Neutrino interactions in FLUKA: NUNDIS

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Neutrinos in FLUKA

- Generators of neutrino-nucleon interactions:
  - QuasiElastic
  - Resonance
  - DIS

Acta Phys.Polon. B40 (2009) 2491-2505
CERN-Proceedings-2010-001 pp.387-394.

- 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 interactions can be directly transported in the detector (or other) materials
- Used for all ICARUS simulations/publications

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

Quasi Elastic and Resonant

QE

- Following Llewellyn Smith formulation
- $M_A = 1.03$, $M_V = 0.84$
- Lepton masses accounted for

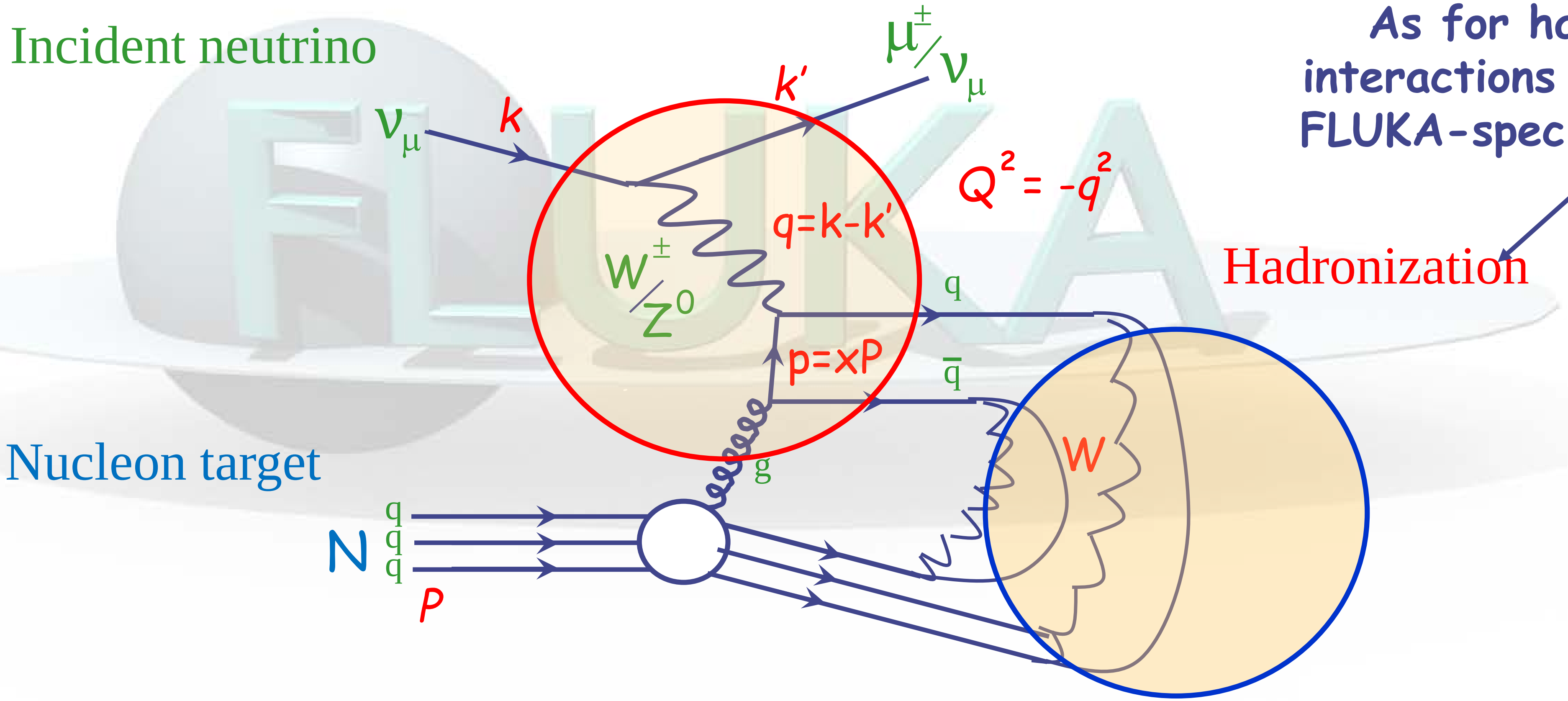
Resonance production

- 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

DIS (NUNDIS)

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



As for hadronic interactions in FLUKA
FLUKA-specific model

Sample x and Q^2 from double differential cross sections

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

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

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

$$F_2^{\nu p}(Q^2,x) = 2x[d+\bar{u}+s+\bar{c}]$$
$$xF_3^{\nu p}(Q^2,x) = 2x[d-\bar{u}+s-\bar{c}]$$

$$A_1 = y\left(xy+\frac{m_\ell^2}{2ME_\nu}\right)$$
$$A_2 = 1-y\left(1+\frac{Mx}{2E_\nu}\right)-\frac{m_\ell^2}{4E_\nu^2}$$
$$A_3 = \pm y\left[x\left(1-\frac{y}{2}\right)-\frac{m_\ell^2}{4ME_\nu}\right]$$
$$A_4 = \frac{m_\ell^2}{2ME_\nu}\left(y+\frac{m_\ell^2}{2ME_\nu x}\right)$$
$$A_5 = -\frac{m_\ell^2}{ME_\nu}$$

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:
$$F_4 = 0\,,$$
$$F_5 = \frac{F_2}{x}.$$

Quark dependence $q_i(Q^2,x)$ determined from Parton Distribution Functions (PDFs)

www.fluka.org

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.
...	

NUNDIS WORKS WITH THESE PDFs

DEFAULT OPTION

In the NLO (DIS) version

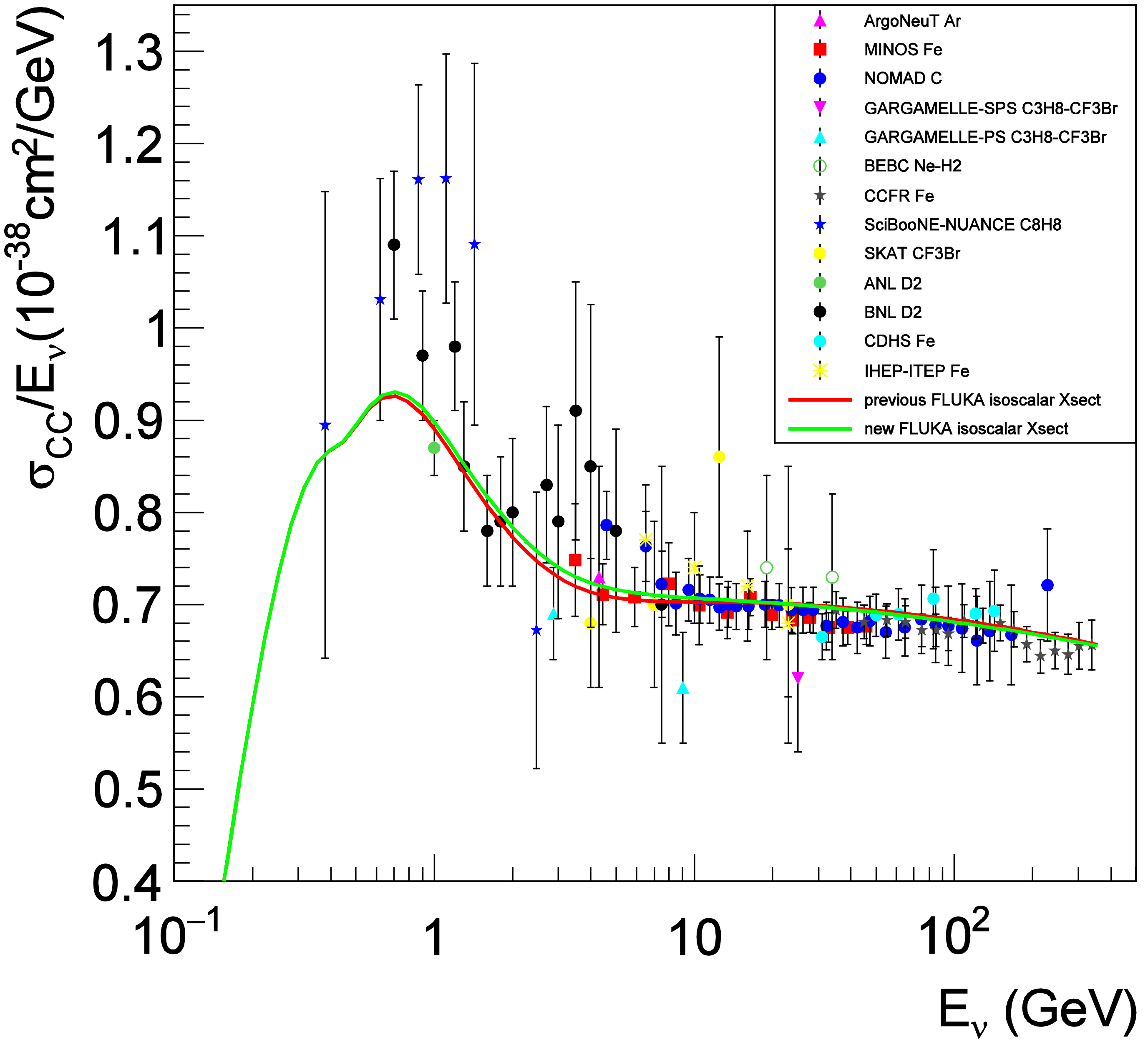
M. Gluck, E. Reya and A. Vogt, Eur. Phys. J. C5 (1998) 461

With extrapolation to $Q^2 = 0$ as in

M. Bertini et al. 1996

Comparison with data on total cross section

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



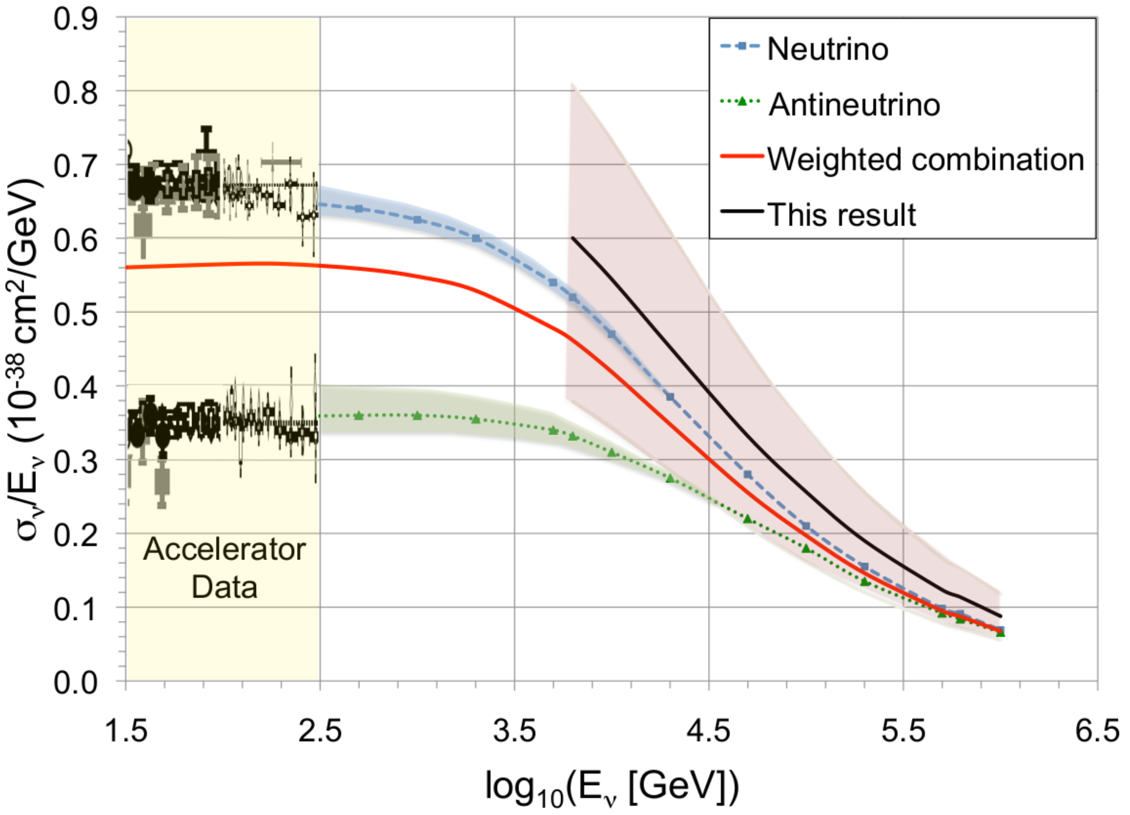
At higher energies

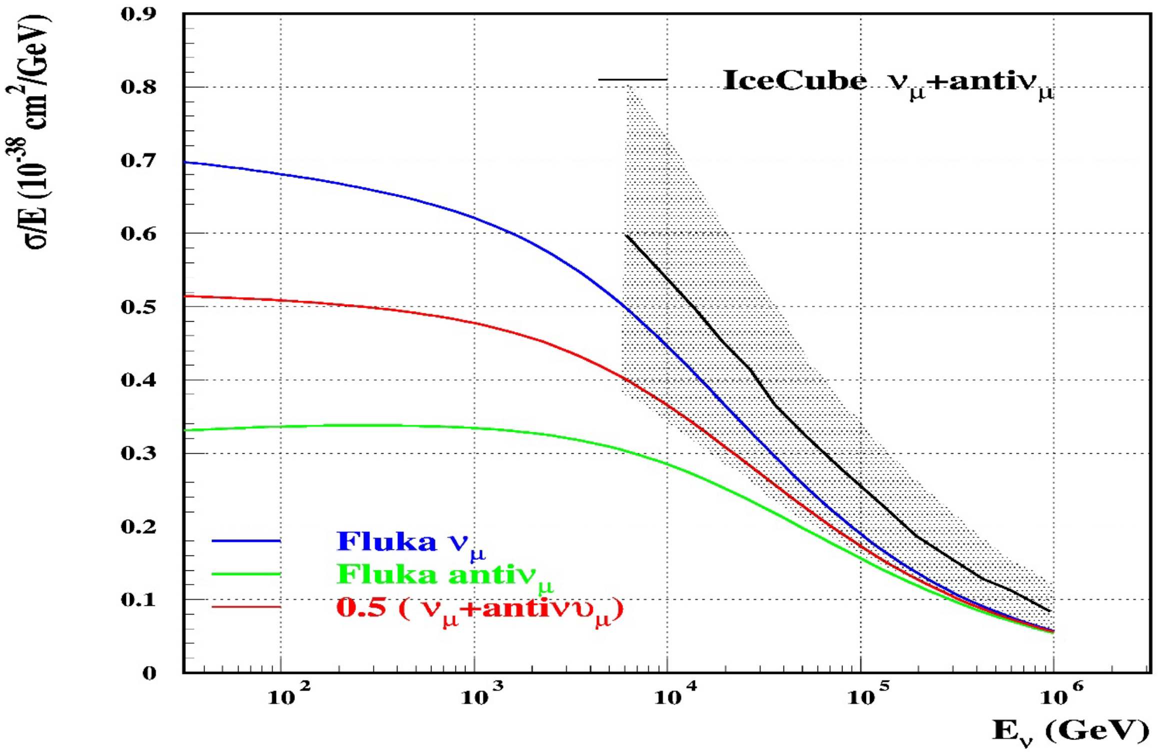
IceCube cross section data, Muon neutrino and antineutrino , "weighted combination" ?

arXiv:1711.08119 , *Nature* **51**,596 (2017)

Blue and green: "standard model predictions"

FLUKA results





Hadronization

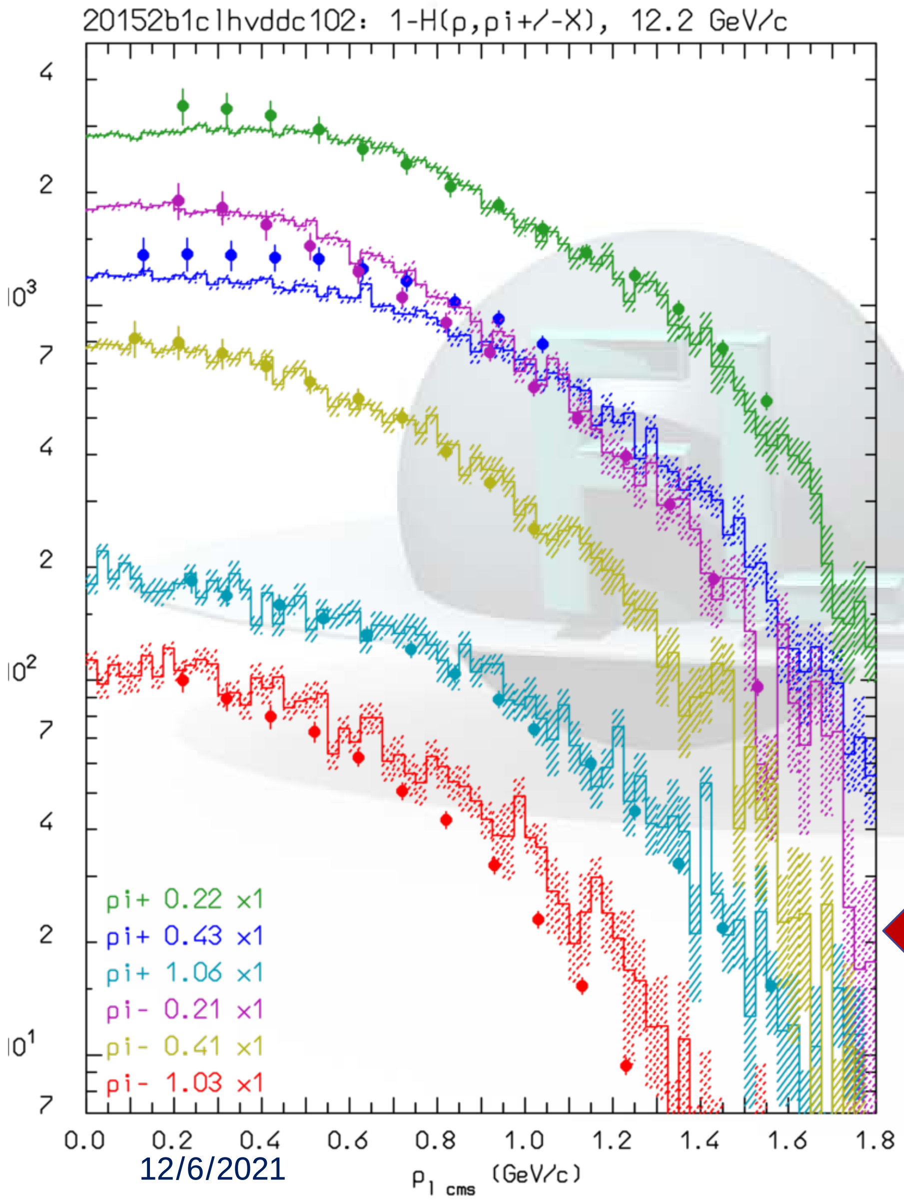
Implementation FLUKA-native (evolution of old BAMJET)

- Assumes chain universality
- Fragmentation functions from hard processes and e+e− scattering
- Transverse momentum from uncertainty considerations
- Mass effects at low energies (change fragmentation function to account for the need to create real hadrons)
- Chains generated at very low energy→ create single resonances
- Chains generated at low energy → **"phase space explosion"** constrained in p_T , including baryons, mesons, resonances.

The same functions and parameters for all reactions and energies

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

Effect of low √s chain treatment (see later for ν)

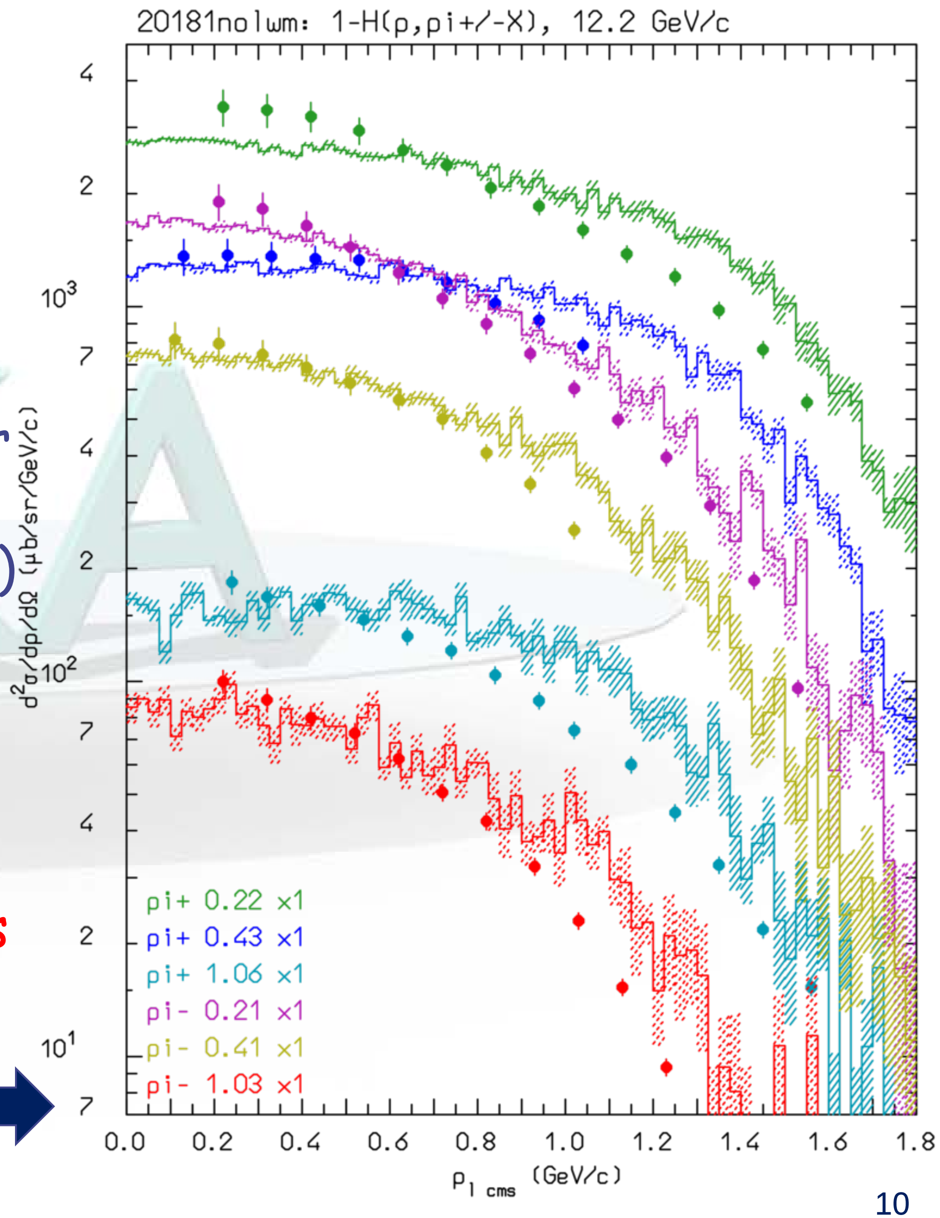


Pion+ production
From p-p collisions
At 12.2 GeV/c

Longitudinal momentum in cms for different p_T^2 values
PRL 23, 1055 (1969)
(ZGS Argonne)

Data ==points
Fluka == histos

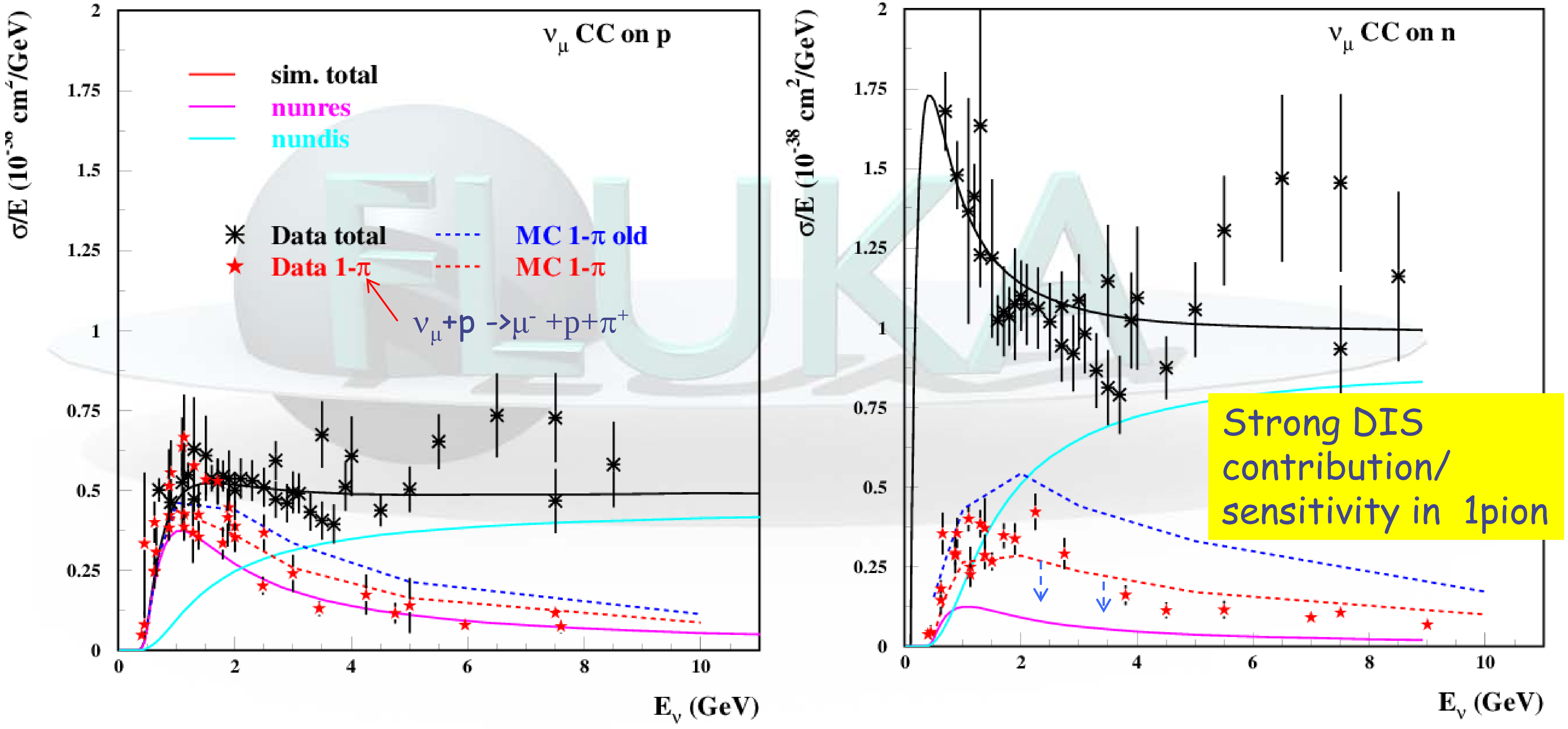
Left: with low mass phase space hadronization
Right: without



Single pion production

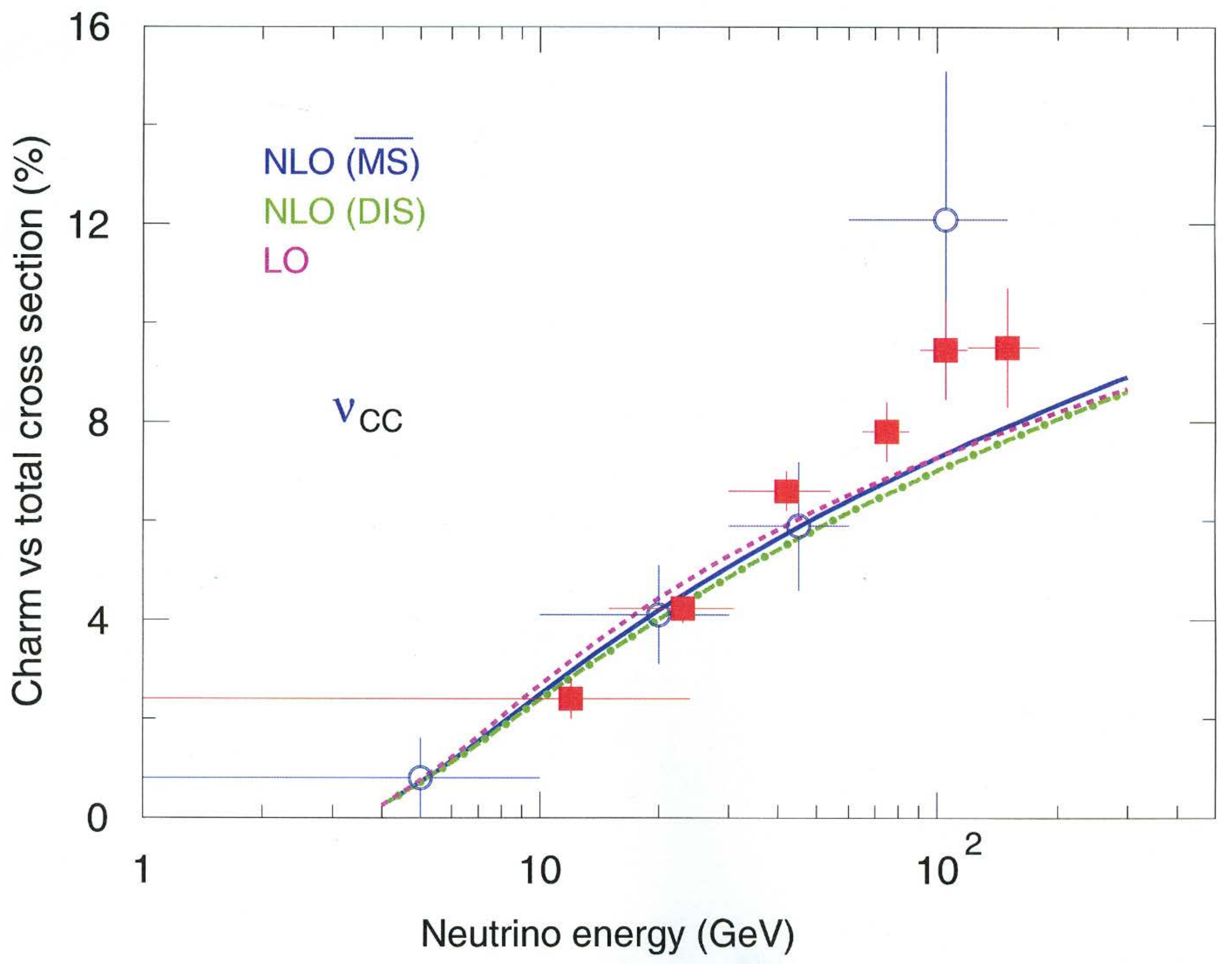
NDS 120, 211 (2014)

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



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).



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}

Nucleon Fermi Motion in FLUKA

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

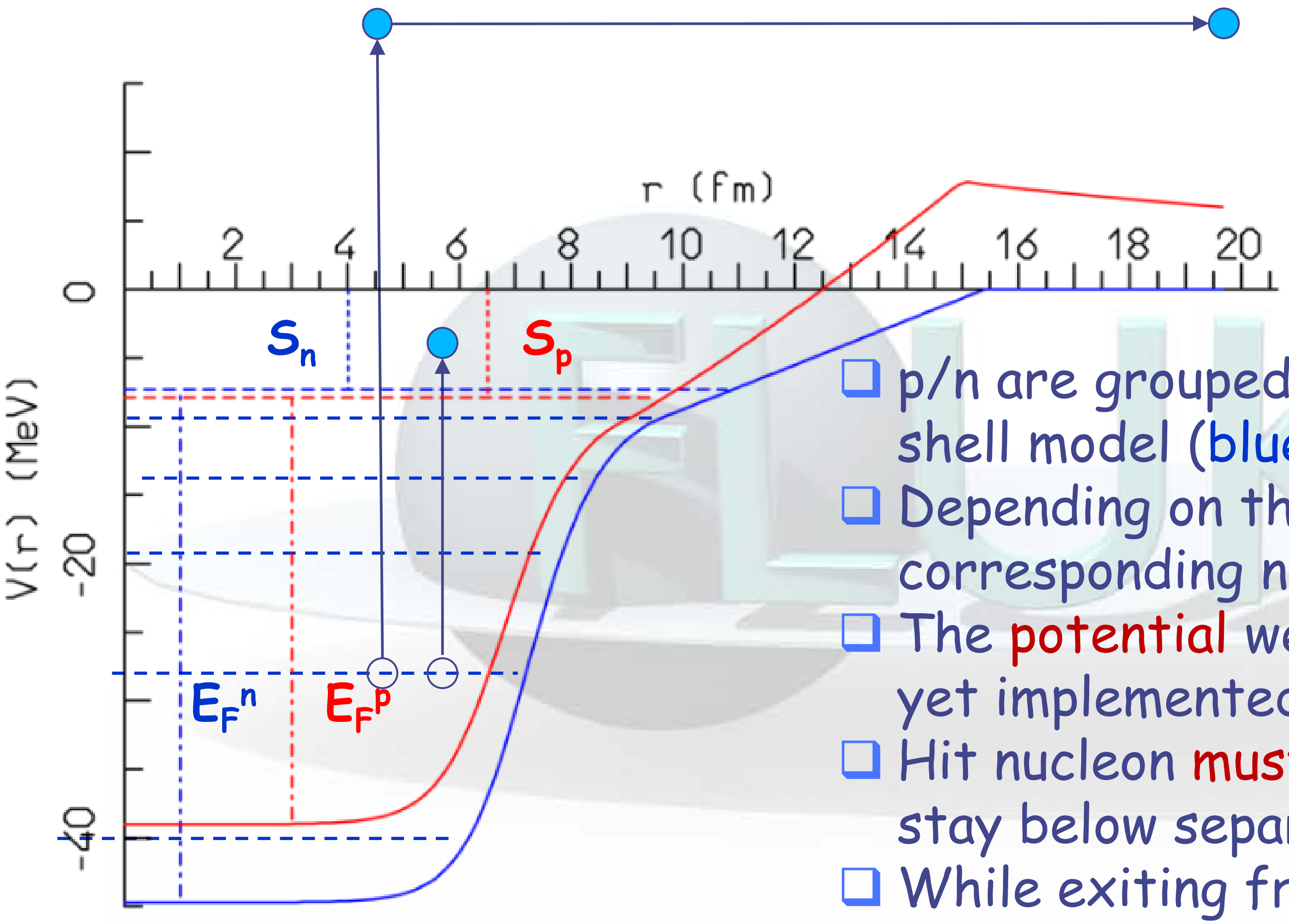
  Momentum distribution $\propto \frac{dN}{dk} = \frac{|k|^2}{2\pi^2}$

  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
- Nucleons are bound in the nuclear well

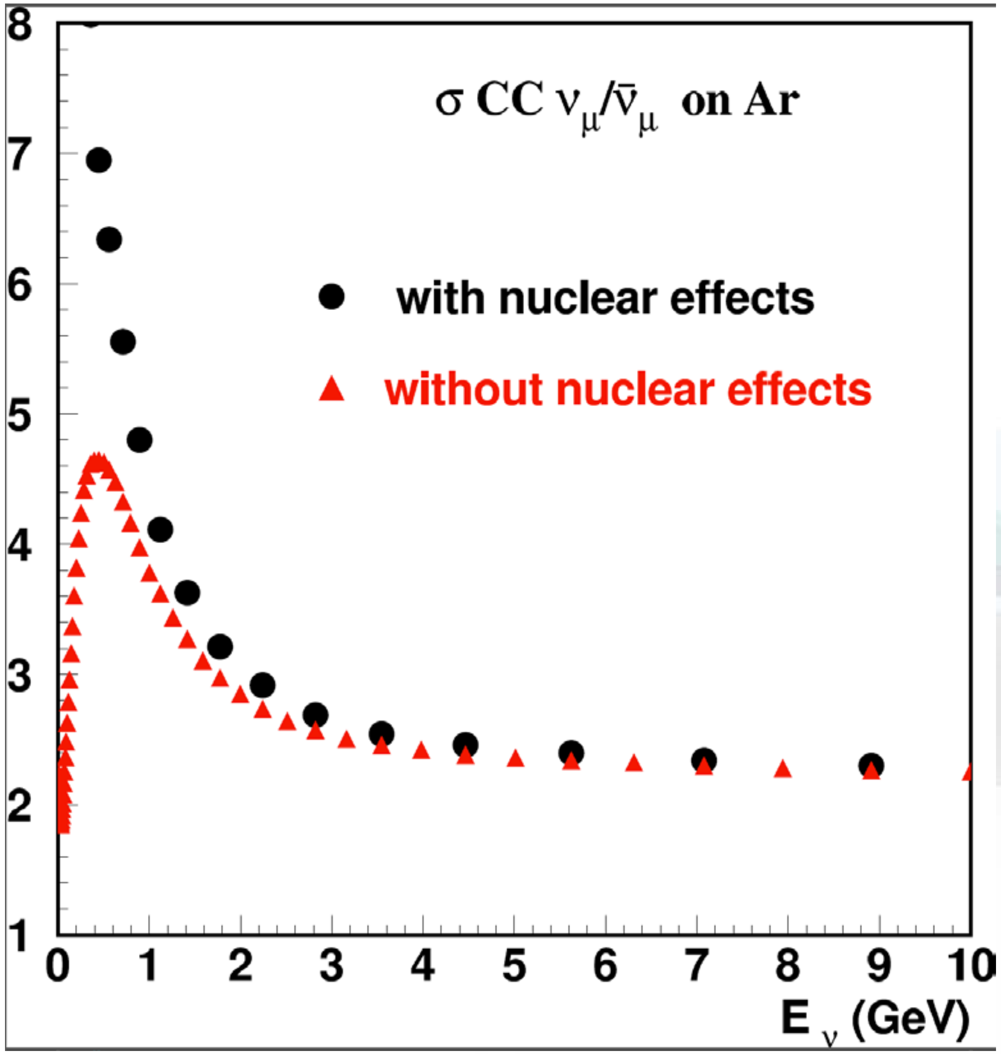
Nucleon levels inside the nuclear potential: schematic drawing



- Blue: neutron
- Red: proton

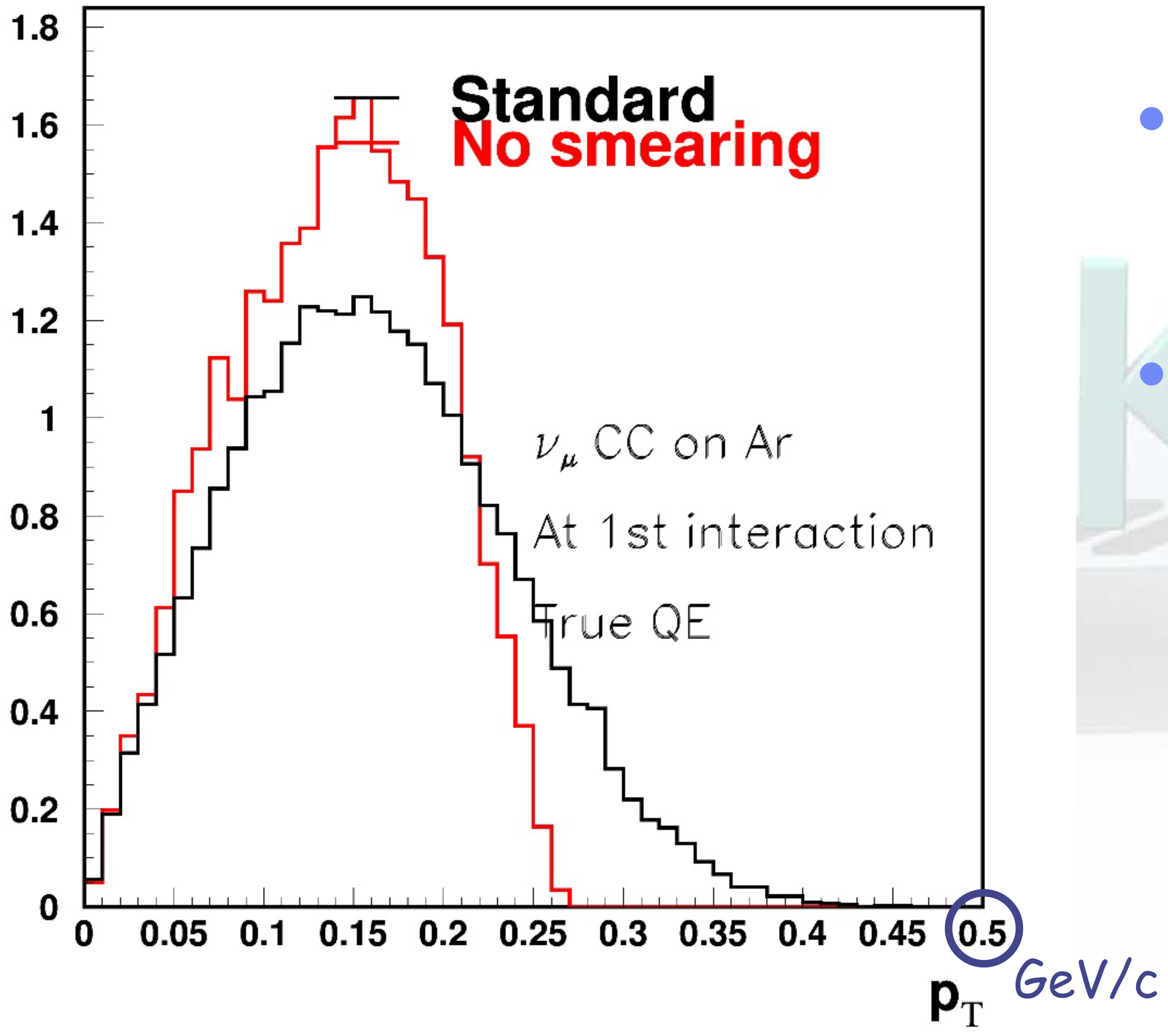
- p/n are grouped on energy levels spaced according to the shell model (blue lines, shown for neutrons)
- Depending on the level, the maximum radius for the corresponding nucleon is less or equal to the nuclear radius
- The potential well depth depends on the nucleon energy (not yet implemented for neutrino and electron interactions)
- Hit nucleon must go above Fermi level (Pauli blocking), can stay below separation energy.
- While exiting from the nucleus, the nucleon moves in the nuclear potential, changing kinetic energy and direction
- The residual nucleus is often left in an excited state ➔ particle emission
- Changing A or Z ➔ Q value

Pauli + Q value example



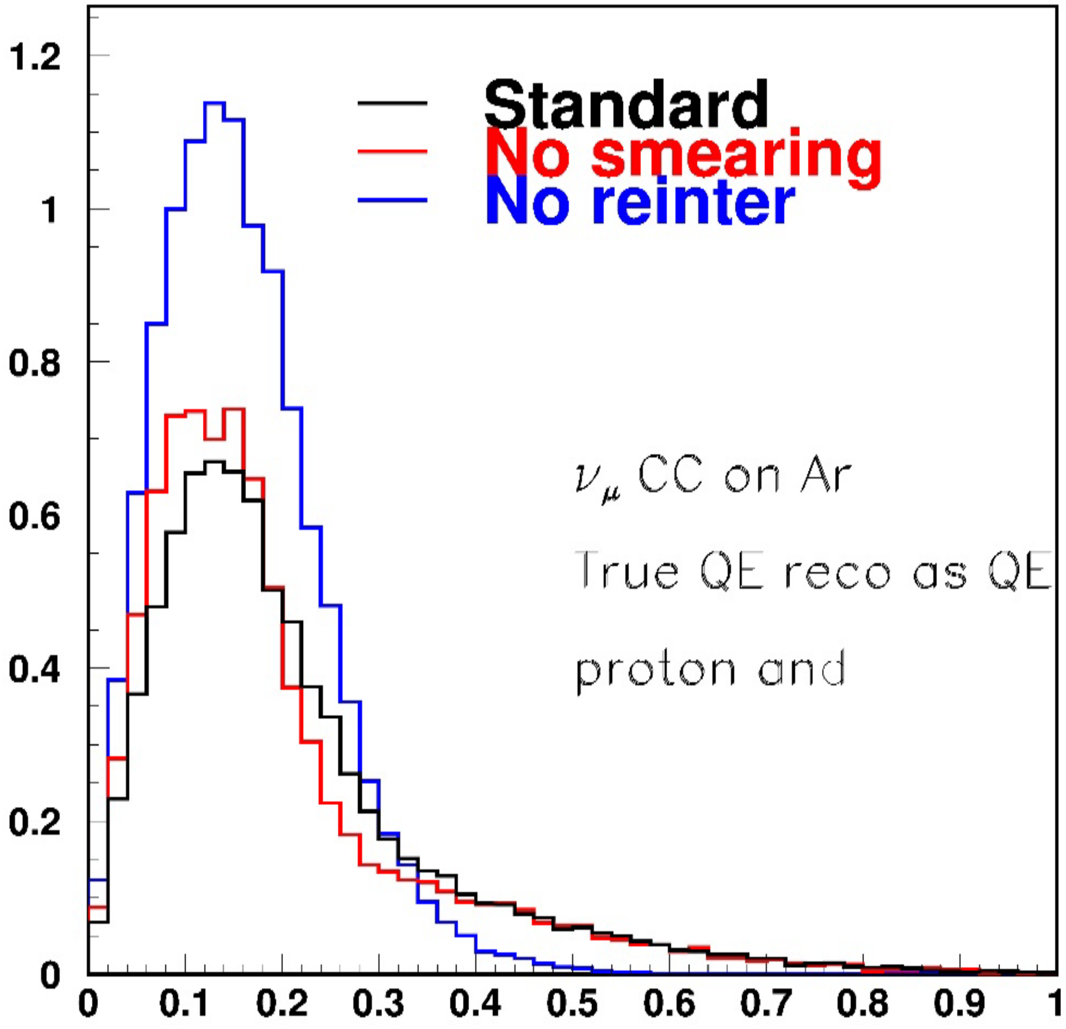
- ν_μ CC interactions on Ar : ratio of neutrino/antineutrino cross section vs neutrino energy
- Antineutrino: lower q^2 ➔ more sensitivity to Pauli blocking and reaction Q value (few-MeV more unfavorable in case of anti-nu)

Momentum smearing on Fermi: example

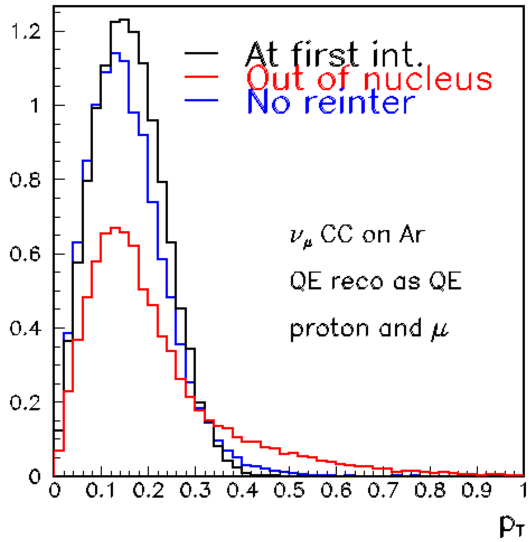


- ν_μ CC interactions on Ar. Neutrino energy spectrum as in DUNE (~3GeV)
- Plot: total transverse momentum (proton + muon) from QE interactions at the primary interaction, before ANY final state effect.
- With (black) and without fermi momentum smearing

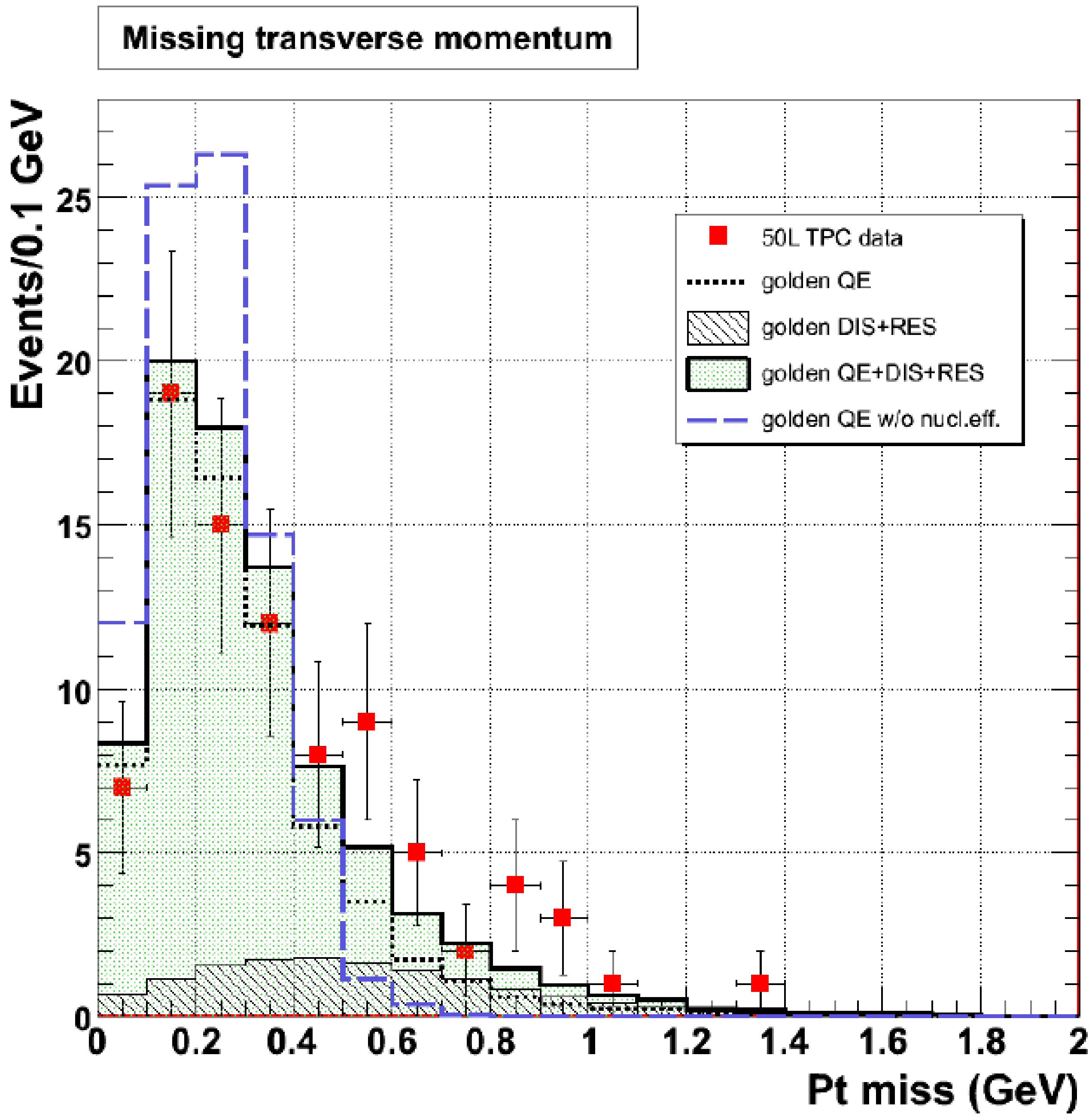
Fermi momentum: smeared by FSI



- ν_μ CC interactions on Ar. Neutrino energy spectrum as in DUNE (~3GeV)
- Plot: total transverse momentum (proton + muon)
- QE interactions reconstructed as QE interactions (1p, 1μ, no thresholds) outside the nucleus.
- With and without smearing, with and without reinteractions (effects of the nuclear binding/potential are always in)



The 50l LAr TPC in the WANF neutrino beam



Phys.Rev. D74 (2006) 112001

- Broad band spectrum, <E>=24.3 GeV
- 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)

a special FSI : 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

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

Note: in the particle frame, not lab

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:

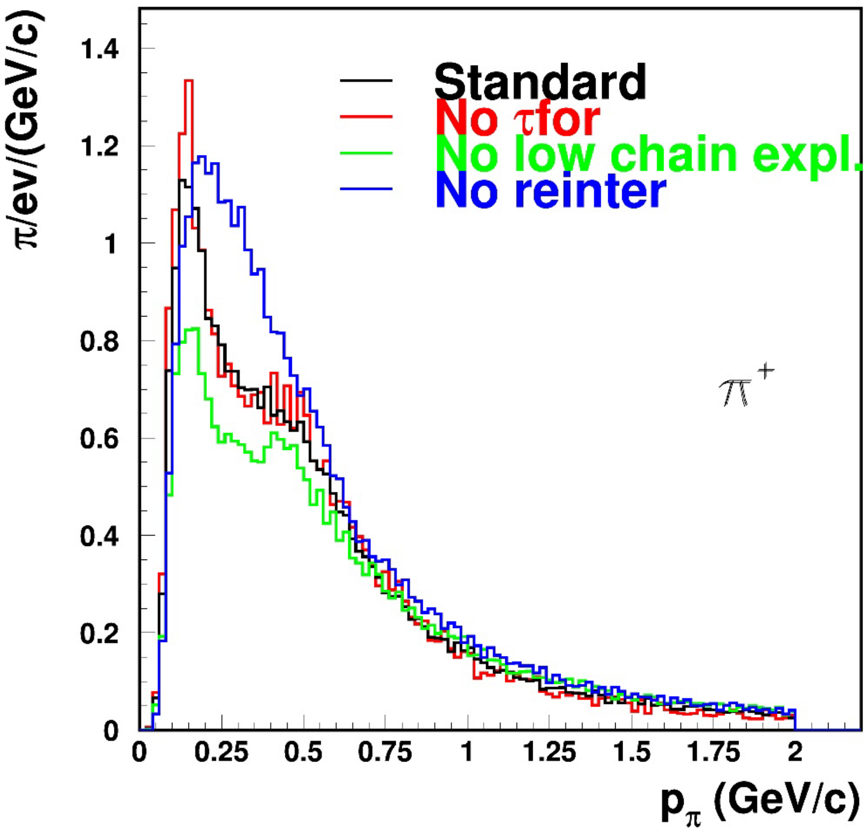
$$\Delta x_{for} \leq R_A \approx r_0 A^{\frac{1}{3}}$$

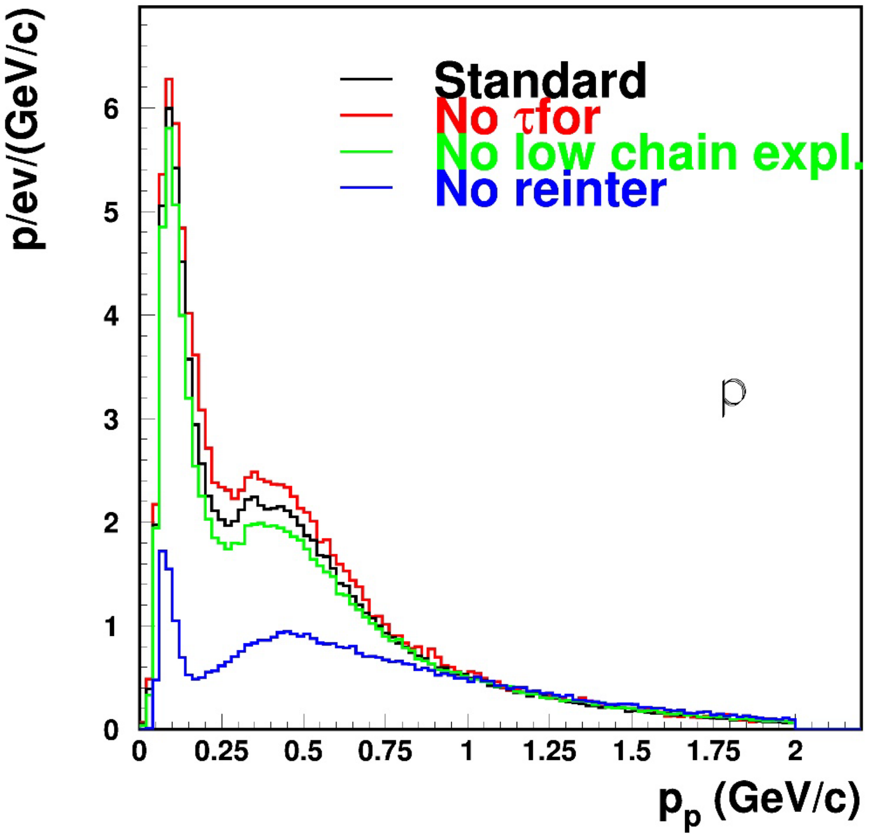
Decrease of the reinteraction probability, ~proportional to particle momentum

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

Effect of Formation zone etc.

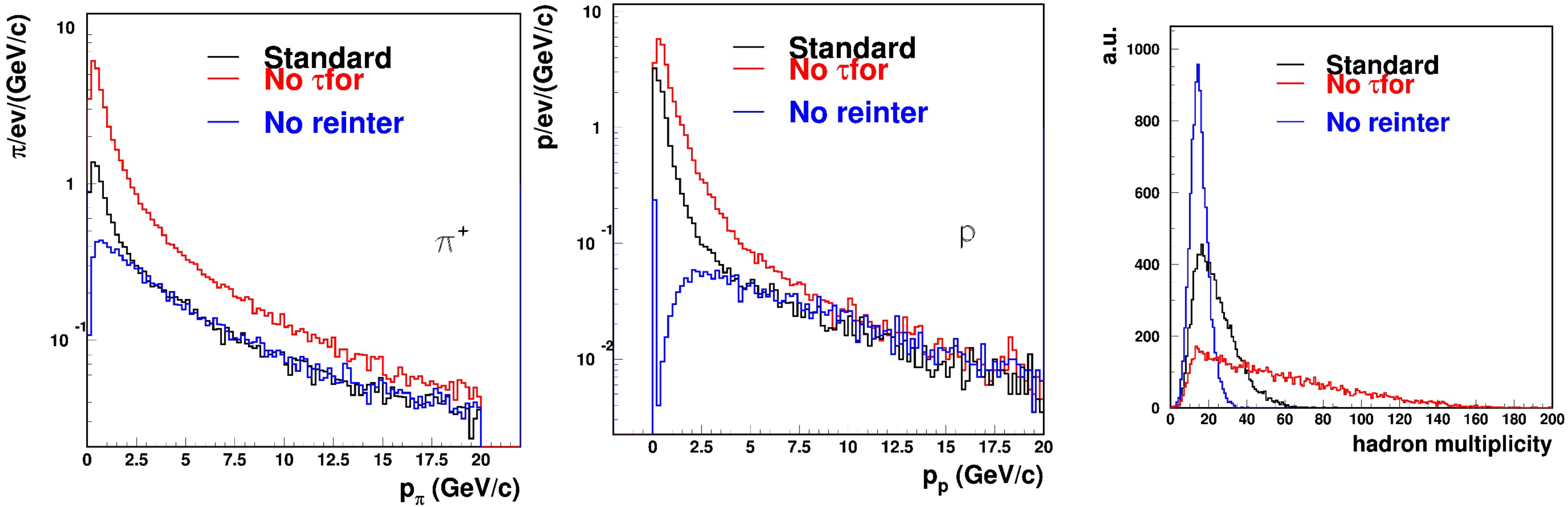
- DUNE spectrum, numu-CC on Ar. Pion (left) and proton (right) momentum spectra in various conditions, cut at 2 GeV/c.
- Note the effect of DIS treatment on pions, of reinteractions on both..in opposite way
- Formation zone has a small effect at these energies



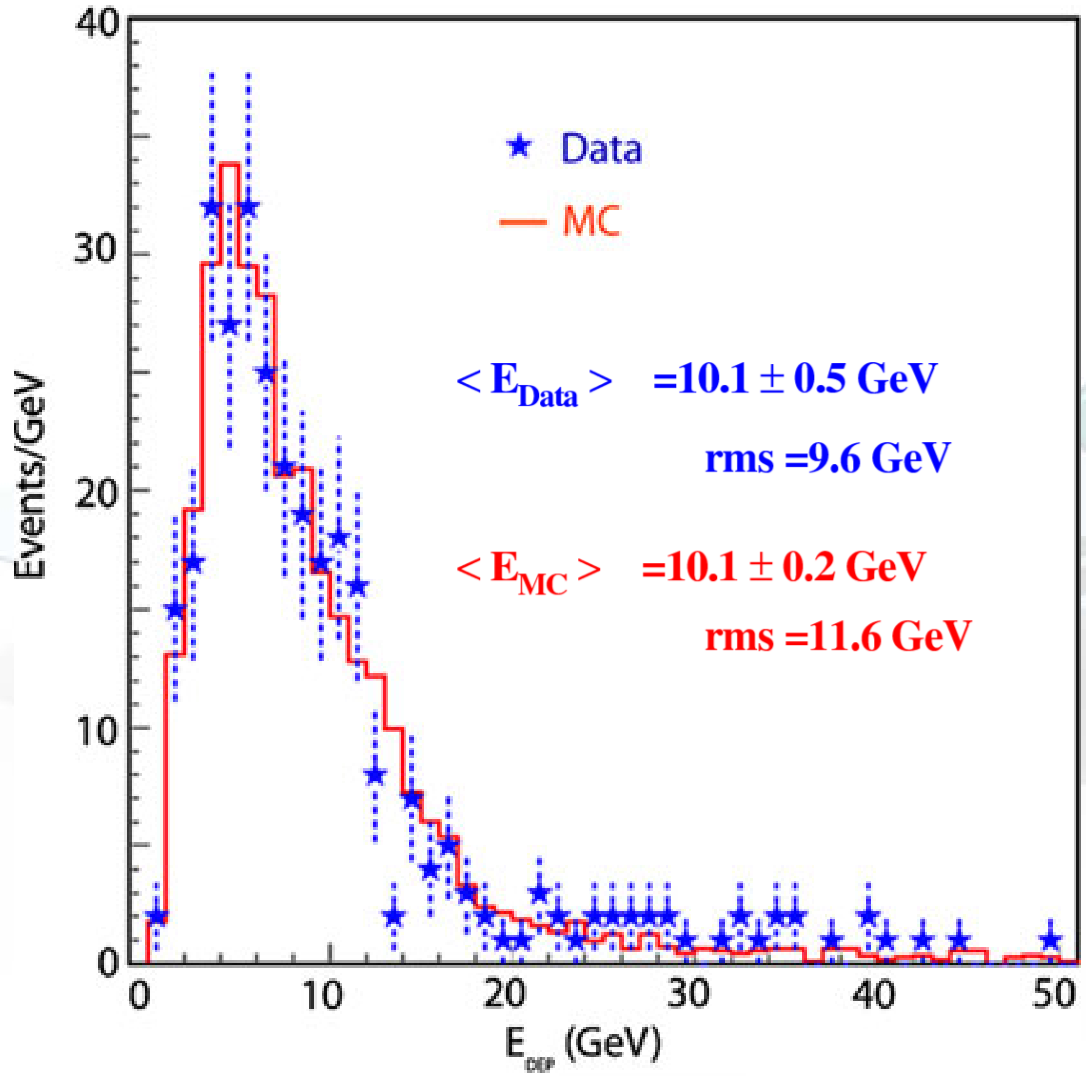


Effect of Formation zone etc., 1TeV

- 1TeV neutrinos, numu-CC on Ar, spectra cut at 20 GeV/c
- Here the formation zone has a huge effect



CNGS data



Distribution of total deposited energy in the T600 detector
CNGS numuCC events (~20 GeV Eν peak)

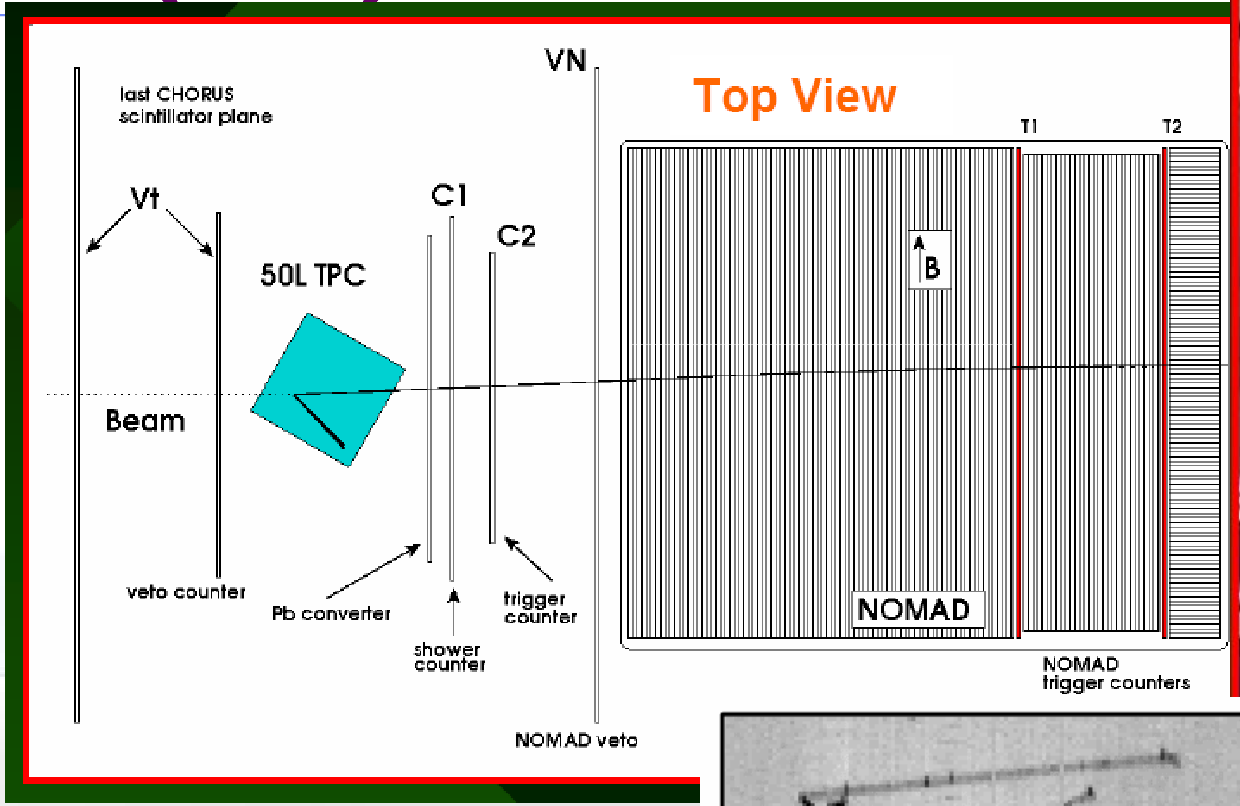
Same reconstruction in MC and Data
Neutrino fluxes from FLUKA cngs simulations

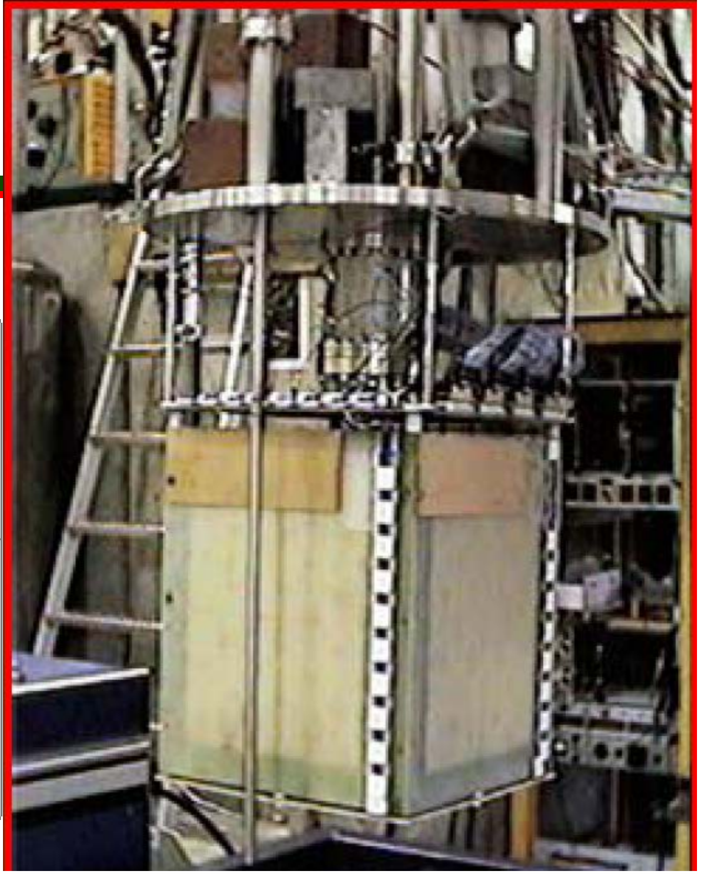
Absolute agreement on neutrino rate within 6%

Eur. Phys. J. C (2013) 73:2345
Phys. Lett. B (2014)

Backup

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

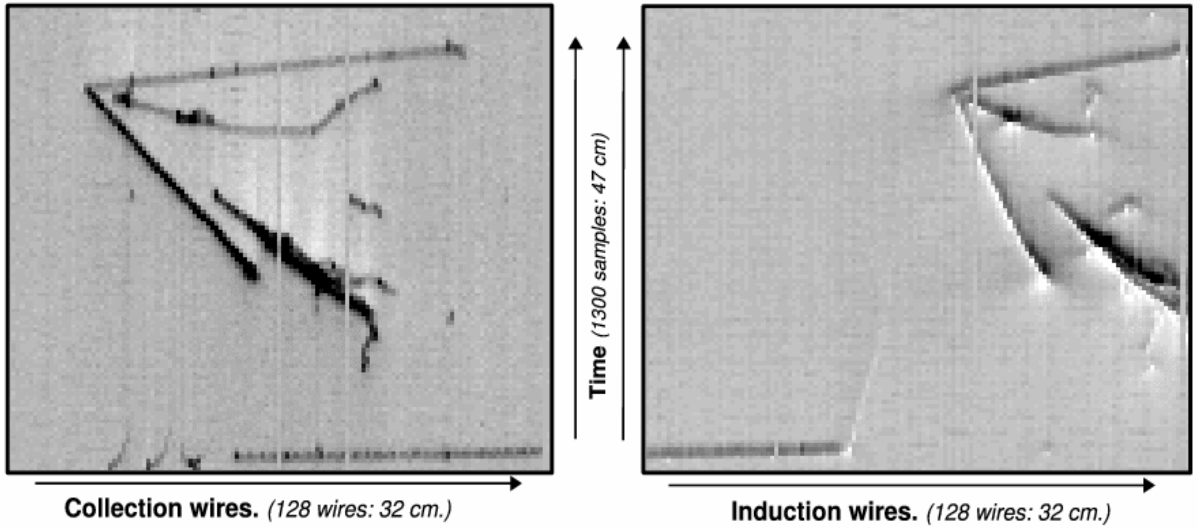




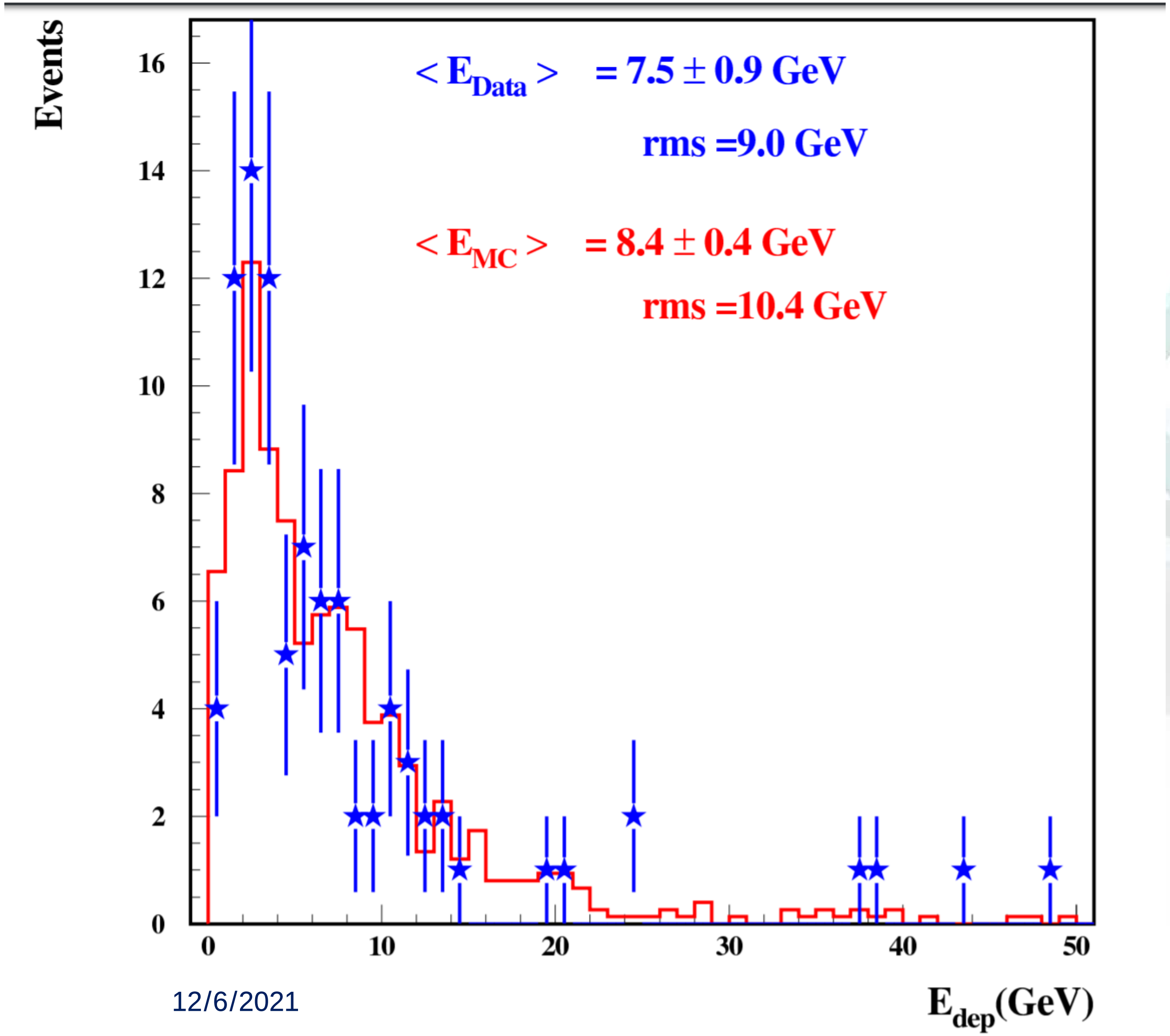
Trigger and μ reconstruction: NOMAD

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

Phys.Rev. D74 (2006) 112001



CNGS data



Distribution of total deposited energy in the T600 detector
CNGS nuNC

Same reconstruction in MC and Data
Neutrino fluxes from FLUKA cngs simulations

Only events with Edep > 500 Mev

Nuclear cascade in lowenergy nuclear breakup

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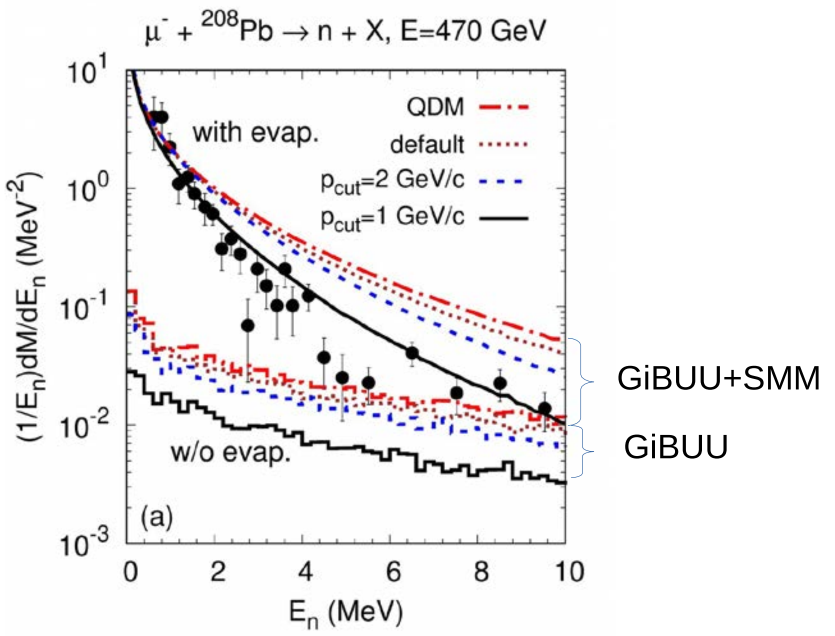
In collaboration with

Mark Strikman

Pennsylvania State University, University Park, PA 16802, USA

CFNS Adhoc Workshop: Target Fragmentation Physics with EIC, 28-30.09.2020

The neutron spectrum contains both the preequlibrium part (cascade particles) and the equilibrium part from the decay of the excited residual nucleus.



E665 data from
M.R. Adams et al., PRL 74, 5198 (1995)

Cuts:
$\nu > 20$ GeV,
$Q^2 > 0.8$ GeV^2.

- almost all neutrons below 1 MeV are statistically evaporated;
- sensitivity to the model of hadron formation for $E_n > 5$ MeV;
- E665 data for lead target can be only described with very strong restriction on the FSI of hadrons (p_{cut}=1 GeV/c) in agreement with earlier calculations M. Strikman, M.G. Tverskoy, M.B. Zhalov, PLB 459, 37 (1999)

AL, M. Strikman, PRC 101, 014617 (2020), arXiv:1812.08231

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

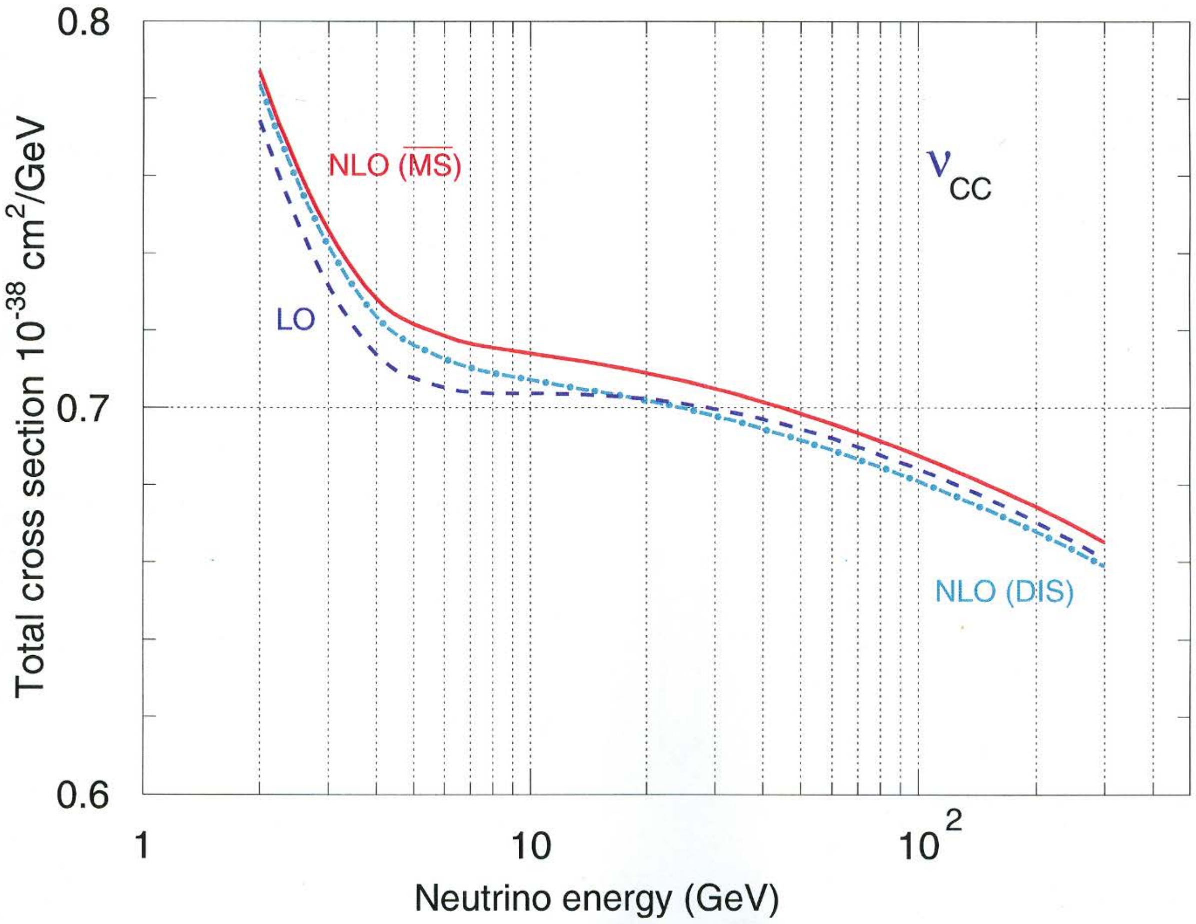
More on pdfs

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

Nucleon correlation function:

Correlation function: it can be computed within the Fermi-gas model

Due to the anti-symmetrization of the fermion's wave function, given a nucleon in a position $\vec{r}$ *in a nucleus with density* ρ_0, *the probability of finding another like nucleon in a position* $\vec{r}\,'$ *is decreased for small values of the distance* $d = |\vec{r} - \vec{r}\,'|$ *by a factor*

$$g(x) = 1 - \frac{1}{2}\left[\frac{3}{x^2}\left(\frac{\sin x}{x} - \cos x\right)\right]^2$$

where $x = K_F \cdot d$, *and the factor 1/2 in front of the parenthesis accounts for the two possible spin orientations.*

Nucleon hard core effects are also taken into account, forbidding to "find" a nucleon of the same or different type at less than 1-1.5 fm distance. This check is applied at every possible re-interaction, checking against all nucleons already involved in previous interactions

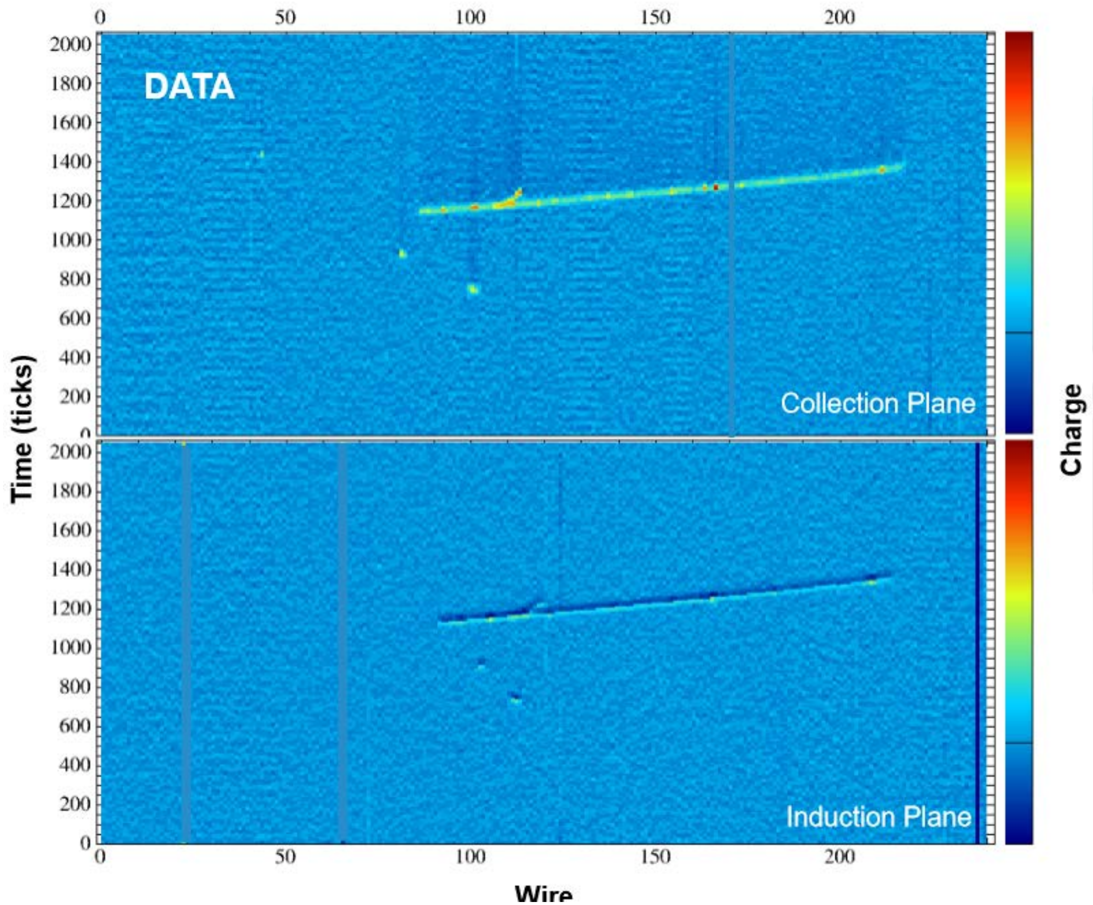
First Demonstration of LArTPC MeV-Scale Physics in ArgoNeuT

APS_April2018

Ivan Lepetic

ILLINOIS INSTITUTE OF TECHNOLOGY

For the ArgoNeuT Collaboration



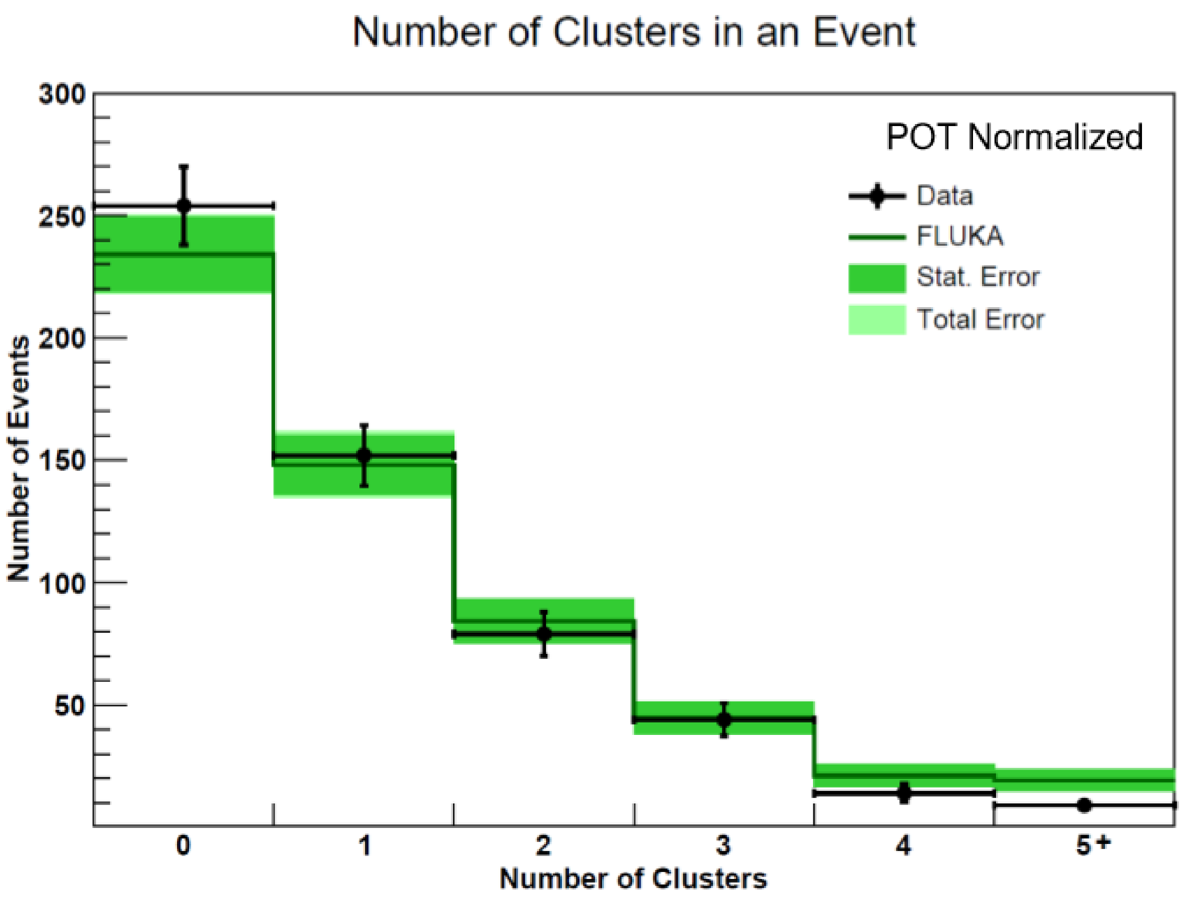
Low-energy gammas produced by neutrino-nucleus interactions in ArgoNeuT

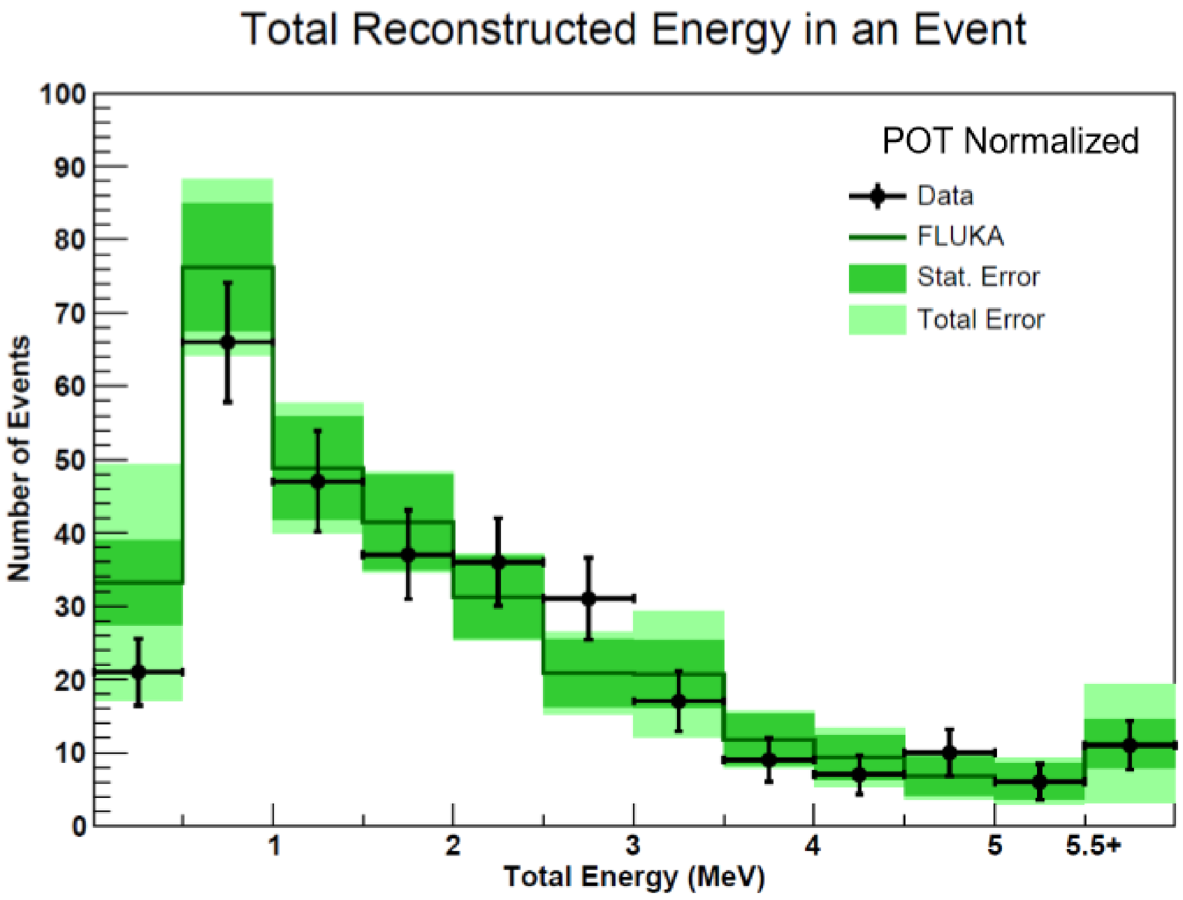
Photons from neutrino-produced nuclear de-excitation and inelastic neutron scattering –

e.g. ν_μ + 40Ar → μ– + p + 39Ar*

→ 39Ar + γ

Data and FLUKA





$\chi 2$/ndf = 9.62/6. p-value = 0.14

$\chi 2$/ndf = 7.74/12. p-value = 0.81

Agreement is far worse if either de-excitation or neutron produced gammas are removed.

Effect of formation zone on residuals

Experimental and computed residual nuclei mass distribution

Ag(p,x)X at **300 GeV** (top)
Au(p,x)X at **800 GeV** (bottom)

Data from:

Phys. Rev. C19 2388 (1979) and
Nucl. Phys. A543, 703 (1992)

(The heavy fragment evaporation model is key for FLUKA predictions for A< 30)

Ag ***with*** and ***without*** form.zone:

$\langle\pi\rangle$ = 21.1, $\langle E_\pi\rangle$=7.3 GeV

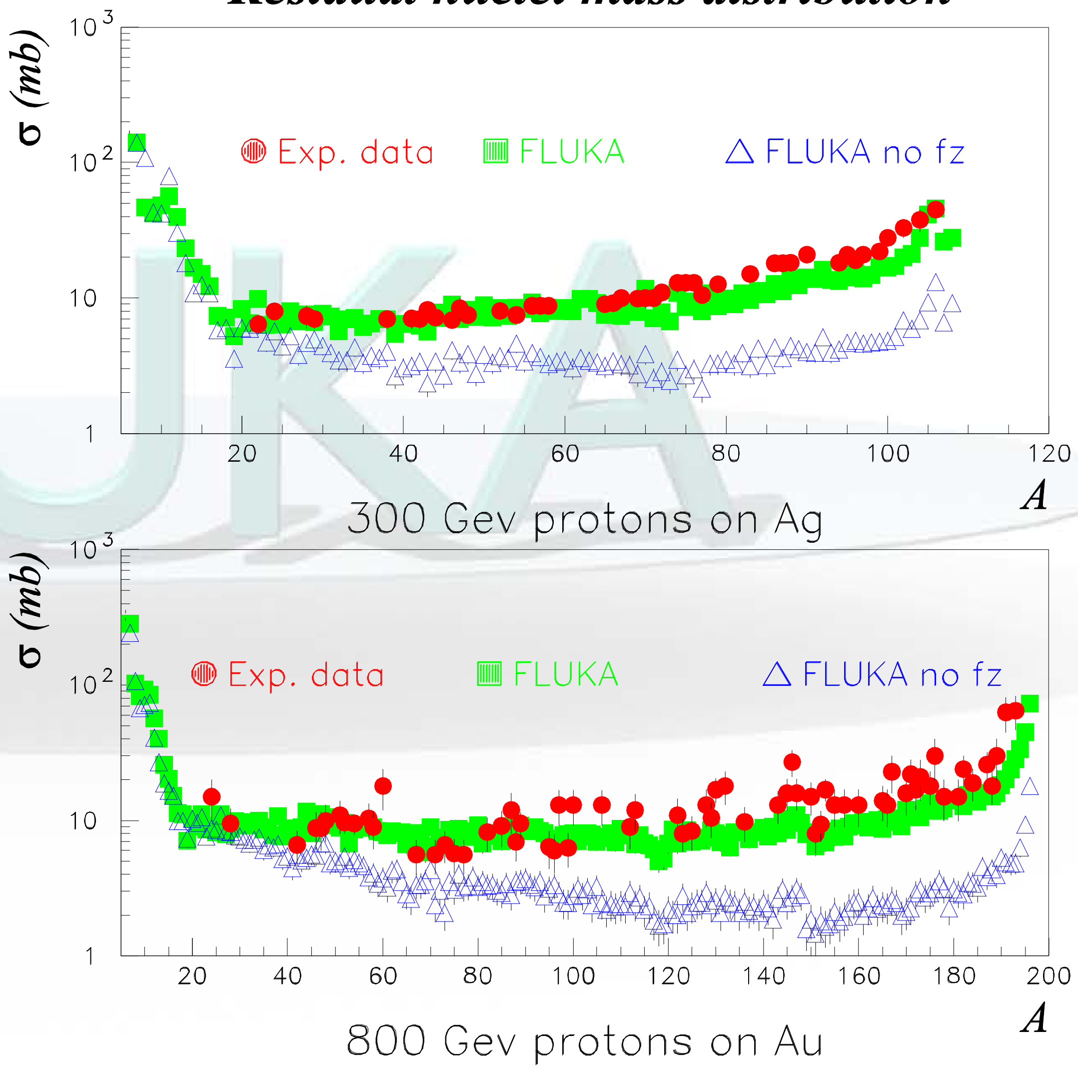
$\langle\pi\rangle$ = 49.7, $\langle E_\pi\rangle$=3.4 GeV

Au ***with*** and ***without*** form.zone:

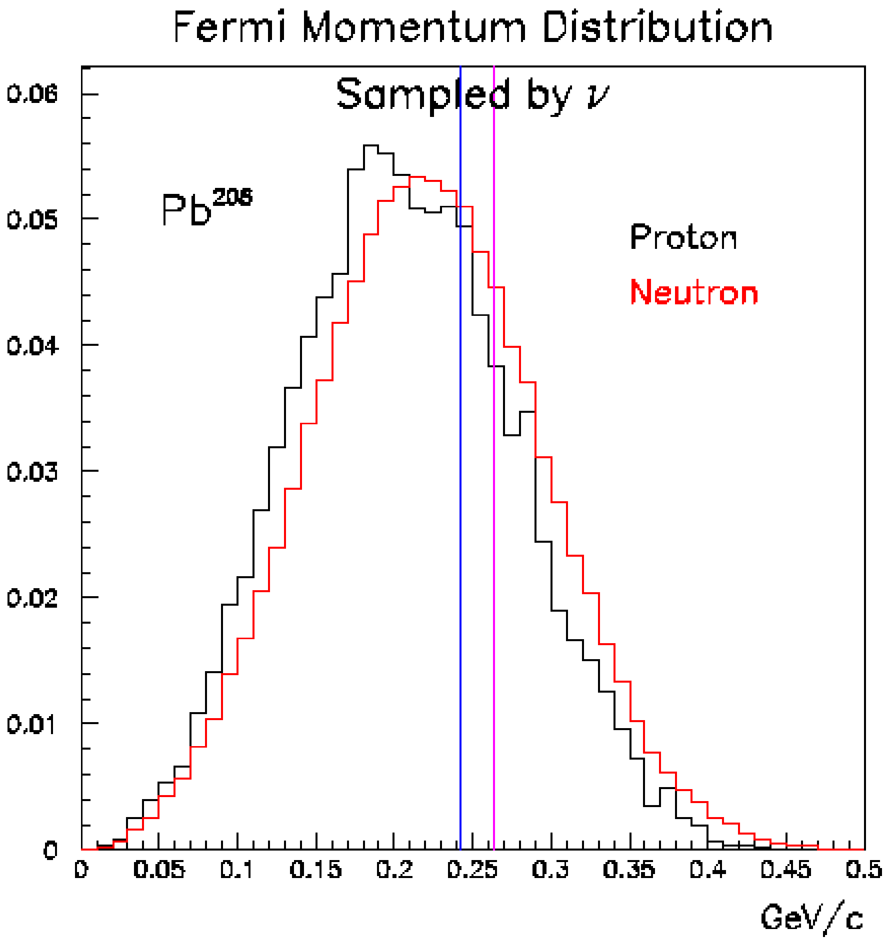
$\langle\pi\rangle$ = 30.1, $\langle E_\pi\rangle$=12.5 GeV

$\langle\pi\rangle$ = 96.0, $\langle E_\pi\rangle$=4.6 GeV

Residual nuclei mass distribution



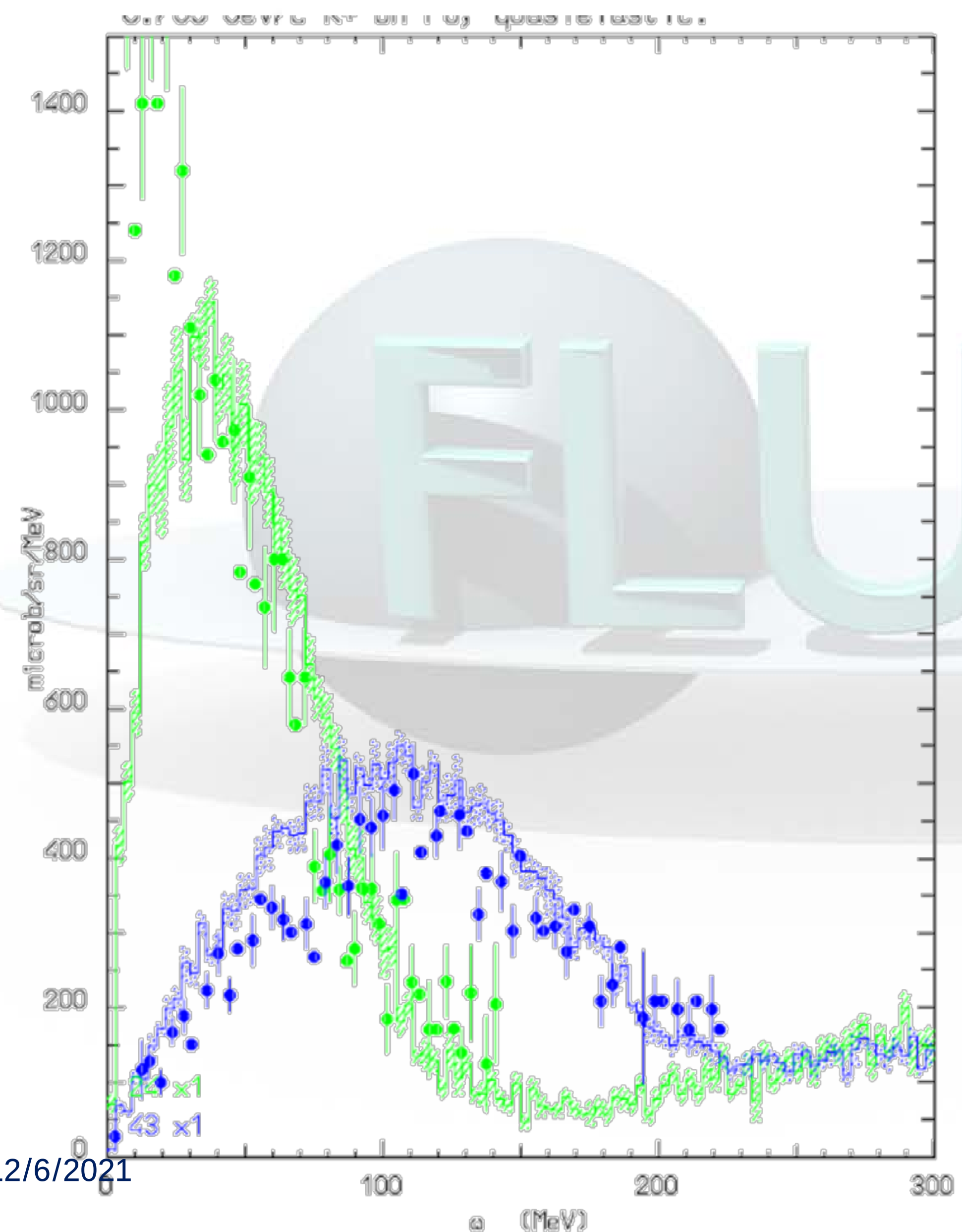
Example of Fermi distribution



Fermi momentum distribution as "seen" by interacting neutrinos on lead.

Vertical lines: maximum Fermi momentum according to un-smeared distribution

Positive kaons as a probe of Fermi motion



K+ and K0

- No low mass S=1 baryons
  - weak K^+N interaction
  - Only elastic and charge exchange up to ≈ 800 MeV/c

K^+ Pb → $K^{+'}$ Pb 705 MeV/c

Residual excitation spectrum

With $K^{+'}$ at 24^0 (green)

at 43^0 (blue)

Histogram : FLUKA

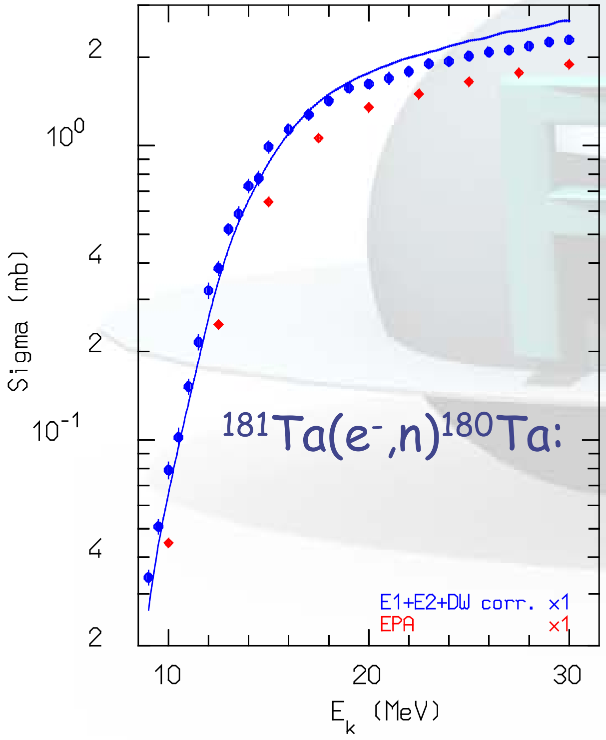
Dots : data (Phys. Rev. C51,669 (1995))

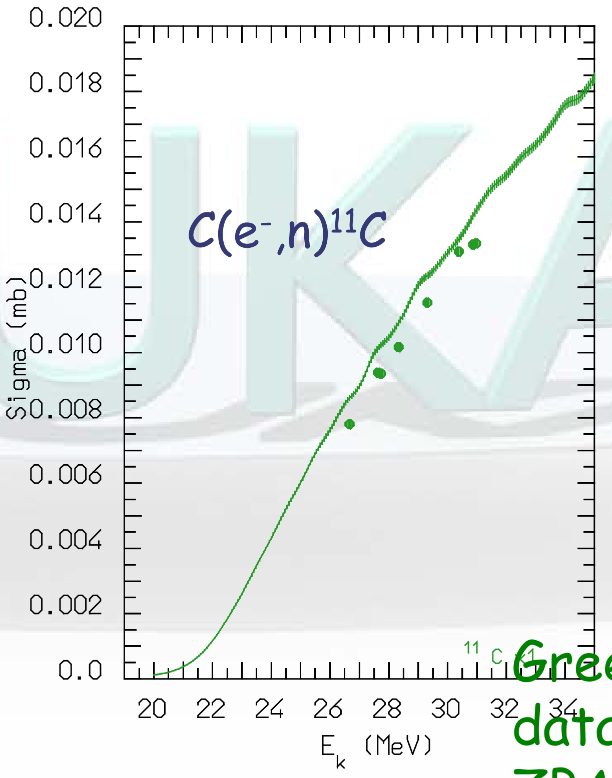
On free nucleon: recoil at 43 MeV or 117 MeV

0-deg tail is elastic on nucleus, not included in sim

Electron scattering

- Quasi-Elastic on nucleon (+ all nuclear)
- Inelastic via virtual photon exchange, recently improved (E1+E2)





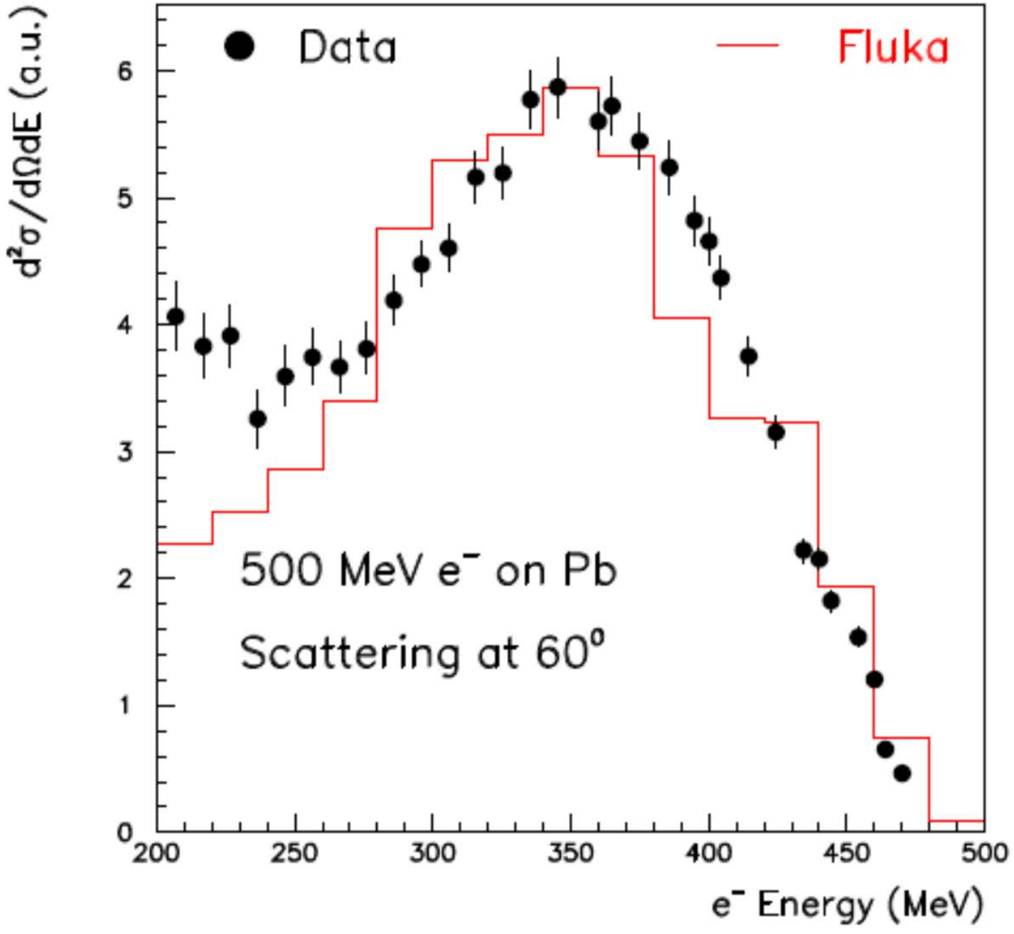
Green symbols: data from ZPA281,35
Green curve: FLUKA

Blue symbols: data from JPG13,515
Blue line: FLUKA new
Red symbols: FLUKA with EPA

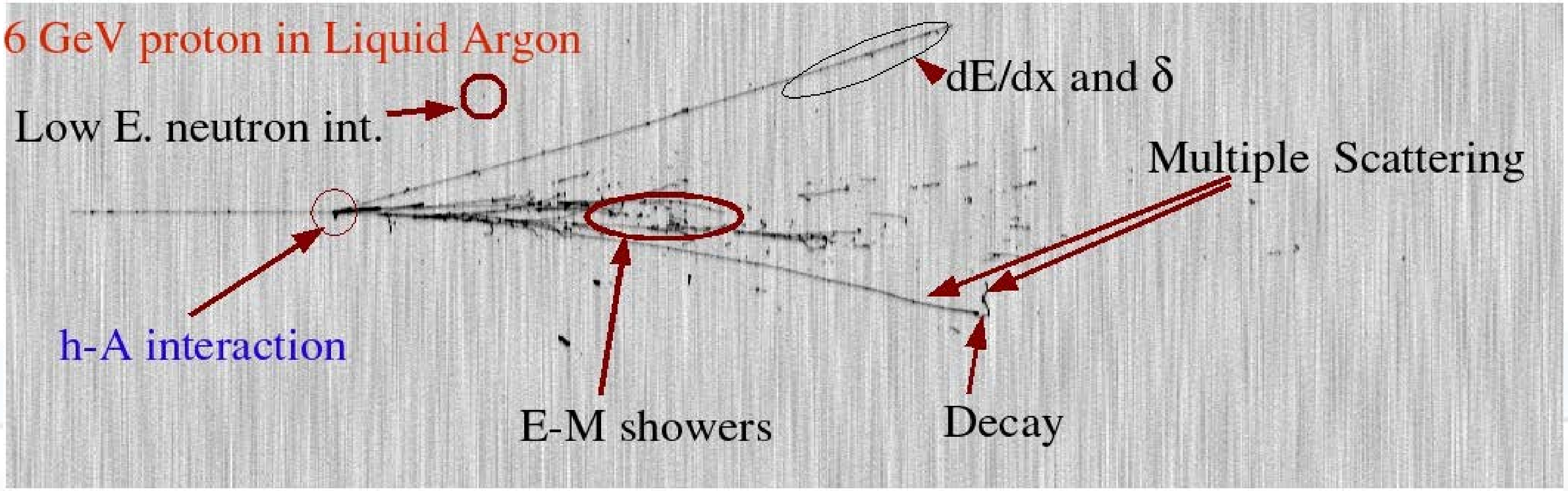
First checks with electrons

- Quasi-Elastic scattering of electrons on Lead, outgoing electron spectrum at 60^0
- Inelastic tail not included in simulation
- To be improved wit the inclusion of energy-dependent nuclear well, as already there for nucleon-induced reactions
- **Much more tests needed**

Dta:
R.R. Whitney et al., Phys Rev C9,2230 (1974)



FLUKA : a multi-purpose Monte Carlo code



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

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

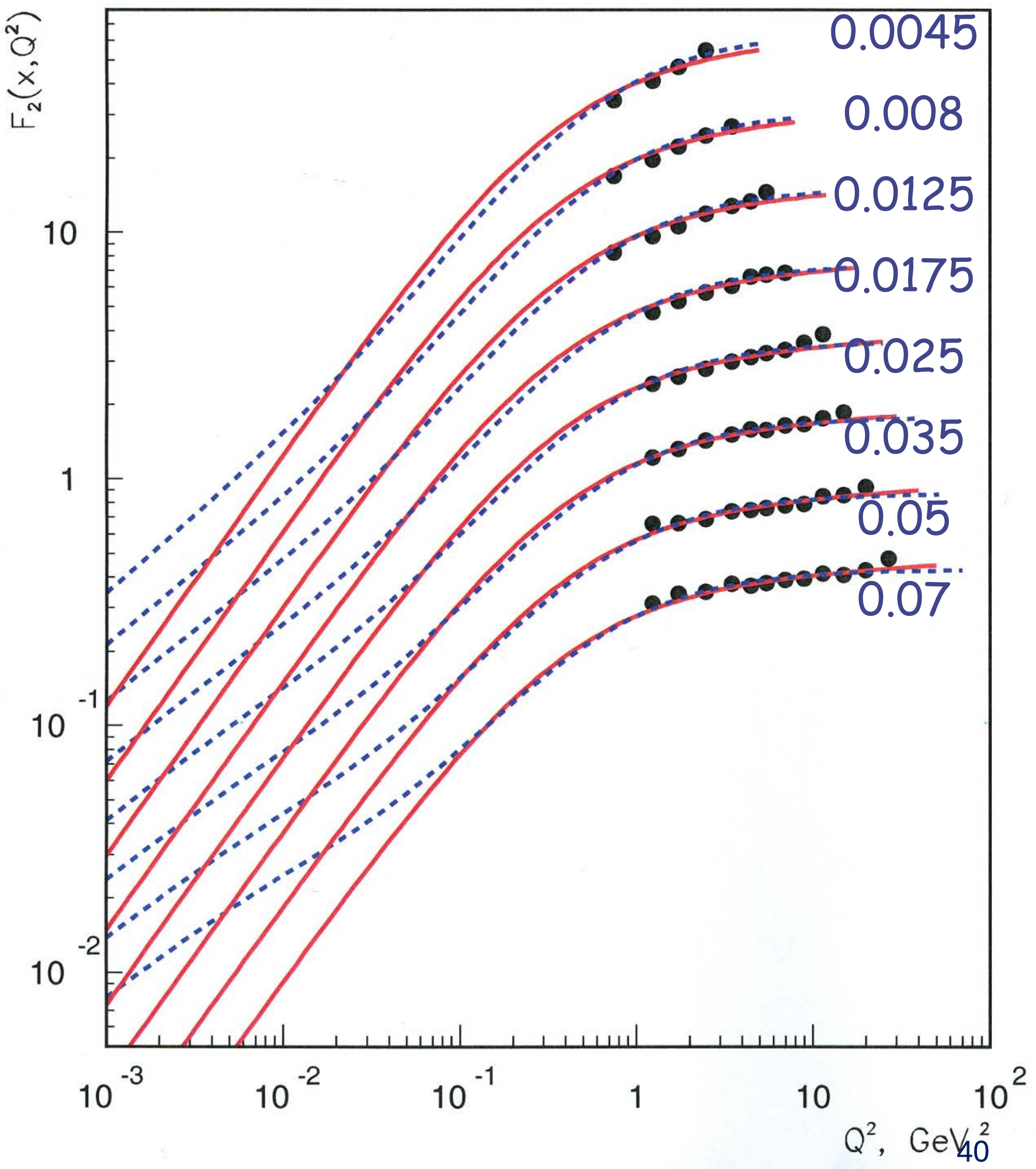
Solid lines: M. Bertini et al. 1996 (Default in NUNDIS)

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

Dashed lines: Donnachie-Landshoff 1994

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

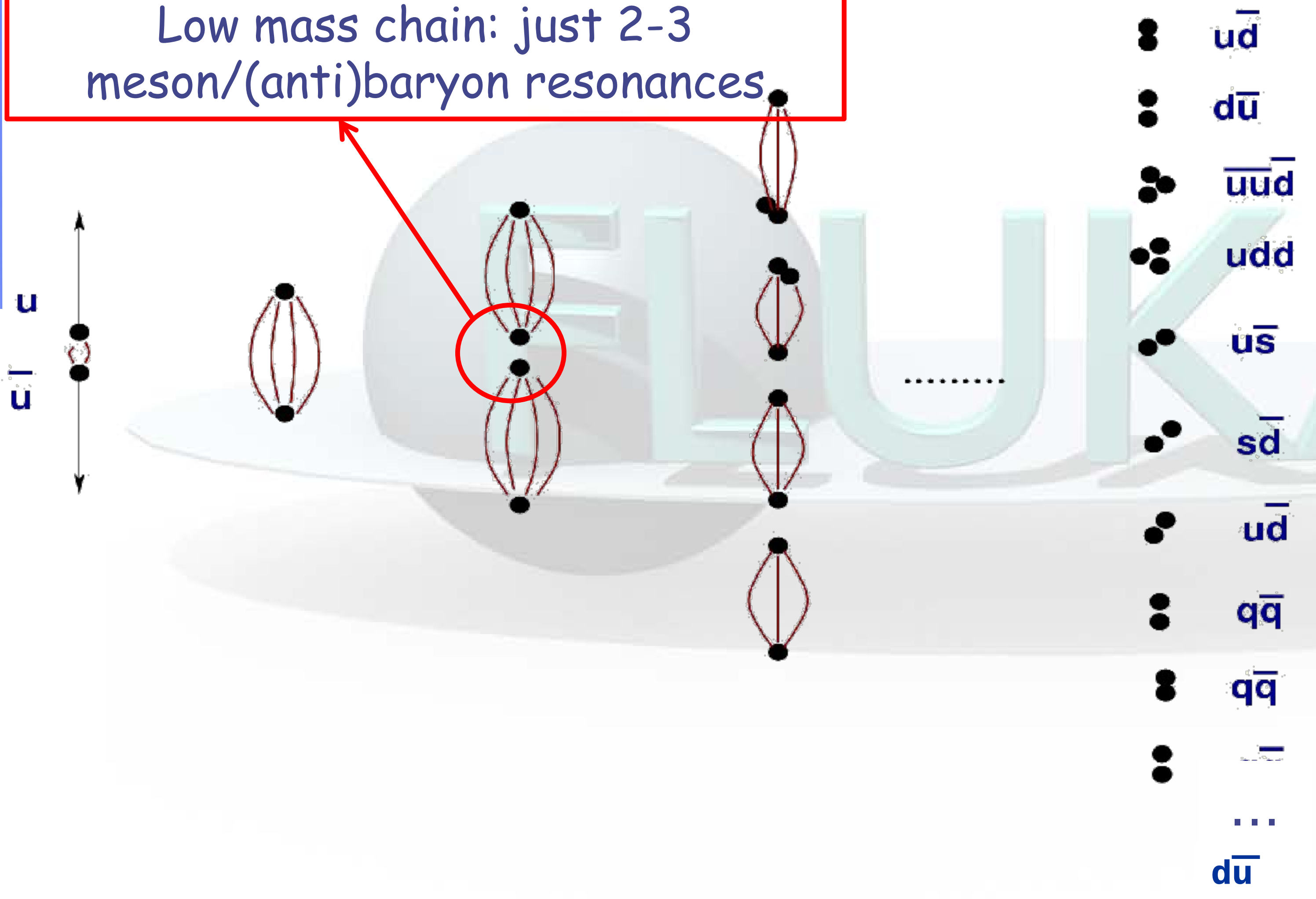
data points from NMC Collab., M. Arneodo et al., Nucl. Phys. B 483 (1997) 3-43
Data/cuves scaled for clarity, factors from 1 to 128



The "hadronization" of chains

An example:

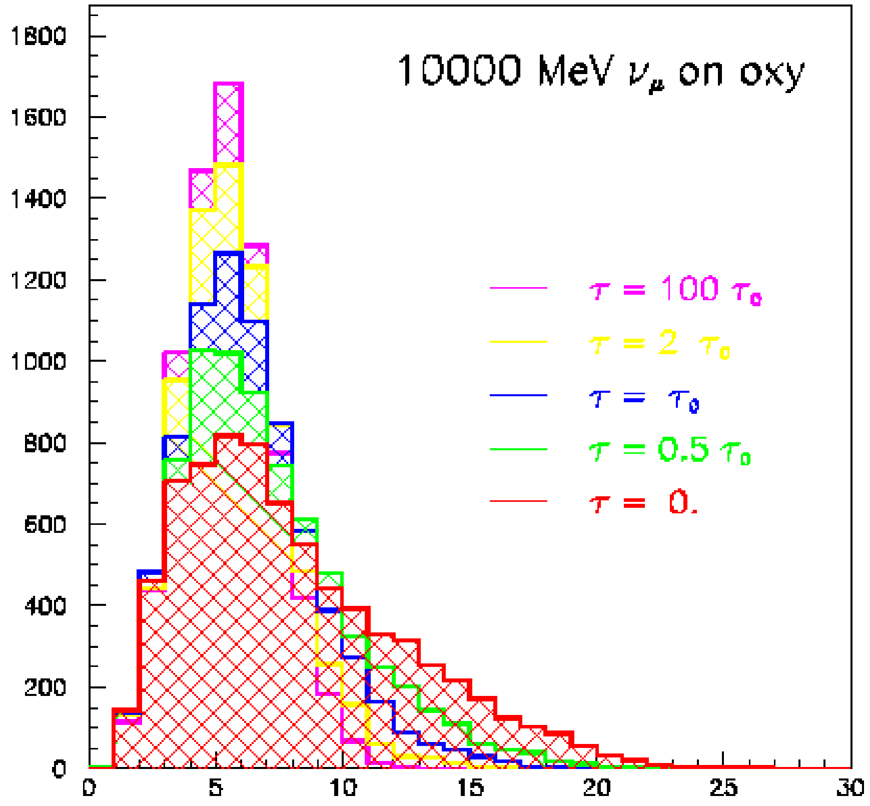
Low mass chain: just 2-3 meson/(anti)baryon resonances



Implementation FLUKA-native (evolution of old BAMJET)

Effect of formation zone, neutrino int.

Total hadron multiplicity



Charged hadron spectra