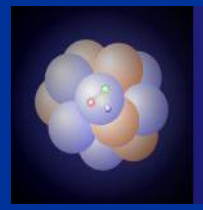
Physics of ν-A Interactions in GiBUU

Ulrich Mosel

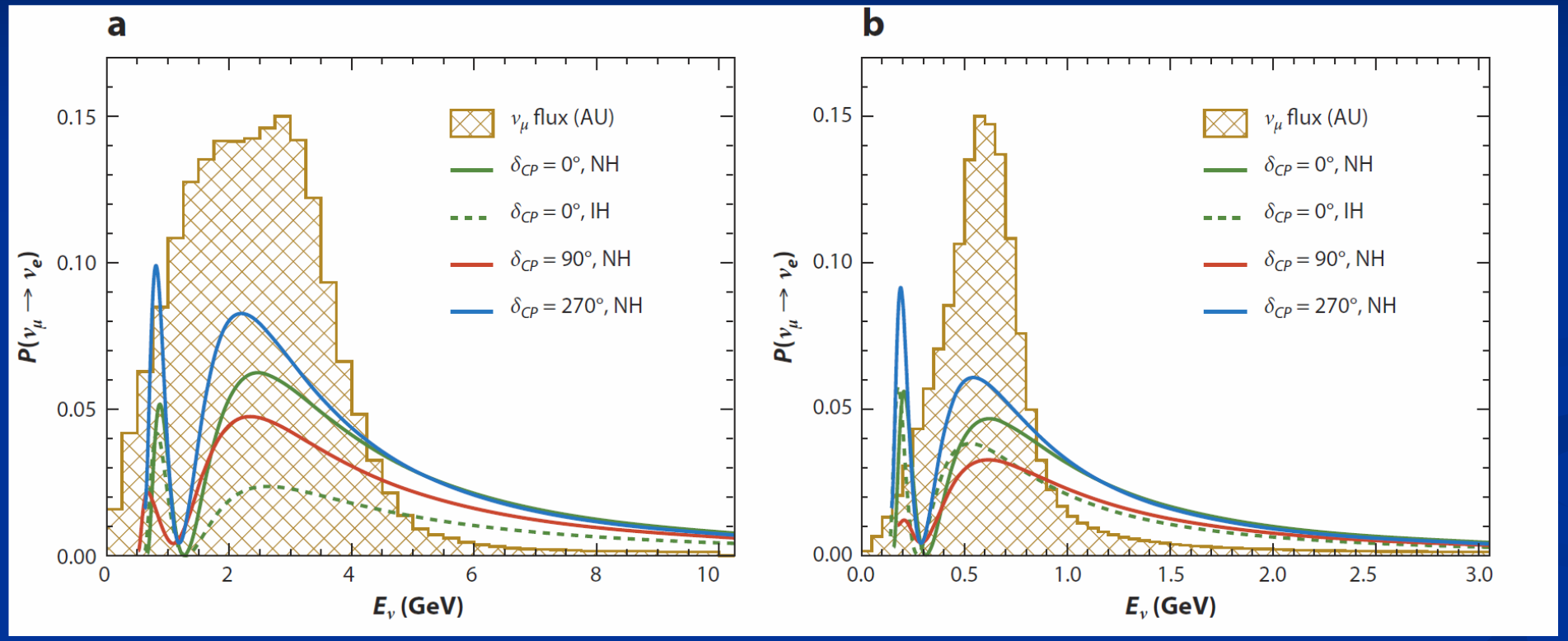


Institut für
Theoretische Physik

JUSTUS-LIEBIG-
UNIVERSITÄT
GIESSEN

Durham 04/2017

Oscillation Signals as $F(E_\nu)$



From:
Diwan et al,
Ann. Rev.
Nucl. Part. Sci 66
(2016)

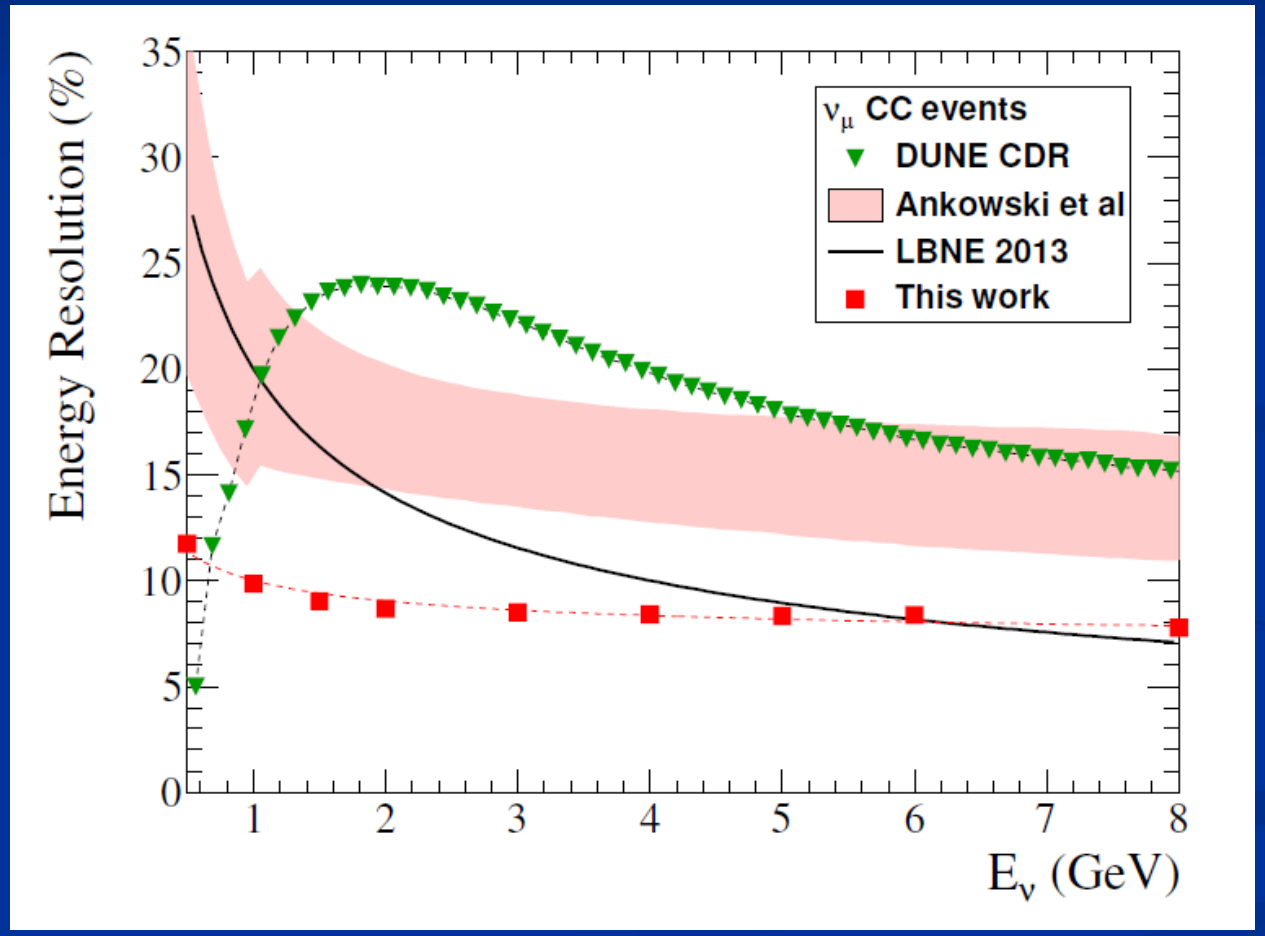
DUNE, 1300 km

HyperK (T2K) 295 km

Energies have to be known within 100 MeV (DUNE) or 50 MeV (T2K)
Ratios of event rates to about 10%

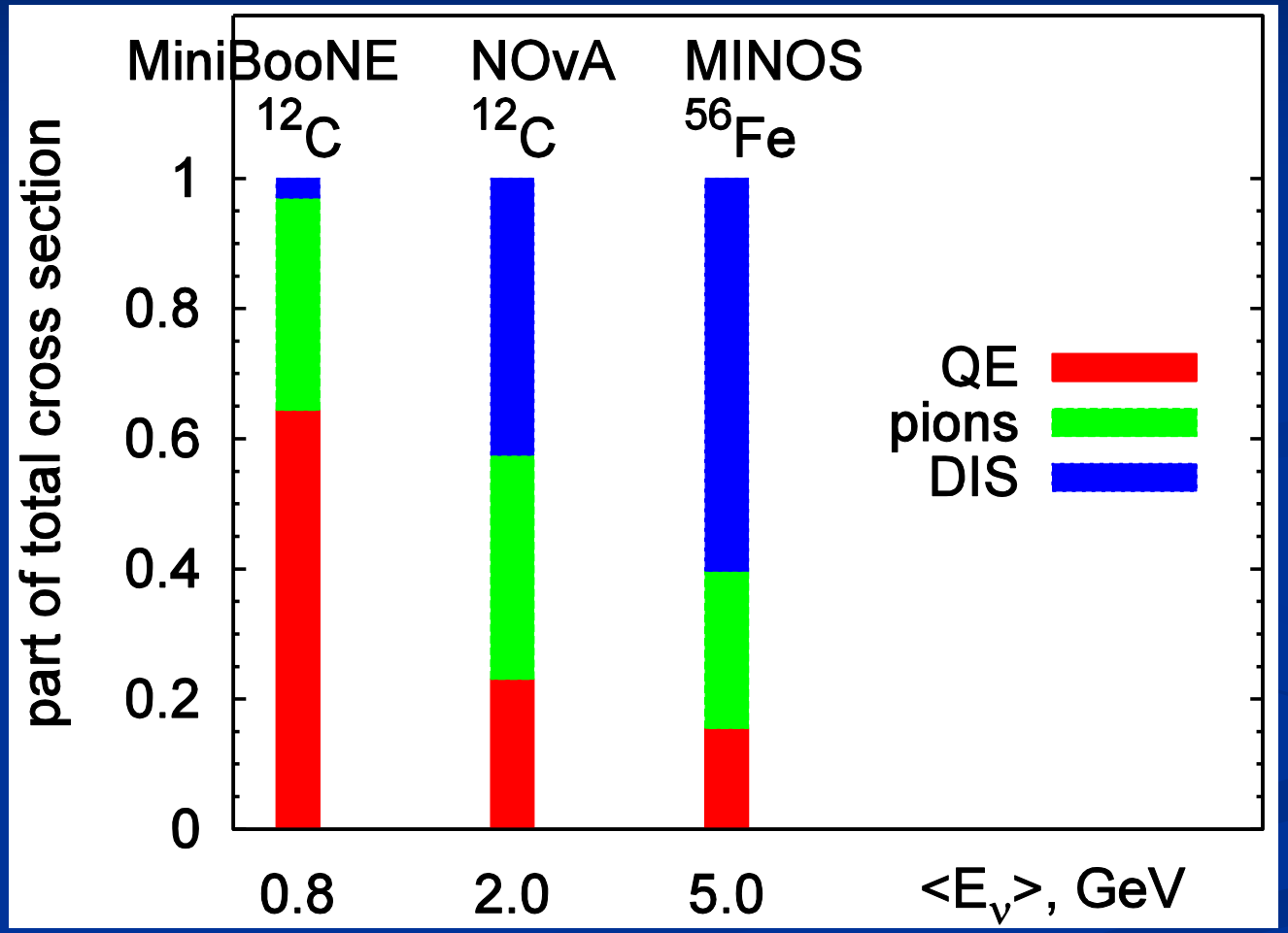
Durham 04/2017

Energy Reconstruction



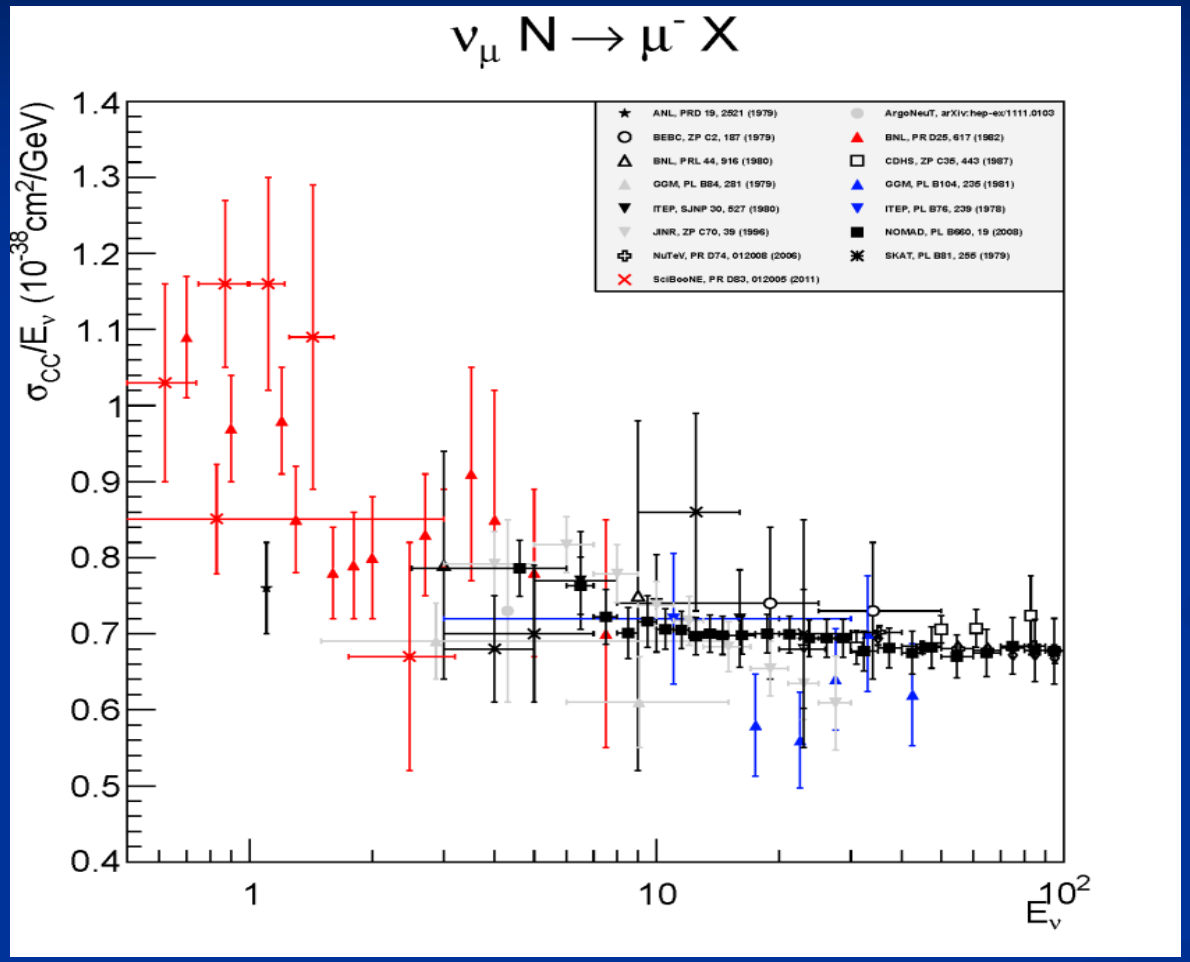
From de Romeri et al, JHEP 1609 (2016) 030

Which Reaction Channels are important ?



Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Neutrino-Nucleon Cross Sections



Experimental error-bars directly enter into nuclear cross sections and limit accuracy of energy reconstruction

BUT: this is only part of the problem, The other part is FSI, since experiments use nuclear targets

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

νA Reaction

- General structure: **approximately** factorizes

full event (four-vectors of all particles in final state)

$\cong$

initial interaction *x* final state interaction

Determines inclusive X-section

Determines the final state particles

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Neutrino Cross Sections: Nucleus

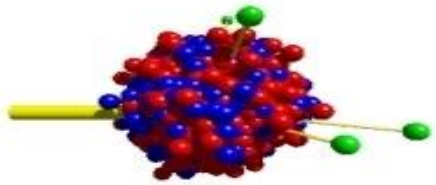
- All targets in long-baseline experiments are nuclei: C, O, Ar, Fe
- Cross sections on the *nucleus*:
  - QE + final state interactions (fsi)
  - Resonance-Pion Production + fsi
  - Deep Inelastic Scattering → Pions + fsi
- Additional cross section on the *nucleus*:
  - Many-body effects, e.g., 2p-2h excitations
  - Coherent neutrino scattering and coh. pion production

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Motivation for GiBUU

- Need the full event for energy reconstruction
- Need to ‚compute backwards' from final state to initial incoming neutrino energy
- Need initial neutrino-nucleon interactions and hadron-hadron final state interactions
- Need to do this in the energy range 0 – 30 GeV

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

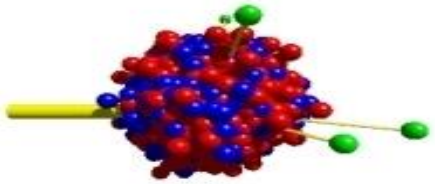


Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- GiBUU was constructed with the aim to encode the „best“ possible theory
- „BEST“ requires
  - All neutrino energies, -> relativistic from outset, includes resonances and DIS
  - All targets
  - Not just inclusive X-sections, but full events
  - Reasonable bound nuclear ground states



Institut für Theoretische Physik, JLU Giessen

GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

- *Initial interactions:*
  - Mean field potential with local Fermigas momentum distribution, nucleons are bound (not so in generators!)
  - Initial interactions calculated by summing over interactions with all bound, Fermi-moving nucleons
  - 2p2h from electron phenomenology
- *Final state interaction:*
  - propagates outgoing particles through the nucleus using *quantum-kinetic transport theory*, fully relativistic (off-shell transport possible).
    Initial and final interactions come from the same Hamiltonian.
    CONSISTENCY of inclusive and semi-inclusive X-sections
- Calculations give final state phase space distribution of all particles, four-vectors of all particles ➔ generator

Pions

- Pion production amplitude
  = resonance contrib + background (Born-terms)
- Resonance contrib
  - *V* determined from e-scattering (MAID)
  - *A* from PCAC ansatz
- Background:
  - Up to about Δ obtained from effective field theory
  - Beyond Δ unknown
  - 2 pi BG totally unknown

GiBUU: new in 2016

- Stable groundstate implemented -> improved hole spectral functions
- 2p2h structure function for all kinematics, fitted to e-scattering, is used for neutrinos as well

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

2p2h excitations: from electrons to neutrinos

- 2p2h: purely transverse, response from e-scattering

$$\frac{d\sigma}{d\Omega dE'} = \frac{G^2}{2\pi^2}E'^2\left[\frac{Q^2}{\vec{q}^{\,2}}\left(G_M^2\frac{\omega^2}{\vec{q}^{\,2}}+G_A^2\right)R_{\sigma\tau}(T)\cos^2\frac{\theta}{2}\right.$$
$$+2\left(G_M^2\frac{\omega^2}{\vec{q}^{\,2}}+G_A^2\right)R_{\sigma\tau}(T)\sin^2\frac{\theta}{2}$$
$$\left.\pm 2\frac{E+E'}{M}G_AG_MR_{\sigma\tau}(T)\sin^2\frac{\theta}{2}\right]$$

from: Martini et al.

$R_{\sigma\tau} \sim W_1$ from electron scattering

R from data analysis of Bosted and Christy for $0 < W < 3.2$ GeV and $0.2 < Q^2 < 5$ GeV^2

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Quantum-kinetic Transport Theory for FSI

On-shell drift term

Off-shell transport term

Collision term

$$\mathcal{D}F(x,p) - \mathrm{tr}\left\{\Gamma f, \mathrm{Re}S^{\mathrm{ret}}(x,p)\right\}_{\mathrm{PB}} = C(x,p)\ .$$

$$\mathcal{D}F(x,p) = \{p_0 - H, F\}_{\mathrm{PB}} = \frac{\partial(p_0 - H)}{\partial x}\frac{\partial F}{\partial p} - \frac{\partial(p_0 - H)}{\partial p}\frac{\partial F}{\partial x}$$

H contains mean-field potentials

Describes time-evolution of *F(x,p)*

$$F(x,p) = 2\pi g f(x,p)\,\mathcal{P}(x,p)$$

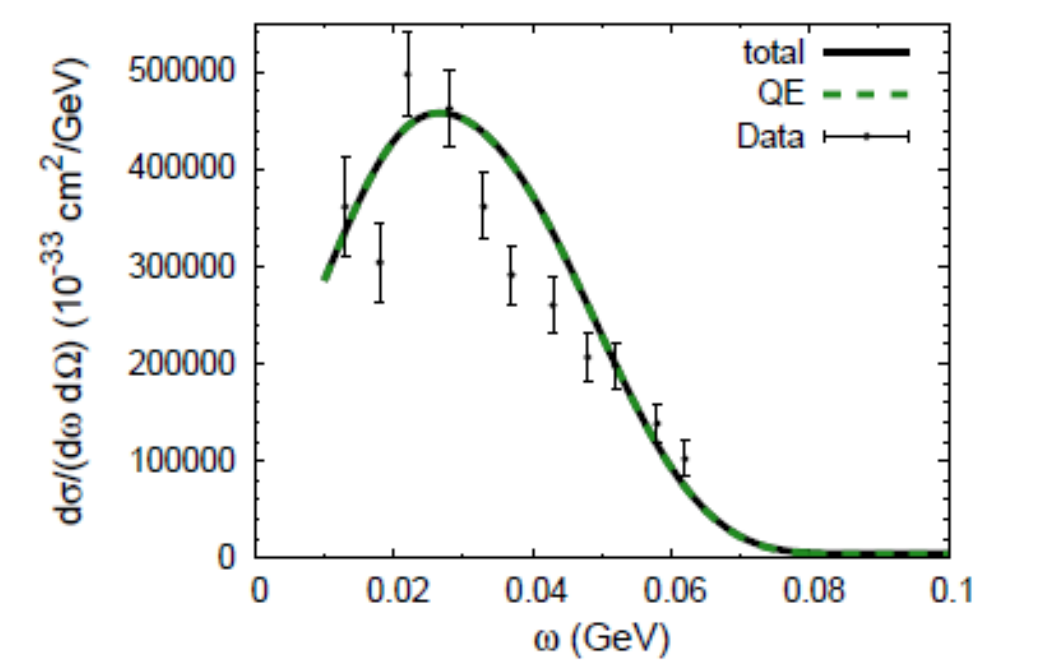
Spectral function

Phase space distribution

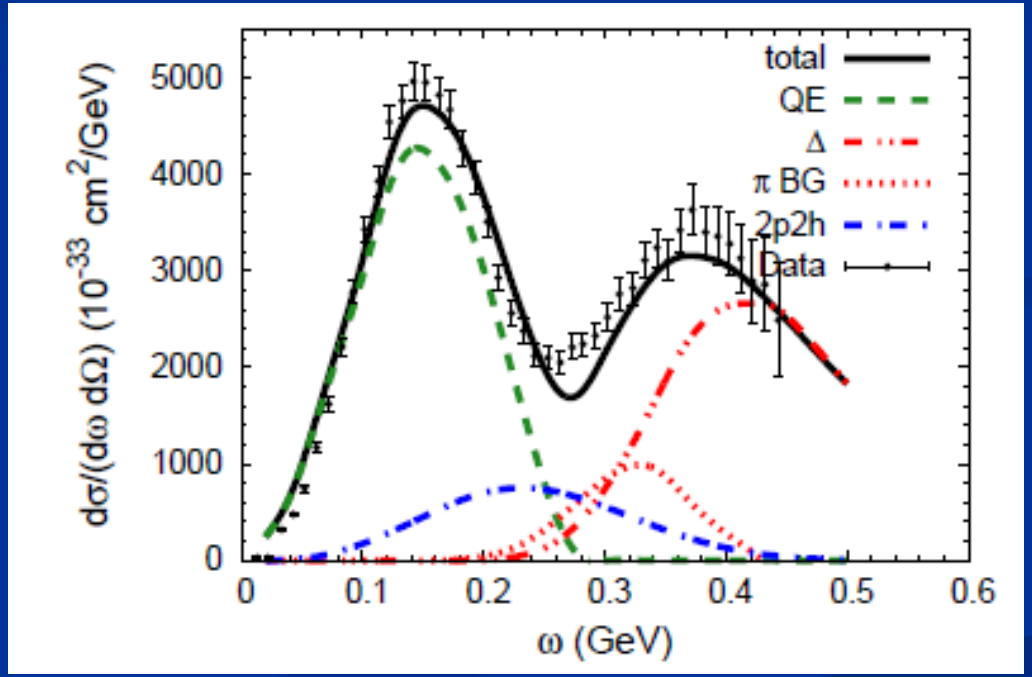
Kadanoff-Baym equations with BM offshell term

Test with Electron Data: QE + Res

- a necessary check for any generator development



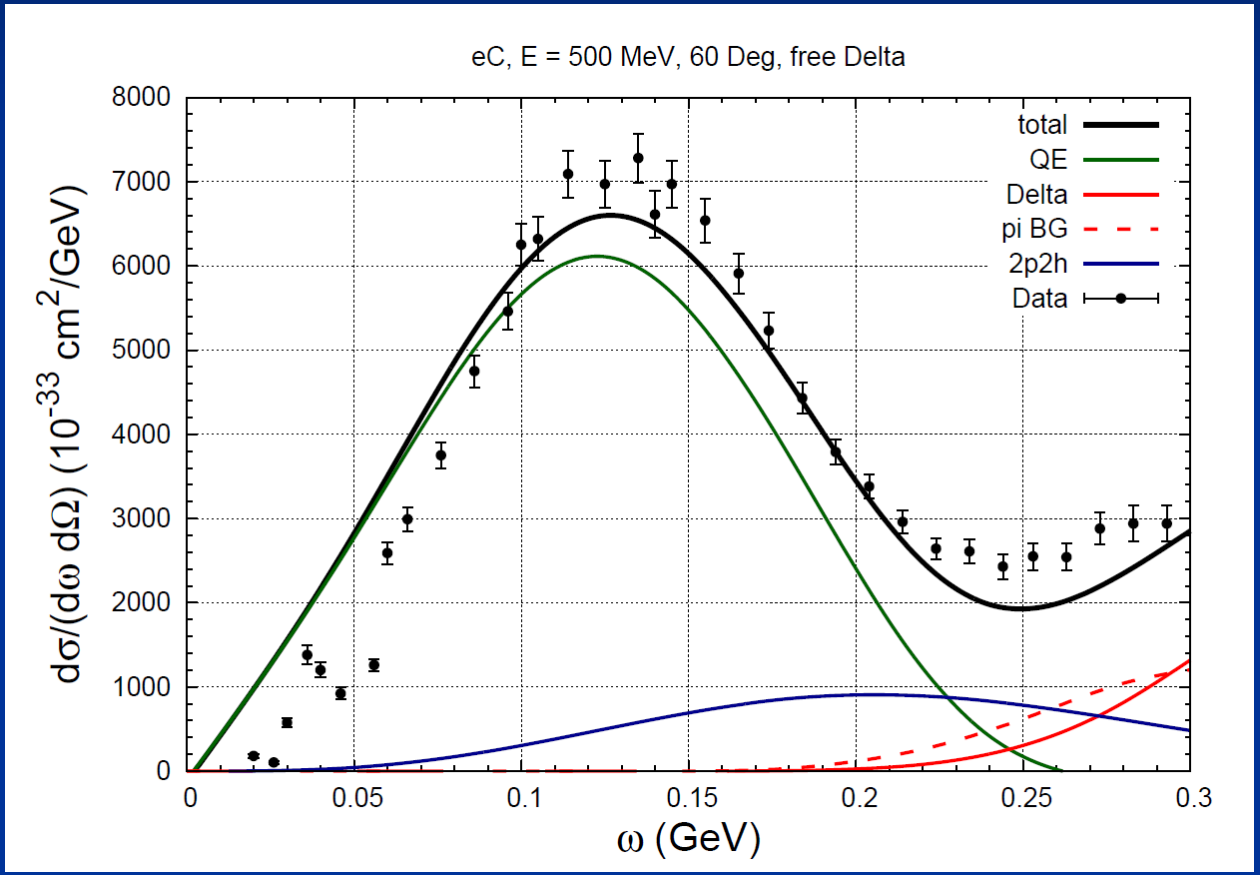
0.24 GeV, 36 deg, $Q^2 = 0.02$ GeV^2



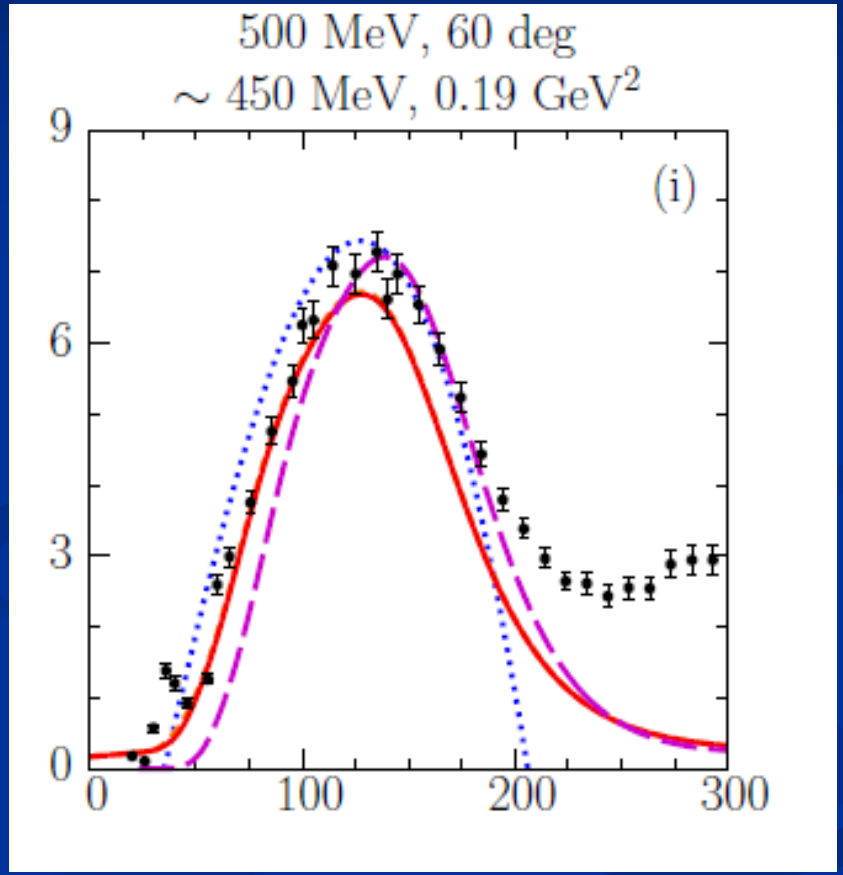
0.56 GeV, 60 deg, $Q^2 = 0.24$ GeV^2

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Test with Electron Data: : QE + Res

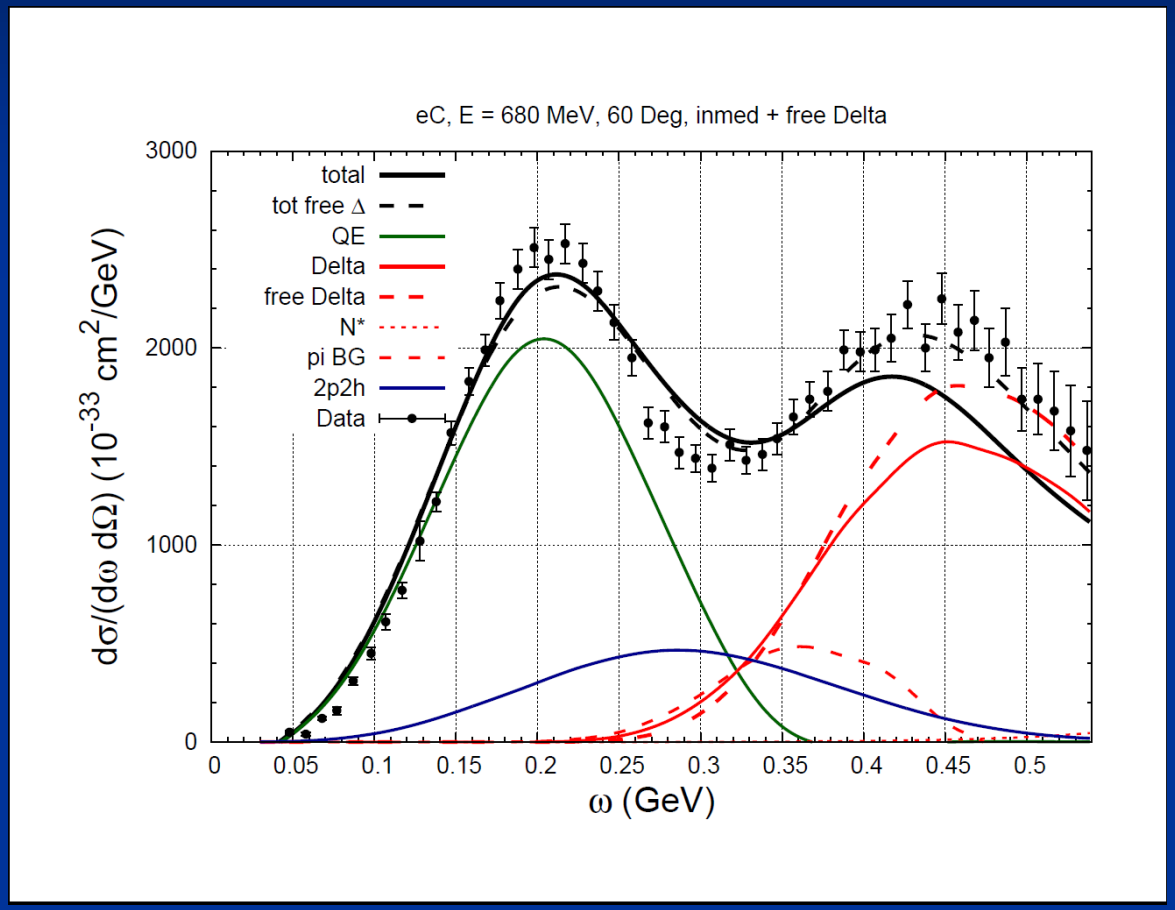


GiBUU 2016

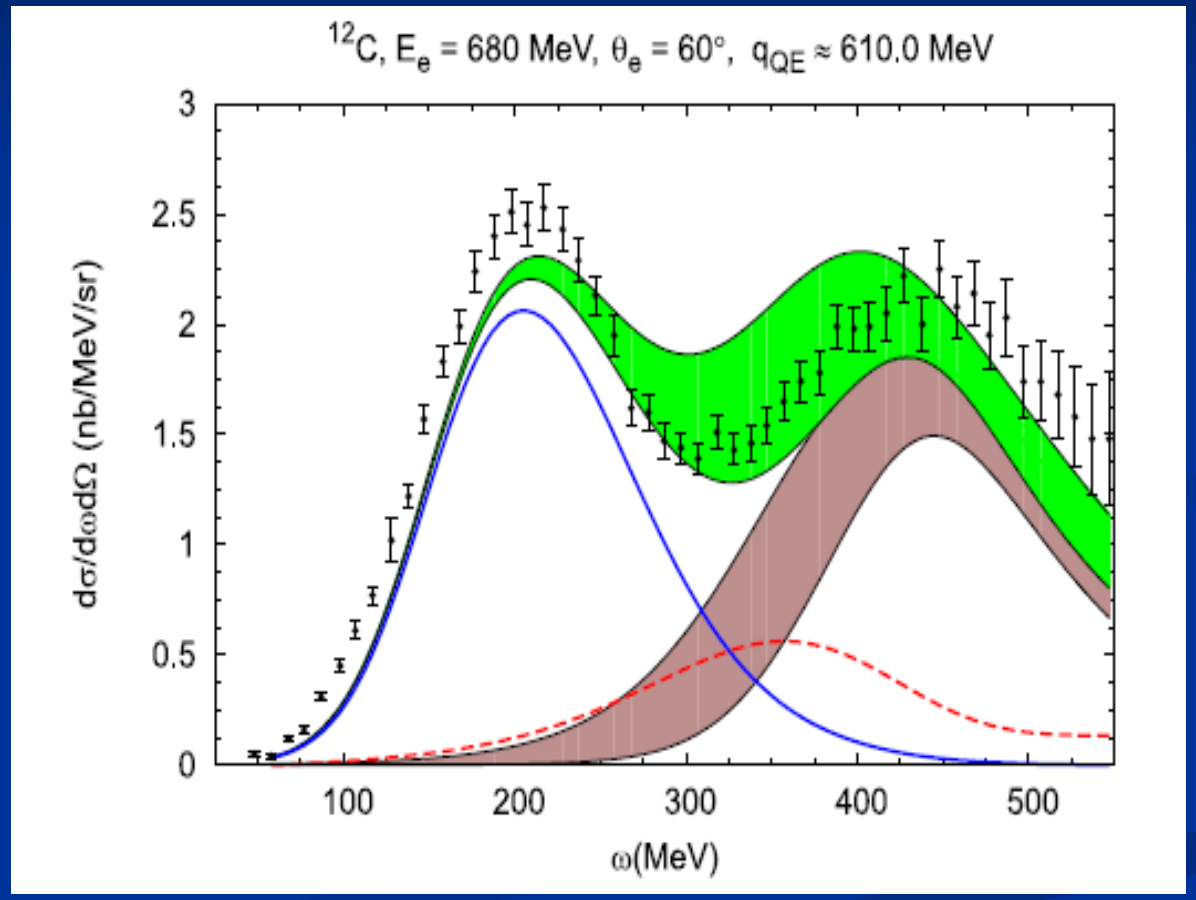


Ankowski. Benhar, Sakuta

Test with Electron Data : QE + Res



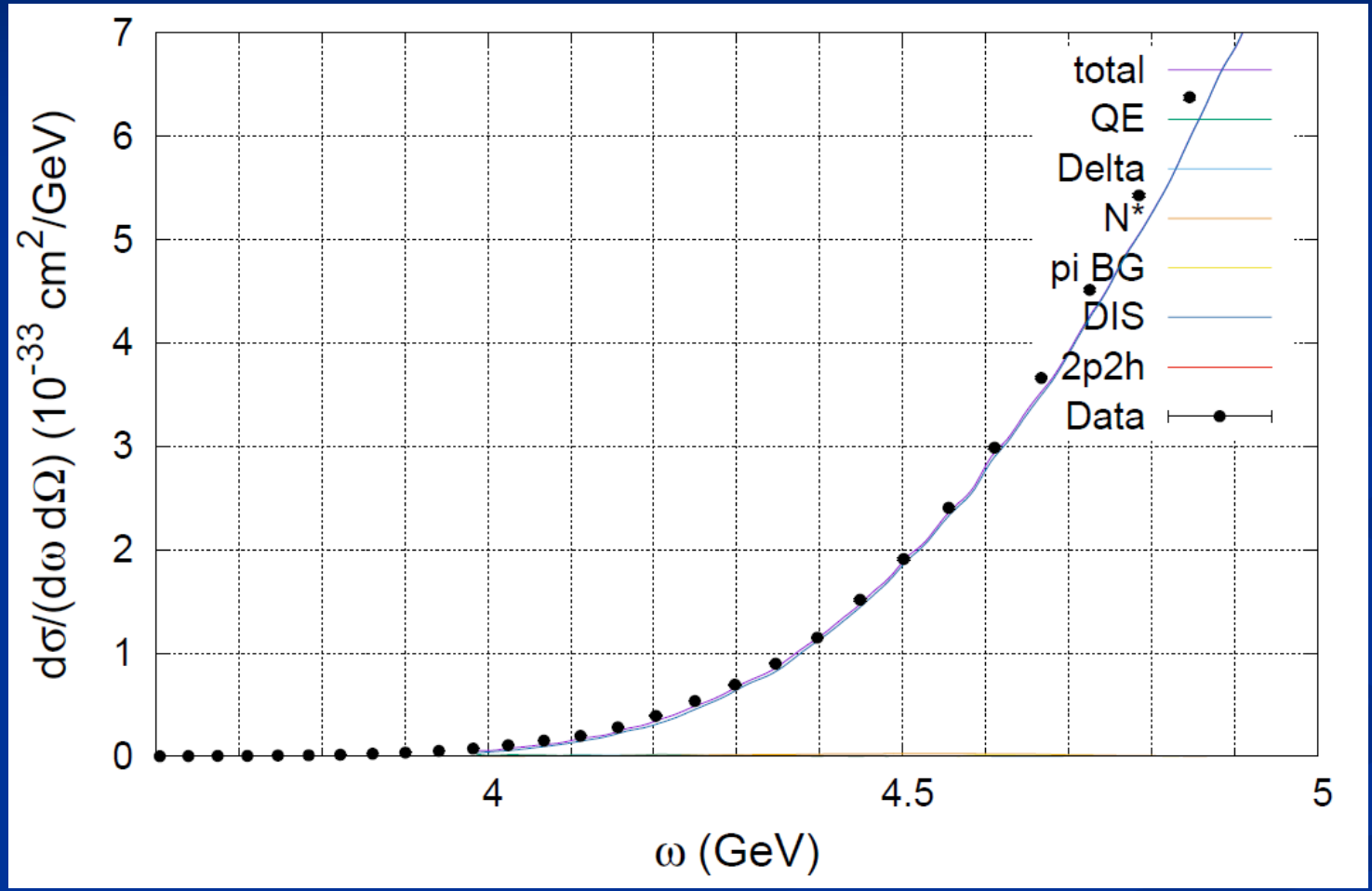
GiBUU



M.V. Ivanov et al, J.Phys. G43 (2016) 045101

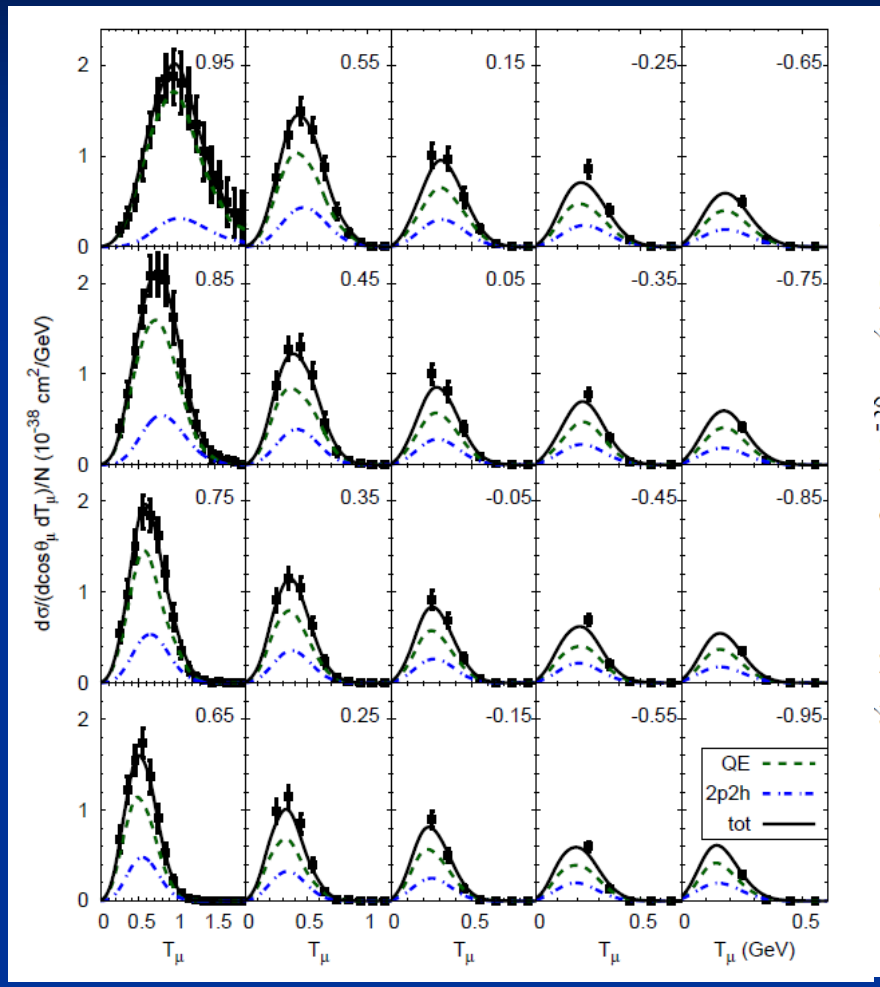
Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Test with Electron Data: DIS

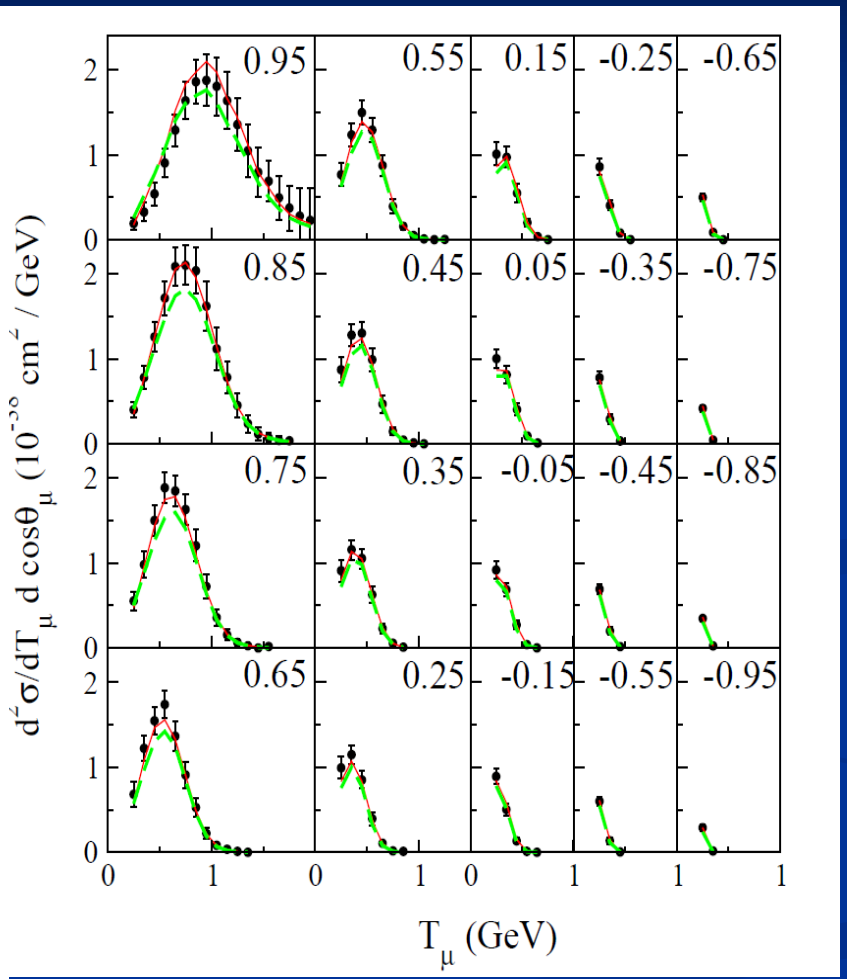


E = 5.766 GeV
Theta = 50 Deg.

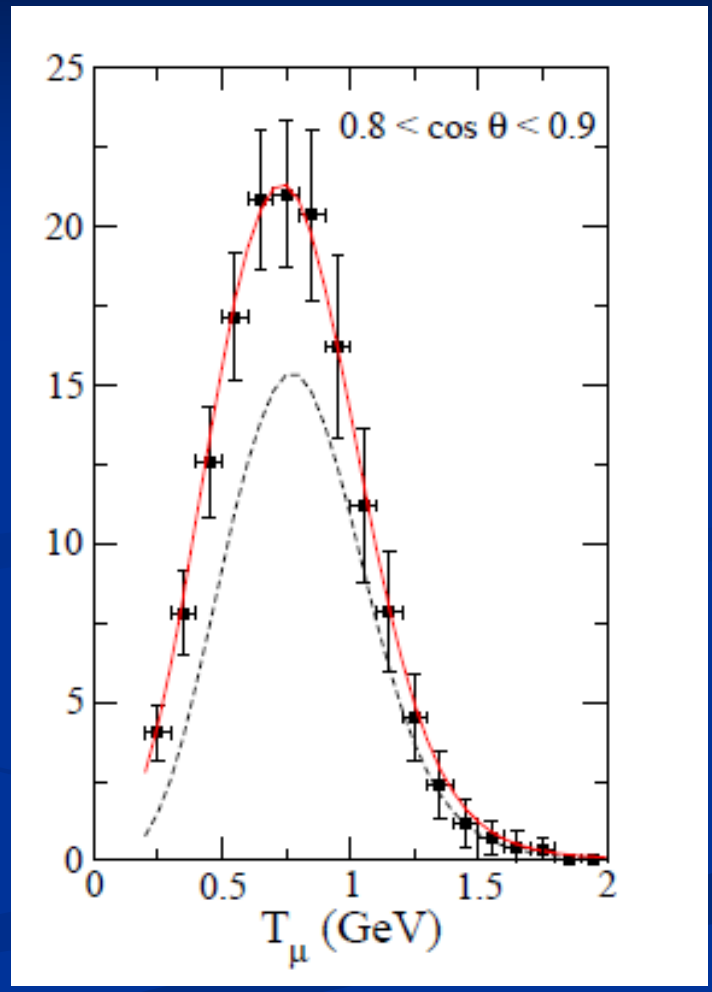
MiniBooNE Neutrinos



GiBUU 2016: no data adjustment



Nieves et al: 10% data adjustment

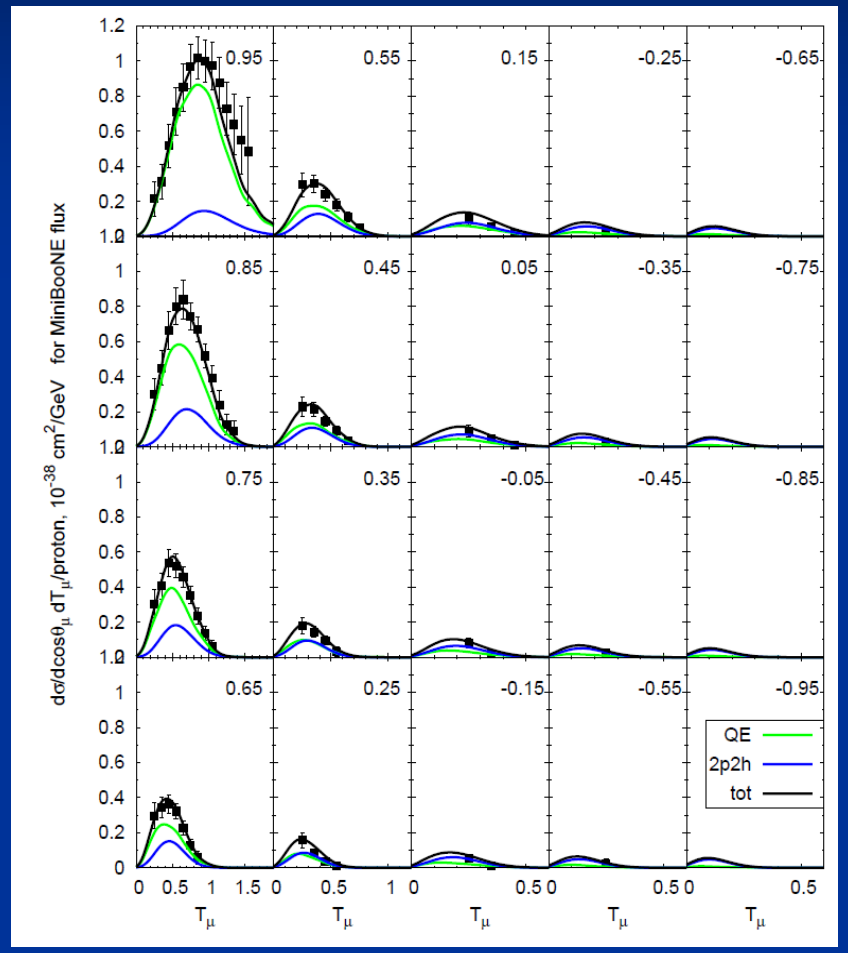


Martini: no data adjust

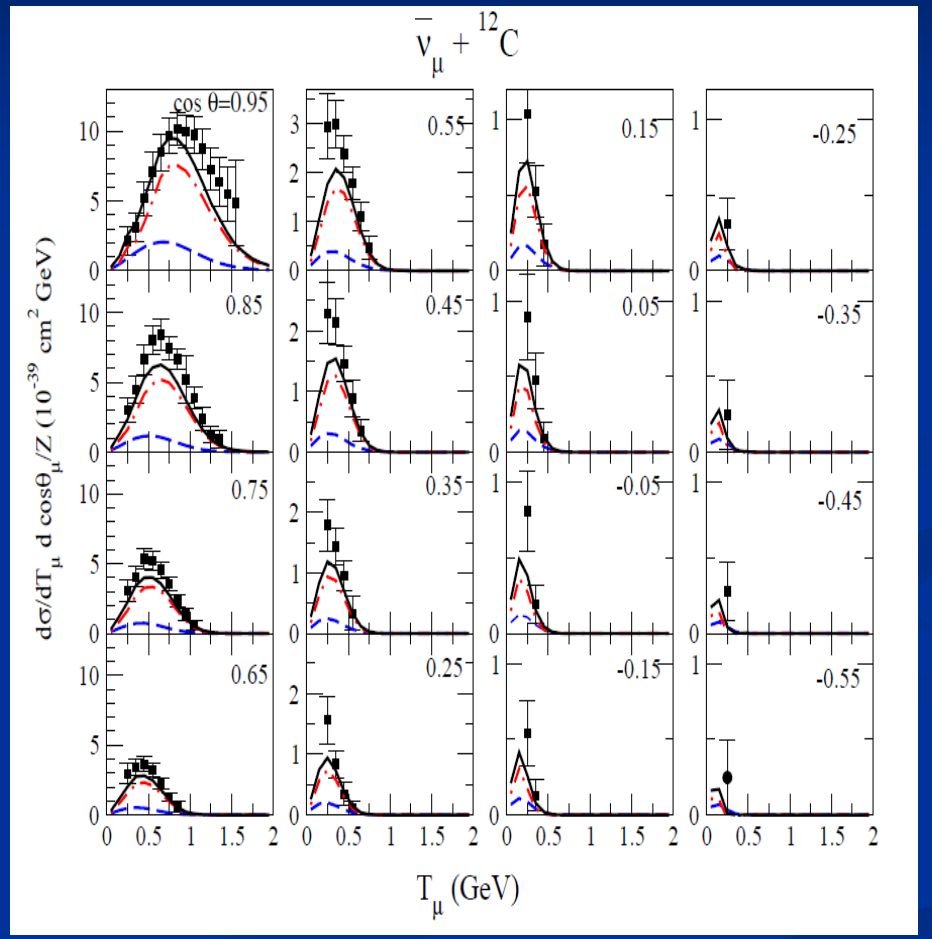
Durham 04/2017

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

MiniBooNE Anti-Neutrinos



GiBUU 2016

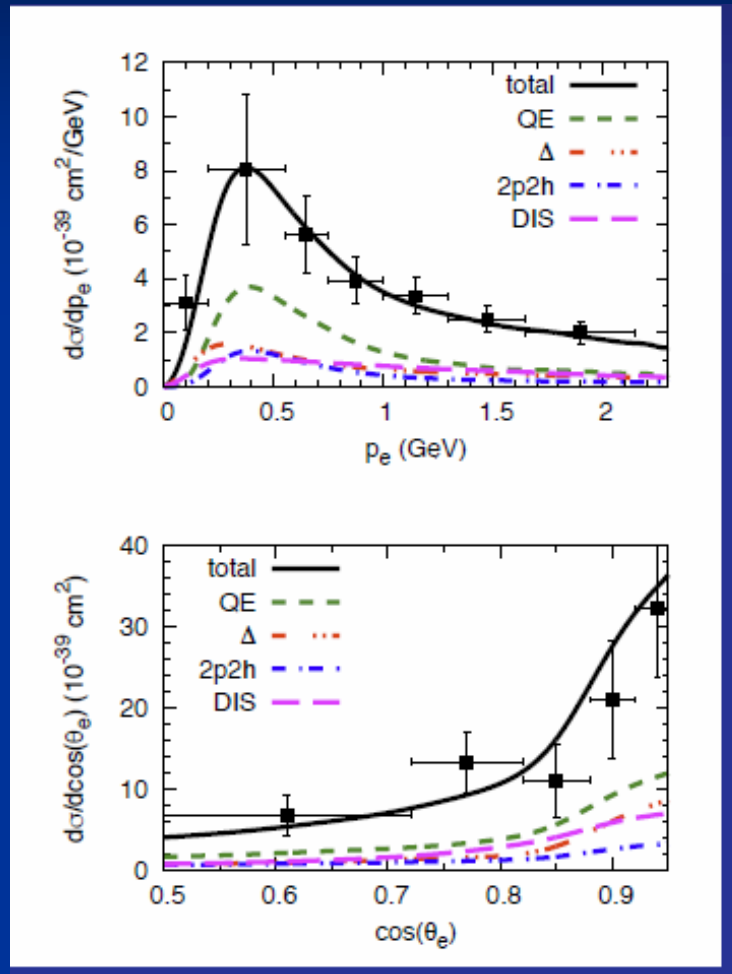


Nieves

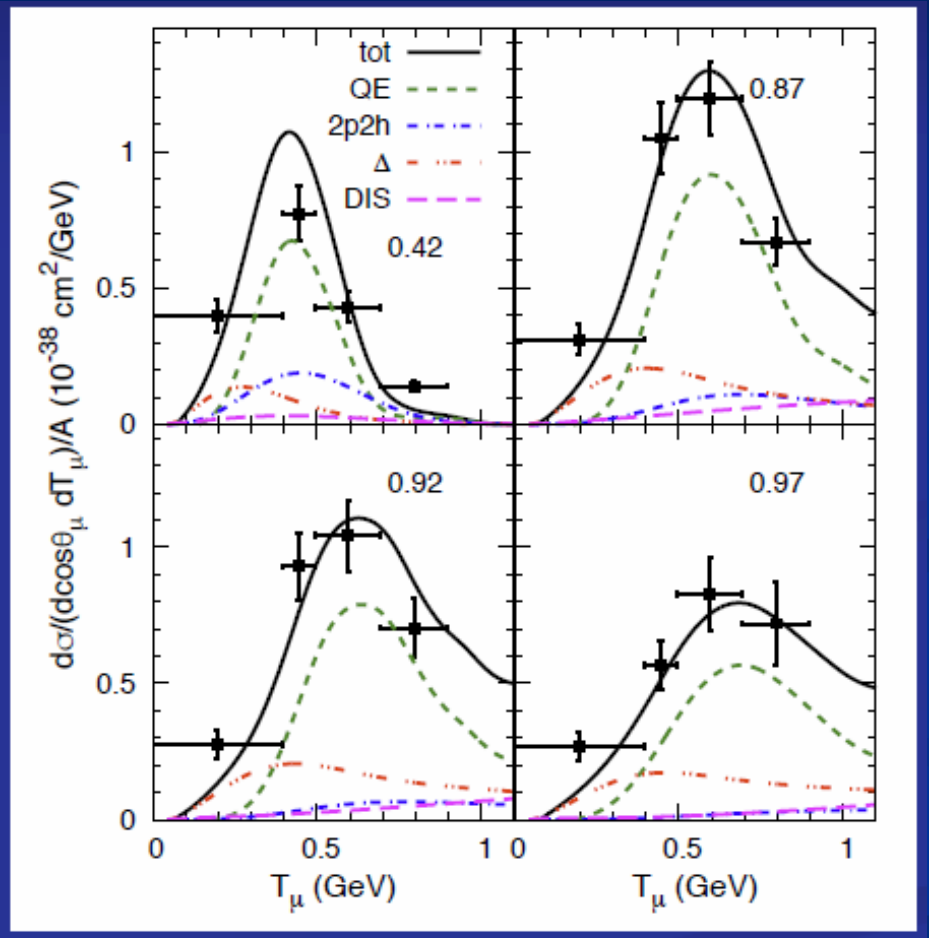
Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Comparison with T2K incl. Data

T2K, ν_e



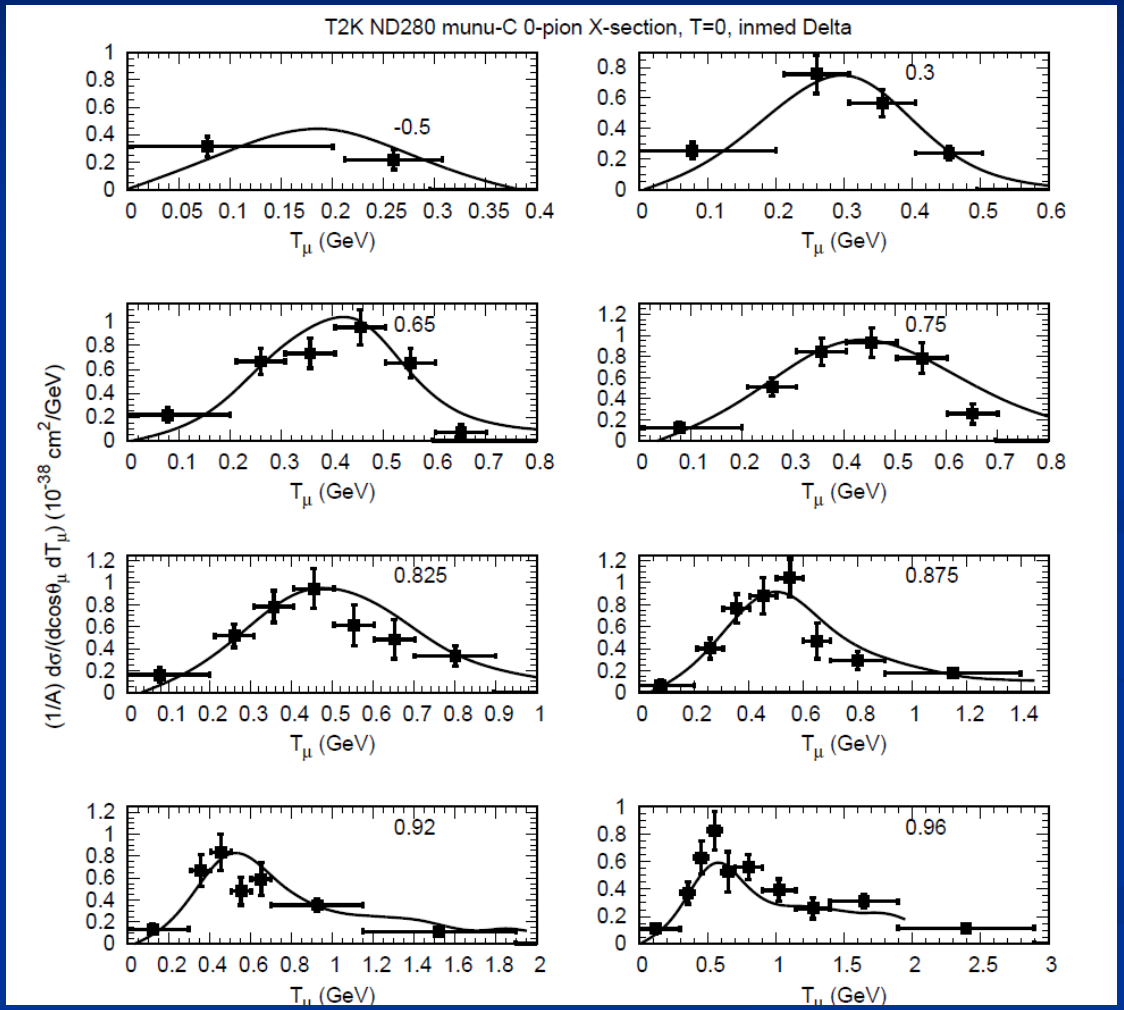
T2K, ν_μ



Agreement for different neutrino flavors

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

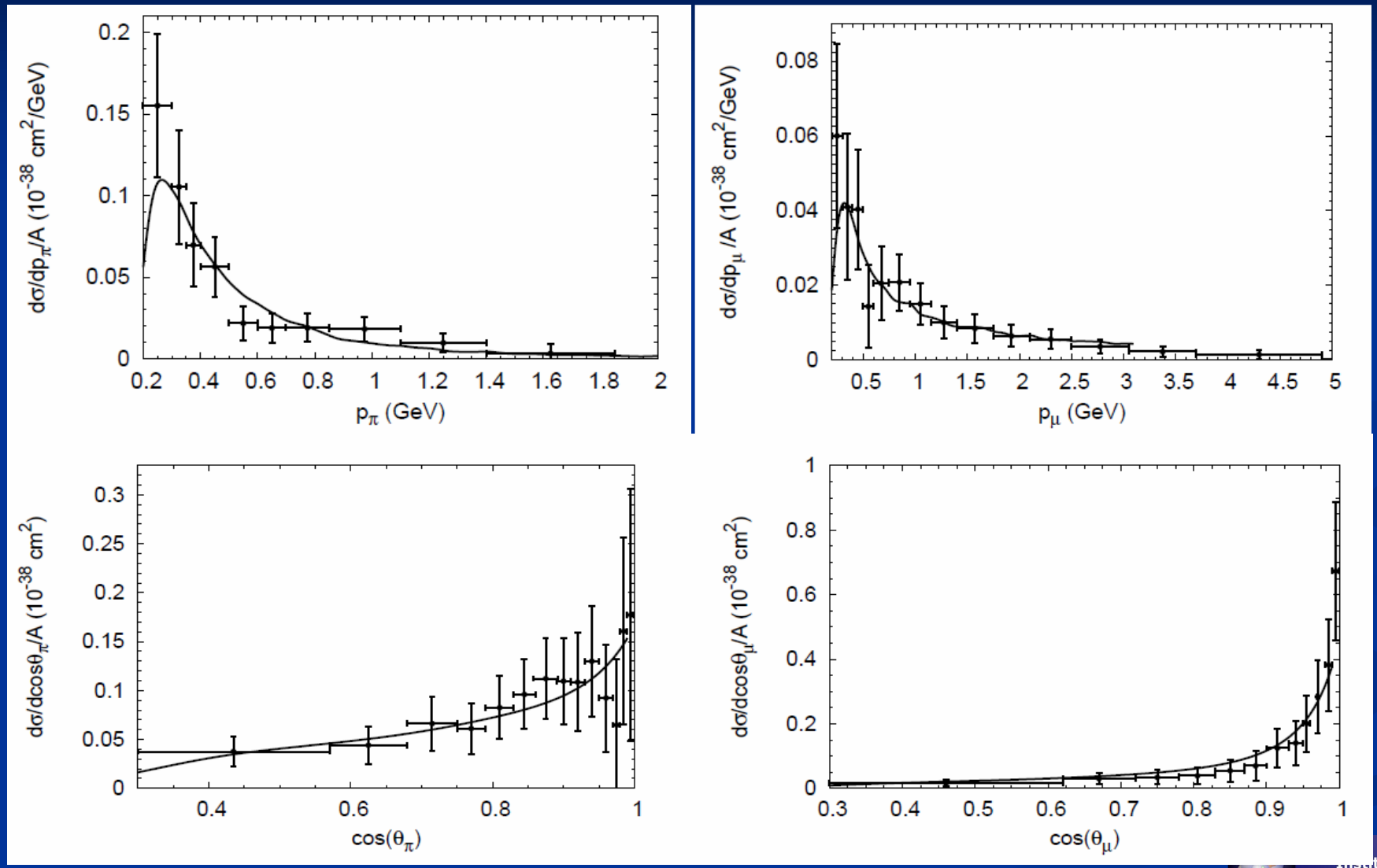
T2K 0pion = QE + 2p2h + stuck pions



Data: T2K ND280

Phys.Rev. D93 (2016) no.11, 112012

T2K ND280 Pions on Water

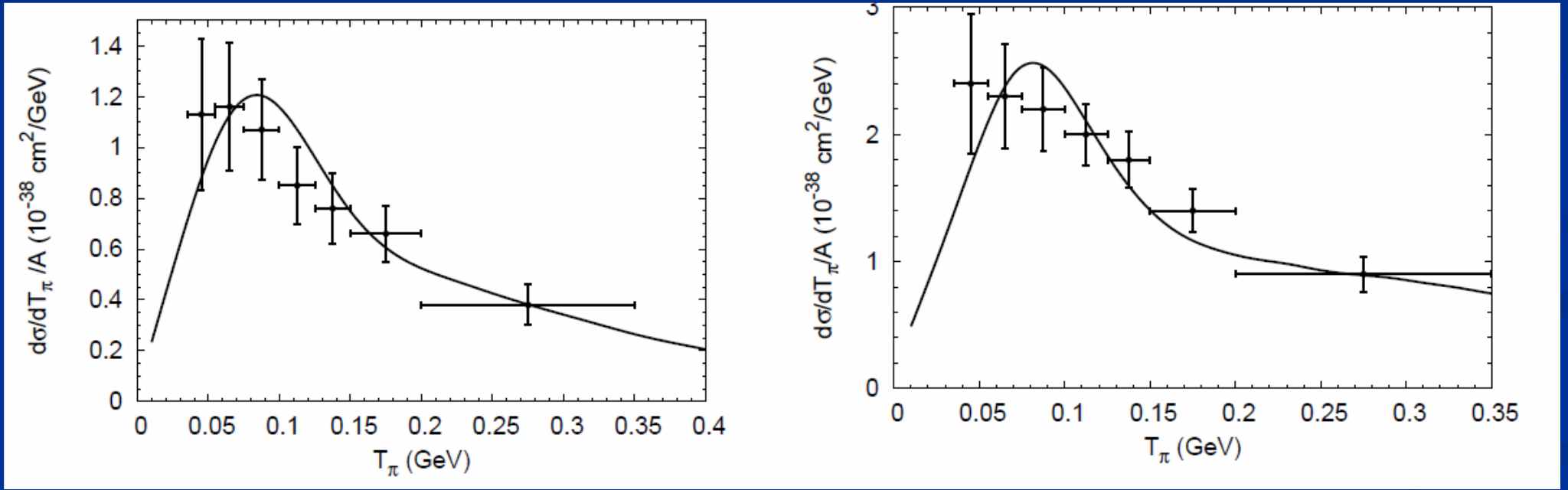


Data: T2K ND

Phys.Rev. D95 (2017) no.1, 012010

MINERvA Pions

CC charged pions

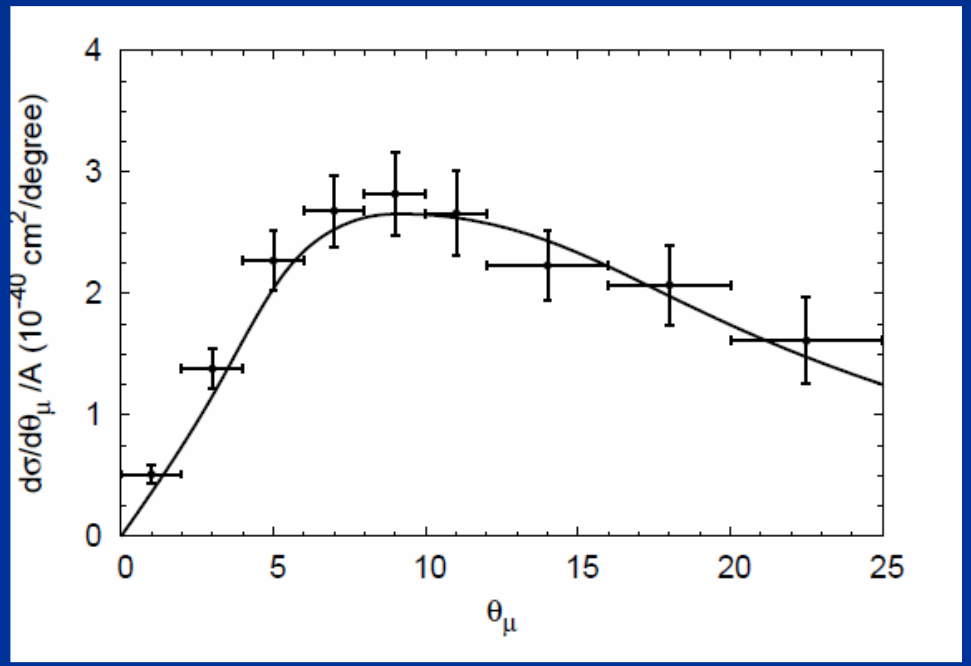


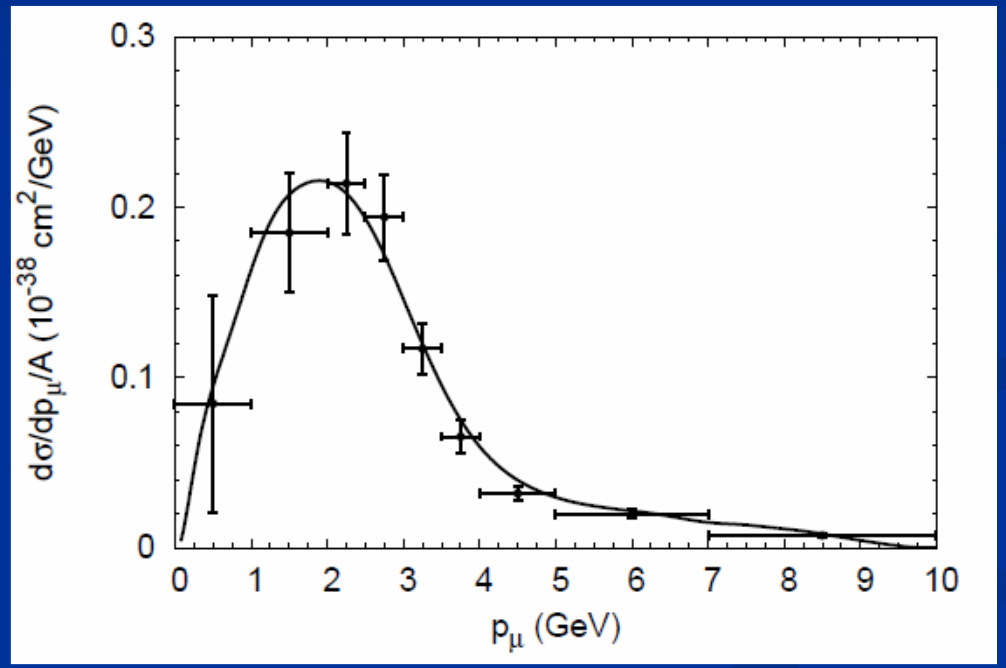
W < 1.4 GeV

W < 1.8 GeV, multiple pions

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

MINERvA Pions

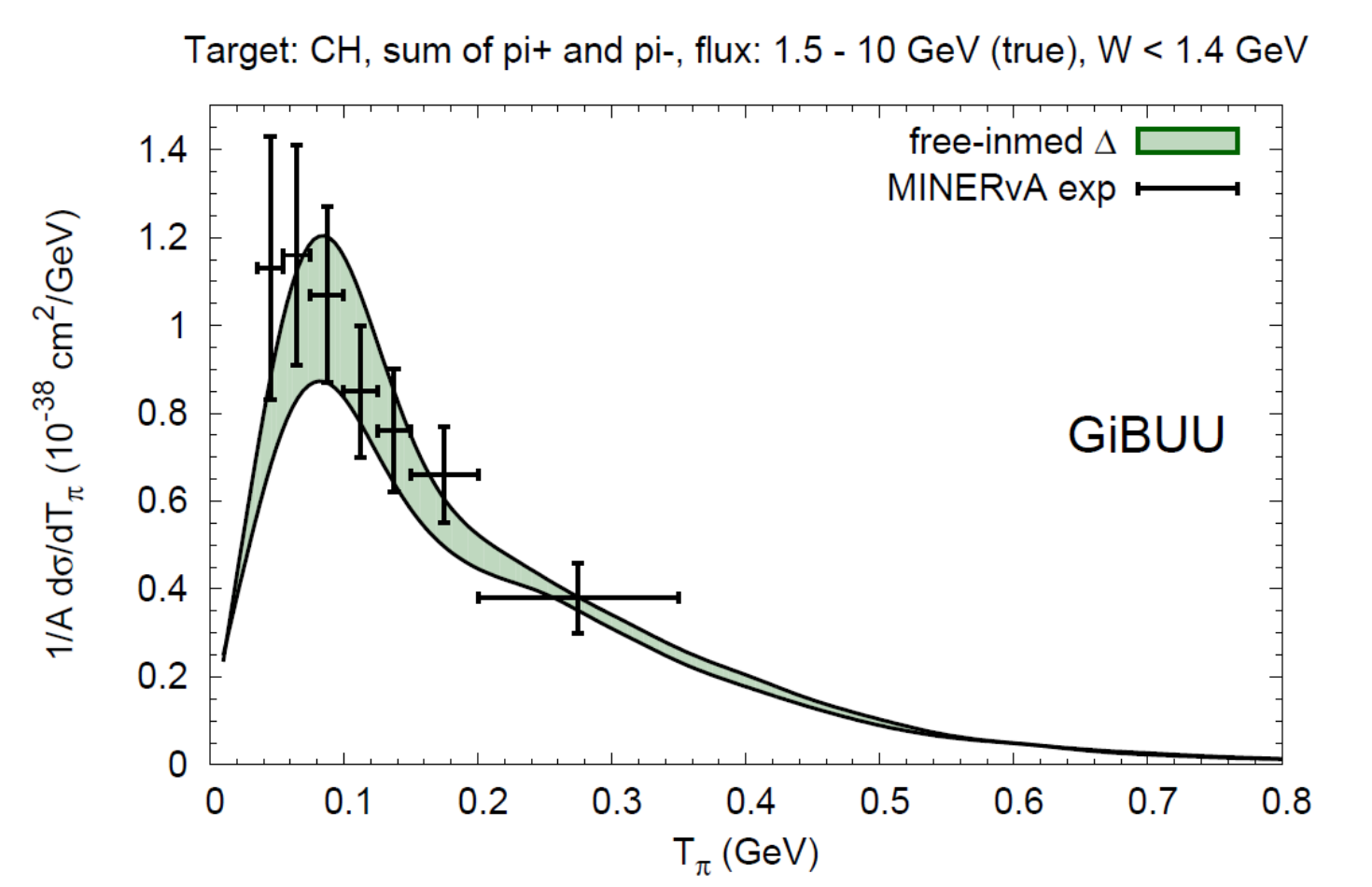




W < 1.8 GeV

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

MINERvA Pions: Theoretical Uncertainty



Sensitivity to collional broadening of Δ

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Sensitivity of T2K to Energy Reconstruction

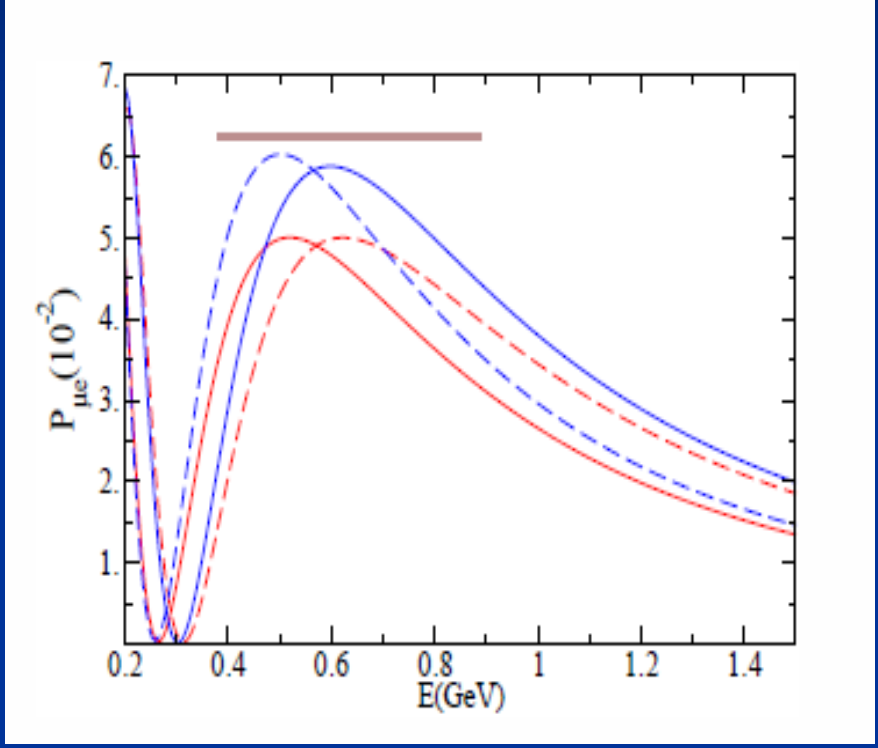
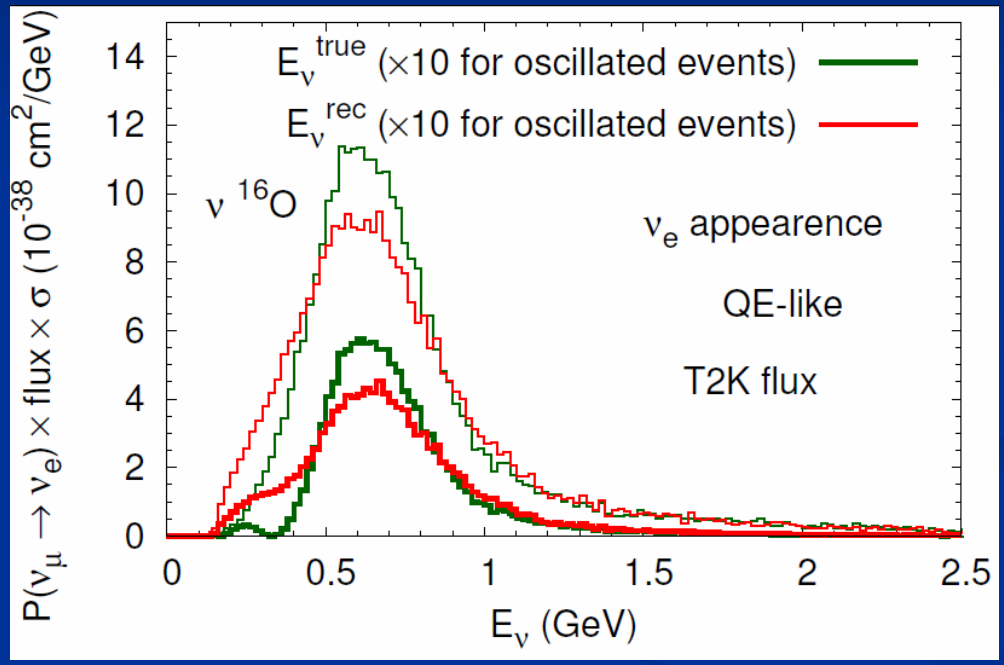


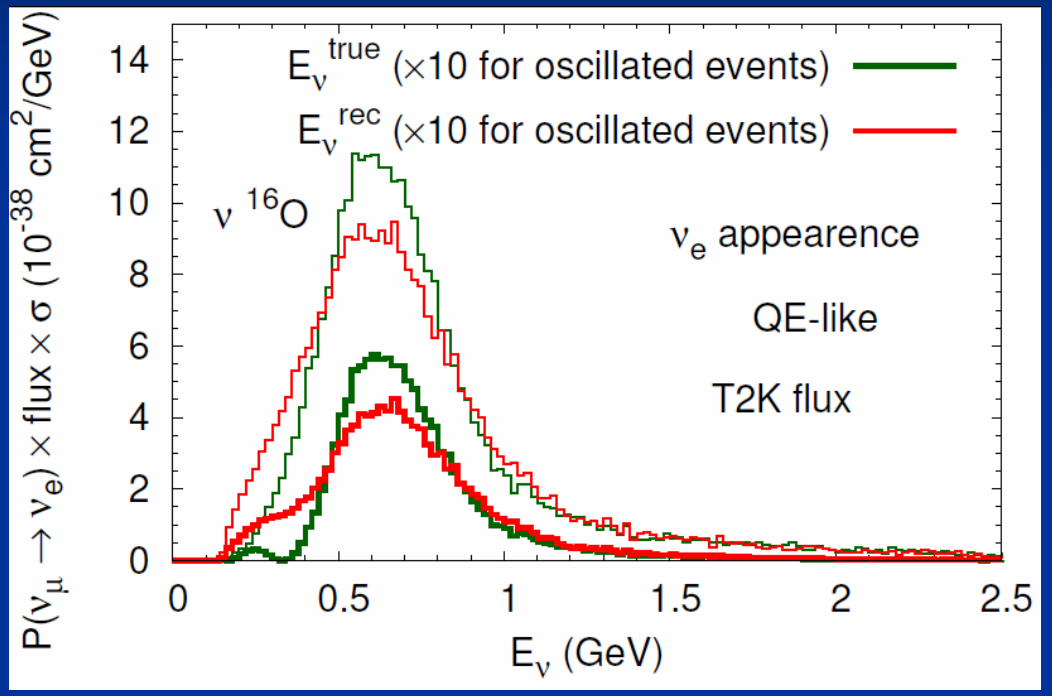
Fig. 2. $\mathcal{P}_{\mu e}$ in matter versus neutrino energy for the T2K experiment. The blue curves depict the normal hierarchy, red the inverse hierarchy. Solid curves depict positive θ_{13}, dashed curves negative θ_{13}

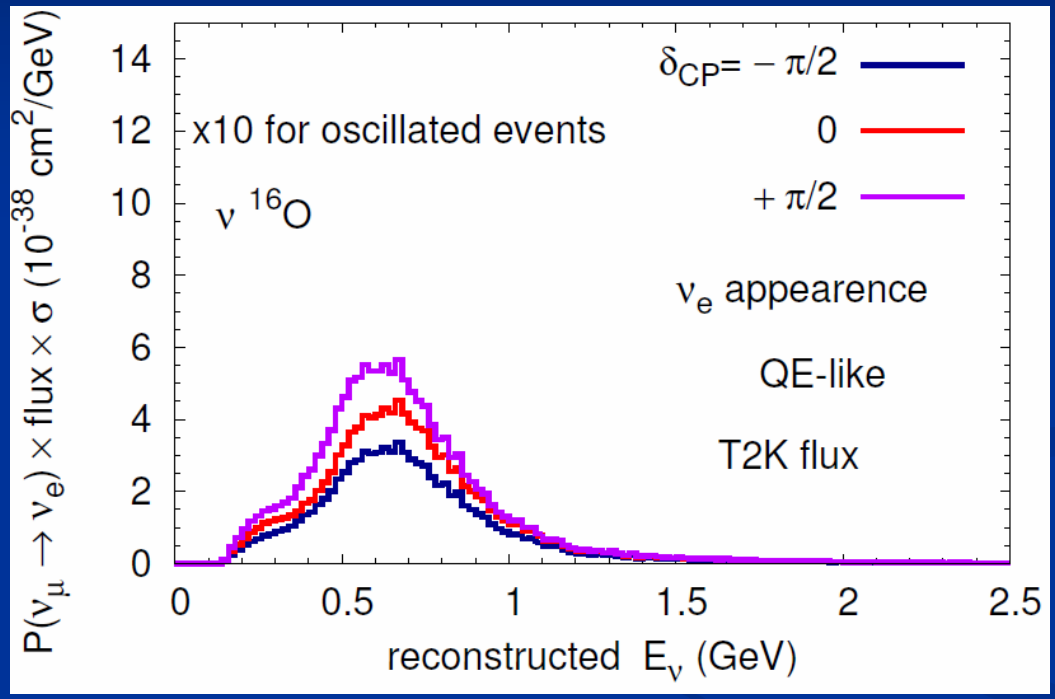
D.J. Ernst et al., arXiv:1303.4790 [nucl-th]



Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Oscillation signal in T2K
δ_{CP} sensitivity of appearance exps





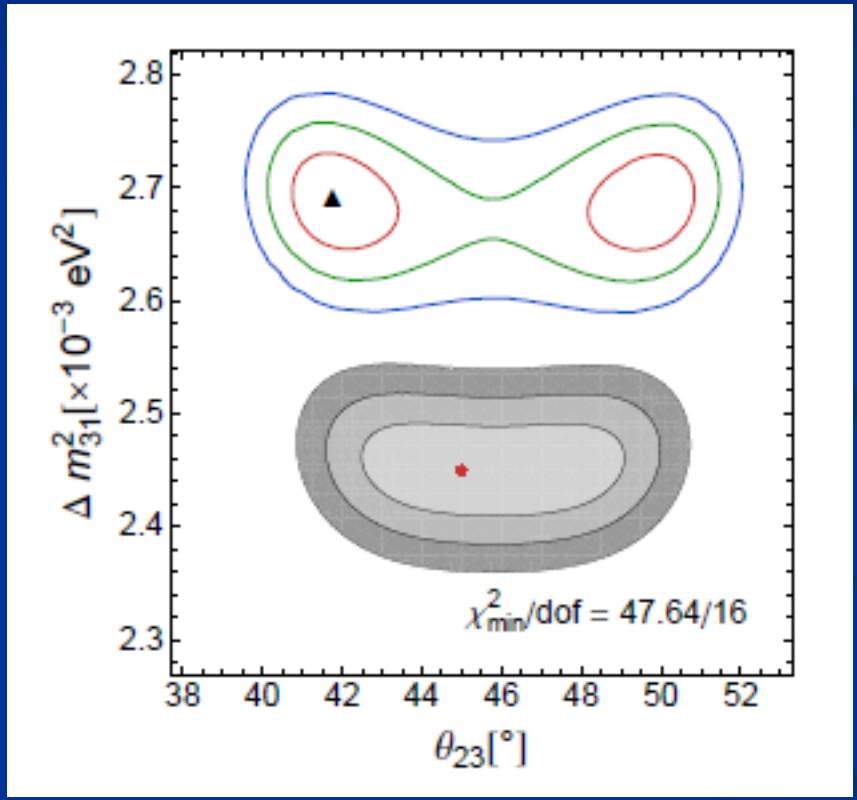
Uncertainties due to energy reconstruction as large as δ_{CP} dependence

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Generator Dependence of Oscillation Parameters

GiBUU-GENIE

GiBUU-GiBUU



From: P. Coloma et al, Phys.Rev. D89 (2014) 073015

Nature: GiBUU
Generator: GENIE

T2K Flux

Summary

- GiBUU gives *both inclusive X-sections and full events.*
- GiBUU describes inclusive electron and neutrino data, *without any tuning, both QE and pion production.* Agreement is comparable with that of any other theory
- GiBUU works in *all energy regimes*, both BNB and MINERvA/LBNF energies
- GiBUU works for *all nuclei*
- GiBUU is *publicly available*: gibuu.hepforge.org

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

GiBUU: References

- 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
4. Mosel et al, arXiv:1702.04932
   pion production comparison of MiniBooNE, T2K and MINERvA

Institut für Theoretische Physik
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN