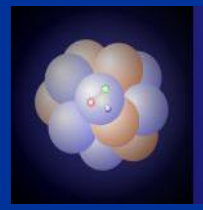
GiBUU-Physics of ν-A Interactions

Ulrich Mosel



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GiBUU Status

- GiBUU is a fairly mature project
- During the last year only a few internal, technical improvements have happened
  (will find their way into GiBUU v 2018 later this year)

- In this talk I will, therefore, concentrate on new results and new problems

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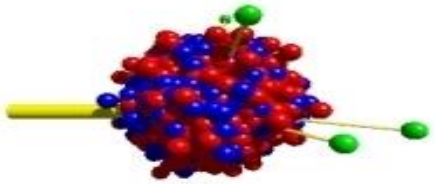

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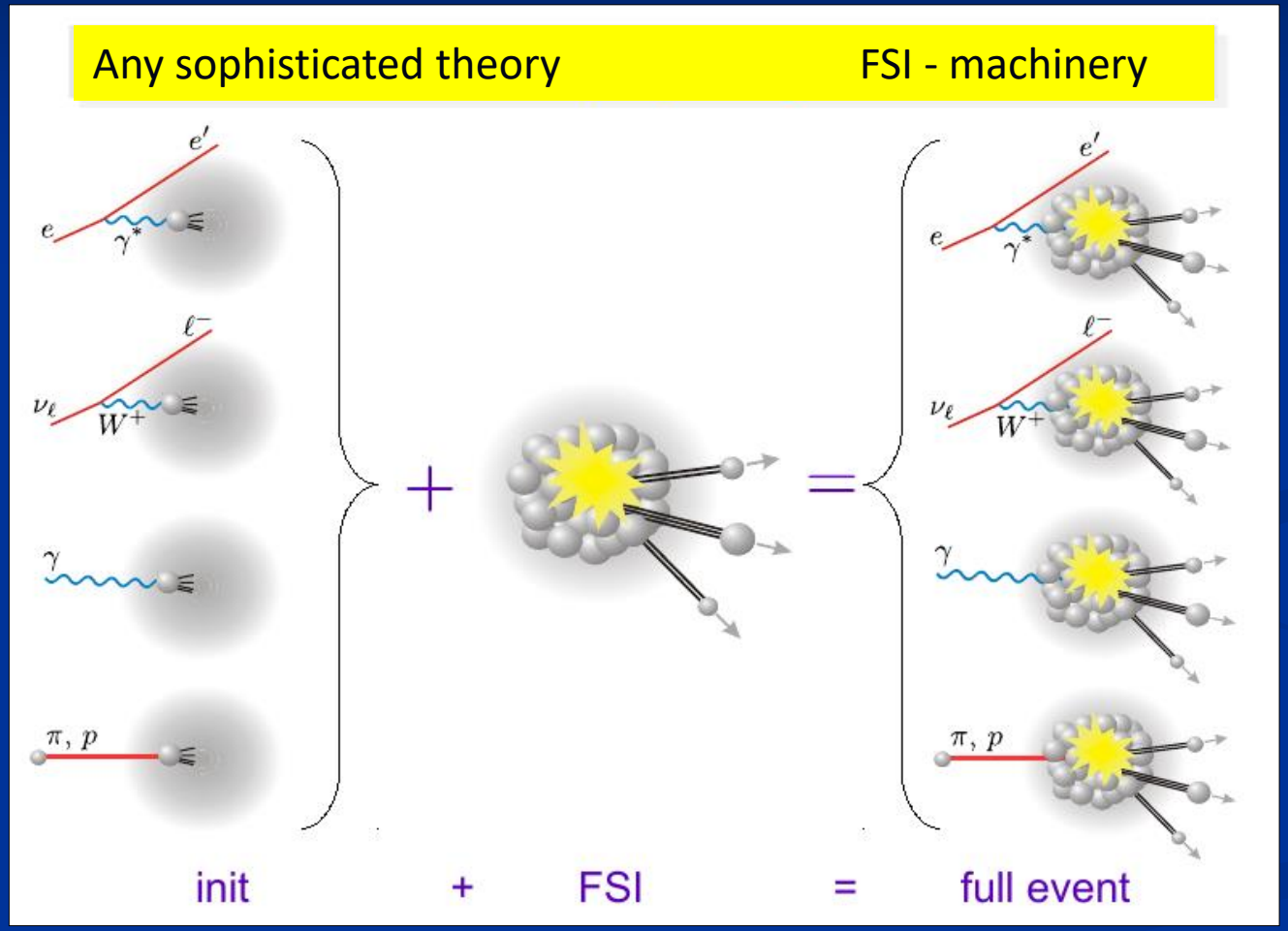
GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **GiBUU : Quantum-Kinetic Theory and Event Generator**
  based on a BM solution of Kadanoff-Baym equations
- GiBUU propagates phase-space distributions, not particles
- Physics content and details of implementation in:
  Buss et al, Phys. Rept. 512 (2012) 1- 124
- Code from gibuu.hepforge.org, present version GiBUU 2017
  Details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502

GiBUU general structure



Main strenght of GiBUU: FSI
Tested on many different reactions

For neutrinos the flux average in the init state lets you get away with any reasonable theory

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GiBUU Ingredients

- Initial State Interactions (for γ, e, ν)
  - Nuclear Potential, *r*- and *p*-dependent, from realistic energy-density functional
  - Momentum distribution from local Fermi-gas
  - All target nucleons are bound in the potential, minimizes RPA
  - 2p2h from phenomenology: e-scattering
  - Pion production from resonance model MAID 2007
  - DIS from PYTHIA (Kai Gallmeister's talks at SIS/DIS workshop)
- Groundstate must be very same for all processes
  - Bad Example: using different groundstates for QE (free Fermi gas) and 2p2h (local Fermi gas) introduces unphysical (tunable?) degrees of freedom

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GiBUU Ingredients

- Final State Interactions of produced hadrons:
  - Quantum-kinetic treatment, based on Kadanoff-Baym equations (propagates phase-space distributions in potentials, not free particles), no need to worry about binding energy parameters.
- Interaction rates respect time-reversal invariance (as far as possible)
  - Example: pion production and absorption must come from the very same model: π N $\rightarrow$ Δ $\rightarrow$ π N. Any treatment that does not respect this relation violates basic physics principles and introduces artificial (tunable?) parameters.
  - Bad example: pi production by RS, pi absorption by Oset cascade
- Potential of outgoing hadrons is the same as in the initial production
  - Bad example: spectral function for the isi and then free out-propagation introduces unphysical forces into the process

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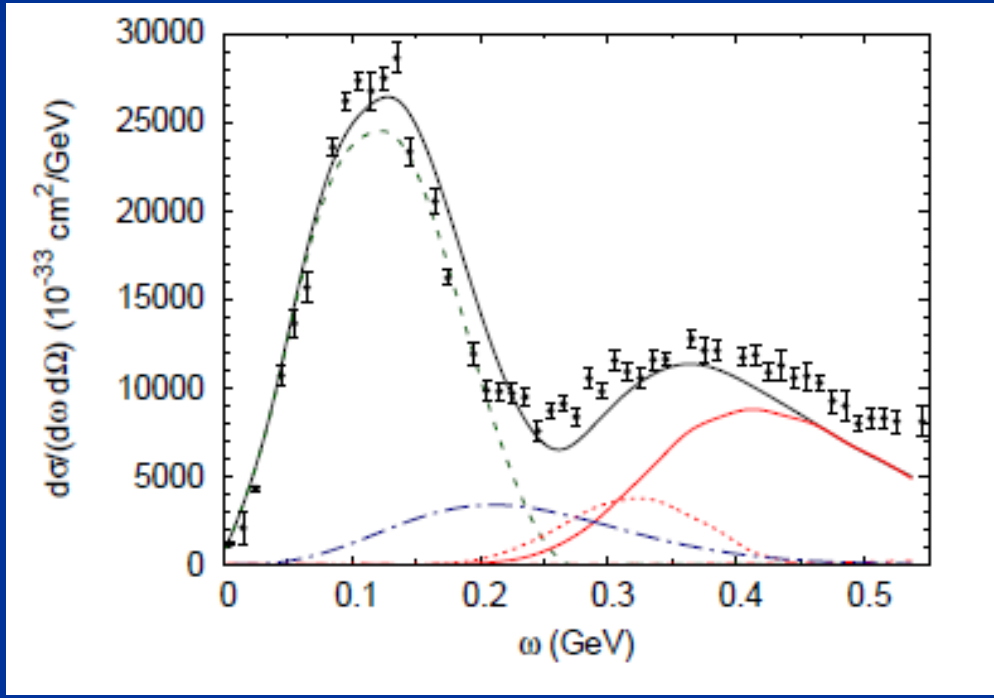
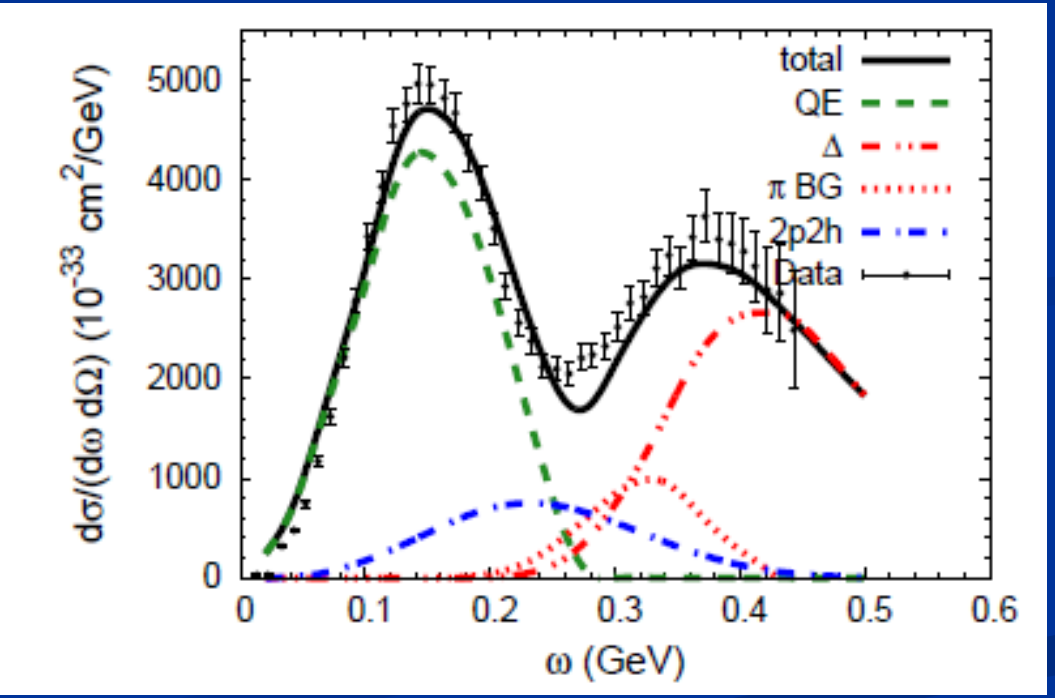
Inclusive QE Electron Scattering

- a necessary check for any generator development



0.737 GeV, 60 deg, $Q^2 = 0.47$ GeV^2 Target: O



0.56 GeV, 60 deg, $Q^2 = 0.24$ GeV^2 Target: C

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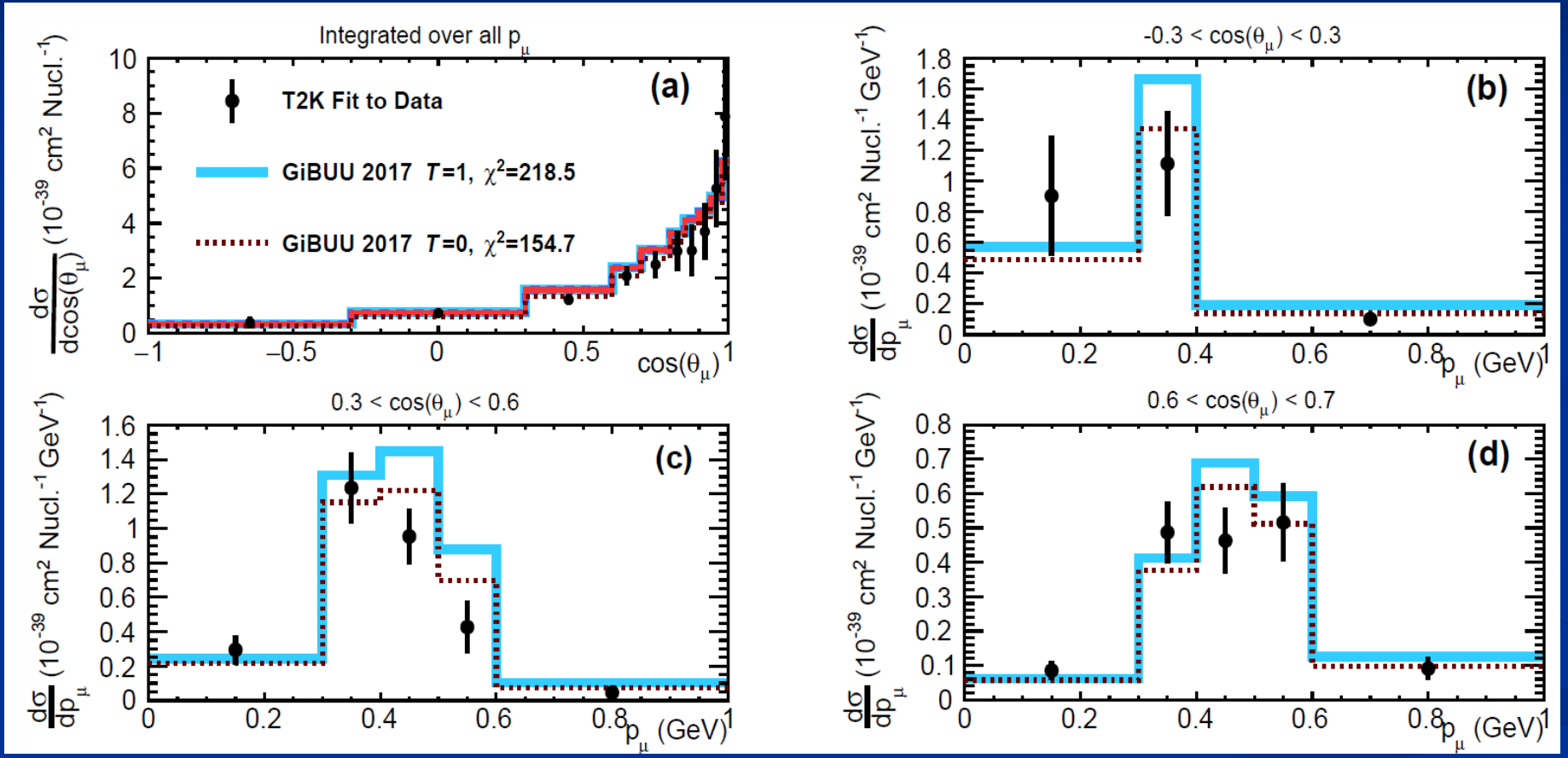
T2K Inclusive Cross Section



Target: CH

S. Dolan et al, Phys. Rev. C 98, 045502 (2018)

GiBUU curves differ by factor 2 in 2p2h

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Intermediate Summary: QE + 2p2h

- QE + 2p2h cross sections (miniBooNE) as well as fully inclusive ones described quite well with GiBUU ‚out of the box', no special tune

- Now: 0-Pion Events

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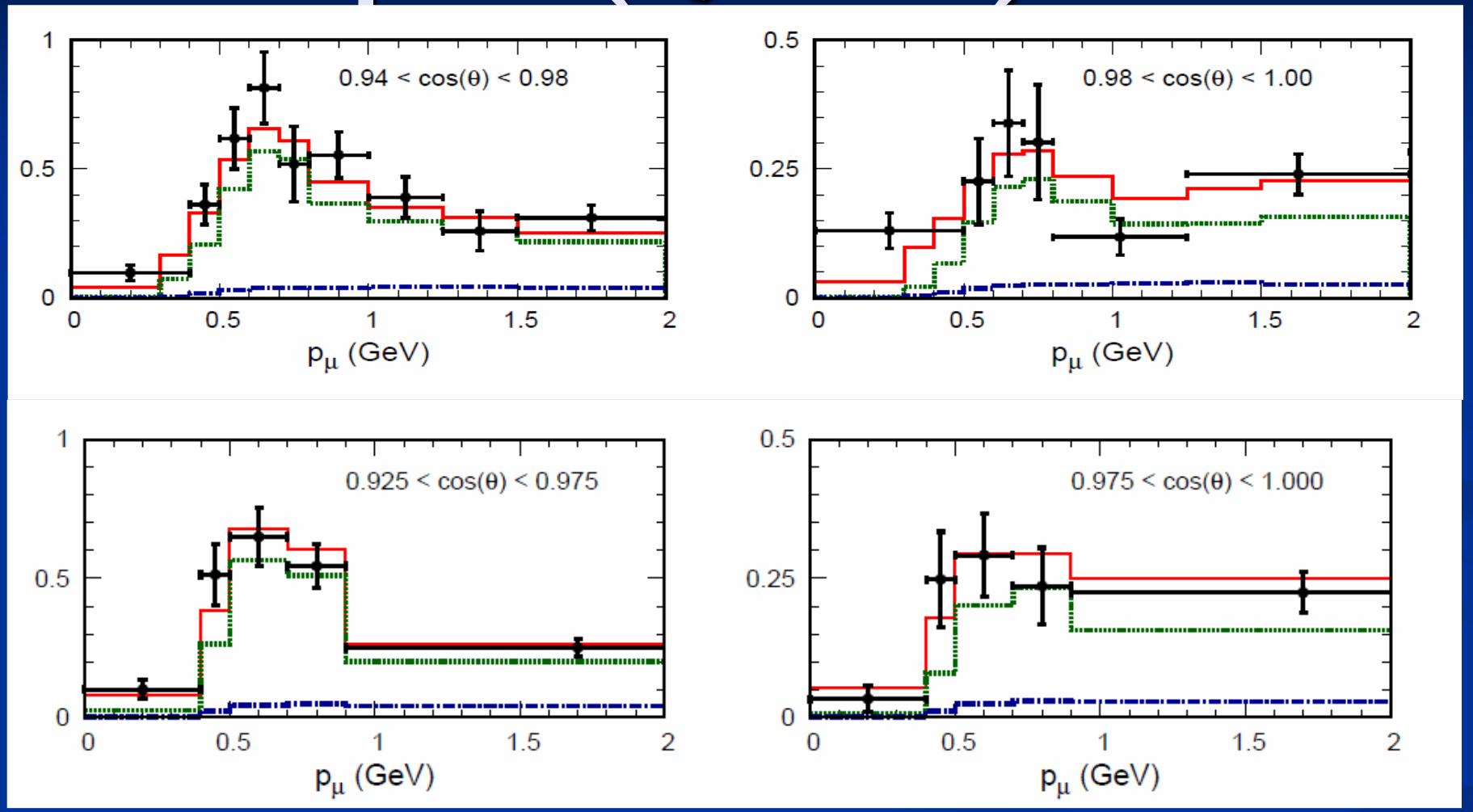
0-pion (QE-like) Events

- CH
- H2O



T2K H2O data ,Phys. Rev. D 97, 012001 (2018), GiBUU calculation: Phys.Rev. C97 (2018) no.4, 045501

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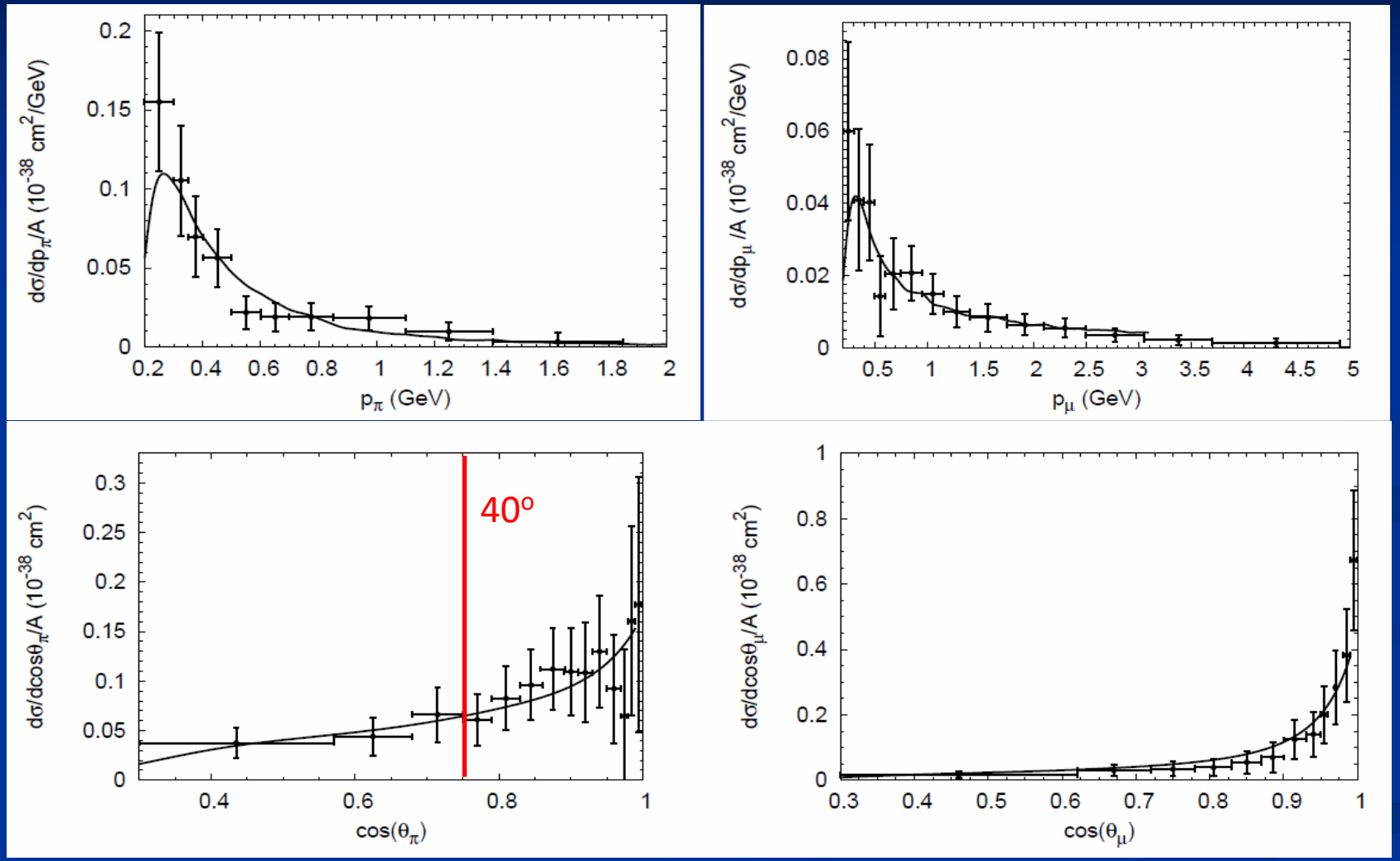
Intermediate Summary: 0-pion events

- 0-pion (QE-like events) are described by GiBUU quite well 'out of the box' . They always contain effects of pion production and absorption, any theory (or generator) for 0-pion must contain these processes!

➔ Inclusive theories without these degrees of freedom
(e.g. scaling approach, GFMC, …)
cannot directly be compared with any experiment,
need additional theory input

- Now: Pions

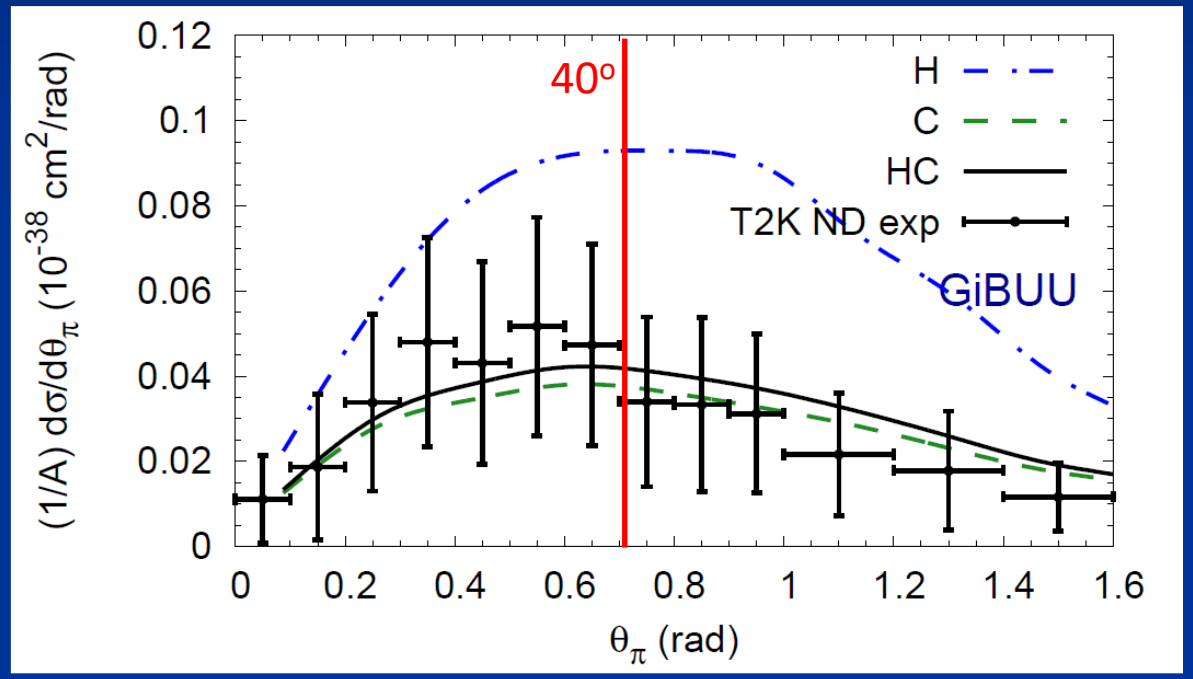
T2K Pi+ on H2O

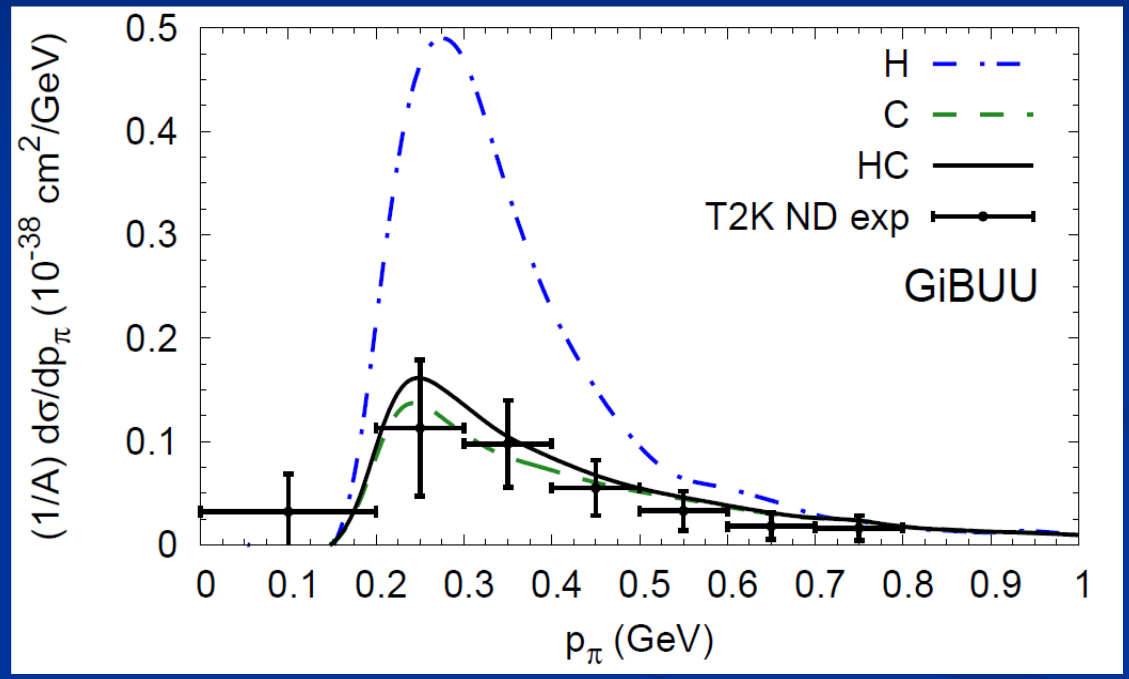


H_2O target

Mosel, Gallmeister,
Phys.Rev. C96 (2017) 015503

T2K ND Pion on HC





Data: T2K,
R. Castillo Fernandez
Barcelona thesis 2015

Calc: GiBUU, arXiv:1708.04528

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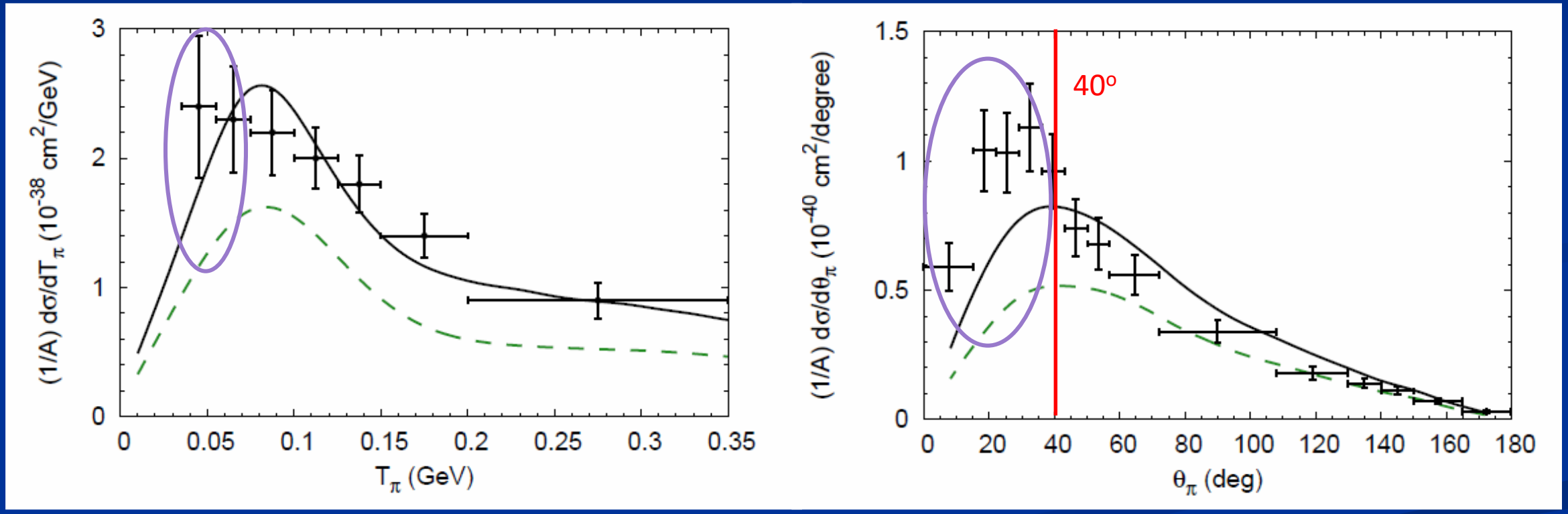
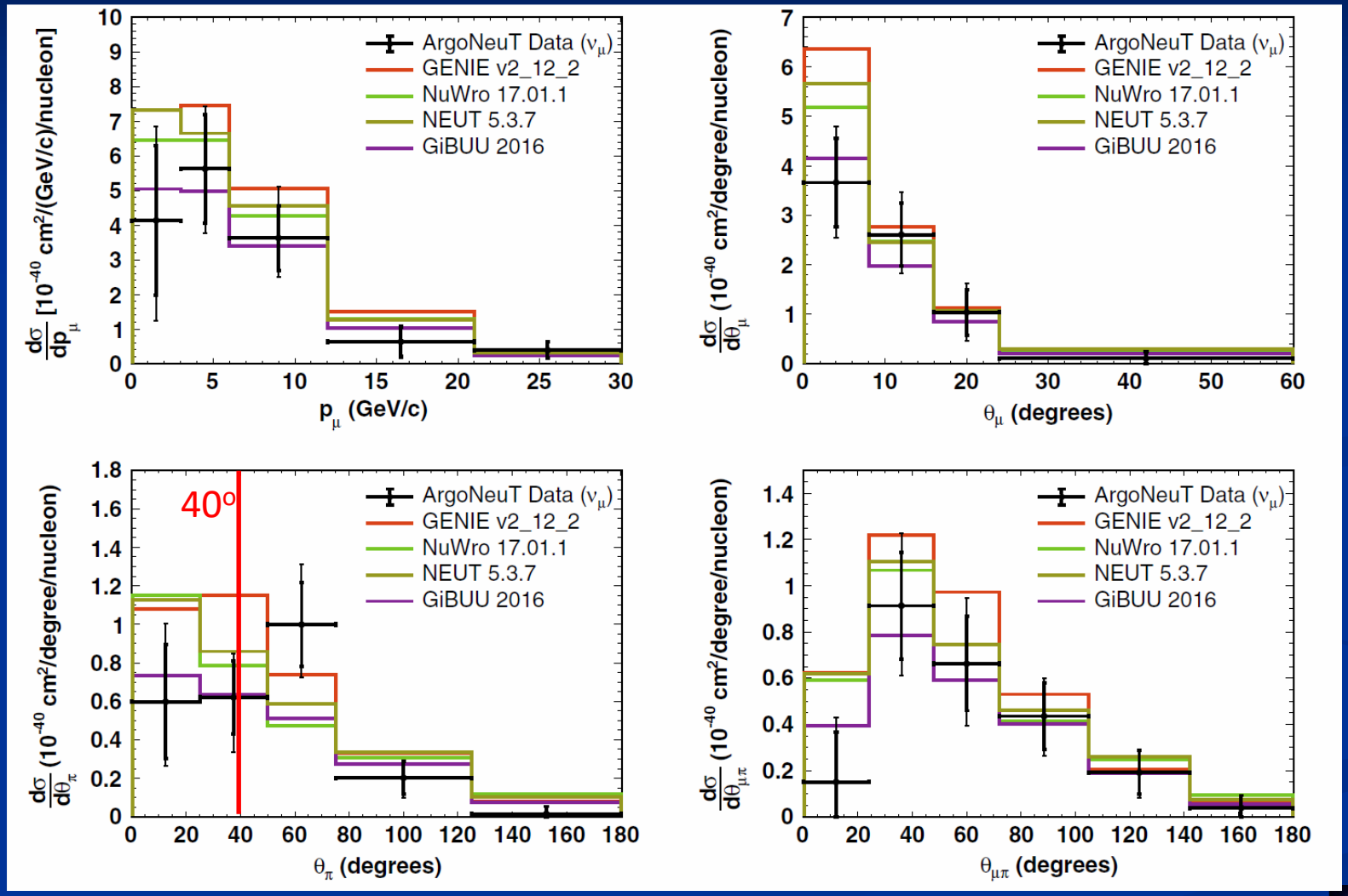
MINERvA Pions

CC charged pions on CH, W < 1.8 GeV, multiple pions



Data: McGivern et al, Phys. Rev. D94, 052005 (2016) GiBUU calc: Phys.Rev. C96 (2017) 015503

$\pi^{+/-}$ Production on LAr



ArgoNeut

Phys.Rev. D98 (2018) 052002

Neutrinos

Excellent agreement of GiBUU with Ar data
NO Tune

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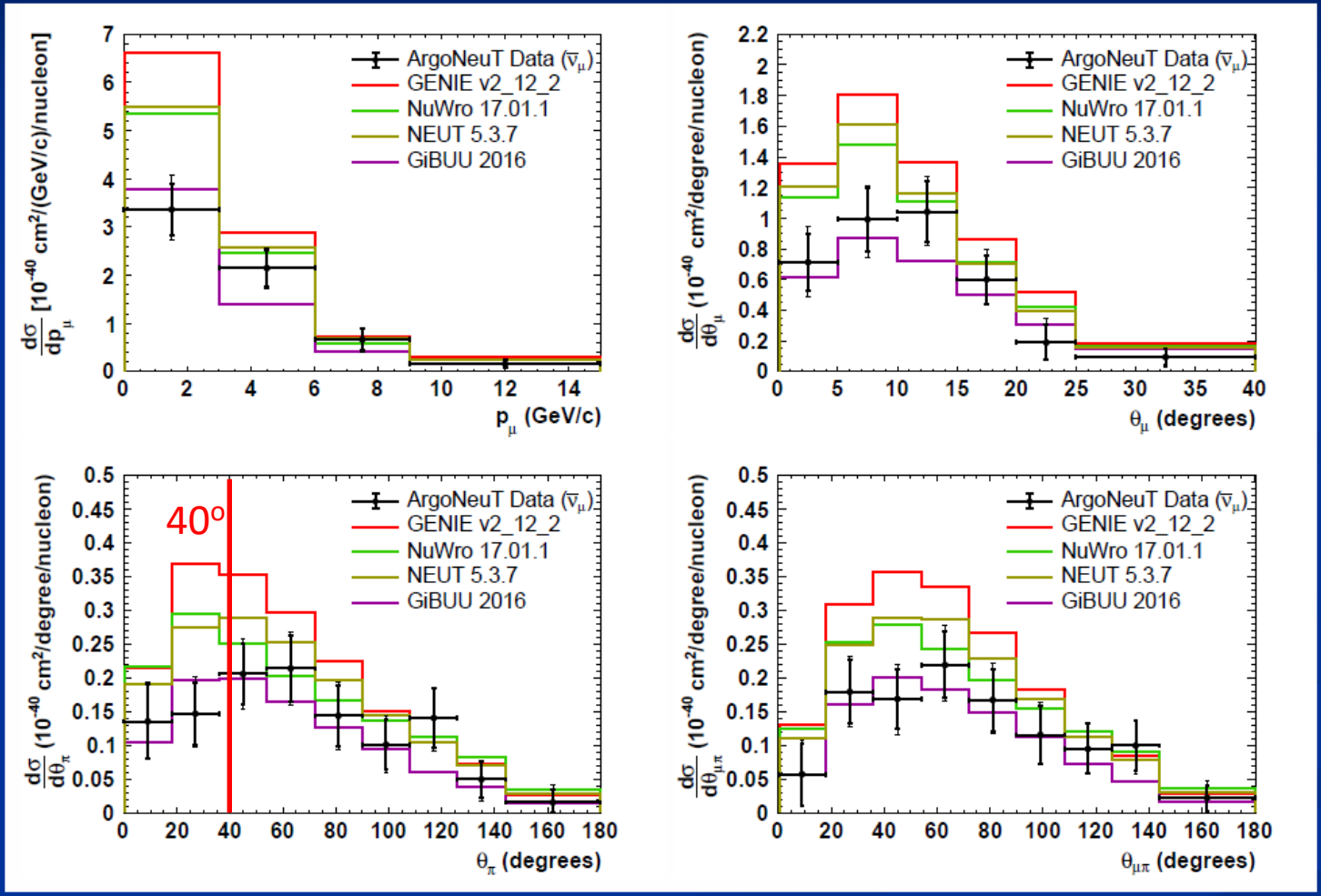
$\pi^{+/-}$ Production on LAr



ArgoNeut

Phys.Rev. D98 (2018) 052002

Antineutrinos

Excellent agreement of GiBUU with Ar data
NO Tune

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Intermediate Summary

- Pion kinetic energy spectra and angular distributions are well described for T2K (C and O targets) and for ArgoNEUT, no special tune
- Pion kinetic energy spectrum for MINERvA quite reasonable, with weak indication of too low X-section at low pion momenta, and clearly low X-section for $\theta < 40$ degrees
  - MINERvA X-section puzzle: data contain generator-produced cuts, *both on flux and on W*, both have to reconstructed!
    -> repeat analysis without flux cuts, replace by cuts on muon kinematics
    if *W* cut, then only on measurable outgoing π-N.

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Challenge: ^{40}Ar (DUNE)

- ^{40}Ar not isospin symmetric, N > Z → T = 2
- What about 2p2h Isospin-dependence?
- Relation of 2p2h to electron scattering process?
- Mass dependence?

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2p2h Theory

- 2p2h X-section assumed to be purely transverse -> only 2 structure functions

$$\frac{d^2\sigma^{2p2h}}{d\Omega dE'} = \frac{G^2}{2\pi^2} E'^2 \cos^2\frac{\theta}{2} \left[2W_1^\nu \left(\frac{Q^2}{2q^2} + \tan^2\frac{\theta}{2} \right) \mp W_3^\nu \frac{E+E'}{M} \tan^2\frac{\theta}{2} \right] .$$

- W_1 for electrons and neutrinos related by the ‚Lyon relation' (Ericsson, Marteau, Martini et al)

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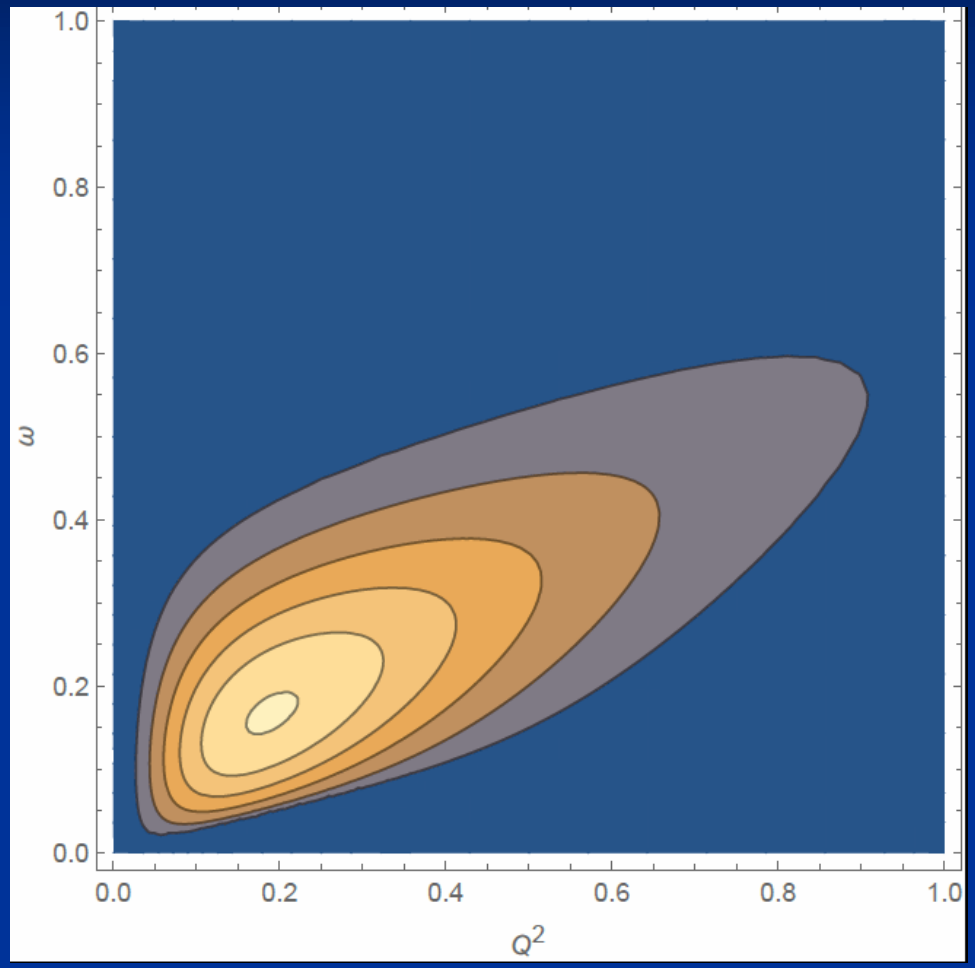
2p2h Theory: Structure Functions



W_1

W_1 from data analysis
of Bosted and Christy
for wide kinematical range
$0 < W < 3.2$ GeV
and $0.2 < Q^2 < 5$ GeV^2

Ericsson, Marteau, Martini:

$$W_1^e = G_M^2 \frac{\omega^2}{\mathbf{q}^2} R_T^e$$

$$W_1^\nu = \left(G_M^2 \frac{\omega^2}{\mathbf{q}^2} + G_A^2 \right) R_T^e \, 2(\mathcal{T}+1)$$

From Wigner-Eckart theorem (Walecka)

2p2h Theory: Isospin dependence

- W_1 and W_3 related by ‚Walecka relation'

$$W_3^{\nu} = 2 G_A G_M \, R_T^e \, 2(\mathcal{T}+1)$$

$\mathcal{T}$ = isospin of target

Crucial assumption:

neutrinos and electrons populate final states that are isobaric analogues:

- for 1p1h excitations experimentally verified as seen in comparing the QE peaks
- For 2p2h excitations:
  - T2K data have clear preference for T = 0 (Dolan et al),
  - MINERvA data have T=0 and T=1 close by, with slight preference for T=1
- Big factor for Ar40: T=2 for Ar, T= 0 for C → factor 3 for Ar, compared to C

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2p2h Theory: A-dependence

- A-dependence? Two extremes:
  - If 2p2h is long-range interaction, then $P_{NN} \sim A^2$
  - If 2p2h is zero-range interaction, then (naively) $P_{NN} \sim A$
  - More sophisticated zero-range: $$P_{NN} = \int \mathrm{d}^3 r\, \rho^2(\mathbf{r}) = A \langle \rho \rangle$$

➔ $$P_{NN}(A) = 0.145A - 0.147A^{2/3} \quad (\mathrm{fm}^{-3})$$

Surface effect:
Mosel, Gallmeister: Phys.Rev. C94 (2016) 034610

P_{NN}(Ar40) / P_{NN}(C12) = 4.2 instead of 3.3 due to surface effect

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GiBUU Summary

- GiBUU is a (nearly) consistent theory and code framework for $e + A$ and $\nu + A$ reactions
- GiBUU is not tuned to data, but tries to learn from comparison with data, all results were obtained with the code ‚out of the box'
- GiBUU works with bound nucleons in a mean-field potential, minimizing effects of RPA and no need to worry about binding energy parameters
- GiBUU works with the same groundstate for all reaction types
  - GiBUU relates neutrino 2p2h processes to electron 2p2h

    Problems: A-dependence, isospin dependence

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GiBUU Summary II

- GiBUU describes the QE+2p2h data from MiniBooNE
  - average mean fields are good enough for flux integrated X-sections
- GiBUU describes the pion-data for T2K (on H2O and CH) and ArgoNeut (Ar40), misses the forward pions for MINERvA on CH2
  (cuts? Coherent?)
- GiBUU describes the 0-pion events on water; pion reabsorption events are essential, in particular at forward directions. Must be contained in any description of 0-pion data.
- For Ar40 the 2p2h contribution is of relatively minor importance for the total inclusive X-section, but has *A*- and *T*-dependence as open problems

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GiBUU

- Essential References:
  1. Buss et al, Phys. Rept. 512 (2012) 1
     contains both the theory and the practical implementation of transport theory
  2. Gallmeister et al., Phys.Rev. C94 (2016), 035502
     contains the latest changes in GiBUU2016
  3. Mosel, Ann. Rev. Nucl. Part. Sci. 66 (2016) 171
     short review, contains some discussion of generators
- The work reported here was done in collaboration with Kai Gallmeister

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Discussion

If you have any questions on this talk send an e-mail to

mosel@physik.uni-giessen.de

Or, if it is of wider interest to the NUSTEC mailing list to get a broader discussion started

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