NuSTEC Workshop on Neutrino Shallow- and Deep-Inelastic scattering (S&DIS) interactions

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Queen Mary University of London
NuSTEC board meeting, Fermilab, Dec. 10, 2018

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Why a workshop on the SIS/DIS region?

- By far the majority of contemporary studies in ν-nucleus interactions have been of QE and Δ production that is $W \leq 1.4$ GeV
- Why study Deep-Inelastic Scattering??
- Better understand the quark / parton structure of the free and bound nucleon.
- Test the predictions of (nuclear) Quantum Chromodynamics (QCD).
- Since ***over 50% of the DUNE events*** have W greater than the Delta mass ($W \approx\geq$ 1.4 GeV), we need to consider what we do(little)/do-not(big) know about this region!

J. Morfin @ NuFACT2018

Christophe Bronner, NuInt18

Why a workshop on the SIS/DIS region?

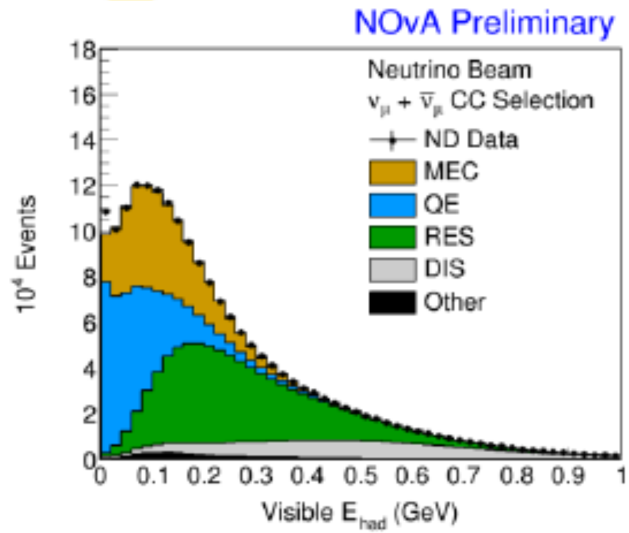
GENIE Tuning

From **NOvA ND data**:

- 10% increase in non-resonant inelastic scattering (DIS) at high W.

M. Muether "Deep Inelastic Scattering Impact on NOvA"

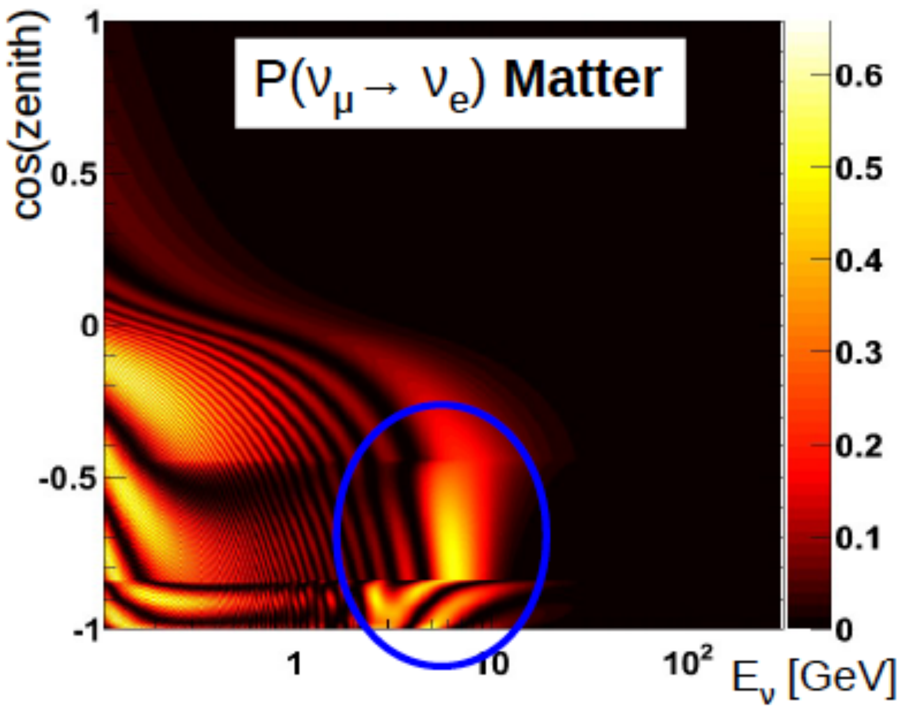
FHC Tune



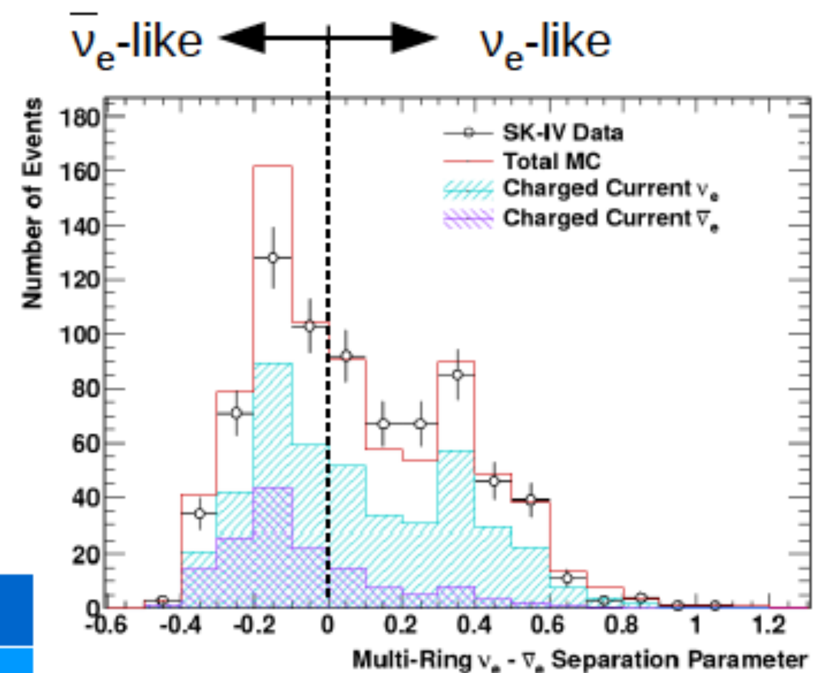
- Good agreement between MC and data in general.
- DIS has significant impact at high visible E_{had}.
- W distributions do not include the high-W DIS correction.
- Most DIS is in the "transition" regions.

Christophe Bronner, NuInt18

Why a workshop on the SIS/DIS region?



Likelihood separation based on differences between DIS interactions of neutrinos and anti-neutrinos



	Neutrino	Anti-neutrino
Nb of rings	More	Less
Nb of Michel e-	More	Less
Transverse momentum	Larger	smaller

CB, “SIS/DIS interactions and

Christophe Bronner, NuInt18

2. Workshop overview

Gran Sasso Science Institute
- Oct. 11-13, 2018
- https://indico.cern.ch/event/727283/

34 participants
- 15 theorists
- 19 experimentalists

9am - 6pm every day
- 7.8-hour theory talks
- 6.5-hour experiment talks
- 8.5-hour discussion & coffee time

2. Topics

Total 7 sessions

1. General introduction and considerations from non-neutrino communities.

2. Overview of generator treatments of the SIS and DIS region.

3. Sensitivity of oscillation parameters to the SIS and DIS region.

4. Resonances and non-resonant contribution with W>Delta: Theory and Experiment.

5. The transition from SIS to DIS: Theory and Experiment.

6. Current status of nuclear QCD and nuclear PDFs: Theory and Experiment.

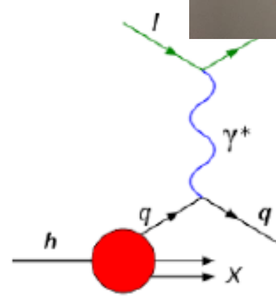
7. Hadronization in the nuclear environment: Theory and Experiment.

2.1 General introduction and considerations from non-neutrino communities

Thia Keppel (JLab) gave an overview talk of JLab programs which cover all topics of this workshop!

Electron Scattering Measurements Applied to Neutrino Interactions on Nuclei

- Precision measurements of vector components of cross sections
  - Nucleons and nuclei, A-dependence
  - Form factors
  - Resonances
  - Deep Inelastic Scattering
  - Quark-hadron duality studies
- Parity violating electron scattering
  - As above!
- Precision decomposition of nuclear effects – within nuclei
  - Smearing/momentum distributions
  - Including short range correlations
  - Additional two body effects (meson exchange currents)
  - EMC effect
  - Shadowing and anti-shadowing
- Nuclear interactions
  - Hadronization
  - Final state interactions

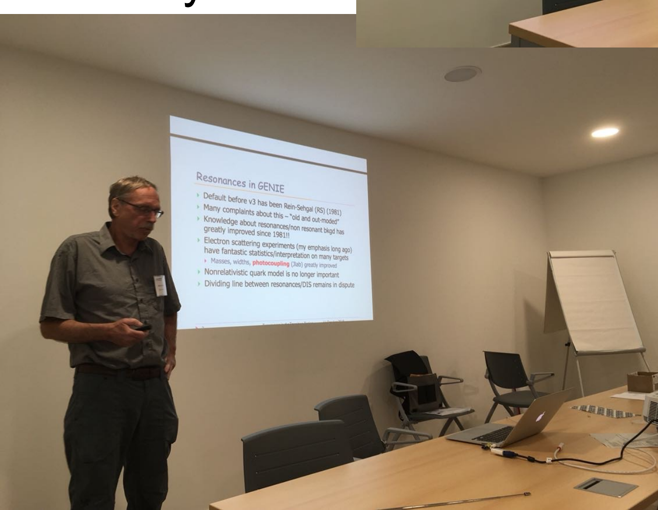


2.2 Overview of generator treatments of the SIS and DIS region

- Rein-Sehgal model by Steve Dytman (Pittsburgh)
- Bodek-Yang model by Un-ki Yang (Seoul Nat.l U)
- 4 talks to cover all generators (GENIE, NEUT, NuWro, GiBUU)
- Generator comparisons by Christophe Bronner (ICRR)

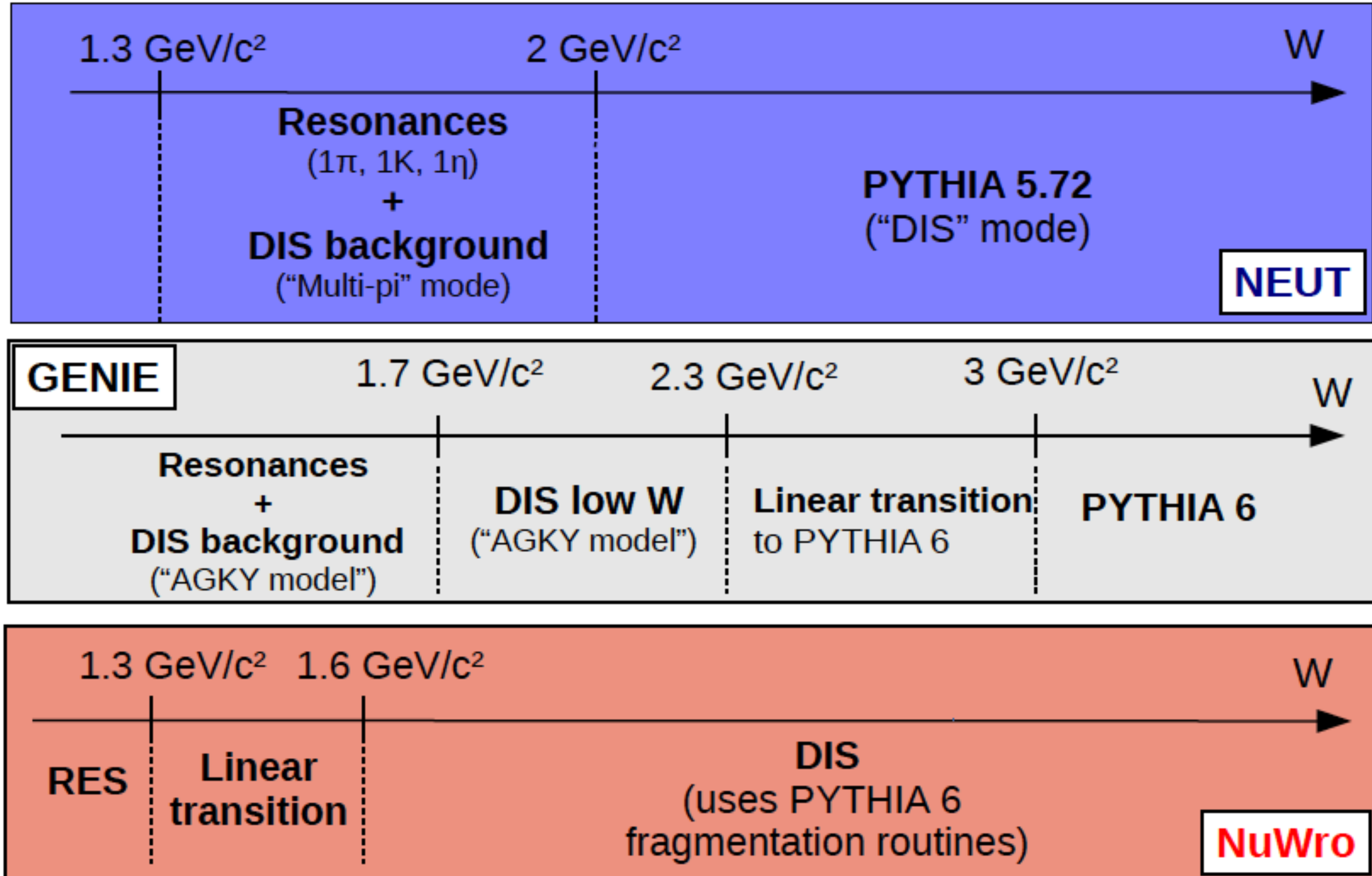
Un-ki Yang

Steve Dytman



Christophe Bronner

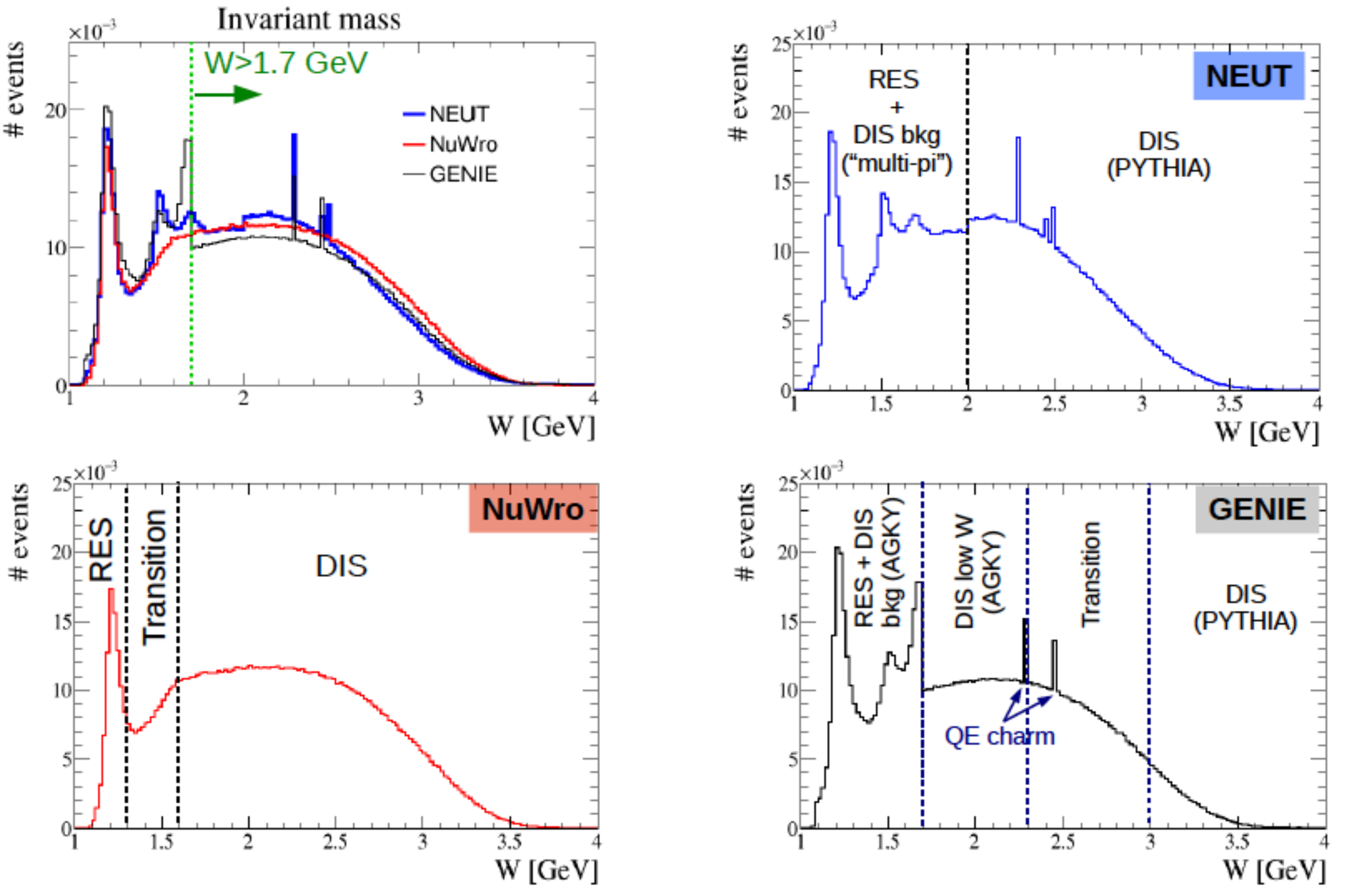
SIS/DIS region in the generators



CB, "Generator comparisons SIS/DIS region"

Invariant mass distribution

ν_μ on Fe, E_ν=6.0 GeV



2.3 Sensitivity of oscillation parameters to the SIS and DIS region

- NOvA by Matt Muether (Wichita State)
- T2K/SuperK by Christophe Bronner (ICRR)

Un-ki Yang

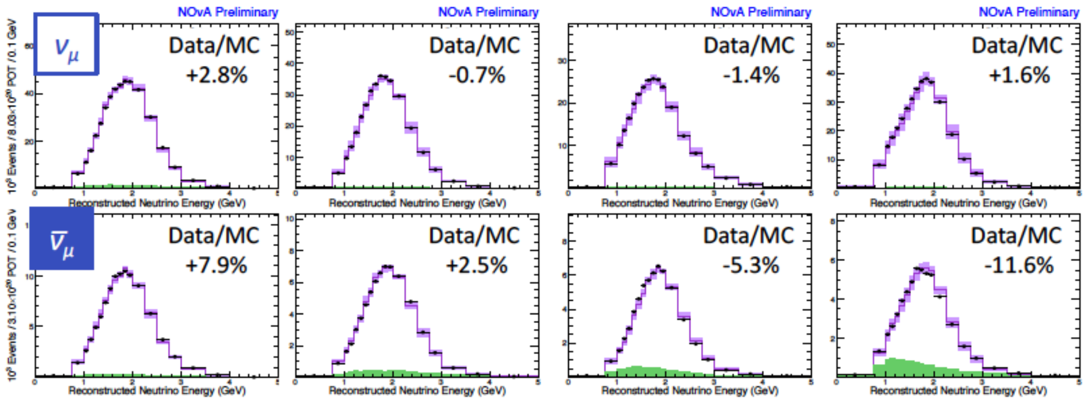
This cannot be true…

Binning for Sensitivity: ν_μ Events

Data
Area-normalized MC
Shape-only systematics
Wrong-sign

Quantile 1
Best Resolution ~6%

Quantile 4
Worst Resolution ~12%



- Data-MC shape agreement good within each quantile.
- Extrapolate each separately.

11

Wichita State University

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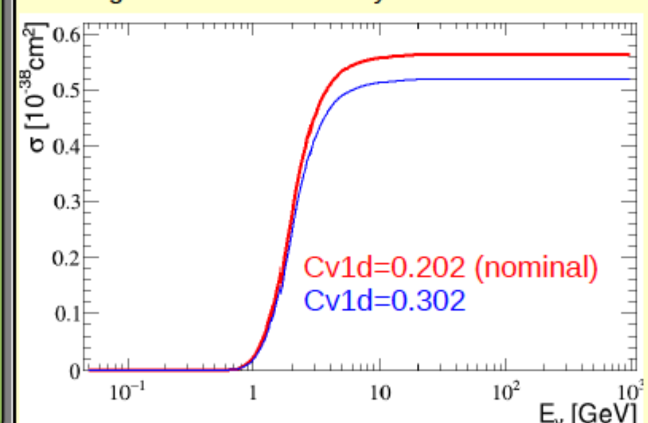
reduced χ^2 of the fit to the charged-lepton data"

- But:
- no correlations of the errors between parameters
- no error on some of the parameters

"Cv1d , Cv2d and Cs have very small effect on the χ^2 and hence have been neglected" D. Bhattacharya PhD's thesis



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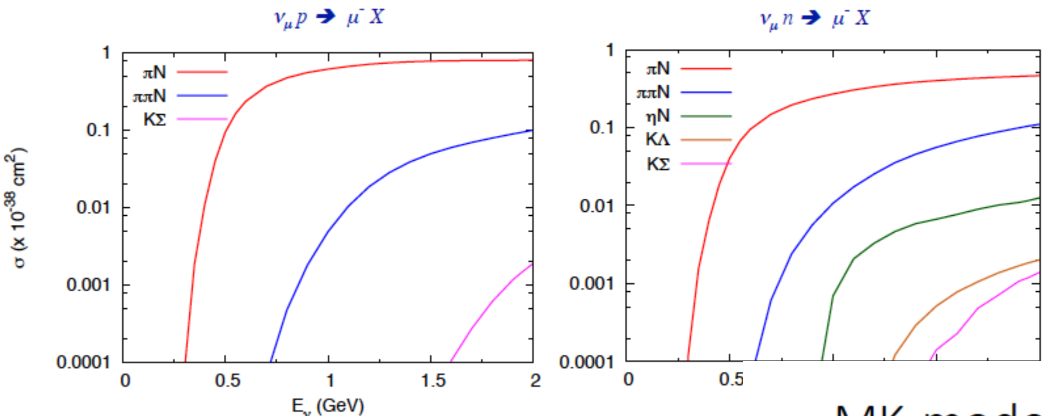
2.4 Resonances and non-resonant contribution with W>Δ:Theory & Experiment

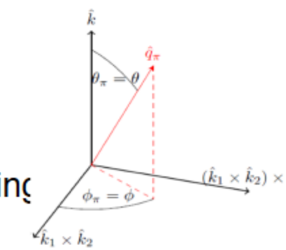
- DCC model by Satoshi Nakamura (Osaka→IHEP China)
- MK model by Minoo Kabirnezhad (Oxford)
- high-W study by Steve Dytman (Pittsburgh)



- πN & $\pi\pi N$ are main channels in few-Ge
- DCC model gives predictions for all final st
- ηN, KY cross sections are $10^{-1} - 10^{-2}$ sma

MK-model

M. Kabirnezhad, Phys. Rev. D **97**, 013002



- MK model is a model for single pion production i.e. resonant and non-resonant interactions including **the interference effects**.
- Uses Rein-Sehgal model to describe resonant interaction (17 resonances) up to W=2 GeV.
- Lepton mass is included.
- non-resonant background is defined by a set of diagrams determined by HNV model. E. Hernandez, J. Nieves and M. Valverde, Phys. Rev. D **76** (2007) 033005

Output of the MK-model
$d\,\sigma/dW\,dQ^2 d\Omega_\pi$

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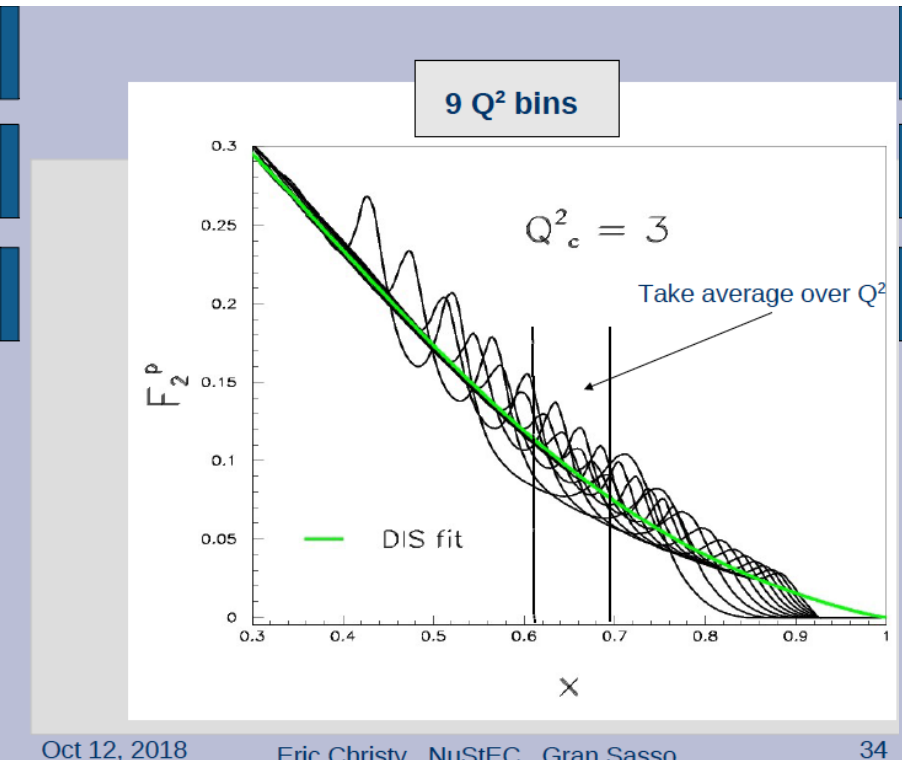
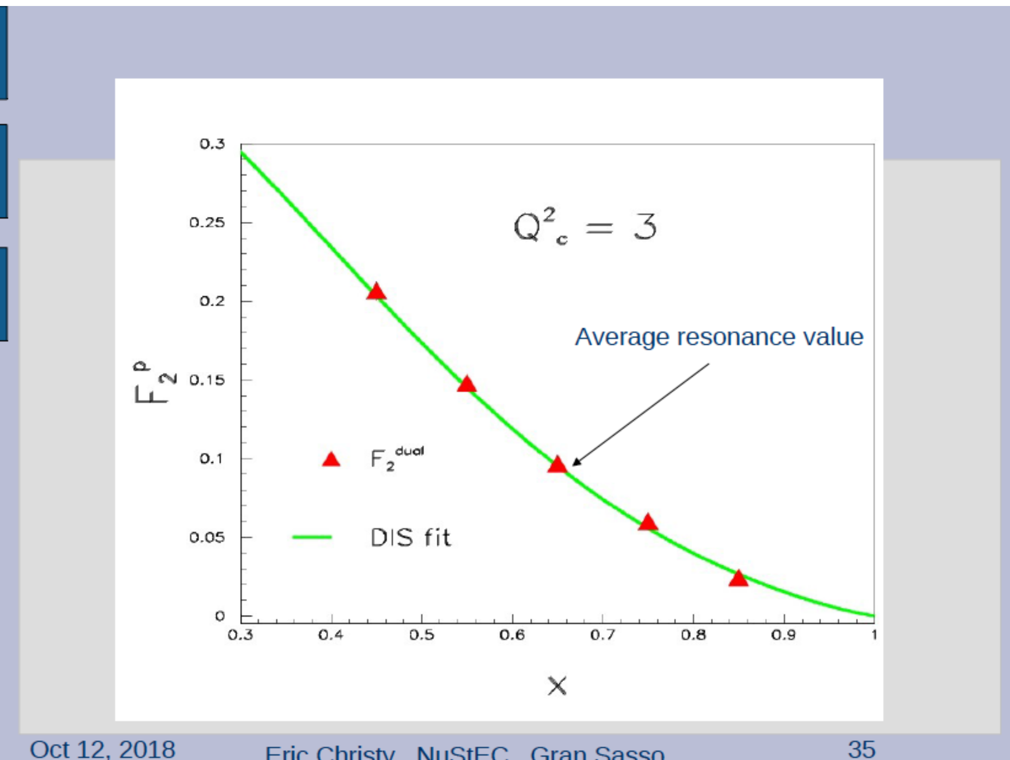
2.5 The transition from SIS to DIS: Theory and Experiment

- Duality in (e,e') by Eric Christy (JLab)
- Duality in ν-A (Dortmund)
- Higher-twist and duality by Huma Haider (AMU)
- Regge theory in transition region by Natalie Jachowicz (Ghent)

"An average over the resonances is intimately related to the scaling curve, (not the diffractive or the coherent scattering)"





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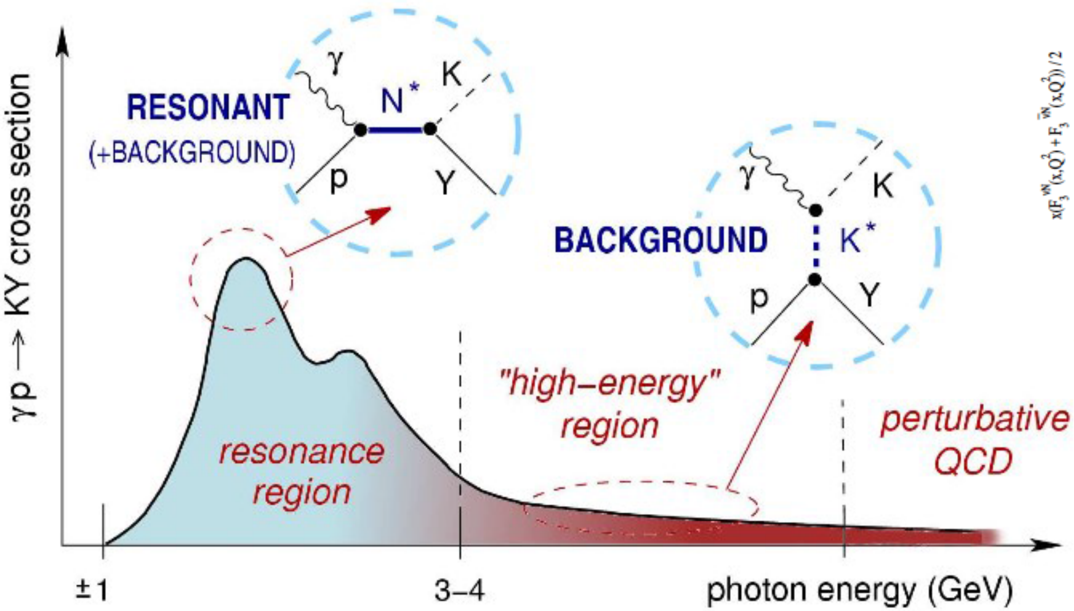
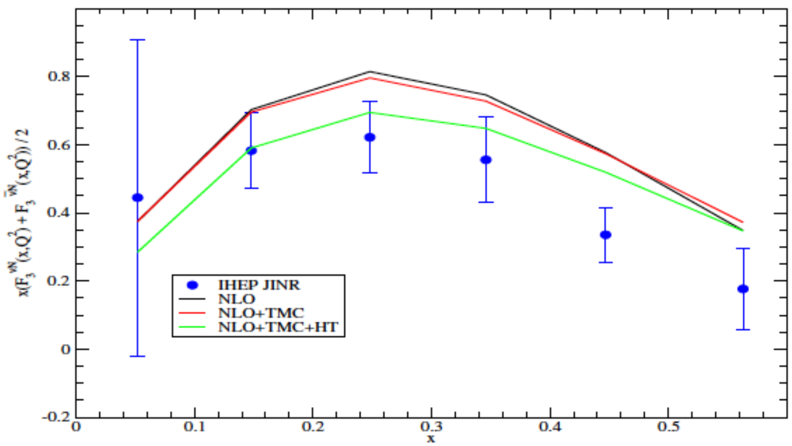


Comparison of $\frac{xF_3^{\nu N}(x,Q^2)+xF_3^{\bar{\nu} N}(x,Q^2)}{2}$ with the experimental data



2.6 Current status of nuclear QCD and nuclear PDFs: Theory and Experiment

- Nuclear medium effect 1 by Sajjad Athar (AMU)
- Nuclear medium effect 2 by Sergey Kulagin (JINR)
- Nuclear-dependent PDF by Olek Kusina (IFJ PAN, Poland)

Why nuclear corrections survive at DIS?

Space-time scales in DIS

$$W_{\mu\nu} = \int \mathrm{d}^4x \exp(iq \cdot x) \langle p | [J_\mu(x), J_\nu(0)] | p \rangle$$

$$q \cdot x = q_0 t - |\boldsymbol{q}| z = q_0 t - \sqrt{q_0^2 + Q^2} z \simeq q_0 (t - z) - \frac{Q^2}{2q_0} z$$

- DIS proceeds near the light cone: $|t - z| \sim 1/q_0$ and $t^2 - z^2 \sim Q^{-2}$.
- In the TARGET REST frame the characteristic time and longitudinal distance are NOT small at all: $t \sim z \sim 2q_0/Q^2 = 1/Mx_{\mathrm{Bj}}$. DIS proceeds at the distance ~ 1 Fm at $x_{\mathrm{Bj}} \sim 0.2$ and at the distance ~ 20 Fm at $x_{\mathrm{Bj}} \sim 0.01$.
- Two different regions in nuclei from comparison of coherence length (Ioffe time) $L = 1/Mx_{\mathrm{Bj}}$ with average distance between bound nucleons r_{NN}:
  - $L < r_{\mathrm{NN}}$ (or $x > 0.2$) $\Rightarrow$ Nuclear DIS $\approx$ incoherent sum of contributions from bound nucleons. Nuclear corrections $\sim EL$ and $\sim |\boldsymbol{p}|^2 L^2$ where $E(\boldsymbol{p})$ typical energy (momentum) in the nuclear ground state.
  - $L \gg r_{\mathrm{NN}}$ (or $x \ll 0.2$) $\Rightarrow$ Coherent effects of interactions with a few nucleons are important.

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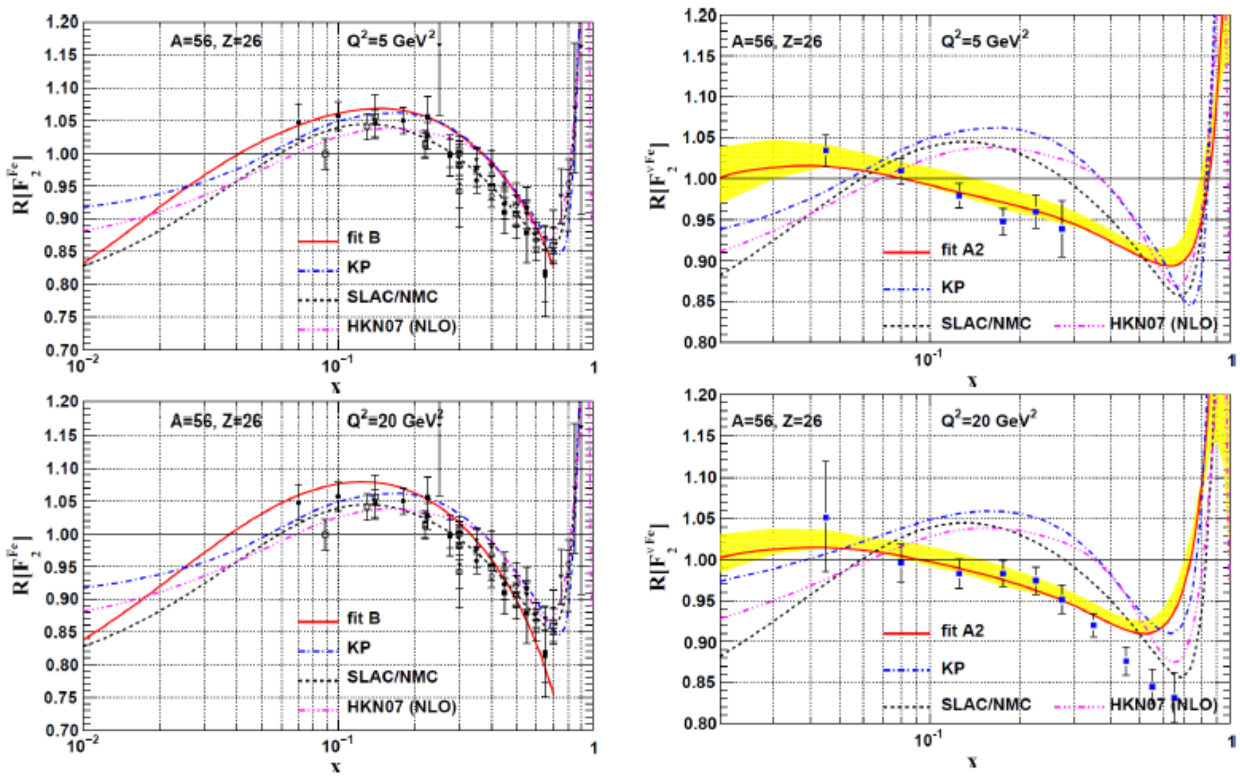
nPDFs from charged-lepton DIS data [PRD 80 (2009) 094004]

$F_2^{\ell^\pm \mathrm{Fe}}/F_2^{\ell^\pm \mathrm{D}}$ $F_2^{\nu \mathrm{Fe}}/F_2^{\nu \mathrm{D}}$ [PRD 77 (2008) 054013]



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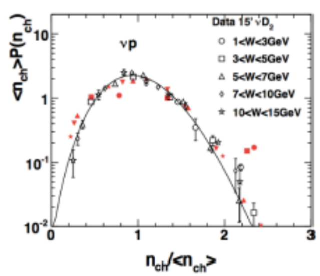
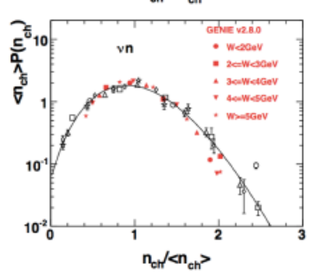
2.7 Hadronization in the nuclear environment: Theory and Experiment

- PYTHIA by Stefan Prestel (Lund)
- AGKY model by Costas Andreopoulos (Liverpool)
- FLUKA by Sara Paola (CERN)
- GiBUU by Kai Gallmeister (Frankfurt)
- SIS systematic errors by TK (Queen Mary)

Empirical low-W model: KNO scaling

KNO scaling: $< n > P(n) = f(n/ < n >)$ is independent of W [Z.Koba, H.B.Nielsen, P.Olesen, Nucl.Phys.B40,317(1972)]





The function $f(z = n/ < n >)$ is parameterized using the Levy function with parameter c:

$$L(z; c) = \frac{2e^{-c}c^{cz+1}}{\Gamma(cz+1)}$$

The following parameters c were determined by a GENIE fit to data:

	νp	νn	$\bar{\nu} p$	$\bar{\nu} n$
c	7.93	5.22	as in νn	as in νp

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2.7 Hadronization in the nuclear environment: Theory and Experiment

Type	type of error	approach	ongoing issue	size of error
resonance	Single pion production	Form factors, external data on e and nu	MiniBooNE-MINERvA data tension	large, but studied well
SIS	Non-resonant background	External data on e and nu	Not many studies. Very phenomenological	???
SIS	Bodek-Yang correction	Change Bodek-Yang parameters by eyes	There is are correlations on model parameters	maybe large?
SIS	Higher resonance	???	MC must be wrong	???
DIS	differential xs	NuTeV-GENIE comparison (bottom-up)	Disagreement seen only at very low x (<0.03)	1-2% by GENIE
DIS	A-scaling, empirical	MINERvA-GENIE (bottom-up)	No understanding MINERvA data	maybe large?
DIS	A-scaling, nuclear PDF	From nuclear PDF, CT10? nCTEQ? (top-down)	GRV98 is only compatible with B-Y correction	expected to be small
Hadronization	low W averaged charged hadron multiplicity	Change AGKY model parameters	Not many data.	maybe large?
Hadronization	high W averaged charged hadron multiplicity	bubble chamber-PYTHIA comparison	Lund string function need to be tune for lowE	1-2% by GENIE

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Some of systematic errors are identified to be dangerous…,
- What kind of systematic errors do we have on nuSIS&DIS?