NUX - neutrino generator

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The First International Workshop on
Neutrino-Nucleus Interactions in the Few GeV Region

December 13-16, 2001, KEK, Tsukuba, Japan

History

- NUX was born in December 1998, when one of us (A.R.) realized that the neutrino generator used in NOMAD based on LEPTO and JETSET could not be easily ported to the low incoming neutrino energy environment. Going to low energies would have necessitates rewriting many parts of the old NOMAD generator.
- NUX has been widely used within ICARUS to perform all the simulation studies presented in the various documents, proposals, etc. NUX-FLUKA is the official MC program of ICARUS.
- It has been « cross-checked » with the NOMAD data.

Features of NUX

- Wide incoming neutrino energy range: 10 MeV $< E_\nu <$ 10 TeV
- All incoming neutrino flavor: electron, muon, and tau, neutrino and anti-neutrinos
- Neutral and charged currents
- Masses of lepton and of target fully included
- Optimized also for low Q^2 and low W^2
- Neutrino processes in leading order (no gluon emission, no PS)
- Charm production (slow rescaling with m_c and mass of target, only CC mode)
- Polarized tau production and decays
- Nuclear target of any Z or A
- Fully exclusive event generation
- Fully embeeded in FLUKA nuclear model (NUX-FLUKA work by A. Ferrari, A. Rubbia, P. Sala) for accurate treatment of nuclear target.

Kinematics (I)

- We adopted a consistent use of lepton *m* and nucleon mass *M* in kinematics
- At event generation, the incoming neutrino and target nucleon system is boosted/rotated so that the neutrino travels in z-direction and the target nucleon is at rest. The event is generated in this frame.

$$\nu_\ell(k^\mu) + N(p^\mu) \rightarrow \ell^-(k^{\mu'}) + X(p^{\mu'})$$

$$k^\mu = (E,0,0,E) \quad p^\mu = (M,\vec{0}) \quad k^{\mu'} = (E',k'\sin\theta,0,k'\cos\theta)$$

e.g.

$$s = 2ME + M^2 \qquad xy = \frac{Q^2}{s-M^2} \qquad Q^2 = -m^2 + 2E(E' - k'\cos\theta)$$

$$E' = (1-y)E \quad k_z' = \frac{(1-y)E^2 - Q^2 - m^2}{2E}$$

$$\left(k_T'\right)^2 = -m^2 - (Q^2+m^2)\left[\frac{Q^2+m^2}{4E^2} - (1-y)\right]$$

- The generated event is boosted/rotated back to original system (ϕ rotation is trivial). After the generation of each event, energy-momentum conservation is explicitely checked and traced (rounding errors, etc…)

Kinematics (II)

- **Kinematical boundaries also include nucleon mass M and outgoint lepton mass m:**

$$\frac{m^2}{s-M^2} \le x \le 1 \quad \mathit{and} \qquad A-B \le y \le A+B$$

$$A = \frac{1}{2}\left(1-\frac{m^2}{2MEx}-\frac{m^2}{2E^2}\right) \Big/ \left(1+x\frac{M}{2E}\right)$$

$$B = \frac{1}{2}\left(\left(1-\frac{m^2}{2MEx}\right)^2-\frac{m^2}{E^2}\right)^{1/2} \Big/ \left(1+x\frac{M}{2E}\right)$$

Effects mostly important for ν_τ but also for muon and electron near threshold.

Dynamics (I)

- **Combining the different « bits and pieces » of the neutrino cross-sections has been traditionally difficult due to the requirement to extent the kinematical region to**

$$Q^2 \to 0 \quad and/or \quad W \to M$$

- **Subdivided into 3 main processes:**
  - Quasi-elastic (x=1) $\nu N \to lN$ or $\nu N \to \nu N$
  - Inelastic
    - κ At least one pion produced
  - Charm
- **Remarks**
  - « Resonances final states » produced in ad-hoc way, but not yet treated specially (see later)
  - Coherent production to be included
  - Quasi-elastic « charm production » implemented, being debugged

Dynamics (II) - inelastic

- **Definition of inelastic**
  - Anything that produces at least a pion
- **Formalism**
  - Based on parton model (e.g. DIS)
- **Input**
  - Default structure functions GRV 94 HO (DIS,NLL)
  - Evolution of pdf stopped below $Q^2=0.4$ GeV^2
- **Kinematical boundaries**
  - No cut on Q^2 , i.e. $Q^2>0$ GeV^2
  - Invariant mass range **$W > M+m_\pi+\varepsilon$** where $\varepsilon=10$ MeV
- **Differential cross-section (mass included, no higher twist)**

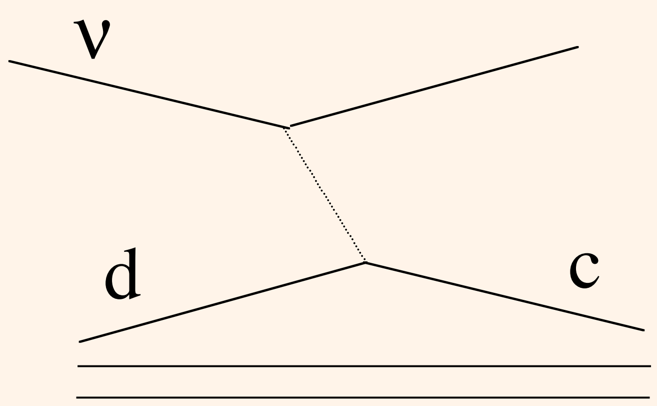
$$\frac{d^2\sigma}{dxdy} \propto \left(xy + \frac{m^2}{2ME} \right) y \left(\frac{F_2}{2x} \right) + \left(1 - y - \frac{Mxy}{2E} - \frac{m^2}{4E^2} \right) F_2 \pm \left(xy(1-y/2) - \frac{ym^2}{4ME} \right) F_3 - \frac{m^2}{2ME} \left(\frac{F_2}{x} \right)$$

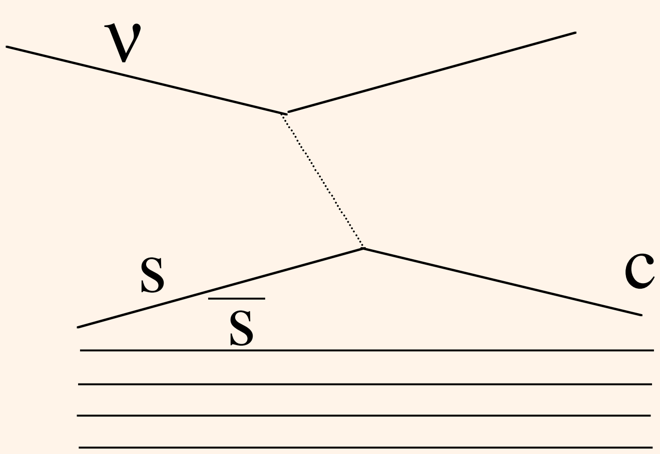
Fragmentation

- **Relies on a modified version of JETSET 7.4 and use LUND fragmentation**
- **Used only to determine exclusive final state for $W > M+2m_\pi$**
- **Tuning**
  - PARJ(2)=ssbar suppression = 0.21
  - Gaussian Pt^2 distribution PARJ(21)=0.44, PARJ(23)=0.01
  - Remaining energy cutoff PARJ(33)=0.2 GeV
- **For $M+m_\pi < W < M+2m_\pi$ use phase space into baryon+pion, via Δ resonance.**
- **Special treatment of charm fragmentation (see later)**

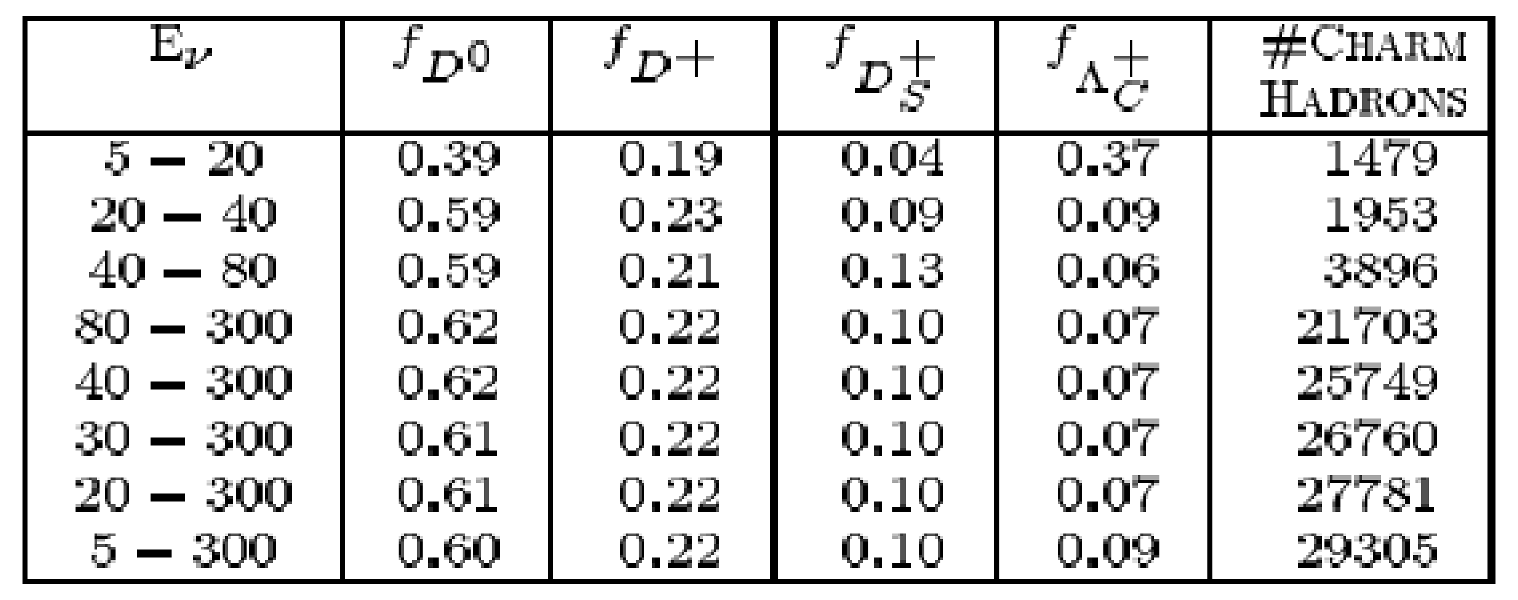
Dynamics - Charm

- LO slow-rescaling cross-section, $m_c = 1.3$ GeV
- Only charged current process (NC under investigation)
- Cabbibbo-suppressed and allowed contributions
- Fragmentation of charm hadrons treated specially to reproduce *z* and Pt^2 data
- Baryon and meson fractions tuned by proper mixing of quark lines in final state



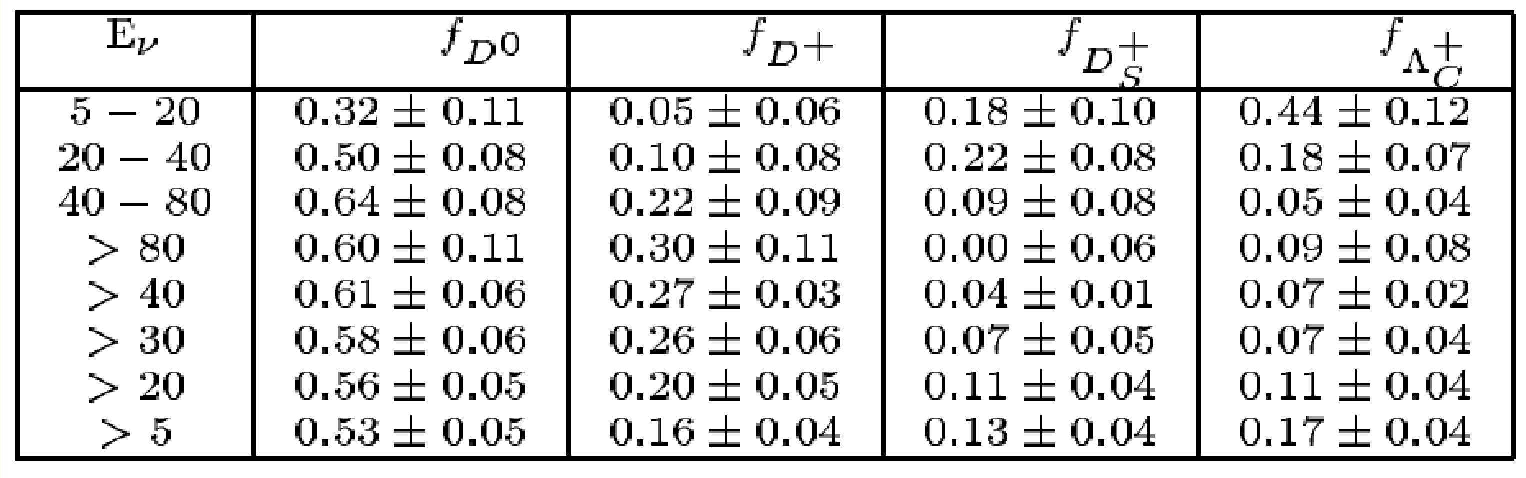


Charm fragmentation



E_ν	f_{D^0}	f_{D^+}	$f_{D_S^+}$	$f_{\Lambda_C^+}$	#CHARM HADRONS
5 – 20	0.39	0.19	0.04	0.37	1479
20 – 40	0.59	0.23	0.09	0.09	1953
40 – 80	0.59	0.21	0.13	0.06	3896
80 – 300	0.62	0.22	0.10	0.07	21703
40 – 300	0.62	0.22	0.10	0.07	25749
30 – 300	0.61	0.22	0.10	0.07	26760
20 – 300	0.61	0.22	0.10	0.07	27781
5 – 300	0.60	0.22	0.10	0.09	29305

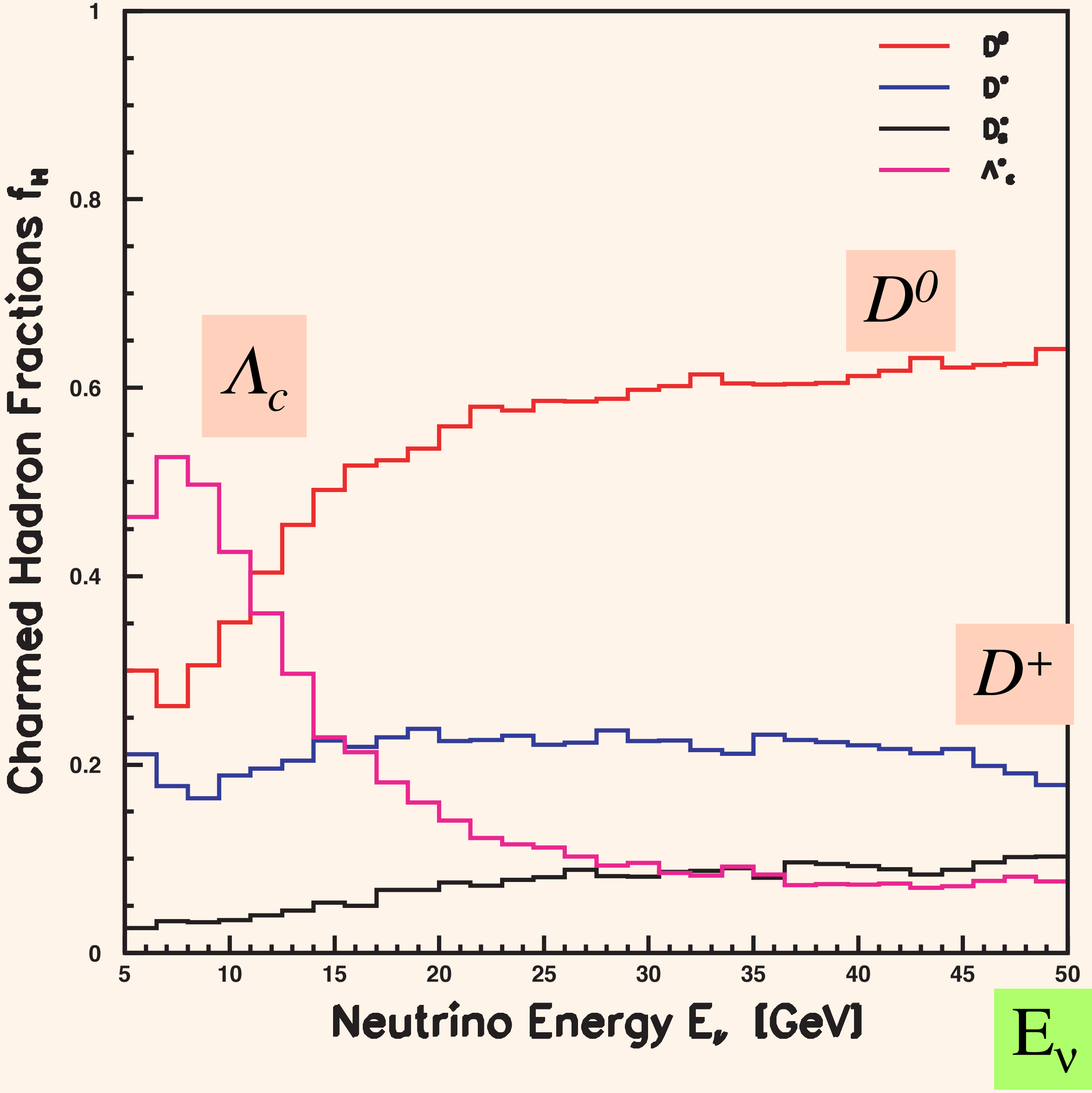
NUX



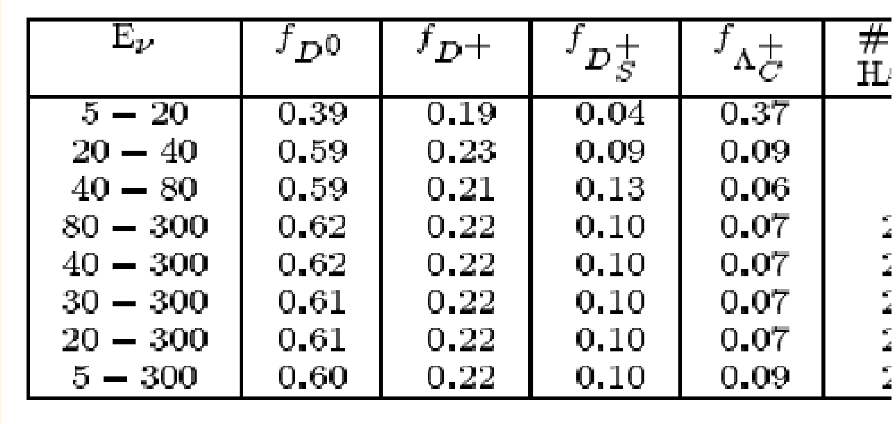
E_ν	f_{D^0}	f_{D^+}	$f_{D_S^+}$	$f_{\Lambda_C^+}$
5 – 20	0.32 ± 0.11	0.05 ± 0.06	0.18 ± 0.10	0.44 ± 0.12
20 – 40	0.50 ± 0.08	0.10 ± 0.08	0.22 ± 0.08	0.18 ± 0.07
40 – 80	0.64 ± 0.08	0.22 ± 0.09	0.09 ± 0.08	0.05 ± 0.04
> 80	0.60 ± 0.11	0.30 ± 0.11	0.00 ± 0.06	0.09 ± 0.08
> 40	0.61 ± 0.06	0.27 ± 0.03	0.04 ± 0.01	0.07 ± 0.02
> 30	0.58 ± 0.06	0.26 ± 0.06	0.07 ± 0.05	0.07 ± 0.04
> 20	0.56 ± 0.05	0.20 ± 0.05	0.11 ± 0.04	0.11 ± 0.04
> 5	0.53 ± 0.05	0.16 ± 0.04	0.13 ± 0.04	0.17 ± 0.04

T. Bolton
hep-ex/9708014
E531 data

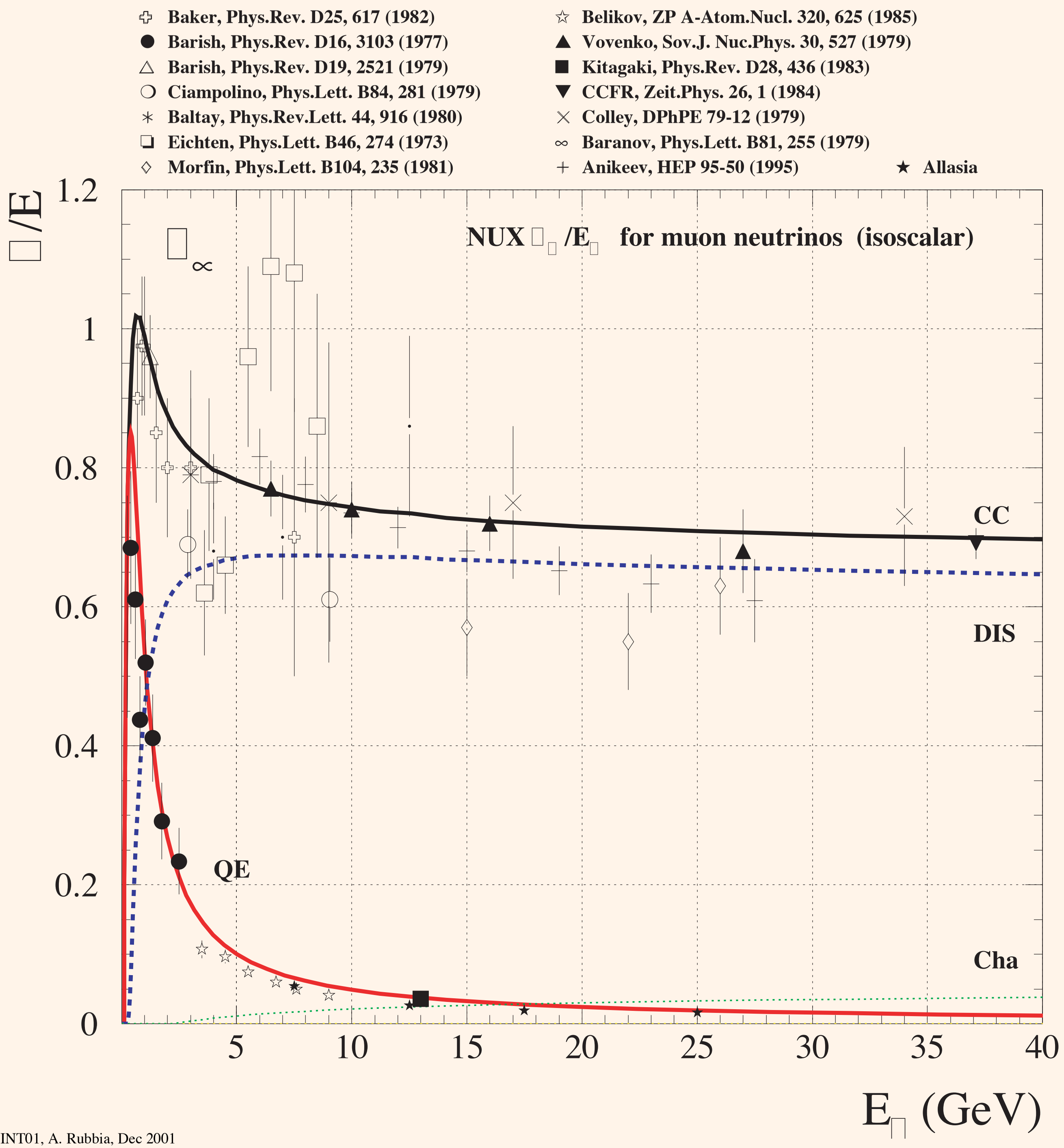
Charmed hadron fractions



Fragmentation in charm events

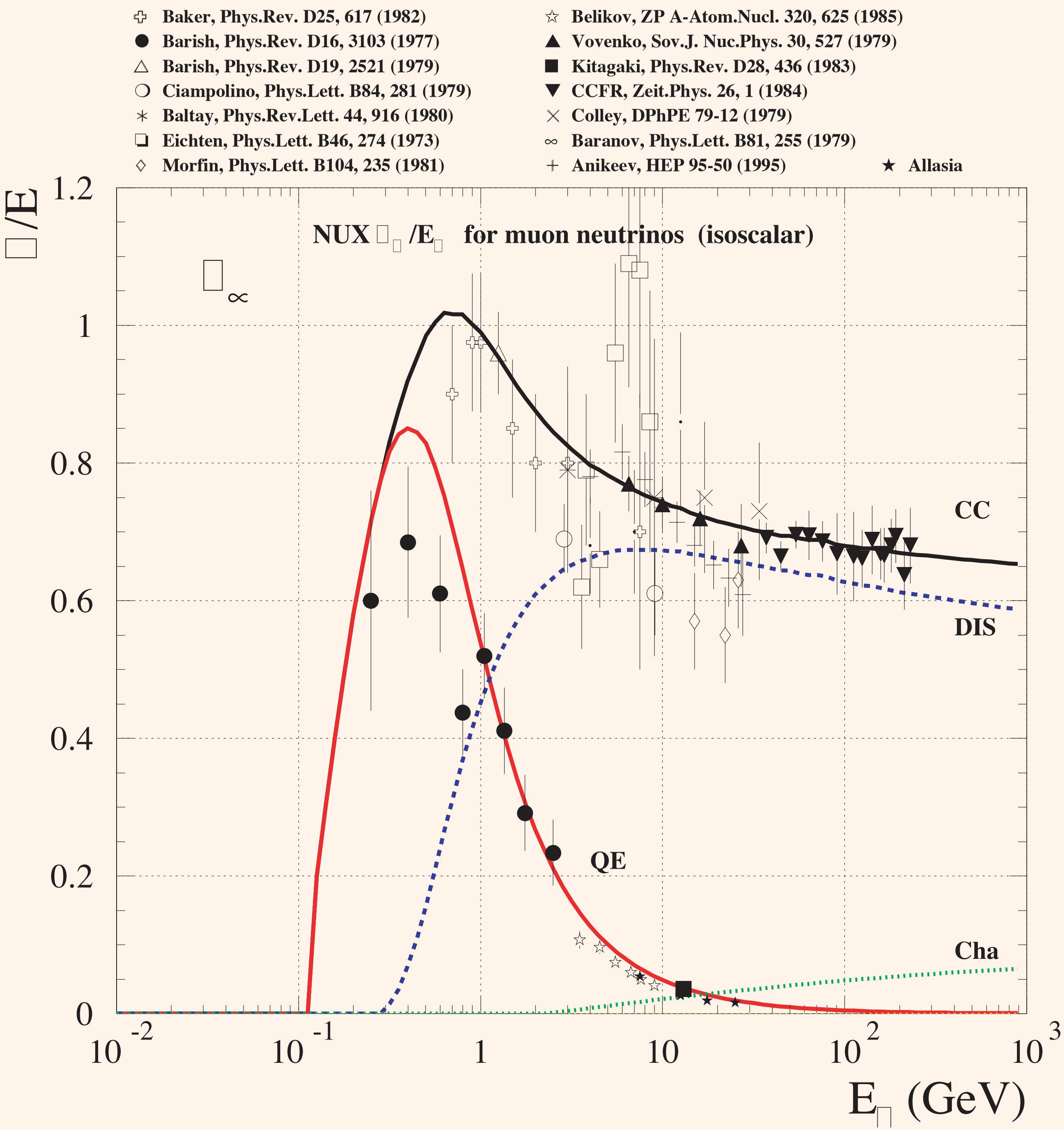


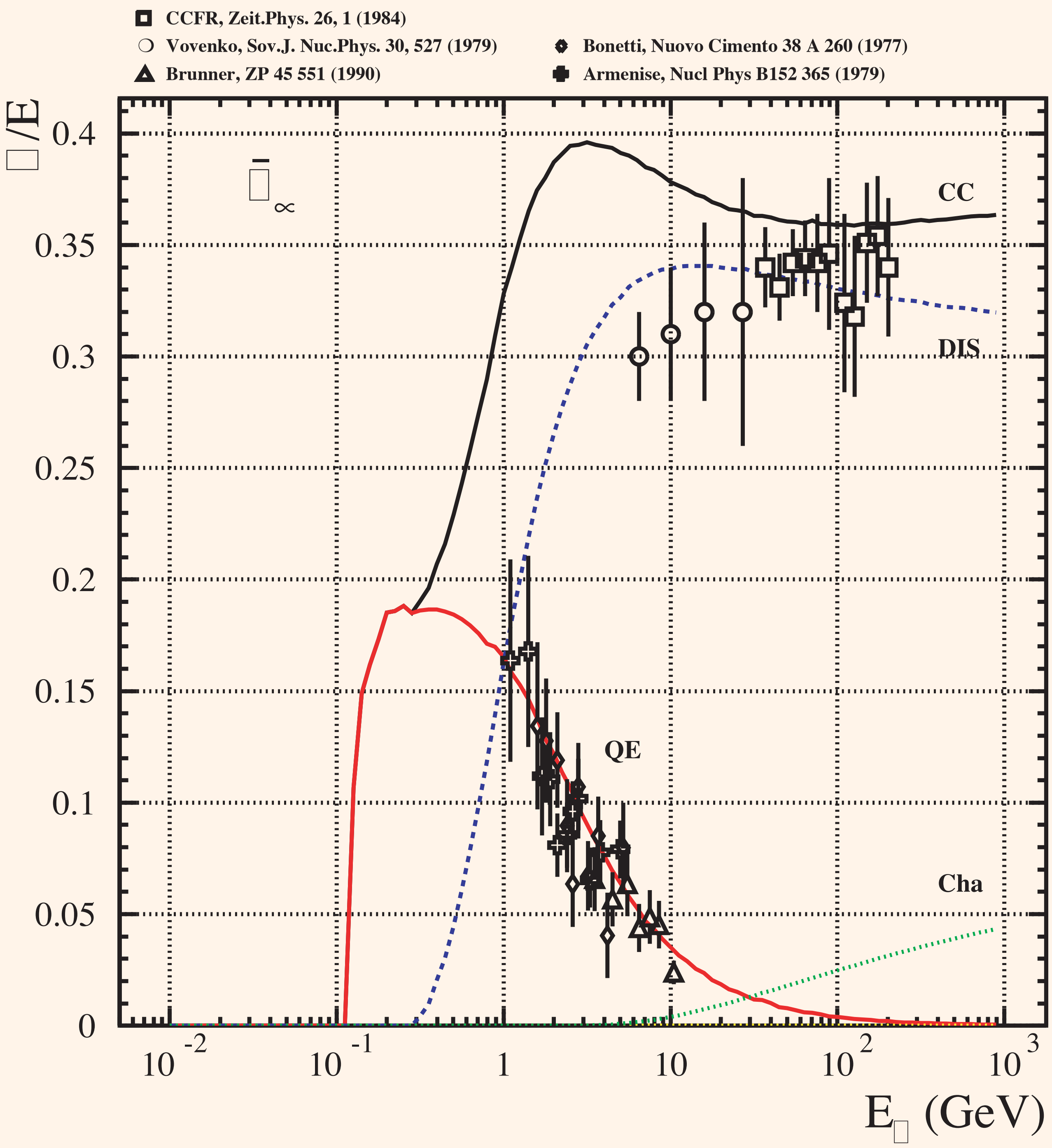
E_ν	f_{D^0}	f_{D^+}	$f_{D_S^+}$	$f_{\Lambda_C^+}$	# H
5 – 20	0.39	0.19	0.04	0.37	
20 – 40	0.59	0.23	0.09	0.09	
40 – 80	0.59	0.21	0.13	0.06	
80 – 300	0.62	0.22	0.10	0.07	
40 – 300	0.62	0.22	0.10	0.07	
30 – 300	0.61	0.22	0.10	0.07	
20 – 300	0.61	0.22	0.10	0.07	
5 – 300	0.60	0.22	0.10	0.09	



Comparison of σ/E_ν for QE and total processes between data and NUX between 0 and 40 GeV

Comparison of σ/E_ν for QE and total processes between data and NUX between 10 MeV and 200 GeV



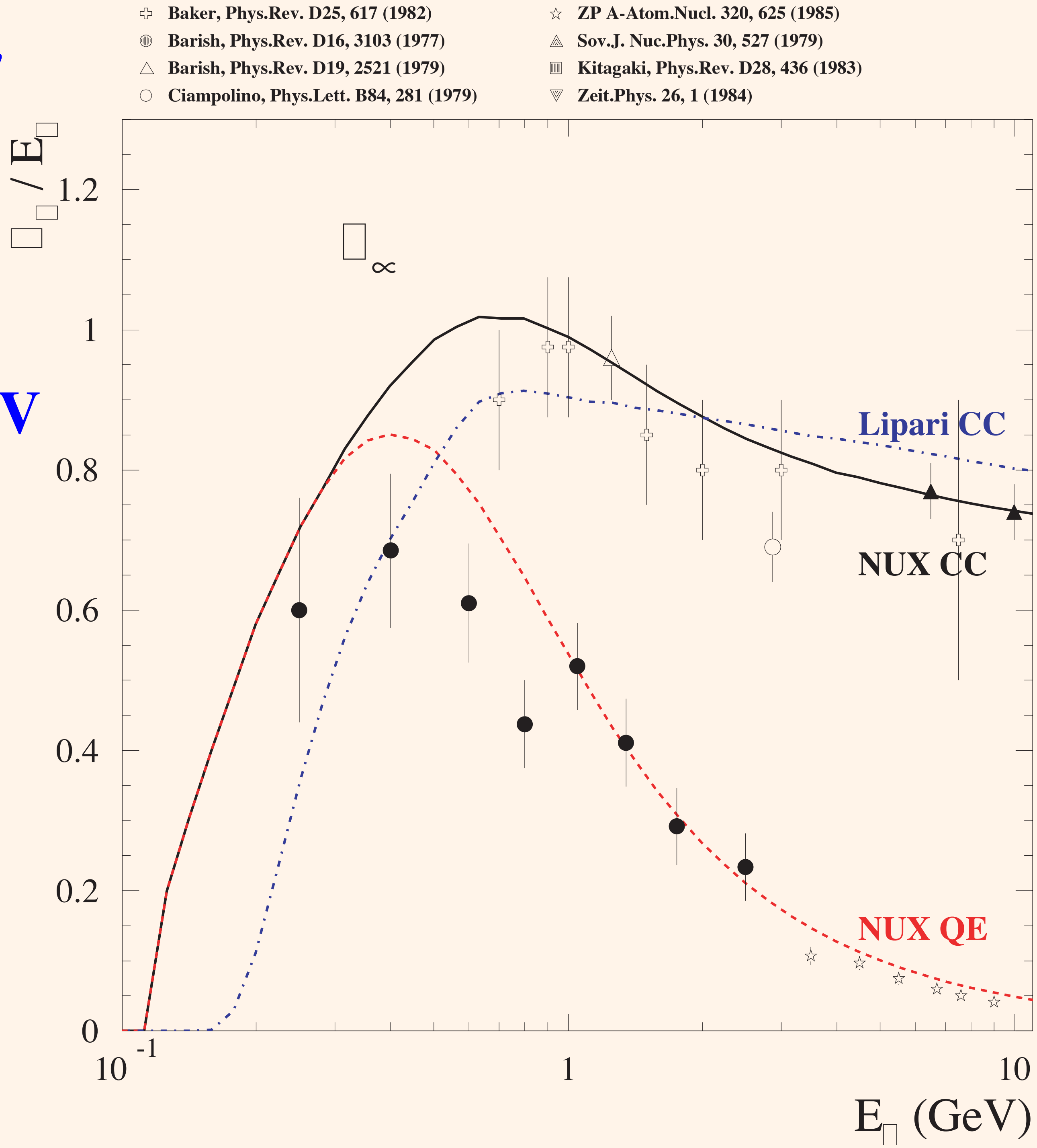


Comparison of σ/E_ν for QE and total processes between data and NUX between 10 MeV and 200 GeV

$\overline{\nu}_\mu$

Comparison of σ/E_ν for QE and total processes between Lipari and NUX between 100 MeV and 10 GeV

(NUX without nuclear effects)



Nuclear model

- **Nuclear effects play an important role in modifying**
  - The total cross-section
  - The visible event kinematics
  - The exclusive final states
- **The simplest effects:**
  - Fermi motion of the hit nucleon
  - Pauli-blocking
- **More « tricky » effects**
  - Reinteraction of the produced hadrons
    - κ Can introduce significant change in energy, number and identity of hadrons (e.g. pion absorption, charge exchange, inelastic)
  - Motion through nuclear mean field and Coulomb field, which modifiy energy and momentum (magnitude and direction)

Rely on well-proven FLUKA code

FLUKA: generalities

FLUKA

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[†] **CERN,** [&] **INFN Milan and CERN,** [*] **Siegen University**

Interaction and transport MonteCarlo code

- Hadron-hadron and hadron-nucleus interactions 0-100 TeV
- Nucleus-nucleus interactions 0-10000 TeV/n: *under development*
- Electromagnetic and μ interactions 1 keV-100 TeV
- Neutrino interactions
- Charged particle transport including all relevant processes
- Transport in magnetic field
- Combinatorial (boolean) geometry
- Neutron multigroup transport and interactions 0-20 MeV
- Analogue or variance reduction calculations

The FLUKA hadronic models

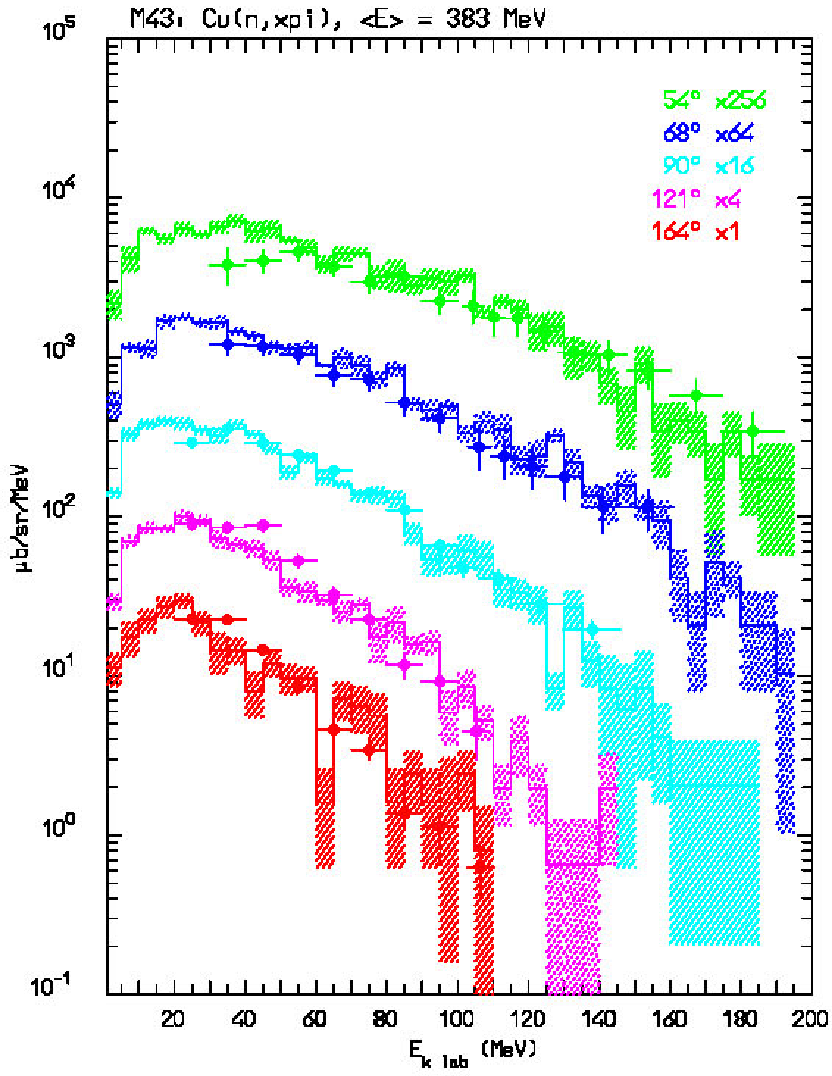
Building block: Hadron-Nucleon

Elastic, charge exchange, resonance production, Dual Parton Model

Inside the nucleus

Initial state effects	Fermi Motion of target nucleons, Nuclear Potential for target and projectile, Glauber multiple scattering, many-body absorption, collective excitations..
	Generalized Intranuclear Cascade
Final state effects	Towards equilibrium : • Preequilibrium: statistical repartition of energy • Evaporation from a thermalized system, fission, Fermi Break-up • Nuclear deexcitation through γ rays

Hadronic interactions at intermediate energies



PEANUT

GINC + preequilibrium+..

quantistic effects (Pauli blocking, formation zone..)

nuclear potentials and curvature of trajectories,

many-body effects

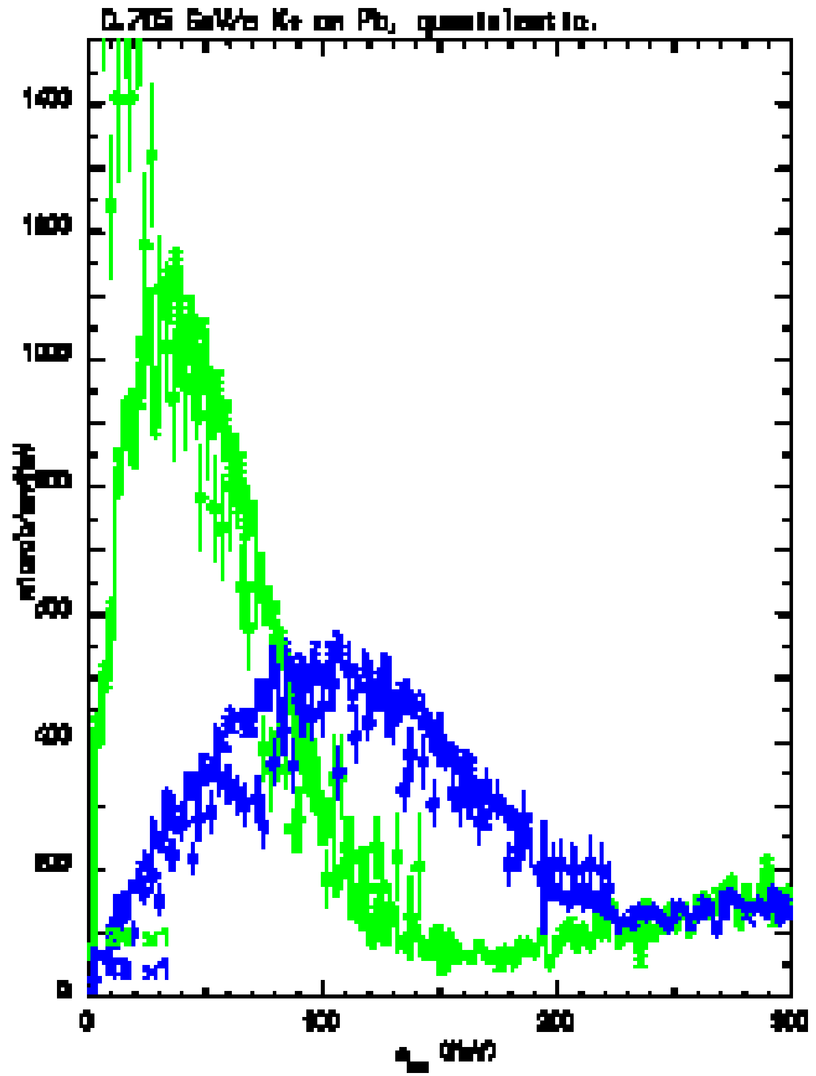
relativistic kinematics

binding energies, ..

Example: n+Cu→ πX, at 383 MeV. Exp. data (symbols) from

Buchle et al. **NPA515**, (1990) 541

Positive Kaons : example



K^+ K^0

No low mass S=1 baryons →

weak K^+N interaction

only elastic and ch. exch. up to

≈ 800 MeV/c

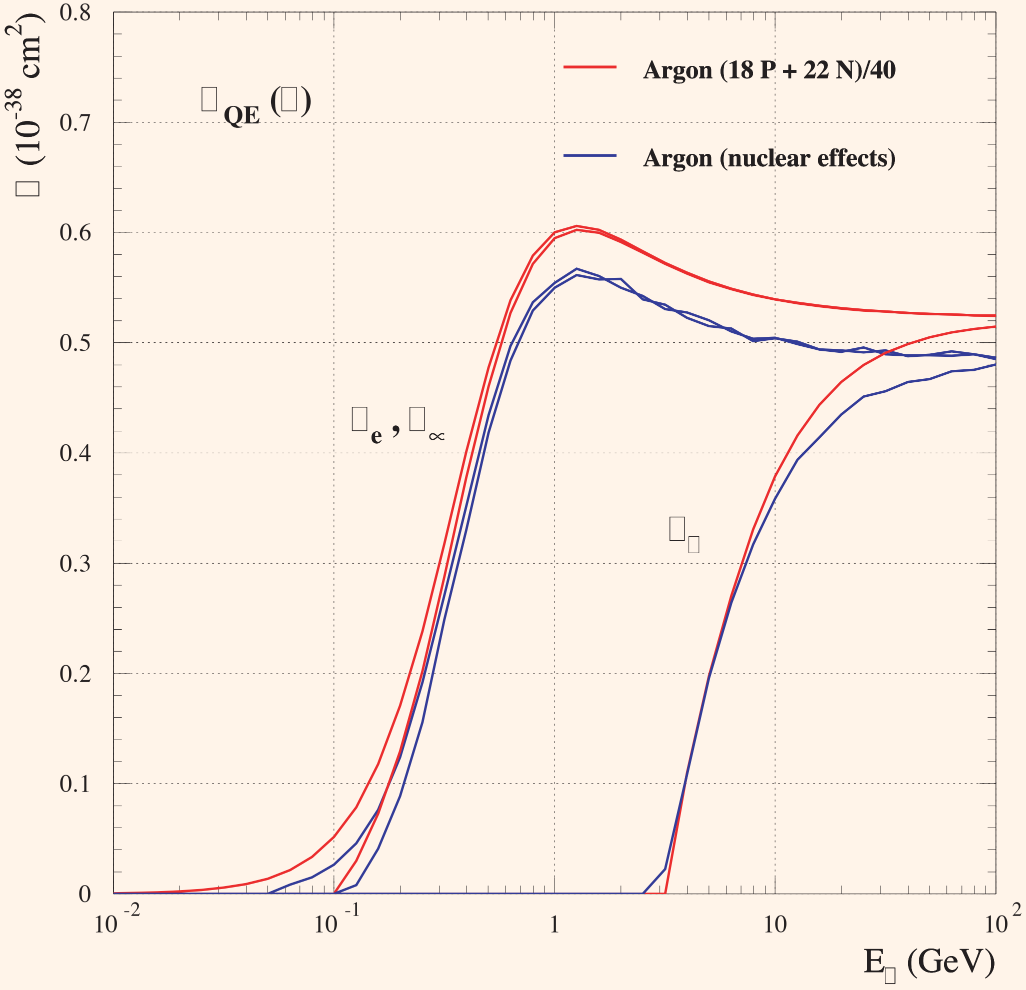
$(K^+, K^{+\prime})$ on Pb vs residual excitation, 705 MeV/c, at 24° and 43°.

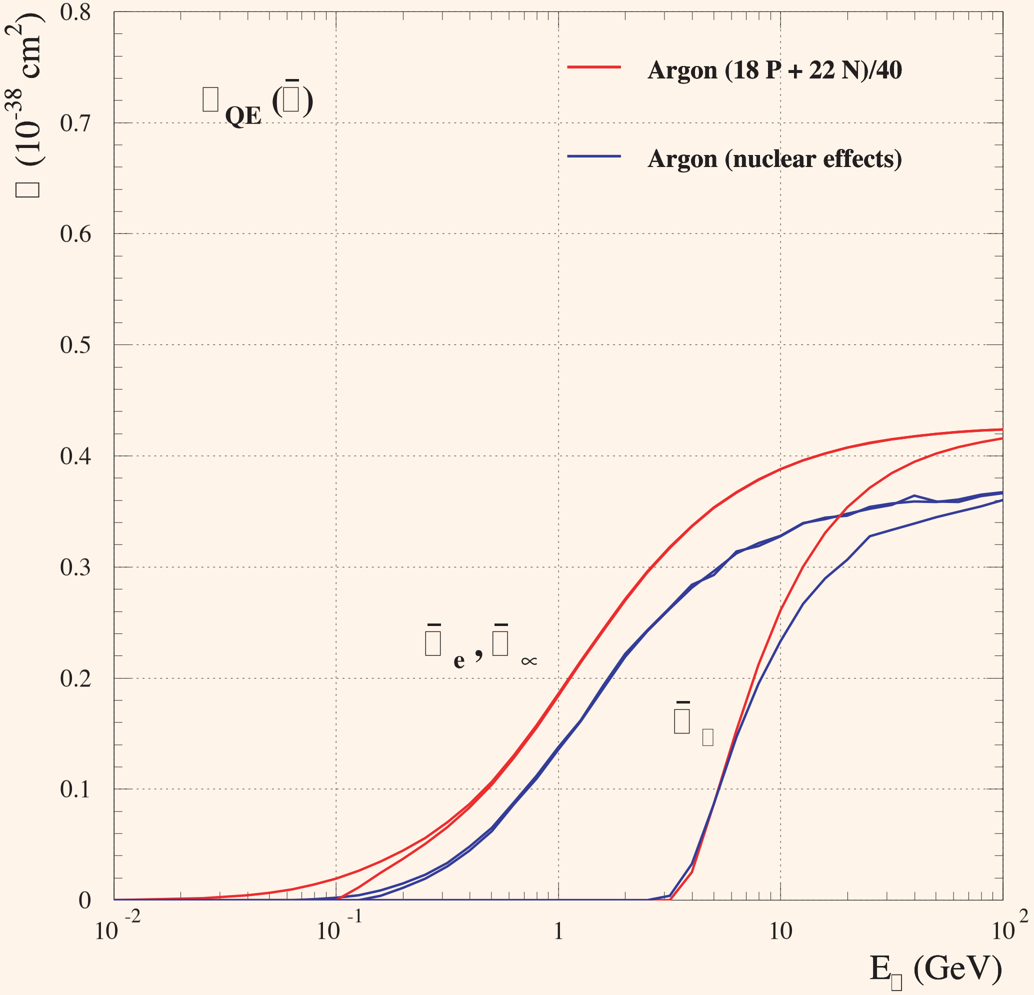
Histo: FLUKA, dots: data (Phys. Rev. C51, 669 (1995))

On free nucleon: recoil energy :

43 MeV at 24° , 117 MeV at 43°.

Effect on QE cross-section

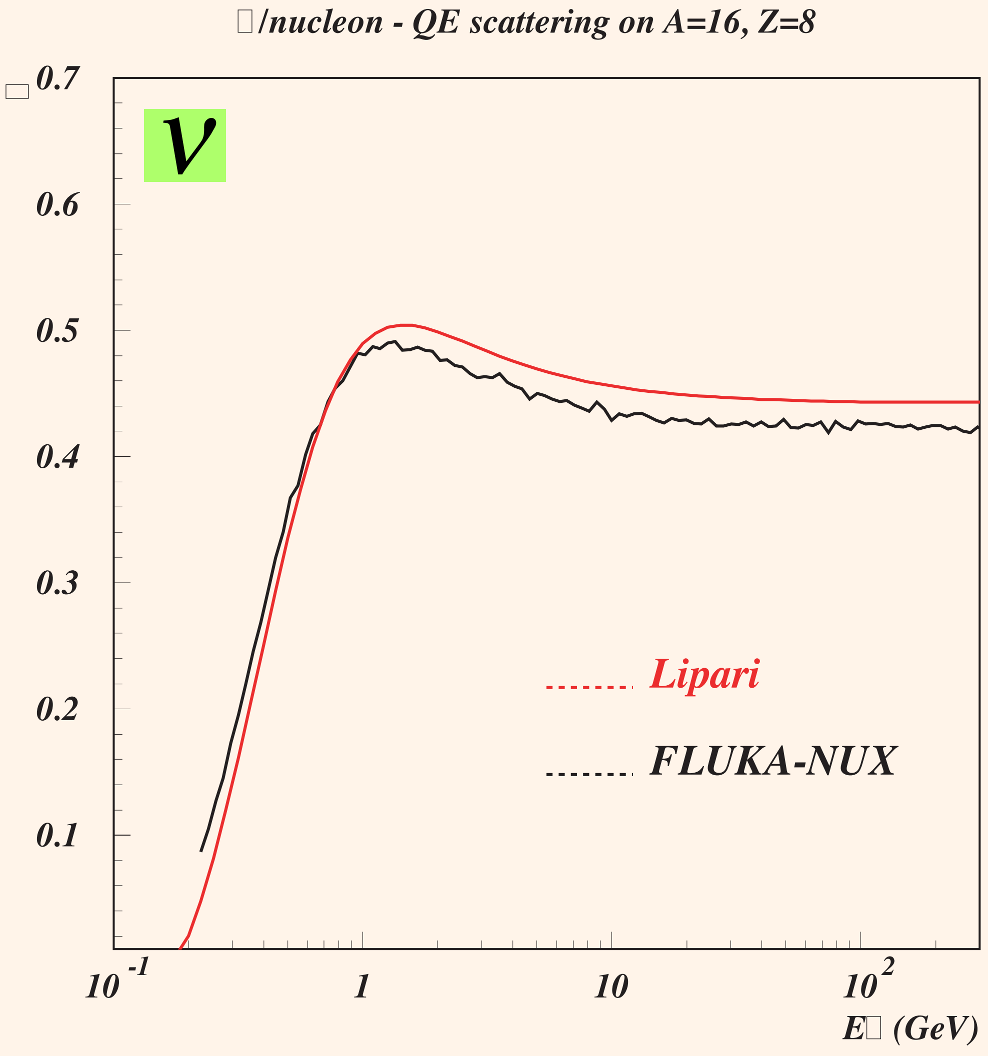


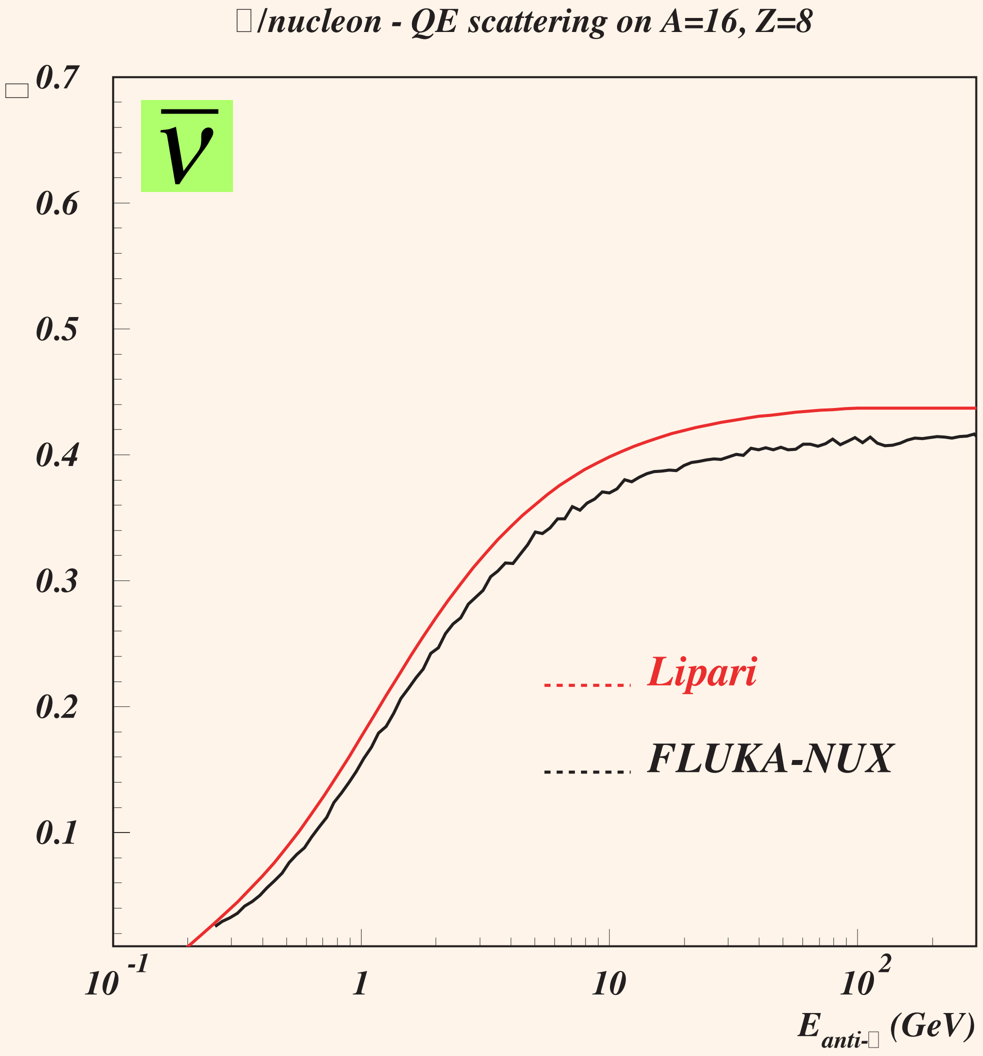


Pauli-blocking effect: expect a suppression at low Q^2

Comparison of nuclear effects on cross-section from Lipari and NUX on Oxygen.

G. Battistoni





G. Battistoni

Comparison NUX and Lipari(98)
Event rates per kt-yr
$0.1<E_\nu<100$ GeV at Kamioka using FLUKA3D flux

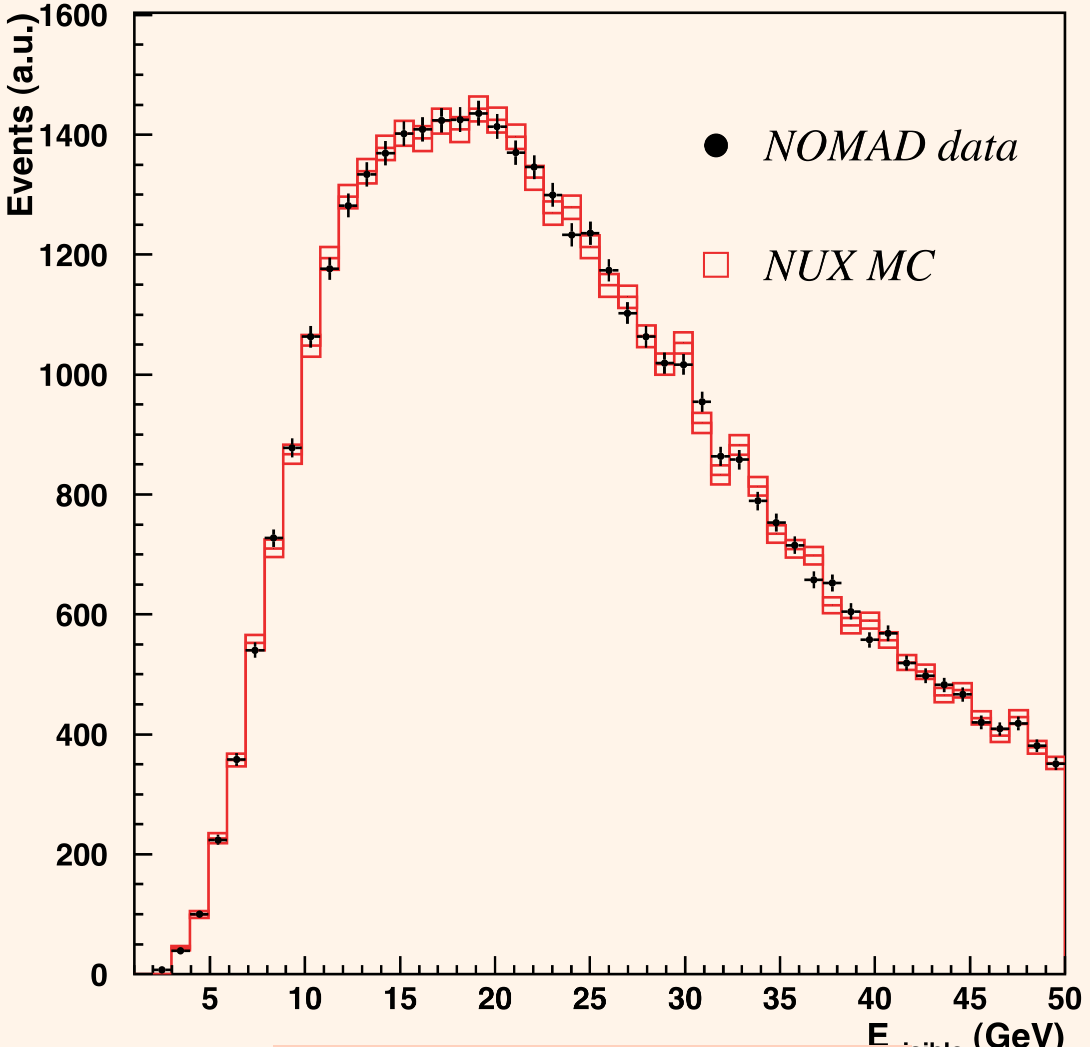
NUX	CC	NC	QE	inelastic
ν_e	44.9	6.3	25.8	19.1
anti ν_e	12.1	2.3	5.7	6.4
N_μ	81.6	14.7	43.9	37.7
anti ν_μ	25.1	5.9	12.1	13.0

Lipari	CC	NC	QE	RES	DIS	DIS+ RES	NC	NC-DIS
ν_e	39.5	5.7	21.9	8.3	9.2	17.5	2.9	2.9
anti ν_e	11.7	2.3	6.2	3.0	2.5	5.5	1.3	1.0
ν_μ	74.3	12.7	39.9	13.6	20.9	34.5	5.7	7.1
anti ν_μ	26.1	5.9	13.4	6.1	6.6	12.7	3.0	2.9

Comparison with NOMAD data

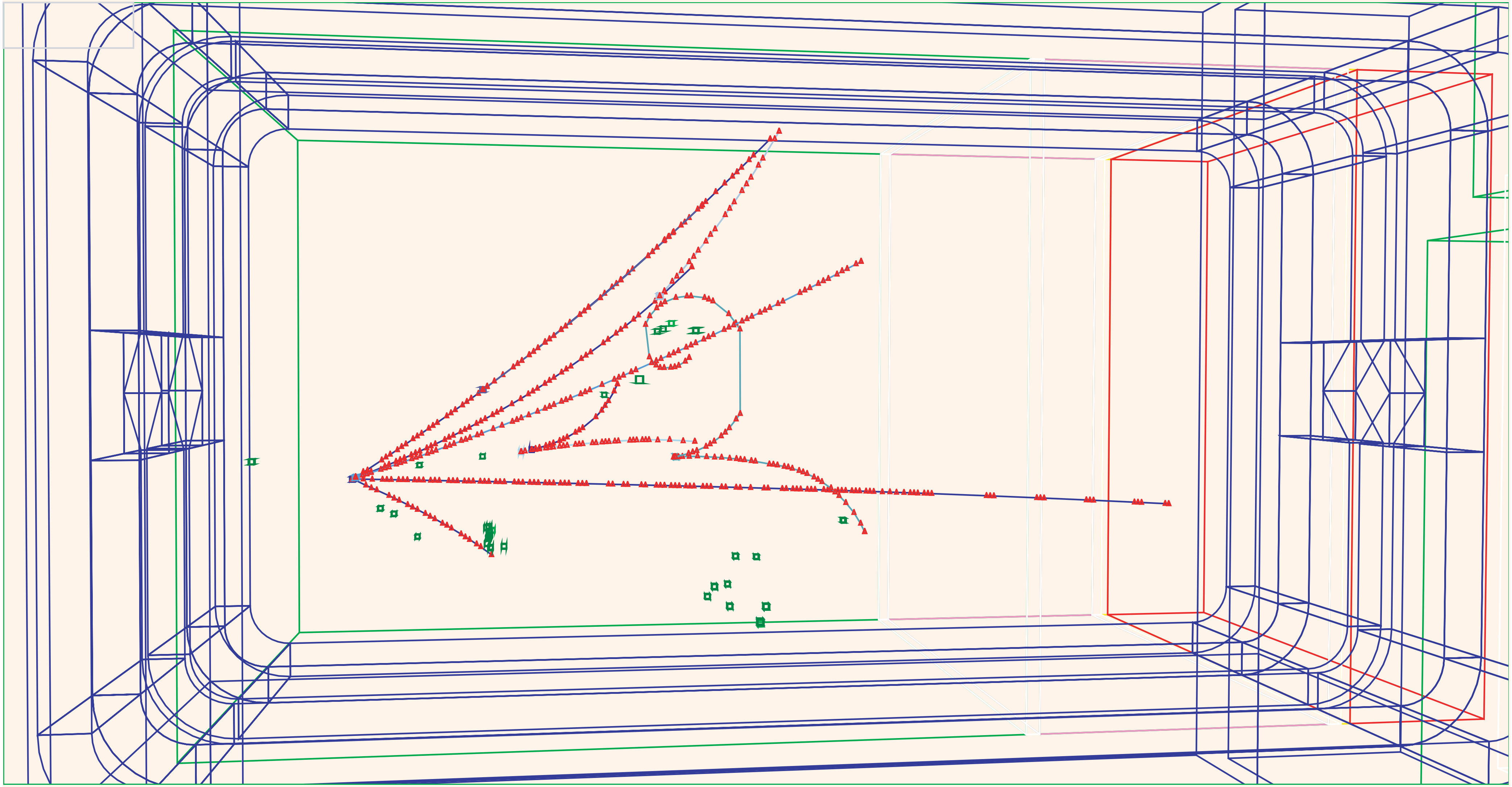
- **Concentrate on dominant ν_μ charged current sample**
- **A relatively high energy beam, events peaked around 20 GeV, 40 GeV on average**
- **NOMAD can measure all final state particles independently; use energy-flow algorithm developped for oscillation analyses.**

Reconstruct
1. Lepton
2. Recoling jet

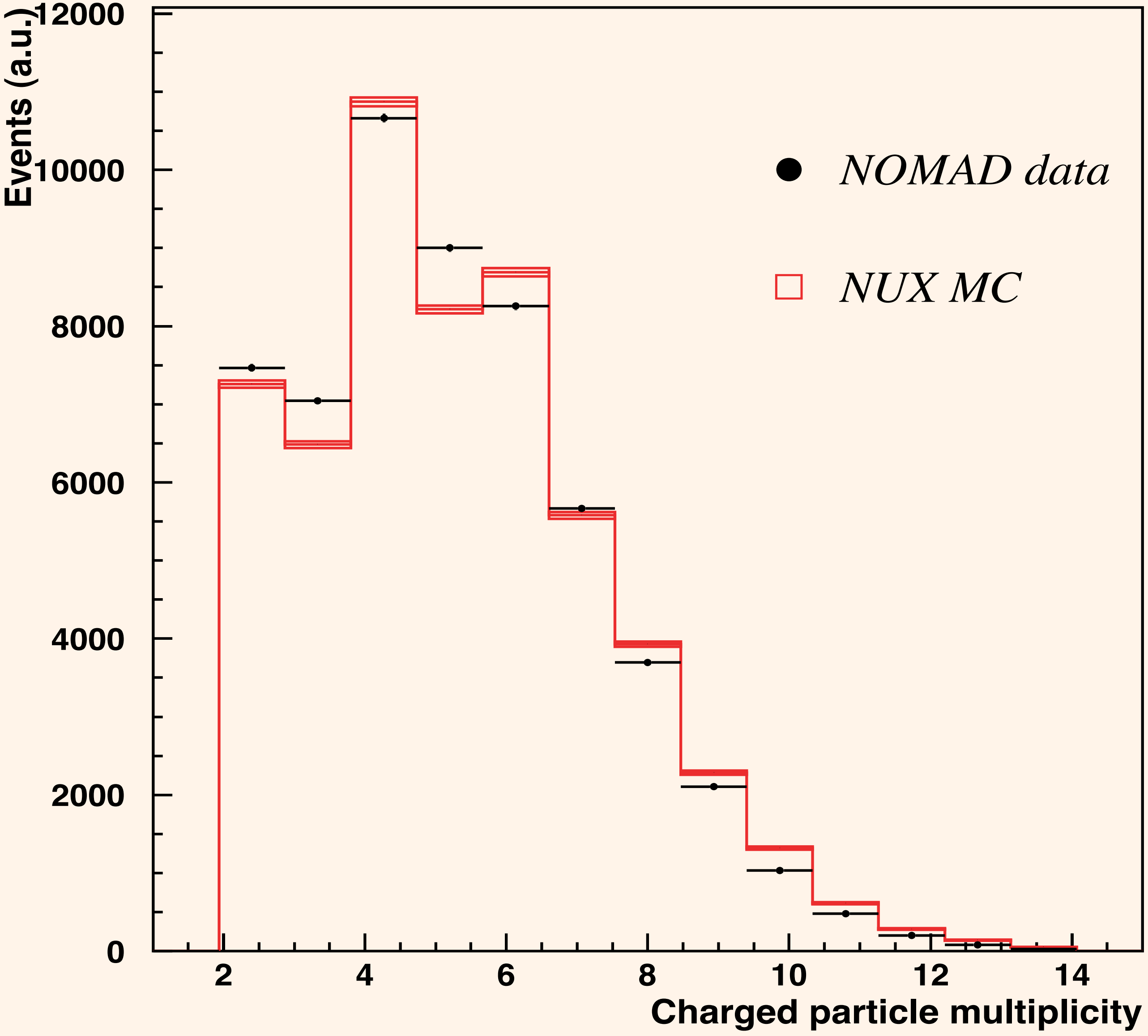


$$E_{vis} = E_{\mu} + E_{jet}$$

NOMAD Event:

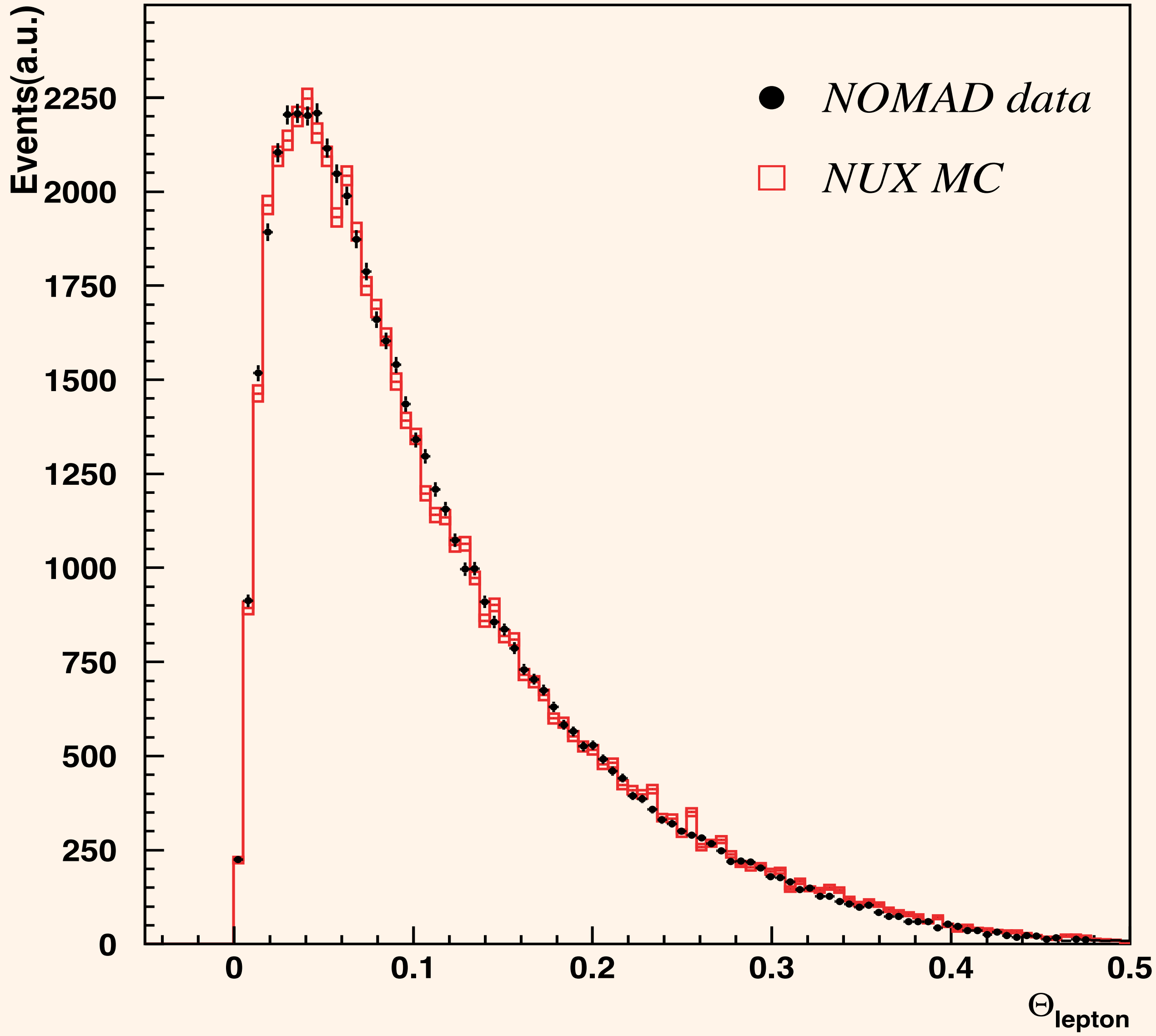


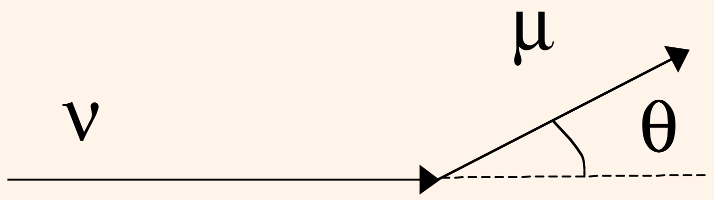
Charged multiplicity at vertex



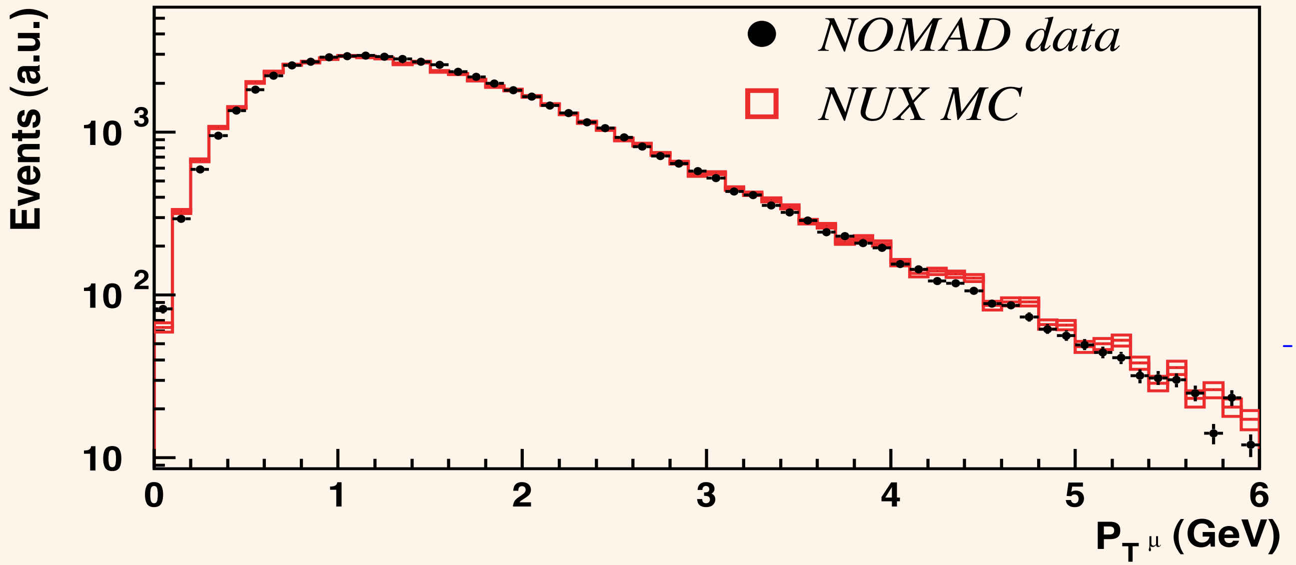
- Odd/even structure reminiscent of interactions on neutrons/protons
- Very sensitive to nuclear effects, due to charge exchange, inelastic processes, nuclear evaporation, which can produce soft tracks around the primary vertex.

Muon angle w.r.t. beam

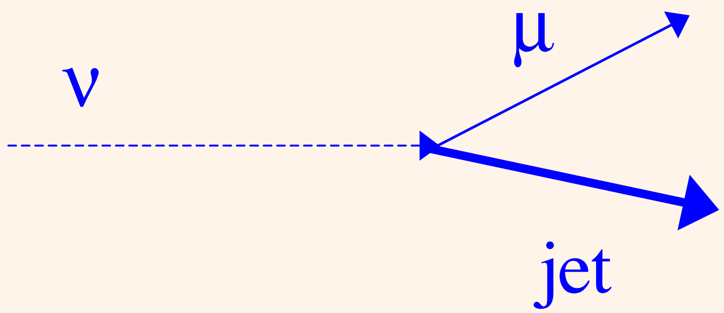


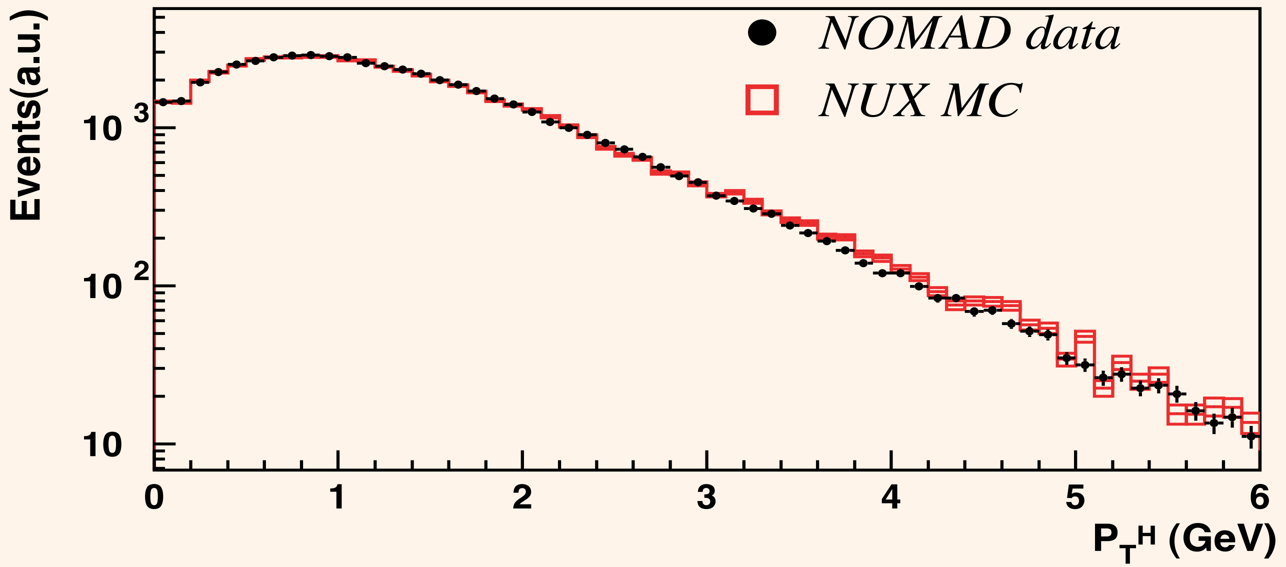


Tranverse momenta



Transverse momentum outgoing lepton

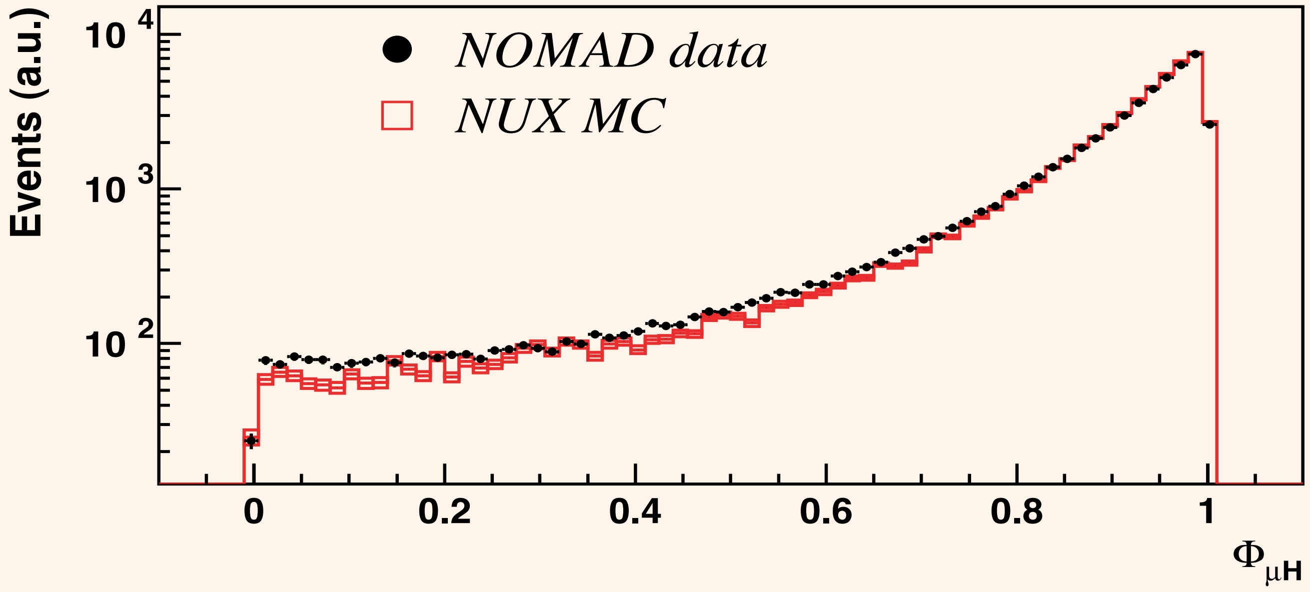


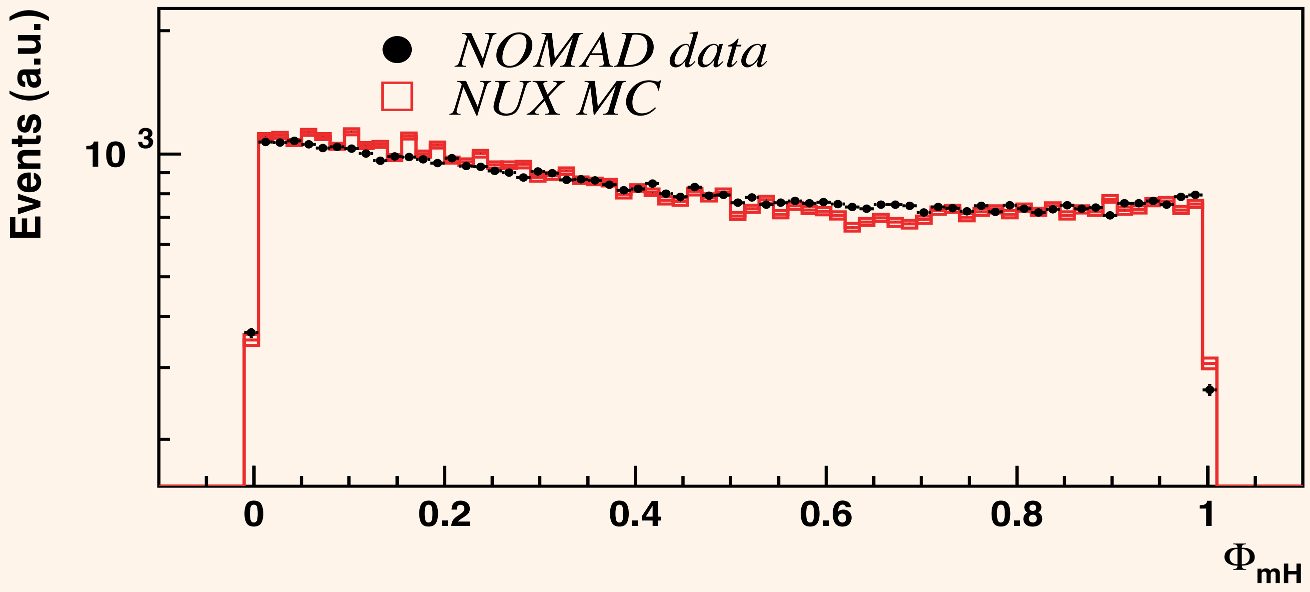


Transverse momentum hadronic jet

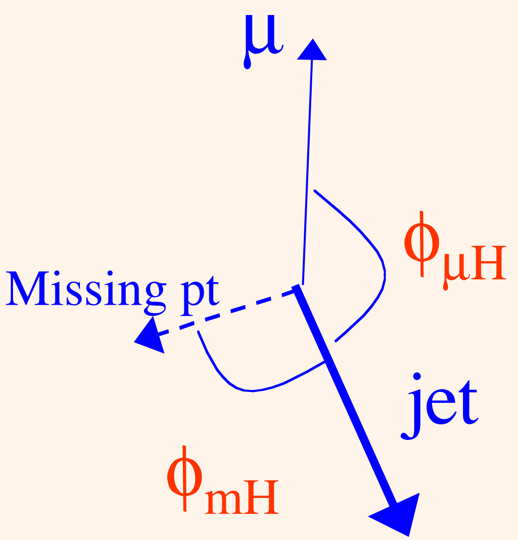
Hadronic jet most sensitive to fragmentation, nuclear effects, …

Angular correlation



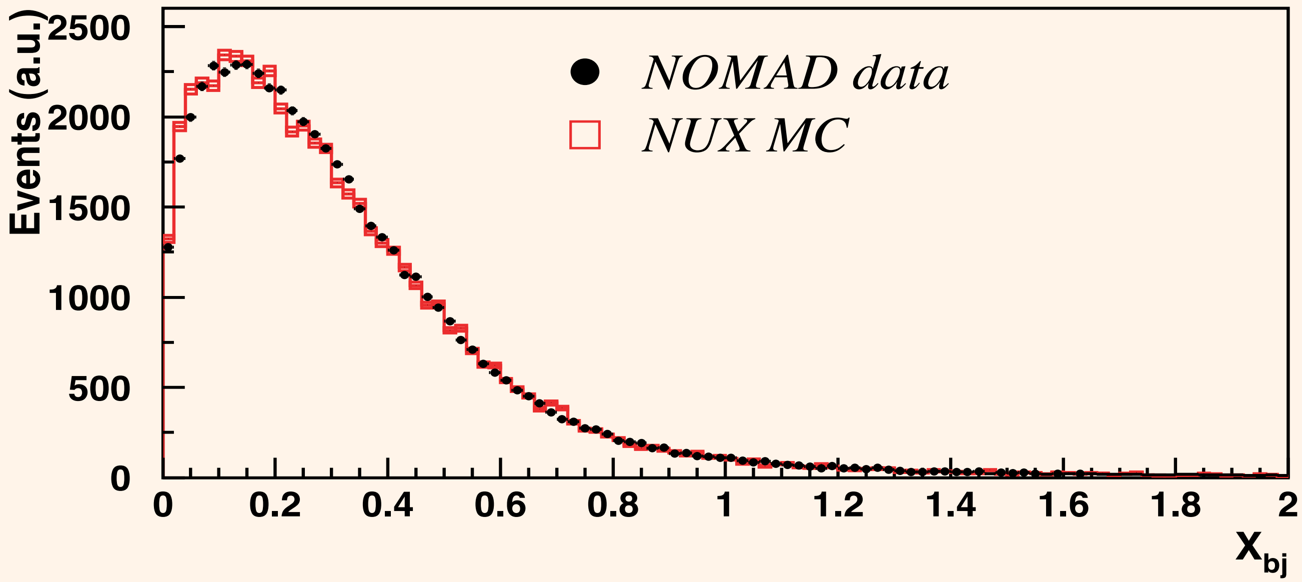


Transverse plane:



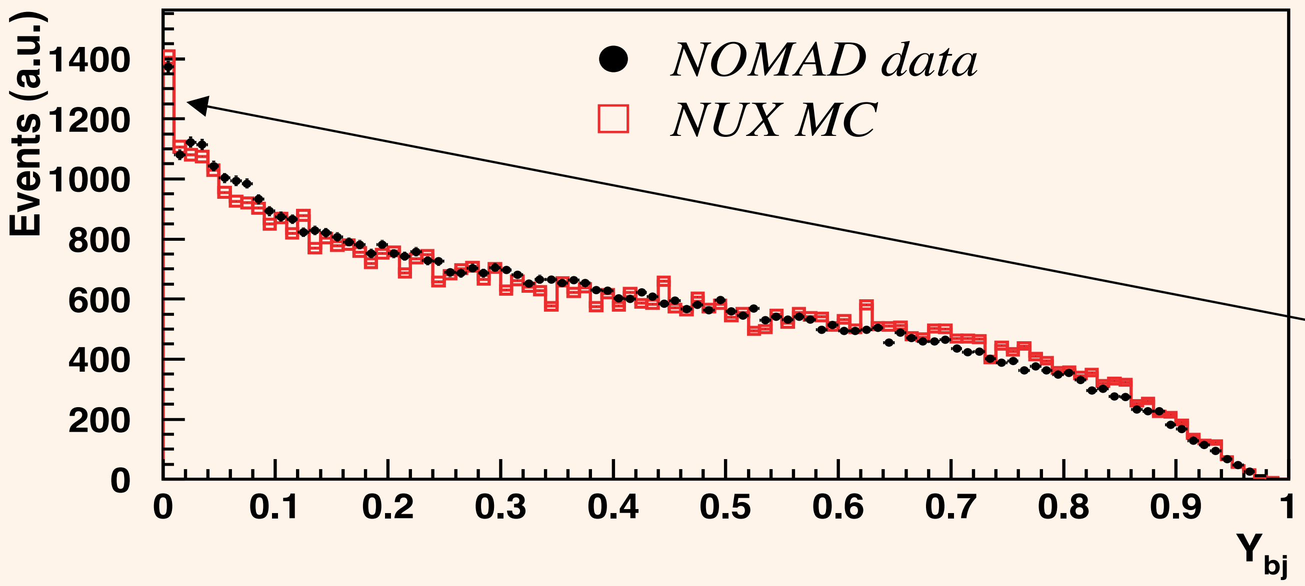
Hadronic jet direction very sensitive to fragmentation, nuclear effects, …

Scaling variables



Xbj

GRV 94 HO (DIS,NLL)

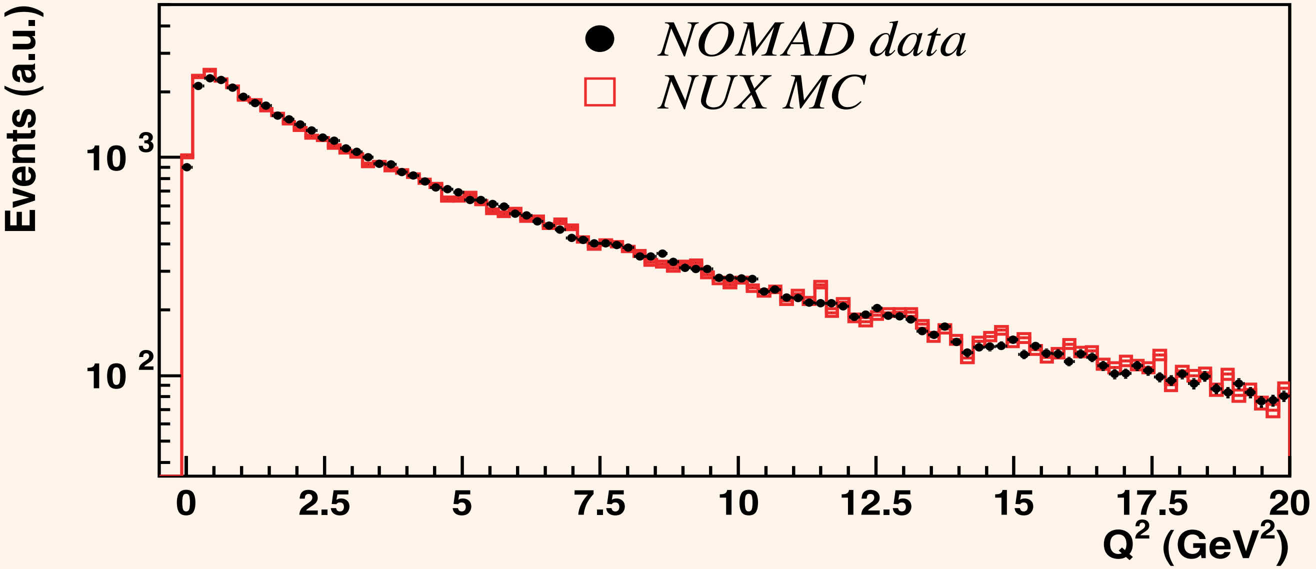


Ybj

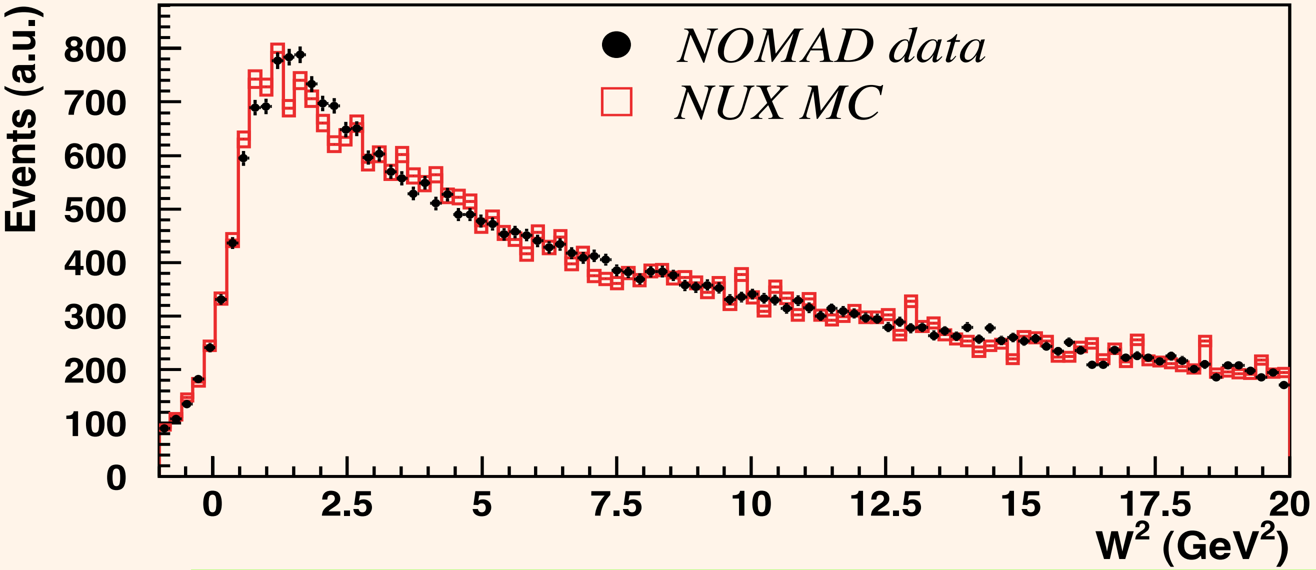
Low-y peak
well
reproduced

NUINT01, A. Rubbia, Dec 2001

Kinematical variables



Q^2



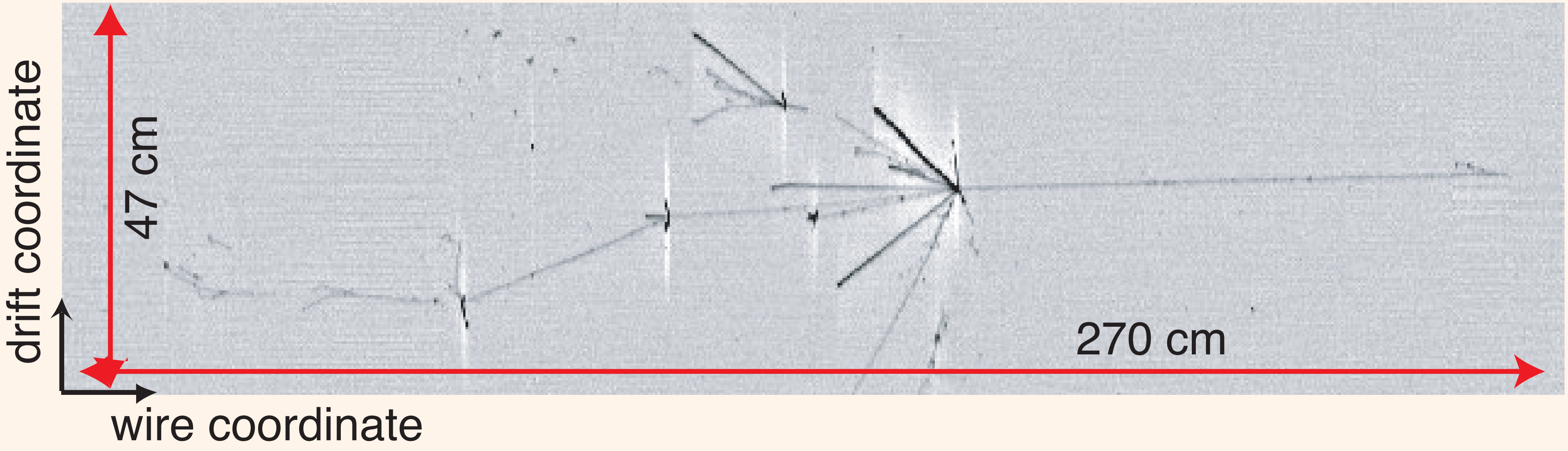
W^2

Hadronic jet invariant mass (computed from lepton and Evis)

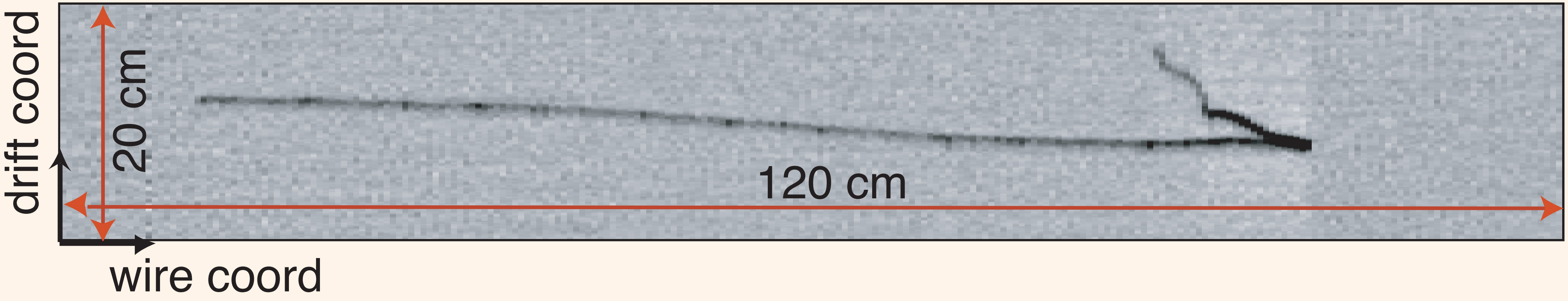
In NOMAD, we did not have the possibility to easily resolve « resonances »!

ICARUS T600 Event:

Run 308 Event 160 Collection view



Run 909 Event 21 Collection view

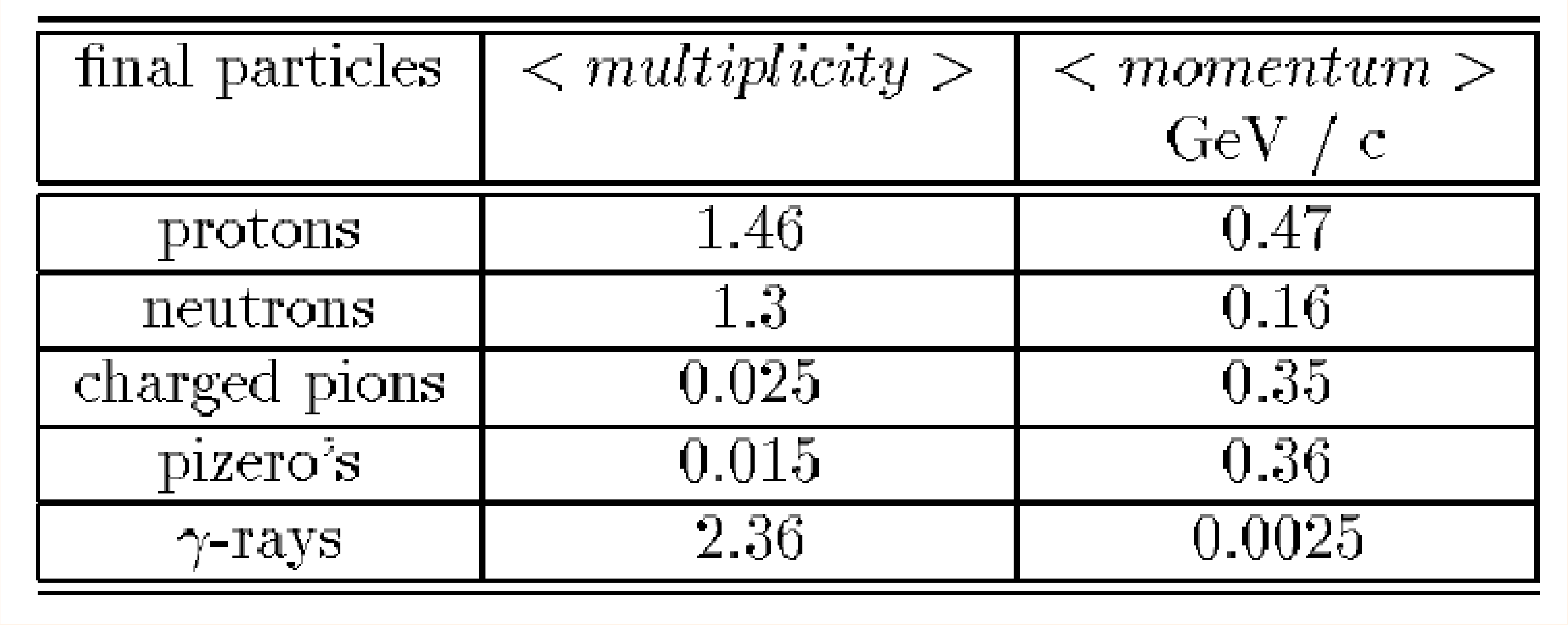


ICARUS MC study

- While waiting for data, study performance at low energy, aimed at atmospheric neutrino studies.
- We define a « QE » event as an event with
  - One lepton
  - One proton with $T_p > 150$ MeV
  - No pion with $T_\pi > 15$ MeV
- These cuts are aimed at suppressing « evaporation » nucleons.
- Similar cuts can be imposed to select proton-pion, neutron-pion final states.

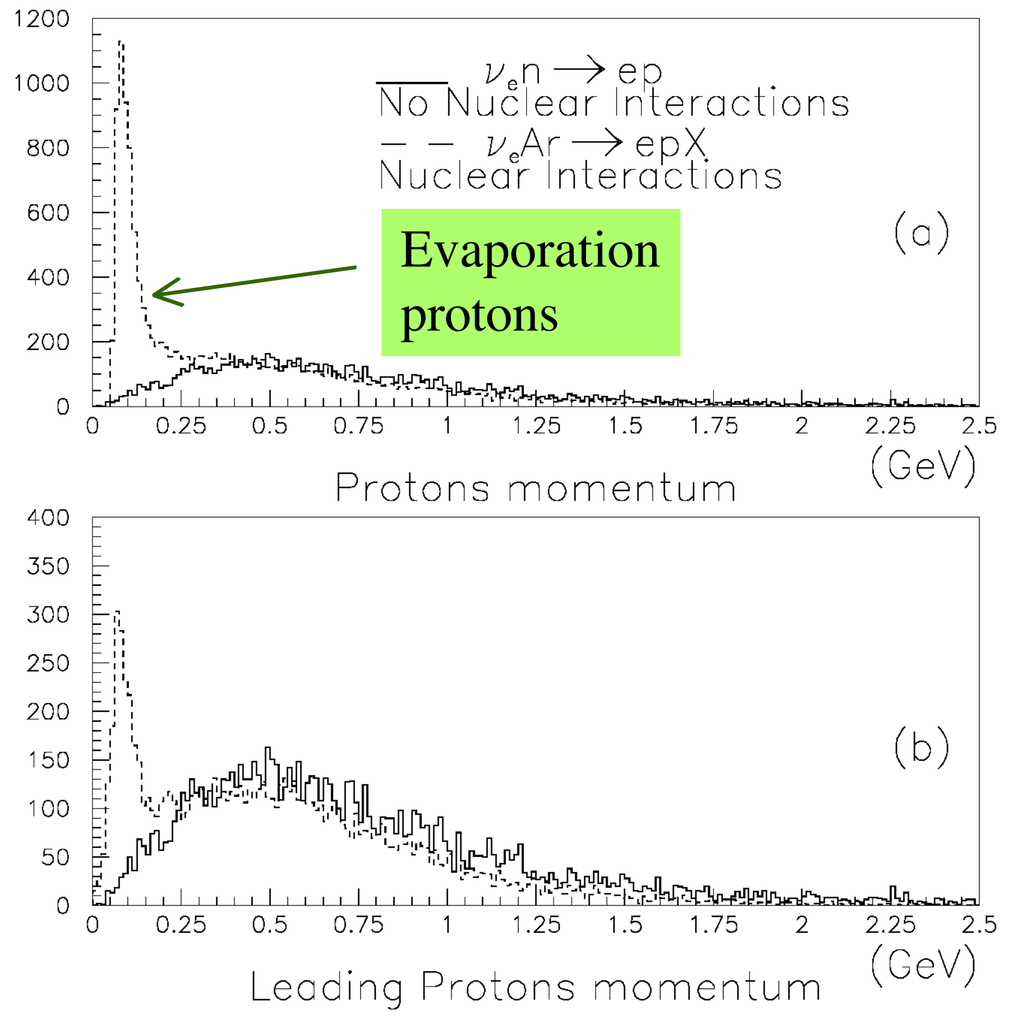
Exclusive final state in QE events

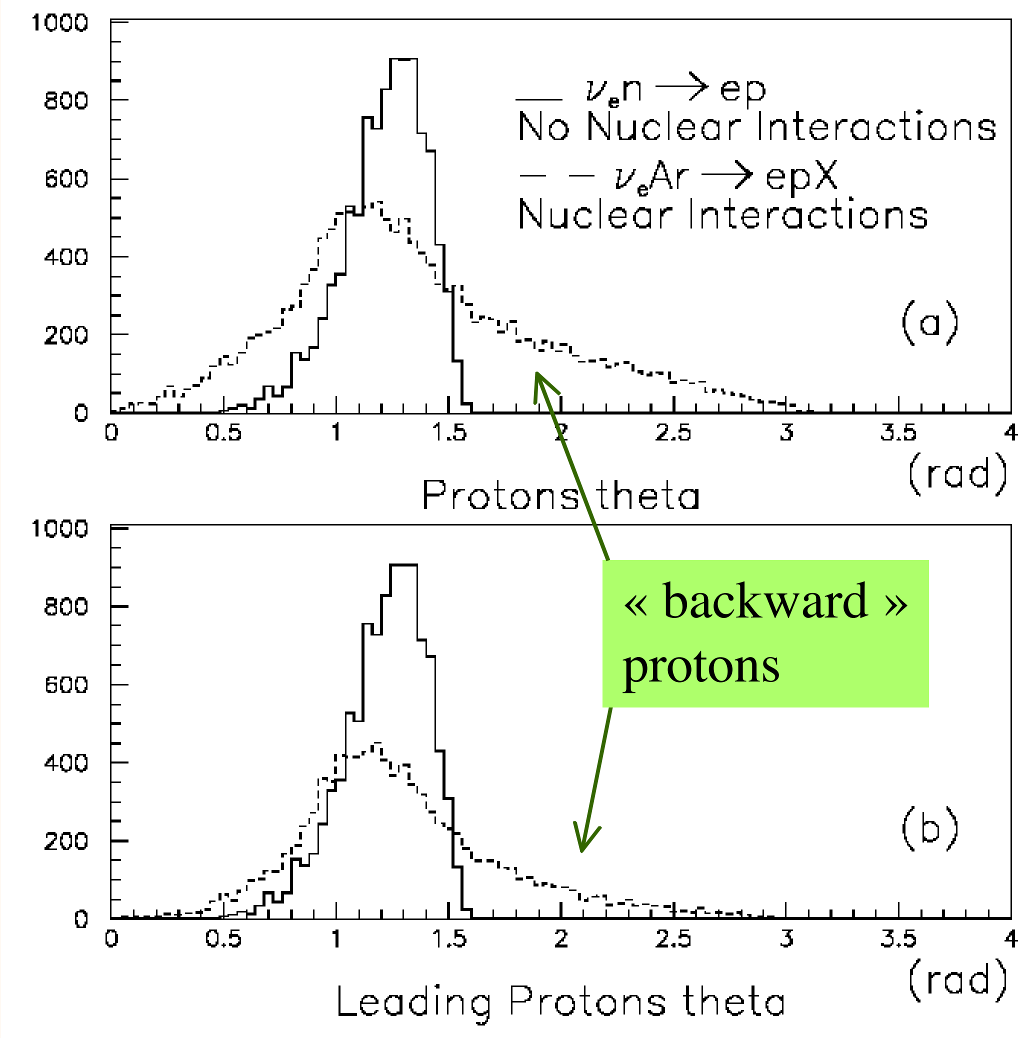
- Additional protons and neutrons from nuclear evaporation and reinteractions.
- Few pions created.



final particles	$< multiplicity >$	$< momentum >$ GeV / c
protons	1.46	0.47
neutrons	1.3	0.16
charged pions	0.025	0.35
pizero's	0.015	0.36
γ-rays	2.36	0.0025

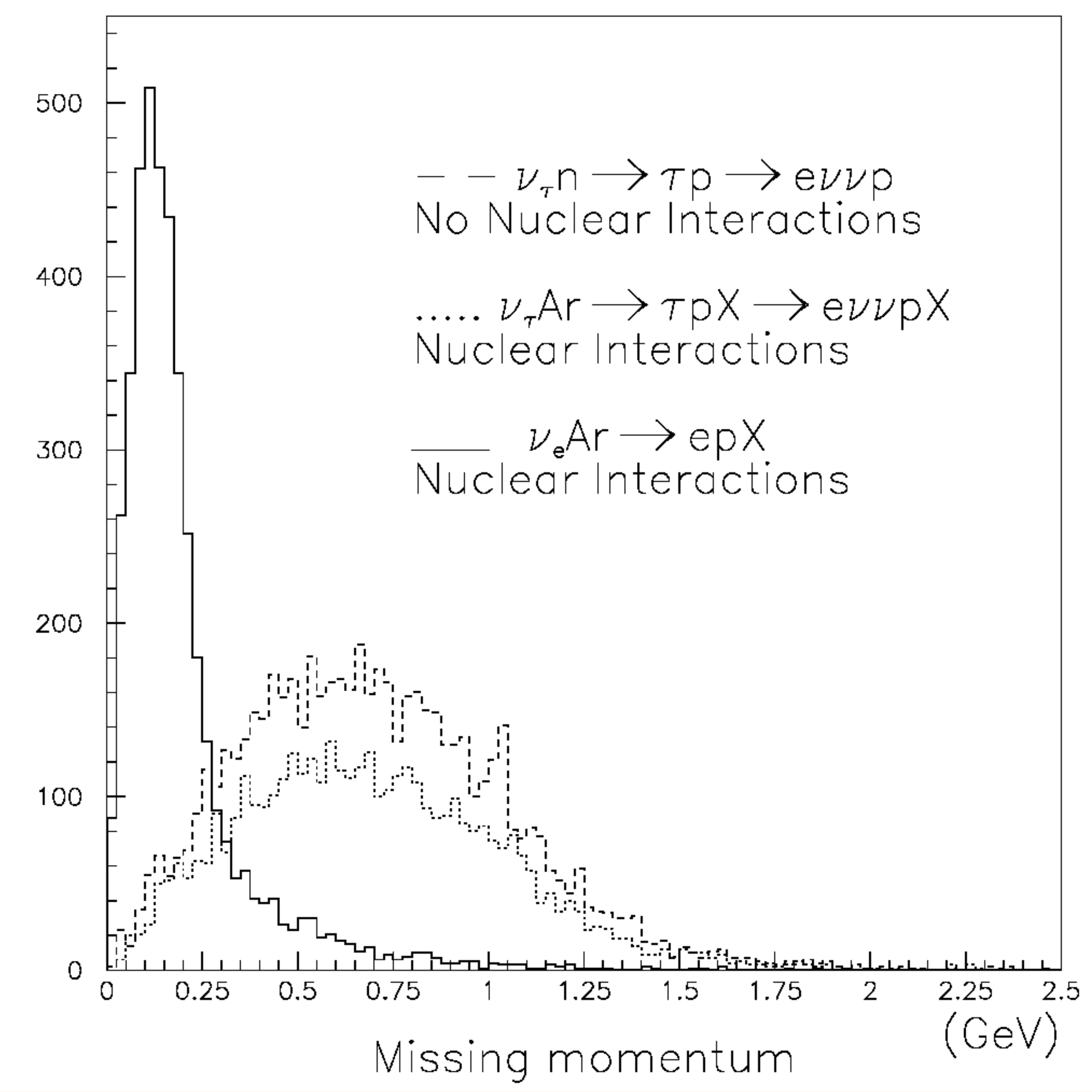
Kinematics in QE events





- **Protons directly mostly affected by Fermi motion, but also mean nuclear potential and possible reinteractions.**

Kinematical closure of QE events



- Relevant for kinematical searches of tau neutrino
- Fermi motion and reinteractions
- Introduce apparent transverse momentum since recoil nucleus not seen.

Exclusive baryon-meson (Δ) final state

- **Study generated $\Delta^{++}\rightarrow p\pi^{+}$, $\Delta^{+}\rightarrow p\pi^{0}$, and $\Delta^{+}\rightarrow n\pi^{+}$ final states before nuclear reinteractions**
- **As expected, these exclusive final states are highly affected by nuclear effects.**
  - Difficulty in « comparing » with final state in actual experiment, unless on free nucleon target.

final particles	$\Delta^{++} \rightarrow p\pi^{+}$ $< multipl. >$	$< p >$ GeV	$\Delta^{+} \rightarrow p\pi^{0}$ $< multipl. >$	$< p >$ GeV	$\Delta^{+} \rightarrow n\pi^{+}$ $< multipl. >$	$< p >$ GeV
protons	2.58	0.42	2.47	0.45	1.75	0.28
neutrons	2.94	0.16	2.47	0.20	2.98	0.38
charged pions	0.61	0.44	0.09	0.30	0.76	0.59
pizero's	0.05	0.26	0.66	0.59	0.05	0.30
γ-rays	2.19	0.0021	2.31	0.0026	2.37	0.0025

Final state « mixing »

Actual « free nucleon » state

classification	$\Delta^{++} \to p\pi^+$	$\Delta^+ \to p\pi^0$	$\Delta^+ \to n\pi^+$
"QE event"	19%	15%	10%
1 charged pion event	57%	5%	69%
1 neutral pion event	3%	62%	3%
"$\Delta^{++} \to p\pi^+$"	42%	3%	10%
"$\Delta^+ \to p\pi^0$"	2%	48%	1%
"$\Delta^+ \to n\pi^+$"	11%	0	56%
more than 1 pion	3 %	4%	5 %
no pions, > 1p with $T_p > 150$MeV	7%	5%	2%
no pions, and protons with $T_p > 60$MeV	9%	7%	9%
no pions, no protons with $T_p > 60$MeV	2%	2%	3%

Bound nucleon final states

We are hoping for more theoretical input (e.g. how to treat Δ-resonance in nuclear matter) and experimental input (possibly on different targets) to clarify situation of resonances.

Conclusion

- **NUX has so far been very successful at reproducing NOMAD data.**
- **NUX clearly suffers from lack of experimental data**
  - How could K2K and FNAL Booster data benefit us?
  - It could be possible to generate NUX-files for O, p, or other targets.
  - A new experiment with different targets in a well controlled neutrino flux would be most welcome.
- **Depending on the outcome of this workshop, one could create a NUX-Web-page if retained useful.**