NuWro (WroNG) FIRST YEARS

Jarek Nowak

Lancaster University

OUTLINE

- Key stages of the development of the MC generator by group from Wroclaw
- I will cover the 2002-2006 period (my PhD project)
- In this period people developing the code:
  - C.Juszczak, K.Graczyk, JN and J. Sobczyk
- Motivations for a new generator
- Ideas how to approach key elements of the generator

INITIAL IDEA FOR NEW MC GENERATOR

- The original idea is hidden in the the beginning of XXI century.
  - NuInt workshops at KEK and UC Irvine
  - Composition of the group.
  - Encouragement from Danka Kielczewska
  - Use MC to compare new developments in modelling with data
- The state of the MC generators was rather grim in those days
  - NUEGEN
  - NUANCE
  - NEUT
  - GENEVE
  - NUX
- All generators were written for specific experiments with limitations of their applicability.

THE FIRST IDEA FOR A NEW GENERATOR

- The original motivation: to improve NUX+FLUKA scheme (no resonance production)
- A new treatment of the resonance region
- Only Δ resonance: nuclear effects should smear out other resonances and average treatment of them should be sufficient - Quark-Hadron duality
- A tool to investigate nuclear effects (e.g spectral function, nuclear potential)

APPROACH

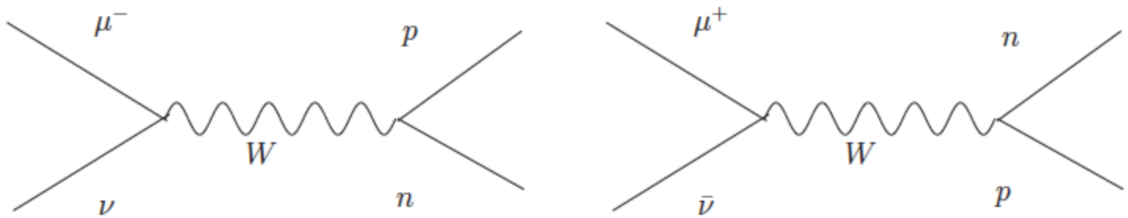
- The ingredients of the generators were obvious (CC)

$$\sigma_\nu = \sigma^{CC}_{QE} + \sigma^{CC}_{SPP} + \sigma^{CC}_{DIS} + \sigma^{NC}_{QE} + \sigma^{NC}_{SPP} + \sigma^{NC}_{DIS}$$

- Primary vertex: 3 separate dynamical mechanisms
- Quasi-elastic scattering (Llewellyn-Smith)
- Single pion production
  - Smooth gluing Δ excitation and DIS exclusive SPP channels for hadronic invariant mass W $\in$ (1.3, 1.6)GeV
  - Non-resonant background
- More inelastic (DIS)
  - Pythia fragmentation

CCQE

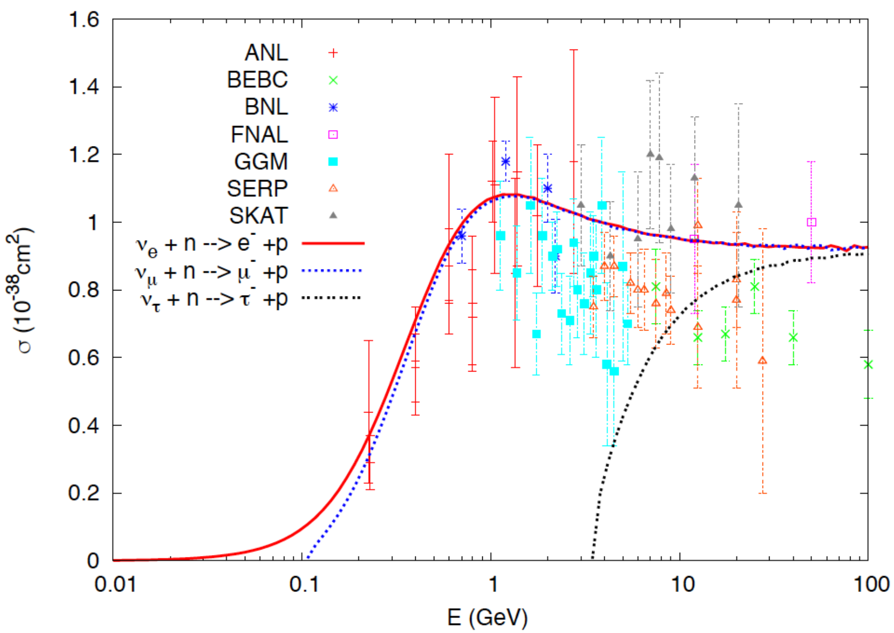
- We started with a simple generator for CCQE + nuclear effects
  - QE as in Llewellyn Smith
  - Fermi Gas implementations from Smith-Monitz and Bodek-Ritchie
  - Local Density approximation with effective potential
  - Form factors, BBA03, BBBA05, Kelly

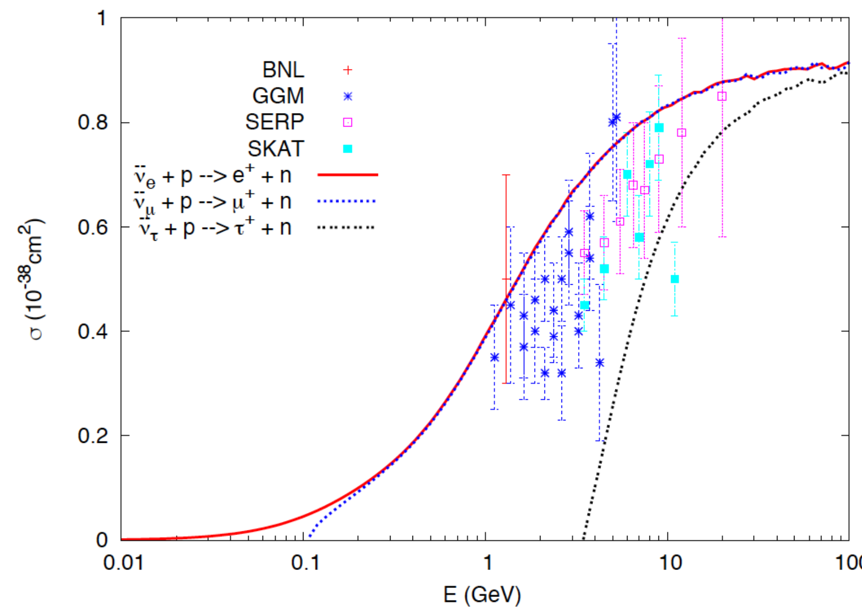


$$\frac{d\sigma^{\nu,\bar{\nu}}}{d|q^2|} = \frac{M^2 G^2 \cos^2\theta_C}{8\pi E_\nu^2}\left[A(q^2) \mp B(q^2)\frac{(s-u)}{M^2} + C(q^2)\frac{(s-u)^2}{M^4}\right].$$

COMPREHENSIVE COMPARISONS TO DATA

- Comparisons to "old" data





NUCLEAR MODELS - LDA

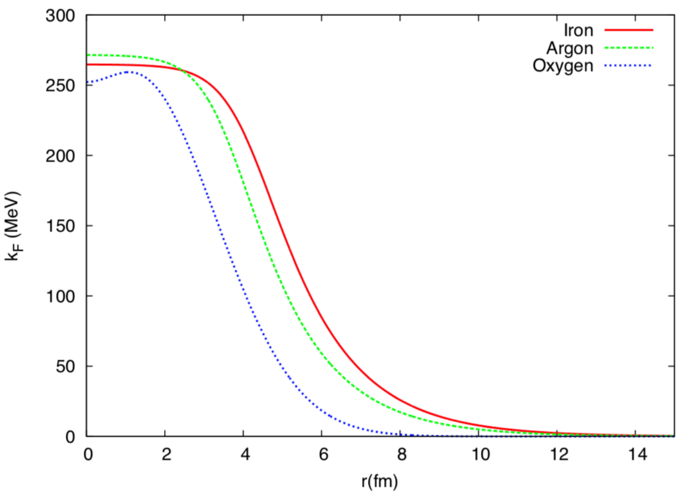
- It was always clear to us that the constant density Fermi Gas model cannot be sufficient to model the nucleus in neutrino interactions
- The Local Density Approximation (LDA) was previously used (e.g Oset et al.) but not in neutrino MC generators, AFAIK.
- We needed
  - Density of the nuclei
  - Nuclear potential
  - Four-momentum conservation

NUCLEAR DENSITY

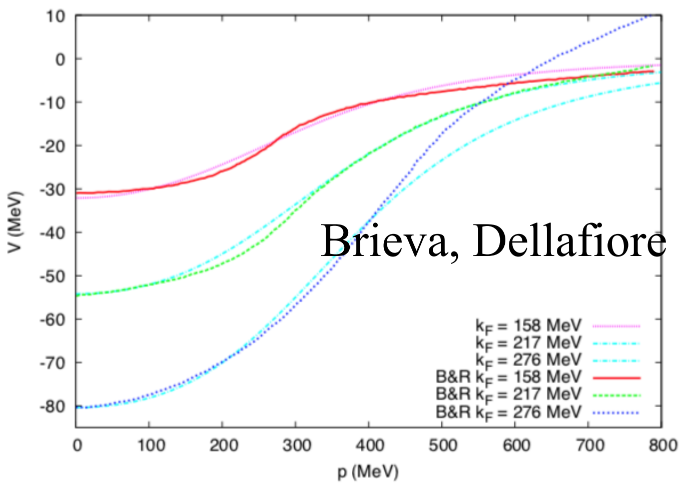
- The fermi momentum is related to the density

$$k_F = \left(\frac{3\pi^2}{2}\rho\right)^{1/3}$$

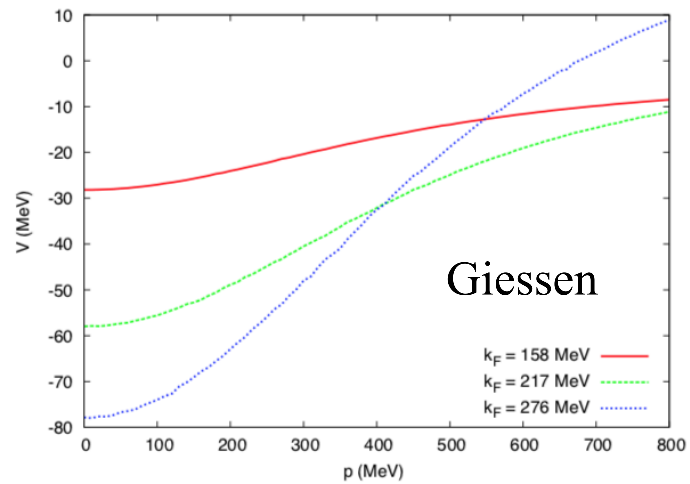
- The density of the nuclei were taken from C. W. De Jager, H. De Vries and C. De Vries, Atom. Data Nucl. Data Tabl. 36 (1987) 495
- This was the most difficult article to find: missing from Wroclaw, CERN and Fermilab libraries. Eventually I found it at INFN Milan.



EFFECTIVE POTENTIAL



Nucl. Phys. A 292 (1977) 445



Phys. Rev. C 38 (1988) 2101

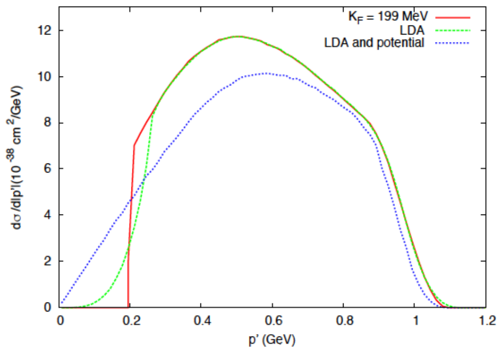
- We used the Brieva, Dellafiore results and parametrized their momentum dependent potential.
- Only a few years later we compare it to the potential from BUU model and it seem to be extraordinarily similar.

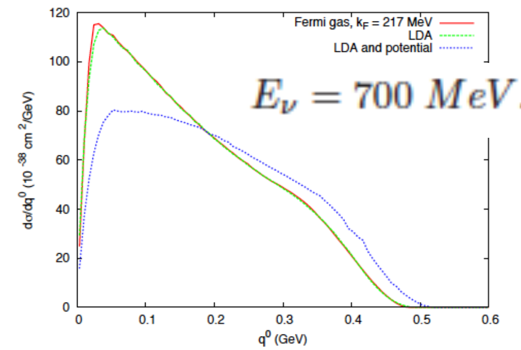
$$V\left(k_F, p\right) = -\frac{\left(ak_F\right)^2\left(k_F + b\right)}{c^4 + d^3 k_F + e^3 p^2/k_F + p^4},$$

$$V(\vec{r},\ \vec{p}) = A\frac{\rho(\vec{r})}{\rho_0} + B\left(\frac{\rho(\vec{r})}{\rho_0}\right)^{\tau} + \frac{2C}{\rho_0} g \int \frac{dp'}{(2\pi)^3} \frac{f\left(\vec{r}, \vec{p}\right)}{1 + \left(\frac{\vec{p}-\vec{p}'}{\Lambda}\right)^2},$$

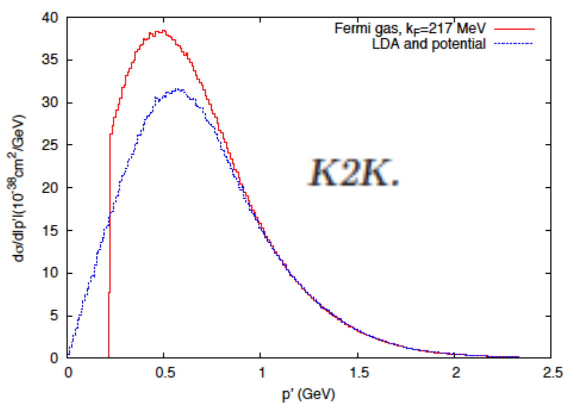
NUCLEAR MODELS -LDA

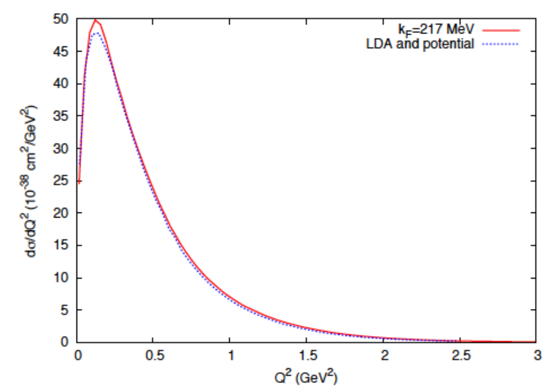
- We hoped that the new approach would explain the results from K2K





- The 500MeV/c cut for K2K was to strong to see any effect of the LDA

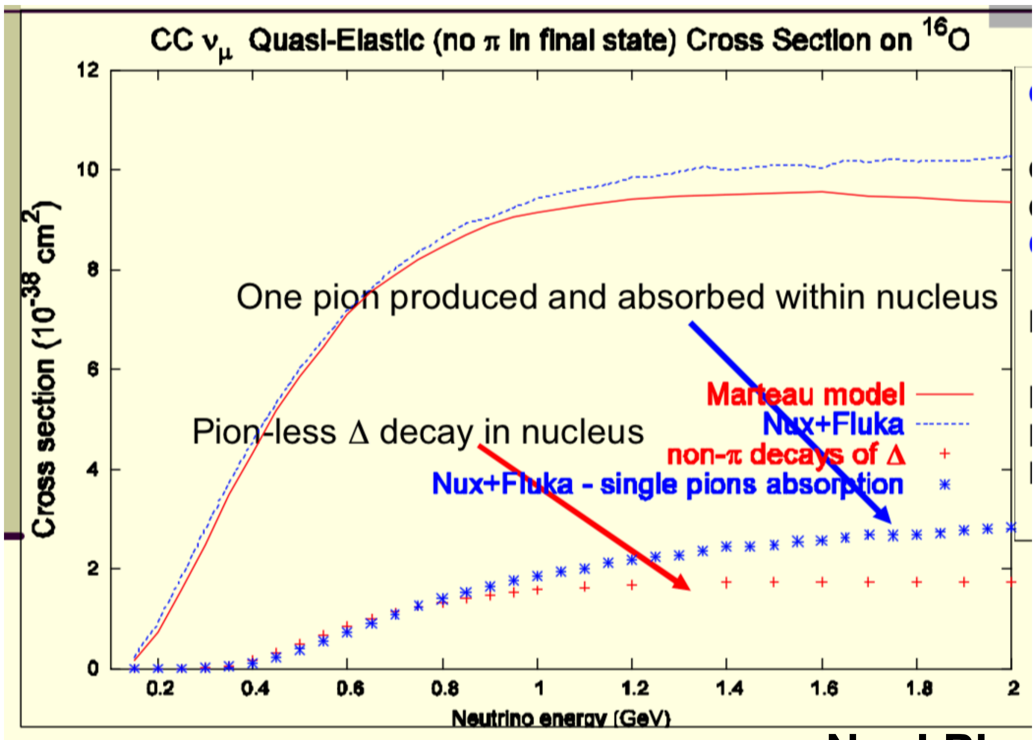




Eur. Phys. J. C 39 (2005) 195

np-nh MODELS

- One of the first tasks for Jan was to recalculate the Marteau model np-nh. (main source was Marteu's thesis in French)
- I looked into modeling of CCQE events in NUX (I was reading thesis by F. Sartogo in Italian).
- We started using the idea of QE-like events and 0π events



J.Nowak, NuInt04, Gran Sasso

Nucl.Phys.Proc.Suppl. 139 (2005) 272-277

PION PRODUCTION

- The pion production was modelled with excitation of Δ only

$$\frac{d^2\sigma}{dW\,dQ^2} = G^2 cos^2_C \frac{W g(W)}{4\pi^4} M E^2 \Bigg(-(Q^2+m^2)W_1 + \frac{W_2}{M^2}(2(pk)(pk') - \frac{M^2}{2}(Q^2+m^2))$$

$$\frac{W_3}{M^2}\Big(Q^2(kp) - 1/2(Q^2+m^2)(pq)\Big) + \frac{W_4}{M^2}\frac{m^2}{2}(Q^2)+m^2) - \frac{W_5}{M^2}m^2(kp)\Bigg)$$

- Form factors taken from L. Alvarez-Ruso, S.K. Singh and M.J.Vincento Vascas, Phys. Rev. C59, 3386(1999)
- K.Graczyk performed analysis for Δ excitation

DEEP INELASTIC SCATTERING 2004

- The DIS cross section is very easy

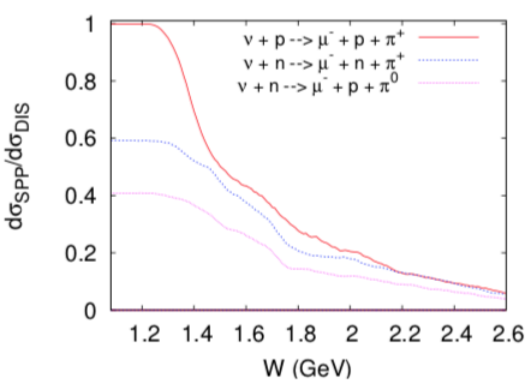
$$\frac{d^2\sigma^{\nu(\bar{\nu})}(E)}{dxdy} = \frac{G_F^2 ME}{\pi}\left[\left(xy^2 + \frac{ym^2}{2ME}\right)F_1\left(x,Q^2\right)\right.$$
$$+\left(1 - y - \frac{Mxy}{2E} - \left(\frac{m}{2E}\right)^2 - \frac{m^2}{2MEx}\right)F_2\left(x,Q^2\right)$$
$$\left.\pm\left(xy - \frac{xy^2}{2} - \frac{ym^2}{4ME}\right)F_3\left(x,Q^2\right)\right]$$

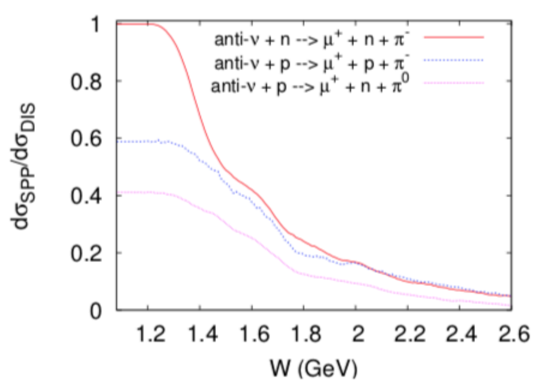
$$F_1\left(x,Q^2\right) = \sum_j\left[q_j\left(x,Q^2\right) + \bar{q}_j\left(x,Q^2\right)\right]$$
$$F_3\left(x,Q^2\right) = 2\sum_j\left[q_j\left(x,Q^2\right) - \bar{q}_j\left(x,Q^2\right)\right]$$
$$F_2\left(x,Q^2\right) = 2xF_1\left(x,Q^2\right)$$

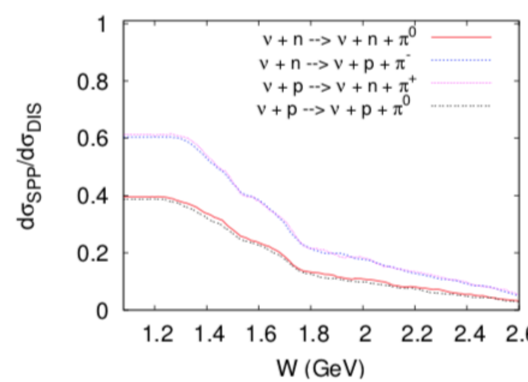
- q_j - Parton Distribution Function(PDF).
- At first we used GRV94 with Bodek-Yang modifications
- Later we also implemented the GPV98 with Bodek-Yang modifications.
- Eur. Phys. J. C 5 (1998) 46, Nucl. Phys. Proc. Suppl. 112 (2002) 70).

"CHEAP" HADRONIZATION

- The fragmentation and hadronization are difficult so for the first approach we only use the SPP channels.
- We used Pythia to get four-vectors for states with the 1 π
- F^{SPP} is a contribution of the single pion production channel in overall DIS cross section, reconstructed using LUND fragmentation algorithm.







TRANSITION REGION

- Smooth transition from Δ excitation to DIS single pion channels

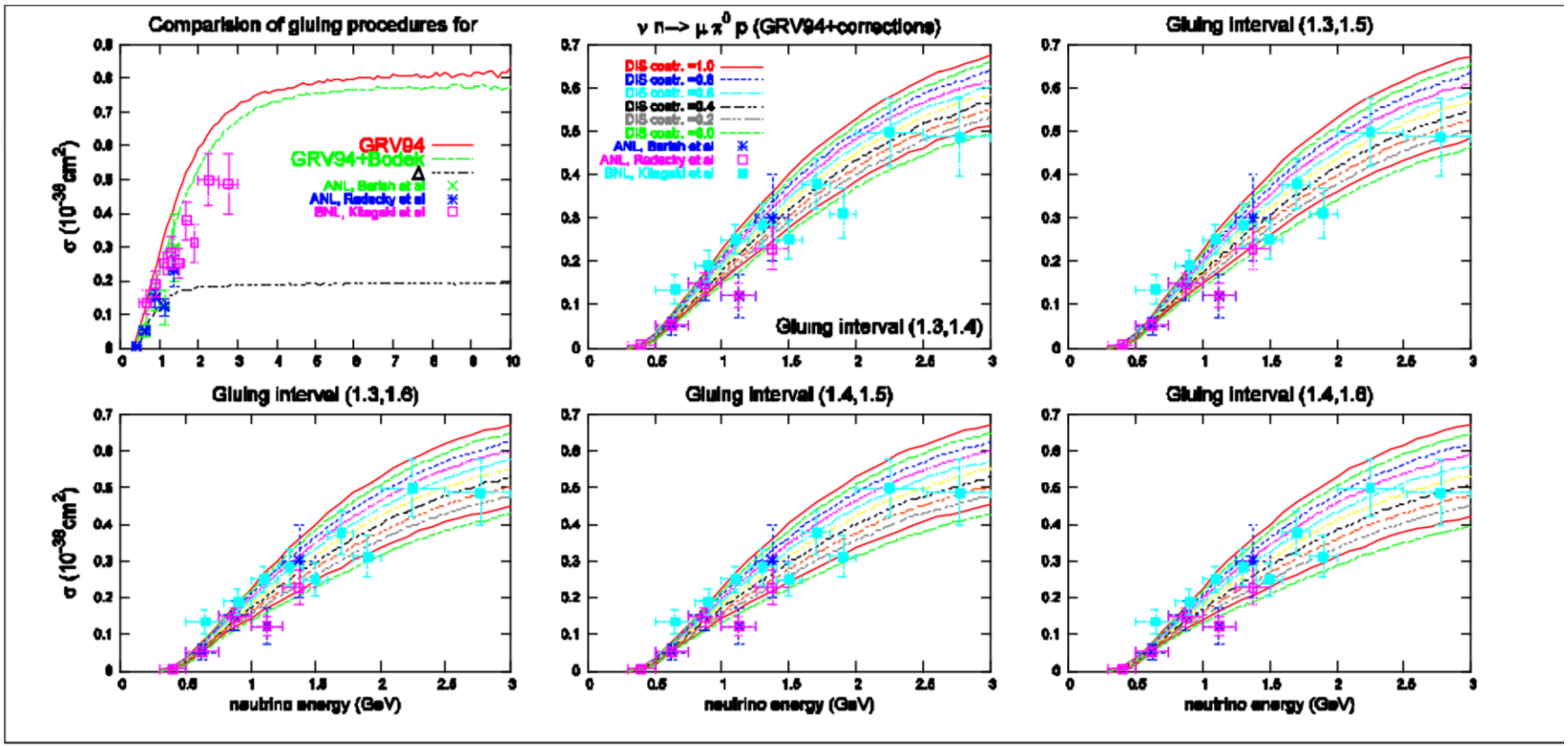
$$\frac{d\sigma^{SPP}}{dW} = \frac{d\sigma^{\Delta}}{dW}(1-\alpha(W)) + \frac{d\sigma^{DIS}}{dW}F^{SPP}(W)\alpha(W) \quad (9)$$

$$\begin{aligned} \alpha(W) &= \Theta(1.3GeV - W)\frac{W - W_{th}}{W_{min} - W_{th}}\alpha_0 \\ &+ \Theta(W_{max} - W)\Theta(W - W_{min})\frac{W - W_{min} + \alpha_0(W_{max} - W)}{W_{max} - W_{min}} \\ &+ \Theta(W - W_{max}) \end{aligned}$$

- The idea is justified by the quark-hadron quality → smearing of the maxima from resonances due to nuclear effects.

PIONZERO GRV94+CORRECTIONS

- With a ready algorithm we perform simple fitting to get the parameters of the model.



J.Sobczyk, NuInt04, Gran Sasso

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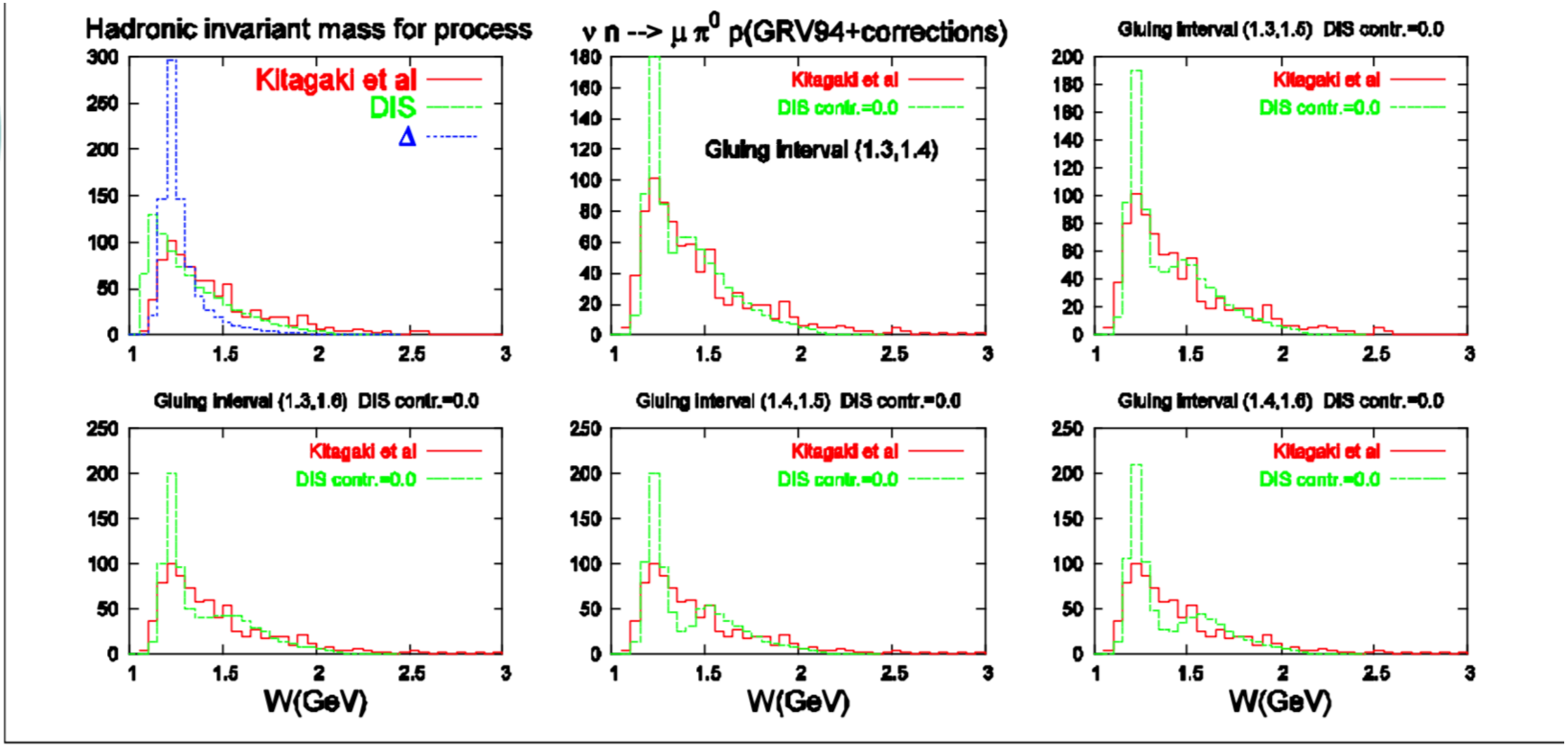

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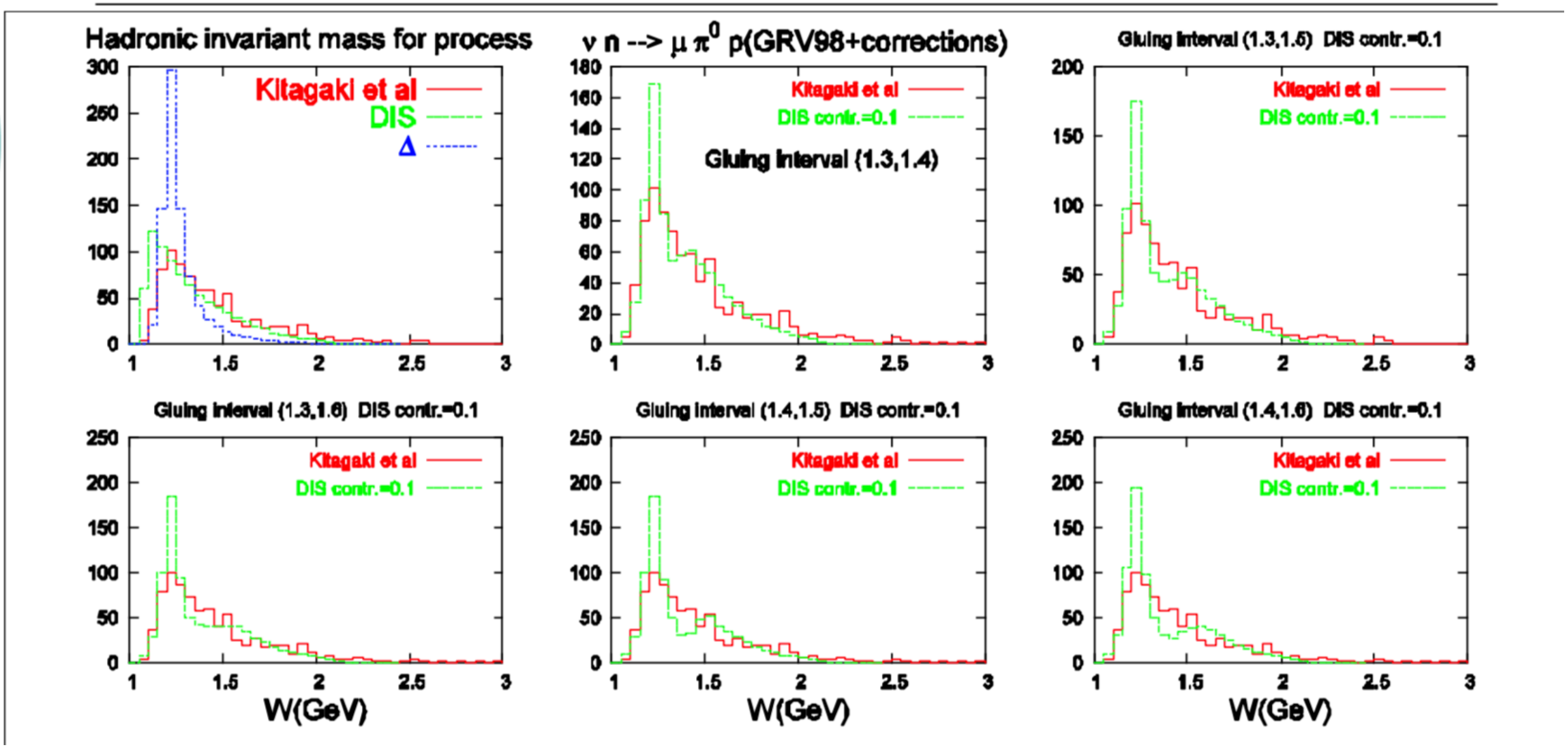

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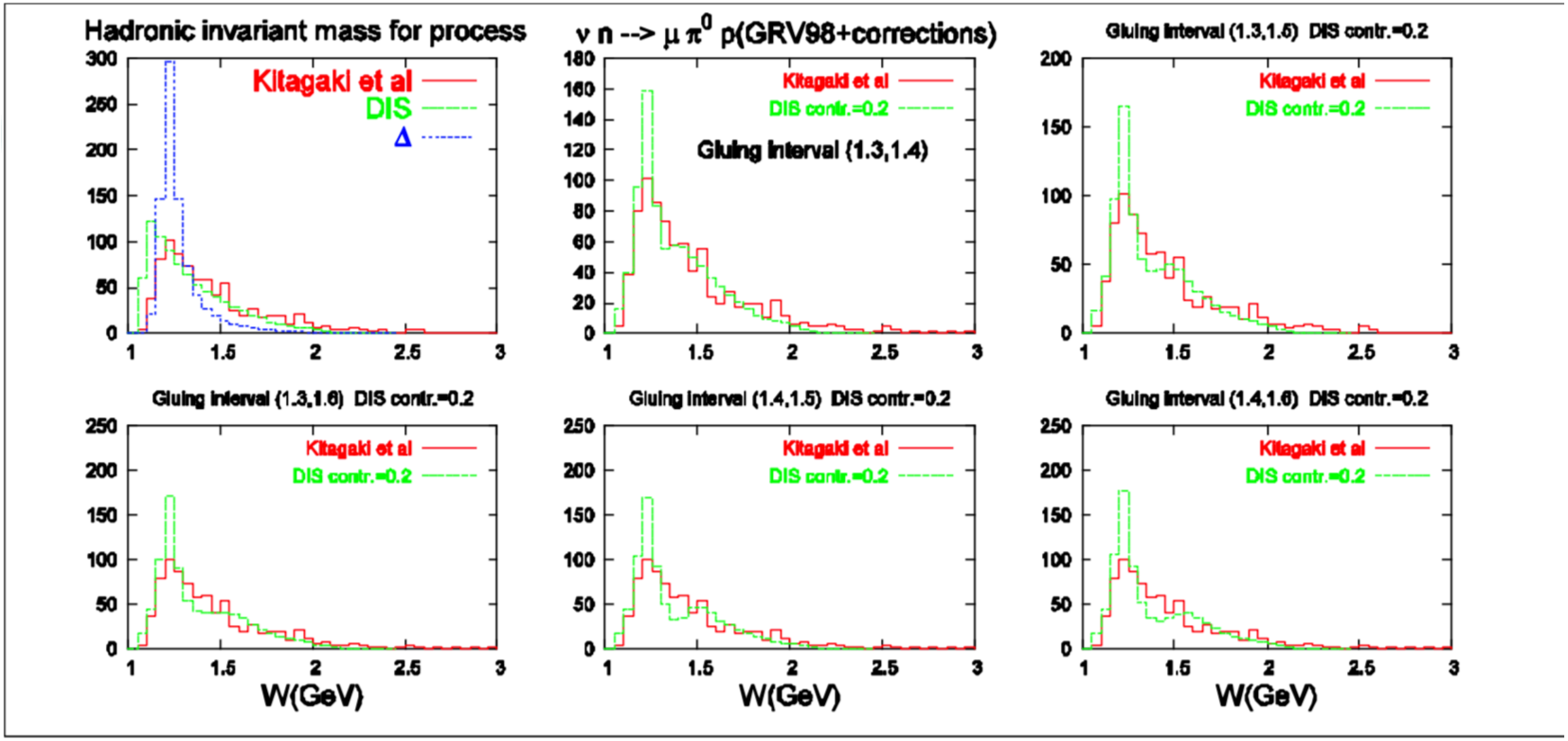

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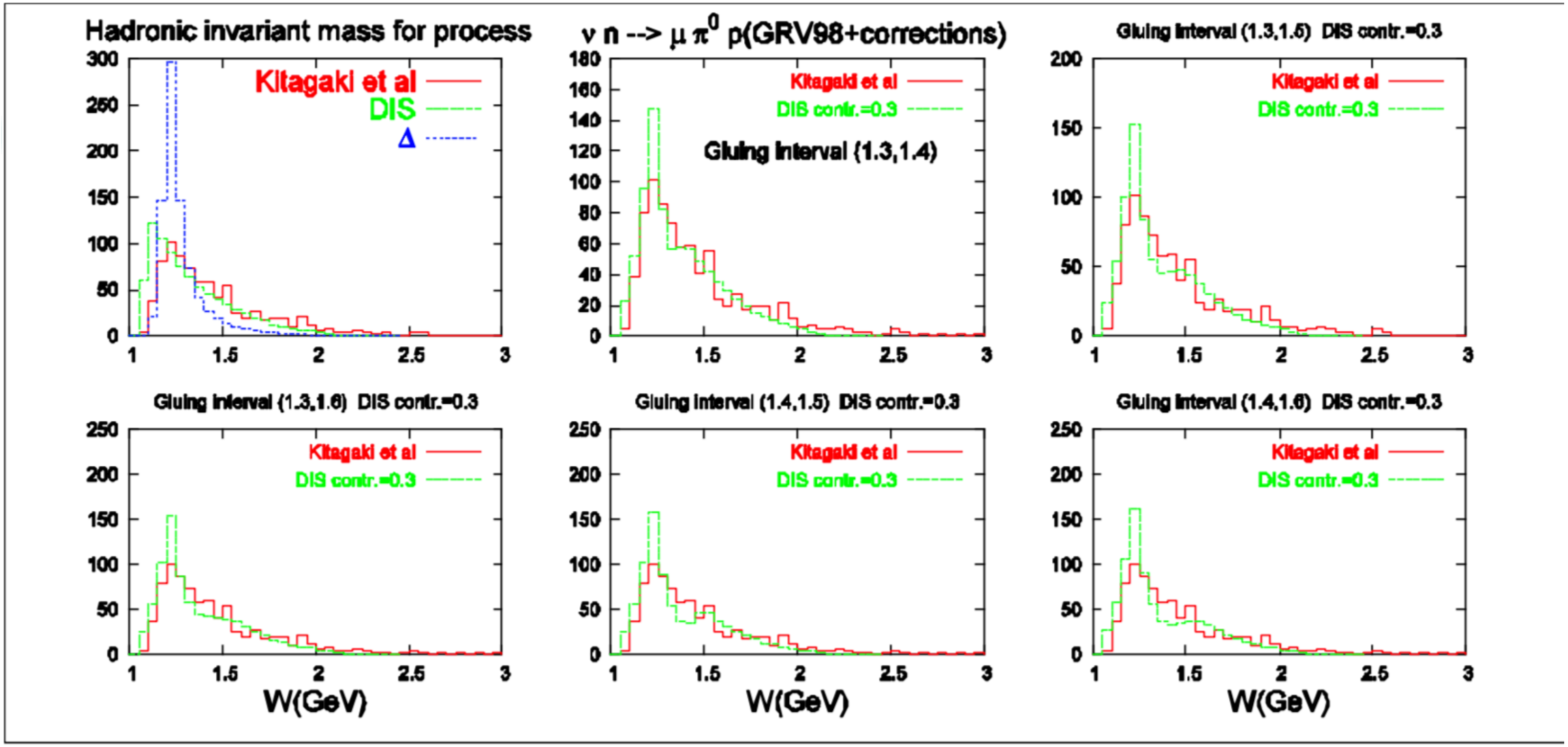

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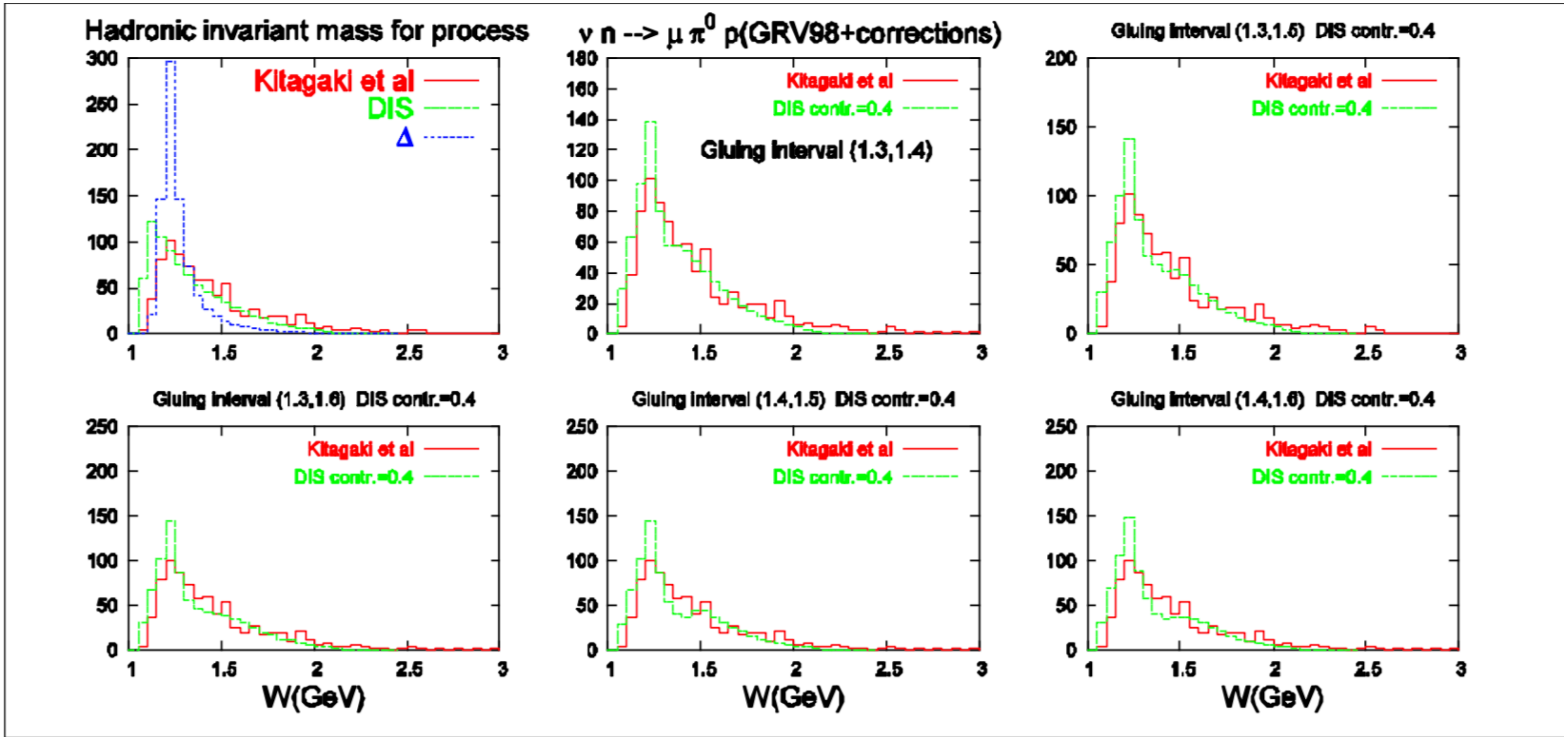

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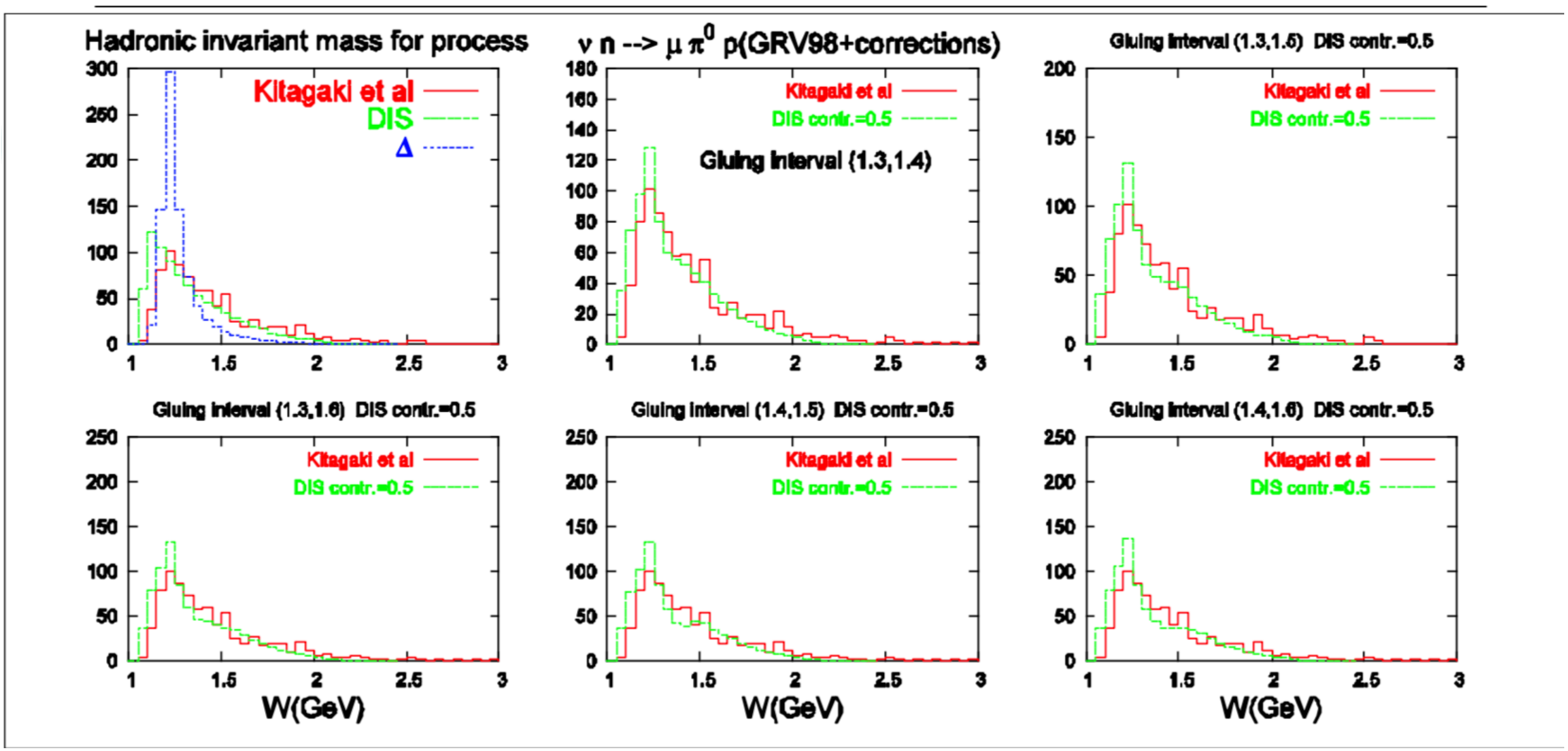
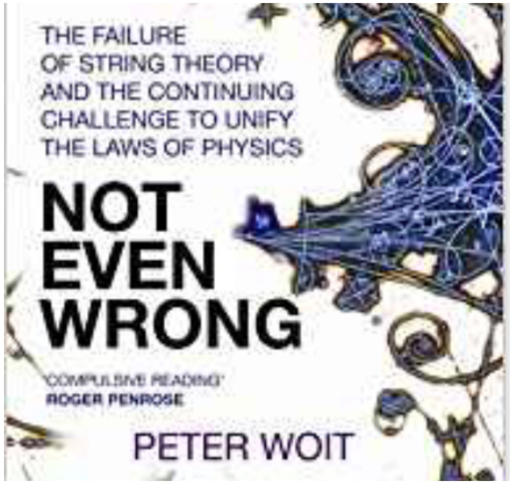


NUINT 04

- At NuInt04 we presented the generator as WroNG (Wroclaw Neutrino Generator)

- If you remember that three out of four of the developers used to work in the string theory it is an improvement



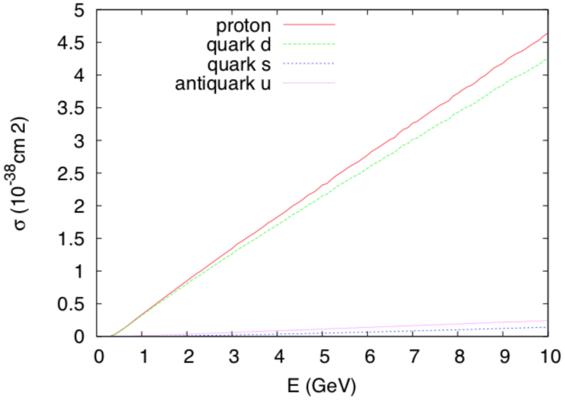
FRAGMENTATION ALGORITHM

- Pythia can generate events only for Eν > 10GeV.
- However, in fragmentation routines of PYTHIA lower energies are allowed -> We needed to redo the fragmentation
- Cross section is a sum of contribution from separate quarks
  - Cross section for scattering on quark qi (valance or sea quark)

$$\frac{d^2\sigma^{\nu q_i \to \mu q_j}}{dW\,d\nu} \sim q_i K_i$$

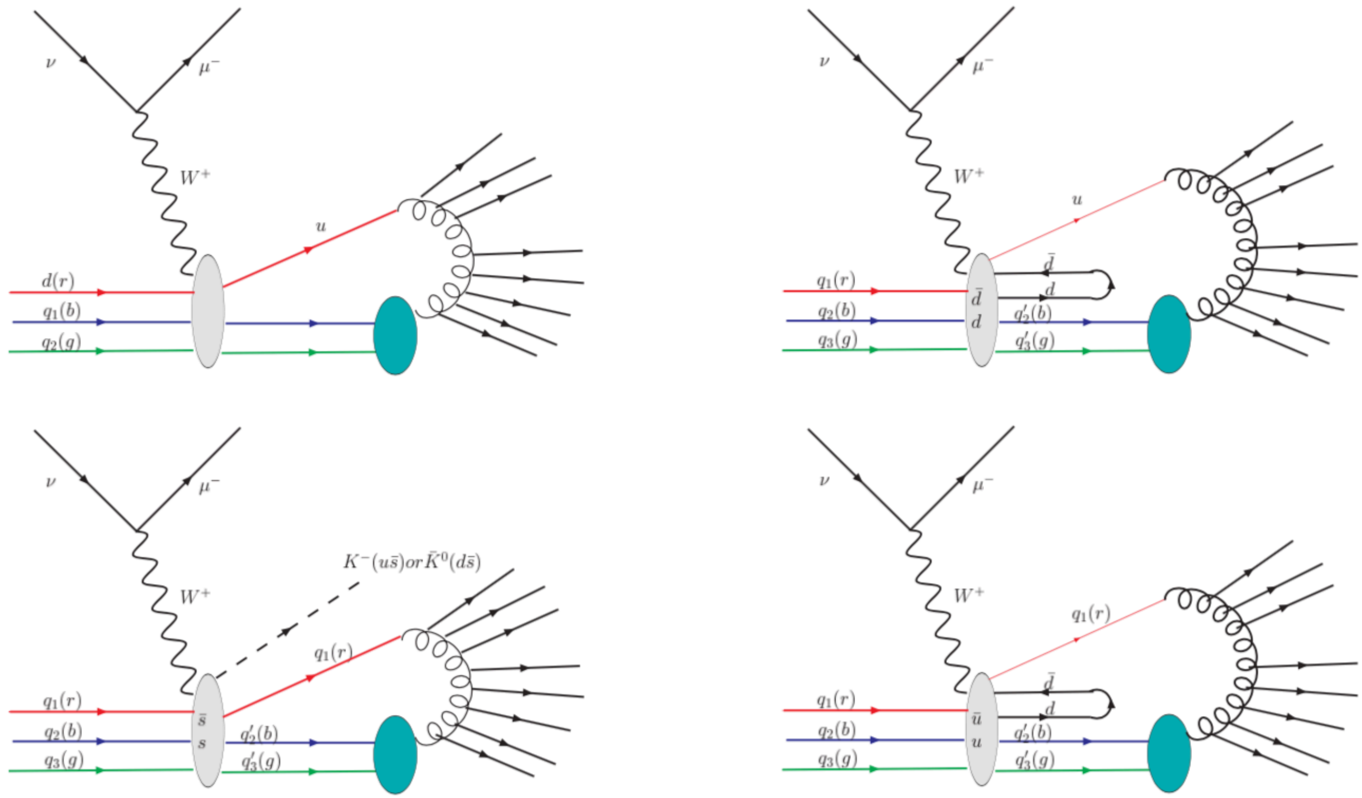
  - Ki kinematic factor for quark q_i.
  - Probability of reaction on a quark is given as follows

$$P(q_i) = \frac{\frac{d\sigma^{q_i}(E)}{dW\,d\nu}}{\sum_i \frac{d\sigma^{q_i}(E)}{dW\,d\nu}}$$



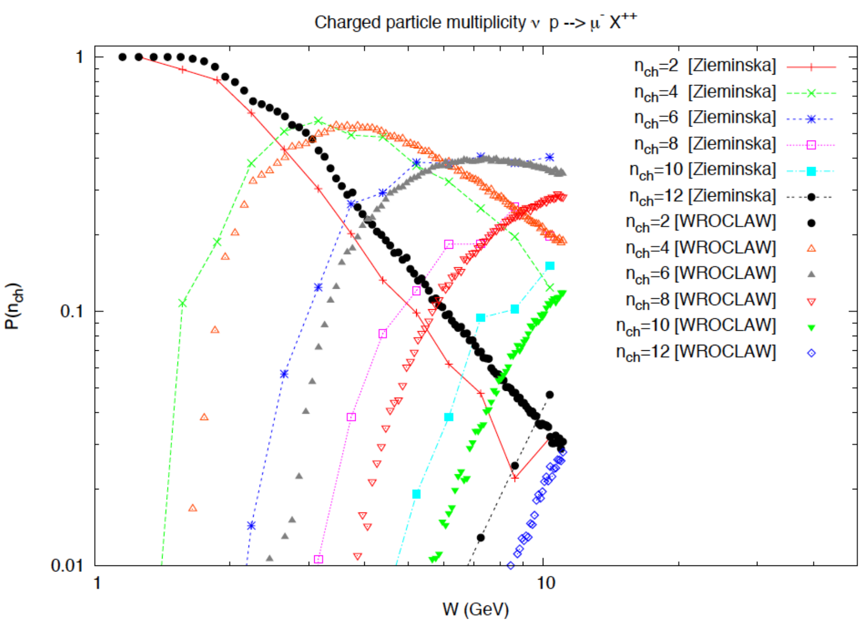
FRAGMENTATION ALGORITHM

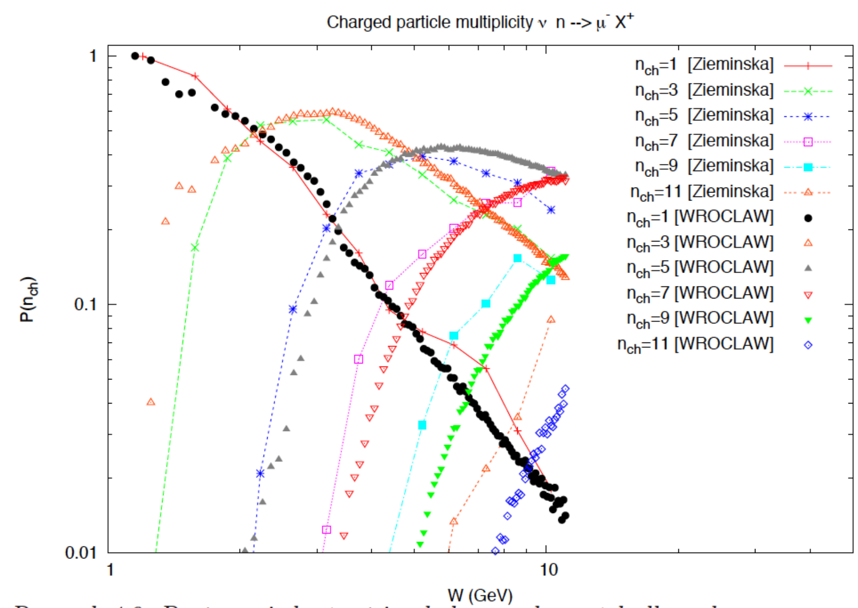
- Illustration of the scattering on parton inside nucleon for CC interaction



DEEP INELASTIC SCATTERING

- Charged-hadron multiplicity $P\ (n_{ch}) = \sigma(n_{ch}/\ \sigma(n_{ch})$

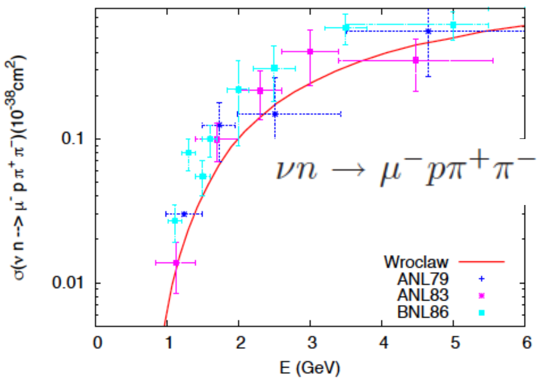


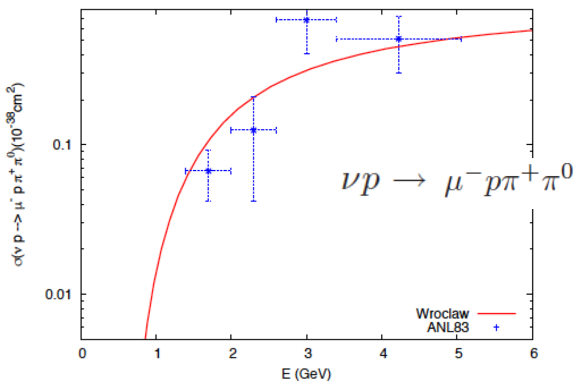


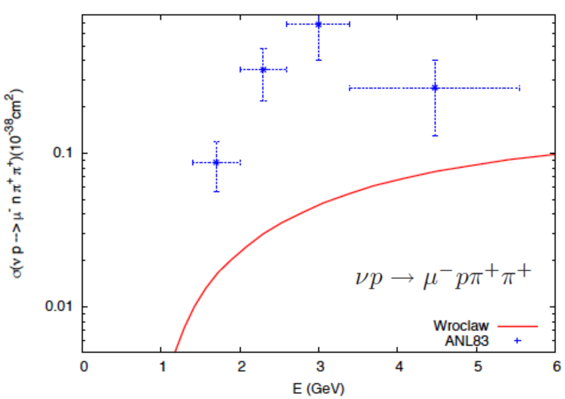
D. Zieminska et al. Phys. Rev. D27, 47(1983)

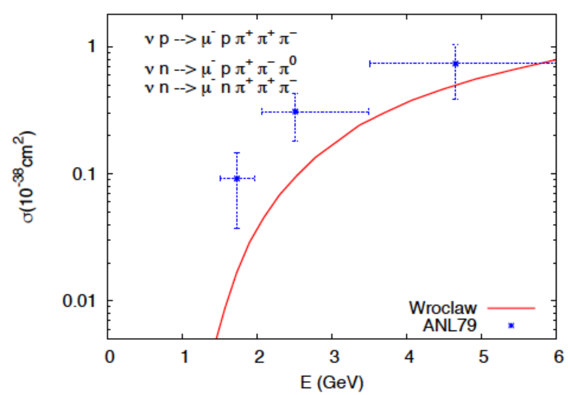
TWO PION PRODUCTION

We also started looking into exclusive channels to test our approach









FINAL PRODUCT IN 2006

- In 2005 all the basic components were ready and implemented
- By 2006 we added missing elements: NC and antineutrinos
- We got the Lipari plots