Single Pion Production in NuWro and other MC generators

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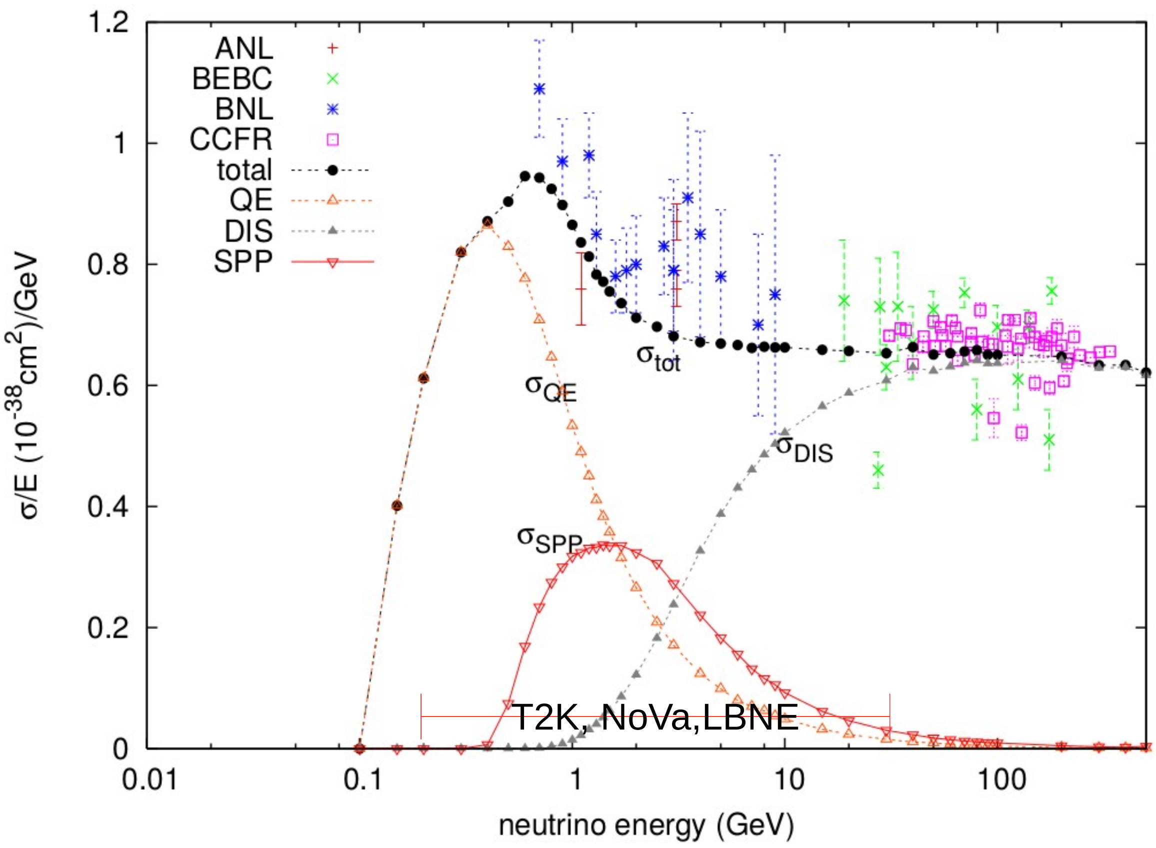
Motivation

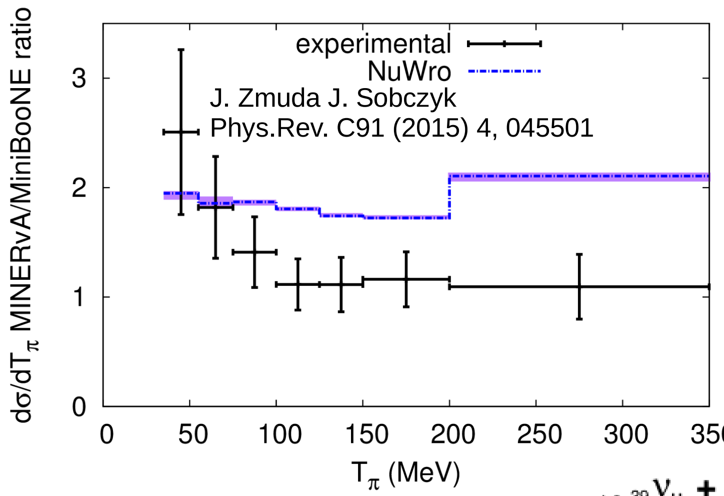
- SPP: large part of the neutrino-nucleus cross section at interesting energy range
- Large theoretical uncertainties in the primary vertex, multiple available models for resonant and coherent processes (Rein-Sehgal, Berger-Sehgal, Sato-Lee, Hernandez-Nieves-Valverde, GiBUU...), +nonperturbative nuclear effects!

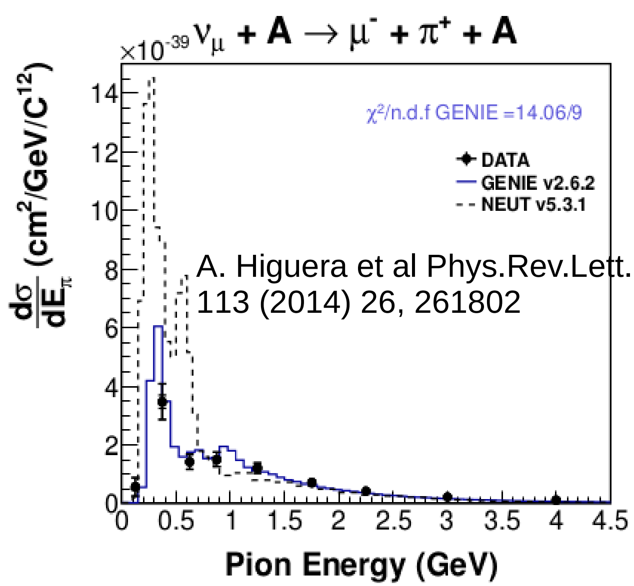
J. Nowak PhD thesis

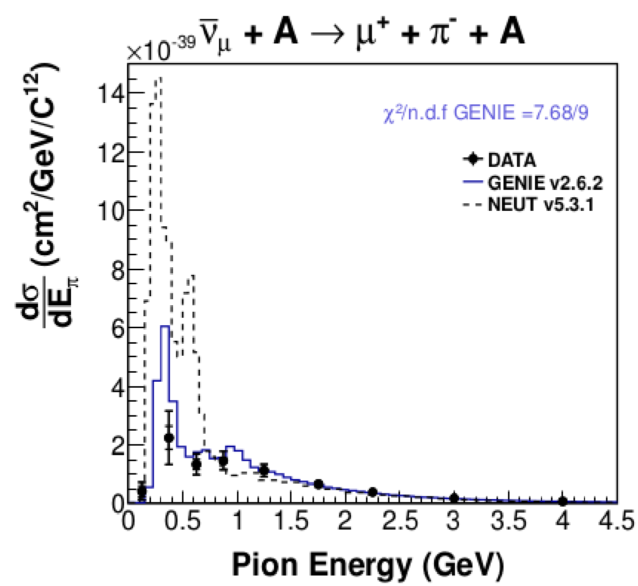


Motivation

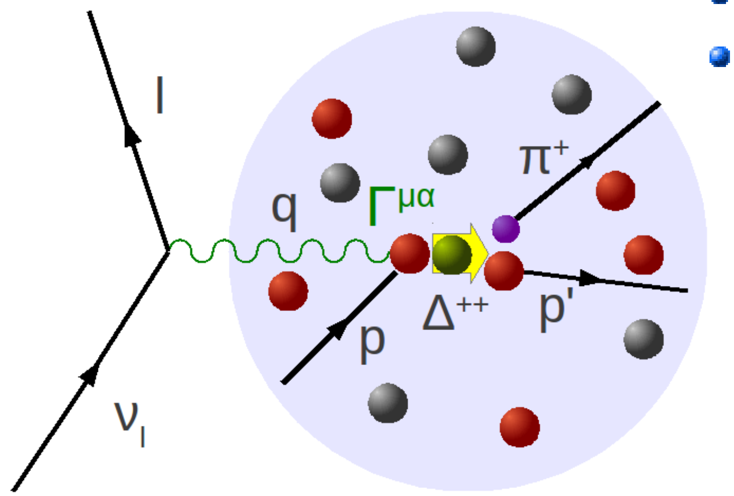
- Problem of final state interactions (FSI): eitherMetropolis cascade or coupled-channel equatios
- Experimental uncertainties on the axial transition amplitude parameters (~15% on the best-known Δ(1232) resonance form factors) → problems in understanding of data with our MC





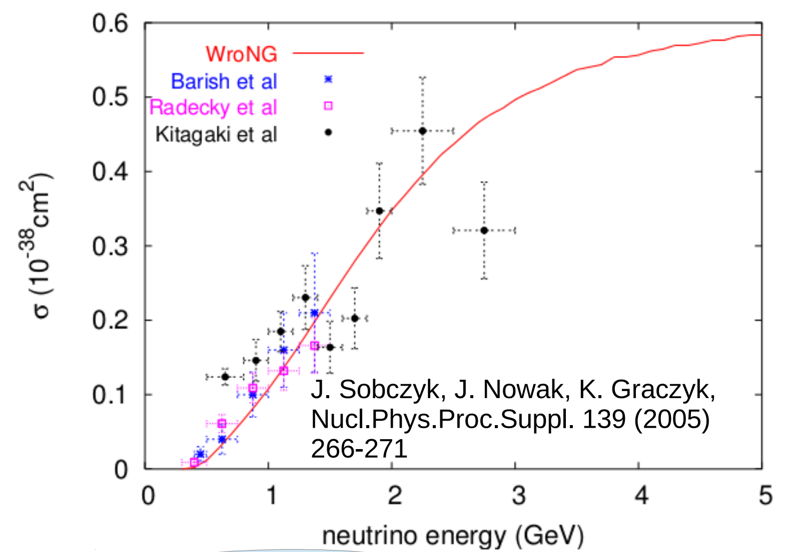


NuWro- RES process



- Interaction on a nucleon in (local) Fermi gas ((L)FG)
- Δ(1232) resonance - isobar model, multiple form factor sets available. Default: best fit to ANL+BNL data sets [1]

- Heavier resonances: none; „washed out" by Fermi motion + 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).

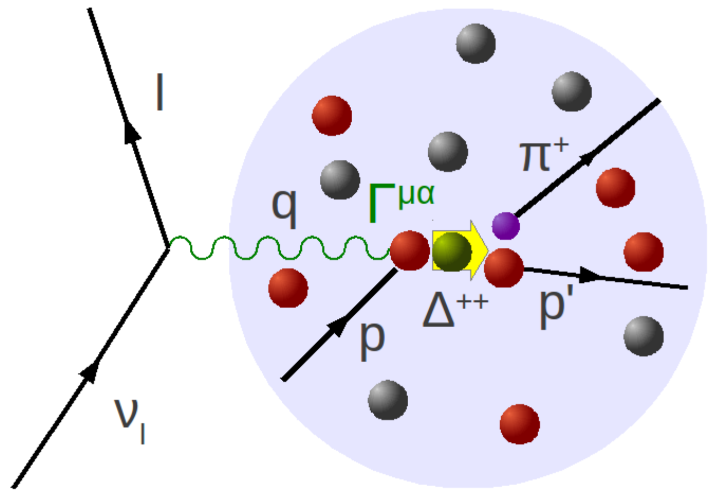


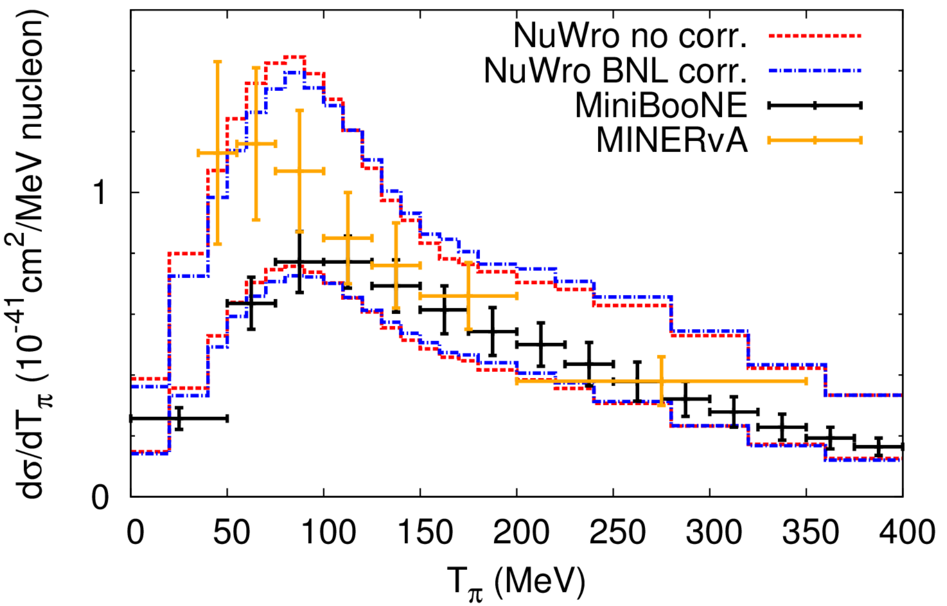
First name of NuWro! :)

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

[1] K. Graczyk, D. Kiełczewska, P. Przewłocki, J. Sobczyk Phys. Rev. D80 (2009) 093001

RES process in NuWro





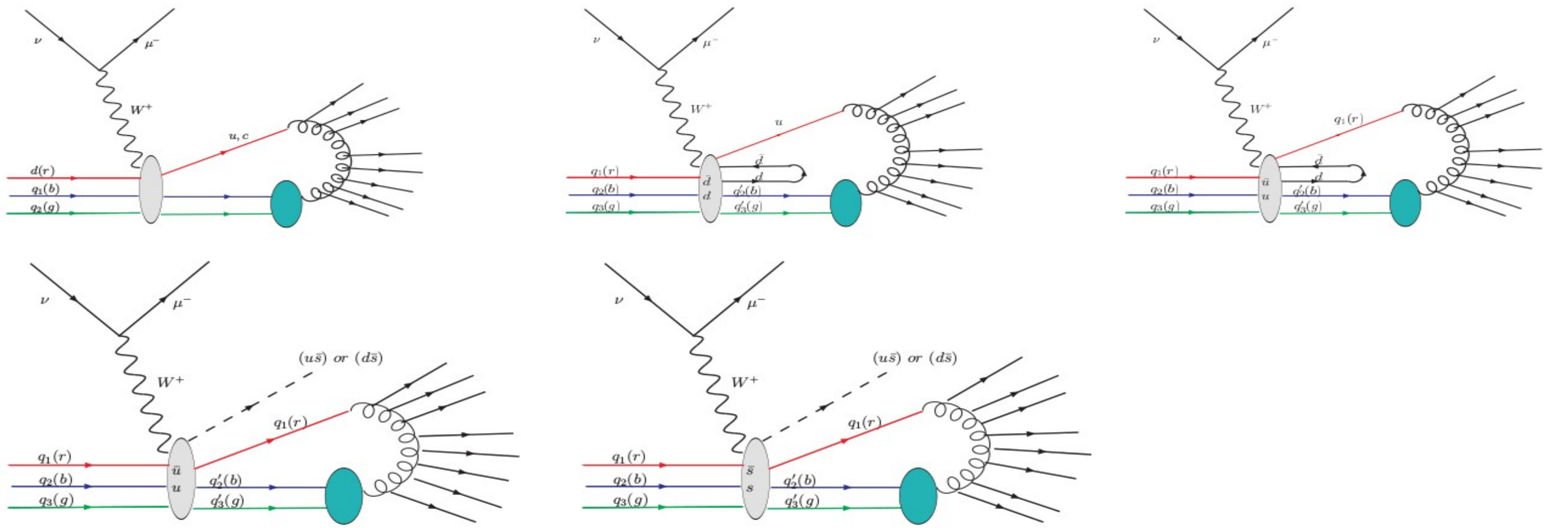
- Recent features (**more details on NuWro- Jan's talk on Friday**):
  - Δ(1232) resonance decay anisotropy correction (density matrix measured in ALN[1]/BNL[2] experiments
  - Δ(1232) self-energy effects [3] (pionless decays, corrections to SPP)-approximation

[1] G.M. Radecky et al, Phys. Rev. D25 (1982) 1161.

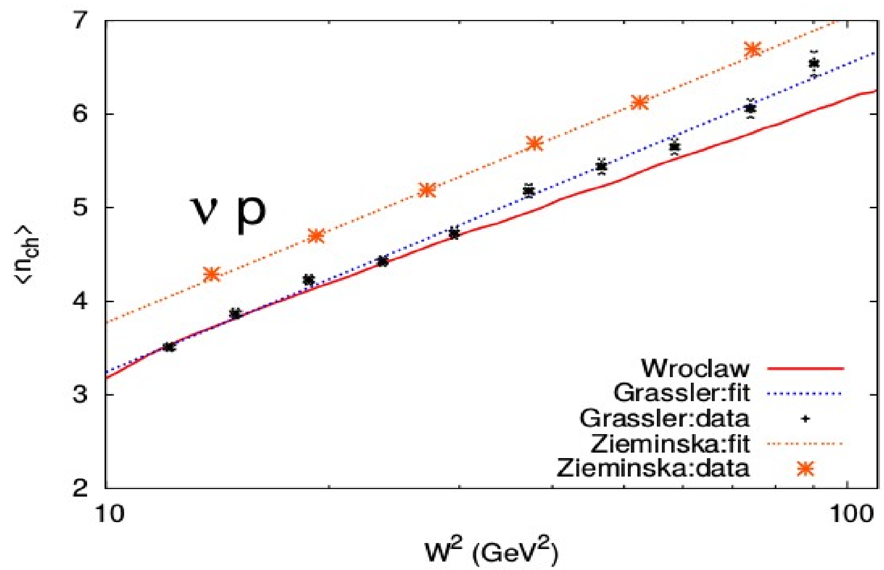
[2] T. Kitagaki et al., Phys. Rev. D34 (1986) 2554.

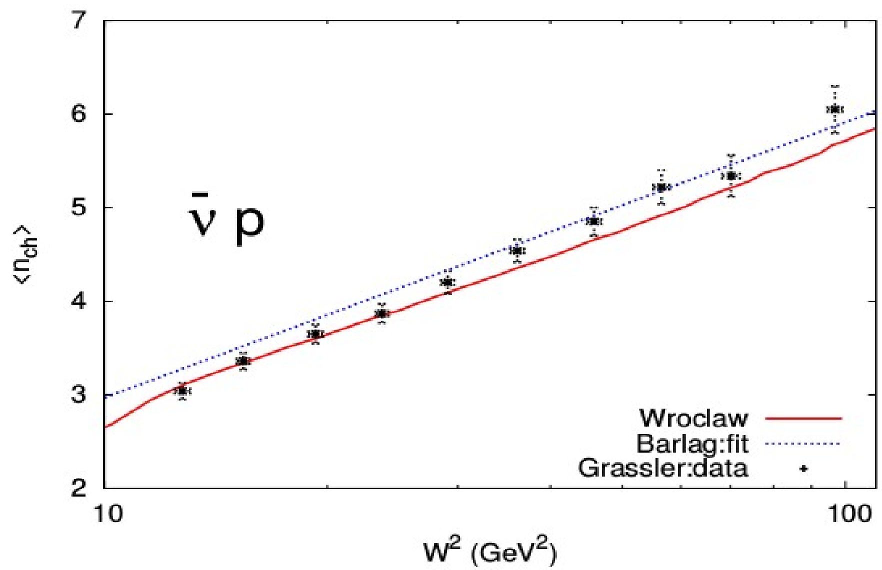
[3] E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987))

DIS process- multiple pion source

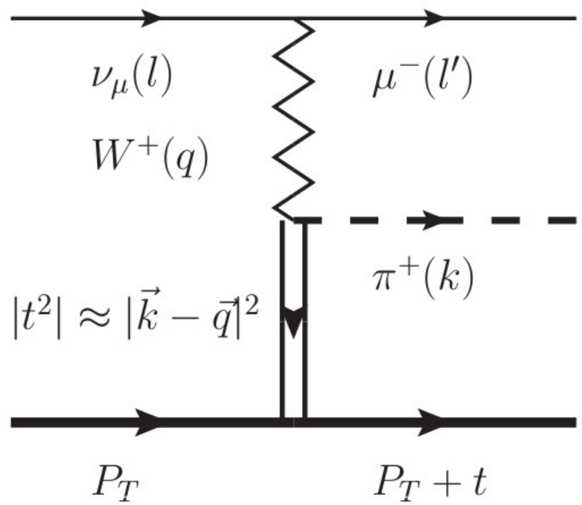


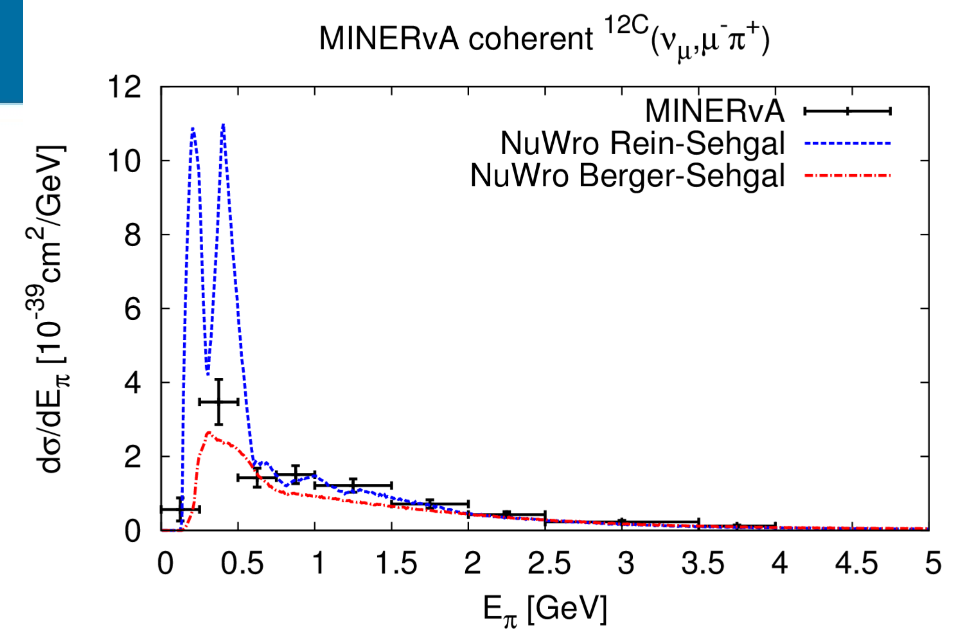
- PYTHIA/LUND algorithm fine-tuned to hadron multiplicity data by J. Nowak in his Ph. D. Thesis (this slide's pictures source).

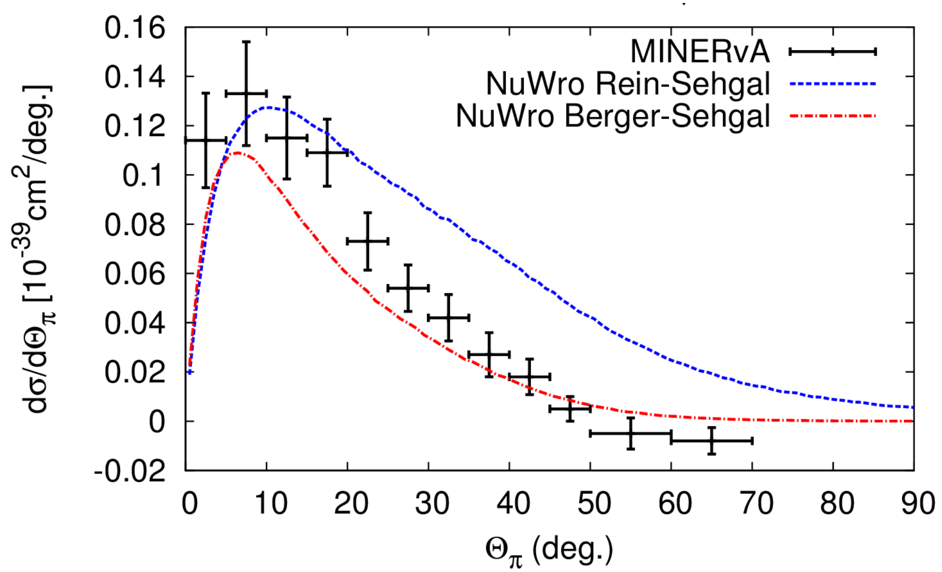




COH process







- Coherent pion production through t-channel exchange, nucleus left in the ground state (Adler PCAC -based Models).
- Both Rein-Sehgal [1] and Berger-Sehgal [2] models available. Comparison to MINERvA data [3]. Work-in-progress, „hot" topic for NEUT as well (P. Martins).

[1] Rein & Sehgal, Nucl. Phys. B 223 (1983)

[2] Berger & SehgalPhys. Rev. D 79, 053003 (2009)

[3]A. Higuera et al., Phys. Rev. Lett. 113, 261802 (2014)

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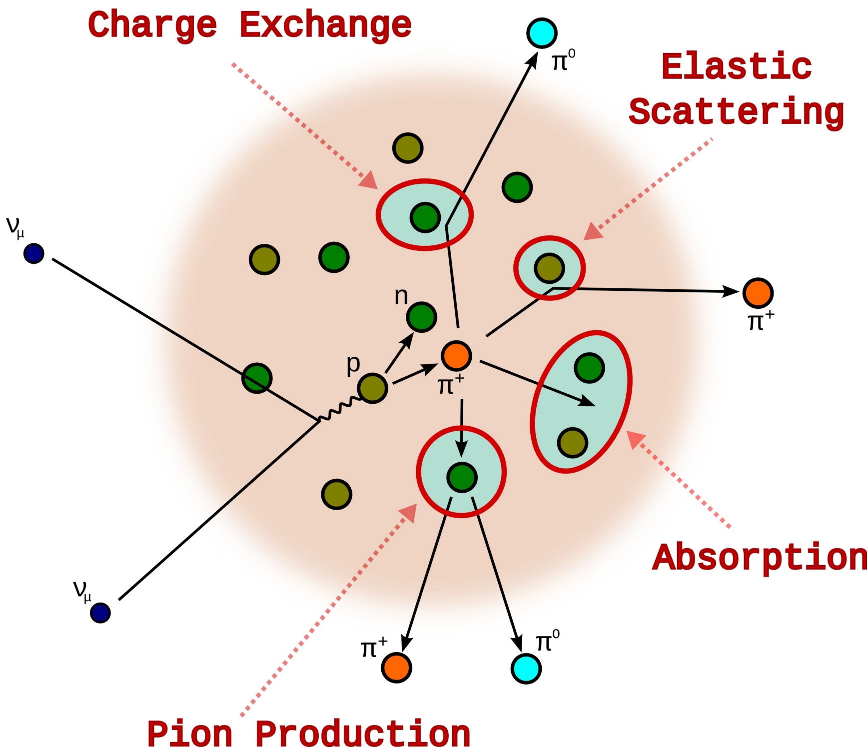
Final State Interactions in NuWro

- All particles (besides COH) start inside nucleus.

- FSI cascade (Phys.Rev. C86 (2012) 015505) :
  - Metropolis algorithm [1]
  - Local density approximation
  - For pion charge exchange, elastic scattering and absorption up to 350 MeV ← Oset model [2]
  - Beyond 350 MeV: available pion-nucleon scattering data.
  - Mean free path from xs, but step < 0.2 fm
  - Additional effect: formation time (FT)/ formation zone (FZ): minimal distance/time before the created particles can interact:different models and parameters. NuWro:



(by T. Golan)

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

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

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

[1] N. Metropolis et al., Phys. Rev. 110, 185 (1958); N. Metropolis et al., ibid. 110, 204 (1958).

[2] 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 (19

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 :

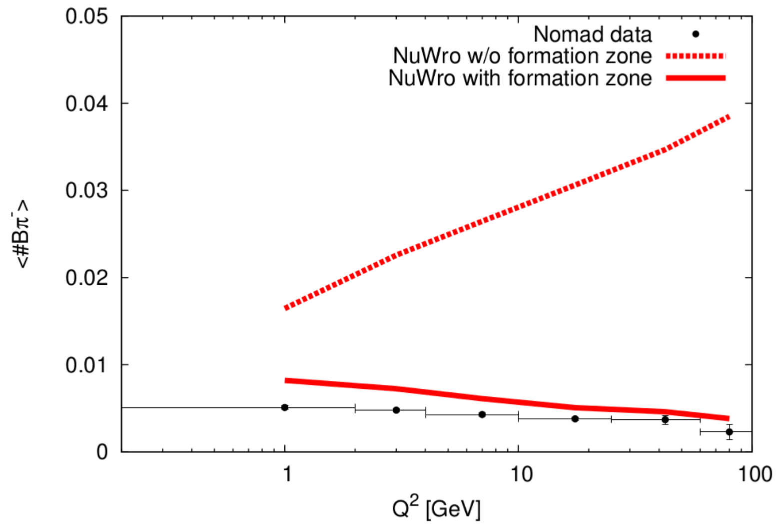


FIG. 7. Average number of backwards going pions as a function of Q^2 in the NOMAD experiment.

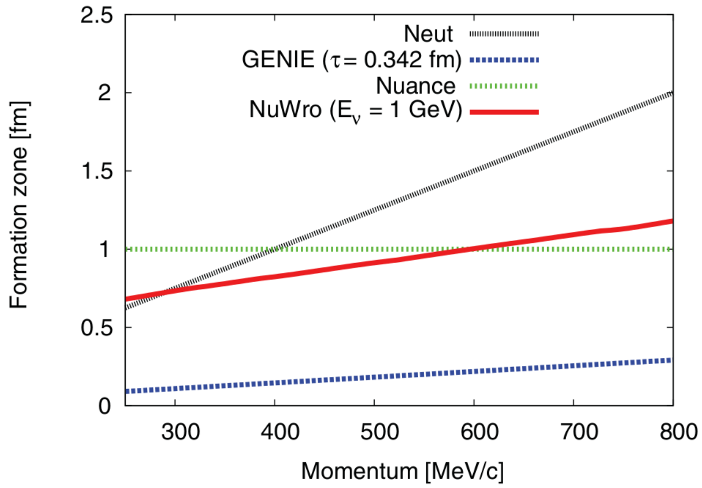


FIG. 12. (Color online) Laboratory frame nucleon formation zone as a function of nucleon momentum.

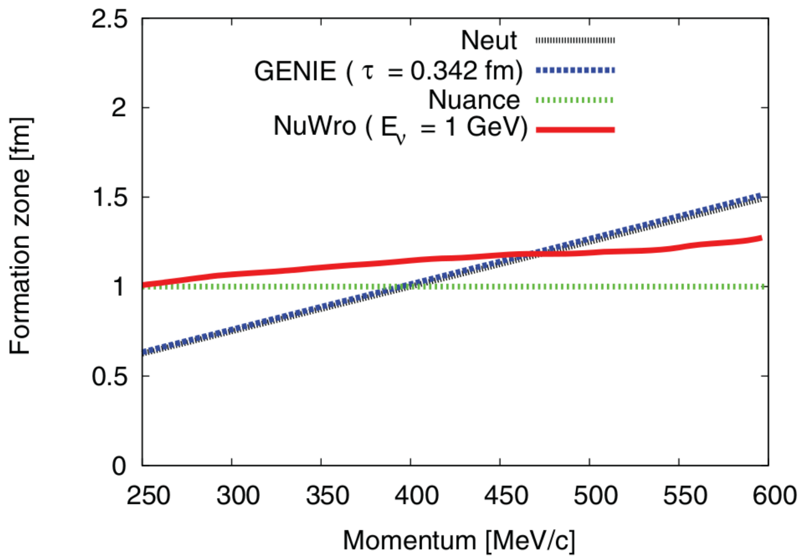


FIG. 13. (Color online) Laboratory frame pion formation zone as a function of pion momentum.

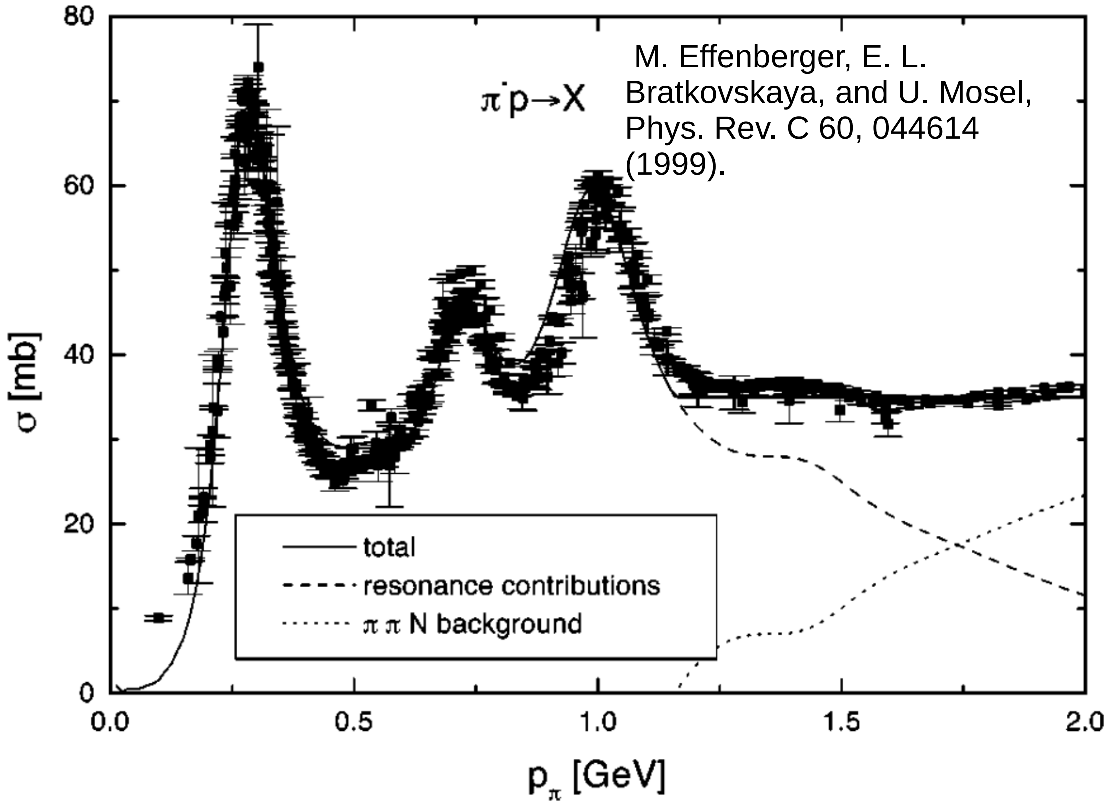
Pion production in GiBUU

- 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 m*):

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

3) All known resonances up to D_{35}(2350) with their decay channels and widths from PDG data



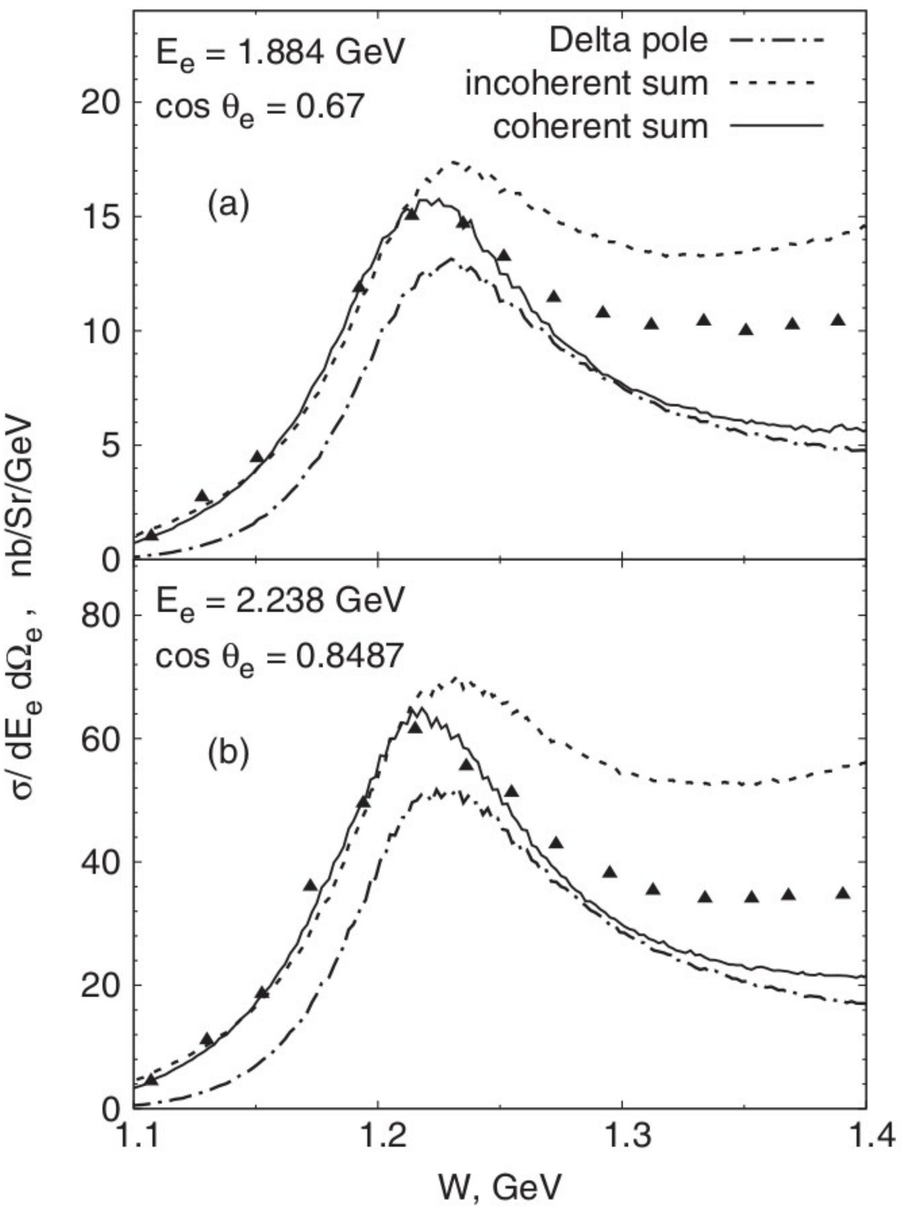
M. Effenberger, E. L. Bratkovskaya, and U. Mosel, Phys. Rev. C 60, 044614 (1999).

Pion production in GiBUU

- Giessen Boltzmann–Uehling–Uhlenbeck (GiBUU) model:

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)[1].
7) Other sources of initial pions: nonresonant backround in the Δ(1232) region (adaptation of HNV model[2]) : 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)



[1] E. Oset and L. L. Salcedo, Nucl. Phys. A 468, 631 (1987)
[2]E. Hernandez, J. Nieves, M. Valerde PRD 76, 033005 (2007)

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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 [1] the gradient approximation and the approximation for off-shell transport [2].

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.
3) Background terms- immediate decay into πN
4) Coupled channels. Effectively FSI-produced pions coming from initial QE/2p2h as in NuWro cascade.

[1] L. Kadanoff and G. Baym, Quantum statistical mechanics (Benjamin, New York, 1962) .
[2]W. Botermans and R. Malfliet, Phys.Rept. 198, 115 (1990).:

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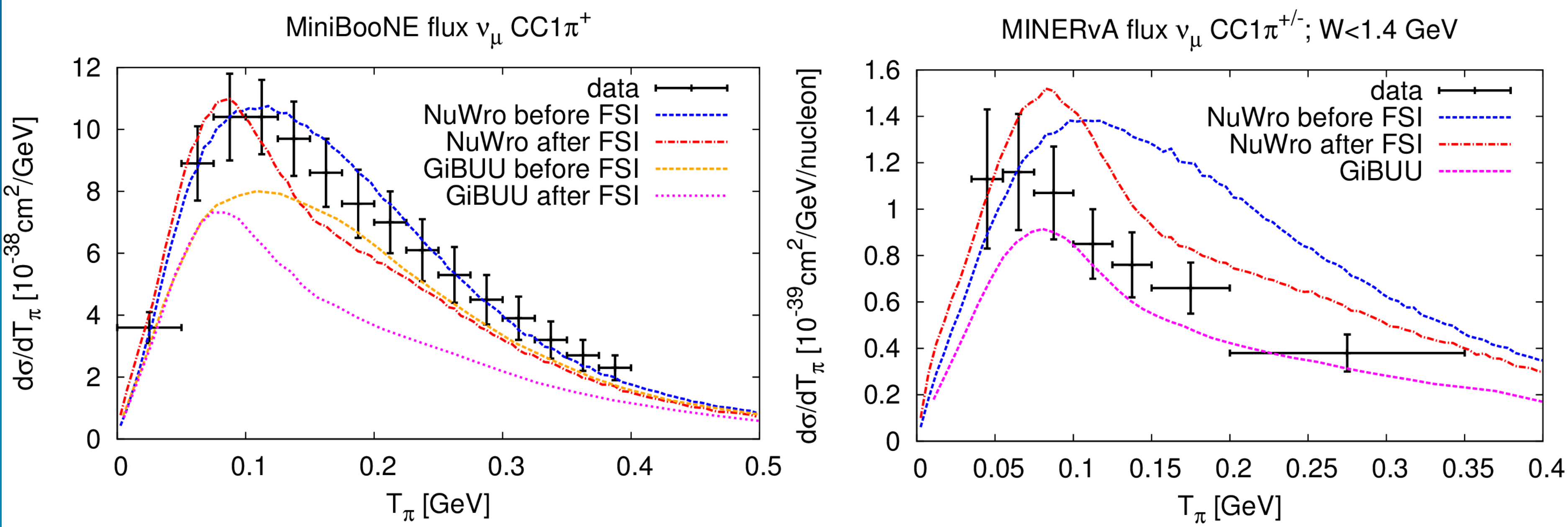
Comparison GiBUU vs. NuWro vs. MiniBooNE vs. MINERvA

- Some comparison between NuWro, GiBUU and data (GiBUU default Δ resonance form factors fit to ANL data, following results of C. Wilkinson et al. [1] GiBUU points scan from [2]



- Different physical models, similar effects of FSI (inelastic π+N → Δ)
- MINERvA [3]: higher beam energy than MibiBooNE 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. **Will get better after flux corrections?**

[1] C. Wilkinson et al.], P. Rodrigues, S. Cartwright, L. Thompson, and K. McFarland Phys.Rev. D90, 112017 (2014),
[2] O. Lalakulich and U. Mosel Phys.Rev. C87 (2013) 014602)
[3] B. Eberly et al arXiv:1406.6415v3 [hep-ex]
[4] A.A. Aguilar-Arevalo et al. Phys.Rev. D83 (2011) 052007

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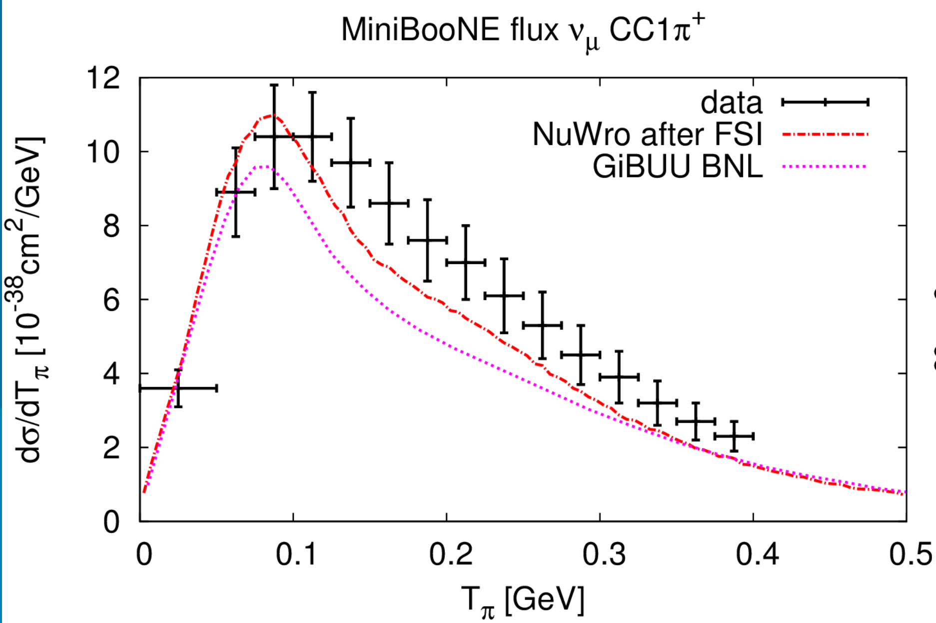
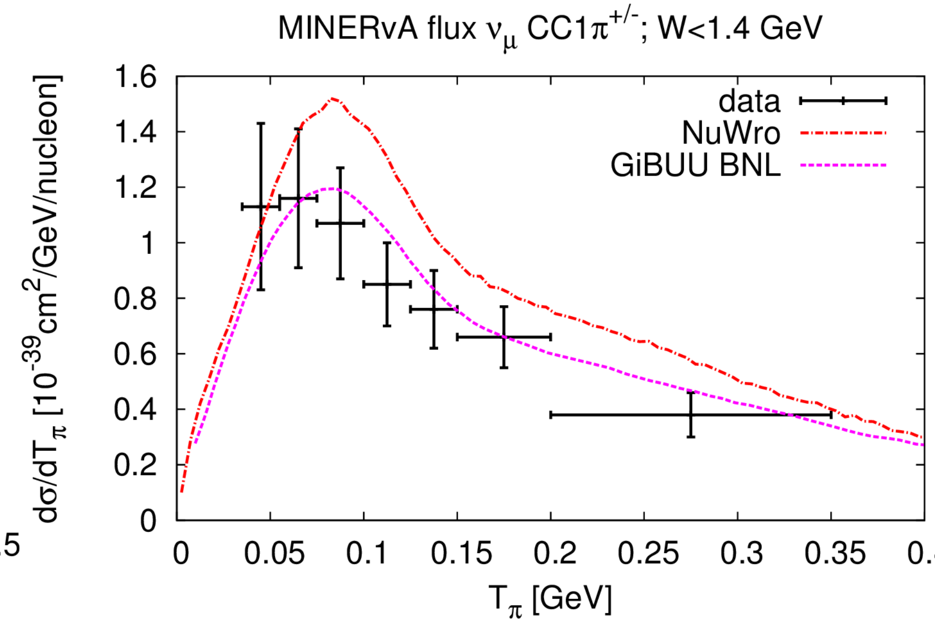
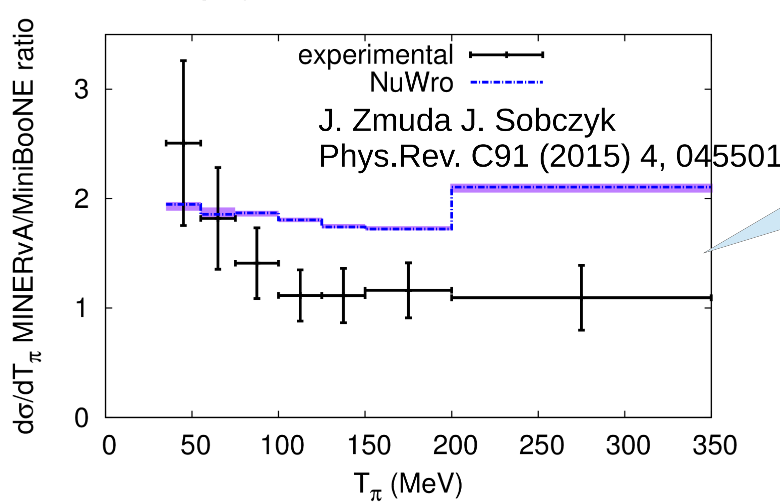
Comparison GiBUU vs. NuWro vs. MiniBooNE vs. MINERvA

- What about GiBUU+ overestimated form factors from BNL data set [1]?





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



Better if MINERvA after flux correction?

[1] O. Lalakulich and U. Mosel Phys.Rev. C87 (2013) 014602)

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

Single pion production via resonance in NEUT

Use the model by Rein and Sehgal

- 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

- 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)

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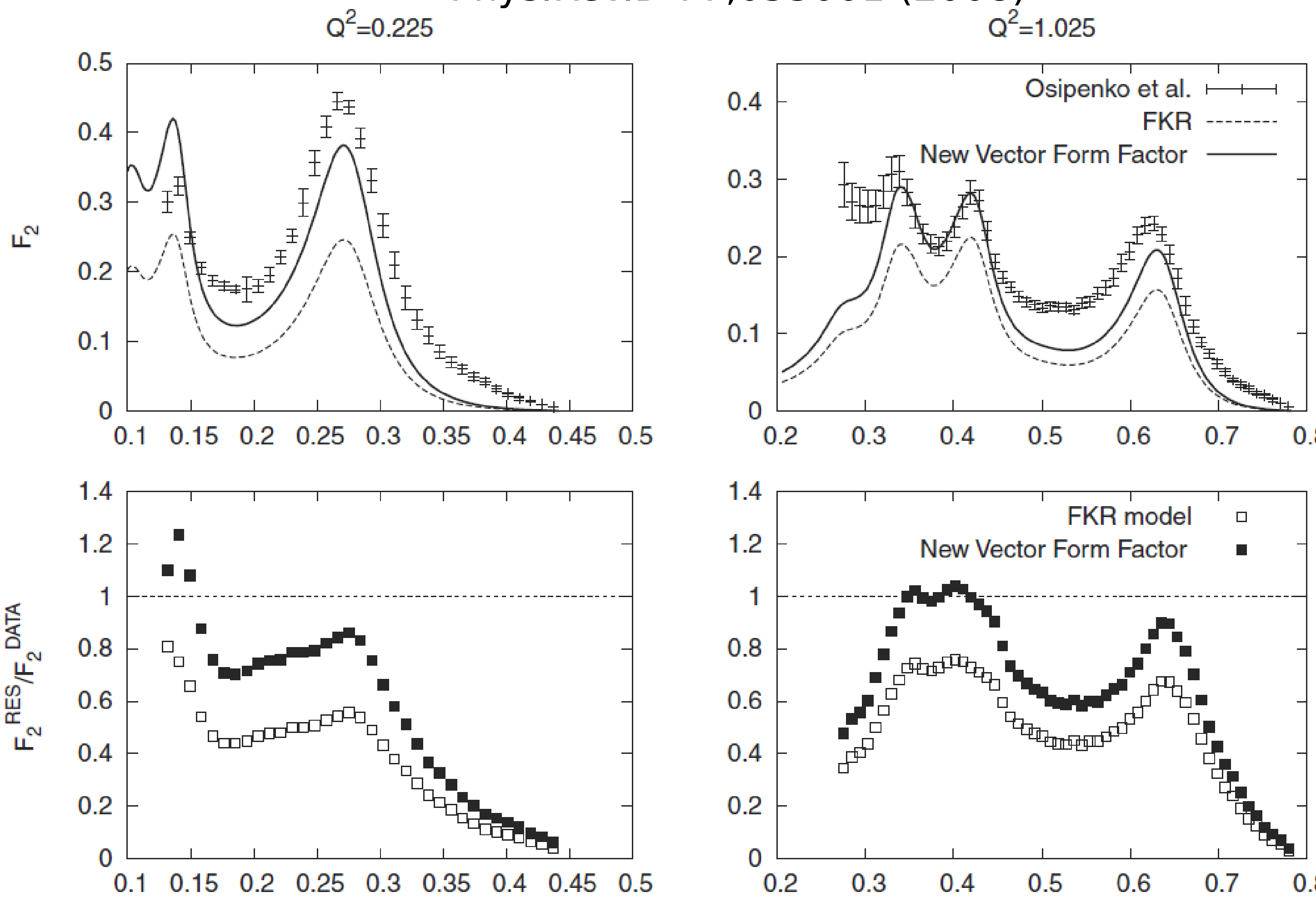
Pion Production in NEUT (thanks to Y. Hayato for slides!)

Single pion production via resonance in NEUT

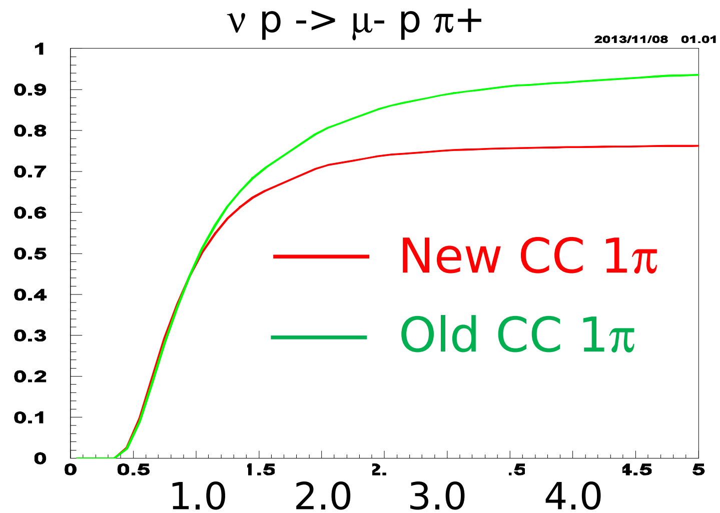
Attempts to improve the vector form factor in Rein-Sehgal model

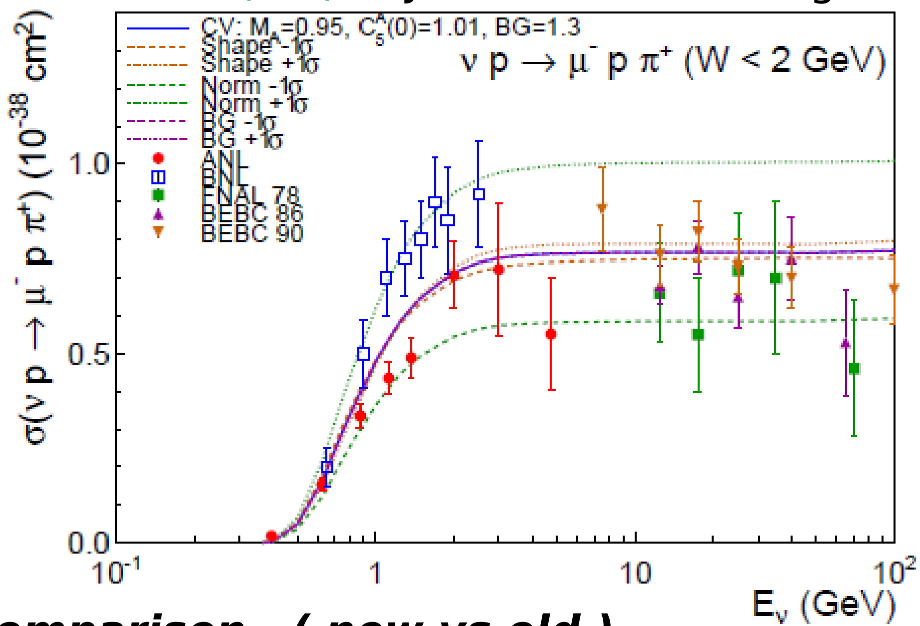
Prescription by K.M. Graczyk and J.T. Sobczyk
Phys.Rev.D 77,053001 (2008)



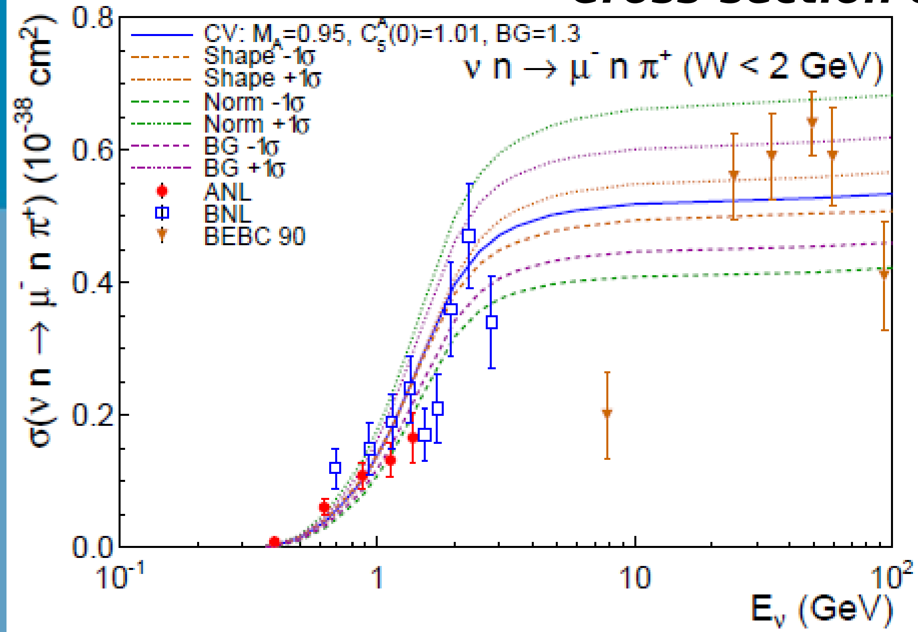
Pion Production in NEUT (thanks to Y. Hayato for slides!)

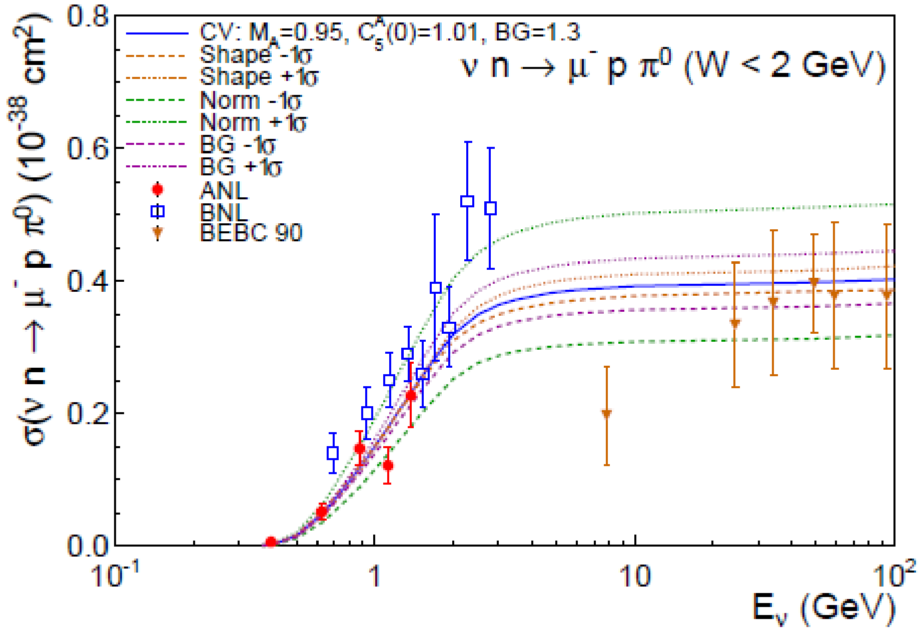
Axial part: fits $C^5_A(0)$ (1.01), M_A (0.95 GeV) and scale (1.3) of J=1/2 nonres. background To ANL/BNL bubble chamber data





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!)

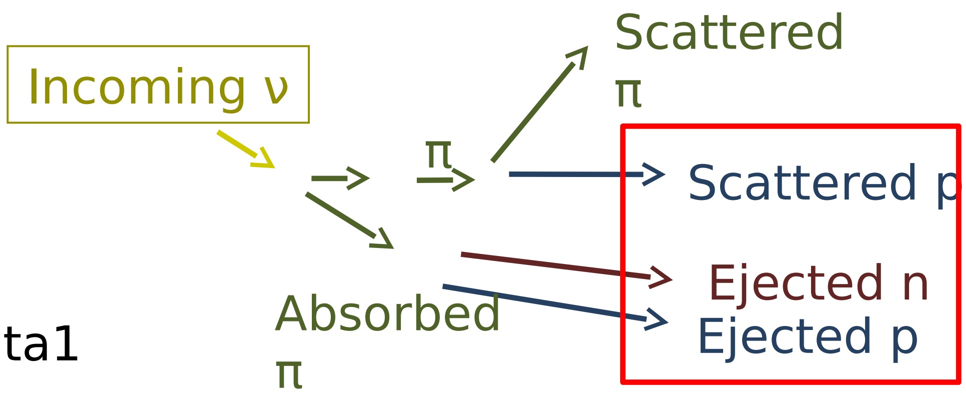
Single pion production via resonance in NEUT - FSI

- Simulated with the cascade model
- Simulated interactions
  - inelastic scattering
    - incl. charge exchange & particle production ($\pi N \to \pi \pi N$)
  - 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!)

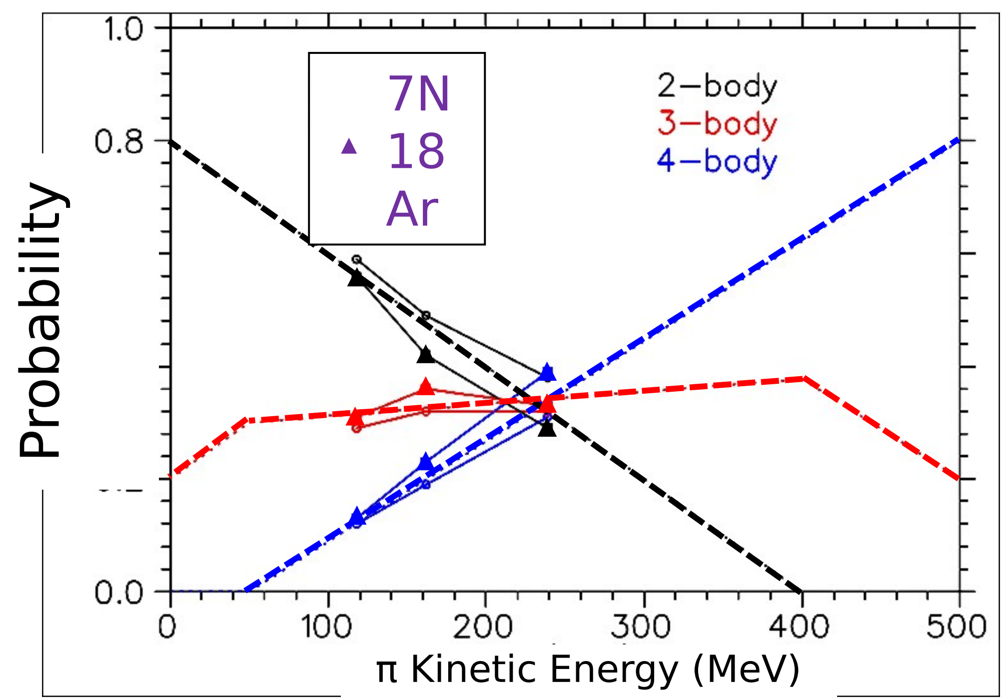
Single pion production via resonance in NEUT

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

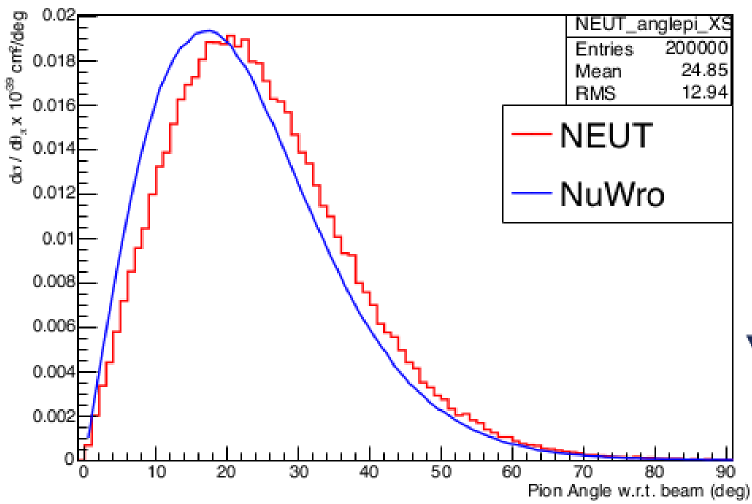


(P. de Perio / R. Tacik)

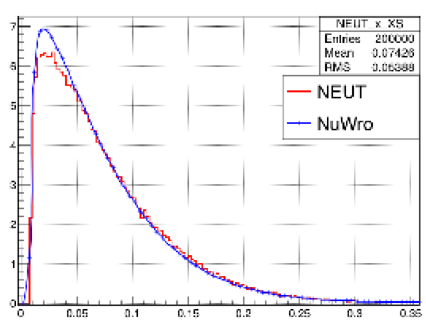
[1] Rowntree *et al*. Phys. Rev. C60 (99) 054610
[2] Ritchie, Phys. Rev. C 44, 533

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

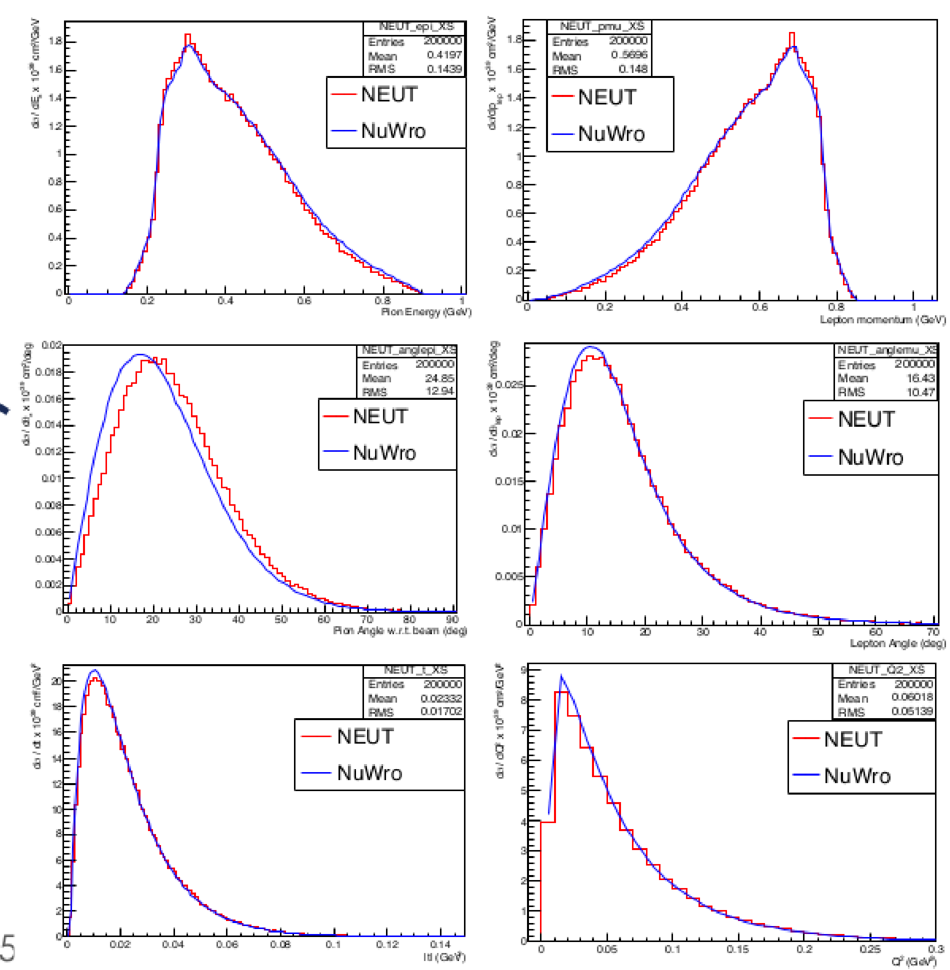
- Work done with Jakub Zmuda.
- Compare all the kinetic variables for CC and NC at fixed neutrino energies of 1, 3 and 5 GeV. (back-up slides)
- Overall, there is a good agreement, except for the pion angle at low energy.



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



CC 1 GeV



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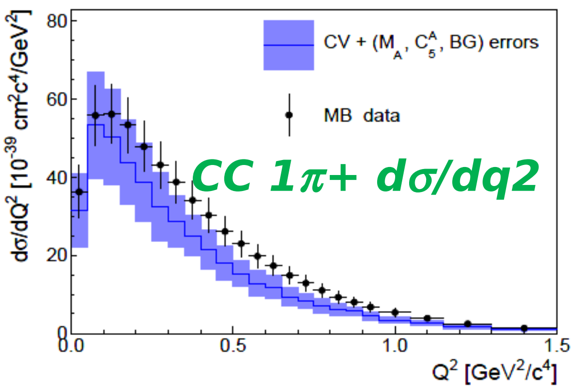
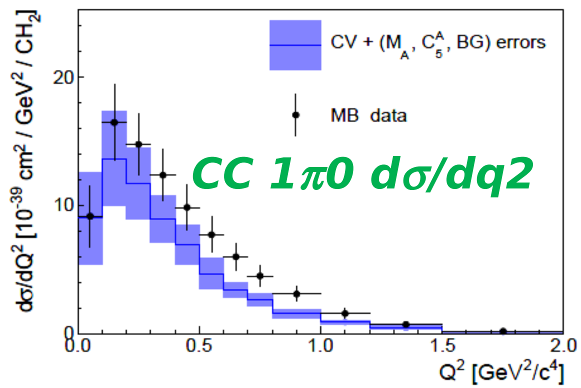
Pion Production in NEUT (thanks to Y. Hayato for slides!)

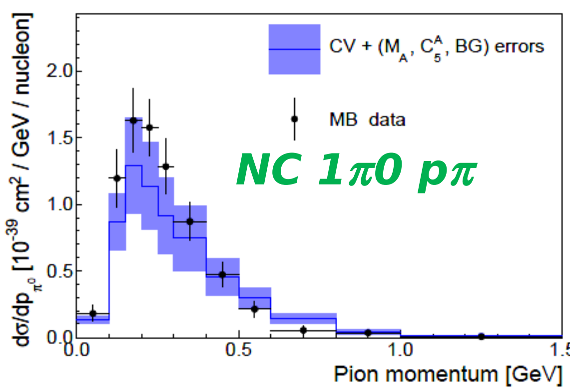
Comparisons with data from MiniBooNE and MINERvA



(a) MiniBooNE CC1π^+

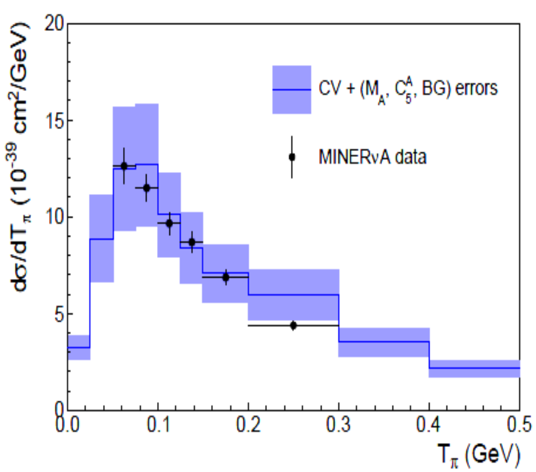


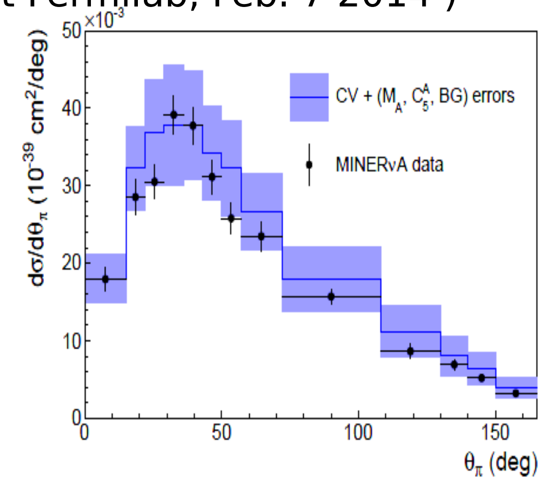
(b) MiniBooNE CC1π^0



(c) MiniBooNE NC1π^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)





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)

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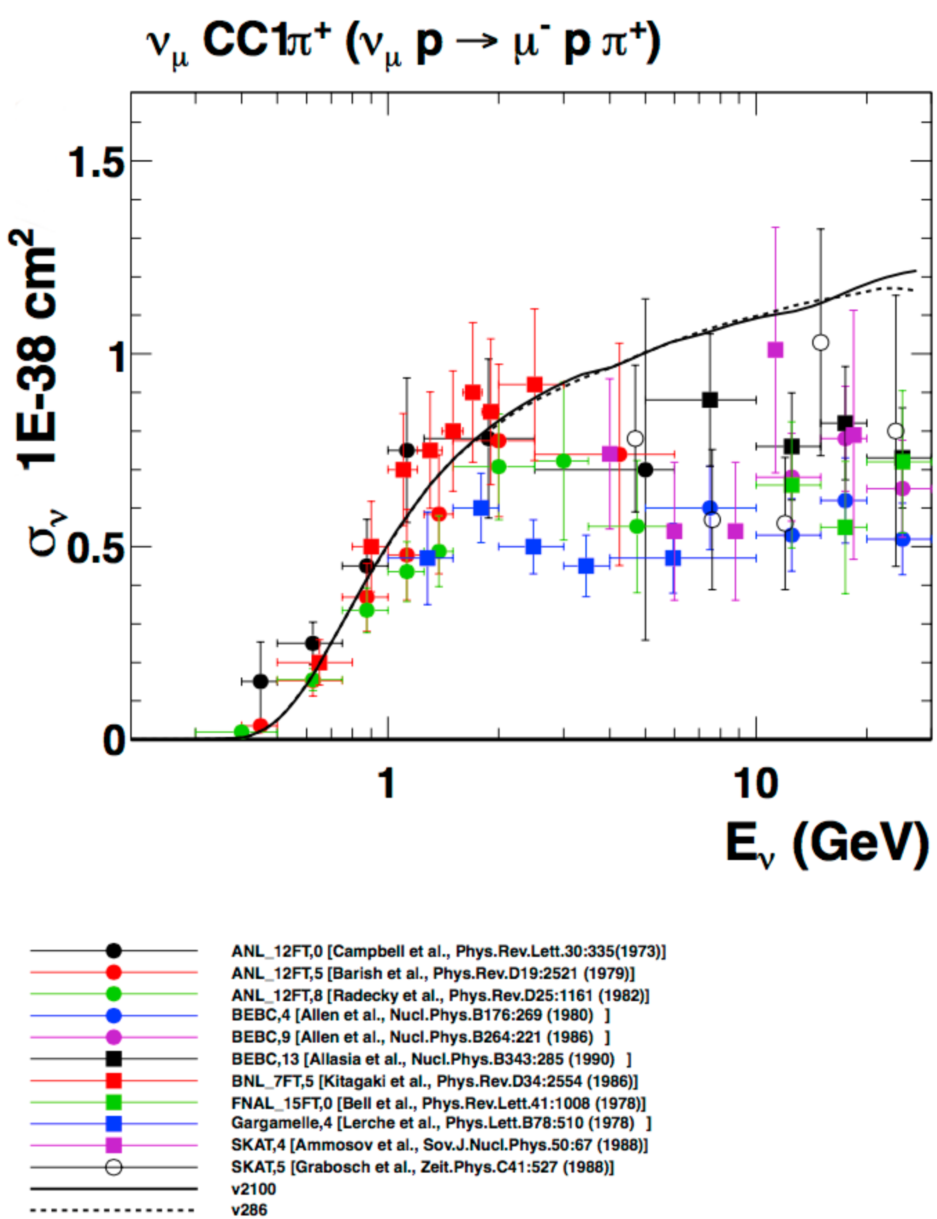
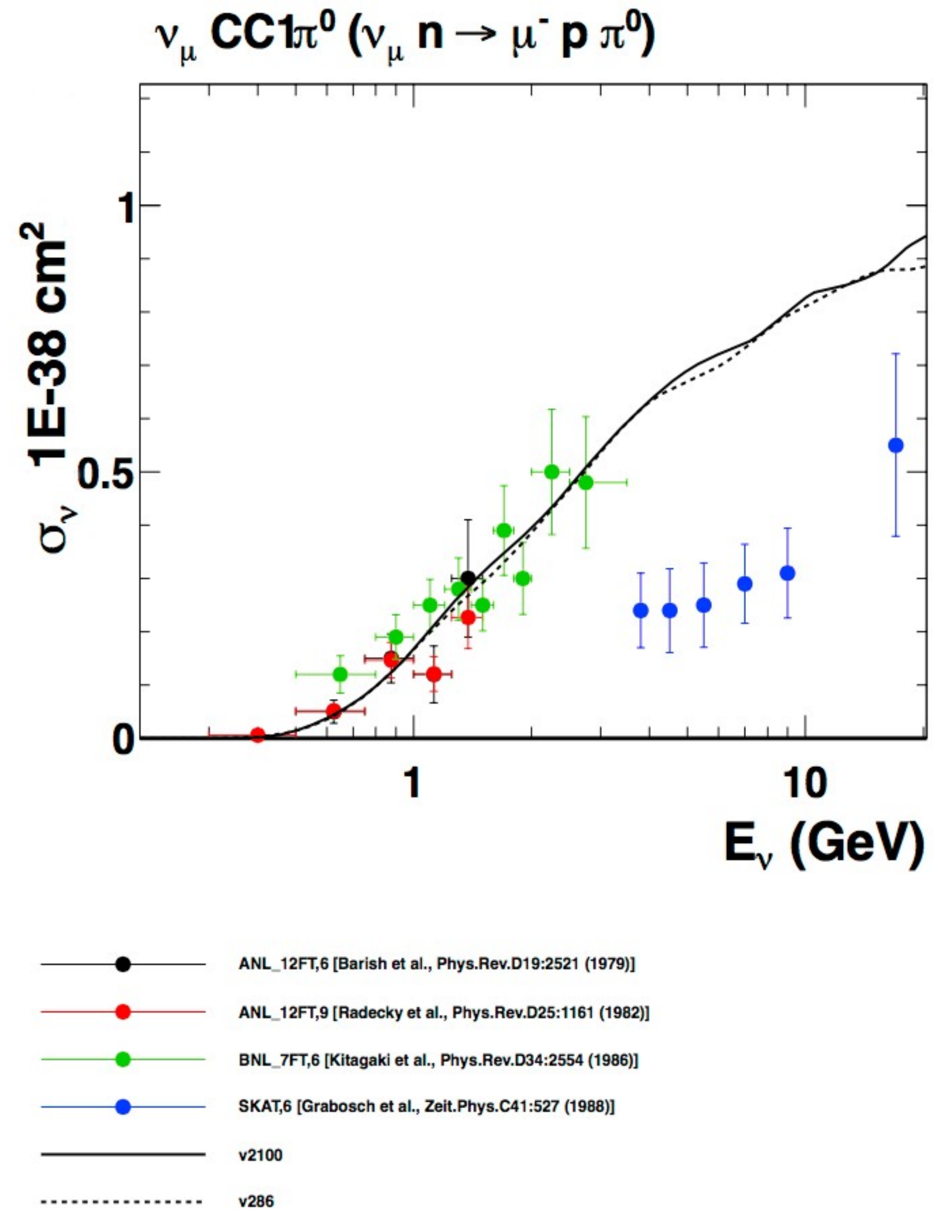
Pion Production in GENIE (thanks to C. Andreopoulos for slides!)

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

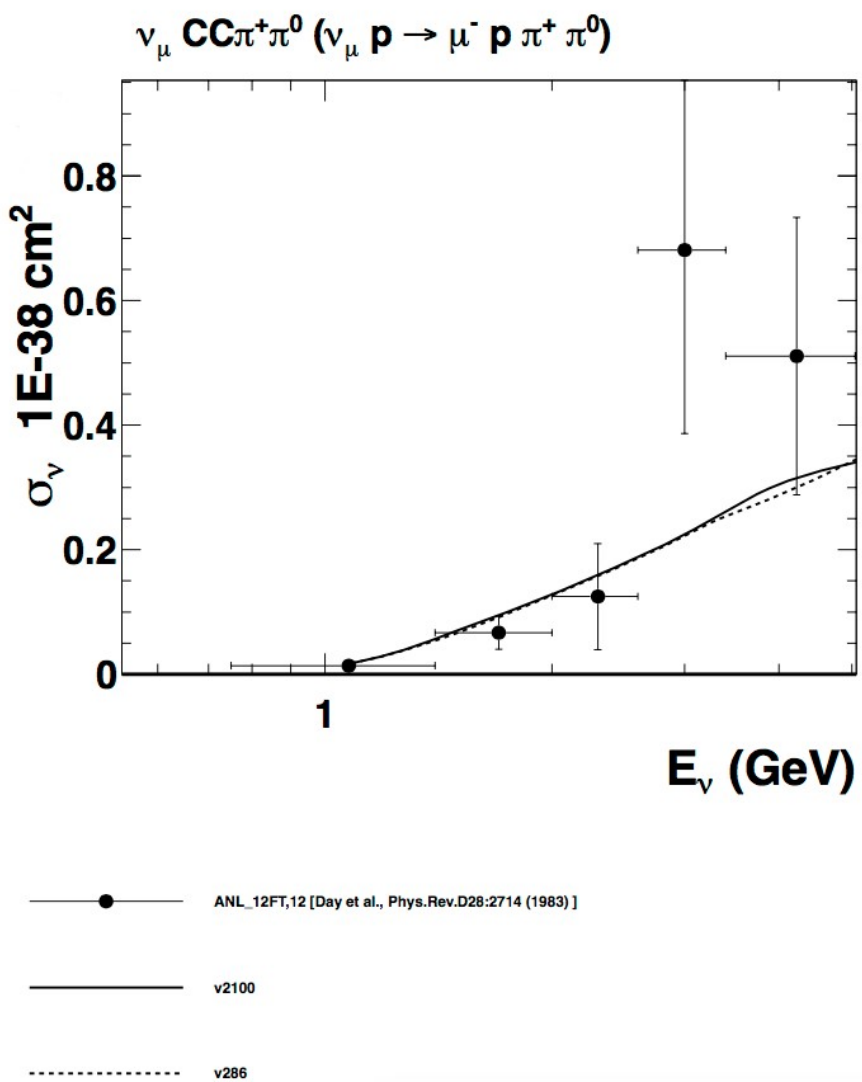
- BY: An effective LO model / Higher twist terms and target mass corrections accounted for via a new scaling variable and modification to the low-Q2 pdfs.
  - *The longitudinal structure function is taken into account using the Whitlow R (FL / 2xF1) parameterization.*
  - *Shadowing, anti-shadowing and 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*

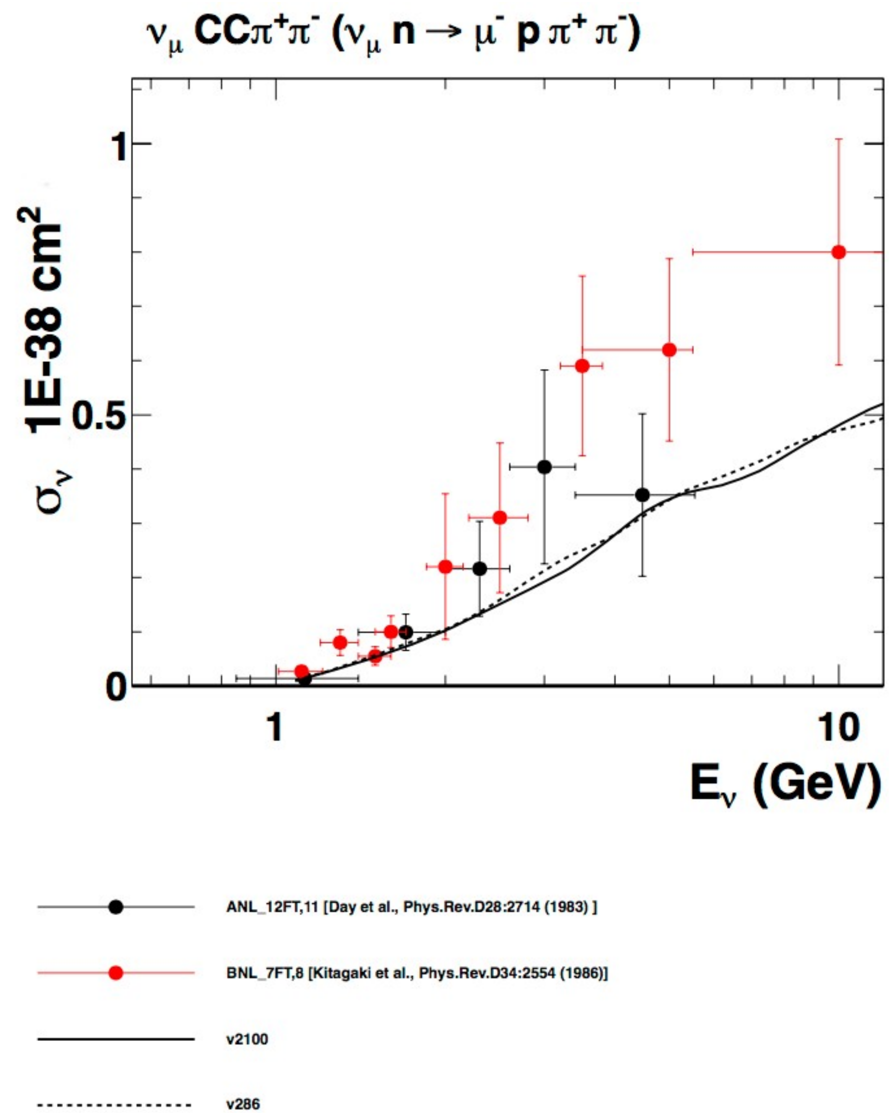
Pion Production in GENIE (thanks to C. Andreopoulos for slides!)



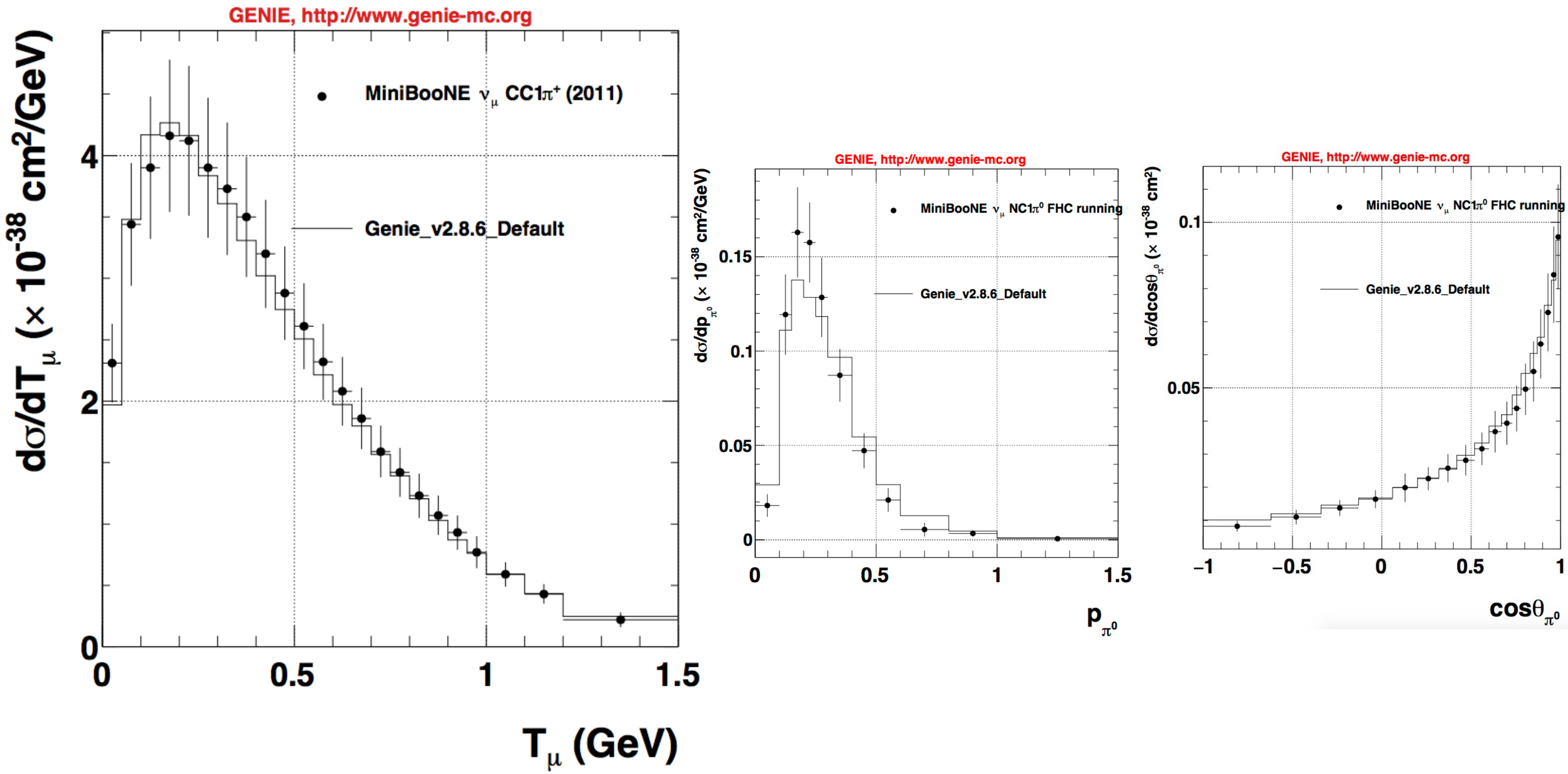


Pion Production in GENIE (thanks to C. Andreopoulos for slides!)





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



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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 resonances propagate before decay!)
NEUT	FG	Rein-Sehgal (with corrections)	J=1/2 background	PYTHIA 6	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. All generators miss some important pion production/ absorption channel?

Thank you for your attention!

We cordially invite you to our Winter School!

http://ift.uni.wroc.pl/~karp52