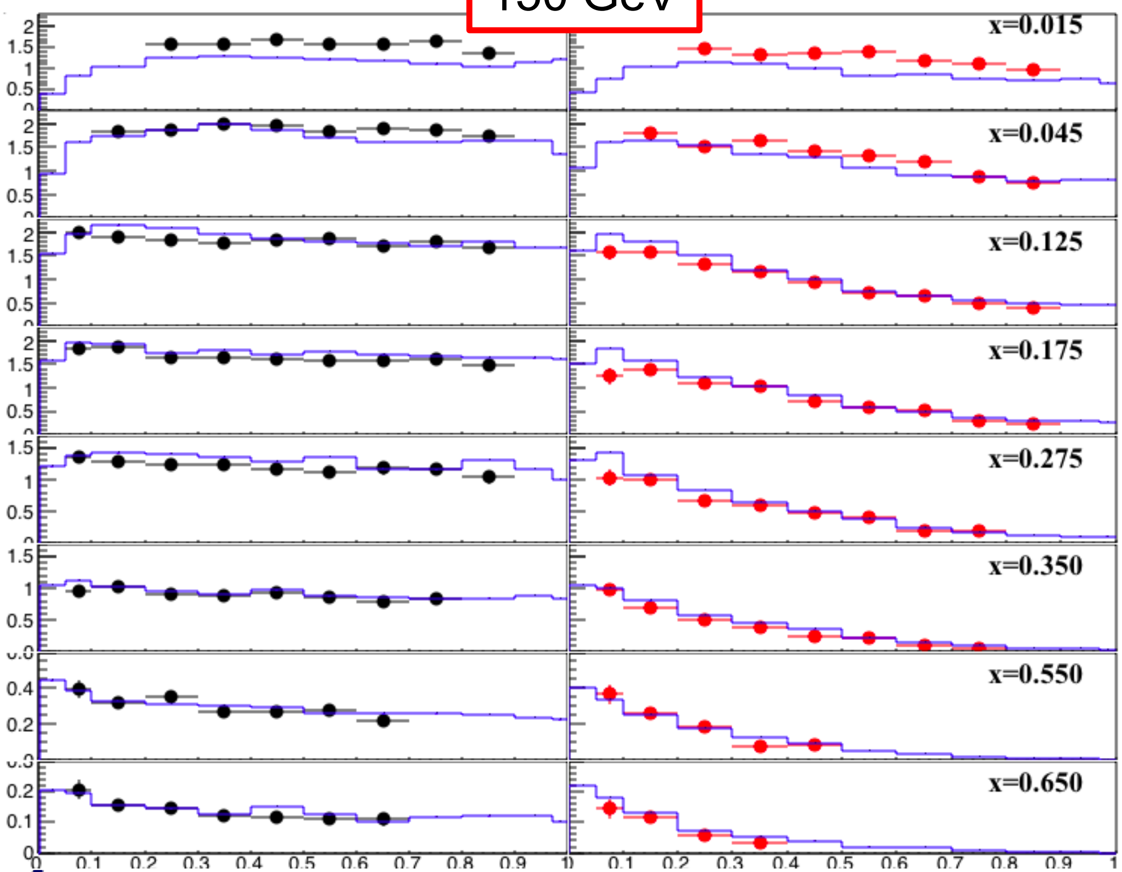


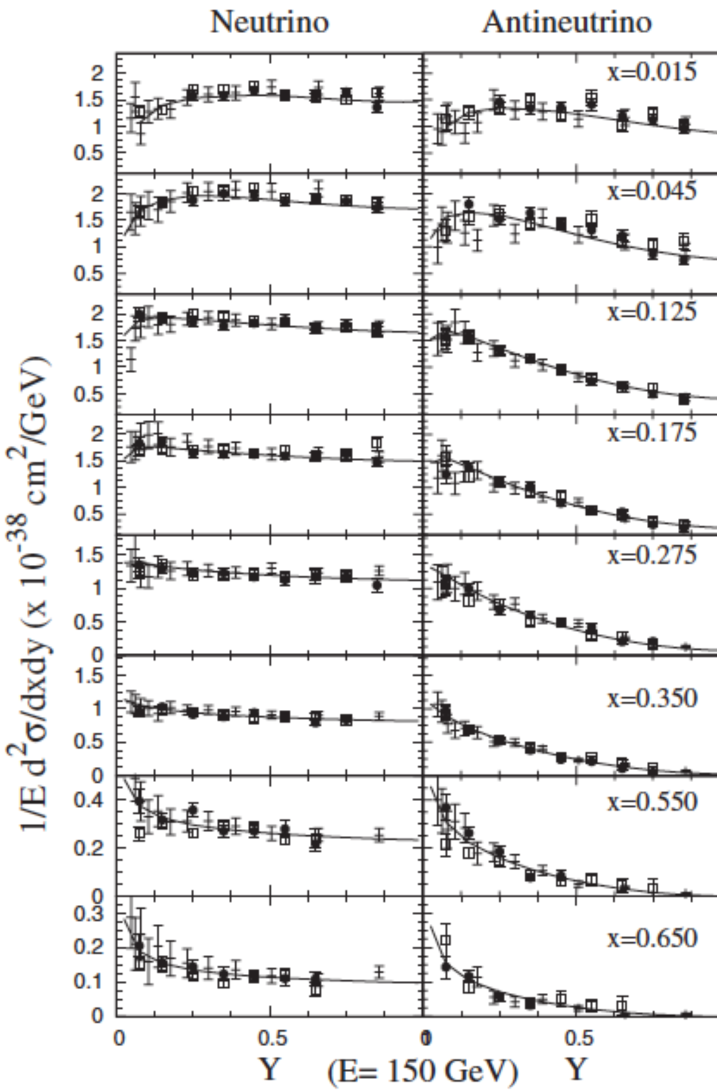
# 5. GENIE-NuTeV comparison

NuTeV ν-Fe and antiν-Fe
differential cross section (x, y, Eν)

GENIE v2.10.6
- By definition, GENIE reproduce NuTeV data
- Agreement at very low x is poor

150 GeV



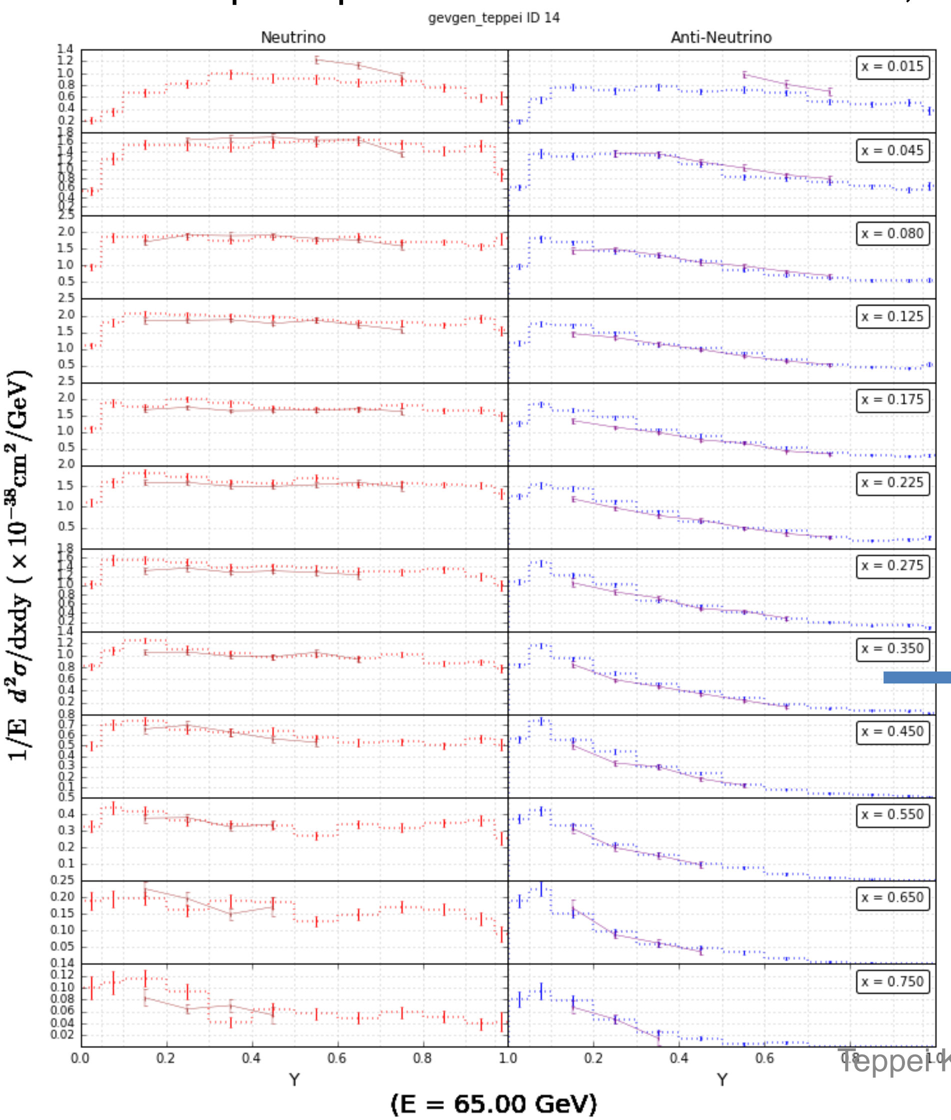



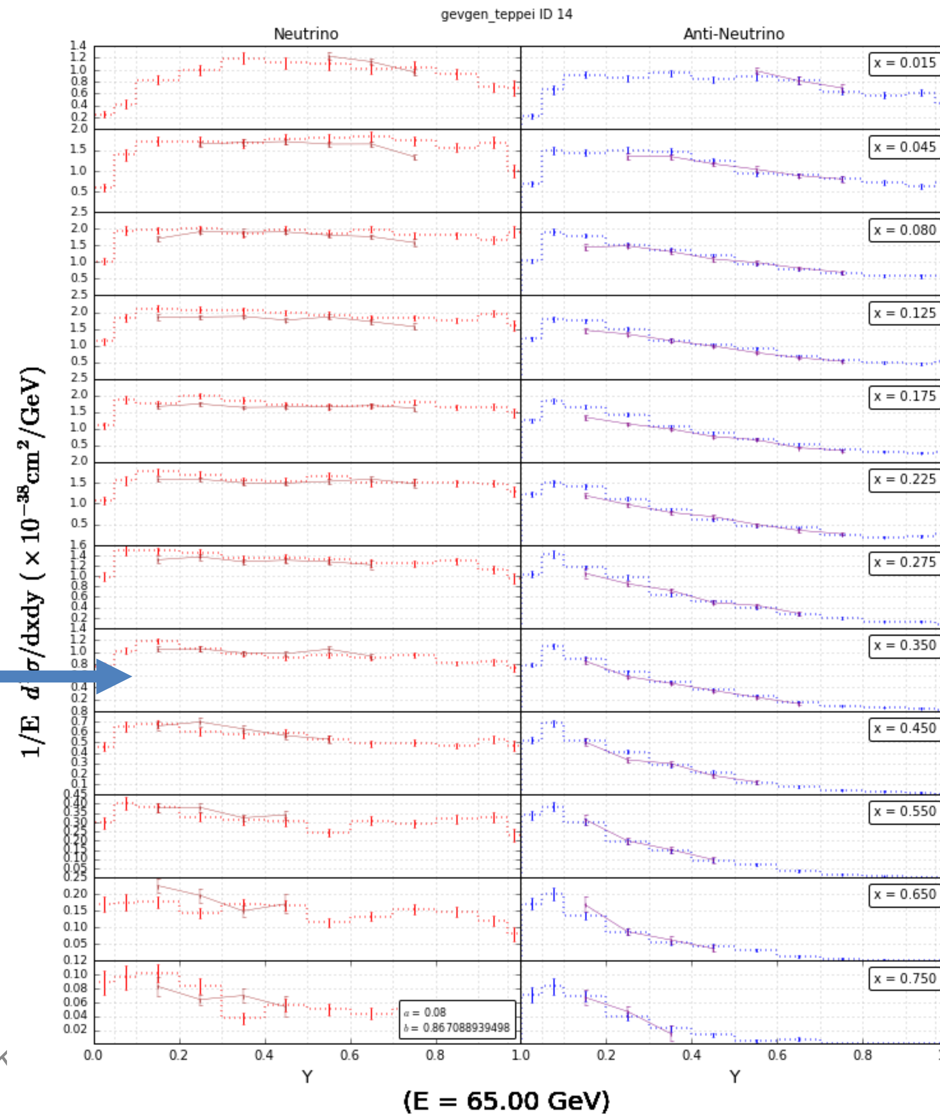
# 5. DIS differential cross section error

$$F(x,y) = bx^{-a}$$

## GENIE-NuTeV comparison

- simple 2-parameter model with a= 0.08, b=0.87 (for a trial)



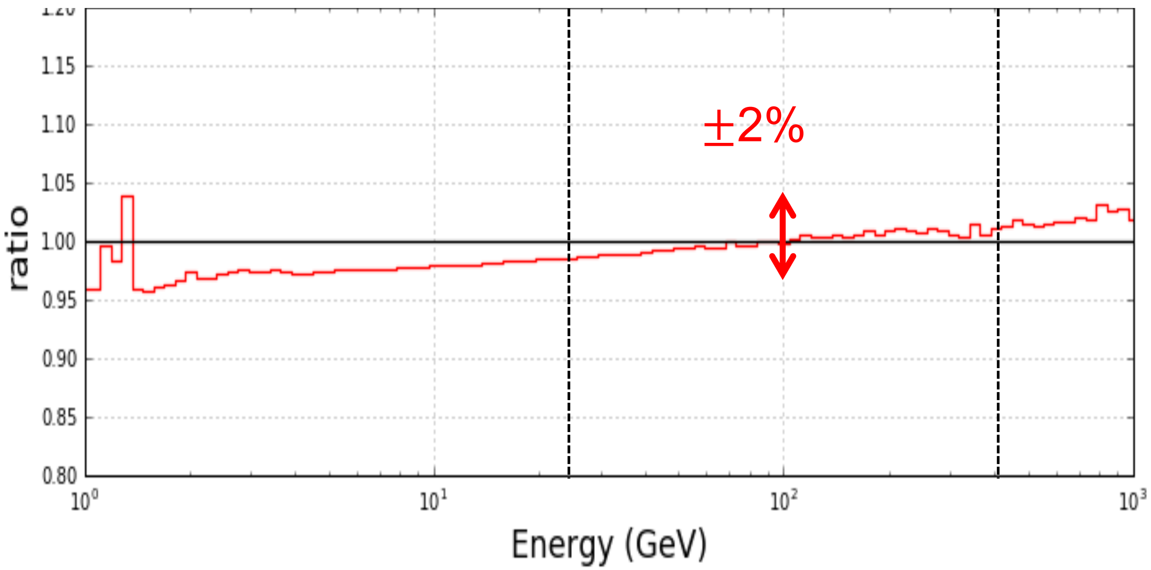



# 5. DIS differential cross section error

$$F(x, y) = bx^{-a}$$

GENIE-NuTeV comparison
- simple 2-parameter model with a= 0.08, b=0.87 (for a trial)
- it has 2-3% shift of energy spectrum in 30-200 GeV
- However, the shift (~error) is larger than ±2% at <10GeV and >300 GeV

Impact of low energy sample DIS re-weighting



# 5. DIS differential cross section error, summary

There may be ~3% energy scale error on DIS cross section below 10 GeV and negligible effect on current IceCube analysis. This error looks safe for any iron target experiments.

| DIS or Hadronization | type of error | approach | size |
|---|---|---|---|
| DIS | quark-hadron duality | play with Bodek-Yang parameters (by eyes) | maybe large? |
| DIS | differential xs | NuTeV-GENIE comparison (bottom-up) | 3% by GENIE study |
| DIS | A-scaling | MINERvA-GENIE (bottom-up) | ???? |
| DIS | PDF | From nuclear PDF, CT10? nCTEQ? (top-down) | ???? |
| Hadronization | low W averaged charged hadron multiplicity | play with KNO parameters (by eyes) | ???? |
| Hadronization | high W averaged charged hadron multiplicity | bubble chamber-PYTHIA comparison (bottom-up) | ???? |

1. IceCube neutrino observatory
2. IceCube low energy physics
3. DIS-Hadronization systematic errors
4. DIS quark-hadron duality error
5. DIS differential cross section error
6. **DIS A-scaling error**
7. DIS PDF error
8. Low-W hadronization error
9. High-W hadronization error
10. Conclusions

MINERvA,PRD93(2016)071101
HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028 ,nCTEQ, PRD80(2009)094004

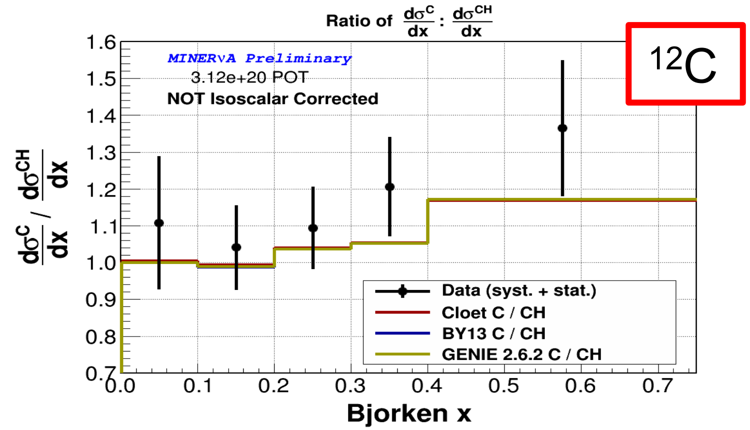
# 6. Neutrino nuclear-dependent DIS processes

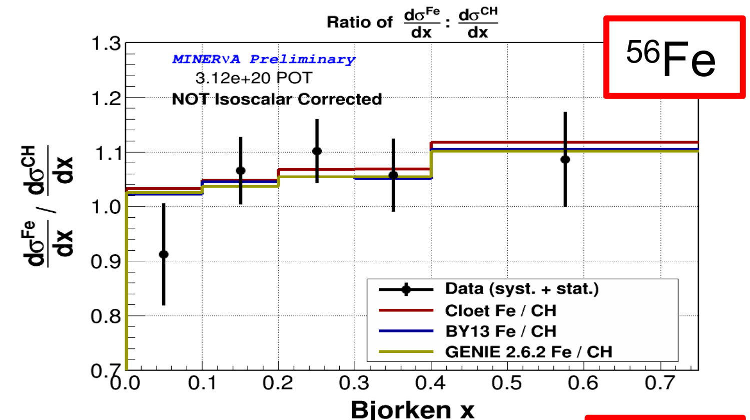
## Basic ingredients

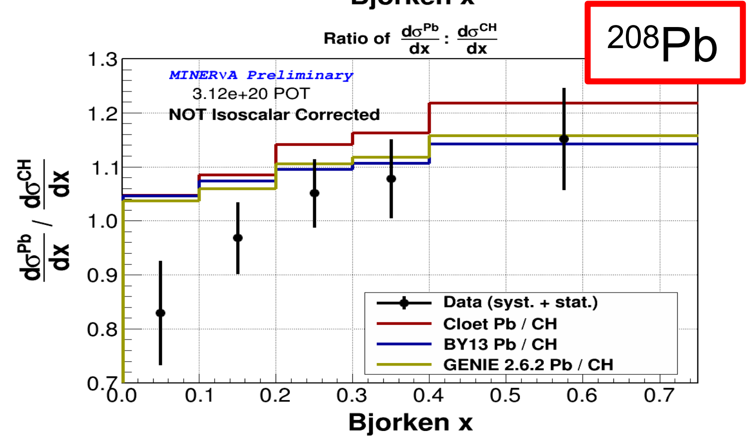
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS

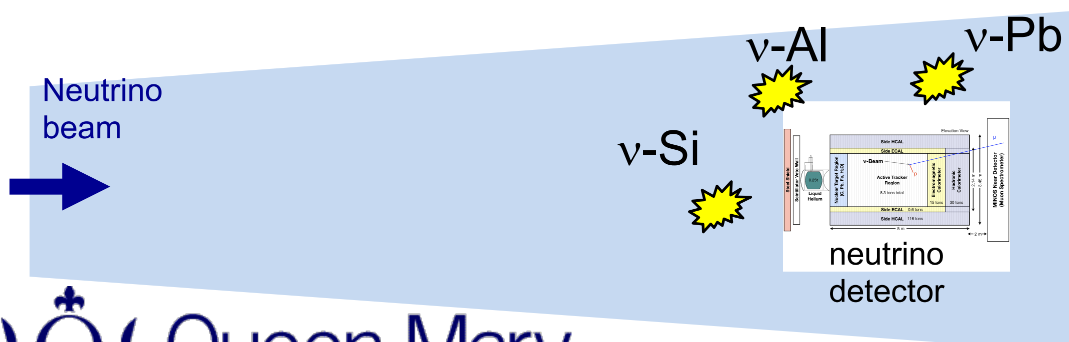
## MINERvA DIS target ratio data (C, Fe, Pb)

- Neutrino nuclear-dependent DIS effects may be different from charged lepton sector
- Neutrino beam is like a "shower", and it interacts with all materials surrounding the vertex detector. MC needs to simulate all neutrino interactions for all inactive materials.



MINERvA,PRD93(2016)071101

# 6. DIS A-dependent error

$$\frac{d\sigma^A}{dx}\bigg/\frac{d\sigma^{CH}}{dx} = \frac{10A}{(-0.0084A^2+9.9A+16)} + \frac{0.95(15-A)}{A}x + \frac{0.95(A-13.25)}{(A-10)}x^2$$

Liam Hartley
(Queen Mary)

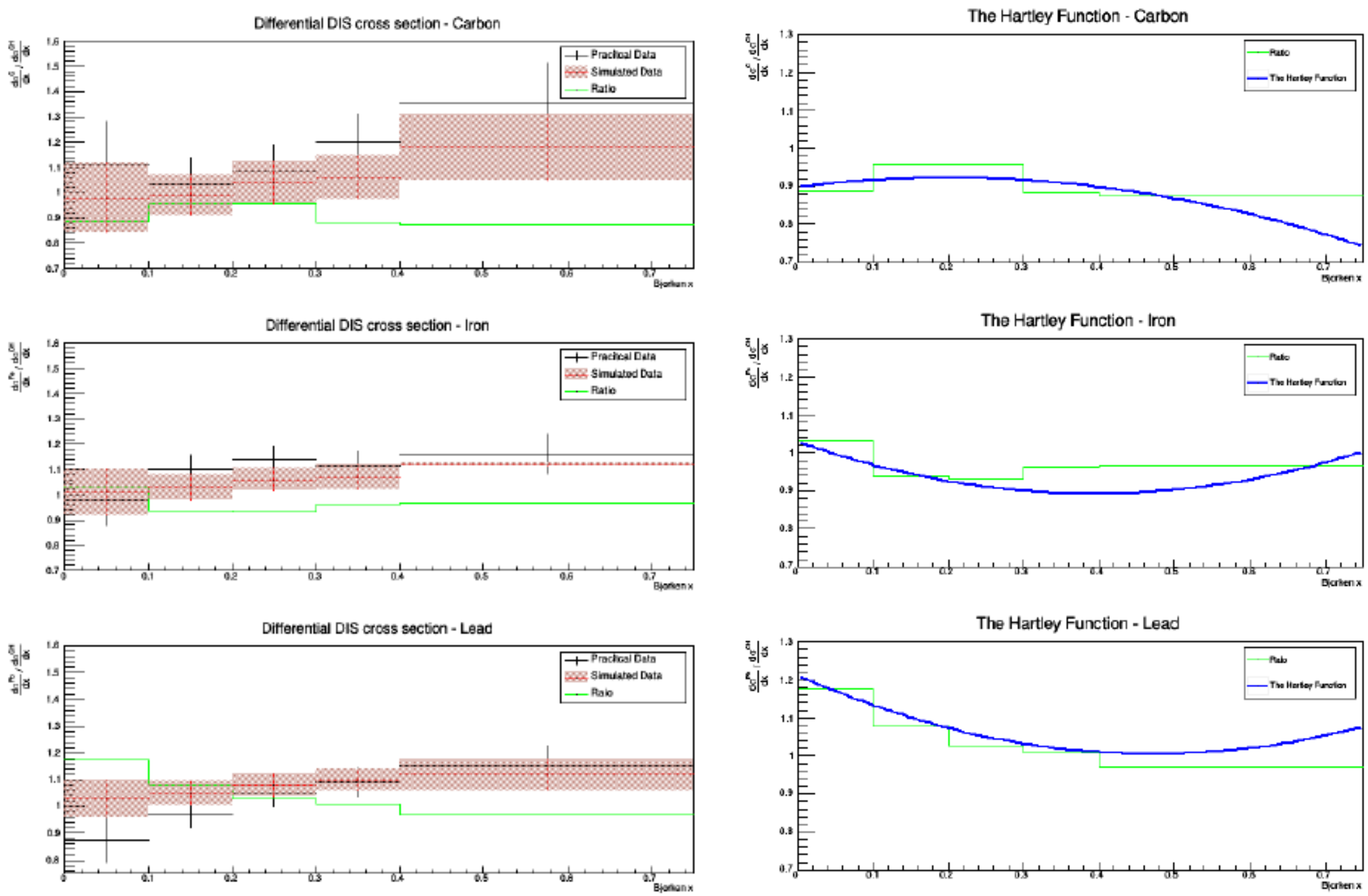
## GENIE-MINERvA comparison

- Make a polynomial scaling function in A from data-MC ratio.
- Weight GENIE with function of x
- Bottom-up A-dependent DIS correction in x

ν-C

ν-Fe

ν-Pb




Queen
University of Lor

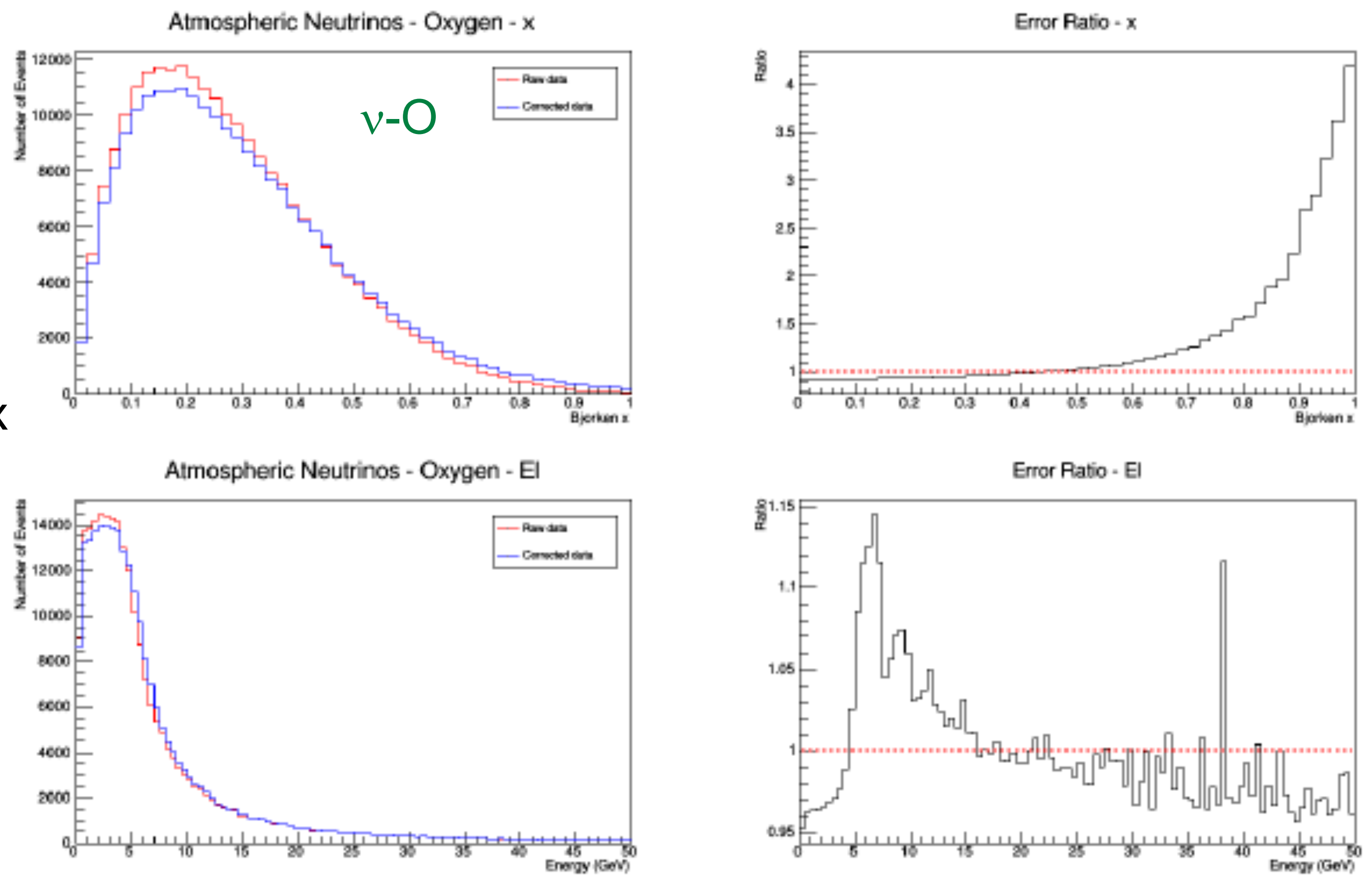
# 6. DIS A-dependent error

$$\frac{d\sigma^A}{dx} / \frac{d\sigma^{CH}}{dx} = \frac{10A}{(-0.0084A^2 + 9.9A + 16)} + \frac{0.95(15-A)}{A}x + \frac{0.95(A-13.25)}{(A-10)}x^2$$

GENIE-MINERvA comparison

- Make a polynomial scaling function in A from data-MC ratio.
- Weight GENIE with function of x
- Bottom-up A-dependent DIS correction in x
- Make prediction of correction in any targets, for example oxygen

Reasonably large variation (~10-20%) in x (under investigation)



# 6. DIS A-dependent error

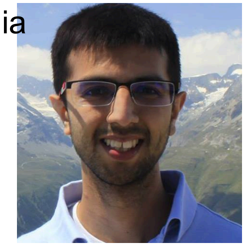
- Goal is to make event weight with function of Ev, x, y, etc, for IceCube oscillation program
- All errors are expected to be unimportant (?)

| DIS or Hadronization | type of error | approach | size |
|---|---|---|---|
| DIS | quark-hadron duality | play with Bodek-Yang parameters (by eyes) | maybe large? |
| DIS | differential xs | NuTeV-GENIE comparison (bottom-up) | 3% by GENIE study |
| DIS | A-scaling | MINERvA-GENIE (bottom-up) | maybe large? |
| DIS | PDF | From nuclear PDF, CT10? nCTEQ? (top-down) | ???? |
| Hadronization | low W averaged charged hadron multiplicity | play with KNO parameters (by eyes) | ???? |
| Hadronization | high W averaged charged hadron multiplicity | bubble chamber-PYTHIA comparison (bottom-up) | ???? |

1. IceCube neutrino observatory
2. IceCube low energy physics
3. DIS-Hadronization systematic errors
4. DIS quark-hadron duality error
5. DIS differential cross section error
6. DIS A-scaling error
7. **DIS PDF error**
8. Low-W hadronization error
9. High-W hadronization error
10. Conclusions

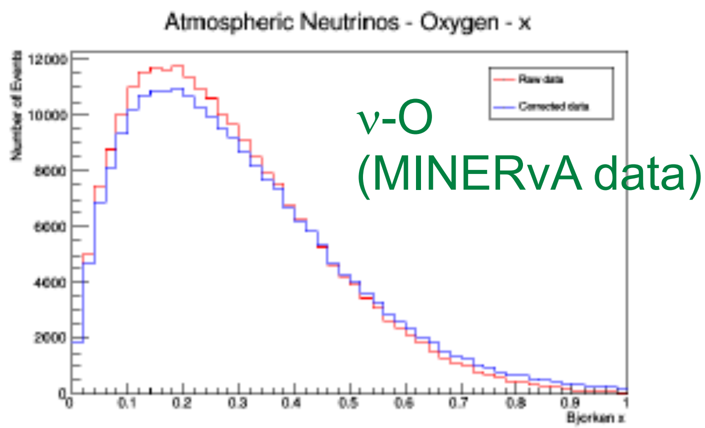
# 7. DIS PDF error

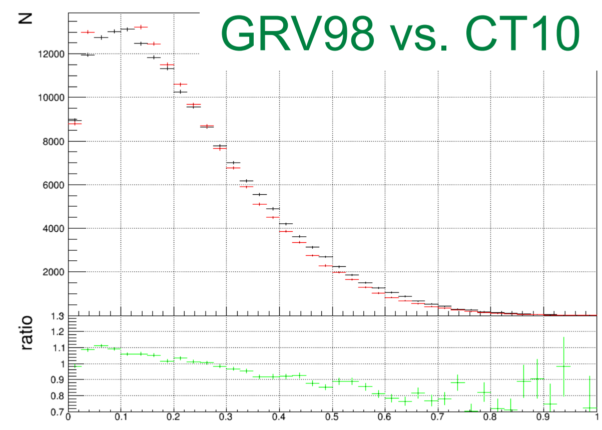
Shivesh Mandalia
(Queen Mary)

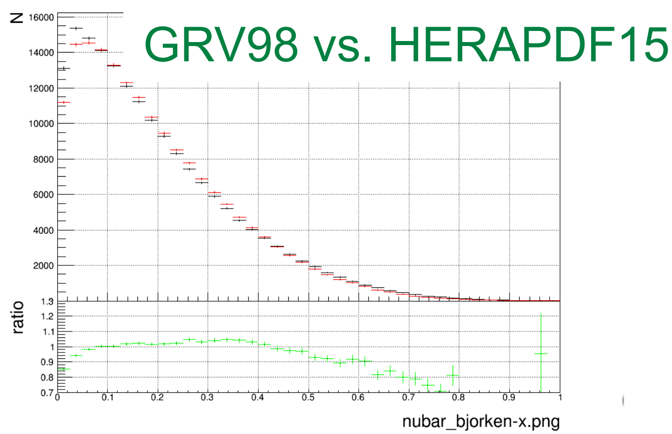


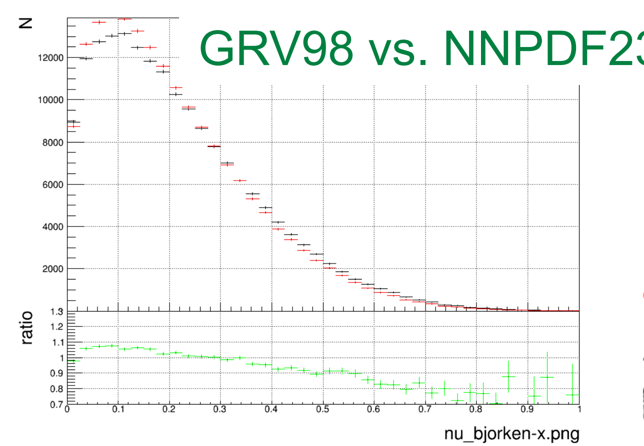
We tried to use couple of PDF from LHA PDF
- CT10 (NLO)
- HERAPDF15 (NLO)
- NNPDF23 (NLO)

These PDFs give different results from GRV98, which one is right?




Queen Mary
University of London

# 7. DIS PDF error

- Goal is to make event weight with function of Ev, x, y, etc, for IceCube oscillation program
- All errors are expected to be unimportant (?)

| DIS or Hadronization | type of error | approach | size |
|---|---|---|---|
| DIS | quark-hadron duality | play with Bodek-Yang parameters (by eyes) | maybe large? |
| DIS | differential xs | NuTeV-GENIE comparison (bottom-up) | 3% by GENIE study |
| DIS | A-scaling | MINERvA-GENIE (bottom-up) | maybe large? |
| DIS | PDF | From nuclear PDF, CT10? nCTEQ? (top-down) | maybe large? |
| Hadronization | low W averaged charged hadron multiplicity | play with KNO parameters (by eyes) | ???? |
| Hadronization | high W averaged charged hadron multiplicity | bubble chamber-PYTHIA comparison (bottom-up) | ???? |

1. IceCube neutrino observatory
2. IceCube low energy physics
3. DIS-Hadronization systematic errors
4. DIS quark-hadron duality error
5. DIS differential cross section error
6. DIS A-scaling error
7. DIS PDF error
8. **Low-W hadronization error**
9. High-W hadronization error
10. Conclusions

AGKY model, EPJC63(2009)1
TK and Mandalia, JPhysG42(2015)115004, arXiv:1602.00083

# 8. Low-W hadronization model

Carl Stanley
(Queen Mary)

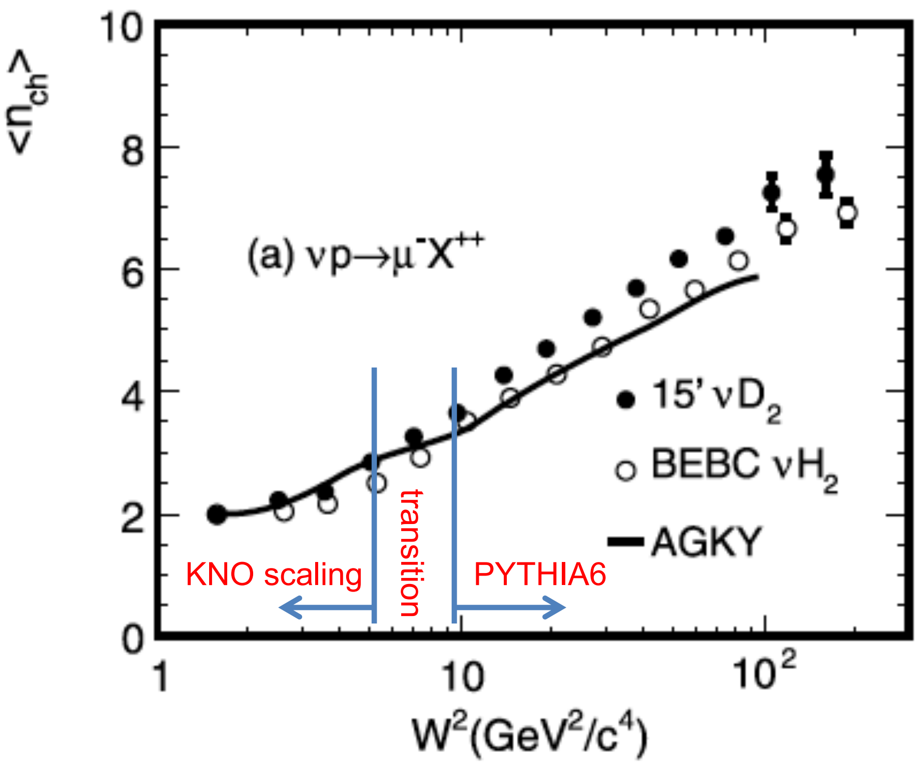
In AGKY model, hadronization model is a combination of 2 models.

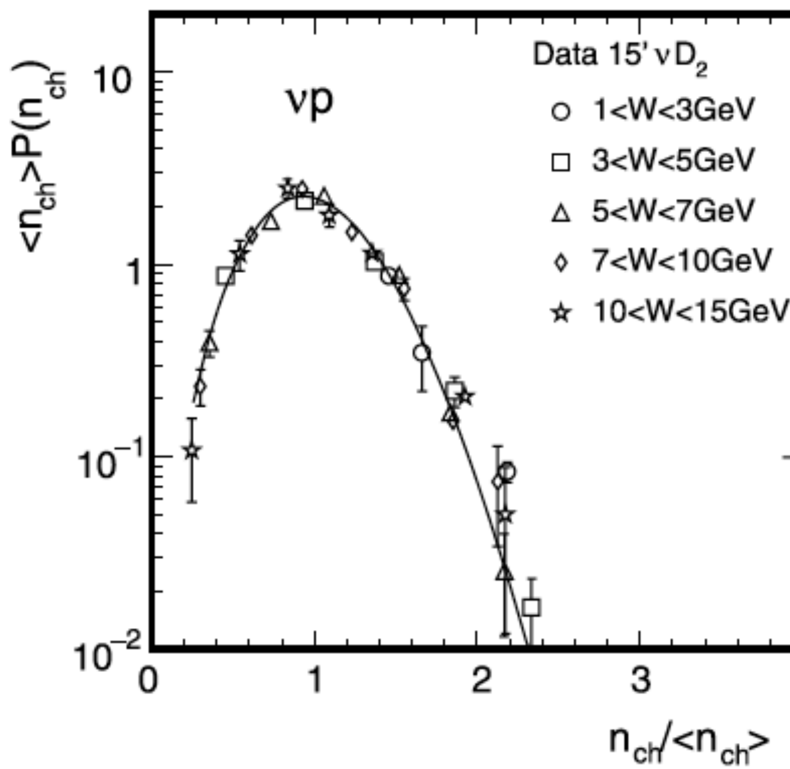
KNO-scaling based model (low W hadronization)

- Data-driven model (agree with bubble chamber data, by construction)
- Averaged charged hadron multiplicity $\langle n_{ch} \rangle$ is chosen from data, with empirical function
- Averaged neutral hadron multiplicity is chosen from isospin.
- Then variance of multiplicity is chosen from KNO-scaling law.

$$\langle n_{ch} \rangle = a_{ch} + b_{ch} \cdot \ln(W^2)$$

$$\langle n \rangle \cdot P(n) = \frac{2e^{-c} c^{cn/\langle n \rangle + 1}}{\Gamma(cn/\langle n \rangle + 1)}$$



AGKY model, EPJC63(2009)1
TK and Mandalia, JPhysG42(2015)115004, arXiv:1602.00083

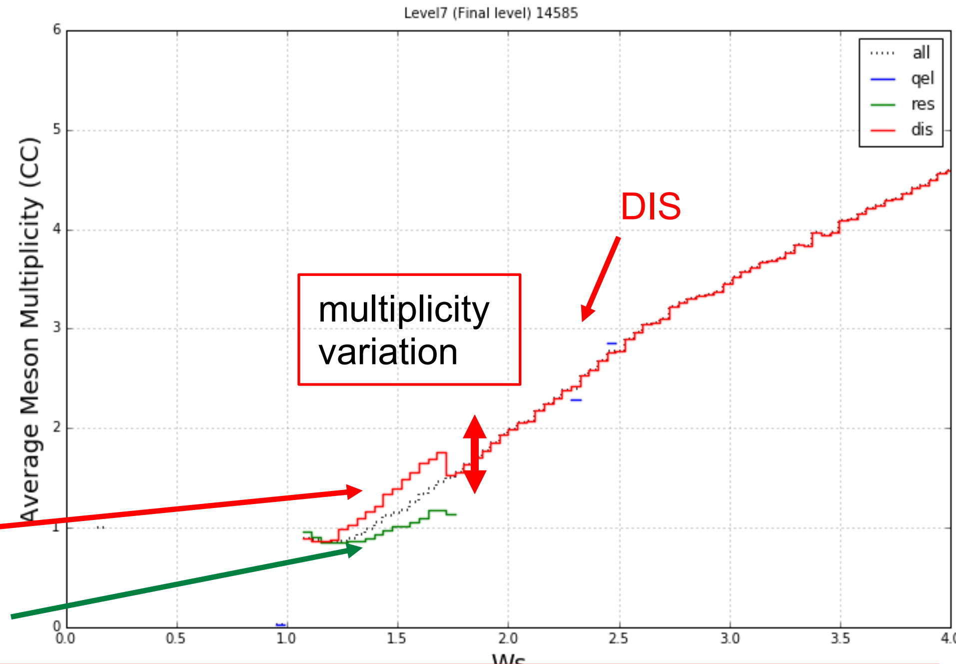
# 8. Low-W hadronization error

I added ±25% variation on "$b_{ch}$" parameters
→ This imitate discontinuity of hadron multiplicity

It looks to cover existing data variation

Then translate this variation in terms of hadron visible energy

$$y^{\text{eff}} = \frac{E_{\text{h}}^{\text{vis}}}{E_{\text{h}}^{\text{vis}} + E_{\mu}}, \quad E_{\text{h}}^{\text{vis}} = \sum_{E_{\text{h}}^{i} > E_{\text{th}}^{i}} T_{\text{h}}^{i} + \sum E_{\gamma}^{i}.$$

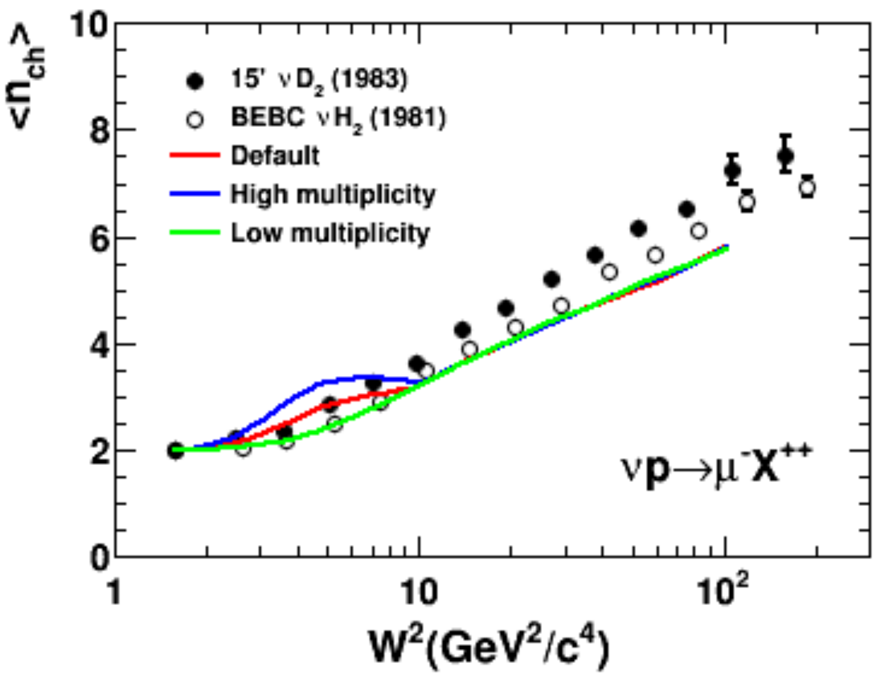



multiplicity variation

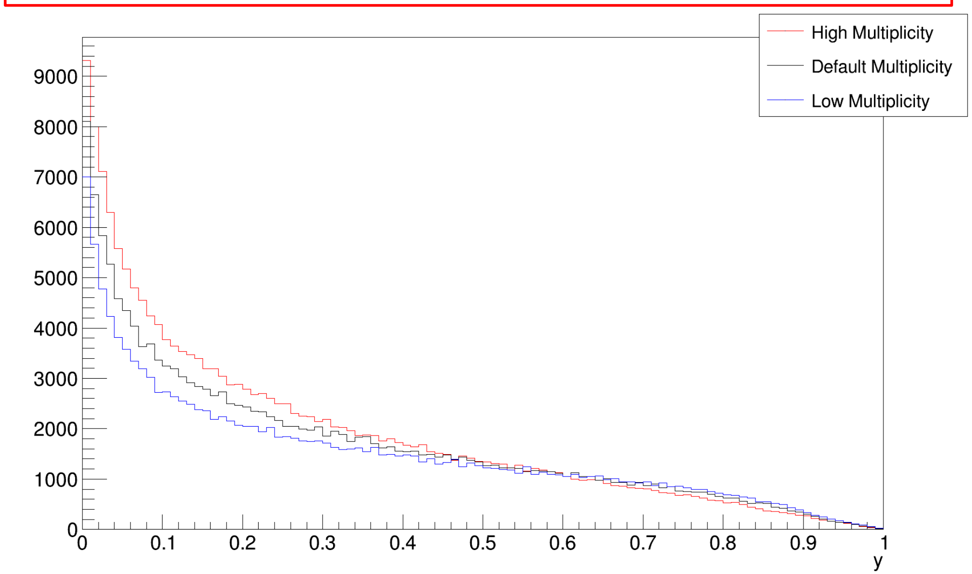
DIS

non-resonance background

resonance contribution




Reasonably large variation (~10-20%) in y (under investigation)



# 5. Low-W hadronization error, summary

This error may or may not be important for current and future oscillation experiments.
→ There is interplay with resonance region (baryonic resonant and non-resonant background models).

| DIS or Hadronization | type of error | approach | size |
|---|---|---|---|
| DIS | quark-hadron error | play with Bodek-Yang parameters (by eyes) | maybe large? |
| DIS | differential xs | NuTeV-GENIE comparison (bottom-up) | 3% by GENIE study |
| DIS | A-scaling | MINERvA-GENIE (bottom-up) | maybe large? |
| DIS | PDF | From nuclear PDF, CT10? nCTEQ? (top-down) | maybe large? |
| Hadronization | low W averaged charged hadron multiplicity | play with KNO parameters (by eyes) | maybe large? |
| Hadronization | high W averaged charged hadron multiplicity | bubble chamber-PYTHIA comparison (bottom-up) | ???? |

1. IceCube neutrino observatory
2. IceCube low energy physics
3. DIS-Hadronization systematic errors
4. DIS quark-hadron duality error
5. DIS differential cross section error
6. DIS A-scaling error
7. DIS PDF error
8. Low-W hadronization error
9. **High-W hadronization error**
10. Conclusions

Kuzmin and Naumov, PRC88(2013)065501
Gallmeister and Falter, PLB630(2005)40

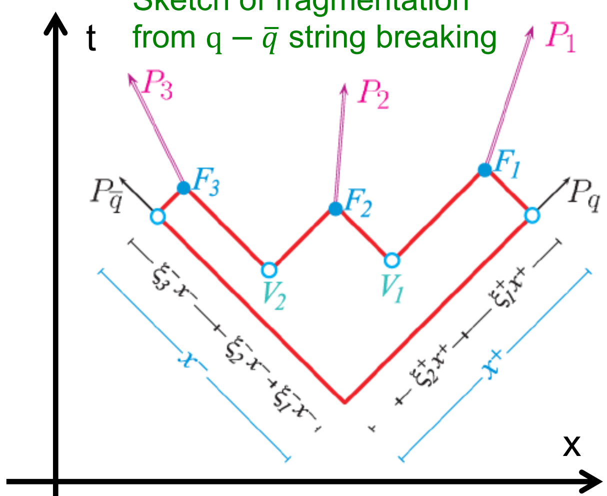
# 9. High-W hadronization model

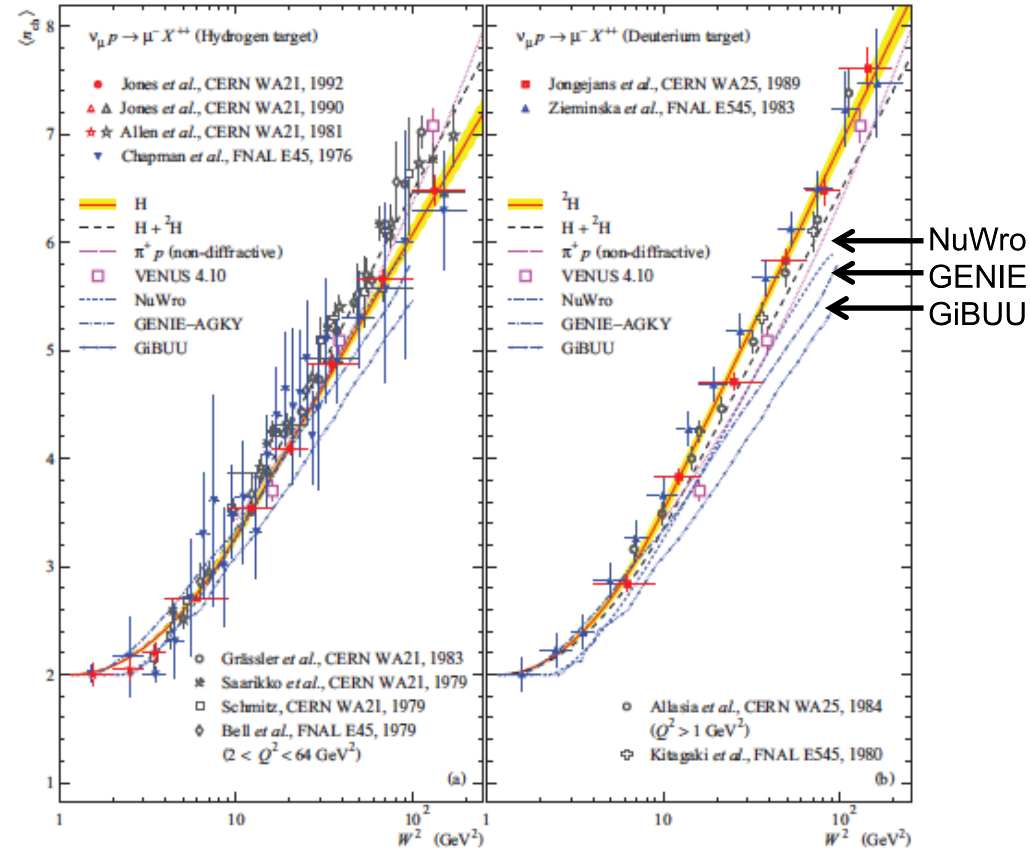
## Kuzmin-Naumov fit

- They systematically analysed all bubble chamber data
  - Difference of hydrogen and deuterium data
  - Presence of kinematic cuts
  - Better parameterization

All PYTHIA-based models underestimate averaged charged hadron multiplicity data (GiBUU, GENIE, NuWro, NEUT)

Sketch of fragmentation from $q - \bar{q}$ string breaking



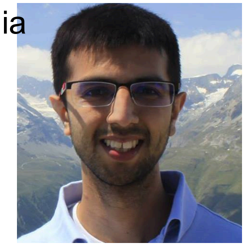




Average charged hadron multiplicity with function of $W^2$

Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
Gallmeister and Falter, PLB630(2005)40, TK and Mandalia,JPhysG42(2015)115004

# 9. High-W hadronization model

Shivesh Mandalia
(Queen Mary)



$$E_{\mathrm{h}}^{\mathrm{vis}} = \sum_{E_{\mathrm{h}}^{i} > E_{\mathrm{th}}^{i}} T_{\mathrm{h}}^{i} + \sum E_{\gamma}^{i}.$$

$$y^{\mathrm{eff}} = \frac{E_{\mathrm{h}}^{\mathrm{vis}}}{E_{\mathrm{h}}^{\mathrm{vis}} + E_{\mu}}.$$

## Averaged charged hadron multiplicity $\langle n_{ch} \rangle$

- PYTHIA6 with tuned Lund string function can reproduce $\langle n_{ch} \rangle$ data both neutrino and antineutrino.

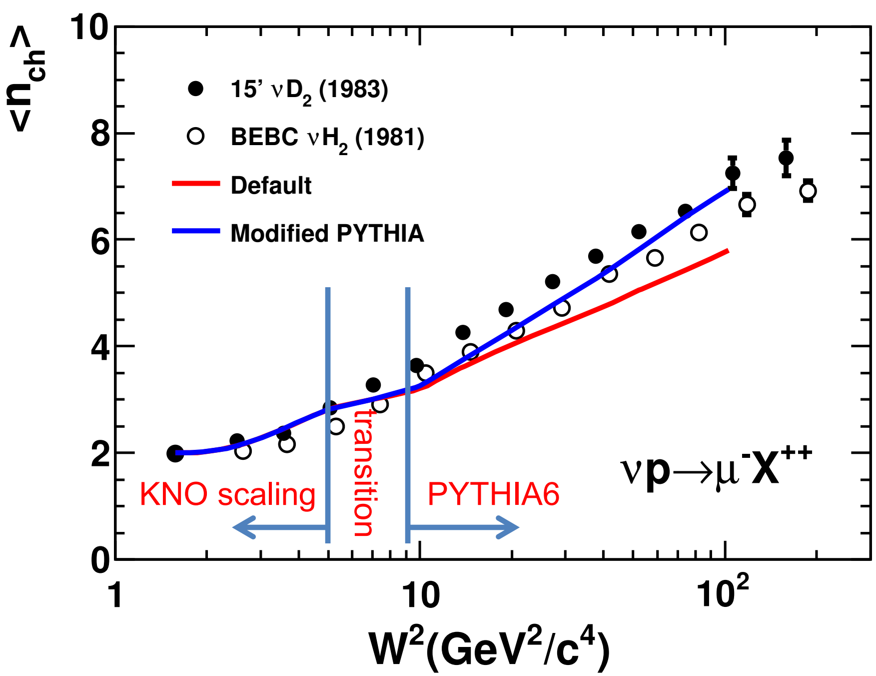
Lund string function

hadron energy distribution from iterative process

tunnelling probability

$$f(z) \propto z^{-1}(1-z)^{a} \cdot exp\left(\frac{-bm_{\perp}^{2}}{z}\right)$$

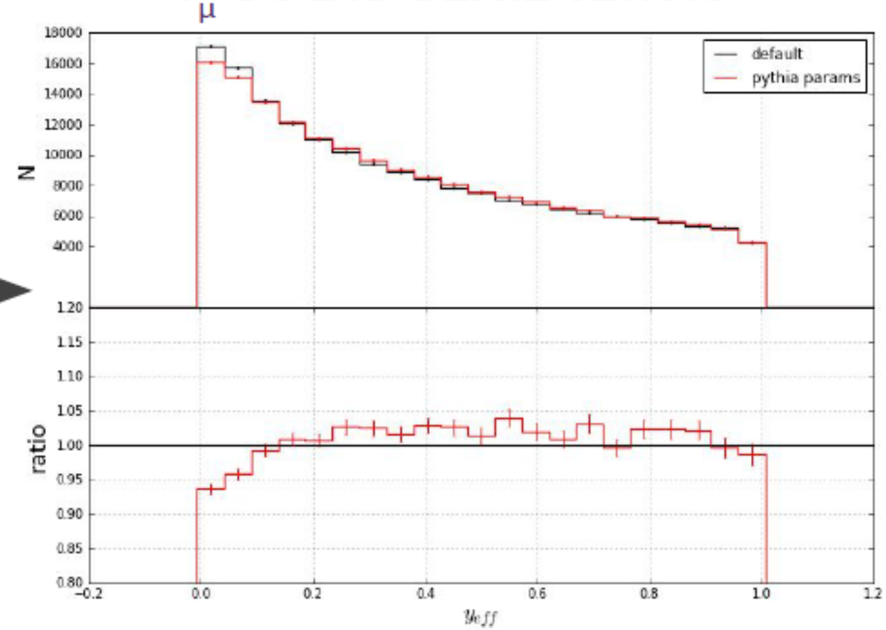
Neutrino average charged hadron multiplicity




## Hadronization error propagation

- Difference of averaged charged hadron multiplicity is translated to visible hadron energy, then effective inelasticity. Impact of hadronization error is small for experiments which only measure hadron shower.

$\nu_\mu$ CC DIS GENIE v2.10.0



TK and Mandalia,JPhysG42(2015)115004
Zieminska et al (Fermilab 15'),PRD27(1993)47

# 9. High-W hadronization dispersion error?

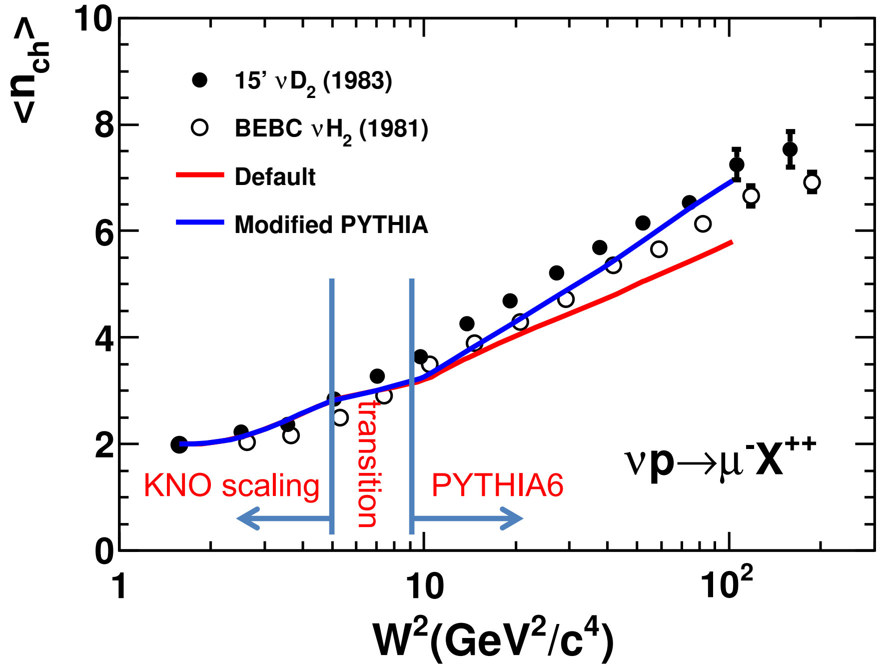
Shivesh Mandalia
(Queen Mary)

## Bubble chamber topological cross section data

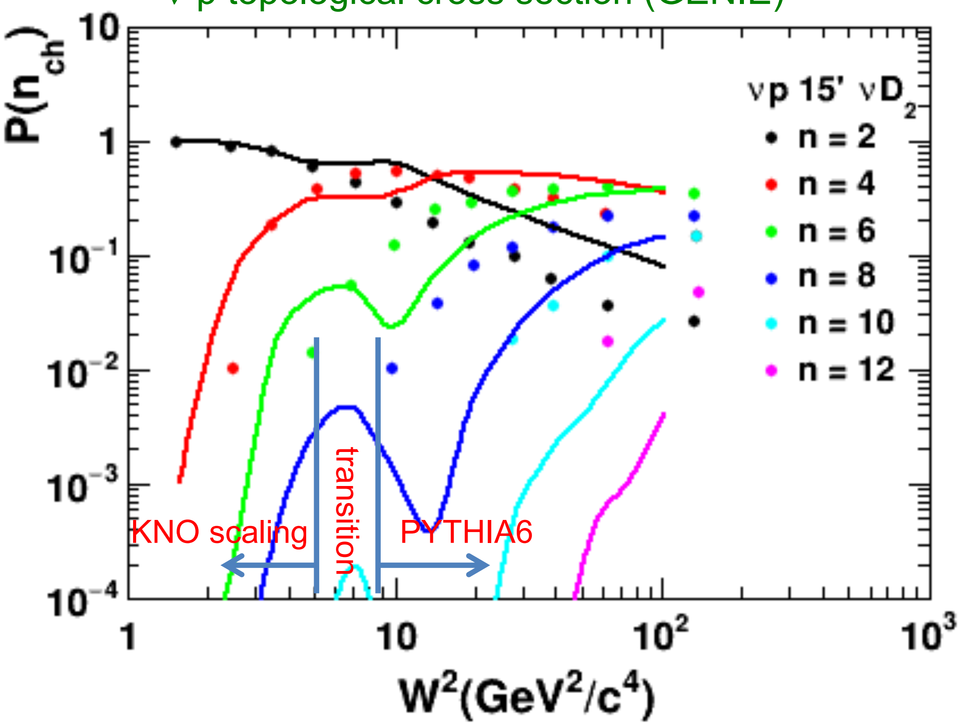
Although averaged charged hadron multiplicity makes continuous curve, topological cross sections are discontinuous, because multiplicity dispersion by PYTHIA6 is much narrower than bubble chamber data.

If the experiment is sensitive to exclusive hadron channels (T2K, DUNE, etc), you need to re-think how to propagate hadronization error…

Neutrino average charged hadron multiplicity




ν-p topological cross section (GENIE)



# 9. High-W hadronization error, summary

This error gives negligible effect for current IceCube analysis.
→ We can evaluate averaged charged hadron multiplicity error. But evaluations of any other errors are difficult (averaged neutral hadron multiplicity, dispersions, topological cross sections).

| DIS or Hadronization | type of error | approach | size |
|---|---|---|---|
| DIS | quark-hadron duality | play with Bodek-Yang parameters (by eyes) | maybe large? |
| DIS | differential xs | NuTeV-GENIE comparison (bottom-up) | 3% by GENIE study |
| DIS | A-scaling | MINERvA-GENIE (bottom-up) | maybe large? |
| DIS | PDF | From nuclear PDF, CT10? nCTEQ? (top-down) | maybe large? |
| Hadronization | low W averaged charged hadron multiplicity | play with KNO parameters (by eyes) | maybe large? |
| Hadronization | high W averaged charged hadron multiplicity | bubble chamber-PYTHIA comparison (bottom-up) | few % by GENIE study JPhysG42(2015)115004 |

1. IceCube neutrino observatory

2. IceCube low energy physics

3. DIS-Hadronization systematic errors

4. DIS quark-hadron duality error

5. DIS differential cross section error

6. DIS A-scaling error

7. DIS PDF error

8. Low-W hadronization error

9. High-W hadronization error

**10. Conclusions**

# Conclusions

This moment, neutrino interaction systematics are not important for IceCube oscillation programs.

For future 2-10 GeV oscillation experiments (NOvA, DUNE, Hyper-K, PINGU, ORCA, INO, etc), we investigate 6 new systematics on DIS and hadronization processes.

1. DIS quark-hadron duality error
2. DIS double differential cross section error
3. DIS A-scaling error
4. DIS PDF error
5. Low-W hadronization error
6. High-W hadronization error

(2) and (6) are evaluated to be small and have been used in IceCube. (1), (3), (4), (5) are potentially large and they need further investigation.

This list is not exhaustive.

# Neutrino Shallow and Deep-Inelastic scattering, GSSI, Oct 11-13

http://nustec.fnal.gov/nuSDIS18/

A dedicated workshop for physics related to DUNE, NOvA, HyperK, etc

- generator developments, impact on oscillation analyses
- higher resonance and non-resonance contributions
- low Q2 low W DIS
- nuclear modifications and nuclear-dependent PDFs
- neutrino hadronization problem

NuInt18, GSSI, Oct. 15-19
https://indico.cern.ch/event/703880/


Subscribe "NuSTEC News"

E-mail to listserv@fnal.gov, Leave the subject line blank, Type "subscribe nustec-news firstname lastname"

(or just send e-mail to me, katori@FNAL.GOV)

like "@nuxsec" on Facebook page, use hashtag #nuxsec

# IceCube-Gen2 collaboration

**Thank you for your attention!**

Subscribe “NuSTEC News”

E-mail to listserv@fnal.gov, Leave the subject line blank, Type "subscribe nustec-news firstname lastname"

(or just send e-mail to me, katori@FNAL.GOV)

like “@nuxsec” on Facebook page, use hashtag #nuxsec

# Backup

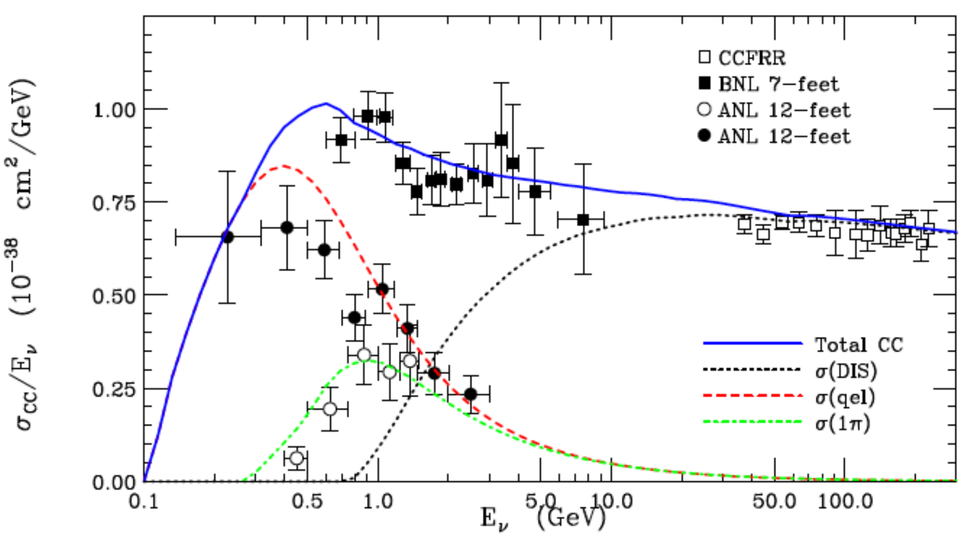
# 2. Dark age of neutrino interaction physics

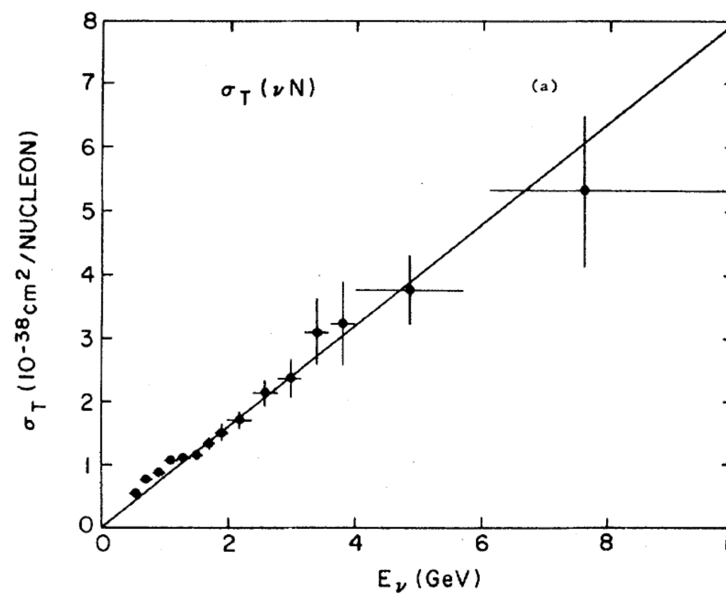
(1) Measure interaction rate
(2) Divide by known cross section to obtain flux
(3) use this flux, measure cross-section from measured rate

What you get? OF COURSE the cross section you assume!

Phys. Rev. D [redacted]

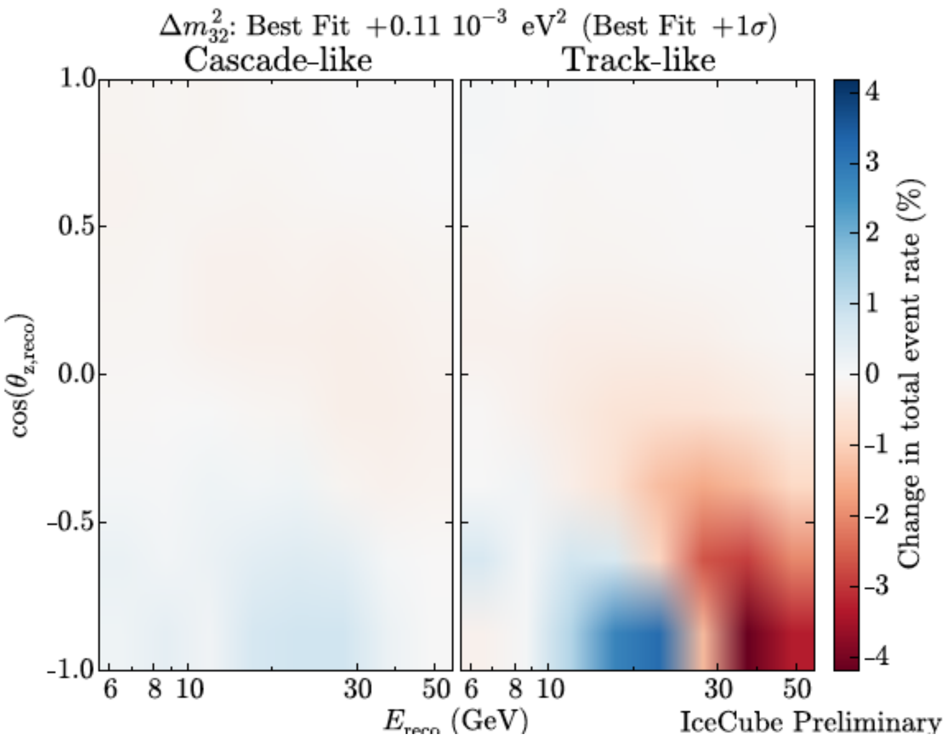
The distribution of events in neutrino energy for the 3C $\nu d \rightarrow \mu^- p p_s$ events is shown in Fig. 4 together with the quasielastic cross section $\sigma(\nu n \rightarrow \mu^- p)$ calculated using the standard $V-A$ theory with $M_A = 1.05 \pm 0.05$ GeV and $M_V = 0.84$ GeV. The absolute cross sections for the CC interactions have been measured using the quasielastic events and its known cross section.[4]

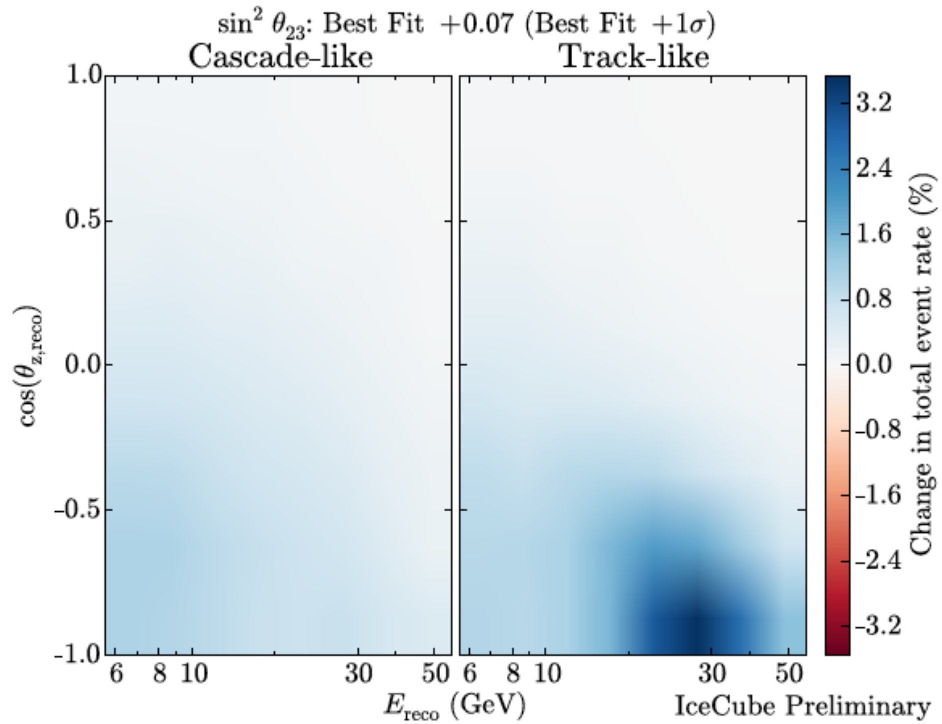


# 2. DeepCore oscillation analysis

Oscillation fit is dominated around ~30 GeV neutrinos.

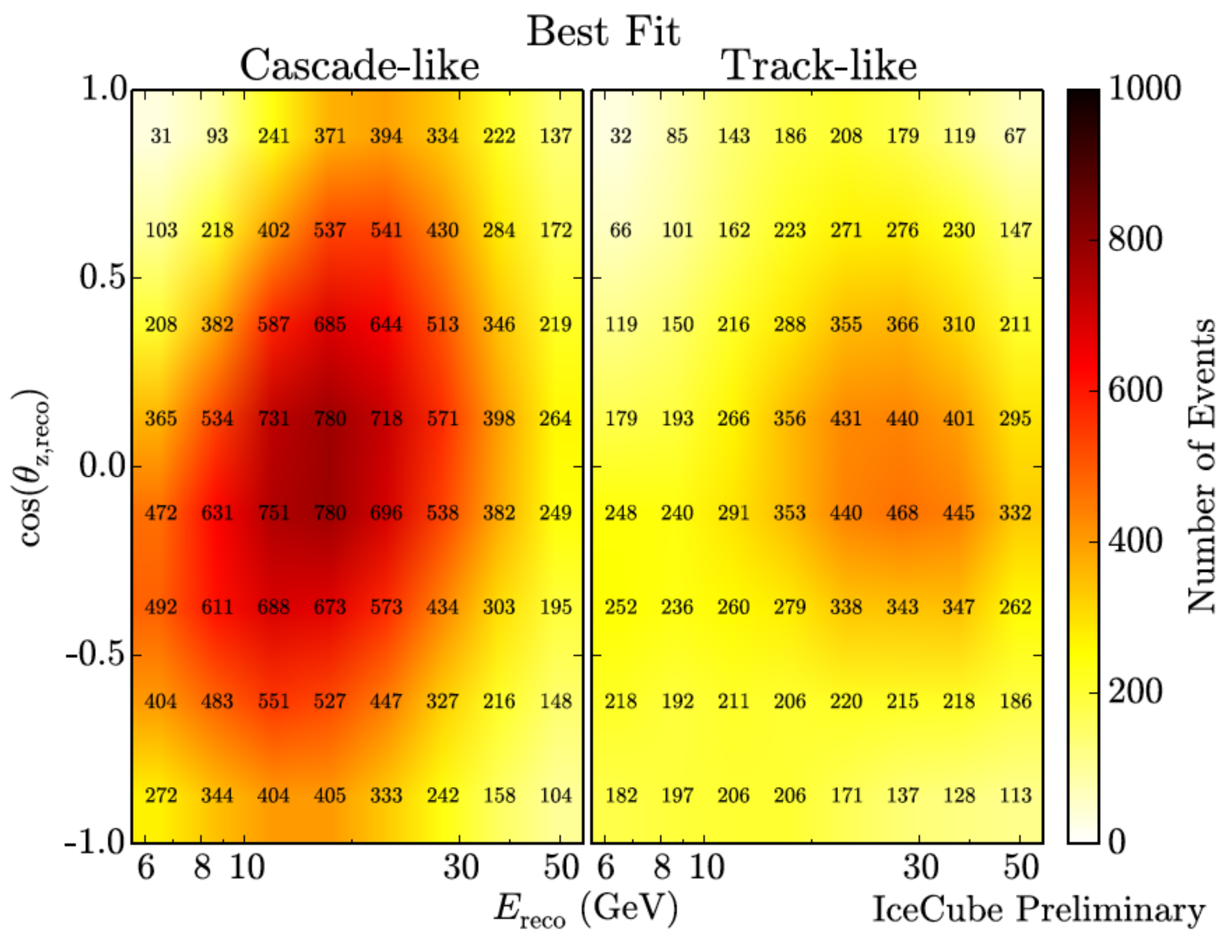



| 20 GeV | Track | Cascade |
|---|---|---|
| ΔE | 24% | 29% |
| Δθ | 10° | 16° |

# 2. DeepCore oscillation analysis

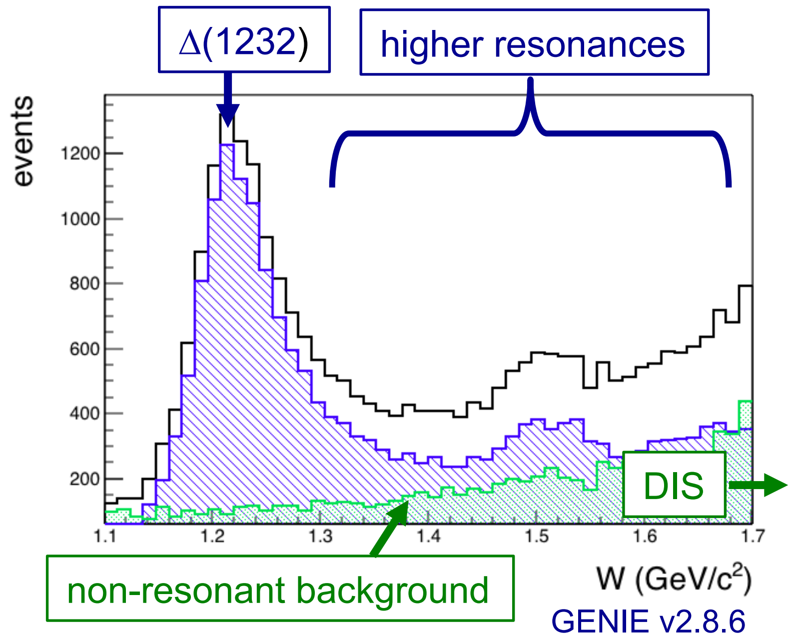
Majority of events are 10-30 GeV
 - 3-year data



# 3. Physics of Δ resonance

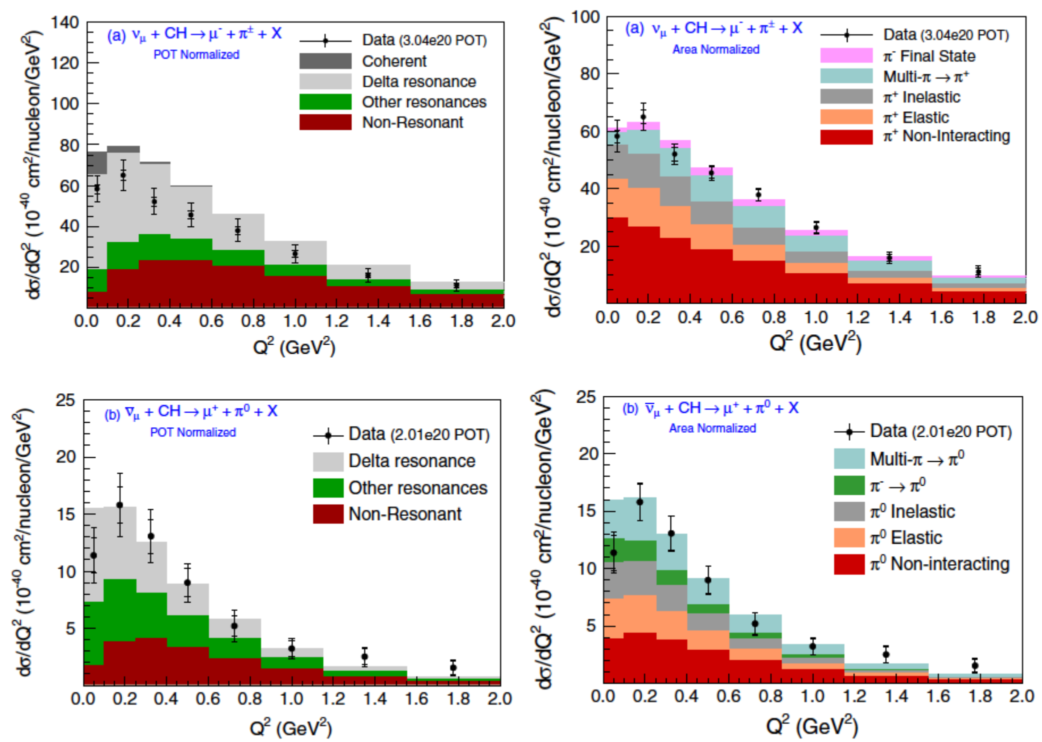
Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS




MINERvA $\nu$CC1$\pi^+$ and $\bar{\nu}$CC1$\pi^o$ data simultaneous study

- Interaction channels and FSIs are studied within GENIE
- this moment, there is no clear way to tune MC for Δ
- $\bar{\nu}$CC1$\pi^-$ and $\nu$CC1$\pi^o$ will be added (Ramirez, NuInt2017)



Nakamura et al,Rep.Prog.Phys.80(2017)056301

# 3. Physics of higher resonances

### Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS

### DCC model

- Total amplitude is conserved
- Channels are coupled (pN, ppN, etc)
- 2 pion productions ~10% at 2 GeV

Role of high W resonances in neutrino experiments is not understood (and probably modelled incorrectly). GENIE highW events are usually tuned down in MINERvA hadron analyses

DCC model vs. electro-pionproduction data

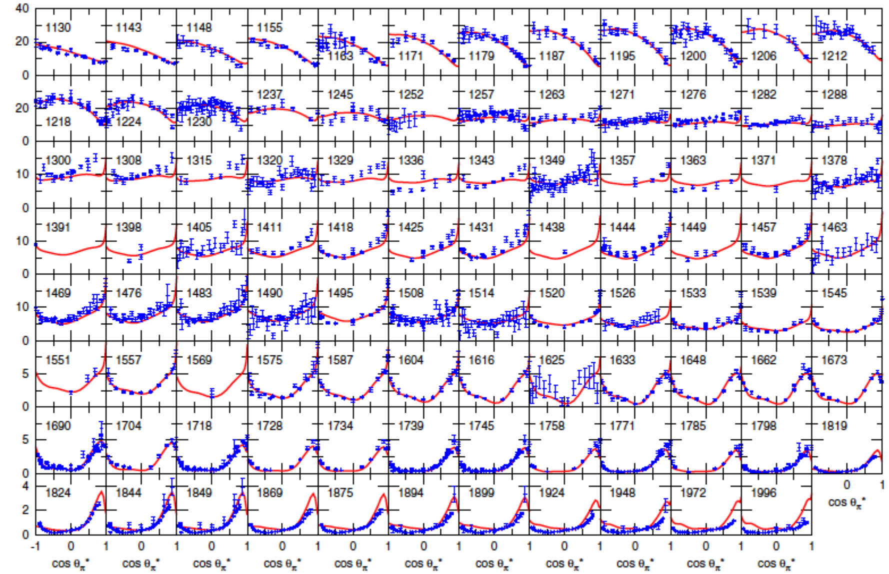
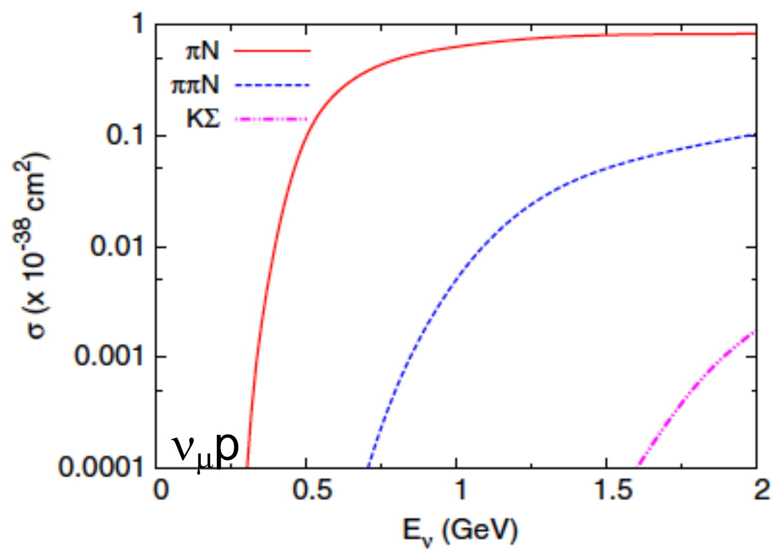
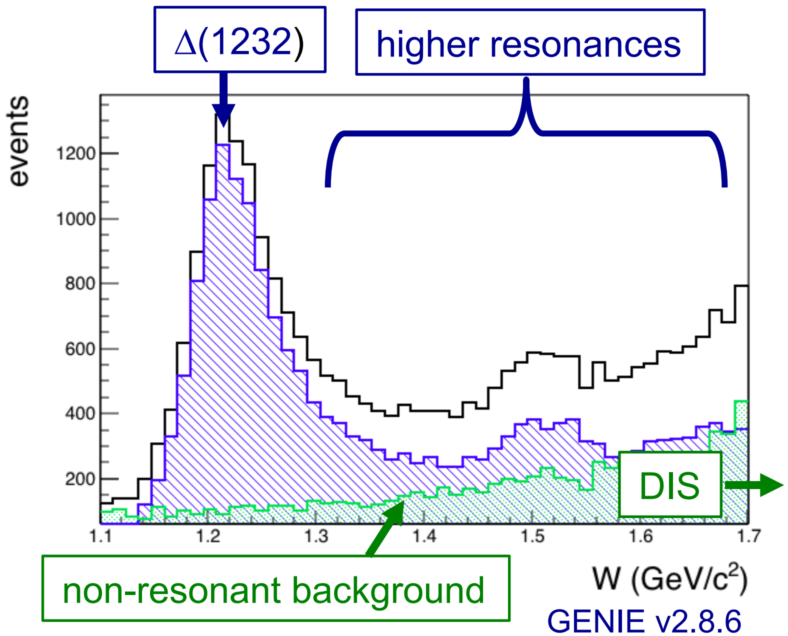



FIG. 8 (color online). Unpolarized differential cross sections, $d\sigma/d\Omega^*_\pi$ (μb/sr), for $\gamma n \to \pi^- p$. The data are from Refs. [55–78].



# 3. Physics of non-resonant background

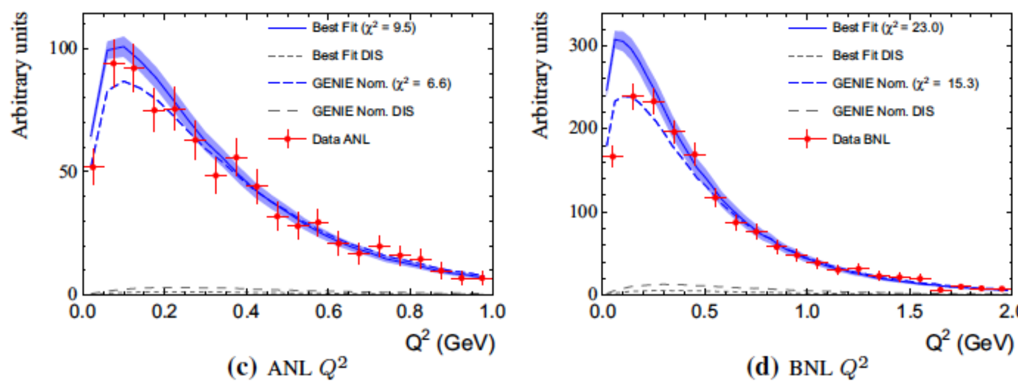
Basic ingredients
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS




Non-resonant component and resonances are incoherently added (=wrong, but easy to simulate).

Non-resonant background is identified to be DIS at higher W.

Non-resonant background in GENIE needs to be reduced more than 50%.




But by doing this hadronization would make large discontinuity.

Bloom and Gilman, PRL25(1970)1140
Graczyk et al,NPA781(2007)227, Lalakulich et al, PRC75(2007)015202

# 3. Quark-Hadron Duality

Nachtmann variable

$$\xi = \frac{2x}{\left(1+\sqrt{1+\frac{4x^2M^2}{Q^2}}\right)}$$

## Basic ingredients

1. $\Delta$(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS

## GRV98 LO PDF + Bodek-Yang correction

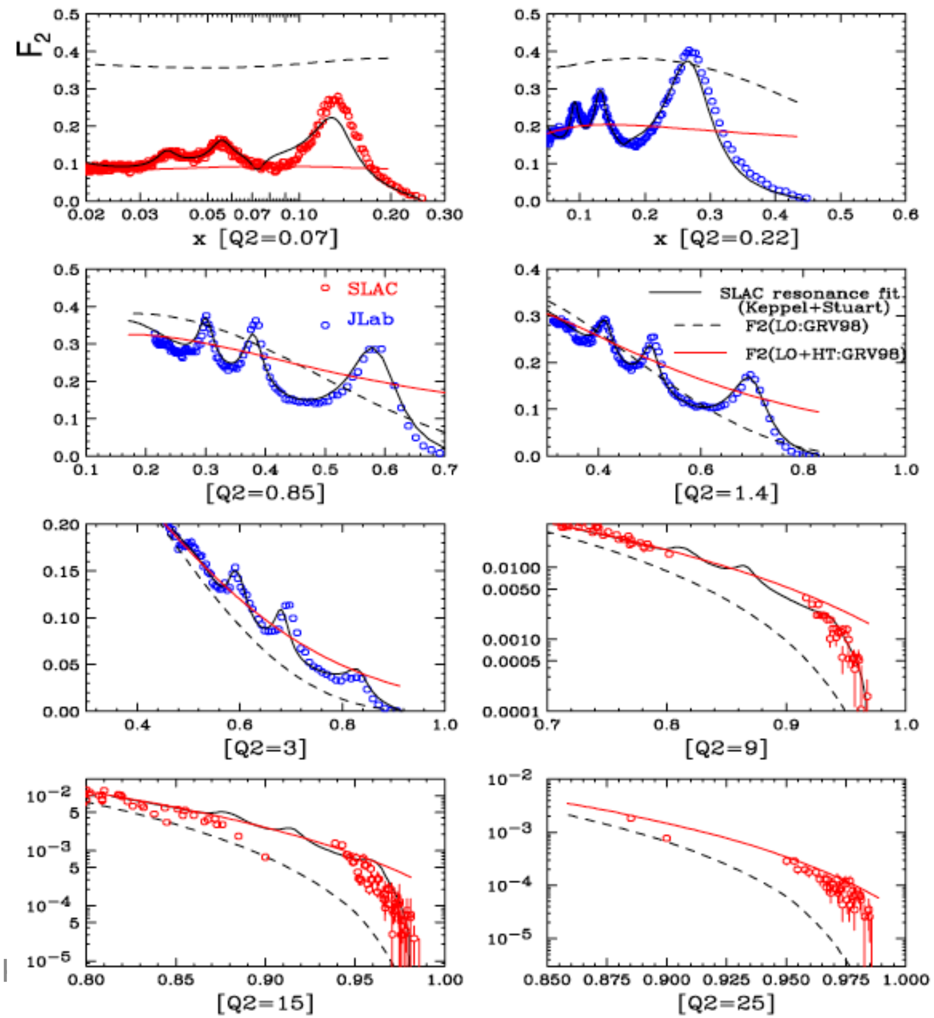
- GRV98 for low $Q^2$ DIS
- Bodek-Yang correction for QH-duality
- 20 years old, outdated
- not sure how to implement systematic errors

$$\xi \rightarrow \xi_\omega = \frac{2x\left(1+\frac{M_f^2+B}{Q^2}\right)}{\left(1+\sqrt{1+\frac{4x^2M^2}{Q^2}}\right)+\frac{2Ax}{Q^2}}$$

$$K_{valence}(Q^2) = [1-G_D^2(Q^2)]\cdot\left(\frac{Q^2+C_{v2}}{Q^2+C_{v1}}\right)$$

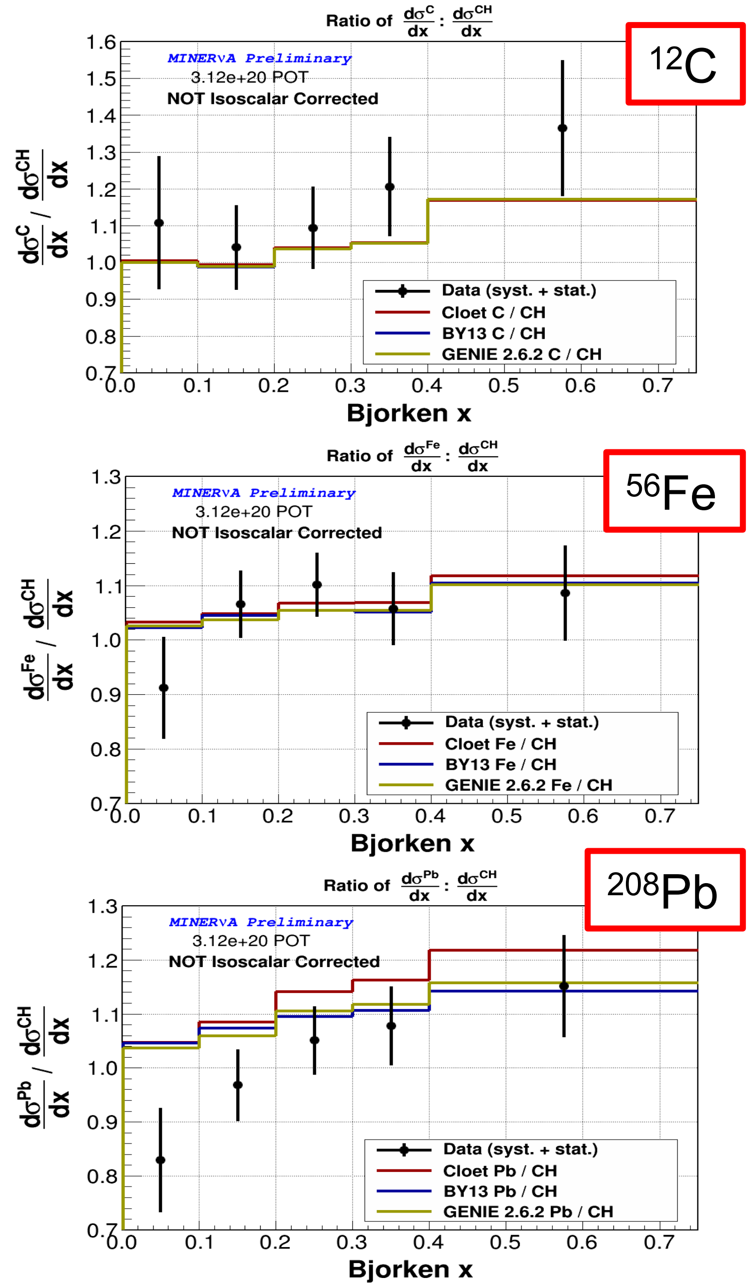
$$K_{sea}(Q^2) = \frac{Q^2}{Q^2+C_{s1}}$$

Proton F2 function GRV98-BY correction vs. data



MINERvA,PRD93(2016)071101
HKN,PRC76(2007)065207, EPS,JHEP04(2009)065, FSSZ,PRD85(2012)074028 ,nCTEQ, PRD80(2009)094004

# 3. Neutrino nuclear-dependent DIS processes

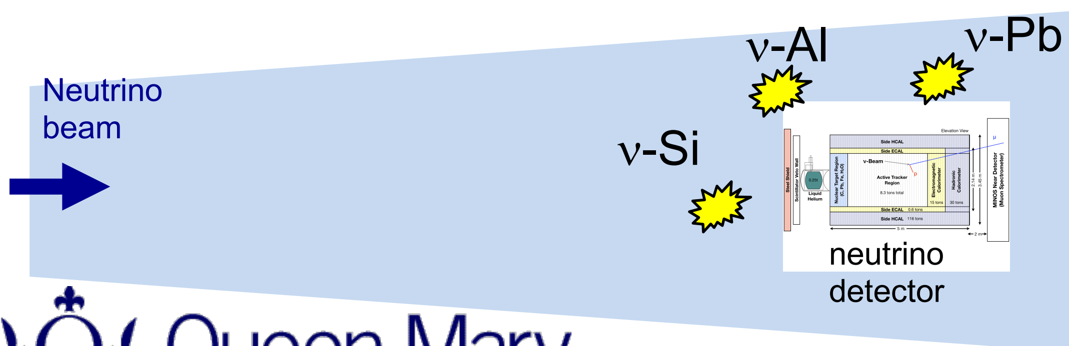



## Basic ingredients

1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$, low W DIS
5. Nuclear dependent DIS

## MINERvA DIS target ratio data (C, Fe, Pb)

- Neutrino nuclear-dependent DIS effects may be different from charged lepton sector
- Why we care? Because neutrino beam is like a “shower”, and it interacts with all materials surrounding the vertex detector. MC needs to simulate neutrino interactions (and particle propagations) for all inactive materials.




Queen Mary
University of London

AGKY, EPJC63(2009)1
TK and Mandalia,JPhysG42(2015)115004

# 3. GENIE SIS model

GENIE is the most widely used neutrino interaction generator

Cross section

$W^2<2.9$ GeV$^2$ : RES

$W^2>2.9$ GeV$^2$ : DIS

Hadronization

$W^2<5.3$GeV$^2$ : KNO scaling based model

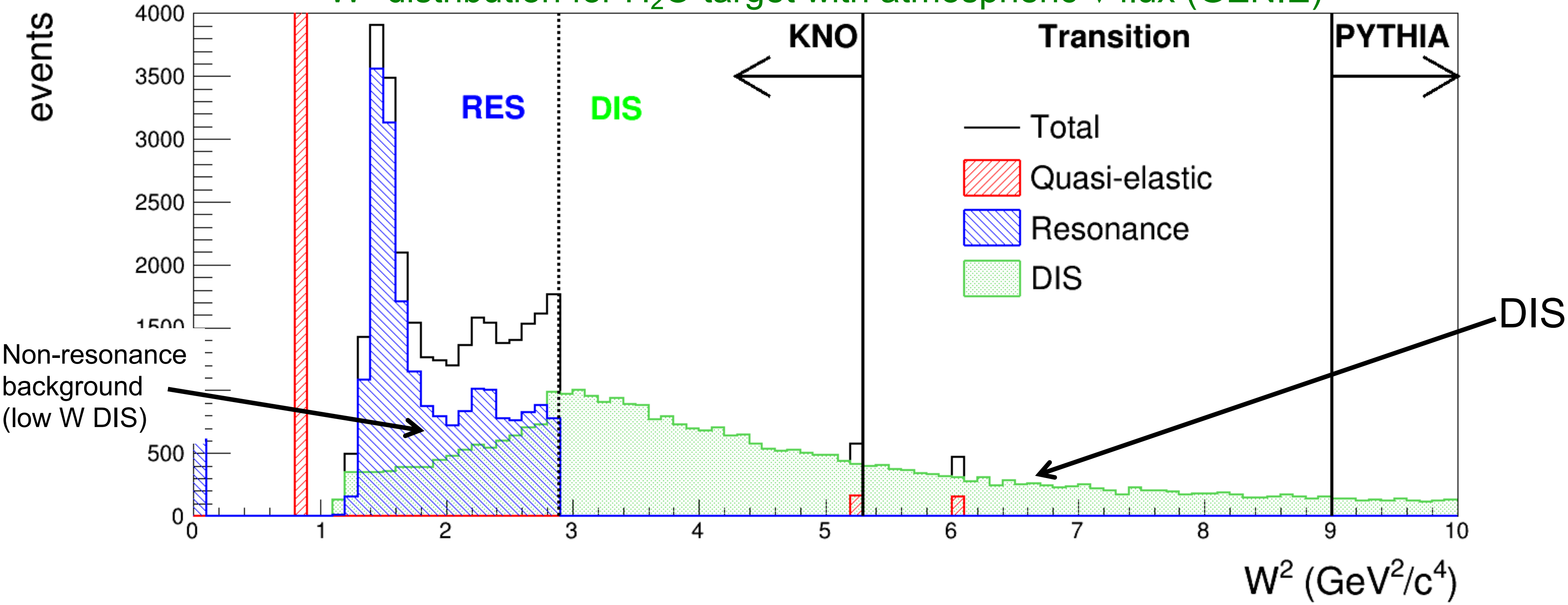
2.3GeV$^2$<$W^2$<9.0GeV$^2$ : transition

9.0GeV$^2$<$W^2$ : PYTHIA6

There are 2 kind of "transitions" in SIS region
- cross-section
- hadronization

$W^2$ distribution for $H_2O$ target with atmospheric-ν flux (GENIE)

GENIE v2.8.0




University of London

# 3. NEUT SIS model

NEUT is the generator used by all Japanese neutrino programs (T2K, SuperK, etc)

**Cross section**

$W^2<4\ GeV^2$ : RES

$W^2>4\ GeV^2$ : DIS

**Hadronization**

$W^2<4 GeV^2$ : KNO scaling based model

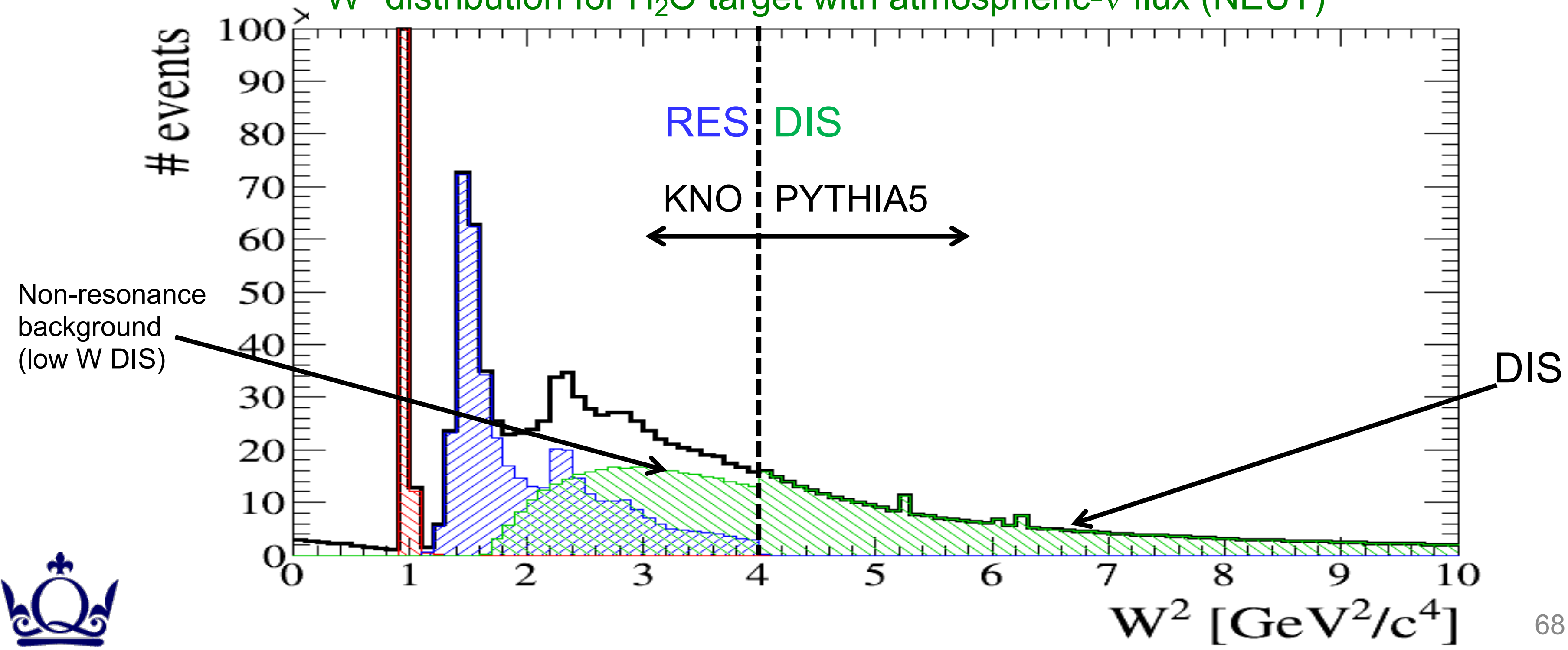
$4GeV^2<W^2$ : PYTHIA5

There are 2 kind of “transitions” in SIS region

- cross-section
- hadronization

plot made by Christophe Bronner (IPMU)

$W^2$ distribution for $H_2O$ target with atmospheric-$\nu$ flux (NEUT)




University of London

# 3. NuWro SIS model

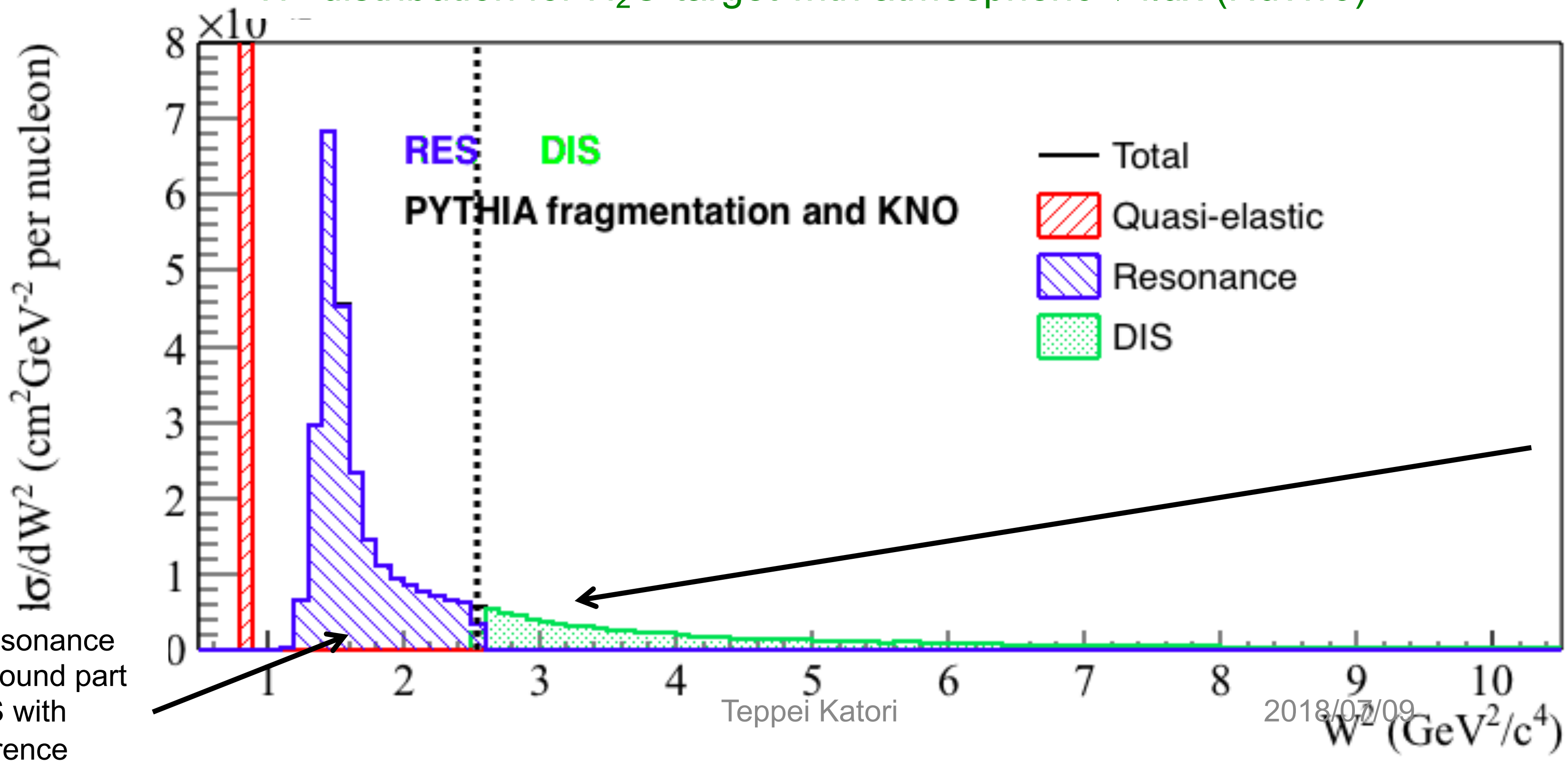
NuWro is often used for some studies because of user-friendly structure

Cross section
$W^2 < 2.5\ GeV^2$ : RES
$W^2 > 2.5\ GeV^2$ : DIS
Hadronization
- PYTHIA fragmentation
- KNO scaling

There are 2 kind of "transitions" in SIS region
- cross-section
- hadronization

File made by Luke Pickering (MSU)

$W^2$ distribution for $H_2O$ target with atmospheric-ν flux (NuWro)




DIS

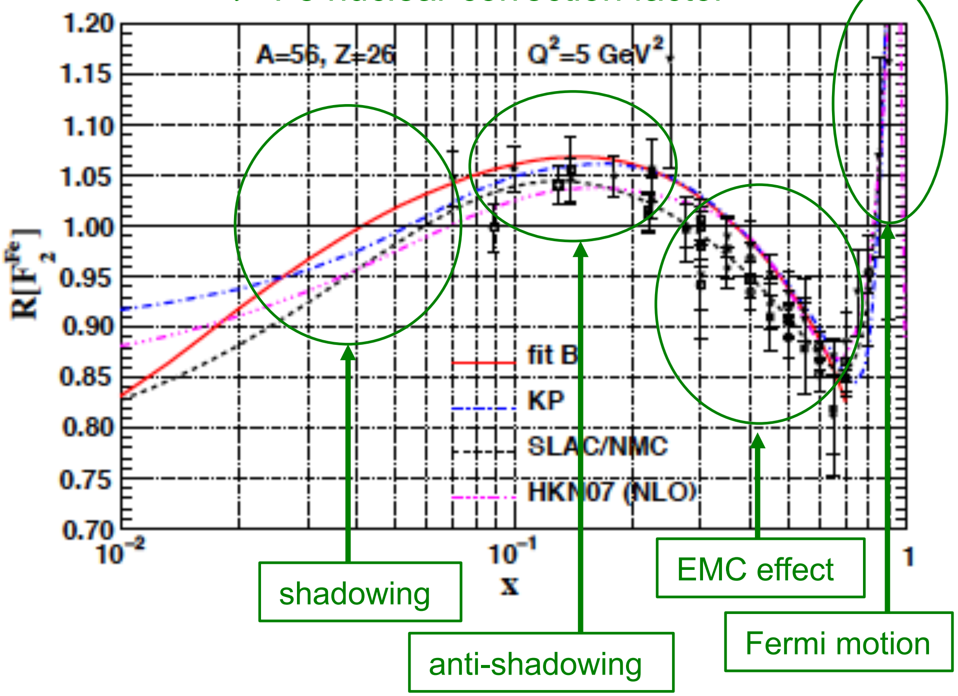
Non-resonance background part of RES with interference

# 3. Nuclear dependent DIS process

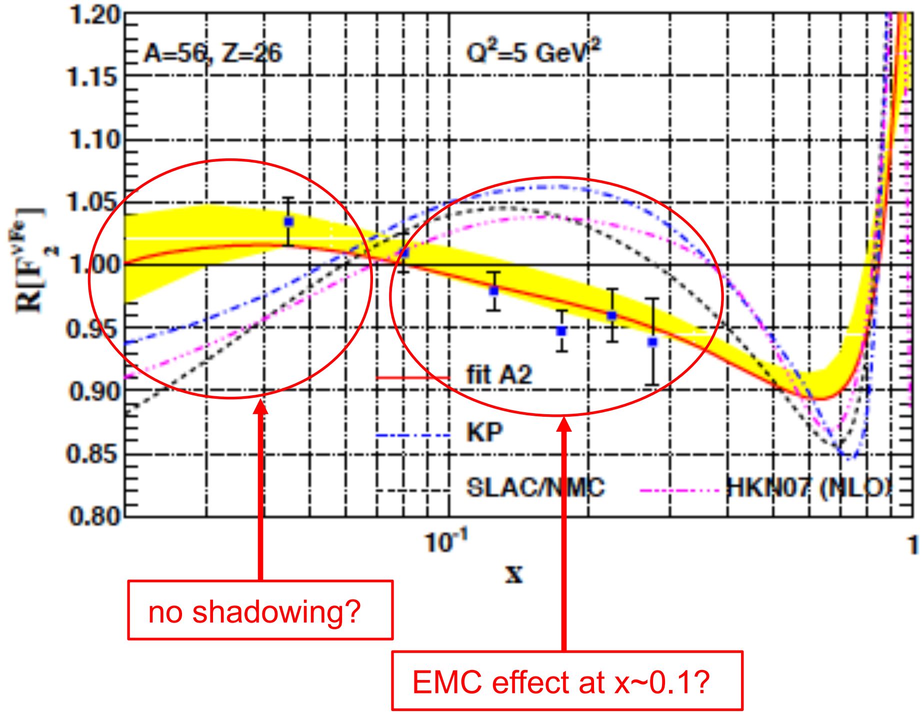
1. Δ(1232)-resonance
2. higher resonances
3. non-resonant background
4. low $Q^2$ , low W DIS
5. Nuclear dependent DIS

Nuclear PDF
- Shadowing, EMC effect, Fermi motion
- Theoretical origin is under debate
- Various models describe charged lepton data
- Neutrino data look very different

$\ell^{\pm}$-Fe nuclear correction factor




ν-Fe nuclear correction factor

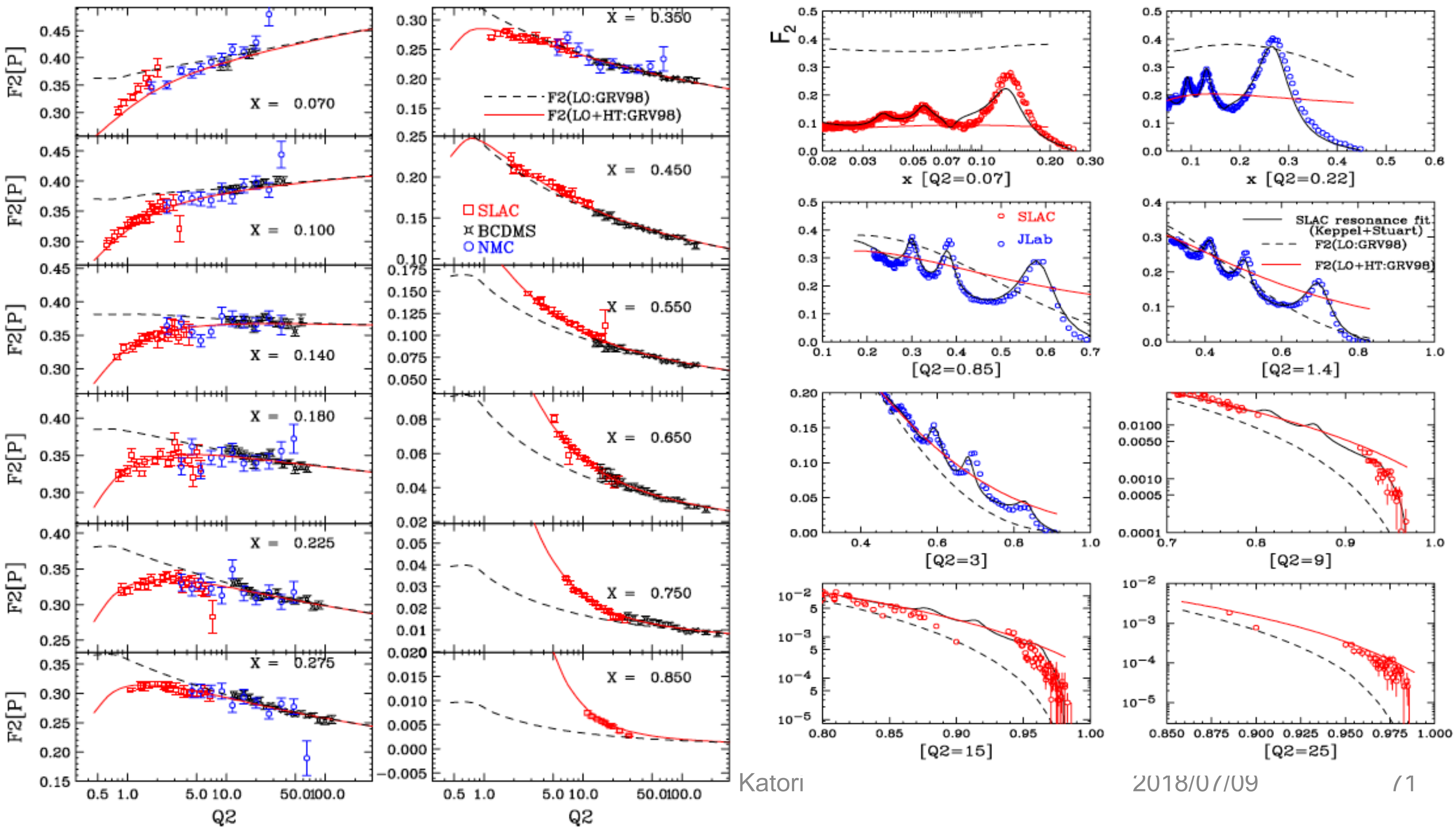


Bodek and Yang, AIP.Conf.Proc.670(2003)110,Nucl.Phys.B(Proc.Suppl.)139(2005)11

# 4. Bodek-Yang correction for low $Q^2$ DIS

GRV98 is a PDF designed for low Q2 region. Bodek-Yang correction makes GRV98 to work even lower Q2, or “duality” region by adding higher twist effect

Proton F2 function GRV98-BY correction vs. data



# 4. Bodek-Yang correction for low $Q^2$ DIS

Nachtmann variable $$\xi = \frac{2x}{\left(1 + \sqrt{1 + \frac{4x^2M^2}{Q^2}}\right)}$$

In GENIE, there are 11 parameters to control "Bodek-Yang correction" on GRV98 LO PDF
- A: high order twist correction
- B: quark transverse momentum
- Cvu1, Cvu2: valence u-quark PDF correction
- Cvd1, Cvd2: valence d-quark PDF correction
- Cs1u, Cs1d: sea u- and d-quark PDF correction
- x0, x1, x2: d(x)/u(x) correction

$$\xi \rightarrow \xi_\omega = \frac{2x\left(1 + \frac{M_f^2 + B}{Q^2}\right)}{\left(1 + \sqrt{1 + \frac{4x^2M^2}{Q^2}}\right) + \frac{2Ax}{Q^2}}$$

$$K_{valence}(Q^2) = [1 - G_D^2(Q^2)] \cdot \left(\frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}\right)$$

$$K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_{s1}}$$

| parameter | impact (%) 1 year | 3 year | 5 year |
|---|---|---|---|
| hierarchy | 100.0 | 100.0 | 100.0 |
| $\Delta m^2_{31}$ | 38.8 | 37.9 | 37.6 |
| Energy scale | 21.2 | 21.4 | 21.7 |
| $A_{eff}$ scale | 15.2 | 13.2 | 11.4 |
| $\theta_{23}$ | 3.4 | 4.8 | 5.7 |
| $\nu_e/numu$ ratio | 0.5 | 1.7 | 2.6 |
| $nu/\overline{\nu}$ ratio | 0.5 | 1.2 | 2.3 |
| $M_A^{RES}$ | 1.2 | 2.0 | 1.7 |
| $C_{V1u}^{BY}$ | 0.1 | 0.3 | 0.3 |
| $C_{V2u}^{BY}$ | 0.0 | 0.0 | 0.2 |
| $\theta_{13}$ | 0.0 | 0.1 | 0.2 |
| $A_{HT}^{BY}$ | 0.0 | 0.0 | 0.0 |
| $M_A^{CCQE}$ | 0.0 | 0.0 | 0.0 |
| $B_{HT}^{BY}$ | 0.0 | 0.0 | 0.0 |

DIS errors

PINGU LoI variations

| Name | nominal value | uncertainty (%) |
|---|---|---|
| $M_A^{CCQE}$ | 0.99 | $-15, +25$ |
| $M_A^{RES}$ | 1.120 | $\pm 20$ |
| $A_{HT}^{BY}$ | 0.538 | $\pm 25$ |
| $B_{HT}^{BY}$ | 0.305 | $\pm 25$ |
| $C_{V1u}^{BY}$ | 0.291 | $\pm 30$ |
| $C_{V2u}^{BY}$ | 0.189 | $\pm 30$ |

# 4. Bodek-Yang correction errors

Parameter variations are defined
- errors A and B: I follow Joshua's choice
- errors on PDF correction: 30% for all
- errors on d(x)/u(x): next page

| BY-parameters | CV | error |
|---|---|---|
| A | 0.538 | ±25% |
| B | 0.305 | ±25% |
| CsU | 0.363 | ±30% |
| CsD | 0.621 | ±30% |
| Cv1U | 0.291 | ±30% |
| Cv2U | 0.189 | ±30% |
| Cv1D | 0.202 | ±30% |
| Cv2D | 0.255 | ±30% |
| X0 | -0.00817 | +0.00817 |
| X1 | 0.0506 | -0.0506 |
| X2 | 0.0798 | -0.0798 |

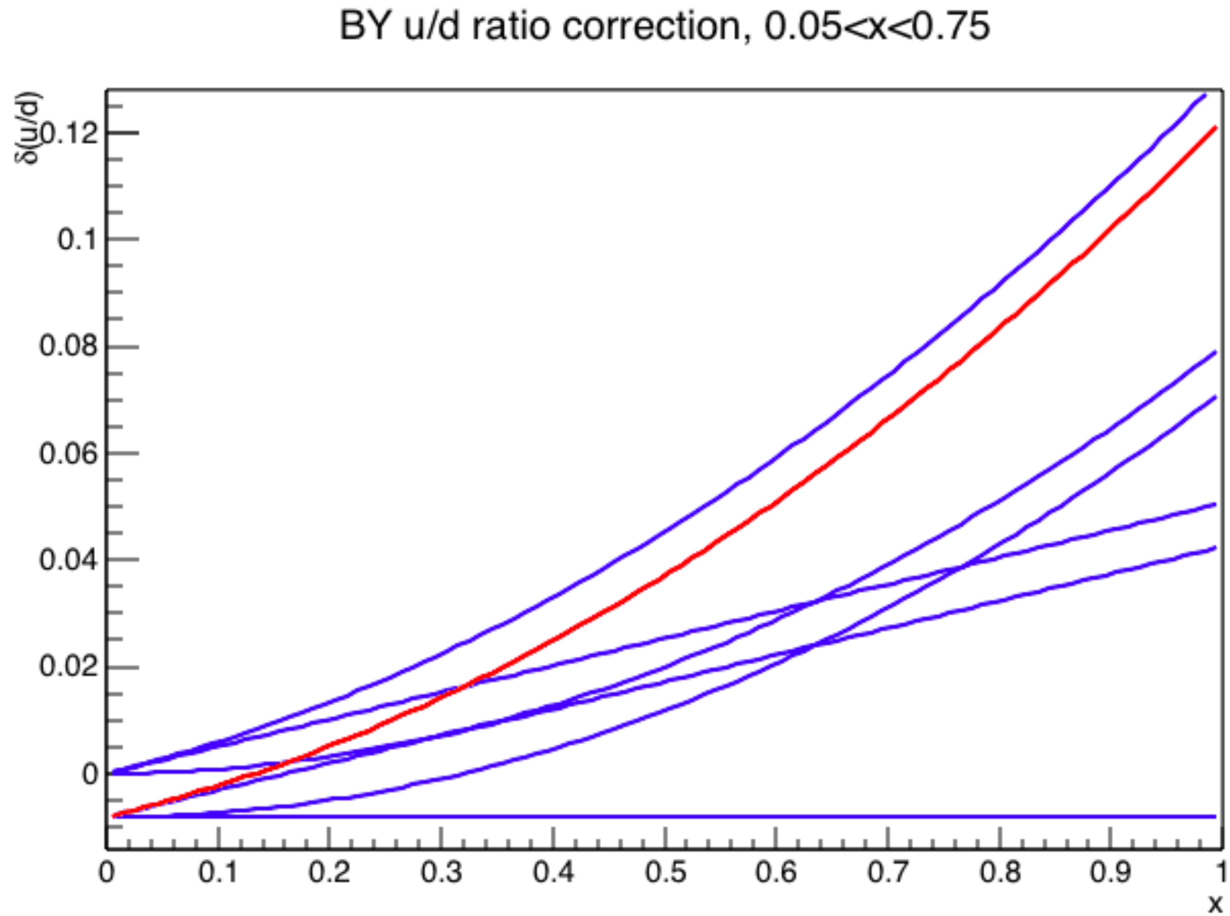
Since no correlations of parameters are available, 9 BY-systematic study samples are made to maximize of parameter variation effects

| sample | sample |
|---|---|
| 1 | default |
| 2 | A+δA, B-δB |
| 3 | A-δA, B+δB |
| 4 | CsU+δCsU, CsD-δCsD |
| 5 | CsU-δCsU, CsD+δCsD |
| 6 | Cv1U+δCv1U, Cv2U-δCv2U |
| 7 | Cv1U-δCv1U, Cv2U+δCv2U |
| 8 | Cv1D+δCv1D, Cv2D-δCv2D |
| 9 | Cv1D-δCv1D, Cv2D+δCv2D |
| 10 | X0=0, X1=0, X2=0 |

# 4. d(x)/u(x) variation study

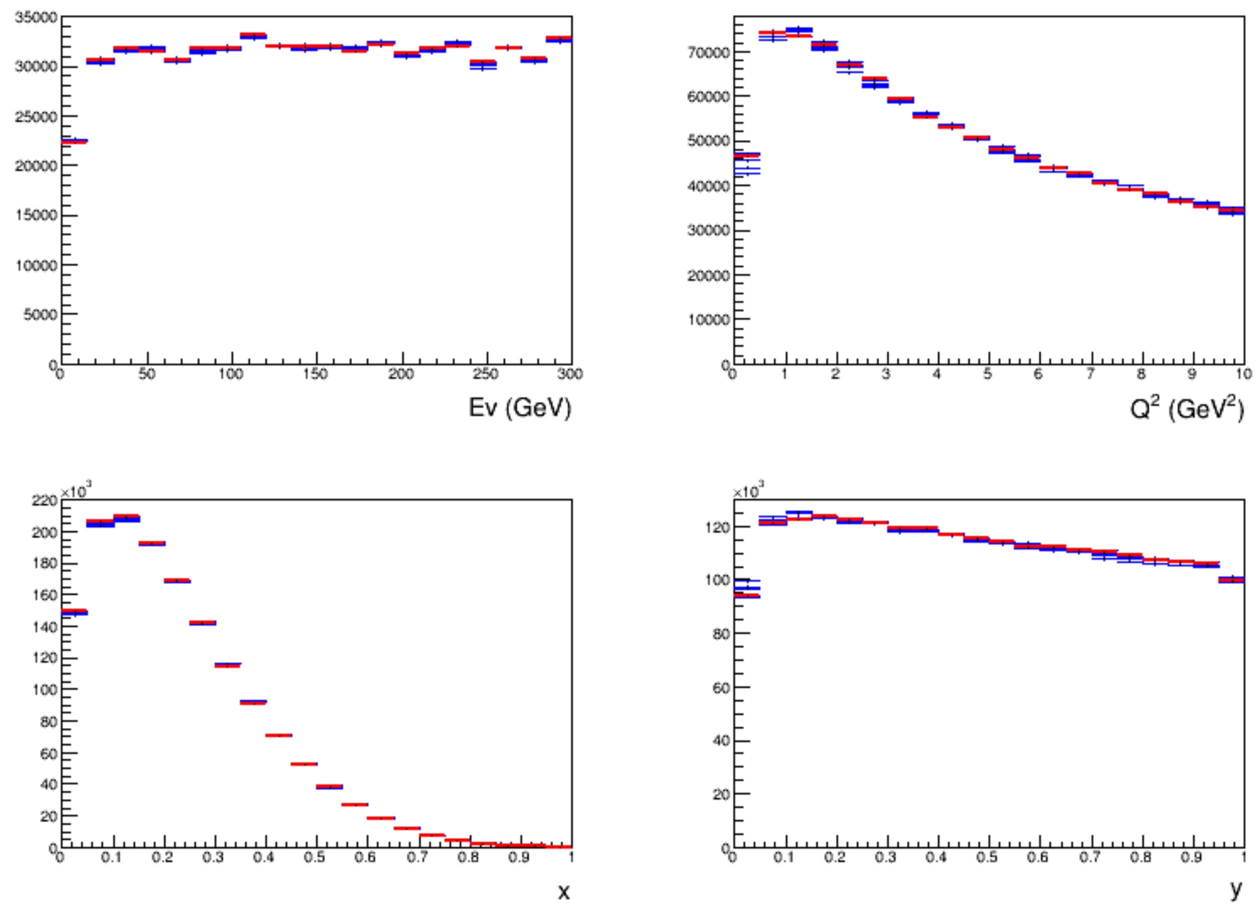
$\delta(d(x)/u(x)) = X0 + X1*x + X2*x^2$

- 2nd order polynomial describe this error, ~10% effect at large x
- A reasonable choice of envelope is when the function is 0.



# 4. Results

BY parameter variation make small variations in Ev, Q2, x, y.




Queen Mary
University of London

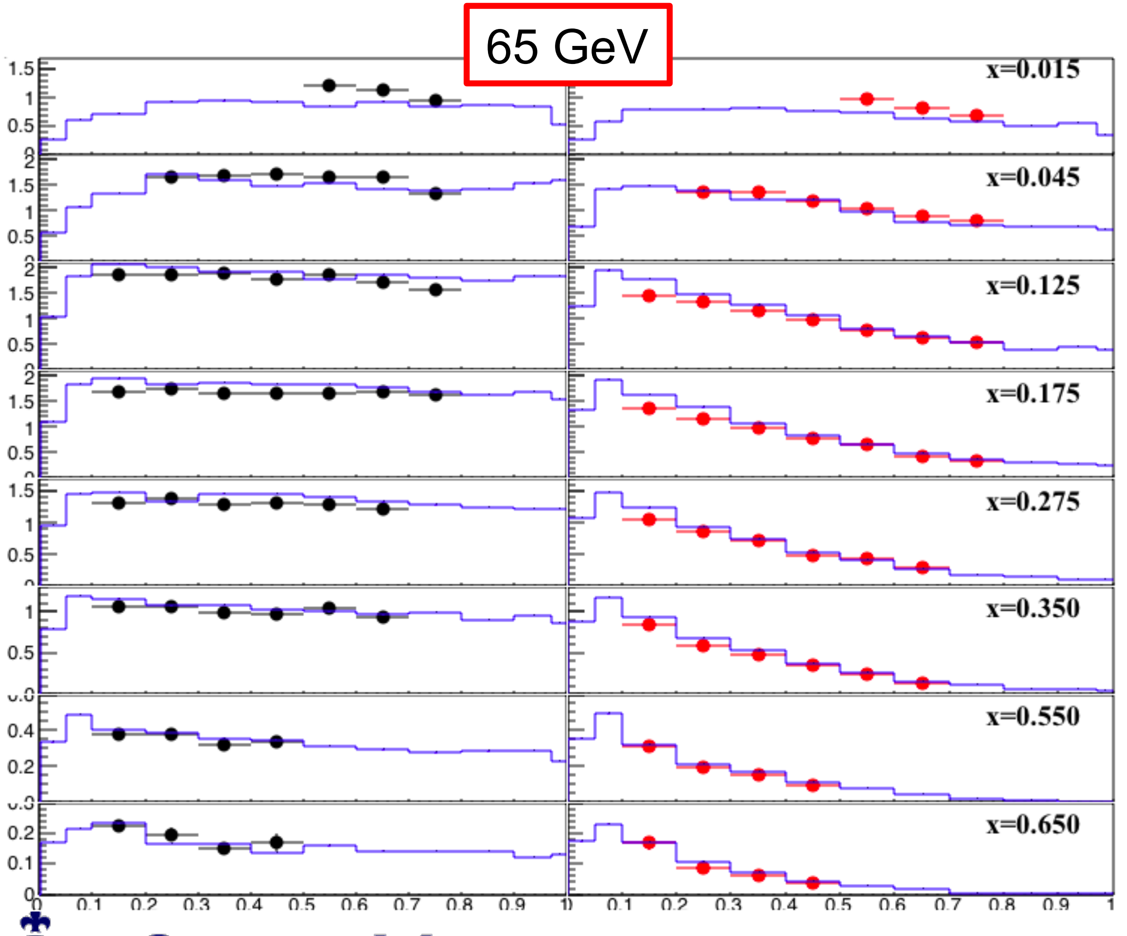
NuTeV, PRD74(2006)012008

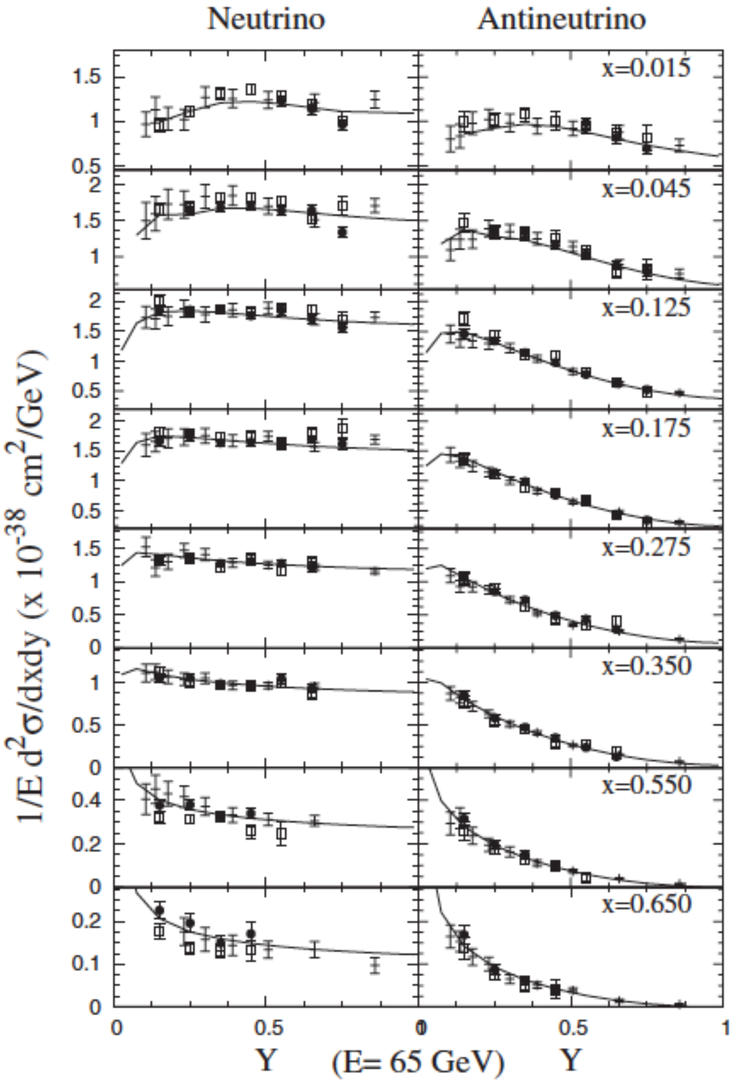
Shivesh Mandalia
(Queen Mary)

# 5. GENIE-NuTeV comparison

NuTeV ν-Fe and antiν-Fe
differential cross section (x, y, Eν)

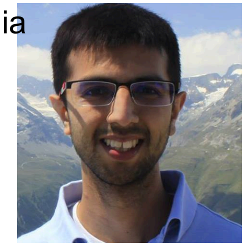
GENIE v2.10.6
- By definition, GENIE reproduce NuTeV data
- Agreement at very low x is poor




Queen Mary
University of London

Shivesh Mandalia
(Queen Mary)

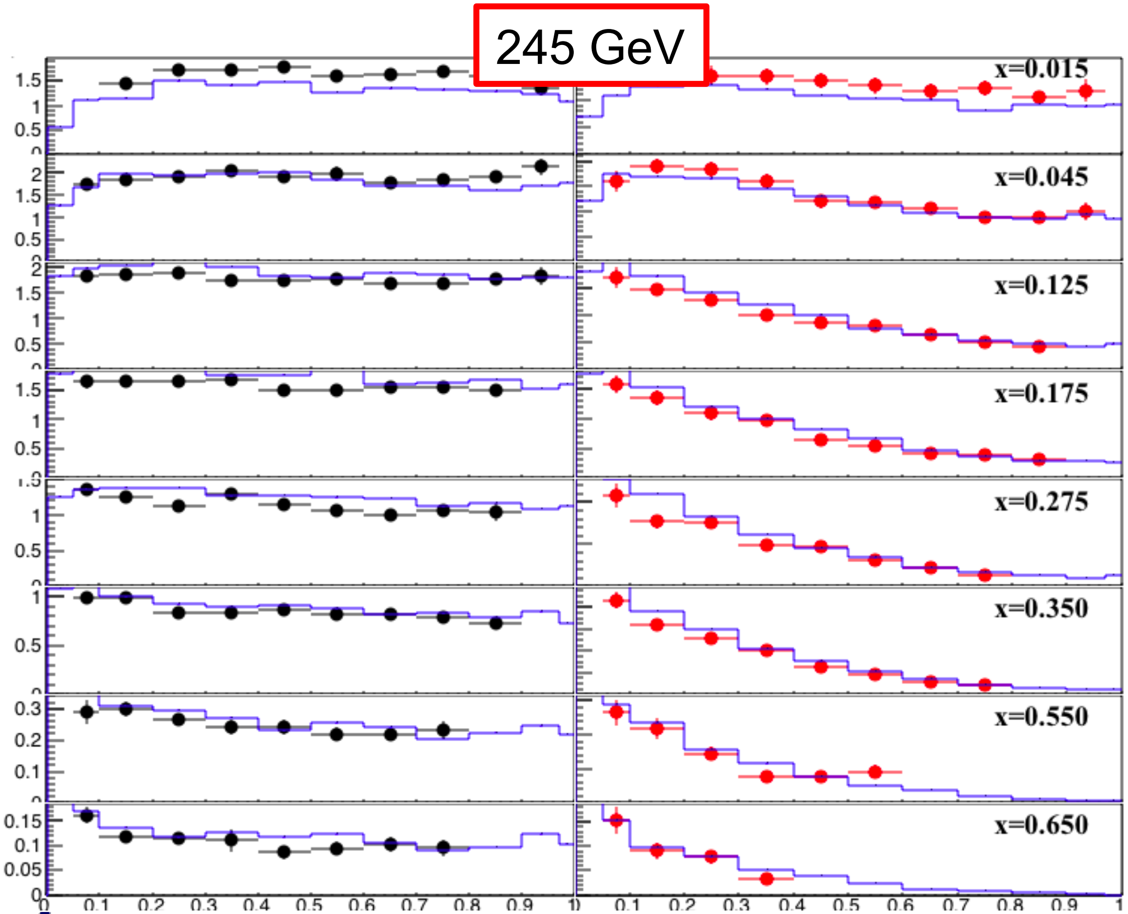


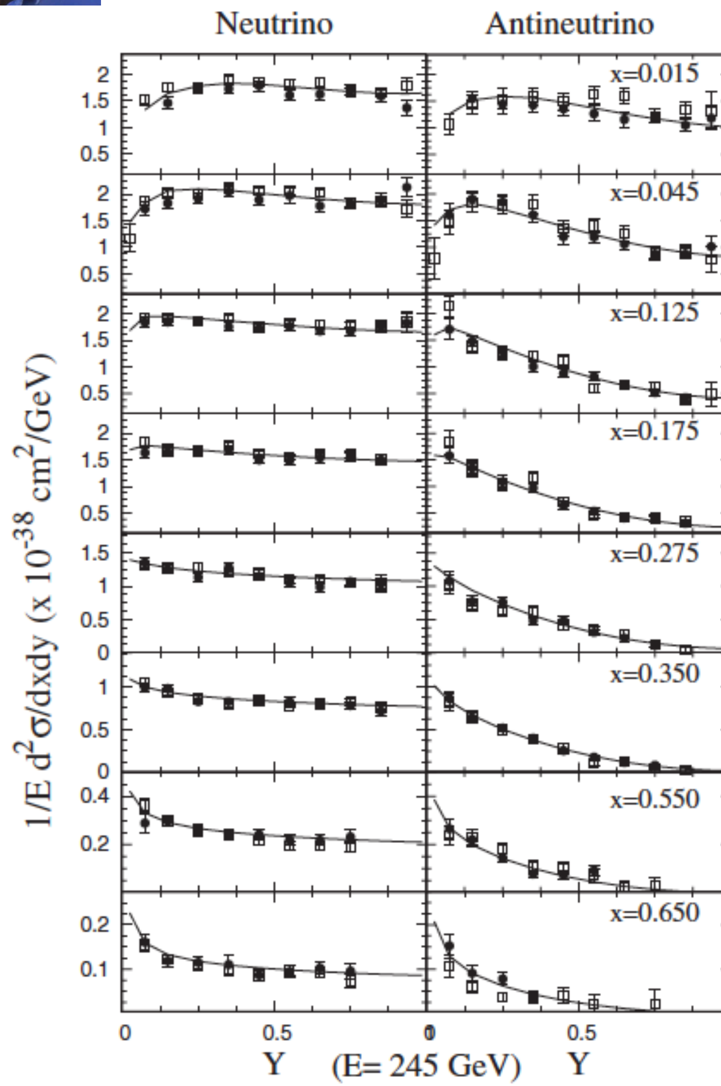
# 5. GENIE-NuTeV comparison

NuTeV ν-Fe and antiν-Fe differential cross section (x, y, Eν)

GENIE v2.10.6

- By definition, GENIE reproduce NuTeV data
- Agreement at very low x is poor




Queen Mary
University of London

Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
Gallmeister and Falter, PLB630(2005)40, TK and Mandalia,JPhysG42(2015)115004

# 9. High-W hadronization model error

Shivesh Mandalia
(Queen Mary)

Averaged charged hadron multiplicity $\langle n_{ch} \rangle$

- PYTHIA6 with tuned Lund string function can reproduce $\langle n_{ch} \rangle$ data both neutrino and antineutrino.

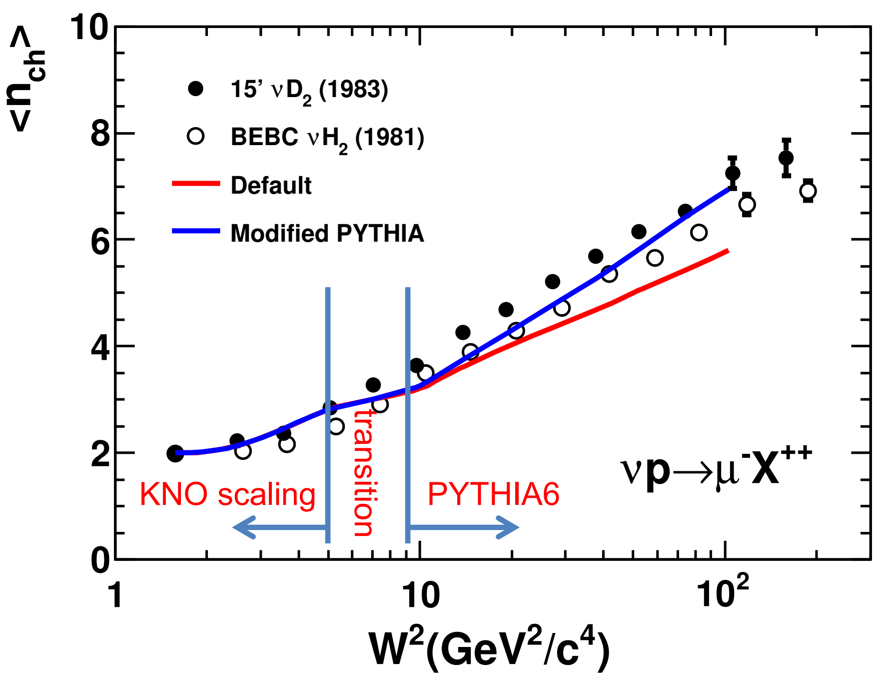
$$E_{\rm h}^{\rm vis} = \sum_{E_{\rm h}^i > E_{\rm th}^i} T_{\rm h}^i + \sum E_\gamma^i.$$

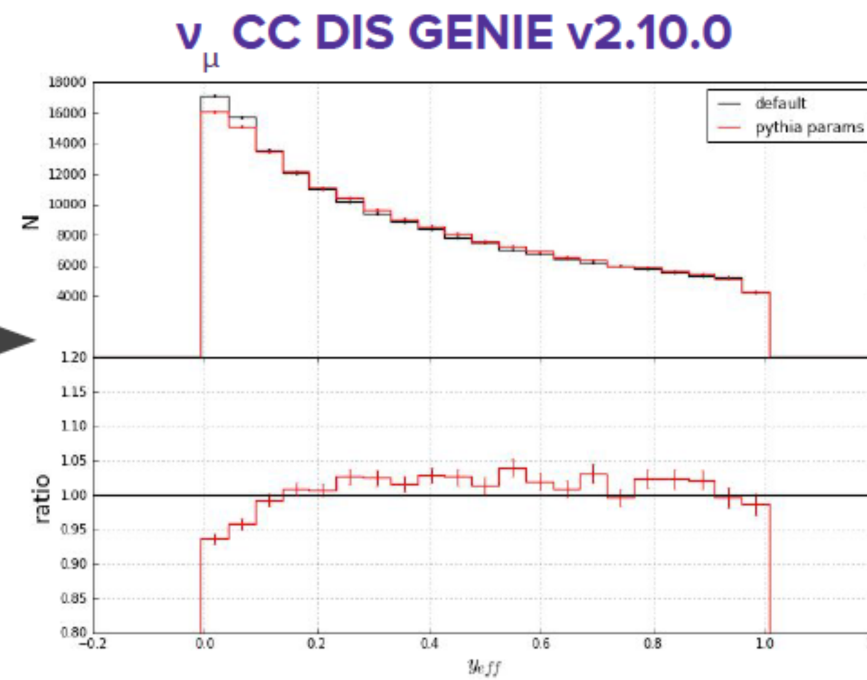
$$y^{\rm eff} = \frac{E_{\rm h}^{\rm vis}}{E_{\rm h}^{\rm vis} + E_\mu}.$$

Hadronization error propagation

- Difference of averaged charged hadron multiplicity is translated to visible hadron energy, then effective inelasticity. This is applied to variation of inelasticity error in simulation. Impact of hadronization error is small for experiments which only measure hadron shower

Neutrino average charged hadron multiplicity



TK and Mandalia, JPhysG42(2015)115004
Zieminska et al (Fermilab 15'), PRD27(1993)47

# 8. High-W hadronization dispersion error?

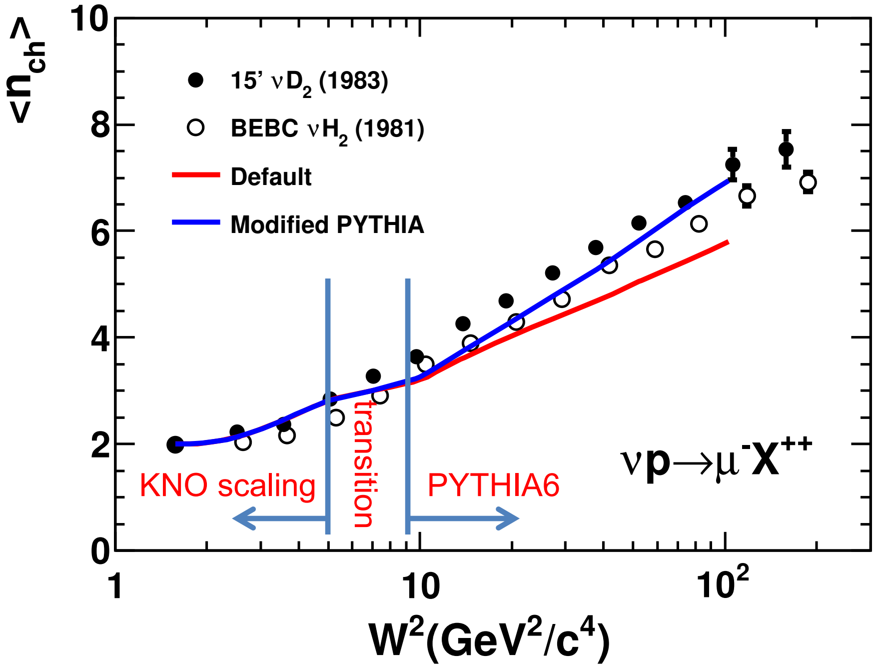
Shivesh Mandalia
(Queen Mary)

## Bubble chamber topological cross section data

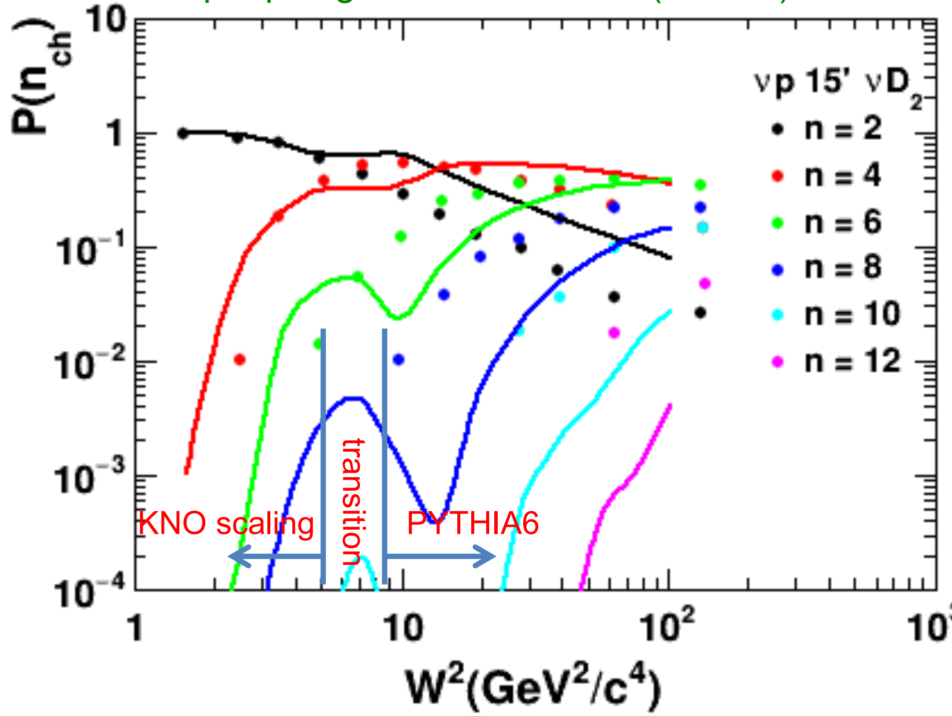
Although averaged charged hadron multiplicity makes continuous curve, topological cross sections are discontinuous, because multiplicity dispersion by PYTHIA6 is much narrower than bubble chamber data.

If the experiment is sensitive to hadron counting, you need to re-think how to propagate hadronization error…

Neutrino average charged hadron multiplicity




ν-p topological cross section (GENIE)



TK and Mandalia,JPhysG42(2015)115004
Zieminska et al (Fermilab 15'),PRD27(1993)47, Nowak, arXiv:hep-ph/0608108

# 8. High-W hadronization dispersion error?

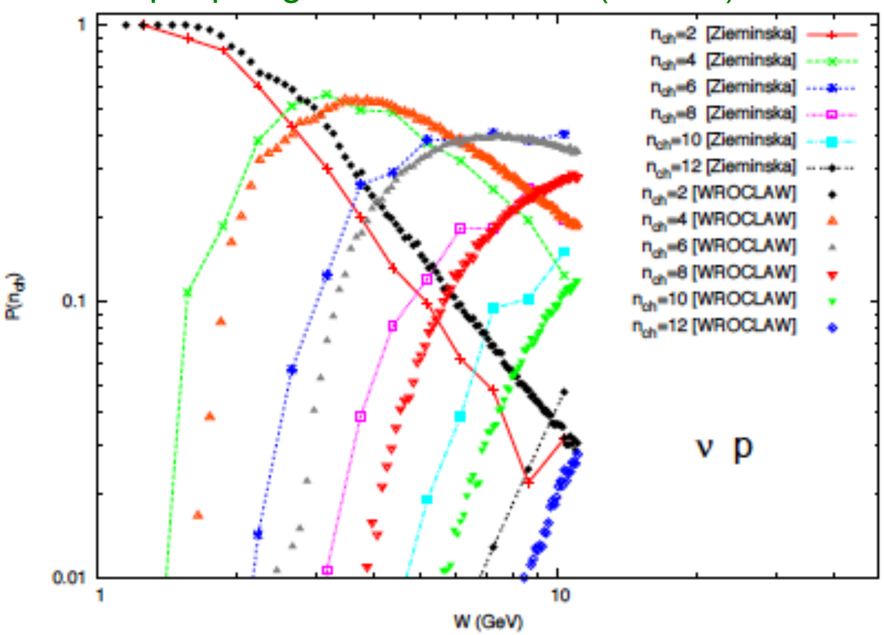
Shivesh Mandalia
(Queen Mary)

### Bubble chamber topological cross section data

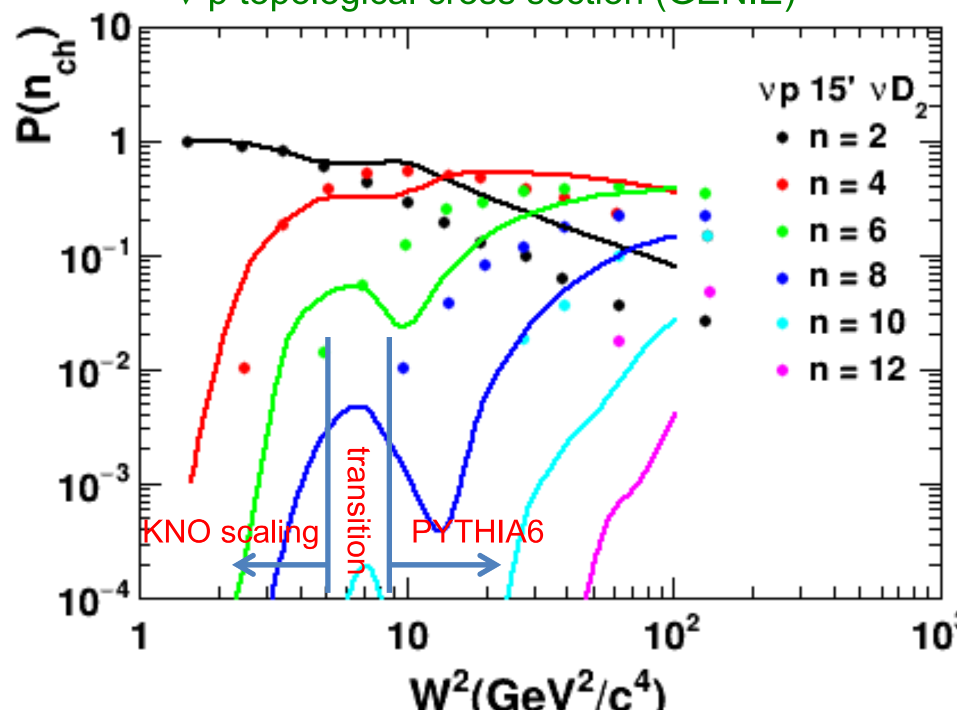
Although averaged charged hadron multiplicity makes continuous curve, topological cross sections are discontinuous, because multiplicity dispersion by PYTHIA6 is much narrower than bubble chamber data.

If the experiment is sensitive to hadron counting, you need to re-think how to propagate hadronization error…

ν-p topological cross section (NuWro)




ν-p topological cross section (GENIE)




Queen Mary
University of London

Tep

# NuSTEC (Neutrino Scattering Theory-Experiment Collaboration)

http://nustec.fnal.gov/

NuSTEC promotes the collaboration and coordinates efforts between
- theorists, to study neutrino interaction problems
- experimentalists, to understand nu-A and e-A scattering problems
- generator builders, to implement, validate, tune, maintain models

Theorists
Luis Alvarez Ruso (co-spokesperson, IFIC, Spain)
Mohammad Sajjad Athar (Aligarh Muslim University, India)
Maria Barbaro (University of Turin, Italy)
Omar Benhar (Sapienza University of Rome, Rome, Italy)
Richard Hill (University of Kentucky and Fermilab, USA)
Patrick Huber (Center for neutrino physics, Virginia Tech, USA)
Natalie Jachowicz (Ghent University, Belgium)
Andreas Kronfeld (Fermilab, USA)
Marco Martini (IRFU Saclay, France)
Toru Sato (Osaka, University, Japan)
Rocco Schiavilla (Old Dominion Univ. and Jefferson Lab, USA)
Jan Sobczyk (nuWro representative, University of Wroclaw, Poland)

Experimentalists
Sara Bolognesi (CEA-IRFU, France)
Steve Brice (Fermilab, USA)
Raquel Castillo Fernández (Fermilab, USA)
Dan Cherdack (Colorado State University, USA)
Steve Dytman (University of Pittsburgh, USA)
Andy Furmanski (University of Manchester, UK)
Yoshinari Hayato (NEUT representative, ICRR, Japan)
Teppei Katori (Queen Mary University of London, UK)
Kendall Mahn (Michigan State University, USA)
Camillo Mariani (Center for neutrino physics, VirginiaTech, USA)
Jorge G. Morfin (co-spokesperson, Fermilab, USA)
Ornella Palamara (Fermilab, USA)
Jon Paley (Fermilab, USA)
Roberto Petti (University of South Carolina, USA)
Gabe Perdue (GENIE representative, Fermilab, USA)
Federico Sanchez (IFAE, University of Barcelona, Spain)
Sam Zeller (Fermilab, USA)

# NuSTEC white paper

https://arxiv.org/abs/1706.03621

- It addresses all topics of neutrino-nucleus scattering around 1-10 GeV.

Progress in Particle and Nuclear Physics 100 (2018) 1–68

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

ELSEVIER

Review

## NuSTEC[1] White Paper: Status and challenges of neutrino–nucleus scattering

L. Alvarez-Ruso [a], M. Sajjad Athar [b], M.B. Barbaro [c], D. Cherdack [d], M.E. Christy [e], P. Coloma [f], T.W. Donnelly [g], S. Dytman [h], A. de Gouvêa [i], R.J. Hill [j,f], P. Huber [k], N. Jachowicz [l], T. Katori [m], A.S. Kronfeld [f], K. Mahn [n], M. Martini [o], J.G. Morfín [f,*], J. Nieves [a], G.N. Perdue [f], R. Petti [p], D.G. Richards [q], F. Sánchez [r], T. Sato [s,t], J.T. Sobczyk [u], G.P. Zeller [f]

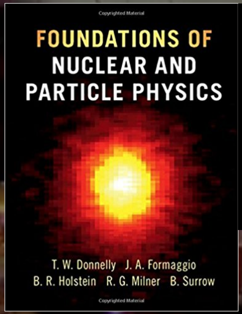
# NuSTEC school

NuSTEC Training in Neutrino-Nucleus Scattering Physics
Nov.8-14, 2015, Okayama, Japan

## NuSTEC school, Fermilab, USA (Nov. 7-15, 2017)

- NuSTEC school is dedicated for students/postdocs to learn physics of neutrino interactions, both for theorists, and experimentalists

1. The Practical Beauty of Neutrino-Nucleus Interations (1 hour) - Dr. Gabe Perdue (Fermilab)
2. Introduction to electroweak interactions on the nucleon (3 hours) - Prof. Richard Hill (University of Kentucky and Fermilab)
3. Introduction to $\nu$-nucleus scattering (3 hours) - Prof. Wally Van Orden (Old Dominion University&JLab, VA)
4. Strong and electroweak interactions in nuclei (3 hours) - Dr. Saori Pastore (Los Alamos National Lab., NM)
5. Approximate methods for nuclei (I) (2 hours) - Dr. Artur Ankowski (Virginia Tech, VA)
6. Approximate methods for nuclei (II) (2 hours) - Prof. Natalie Jachowicz (Ghent University, Belgium)
7. Ab initio methods for nuclei (2 hours) - Dr. Alessandro Lovato (Argonne National Lab, IL)
8. Pion production and other inelastic channels (3 hours) - Prof. Toru Sato (Osaka University, Japan)
9. Exclusive channels and final state interactions (3 hours) - Dr. Kai Gallmeister (Goethe University Frankfurt, Germany)
10. Inclusive e- and $\nu$-scattering in the SIS and DIS regimes (3 hrs) - Prof. Jeff Owens (Florida State University, FL)
11. Systematics in neutrino oscillation experiments (3 hours) - Dr. Sara Bolognesi (CEA Saclay, France)
12. Generators 1: Monte Carlo methods and event generators (3 rs) - Dr. Tomasz Golan (Univ. Wroclaw, Poland)
12. Generators 2: Nuisance (2 hours) - Dr. Patrick Stowell (Univ. Sheffield, UK)




## Foundation of Nuclear and Particle Physics

- Cambridge University Press (2017), ISBN:0521765110
- Authors: Donnelly, Formaggio, Holstein, Milner, Surrow
- The first textbook on this subject!