GENIE (mostly single) pions

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Outline

- GENIE's pion production model(s)
  - "Nuclear" models for the ground state.
    - See earlier 1p1h talk...
  - Free nucleon model:
    - Form factors
    - Differential cross section algorithms
  - Resonant production
  - Coherent production

  - Note: again we will largely ignore the remnant nucleus and FSI in this presentation.

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Documentation

- Physics and Users Manual contains some detail (non-exhaustive example below):
  - https://arxiv.org/abs/1510.05494
  - Please feel empowered to contribute. (Classic OSS "first contribution" is documentation.)

Baryon Resonance Production: The production of baryon resonances in neutral and charged current channels is included with the Rein-Sehgal model [36]. This model employs the Feynman-Kislinger-Ravndal [37] model of baryon resonances, which gives wavefunctions for the resonances as excited states of a 3-quark system in a relativistic harmonic oscillator potential with spin-flavor symmetry. In the Rein-Sehgal paper the helicity amplitudes for the FKR model are computed and used to construct the cross sections for neutrino-production of the baryon resonances. From the 18 resonances of the original paper we include the 16 that are listed as unambiguous at the latest PDG baryon tables and all resonance parameters have been updated. In our implementation of the Rein-Sehgal model interference between neighboring resonances has been ignored. Lepton mass terms are not included in the calculation of the differential cross section, but the effect of the lepton mass on the phase space boundaries is taken into account. For tau neutrino charged current interactions an overall correction factor to the total cross section is applied to account for neglected elements (pseudoscalar form factors and lepton mass terms) in the original model. The default value for the resonance axial vector mass m_A is 1.12 GeV/c^2, as determined in the global fits carried out in Reference [38].

Coherent Neutrino-Nucleus Scattering: Coherent scattering results in the production of forward going pions in both charged current ($\nu_\mu + A \to \mu^- + \pi^+ + A$) and neutral current ($\nu_\mu + A \to \nu_\mu + \pi^0 + A$) channels. Coherent neutrino-nucleus interactions are modeled according to the Rein-Sehgal model [39]. Since the coherence condition requires a small momentum transfer to the target nucleus, it is a low-Q^2 process which is related via PCAC to the pion field. The Rein-Sehgal model begins from the PCAC form at Q^2=0, assumes a dipole dependence for non-zero Q^2, with $m_A = 1.00$ GeV/c^2, and then calculates the relevant pion-nucleus cross section from measured data on total and inelastic pion scattering from protons and deuterium [40]. The GENIE implementation is using the modified PCAC formula described in a recent revision of the Rein-Sehgal model [41] that includes lepton mass terms.

Resonant production

- Multiple models
  - Rein-Sehgal
  - Berger-Sehgal
  - Berger-Sehgal-Kuzmin-Lyubushkin-Naumov (!)
  - Kuzmin-Lyubushkin-Naumov
  - (P33) Paschos-Lalakulich   [actually, not fully sure if this is complete/runs]

D.Rein and L.M.Sehgal, Neutrino Excitation of Baryon Resonances and Single Pion Production, Ann.Phys.133, 79 (1981)

Kuzmin, Lyubushkin, Naumov Mod. Phys. Lett. A19 (2004) 2815

KLN Modifications based on a MiniBooNE tune courtesy of J. Nowak and S. Dytman.

Rein Sehgal (the model we all love to hate)

- Model employs the Feyman-Kislinger-Ravndal model of baryon resonances.
- RS computes helicity amplitudes for the FKR model and uses them to construct cross sections for neutrino production of baryon resonances.
- Original paper had 18 resonances - we include the 16 listed as unambiguous in the PDG (as of... 2008?). Interference between neighboring resonances is ignored.
- Lepton mass terms are not included in the original RS, but the effects of lepton mass on phase space boundaries is included.
- Resonance M_A is 1.12 GeV/c^2.

Berger-Rein-Sehgal Resonant Pion

K. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Mod.Phys.Lett. **A19**, 2919 (2004), hep-ph/0403110.

C. Berger and L. Sehgal, Phys.Rev. **D76**, 113004 (2007), 0709.4378.

- The Berger-Sehgal and Kuzmin-Lyubushkin-Naumov models for N^* resonances are very similar to the default Rein-Sehgal model, but include the effects due to the muon mass.
- BS includes an extra diagram that is not found in KLN.
- Much of the original code for the resonance couplings is untouched.

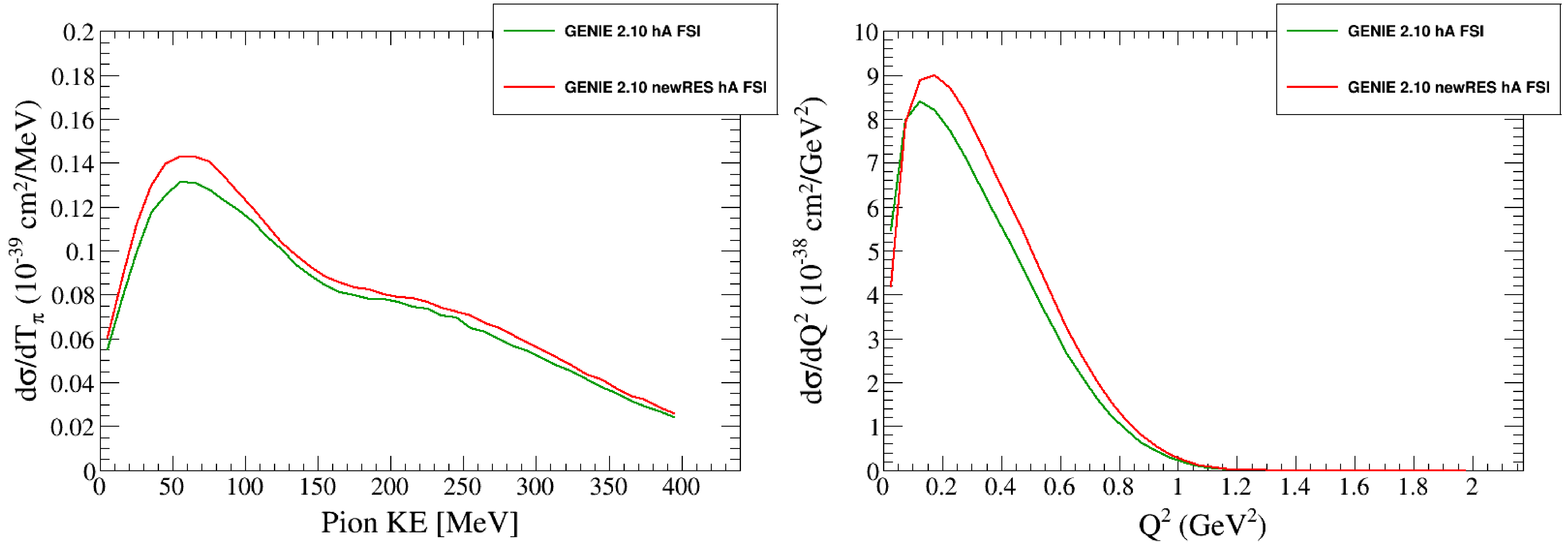


Figure 8: Comparison of new model (Berger-Sehgal with new form factors) with default model.

- Work in MiniBooNE also improved the form factors which have remained unchanged in the Rein-Sehgal resonance model.
- These are also included with parameters (`miniboonеGV` and `miniboonеGA` for new vector and axial form factors) in UserPhysicsOptions.xml.
- Figure shows the effect of adding the components of the model one at a time. (This uses the same code as in the GENIE validations.)
- S. Dytman, J. Nowak (Lancaster), I. Kakorin (JINR)

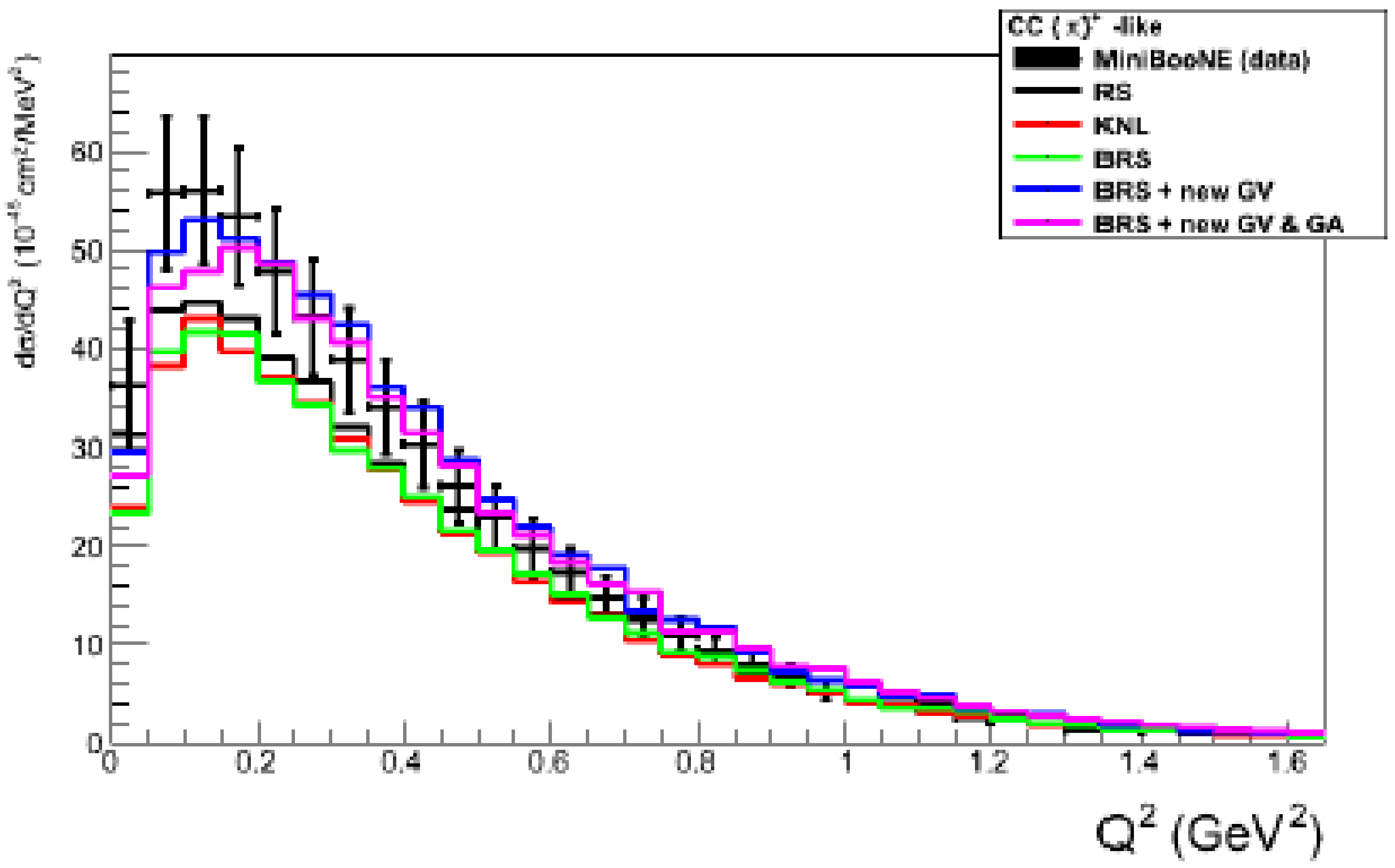
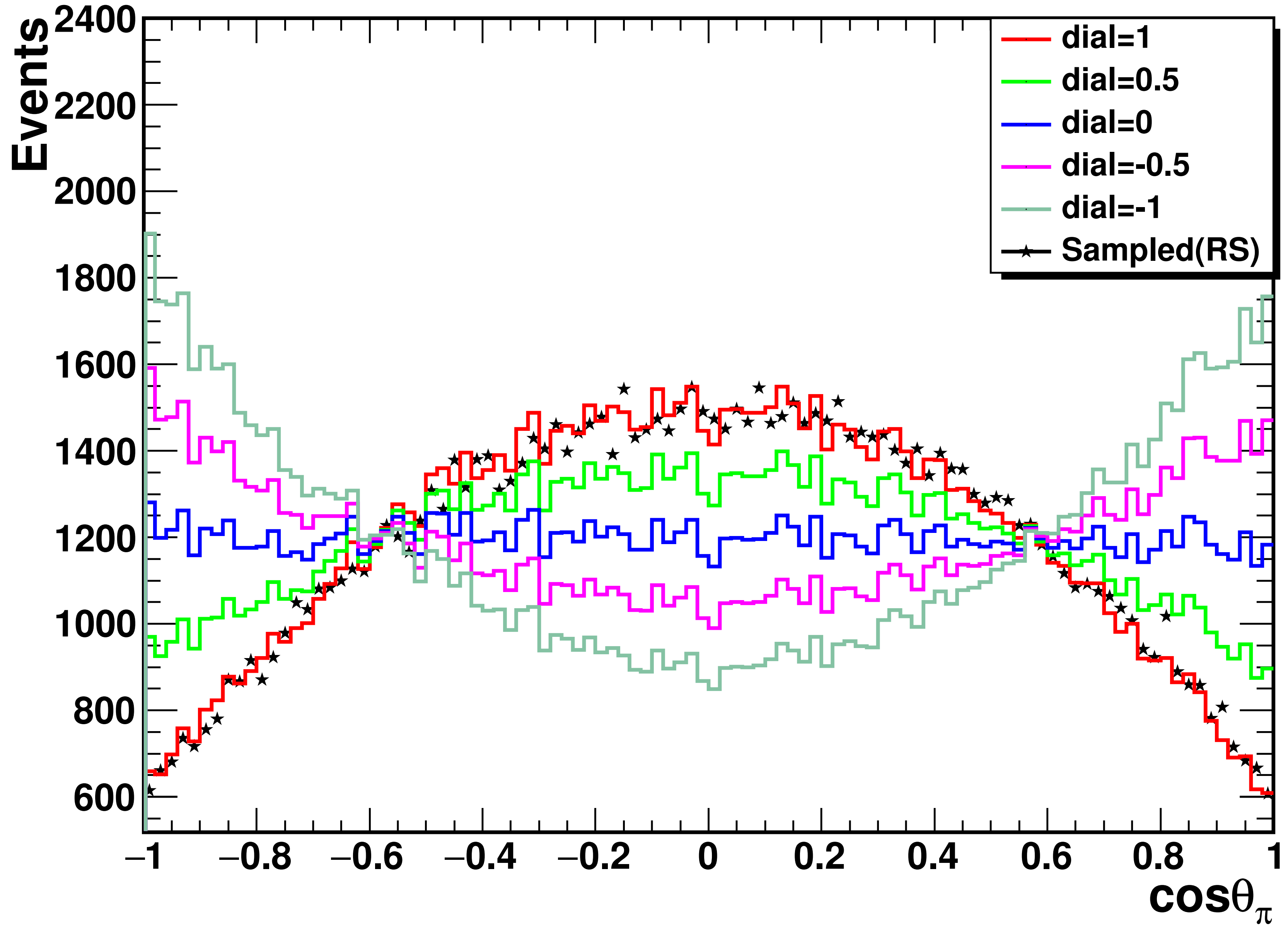


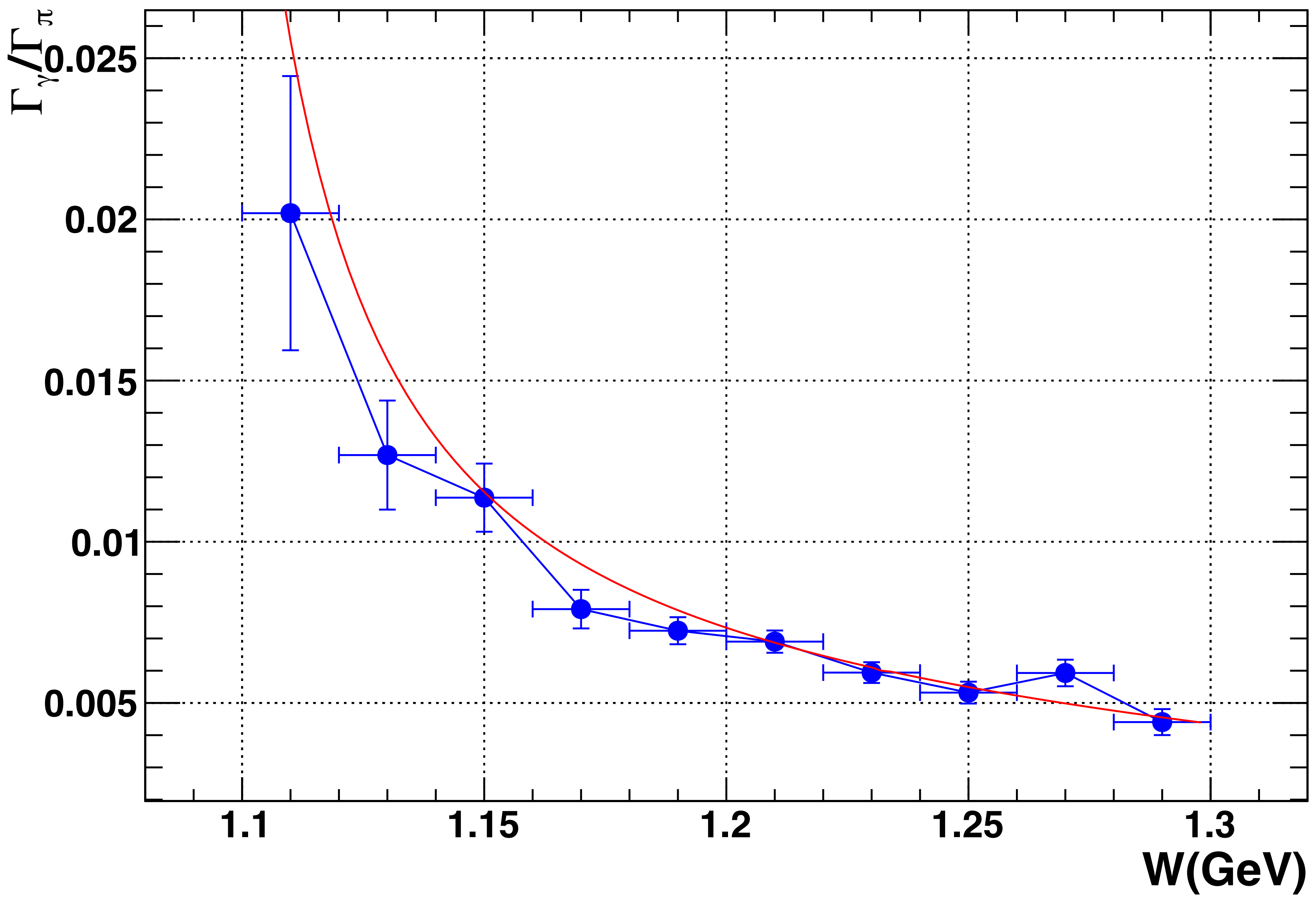
Figure 7: Comparison of new model with MiniBooNE data (J.Nowak).

"Recent" resonance model updates

- The angular distribution of pions from the decay of resonance states was changed in 2.10.0 from isotropic to non-isotropic.
- The cross section for Δ → Nγ was improved: corrected the lower limit in W and fixed the ratio of the widths Δ → Nγ to Δ → Nπ (previously fixed at 0.006).



Comparing generated (new) to re-weighted isotropic (old)



Compare GENIE to theoretical expectation.

(L. Jiang)

Transition region

- The total inelastic differential cross section is

$$\frac{d^2\sigma^{inel}}{dQ^2dW} = \frac{d^2\sigma^{RES}}{dQ^2dW} + \frac{d^2\sigma^{DIS}}{dQ^2dW}$$

- The RES term represents the contribution from all low multiplicity inelastic channels that proceed through resonance production:

$$\frac{d^2\sigma^{RES}}{dQ^2dW} = \sum_k \left(\frac{d^2\sigma^{R/S}}{dQ^2dW}\right)_k \cdot \Theta(Wcut - W)$$

- k runs over resonances, Wcut is model parameter.

Transition region

- The DIS term of the inelastic cross section uses Bodek-Yang scaled to get agreement in the total cross section.

$$\frac{d^2\sigma^{DIS}}{dQ^2dW} = \frac{d^2\sigma^{DIS,BY}}{dQ^2dW} \cdot \Theta(W - Wcut) + \\ + \frac{d^2\sigma^{DIS,BY}}{dQ^2dW} \cdot \Theta(Wcut - W) \cdot \sum_m f_m$$

- m refers to multiplicity, so f_m relates the total DIS xsec to its paired multiplicity channel. f_m = R_m x p_had_m, where R_m is a tunable parameter, and p_had_m is the probability (from hadronization model) that DIS final state multiplicity is m.
  - This couples the DIS xsec and the hadronization model.

Coherent pion production

- Multiple models
  - Rein-Sehgal (updated with letpon mass terms)
  - Berger-Sehgal
  - Rein model (diffractive)

(We'll fill up the blank part of the slide with the national Mammal of the United States.)

Berger-Sehgal Coherent Pion

- Actually two new models - one version as presented in PRD 79 053003 (2009) and another with custom modifications to relax the "infinite target mass" assumptions.
  - Very little difference in the cross sections, largely validating the original assumption.
  - "Finite mass" model is a triple-differential integral (can integrate out the t-dependence in the cross section as presented in Berger and Sehgal's paper), so it is a bit slower.

The models may be activated by setting either

```
<param type="alg" name="XSecModel@genie::EventGenerator/COH-CC">
  genie::BergerSehgalCOHPiPXSec2015/Default </param>
<param type="alg" name="XSecModel@genie::EventGenerator/COH-NC">
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```

or

```
<param type="alg" name="XSecModel@genie::EventGenerator/COH-CC">
  genie::BergerSehgalFMCOHPiPXSec2015/Default </param>
<param type="alg" name="XSecModel@genie::EventGenerator/COH-NC">
  genie::BergerSehgalFMCOHPiPXSec2015/Default </param>
```

BS vs RS

Kinematic Term

$$\frac{d\sigma^{NC}}{dQ^2\ dy\ dt} = \frac{G_F^2 f_\pi^2}{4\pi^2}\frac{E}{|\mathbf{q}|}u\ v\ G_A^2\frac{d\sigma\left(\pi^0 N \to \pi^0 N\right)}{dt}$$

BS

$$\frac{E_\nu uv}{|\mathbf{q}|} = \frac{(1-y)\,E_\nu}{\sqrt{y^2E_\nu^2+Q^2}}\left(1-\frac{Q^2}{4\,(1-y)\,E_\nu^2}\right)$$

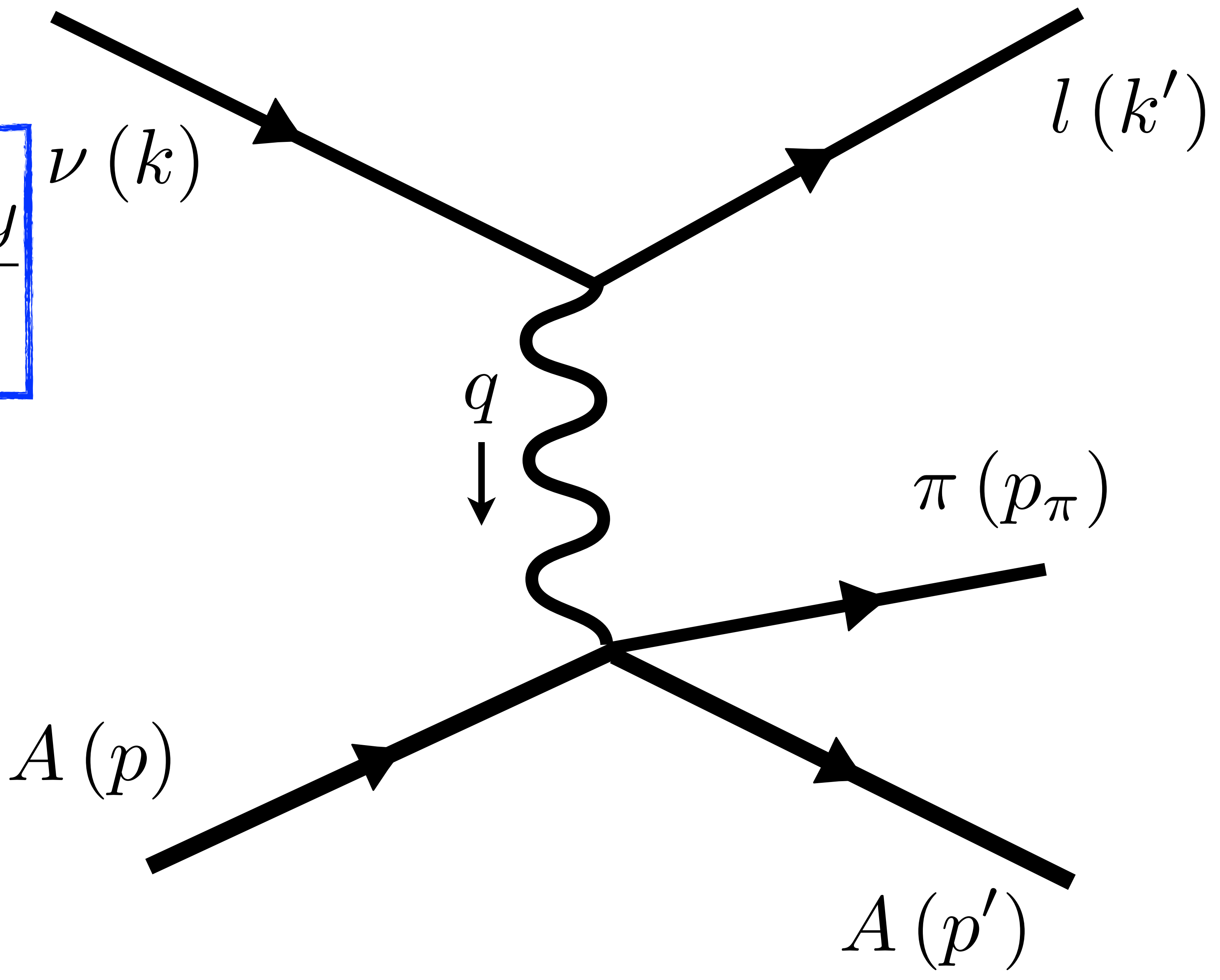
RS (Q²=0)

$$\frac{E_\nu uv}{|\mathbf{q}|} \to \frac{1-y}{y}$$

$$\left[\left(G_A - \frac{1}{2}\frac{Q^2_{\min}}{Q^2+m_\pi^2}\right)^2 + \frac{y}{4}\left(Q^2-Q^2_{\min}\right)\frac{Q^2_{\min}}{\left(Q^2+m_\pi^2\right)^2}\right]$$

Lepton Mass Correction (BS)

$$Q^2_{\min} = m_l^2\frac{y}{1-y} \qquad G_A = \frac{m_A^2}{m_A^2+Q^2}$$



BS "Style"

$$\frac{d\sigma_{\rm el}}{dt} = A_1 e^{-b_1 t}$$

TABLE I. Coefficients A_1, b_1 of Eq. (16).

T_π (GeV)	A_1 (mb/GeV²)	b_1 (1/GeV²)
0.076	11 600	116.0
0.080	14 700	109.0
0.100	18 300	89.8
0.148	21 300	91.0
0.162	22 400	89.2
0.226	16 400	80.8
0.486	5730	54.6
0.584	4610	55.2
0.662	4570	58.4
0.776	4930	60.5
0.870	5140	62.2

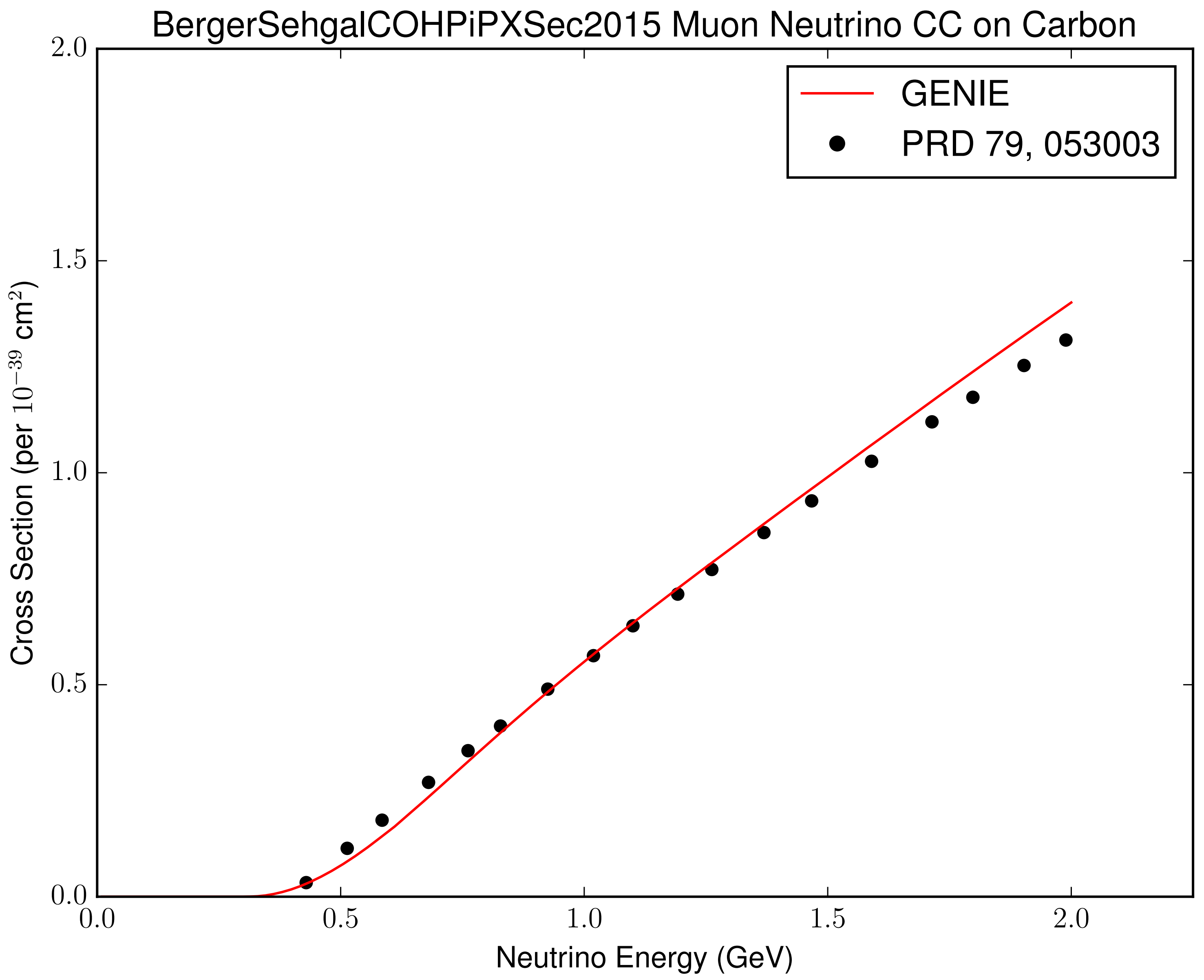
RS "Style"

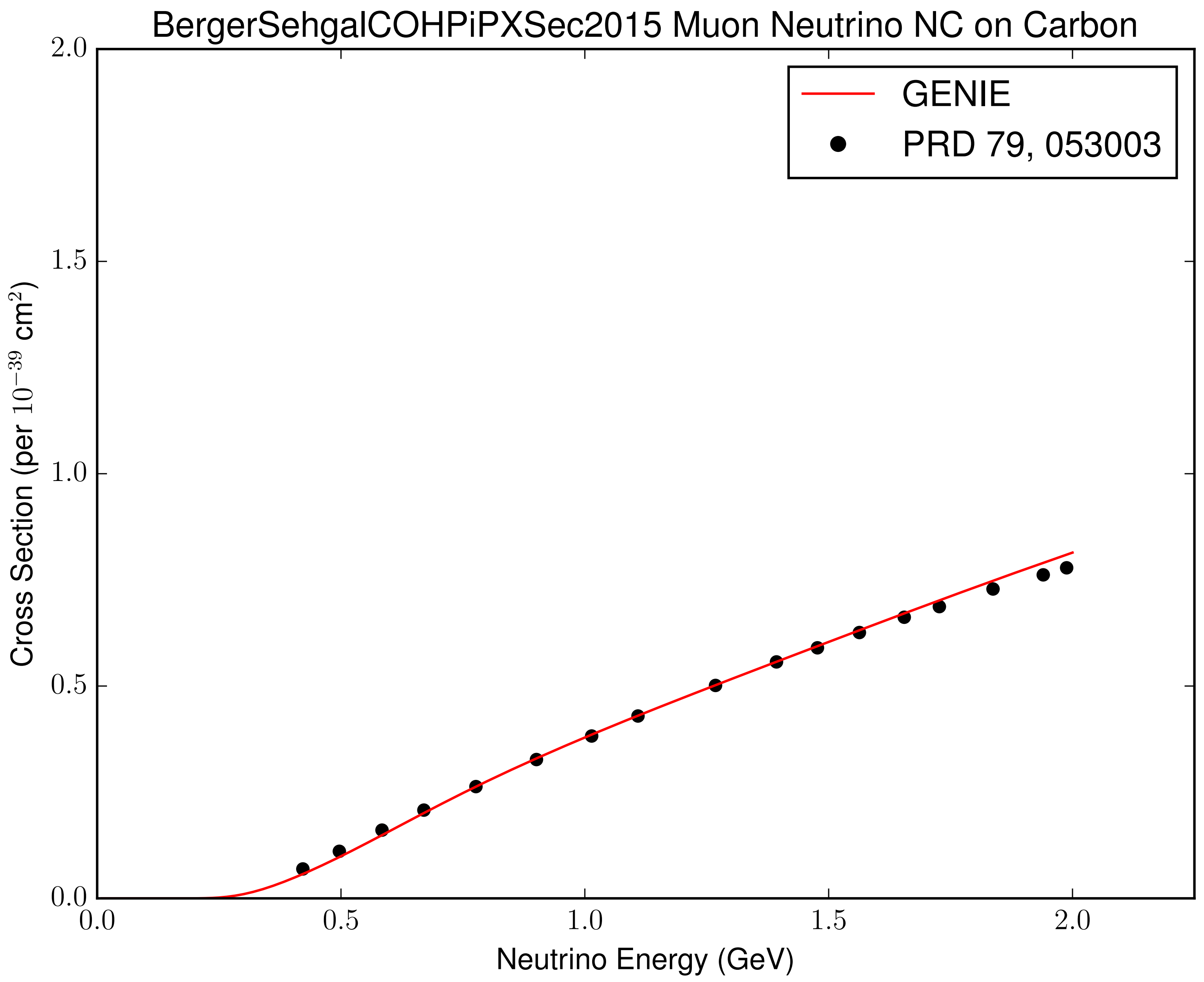
$$\frac{d\sigma\left(\pi N \to \pi N\right)}{dt} = A^2\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} e^{-bt}F_{abs}$$

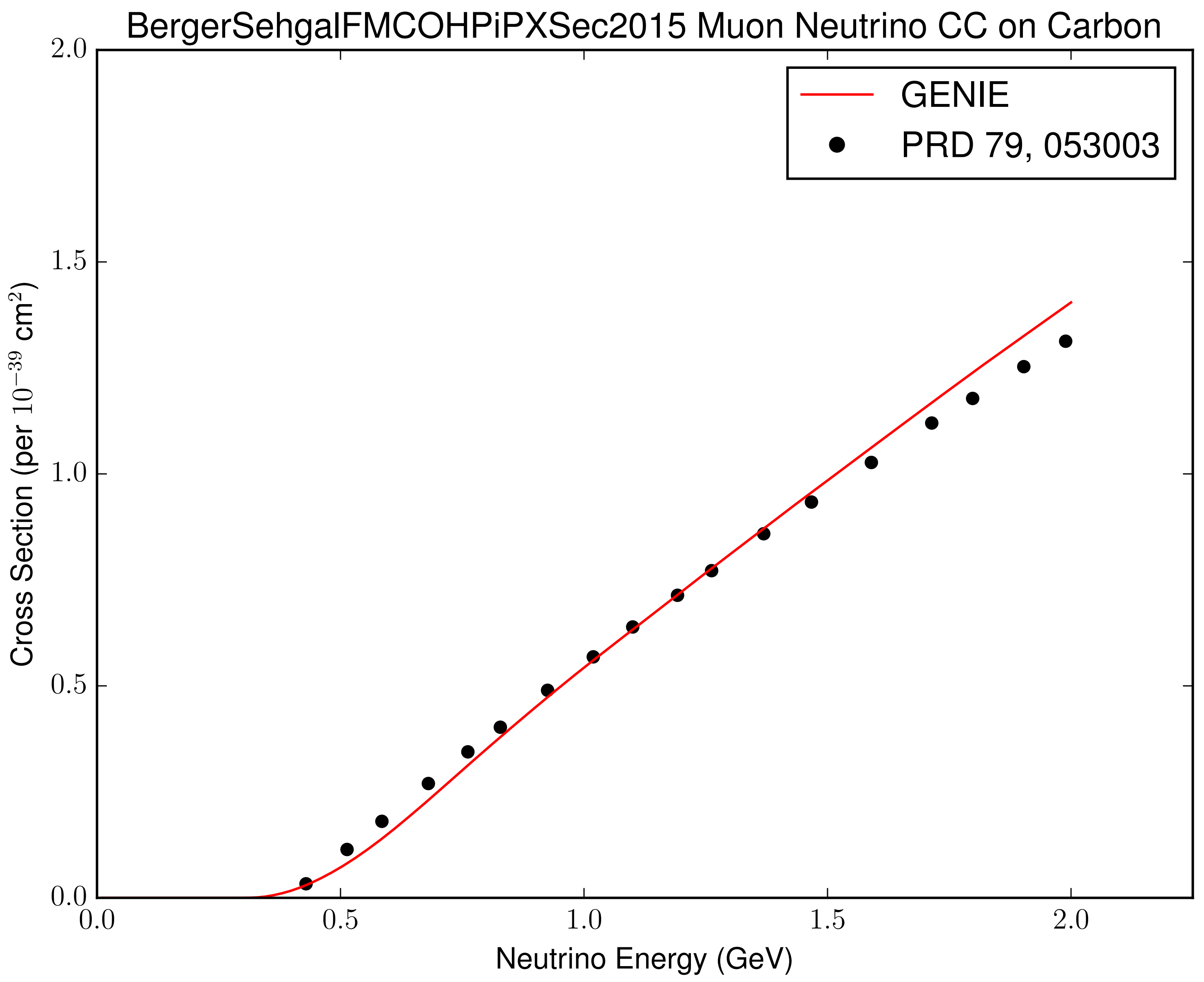
$$\left.\frac{d\sigma_{el}}{dt}\right|_{t=0} = \frac{1}{16\pi}\left(\frac{\sigma_{tot}^{\pi^+p}+\sigma_{tot}^{\pi^-p}}{2}\right)^2$$

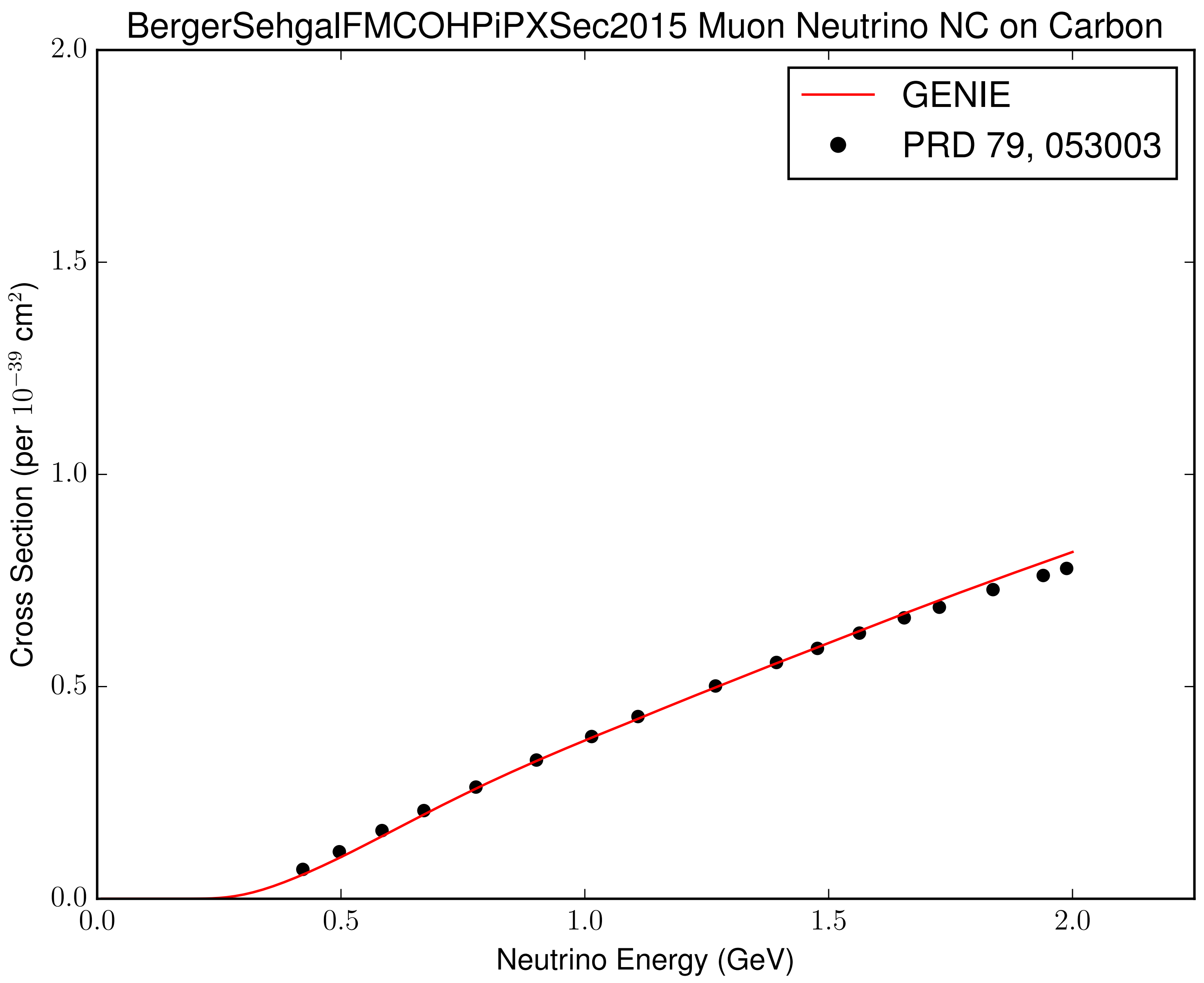
$$b = \frac{1}{3}R_0^2A^{2/3}$$

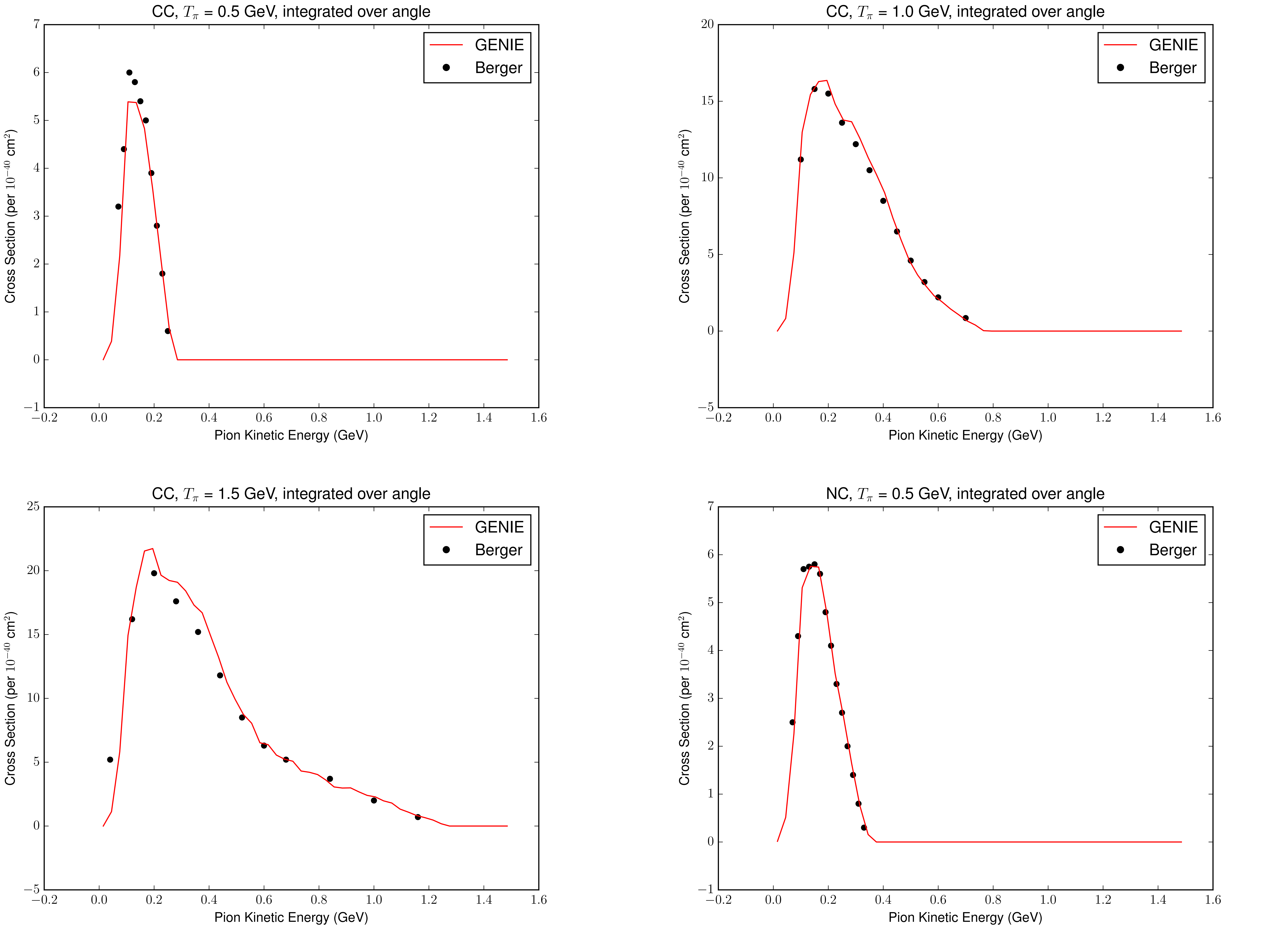
$$F_{abs} = \exp\left(-\frac{9A^{1/3}}{16\pi R_0^2}\sigma_{inel}\right)$$

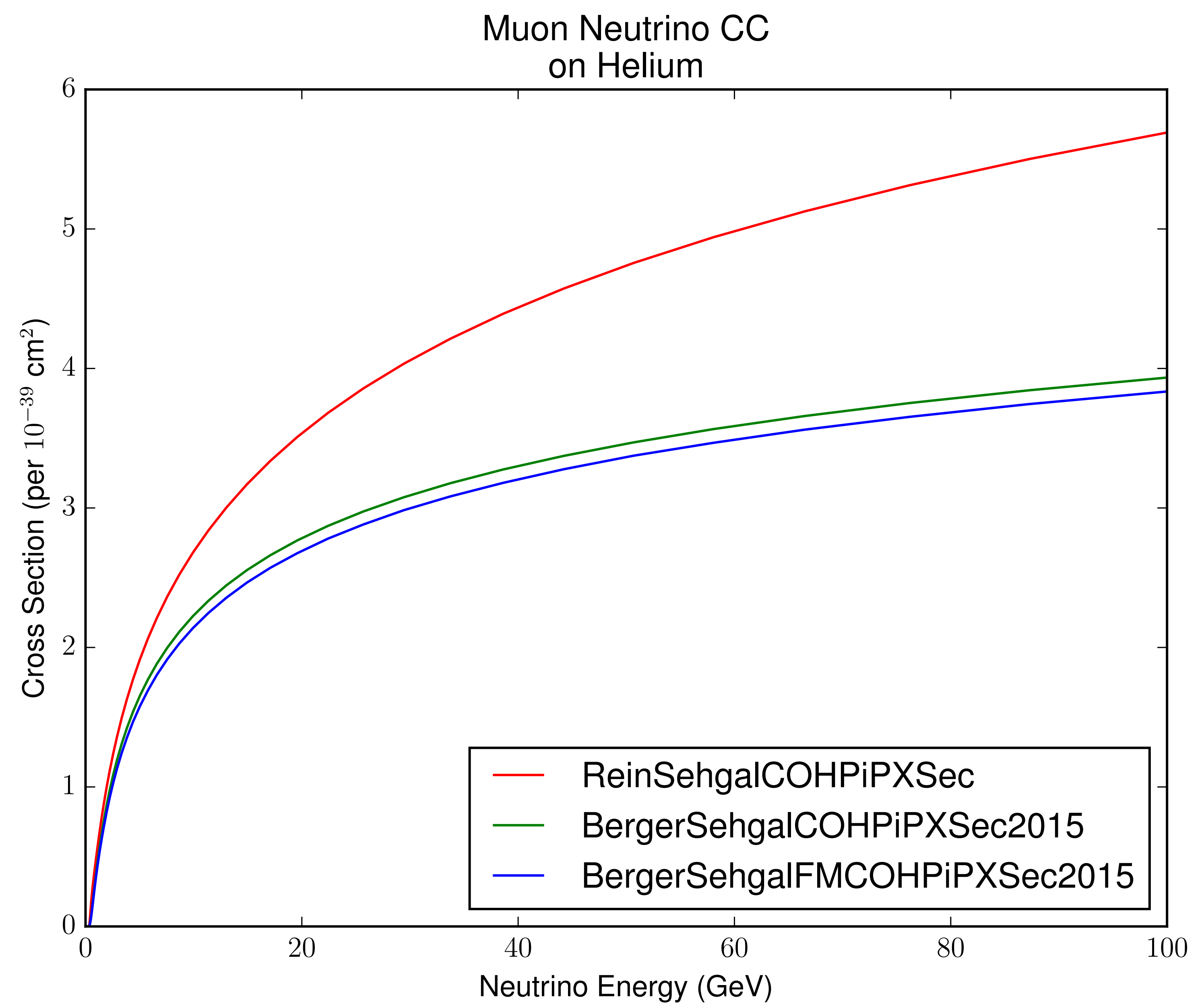

BergerSehgalCOHPiPXSec2015 Muon Neutrino CC on Carbon
GENIE
PRD 79, 053003
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
0.0
0.5
1.0
1.5
2.0

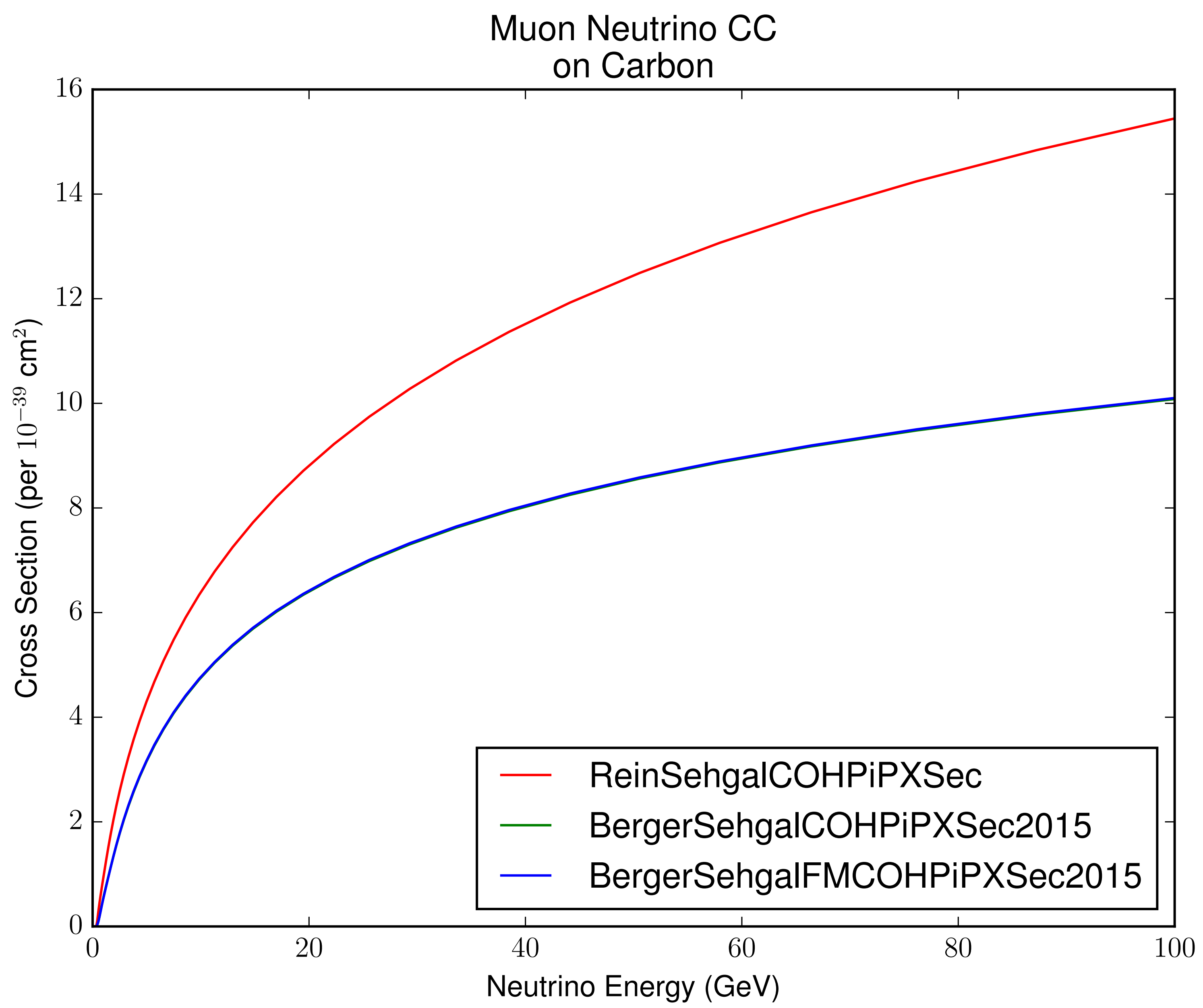

BergerSehgalCOHPiPXSec2015 Muon Neutrino NC on Carbon
GENIE
PRD 79, 053003
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
0.0
0.5
1.0
1.5
2.0

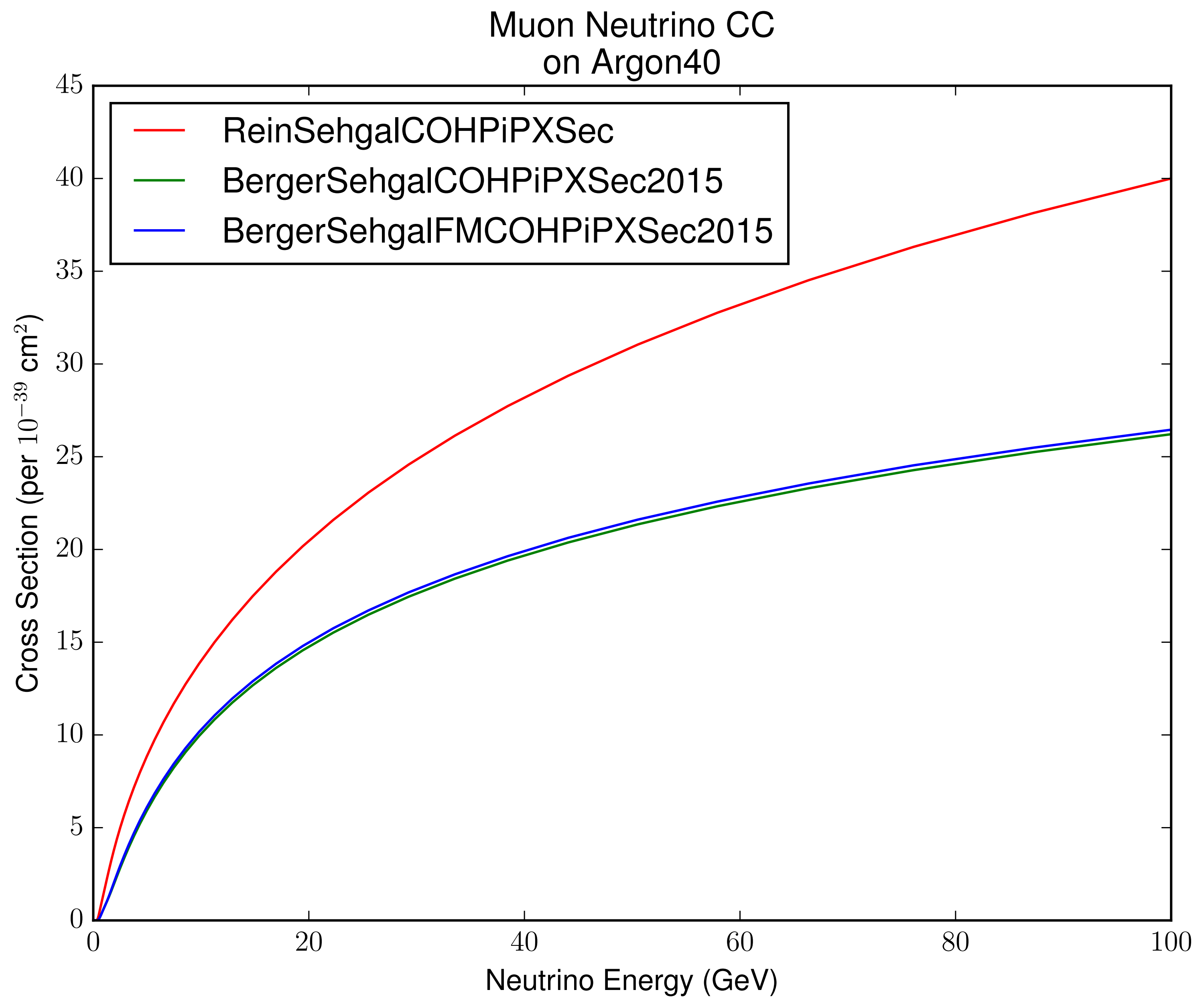

BergerSehgalFMCOHPiPXSec2015 Muon Neutrino CC on Carbon
GENIE
PRD 79, 053003
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
0.0
0.5
1.0
1.5
2.0

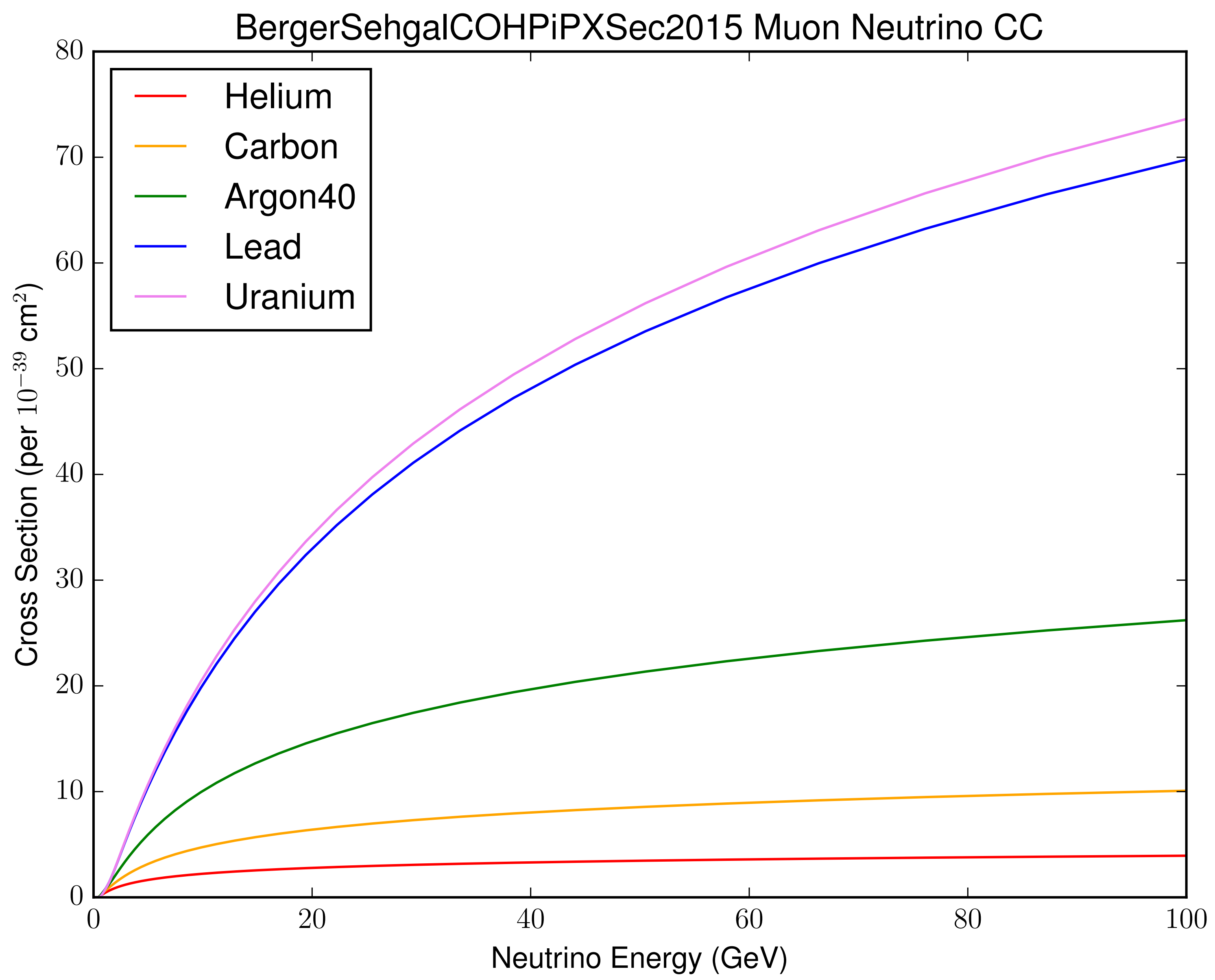

BergerSehgalFMCOHPiPXSec2015 Muon Neutrino NC on Carbon
GENIE
PRD 79, 053003
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
0.0
0.5
1.0
1.5
2.0


CC, T_π = 0.5 GeV, integrated over angle
CC, T_π = 1.0 GeV, integrated over angle
CC, T_π = 1.5 GeV, integrated over angle
NC, T_π = 0.5 GeV, integrated over angle
GENIE
Berger
Cross Section (per 10^{-40} cm^2)
Pion Kinetic Energy (GeV)


Muon Neutrino CC
on Helium
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
0
1
2
3
4
5
6
0
20
40
60
80
100
ReinSehgalCOHPiPXSec
BergerSehgalCOHPiPXSec2015
BergerSehgalFMCOHPiPXSec2015


Muon Neutrino CC
on Carbon
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
0
2
4
6
8
10
12
14
16
0
20
40
60
80
100
ReinSehgalCOHPiPXSec
BergerSehgalCOHPiPXSec2015
BergerSehgalFMCOHPiPXSec2015


Muon Neutrino CC
on Argon40
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
0
5
10
15
20
25
30
35
40
45
0
20
40
60
80
100
ReinSehgalCOHPiPXSec
BergerSehgalCOHPiPXSec2015
BergerSehgalFMCOHPiPXSec2015


BergerSehgalCOHPiPXSec2015 Muon Neutrino CC
Cross Section (per 10^{-39} cm^2)
Neutrino Energy (GeV)
0
10
20
30
40
50
60
70
80
0
20
40
60
80
100
Helium
Carbon
Argon40
Lead
Uranium

Rein model (diffractive)

D. Rein, Nucl. Phys. B278, 61 (1986).

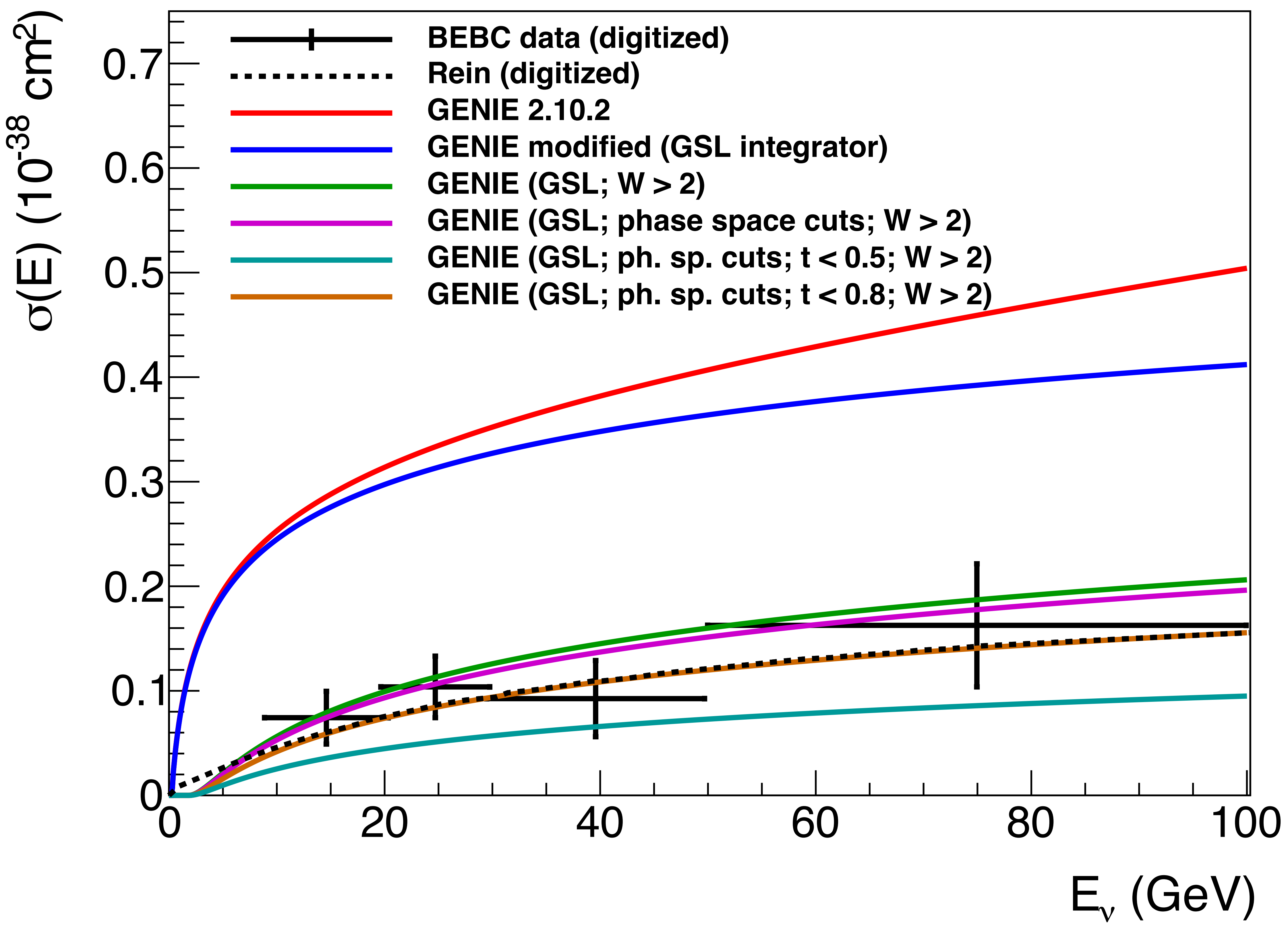


Figure 1: CC total cross section vs. neutrino energy for various versions of the GENIE implementation of Rein's model[1] for neutrino scattering, $\nu p \to \mu^- \pi^+ p$ (colored curves) compared to the prediction from Rein (digitized from Ref. [1]; dashed line), as well as data from BEBC as included in Ref. [1] (crosses). (All GENIE predictions use $b = 7\,\mathrm{GeV}^{-2}$, as in Rein's prediction.) The BEBC data are for a sample with an explicit $W < 2$ cut, which is applied for the green, magenta, brown, and cyan curves as indicated in the legend. In the legend, "phase space cuts" correspond to the Q^2 and W restrictions mentioned in the text in sec. 3.2. A cut on $t < t_{max} = 1.0\,\mathrm{GeV}^2$ is always implied unless a different cut is indicated in the legend.

Rein model (diffractive)

D. Rein, Nucl. Phys. B278, 61 (1986).

We altered the integration method to use a new subclass of XSecIntegratorI, genie::DFRXSec, so that the GSL integrator could be used instead of the hard-coded grid integration. In conjunction with this, we removed the analytic integration over t (since t_{min}depends on x and y) and added a new utility class genie::utils::gsl::d3XSec_dxdydt_E to enable 3D numerical integration in (x,y,t) space. The effect on the total cross section can be seen by comparing the red (2.10.2) and blue (new) curves in fig. 1. We note that though there is a difference between the methods, the prediction resulting from the new implementation is much closer to Rein's in shape than the GENIE 2.10.2 version.

(Model updated by J. Wolcott)

Outlook and conclusions

- M. Kabirnezhad is working on implementing her non-resonant pion production model in GENIE from Oxford.
- MIT group's comparisons to electrons is shining a harsh light on this model and motivating efforts to improve the situation.
- Careful re-tuning of RS will extend the life of the model into v3, but we are actively seeking alternatives.

Thanks!

now...

Back up!

Rein model (diffractive)

D. Rein, Nucl. Phys. B278, 61 (1986).

The Rein model offers a triply differential cross section in x, y, and t (eqn. 6 in Ref. [1]). As it stands in GENIE 2.10.2, this cross section is integrated to yield a total cross section in two steps:

1. Analytically integrate the t-dependence (e^{-bt}) from $t_{min} = \left(\frac{m_\pi^2}{2E_\pi}\right)^2$ to a hard-coded t_{max} (currently $1.0\,\mathrm{GeV}^2$).
2. Numerically integrate the x- and y-dependence by stepping through a grid in (x, y)-space in both variables. x ranges from $x_{min} = 0$ to $x_{max} = 1$; y ranges from $y_{min} = \frac{m_\pi}{E_\nu}$ (proton, pion at rest) to $y_{max} = 1 - \frac{m_l}{E_\nu}$ (muon at rest).

There are several problems with this approach:

(Model updated by J. Wolcott)

Rein model (diffractive)

D. Rein, Nucl. Phys. B278, 61 (1986).

- The t_{min} expression above is an approximation assuming the target is infinitely massive (originating from coherent scattering). This is a poor approximation in diffractive scattering from hydrogen, where the single proton in the nucleus is only a factor of 5 more massive than the other outgoing particles of the reaction.
- Not all values in the $(0, 1) \times \left(\frac{m_\pi}{E_\nu}, 1 - \frac{m_l}{E_\nu}\right)$ (x, y)-space are allowed because x and y relate to Q^2 and W, and these in turn are connected to the incident neutrino energy (which sets upper limits for both parameters).
- The numerical grid integration is slow and not especially accurate.

(Model updated by J. Wolcott)

Rein model (diffractive)

D. Rein, Nucl. Phys. B278, 61 (1986).

Finally, the upper bound t_{max} is a quasi-arbitrary parameter in the model because there is not a well-defined theoretical transition between diffractive scattering and non-resonant pion production in the more deeply inelastic regime. Rein himself seems to suggest $t_{max} = 0.5\,\mathrm{GeV}^2$, while the GENIE 2.10.2 default was $t_{max} = 0.5\,\mathrm{GeV}^2$. Empirically we find that demanding $t < t_{max} = 0.8\,\mathrm{GeV}^2$ yields superior agreement with Rein's curve (apart from the cross section at very low E_ν, where we believe Rein's curve is in error as it does not exhibit the effect of the $W > 2$ threshold needed to correspond to the BEBC data); see fig. 1 (cyan vs. brown vs. dashed black curves).

(Model updated by J. Wolcott)