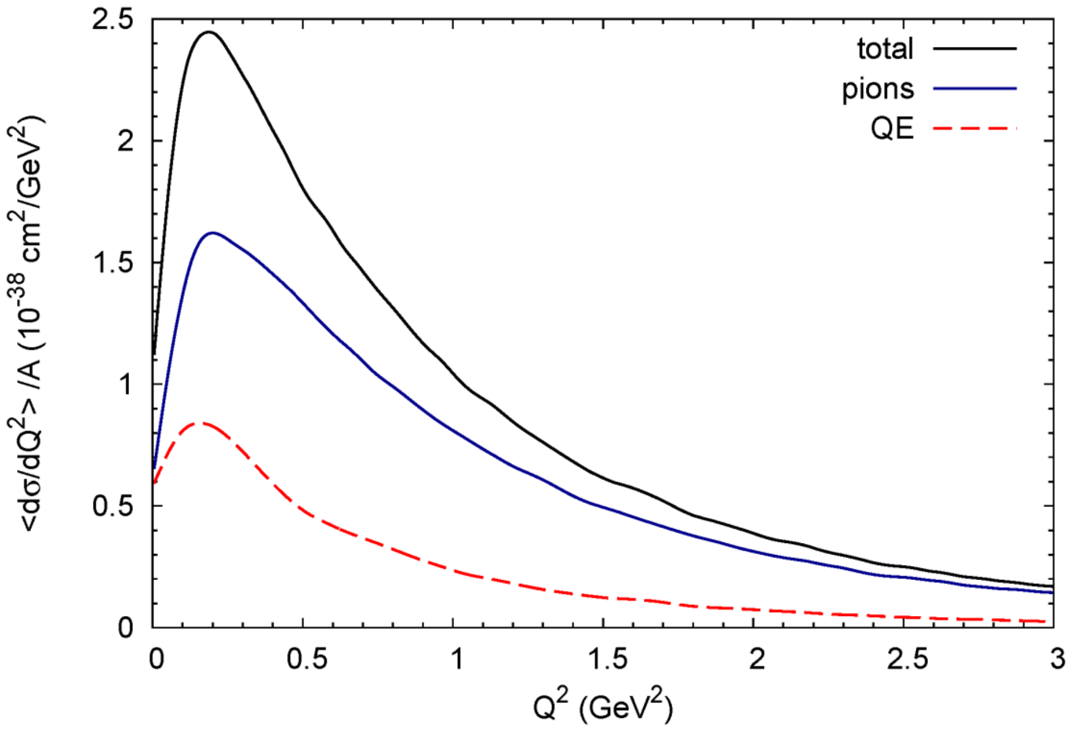
GiBUU
a general introduction

Giessen Boltzmann-Uehling-Uhlenbeck

With Kai Gallmeister, Frankfurt

Reaction Types at DUNE



Pions: Resonance + DIS

QE: ‚true‘ QE + 2p2h

Necessary for DUNE:

1. Control not only of QE and resonance pions, but also DIS
2. Relativity of all outgoing particles correct

GiBUU

- GiBUU
= The Giessen Boltzmann-Uehling-Uhlenbeck Project
- flexible tool for simulation of nuclear reactions
  - e+A
  - γ+A
  - ν+A
  - hadron+A (p+A, π+A)
- and
  - A+A
- energies: 10 MeV … 10-100 GeV
- degrees of freedom: Hadrons (Baryons, Mesons)
- propagation and collisions of particles in mean fields
- Boltzmann-Uehling-Uhlenbeck equation

Institut für Theoretische Physik, JLU Giessen

GiBUU

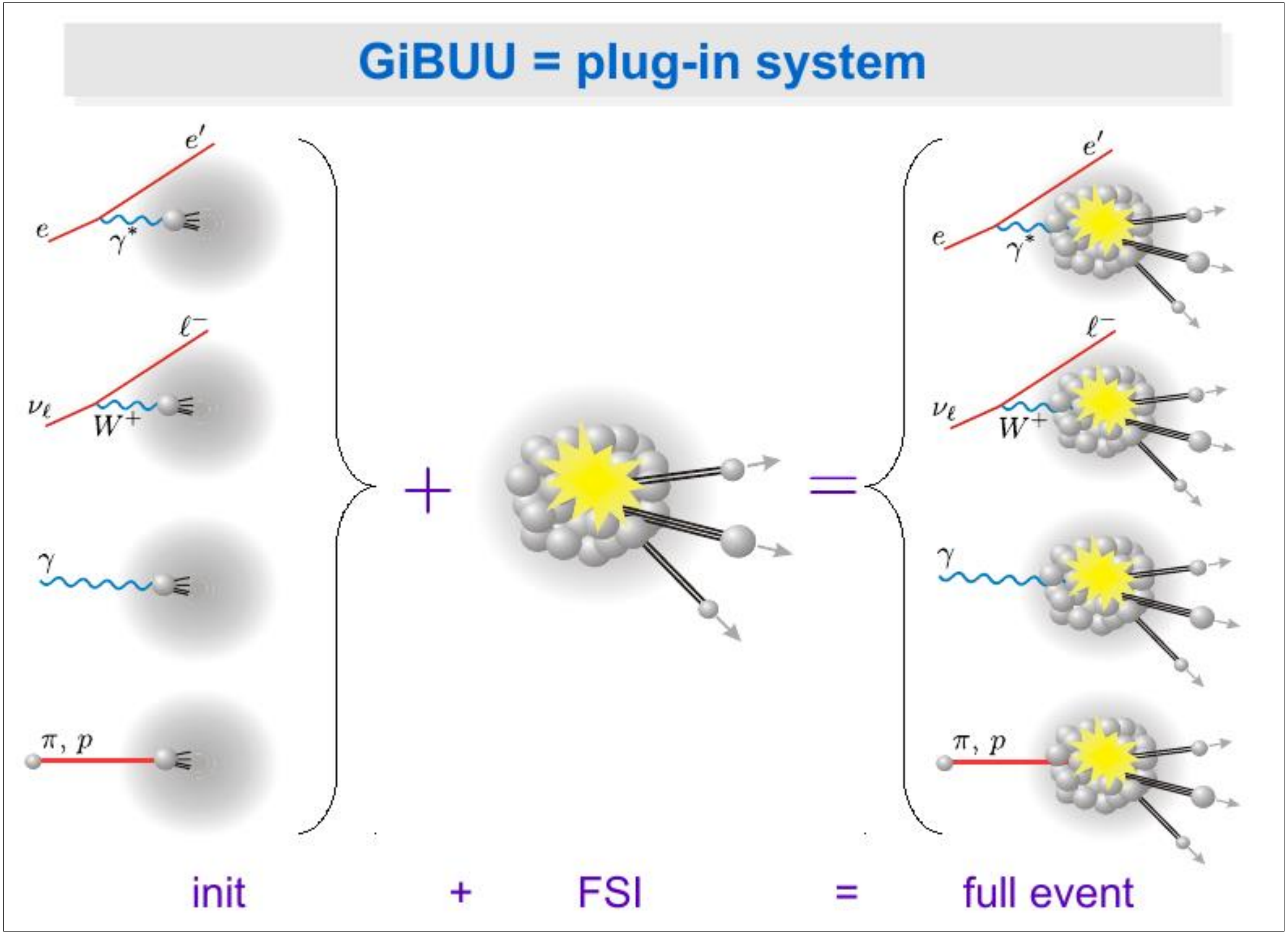
The Giessen Boltzmann-Uehling-Uhlenbeck Project

- **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,,latest version GiBUU 2017
  Details in Gallmeister et al, Phys.Rev. C94 (2016) no.3, 035502

GiBUU in one picture



Some classical kinetic theory

- distribution function $f(x,p) \quad x = (t, \vec{x}\,),\ p = (E, \vec{p}\,)$
describes phase-space distribution of (single) particles
- number of particles in a given phase-space volume:

$$\Delta N = f(x,p)\,\Delta^3 x \Delta^3 p$$

- for each particle species: $f_N,\ f_\pi,\ f_\Delta,\ ,\ldots$

- continuity equation for free, non-interacting particles

$$p^\mu \partial_\mu\, f(x,p) = 0$$

straight line propagation of particles, no collisions

- adding external forces (mean field potentials): Vlasov eq.

$$[\partial_t + (\nabla_p E)\nabla_r - (\nabla_r E)\nabla_p]\, f(x,p) = 0$$

propagation through mean field, no collisions

Adding collisions

- forget about mean fields, but add collisions…
- continuity eq. + collision term → Boltzmann eq.

$$p^\mu \partial_\mu f(x,p) = C(x,p)$$

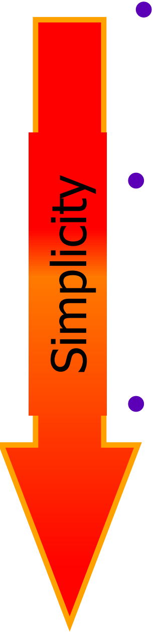
- collision integral has gain and loss term

$$C(x,p) = C_{\text{gain}}(x,p) + C_{\text{loss}}(x,p)$$

- mean fields and collision term:
  - Boltzmann-Uehling-Uhlenbeck eq. (BUU or VUU)

$$\left[\partial_t + (\nabla_p H_i)\nabla_r - (\nabla_r H_i)\nabla_p\right] f_i(\vec{r},t,\vec{p}) = C\left[f_i, f_j, \ldots\right]$$

Theoretical Basis of GiBUU



- Kadanoff-Baym equation (1960s)
  - full equation not (yet) feasible for real world problems
- Boltzmann-Uehling-Uhlenbeck (BUU) models: GiBUU
  - Boltzmann equation as gradient expansion of Kadanoff-Baym equatio
    Botermans-Malfliet representation (1990s)
- Cascade models
  (typical event generators, GENIE, NEUT, NuWro, …)
  - Nuclei are not bound, no mean-fields, primary interactions and FSI
    consistent, reweighting of different interaction types, ….

GiBUU vs Generators

- GiBUU has potentials for nucleons and hadrons, nuclei are bound
- It is consistent: same groundstate for all processes
- It has same potentials in first interactions and fsi
- It follows phase-space distributions and spectral functions of hadrons throughout the nuclear volume (off-shell transport)
- It is based on present-day's nuclear theory
- All results are obtained with downloadable code ‚out of the box'
- GiBUU does not describe any coherent processes
- GiBUU does not contain any detector geometry effects

Quantum-kinetic Transport Theory from non-equilibrium Green's function method

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

KB equations with BM offshell term

So far, not fully used for neutrino-A reactions
Essential for any in-medium physics

Propagation of Hadrons

- Hadrons are propagated within their self-energies, i.e. potentials (nucleons always, mesons optional)

- Because of potentials nucleon trajectories are not straight lines, as in MC, but have to be time-integrated
- → increases computing time, but no need to introduce tunable fudge factors such as a binding energy: nucleons become unbound when they leave the nucleus

Degrees of Freedom

- GiBUU is purely hadronic (no partonic phase)
- leptons: usually not ‚transported‘, but
  - e+N, nu+N, gamma+N initial events
  - leptonic/photonic decays
- 61 baryons, 22 mesons
  (strangeness and charm included, no bottom)
- properties from Manley analysis (PDG for strange/charm)

- in principle one needs:
  - cross sections for collisions between all of them (all energies)
  - mean-field potentials for all species
- often not known, thus use hypothesis/models/guesses

Mean-field potentials

- two types of mean-field potentials:
  - non-relativistic Skyrme-type potentials
  - relativistic mean fields (RMF)

- potential may enter single-particle energy as

$$H = \sqrt{(m+V)^2 + (\vec{p} + \vec{U}\,)^2} + U_0$$

- RMF is Lorentz vector U
- Skyrme enters as U_0, bound to specific frame (LRF)

- Scalar Potential V: mass shift

Skyrme/Welke-like potential

$$U_0(x,\vec{p}) = A\frac{\rho}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$
$$+ \frac{2C}{\rho_0}\sum_{i=p,n}\int \frac{g\mathrm{d}^3p'}{(2\pi)^3}\frac{f_i(x,\vec{p}')}{1+(\vec{p}-\vec{p}')^2/\Lambda^2}$$
$$+ d_{\mathrm{symm}}\frac{\rho_p(x)-\rho_n(x)}{\rho_0}\tau_i$$

$$\rho_0 = 0.168\,\mathrm{fm}^{-3}$$

- defined in local rest frame (LRF, baryon current vanishes)
- six parameters, fixed to
  - nuclear binding energy of 16 MeV at $\rho=\rho_0$ (iso-spin symm. matter)
  - nuclear-matter incompressibility *K*=200-380 MeV
  - pA data as function of energy, up to about 1GeV

GiBUU was constructed with the aim to encode the „best possible“ theory

Initial interactions

- Mean field potential with local Fermigas momentum distribution, nucleons are bound
  1. Pick density distribution of target
  2. Calculate potential V(r,p) from E[**ρ,**p] functional
  3. Calculate local TF momentum distribution → $E_F(r)$
  4. Iterate potential so that E_F = constant over nuclear volume

- Initial interactions are calculated by summing over interactions with all bound, Fermi-moving nucleons

Collision term

- contains one-, two-, and three-body collisions

$$C = C_{1\to X} + C_{2\to X} + C_{3\to X}$$

(1) resonance decays

(2) two-body collisions

- elastic and inelastic
- any number of particles in final state
- baryon-meson, baryon-baryon, meson-meson

(3) three-body collisions (relevant for pi absorption)

- low energies: cross sections based on resonances

$$\text{e.g. } \pi N \to N^*, \; NN \to NN^*$$

- high energies: string fragmentation

Collision term

- 2-to-2 term $(12 \leftrightarrow 1'2')$

$$C^{(2,2)}(x, p_1)$$

$$= C^{(2,2)}_{\text{gain}}(x, p_1) - C^{(2,2)}_{\text{loss}}(x, p_1)$$

$$= \frac{\mathcal{S}_{1'2'}}{2p_1^0 g_{1'} g_{2'}} \int \frac{\mathrm{d}^4 p_2}{(2\pi)^4 2p_2^0} \int \frac{\mathrm{d}^4 p_{1'}}{(2\pi)^4 2p_{1'}^0} \int \frac{\mathrm{d}^4 p_{2'}}{(2\pi)^4 2p_{2'}^0}$$

$$\times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_{1'} - p_{2'}) \overline{|\mathcal{M}_{12\to 1'2'}|^2}$$

$$\times [F_{1'}(x, p_{1'}) F_{2'}(x, p_{2'}) \overline{F}_1(x, p_1) \overline{F}_2(x, p_2)$$

$$- F_1(x, p_1) F_2(x, p_2) \overline{F}_{1'}(x, p_{1'}) \overline{F}_{2'}(x, p_{2'})]$$

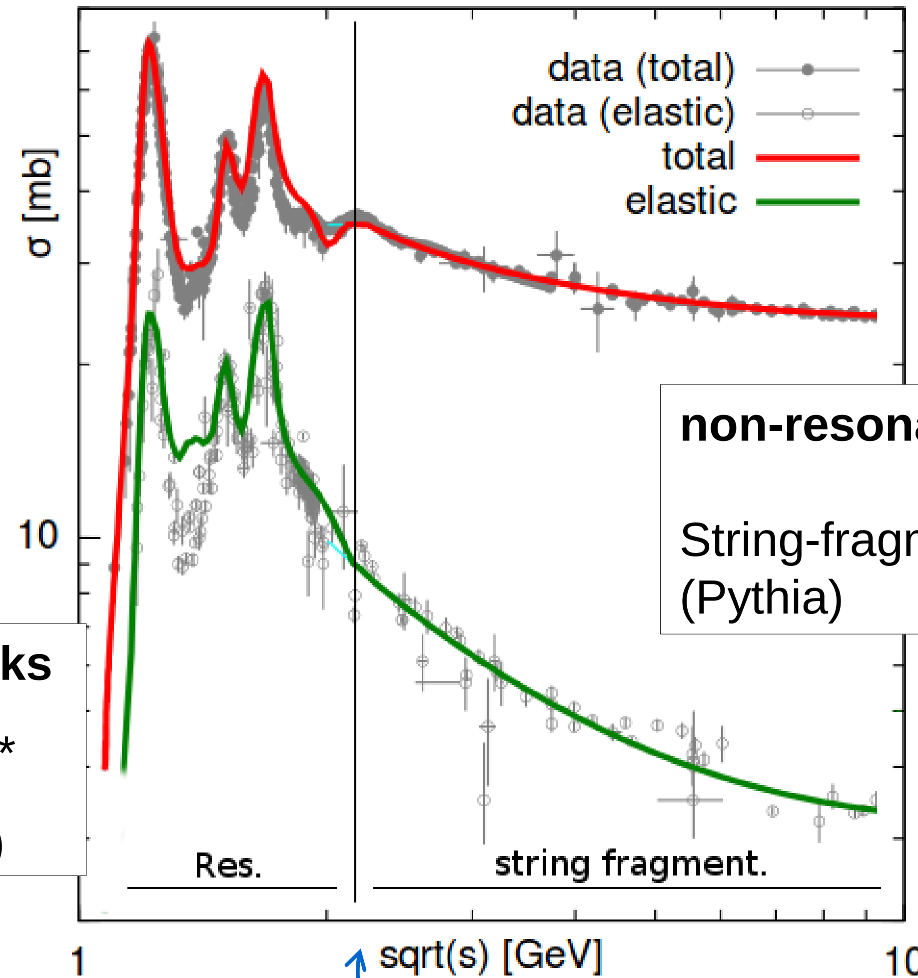
$$F(x, p) = 2\pi g \, f(x, p) \, \mathcal{A}(x, p)$$

$$\overline{F}(x, p) = 2\pi g \, [1 - f(x, p)] \, \mathcal{A}(x, p)$$

Pauli-blocking

Baryon-Meson collisions

- example: πN cross section



non-resonant

String-fragmentation (Pythia)

clear resonance peaks

excitation of N* and Δ*

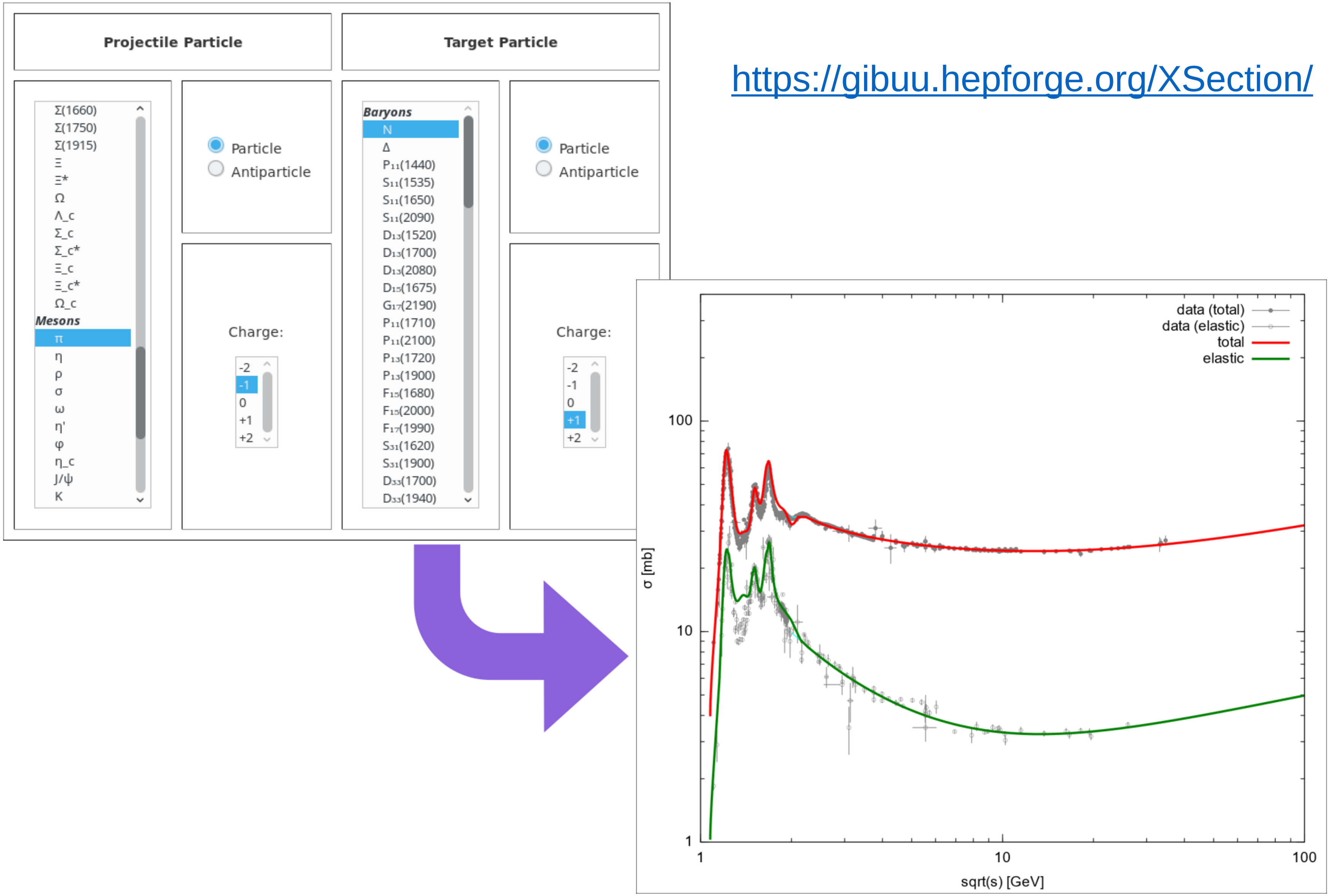
(Breit-Wigner shapes)

$$\mathcal{A}(p) = \frac{1}{\pi} \frac{\sqrt{p^2}\Gamma}{(p^2 - M_0^2)^2 + p^2\Gamma^2}$$

$$\sqrt{s} = 2.2 \pm 0.2\,\mathrm{GeV}$$

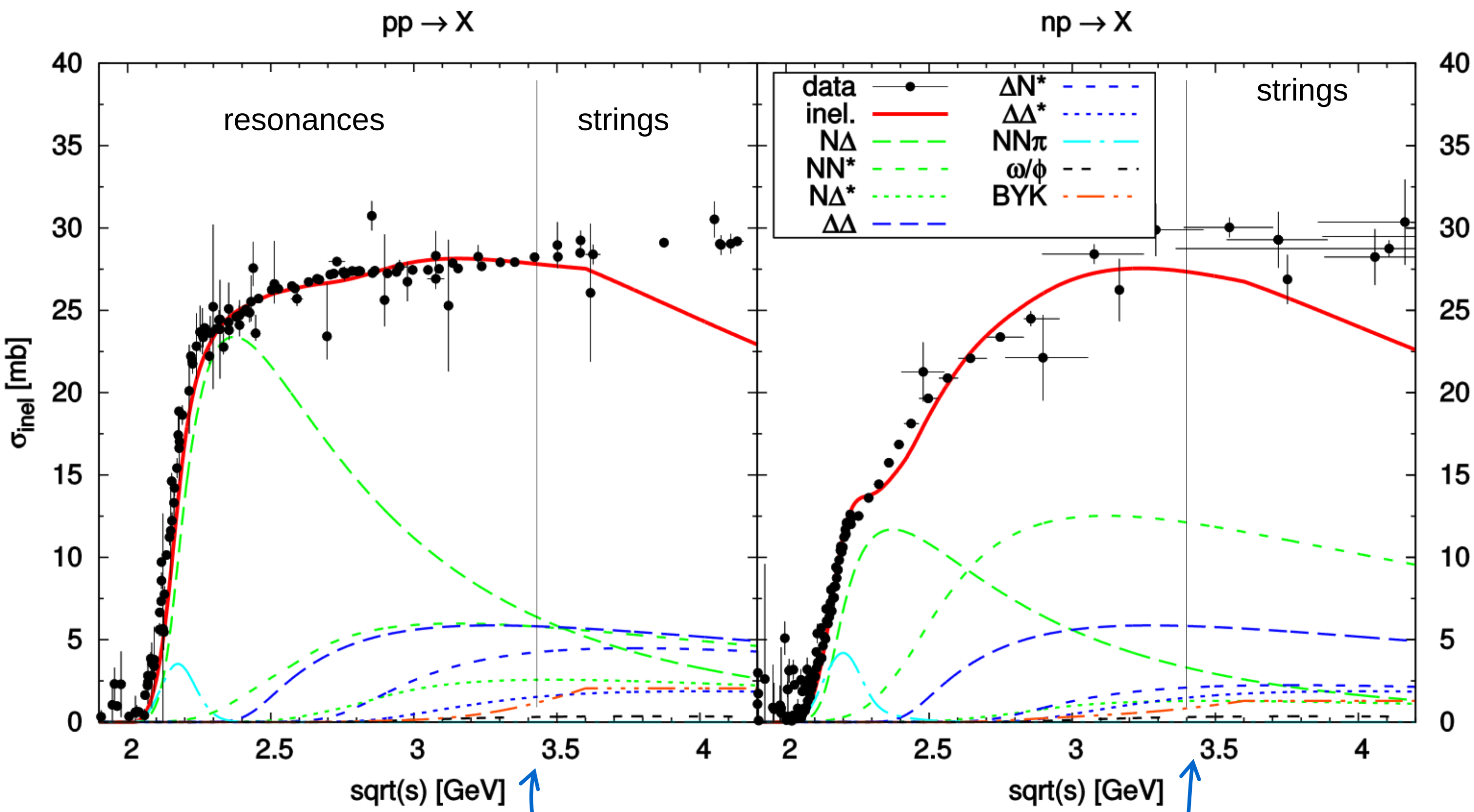
Cross section plotter on GiBUU homepage

https://gibuu.hepforge.org/XSection/



Baryon-Baryon Collisions

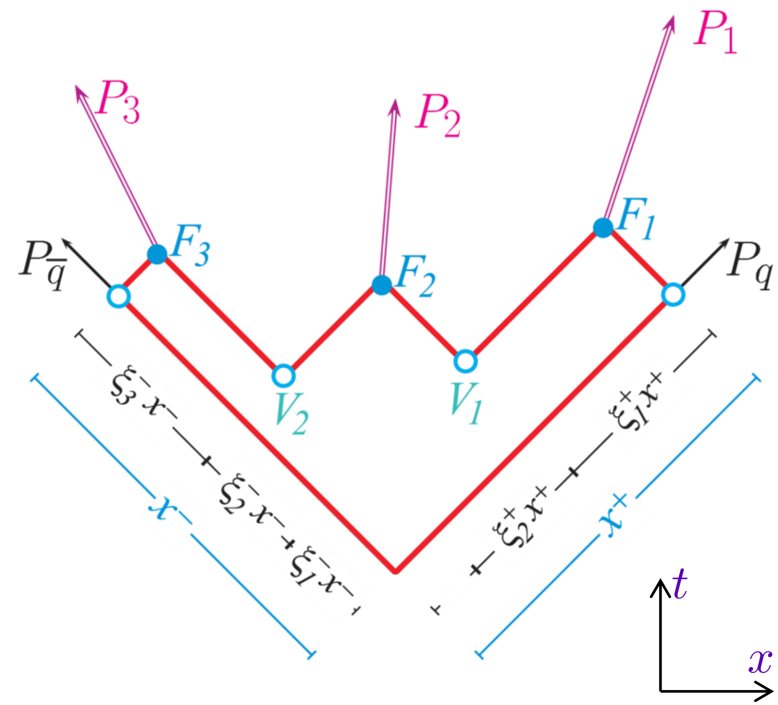
- low energy: resonance model, high energy: string model
- no nice peaks due to two-body kinematics
- *NN*→*NR*,Δ*R* (*R*=Δ,*N**,Δ*)



$\sqrt{s} = 3.4 \pm 0.1\,\mathrm{GeV}$

(Lund) String-fragmentation (Pythia)

- *idea:*
hard qq scattering (pQCD)
creates a color flux tube ('string')
which then fragments into hadrons
(via qq pair production)

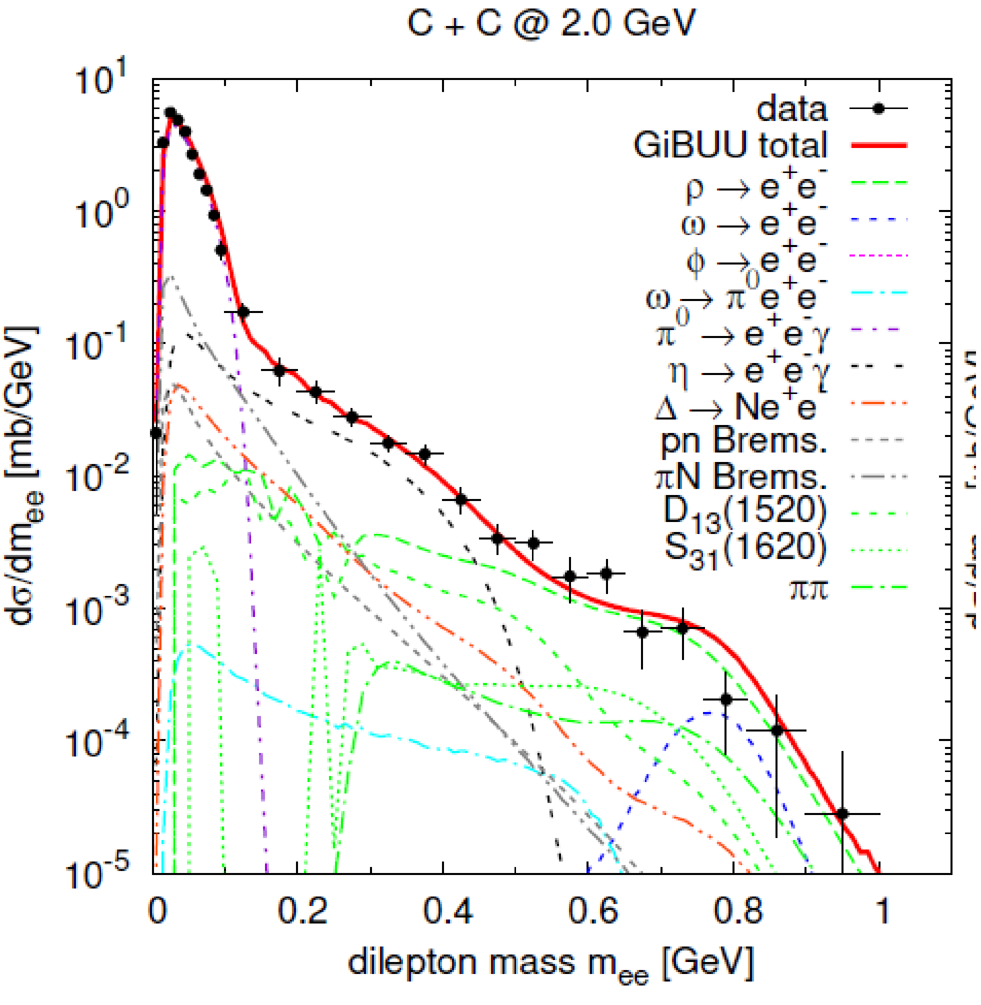


- high energy: 10 GeV...
- "Lund string model"
implementation: Pythia (Jetset)
- only low-lying resonances
- phenomenological fragmentation function
(when and how does a string break?)
- parameters fitted to data (different 'tunes‘, e.g. to HERMES data, available)

GiBUU Practical Points

- The code can be downloaded from gibuu.heforge.org
- The code is documented by robodoc: generates documentation on homepage
- The code generates event files with four-vectors of all outgoing particles. This info can be used to put in detector acceptances, ….
- The code also produces many semi-inclusive cross sections. These are calculated without any cuts etc
- Running time: ~ 1-2 hours for inclusive X-sections without time-development, ~ 1 day for fully exclusive events

Test for inverse Reaction: timelike photon production



Dilepton spectrum in the HADES experiment

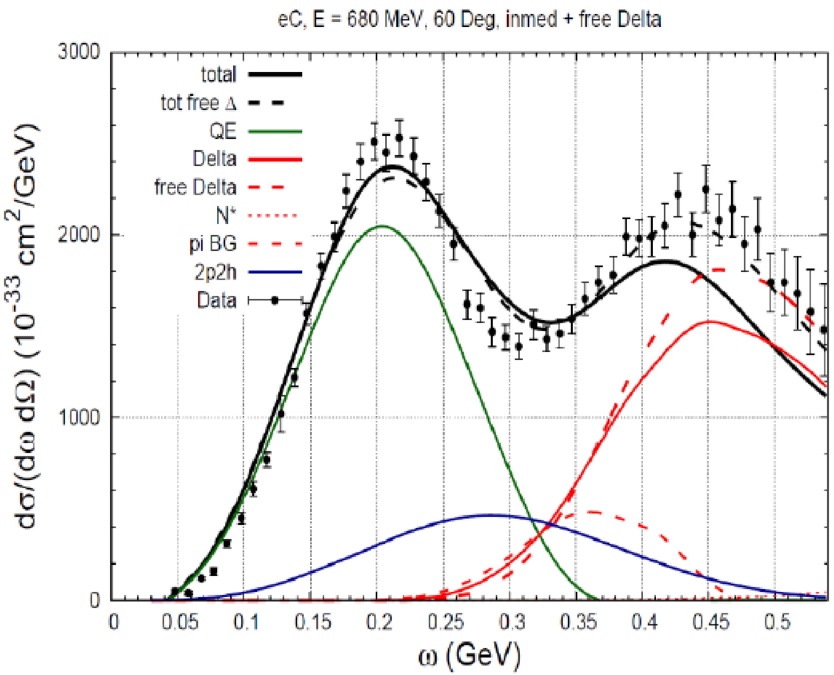
Test with e-Scattering Data

- Necessary Test!
  (often said, but seldom done in generators)

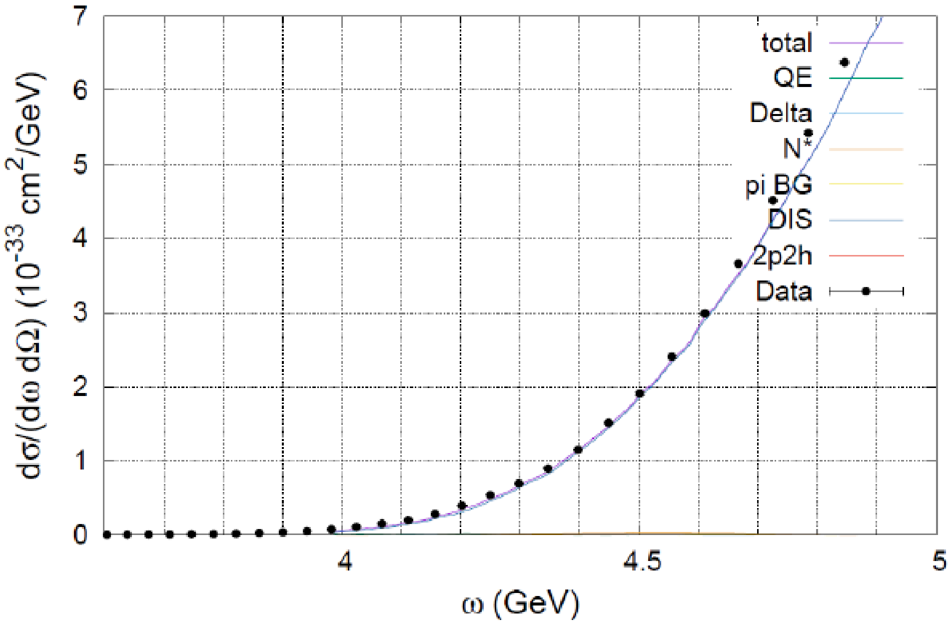
- Test not in some special modules, but same code modules as for neutrinos

Test with electron Data: QE+Res

- a necessary test



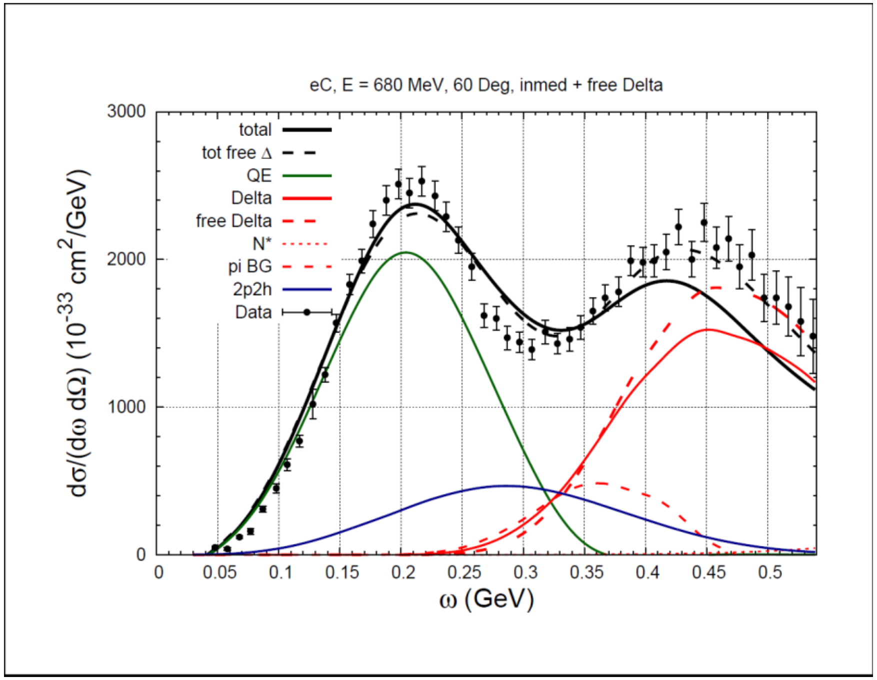
$Q^2 = 0.32$ GeV^2



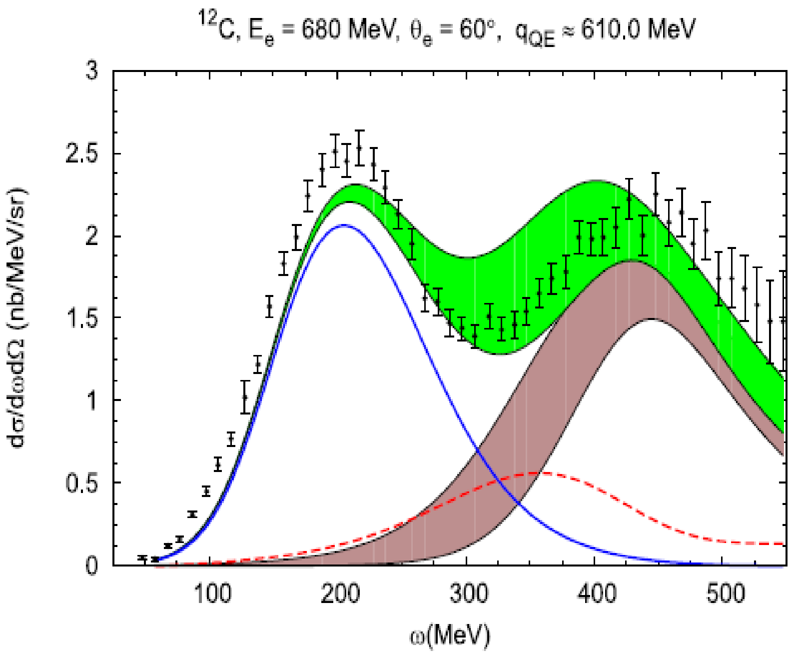
E = 5.766 GeV, 50 deg, $Q^2 = 7.3$ GeV^2

^{12}C

Test with Electron Data : QE + Res

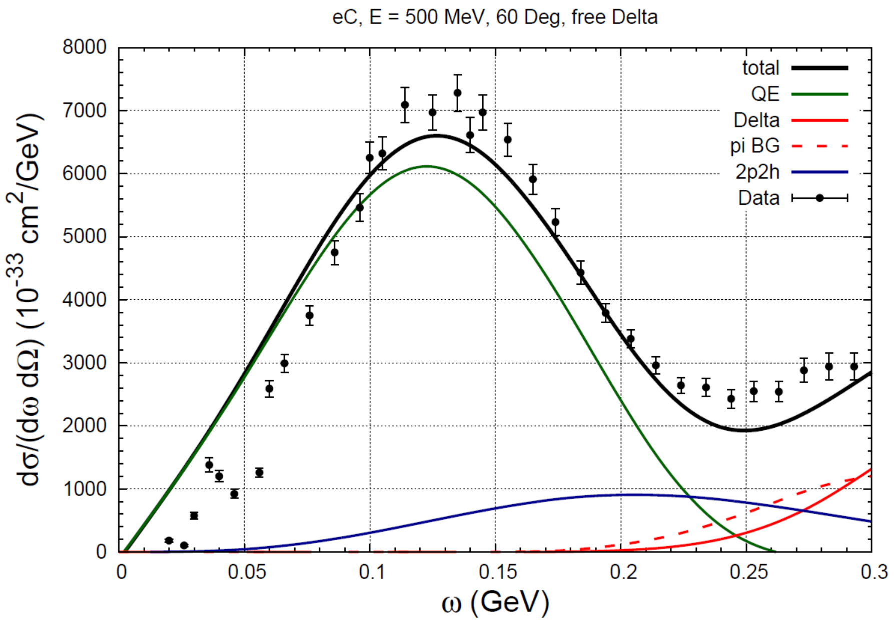


GiBUU

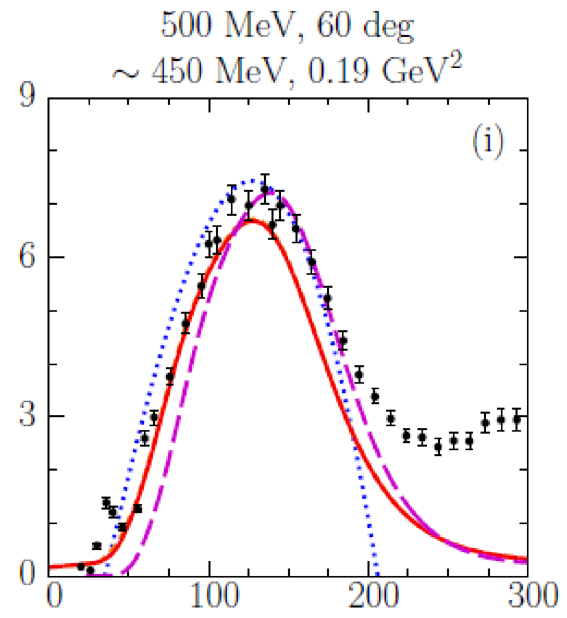


Scaling: M.V. Ivanov et al, J.Phys. G43 (2016) 045101

Test with Electron Data: : QE + Res



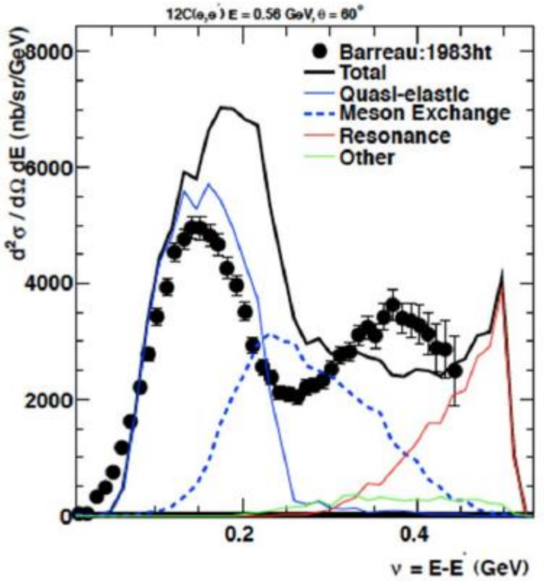
GiBUU 2016

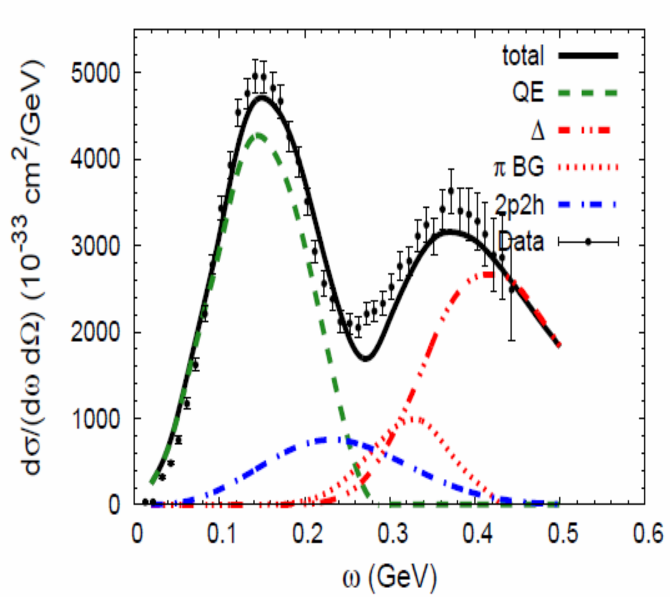


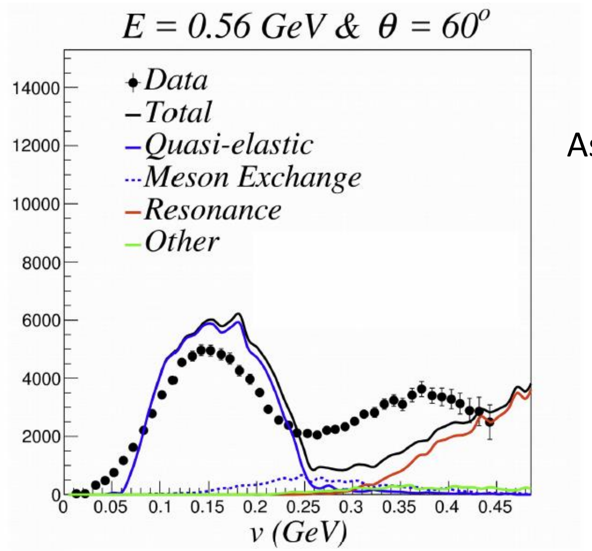
Ankowski. Benhar, Sakuta

GENIE vs GiBUU

GENIE, from S.Dytman, BNL meet, Febr. 2015



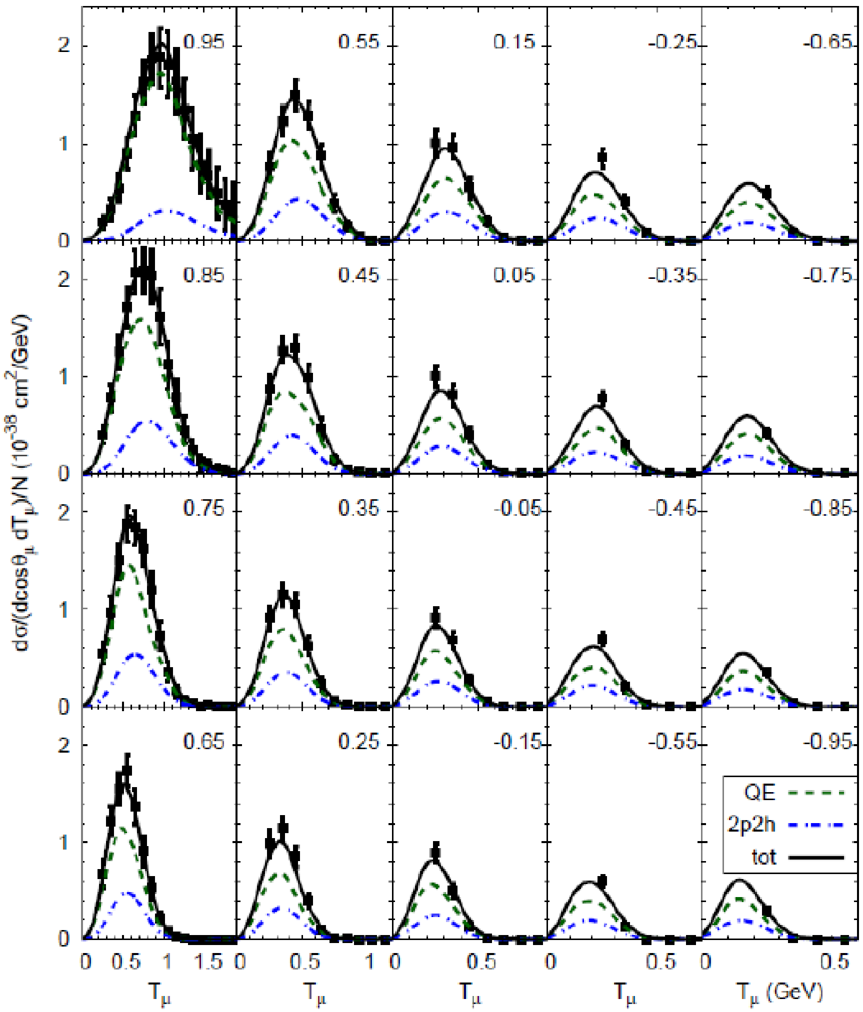


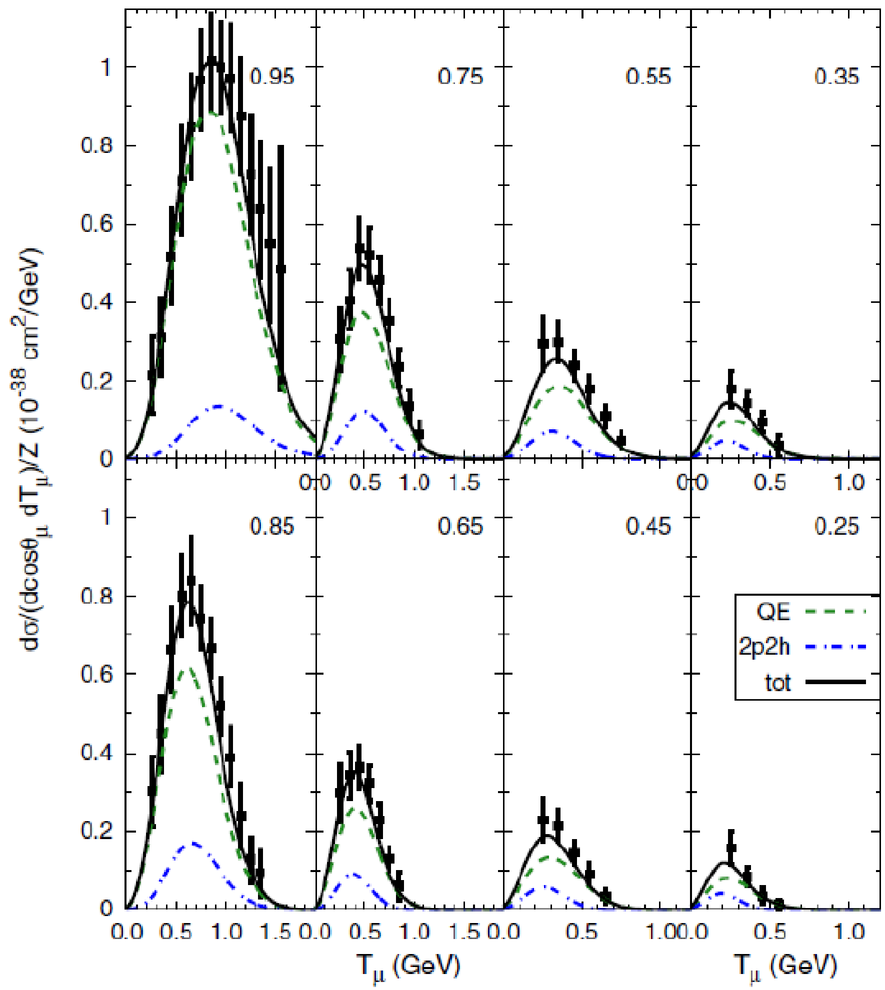


Ashkenazi, INT June 2018

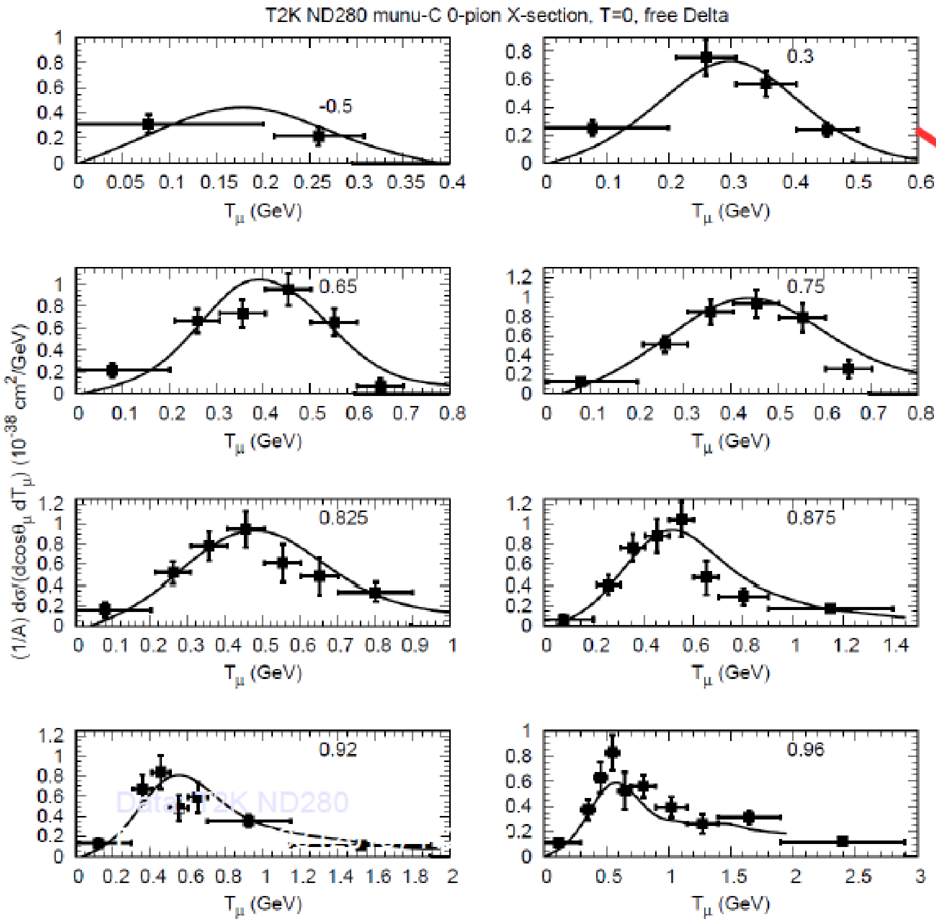
GiBUU describes electron data over wide kinematical range without any special tune, out of the box, and for different targets

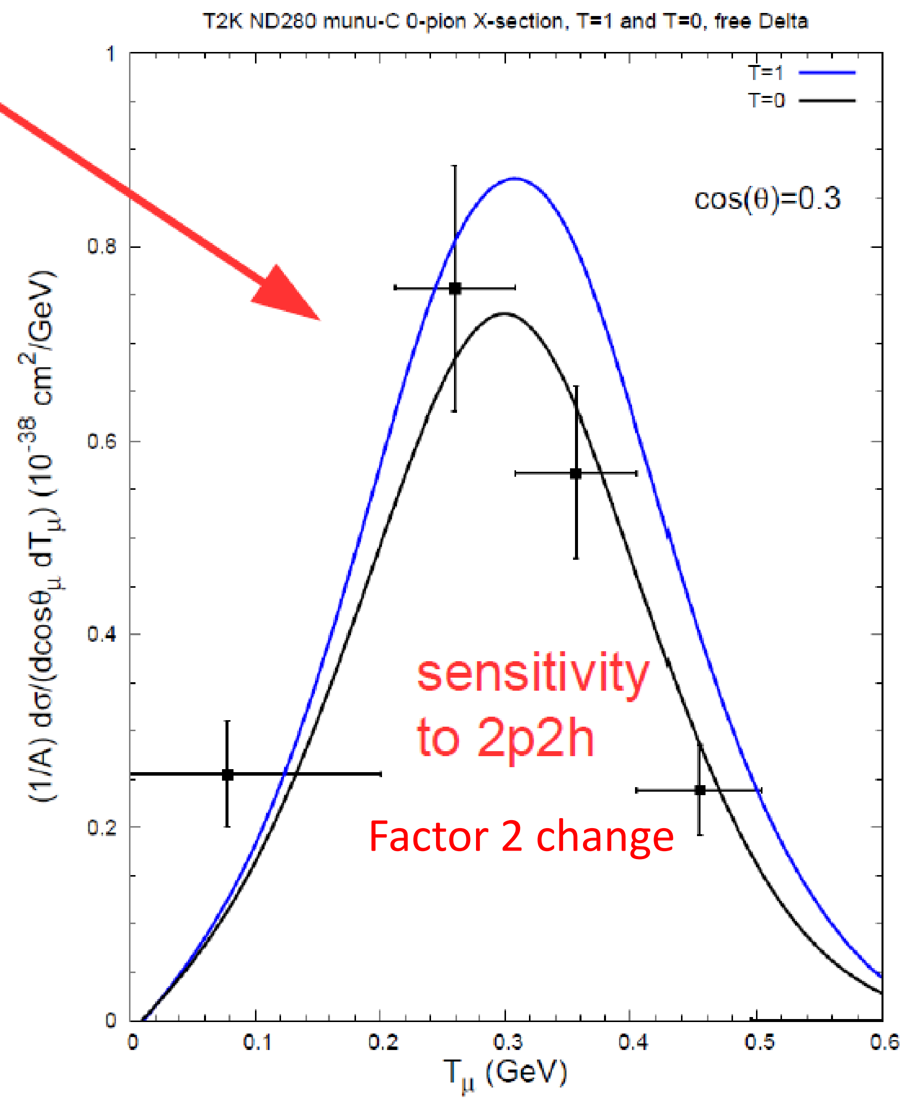
MiniBooNE 0pion = QE + 2p2h





T2K 0pion = QE + 2p2h + stuck pions



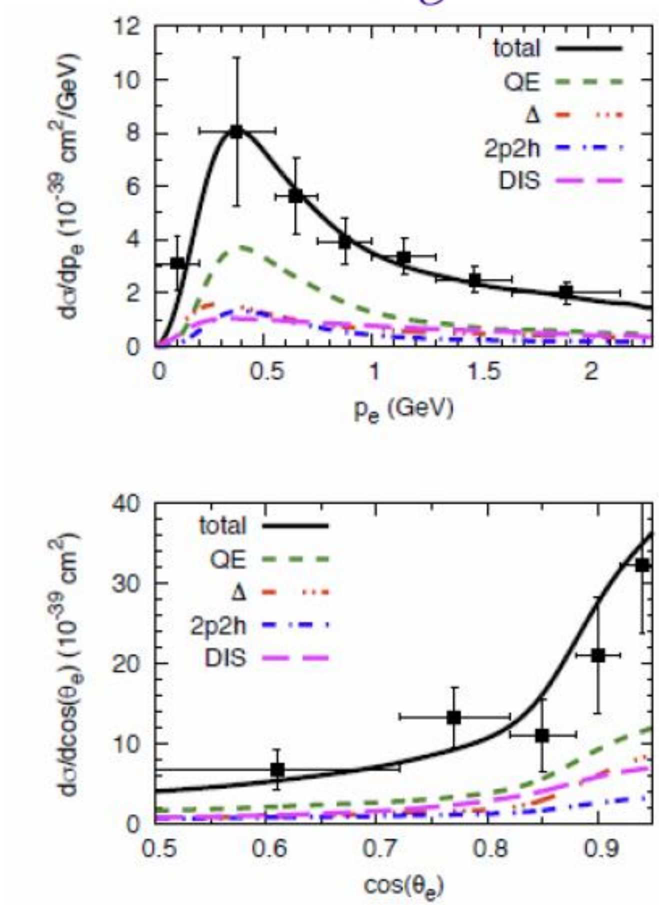


Data: T2K ND280
Phys.Rev. D93 (2016) 112012

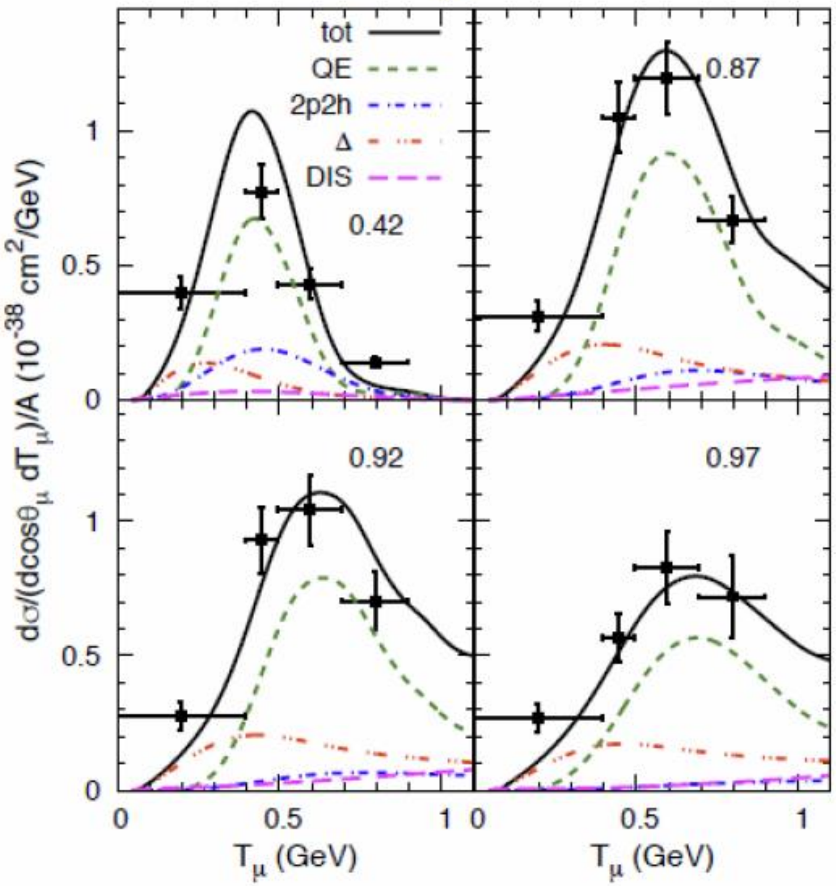
T2K incl. Data

- agreement for different neutrino flavors

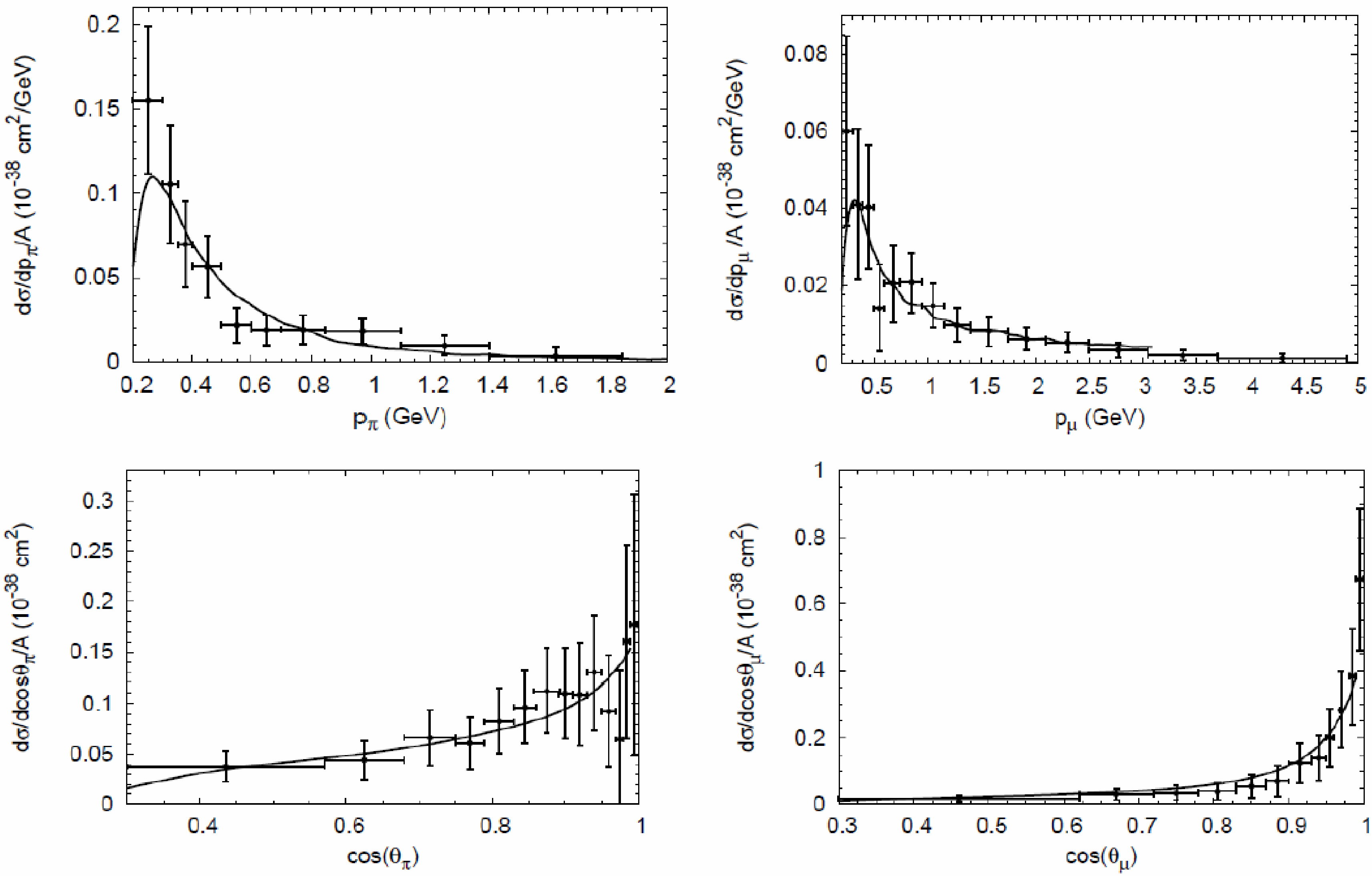
ν_e



ν_μ



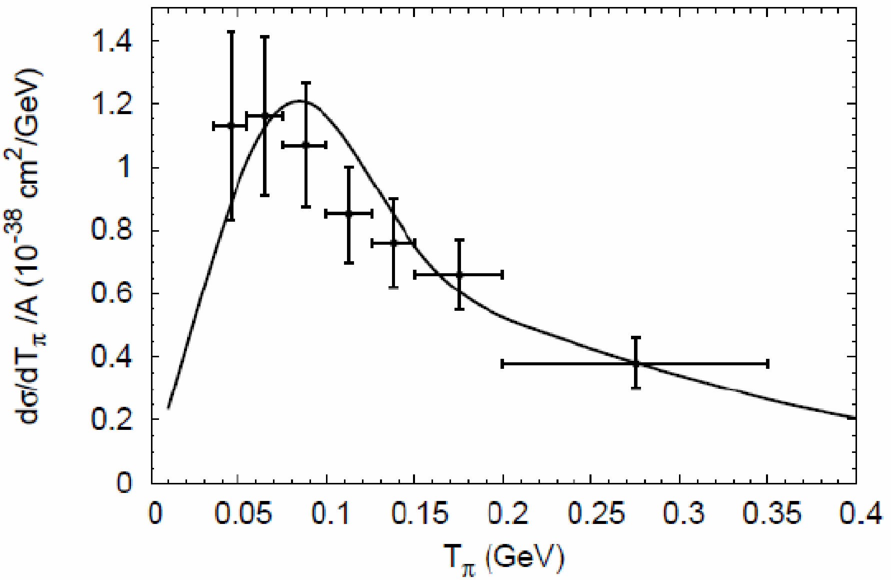
T2K ND280 pions on water



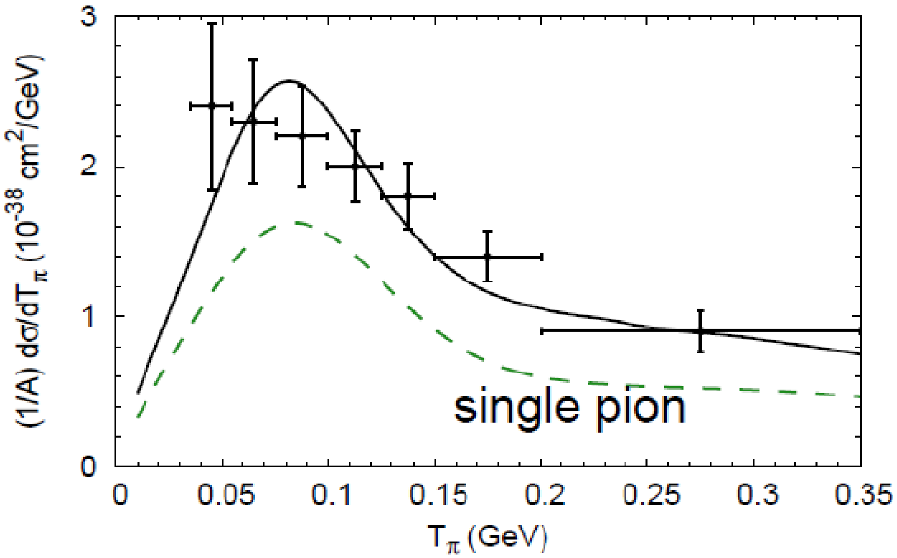
Data: T2K ND280
Phys.Rev. D95 (2017) 012010

MINERvA pions

- CC charged pions

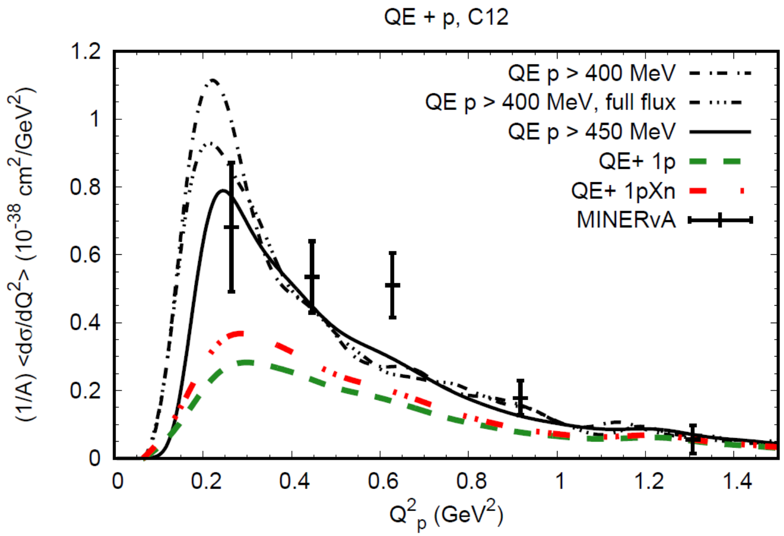


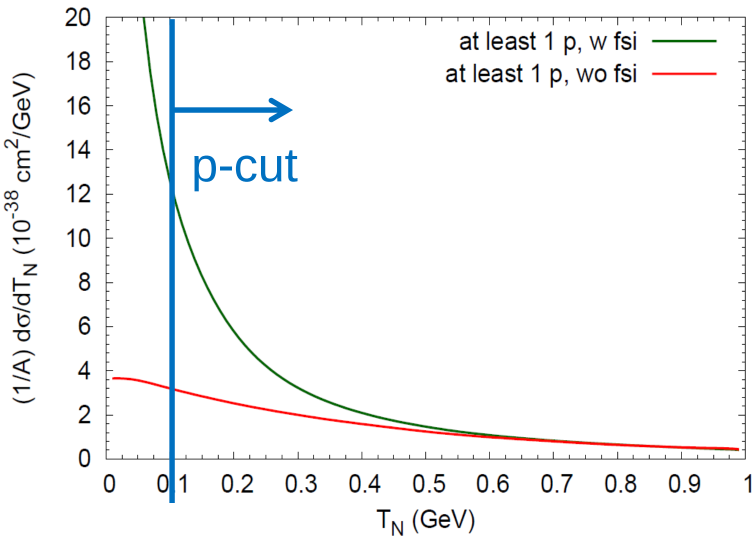
W < 1.4 GeV



W < 1.8 GeV, multiple pions

MINERvA QE + 2p2h: 1 mu + p





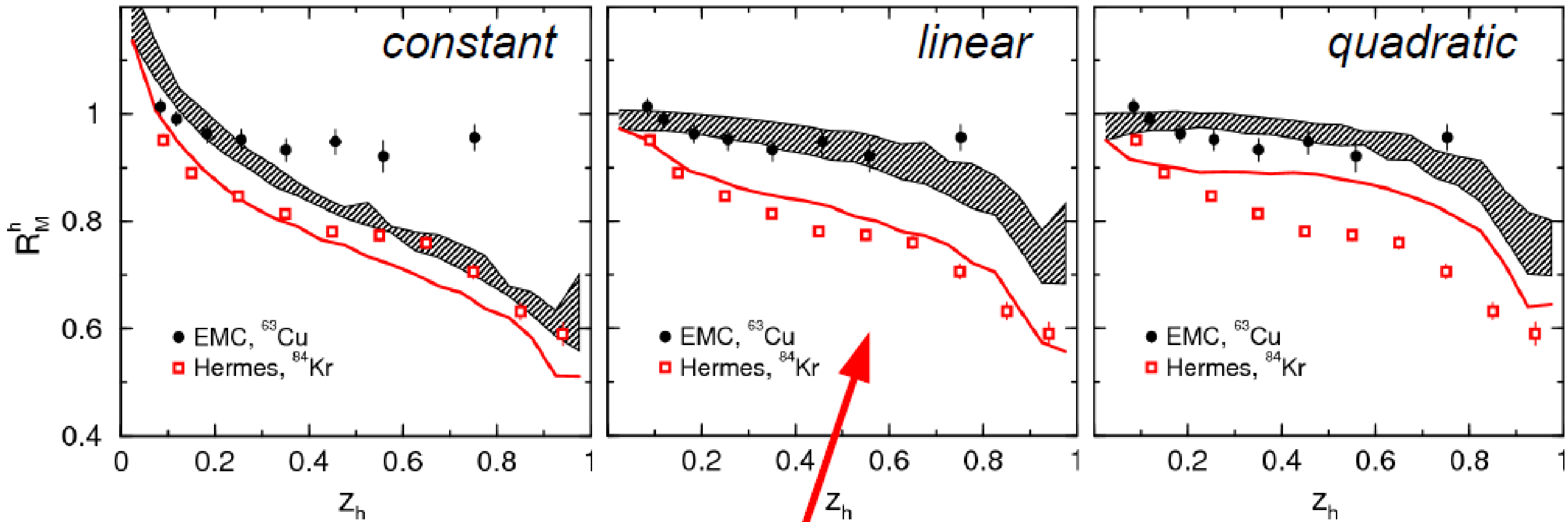
One and only one p is a clean indicator of QE

Data are fsi-dominated

Need more particle spectra and multiplicities from experiment

EMC & Hermes

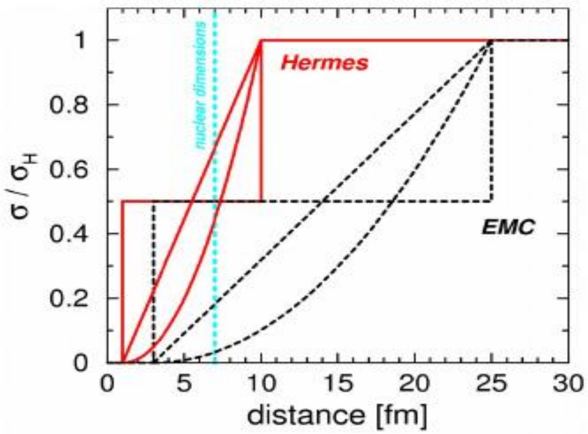
describe simultanously: • EMC@100...280 GeV • Hermes@27 GeV



pre-hadronic cross section:

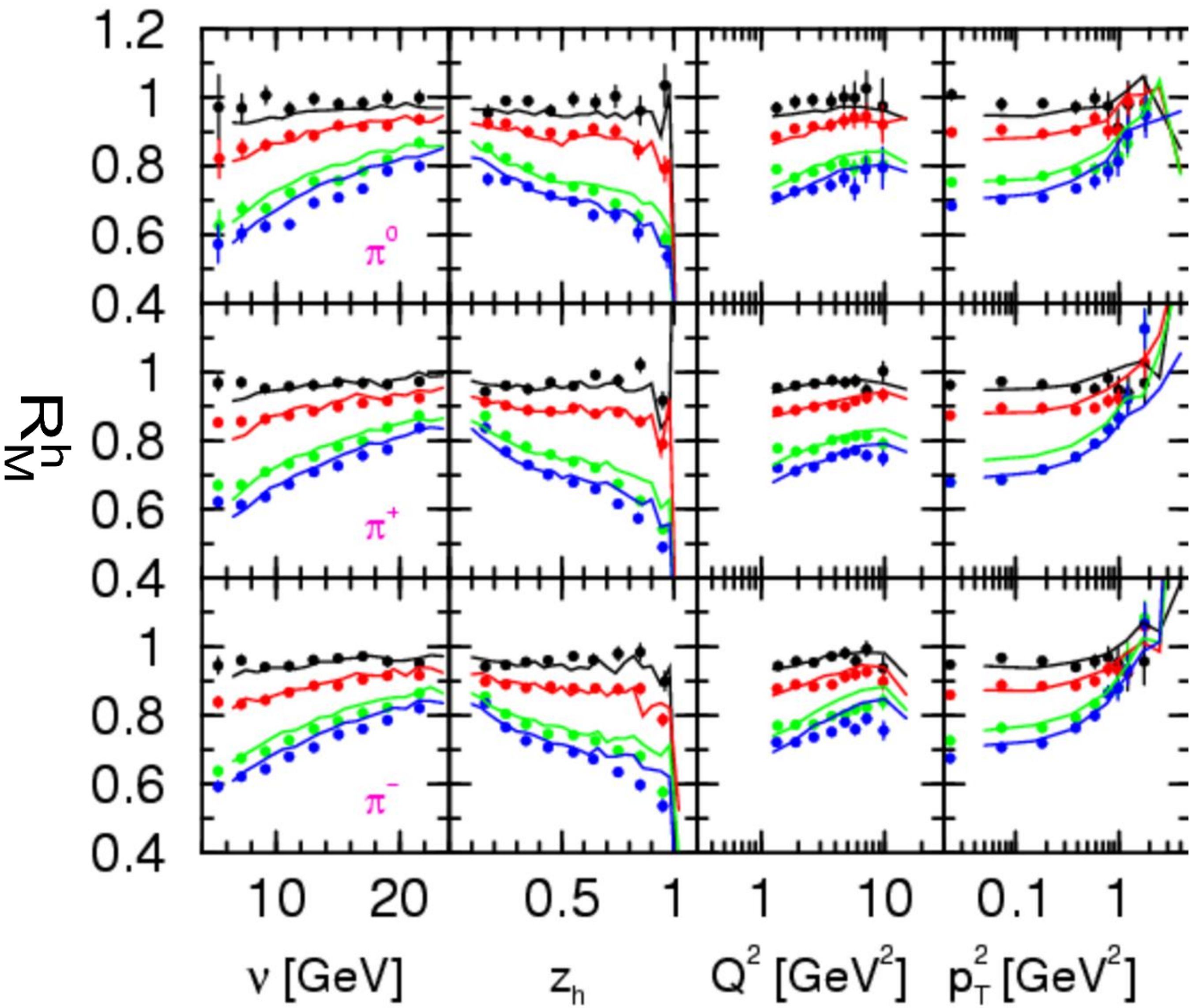
linear increase with time

$$\frac{\sigma^*}{\sigma_H} = \frac{r_{\mathrm{lead}}}{Q^2} + \left(1 - \frac{r_{\mathrm{lead}}}{Q^2}\right)\left(\frac{t - t_{\mathrm{P}}}{t_{\mathrm{F}} - t_{\mathrm{P}}}\right)$$



cf. also Dokshitzer et al.; Farrar et al.

Hermes@27: A.Airapetian et al., NPB780(2007)1



Pions

$^{2}d_{1}$

$^{4}He_{2}$

$^{20}Ne_{10}$

$^{84}Kr_{36}$

$^{131}Xe_{54}$

no diffractive

Future of GiBUU

- At present, we have no plans to implement new features (which ones???)
- We will do bugfixes for the present code and make minor technical additions (e.g. root output)
- Will improve documentation and help outside users to get started in their analyses
- Will encourage outsiders to use and improve the code. This has so far happened for in-medium dilepton physics, for photonuclear reactios and for strangeness production in heavy-ion collisions, but not for the neutrino community