Single Pion Production in NuWro and other MC generators

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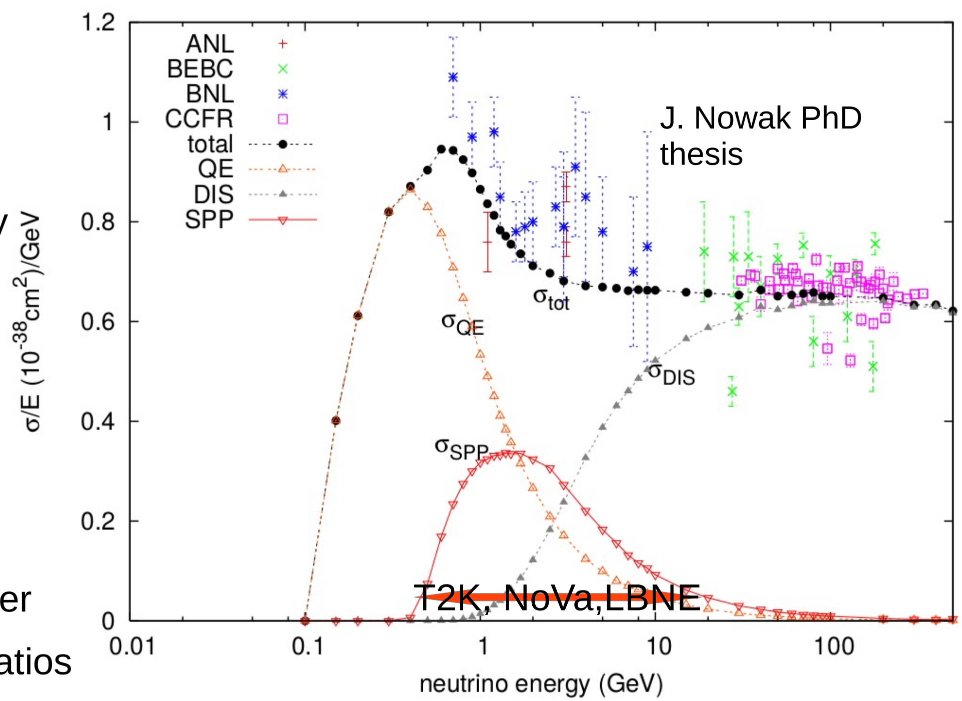
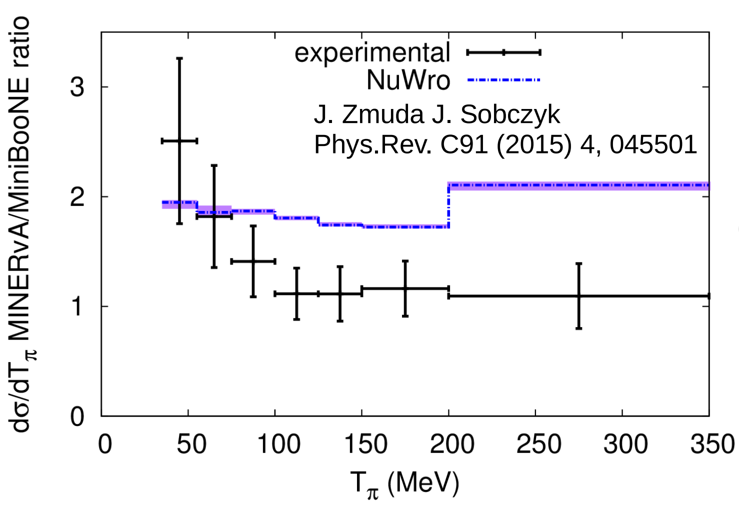
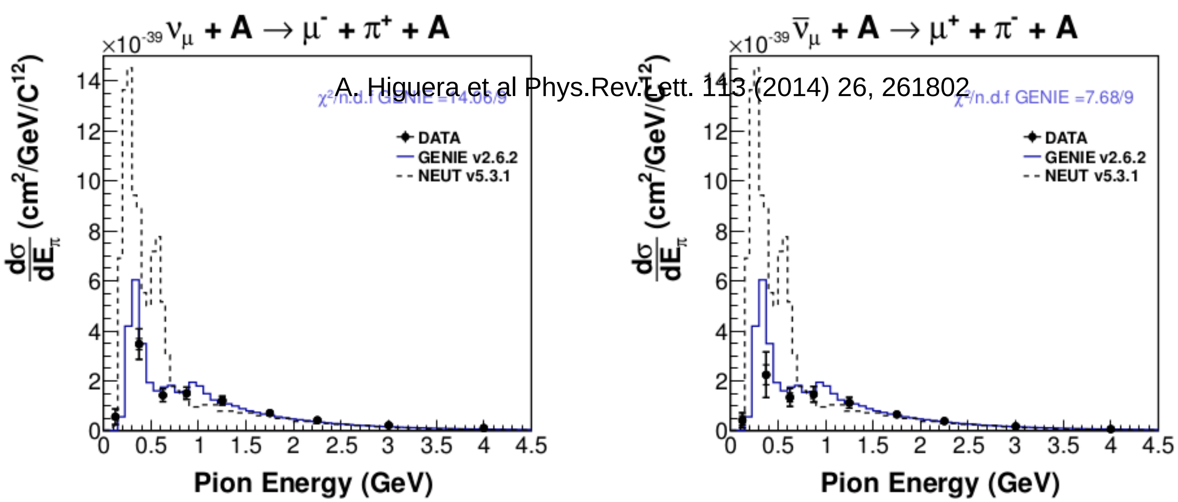
Motivation

- SPP: large part of the neutrino-nucleus cross section at interesting energy range
- Large theoretical uncertainties in the primary vertex, multiple available models for resonant and coherent processes (Rein-Sehgal, Berger-Sehgal, Sato-Lee, Hernandez-Nieves-Valverde, GiBUU...), +nonperturbative nuclear effects!
- Problem of final state interactions (FSI): either Metropolis cascade or coupled-channel equatios
- Experimental uncertainties on the axial transition amplitude parameters (~15% on the best-known Δ(1232) resonance form factors) → problems in understanding of data with our MC







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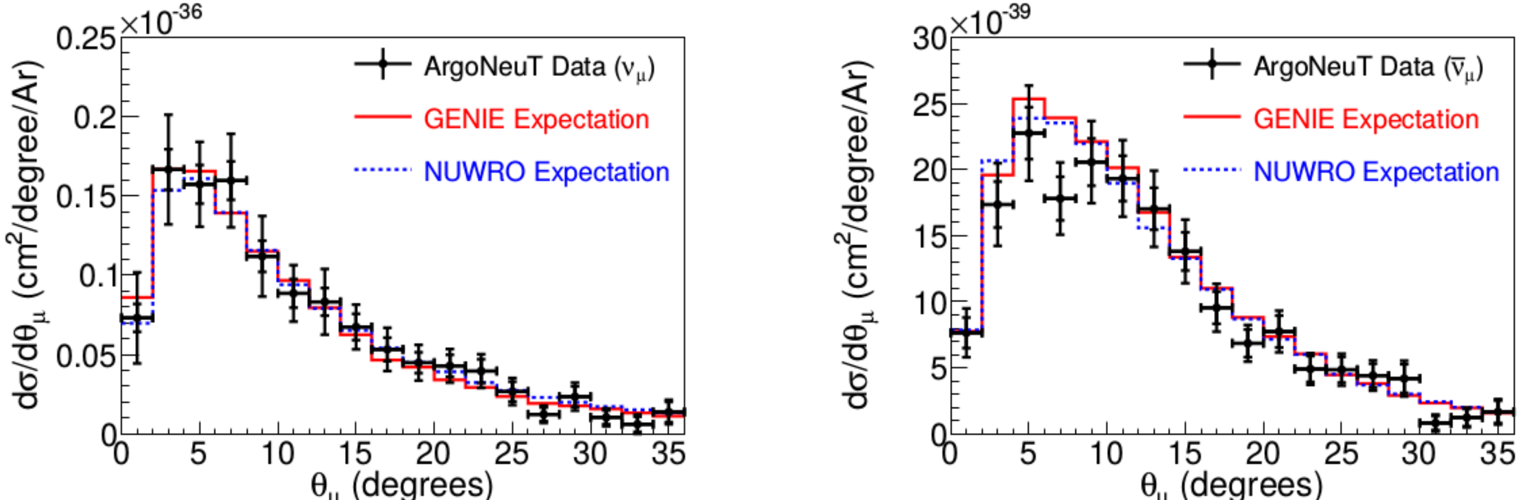
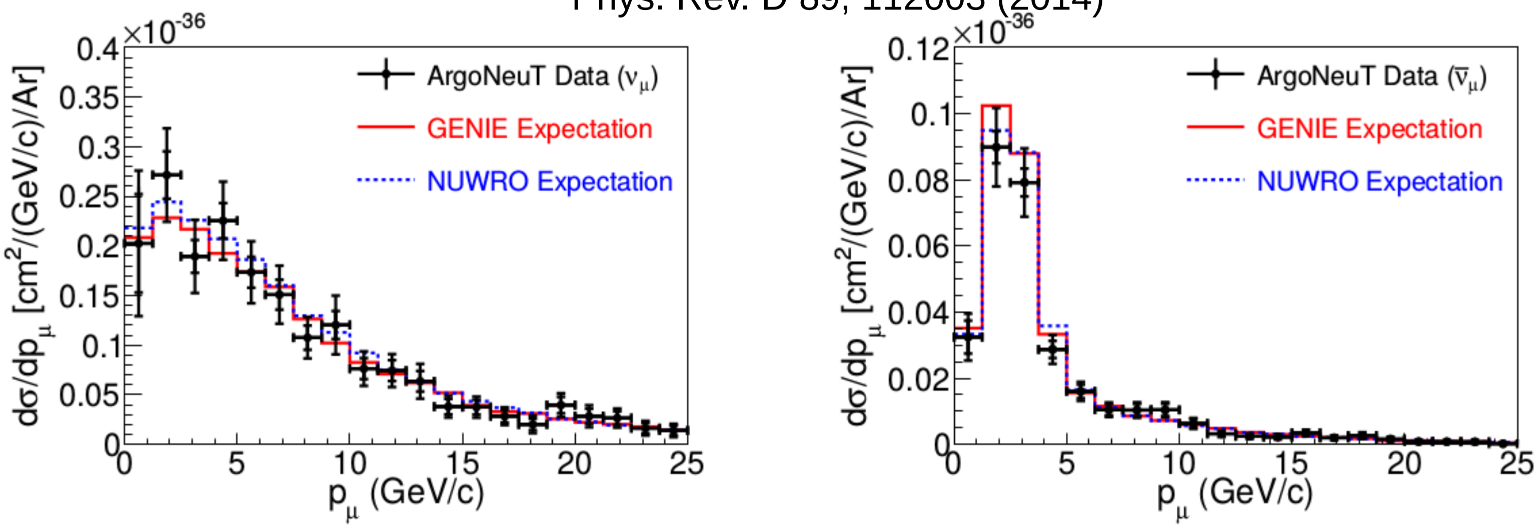
NuWro

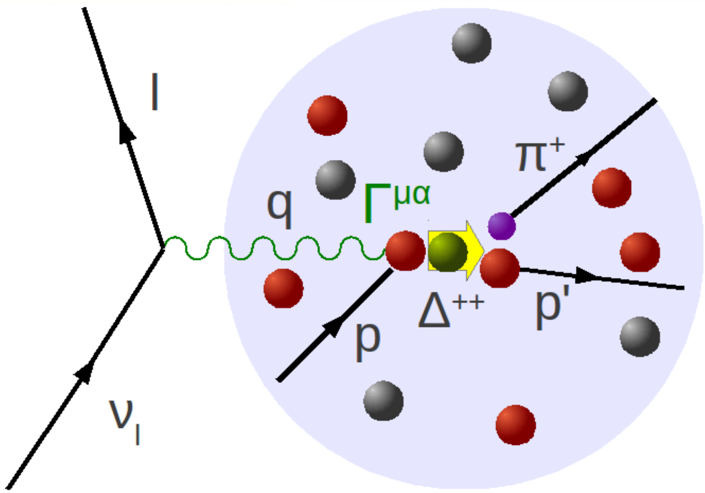
- NuWro- not an official MC of any experiment. Laboratory for new developments.
- ArgoNeut and MINERvA – comparisons to our MC!
- Intensive cross-tests GENIE vs. NuWro by MINERvA (testing GENIE)



Phys. Rev. D 89, 112003 (2014)



NuWro- RES process

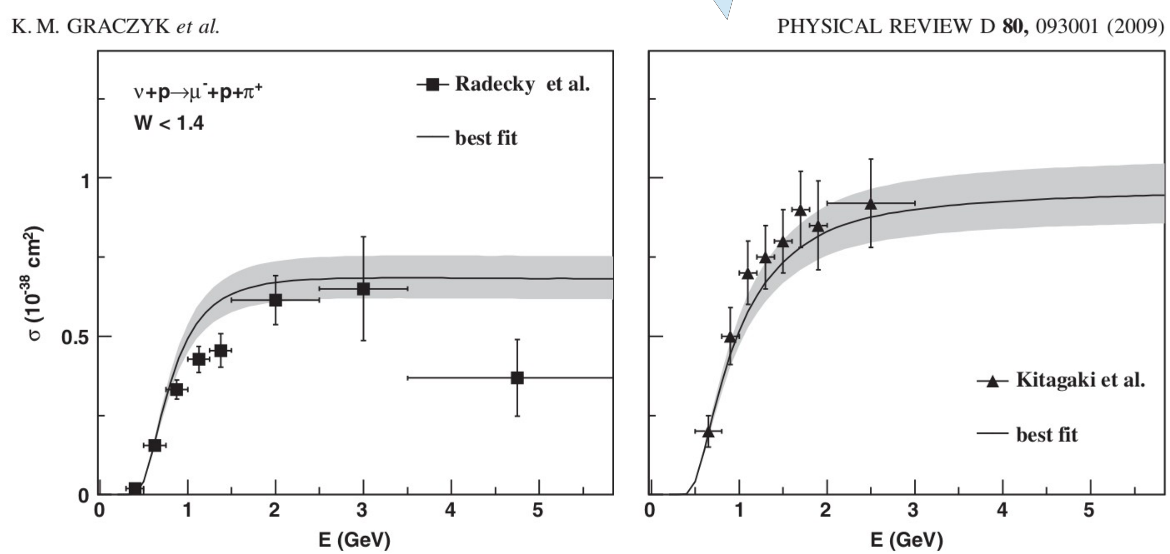


- Interaction on a nucleon in (local) Fermi gas ((L)FG)
- Δ(1232) resonance - isobar model, multiple form factor sets available. Default: best fit from K. Graczyk, D. Kiełczewska, P. Przewłocki, J. Sobczyk Phys. Rev. D80 (2009) 093001

$$\Gamma^{\mu\alpha} = \left[\frac{C_3^V}{M}(g^{\alpha\mu}\not{q}-q^\alpha\gamma^\mu)+\frac{C_4^V}{M^2}(g^{\alpha\mu}q\cdot p_\Delta-q^\alpha p_\Delta^\mu)+\frac{C_5^V}{M^2}(g^{\alpha\mu}q\cdot p-q^\alpha p^\mu)+g^{\alpha\mu}C_6^V\right]\gamma^5+$$
$$+\left[\frac{C_3^A}{M}(g^{\alpha\mu}\not{q}-q^\alpha\gamma^\mu)+\frac{C_4^A}{M^2}(g^{\alpha\mu}q\cdot p_\Delta-q^\alpha p_\Delta^\mu)+C_5^A g^{\alpha\mu}+\frac{C_6^A}{M^2}q^\alpha q^\mu\right]$$

C_5^A=1.19, M_A=0.94 geV

- Vector part: rather well-known from photo- and electroproduction data.
- Axial part: dominated by $C_5^A(Q^2) = \frac{C_5^A(0)}{(1+Q^2/M_{A\Delta}^2)^2}$. $C_5^A(0) \approx 1.2 \propto f^*$. $M_{A\Delta}$: fits to ANL/BNL data.



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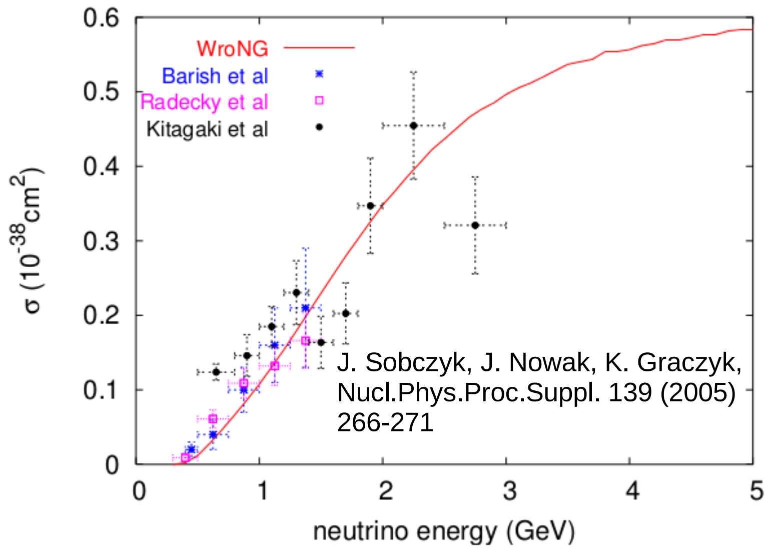
NuWro- RES process

- Heavier resonances: neglected due to „washing out” by fermi motion and the quark-hadron duality hypothesis
- Cross section with smooth passage between the Δ(1232) and DIS (PYTHIA 6) between invariant mass W=1.4 and 1.6 GeV. Part of DIS: nonresonant background (J. Nowak PhD thesis). $f_{SPP}(W)$- fraction of DIS process contributing to SPP.

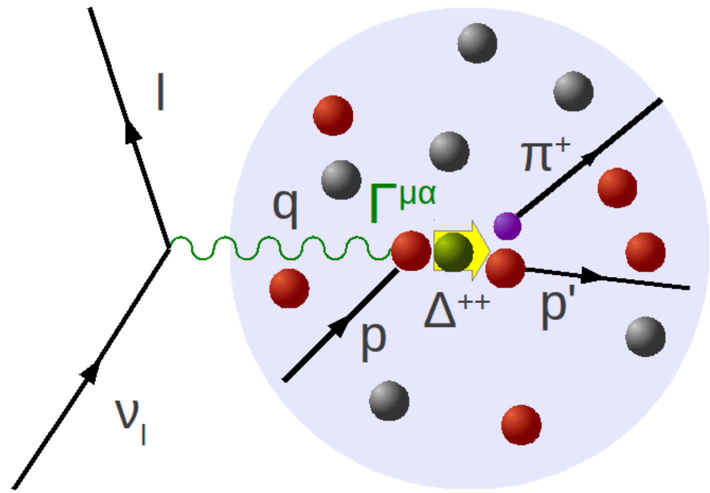
$$\frac{d\sigma^{RES}}{dW}=\frac{d\sigma_{\Delta}}{dW}(1-\alpha(W))+\frac{d\sigma_{DIS}}{dW}f_{SPP}(W)\alpha(W)$$



First name of NuWro! :)

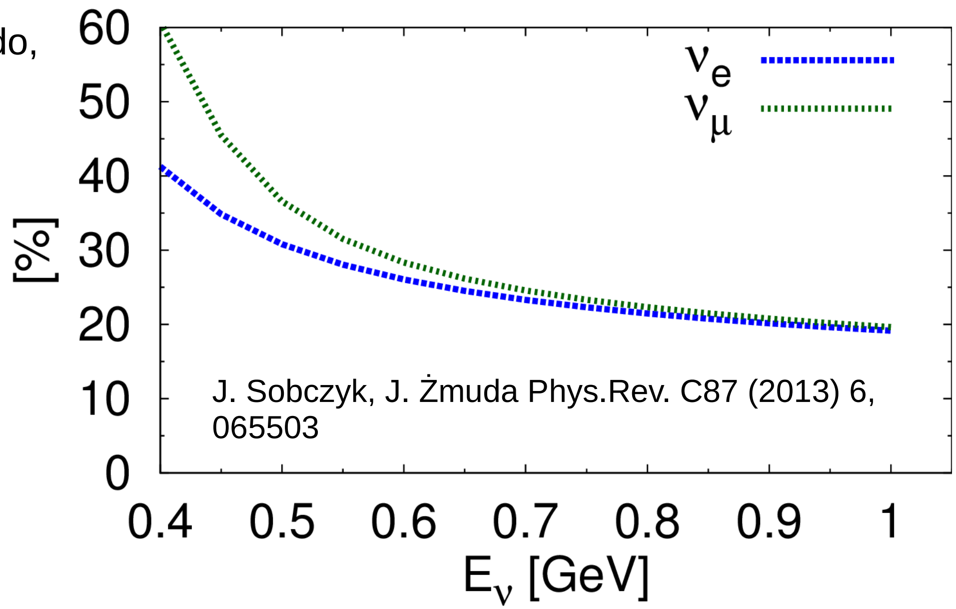
Figure 8. WroNG predictions in the channel $\nu_\mu n \to \mu^- \pi^+ n$ and experimental data (total cross section) from [8] [9]

RES process in NuWro

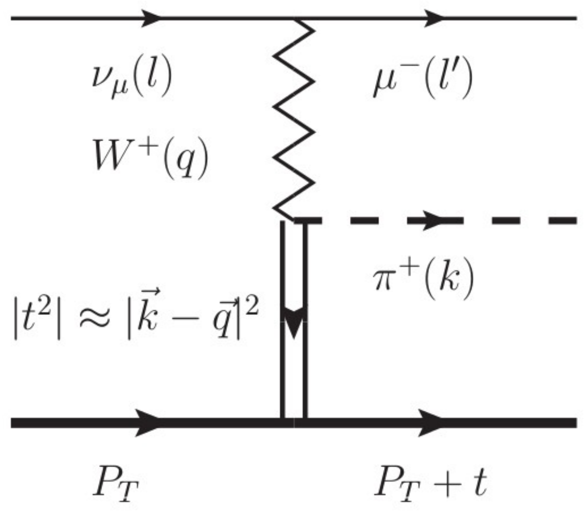


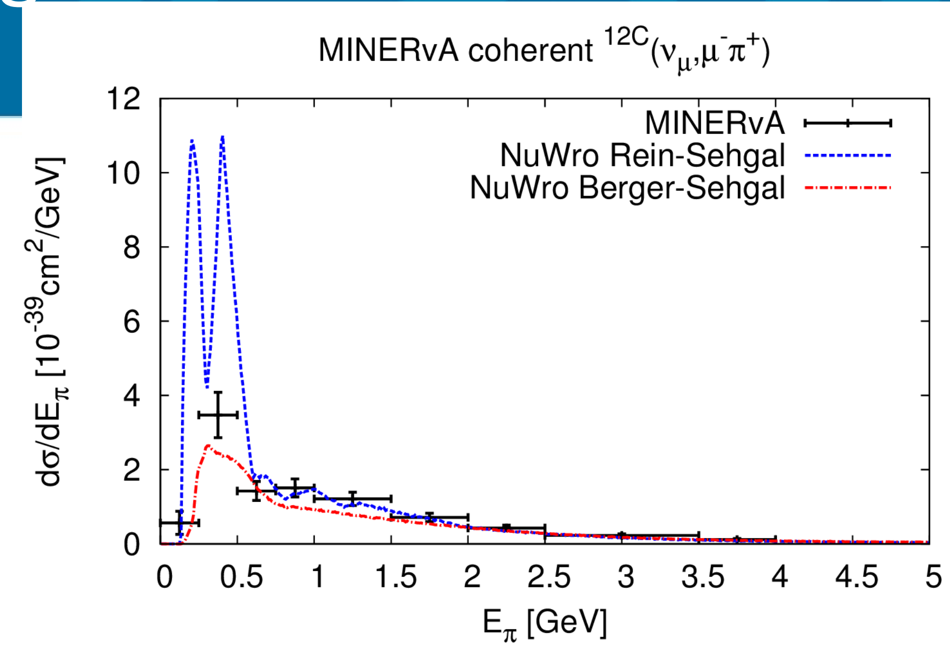
- Recent features:
  - $\Delta(1232)$ resonance decay anisotropy correction (density matrix measured in ALN/BNL experiments (S.J. Barish et al, Phys. Rev. D19 (1979) 2511; G.M. Radecky et al, Phys. Rev. D25 (1982) 1161. T. Kitagaki et al., Phys. Rev. D34 (1986) 2554.)

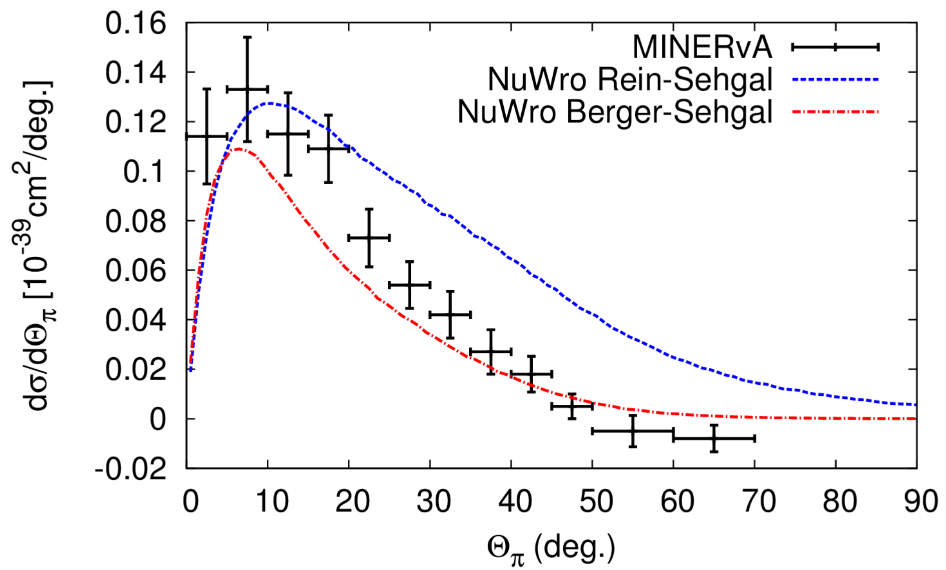
$\Delta(1232)$ self-energy effects (pionless decays, corrections to SPP from E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987)) in an approximate manner (as a total cross-section modification)



COH process

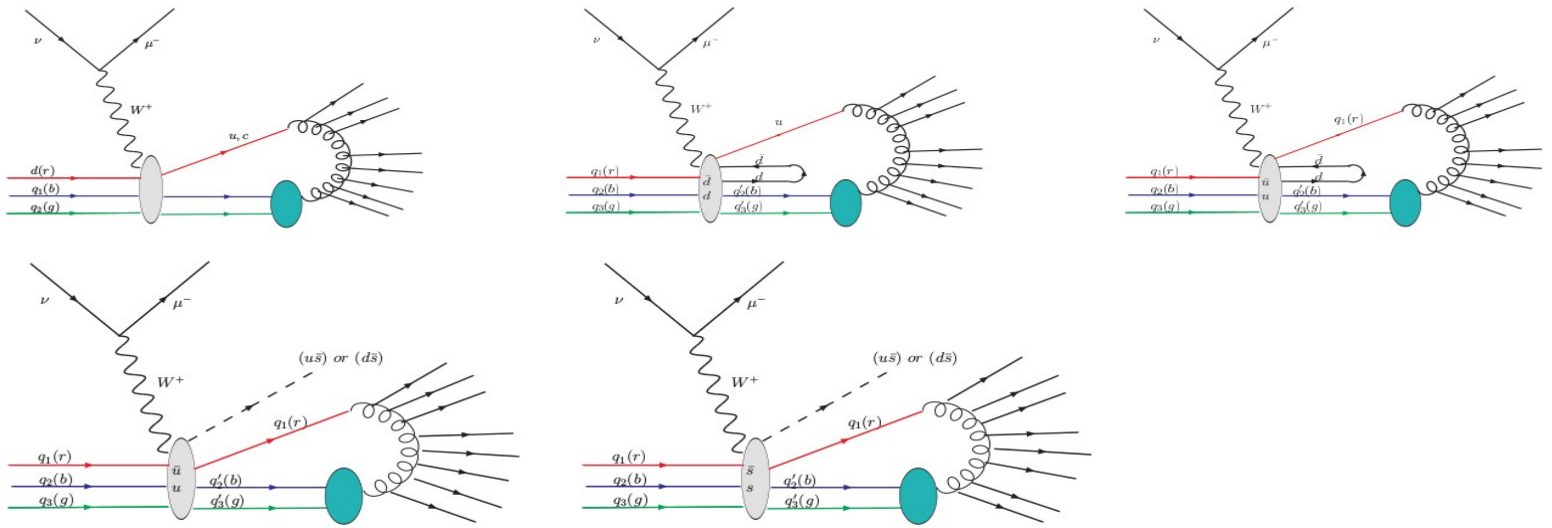




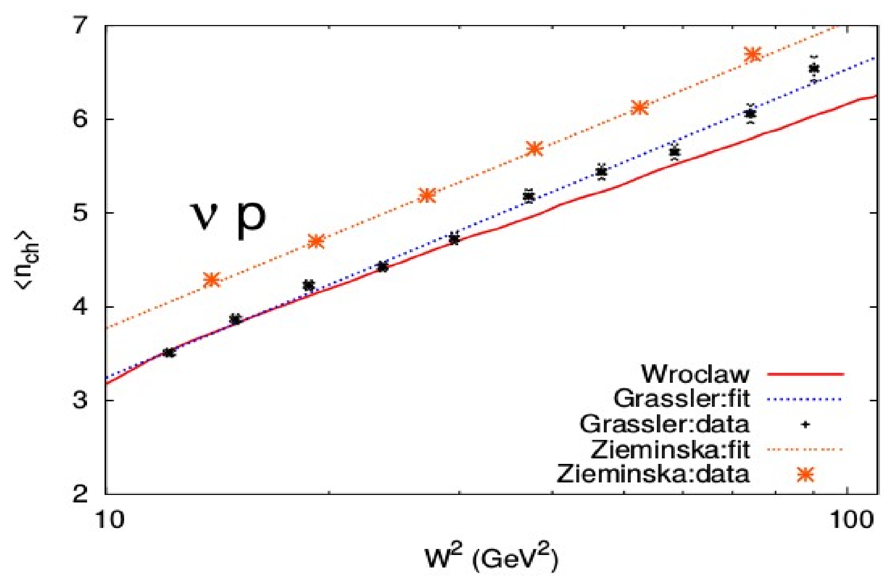


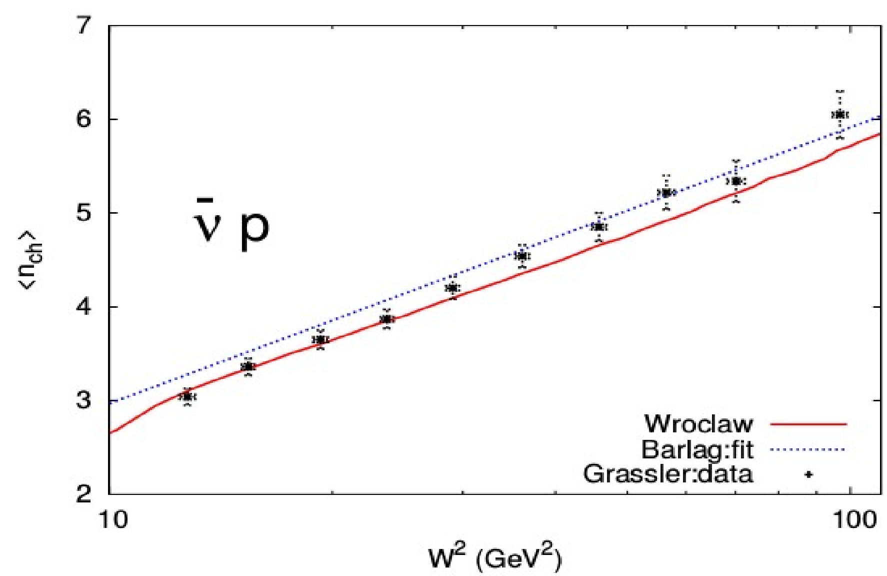
- Coherent pion production through t-channel exchange, nucleus left in the ground state (Adler PCAC -based Models).
- Both Rein-Sehgal (Nucl. Phys. B 223 (1983)) and Berger-Sehgal (Phys. Rev. D 79, 053003 (2009)) models available. Comparison to MINERvA data (Phys. Rev. Lett. 113, 261802 (2014)). Work-in-progress, „hot” topic for NEUT as well (P. M. Martins).

DIS process- multiple pion source



- PYTHIA/LUND algorithm fine-tuned to hadron multiplicity data by J. Nowak in his Ph. D. Thesis (this slide's pictures source).





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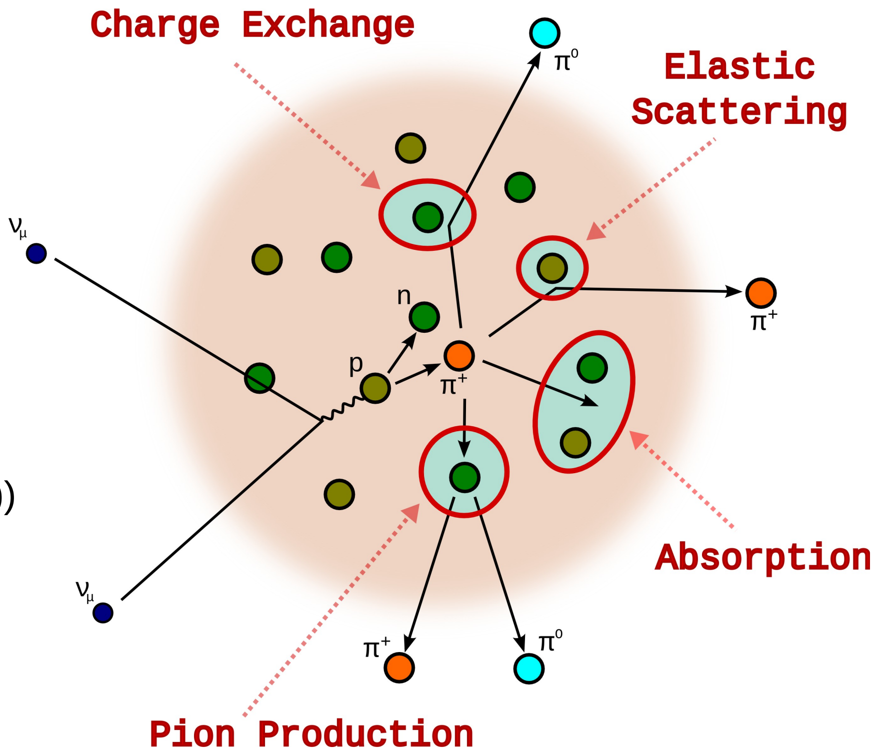
Final State Interactions in NuWro

- All particles start inside nucleus. A lot can happen on their way out (pions from pion-less channels as well):

- FSI cascade (Phys.Rev. C86 (2012) 015505) :
  - Based on N. Metropolis et al., Phys. Rev. 110, 185 (1958); N. Metropolis et al., ibid. 110, 204 (1958).
  - Local density approximation
  - For pion charge exchange, elastic scattering and absorption up to 350 MeV Oset model (E. Oset, L. L. Salcedo, and D. Strottman, Phys. Lett. B 165, 13 (1985); E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987)) is assumed.
  - Outside the above region: available pion-nucleon scattering data.
  - Mean free path from xs, but step < 0.2 fm
  - Additional effect: formation time (FT)/ formation zone (FZ): minimal dist<ance/time before the created particles can interact:different models and parameters. NuWro:



(by T. Golan)

$$QEL: f_t = \frac{E}{|p \cdot q|} \left(coherence\, length,\, p - nucleon\, 4-momentum,\, q - 4-momentum\, transfer,\, E - nucleon\, energy\right)$$

$$RES: f_t = \frac{E_\Delta}{M_\Delta \Gamma_\Delta} \left(\Delta\, resonance\, lifetime\right)$$

$$DIS: f_t = \frac{\tau_0 M^2}{M^2 + p_T^2} \left(Rantf\, with\, transverse\, momentum\right)$$

Formation Zone

(T. Golan, C. Juszczak and J.T. Sobczyk, Phys. Rev. C86 (2012) 015505)

TABLE III. Formation Time models in various Monte Carlo event generators.

MC	QE	RES[a]	DIS
NEUT	–	SKAT	SKAT
FLUKA	Coh length	Rantf	Rantf
GENIE	–	–	Rantf-like
NUANCE	1 fm	1 fm	1 fm

[a]Note that every MC has its own definition of what the RES and DIS terms mean.

Better agreement of MC with data!
(cost of arbitrary parameter)

- Importance of Formation Zone for DIS

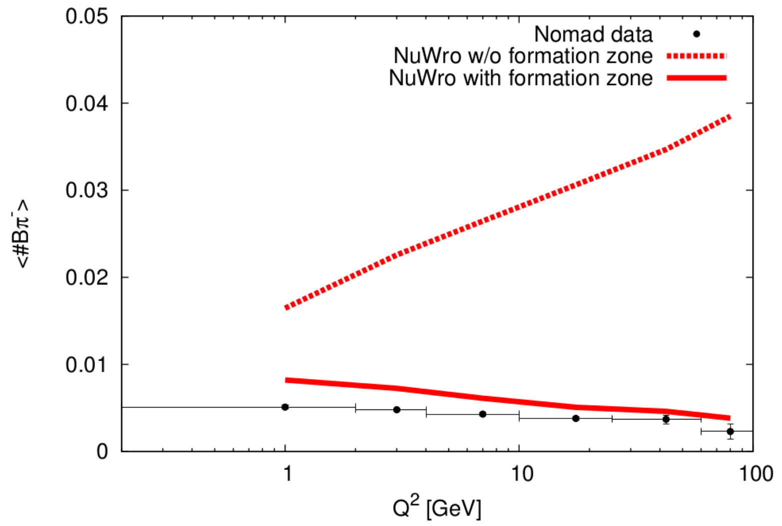


FIG. 7. Average number of backwards going pions as a function of Q^2 in the NOMAD experiment.

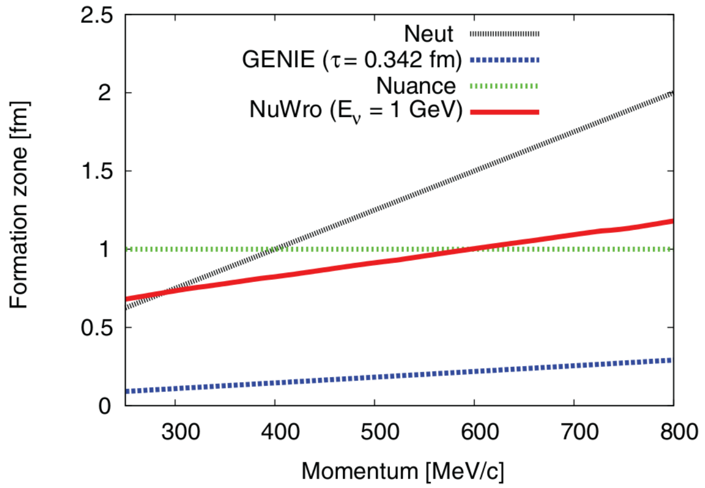


FIG. 12. (Color online) Laboratory frame nucleon formation zone as a function of nucleon momentum.

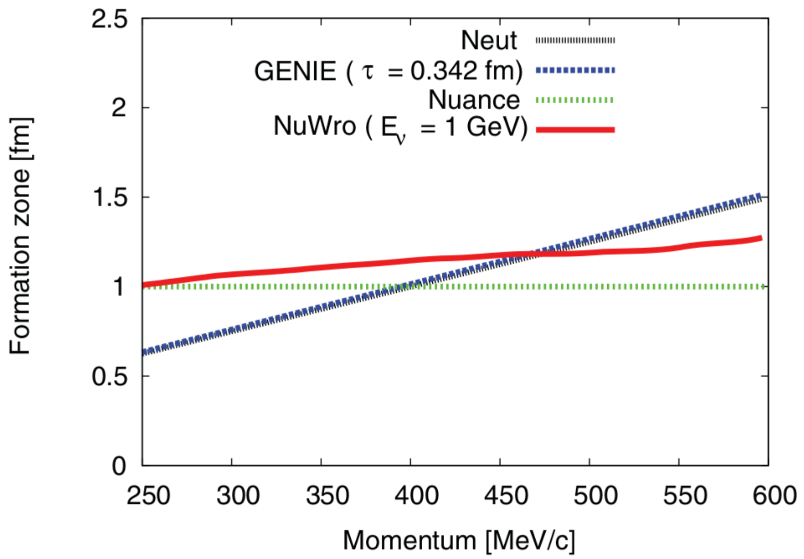
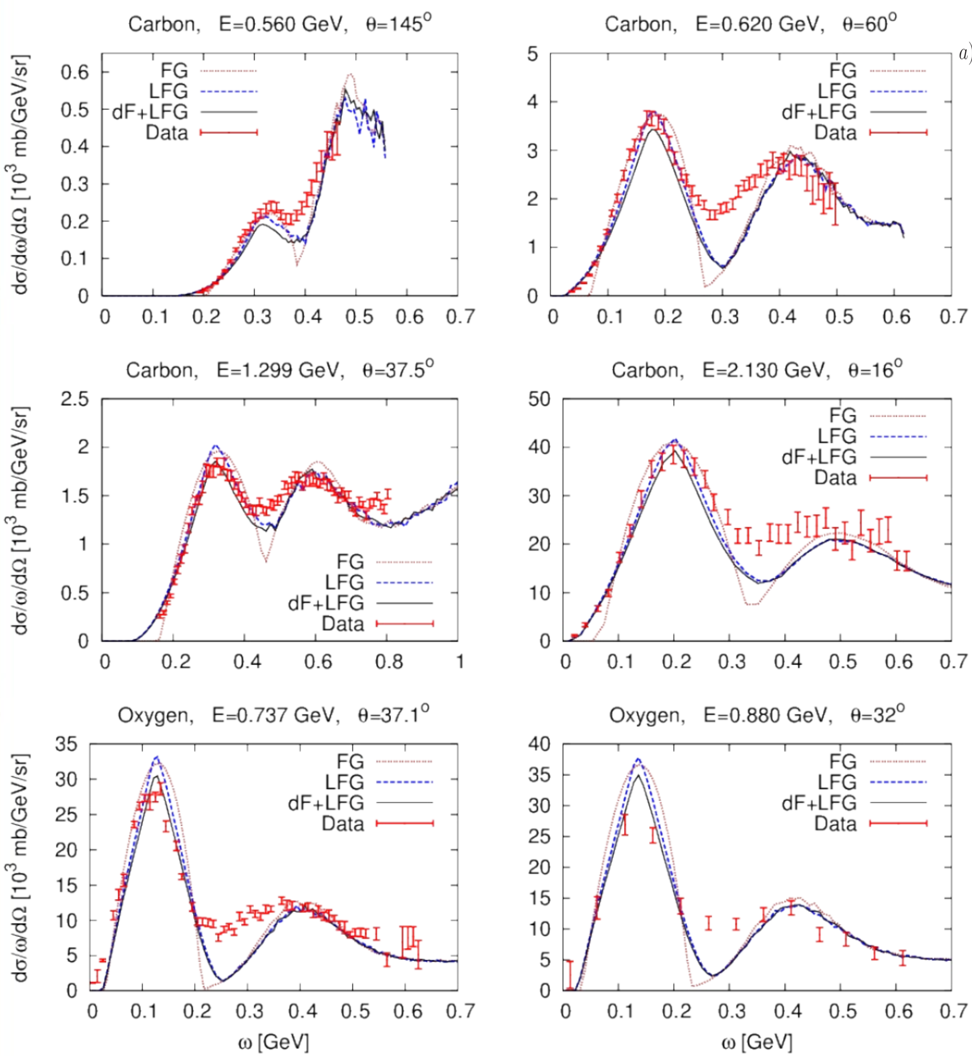


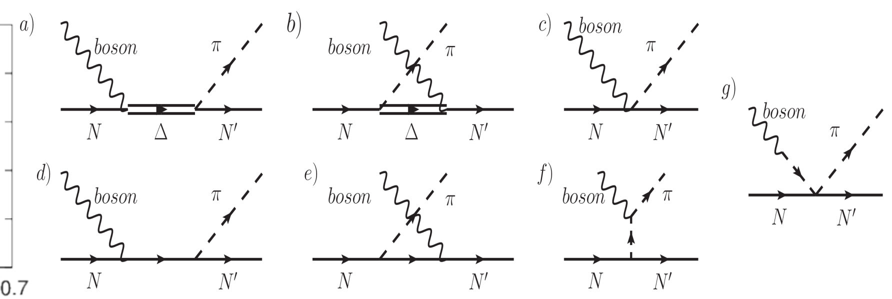
FIG. 13. (Color online) Laboratory frame pion formation zone as a function of pion momentum.

Electron scattering

- Current work-in-progress
- Already included: quasielastic and single pion production
- The latter with Delta selfenergy and microscopic model for nonresonant background

(E. Hernandez, J. Nieves, M. Valerde
PRD 76, 033005 (2007))





- **Testing all models on very accurate data!**

J. Ż., K. Graczyk, C. Juszczak, J. Sobczyk arXiv:1510.03268,
To appear in Acta Physica Polonica B

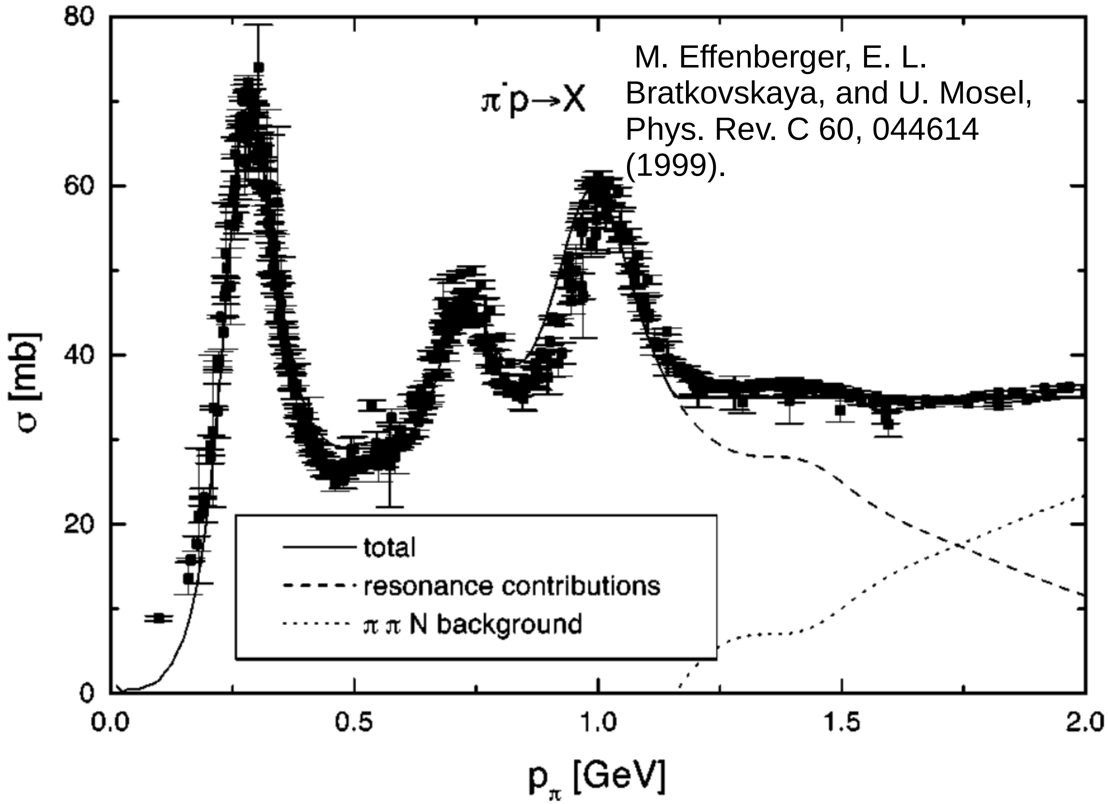
Pion production in GiBUU

- Giessen Boltzmann–Uehling–Uhlenbeck (GiBUU) model (following U.Mosel Phys.Rev. C91 (2015) 6, 065501):

1) Initial interaction on a nucleon in a local Fermi gas
2) Hole spectral function of the nuclon (with position and momentum dependent effective mass):

$$P_h(p,E)=g\int d^3r\,\theta(p_F(r)-|p|)\,\theta(E)\,\delta\left(E-m^*(p,r)+\sqrt{|p|^2+m^*(p,r)^2}\right)$$

3) Excitation of a whole series of resonances up to D_{35}(2350) with their decay channels and widths from PDG data (Phys. Lett. B667, 1 (2008))

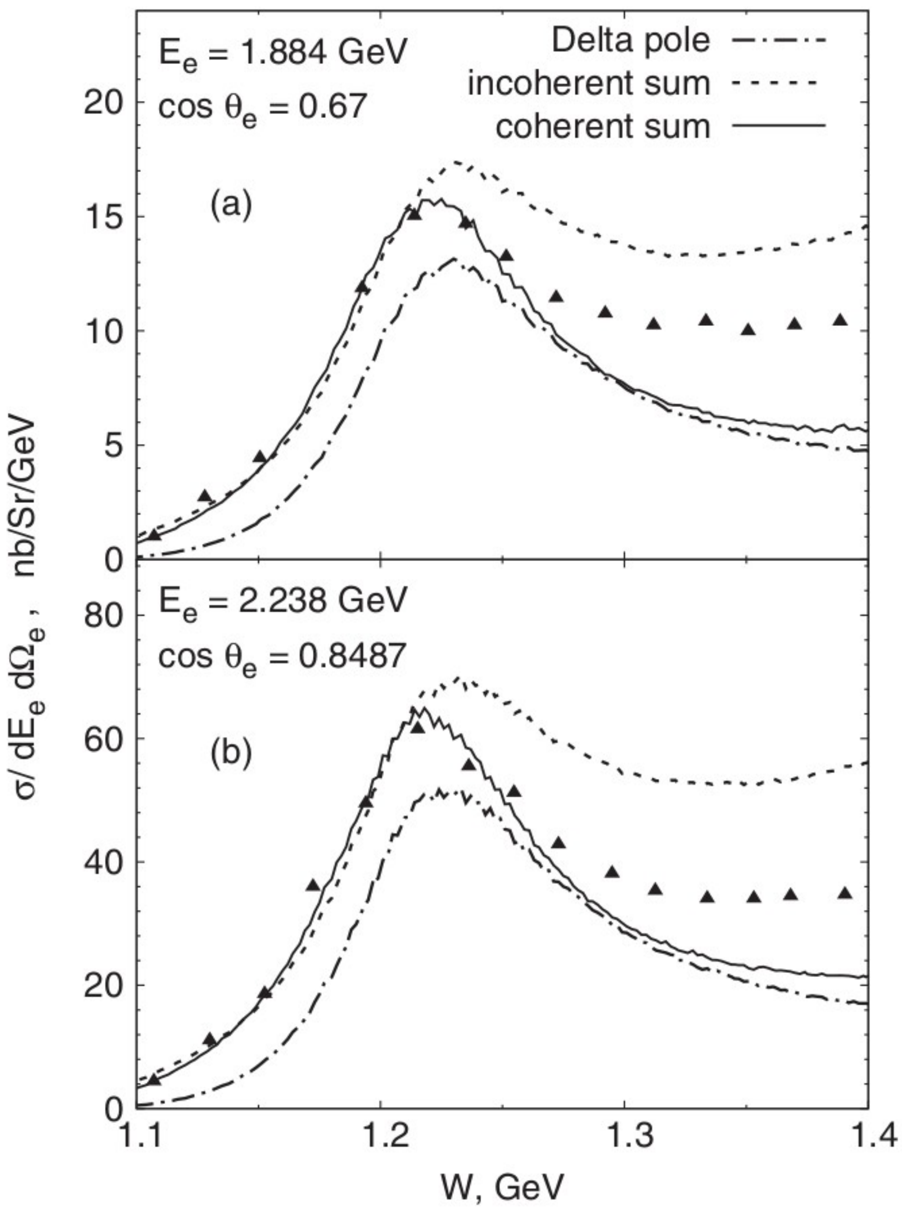


Pion production in GiBUU

- Giessen Boltzmann–Uehling–Uhlenbeck (GiBUU) model (following U.Mosel Phys.Rev. C91 (2015) 6, 065501):

4) Resonance vector form-factors from MAID http://wwwkph.kph.uni-mainz.de/.
5) Axial form factors of the Δ(1232) resonance: fits to ANL/BNL data; other resonances: leading form factor from Goldberger-Treiman relation, dipole with M_A=1 GeV (wild guess, no data on that)
6) In medium effects: spectral function with final nucleon Pauli Blocking (momentum- and energy-dependent!) for each resonance and collisional broadening of Δ(1232) E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987).
7) Other sources of initial pions: nonresonant backround in the Δ(1232) region (adaptation of E. Hernandez, J. Nieves, M. Valerde PRD 76, 033005 (2007): background+ resonance-background interference terms) and DIS from PYTHIA (passage around 2 GeV)
8) No coherent/diffractive production!

O. Lalakulich, T. Leitner, O. Buss, U. Mosel
PHYSICAL REVIEW D **82,** 093001 (2010)



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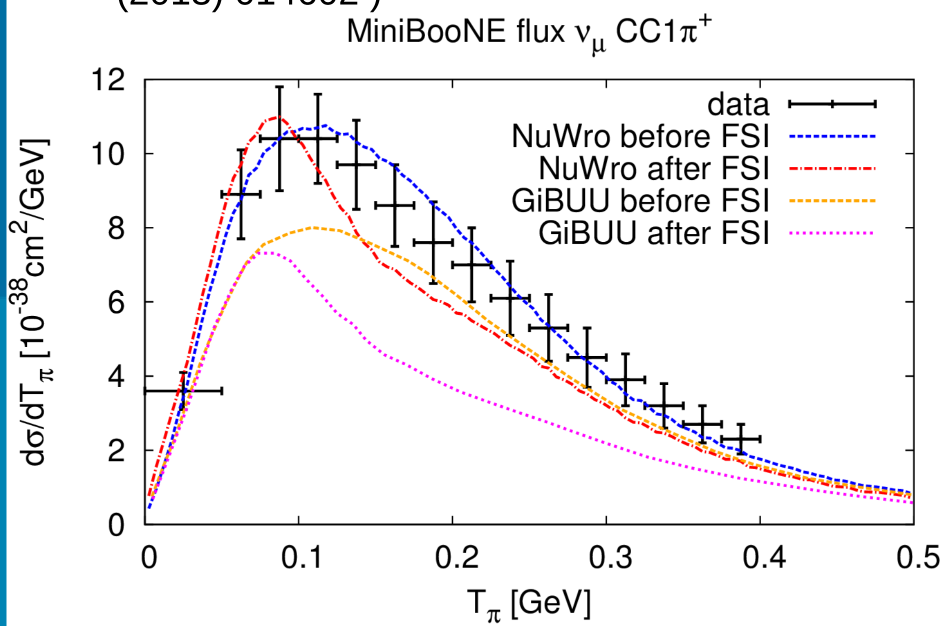
FSI in GiBUU

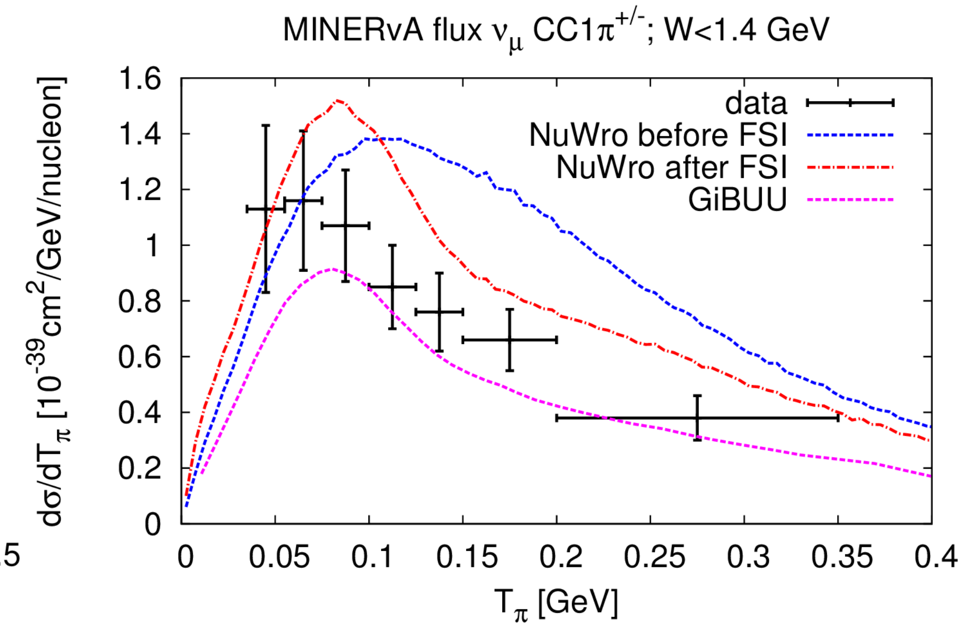
- Giessen Boltzmann–Uehling–Uhlenbeck model: propagate resonances and other particles in coupled-channel semiclassical transport approach (numerical implementation of Kadanoff-Baym equations from L. Kadanoff and G. Baym, Quantum statistical mechanics (Benjamin, New York, 1962) in the gradient approximation and the approximation for off-shell transport from W. Botermans and R. Malfliet, Phys.Rept. 198, 115 (1990).:

1) All resonances propagate before decay
2) Time evolution of the system given by resonance widths and collission rates, no free parameters such as formation time etc. (but DIS from PYTHIA 6 with „formation time" - linear time-dependence of interaction cross sections → K. Gallmeister, U. Mosel Nucl. Phys. **A801** (2008) 68-79)
3) Background terms- immediate decay into πN
4) Regular Glauber model for pion propagation, not the BUU.
5) Coupled channels. Effectively FSI-produced pions coming from initial QE/2p2h as in NuWro cascade.

Comparison GiBUU vs. NuWro vs. MiniBooNE vs. MINERvA

- Some comparison between NuWro, GiBUU and data (GiBUU default Δ resonance form factors fit to ANL data, following results of C. Wilkinson, P. Rodrigues, S. Cartwright, L. Thompson, and K. McFarland Phys.Rev. D90, 112017 (2014), GiBUU points scan from O. Lalakulich and U. Mosel Phys.Rev. C87 (2013) 014602)

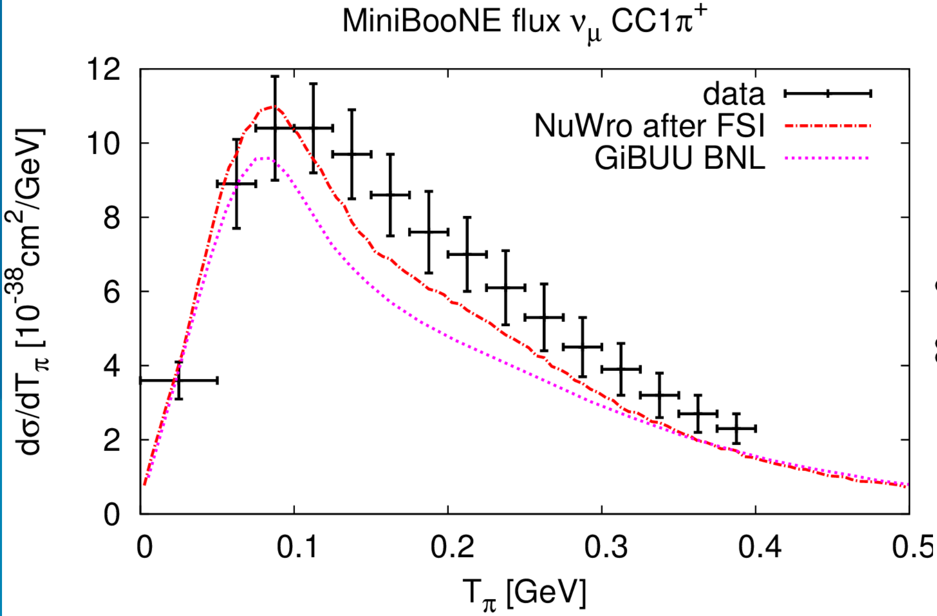


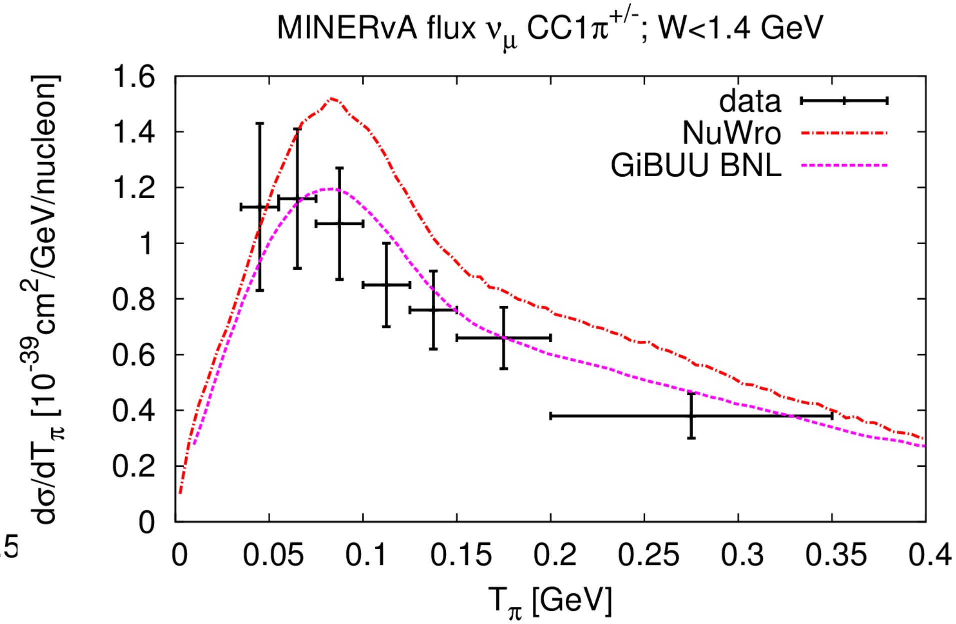


- Different physical models, similar effects of FSI (inelastic π+N → Δ)
- MINERvA (B. Eberly et al arXiv:1406.6415v3 [hep-ex]): higher beam energy than MibiBooNE (A.A. Aguilar-Arevalo et al. Phys.Rev. D83 (2011) 052007) but... W<1.4 GeV (basically just the Δ resonance region) → expecting same physics, similar FSI effects as in NuWro, π^- minor effect.
- MINERvA overestimated MiniBooNE underestimated by NuWro.

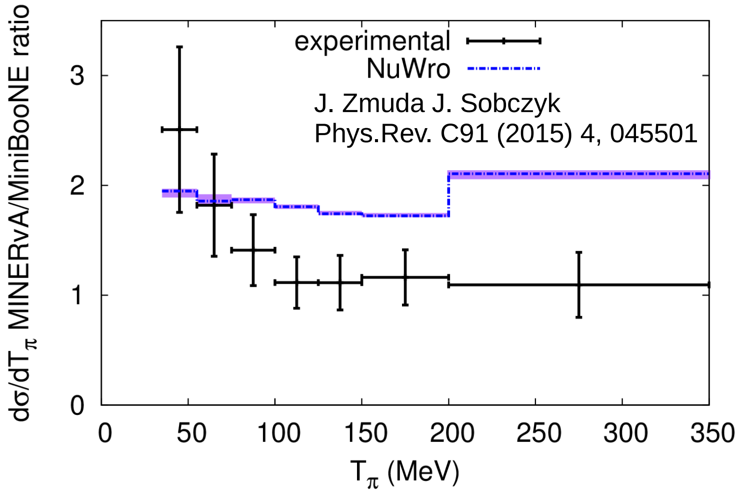
Comparison GiBUU vs. NuWro vs. MiniBooNE vs. MINERvA

- What about GiBUU+ overestimated form factors from BNL data set (O. Lalakulich and U. Mosel Phys.Rev. C87 (2013) 014602)?





- Different generstors with different physical models of initial and final state interactions, same problem.
- The ratio:



Pion Production in NEUT (thanks to Y. Hayato for slides!)

Single pion production via resonance in NEUT

Use the model by Rein and Sehgal (Annals of Physics 133, 79-153 (1981)
(based on the quark model of Feynman, Kislinger and Ravndal (FKR).

- Code to calculate the helicity amplitude
  Provided by the authors

- Calculation of the cross-section ($d\sigma/dq^2dW$)
  Follow the formula in the publications

Add helicity amplitudes as proposed in the original article
to take into account the interference of the resonances
(**plus non-interfering J=1/2 background)**

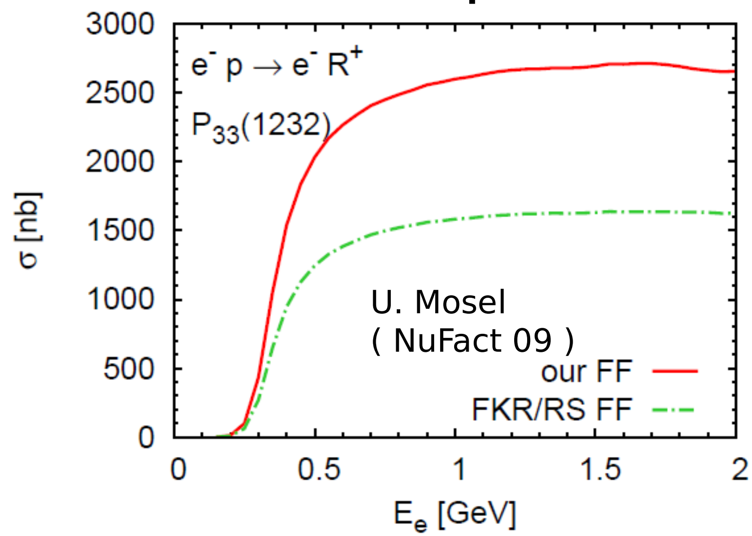
- Lepton mass corrections by the same authors
  have been included

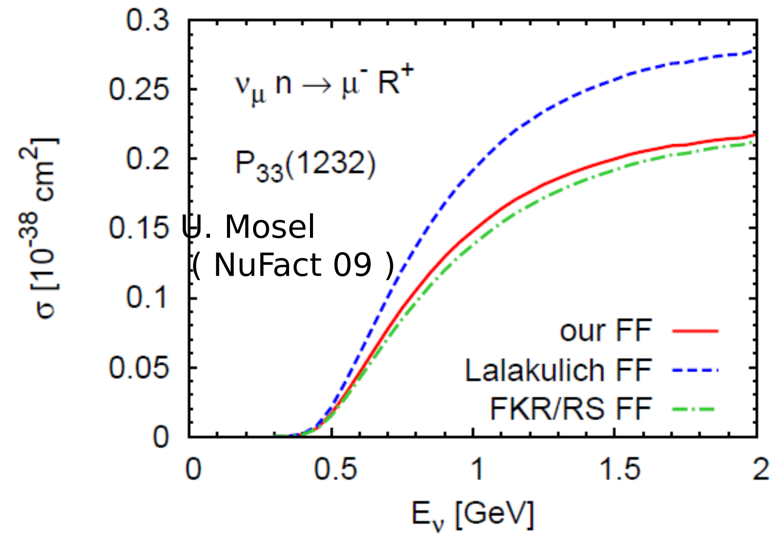
- Two form factors are implemented
  Original form factor by Rein & Sehgal
  $M_A = 1.21\ \mathrm{GeV}/c^2$ was chosen
  Revised form factor by K.M. Graczyk and J.T. Sobczyk
  (explained later)

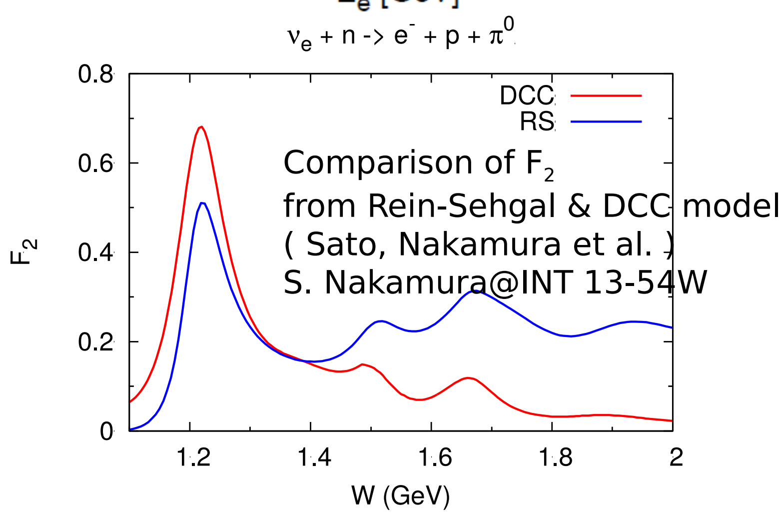
Pion Production in NEUT (thanks to Y. Hayato for slides!)

Known issue in the Rein-Sehgal model

electro-pion production cross-section
can not reproduce data if we use the vector part







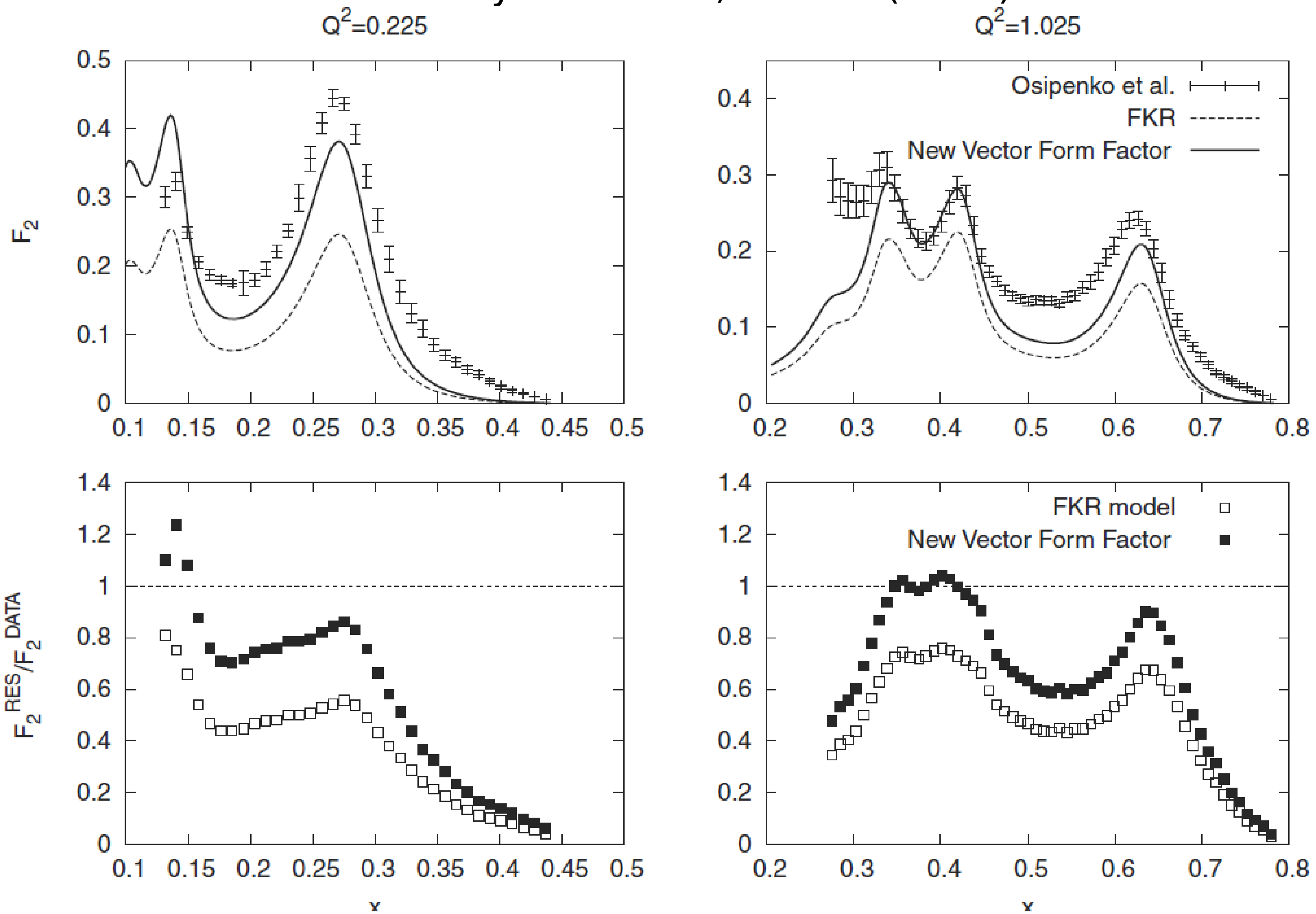
Interestingly, results for neutrino agrees pretty well.
(Including axial current component
makes the cross-section similar.)

Pion Production in NEUT (thanks to Y. Hayato for slides!)

Single pion production via resonance in NEUT

Attempts to improve the vector form factor in Rein-Sehgal model

Prescription by K.M. Graczyk and J.T. Sobczyk
Phys.Rev.D 77,053001 (2008)



Pion Production in NEUT (thanks to Y. Hayato for slides!)

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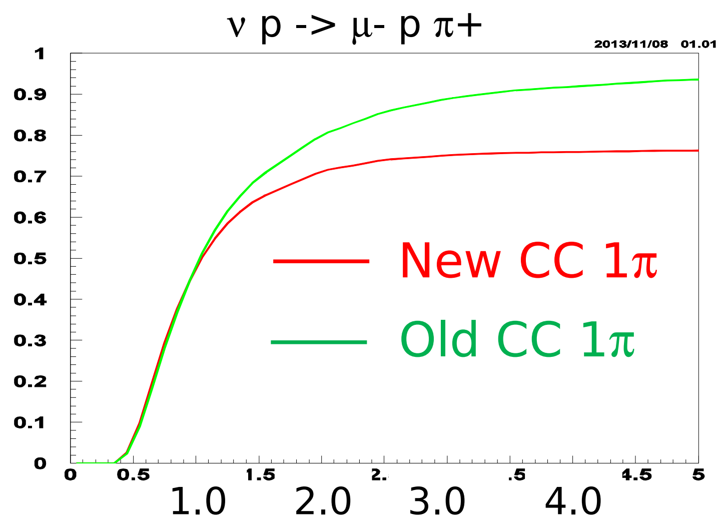
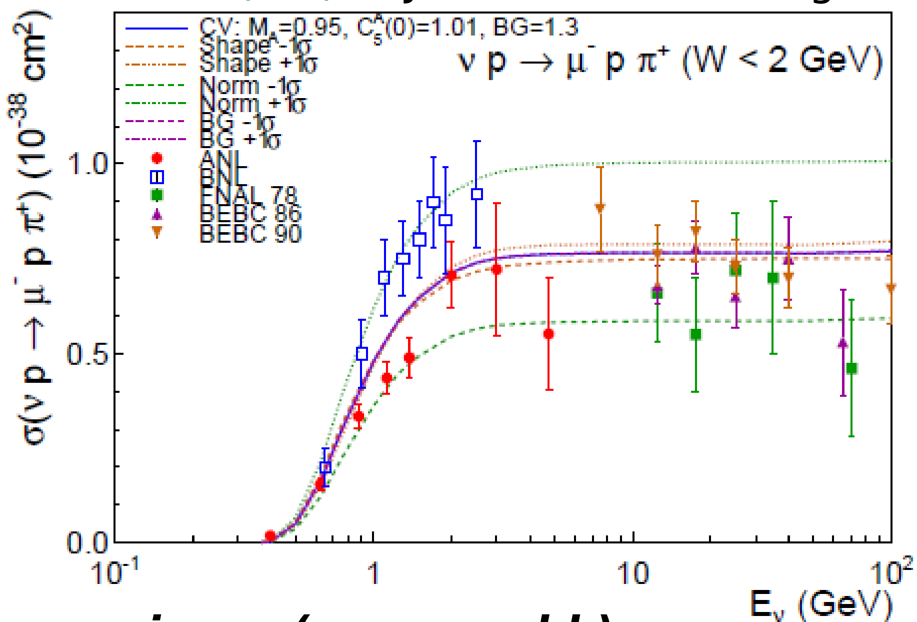
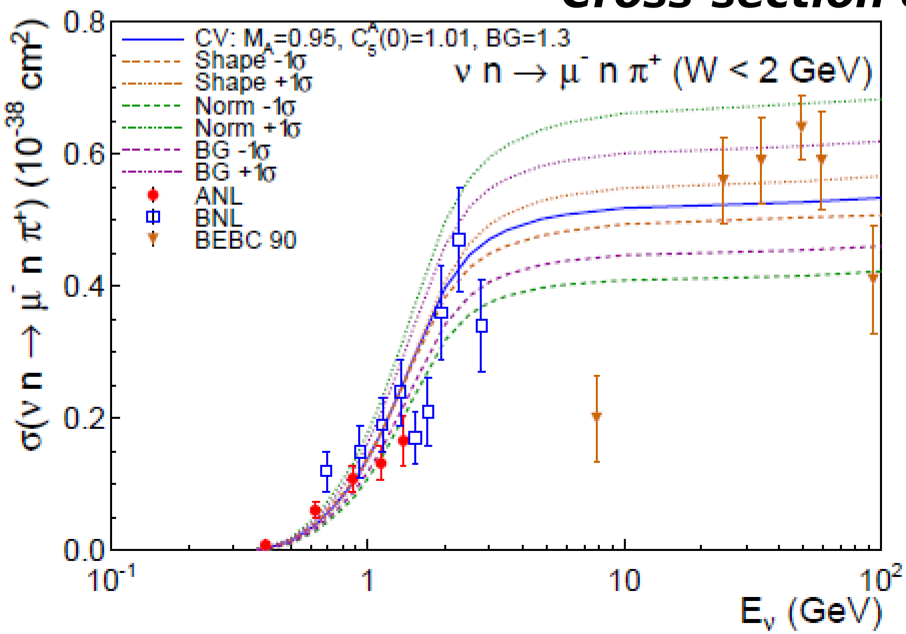
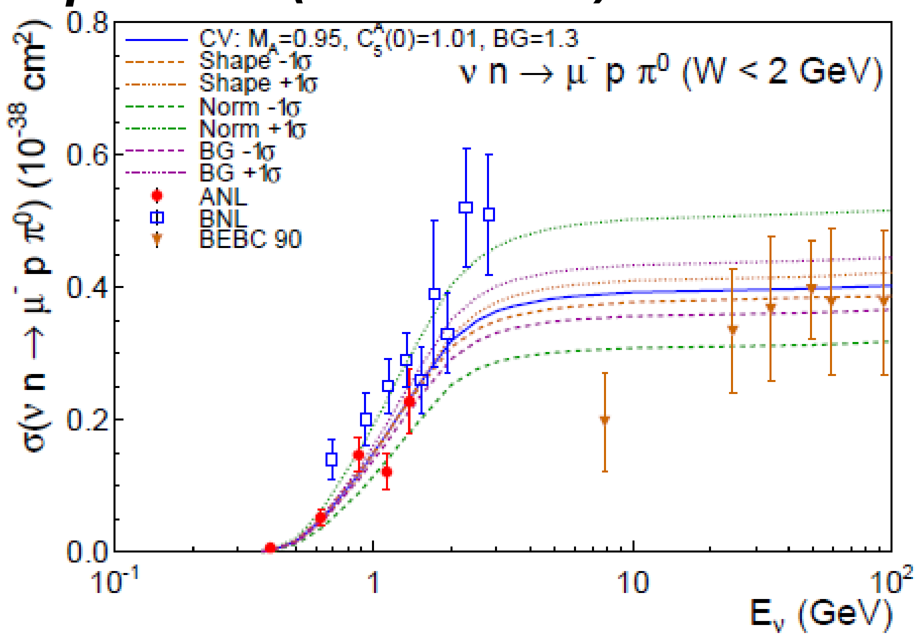
Axial part: fits $C^5_A(0)$ (1.01), M_A (0.95 GeV) and scale (1.3) of J=1/2 nonres. background To ANL/BNL bubble chamber data





Cross-section comparison (new vs old)





Pion Production in NEUT (thanks to Y. Hayato for slides!)

Single pion production via resonance in NEUT

For the interaction in nucleus,
initial interactions are modified

- Pauli-blocking effect is taken into account
  Momentum of nucleon after the decay of delta
  has to be larger than the Fermi surface momentum.
  (2 ~ 3 % of the interactions are prohibited.)

- Pion-less delta decay has been implemented
  20% of the delta are assumed to be absorbed.

$$\nu\, N \rightarrow l\, \Delta$$

$$\Delta\, N \rightarrow N\, N$$

~ no pion is produced but lepton and nucleon are ejected
for the interaction in nucleus.

*) Recently, meson exchange current interaction
was independently added
and ***this feature has been turned off by default***
in the latest release.

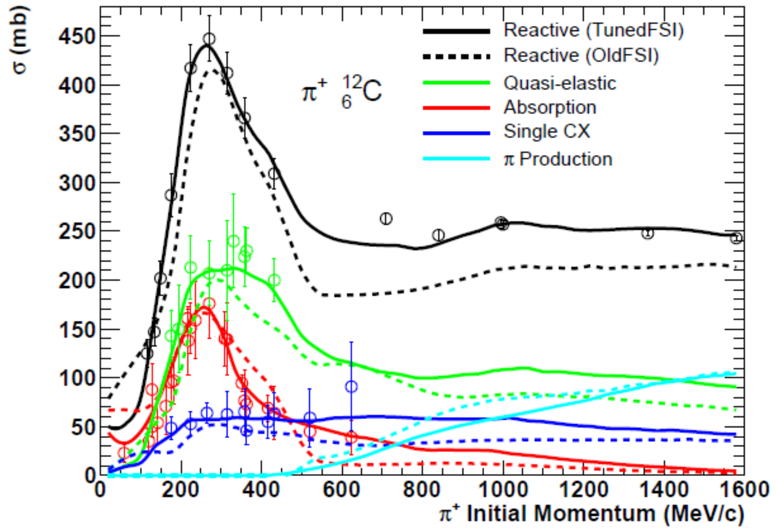
Pion Production in NEUT (thanks to Y. Hayato for slides!)

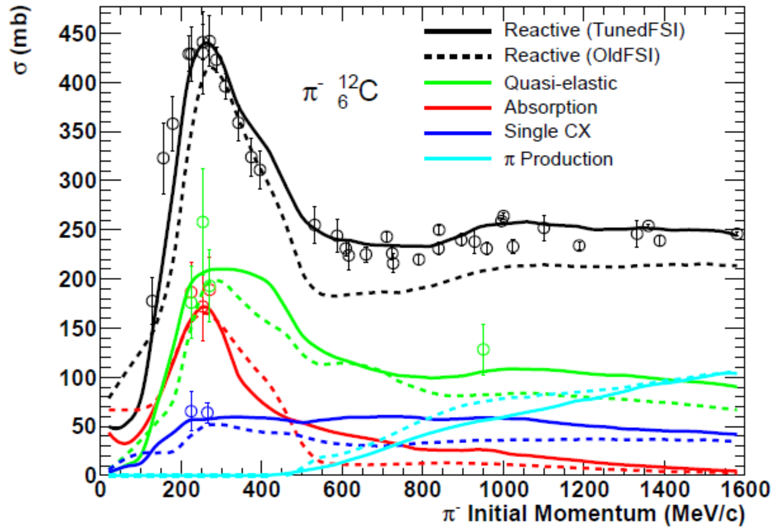
Single pion production via resonance in NEUT - FSI

- Simulated with the cascade model
- Simulated interactions
  - inelastic scattering
    - incl. charge exchange & particle production ($\pi N \rightarrow \pi \pi N$)
  - absorption
- Interaction probability ~ Mean free paths
  - P_π < 500 MeV/c
    - Density dependent mean free path
      - Originally from E. Oset et. al. model
      - Scaled by fitting the π A scattering data
  - P_π > 500 MeV/c
    - Density independent mean free path
      - π-N scattering data + π A scattering data
- Kinematics determination
  - π N phase shift analysis with medium correction (R. Seki et al.)

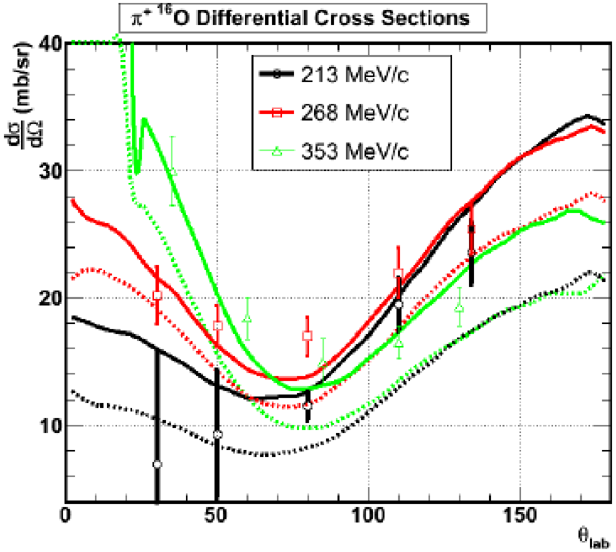
Pion Production in NEUT (thanks to Y. Hayato for slides!)

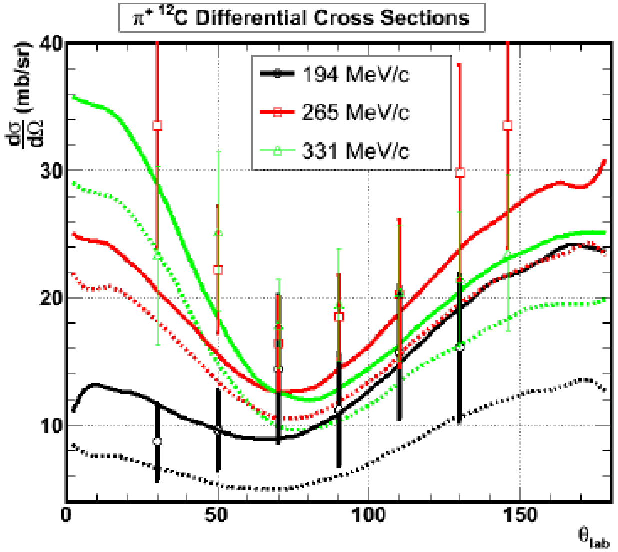
π Carbon scattering interaction cross-sections





π⁺ Oxygen scattering differential cross-sections

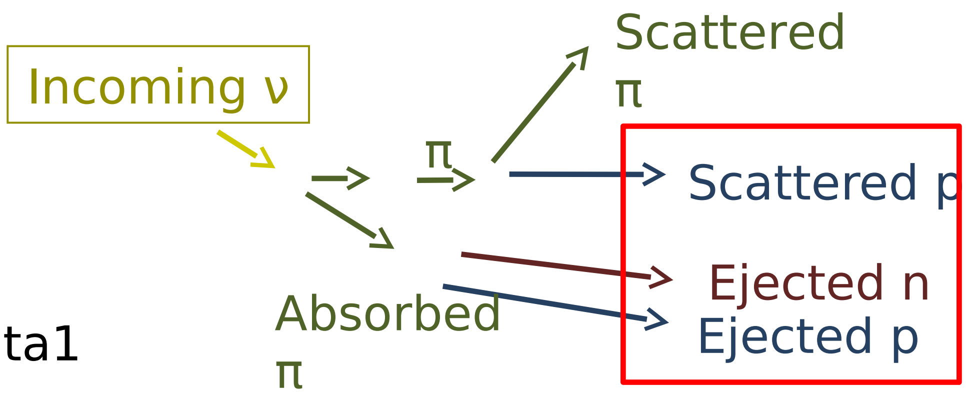




Pion Production in NEUT (thanks to Y. Hayato for slides!)

Single pion production via resonance in NEUT

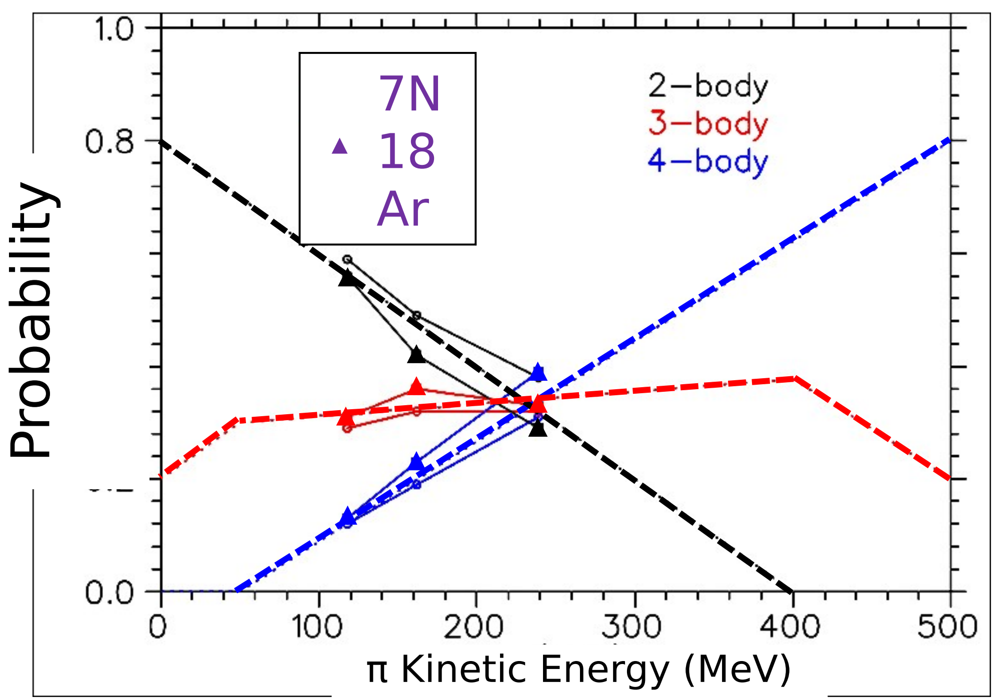
Nucleon emission after π absorption



- # of nucleon emitted after π absorption
  Based on the experimental data1

- Momentum of nucleons for 2 body decay : measurements2

Other cases : Isotropically

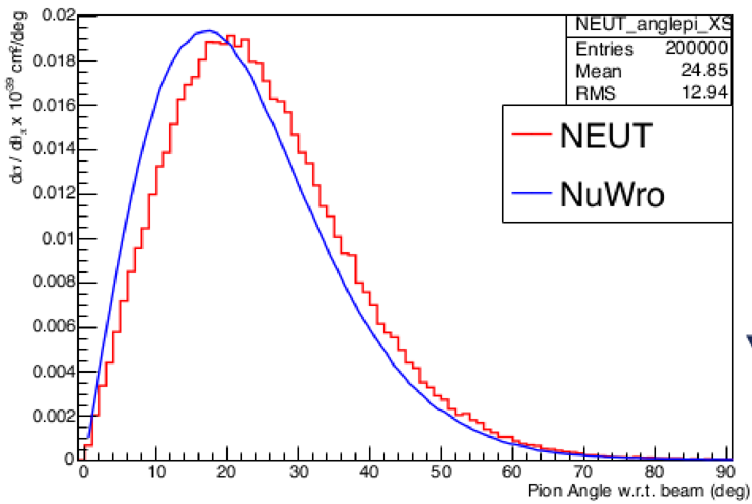


(P. de Perio / R. Tacik)

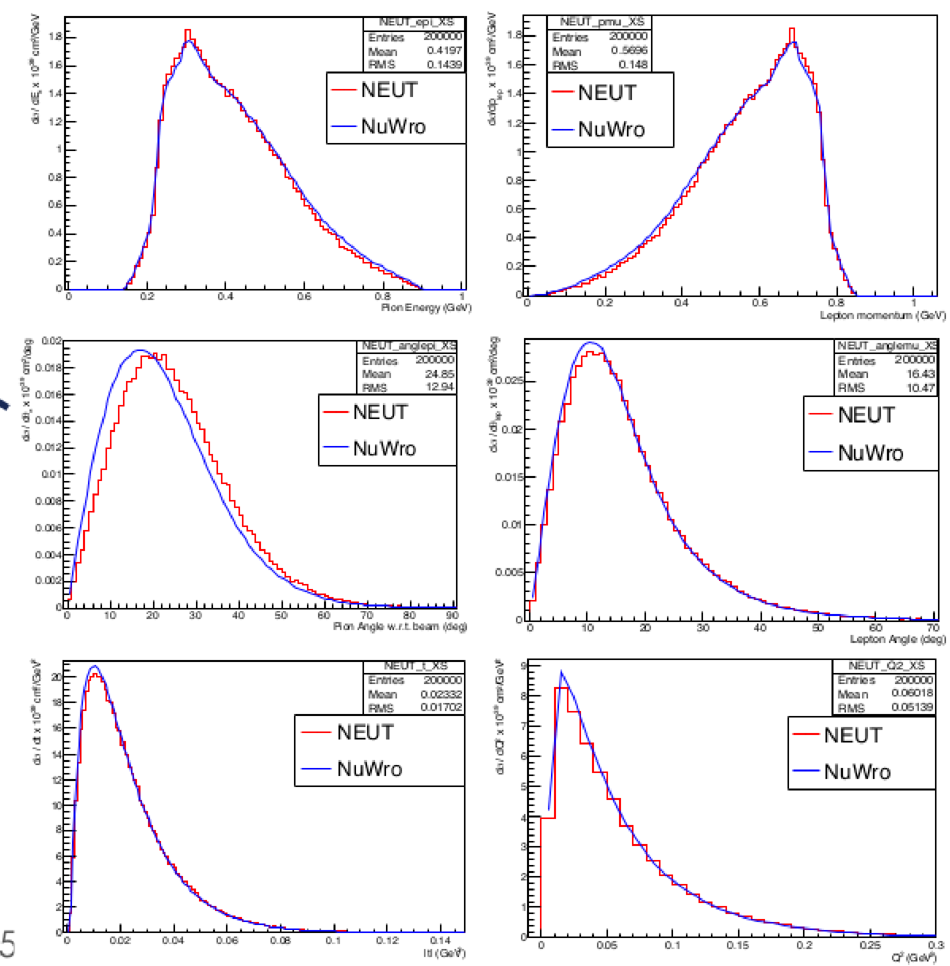
[1] Rowntree *et al*. Phys. Rev. C60 (99) 054610
[2] Ritchie, Phys. Rev. C 44, 533

Coherent pion production: Berger-Sehgal in NEUT (thanks to P. Martins for slides!)

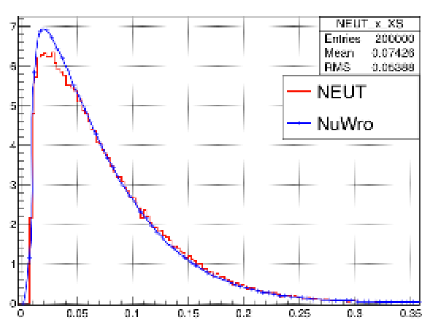
- Work done with Jakub Zmuda.
- Compare all the kinetic variables for CC and NC at fixed neutrino energies of 1, 3 and 5 GeV. (back-up slides)
- Overall, there is a good agreement, except for the pion angle at low energy.



CC 1 GeV



May be due to the different implementations in both generators: NuWro (x , y , t) vs NEUT (x , y , z , Φ)



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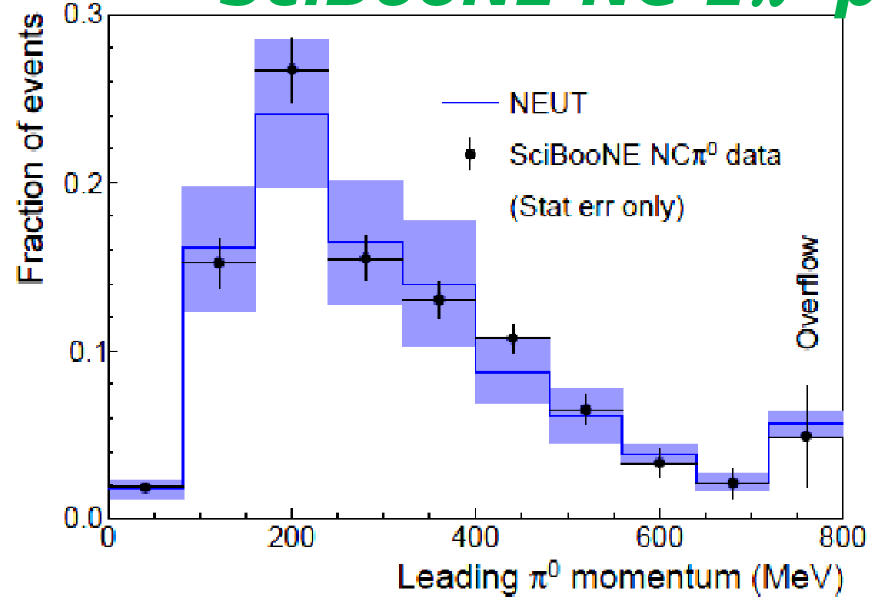
Pion Production in NEUT (thanks to Y. Hayato for slides!)

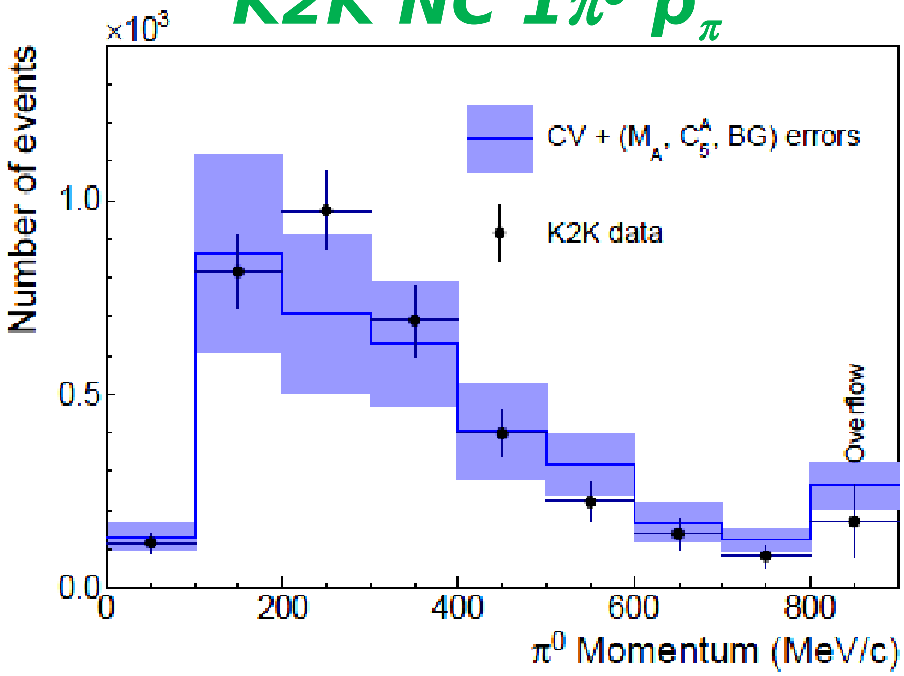
Single pion production via resonance in NEUT

Comparisons with data from K2K and SciBooNE

SciBooNE NC $1\pi^0$ p_π



K2K NC $1\pi^0$ p_π



SciBooNE NC $1\pi^0$ θ_π

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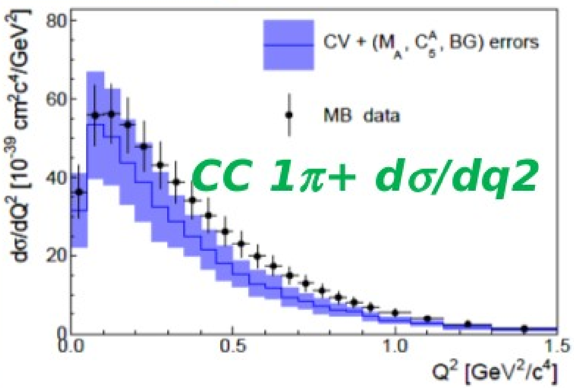
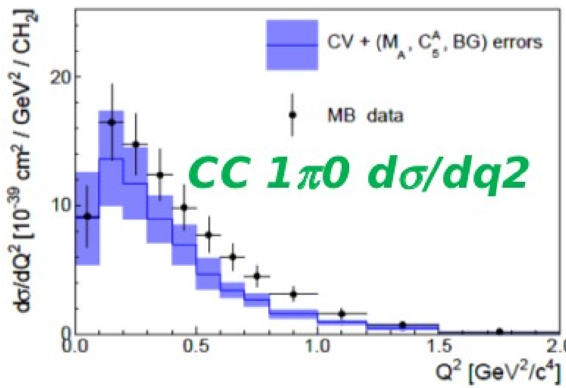
Pion Production in NEUT (thanks to Y. Hayato for slides!)

Comparisons with data from MiniBooNE and MINERvA

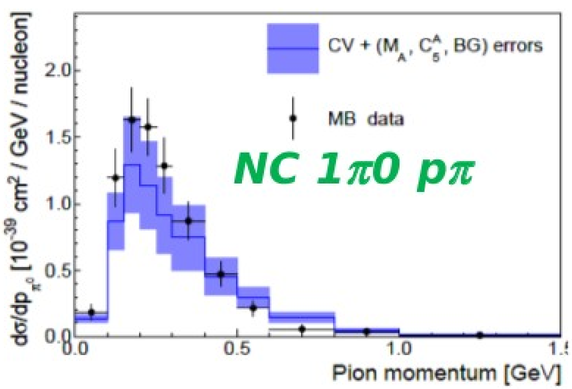


(a) MiniBooNE CC1π^+

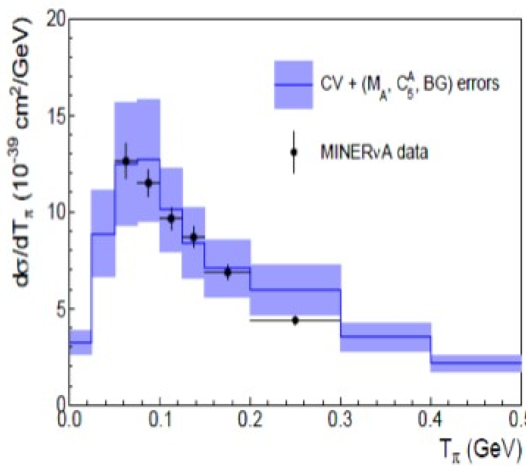


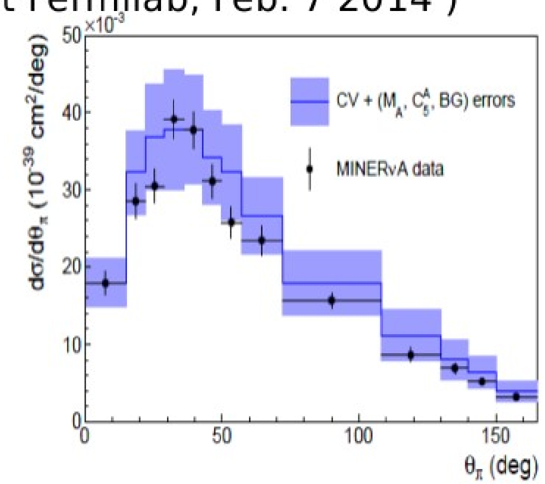
(b) MiniBooNE CC1π^0

Data points are from the results presented by B. Eberly titled "Probing Nuclear Physics with Neutrino Pion Production at MINERvA" (Joint Experimental-Theoretical Seminar at Fermilab, Feb. 7 2014)



(c) MiniBooNE NC1π^0





Central values below MiniBooNE and Some above MINERvA (J.Z.)

Pion Production in GENIE (thanks to C. Andreopoulos for slides!)

Resonance production simulated using an implementation of the **Rein-Sehgal (RS)** model:

- 16 unambiguous resonances (*) taken into account with updated parameters
- Resonance cutoff above a tunable value of W (Wcut = 1.7 GeV/c2)
- Interference between resonances is neglected
- Lepton mass terms not included in the default model
- *However, implementations of the Berger-Sehgal (BS) and Kuzmin-Lyubushkin-Naumov (KLN) models also optionally available in v2.10.0*
- By default, dipole vector and axial form factors (mVres = 0.840 GeV/c2, mAres = 1.12 GeV/c2)
- *"MiniBooNE" tuning optionally available in BS and KLN models*
- For nuclear targets, a Fermi gas model is used
- Coupled to standard GENIE cascade models (INTRANUKE hA and hN models)
- No medium modification for resonances
- No formation zone effects – Resonances are decayed immediately and decay products are propagated through the nucleus
- Resonances are decayed isotropically. All known decay channels with updated branching ratios are used

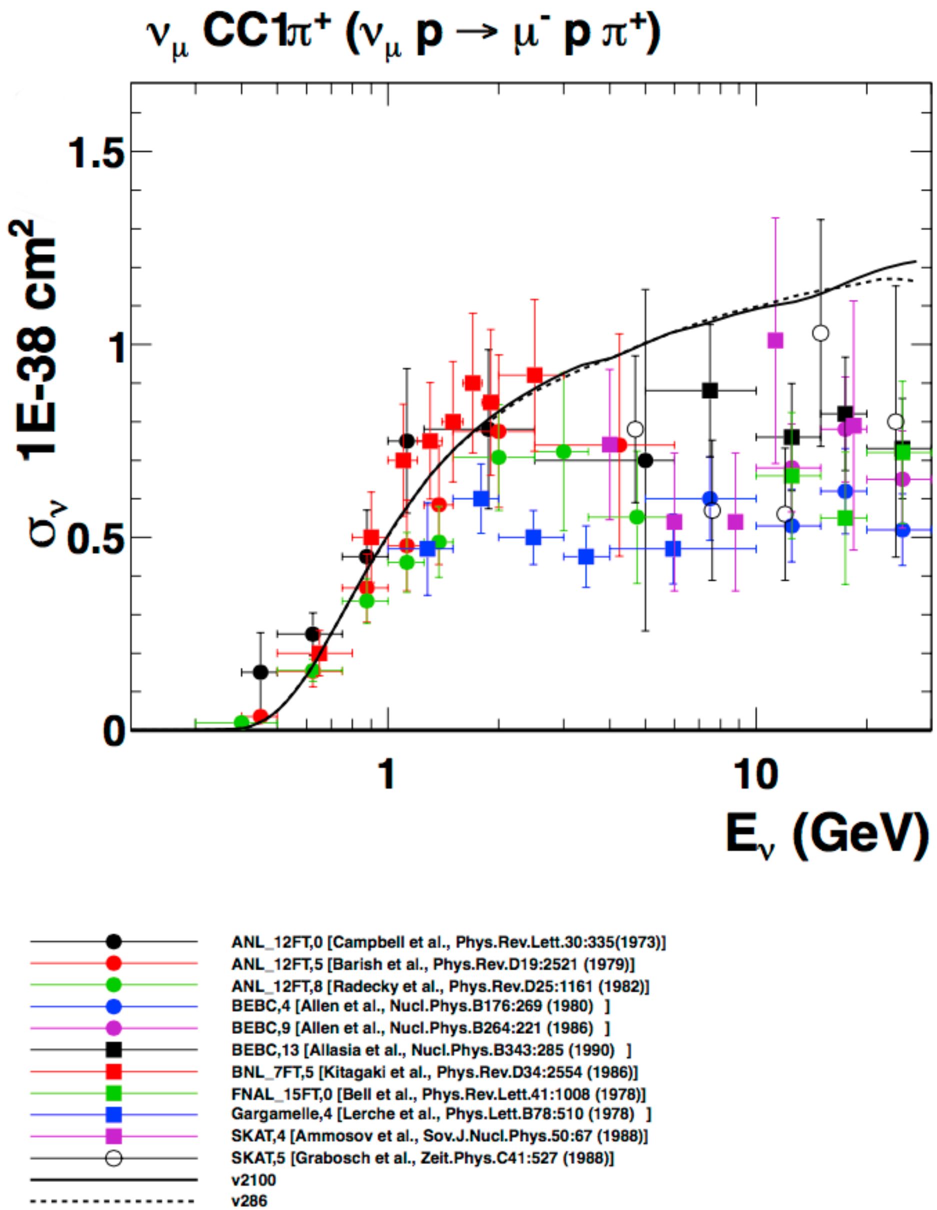
(*) P33(1232), S11(1535), D13(1520), S11(1650), D13(1700), D15(1675), S31(1620), D33(1700), P11(1440), P13(1720), F15(1680), P31(1910), P33(1920), F35(1905), F37(1950), P11(1710)

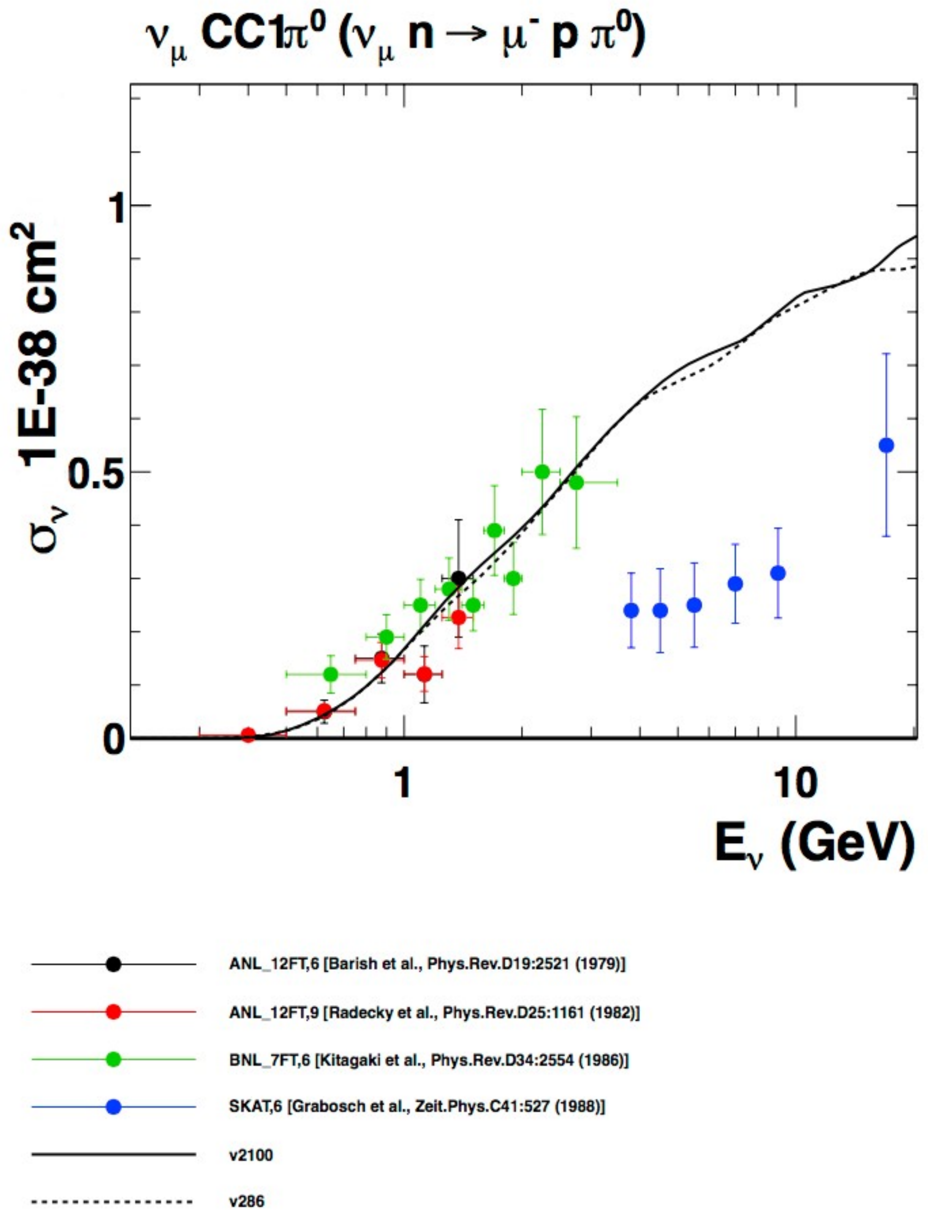
Pion Production in GENIE (thanks to C. Andreopoulos for slides!)

Non-resonance production is simulated using an implementation of the **Bodek-Yang (BY)** model for inclusive production, coupled with the **AGKY** hadronization model

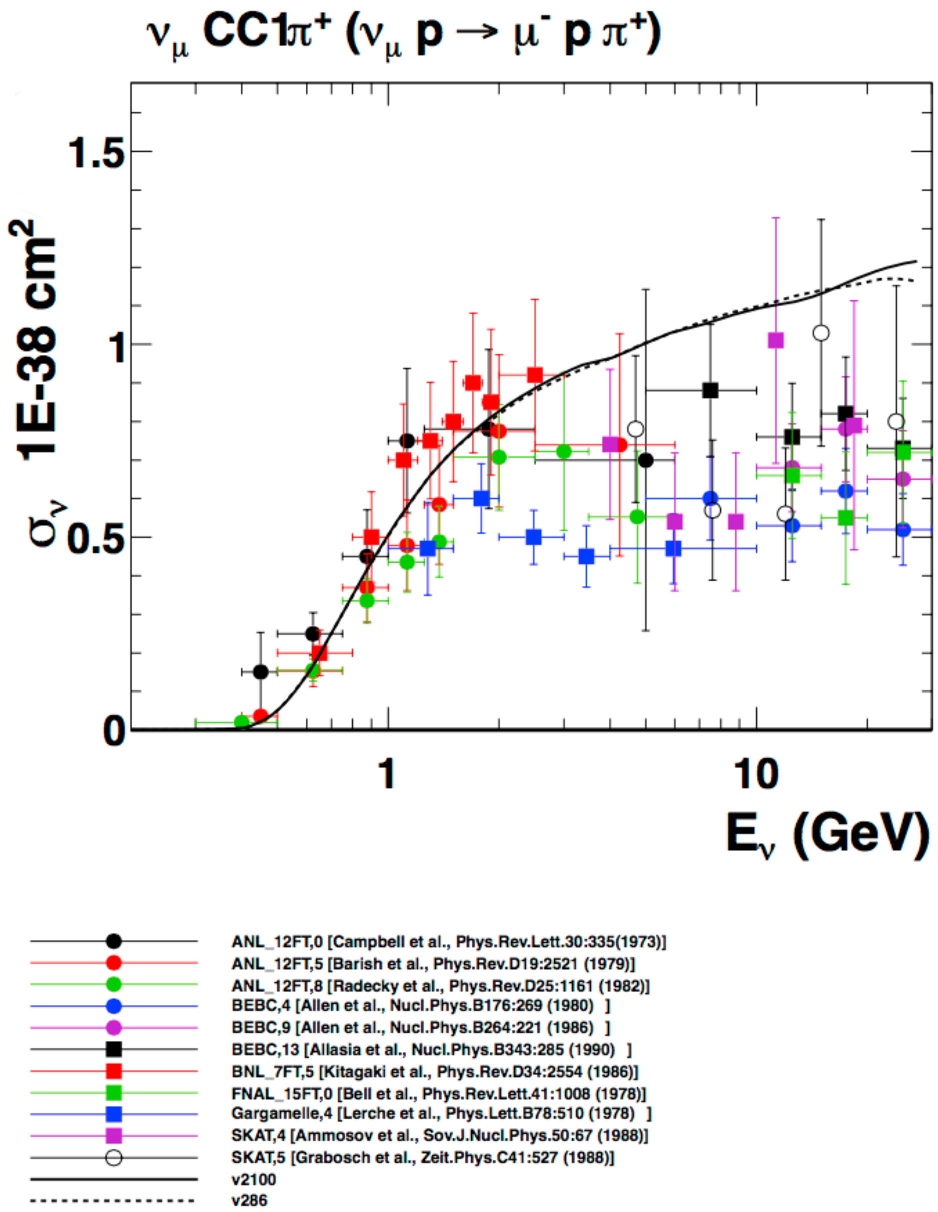
- BY: An effective LO model / Higher twist terms and target mass corrections accounted for via a new scaling variable and modification to the low-Q2 pdfs.
- *The longitudinal structure function is taken into account using the Whitlow R (FL / 2xF1) parameterization.*
- *Shadowing, anti-shadowing and EMC effects included.*
- *Default parameters based on the GRV98LO pdfs*
- *An overall scaling factor of 1.032 is included to match the neutrino cross-section at high energies*
- AGKY: Empirical KNO-based hadronization model; transitions to PYTHIA6 between W = 2.3 – 3.0 GeV/c2
- The BY model is extrapolated to values of W below Wcut and the AGKY model is used to decompose the inclusive cross-section to excusive components.
- *Non-resonance 1π and 2π contributions added to resonance contributions and tuned to bubble chamber data.*
- For nuclear targets, a Fermi gas model is used.
- Coupled to standard GENIE cascade models (INTRANUKE hA and hN models).
- Formation zone effects are taken into account
- *with a formation time 0.342 fm/c for pions and 2.3 fm/c for nucleons*

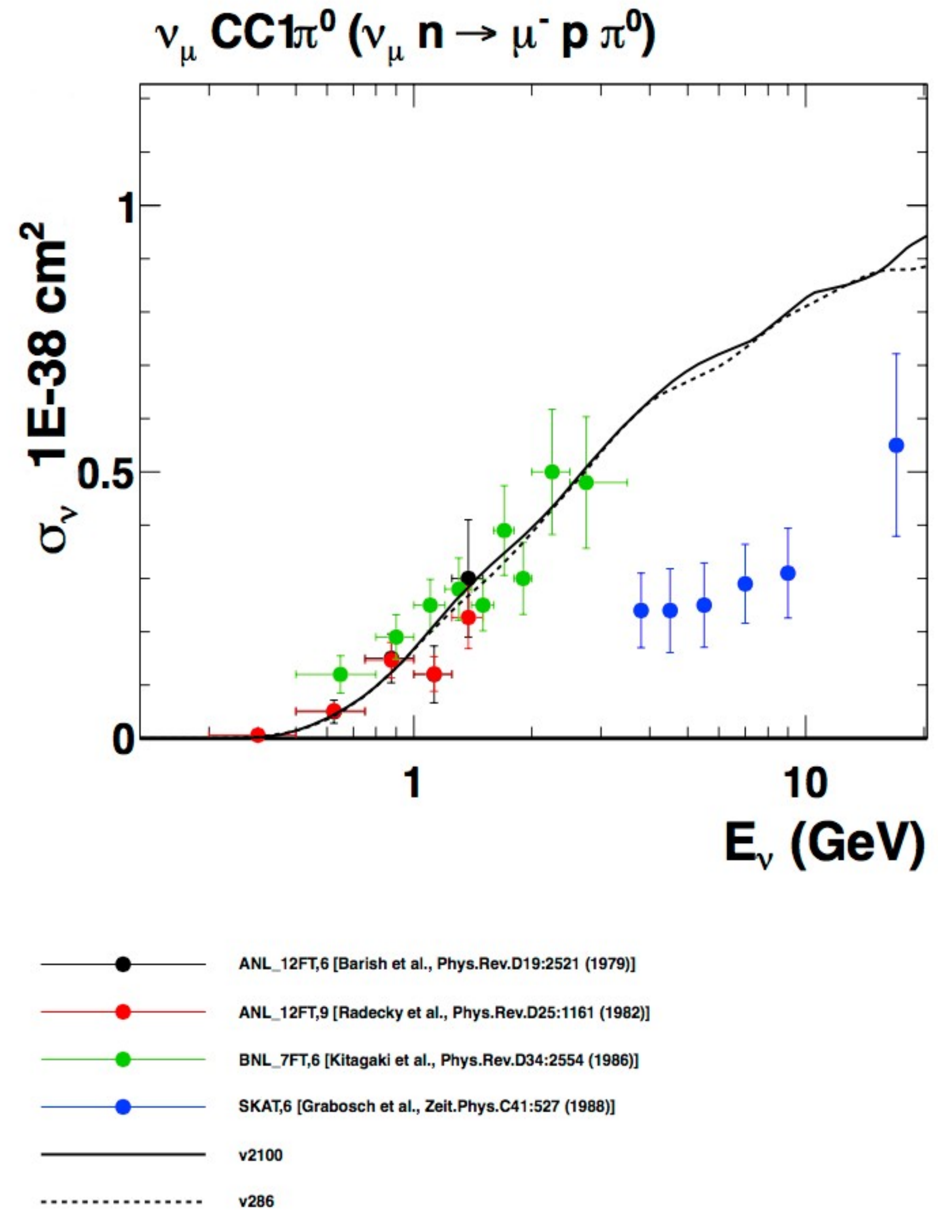
Pion Production in GENIE (thanks to C. Andreopoulos for slides!)



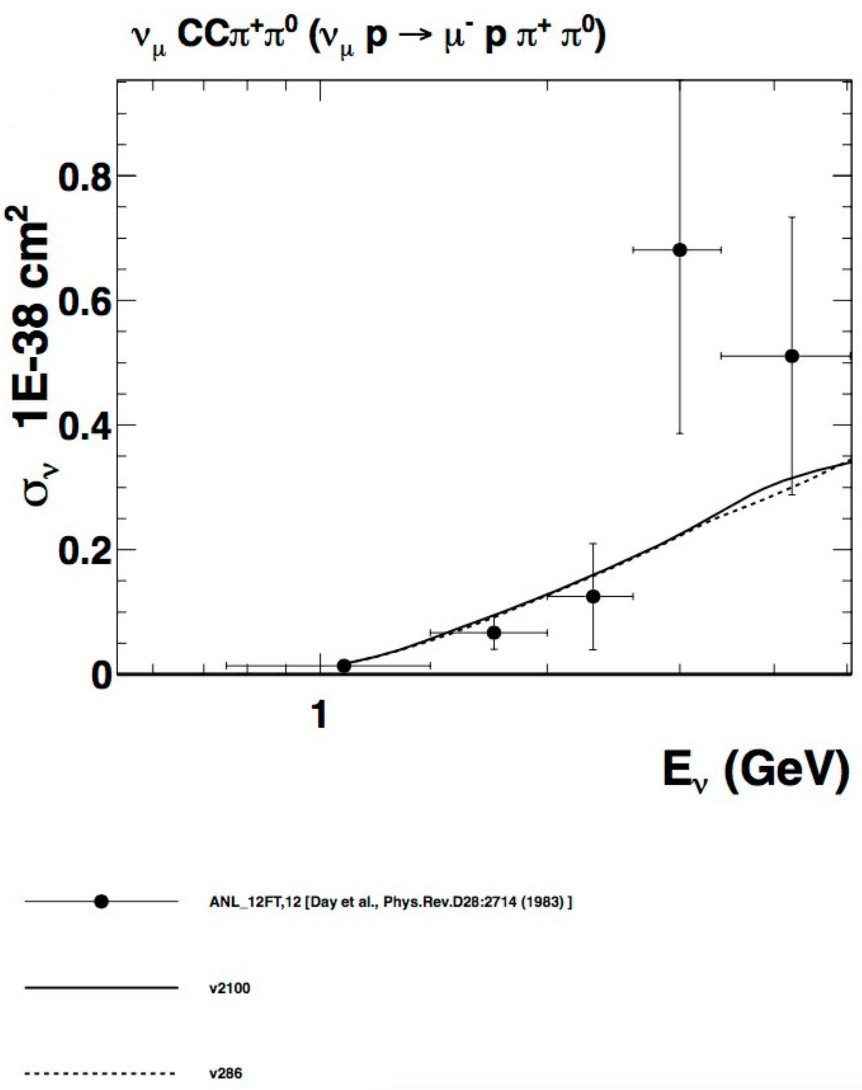


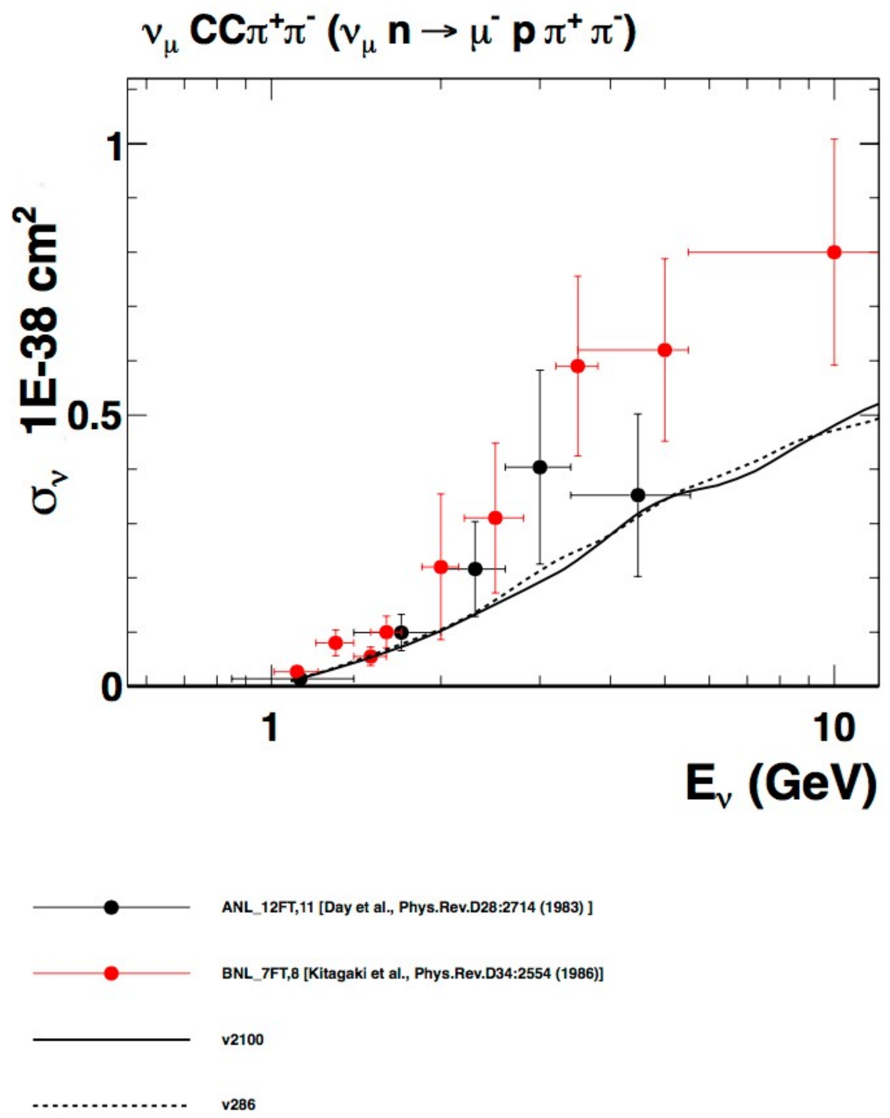
Pion Production in GENIE (thanks to C. Andreopoulos for slides!)



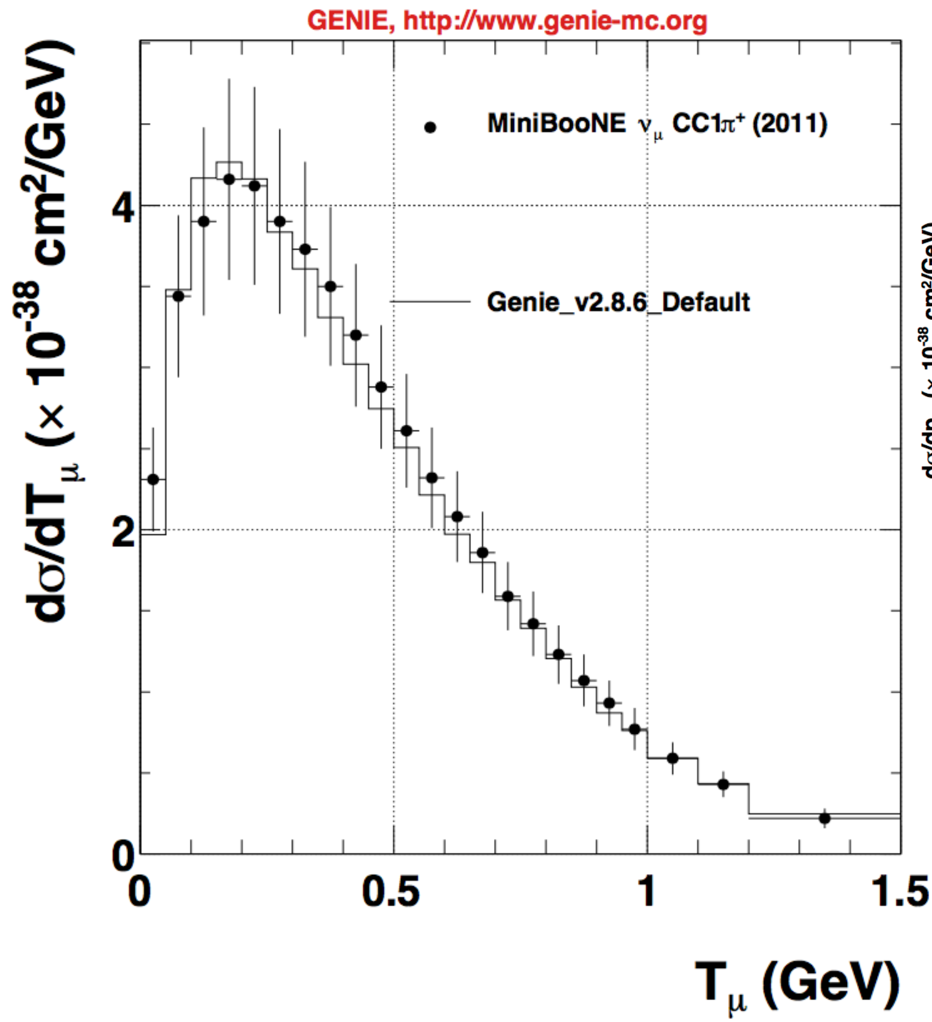


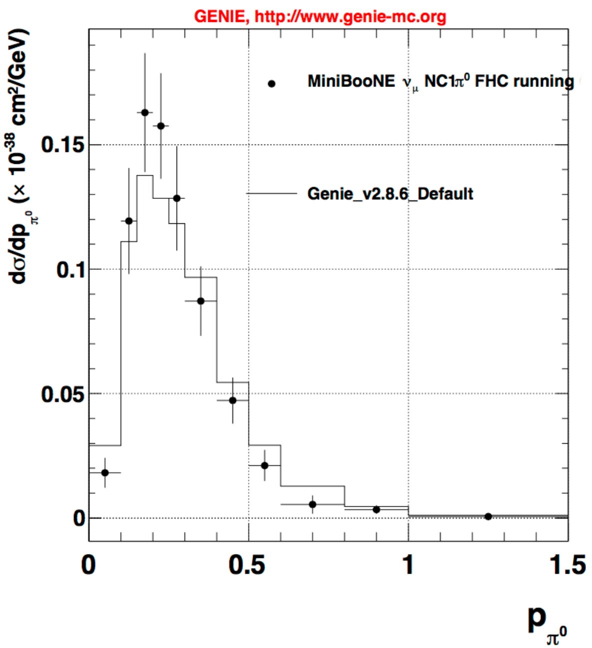
Pion Production in GENIE (thanks to C. Andreopoulos for slides!)

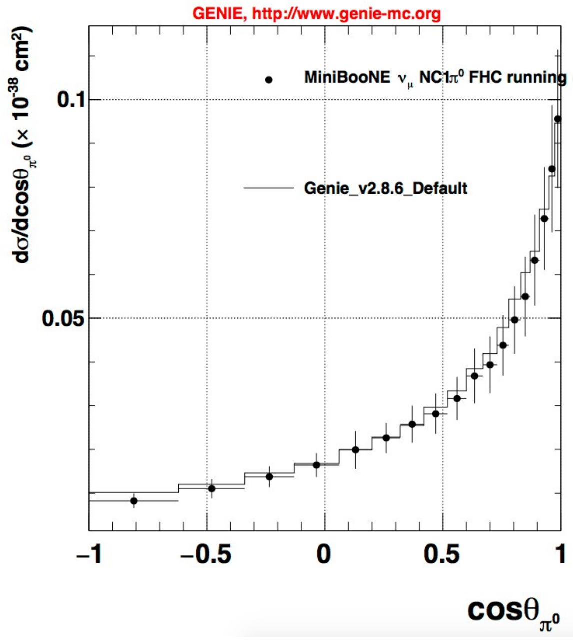




Pion Production in GENIE (thanks to C. Andreopoulos for slides!)







Summary

Generator	Nucleus model	Resonant	Nonresonant background	DIS	COH	FSI	FZ
NuWro	FG/LFG	Δ isobar	From DIS	PYTHIA 6	RS and BS	Cascade	+
GiBUU	LFG	Isobar model up to D35(2350)	Based on HNV in Δ region	PYTHIA 6	-	Off-shell transport equations (but not for mesons)	+ (only for DIS)
NEUT	FG	Rein-Sehgal (with corrections)	J=1/2 background	PYTHIA 5.76	RS and BS	Cascade	+
GENIE	FG	Rein-Sehgal (with corrections)	Bodek-Yang +AGKY	PYTHIA 6	RS, BS and KLN	Cascade	+ (only for DIS)

- Still open questions of possible tensions between MiniBoonE and MINERvA datasets.
- If MINERvA data too low: either too strong absorption from FSI or all generators miss some important pion production channel.