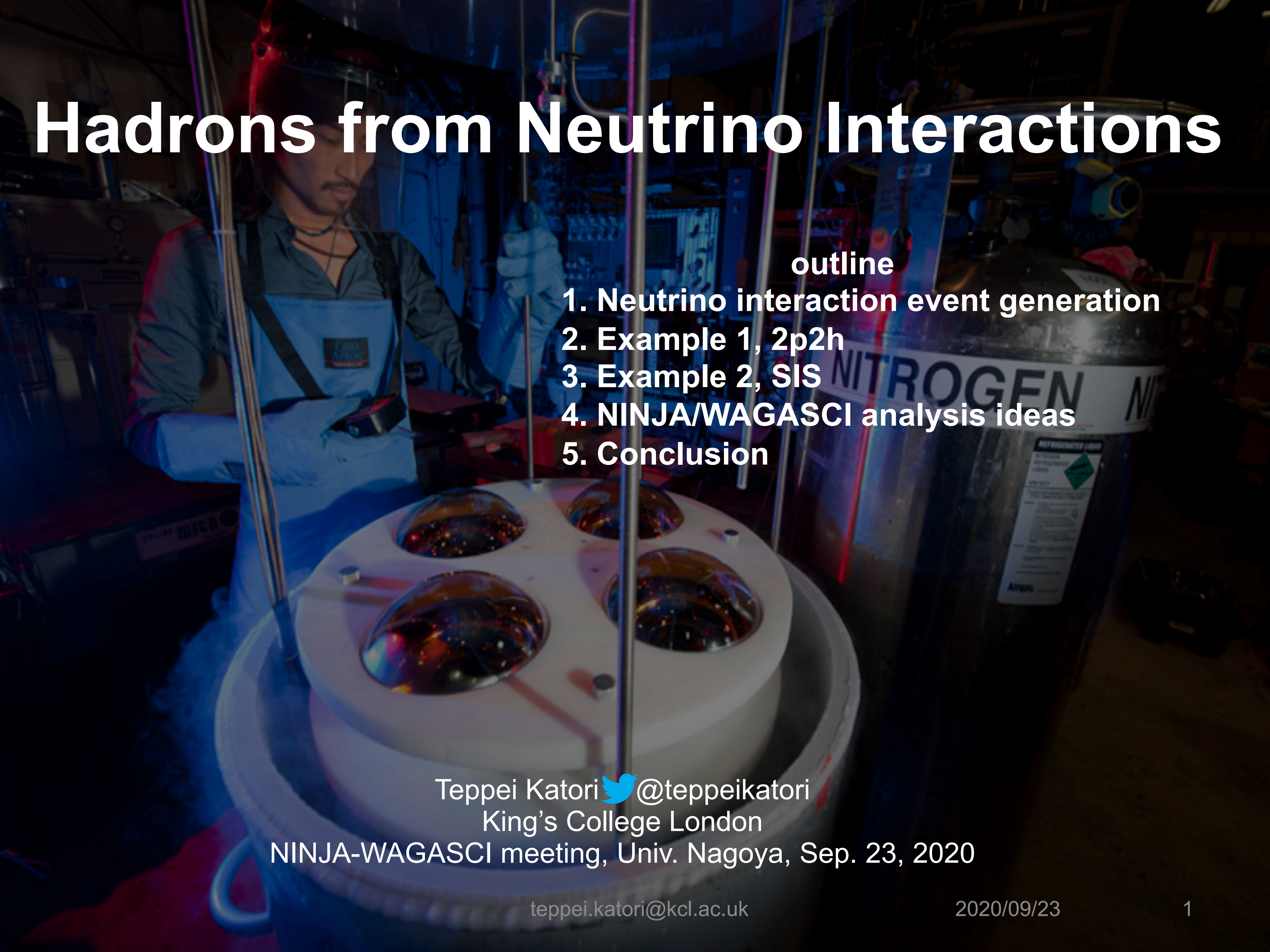

Hadrons from Neutrino Interactions

outline

1. Neutrino interaction event generation
2. Example 1, 2p2h
3. Example 2, SIS
4. NINJA/WAGASCI analysis ideas
5. Conclusion

Teppei Katori @teppeikatori
King's College London
NINJA-WAGASCI meeting, Univ. Nagoya, Sep. 23, 2020

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1. **Neutrino interaction event generation**
2. **Example 1, 2p2h**
3. **Example 2, SIS**
4. **NINJA/WAGASCI analysis ideas**
5. **Conclusions**

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1. Neutrino cross-section formula

Cross-section

- product of Leptonic and Hadronic tensor

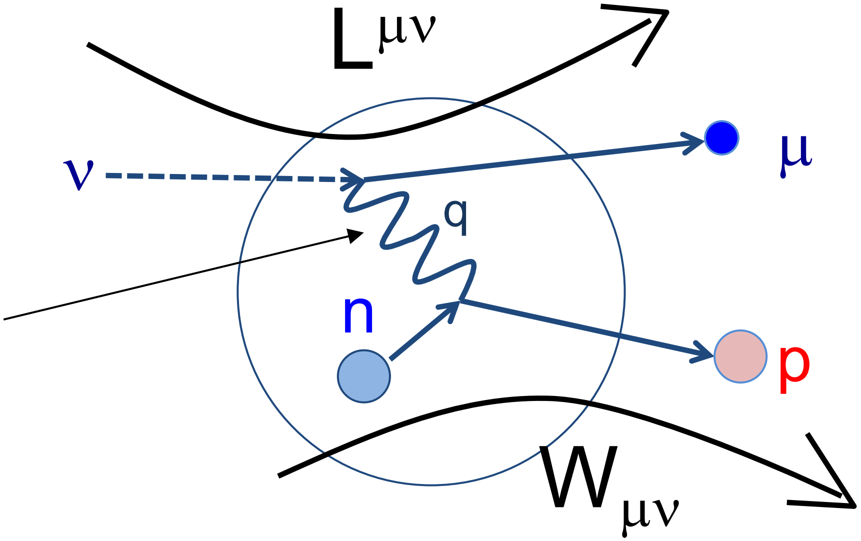
$$d\sigma \sim L^{\mu\nu}W_{\mu\nu}$$

Leptonic tensor

→ the Standard Model (easy)

Hadronic tensor

→ nuclear physics (hard)



energy-momentum transfer vector q

(not necessary off-shell Weak boson)

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1. Neutrino cross-section formula

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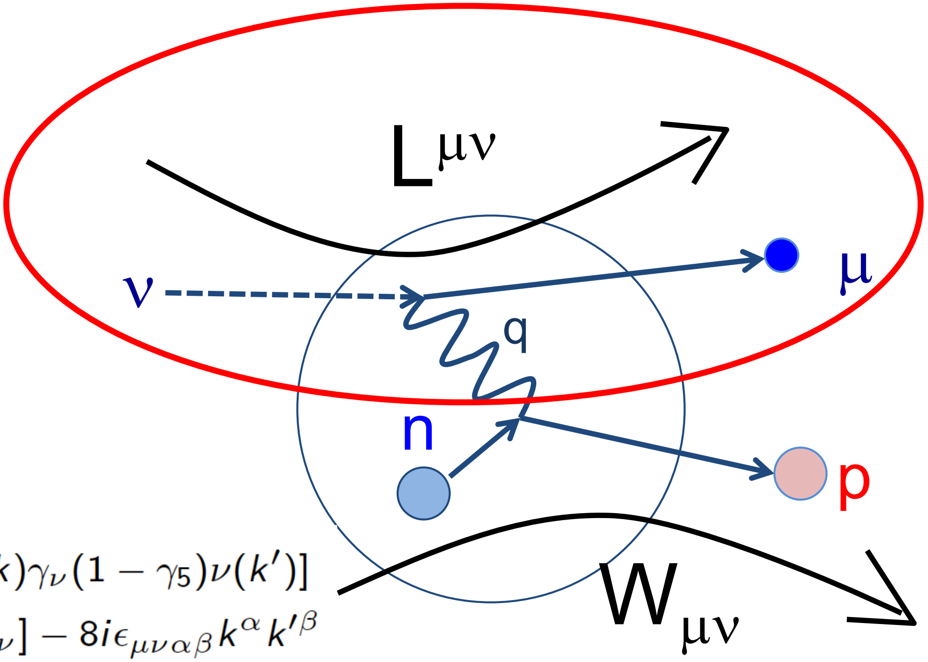

$$\begin{aligned} J_\mu^{(l)} &= \bar{l}(k')\gamma_\mu(1-\gamma_5)\nu(k) \\ \overline{L}_{\mu\nu} &= tr[\bar{\nu}(k')\gamma_\mu(1-\gamma_5)\nu(k)][\bar{\nu}(k)\gamma_\nu(1-\gamma_5)\nu(k')] \\ &= 8[k_\mu k'_\nu + k'_\mu k_\nu - (k\cdot k')\gamma_{\mu\nu}] - 8i\epsilon_{\mu\nu\alpha\beta}k^\alpha k'^\beta \end{aligned}$$

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1. Neutrino cross-section formula

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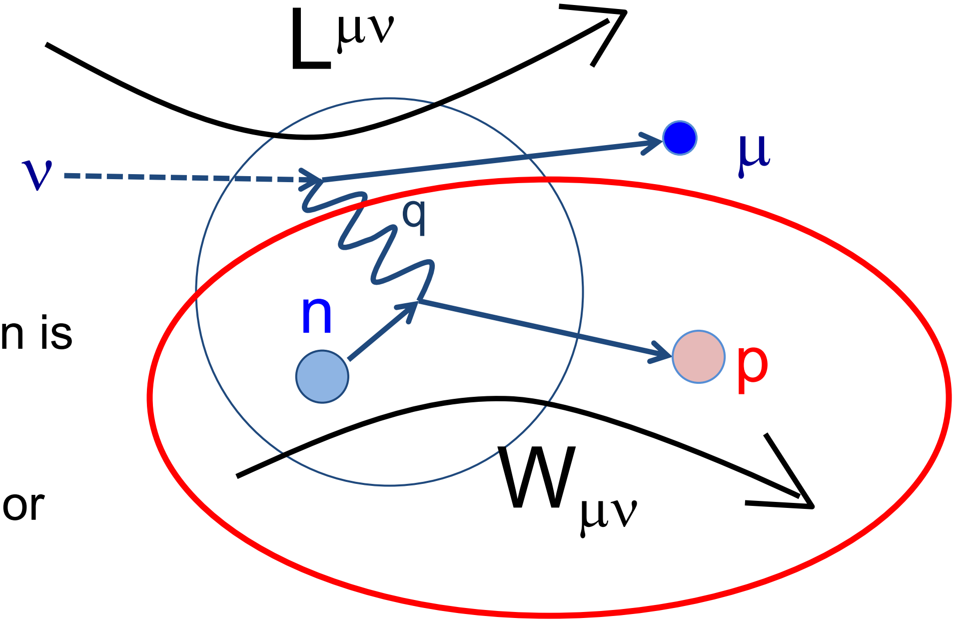


All complication of neutrino cross-section is how to model the hadronic tensor part
→ but this is not today's topic. Let's assume we have the best hadronic tensor

1. Neutrino interaction event generation

Choose neutrino energy from the flux spectrum (Eν)

↓

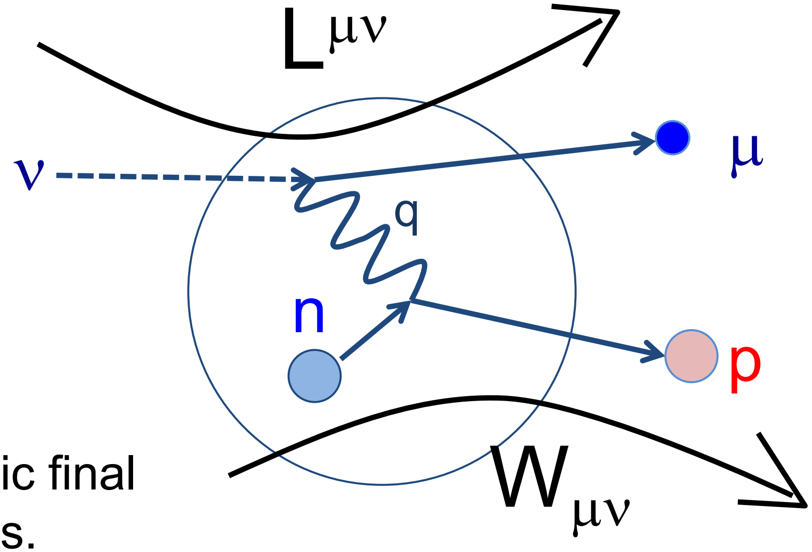
Choose cross-section model (=hadron tensor) and generate energy-momentum transfer vector

- kinematic variables are generated (Q^2, W, x, y, etc)
- lepton kinematics (E_μ, $\cos\theta_\mu$) are generated

↓

Choose hadron model and FSI model

- Hadron final states are generated from given energy-momentum transfer vector
- Apply FSI



Cross-section models (Llewellyn-Smith, Nieves, Martini, etc) don't predict hadronic final states. Single pion models are exceptions.

1. Neutrino interaction event generation

2. **Example 1, 2p2h**

3. Example 2, SIS

4. NINJA/WAGASCI analysis ideas

5. Conclusions

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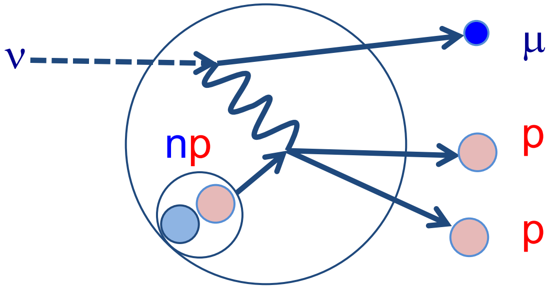
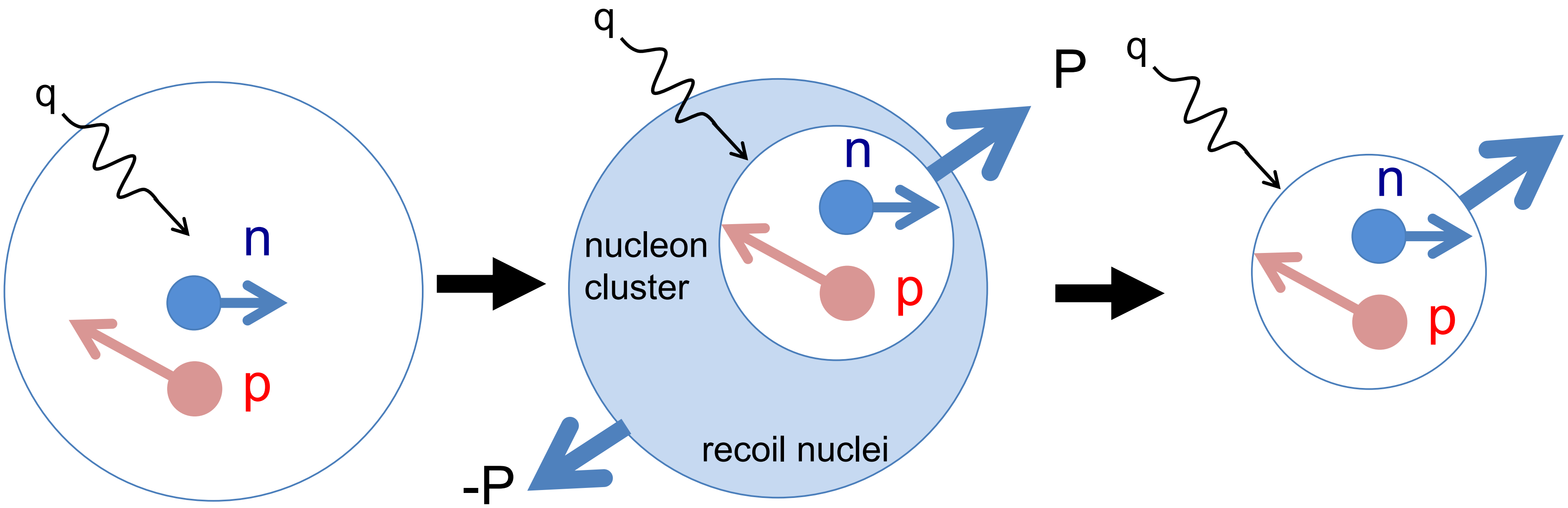
2. 2p2h



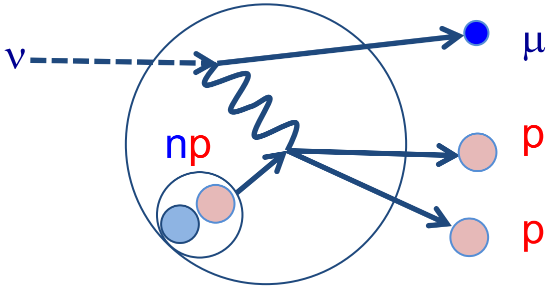
Nucleon cluster model

- Cross-section model define energy-momentum transfer vector (q)
- 1 proton and 1 neutron are chosen from Fermi gas
- They form nucleon cluster with total momentum P
- Rest target nuclei recoil with –P
- This nucleon cluster with momentum P absorb q



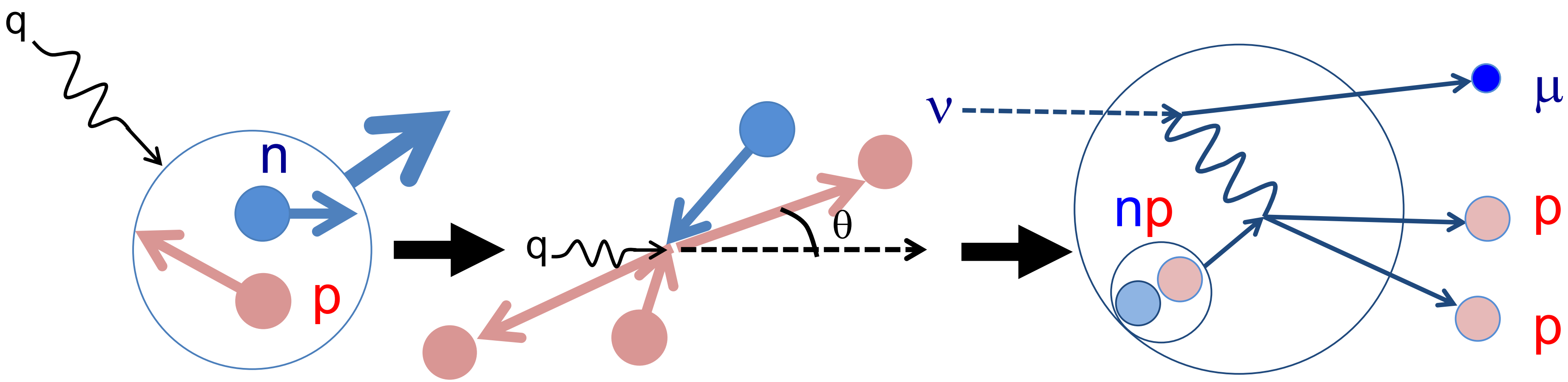
Sobczyk,PRC86(2012)015504, TK(NuInt12),arXiv:1304.6014

2. 2p2h



Nucleon cluster model

- q and P make a CMS frame (hadronic system)
- Hadronic system decays isotropically to 2 protons
- Then they are boosted back to the lab frame to simulate outgoing nucleons
- FSI is applied to them
- Model is independent from Valencia 2p2h etc, but phase space argument says any nucleon emission model will end up this.



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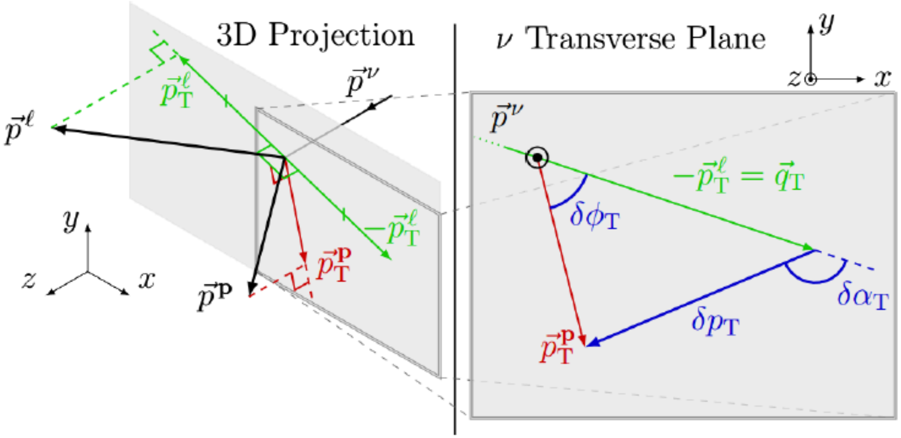
2020/09/23

T2K, PRD98(2018)032003

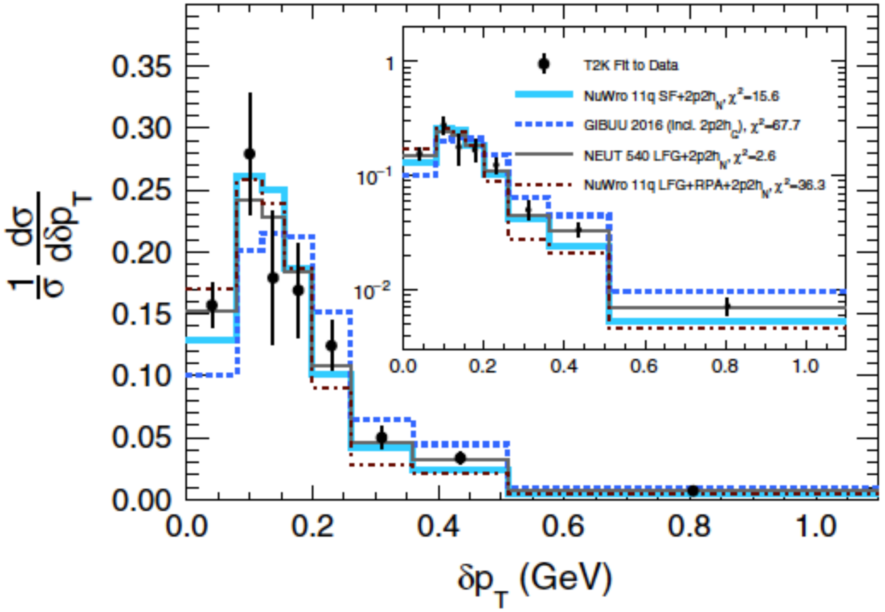
2. T2K mu+p data



data-MC disagreement can be

1. Cross-section model
(momentum transfer vector and lepton kinematics)
2. RFG vs LHG vs SF
(how to sample nucleons)
3. Nucleon cluster model
(how to generate outgoing nucleons)
4. FSI
(how to modify outgoing nucleons)

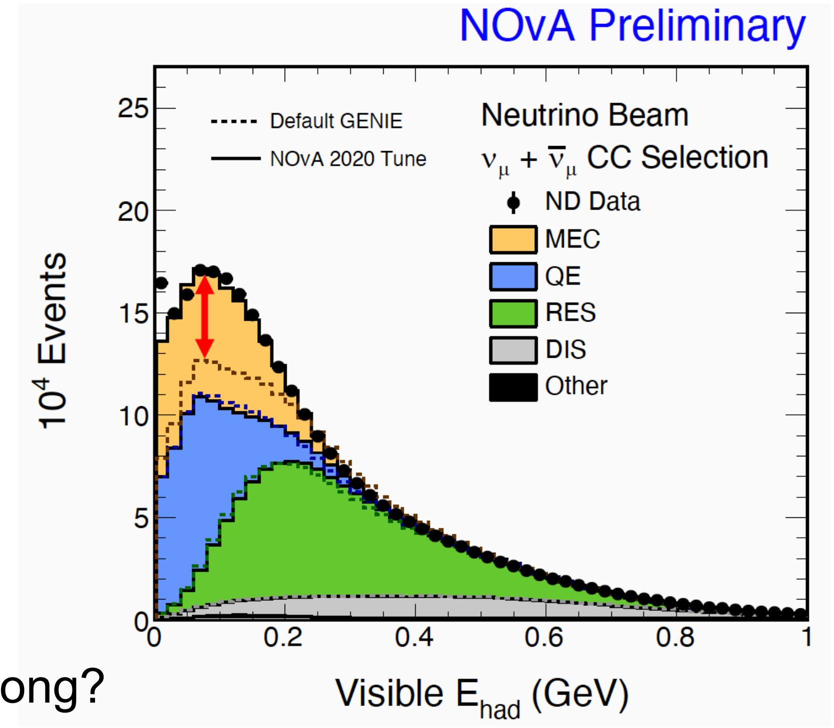
We often skip to discuss (3)



Hadron emission is not a part of 2p2h cross-section model

NOvA, arXiv: 2006.08727

2. 2p2h in NOvA



Significant amount of tuning
T2K: ~40% increase
NOvA:~200% increase

In NOvA, lack of 2p2h is seen
from hadron energy deposit

→ cross-section model (Valencia model) is wrong?
→ hadron+FSI model is wrong?

Hadron emission is not a part of 2p2h cross-section model

1. Neutrino interaction event generation

2. Example 1, 2p2h

3. **Example 2, SIS**

4. NINJA/WAGASCI analysis ideas

5. Conclusions

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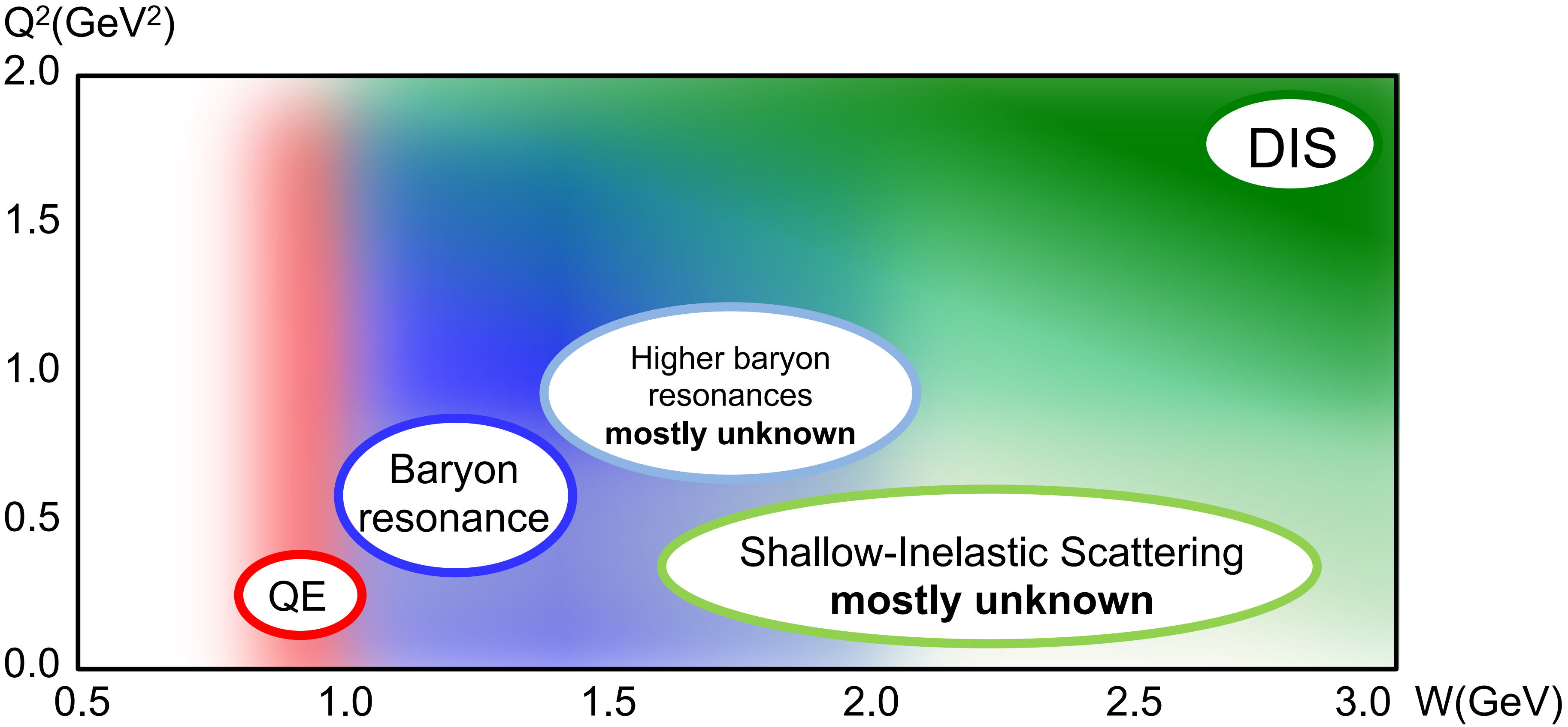
3. SIS, Shallow-inelastic scattering region



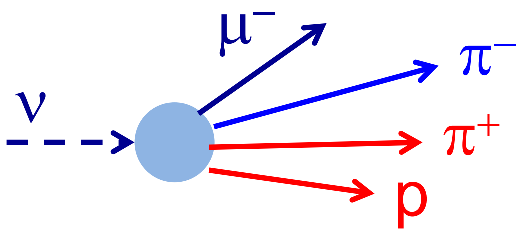
SIS is the kinematic region where interaction switch from hadrons to quarks, very relevant to NOvA and DUNE (and SuperK atmospheric neutrinos)

Bronner and Hartz (NuInt15), JPS Conf. Proc., 010041 (2016)
Connolly, PhD thesis (Univ. Washington, 2014)

This new "multi-pi" is not used in NEUT
(this is a default in GENIE)

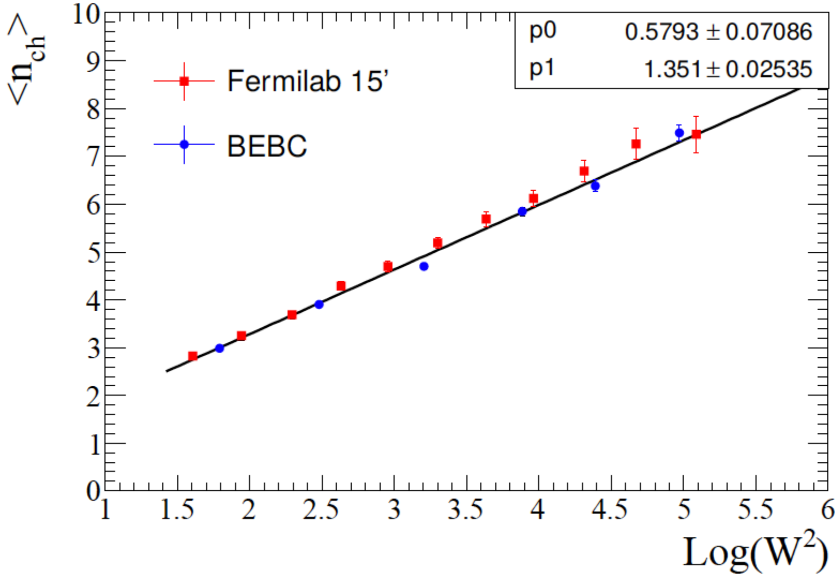
3. SIS, Shallow-inelastic scattering region

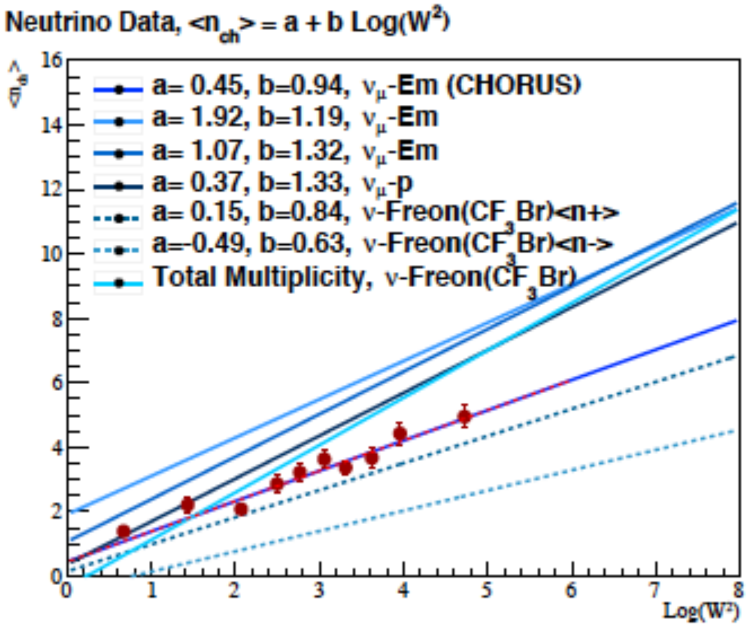
$$< n_{ch} >= a + bLog(W^2)$$



Averaged charged hadron multiplicity $<n_{ch}>$

- $<n_{ch}>$ is modeled with 2 parameter line





Bubble chamber data set don't agree

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AGKY model, EPJC63(2009)1

3. SIS, Shallow-inelastic scattering region

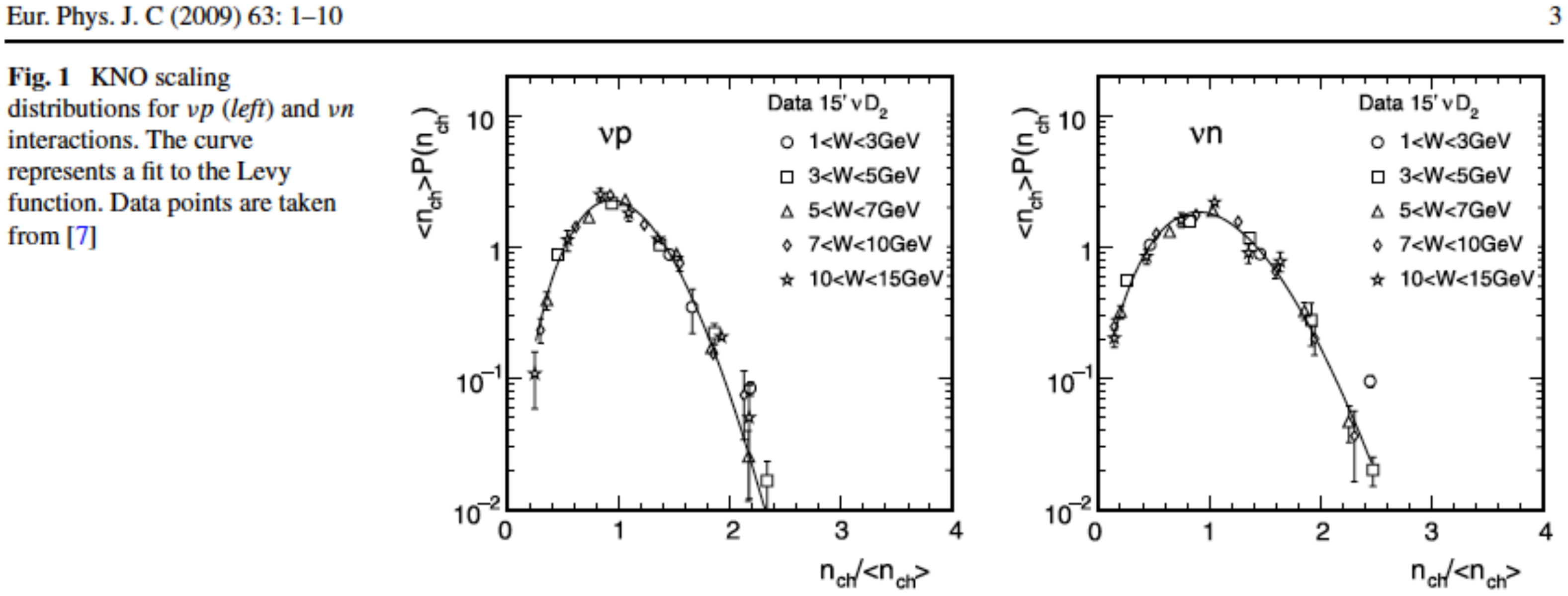
This new “multi-pi” is not used in NEUT
(this is a default in GENIE)

Averaged charged hadron multiplicity $<n_{ch}>$

- $<n_{ch}>$ is modeled with 2 parameter line

KNO scaling law

- Hadron dispersion is generated from data
- By construction, it reproduces bubble chamber dispersion data



Eur. Phys. J. C (2009) 63: 1–10 3

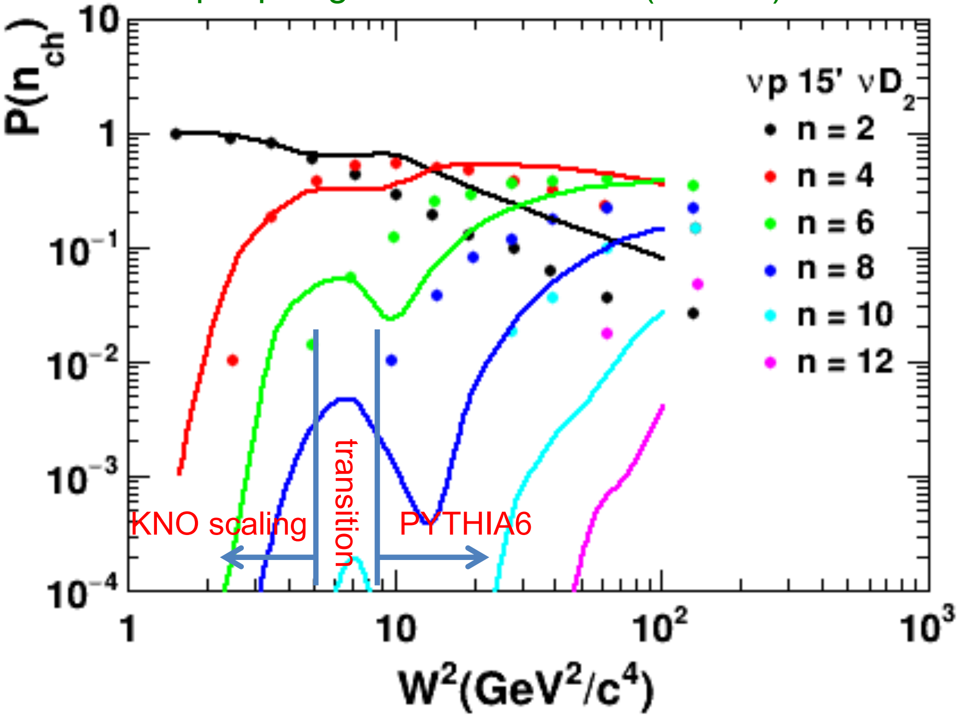
Fig. 1 KNO scaling distributions for *νp* (*left*) and *νn* interactions. The curve represents a fit to the Levy function. Data points are taken from [7]

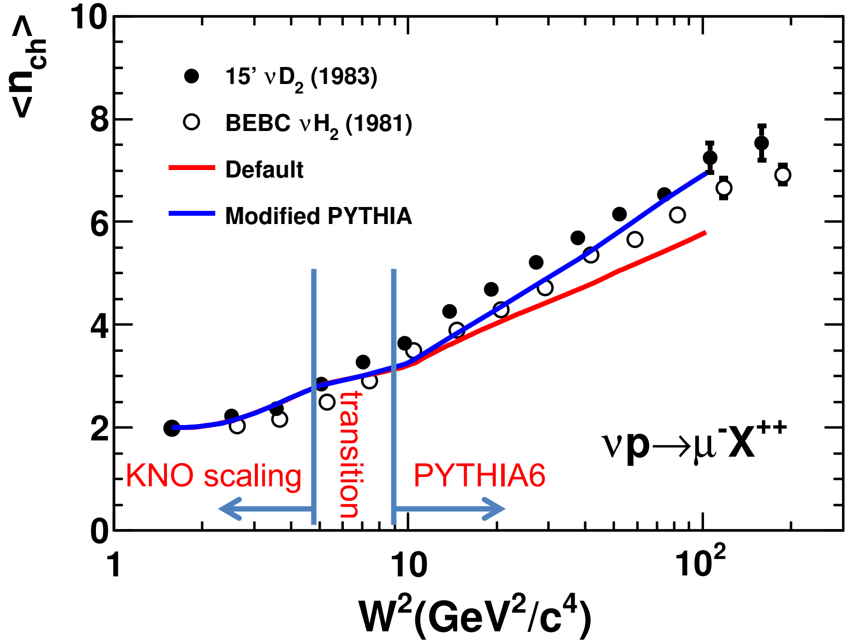
AGKY model, EPJC63(2009)1
TK and Mandalia, JPhysG42(2015)115004, TK et al, arXiv:1602.00083

3. SIS, Shallow-inelastic scattering region

PYTHIA

- High W hadronization is made by PYTHIA6
- PYTHIA6 tuning can control <n_{ch}> to agree with data, but not dispersion
- PYTHIA8 only makes agreement worse


ν-p topological cross section (GENIE)

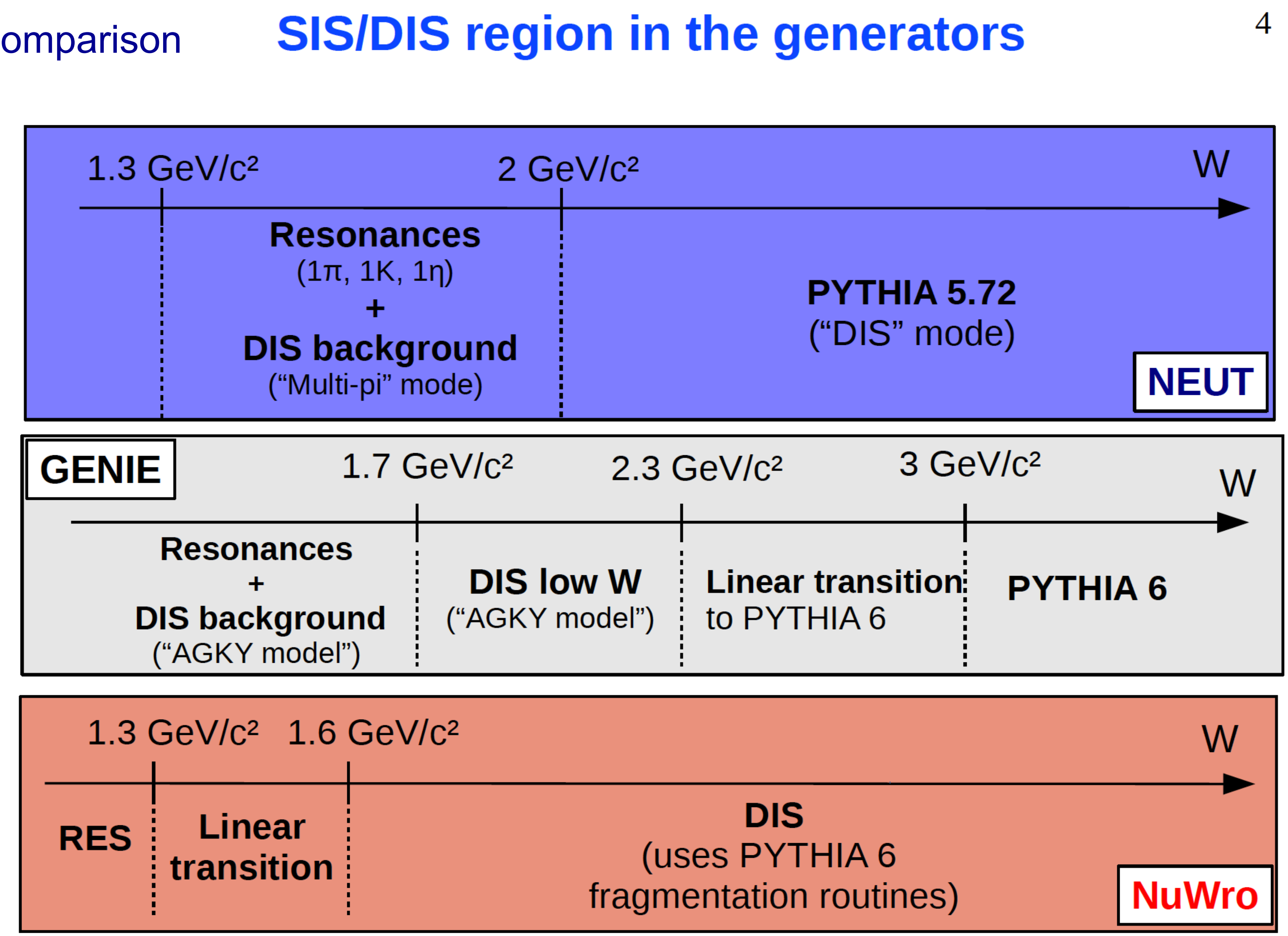

ν-p averaged charged hadron multiplicity (GENIE)

Event-by-event simulation of low W hadron system is challenging

https://nustec.fnal.gov/nuSDIS18/
ArXiv:1907.13252

3. neutrino SIS workshop (2018)

Generator comparison (Bronner)



SIS/DIS region in the generators

NEUT

1.3 GeV/c^2 — 2 GeV/c^2 — W

Resonances
(1π, 1K, 1η)
+
DIS background
(“Multi-pi” mode)

PYTHIA 5.72
(“DIS” mode)

GENIE

1.7 GeV/c^2 — 2.3 GeV/c^2 — 3 GeV/c^2 — W

Resonances
+
DIS background
(“AGKY model”)

DIS low W
(“AGKY model”)

Linear transition
to PYTHIA 6

PYTHIA 6

NuWro

1.3 GeV/c^2 — 1.6 GeV/c^2 — W

RES

Linear transition

DIS
(uses PYTHIA 6
fragmentation routines)

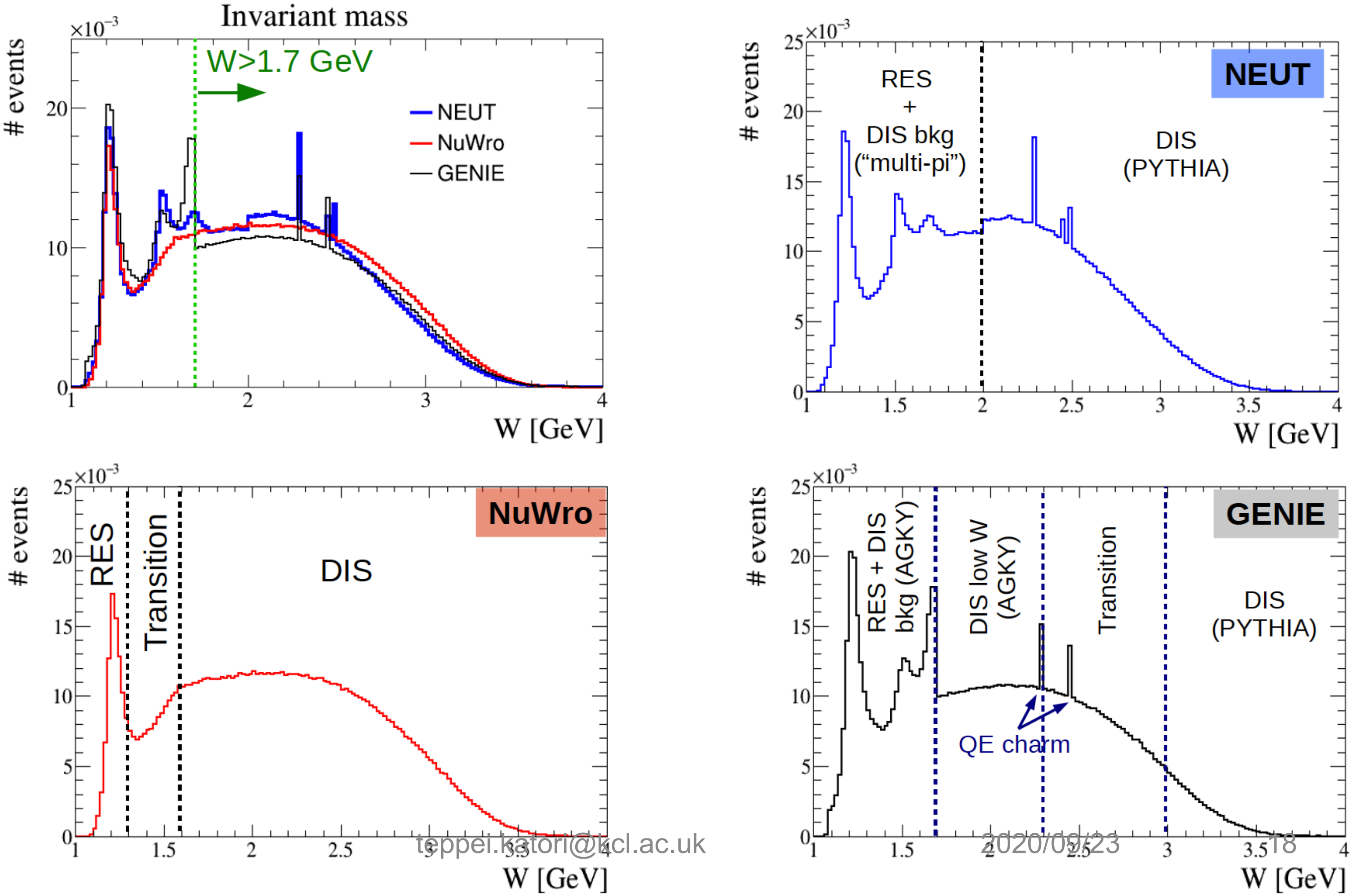
https://nustec.fnal.gov/nuSDIS18/
ArXiv:1907.13252

3. neutrino SIS workshop (2018)

Generator comparison
(Bronner)

Invariant mass distribution

ν_μ on Fe, E_ν=6.0 GeV



Snowmass SIS working group, arXiv:2009.04285
Phys.Rept.773(2018)1

3. neutrino SIS in Snowmass 2021

Number of suggestions to improved SIS physics, both theory and experiment

nu-H/D experiment
- electron scattering can measure RES vector form factors accurately, but RES axial form factors need to be measured

e-A experiment
- High-precision test of neutrino generator models, for example
- Hadron emission model
- Quark-hadron duality model
- Nuclear dependent DIS model

Generator framework
- We need to improve the simulation framework to simulate, including different factorization method

etc

Snowmass 2021 LoI:
Neutrino-induced Shallow- and Deep-Inelastic Scattering

L. Alvarez-Ruso,[1] A. M. Ankowski,[2] M. Sajjad Athar,[3] C. Bronner,[4] L. Cremonesi,[5] K. Duffy,[6] S. Dytman,[7] A. Friedland,[2] A. P. Furmanski,[8] K. Gallmeister,[9] S. Gardiner,[6] W. T. Giele,[6] N. Jachowicz,[10] H. Haider,[3] M. Kabirnezhad,[11] T. Katori,[12] A. S. Kronfeld,[6] S. W. Li,[2] J.G. Morfín,[6] U. Mosel,[13] M. Muether,[14] A. Norrick,[6] J. Paley,[6] V. Pandey,[15] R. Petti,[16] L. Pickering,[17] B. J. Ramson,[6] M. H. Reno,[18] T. Sato,[19] J.T. Sobczyk,[20] J. Wolcott,[21] C. Wret,[22] and T. Yang[6]

[1]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Apartado 22085, 46071 Valencia, Spain
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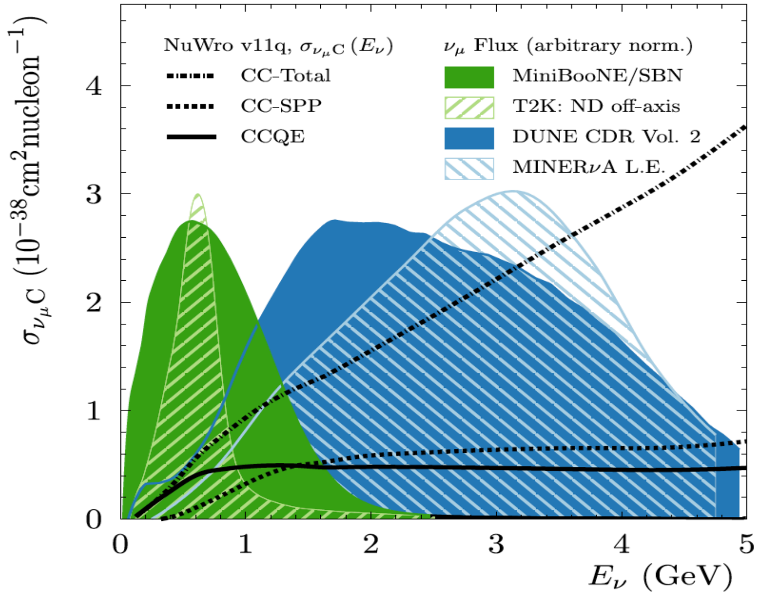
[21]Department of Physics and Astronomy, Tufts University, Medford, MA, 02155, USA
[22]Department of Physics and Astronomy, University of Rochester, Rochester, New York, 14627, USA



1. Neutrino interaction event generation

2. Example 1, 2p2h

3. Example 2, SIS

4. **NINJA/WAGASCI analysis ideas**

5. Conclusions

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4. T2K oscillation results

Internal constraint from WAGASCI

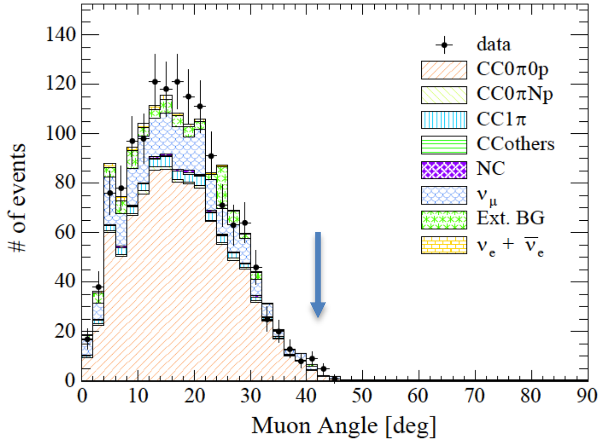
- Data must be taken simultaneously with far detector data
- Directly constrain systematics

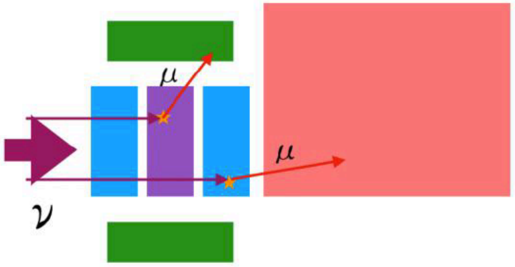
High angle water interaction

- FGD2 angular coverage is limited (SuperK is 4π coverage)
- WAGASCI-WMRD matching?

Hadron production in water

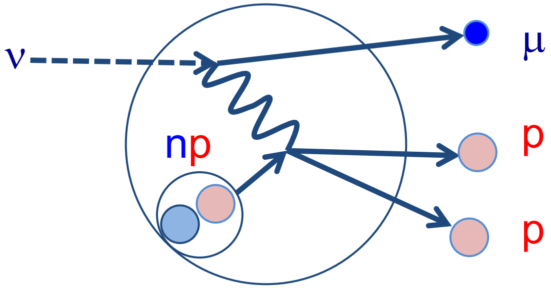
- Tuning of water cross-section parameters (QE, 2p2h)
- Test water FSI parameters





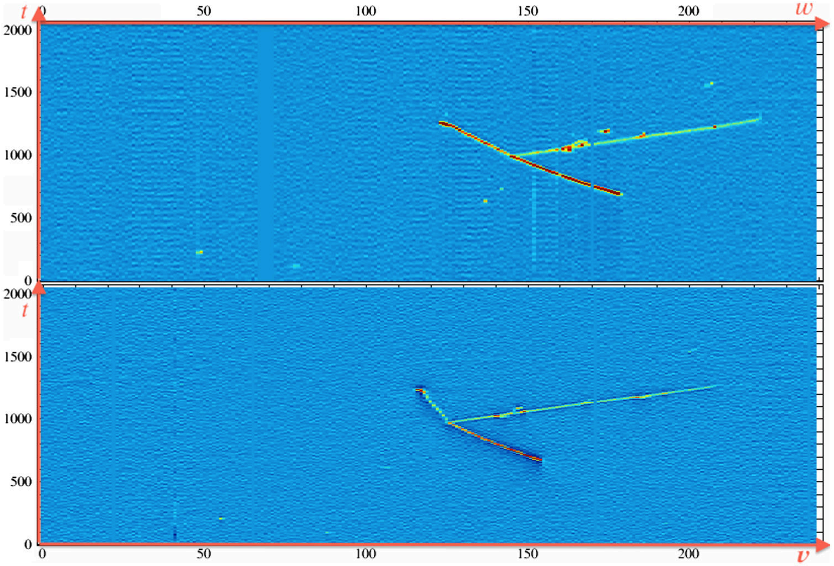
ArgoNeuT, PRD90(2014)012008

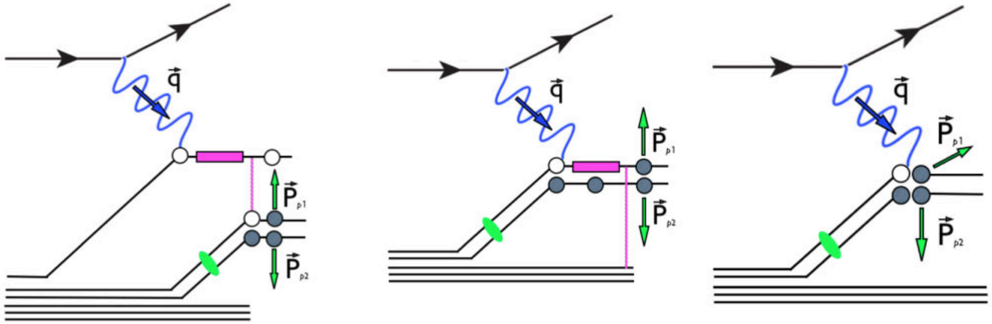
4. Search of nucleon pair



Test 2p2h model
- 2-nucleons are back-to-back in hadronic system
- Hadron measurements can reconstruct initial target

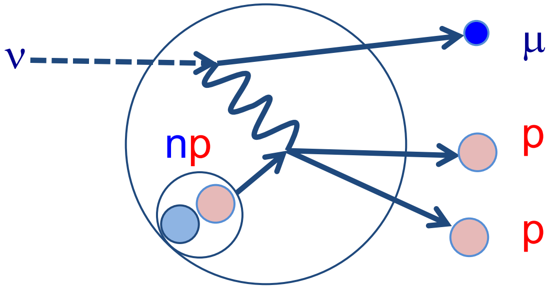
Short range correlation
- Evidence of nucleon correlation
- Pionless Delta production is background





MINERvA, PRD99 (2019) 012004

4. Test vertex energy deposition



Vertex activity

- Energy deposit by low energy hadrons
- Scintillator tracker is not calibrated with Low energy hadrons

Neutrino 2p2h hypothesis

- More energy = more protons

Antineutrino 2p2h hypothesis

- Less energy = more neutrons

RPA correction

- Suppress low energy deposit

NINJA can test these ideas?

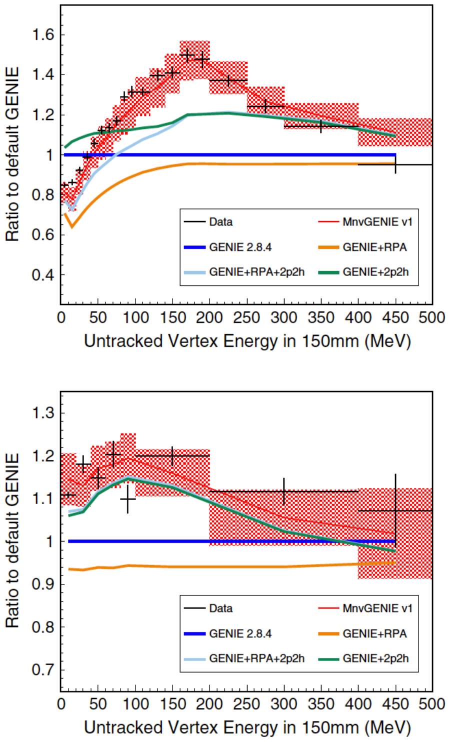


FIG. 36. Ratio of the data and various GENIE predictions to GENIE 2.8.4 of the vertex energy within 150 mm of the reconstructed vertex excluding tracked energy for events with no proton tracks reconstructed (top) and muon plus proton tracks reconstructed (bottom).

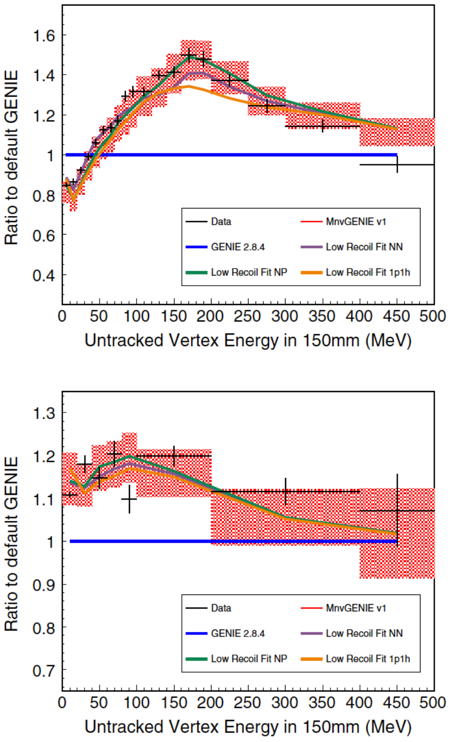


FIG. 37. Ratio of the data and variants of the enhancement via 2p2h nn, 2p2h np or QE-only events to GENIE 2.8.4 for vertex energy within 150 mm of the reconstructed vertex excluding tracked energy for events with no proton tracks reconstructed (top) and muon plus proton tracks reconstructed (bottom).

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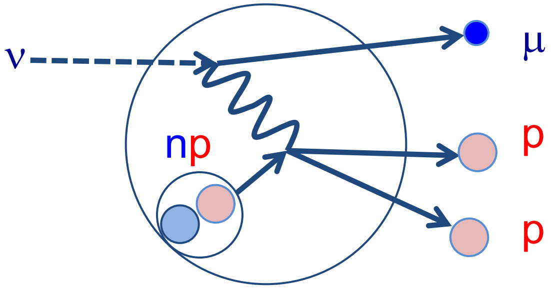
Pandey et al., PRC94(2016)054609, Van Cuyck et al., PRC94(2016)024611
Van Dessel et al., PRC97(2018)044616

4. Test advanced QE-2p2h model



Ghent model

- Based on CRPA, A-dependent QE
- Giant resonance structure is visible in energy transfer and muon energy spectrurm
- Hadron final states are predicted

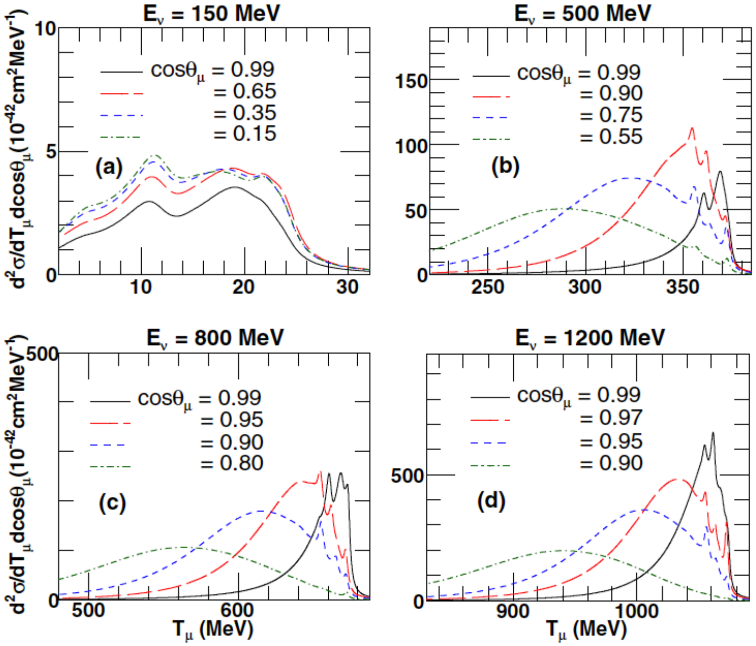
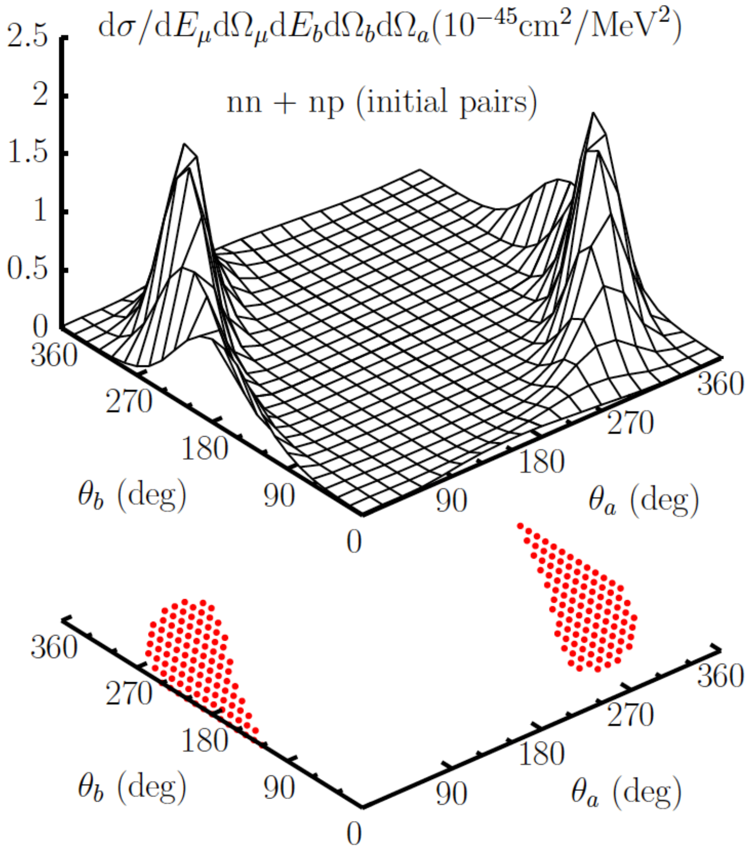


FIG. 13. (Color online) Low-energy excitations in double differential cross sections for ^{12}C(ν_μ,μ^-) plotted as a function of T_μ, for different cos θ_μ values.



NINJA, arXiv:2008.03895

4. Test hadron multiplicity model

NEUT multi-pi model

- Bubble chamber hadron multiplicity data are confusing
- No modern hadron multiplicity data, except CHORUS and NOMAD
- Any data will be useful to test hadron production model

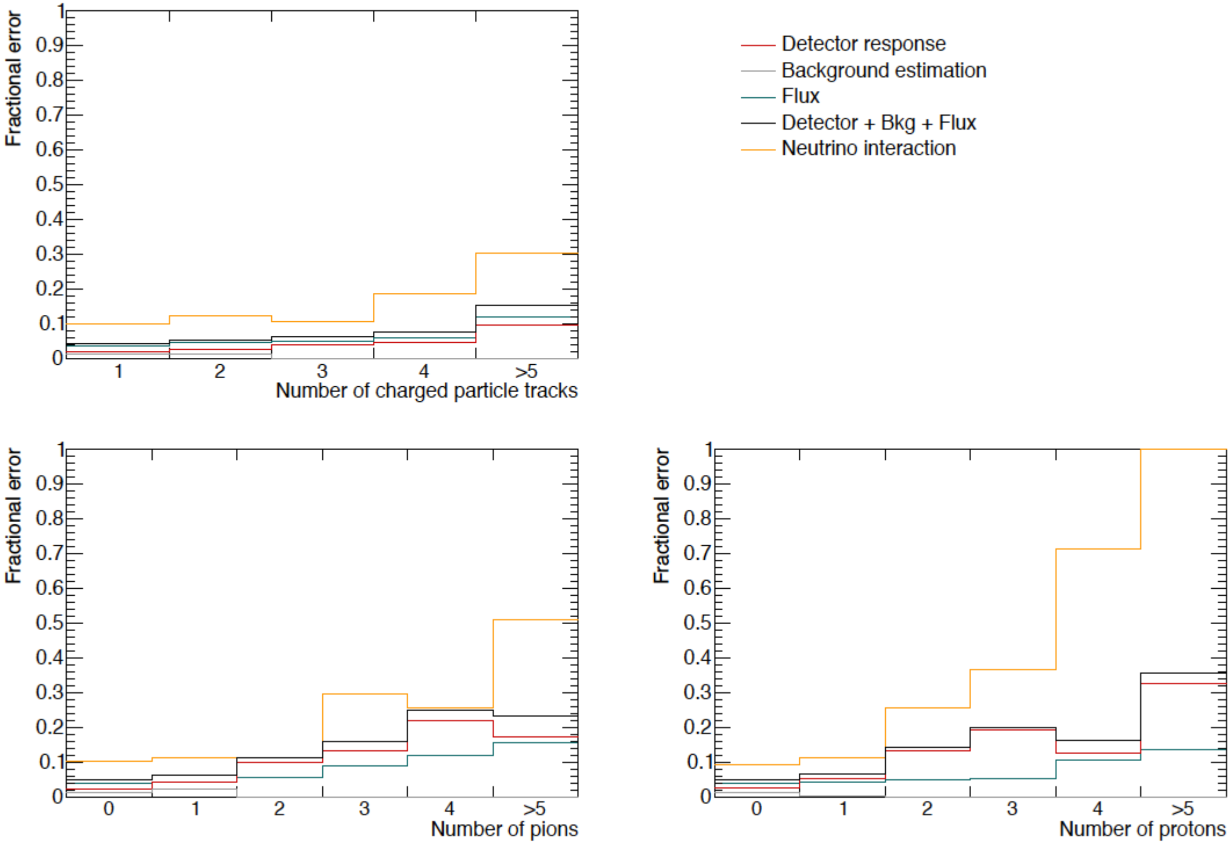


FIG. 11. Summary of the fractional uncertainties of charged particle multiplicity (top), the number of pions (bottom left), and the number of protons (bottom right) with a breakdown by the uncertainties from the neutrino flux, detector response, and background estimation. The uncertainty of neutrino interaction modeling is compared to the other uncertainties.

CHRUS, EPJC51(2007)775

4. CHORUS multiplicity data

CHORUS measured hadron productions for both nu and antinu, but these data are not used for any tunings because the target is emulsion

Emulsion interaction data in NINJA can be compared with CHORUS data?

Table 1. Atomic composition and main features of the nuclear emulsions (Fuji ET-B7) used in the CHORUS experiment [27]

Element	Atomic number	Mass (%)	Mole fraction (%)
Iodine (I)	53	0.3	0.06
Silver (Ag)	47	45.5	11.2
Bromine (Br)	35	33.4	11.1
Sulphur (S)	16	0.2	0.2
Oxygen (O)	8	6.8	11.3
Nitrogen (N)	7	3.1	5.9
Carbon (C)	6	9.3	20.6
Hydrogen (H)	1	1.5	40.0

Mean number of nucleons	36 protons, 45 neutrons
Density	3.73 g/cm^3
Radiation length	2.94 cm
Nuclear interaction mean free path	38 cm
Concentration of AgBr	45.5% in volume

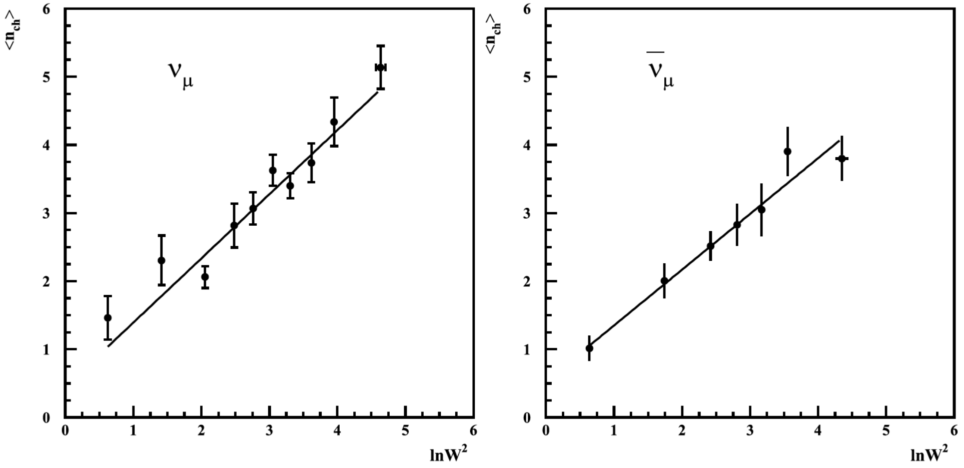


Fig. 3. The hadronic shower prong multiplicity distributions as a function of $\ln W^2$ for ν–A, and $\overline{\nu}$–A interactions

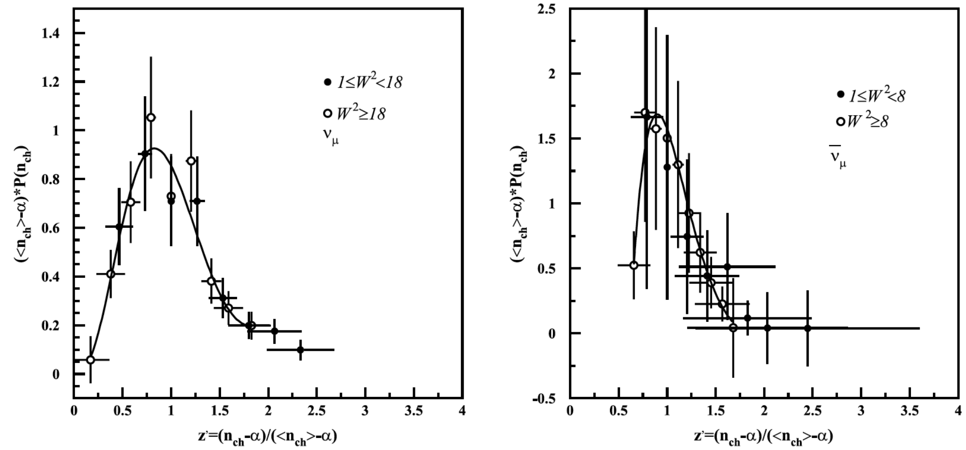
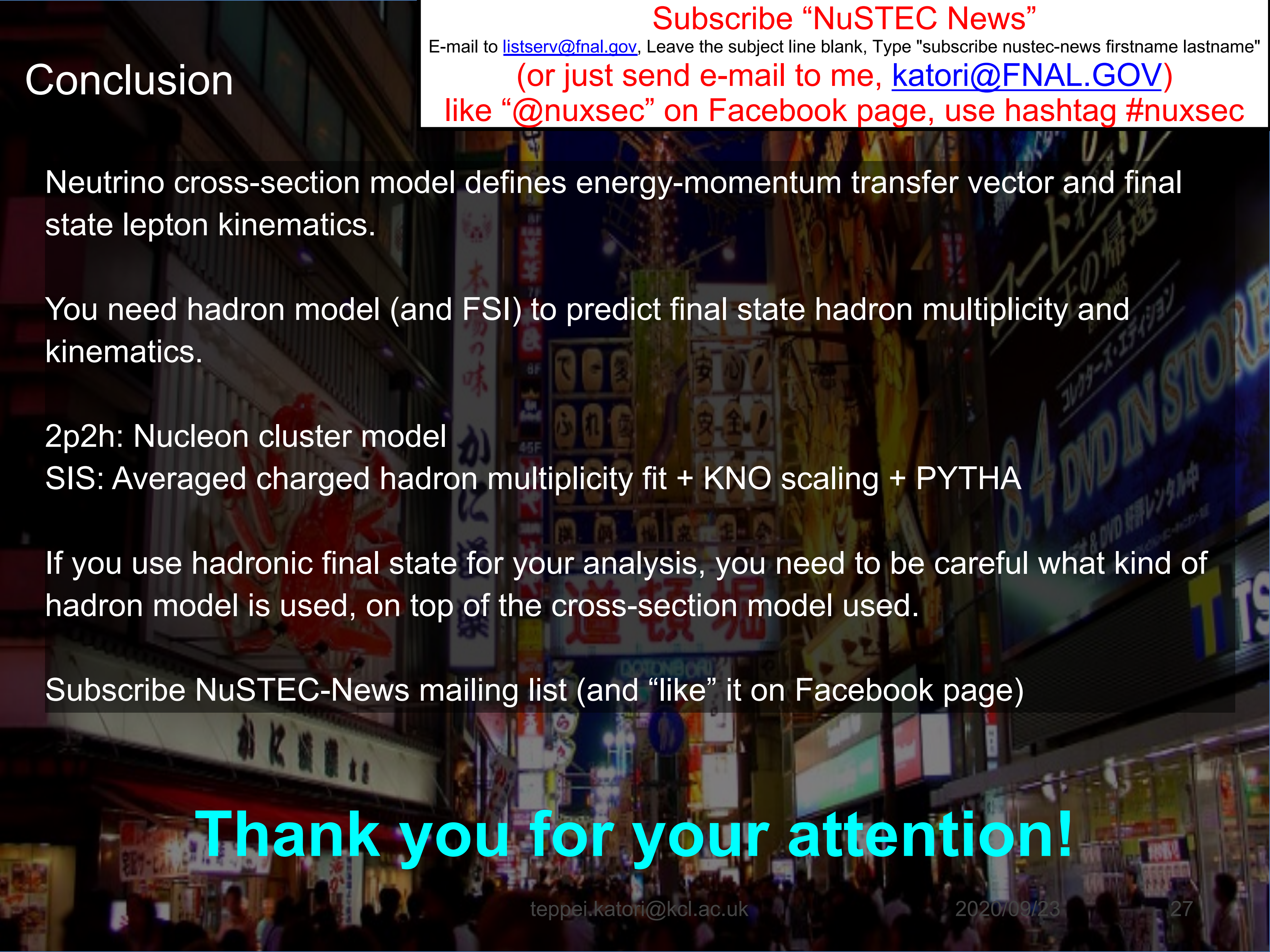


Fig. 5. The KNO scaling distribution for shower prongs. The superimposed curve represents a fit to pp data [37]. The data approximately agree with KNO scaling, i.e., the data points at different W^2 intervals lie approximately on a single curve



Conclusion

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Neutrino cross-section model defines energy-momentum transfer vector and final state lepton kinematics.

You need hadron model (and FSI) to predict final state hadron multiplicity and kinematics.

2p2h: Nucleon cluster model
SIS: Averaged charged hadron multiplicity fit + KNO scaling + PYTHA

If you use hadronic final state for your analysis, you need to be careful what kind of hadron model is used, on top of the cross-section model used.

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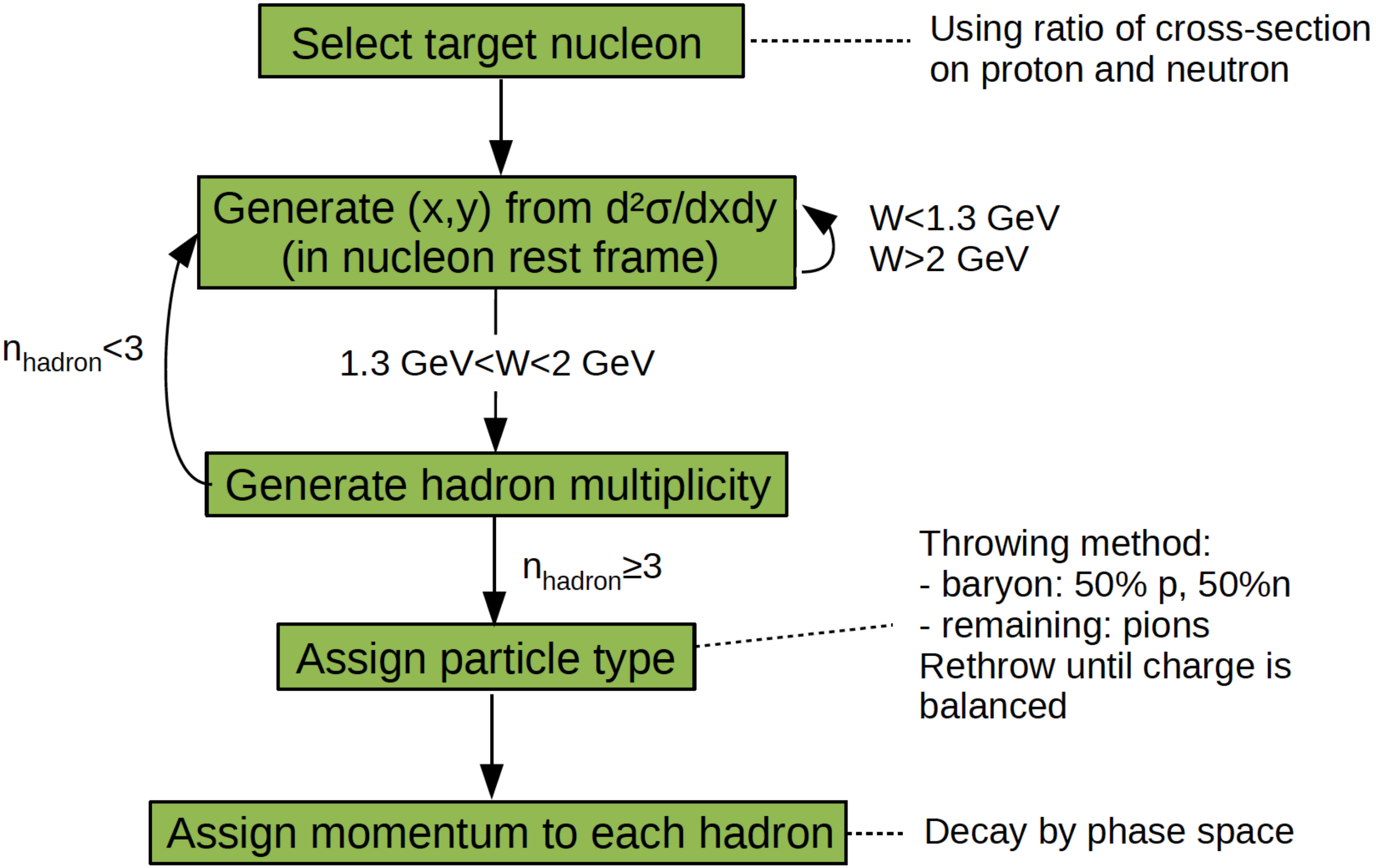
Thank you for your attention!

https://nustec.fnal.gov/nuSDIS18/
ArXiv:1907.13252

3. neutrino SIS workshop (2018)

Default NEUT multi-pi model (Bronner)

Low W model Flow



Select target nucleon

Using ratio of cross-section on proton and neutron

Generate (x,y) from $d^2\sigma/dxdy$ (in nucleon rest frame)

W<1.3 GeV
W>2 GeV

1.3 GeV<W<2 GeV

$n_{hadron}<3$

Generate hadron multiplicity

$n_{hadron} \geq 3$

Assign particle type

Throwing method:
- baryon: 50% p, 50%n
- remaining: pions

Rethrow until charge is balanced

Assign momentum to each hadron

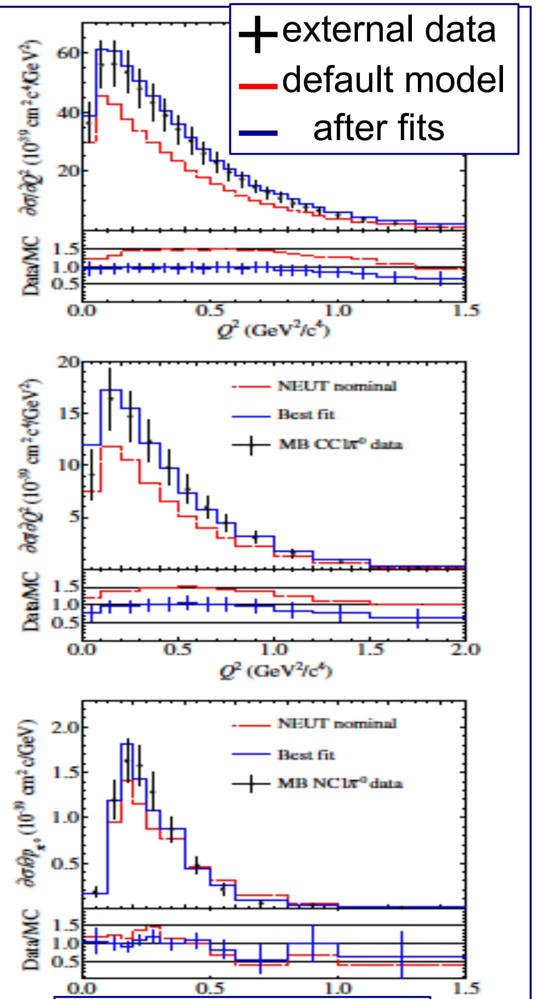
Decay by phase space

4. T2K oscillation results

External constraint

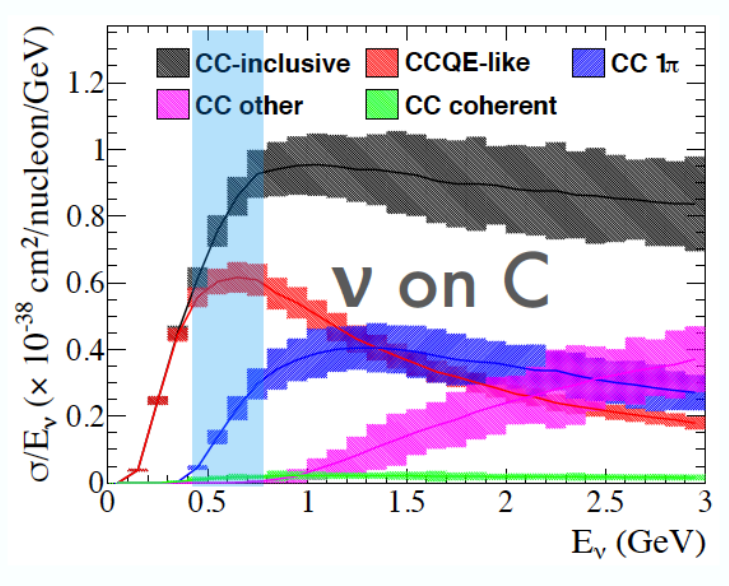
MiniBooNE, MINERvA, SciBooNE

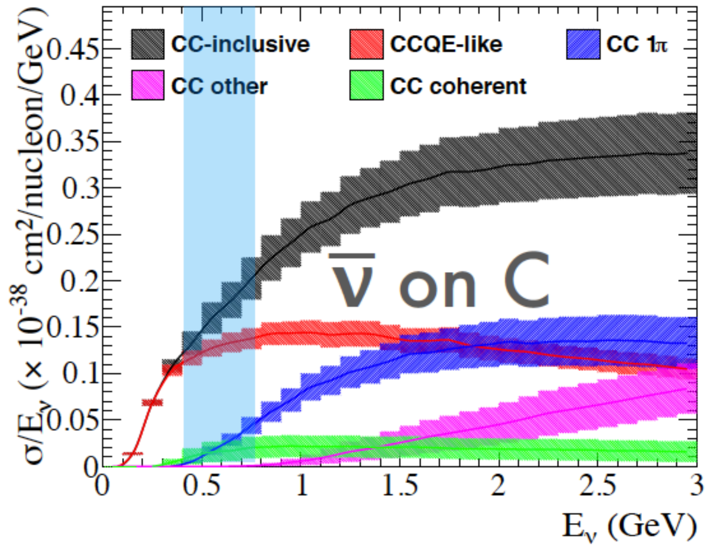
K2K, MINOS, Bubble chambers



External data fit

External data give initial guess of cross-section systematics





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4. T2K oscillation results

External constraint

MiniBooNE, MINERvA, SciBooNE
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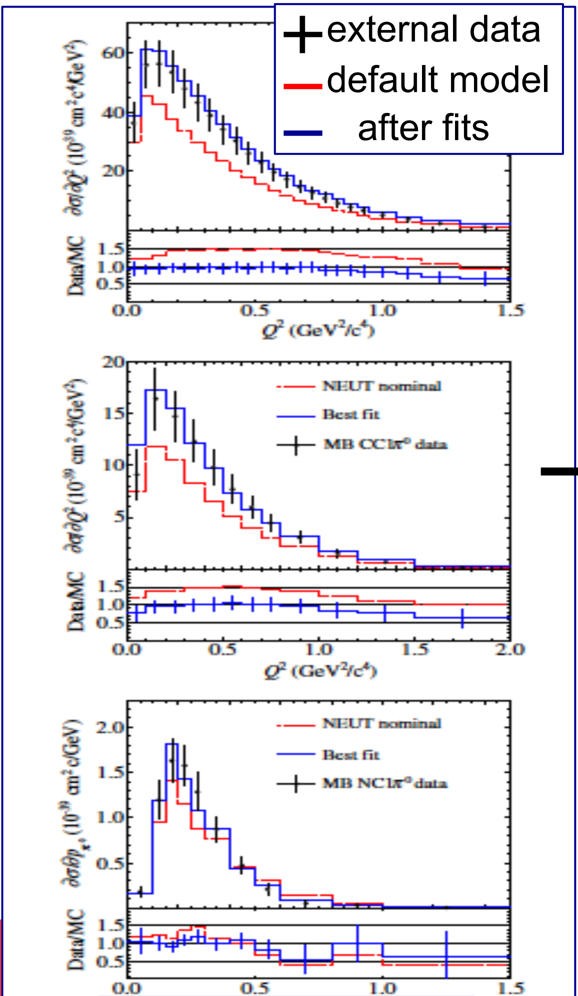
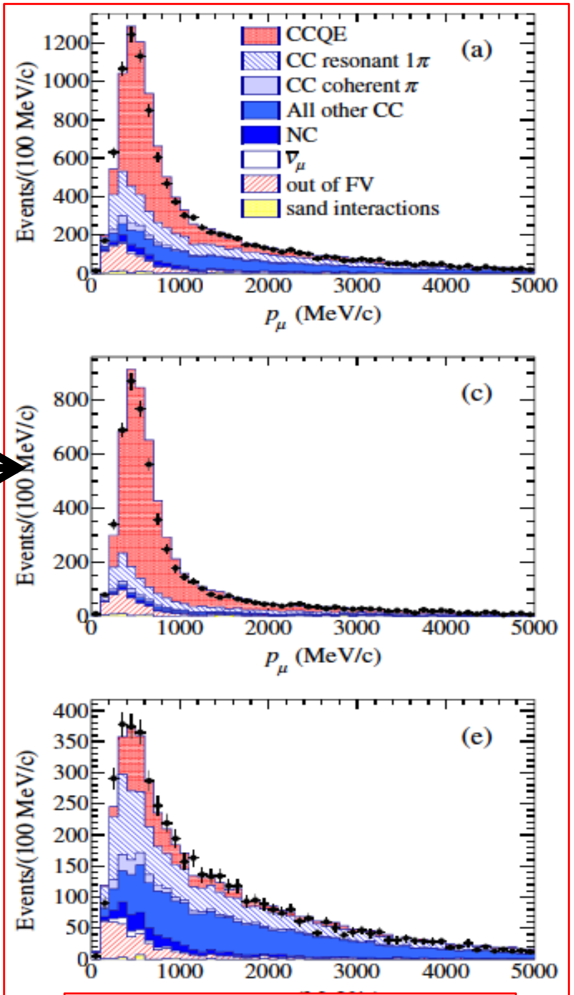


External data fit

Internal constraint

Near detector
oscillation non-sensitive channels

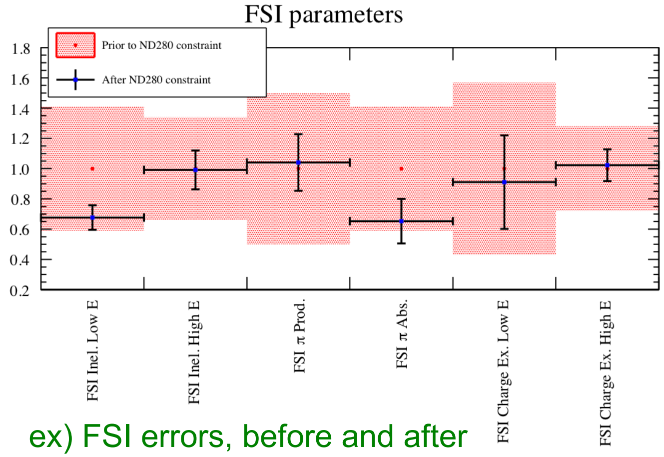


T2K ND280 data fit

Internal data can constrain systematic errors for the event rate (flux x cross-section)

SuperK sample systematic error

sample	Without ND280	With ND280
ν μ-like ring	14.6%	5.1%
ν e-like ring	16.9%	8.8%
$\bar{\nu}$ μ-like ring	12.5%	4.5%
$\bar{\nu}$ e-like ring	14.4%	7.1%



ex) FSI errors, before and after internal constraints

4. T2K oscillation results

External constraint

MiniBooNE, MINERvA, SciBooNE

K2K, MINOS, Bubble chambers

Internal constraint

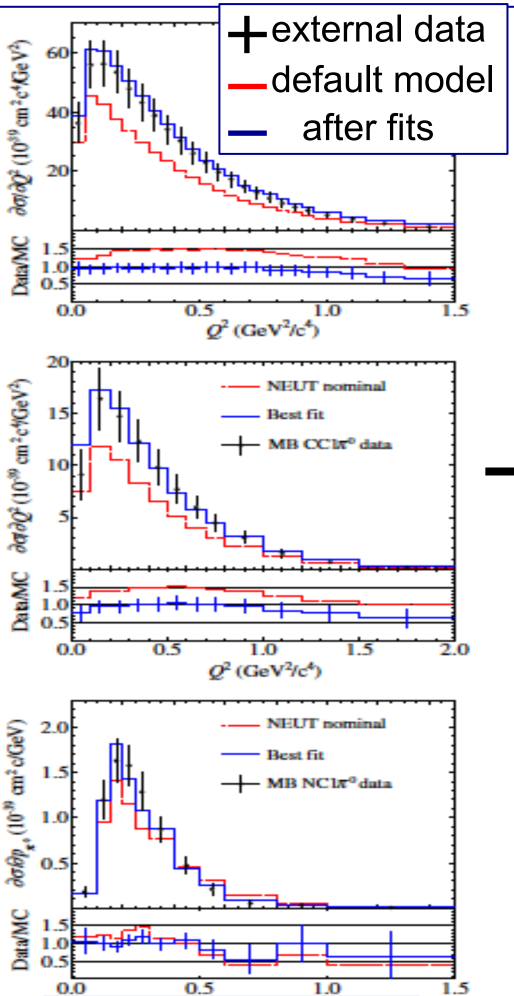
Near detector

oscillation non-sensitive channels

Oscillation fit

Far detector

oscillation samples

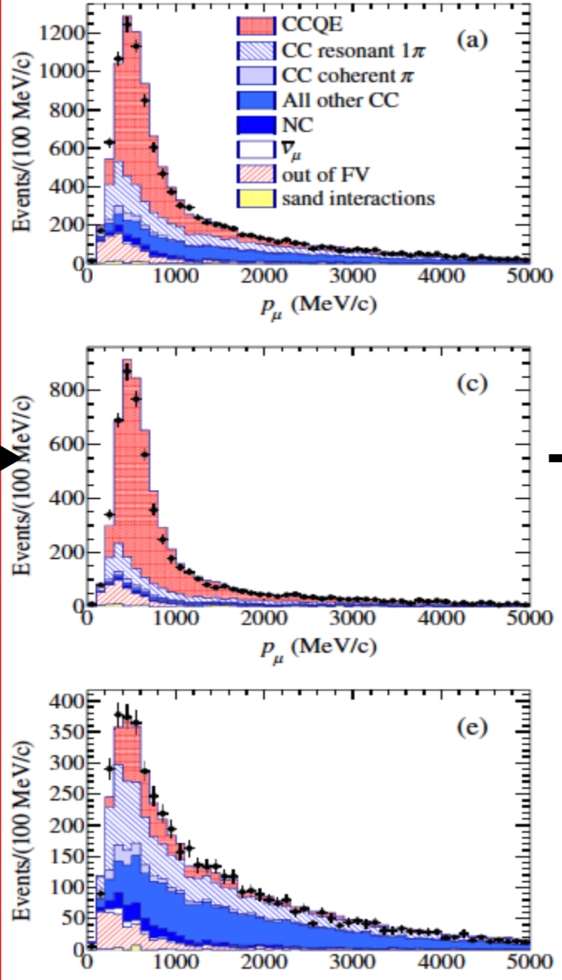


+ external data

— default model

— after fits

External data fit



T2K ND280 data fit