Neutrino interactions in FLUKA: NUNDIS

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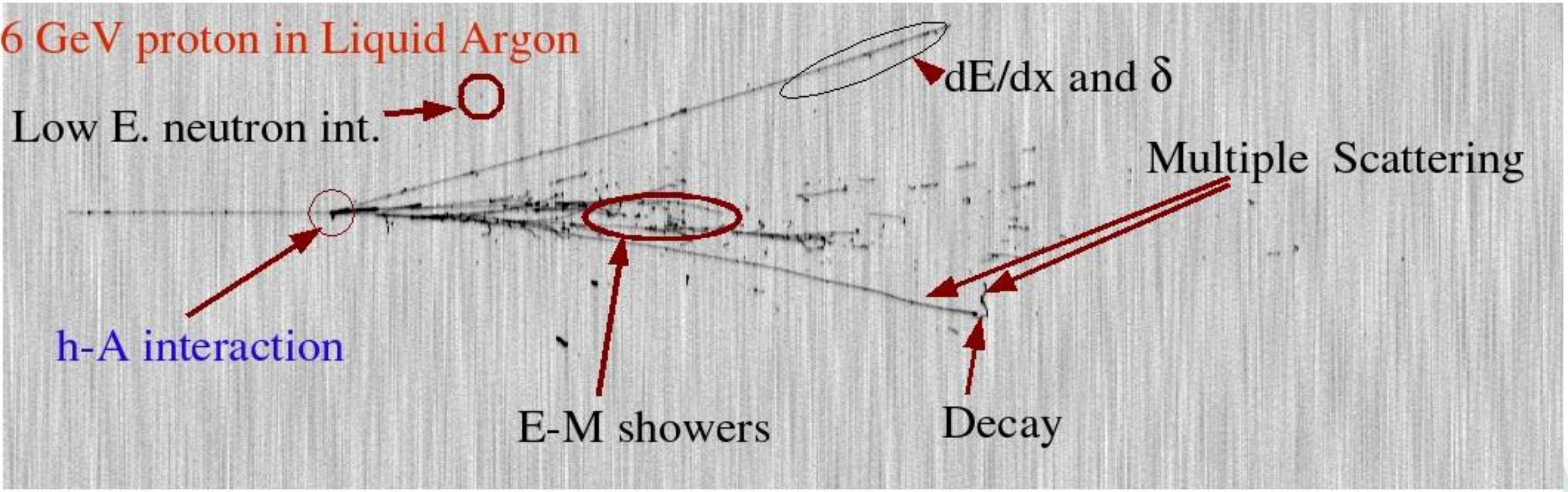
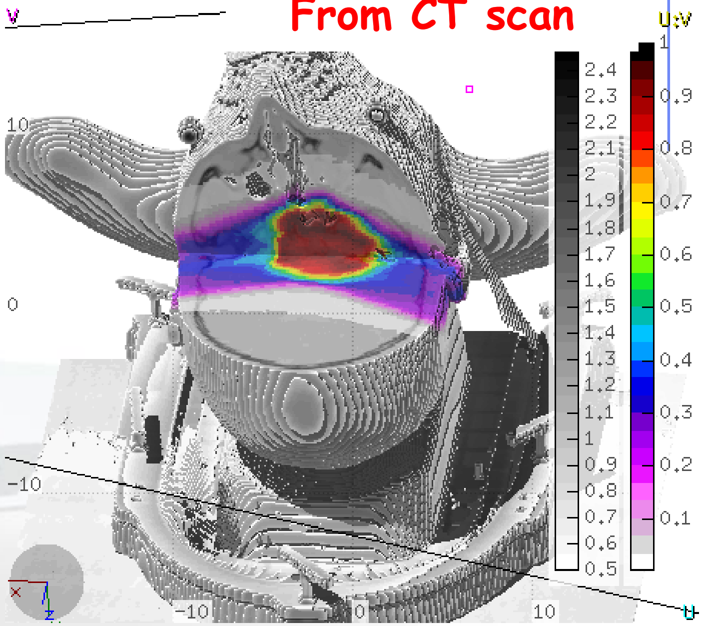
FLUKA : a multi-purpose Monte Carlo code



Dose
2 p Beams
In head geometry
From CT scan



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

>10000 registered users

2 user courses /year

General framework

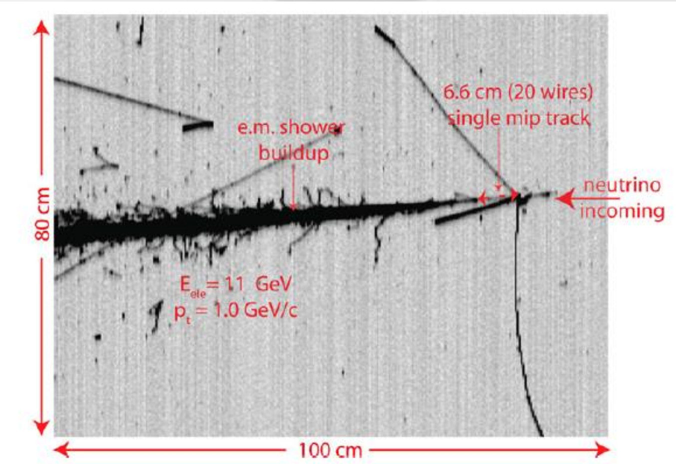
- Nuclear models in FLUKA have been developed along the years, initially for hadron-nucleus reactions,
- Then extended to treat also
  - Photonuclear reactions
  - Muon-nuclear and electro-nuclear via virtual photon exchange
  - Quasi-eleasic electron scattering
  - Muon capture
  - Neutrino interactions
  - Anti-nucleon reactions
- All sharing the same nuclear "environment"
- All DIS share the same hadronization

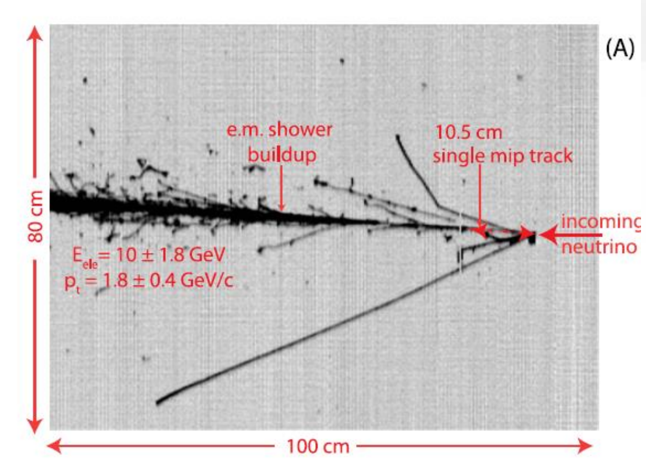
Neutrinos in FLUKA

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

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

MC ν_e CC





Real ν_e CC

Quasi Elastic and Resonant

QE

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

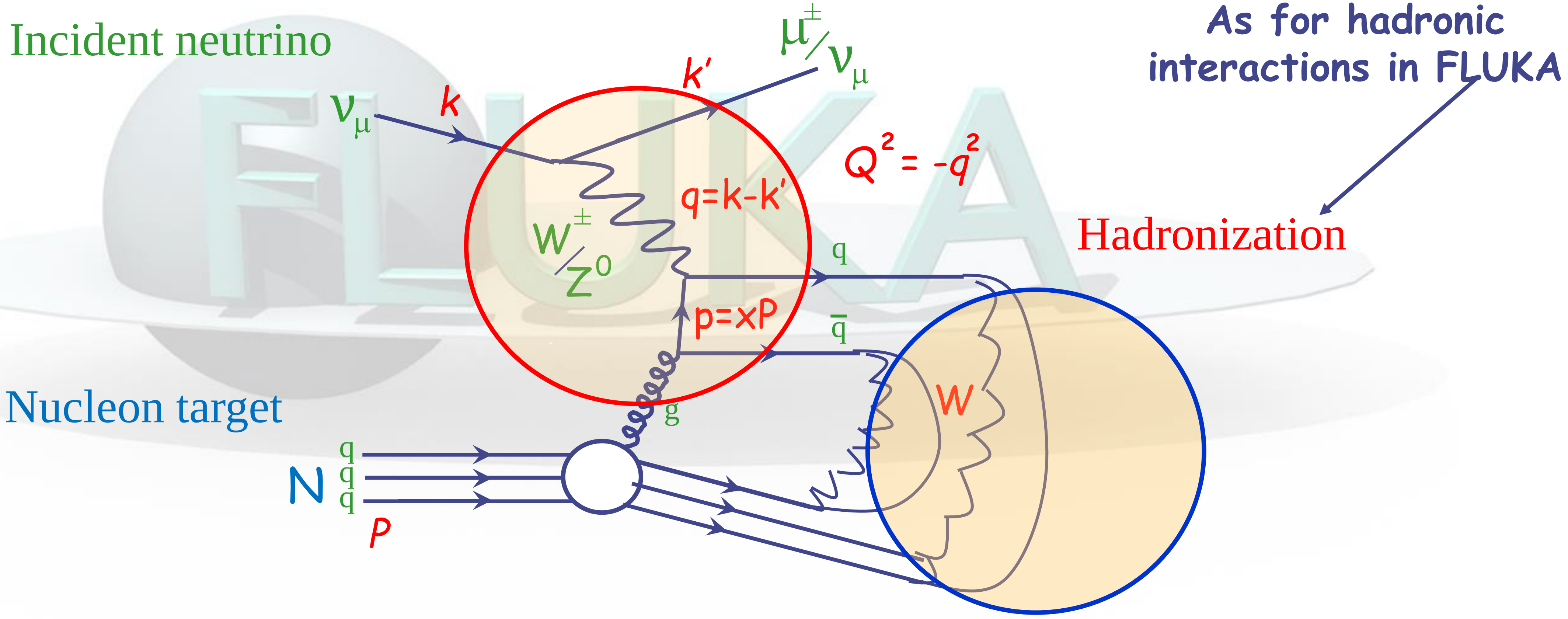
Resonance production

- 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

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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 $F_i(Q^2,x)$

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

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

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:

$$\begin{aligned} F_4 &= 0, \\ F_5 &= \frac{F_2}{x}. \end{aligned}$$

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

In the NLO (DIS) version

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

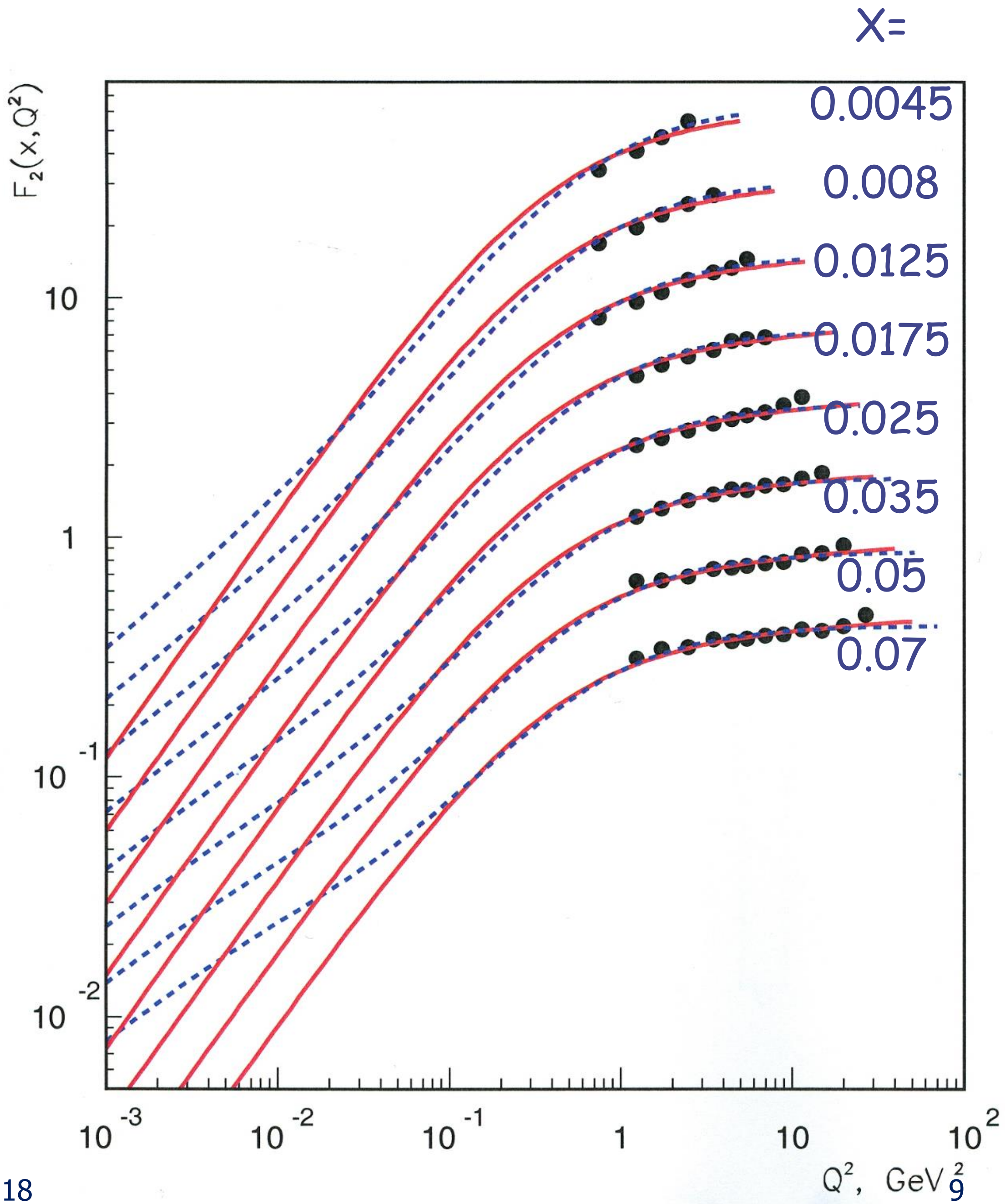
Solid lines: M. Bertini et al. 1996 (Default in NUNDIS)

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

Dashed lines: Donnachie-Landshoff 1994

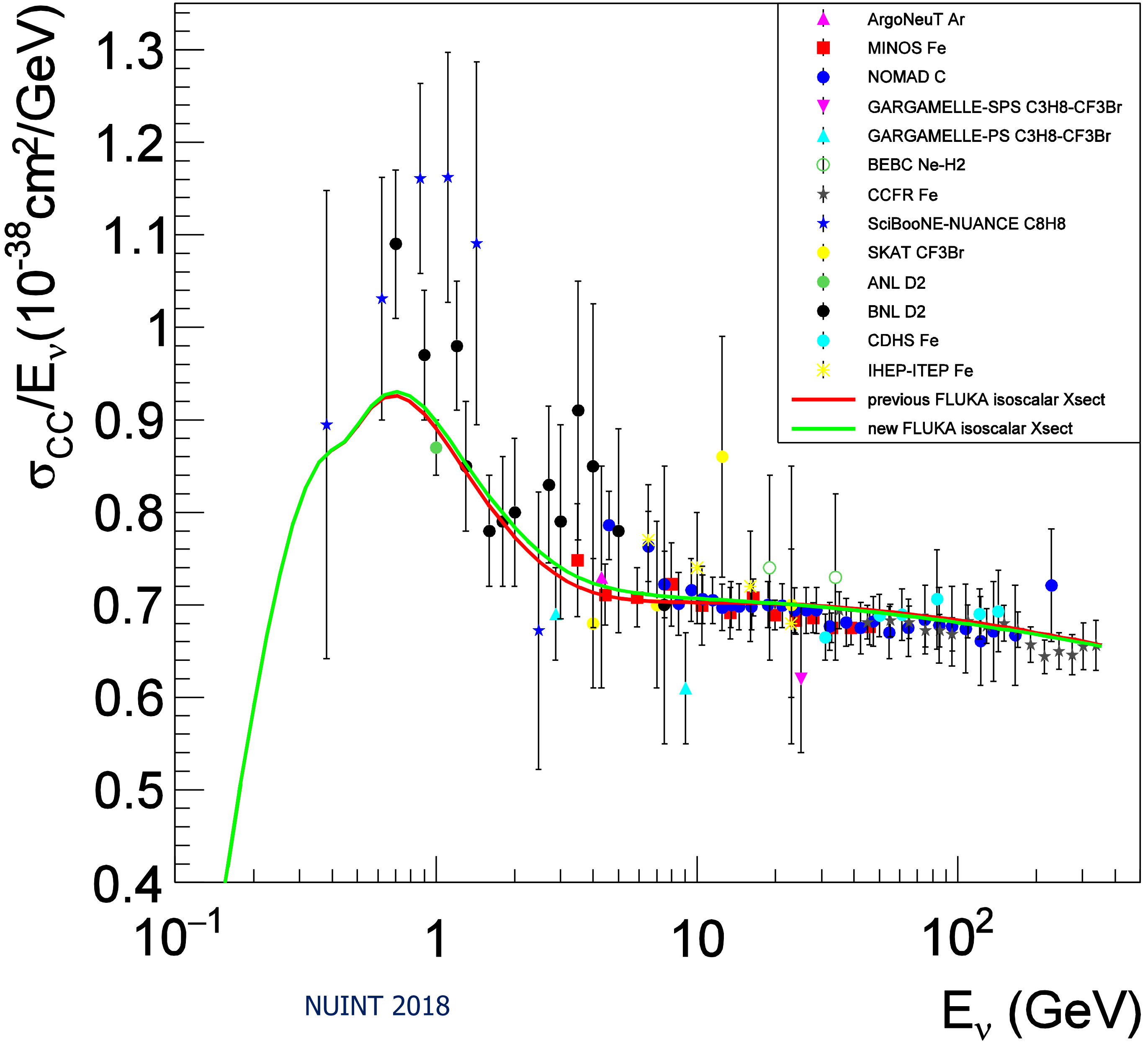
$$F_2(x,Q^2) \sim Ax^{-0.0808}\left(\frac{Q^2}{Q^2+a}\right)^{1.0808} + Bx^{0.4525}\left(\frac{Q^2}{Q^2+b}\right)^{0.5475}$$

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



Comparison with data on total cross section

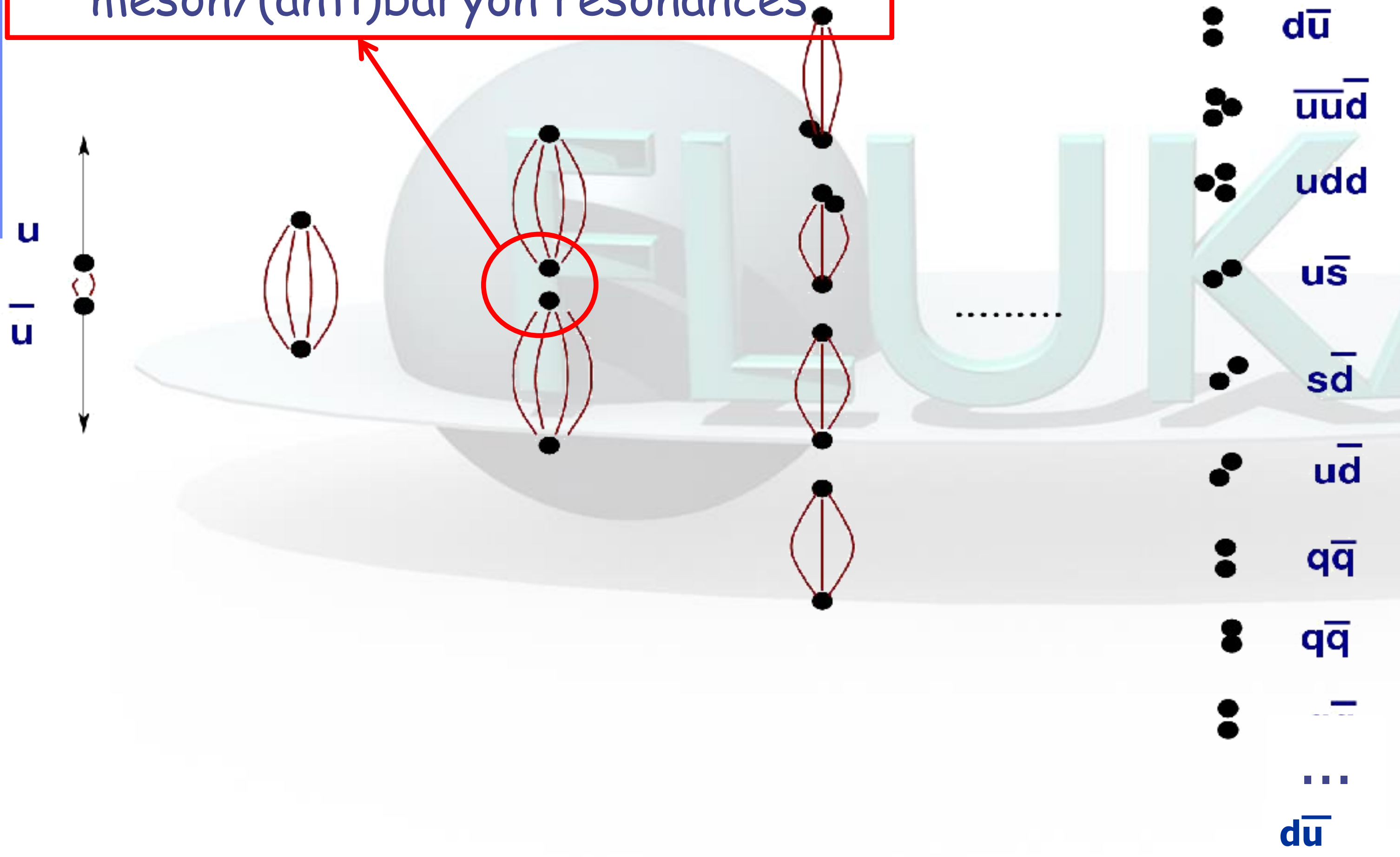
Isoscalar
ν_μ - Nucleon total
CC cross section
Fluka (lines) with
two pdf options
Vs
Experimental data



The “hadronization” of chains

An example:

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



Concepts are the same as in LUND models
Implementation FLUKA-native

In FLUKA:

- 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/few resonances
- Chains generated at low energy → **"phase space explosion"** constrained in p_T , including baryons, mesons, resonances.

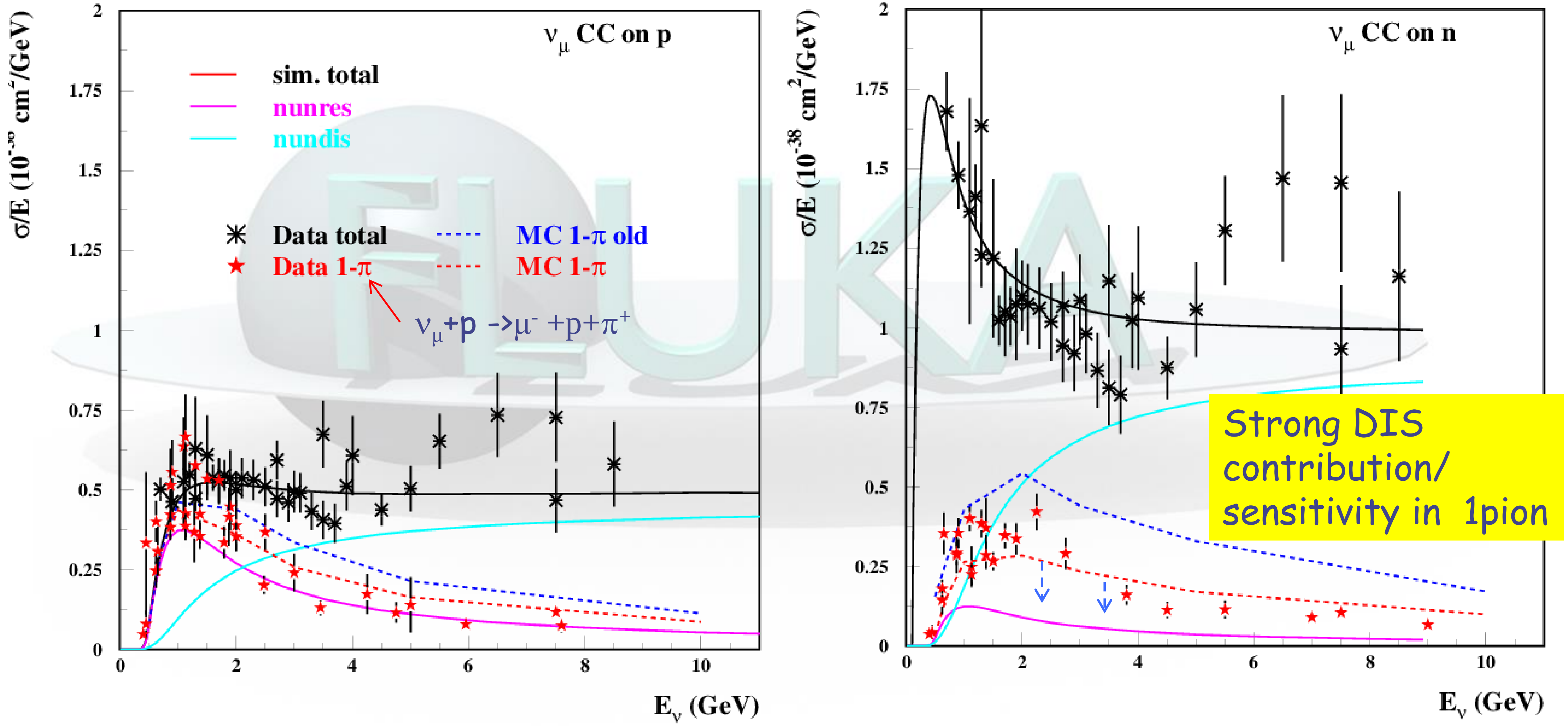
The same functions and parameters for all reactions and energies

- 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

Single pion production

NDS 120, 211 (2014)

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

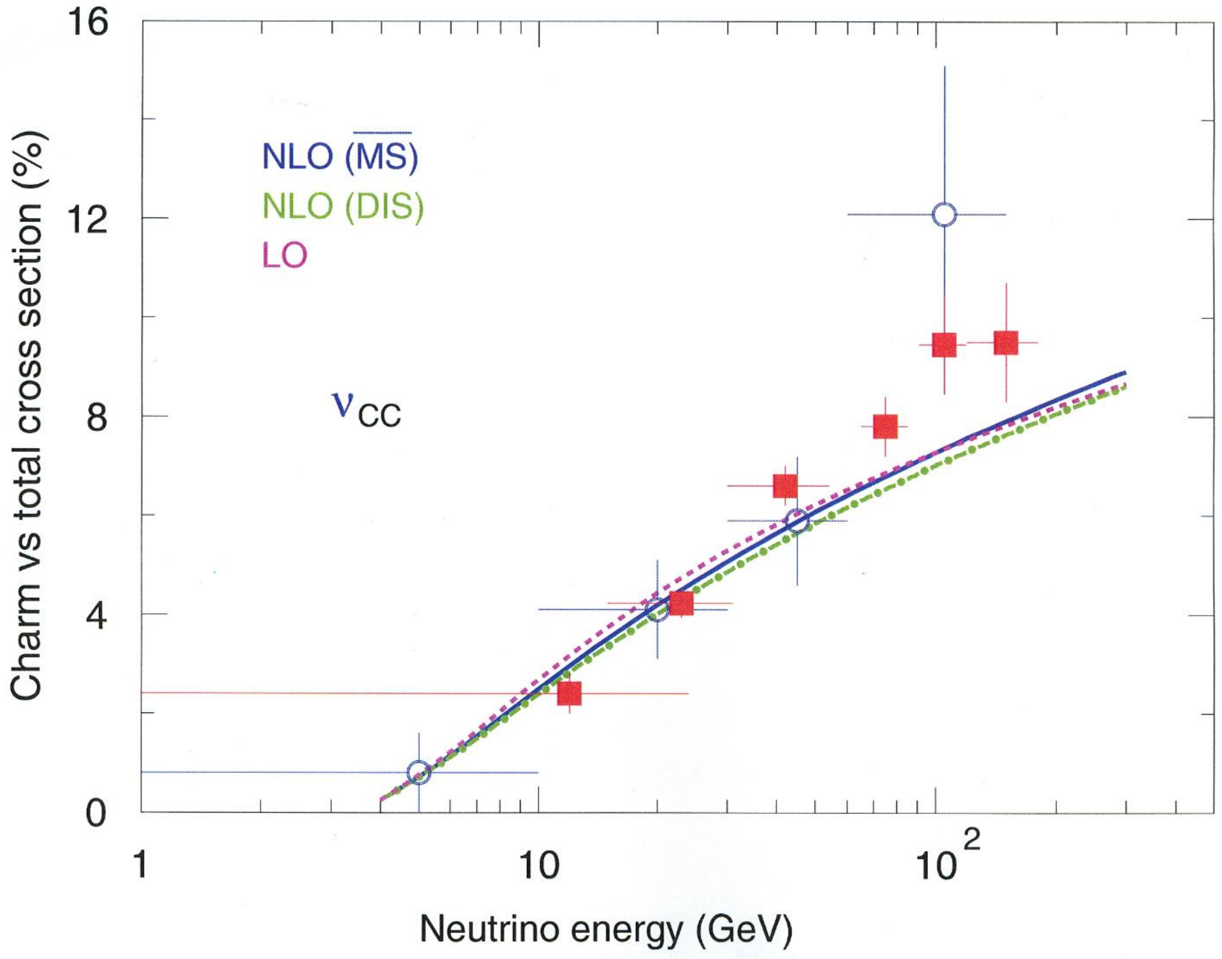


ν_μ+p ->μ^- +p+π^+

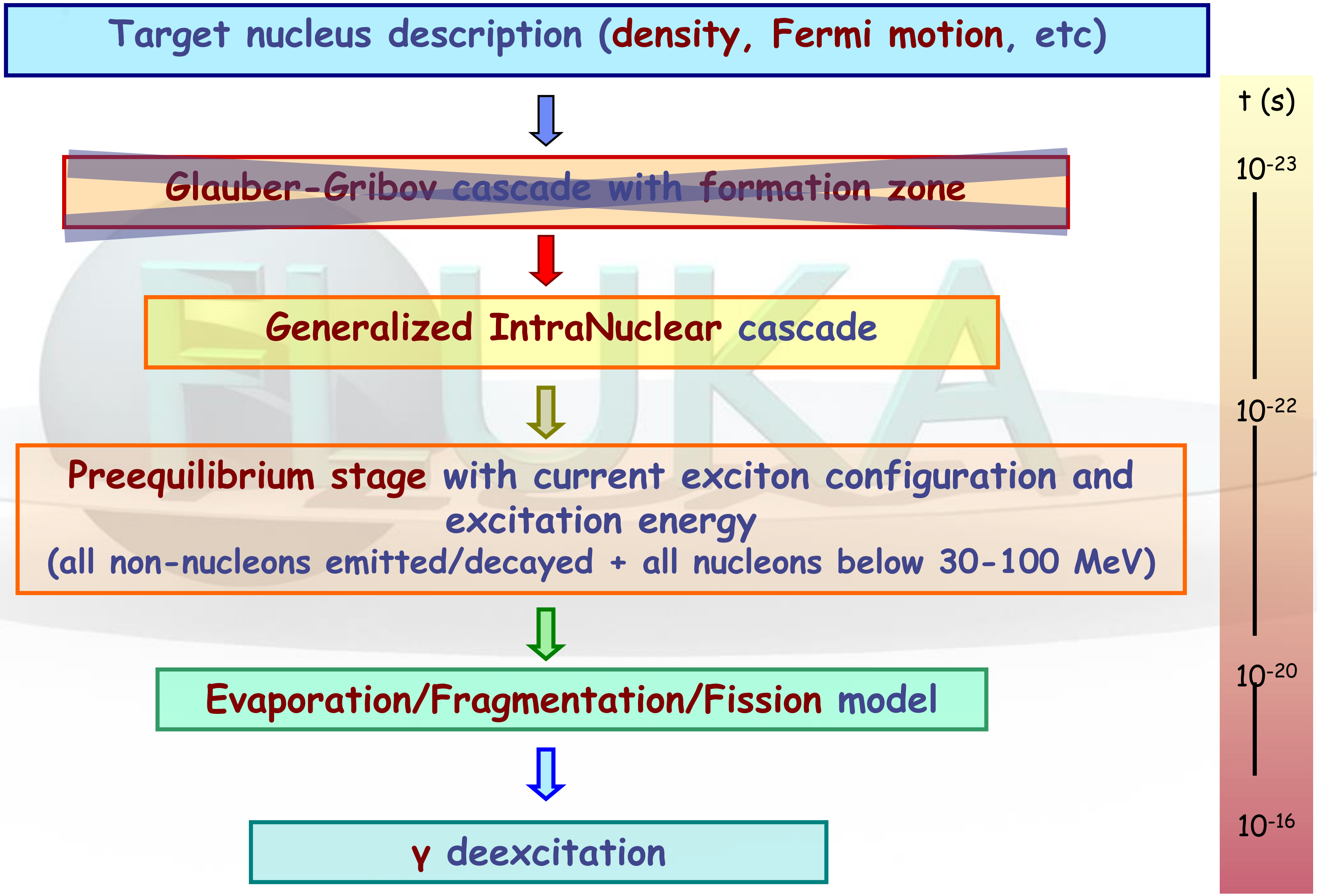
Strong DIS contribution/ sensitivity in 1pion

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

(Generalized) IntraNuclear Cascade

- Primary and secondary particles moving in the nuclear medium according to local Fermi gas model
- Trajectories curved by the nuclear potential
- Interactions according to “free” σ + exceptions (ex. π)
- Fully relativistic
- Multibody absorption for π, μ^-
- Special for K^-, antinucleon, π (phase shifts, annihilation)
- Quantum effects (Pauli blocking, formation zone, correlations…)
- Exact conservation of energy, momenta and all additive quantum numbers, including nuclear recoil
- First excited nuclear levels accounted for (more levels in evaporation/gamma deexc)

Nucleon Fermi Motion in FLUKA

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

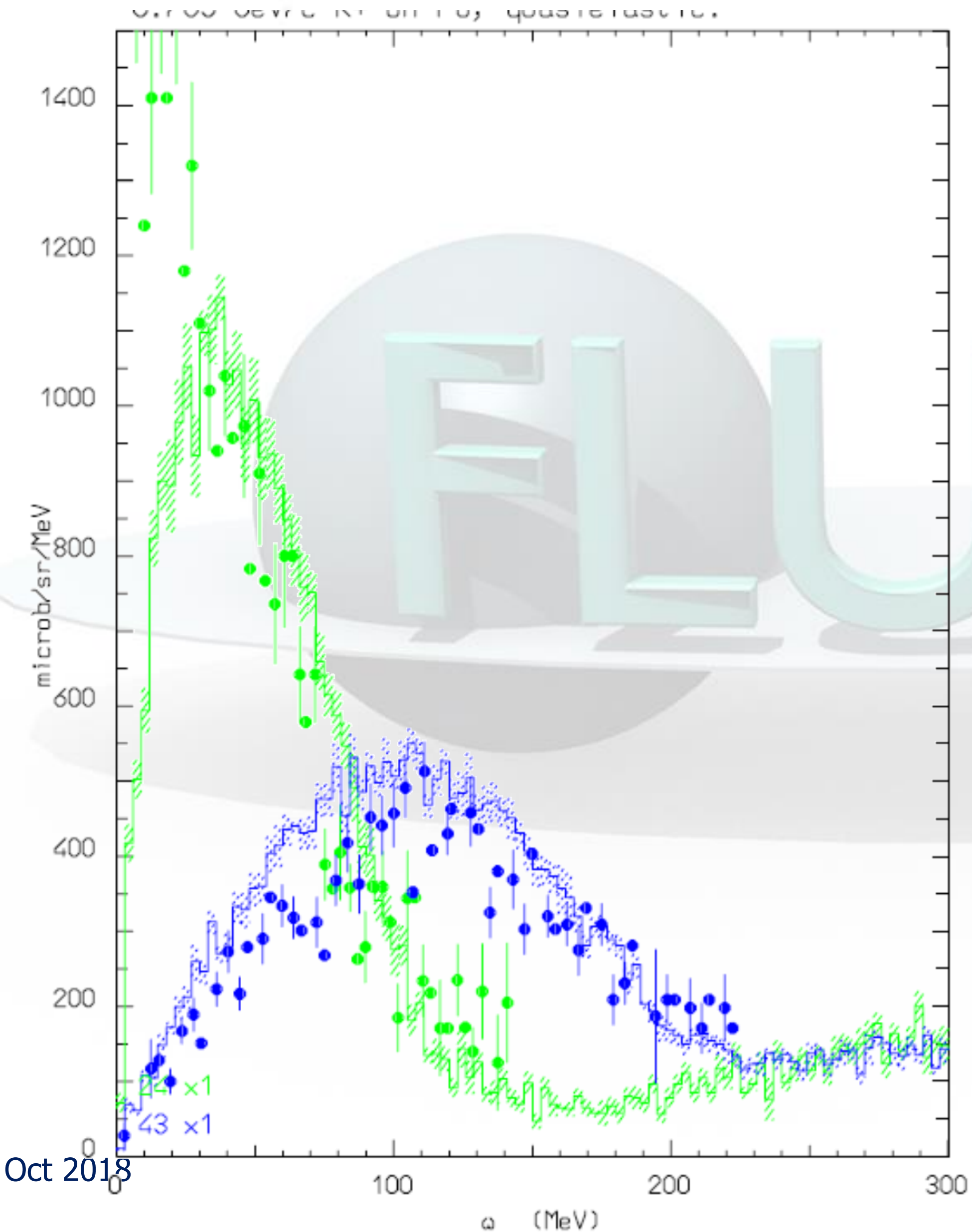
  Momentum distribution $$\propto \frac{dN}{dk} = \frac{|k|^2}{2\pi^2}$$

  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

Positive kaons as a probe of Fermi motion



K^+ and K^0

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

$K^+ Pb \rightarrow K^{+'} Pb$ 705 MeV/c

Residual excitation spectrum

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

at 43^0 (blue)

Histogram : FLUKA

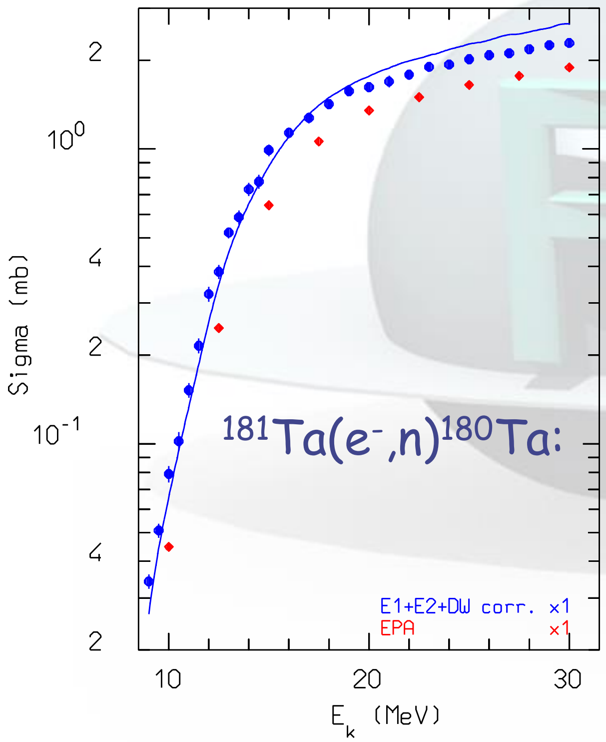
Dots : data (Phys. Rev. C51,669 (1995))

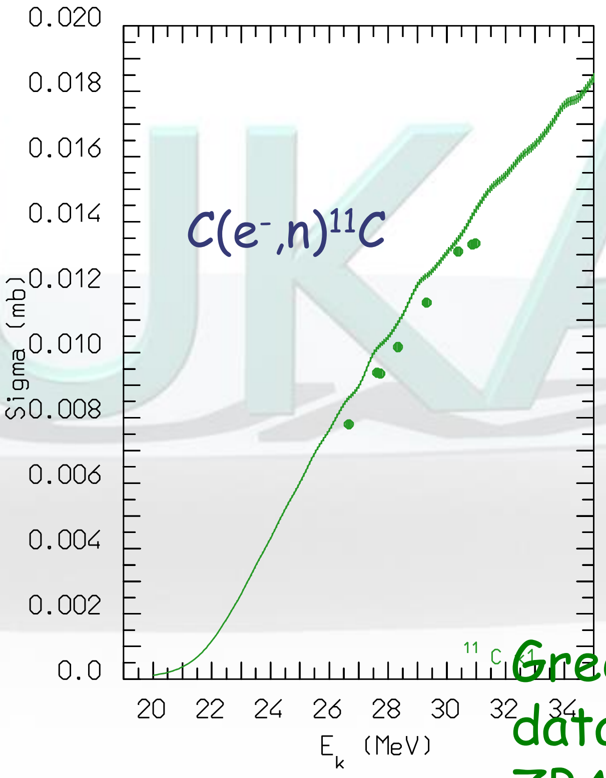
On free nucleon: recoil at 43 MeV or 117 MeV

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)





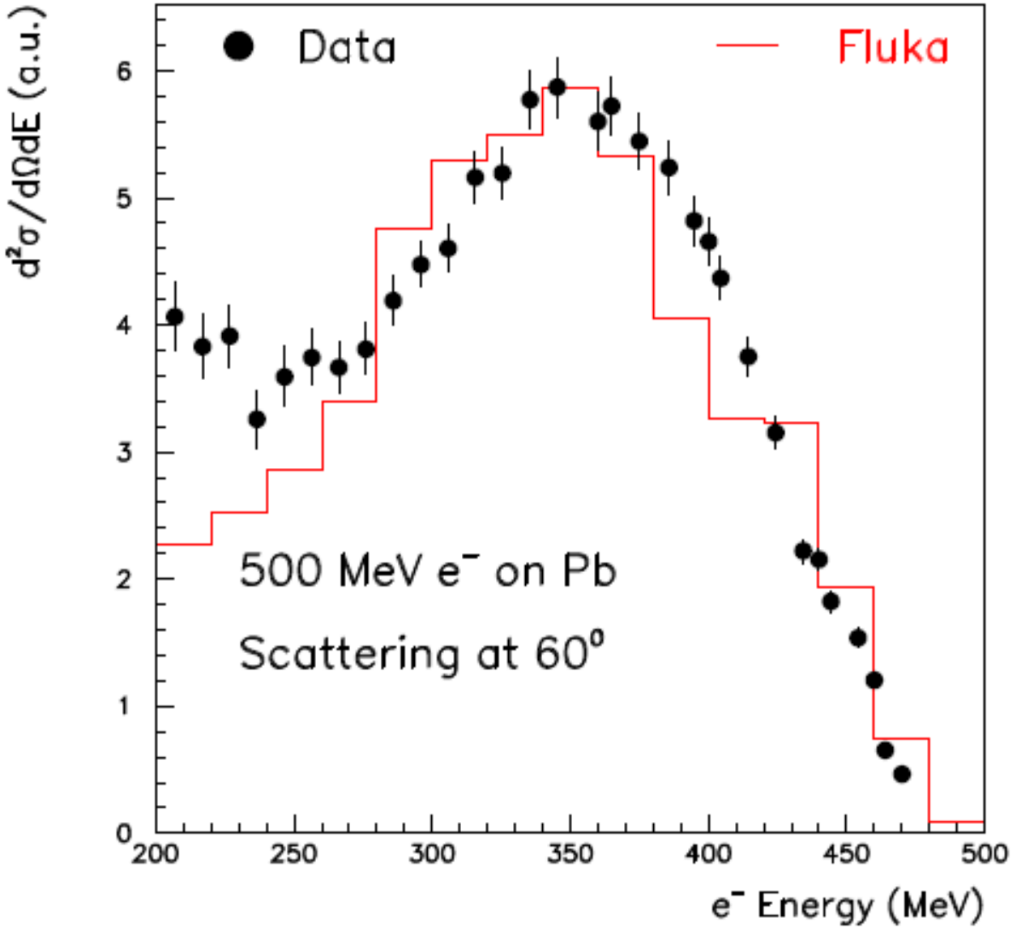
Blue symbols: data from JPG13,515
Blue line: FLUKA new
Red symbols: FLUKA with EPA

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

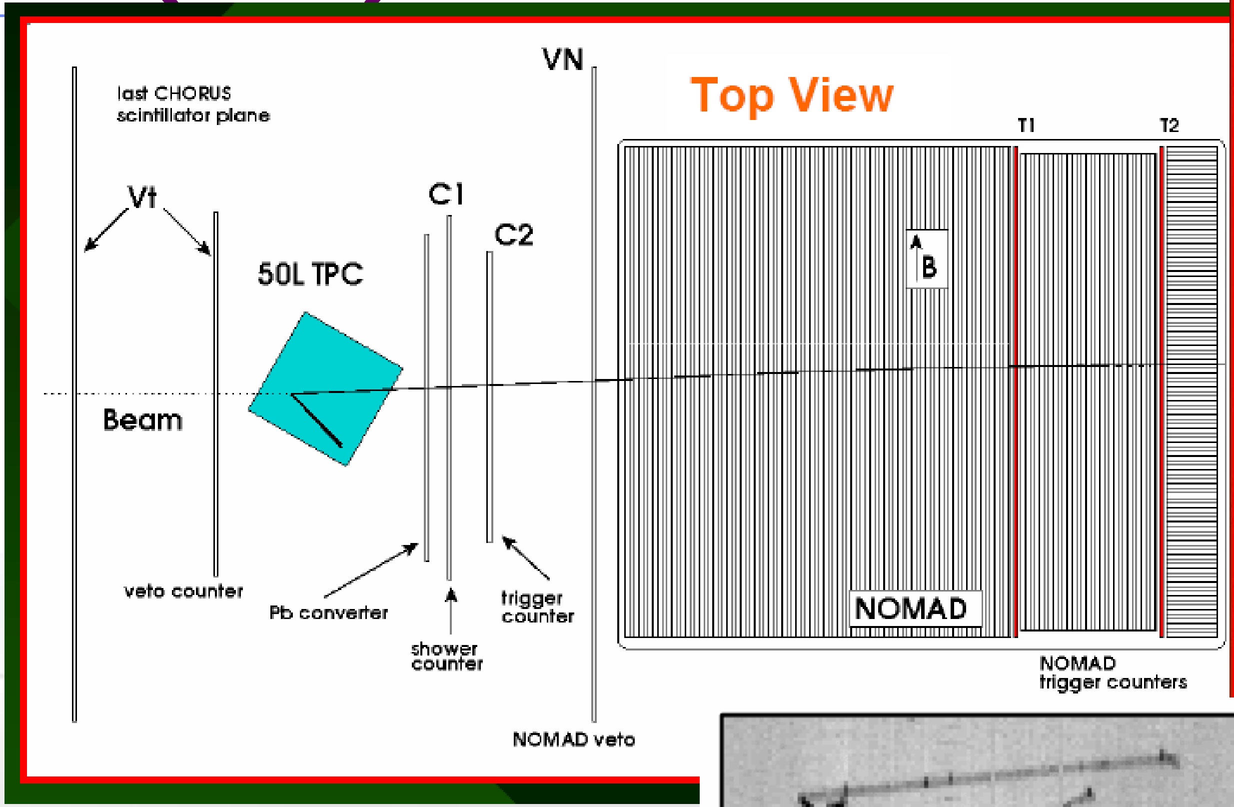
First checks with electrons

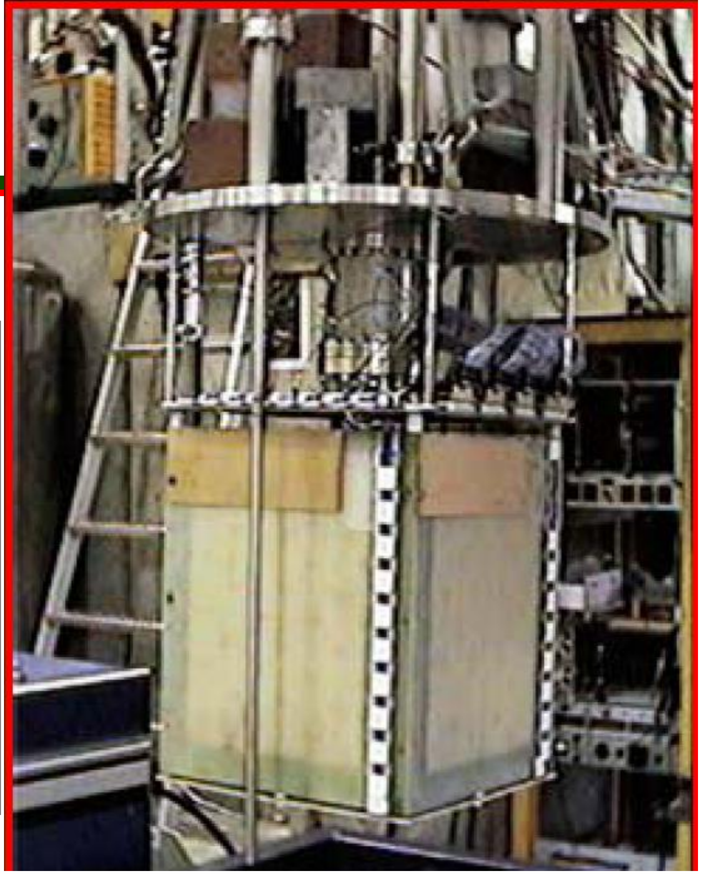
- Quasi-Elastic scattering of electrons on Lead, outgoing electron spectrum at 60^0
- Inelastic tail not included in simulation
- To be improved wit the inclusion of energy-dependent nuclear well, as already there for nucleon-induced reactions
- **Much more tests needed**

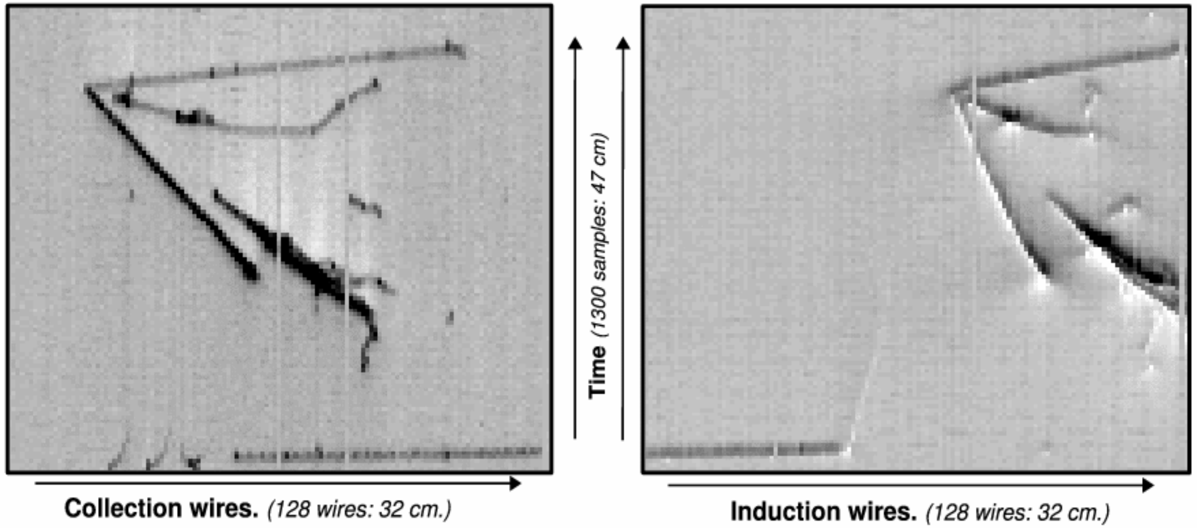
Dta:
R.R. Whitney et al., Phys Rev C9,2230 (1974)



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



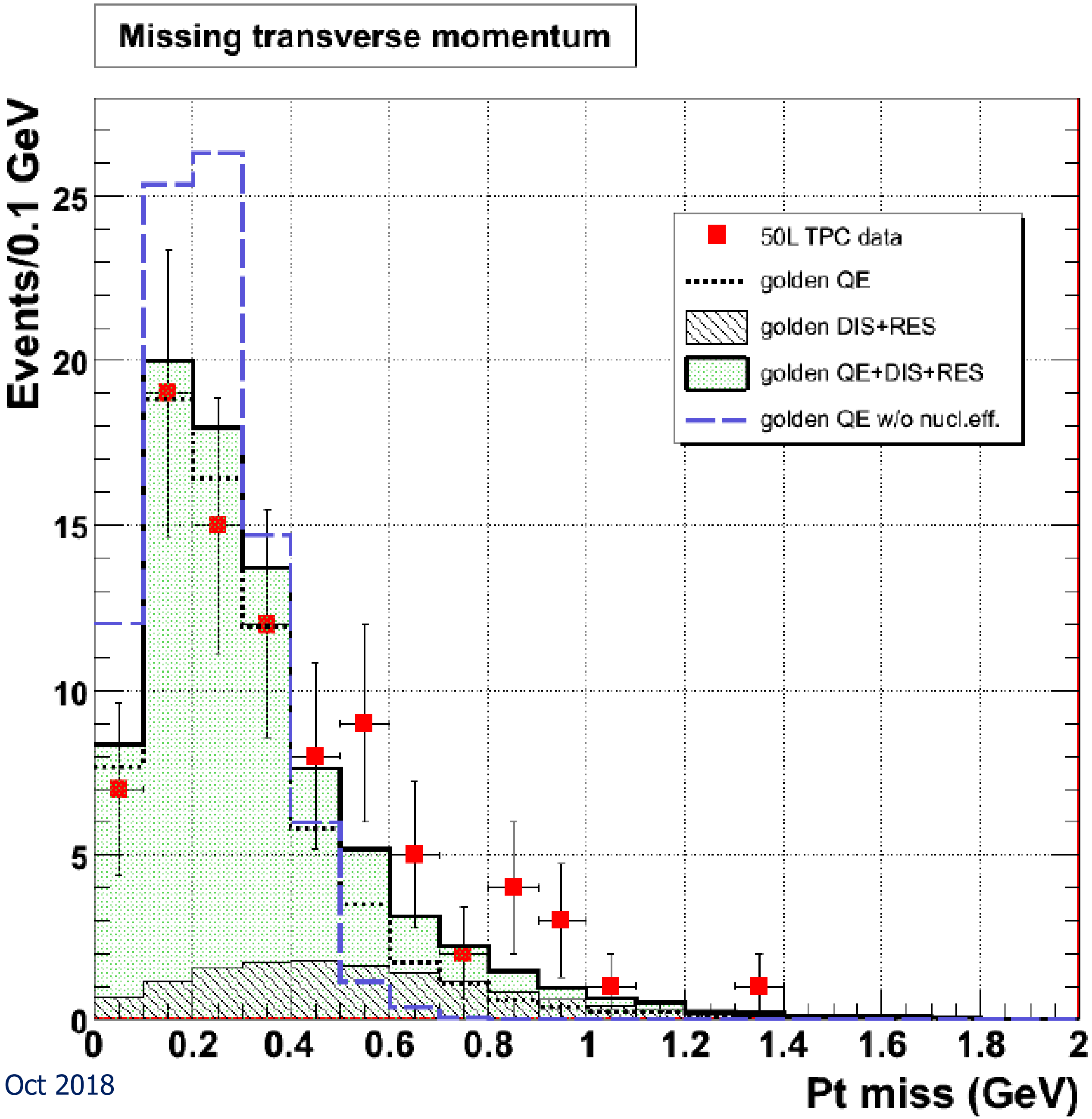




Trigger and μ reconstruction: NOMAD

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

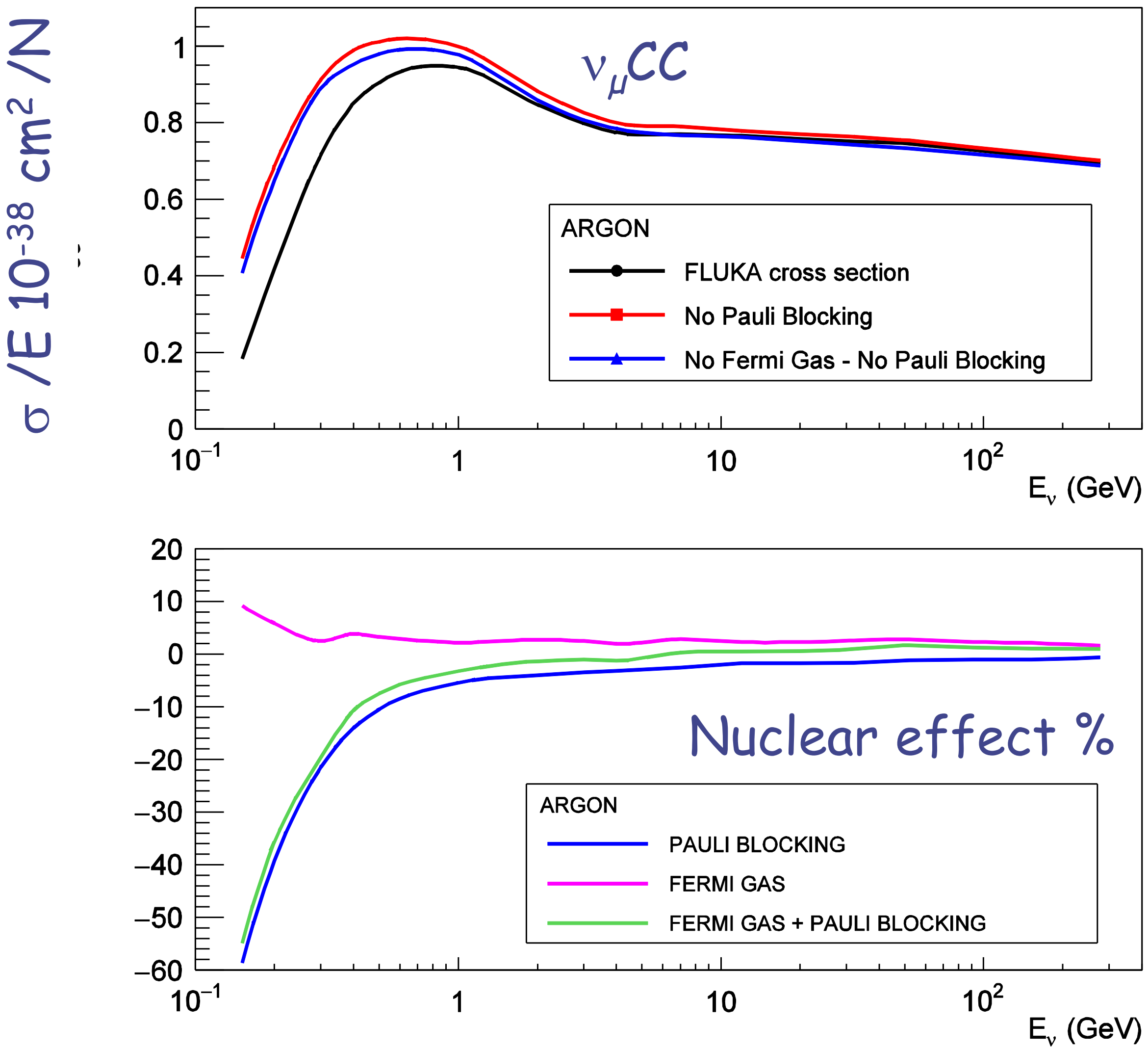
80±9(stat.)±13(syst.→ mainly QE fraction and beam simul)

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)

Total cross section: nuclear effects in Ar



5 GeV < Eν < 50 GeV

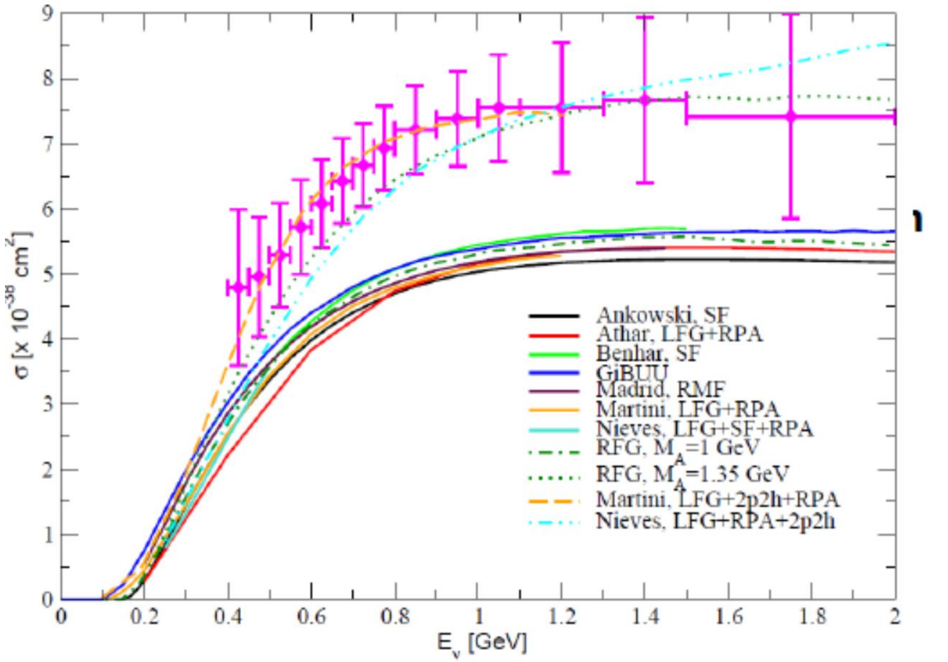
Pauli Blocking effect and Fermi Gas effect separately have an impact of ~ 2-3%

Globally Nuclear effects stay within ±1%

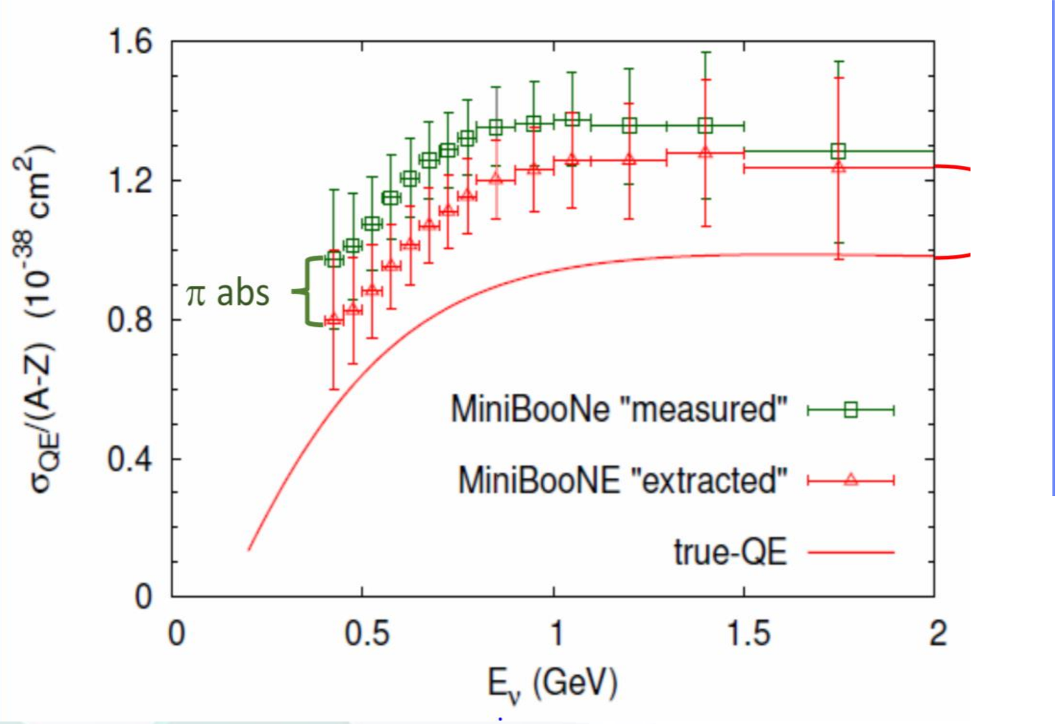
Eν < 5 GeV

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

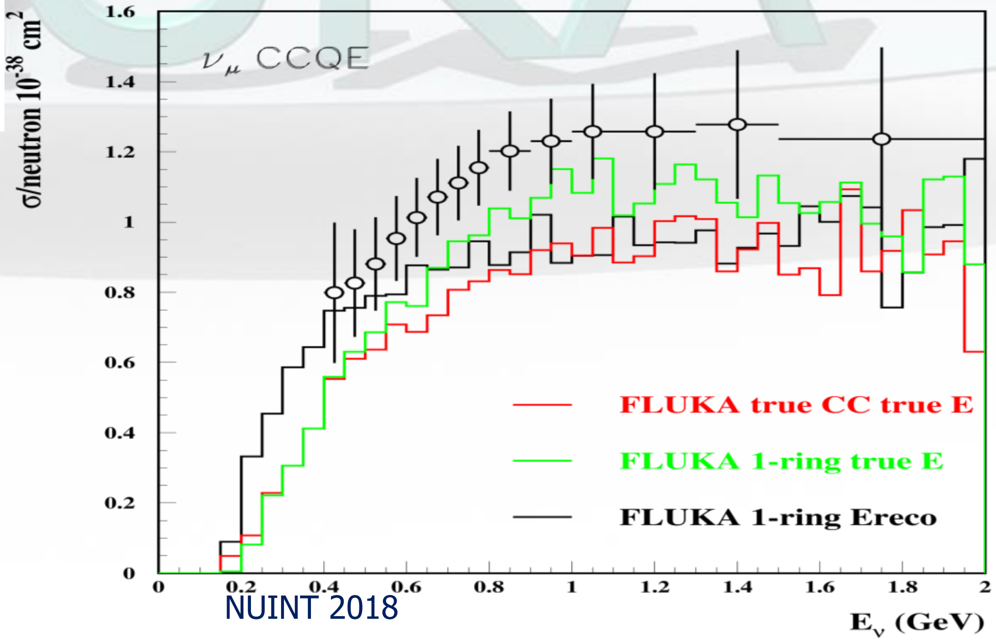
CCQE on 12C



σ [x 10^-38 cm^2]
E_ν [GeV]
0
1
2
3
4
5
6
7
8
9
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Ankowski, SF
Athar, LFG+RPA
Benhar, SF
GiBUU
Madrid, RMF
Martini, LFG+RPA
Nieves, LFG+SF+RPA
RFG, M_A=1 GeV
RFG, M_A=1.35 GeV
Martini, LFG+2p2h+RPA
Nieves, LFG+RPA+2p2h



σ_QE/(A-Z) (10^-38 cm^2)
E_ν (GeV)
0
0.4
0.8
1.2
1.6
0
0.5
1
1.5
2
π abs
MiniBooNe "measured"
MiniBooNE "extracted"
true-QE



σ/neutron 10^-38 cm^2
E_ν (GeV)
ν_μ CCQE
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
FLUKA true CC true E
FLUKA 1-ring true E
FLUKA 1-ring Ereco

Nuclear effects in Minerva

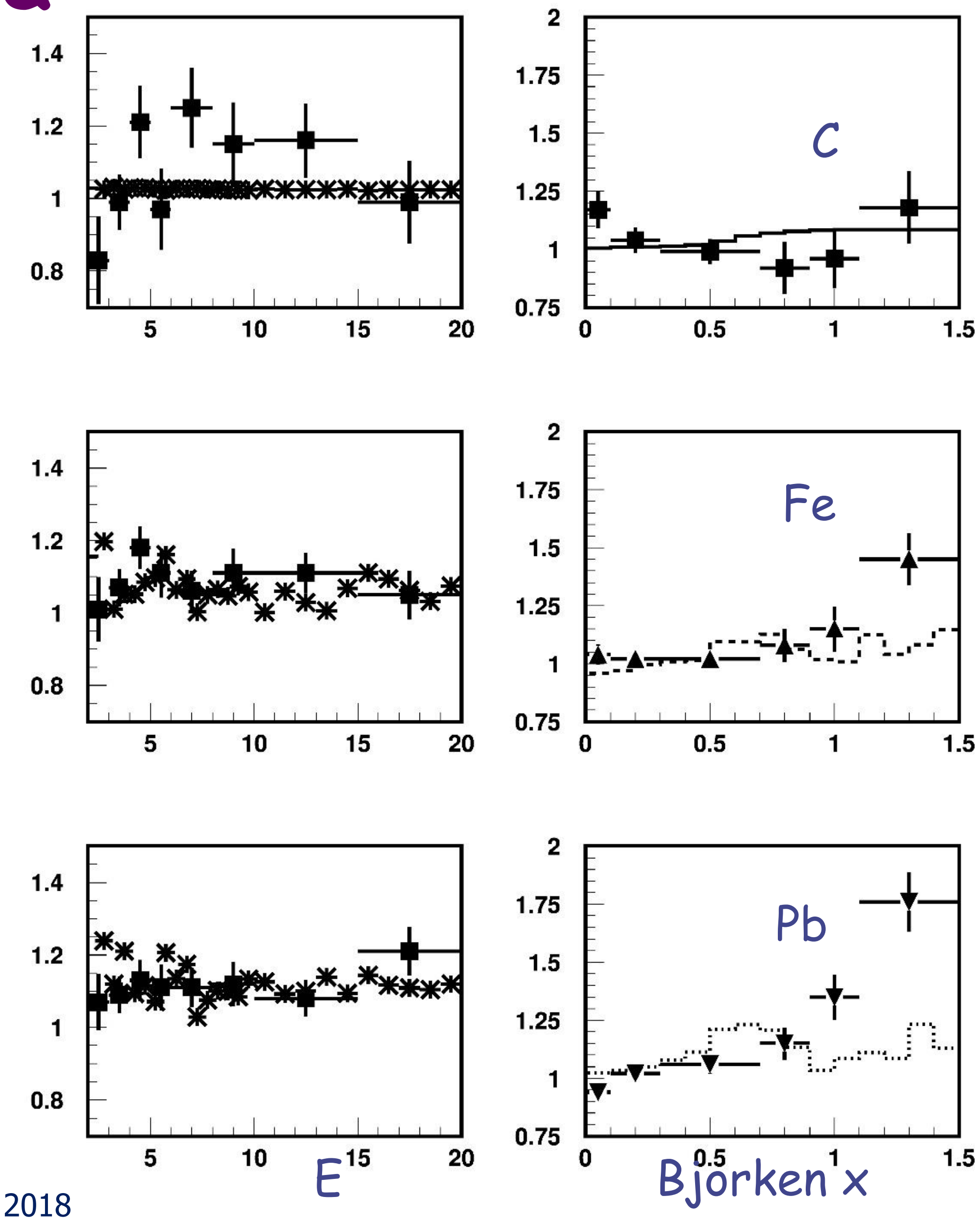
Beam: νμ NuMi Low Energy (average 4 GeV)
Main Target : CH

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

Here: ratio of cross sections per nucleon
/ the one in CH

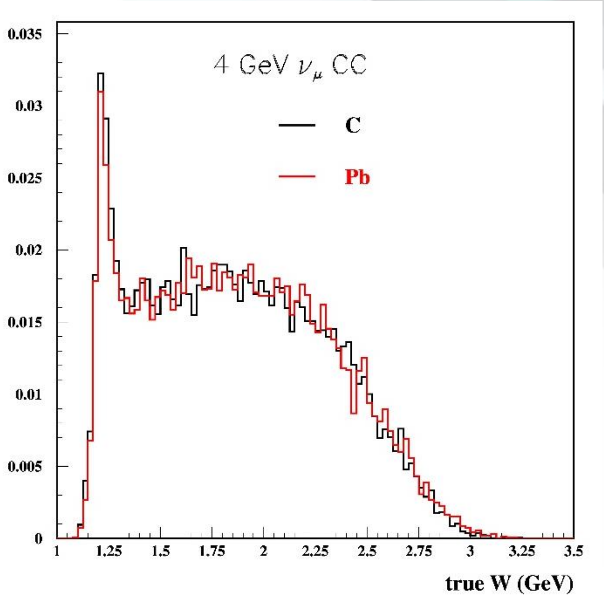
Left: total CC vs neutrino Energy :
squares: data
crosses: FLUKA

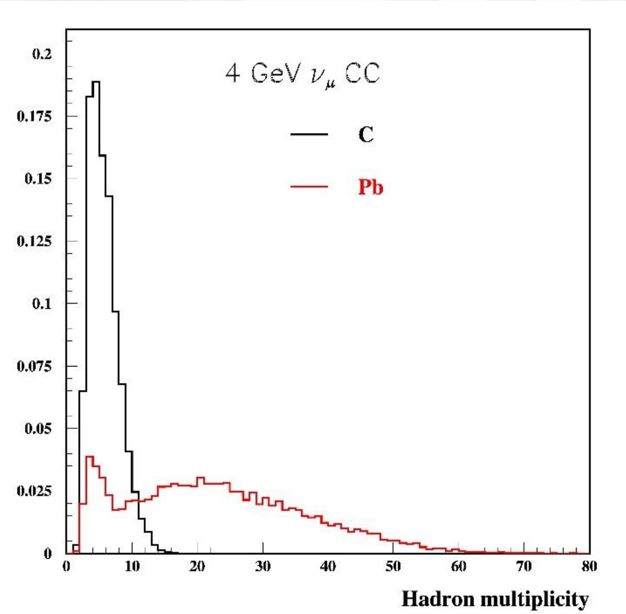
Right: dσ/dx
symbols: data histos: Fluka
expt: reduction at low x and
enhancement at high x with incr. A
Fluka: fails the highest x (same for Genie)

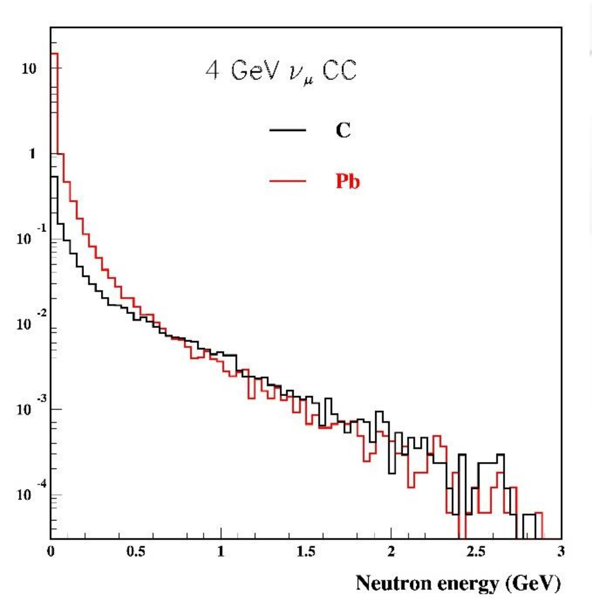


Nuclear effects in Minerva -II

- HOWEVER:
- Bjorken x and neutrino energy are calculated through lepton energy and Hadronic energy
- Ehad = calorimetric energy *calibration constant
- Strongly dependent on, for instance, neutron detection efficiency
- Fraction of energy going into neutrons depends on target
- ➔ would need full simulation







Non-QE

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)

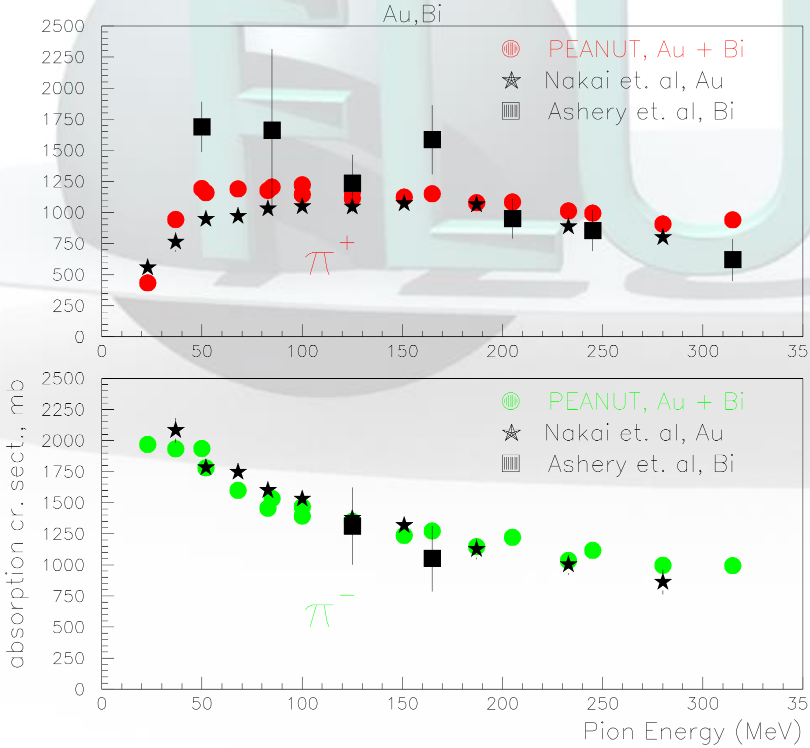
quasielastic scattering, two and three body absorption

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)

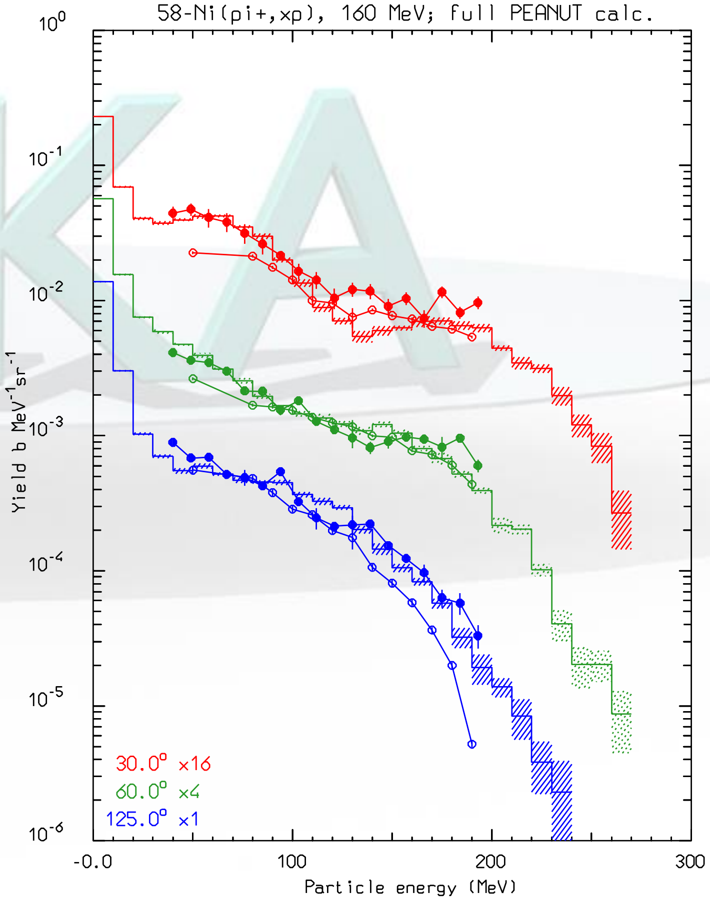


Emitted proton spectra at different angles , 160 MeV π^+ on ^{58}Ni

Phys. Rev. C41,2215 (1990)

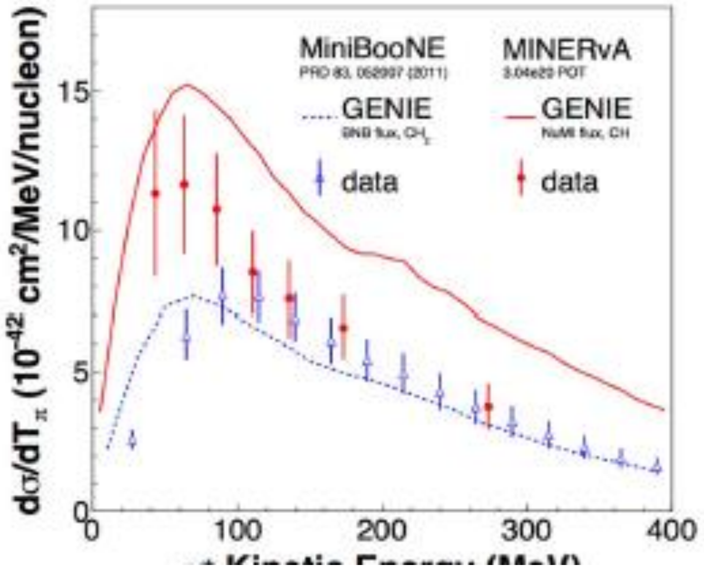
Phys. Rev. C24,211 (1981)

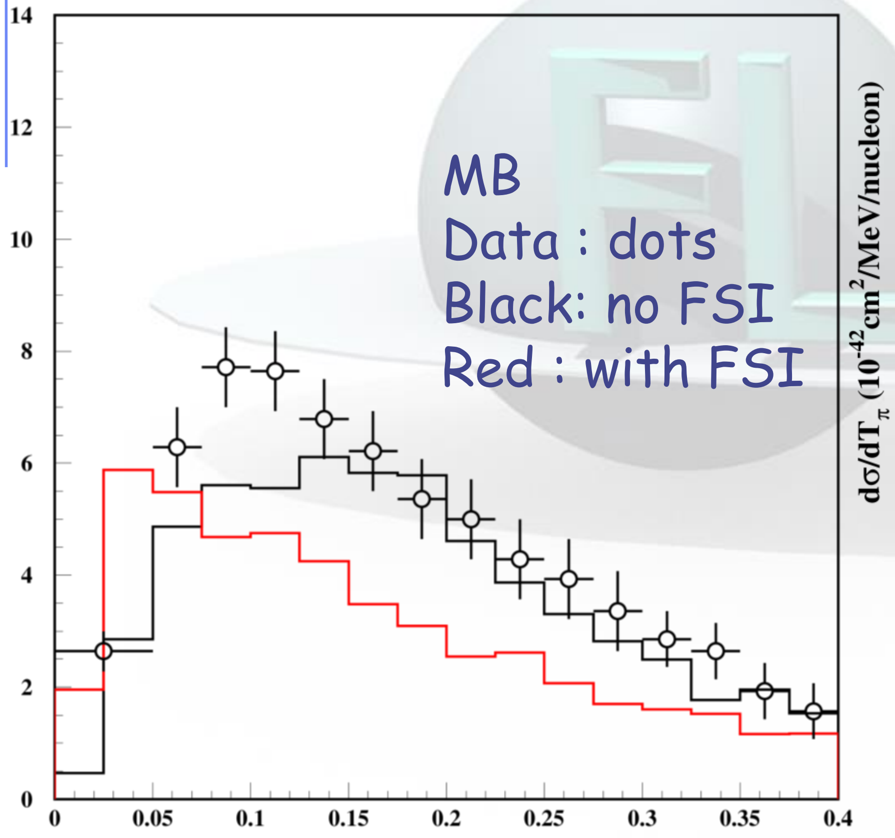
Proton spectra extend up to 300 MeV



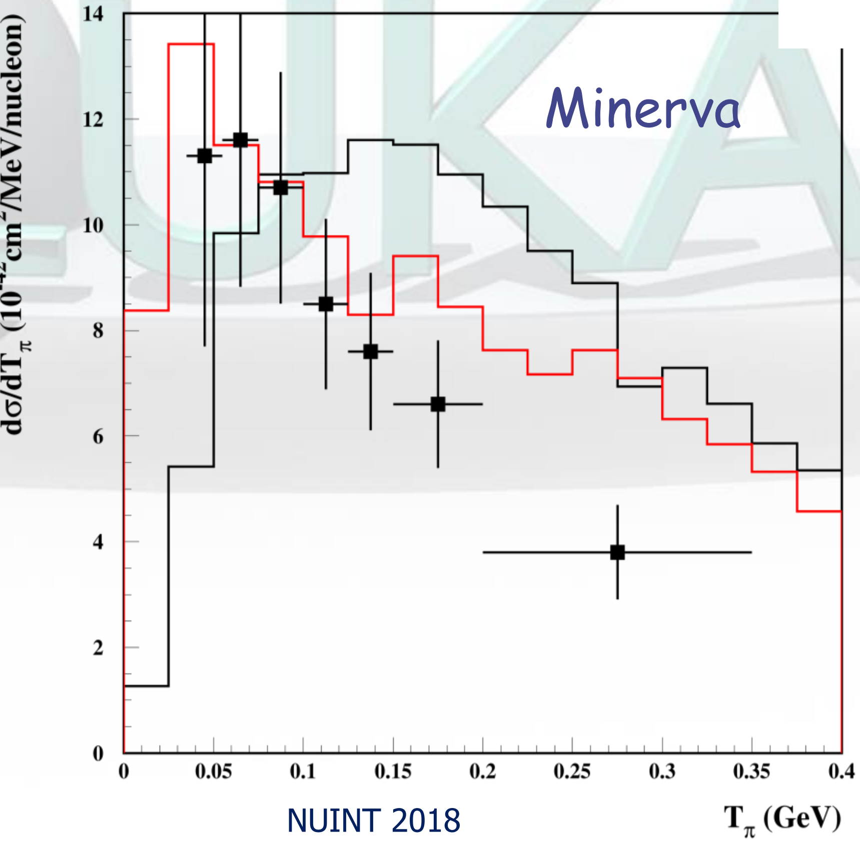
MB and Minerva

Dytman
NUINT14
Genie+FSI





MB
Data : dots
Black: no FSI
Red : with FSI



Minerva

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

another 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

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

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

Particle production: multiplicities

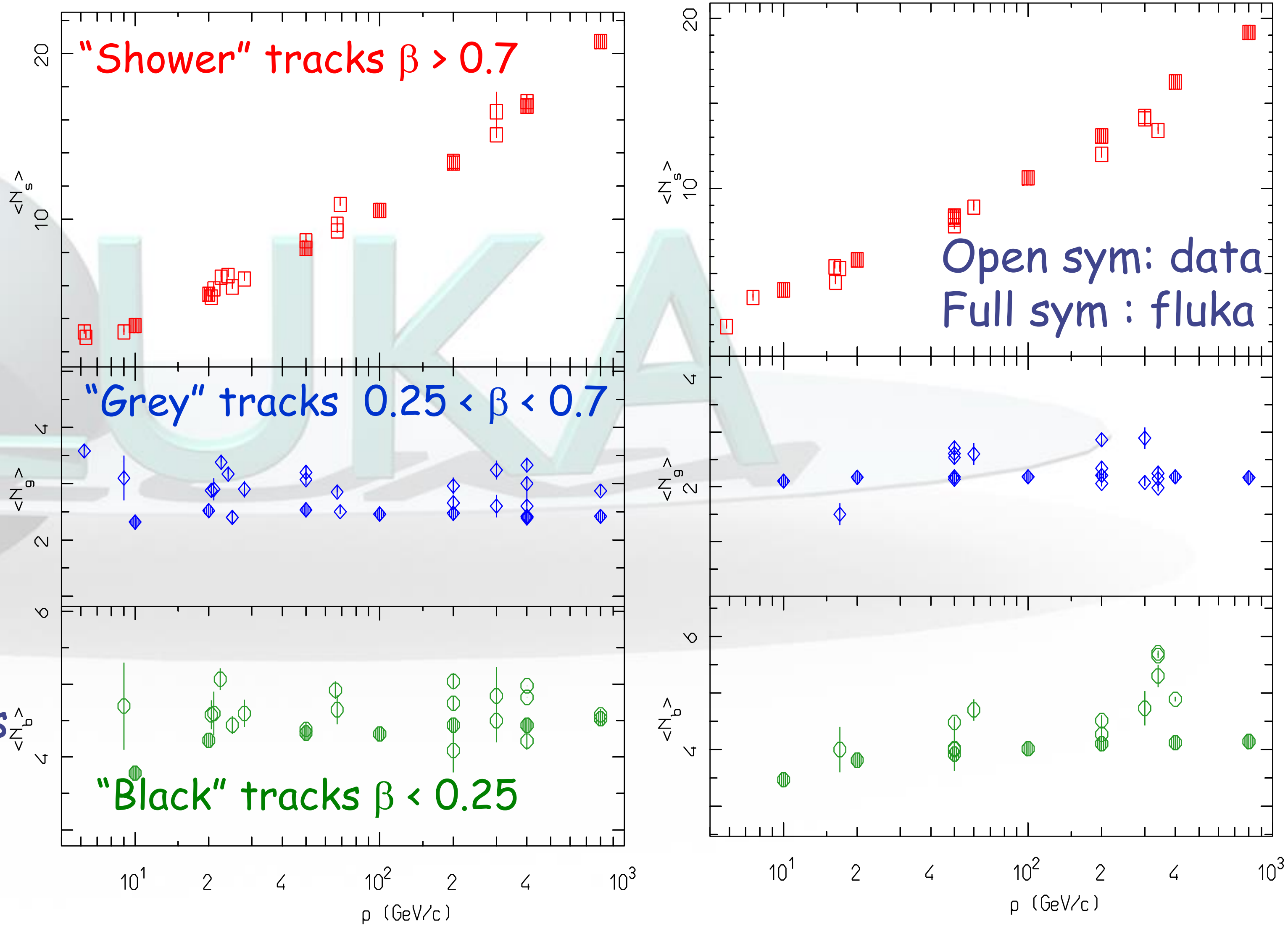
Data:
Phys. Rev. D42, 2187 (1990).
Phys. Rep.144, 187 (1987).

Or: why do you use this funny formation zone?

- shower particle multiplicities increase steadily with projectile energy
- multiplicities of grey and black tracks rapidly saturate at few tens of GeV, and stay constant
- Looks like fast particles are free to escape without inducing cascades
- Note that p-p cross section is rather flat vs energy
- ➔ need mechanism

Protons on emulsion

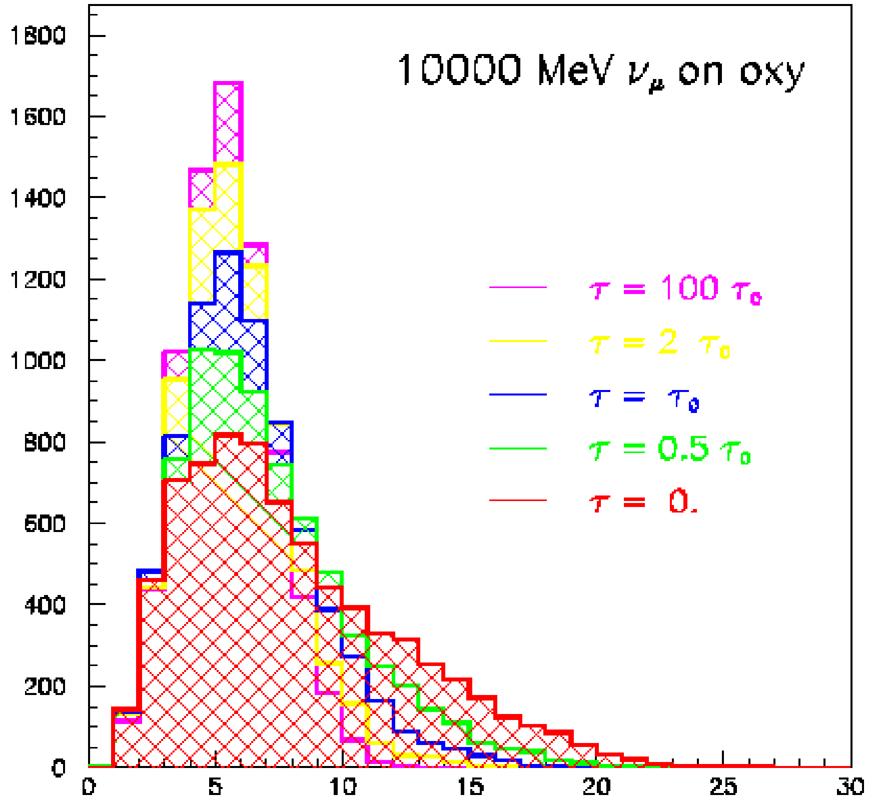
Pion- on emulsion



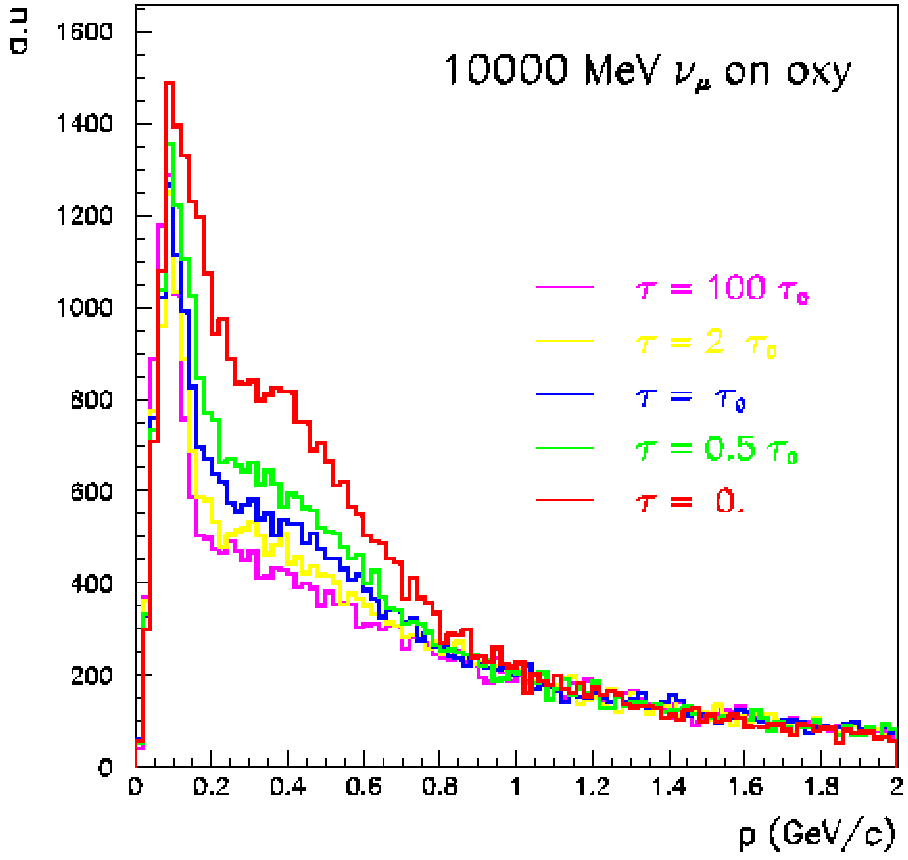
Part. Prod. Versus projectile momentum.

Effect of formation zone

Total hadron multiplicity



Charged hadron spectra

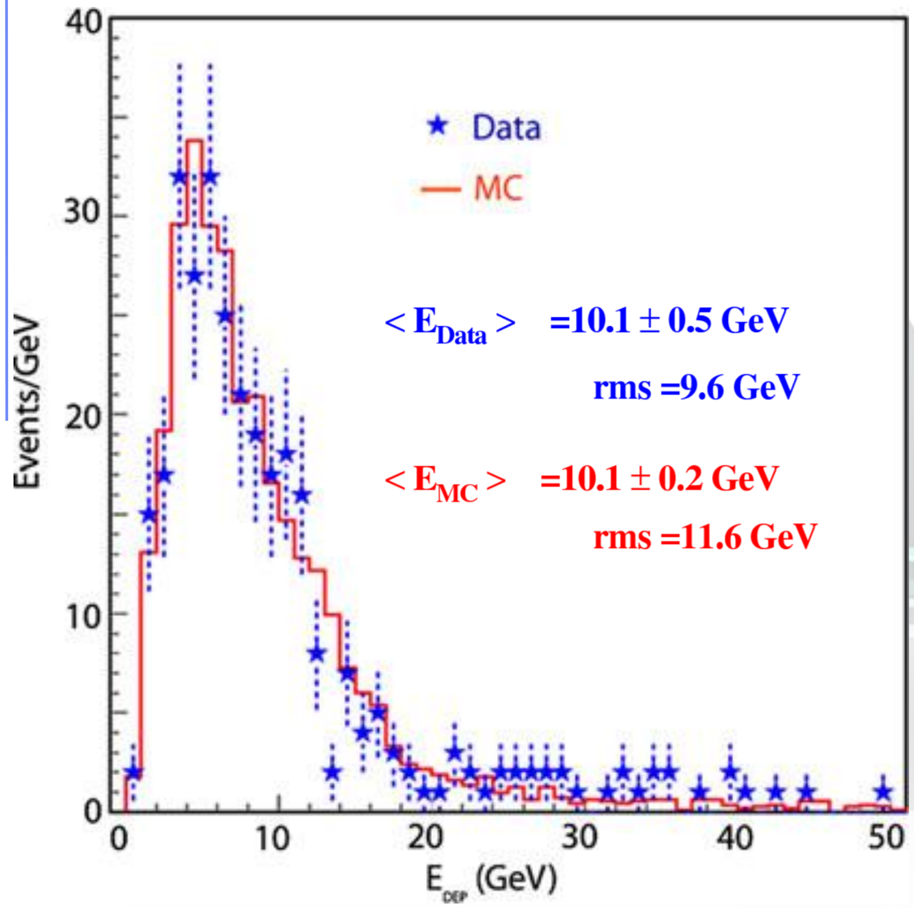


Last steps of the reaction

- The INC in FLUKA is carried on until all involved nucleons drop below 30-50 MeV kinetic (smooth threshold, depends on number of excited nucleons)
- A PRE-EQUILIBRIUM steps comes in : nucleon-hole pairs sharing statistically the residual excitation energy. Exciton number increased by "collisions", particle emission still possible.
- When the exciton number reaches equilibrium, EVAPORATION / FISSION comes in. Statistical, includes nucleons and heavy fragments, includes sub-barrier emission, takes into account single excited levels.
- At excitation energies < separation energy → emission of gamma rays (actually also in competition with evaporation) . Uses atlas of excited levels/transitions whenever available.

CNGS data (≈20 GeV Eν peak)

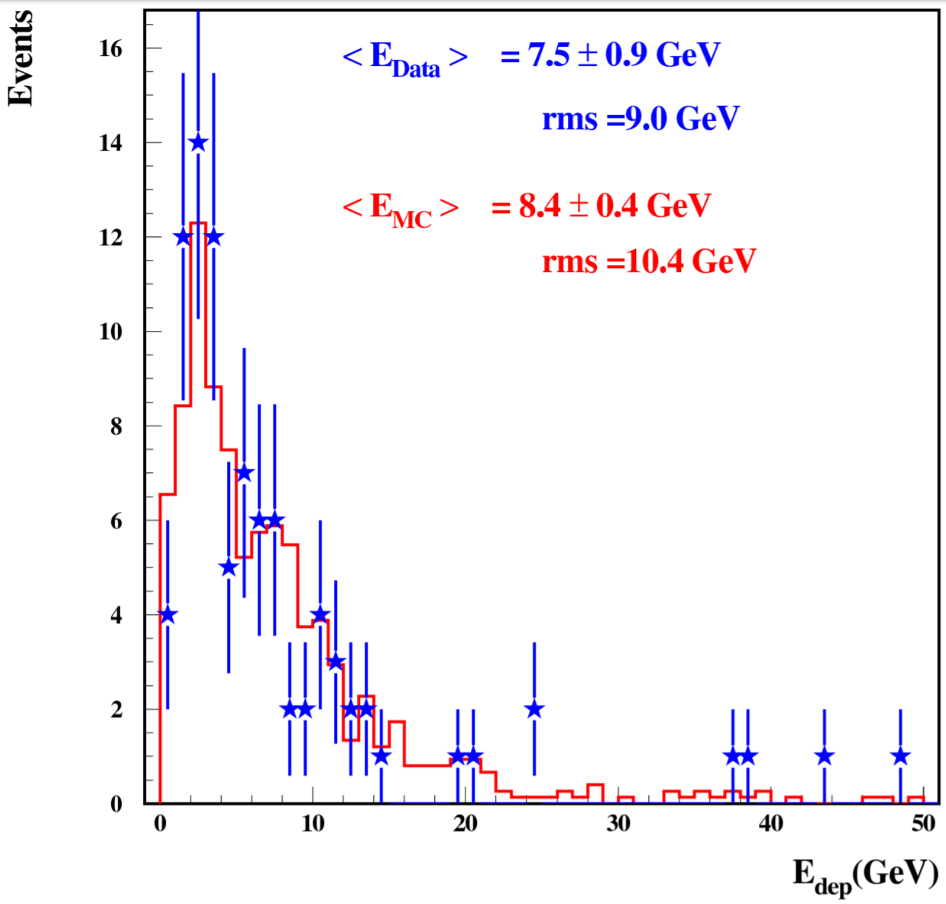
Eur. Phys. J. C (2013) 73:2345
Phys. Lett. B (2014)



Distribution of total deposited energy in the T600 detector

Left:
ν_μ CC events

Right:
ν NC 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)
- ➢ Comparisons against data

Backup

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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 $\pi^+/\ \pi^-$):

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

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

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

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

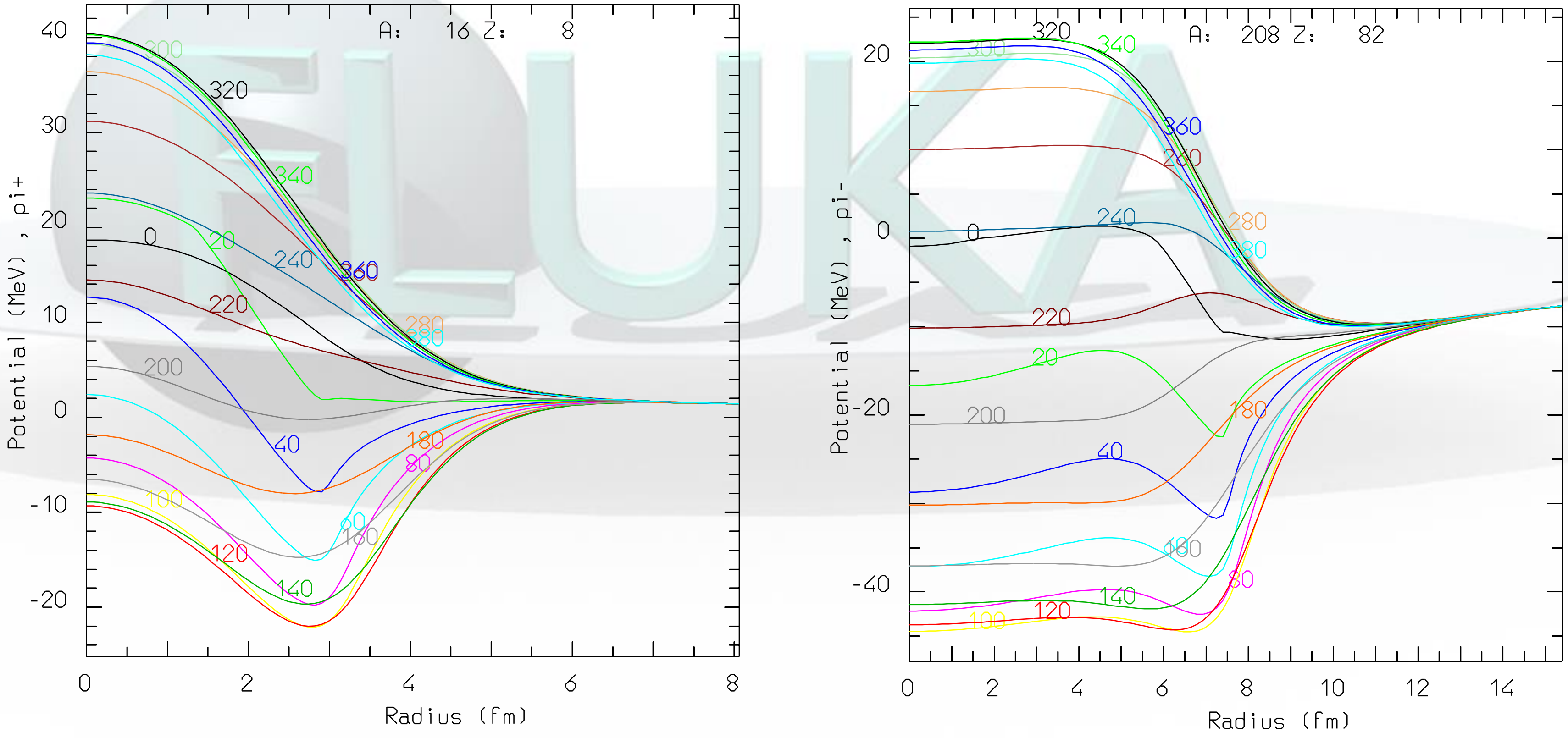
$$2\omega U_{opt}(\omega,r) = -\beta - K^2\frac{\alpha}{1+g\alpha} + \frac{\omega}{2M}\nabla^2\alpha$$

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

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

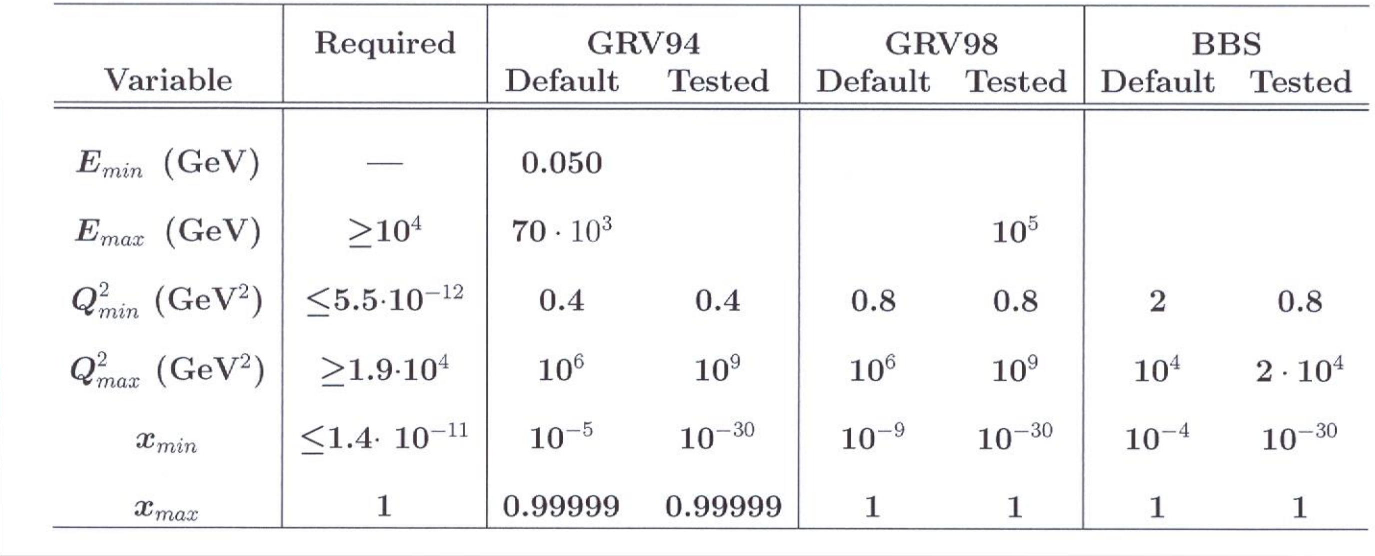
Nuclear potential for pions: examples

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)



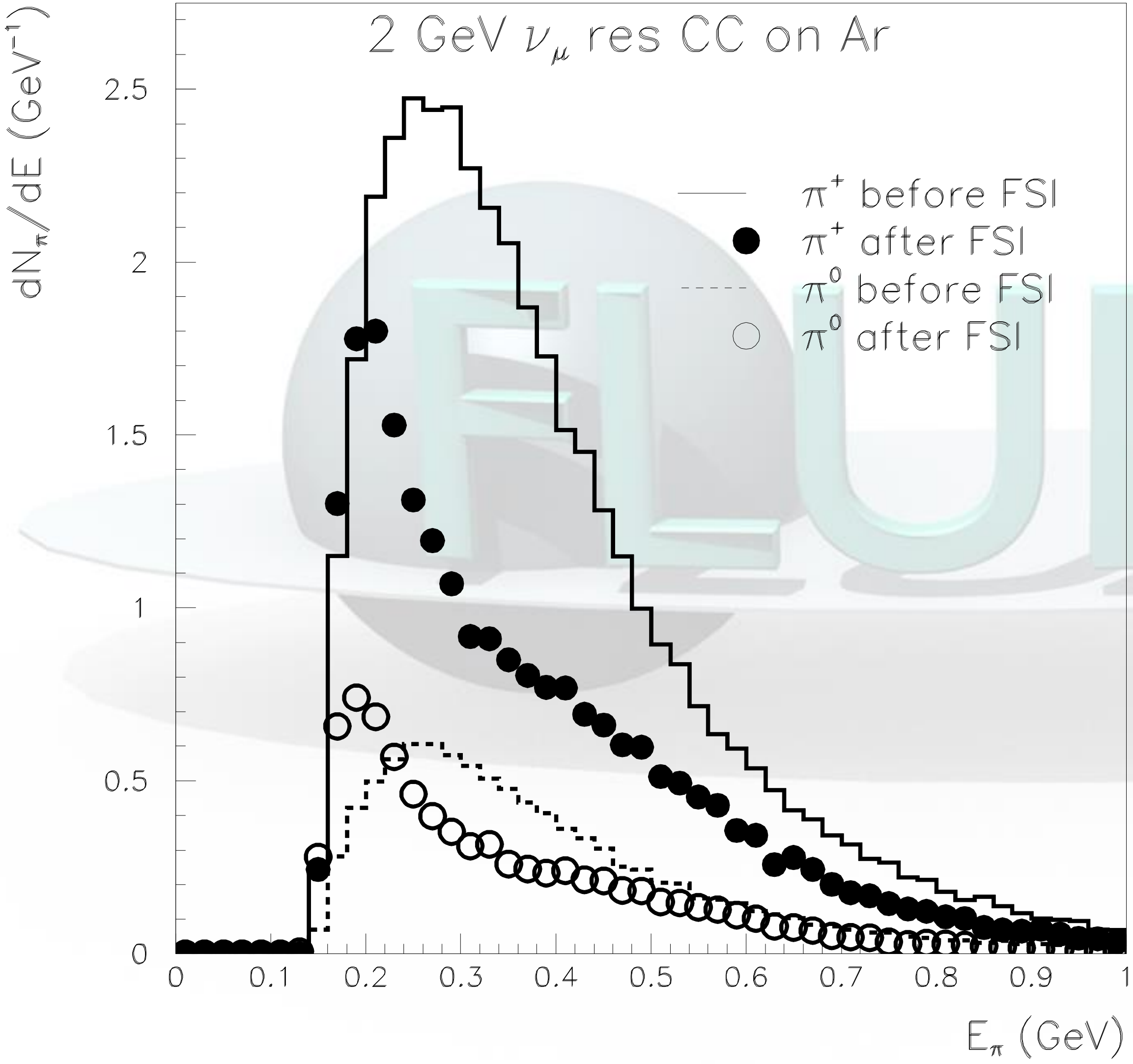
NUNDIS 2015: kinematics

- 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

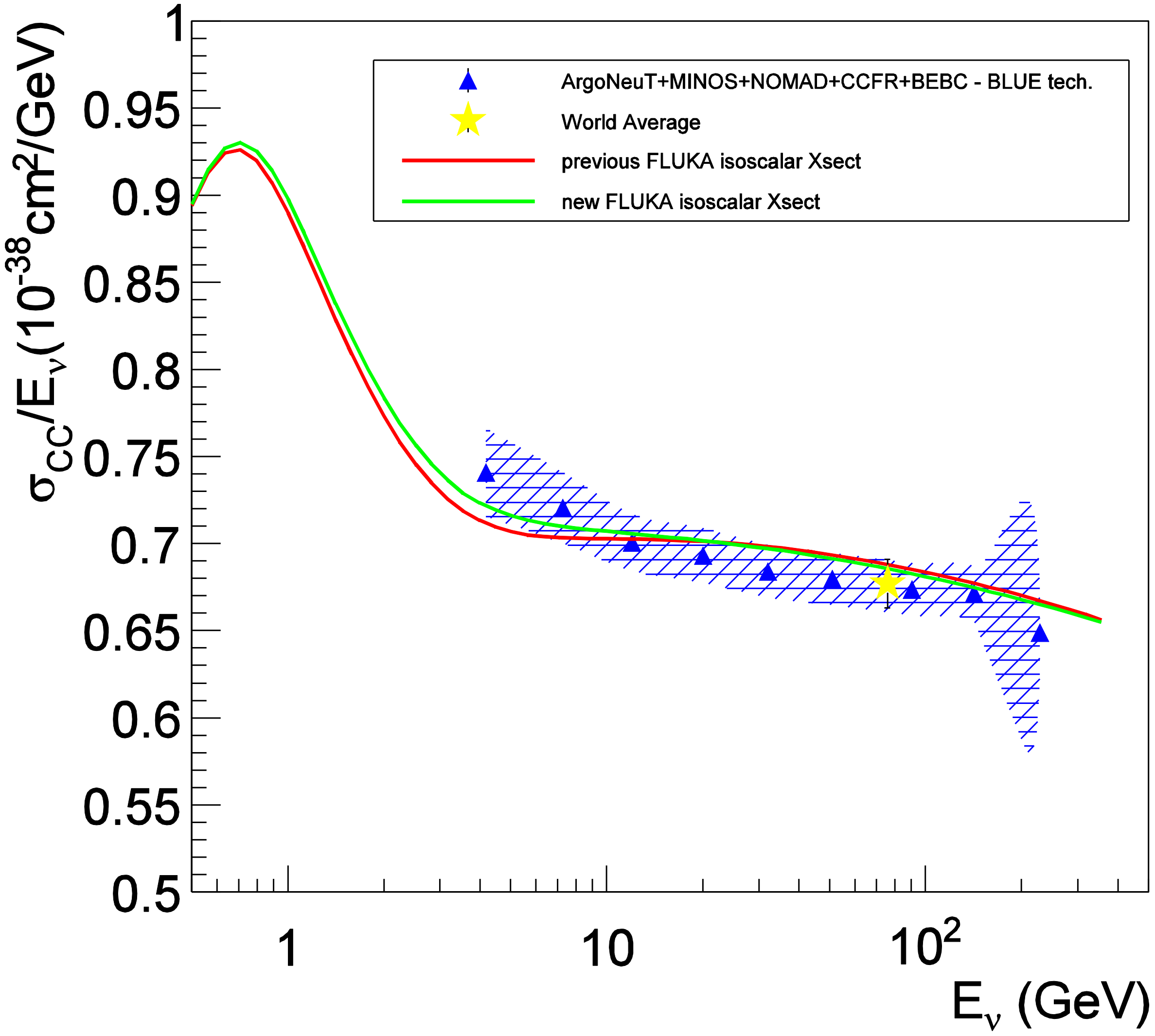
Expected effect in Ar



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

Same, with evaluation of data systematics



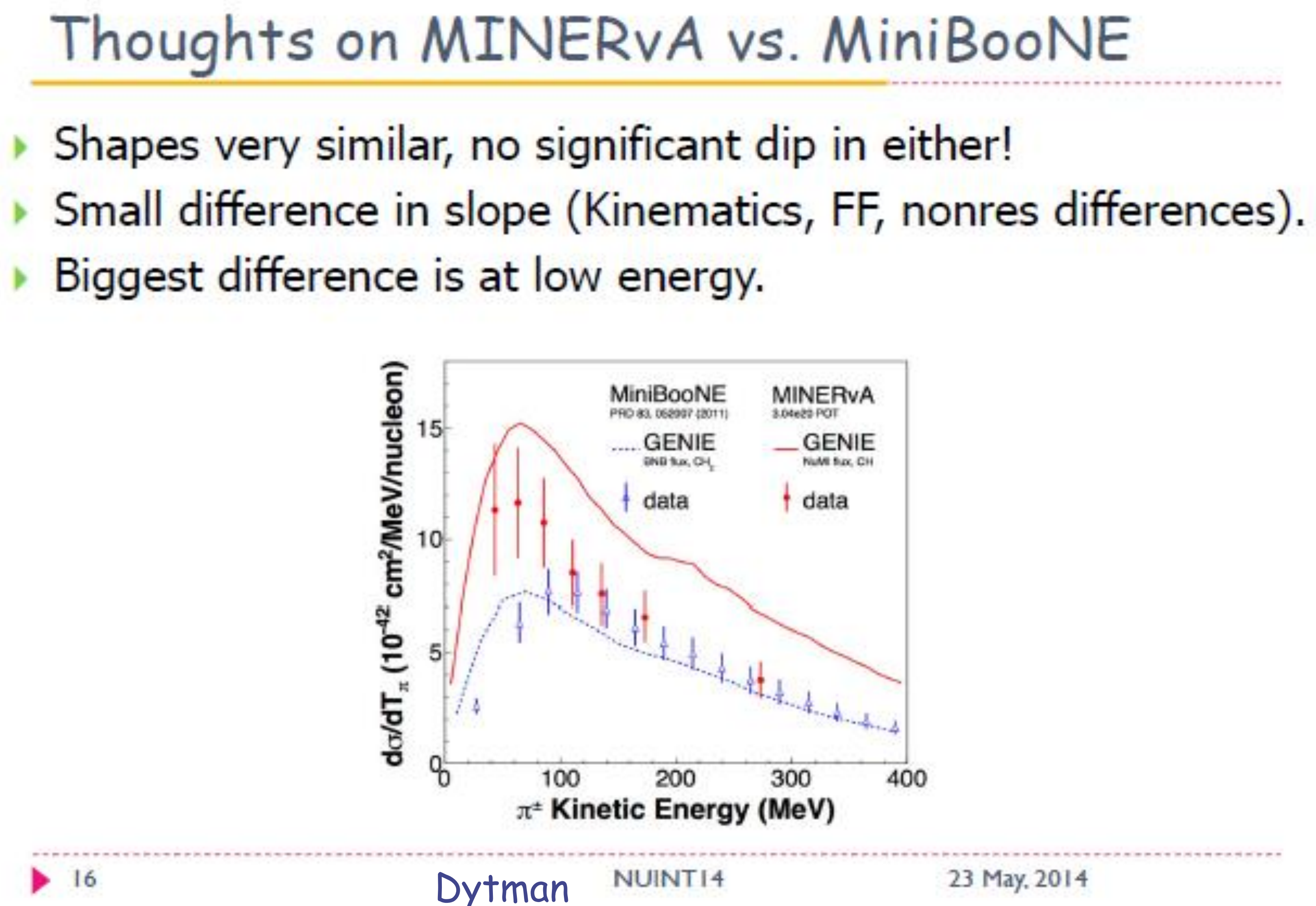
Work in progress: Attempt to compare with a combined estimate from available data and relative systematic error, properly accounting for correlations

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

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.

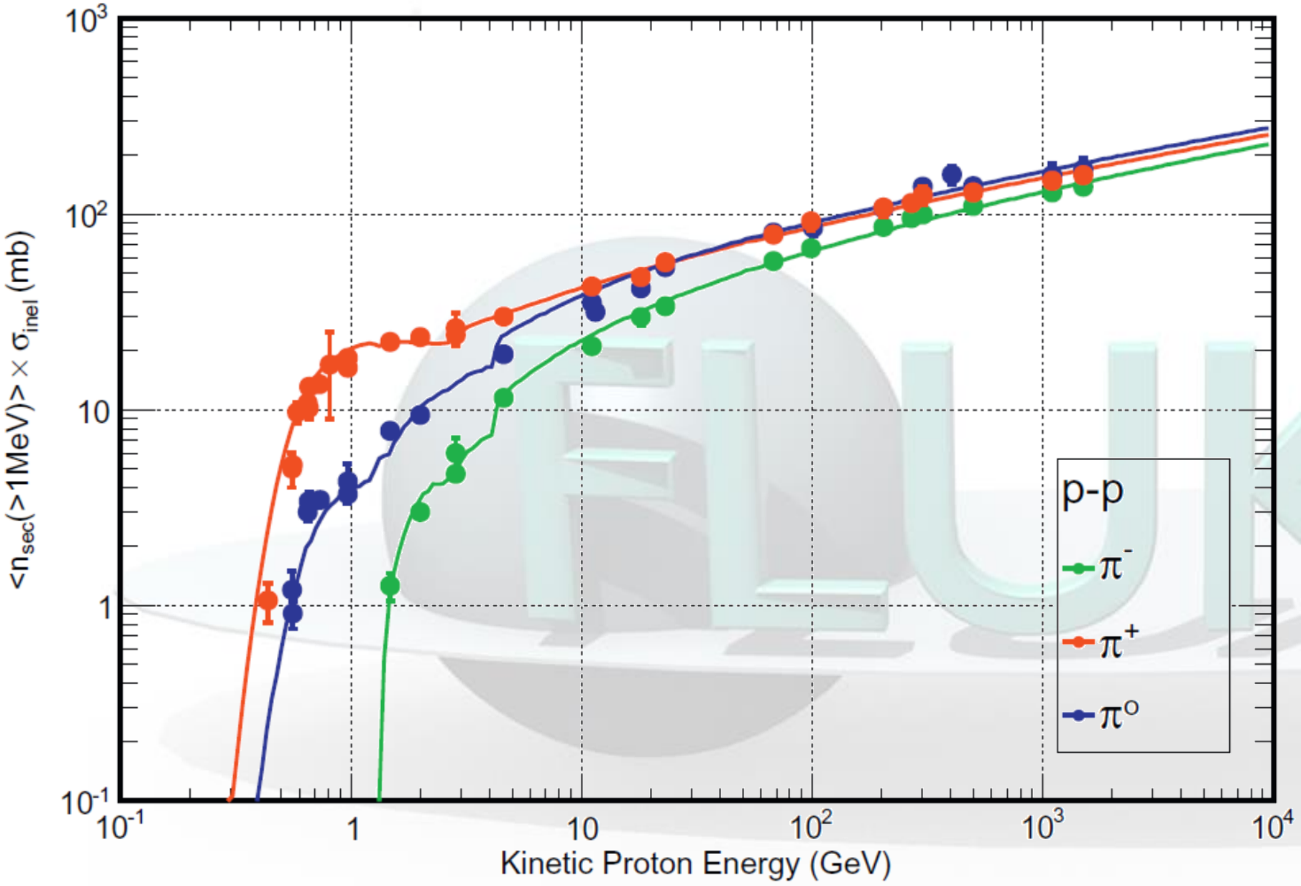
16 NUINT14 23 May, 2014

Dytman

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

Pion production in p-p collisions:



Inclusive cross section for the production of π^0 **(blue)**, π+ **(red)**, and π^- **(green)** in p-p collisions as a function of the proton kinetic energy. Lines: simulations, symbols exp. Data. (figure from AstrPhys81, 21 (2016))

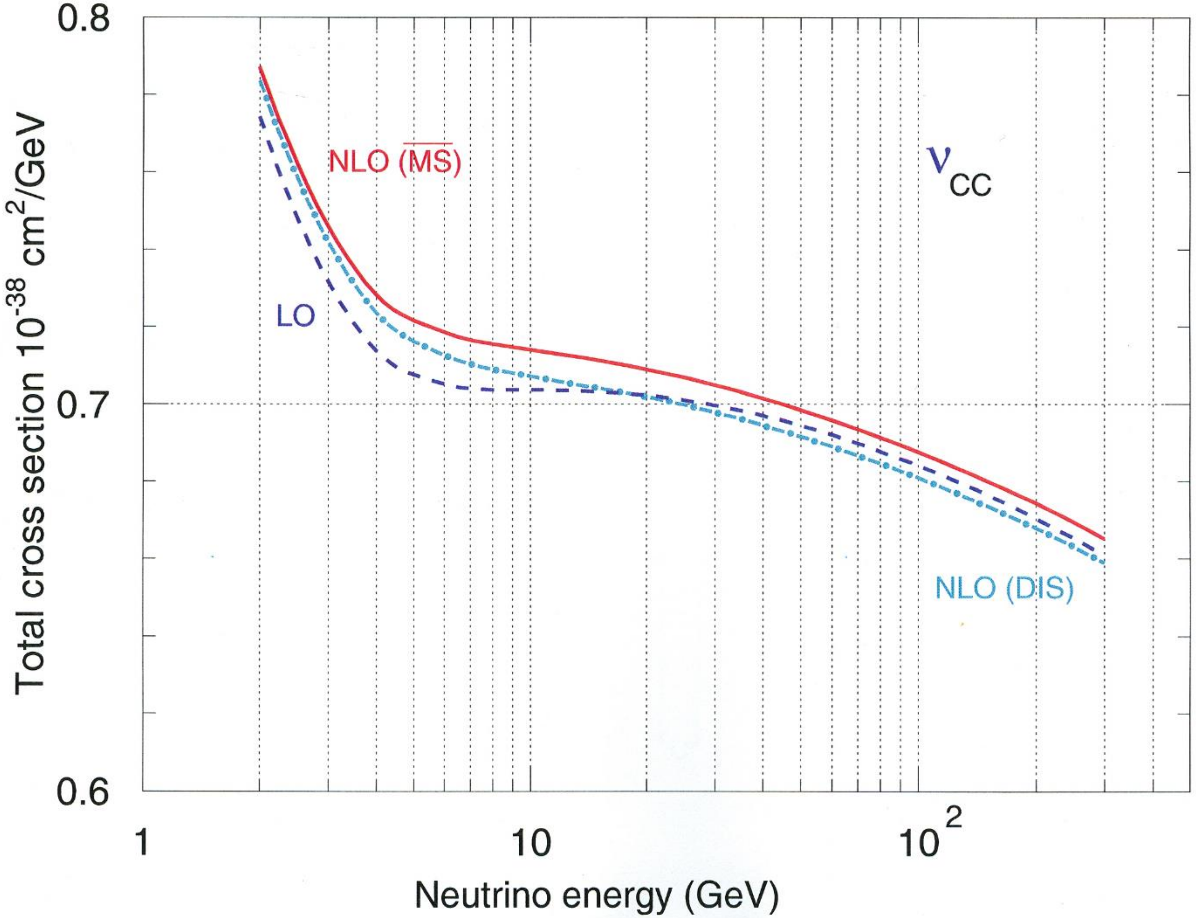
Fig. 2. Inclusive cross sections for the production of π^0 (blue), π^+ (red) and π^- (green) in *p*–*p* collision as function of the incoming proton kinetic energy. Lines: FLUKA simulation; points: data from Ref. [28]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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)

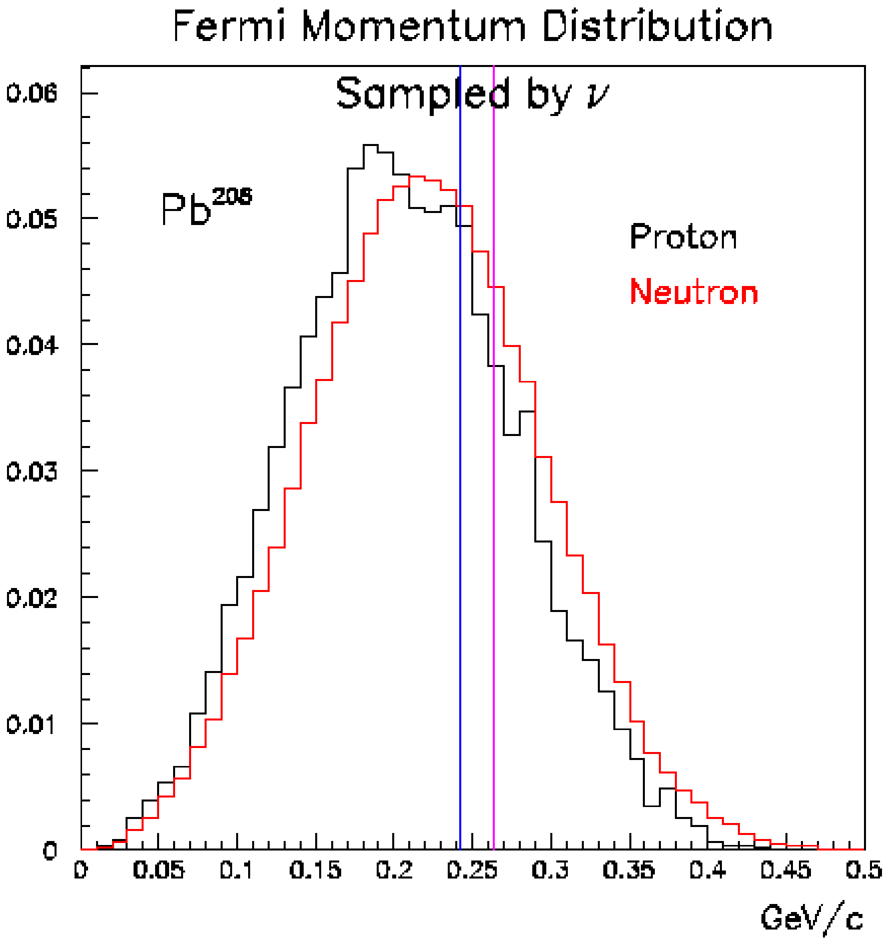
An interesting feature of the GRV98 analysis is a low threshold for the transferred , 4-momentum, $Q^2 = 0.8$ GeV^2



NLO (DIS) is chosen as a default option

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

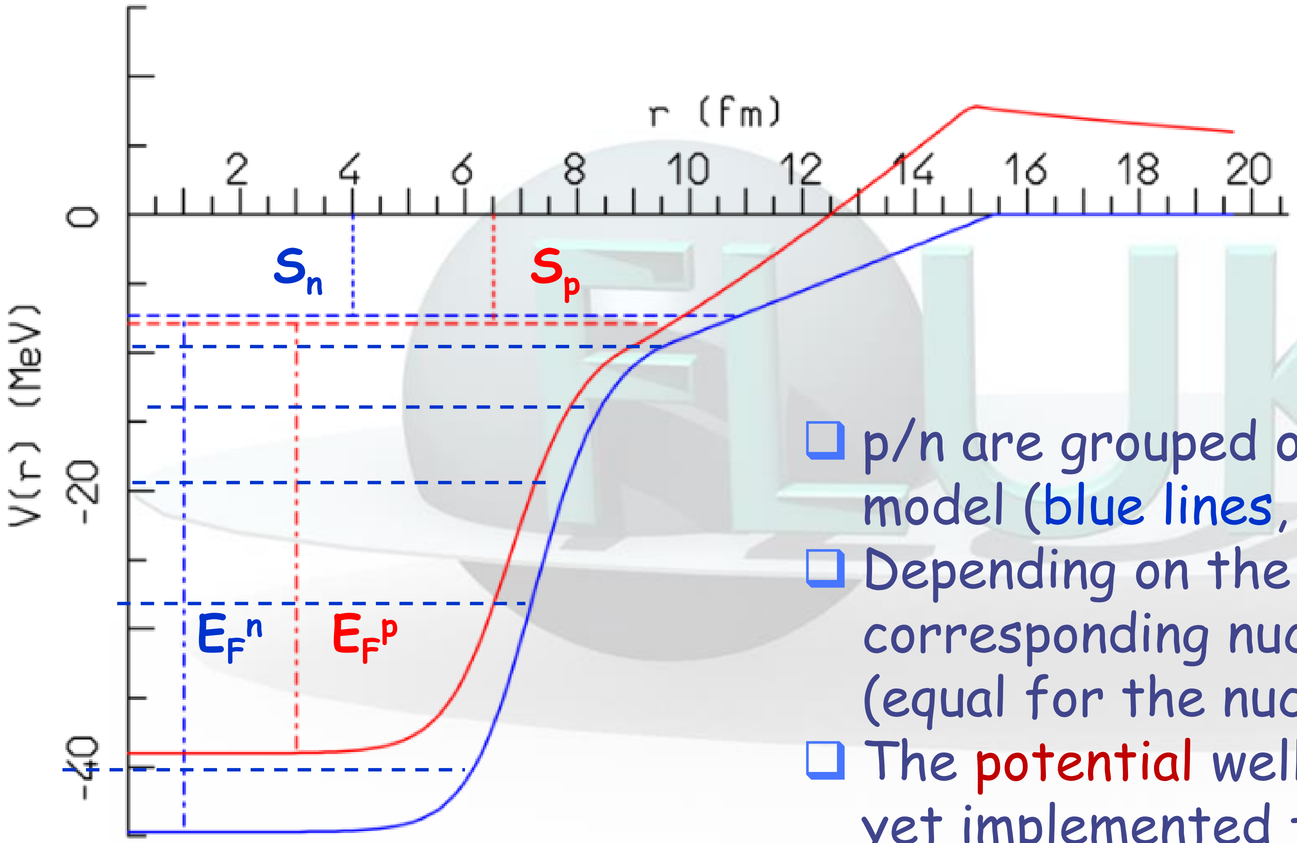
Example of Fermi distribution



Fermi momentum distribution as “seen” by interacting neutrinos on lead.

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

Nucleon levels inside the nuclear potential: schematic drawing



- Blue: neutron
- Red: proton

- ☐ p/n are grouped on energy levels space 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 nucleus radius (equal for the nucleons on the Fermi level)
- ☐ The potential well depth depends on the nucleon energy (not yet implemented for neutrino and electron interactions)
- ☐ Hit nucleon must go above Fermi level, can stay below separation energy.

Nucleon correlation function:

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

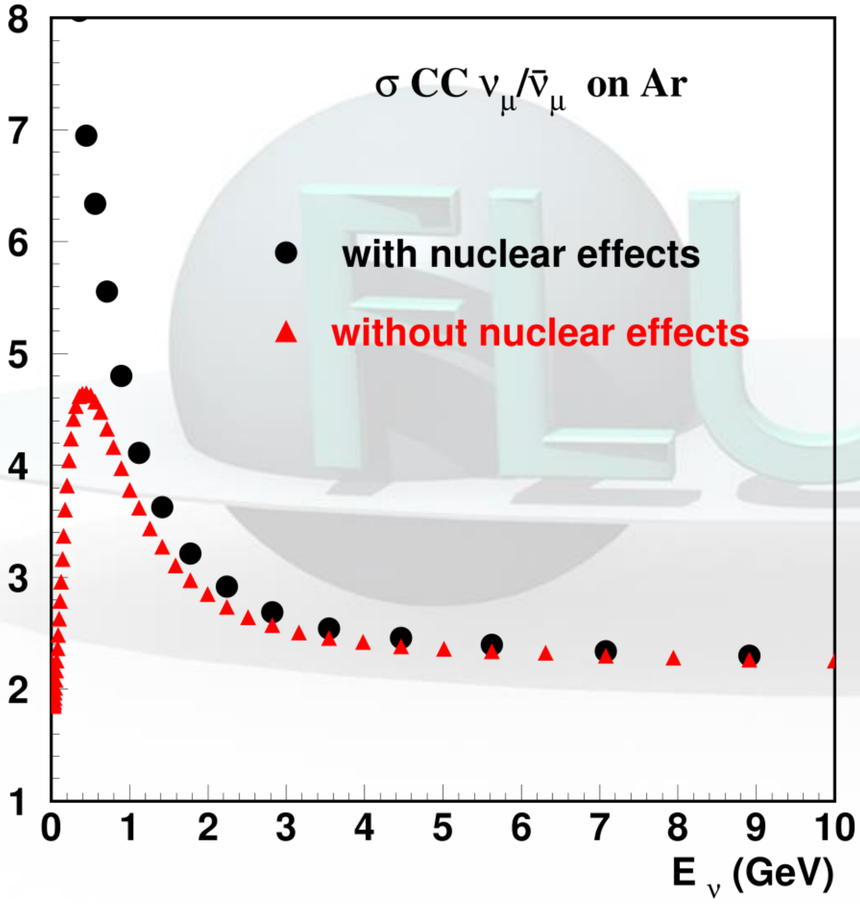
Due to the anti-symmetrization of the fermion's wave function, given a nucleon in a position $\vec{r}$ *in a nucleus with density* ρ_0*, the probability of finding another like nucleon in a position* $\vec{r}\,'$ *is decreased for small values of the distance* $d = |\vec{r} - \vec{r}\,'|$ *by a factor*

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

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

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

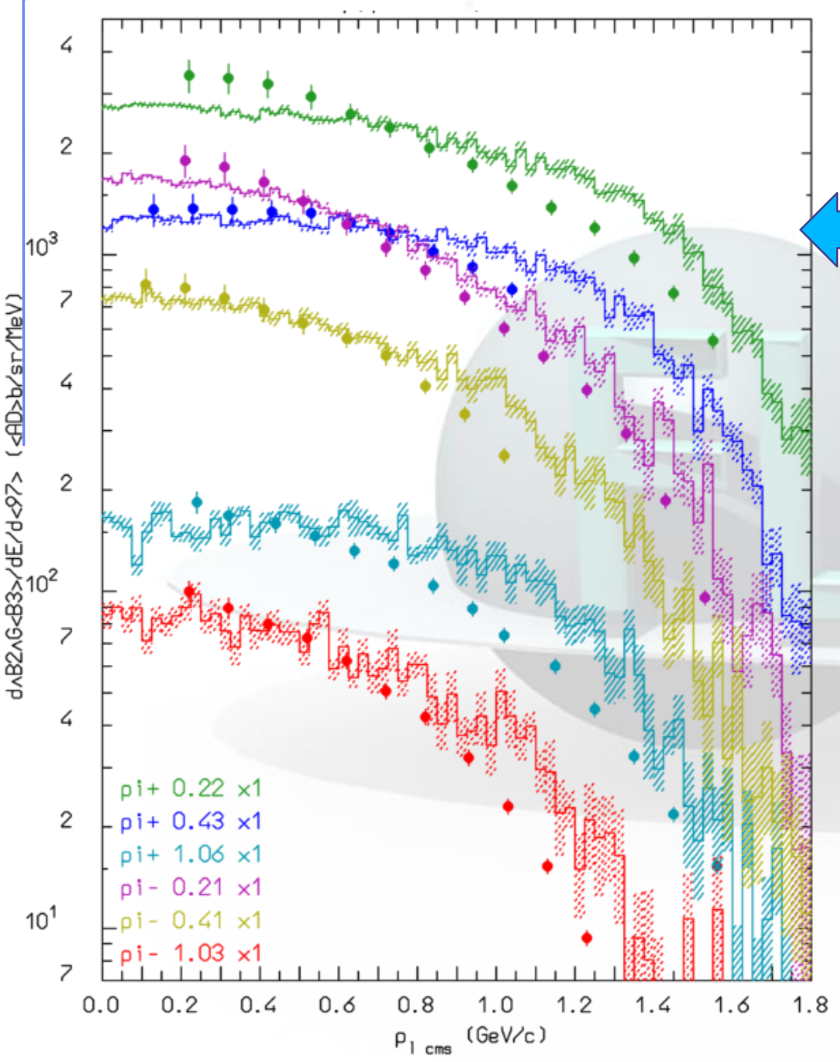
(Generalized) IntraNuclear Cascade

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

  σ_{free} + Fermi motion × $\rho(r)$ + exceptions (ex. π)

  σ_{free} includes inelastic
- 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
- Fully relativistic
- Multibody absorption for π, μ^-
- Special for K^-, antinucleon, π (phase shifts, annihilation)
- 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 levels in evaporation/gamma deexc)

Effect of "low energy explosion"

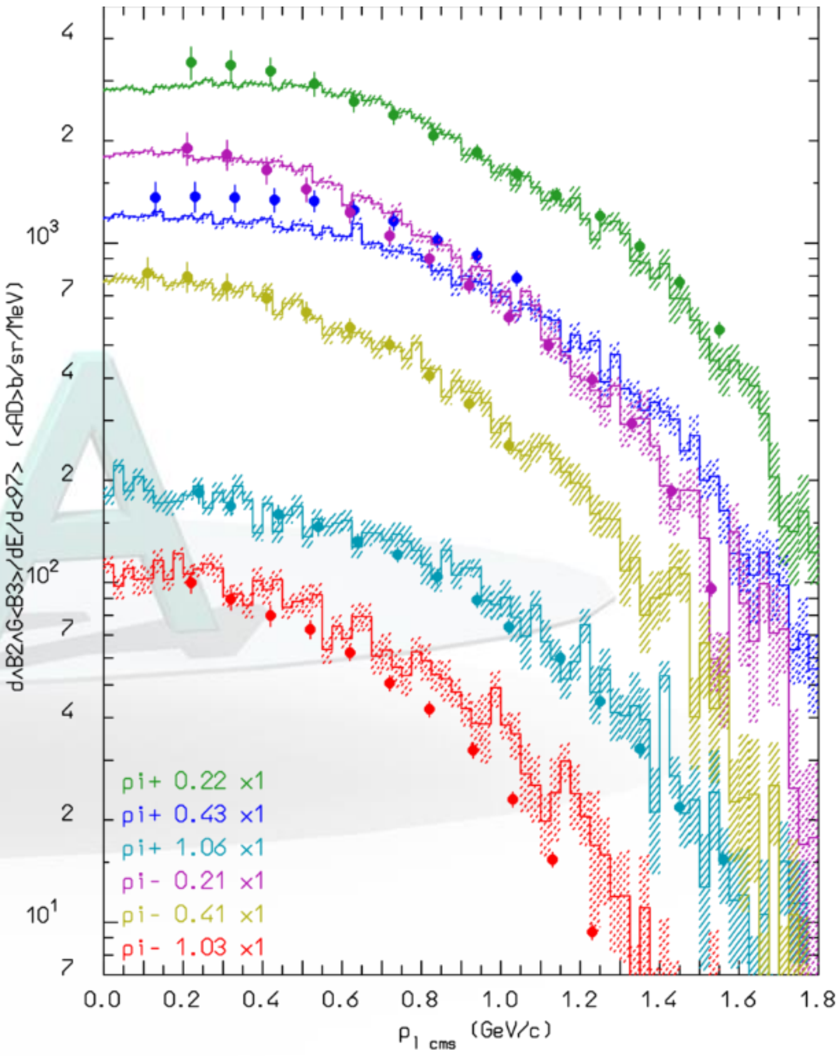


Fluka: histos
Data: symbols

"standard" hadronization

With low-mass chain explosion

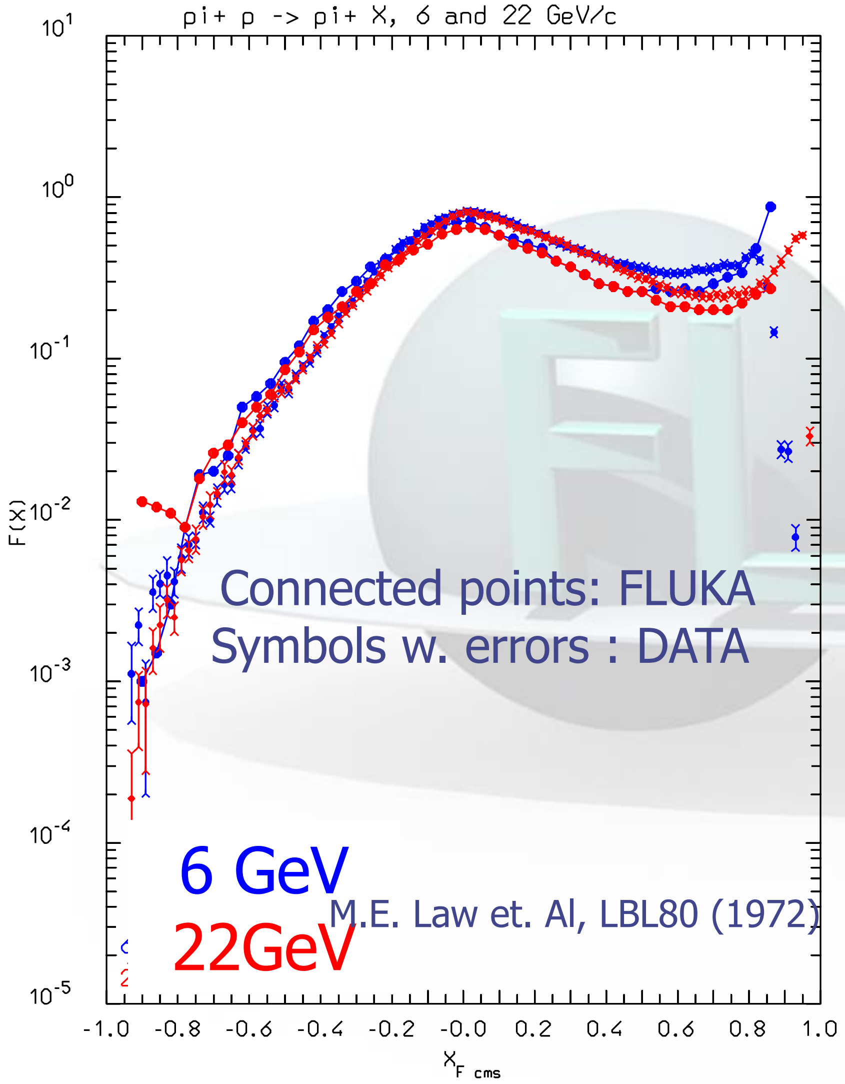
With low-mass chain explosion: much better agreement for forward emission



Pion+ and Pion- emission from proton-proton interactions at 12.6 GeV. Longitudinal momentum distributions at different transverse momenta

Hadronization in hadron-nucleon: examples

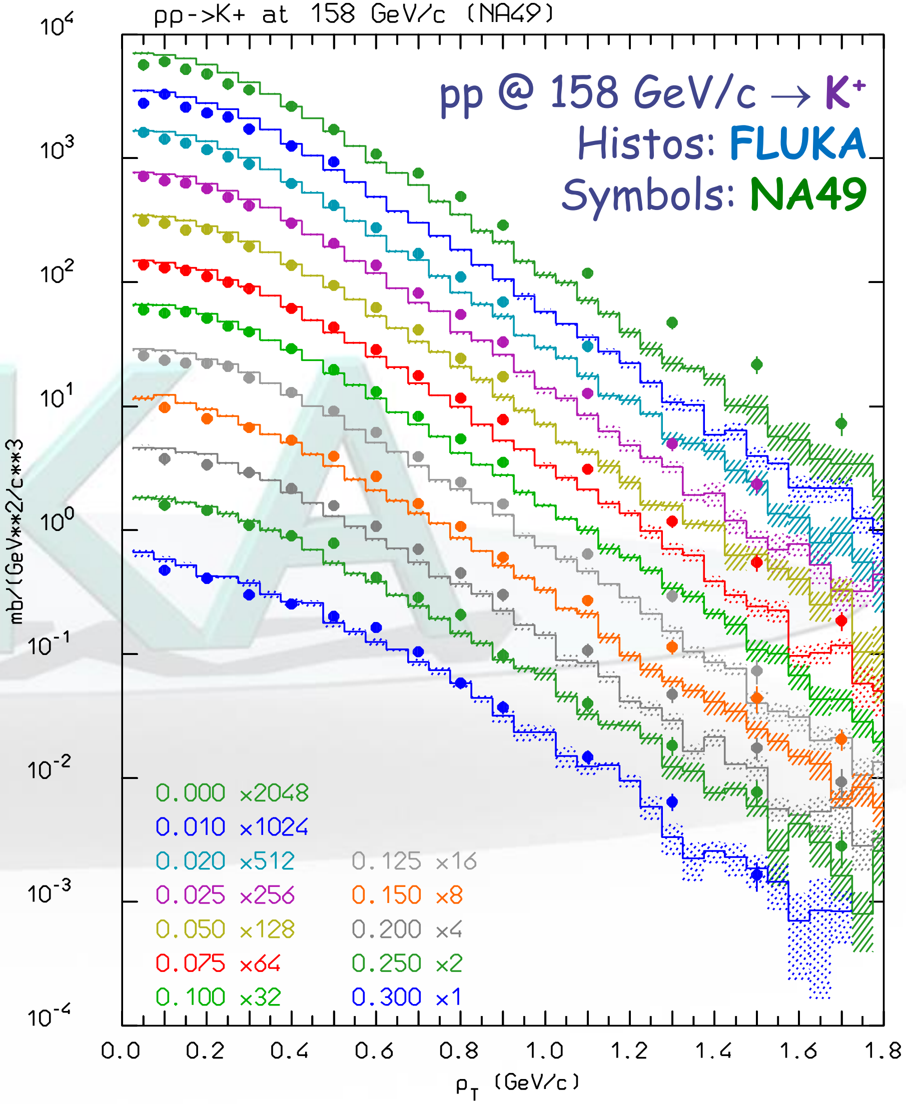
$\pi^+ + p \rightarrow \pi^+ + X$ (6 & 22 GeV/c)



Connected points: FLUKA
Symbols w. errors : DATA

6 GeV
22GeV

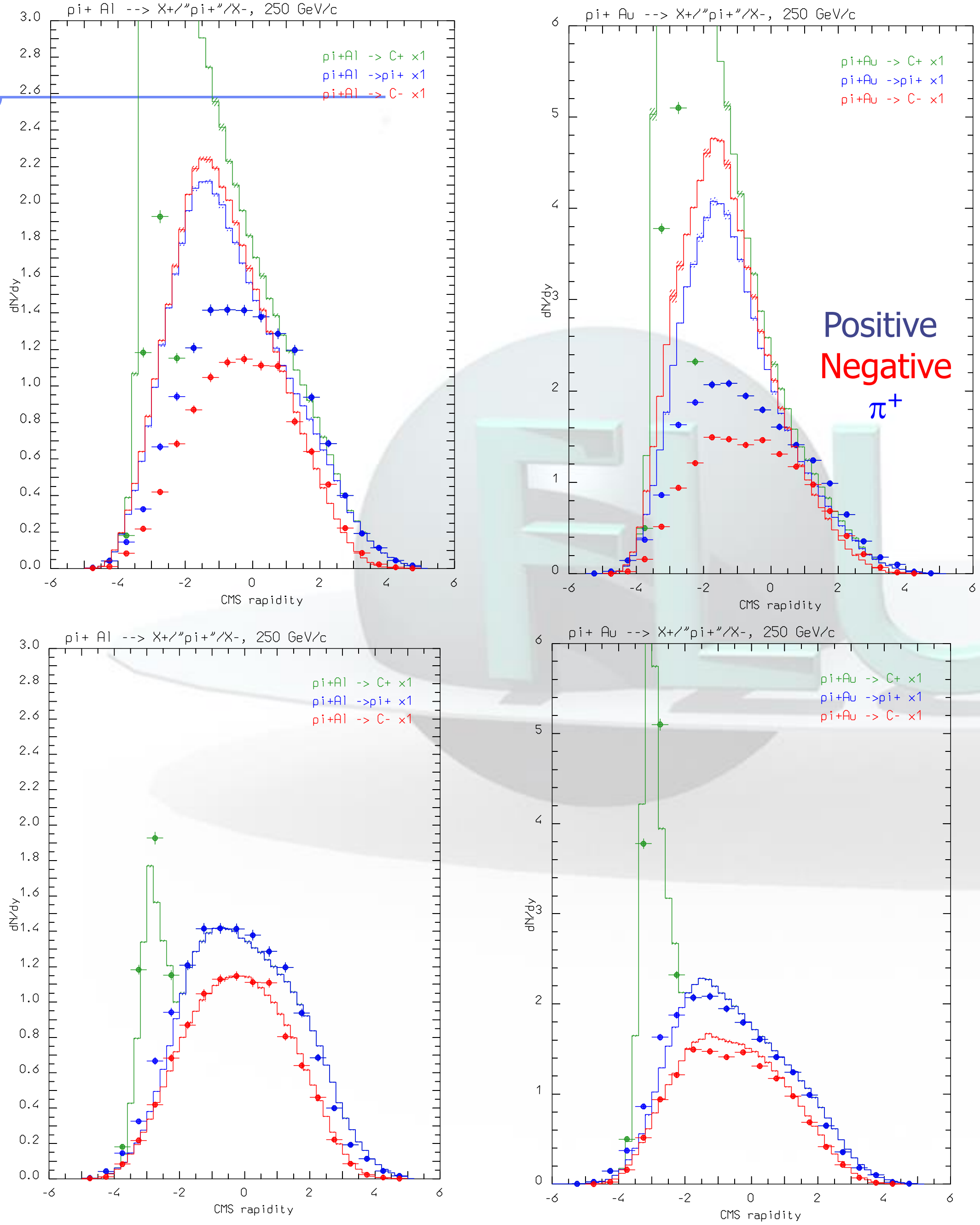
M.E. Law et. Al, LBL80 (1972)



pp @ 158 GeV/c → K^+
Histos: FLUKA
Symbols: NA49

K^+ yield as a function of p_T for different X_F bins, 158 GeV/c protons

Effect/Results on hadron-induced reactions



Rapidity distribution of charged particles produced in 250 GeV π^+ collisions on
 Aluminum (left) and
 Gold (right)
Points: exp. data (Agababyan et al., ZPC50, 361 (1991)).

Top: without formation zone

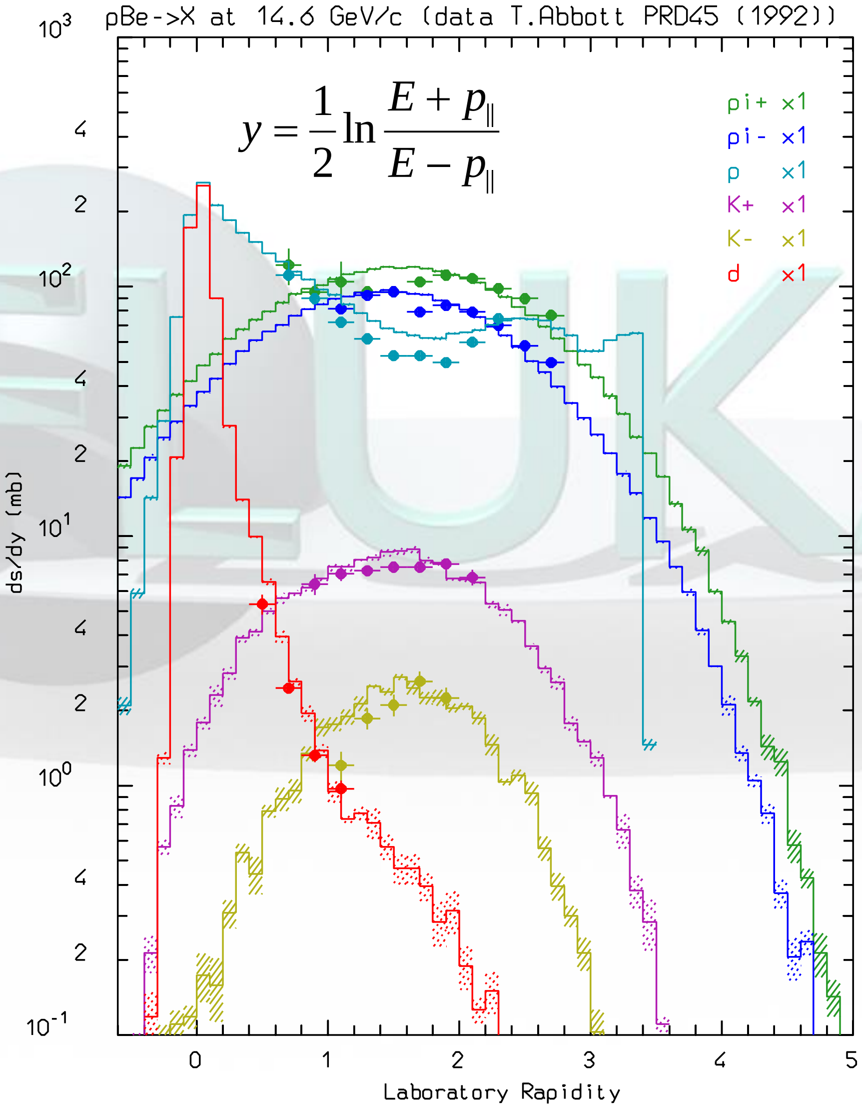
Bottom: with formation zone

More particle production examples: 14.6 GeV/c

Particle prod from protons on Be and Au

Fluka vs

E-802 at BNL



$$y = \frac{1}{2}\ln\frac{E + p_{\parallel}}{E - p_{\parallel}}$$