Neutrino interactions in FLUKA: NUNDIS

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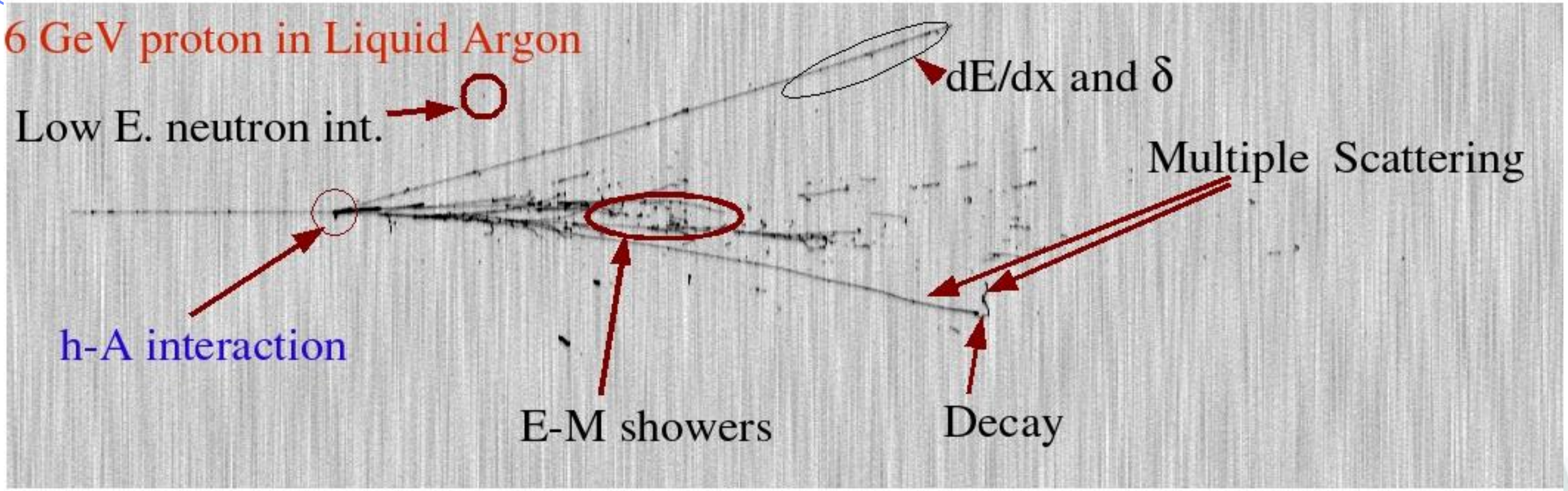
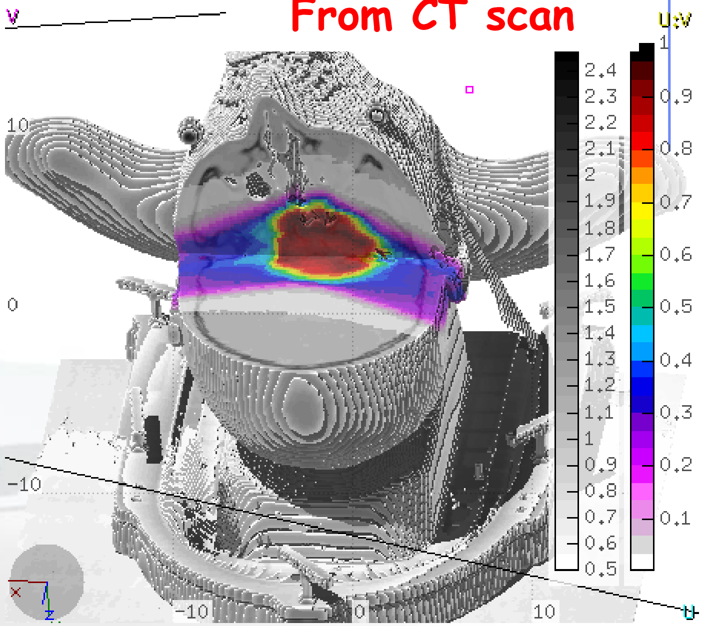
FLUKA : a multi-purpose Monte Carlo code



Dose
2 p Beams
In head geometry
From CT scan



Developed and maintained under an INFN-CERN agreement

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
  - Resonance
  - DIS
- Embedded in FLUKA nuclear modelsfor Initial State and Final State effects
- Only for Argon: absorption of fev-MeV (solar) neutrinos on whole nucleus

- Products of the neutrino interaction can be directly transported in the detector (or other) materials

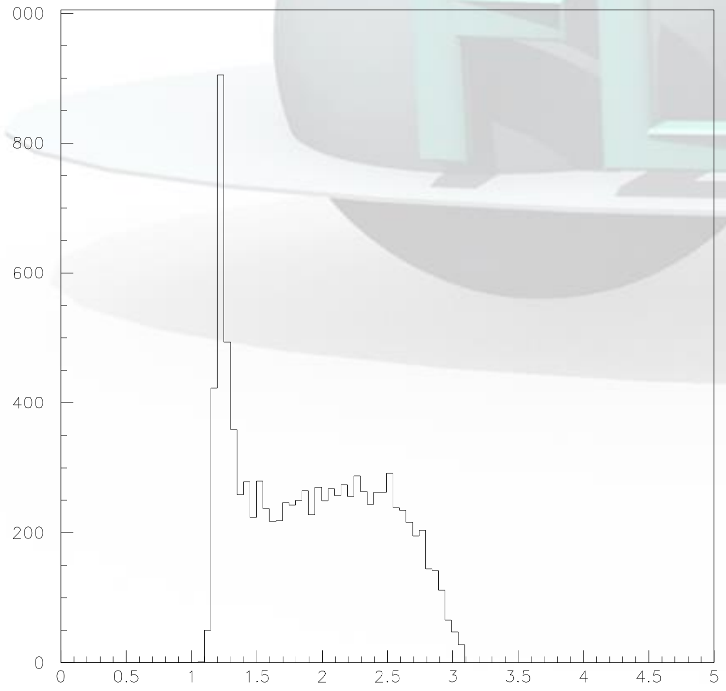
Quasi Elastic

- 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

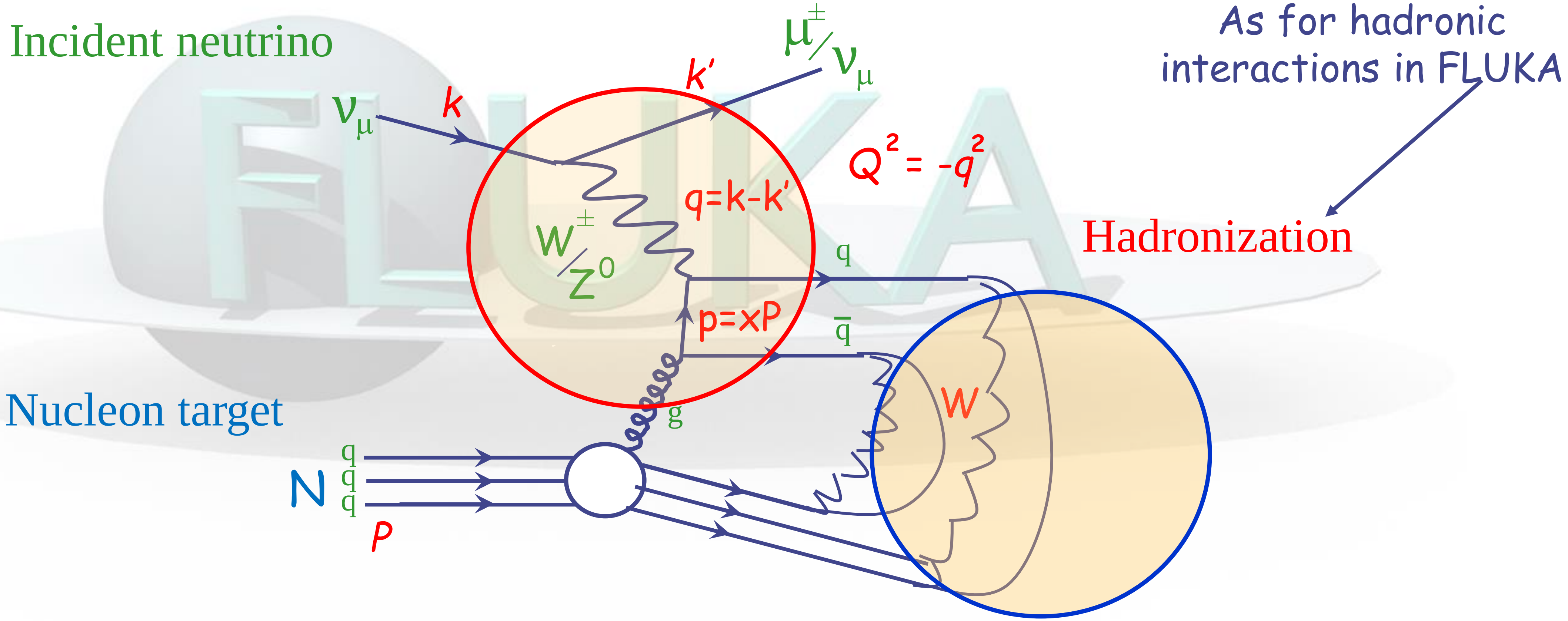
- From Rein-Sehgal formulation
- Keep only Δ production
- No non-resonant background term, assuming that the non-resonant contribution comes from NunDIS
- TRANSITION from RES to DIS: linear decrease of both σ as a function of W



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

www.fluka.org

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

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

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

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

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 $q_i(Q^2,x)$ 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

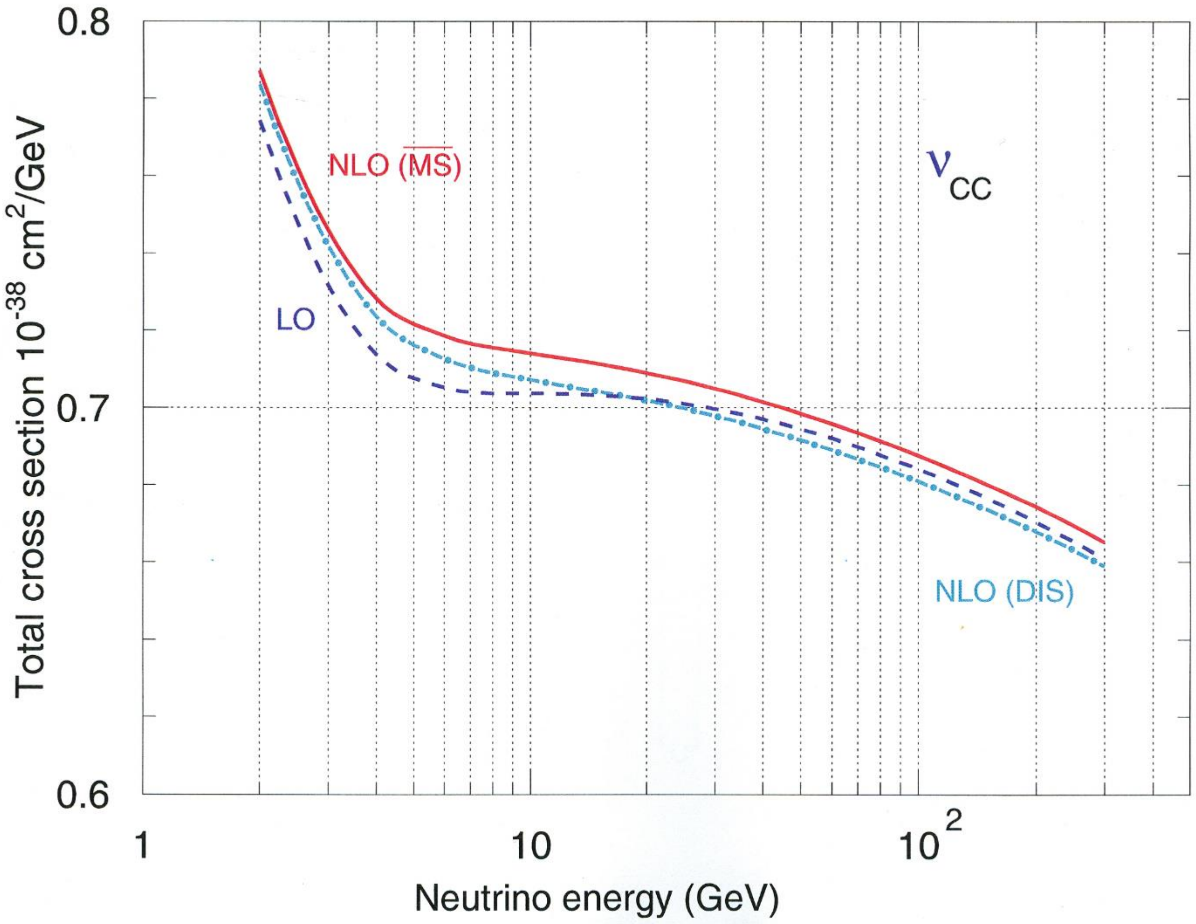
NUNDIS WORKS WITH THESE PDFs

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 MS-bar)
3. Next to leading order analyses (NLO DIS)

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



NLO (DIS) is chosen as a default option

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

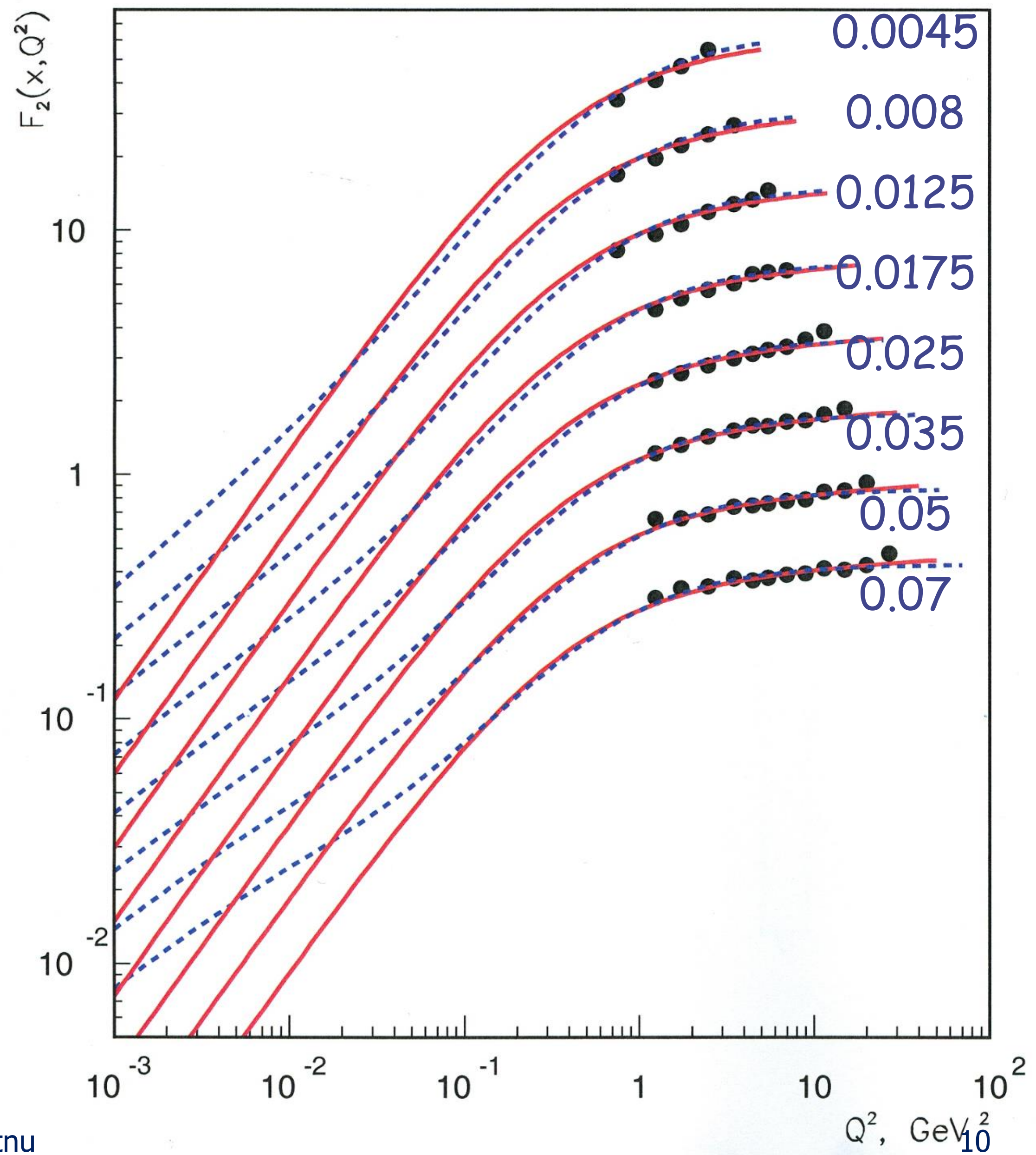
Extrapolation from Q^2 = 1.0 GeV^2 to Q^2 = 0

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

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

Dashed lines: Donnachie-Landshoff 1994

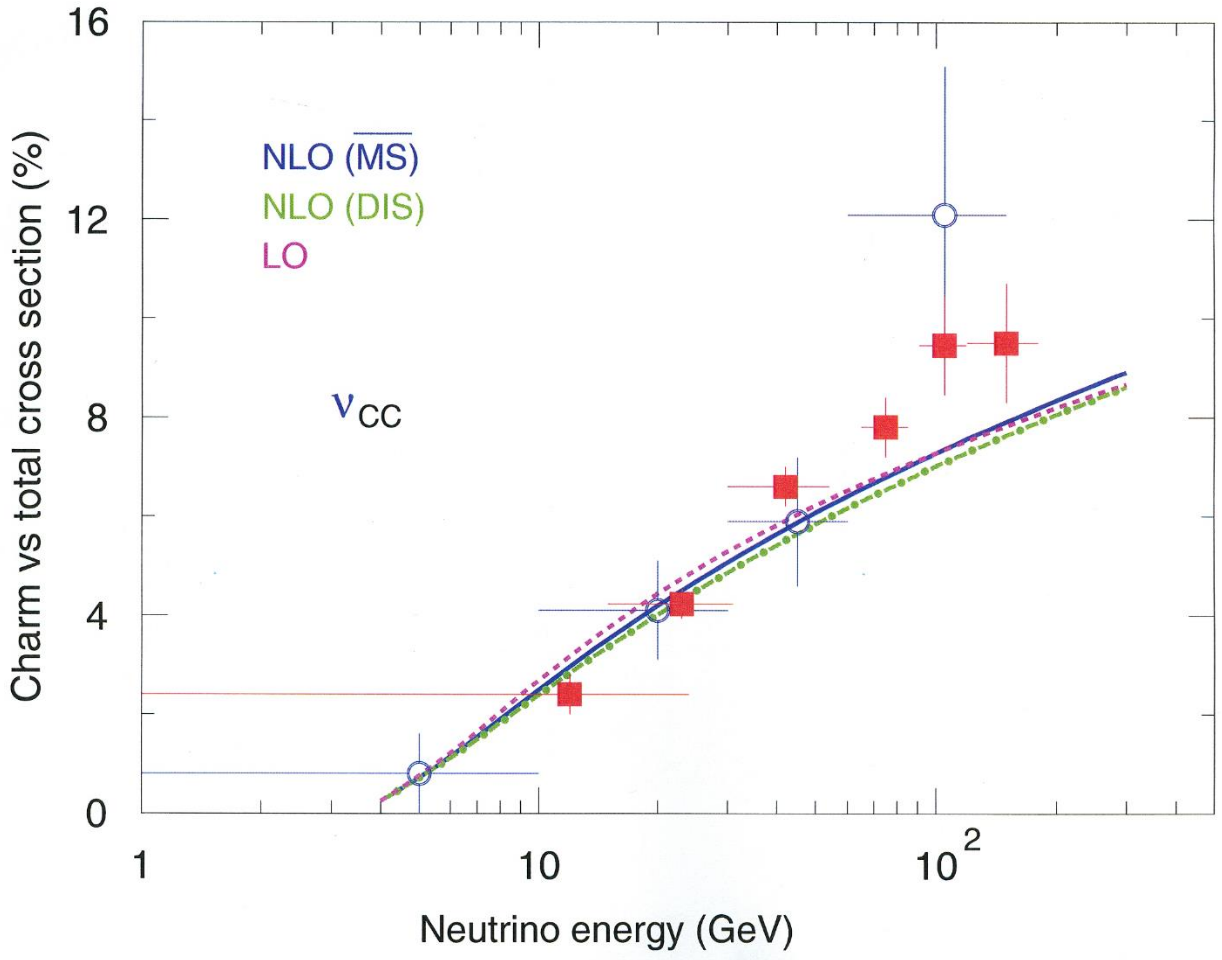
$$F_2(x,Q^2) \sim Ax^{-0.0808}\left(\frac{Q^2}{Q^2+a}\right)^{1.0808} + Bx^{0.4525}\left(\frac{Q^2}{Q^2+b}\right)^{0.5475}$$



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

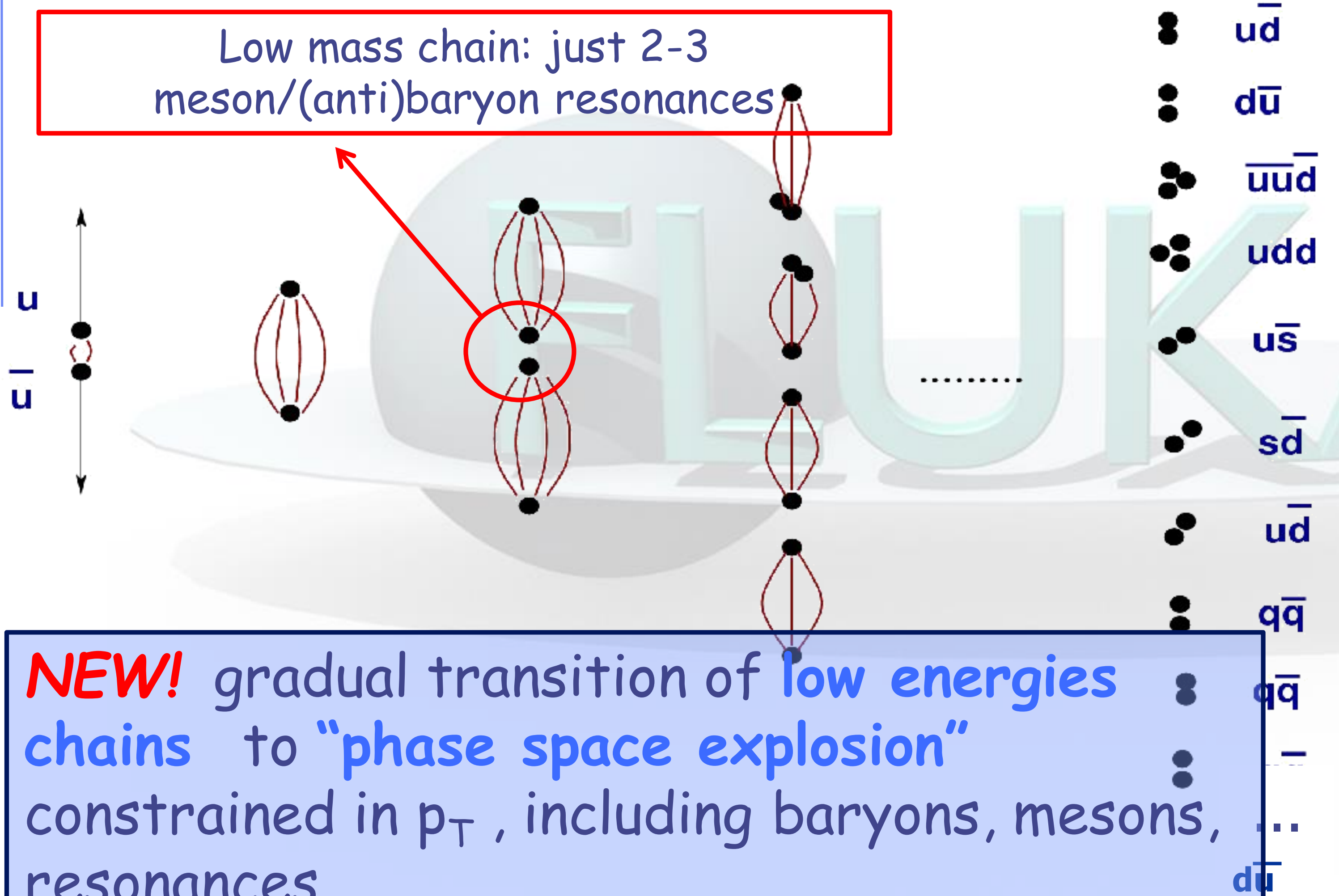
- Ratio of the charm to total cross sections
- Results of NUNDIS simulation with M_c = 1.35 GeV (curves) and experimental data: E531 (open circles) and CHORUS-2011 (filled squares).



The "hadronization" of chains

An example:

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



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

In FLUKA:

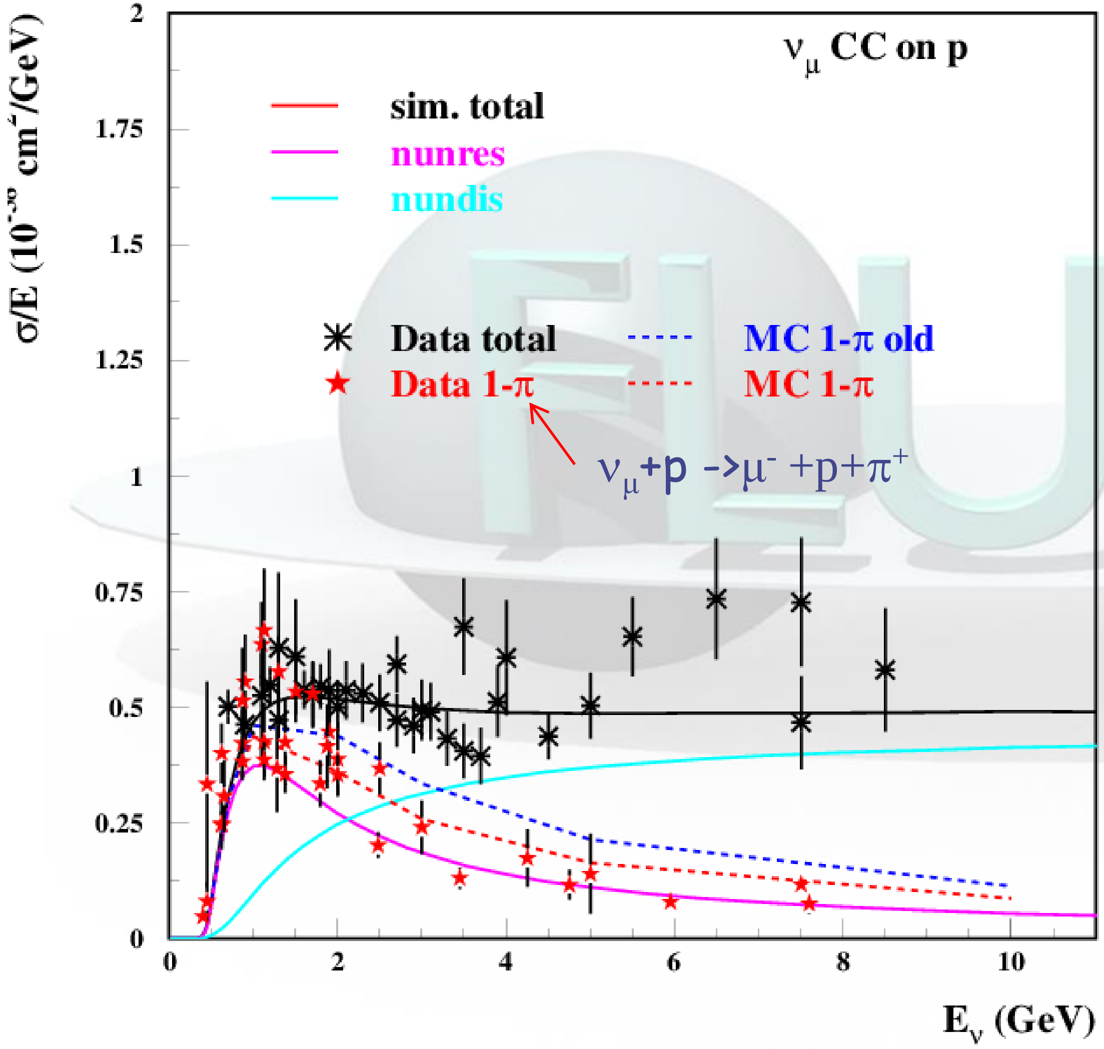
- Assumes chain universality
- Fragmentation functions from hard processes and e+e− scattering
- Transverse momentum from uncertainty considerations
- Mass effects at low energies

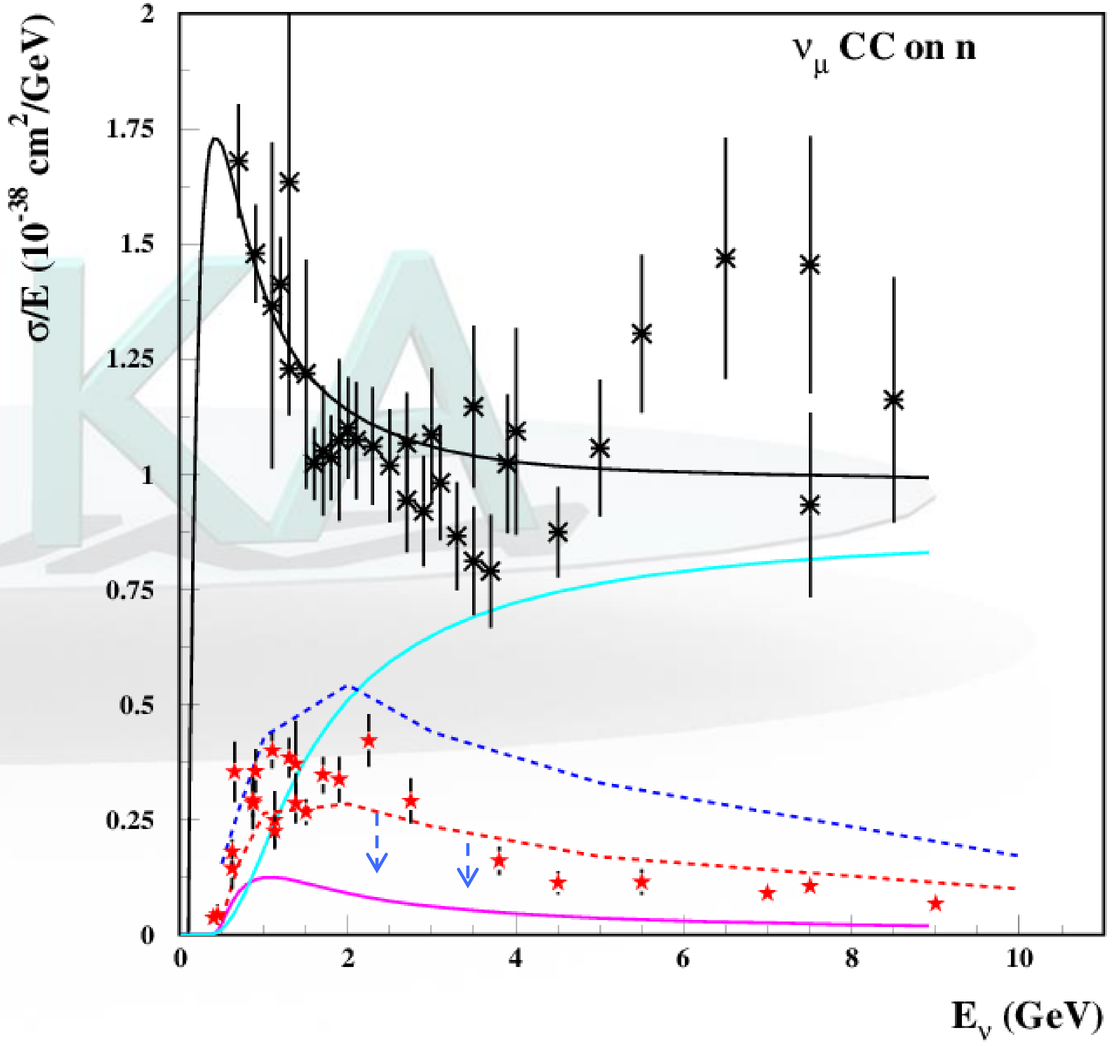
The same functions and (few) parameters for all reactions and energies

- From ν DIS :
  - One quark-diquark chain if interaction of valence quark
  - One quark-diquark plus one q-qbar chain if int on sea quark

Low energy and single pion

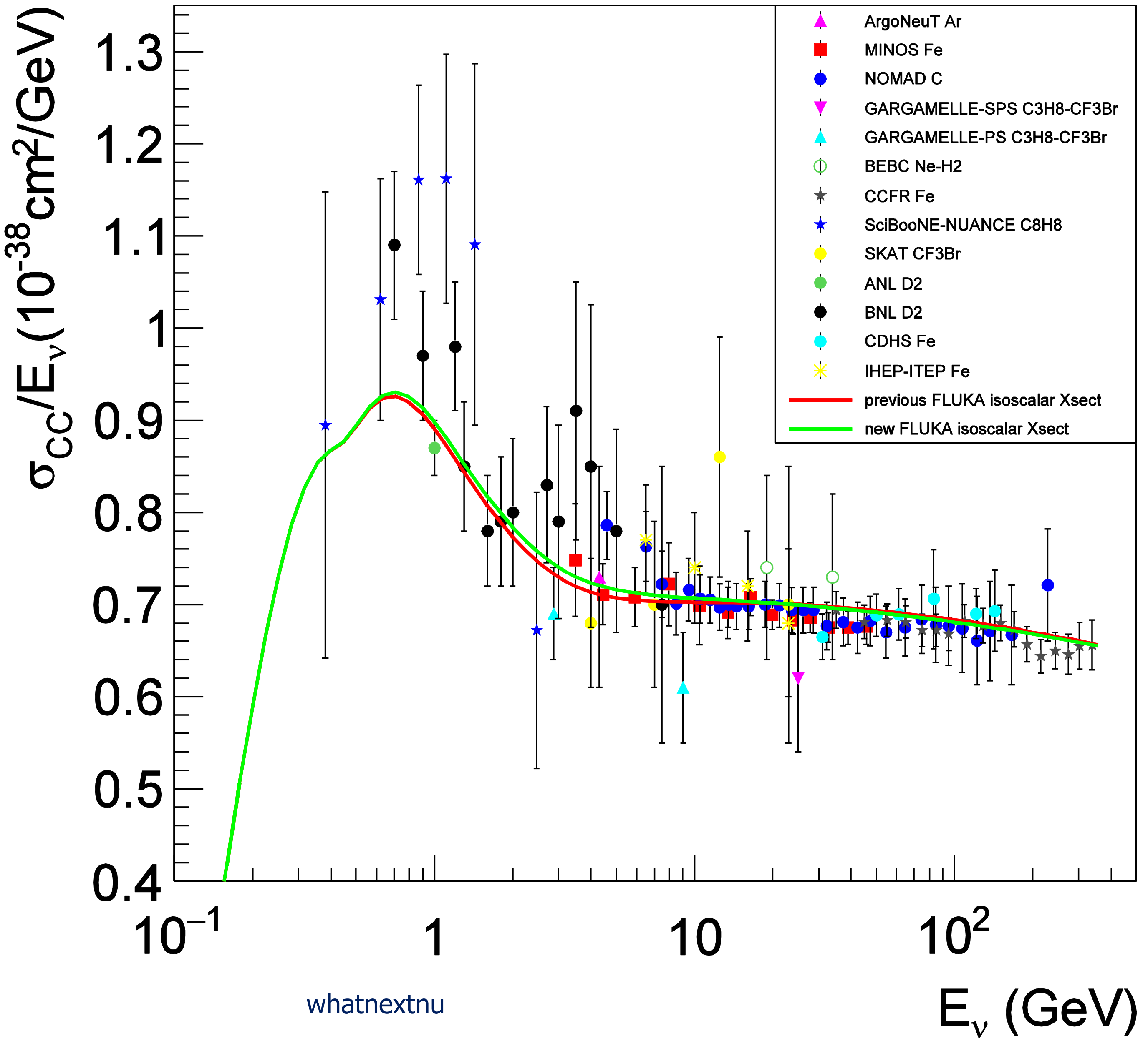
New ***low-mass chain treatment***-> improvements in the **RES-DIS** transition



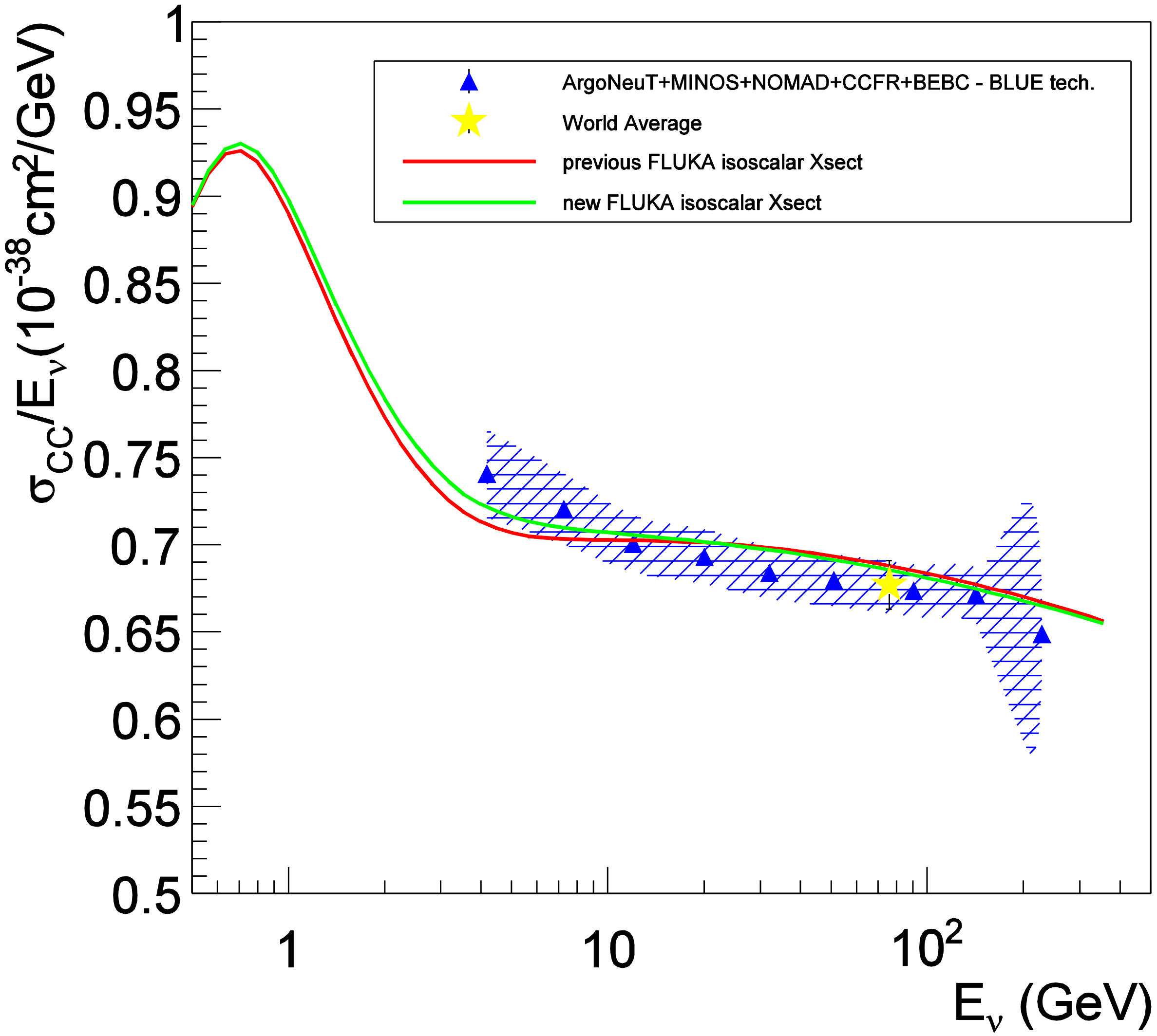


Comparison with data on total cross section

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

Target nucleus description (density, Fermi motion, etc)

⇓

Glauber-Gribov cascade with formation zone

⇓

Generalized IntraNuclear cascade

⇓

Preequilibrium stage with current exciton configuration and excitation energy
(all non-nucleons emitted/decayed + all nucleons below 30-100 MeV)

⇓

Evaporation/Fragmentation/Fission model

⇓

γ deexcitation

t (s)

- 10^{-23}
- 10^{-22}
- 10^{-20}
- 10^{-16}

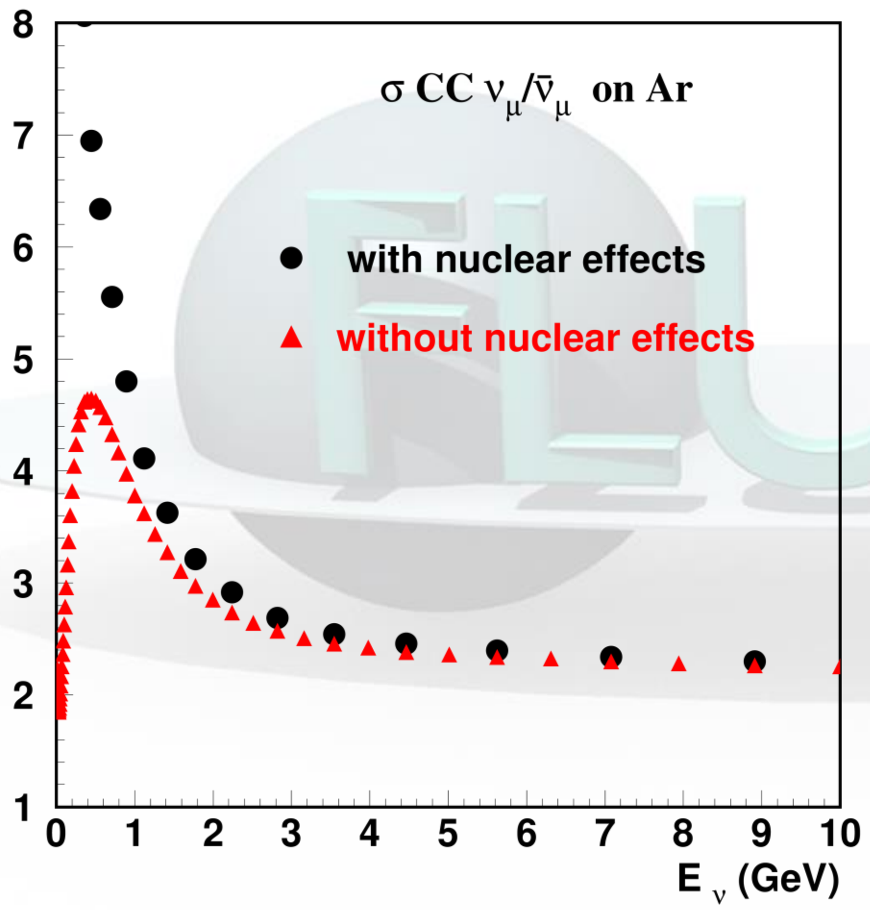
(Generalized) IntraNuclear Cascade

- Primary and secondary particles moving in the nuclear medium
- Target nucleons motion and nuclear potential well according to the Fermi gas model
- Interaction probability

  σ_{free} + Fermi motion × $\rho(r)$ + exceptions (ex. π)
- Glauber cascade at higher energies
- Classical trajectories (+) nuclear mean potential (resonant for π)
- Curvature from nuclear potential → refraction and reflection
- Interactions are incoherent and uncorrelated
- Interactions in projectile-target nucleon CMS → Lorentz boosts

- Multibody absorption for π, μ^-, 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

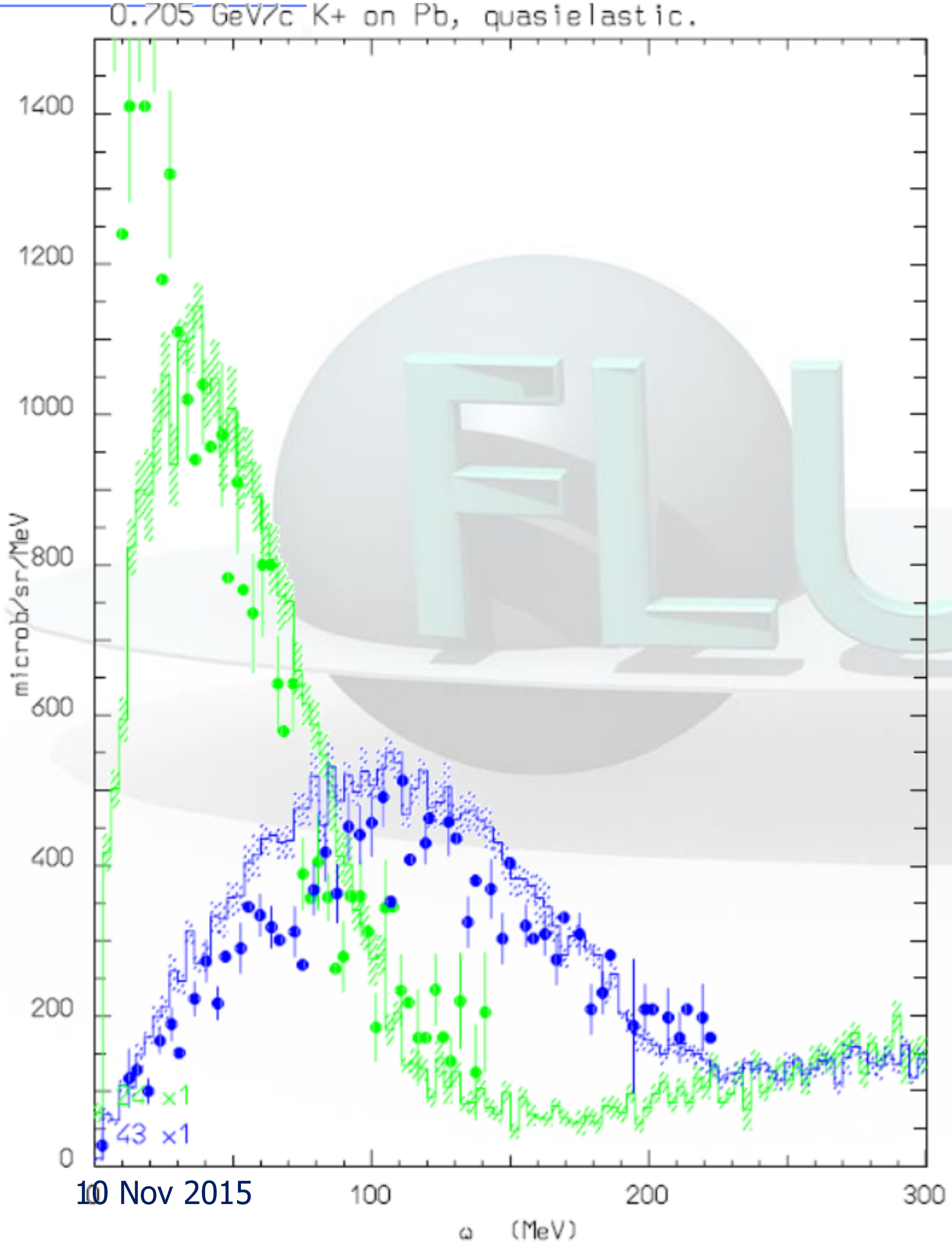
  Momentum distribution $\propto \frac{dN}{dk} = \frac{|k|^2}{2\pi^2}$

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

- Momentum smearing according to uncertainty principle assuming a position uncertainty = √ 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



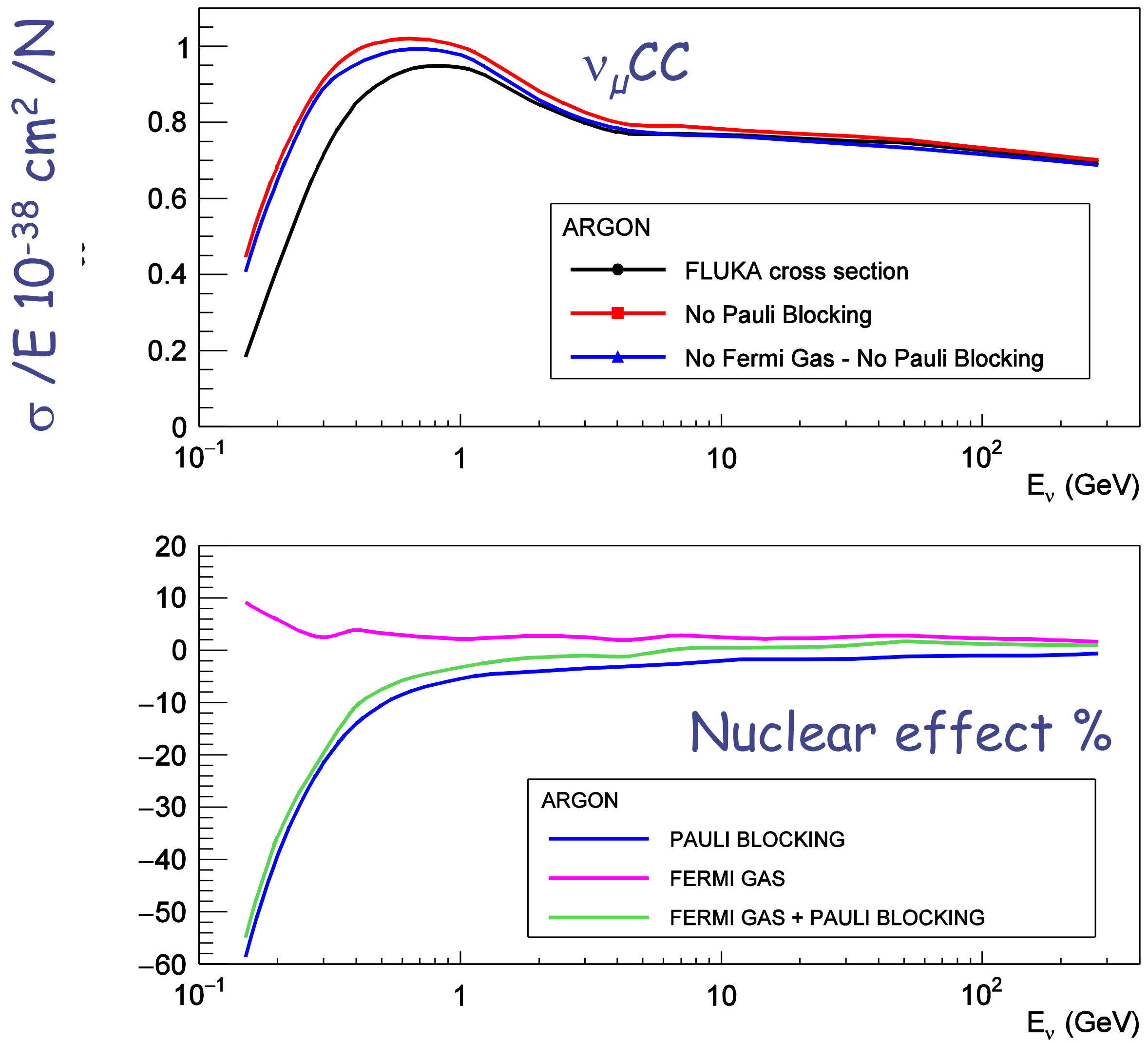
$K^+ \quad K^0$

No low mass S=1 baryons $\rightarrow$ weak K^+N interaction only elastic and ch. exch. up to ≈ 800 MeV/c

$(K^+, K^{+\prime})$ 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 $43°$.

Total cross section: nuclear effects in Ar



5 GeV < Eν < 50 GeV

Pauli Blocking effect and Fermi Gas effect separately have an impact of ~ 2-3%

Globally Nuclear effects stay within ±1%

Eν < 5 GeV

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

Nuclear effects in Minerva

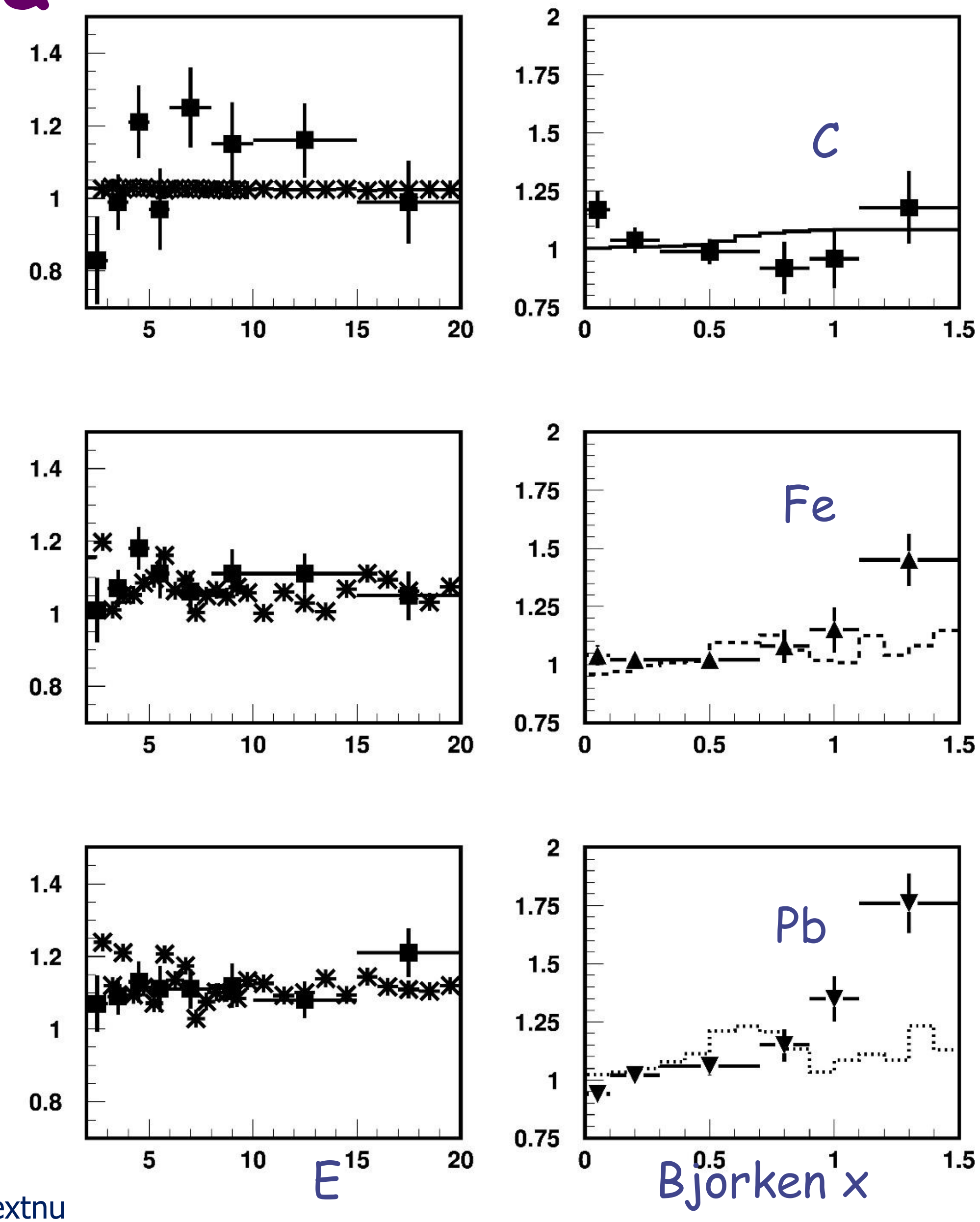
Beam: $\nu\mu$ NuMi Low Energy (average 4 GeV)
Main Target : CH

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// =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:

$$\Delta x_{for} \le R_A \approx r_0 A^{\frac{1}{3}}$$

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 π N interactions ⇒ ⇒ Non resonant channel
⇒ P-wave resonant Δ production

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

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

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

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

$$\tfrac{1}{2}\Gamma_T = \tfrac{1}{2}\Gamma_F - \mathrm{Im}\,\Sigma_\Delta \qquad \Sigma_\Delta = \Sigma_{qe} + \Sigma_2 + \Sigma_3$$

(Oset et al., NPA 468, 631)

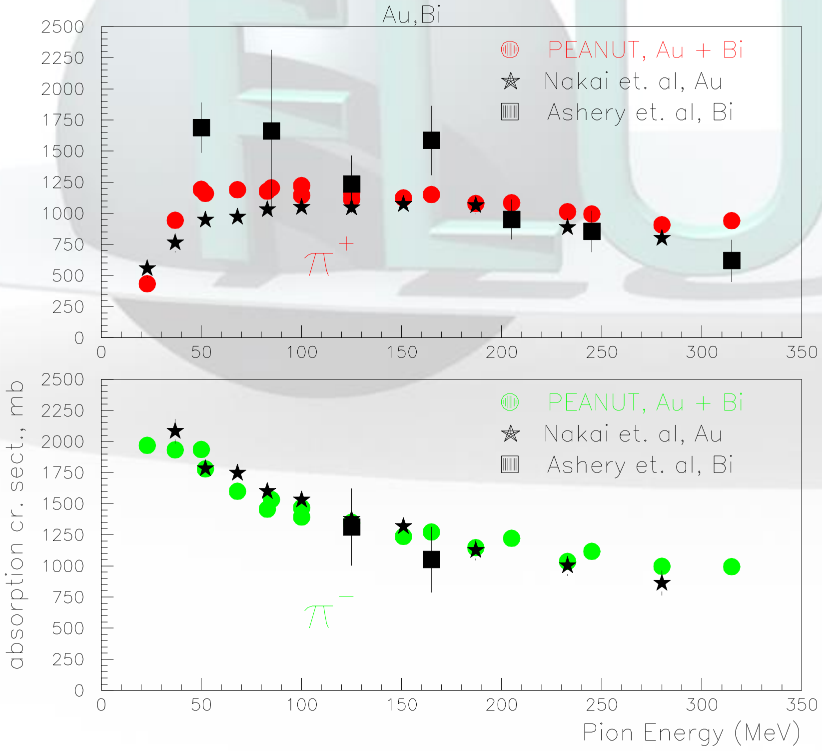
quasielastic scattering, two and three body absorption

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

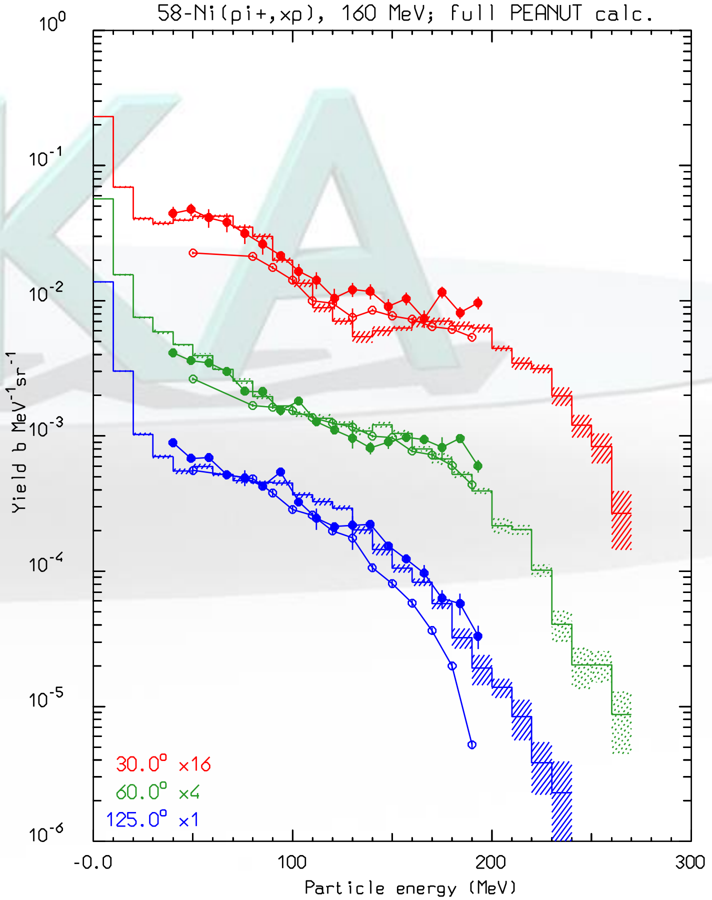
$$\sigma_t^A = \sigma_{res}^A + \sigma_t^{Free} - \sigma_{res}^{Free} + \sigma_s^A \qquad \sigma_s^A(\omega) = \tfrac{4\pi}{p}\left(1 + \tfrac{\omega}{2m}\right)\mathrm{Im}\,B_0(\omega)\rho$$

Pion absorption examples

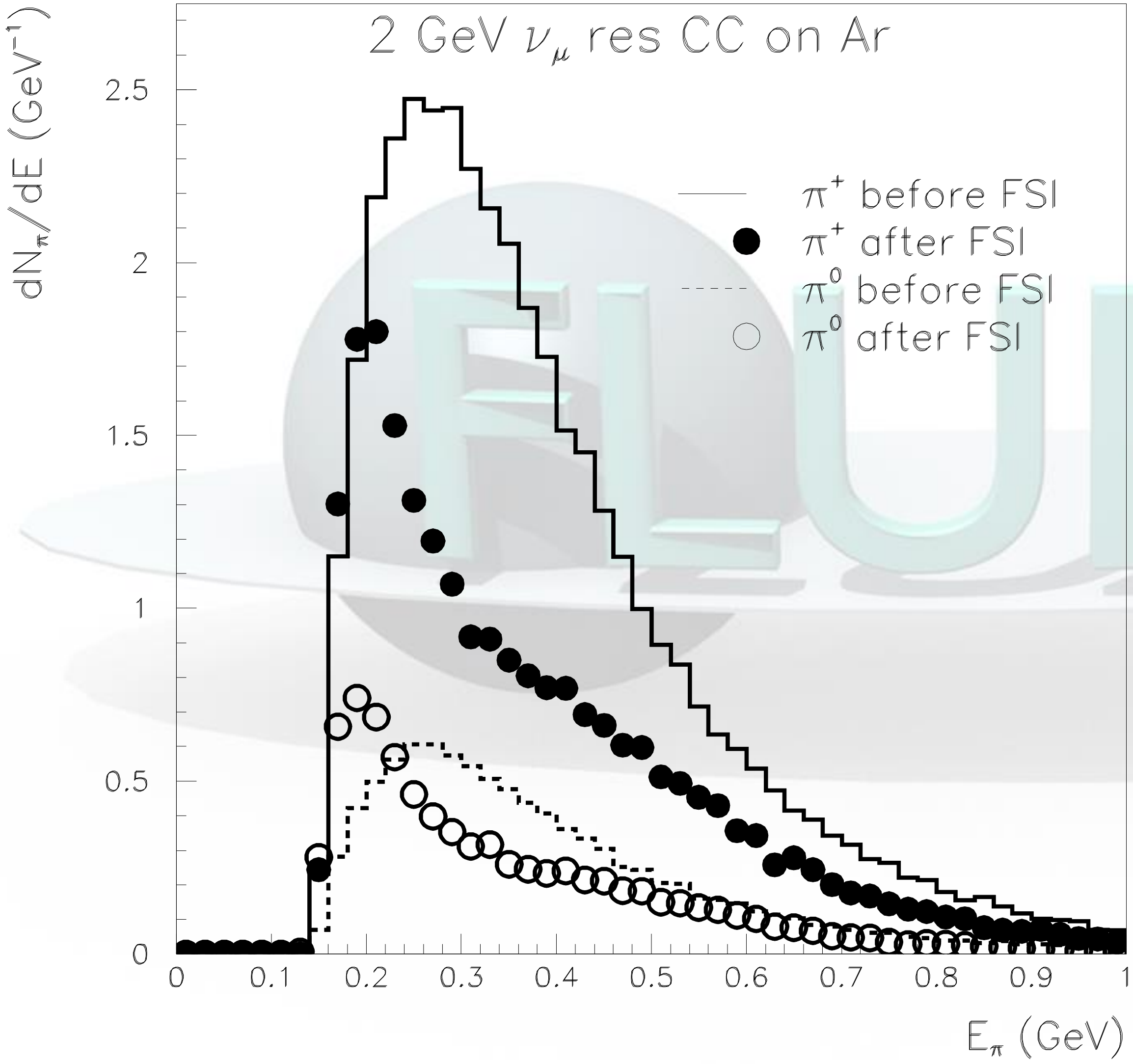
Pion absorption cross section on Gold and Bismuth in the Δ resonance region (multibody absorption in PEANUT)



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



Expected effect in Ar



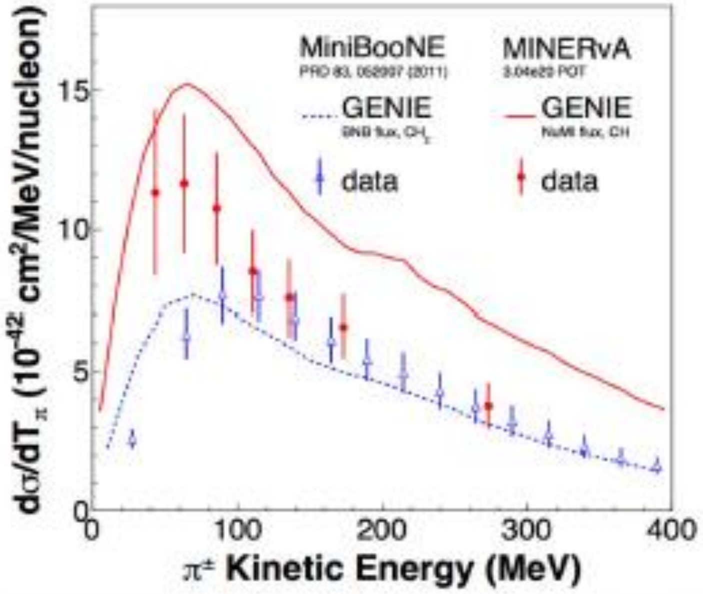
Example of expected effect:
2 GeV ν_μ CC RES interaction in Ar:
Pion production vs pion total E
Lines: before FSI
Symbols: after FSI

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

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.



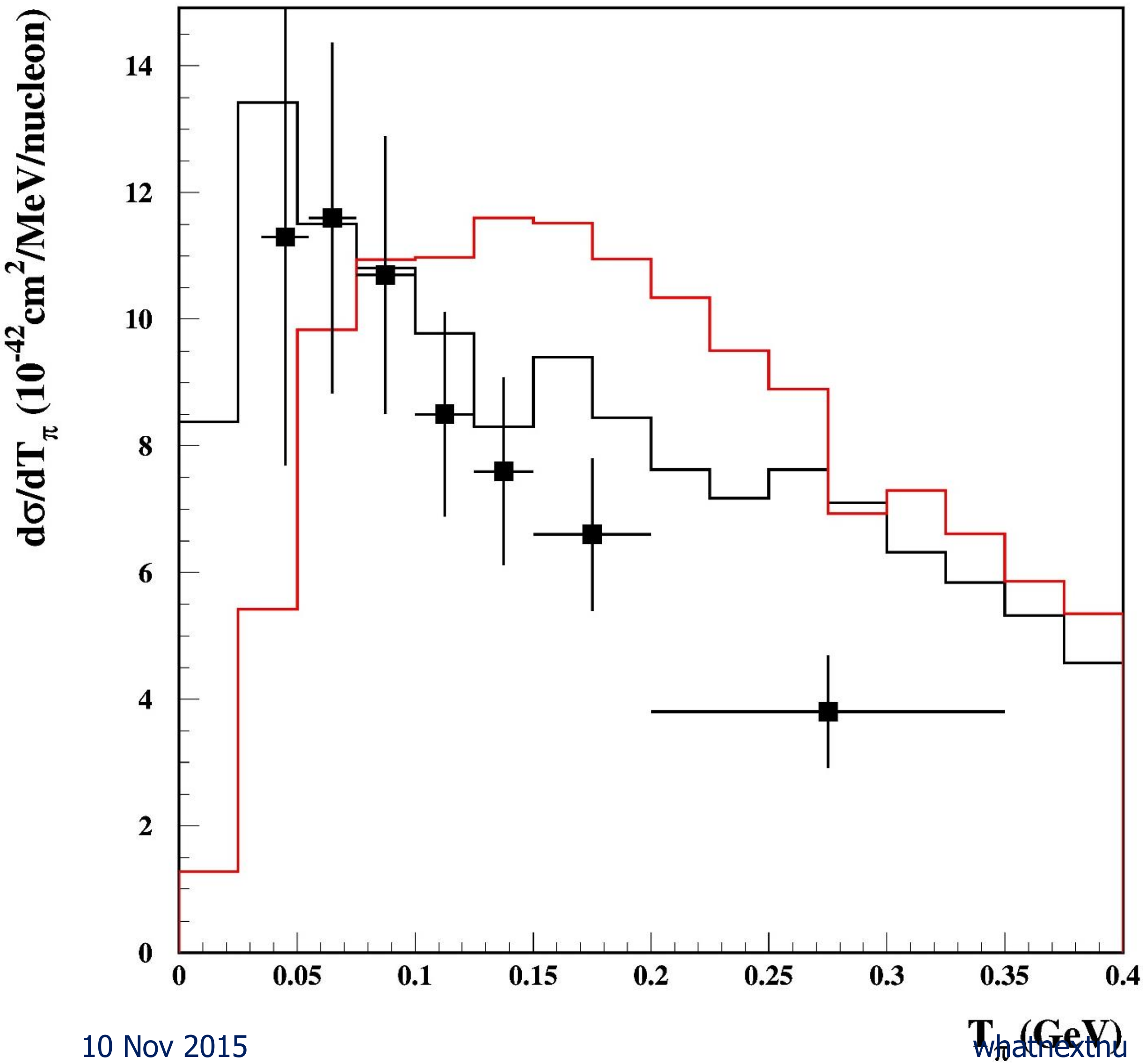
16 Dytman NUINT14 23 May, 2014

MiniBoone : CH_2, $E\nu \approx 0.8$ GeV, cut on single pion, PHYS. REV.D 83, 052007 (2011)

Minerva : CH, $E\nu \approx 4$ GeV, cut on W<1.4 arXiv:1406.6415v3 (2015)

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

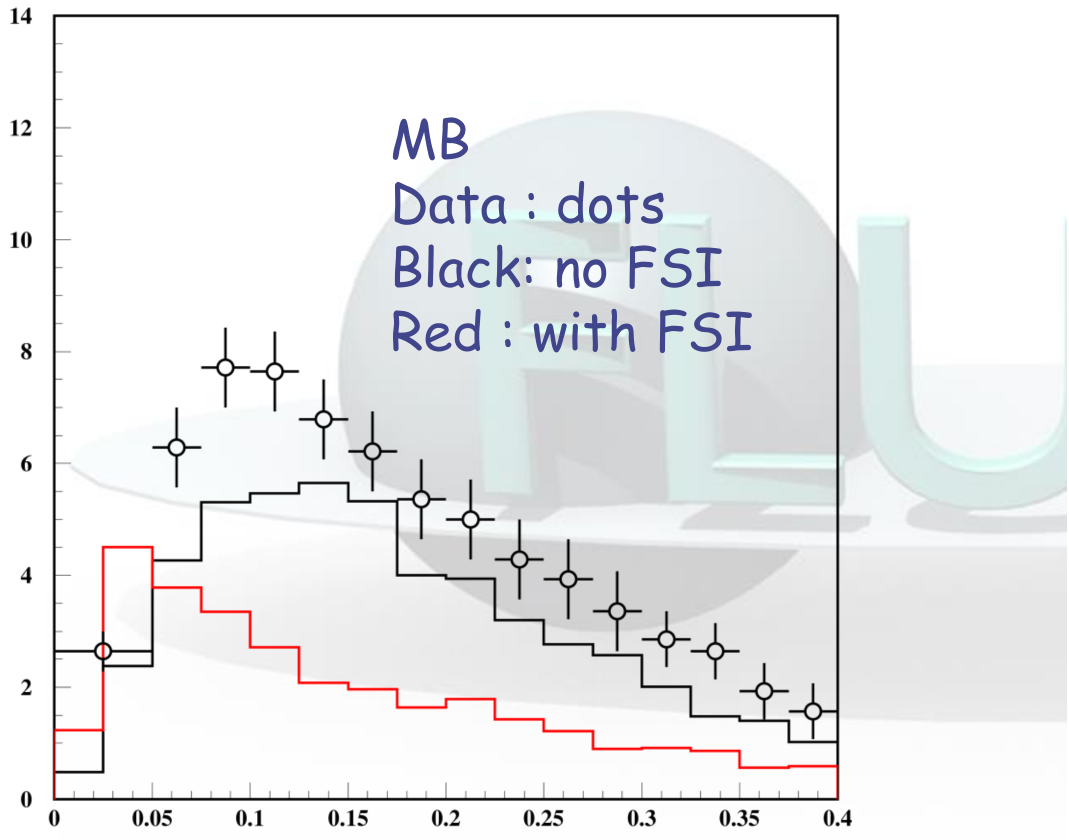
FLUKA (preliminary)

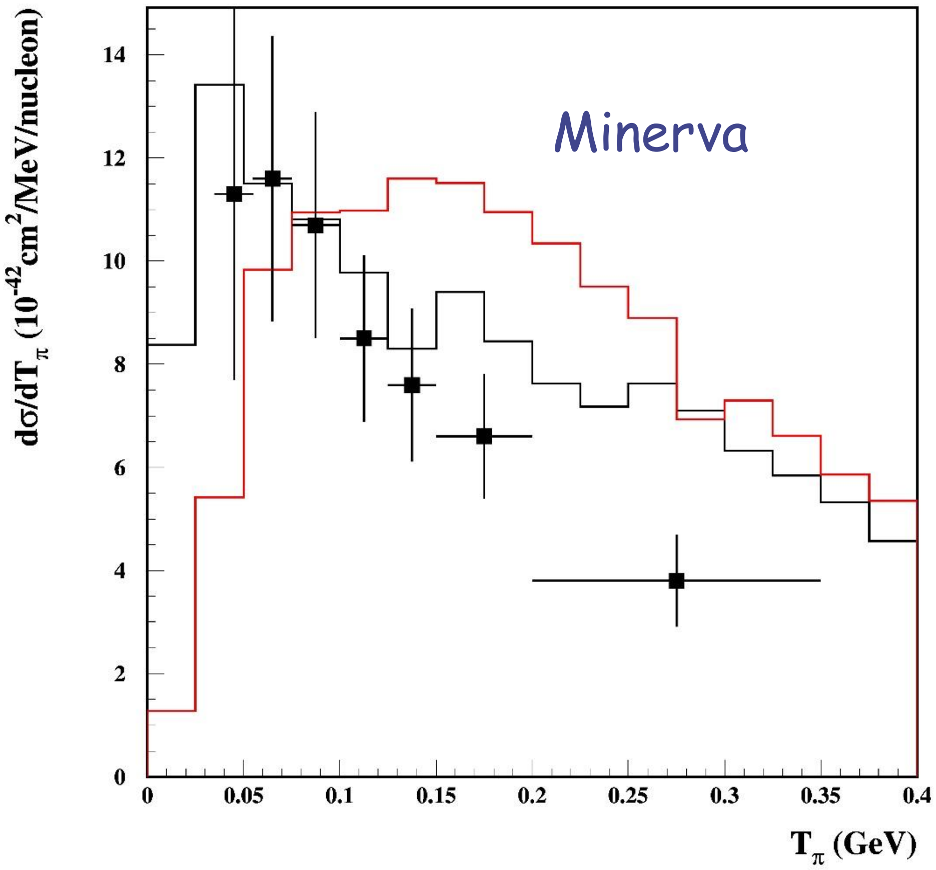


Absolute comparison with Minerνa data on pion production

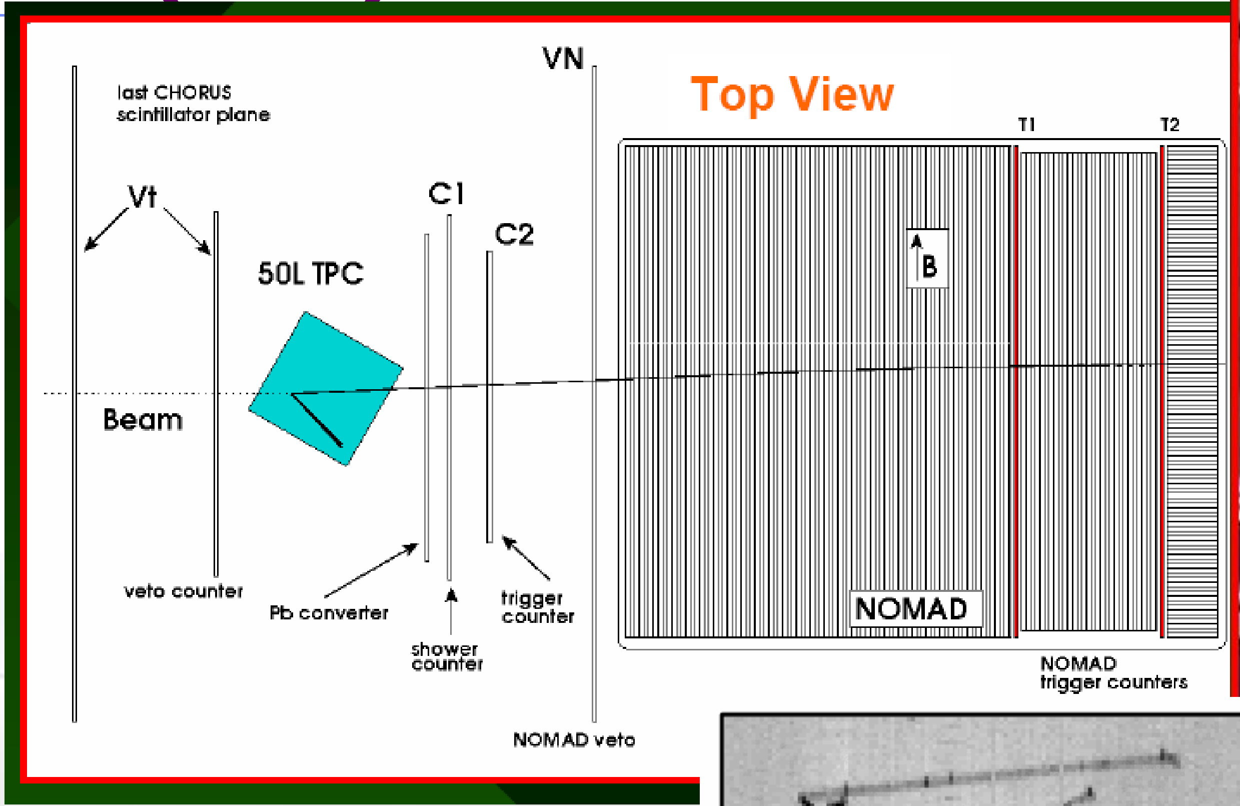
Red: no FSI
Black : with FSI
Symbols: Data

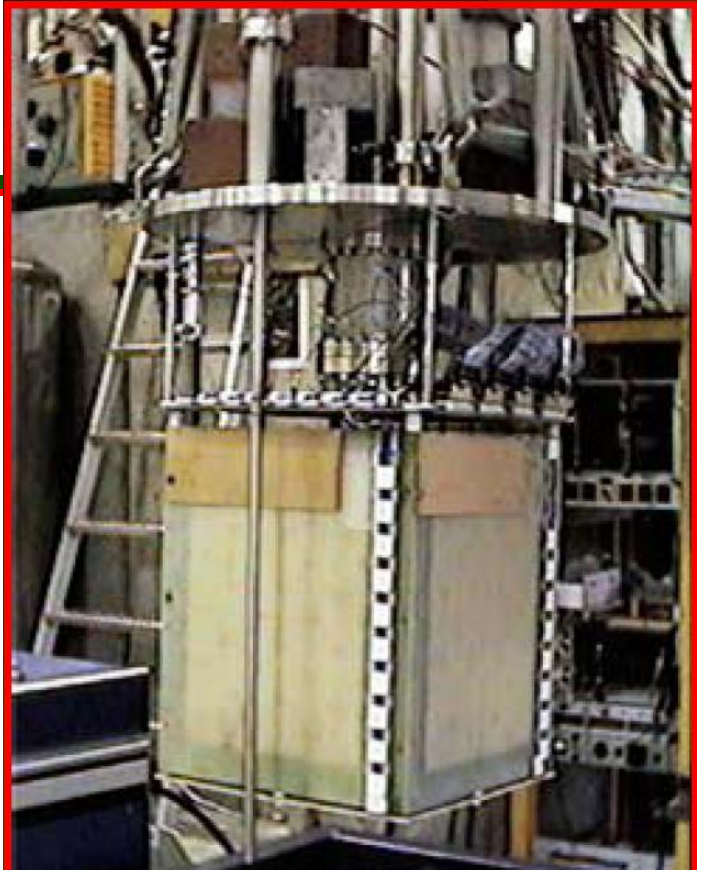
MB and Minerva

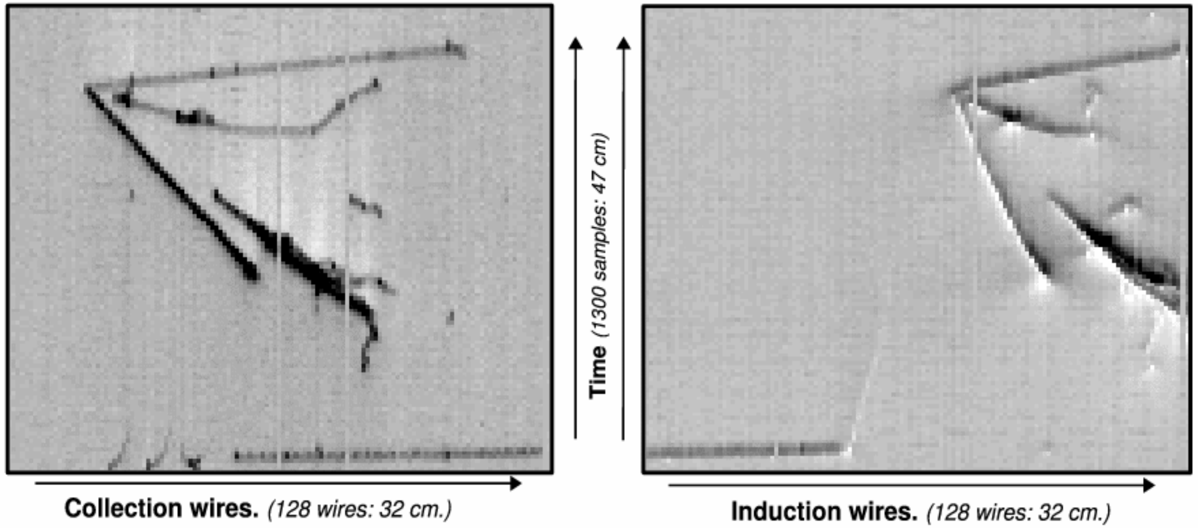




The 50l LAr TPC in the WANF neutrino beam(1997)



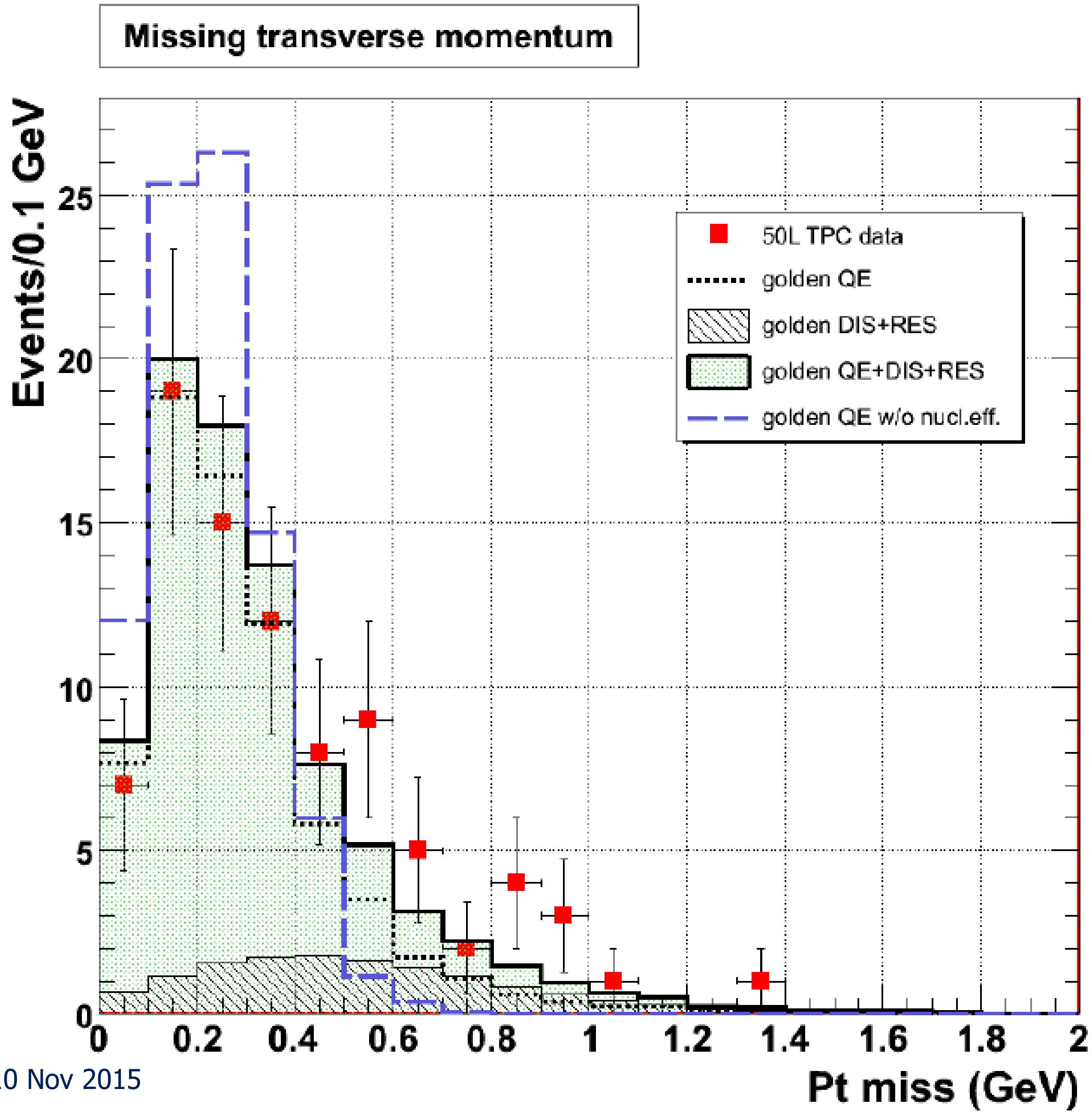




Trigger and μ reconstruction: NOMAD

Event selection: "GOLDEN sample" = 1 μ and 1 proton >40MeV fully contained

Phys.Rev. D74 (2006) 112001



- from 400 QE – golden fraction 16%
- background – additional 20%

finally expected

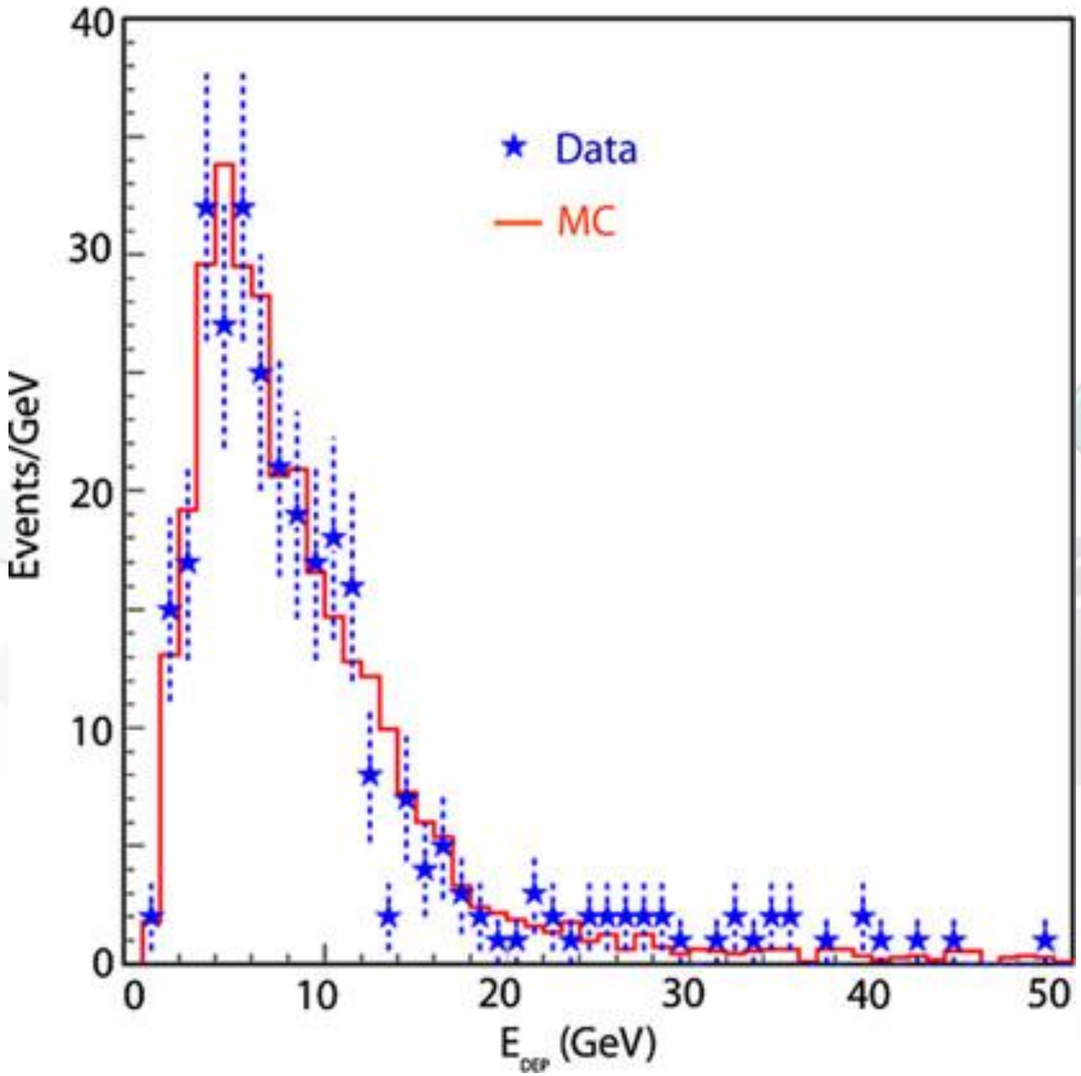
80±9(stat.)±13(syst.→ mainly QE fraction and beam simul)

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!

Backup

The FLUKA international Collaboration

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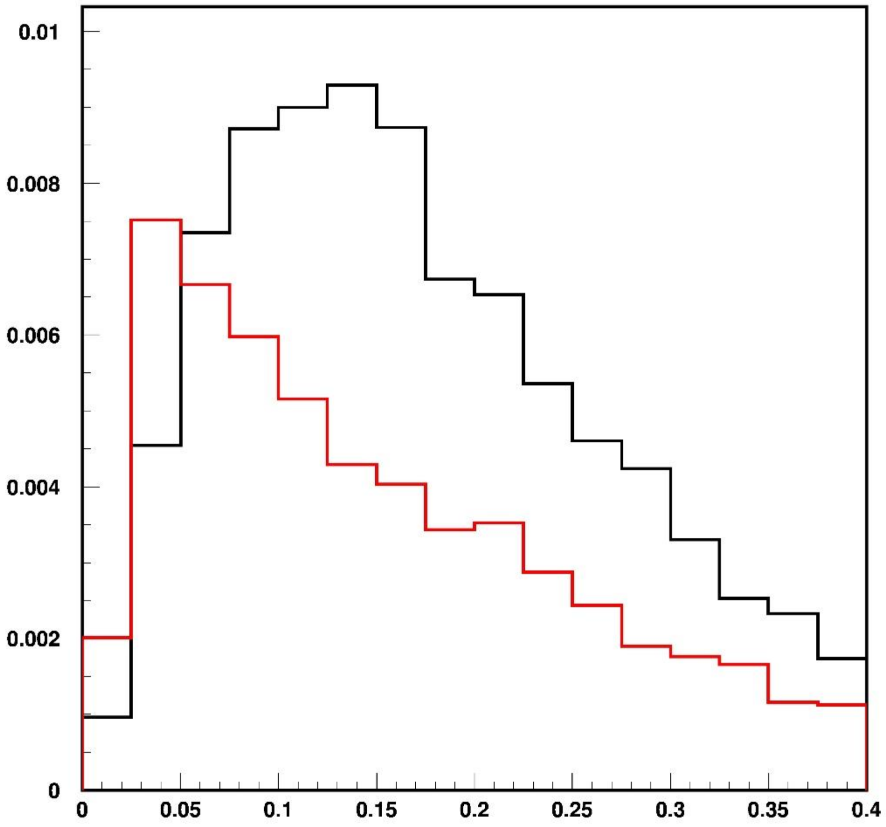

0.01
0.008
0.006
0.004
0.002
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

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

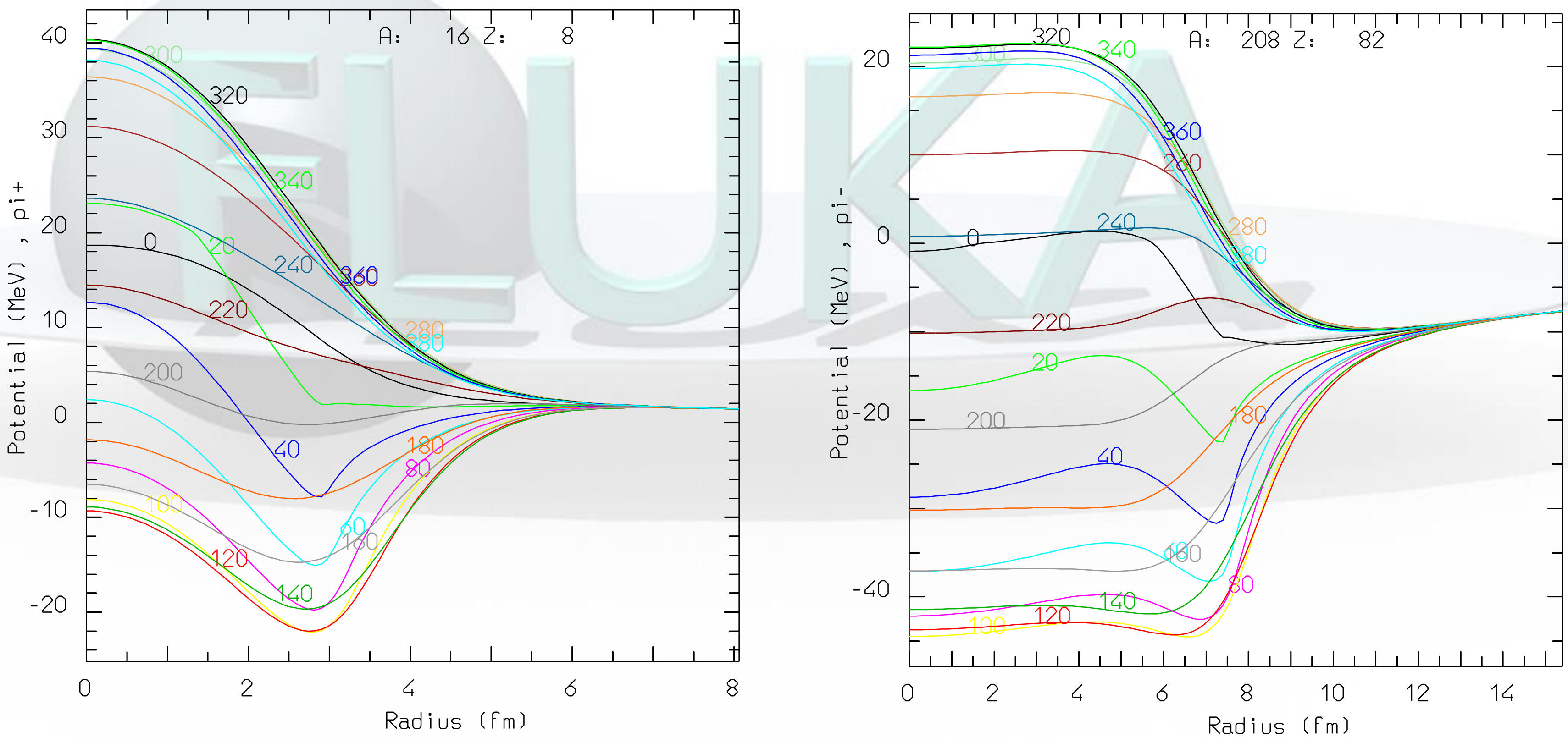
$$2\omega U_{opt}(\omega, r) = -\beta - K^2 \frac{\alpha}{1 + g\alpha} + \frac{\omega}{2M}\nabla^2 \alpha$$

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

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

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 Default	GRV94 Tested	GRV98 Default	GRV98 Tested	BBS Default	BBS Tested
E_{min} (GeV)	—	0.050					
E_{max} (GeV)	$\geq 10^4$	$70 \cdot 10^3$			10^5		
Q^2_{min} (GeV^2)	$\leq 5.5 \cdot 10^{-12}$	0.4	0.4	0.8	0.8	2	0.8
Q^2_{max} (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