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NuWro Monte Carlo Generator of Neutrino Interactions

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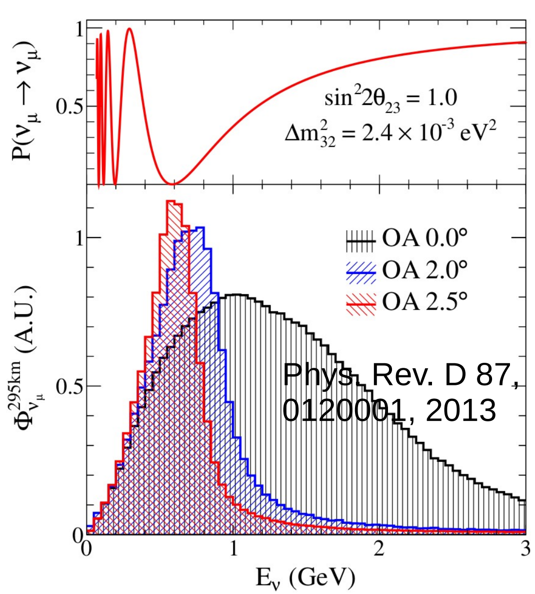
Matter to the Deepest
17.09.2015

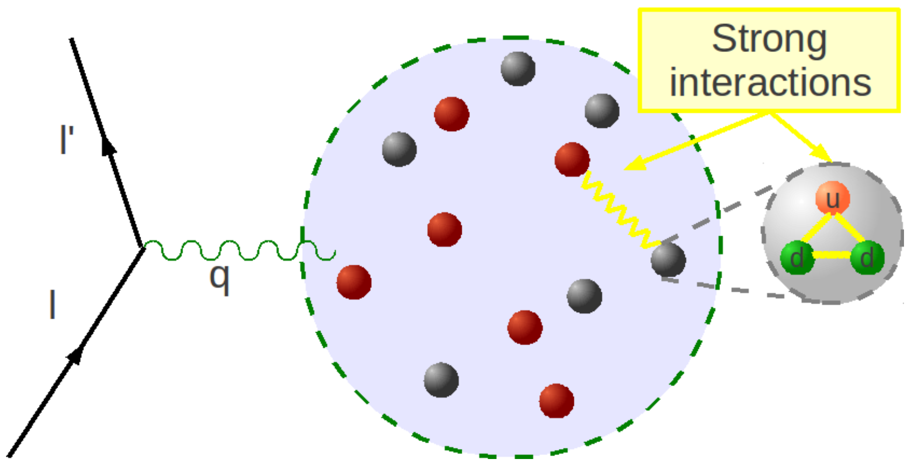
Neutrino oscillation experiments

- Oscillations: neutrino „flavor” state- quantum mixture of „mass” eigenstates
- Lepton flavour appearance or disappearance in the flux -energy-dependent interferometry
- Neutrino accelerator oscillation experiments (T2K, NOvA, MINERvA, LBNE...):

1. Measurement of Standard Model parameters (some completely unknown): neutrino mixing angles Θ_{ij} (PMNS matrix), squared mass differences Δm^2_{ij}, neutrino mass hierarchy, leptonic CP violation
2. Beyond Standard Model physics: oscillation to „sterile” neutrinos?

- Challenging measurement: wide-band beam and interaction on nuclear target





Purpose of MC simulations

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- Monte Carlo: statistical description and tool to understand your experiment with all its systematic and statistical errors.
- Lots of input and dependencies:

  theoretical models, experimental data, engineering knowledge etc.

The transverse response:

$$R_T = \frac{-2}{\pi}\Im\Pi^{11}_{RFG}(q) = \frac{\Omega}{2\pi^2 q}\int_0^{2\pi}\frac{d\phi}{2\pi}\int_{E_{min}}^{E_F} dE(p)A^{11}_N = \quad (4.86)$$

$$= \frac{\Omega}{2\pi^2 q}\int_0^{2\pi}\frac{d\phi}{2\pi}\int_{E_{min}}^{E_F} dE(p)(2p_1^2)\left(F_1^2 - \frac{\tilde{q}_\mu^2}{4M^2}F_2^2\right) - \frac{1}{2}\tilde{q}_\mu^2(F_1+F_2)^2.$$

The p_1^2:

$$p_1^2 = p^2\sin^2\Theta_p\sin^2\phi_p = \left(E(p)^2 - M^2 - \frac{(2E(p)\tilde{q}^0 + \tilde{q}_\mu^2)^2}{4q^2}\right) = \quad (4.87)$$

$$= p^2\sin^2\Theta_p\sin^2\phi_p = \left(-E(p)^2\frac{\tilde{q}_\mu^2}{q^2} - E(p)\tilde{q}^0\frac{\tilde{q}_\mu^2}{q^2} - M^2 - \frac{\tilde{q}_\mu^4}{4q^2}\right)\sin^2\phi_p.$$

And $\int_0^{2\pi}\frac{d\phi}{2\pi}\sin^2\phi = \frac{1}{2}$, thus

$$R_T = -\frac{\Omega}{2\pi^2 q}\left[\left(\frac{E(p)^3}{3}\frac{\tilde{q}_\mu^2}{q^2} + \frac{E(p)^2\tilde{q}^0\tilde{q}_\mu^2}{2q^2} + E(p)(M^2 + \frac{\tilde{q}_\mu^4}{4q^2})\right)\left(F_1^2 - \frac{\tilde{q}_\mu^2}{4M^2}F_2^2\right) + \quad (4.88)$$

$$+ \frac{E(p)}{2}\tilde{q}_\mu^2(F_1+F_2)^2\right]_{E_{min}}^{E_F}.$$

The cross section (per nucleon) in the FG case:

$$\frac{d\sigma}{d\Omega dE'} = \frac{3\sigma_{Mott}}{4k_F^3 q}\left\{\frac{q_\mu^4}{\boldsymbol{q}^4}\left[(\frac{2}{3}E(p)^3 + \tilde{q}^0E(p)^2)\left(F_1^2 - \frac{\tilde{q}_\mu^2}{4M^2}F_2^2\right) + \quad (4.89)\right.\right.$$

$$+ \frac{1}{2}\tilde{q}_\mu^2E(p)(F_1+F_2)^2 - \tilde{q}^{0\,2}E(p)\left(F_1F_2 + \frac{1}{2}(1+\frac{\tilde{q}_\mu^2}{4M^2})F_2^2\right)\Big]_{E_{min}}^{E_F} +$$

$$- \left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\,\mathrm{tg}^2\left(\frac{\theta}{2}\right)\right)\left[\left(\frac{E(p)^3}{3}\frac{\tilde{q}_\mu^2}{q^2} + \frac{E(p)^2\tilde{q}^0\tilde{q}_\mu^2}{2q^2} + E(p)(M^2 + \frac{\tilde{q}_\mu^4}{4q^2})\right)\right.$$

$$\left.\left(F_1^2 - \frac{\tilde{q}_\mu^2}{4M^2}F_2^2\right) + \frac{E(p)}{2}\tilde{q}_\mu^2(F_1+F_2)^2\right]_{E_{min}}^{E_F}\Big\}.$$

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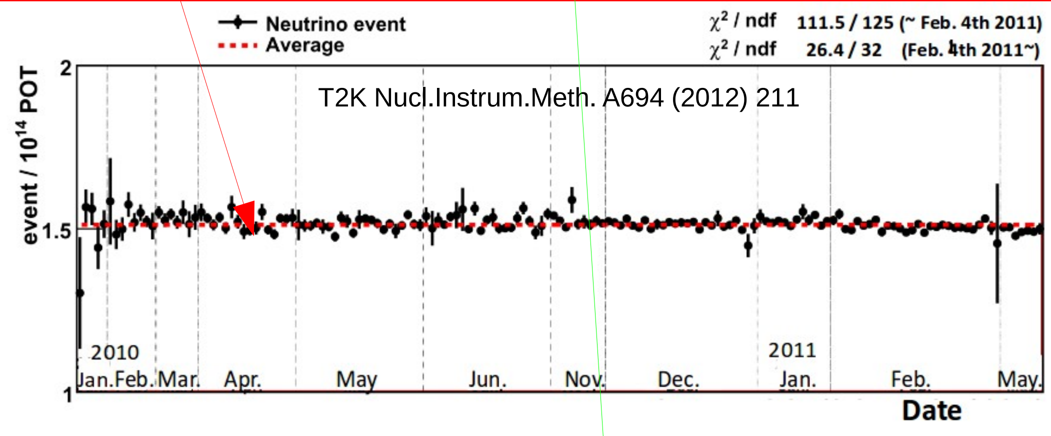
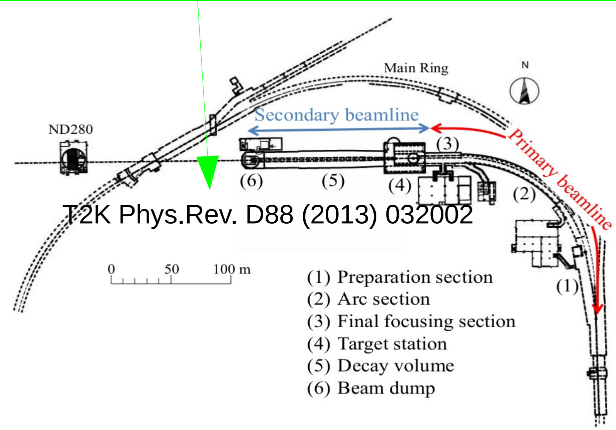


T2K Nucl.Instrum.Meth. A694 (2012) 211



T2K Phys.Rev. D88 (2013) 032002

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Purpose of MC simulations

- Shortly: how to put it all together and get from here:

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$$+ \left.\frac{1}{2}\tilde{q}_\mu^2E(p)(F_1+F_2)^2 - \tilde{q^0}^2E(p)\left(F_1F_2 + \frac{1}{2}(1+\frac{\tilde{q}_\mu^2}{4M^2})F_2^2\right)\right]_{E_{min}}^{E_F} +$$
$$- \left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\,\mathrm{tg}^2\left(\frac{\theta}{2}\right)\right)\left[\left(\frac{E(p)^3}{3}\frac{\tilde{q}_\mu^2}{q^2} + \frac{E(p)^2\tilde{q}^0\tilde{q}_\mu^2}{2q^2} + E(p)(M^2 + \frac{\tilde{q}_\mu^4}{4q^2})\right)\right.$$
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$$- \left(-\frac{q_\mu^2}{\boldsymbol{q}^2} + 2\,\mathrm{tg}^2\left(\frac{\theta}{2}\right)\right)\left[\left(\frac{E(p)^3}{3}\frac{\tilde{q}_\mu^2}{q^2} + \frac{E(p)^2\tilde{q}^0\tilde{q}_\mu^2}{2q^2} + E(p)(M^2 + \frac{\tilde{q}_\mu^4}{4q^2})\right)\right.$$
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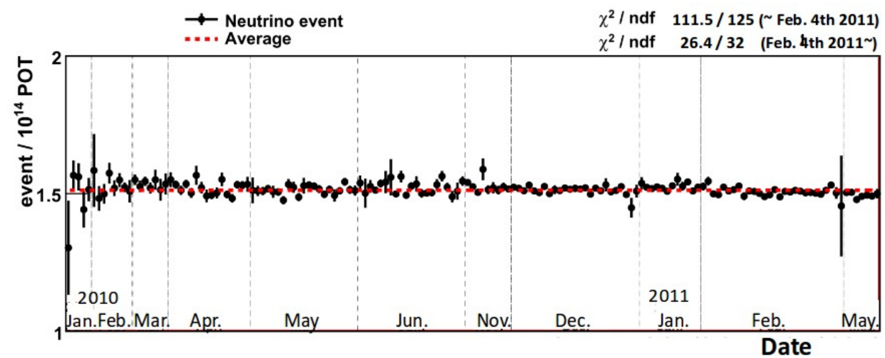
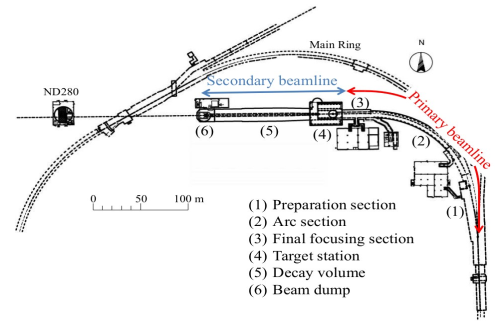
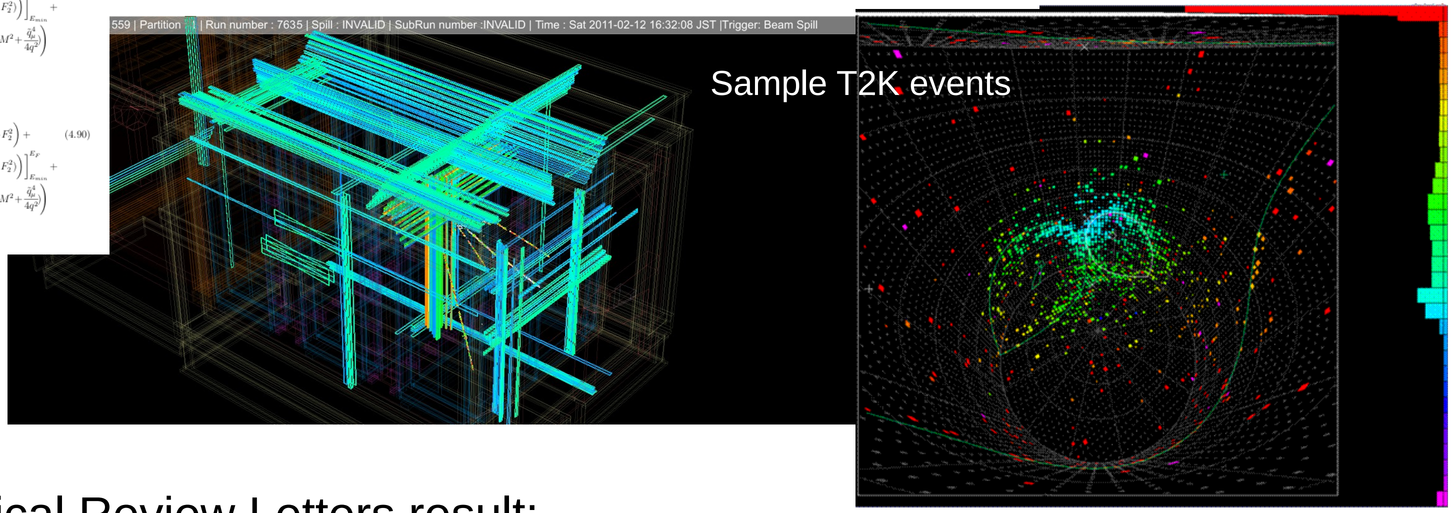






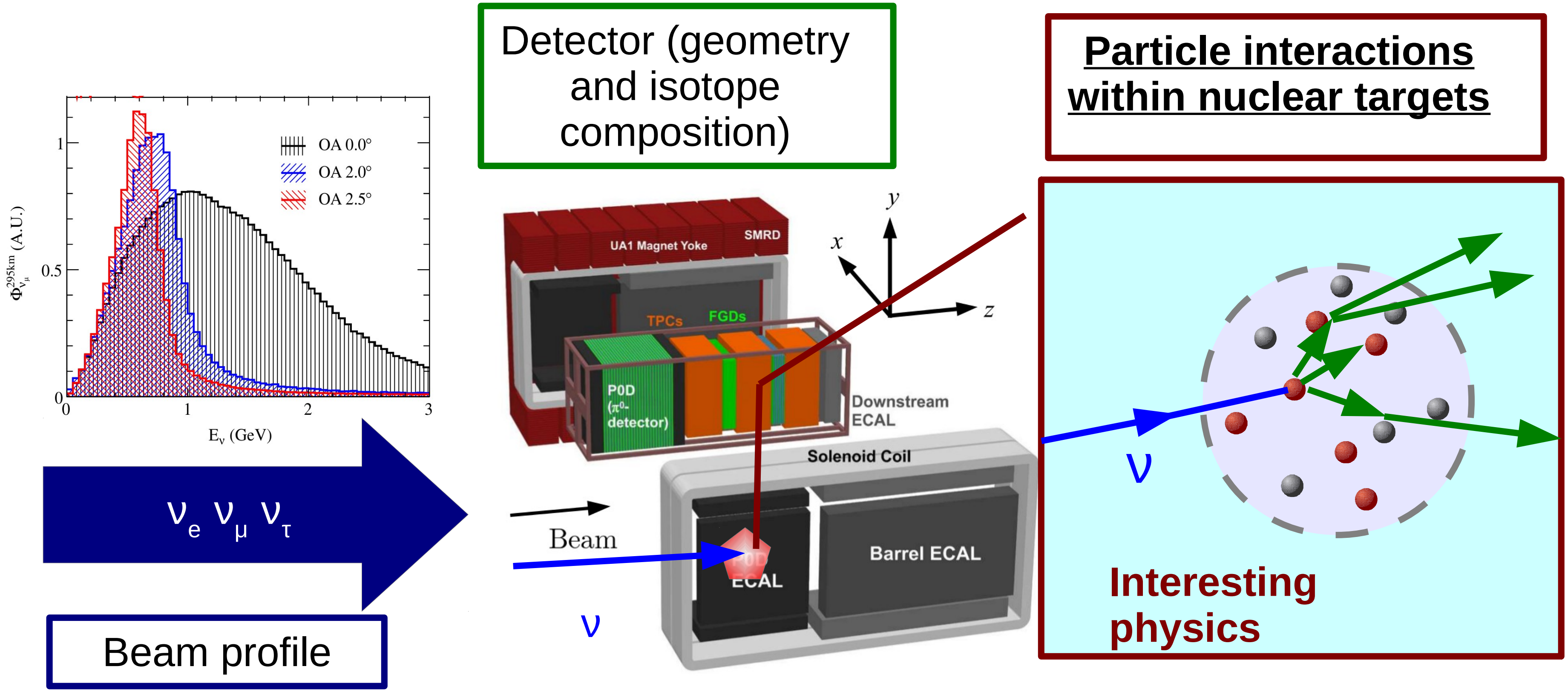
- To the Physical Review Letters result:

phase δ_{CP}. In this neutrino oscillation scenario, assuming $|\Delta m^2_{32}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.5$, $\delta_{CP} = 0$, and $\Delta m^2_{32} > 0$ ($\Delta m^2_{32} < 0$), a best-fit value of $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ ($0.170^{+0.045}_{-0.037}$) is obtained.

„Bridge between theory and experiment”

Neutrino interaction generator

- Typical MC generator in neutrino physics: beam profile, detector, target nucleus interaction vertex and process (dynamics), final state interactions (FSI) (e.g. GENIE, NEUT, **NuWro**)



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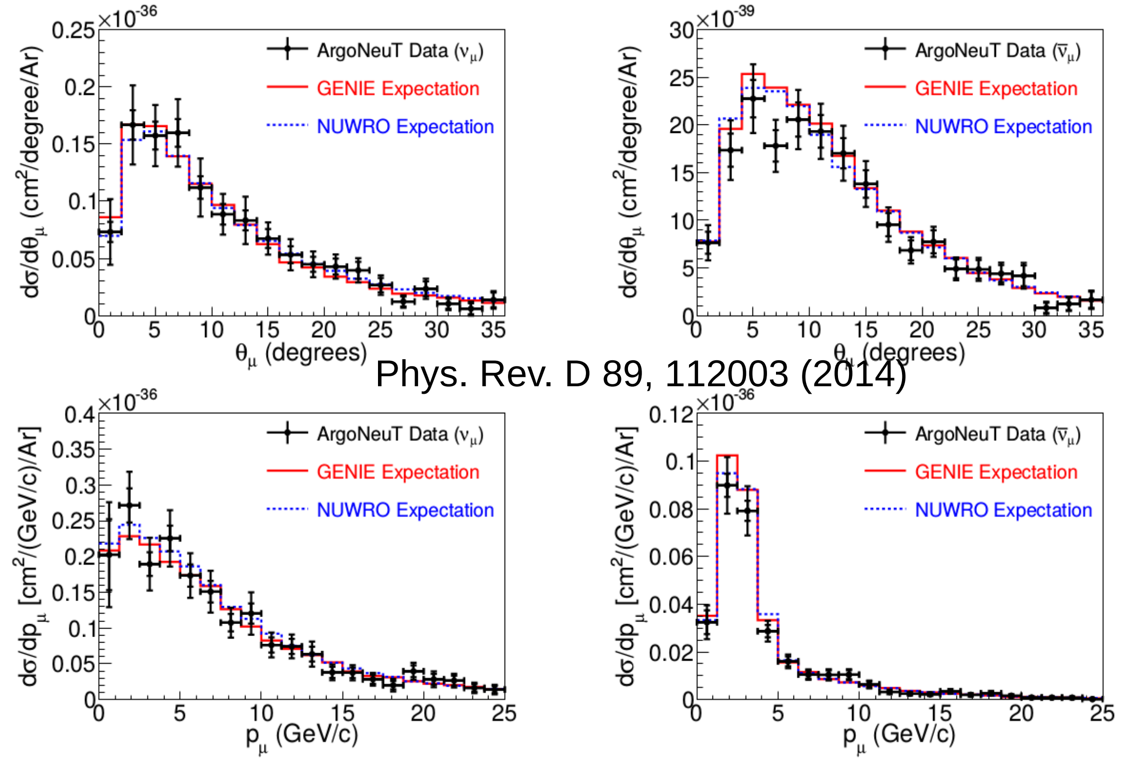
NuWro

- The project started 2005 at the Wrocław University; an important encouragment from Danuta Kiełczewska from Warsaw
- First (natural) name: Wrocław Neutrino Generator: WroNG → changed from marketing reasons... (Jan T. Sobczyk, Jaroslaw A. Nowak, Krzysztof M. Graczyk „WroNG - Wroclaw Neutrino Generator of events for single pion production” Nucl.Phys.Proc.Suppl. 139 (2005) 266)

- Main authors: Jan Sobczyk, Tomasz Golan, Krzysztof Graczyk, Cezary Juszczak, Jarosław Nowak, Jakub Żmuda.
- Collaboration with NCBJ Warsaw on the current T2K data analysis
- Code written in C++ language.

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)**
- **Relatively new components (introduced or developed recently also in GENIE and NEUT):**



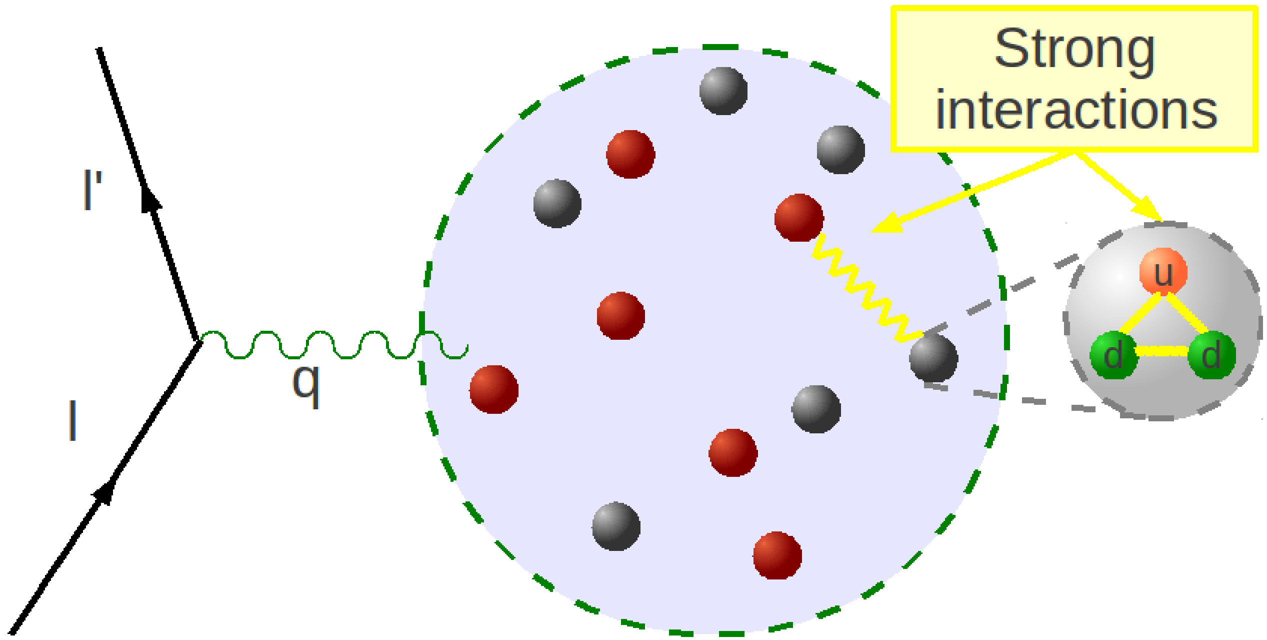
Phys. Rev. D 89, 112003 (2014)

1) Meson exchange currents (two-nucleon currents): <u>**first generator ever!**</u>
2) Random phase approximation (matter polarization on top of RFG)
3) Spectral function (nucleon self-energy plus nuclear shell information)
4) Electron interaction simulation: currently developed!

http://borg.ift.uni.wroc.pl/nuwro/

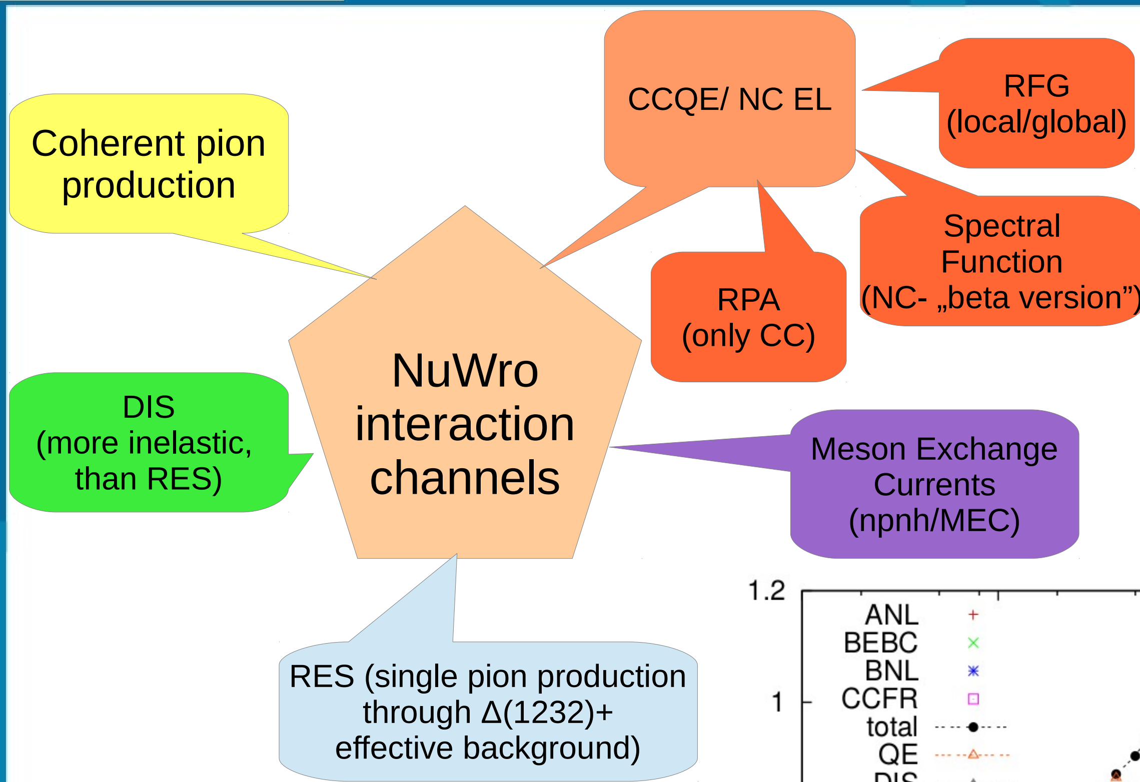
Repository, documentation, NuWro on-line

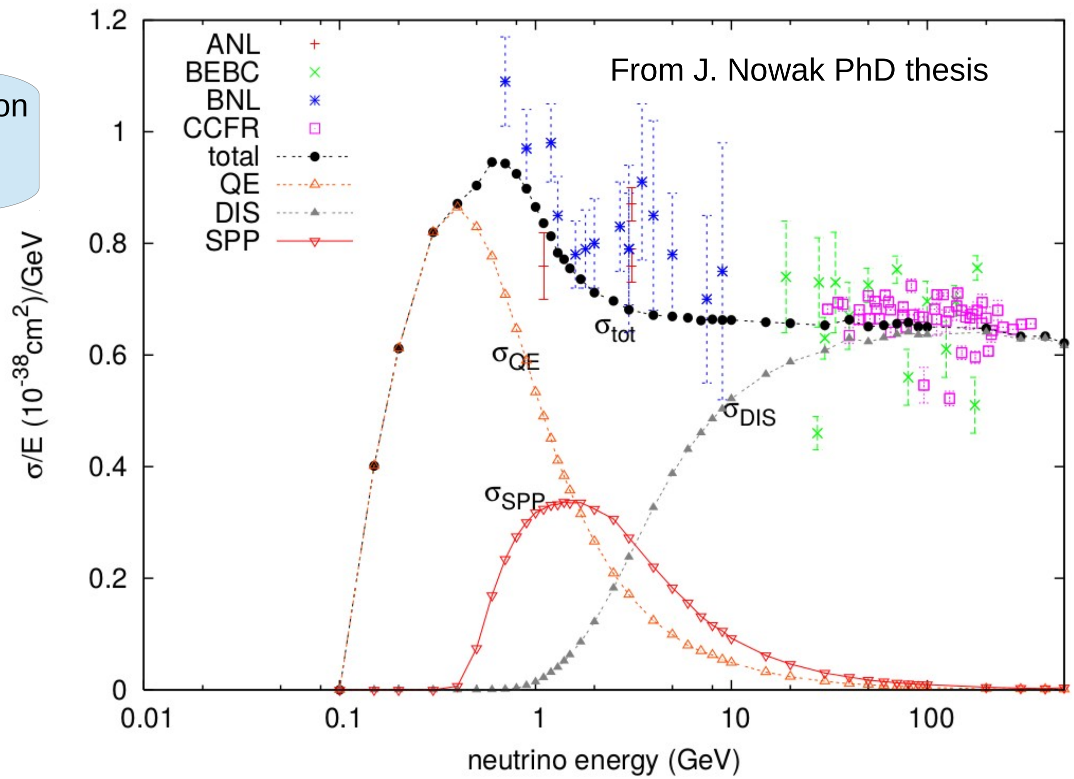
Nuclear target puzzle



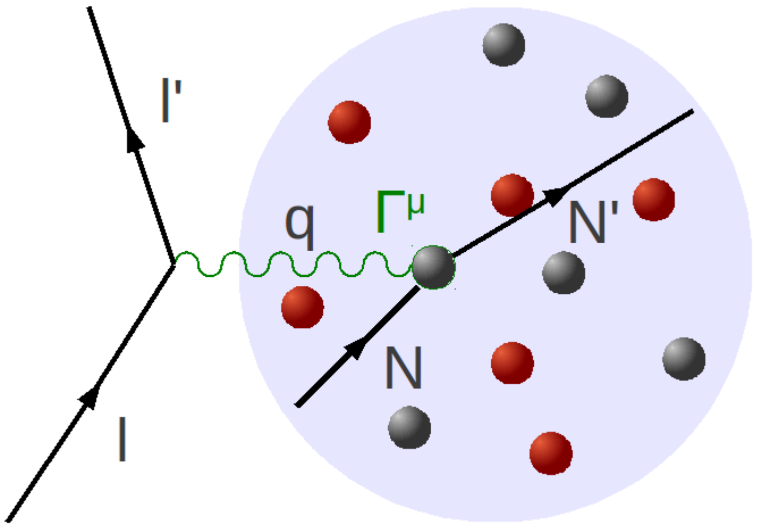
- Initial l and final l' leptons, 4-momentum transfer q
- Strongly bound structure of strongly bound structures
- Multiple effective approximations from many-body quantum mechanics to quark jet fragmentation, nonperturbative nuclear effects.
- Problem of „stitching” it all together

Physical channels in NuWro





(Quasi)elastic process



- CCQE / NCE interaction: interaction with one single nucleon inside the nucleus, no resonance excitation and no extra particles created in the vertex
- NuWro: local or global Fermi gas models plus RPA corrections or spectral function

Spectral Function

- Spectral Function: replacement of usual (local) Fermi distribution for quasielastic event by a probability distribution of removing nucleon with momentum ***p*** leaving the residual nucleus with excitation energy *E*. Extra integral in cross section:

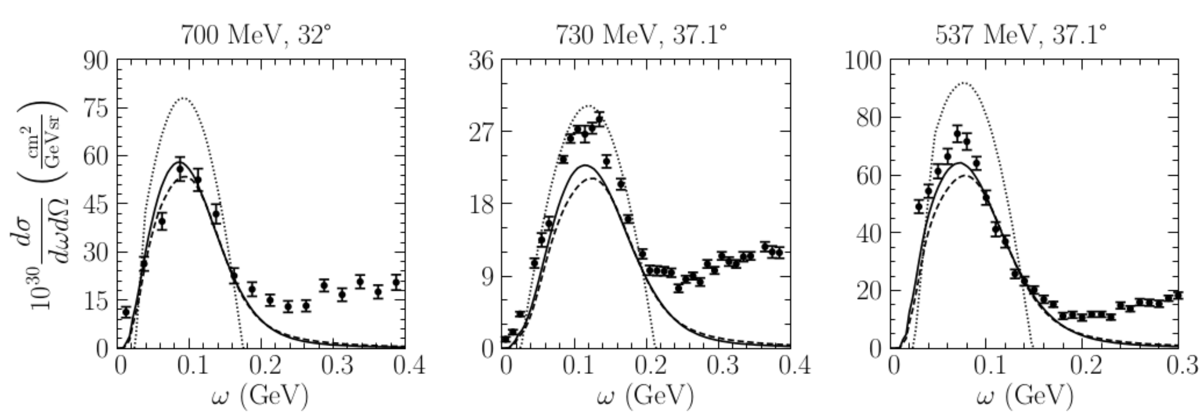
Residual nucleus

Initial nucleus, E_0

$$\Theta(k_F - |\vec{p}|) \to \int P(\vec{p}, E)\, dE = \int \sum_n |\langle \Psi_n^{A-1} | a_{\vec{p}} | \Psi_0^A \rangle|^2 \delta(E_0 + E - E_n)\, dE$$

Nucleon removal (annihilation operator)

- Works of Omar Benhar's group
- In NuWro: implementation based on A. Ankowski PhD thesis by C. Juszczak

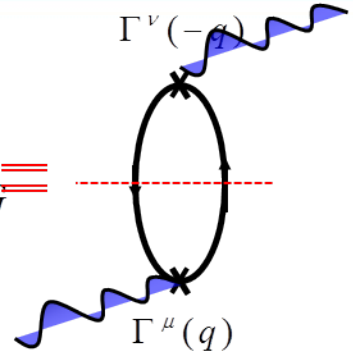


A. Ankowski Ph. D. thesis

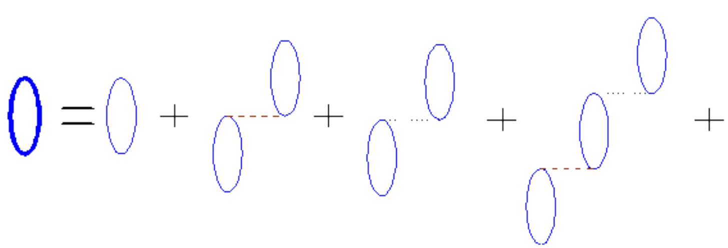
Random Phase (Ring) Approximation

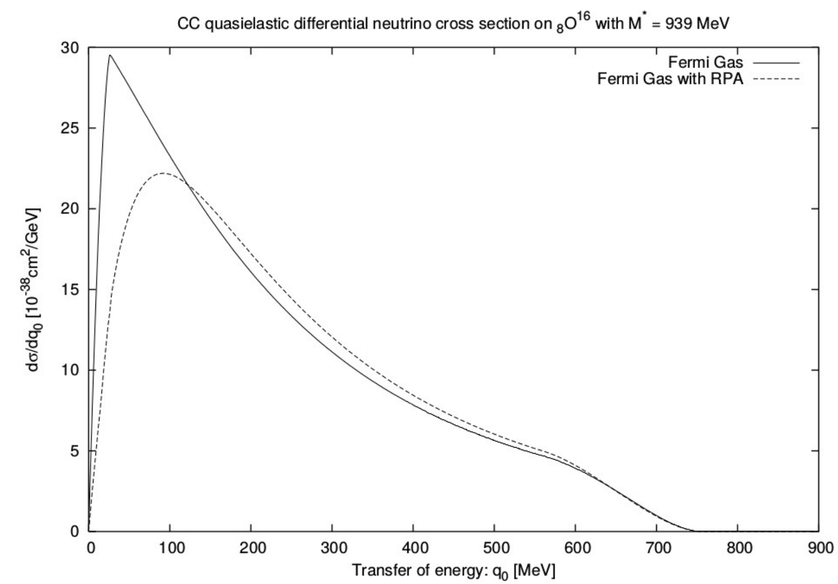
K. Graczyk

$$\mathrm{Im}\ \Pi^{\mu\nu}_{RFG} =$$



$$i\Pi^{\mu\nu}(q) = \int \frac{d^4 p}{(2\pi)^4} Tr\left(G(p+q)\Gamma^\mu G(p)\Gamma^\nu\right)$$



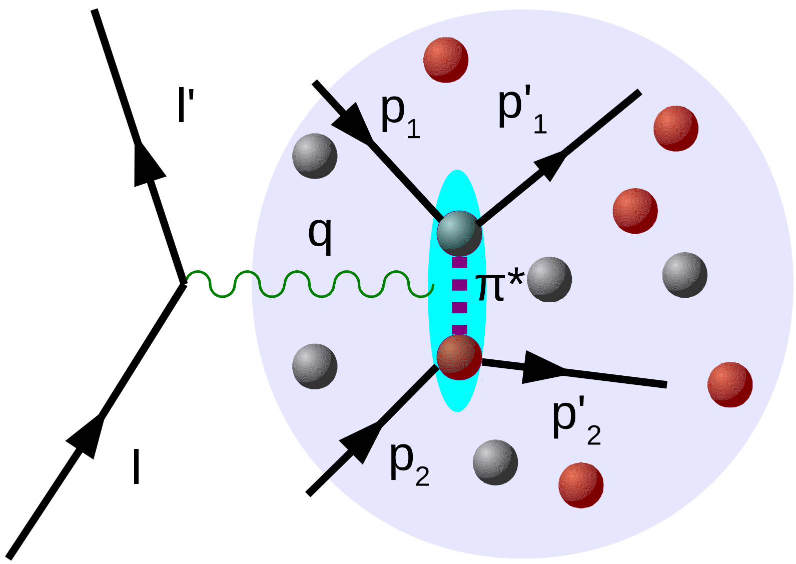


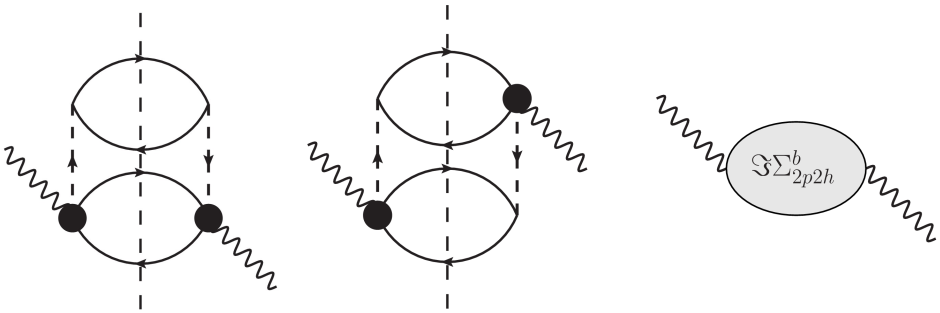
K. Graczyk,J. Sobczyk Eur.Phys.J. C31 (2003) 177-185

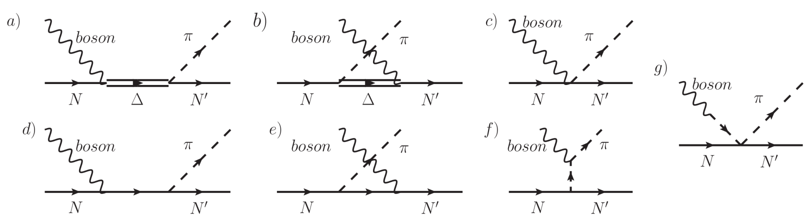
- Nuclear matter nonperturbative polarization effect. Algebraic solution of Dyson equation (by K. Graczyk – relativistic Ring Approximation, implemented by C. Juszczak)

Meson Exchange Currents

- MEC search in neutrino interactions in T2K and ArgoNeuT!
- MEC „cartoon”:



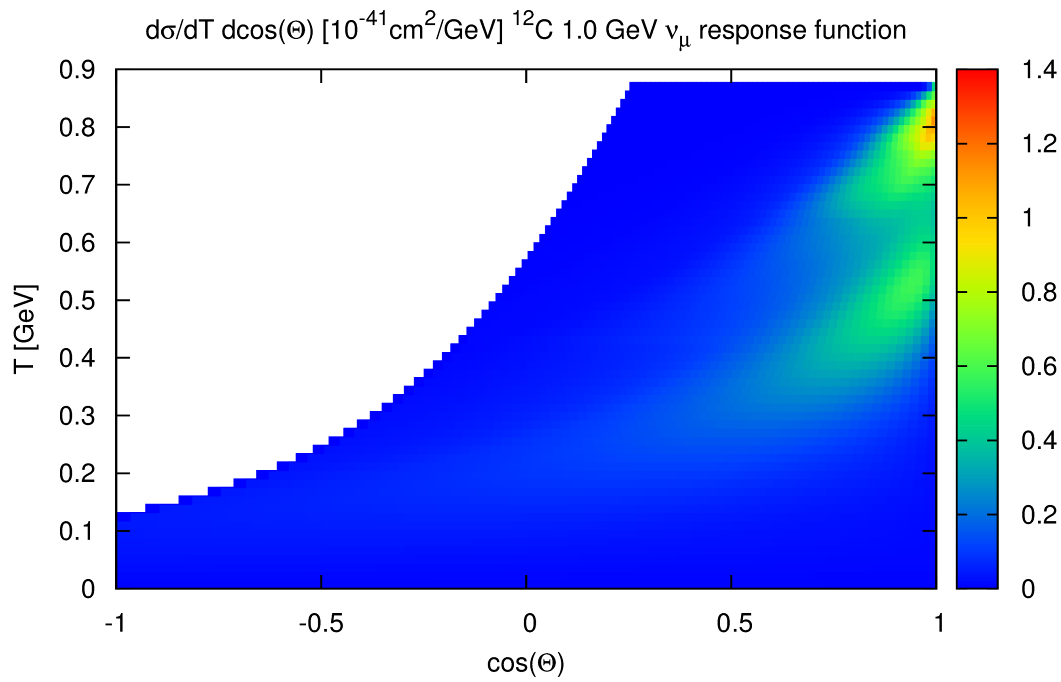




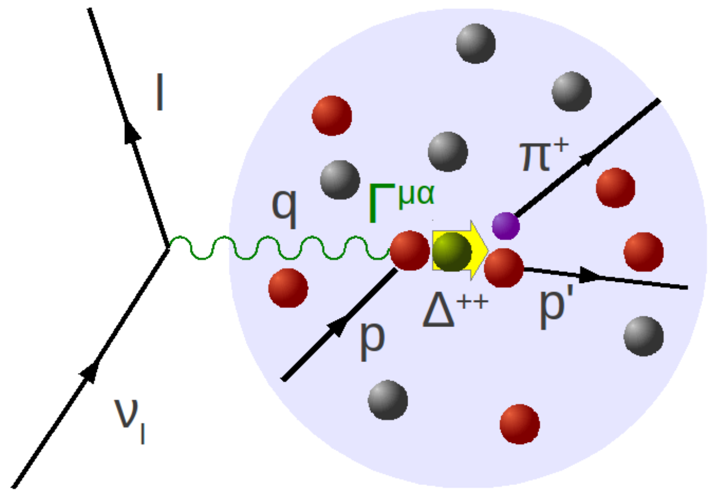
- In NuWro: Transverse Enhancement (effective) and Valencia (microscopic) model.
- All models → inclusive muon double-differential cross sections, no information about nucleon kinematics- effective phase-space algorithm by J. Sobczyk
- Valencia model → numerical nightmare (7-D integrals): implementation with nuclear response function tables (J. Żmuda)

MEC cross section

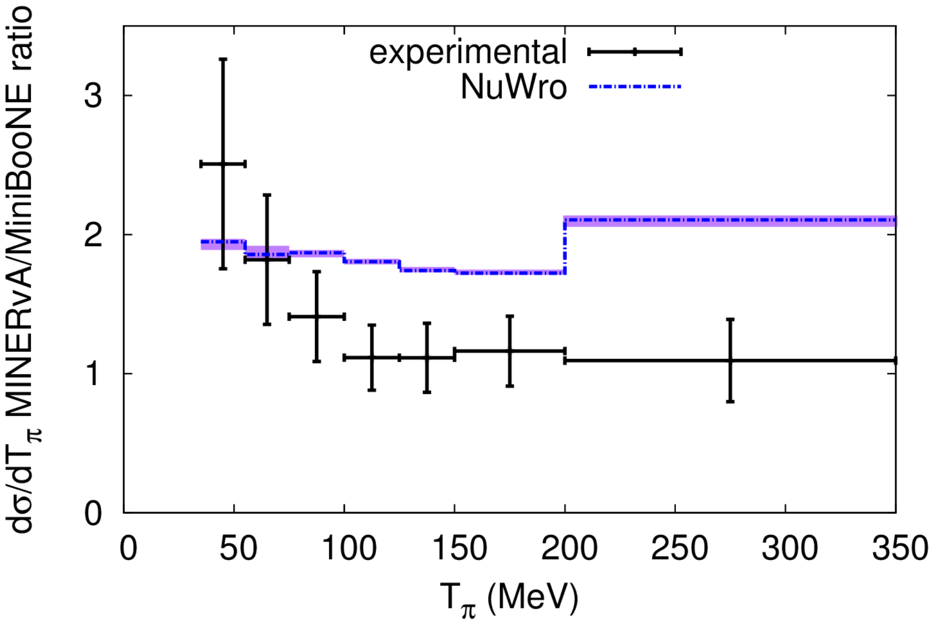
- Sample double-differential (w.r.t. muon energy and cosine of muon angle) Valencia model cross sections for 1 GeV ν_μ scattering off ^{12}C.



RES process



J. Zmuda J. Sobczyk Phys.Rev. C91 (2015) 4, 045501



- Pion production through Δ(1232) excitation plus effective nonresonant background extrapolated from PYTHIA to invariant masses between 1.4 and 1.6 GeV
- Delta selfenergy from E. Oset Nucl. Phys. A 468, 631 (1987) in approximate way.
- New experimental results puzzle: MiniBooNE to MINERvA data ratio?

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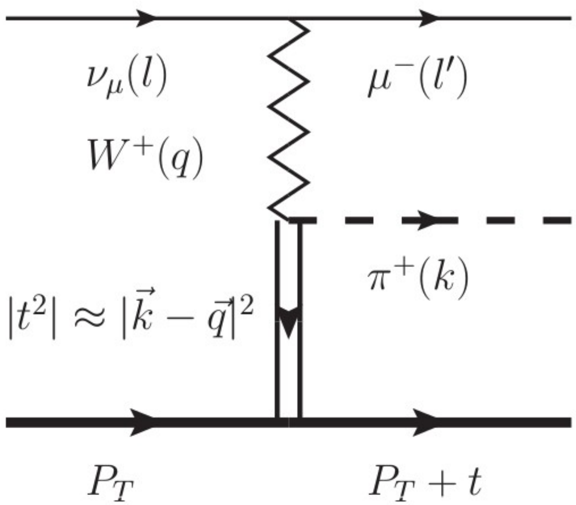
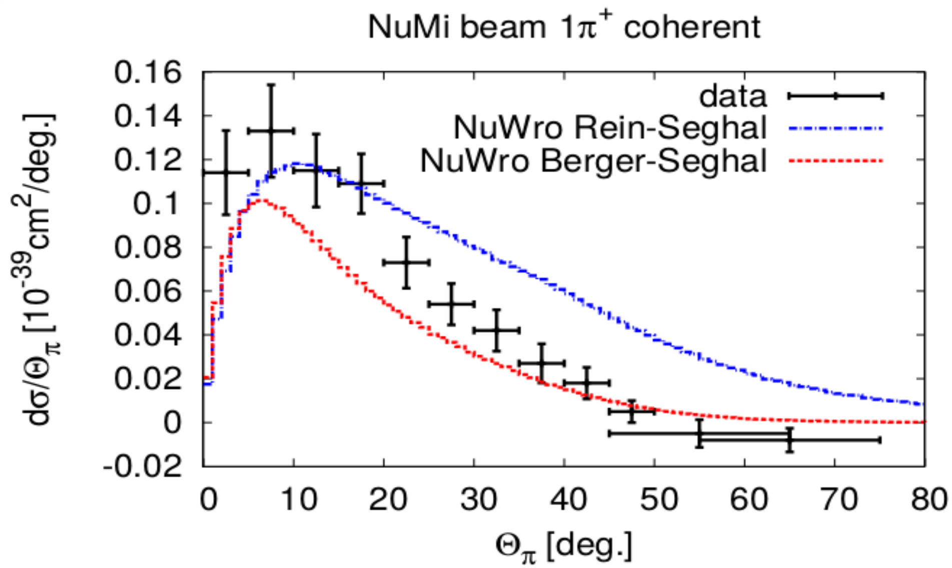
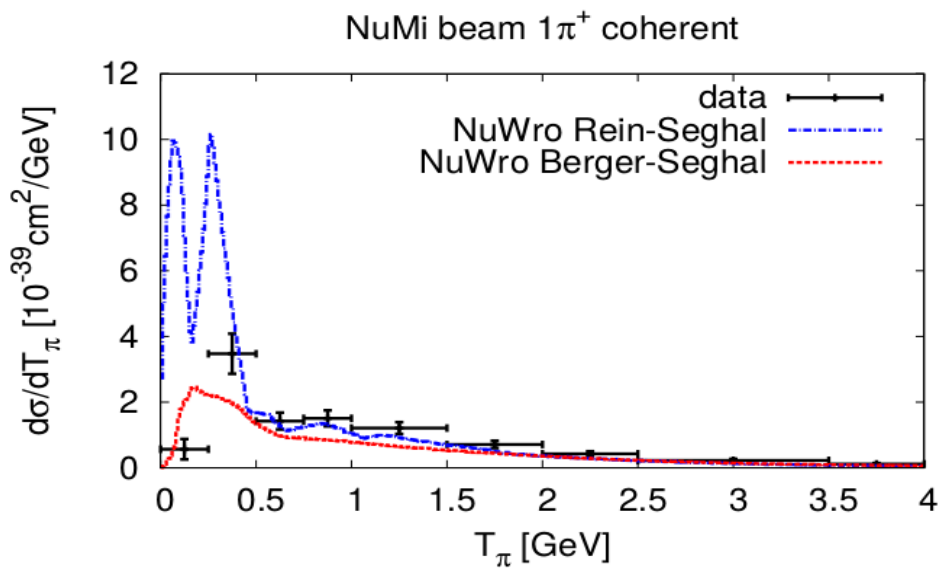
COH process

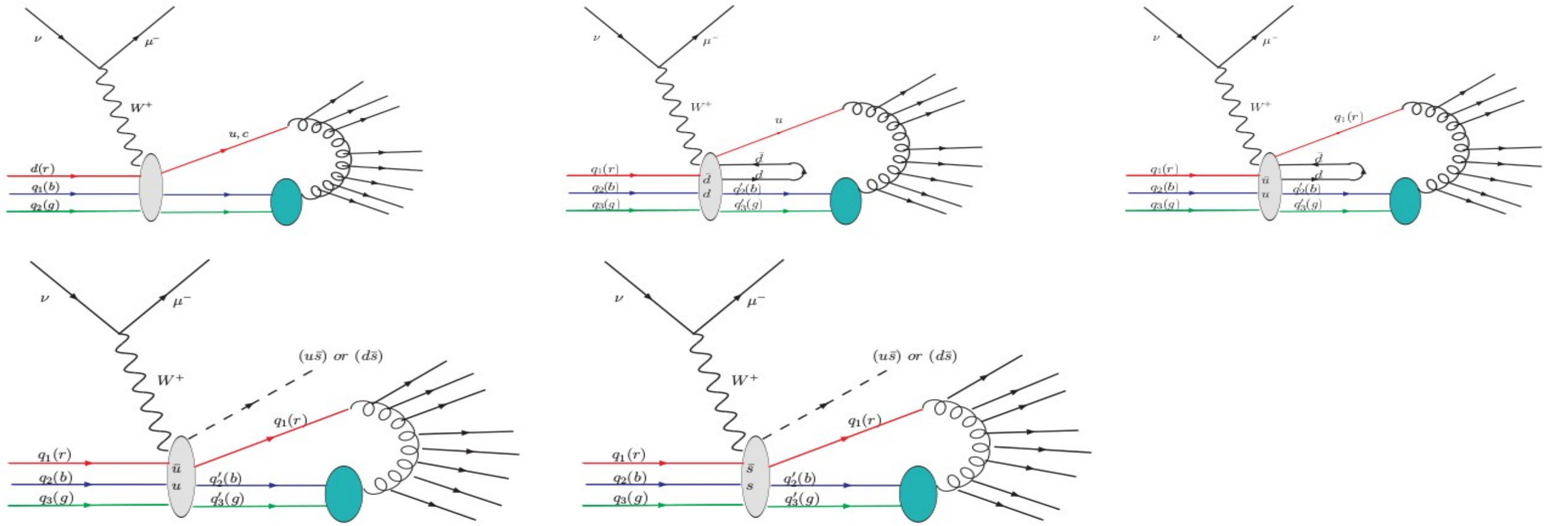




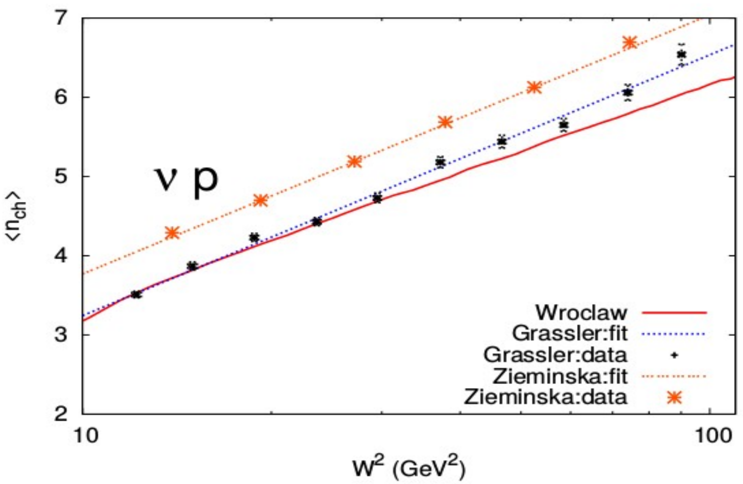


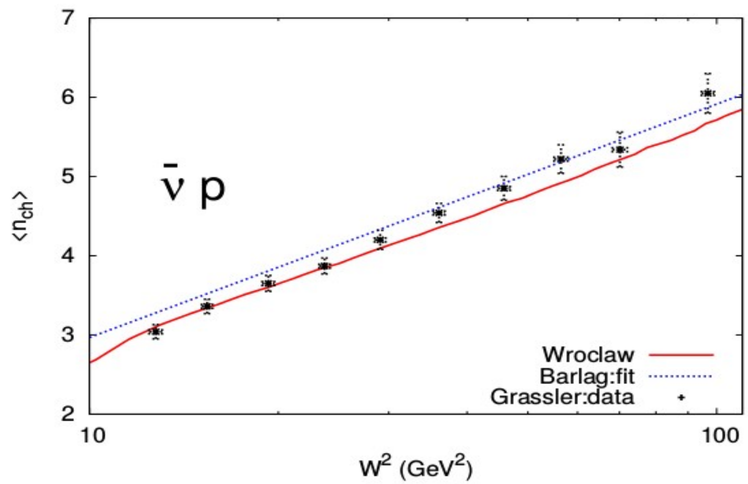
- Coherent pion production through t-channel exchange, nucleus left in the ground state.
- Both Rein-Sehgal (Nucl. Phys. B 223 (1983)) and Berger-Sehgal (Phys. Rev. D 79, 053003 (2009)) models available. Comparison to MINERvA data (Phys. Rev. Lett. 113, 261802 (2014)). Work-in-progress, „hot" topic.

DIS process



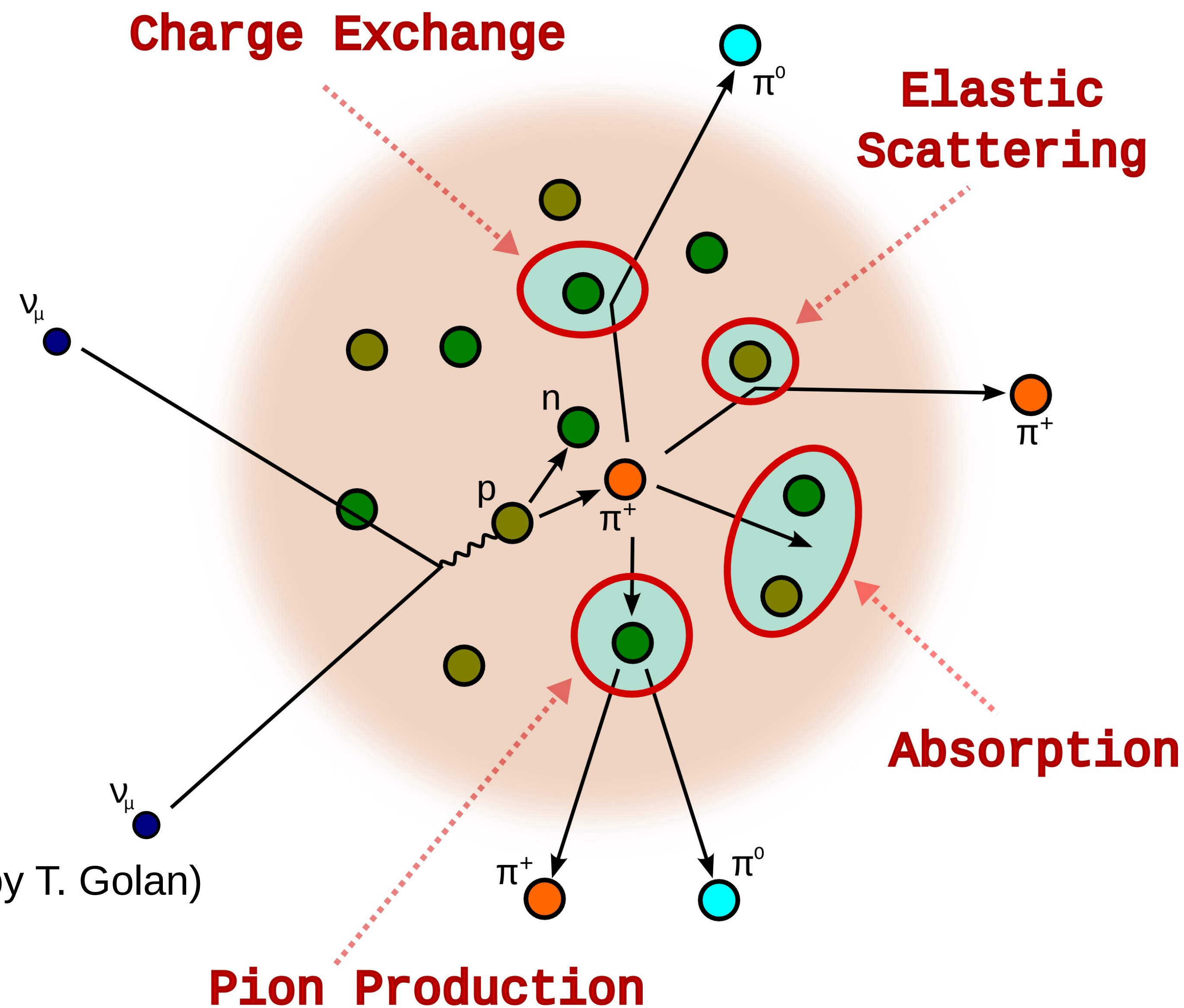
- PYTHIA/LUND algorithm fine-tuned to hadron multiplicity data by J. Nowak in his Ph. D. Thesis (picture source). Everything above the Delta region (quark-hadron duality, heavier resonances „washed out” by nucleon motion)





Final State Interactions

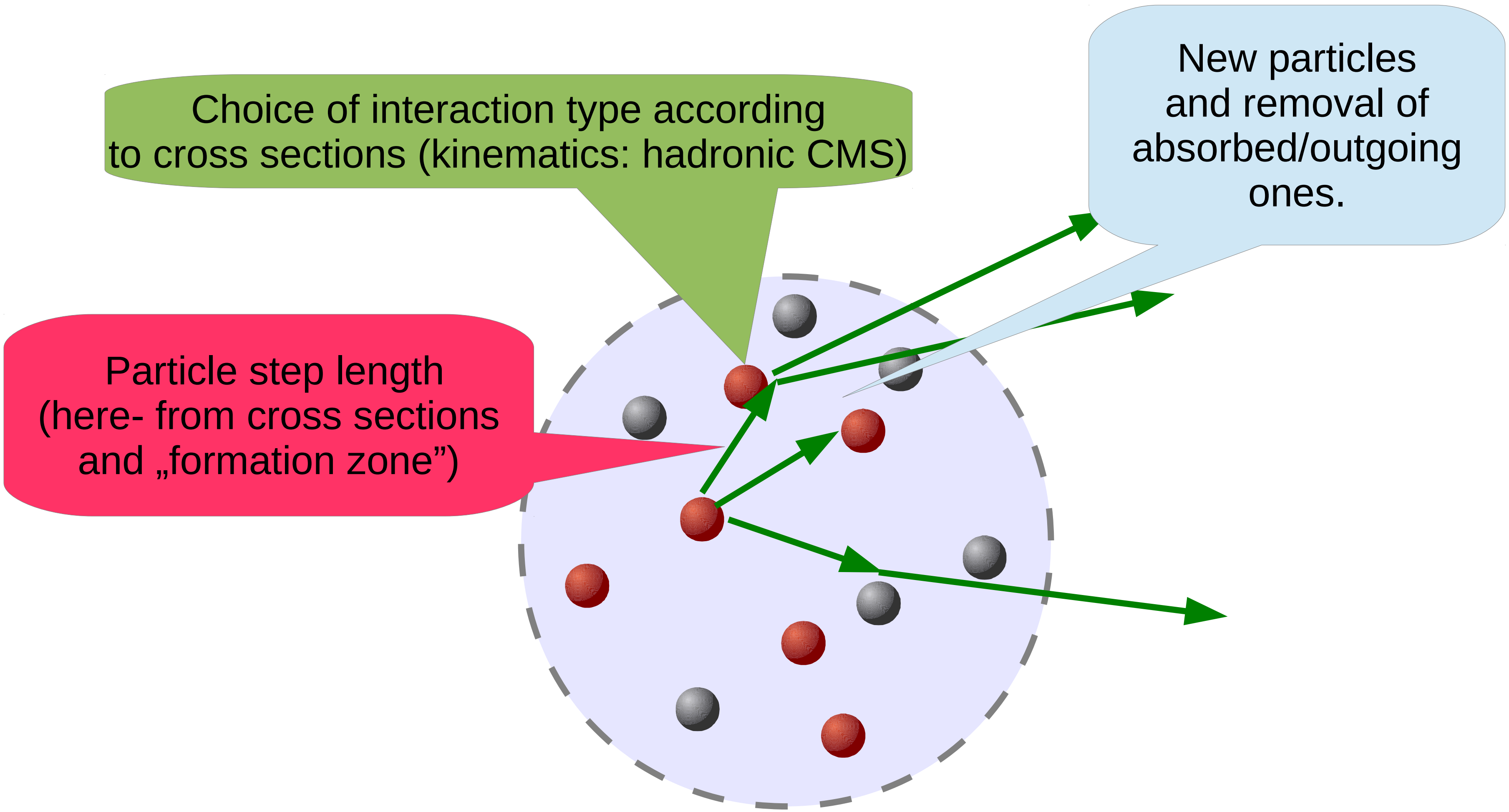
- All particles start inside nucleus. A lot can happen on their way out:



(by T. Golan)

- FSI: either quantum transport equations or intranuclear cascade (NuWro).

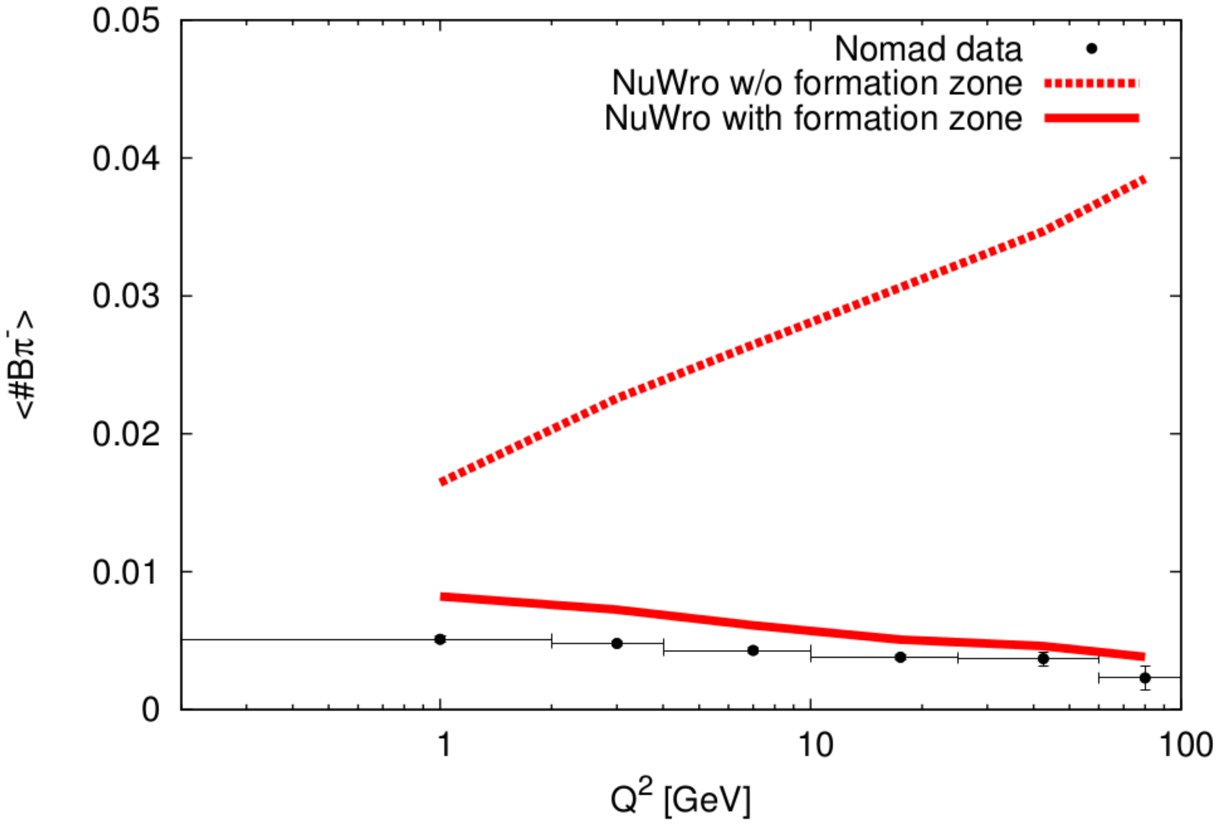
Intranuclear cascade



Intranuclear cascade

- Importance of Formation Zone for DIS (minimal distance traveled by particles before any interaction may occur):

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

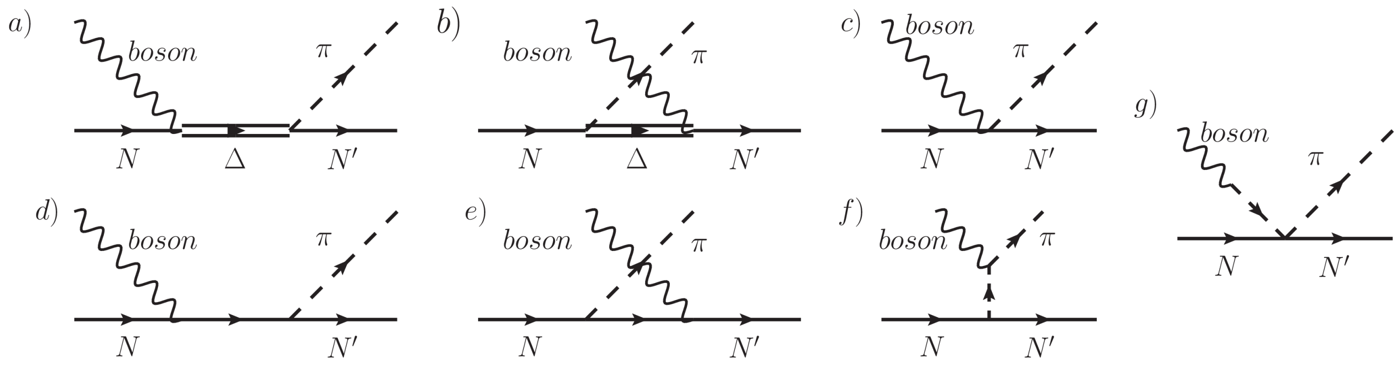


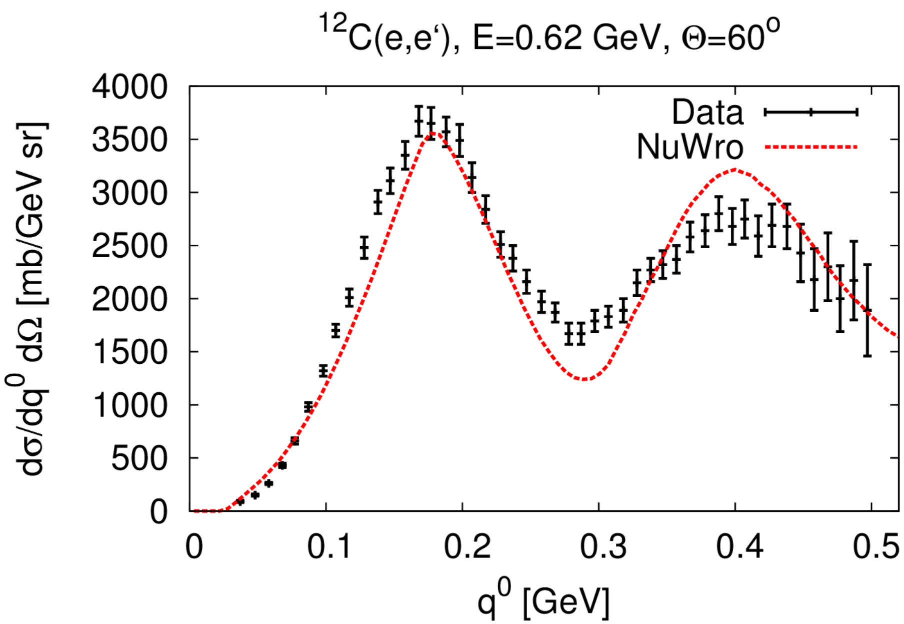
Better agreement of MC with data!

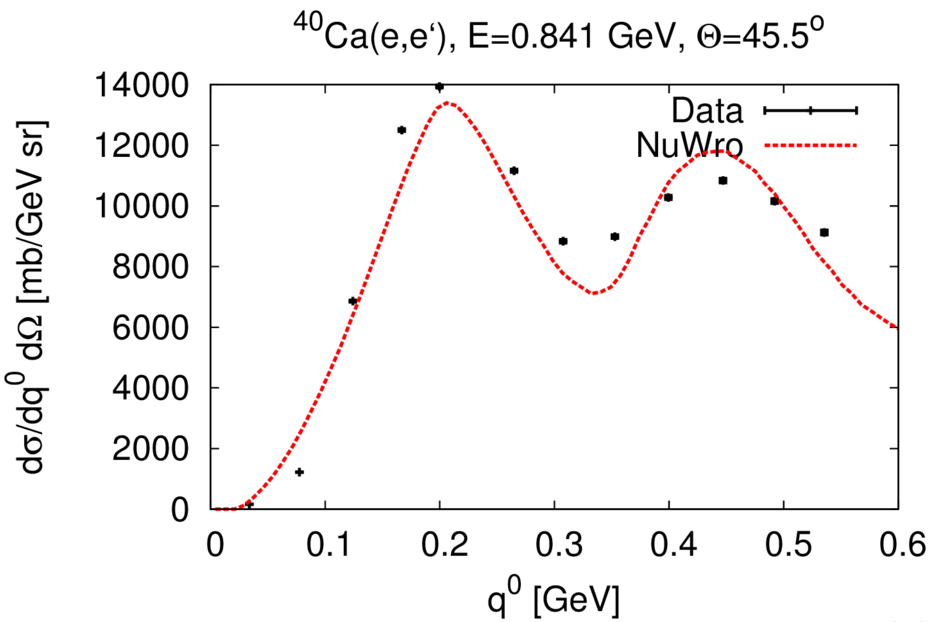
FIG. 7. Average number of backwards going pions as a function of Q^2 in the NOMAD experiment.

Electron scattering

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







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Summary

- NuWro is a versatile MC tool ready to use to neutrino experiment analysis.
- A lot of physical models needed to describe interaction on nuclear targets: from nonrelativistic quantum mechanics to QCD (lack of unified approach to cover them all!).
- Inspiration to other MC developers (e.g. MEC in NEUT and GENIE, Berger-Sehgal)
- Kinematical region for energy transfers between ~100 MeV to ~1 TeV scale covered for neutrinos or from quasielastic to DIS processes.
- Still a lot of room for improvements, developments in lepton-nucleus interaction and high energy nuclear physics (see e.g. NuInt workshops)
- C++ code is being constantly maintained, developed and optimized.
- Very fast algorithm (1 M event event sample can be generated even on laptop machines).

Thank you for your attention!

We cordially invite you to our Winter School!

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