DIS and Hadronization systematic errors

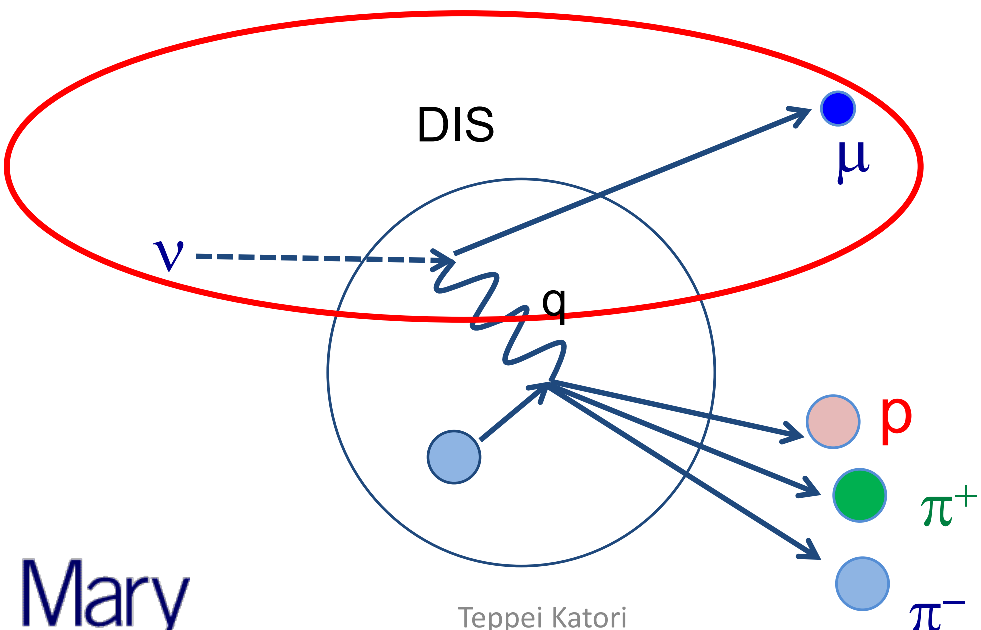
Teppei Katori and Shivesh Mandalia
NuSTEC meeting, Nov. 16, 2017

Queen Mary University of London

0. Neutrino cross section overview

Deep Inelastic Scattering (DIS)

- It defines the probability to scatter a charged lepton by an incident lepton with given energy
- DIS cross section is function of x and y, this is the differential cross section
- DIS cross section integrated in x and y is called total cross section and function of neutrino energy



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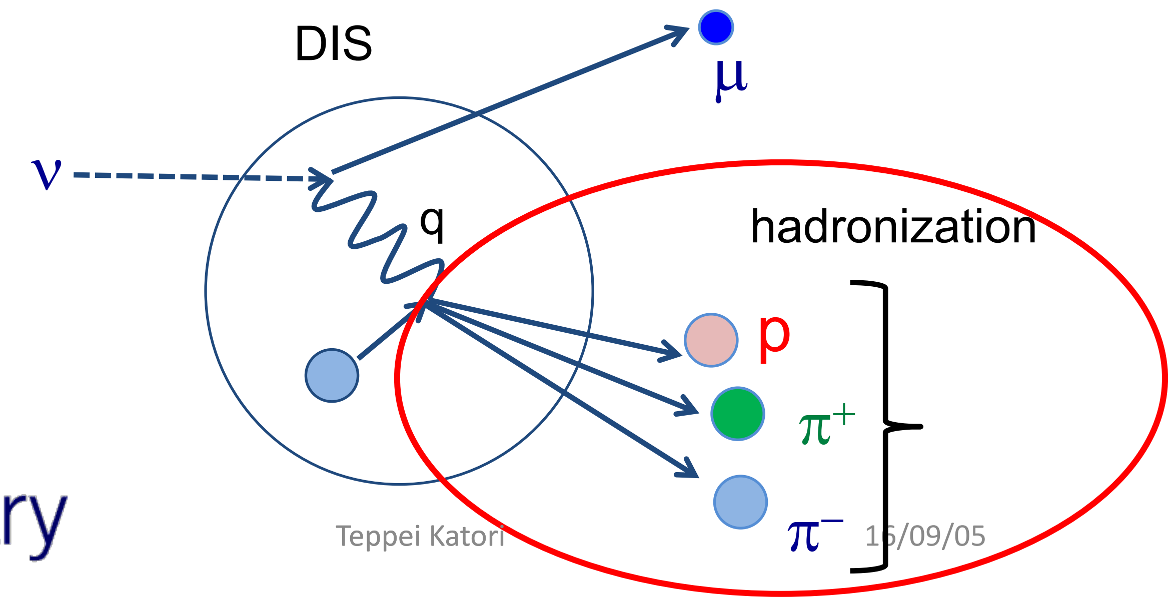
Hadronization

- Hadronization is a process to generate hadrons from given energy-momentum transfer
- number of hadrons (multiplicity), energy, and momentum of outgoing Hadrons are computed, somehow.

DIS and Hadronization are modelled independently



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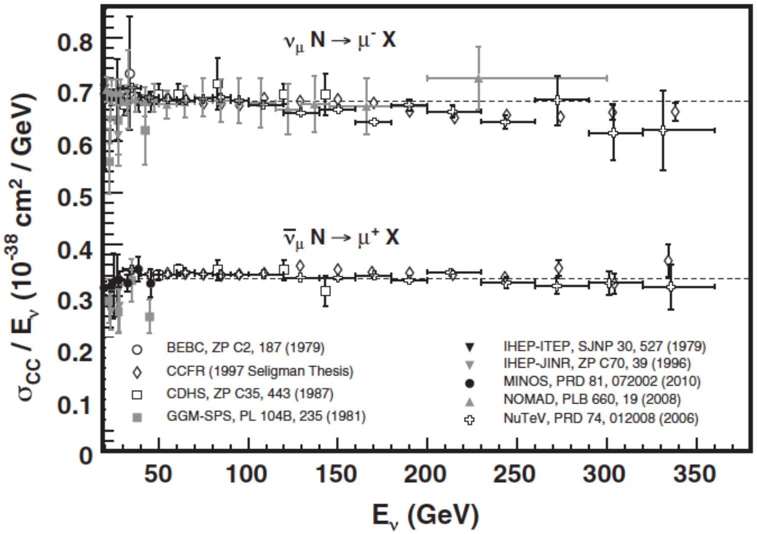
DIS total cross section error ~ 2%

- $\sigma(\nu)/E = 0.677 \pm 0.014 \times 10^{-38}$ (cm^2/GeV)
- This is the error of the charged lepton production rate by a neutrino with given energy (30-200 GeV)
- Most of our analyses need errors of differential cross section error



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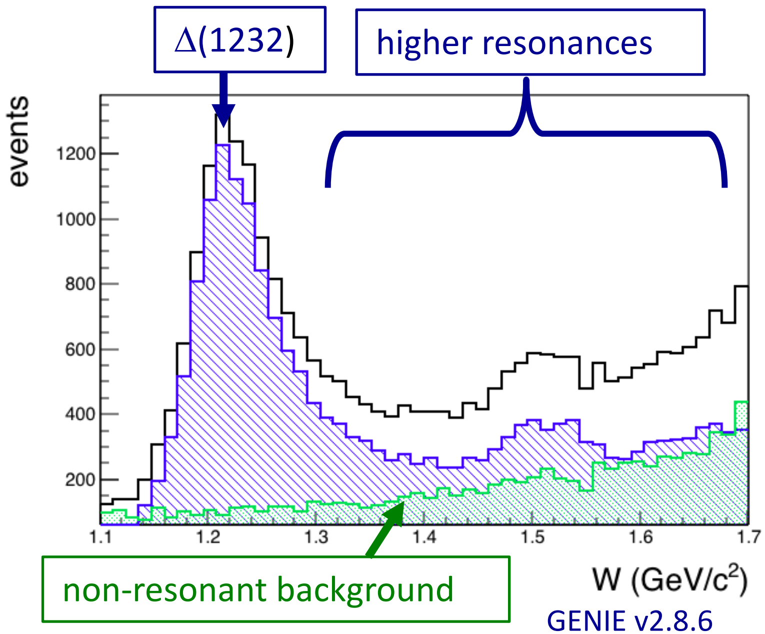
0. SIS region physics

Basic ingredients
- Δ(1232)-resonance
- higher resonances
- non-resonant background



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

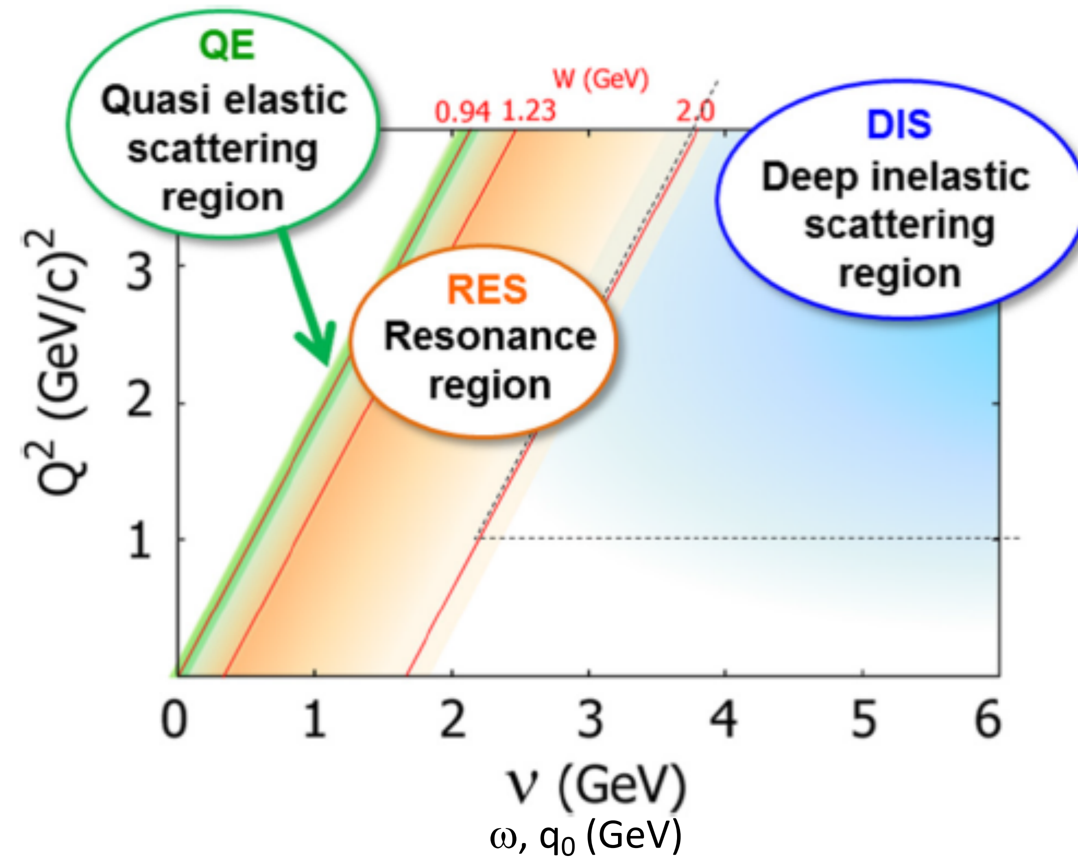


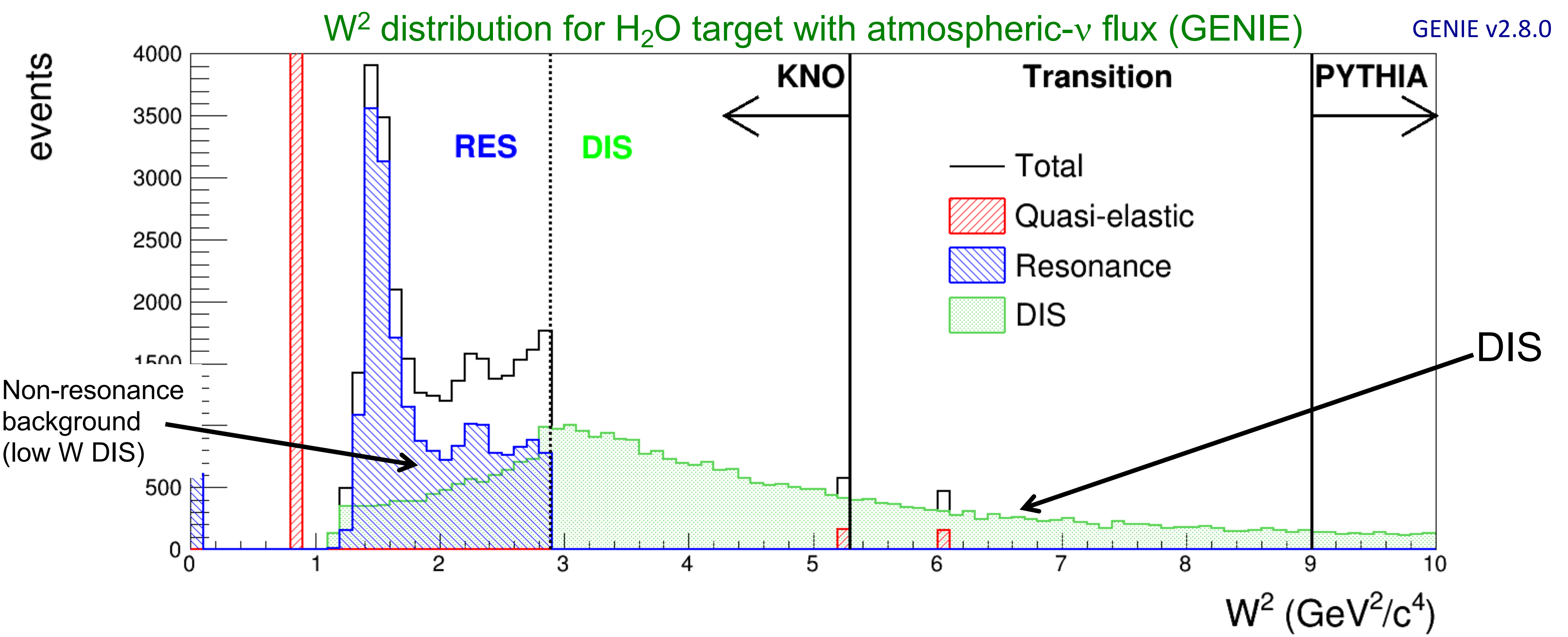
Figure 1. Kinematical regions of the neutrino-nucleus interaction relevant to the next-generation neutrino-oscillation experiments. The energy transfer to a nucleus and the squared four-momentum transfer are denoted by ν and Q^2, respectively.

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

0. GENIE SIS model

Cross section
W^2<2.9 GeV^2 : RES
W^2>2.9 GeV^2 : DIS
Hadronization
W^2<5.3GeV^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



0. NEUT SIS model

Cross section

W^2<4 GeV^2 : RES

W^2>4 GeV^2 : DIS

Hadronization

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

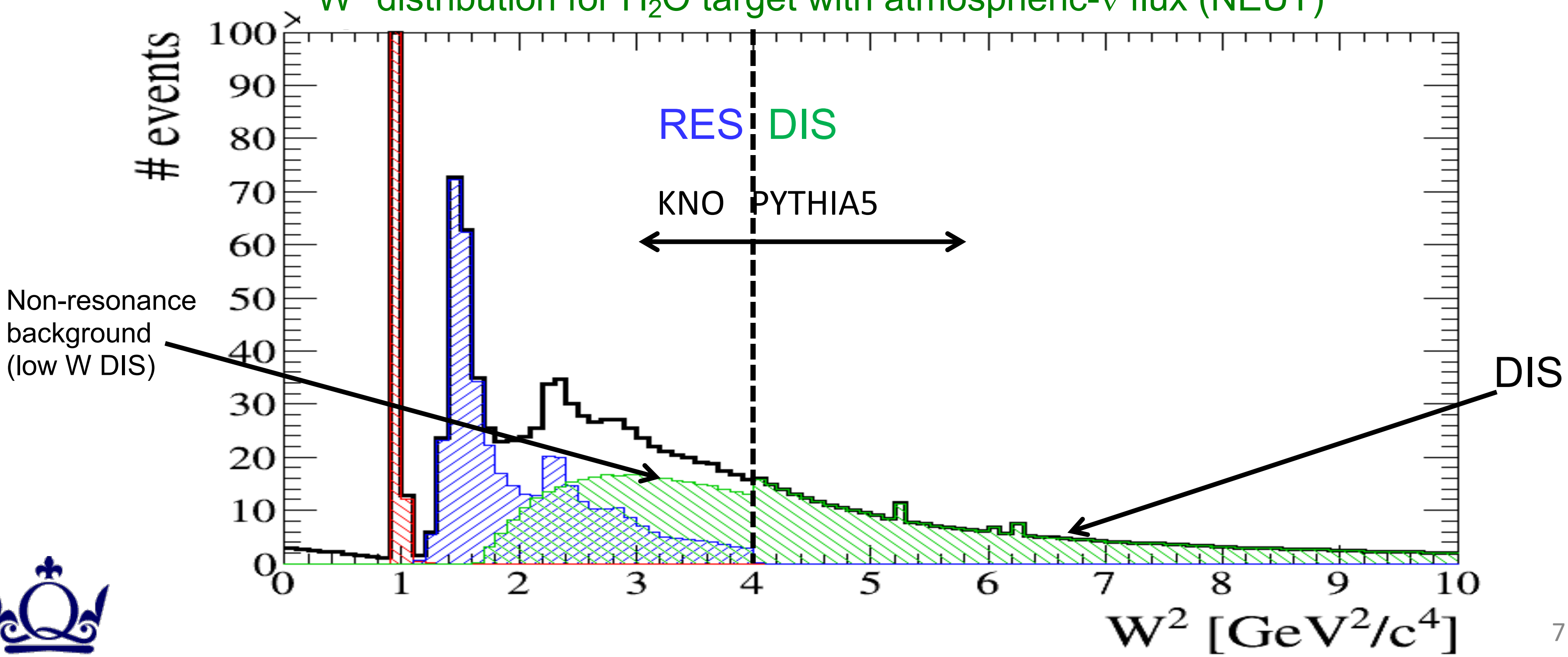
4GeV^2<W^2 : PYTHIA5

There are 2 kind of “transitions” in SIS region

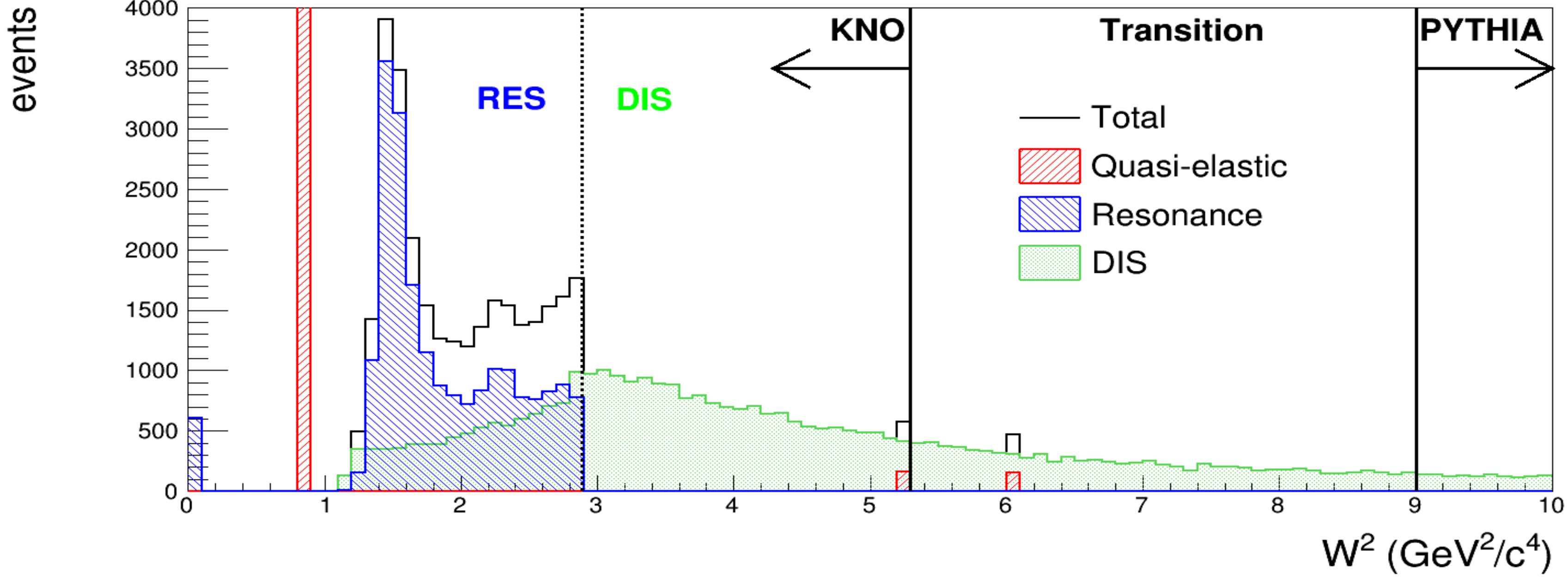
- cross-section
- hadronization

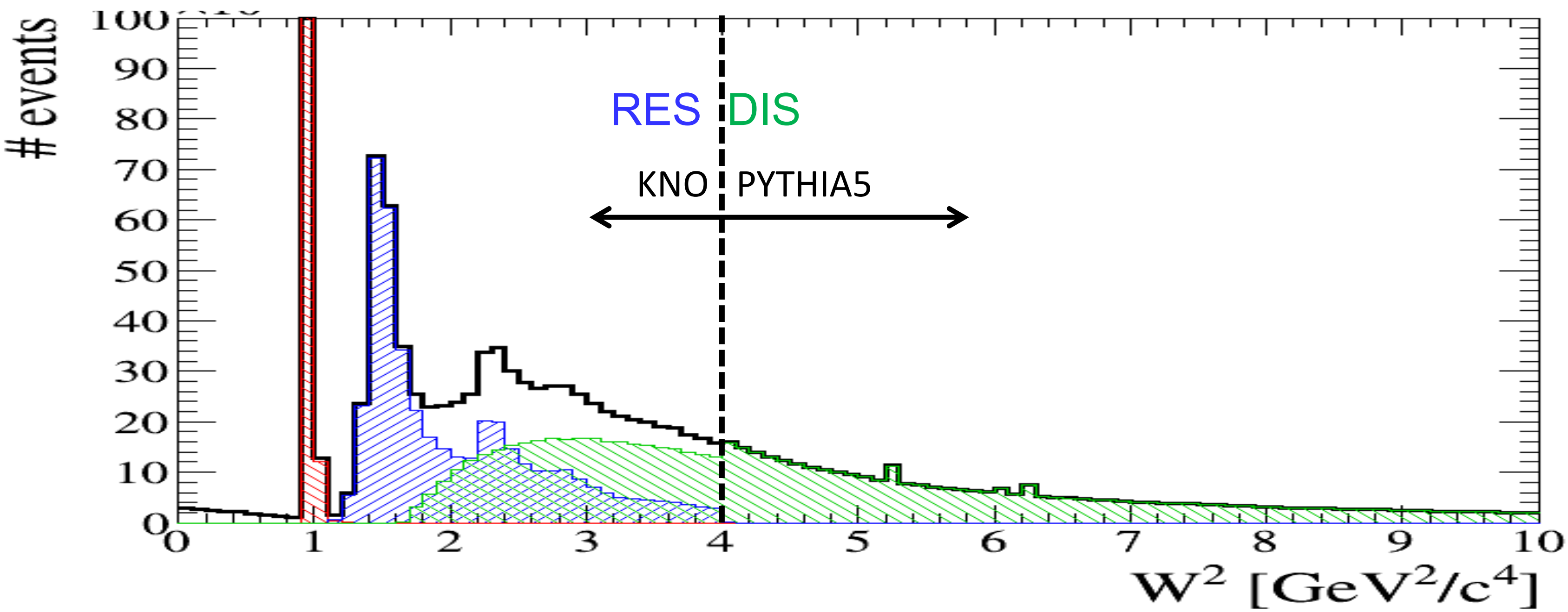
Christophe Bronner (IPMU)

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



0. GENIE vs. NEUT





0. 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 (?)

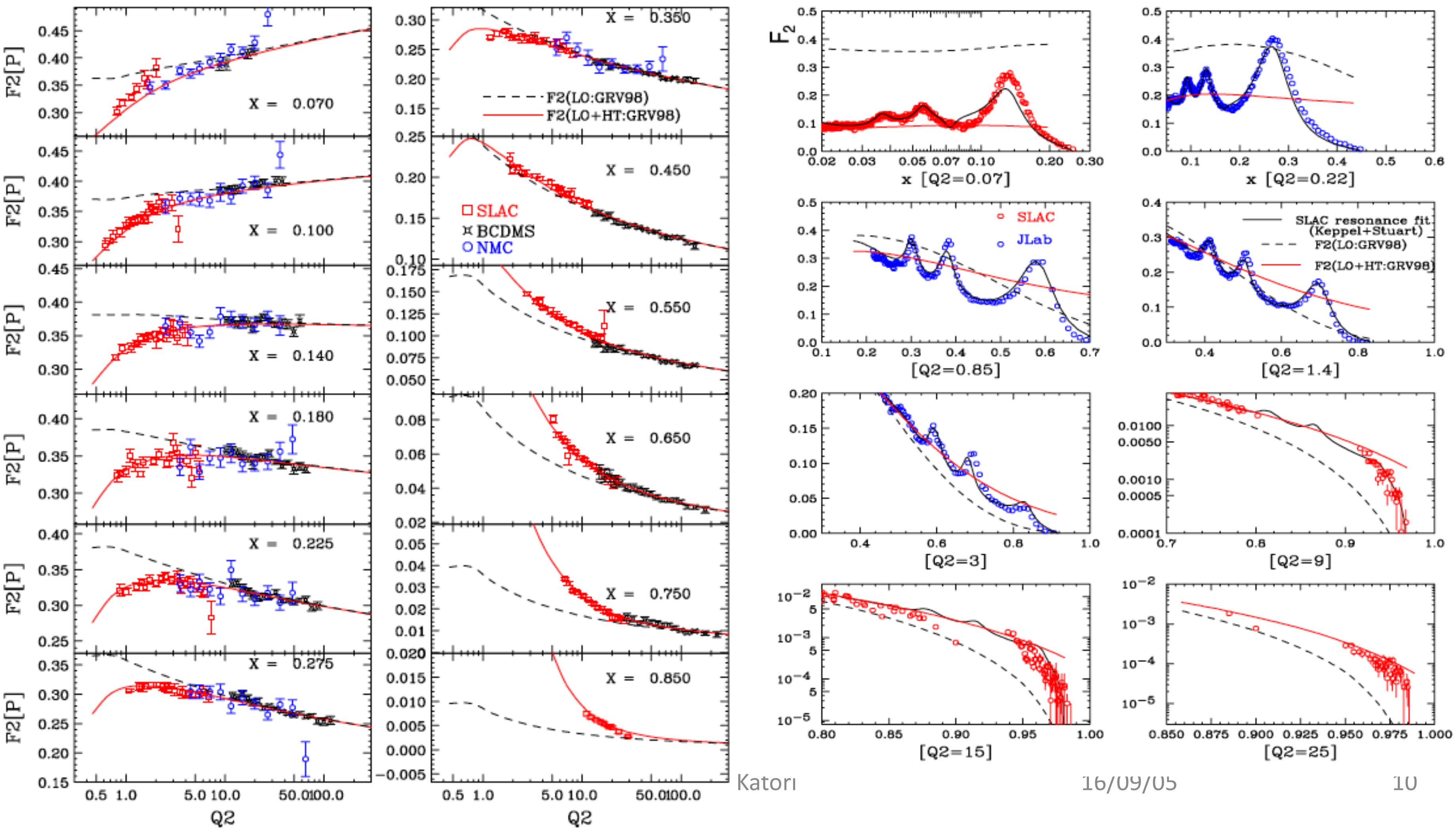
DIS or Hadronization	type of error	approach	size
DIS	Bodek-Yang correction	play with Bodek-Yang parameters (by eyes)	expected to be tiny
DIS	differential xs	NuTeV-GENIE comparison (bottom-up)	????
DIS	A-scaling	MINERvA-GENIE (bottom-up)	????
DIS	PDF	From nuclear PDF, CT10? nCTEQ? (top-down)	????
Hadronization	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)	1-2% by GENIE study

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

1. 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



1. 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

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

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

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

	impact (%)		
parameter	1 year	3 year	5 year
hierarchy	100.0	100.0	100.0
Δm^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
θ_{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
θ_{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	± 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

1. 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

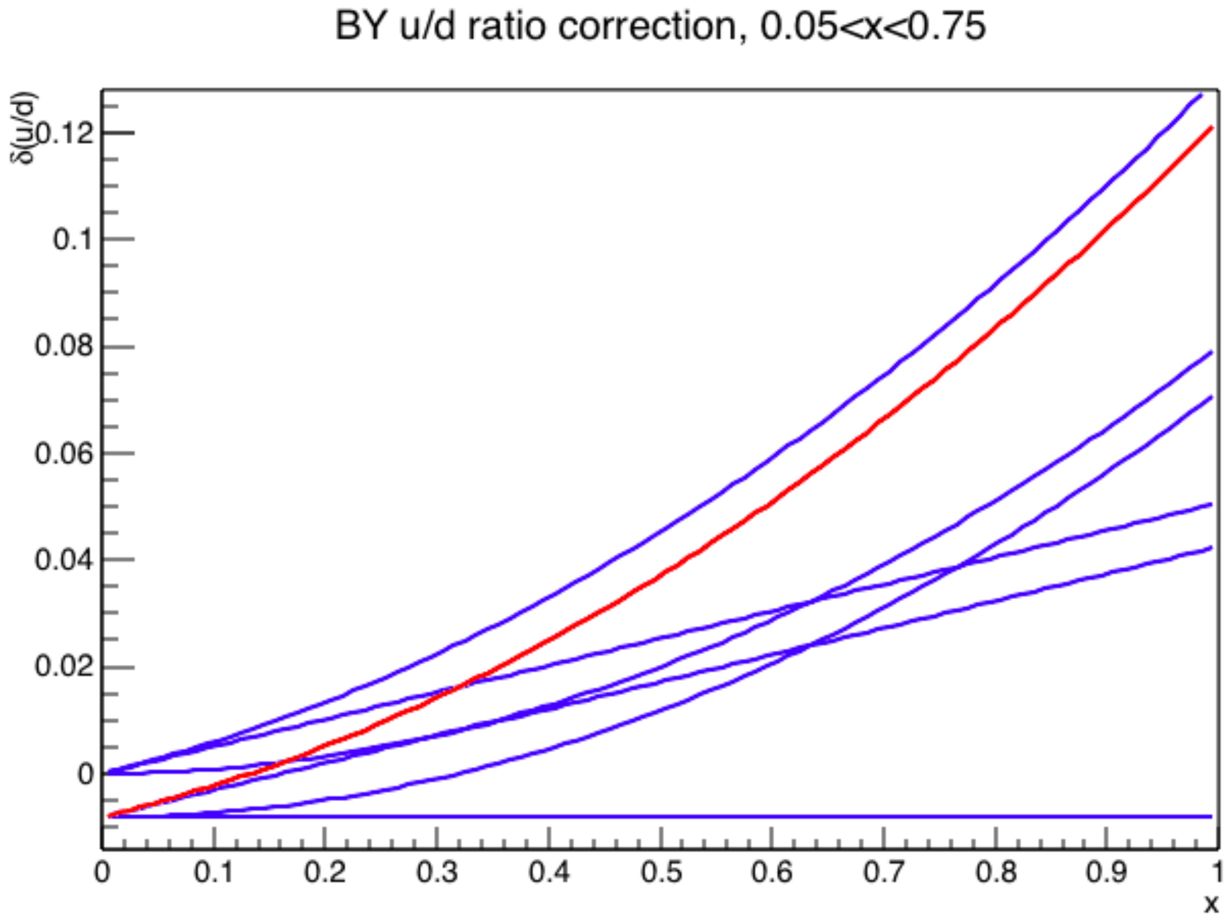
Since no correlations of parameters are available, 9 BY-systematic study samples are made to maximize of parameter variation effects

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

1. d(x)/u(x) variation study

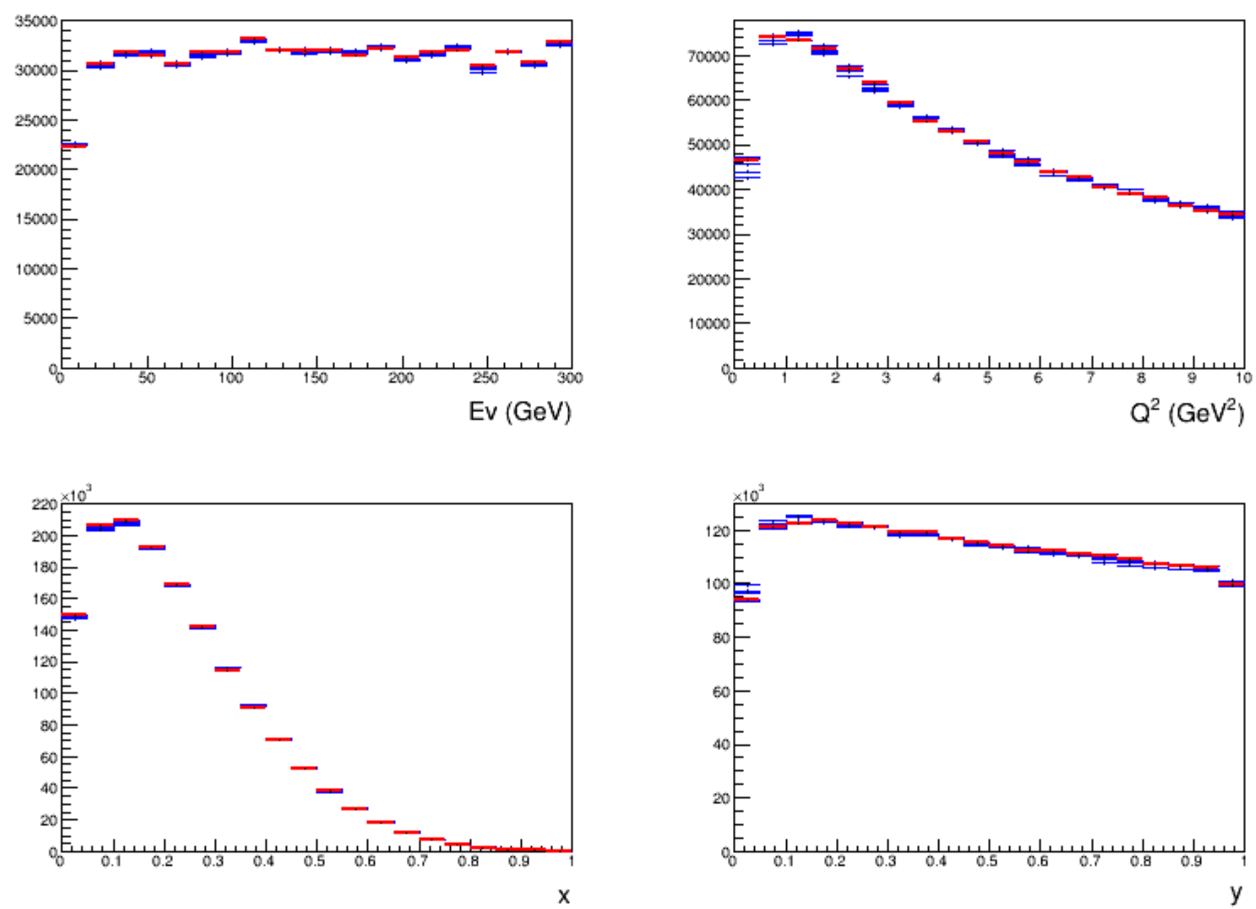
$\delta(d(x)/u(x)) = X0 + X1*x + X2*x^2$

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



1. Results

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



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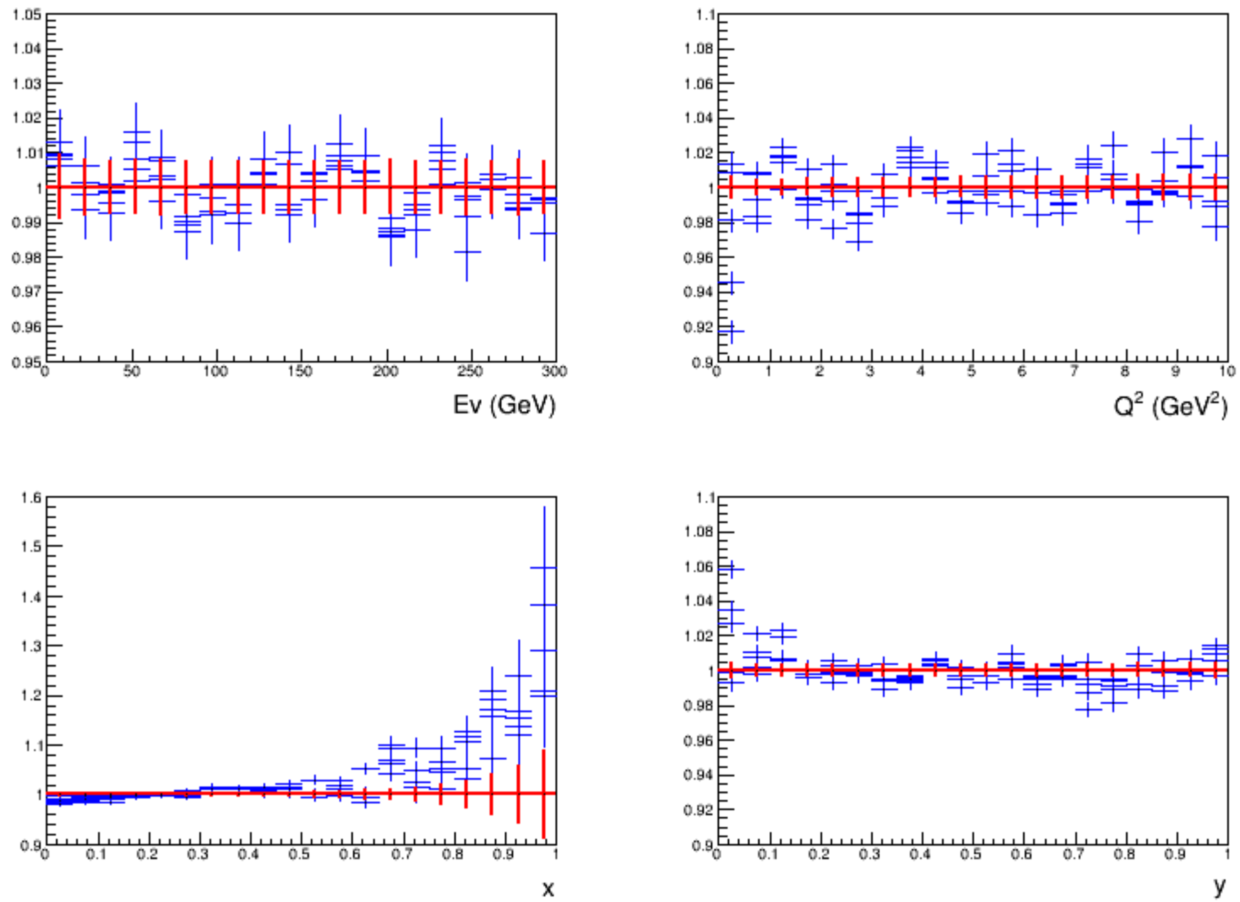
1. Results

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

In general, variation can be large by assuming correlations on parameters



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1. DIS Bodek-Yang correction error

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NuTeV, PRD74(2006)012008

Shivesh Mandalia
(Queen Mary)

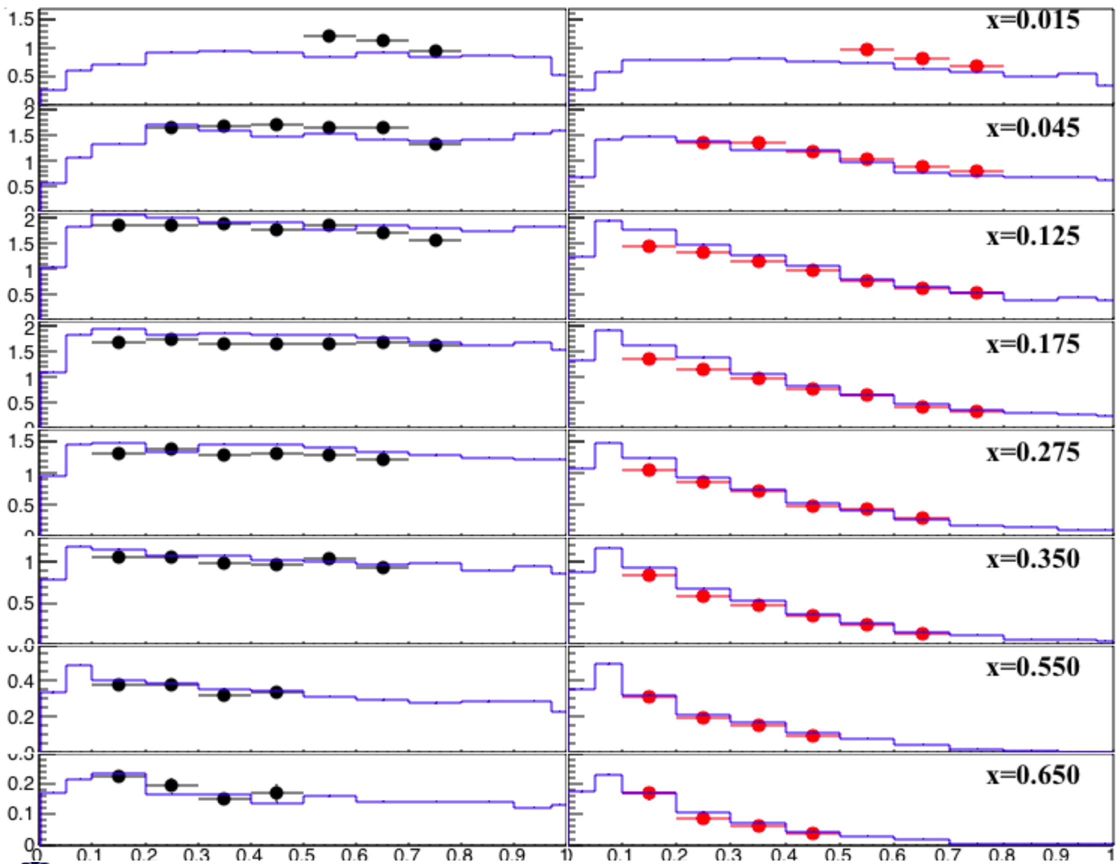
2. GENIE-NuTeV comparison

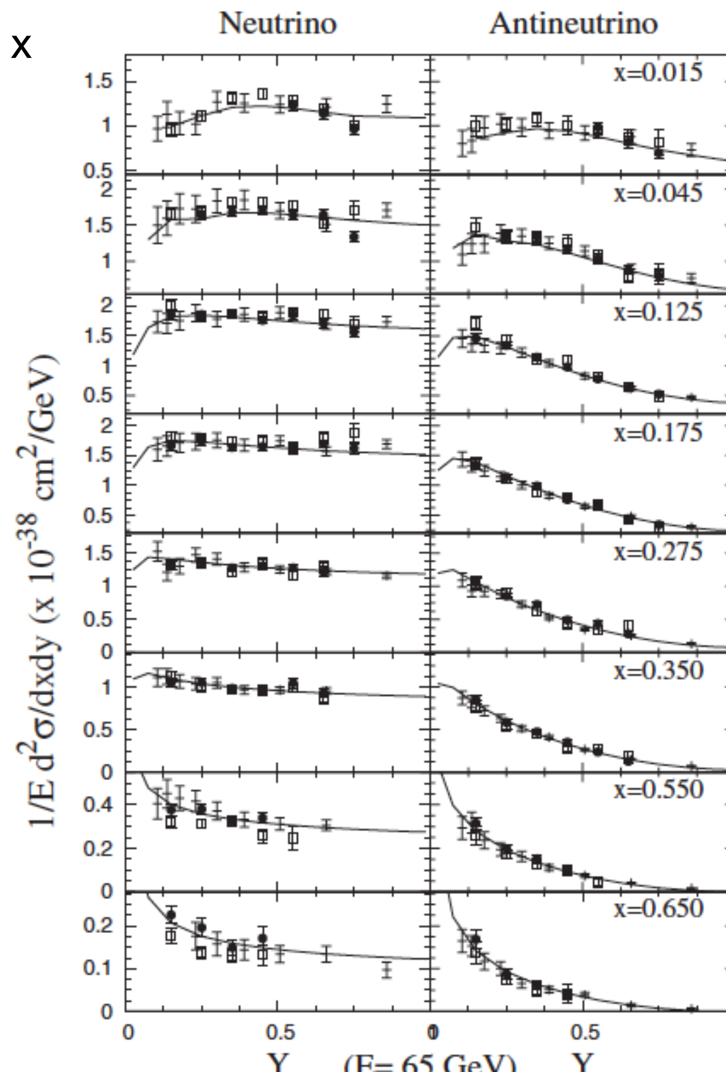
NuTeV ν-Fe and antiν-Fe differential cross section (x, y, Eν)

GENIE v2.10.6

Seems GENIE reproduce NuTeV data except very low x

65 GeV





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NuTeV, PRD74(2006)012008

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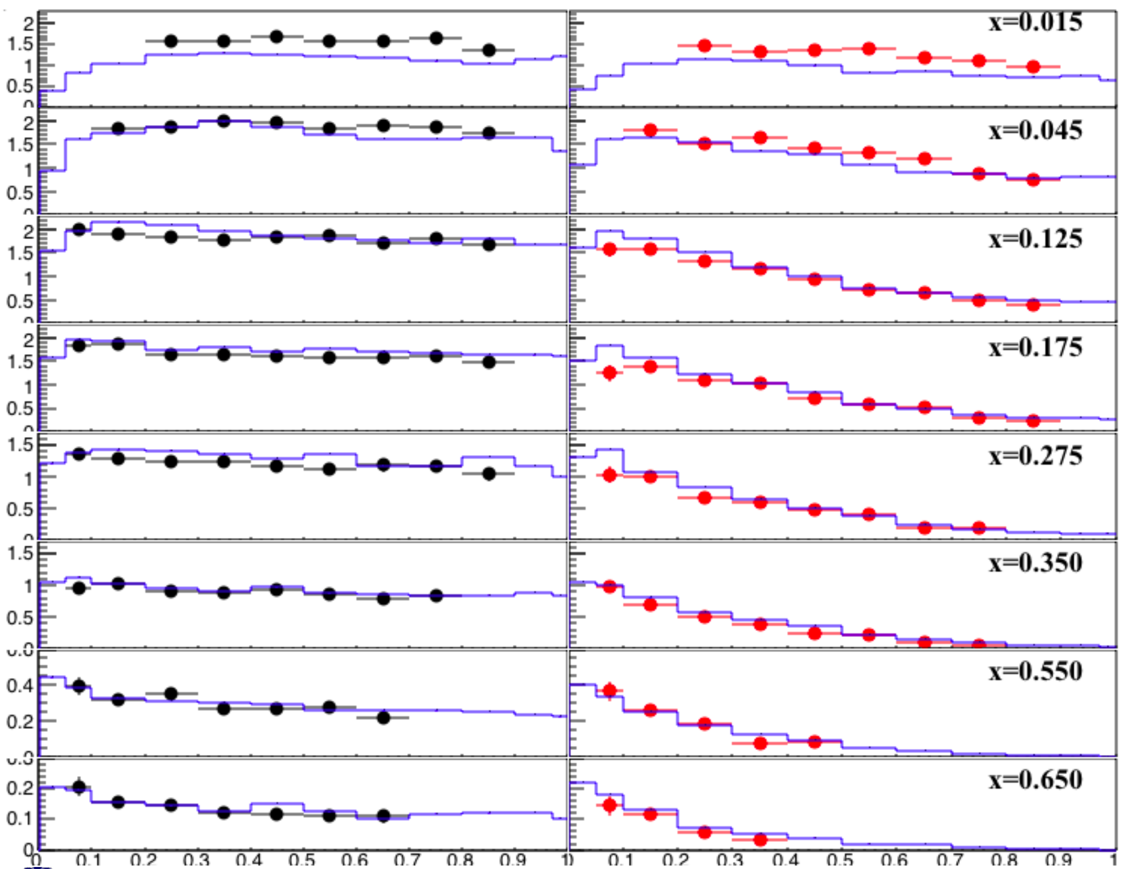
2. GENIE-NuTeV comparison

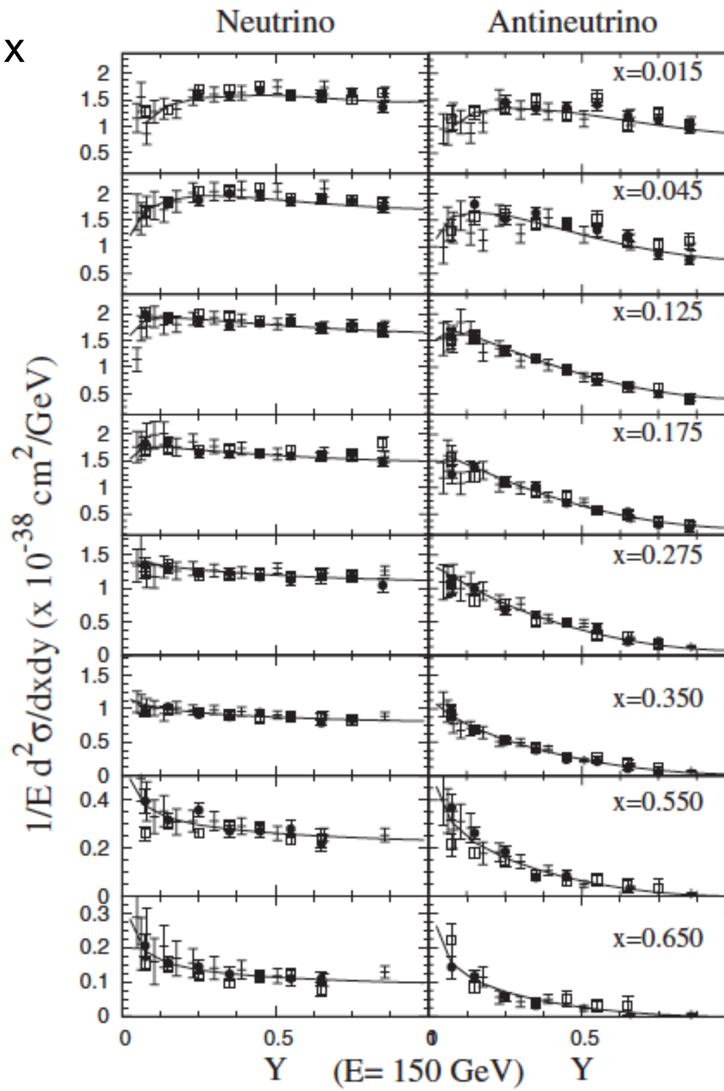
GENIE v2.10.6

Seems GENIE reproduce NuTeV data except very low x

150 GeV



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



NuTeV, PRD74(2006)012008

Shivesh Mandalia
(Queen Mary)

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

GENIE v2.10.6

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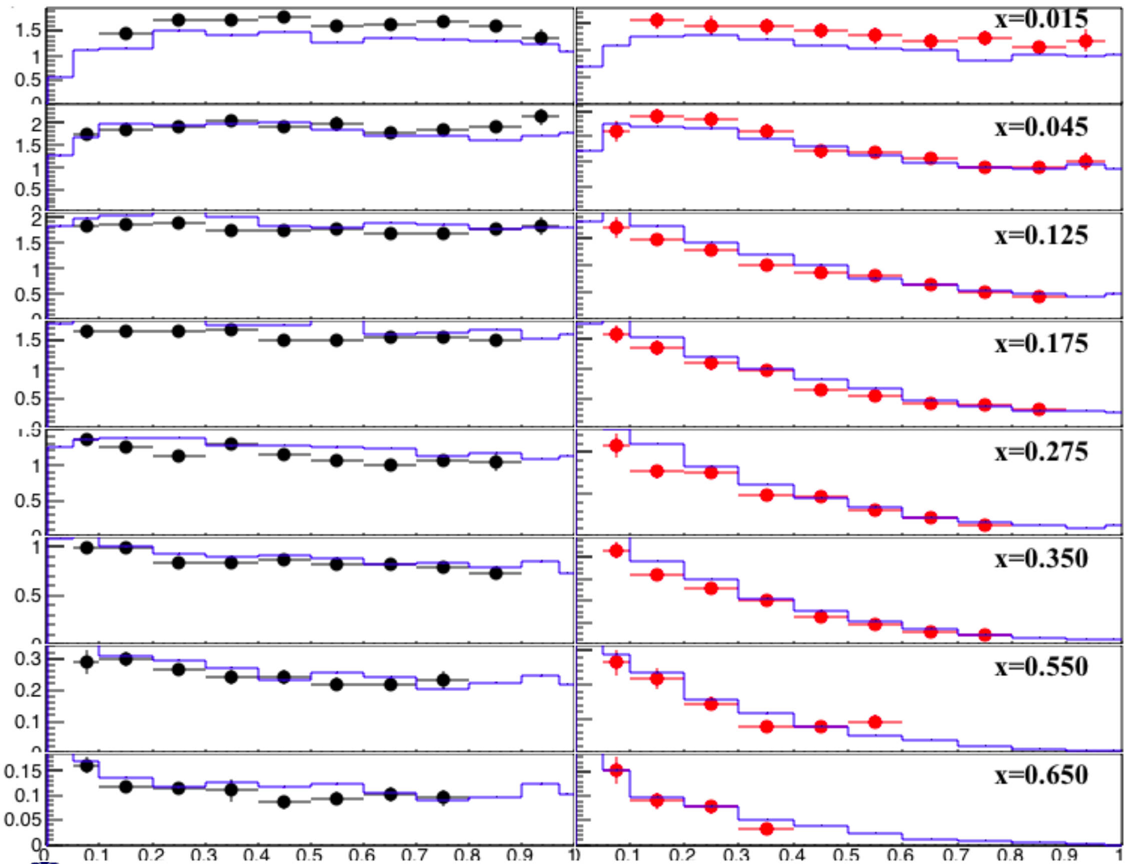
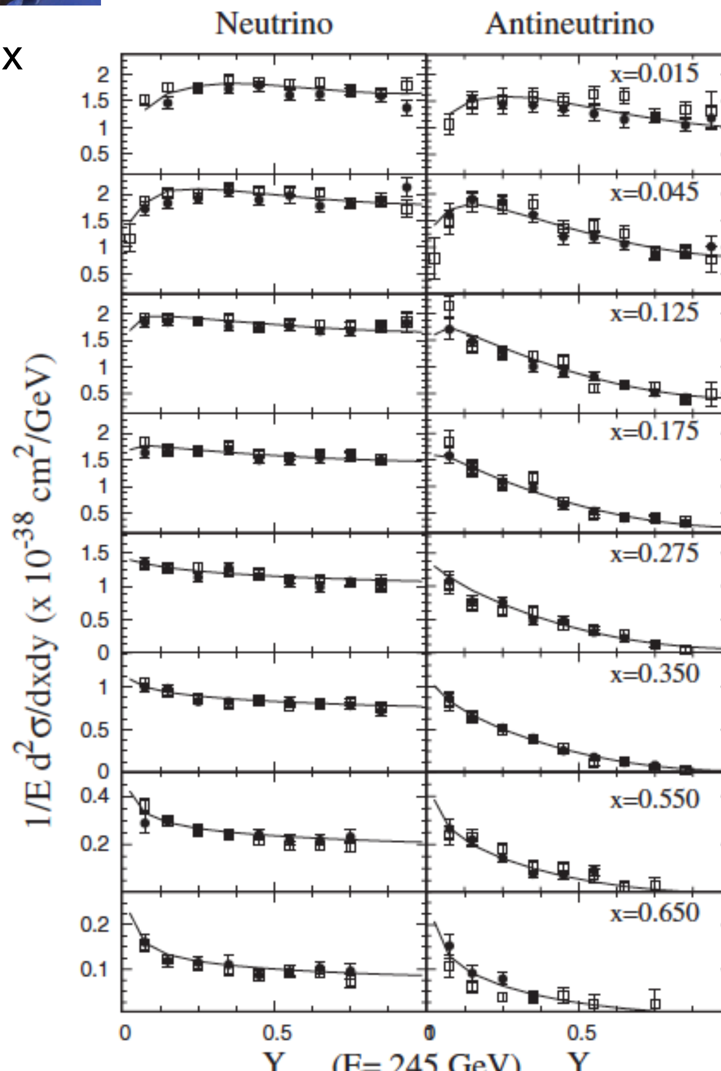
245 GeV





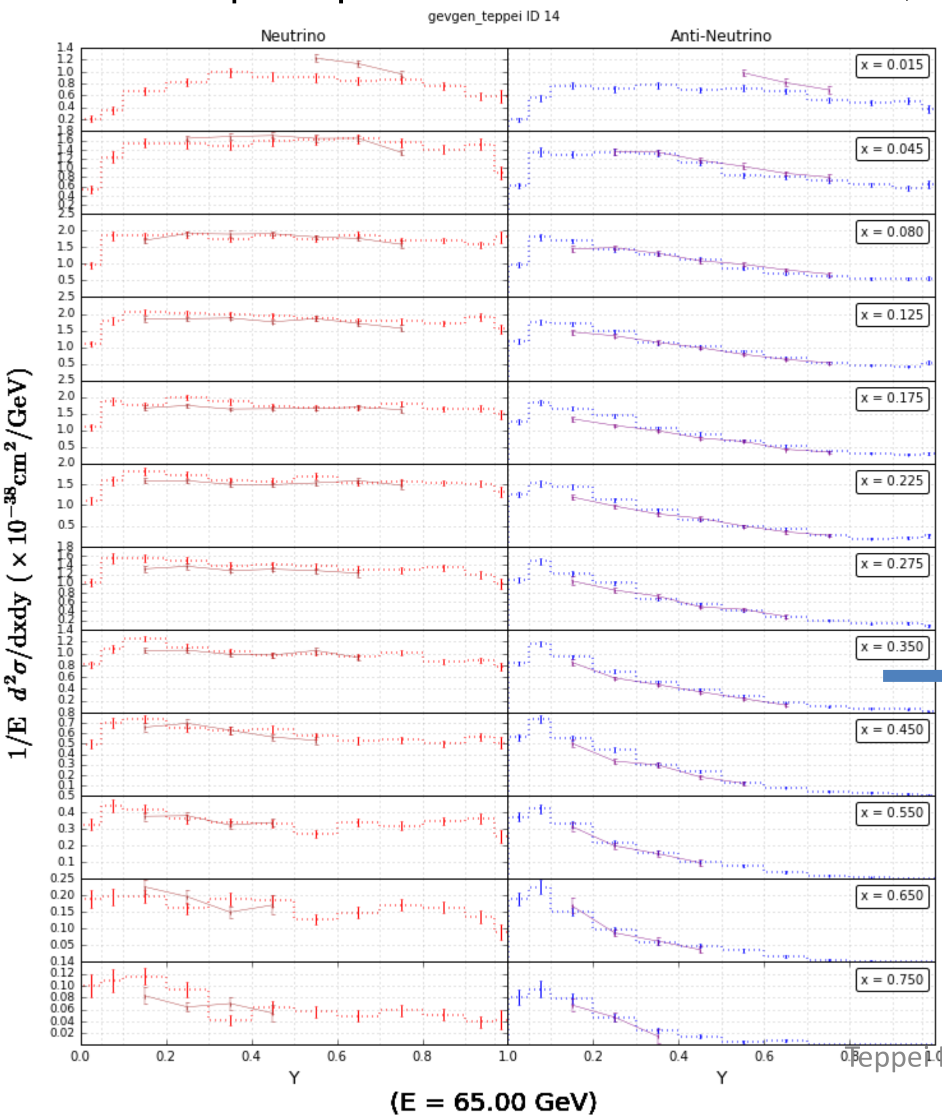
NuTeV, PRD74(2006)012008

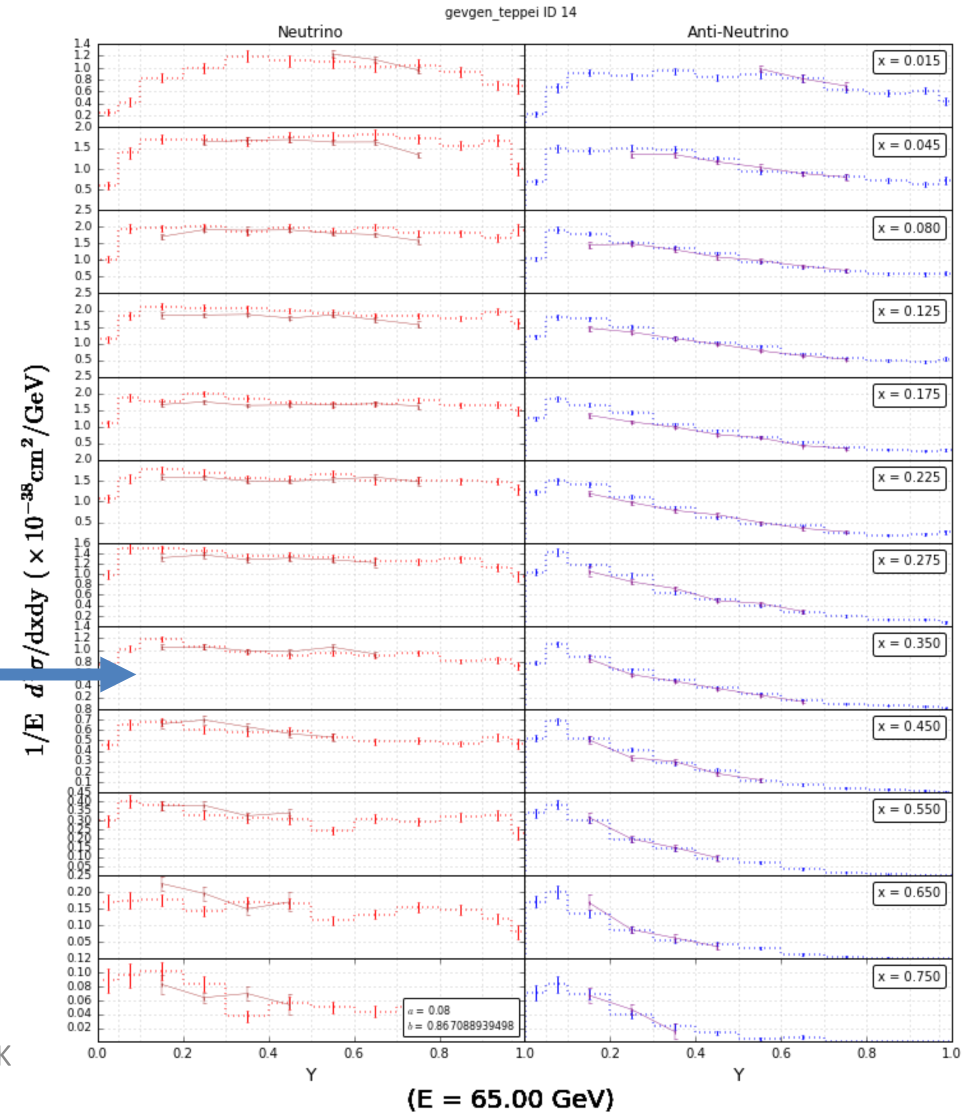
2. DIS differential cross section error

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

GENIE-NuTeV comparison

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





Teppei K

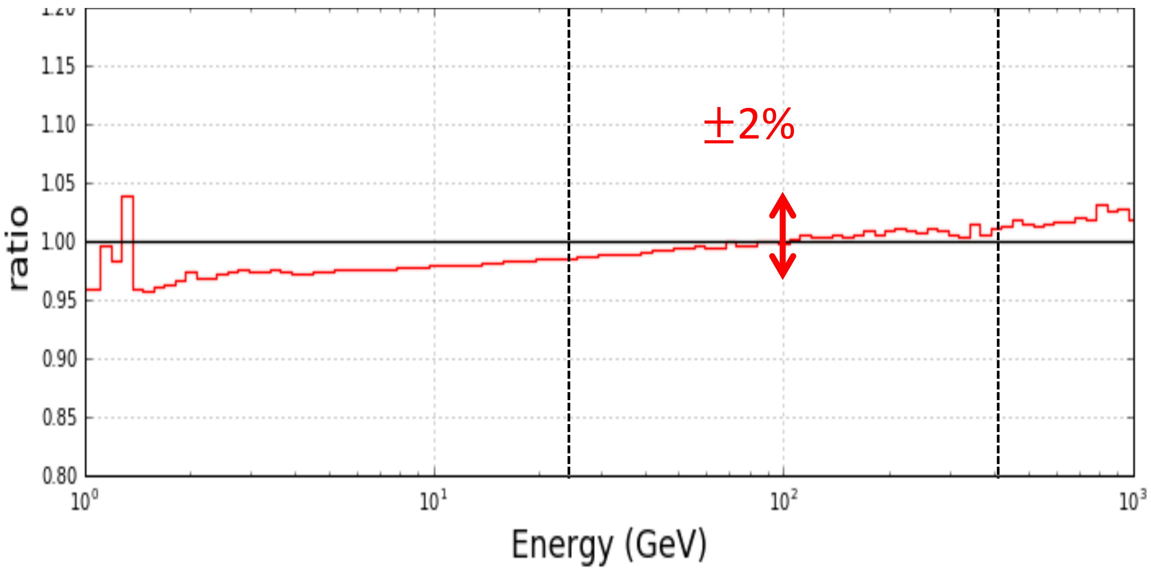
2. DIS differential cross section error

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

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



2. DIS differential cross section error

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MINERvA,PRD93(2016)071101

3. DIS A-dependent error

Liam Hartley
(Queen Mary)

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

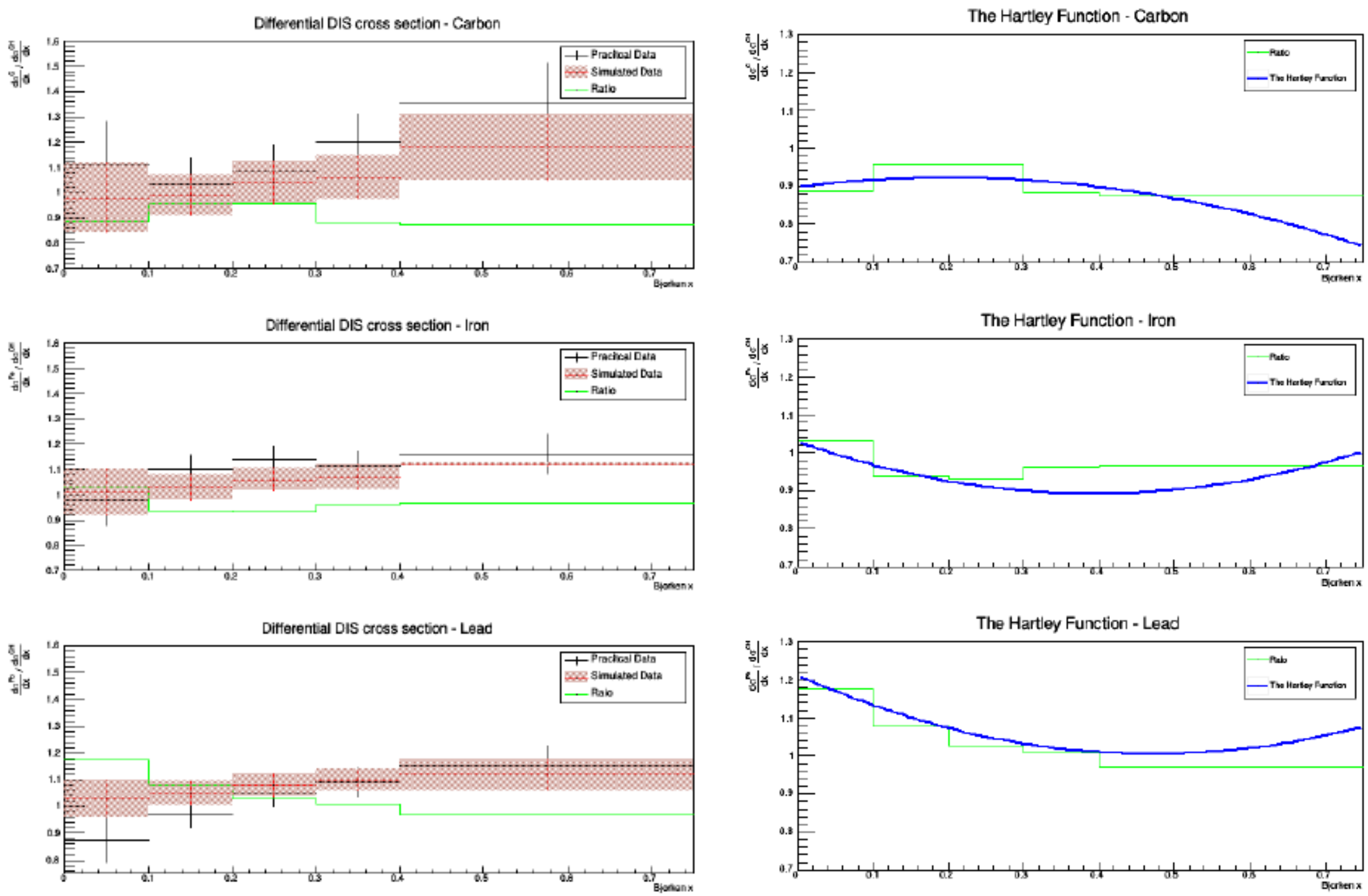
GENIE-MINERvA comparison

- 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

ν-C

ν-Fe

ν-Pb



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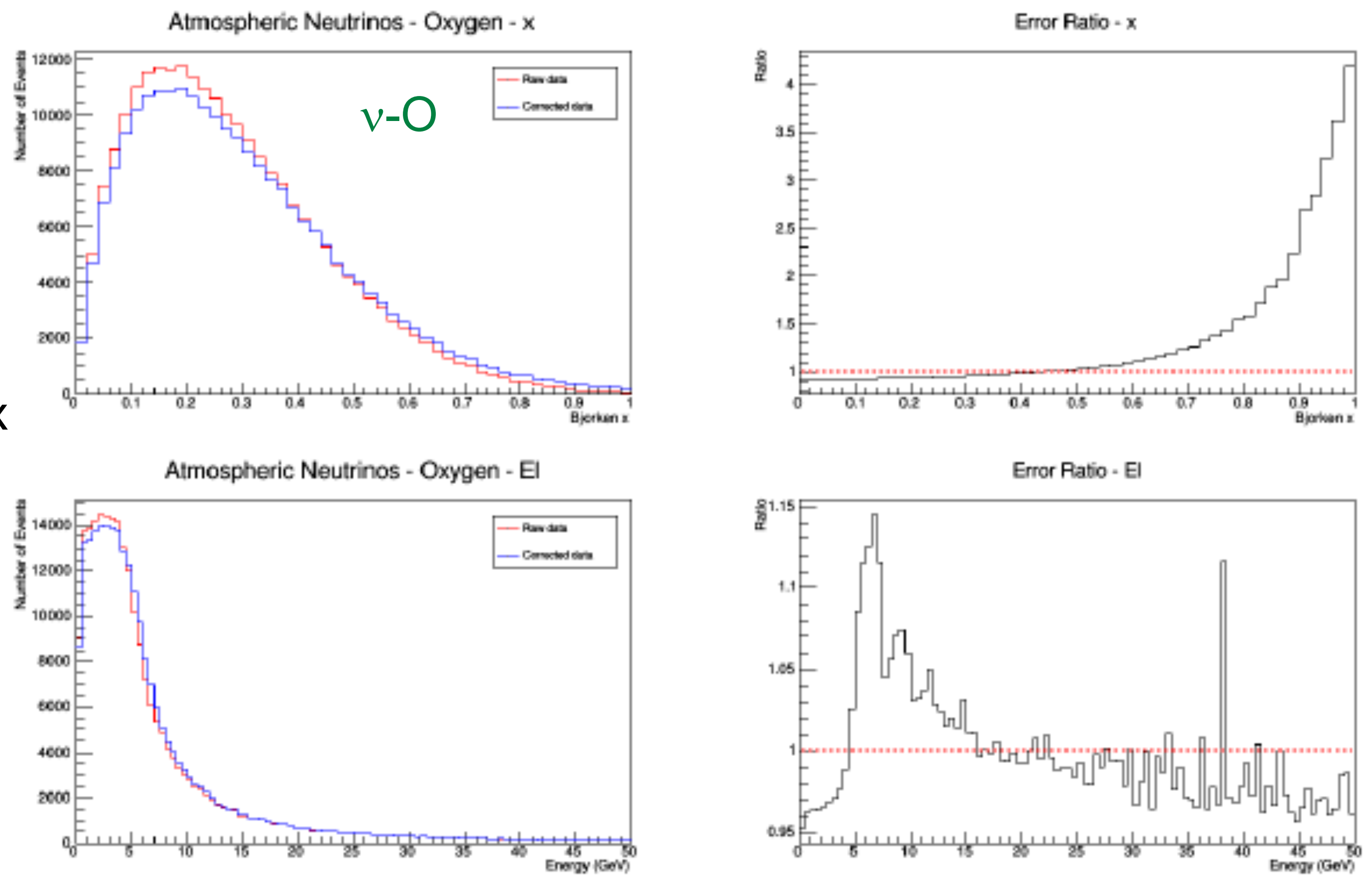
GENIE-MINERvA comparison

- 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)

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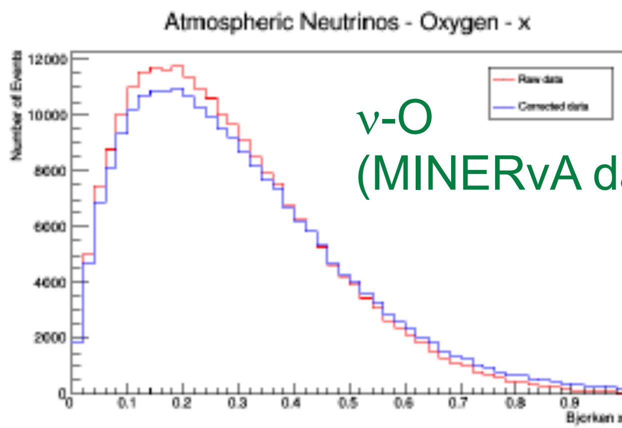
4. DIS PDF error

Shivesh Mandalia
(Queen Mary)

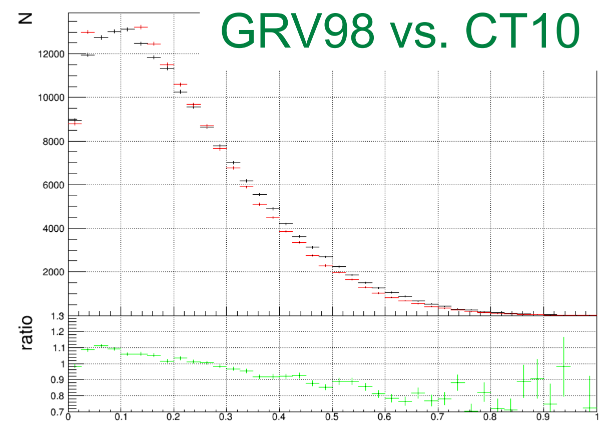
We tried to use couple of PDF from LHA PDF
- CT10 (NLO)
- HERAPDF15 (NLO)
- NNPDF23 (NLO)

As expected(?), PDF variation (top-down error) is smaller and well-controlled.
→ If we use a better PDF, variation would be few %

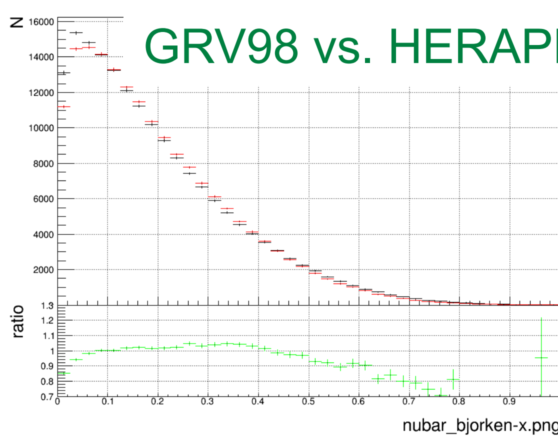


ν-O
(MINERvA data)

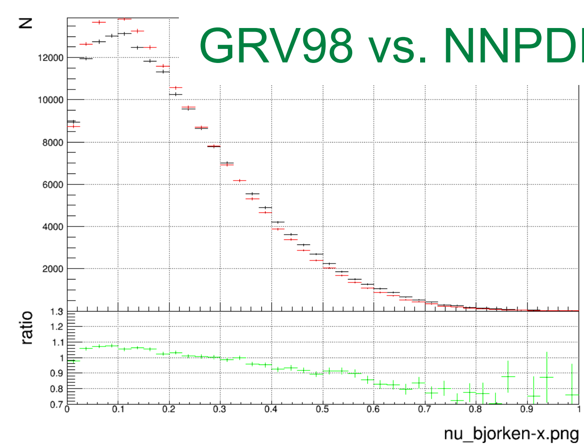
GRV98 vs. CT10



GRV98 vs. HERAPDF15



GRV98 vs. NNPDF23



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

5. Low-W hadronization model

Carl Stanley
(Queen Mary)

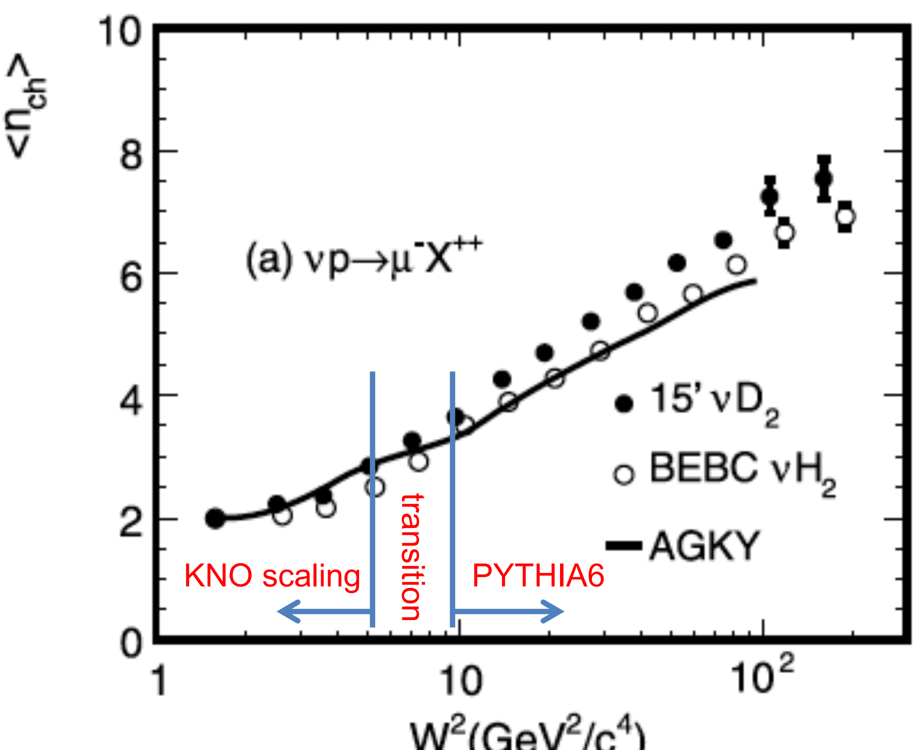
In AGKY model, hadronization model is a combination of 2 models.

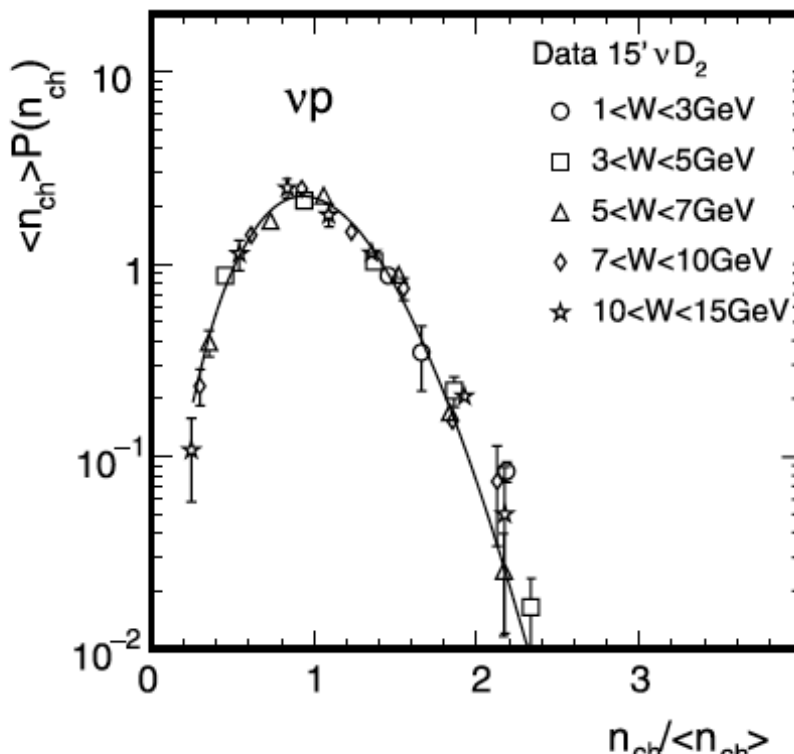
KNO-scaling based model (low W hadronization)

- 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

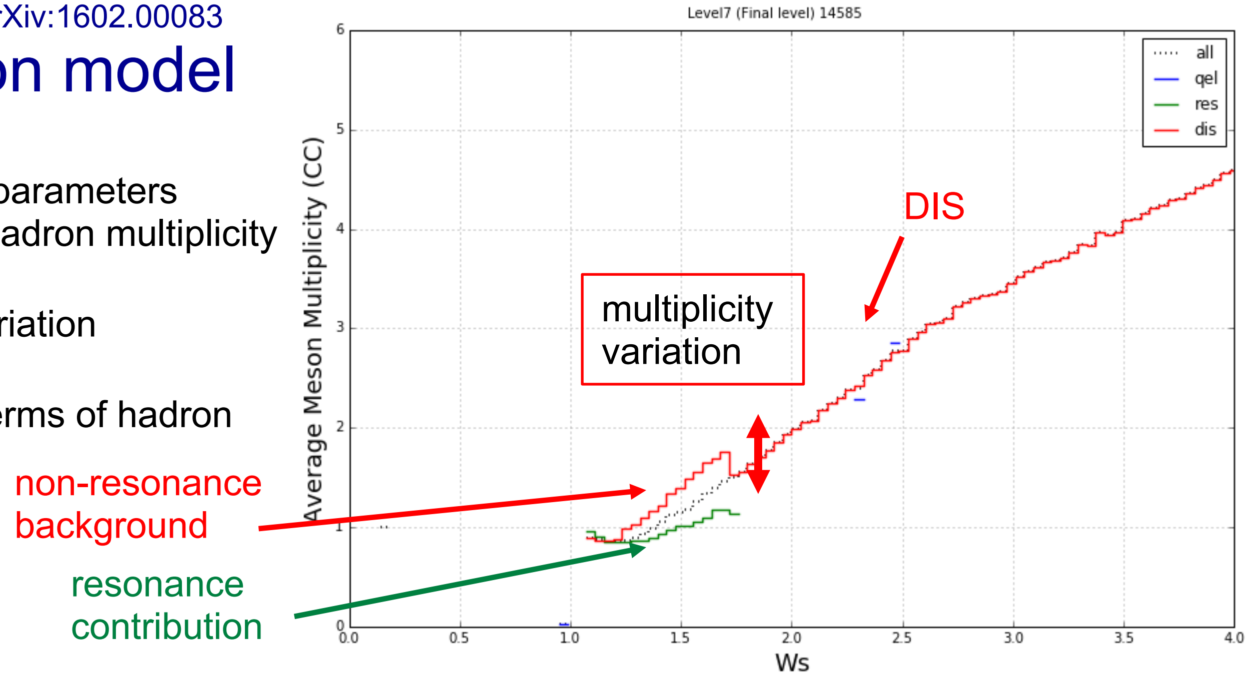
5. Low-W hadronization model

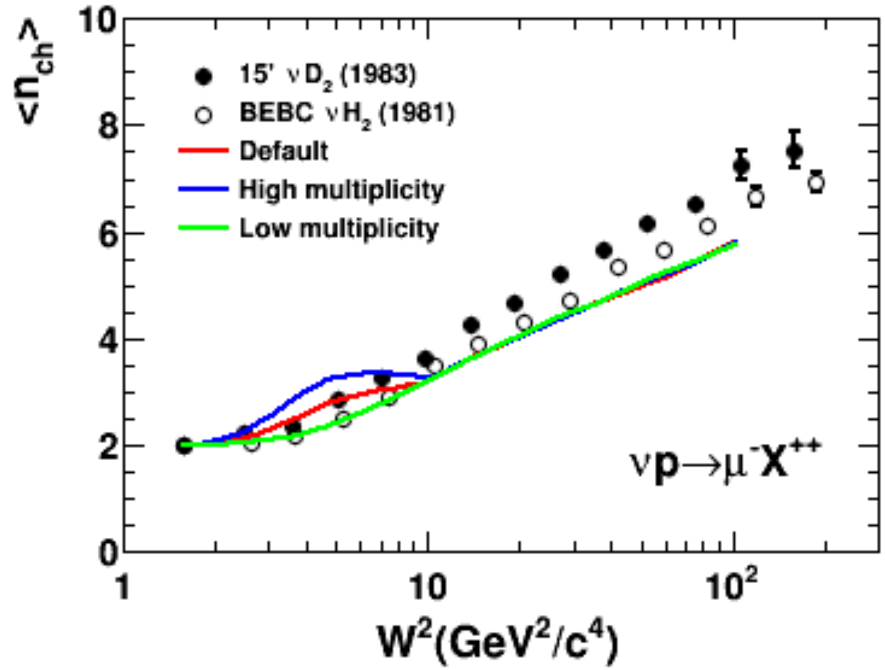
I added ±25% variation on "b_{ch}" parameters
→ This imitate discontinuity of hadron multiplicity

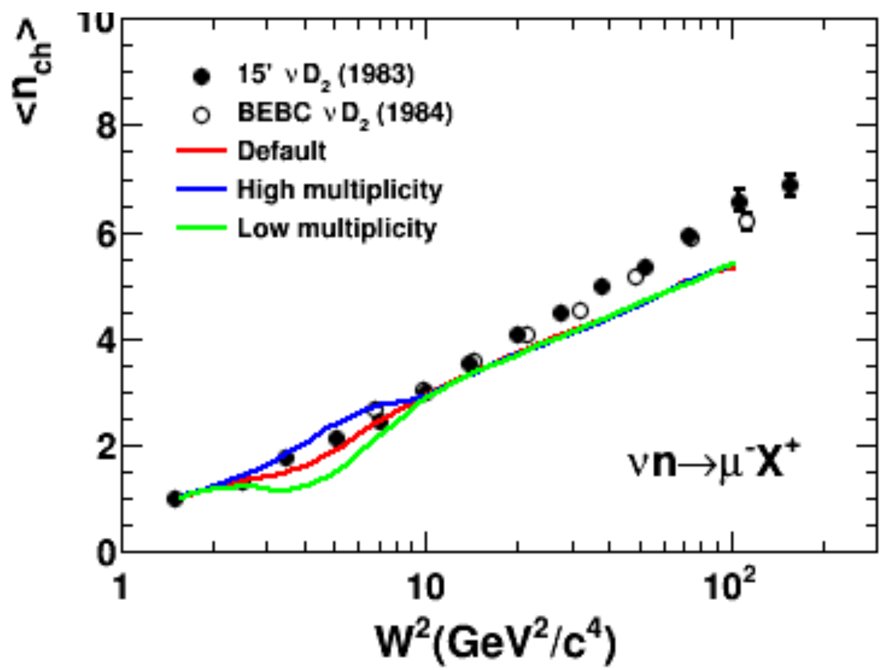
It looks to cover existing data variation

Then translate this variation in terms of hadron visible energy

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







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

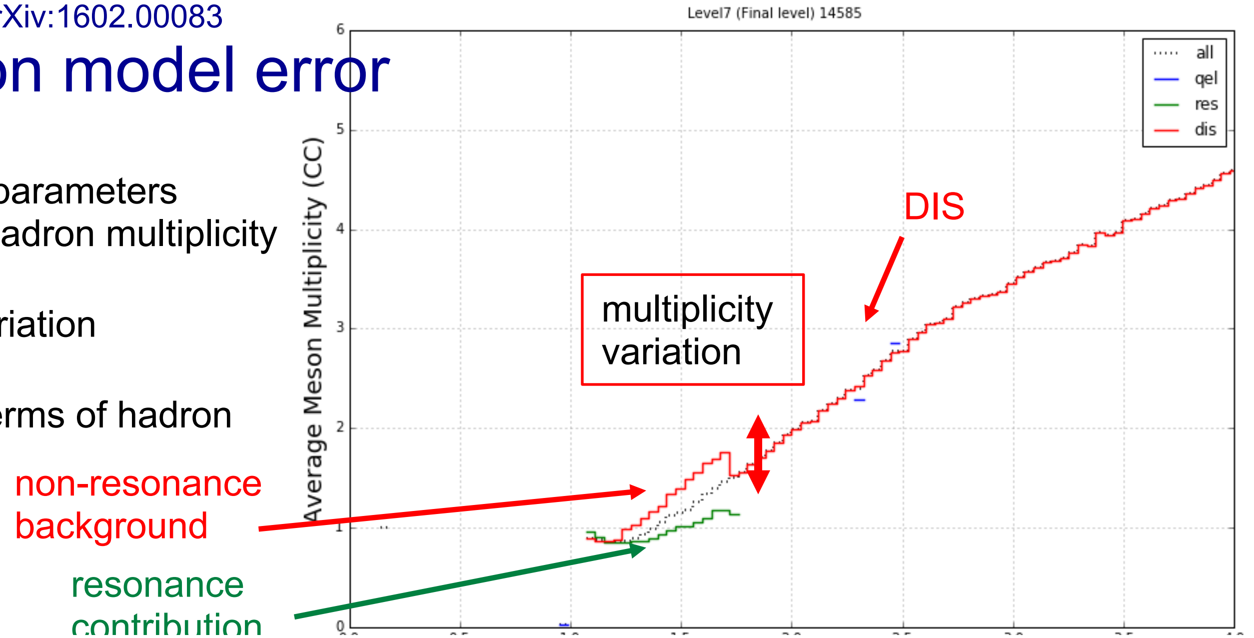
5. Low-W hadronization model error

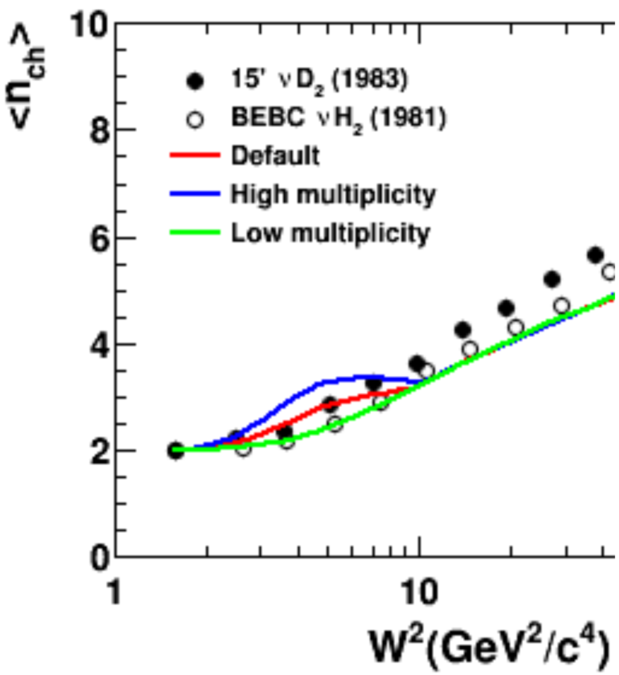
I added ±25% variation on "b_{ch}" parameters
→ This imitate discontinuity of hadron multiplicity

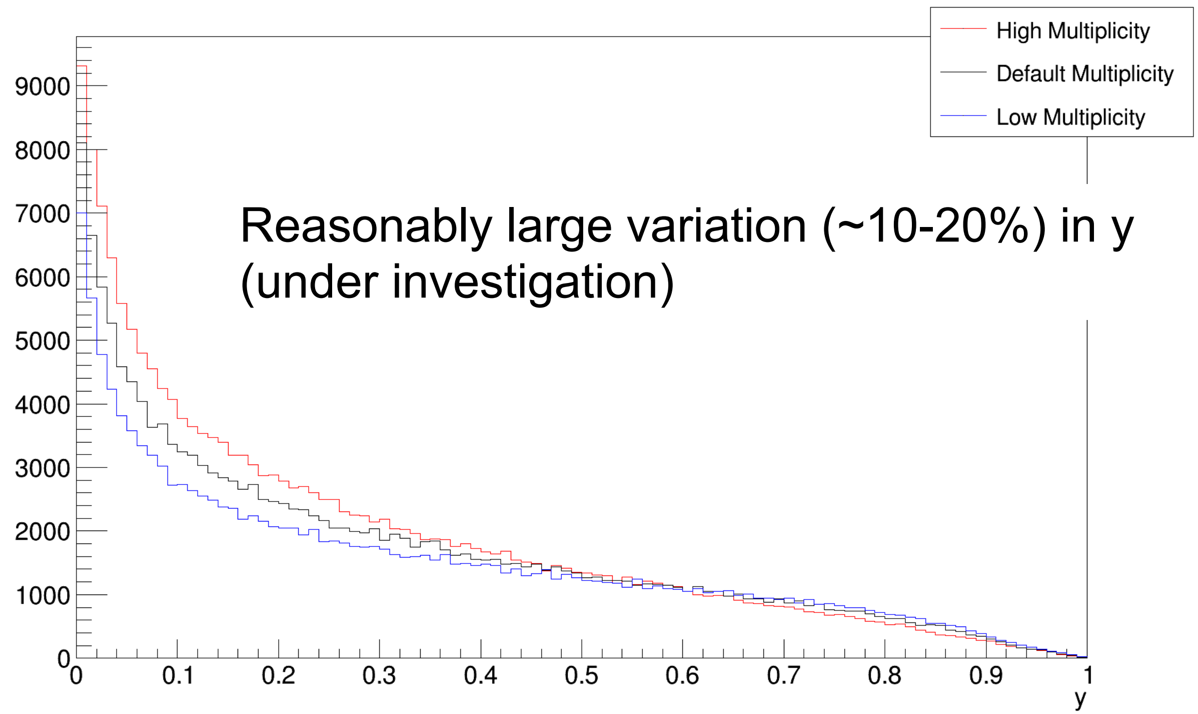
It looks to cover existing data variation

Then translate this variation in terms of hadron visible energy

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







5. Low-W hadronization 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 (?)

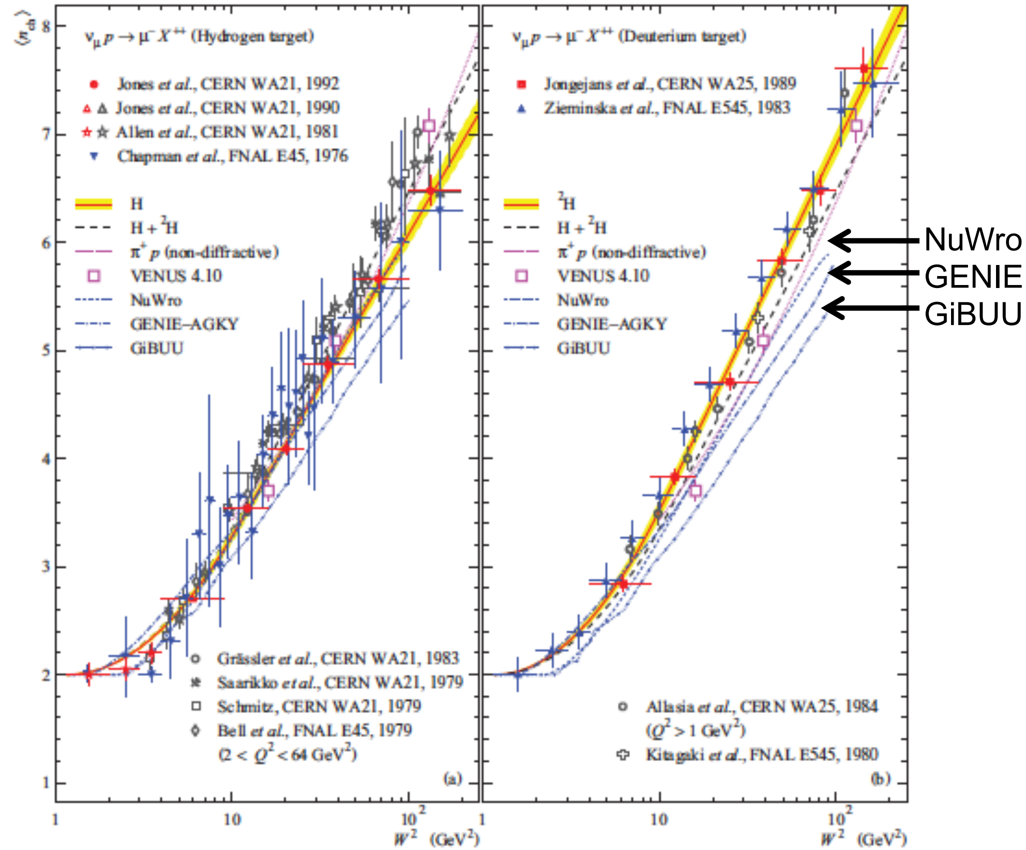
DIS or Hadronization	type of error	approach	size
DIS	Bodek-Yang correction	play with Bodek-Yang parameters (by eyes)	maybe large?
DIS	differential xs	NuTeV-GENIE comparison (bottom-up)	2-3% by GENIE study
DIS	A-scaling	MINERvA-GENIE (bottom-up)	maybe large?
DIS	PDF	From nuclear PDF, CT10? nCTEQ? (top-down)	expected to be tiny
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)	1-2% by GENIE study

6. 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)



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

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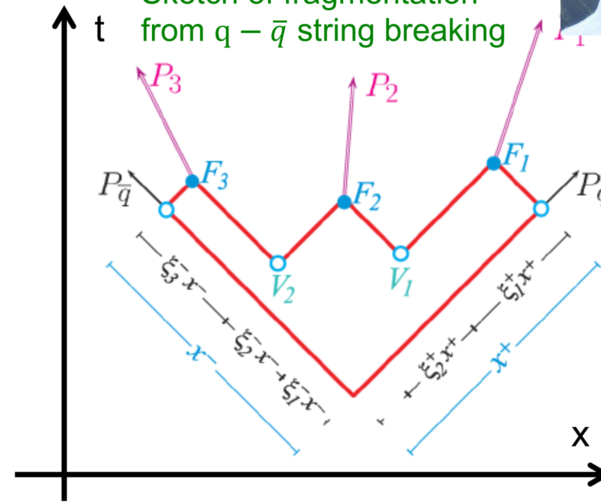
(Queen Mary)

6. High-W hadronization model

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



Averaged charged hadron multiplicity <n_{ch}>

- PYTHIA6 with tuned Lund string function can reproduce <n_{ch}> data both neutrino and antineutrino.

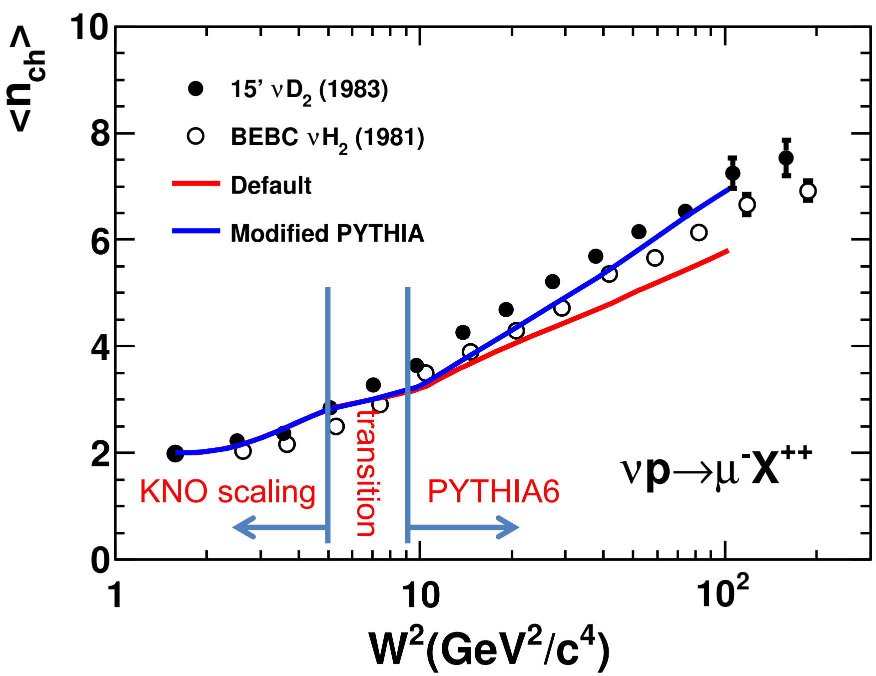
Lund string function

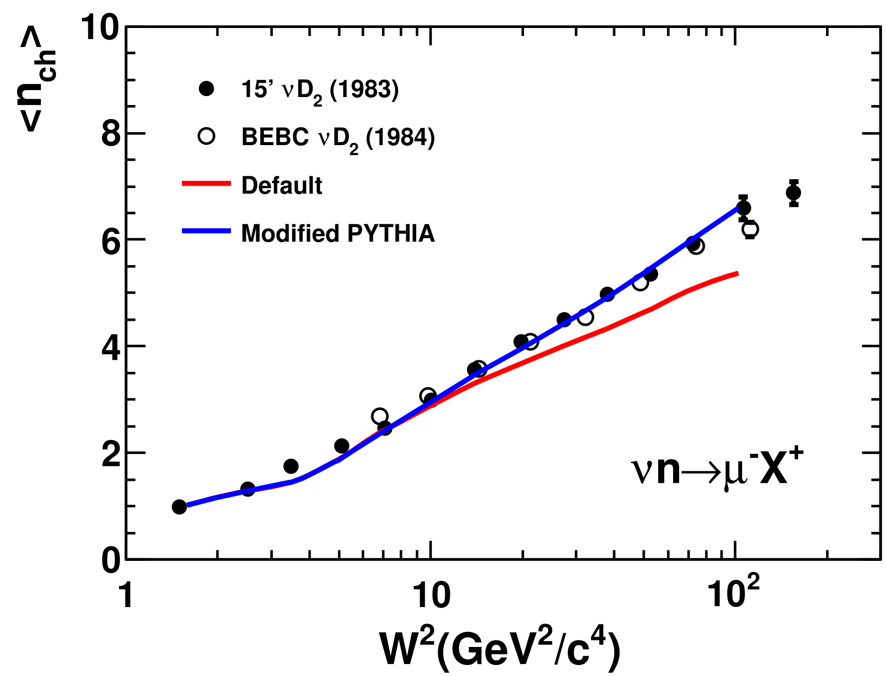
hadron energy distribution from iterative process

tunnelling probability

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

Neutrino average charged hadron multiplicity





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

6. High-W hadronization model

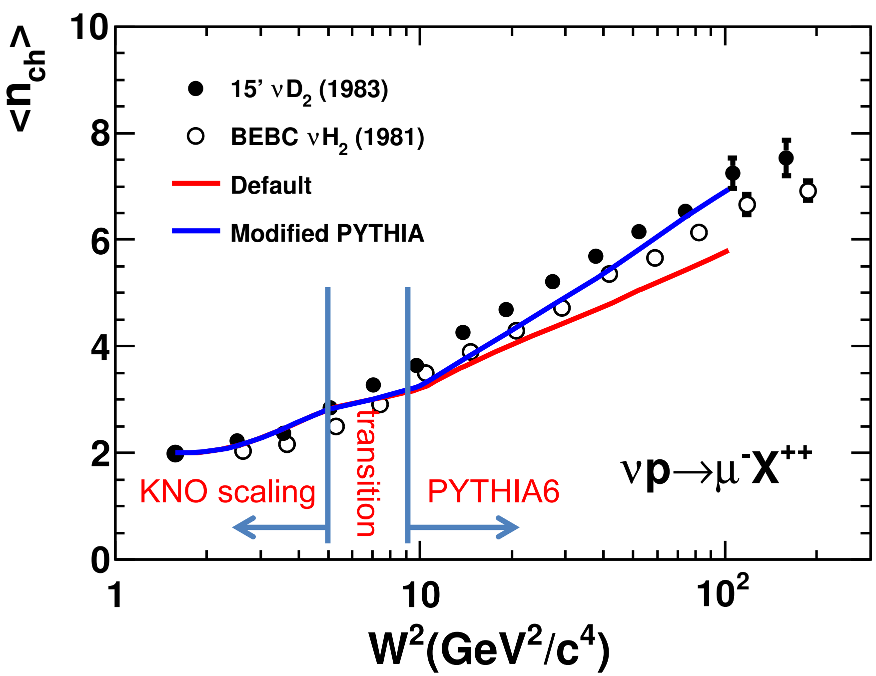
Shivesh Mandalia
(Queen Mary)

Bubble chamber topological cross section data

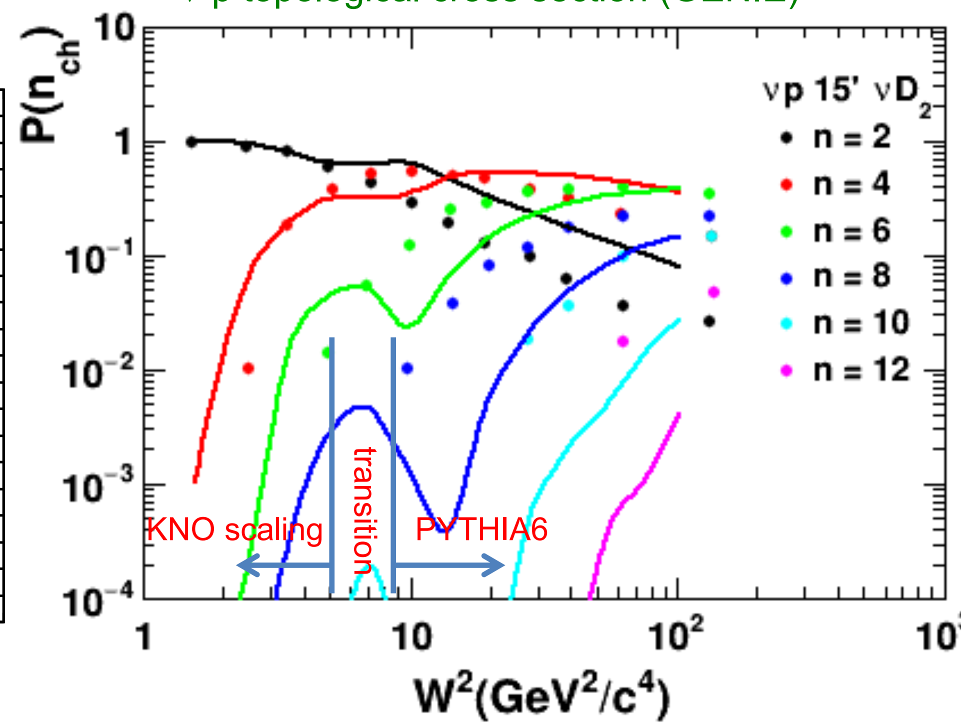
Although averaged charged hadron multiplicity makes continuous curve, topological cross sections are discontinuous, because multiplicity dispersion by PYTHIA6 is much narrower than bubble chamber data.

Impact of hadronization is small for experiments which only measure hadron shower (NOvA, PINGU, ORCA), but large for higher resolution detectors (MINERvA, T2K ND280, LArTPC)

Neutrino average charged hadron multiplicity



ν-p topological cross section (GENIE)



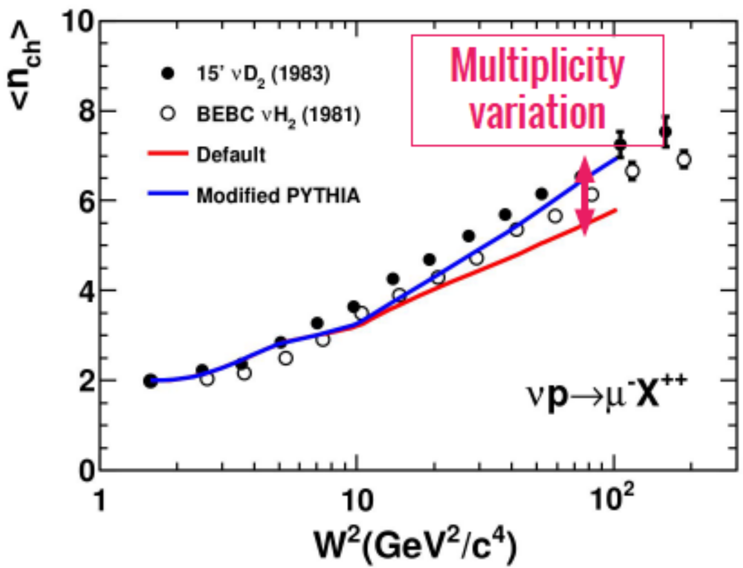
Shivesh Mandalia
(Queen Mary)

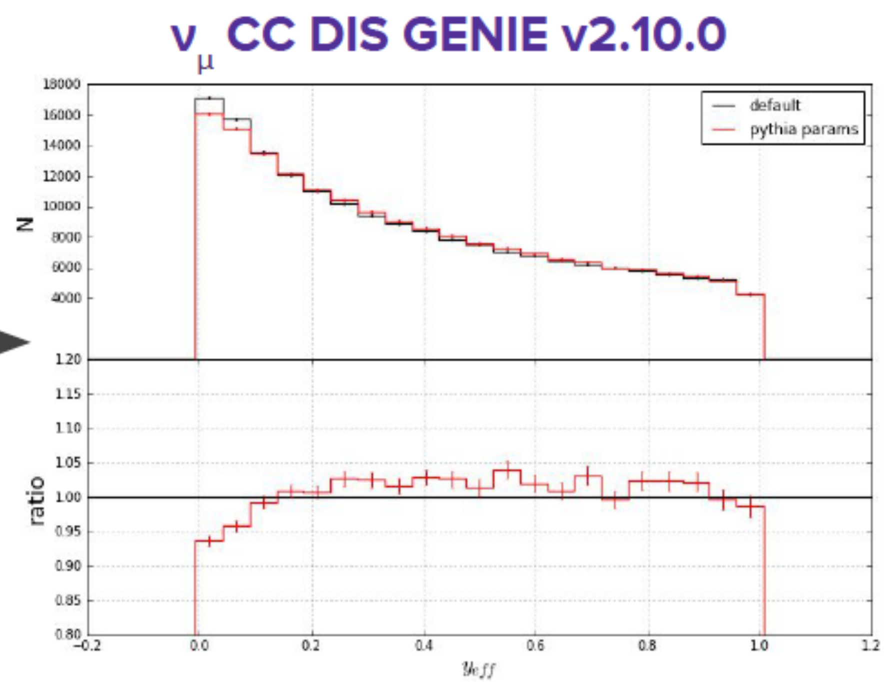
6. High-W hadronization model error

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.

Impact of hadronization is small for experiments which only measure hadron shower (NOvA, PINGU, ORCA), but large for higher resolution detectors (MINERvA, T2K ND280, LArTPC)





7. DIS-hadronization errors, summary

- 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
some study (MSU study)	DIS	Bodek-Yang correction	play with Bodek-Yang parameters (by eyes)	maybe large?
done	DIS	differential xs	NuTeV-GENIE comparison (bottom-up)	1-2% by GENIE study
under investigation	DIS	A-scaling	MINERvA-GENIE (bottom-up)	maybe large?
some study (MSU study)	DIS	PDF	From nuclear PDF, CT10? nCTEQ? (top-down)	expected to be tiny
under investigation	Hadronization	low W averaged charged hadron multiplicity	play with KNO parameters (by eyes)	maybe large?
done JPhysG42(2015)115004	Hadronization	high W averaged charged hadron multiplicity	bubble chamber-PYTHIA comparison (bottom-up)	1-2% by GENIE study

Back up

1. Neutrino cross section overview

GENIE uses “Frankenstein” model…, there are 2 transtions for both cross section and hadronization

Cross section

W^2<2.9 GeV^2 : RES

W^2>2.9 GeV^2 : DIS

Hadronization (AGKY model)

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

5.3GeV^2<W^2<9.0GeV^2 : transition

9.0GeV^2<W^2 : PYTHIA6

ν_μCC on H_2O target with atmospheric neutrino flux in W_{recon}