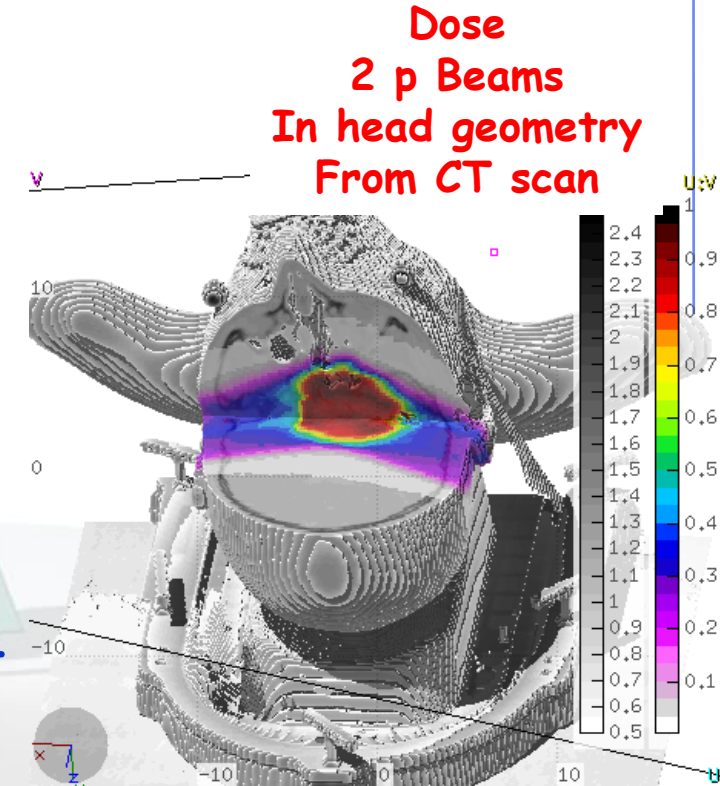
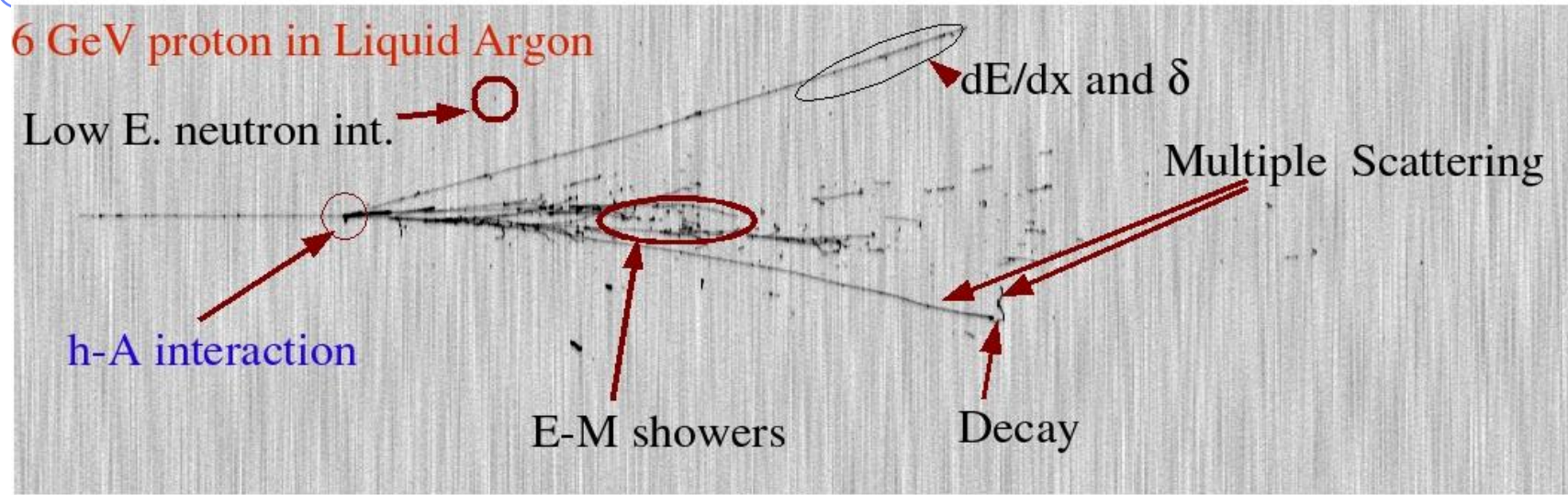




Neutrino interactions in FLUKA: NUNDIS

M. Antonello, G. Battistoni, A. Ferrari, M. Lantz, **P. Sala**, G. Smirnov

FLUKA : a multi-purpose Monte Carlo code



Developed and maintained under an INFN-CERN agreement

Copyright 1989-2015 CERN and INFN

INFN : part of **MC-INFN** (FLUKA and GEANT4)

Web Site: <http://www.fluka.org>

>8000 registered users

2 user courses /year

Neutrinos in FLUKA

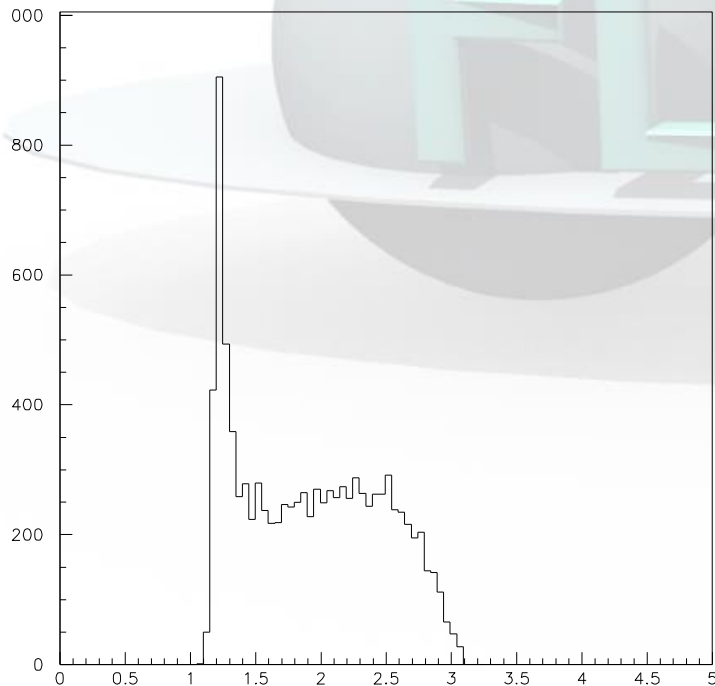
- Generators of neutrino-nucleon interactions:
 - QuasiElastic Acta Phys.Polon. B40 (2009) 2491-2505
 - Resonance CERN-Proceedings-2010-001 pp.387-394.
 - DIS
- Embedded in FLUKA nuclear models for Initial State and Final State effects
- Only for Argon: absorption of few-MeV (solar) neutrinos on whole nucleus
- Elastic scattering on electrons - to be refreshed
- Products of the neutrino interaction can be directly transported in the detector (or other) materials
- Used for all ICARUS simulations/publications

Quasi Elastic

- Following Llewellyn Smith formulation
- $M_A = 1.03$, $M_V = 0.84$
- Lepton masses accounted for
- Polarization of the outgoing lepton is calculated (and used in lepton decay) according to Albright-Jarlskog *
- * later applied also to leptons produced in RES/DIS

Resonance production

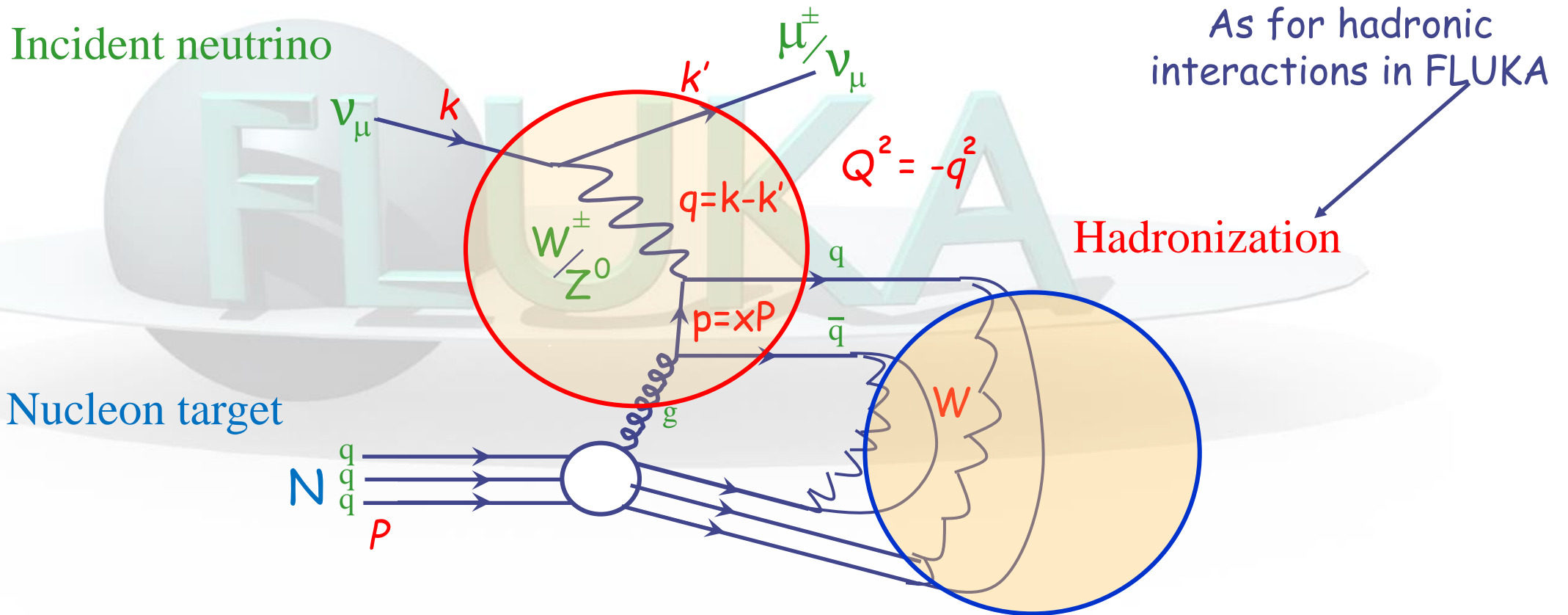
- From Rein-Sehgal formulation
- Keep only Δ production
- No non-resonant background term, assuming that the non-resonant contribution comes from NunDIS
- **TRANSITION** from RES to DIS: linear decrease of both σ as a function of W



Hadronic mass distribution for ν_μ CC on p at 5 GeV

DIS (NUNDIS)

FLUKA hadronization and nuclear interactions work well independently of primary interaction vertex



Sample x and Q^2 from double differential cross sections

$$\frac{d^2\sigma}{dx dQ^2} = \frac{d^2\sigma}{dx dy} \cdot \frac{dy}{dQ^2} = \frac{d^2\sigma}{dx dy} \cdot \frac{1}{2ME_\nu x}$$

$$\frac{d^2\sigma}{dx dy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_{W/Z}^2)^2} \sum_{i=1}^5 A_i(x, y, E_\nu) F_i(Q^2, x)$$

Structure functions $F_i(Q^2, x)$

$$F_2^{\nu p}(Q^2, x) = 2x[d + \bar{u} + s + \bar{c}]$$

$$xF_3^{\nu p}(Q^2, x) = 2x[d - \bar{u} + s - \bar{c}]$$

Callan-Gross relation: $F_1 = \frac{F_2}{2x}$

To be updated to

$$2xF_1(Q^2, x) = F_2(Q^2, x) \frac{1 + 4M^2 x^2 / Q^2}{1 + R(Q^2, x)}$$

Albright-Jarlskog relations:

$$F_4 = 0,$$

$$F_5 = \frac{F_2}{x}.$$

$$A_1 = y \left(xy + \frac{m_\ell^2}{2ME_\nu} \right)$$

$$A_2 = 1 - y \left(1 + \frac{Mx}{2E_\nu} \right) - \frac{m_\ell^2}{4E_\nu^2}$$

$$A_3 = \pm y \left[x \left(1 - \frac{y}{2} \right) - \frac{m_\ell^2}{4ME_\nu} \right]$$

$$A_4 = \frac{m_\ell^2}{2ME_\nu} \left(y + \frac{m_\ell^2}{2ME_\nu x} \right)$$

$$A_5 = -\frac{m_\ell^2}{ME_\nu}$$

Quark dependence $q_i(Q, x)$ determined from Parton Distribution Functions (PDFs)

GRV94	Glück et al., Z. Phys. C67 (1995) 433.
GRV98	Glück et al., Eur. Phys. J. C5 (1998) 461.
BBS	Bourelly et al., Eur. Phys. J. C23 (2003) 487.
CTEQ	J. High Energy Phys. 0207 (2002) 012.
MRST	arXiv:hep-ph/0211080.
Alekhin	Phys. Rev. D68 (2003) 014002.

DEFAULT OPTION

NUNDIS WORKS WITH THESE PDFs

More on pdfs

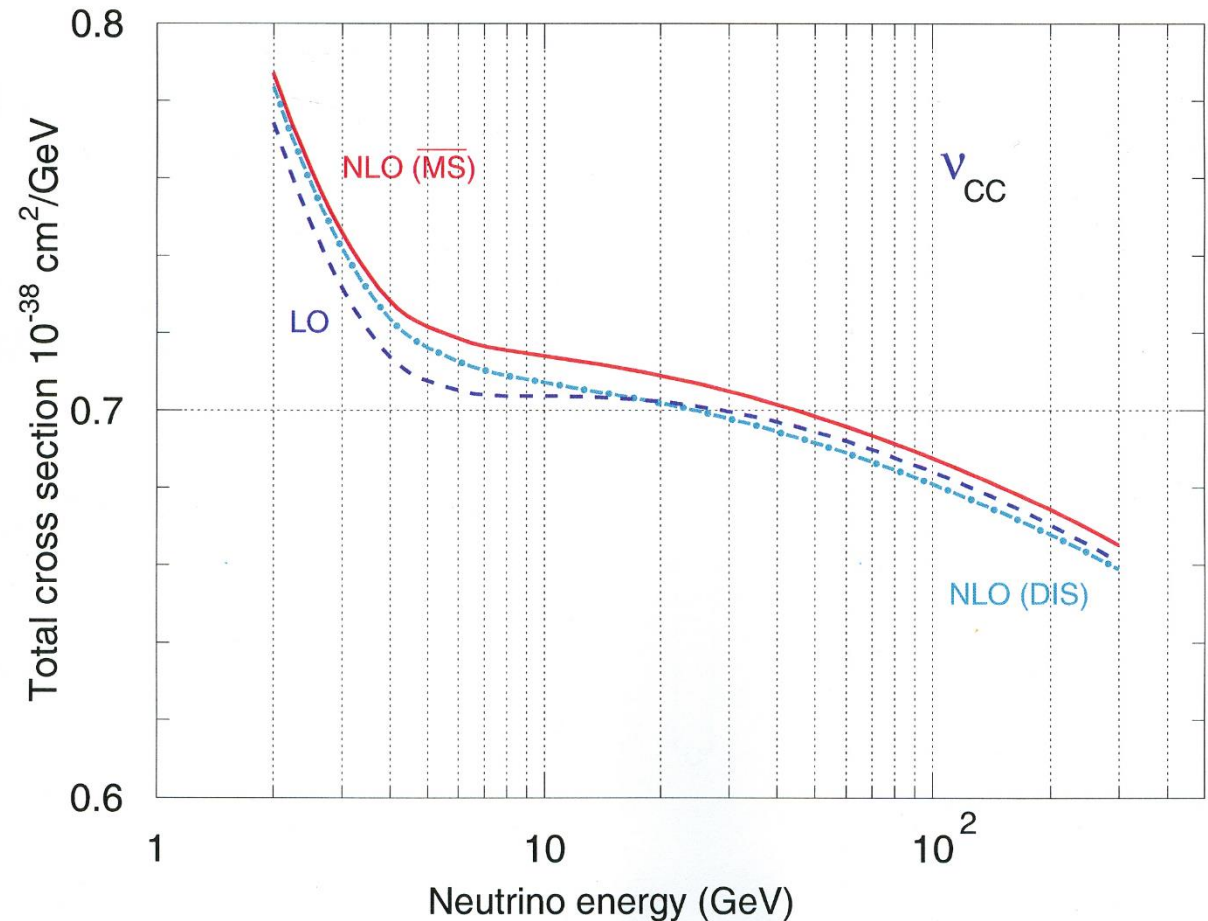
Three versions of pdf from the GRV98 analysis are included as options for evaluating nucleon structure functions

1. Leading order analyses (LO)
2. Next to leading order analyses (NLO $\overline{\text{MS}}$)
3. Next to leading order analyses (NLO DIS)

An interesting feature of the GRV98 analysis is a low threshold for the transferred, 4-momentum, $Q^2 = 0.8 \text{ GeV}^2$

NLO (DIS) is chosen as a default option

M. Gluck, E. Reya and A. Vogt, Eur. Phys. J. C5 (1998) 461



Extrapolation from $Q^2 = 1.0 \text{ GeV}^2$ to $Q^2 = 0$

Solid lines: M. Bertini et al. 1996 (Default in NUNDIS)

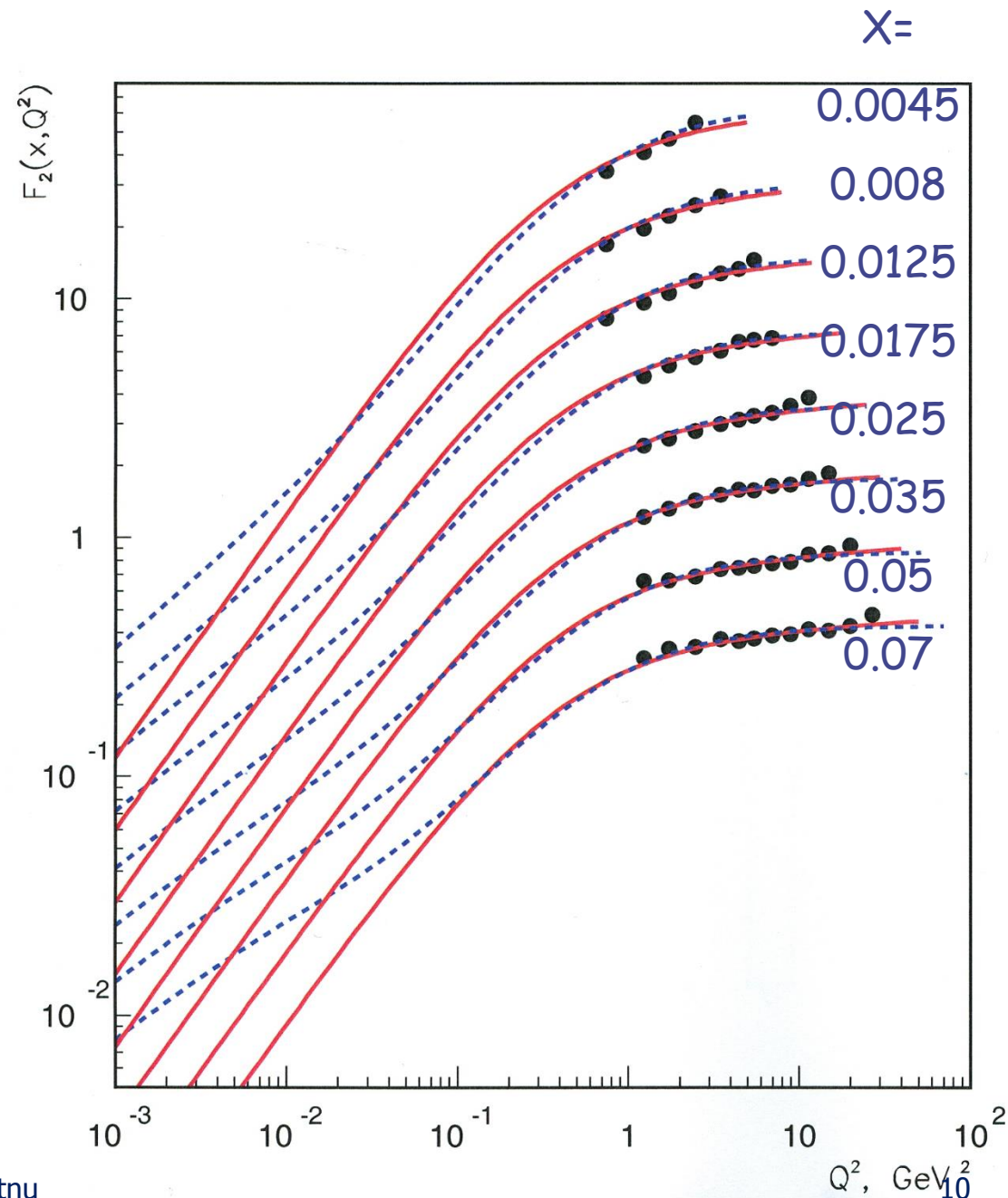
$$F_2(x, Q^2) = A \left[1 + \epsilon \ln(Q^2(1/x - 1) + M^2) \right] \ln(1 + Q^2/(Q^2 + a^2)) .$$

Dashed lines: Donnachie-Landshoff 1994

$$F_2(x, Q^2) \sim Ax^{-0.0808} \left(\frac{Q^2}{Q^2 + a} \right)^{1.0808} + Bx^{0.4525} \left(\frac{Q^2}{Q^2 + b} \right)^{0.5475}$$

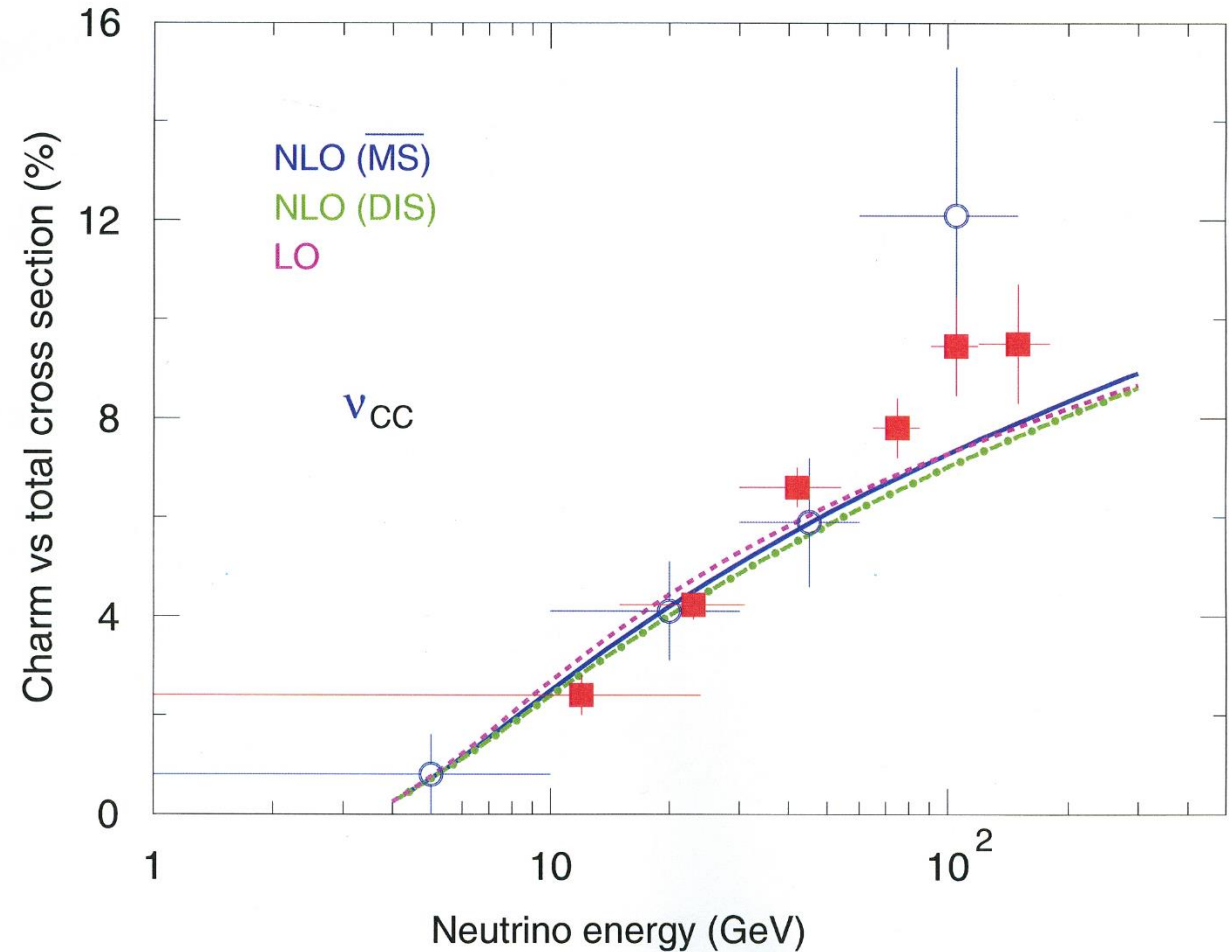
data points from NMC Collab., M. Arneodo et al., Nucl. Phys. B 483 (1997) 3-43

Data/cuves scaled for clarity, factors from 1 to 128



Charm production in neutrino interactions

- Ratio of the charm to total cross sections
- Results of NUNDIS simulation with $M_c = 1.35$ GeV (curves) and experimental data: E531 (open circles) and CHORUS-2011 (filled squares).

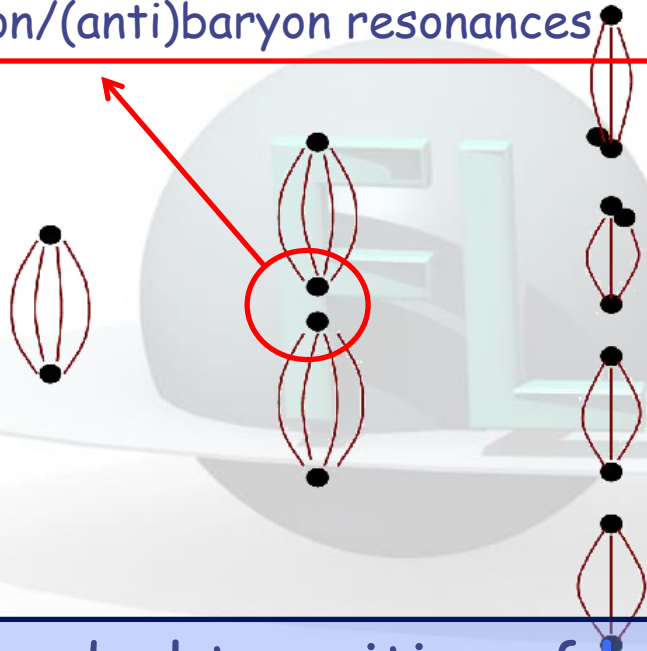


The "hadronization" of chains

An example:

Low mass chain: just 2-3 meson/(anti)baryon resonances

z
 $1/z$



$u\bar{d}$
 $d\bar{u}$
 $\bar{u}u\bar{d}$
 udd
 $u\bar{s}$
 $s\bar{d}$
 $u\bar{d}$
 $q\bar{q}$
 $q\bar{q}$
 \dots
 $d\bar{u}$

In FLUKA:

- Assumes chain universality
- Fragmentation functions from hard processes and $e+e-$ scattering
- Transverse momentum from uncertainty considerations
- Mass effects at low energies

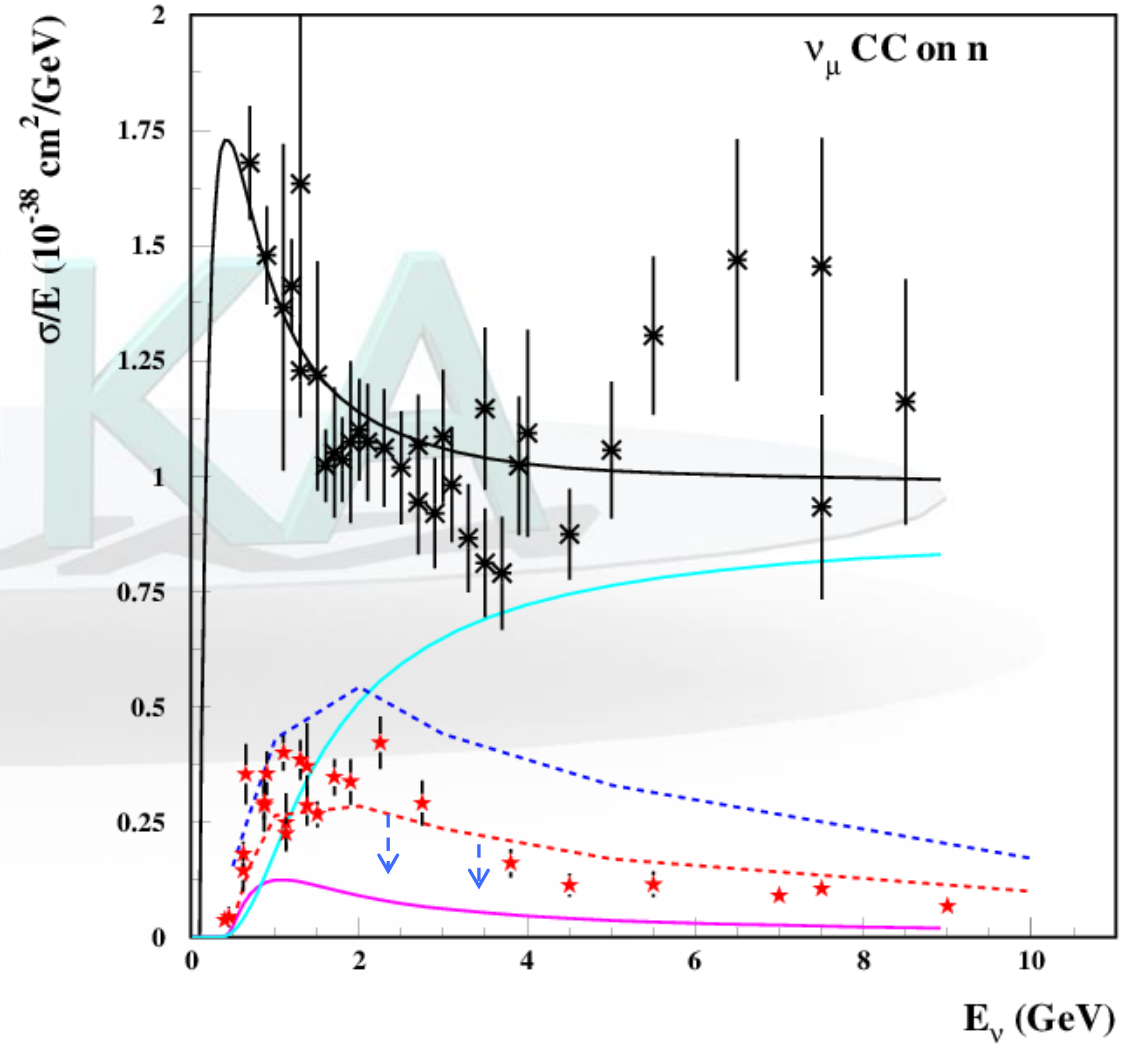
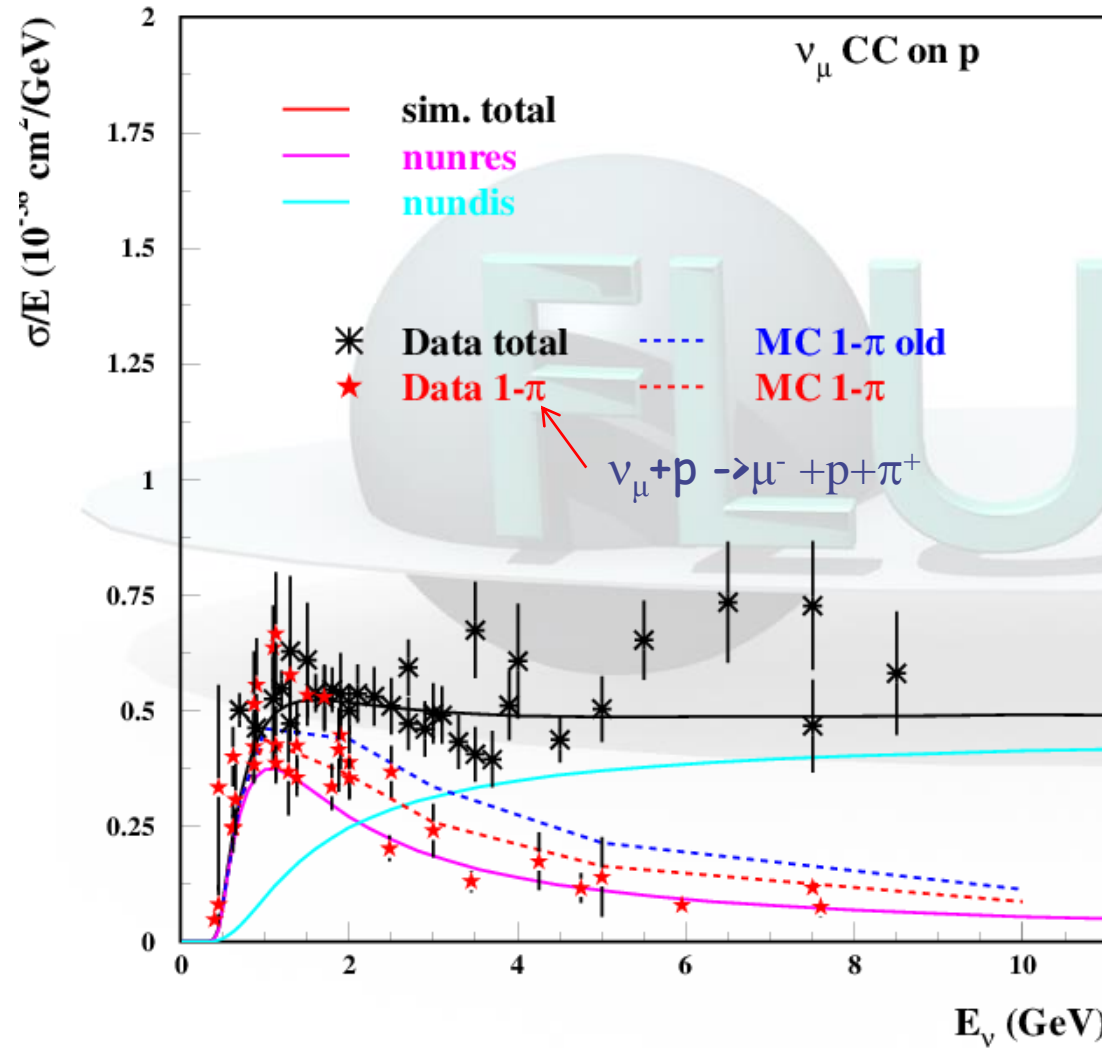
The same functions and (few) parameters for all reactions and energies

NEW! gradual transition of low energies chains to "phase space explosion" constrained in p_T , including baryons, mesons, resonances.

- From ν DIS :
 - One quark-diquark chain if interaction of valence quark
 - One quark-diquark plus one $q-q\bar{q}$ chain if int on sea quark

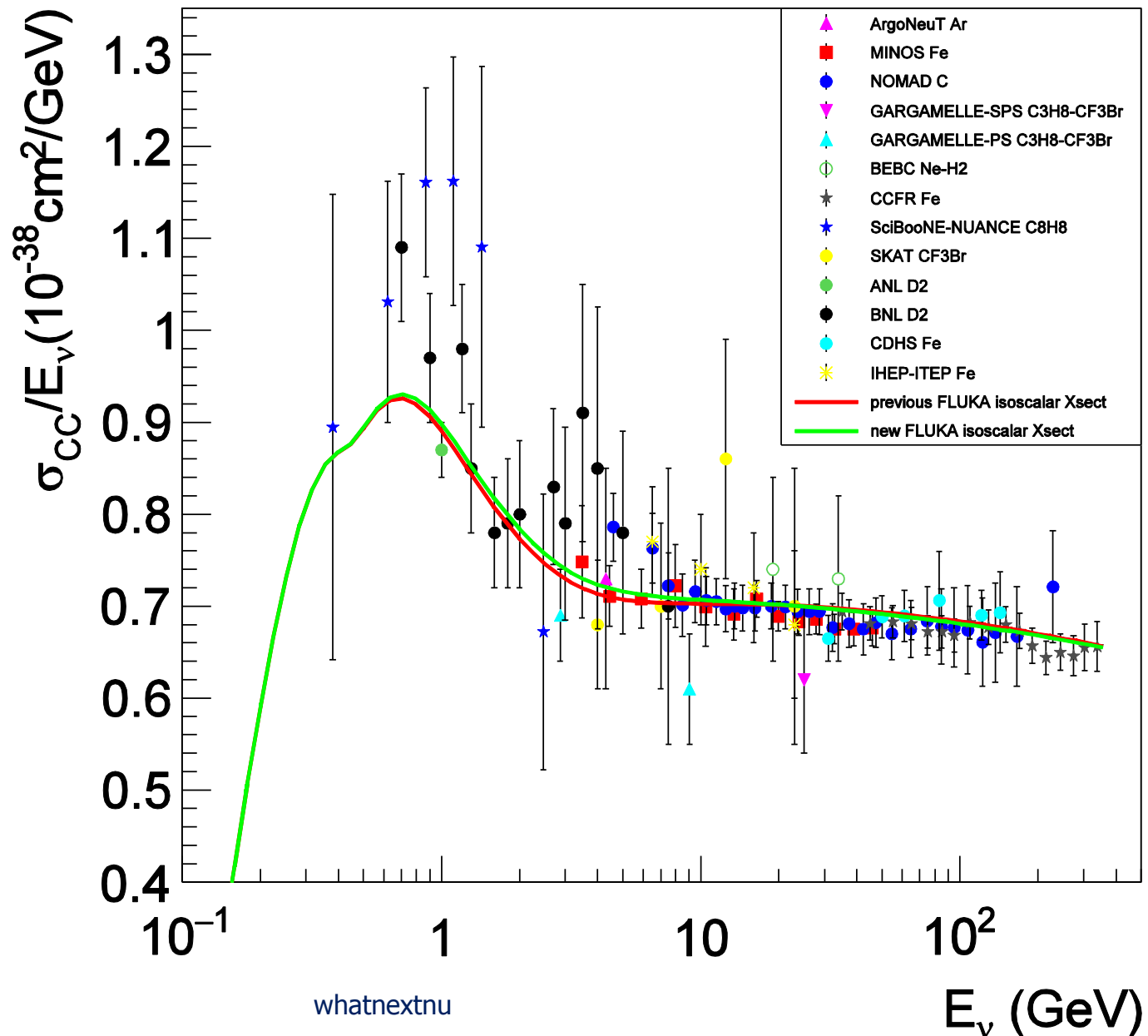
Low energy and single pion

New *low-mass chain treatment* → improvements in the RES-DIS transition

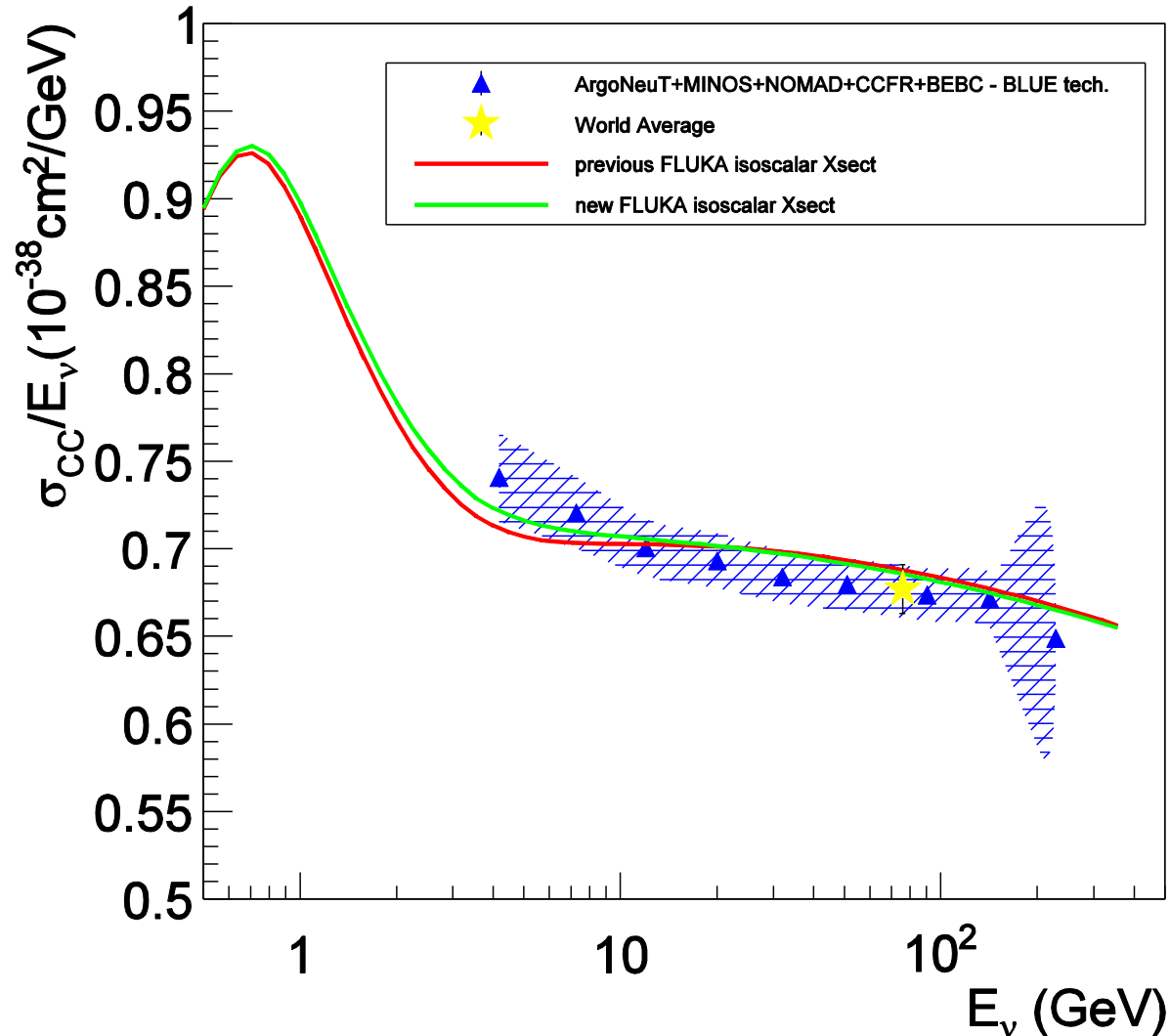


Comparison with data on total cross section

Isoscalar
 ν_μ - Nucleon total
CC cross section
Fluka (lines) with
two pdf options
Vs
Experimental data



Same, with evaluation of data systematics



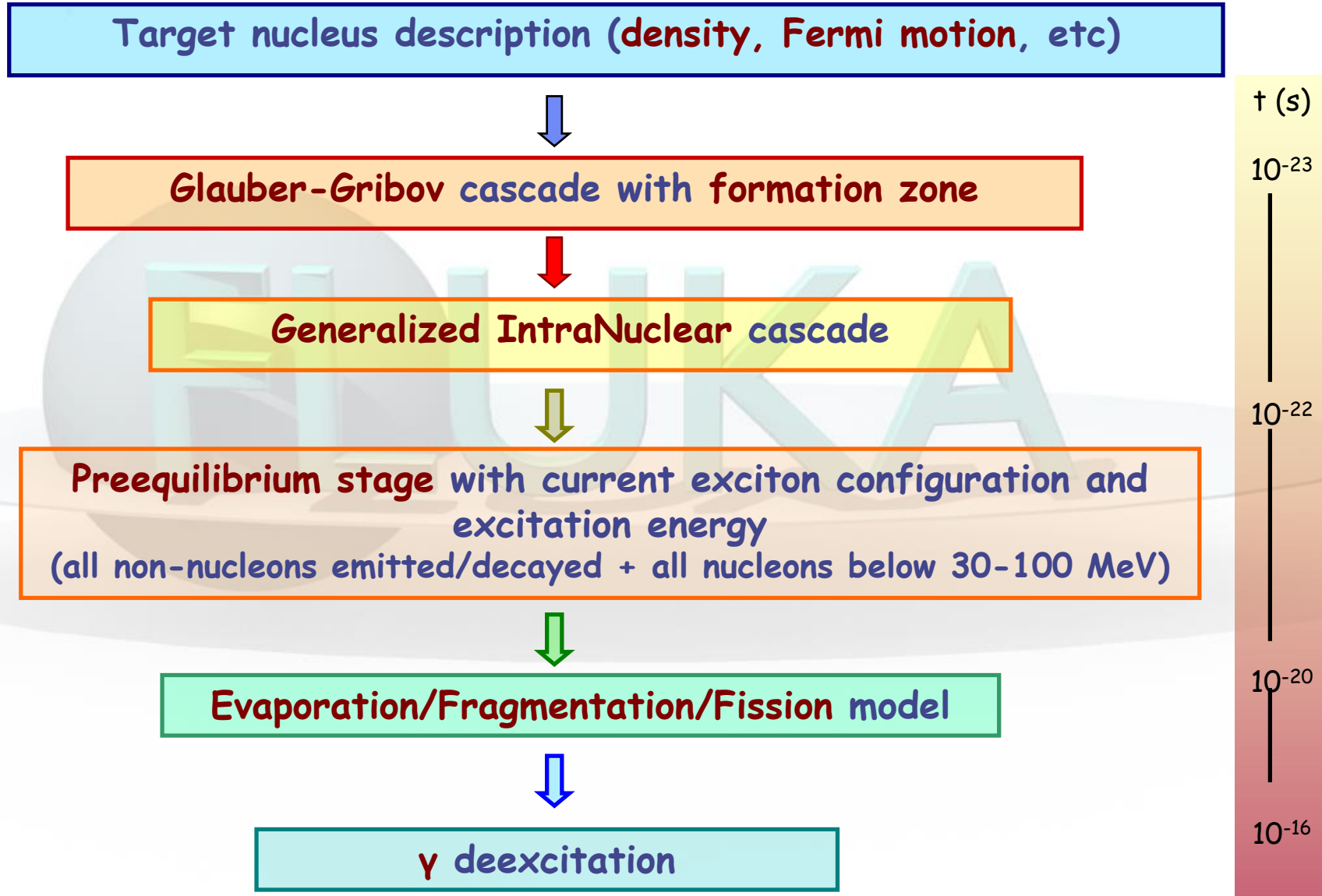
Work in progress: Attempt to compare with a combined estimate from available data and relative systematic error, properly accounting for correlations

Focus on the CNGS energy range (5-30 GeV)

Recent experiments (like MINOS, NOMAD, CCFR 1997): measure the **shape** of neutrino flux, and get the **Absolute normalization** from **Old measurements** at high energy, performed using Narrow Band Beams (CCFR-E701 / CCFRR-E616 / CDHS) or Wide Band Beams (GARGAMELLE / BEBC)

→ Common systematic errors

Nuclear interactions in FLUKA: the PEANUT model

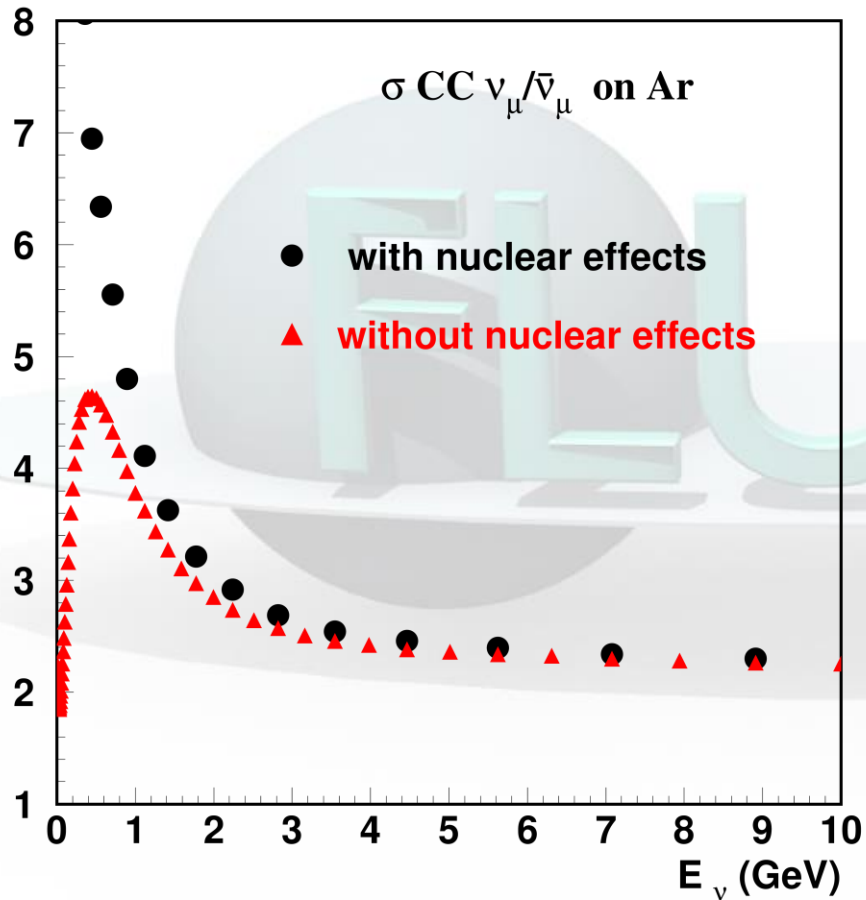


(Generalized) IntraNuclear Cascade

- Primary and secondary particles moving in the nuclear medium
- Target nucleons motion and nuclear potential well according to the **Fermi gas model**
- Interaction probability
 $\sigma_{\text{free}} + \text{Fermi motion} \times \rho(r) + \text{exceptions (ex. } \pi)$
- Glauber cascade at higher energies
- Classical trajectories (+) nuclear mean potential (**resonant for } \pi)**
- Curvature from nuclear potential \rightarrow **refraction and reflection**
- Interactions are incoherent and uncorrelated
- Interactions in projectile-target nucleon **CMS** \rightarrow Lorentz boosts

- **Multibody absorption for } \pi, \mu^-, K^-**
- **Quantum effects** (Pauli, formation zone, correlations...)
- **Exact conservation** of energy, momenta and all additive quantum numbers, including nuclear recoil
- First **excited nuclear levels** accounted for (more in evaporation/gamma deexc)

Effect of Pauli Blocking: example



Ratio of Neutrino/antineutrino σ_{CC} vs
(a) neutrino energy

For interactions in Ar nuclei, ν_{μ}

As calculated with FLUKA

Black: full calculation

Red: simple sum of ν -N cross section

Smaller q^2 in anti-neutrino results in
higher Pauli-blocking probability

Nucleon Fermi Motion in FLUKA

- Fermi gas model: Nucleons = Non-interacting Constrained Fermions

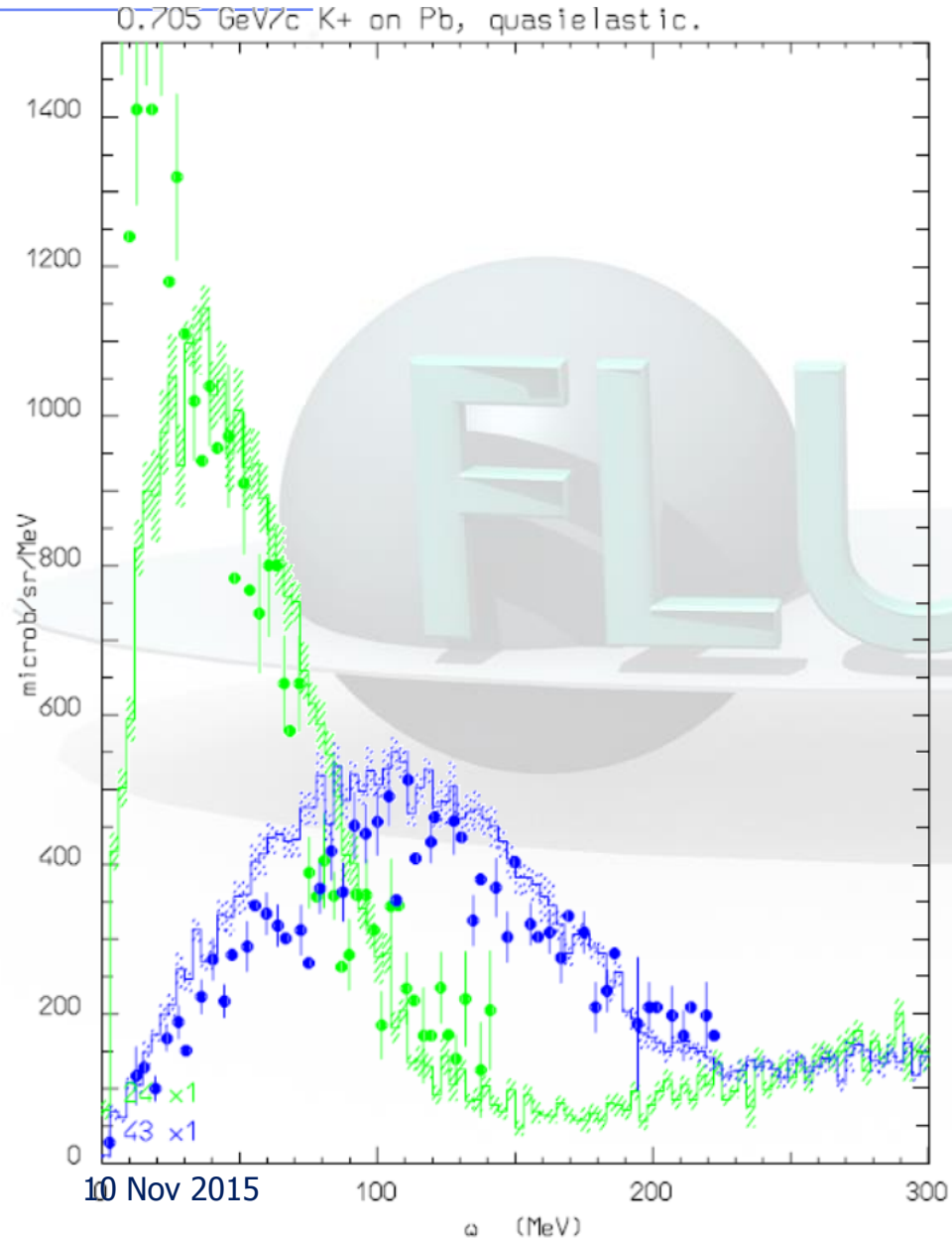
Momentum distribution

$$\propto \frac{dN}{dk} = \frac{|k|^2}{2\pi^2}$$

for k up to a (local) Fermi momentum $k_F(r)$ given by $k_F(r) = [3\pi^2 \rho_N(r)]^{\frac{1}{3}}$

- Momentum smearing according to uncertainty principle assuming a position uncertainty = $\sqrt{2}$ fm
- Nuclear density given by symmetrized Woods-Saxon for $A > 16$ and by a harmonic oscillator shell model for light isotopes
- Proton and neutron densities are different

Positive kaons as a probe of Fermi motion



K^+ K^0

No low mass $S=1$ baryons \rightarrow

weak K^+N interaction

only elastic and ch. exch. up to

≈ 800 MeV/c

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

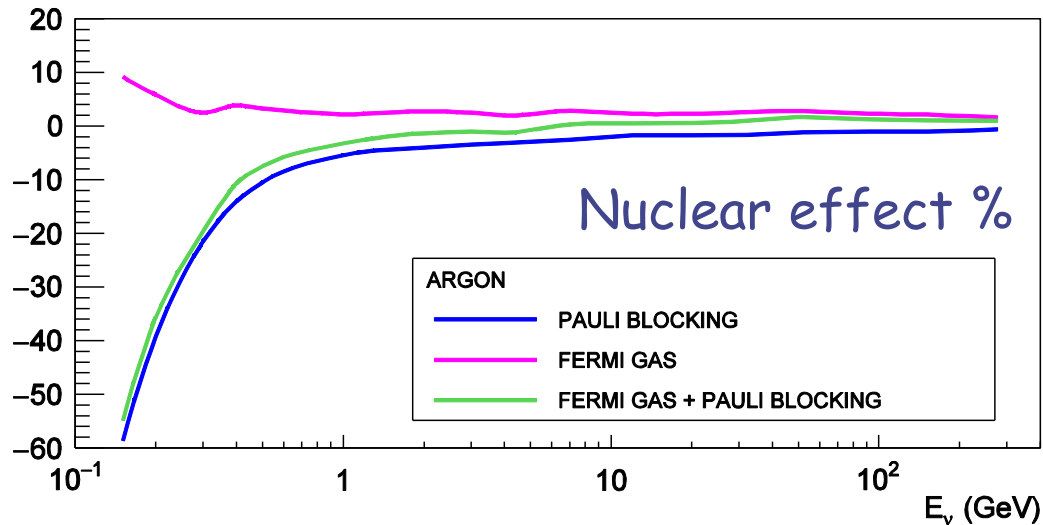
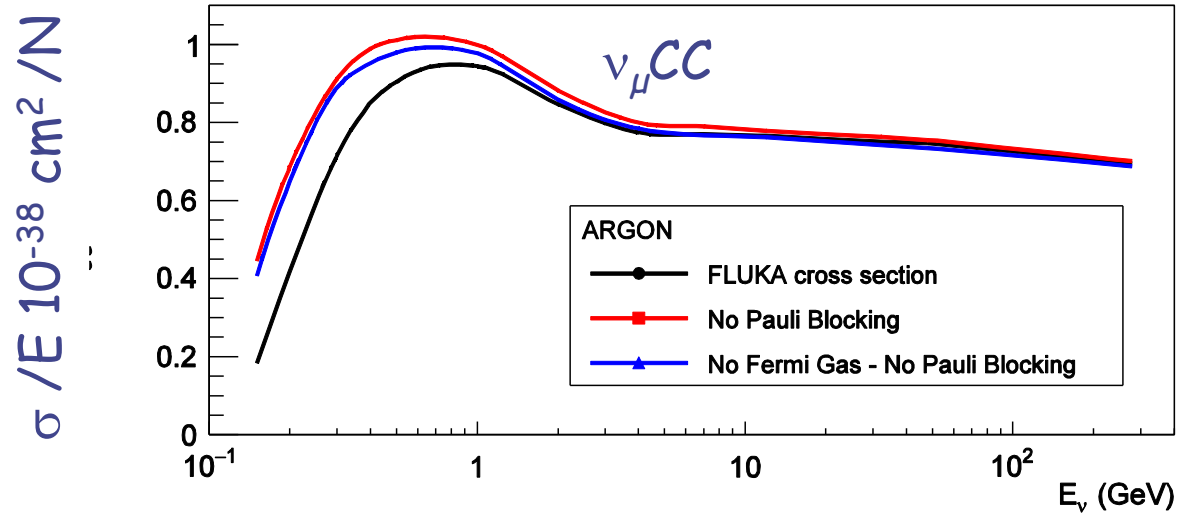
Histo: FLUKA, dots: data (Phys

Rev. C51, 669 (1995))

On free nucleon: recoil energy :

43 MeV at 24° , 117 MeV at 43° .

Total cross section: nuclear effects in Ar



$5 \text{ GeV} < E_{\nu} < 50 \text{ GeV}$
 Pauli Blocking effect
 and Fermi Gas effect
 separately have an
 impact of $\sim 2\text{-}3\%$
Globally Nuclear
 effects stay within
 $\pm 1\%$

$E_{\nu} < 5 \text{ GeV}$

nuclear effects are
 dominated by the
 Pauli Blocking and
 rapidly increase to
 the order of 10% and
 above

Nuclear effects in Minerva

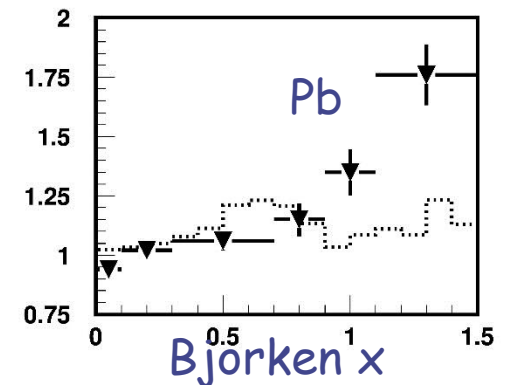
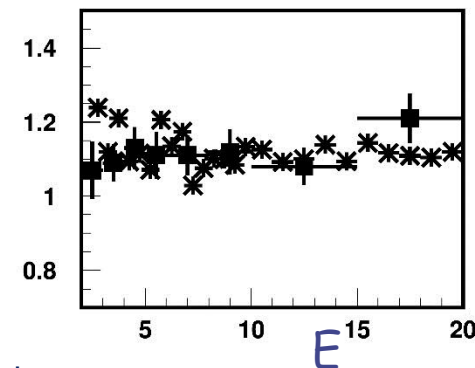
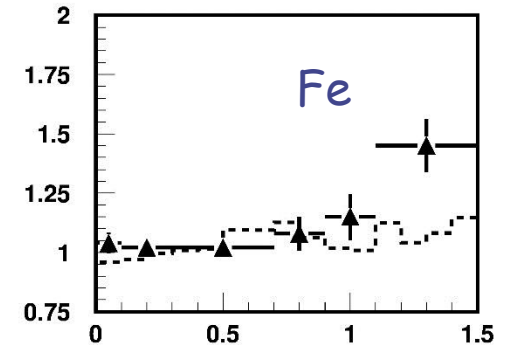
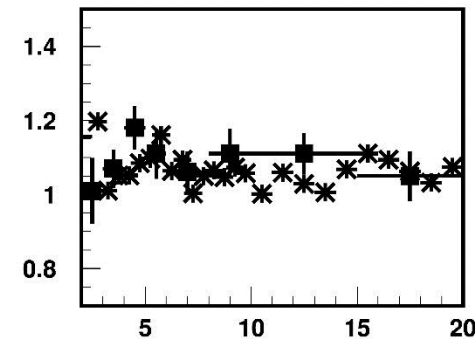
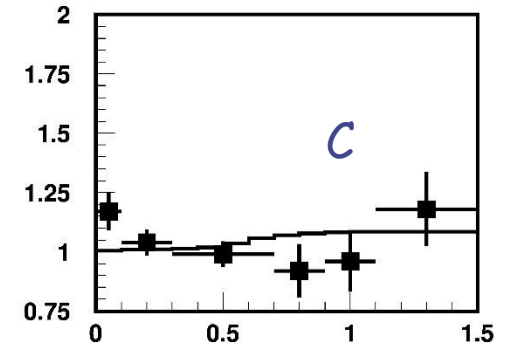
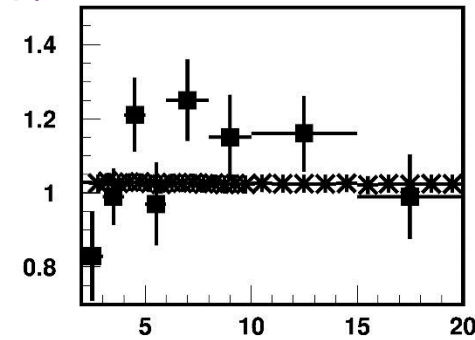
Beam: ν_μ NuMi Low Energy (average 4 GeV)
Main Target : CH

Measured also with C, Fe, Pb targets
PRL 112, 231801 (2014)

Here: ratio of cross sections / the one in CH

Left: total CC vs neutrino Energy :
squares: data
crosses: FLUKA

Right: $d\sigma/dx$
symbols: data histos: Fluka
expt: reduction at low x and
enhancement at high x with incr. A
Fluka: fails the highest x (same for
Genie)



FSI example: Formation zone

Naively: "materialization" time (originally proposed by Stodolski).

Qualitative estimate:

In the frame where $p_{\parallel} = 0$

$$\bar{t} = \Delta t \approx \frac{\hbar}{E_T} = \frac{\hbar}{\sqrt{p_T^2 + M^2}}$$

Particle proper time

$$\tau = \frac{M}{E_T} \bar{t} = \frac{\hbar M}{p_T^2 + M^2}$$

Going to the nucleus system

$$\Delta x_{for} \equiv \beta c \cdot t_{lab} \approx \frac{p_{lab}}{E_T} \bar{t} \approx \frac{p_{lab}}{M} \tau = k_{for} \frac{\hbar p_{lab}}{p_T^2 + M^2}$$

Condition for possible reinteraction inside a nucleus: $\Delta x_{for} \leq R_A \approx r_0 A^{\frac{1}{3}}$

Decrease of the reinteraction probability

Applied also to DIS neutrino interactions and, in an analogue way, to QE neutrino interactions

Pions: nuclear medium effects

Free πN interactions \Rightarrow \Rightarrow Non resonant channel
 \Rightarrow P-wave resonant Δ production

Δ in nuclear medium \Rightarrow decay \Rightarrow elastic scattering, charge exchange
 \Rightarrow reinteraction \Rightarrow Multibody pion absorption

Assuming for the free resonant σ a Breit-Wigner form with width Γ_F

$$\sigma_{res}^{Free} = \frac{8\pi}{p_{cms}^2} \frac{M_\Delta^2 \Gamma_F^2(p_{cms})}{(s - M_\Delta^2)^2 + M_\Delta^2 \Gamma_F^2(p_{cms})}$$

An "in medium" resonant σ (σ_{res}^A) can be obtained adding to Γ_F the imaginary part of the (extra) width arising from nuclear medium

$$\frac{1}{2}\Gamma_T = \frac{1}{2}\Gamma_F - \text{Im}\Sigma_\Delta \quad \Sigma_\Delta = \Sigma_{qe} + \Sigma_2 + \Sigma_3 \quad (\text{Oset et al., NPA 468, 631})$$

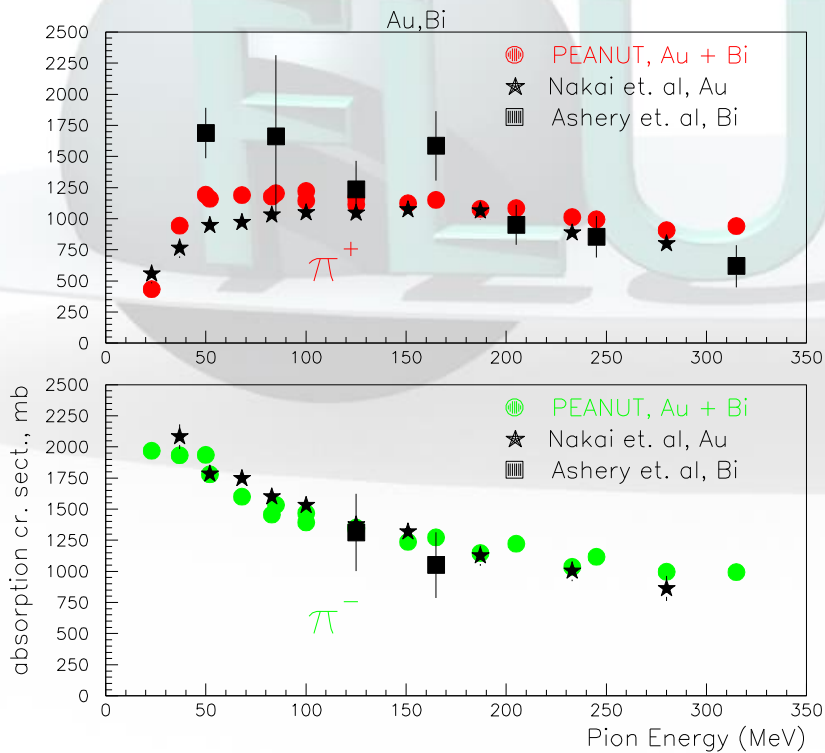
quasielastic scattering, two and three body absorption

The in-nucleus σ_t^A takes also into account a two-body s-wave absorption σ_s^A derived from the optical model

$$\sigma_t^A = \sigma_{res}^A + \sigma_t^{Free} - \sigma_{res}^{Free} + \sigma_s^A \quad \sigma_s^A(\omega) = \frac{4\pi}{p} \left(1 + \frac{\omega}{2m}\right) \text{Im} B_0(\omega) \rho$$

Pion absorption examples

Pion absorption cross section on Gold and Bismuth in the Δ resonance region (multibody absorption in PEANUT)

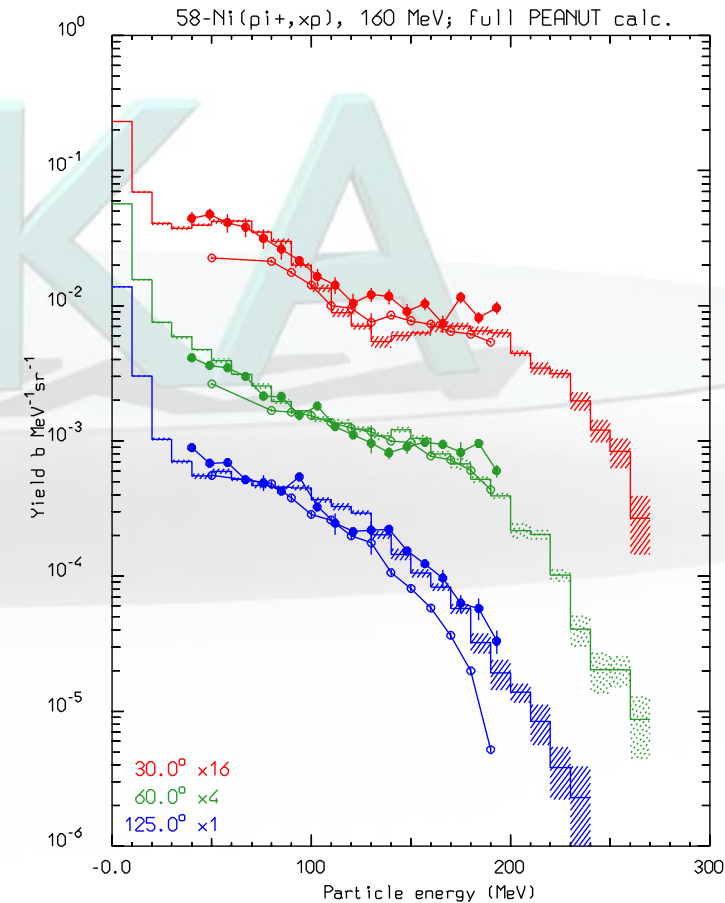


Emitted proton spectra at different angles, 160 MeV π^+ on ^{58}Ni

Phys. Rev. C41,2215 (1990)

Phys. Rev. C24,211 (1981)

Proton spectra extend up to 300 MeV



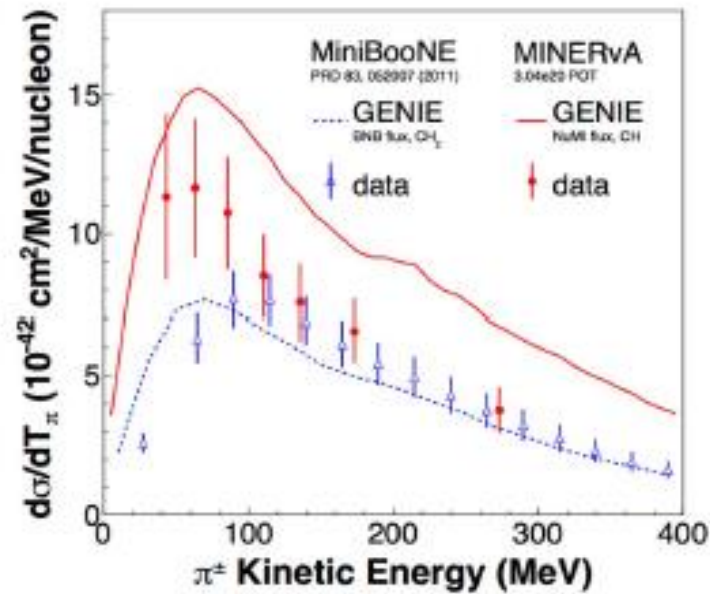
Data on pion production

Thoughts on MINERvA vs. MiniBooNE

- ▶ Shapes very similar, no significant dip in either!
- ▶ Small difference in slope (Kinematics, FF, nonres differences).
- ▶ Biggest difference is at low energy.

MiniBoone : CH₂, E_ν ≈ 0.8 GeV, cut on single pion, PHYS. REV.D 83, 052007 (2011)

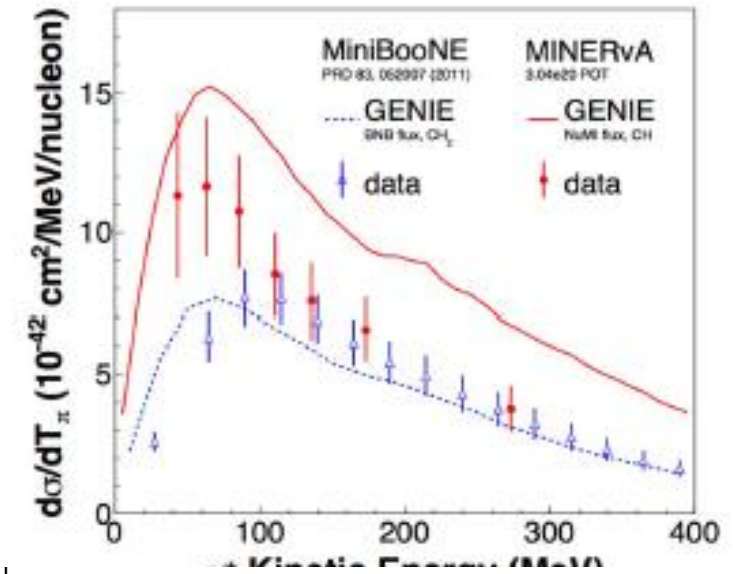
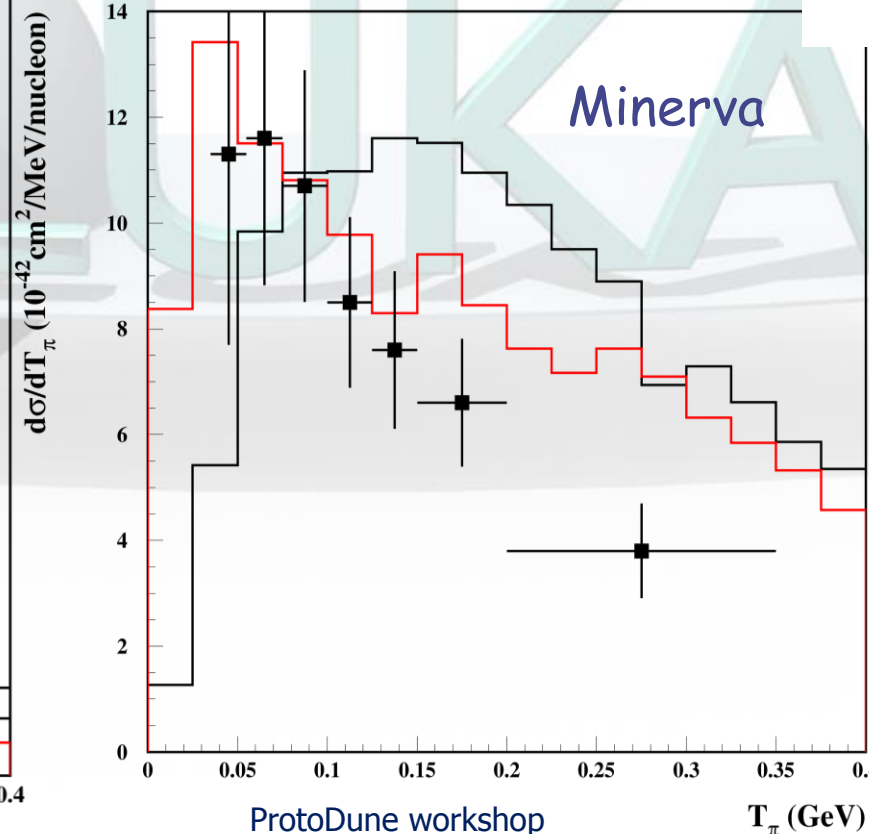
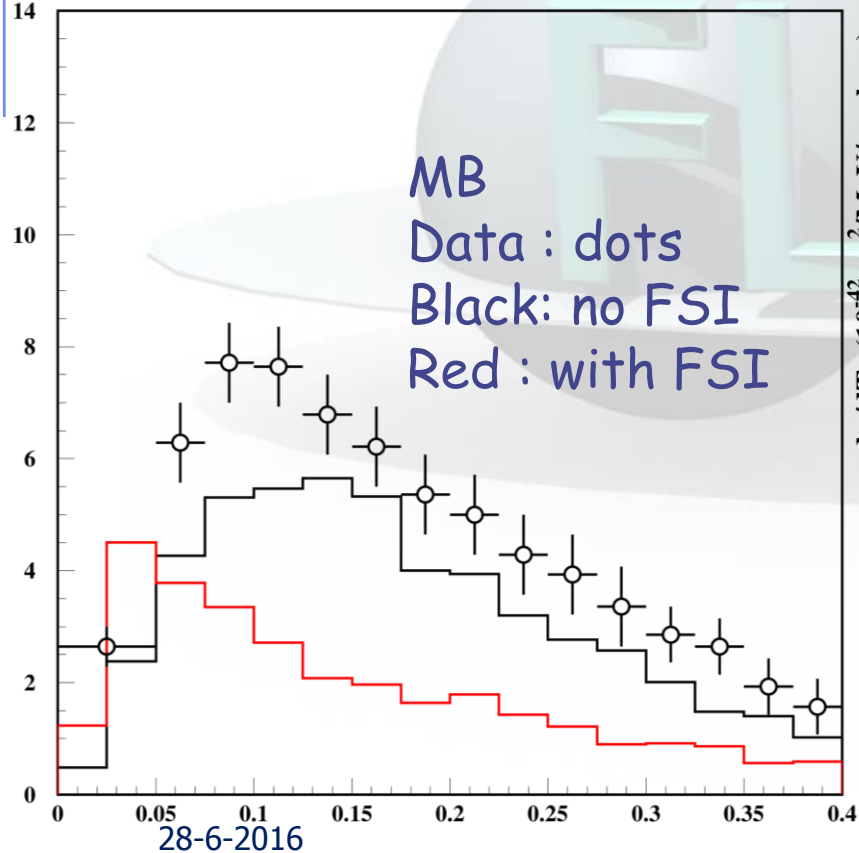
Minerva : CH, E_ν ≈ 4 GeV, cut on W < 1.4 arXiv:1406.6415v3 (2015)



Tension betw the two data sets vs models/ extent of FSI

MB and Minerva

Dytman

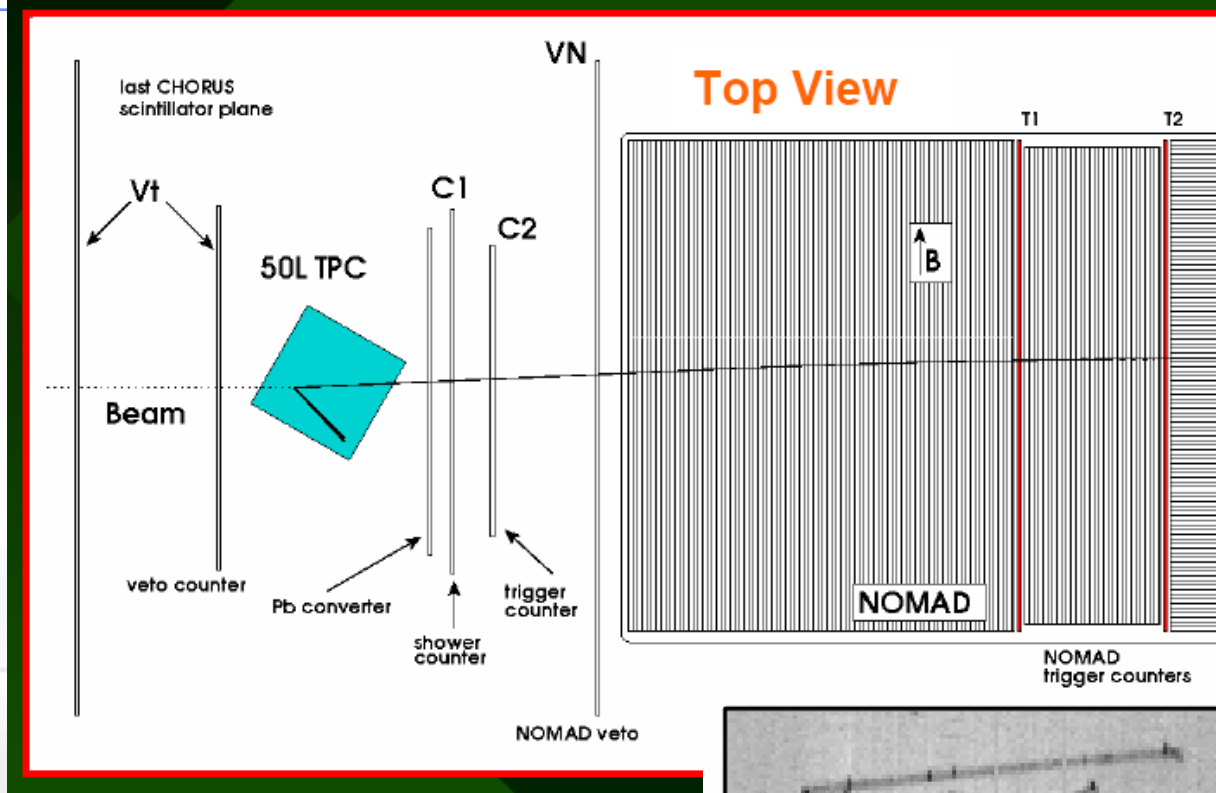


MiniBoone : CH₂, E_v ≈ 0.8 GeV, cut on single pion, PHYS. REV.D 83, 052007 (2011)

Minerva : CH, E_v ≈ 4 GeV, cut on W < 1.4 arXiv:1406.6415v3 (2015)

Tension betw the two data sets vs models/ extent of FSI

The 50L LAr TPC in the WANF neutrino beam(1997)

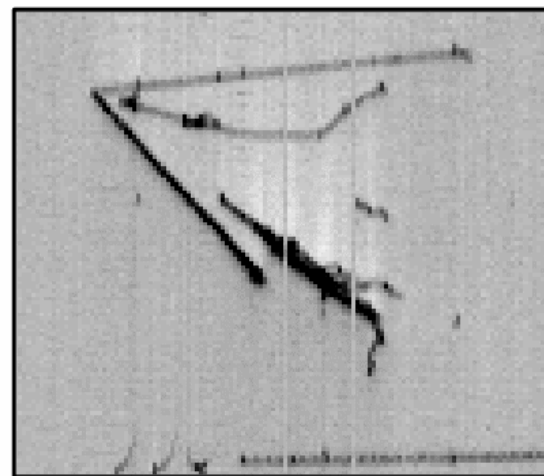


Trigger and μ
reconstruction: NOMAD

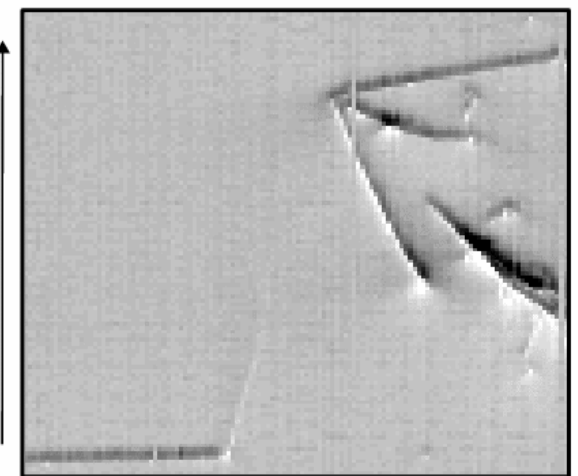
Event selection: "GOLDEN sample"
= 1 μ and 1 proton $>40\text{MeV}$ fully contained

Phys.Rev. D74 (2006) 112001

10 Nov 2015



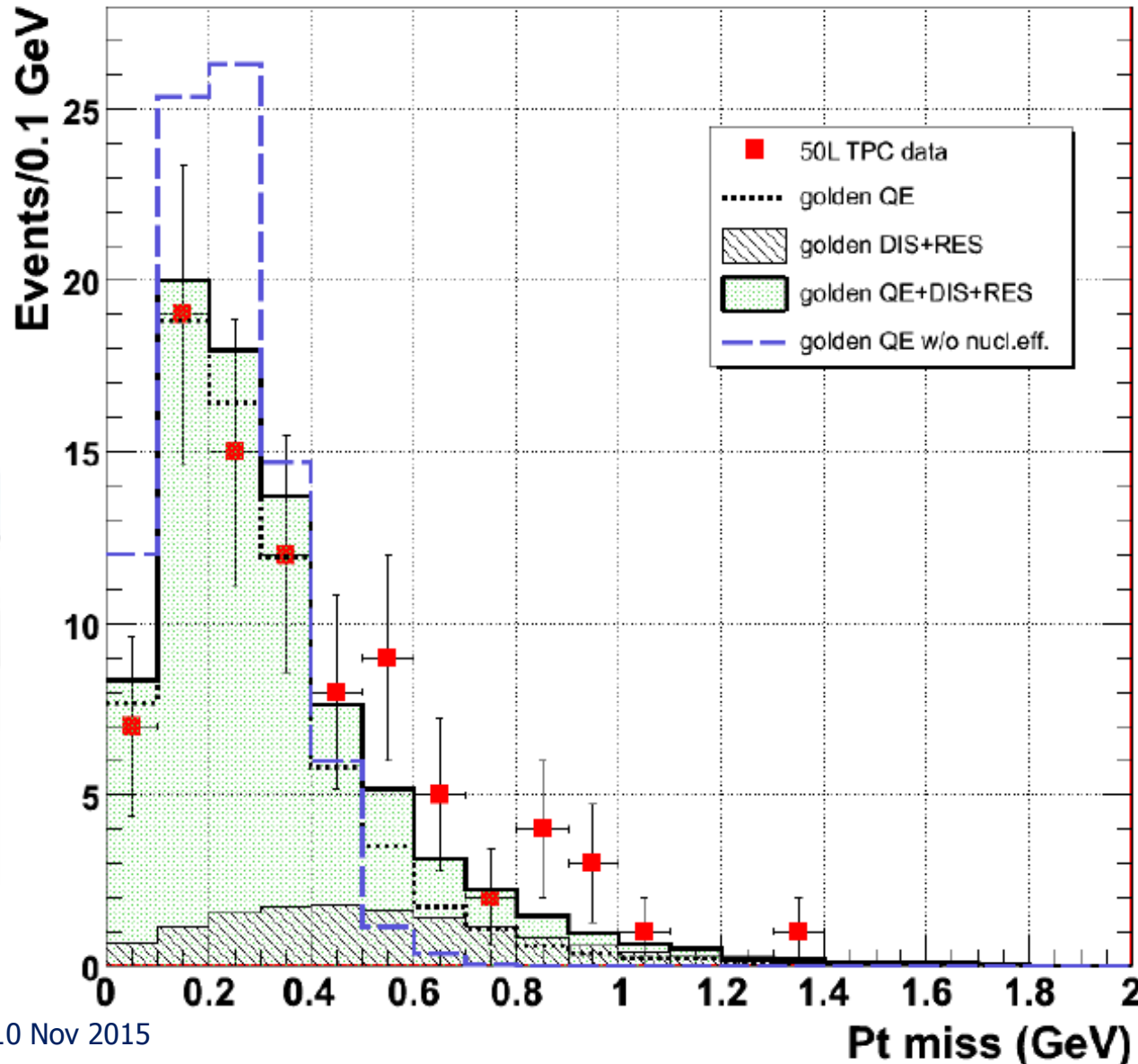
Collection wires. (128 wires: 32 cm.)



Induction wires. (128 wires: 32 cm.)

Time (1300 samples: 47 cm)

Missing transverse momentum



10 Nov 2015

- from 400 QE - golden fraction 16%
- background - additional 20% finally expected

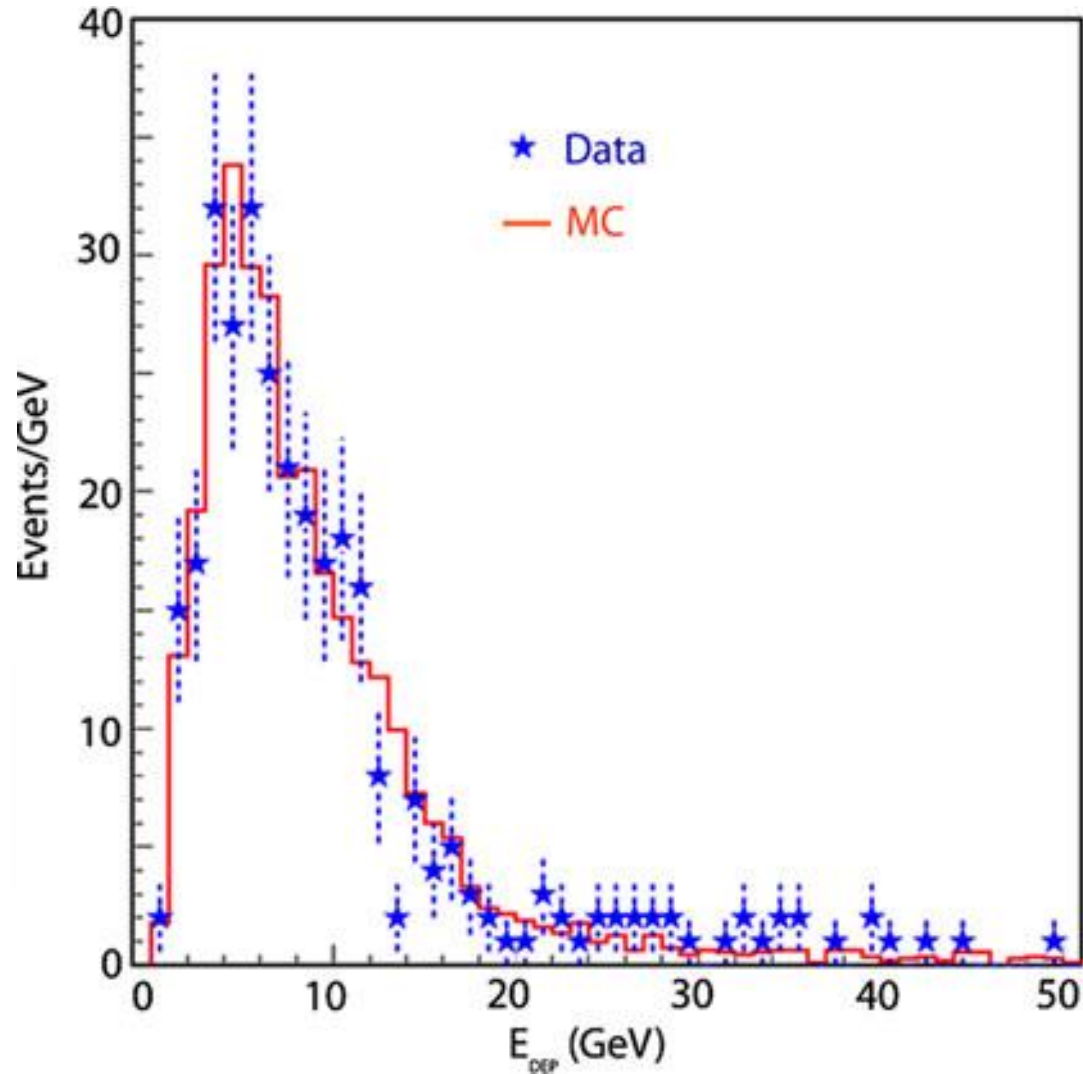
$80 \pm 9(\text{stat.}) \pm 13(\text{syst.}) \rightarrow$ mainly QE fraction and beam simul)

to be compared with **86** events observed

Very good consistency with expectations

Note: here DIS and RES from old coupling with the NUX code (A. Rubbia)

CNGS data



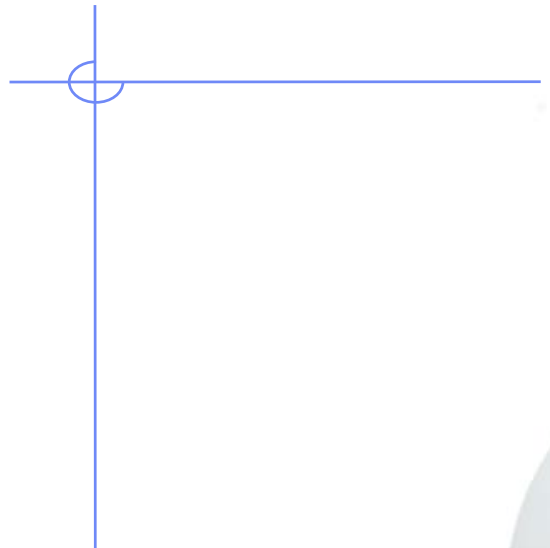
Distribution of total deposited energy in the T600 detector
CNGS numuCC events
Same reconstruction in MC and Data
Neutrino fluxes from FLUKA cngs simulations

Absolute agreement on neutrino rate within 6%

Conclusions and perspectives

- A neutrino event generator (NUNDIS) is implemented in FLUKA
- QE, RES, DIS interactions
- Hadronization as for hadronic interactions in FLUKA
- Nuclear effects from the FLUKA nuclear models
- Encouraging comparisons with expt data

- More has to be done:
 - Coherent pion production
 - Coherent effects (see high x in Minerva and proton pairs in Argoneut)
 - More coherent / nuclear structure effects for low energy QE
 - Meson exchange in QE (high x in Minerva)
 - Radiative corrections in DIS (ongoing)
 - ..nobody likes Rein-Sehgal..
 - Comparisons against data
- **Collaboration is very very welcome!**



The FLUKA international Collaboration



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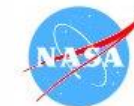
E. Gadioli, M.V. Garzelli, Italy L. Sarchiapone, INFN Legnaro, Italy

P. Colleoni, Ospedale Papa Giovanni XXIII Bergamo, Italy

A. Fontana V.E. Bellinzona INFN Pavia Anna Ferrari, S. Mueller HZDR, Germany

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Nuclear potential for pions

For pions, a complex nuclear potential can be defined out of the π -nucleon scattering amplitude to be used in conjunction with the Klein-Gordon equation

$$\left[(\omega - V_c)^2 - 2\omega U_{opt} - K^2 \right] \Psi = m_\pi^2 \Psi$$

In coordinate space (the upper/lower signs refer to π^+ / π^-):

$$2\omega U_{opt}(\omega, r) = -\beta(\omega, r) + \frac{\omega}{2M} \nabla^2 \alpha(\omega, r) - \nabla \frac{\alpha}{1 + g\alpha(\omega, r)} \nabla$$

$$\beta = 4\pi \left[\left(1 + \frac{\omega}{M} \right) \left(b_0(\omega) \mp b_1(\omega) \frac{N-Z}{A} \right) \rho(r) + \left(1 + \frac{\omega}{2M} \right) B_0(\omega) \rho^2(r) \right]$$

$$\alpha = 4\pi \left[\frac{1}{\left(1 + \frac{\omega}{M} \right)} \left(c_0(\omega) \mp c_1(\omega) \frac{N-Z}{A} \right) \rho(r) + \frac{1}{\left(1 + \frac{\omega}{M} \right)} C_0(\omega) \rho^2(r) \right]$$

Using standard methods to get rid of the non-locality, in momentum space

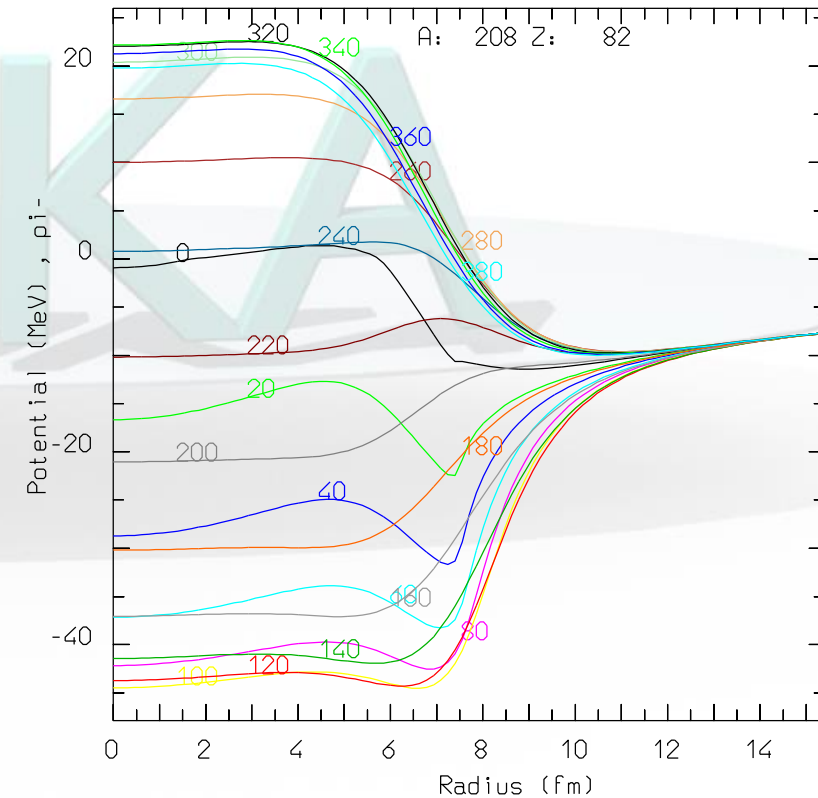
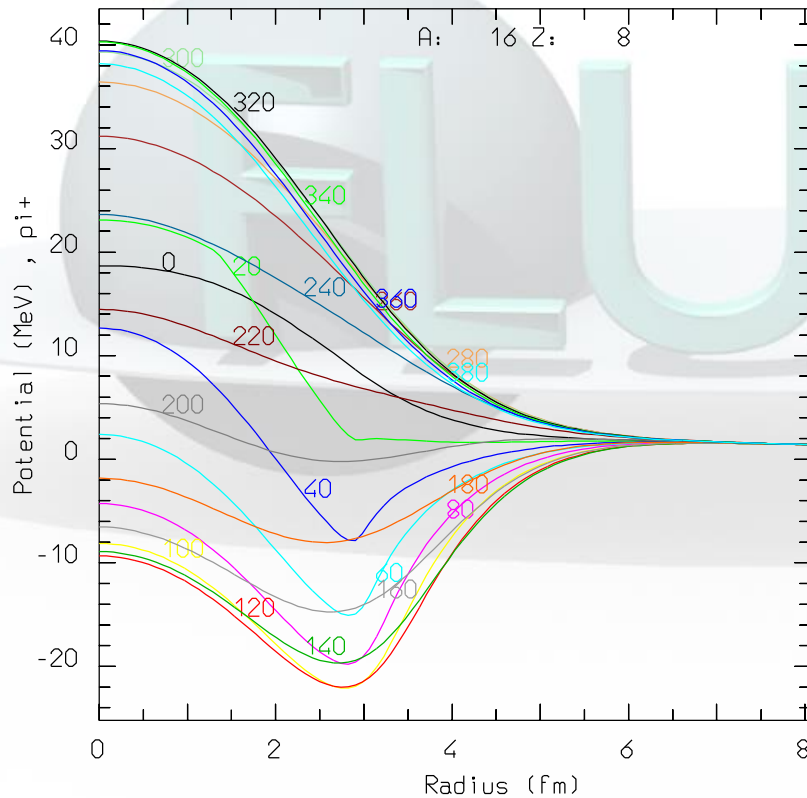
$$2\omega U_{opt}(\omega, r) = -\beta - K^2 \frac{\alpha}{1 + g\alpha} + \frac{\omega}{2M} \nabla^2 \alpha$$

$$K^2 = k_0^2 + V_c^2 - 2\omega V_c^2 - 2\omega U_{opt}(\omega, r) = \frac{k_0^2 + V_c^2 - 2\omega V_c^2 + \beta - \frac{\omega}{2M} \nabla^2 \alpha}{1 - \bar{\alpha}}$$

$$\bar{\alpha} = \frac{\alpha}{1 + g\alpha}$$

Nuclear potential for pions: examples

The real part of the pion optical potential for π^- on ^{16}O (left) and π^+ on ^{208}Pb (right) as a function of radius for various pion energies (MeV)

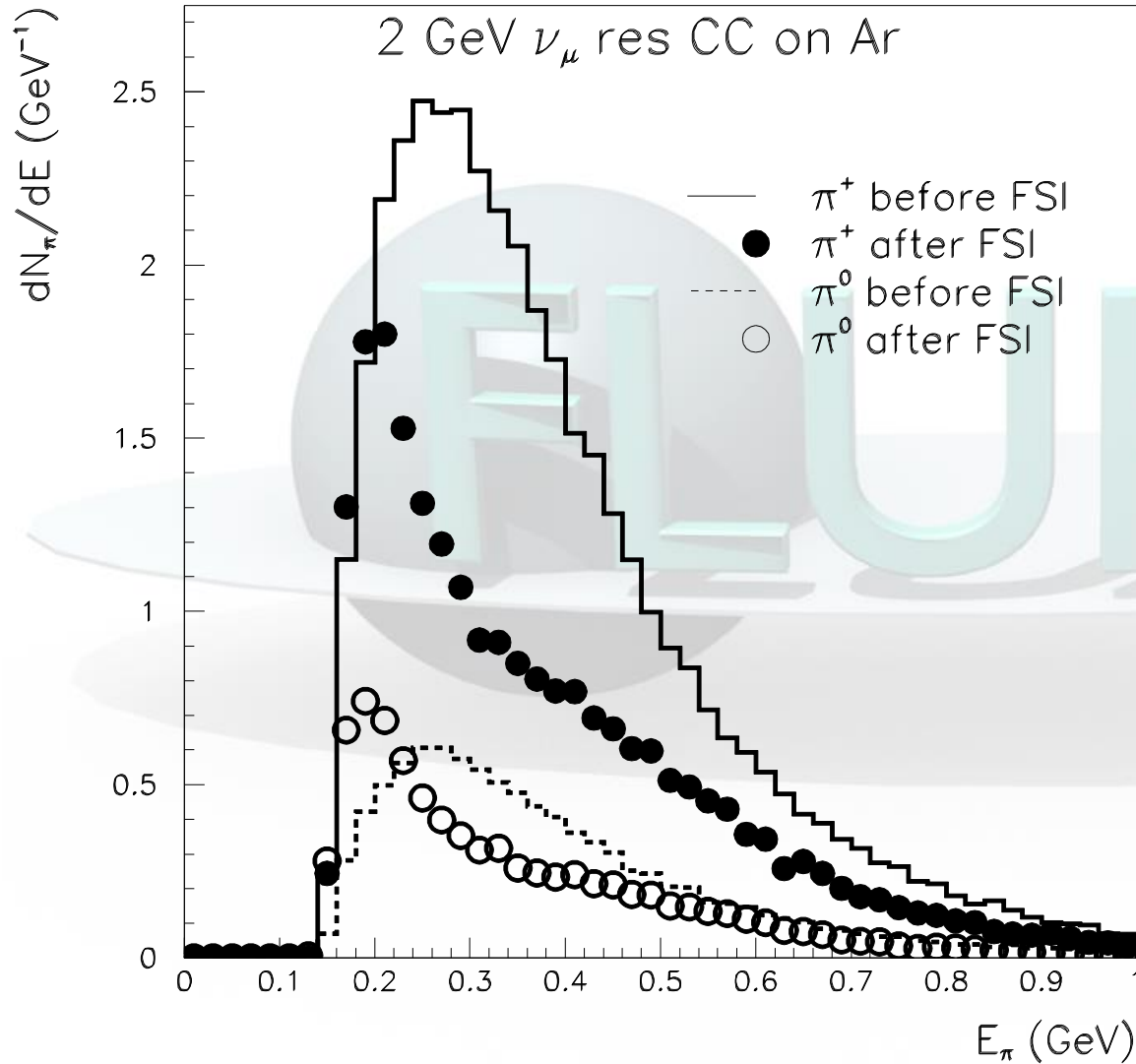


NUNDIS 2015: kinematics

- Considered kinematical limits for the *PDF* available from GRV94, GRV98, and BBS analyses.

Variable	Required	GRV94		GRV98		BBS	
		Default	Tested	Default	Tested	Default	Tested
E_{min} (GeV)	—	0.050					
E_{max} (GeV)	$\geq 10^4$	$70 \cdot 10^3$			10^5		
Q_{min}^2 (GeV ²)	$\leq 5.5 \cdot 10^{-12}$	0.4	0.4	0.8	0.8	2	0.8
Q_{max}^2 (GeV ²)	$\geq 1.9 \cdot 10^4$	10^6	10^9	10^6	10^9	10^4	$2 \cdot 10^4$
x_{min}	$\leq 1.4 \cdot 10^{-11}$	10^{-5}	10^{-30}	10^{-9}	10^{-30}	10^{-4}	10^{-30}
x_{max}	1	0.99999	0.99999	1	1	1	1

Expected effect in Ar



Example of expected effect:
2 GeV ν_μ CC RES interaction in Ar:
Pion production vs pion total E
Lines: before FSI
Symbols: after FSI

Solid and filled symbols: positive pions
Dashed and open symbols: pizero