Science & Technology Facilities Council
Rutherford Appleton Laboratory

The GENIE *

Neutrino Monte Carlo Generator

(a status update)

(*) http://www.genie-mc.org

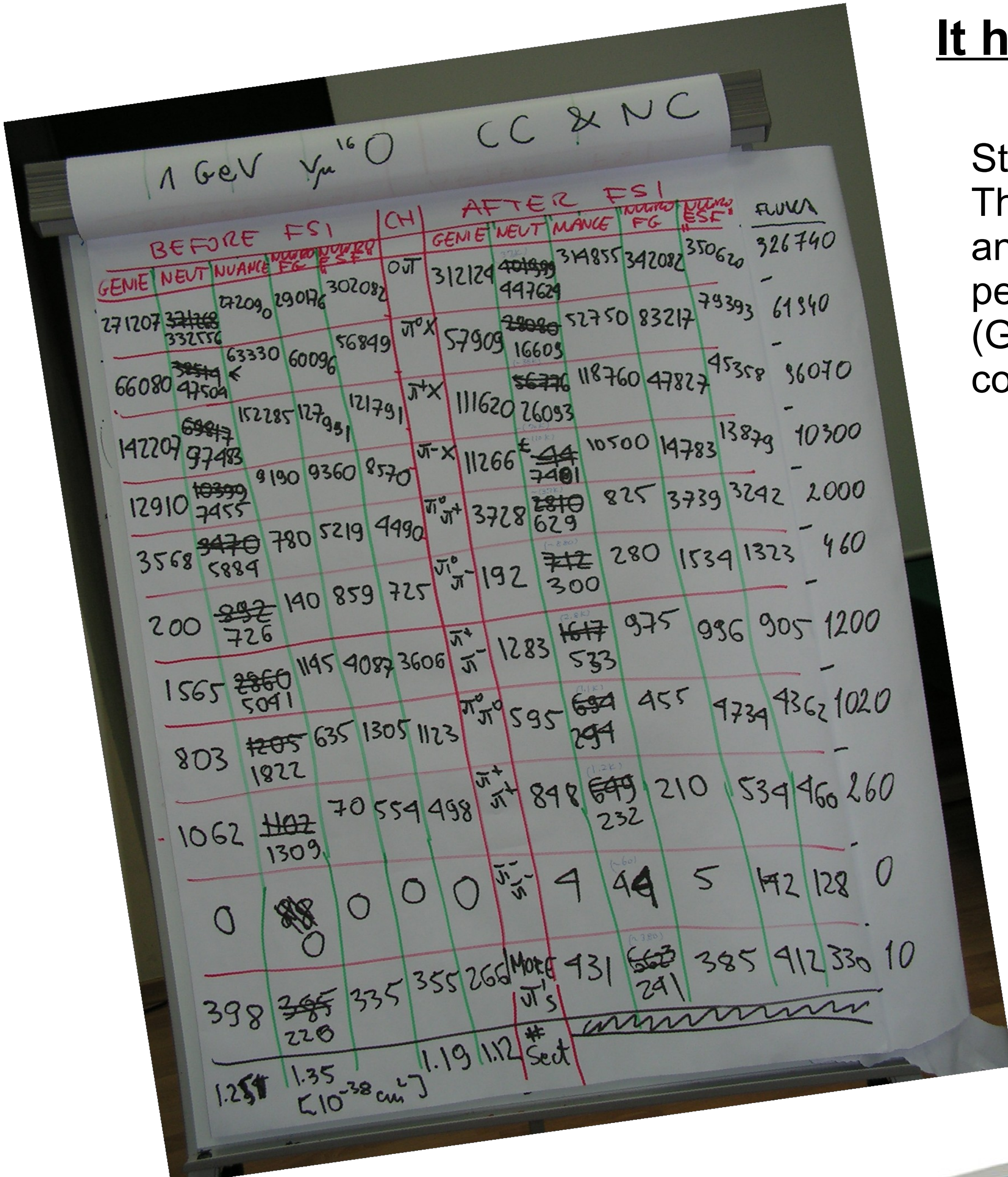
Costas Andreopoulos

45th Karpacz Winter School in Theoretical Physics

Neutrino interactions: from theory to Monte Carlo simulations

Feb 10, 2009

Science & Technology Facilities Council



It has been a fantastic school !

Students worked hard.
They learnt how to use the codes and analyse event samples and performed the first cross-generator (GENIE/NEUT/NUANCE/NuWRO/FLUKA) comparisons we have seen for years!

We had the chance to:
- get feedback from students
- exchange notes with other experts

Very instructive for all of us.

Jan, Danuta, Artur, Cezary, all

THANK YOU!

Outline

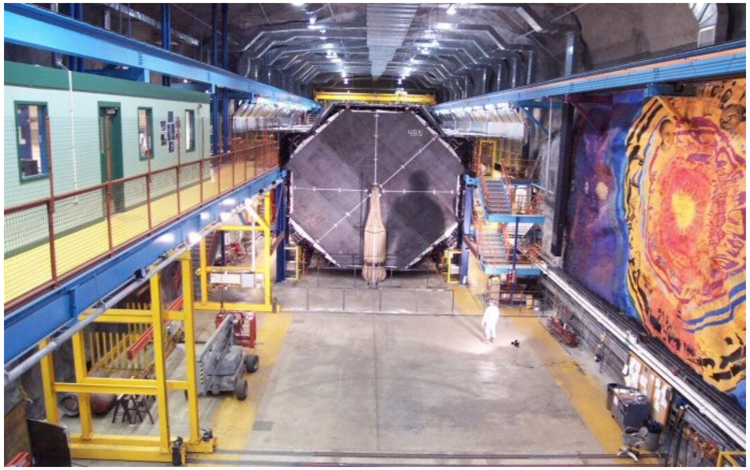
- GENIE – Overview (& a bit of history)
- Current production release *(v2.4.2)*: Physics & capabilities
- Improvements in upcoming releases

A bit of history

GENIE evolved from *neugen* / Many models within GENIE have long history.

Neugen originates from the Soudan2 expt.

Soudan2: A proton decay experiment in the ~80's
Back then: vA a background.



Heavily re-developed for MINOS analyses

Cross section model partially re-written / re-tuned.

Hadronic simulations almost completely re-written.
Many year*FTE effort!

NuINT01 / 'Call to arms'

[early ~2000]

- **Entering a precision era in neutrino physics**:
  Neutrino interaction uncertainties start to matter!
- **Also, changes in software devel paradigm**:
  C++ expt. offline softw., Geant4, ROOT

Needed a Universal Neutrino MC

Many (~ 6+) major fortran generators in use.
Developed by small groups / very experiment-specific.
Mostly 'similar' but with no trivial / not understood differences.

For the longer term, the efforts of many will be required to produce a carefully-tested and universal model of neutrino interactions. In addition to purely technical considerations, theoretical guidance and new experimental data will be vital. Still, with the success of NUINT'01 and the promise of renewed and expanded collaboration punctuated and reinforced by future NUINT workshops, it is not too optimistic to hope that within a relatively few years, members of the neu-

Weak Interactions (Springer, Berlin 2000).
10. R. A. Smith and E. J. Moniz, Nucl. Phys. B 43 (1972) 605. [Erratum-ibid. B 101 (1975) 547].
11. K. F. Liu, S. J. Dong, T. Draper and W. Wilcox, Phys. Rev. Lett. 74 (1995) 2172 [arXiv:hep-lat/9406007].
12. L. A. Ahrens et al., Phys. Rev. D 35 (1987) 785.
13. A. Pais, Annals Phys. 63 (1971) 361.

From D.Casper's NuINT01 conference proceedings

GENIE

<u>**Generates Events for Neutrino Interaction Experiments**</u>

A Neutrino Monte Carlo Generator (and extensive toolkit)

Validity:
from few MeV to many hundreds of GeV / handles all nuclear targets

Large scale effort:
110,000 lines of C++

Modularity / Flexibility / Extensibility:
Models can be swapped in/out. Models can be easily reconfigured. All done consistently.

Licensed:
To ensure <u>openness</u> and synergies between experiments

State of the art physics:
GENIE has lots of developers & support. Draws heavily from many people's expertise

Full list of collaborators at http://collaboration.genie-mc.org

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Who is using GENIE now?

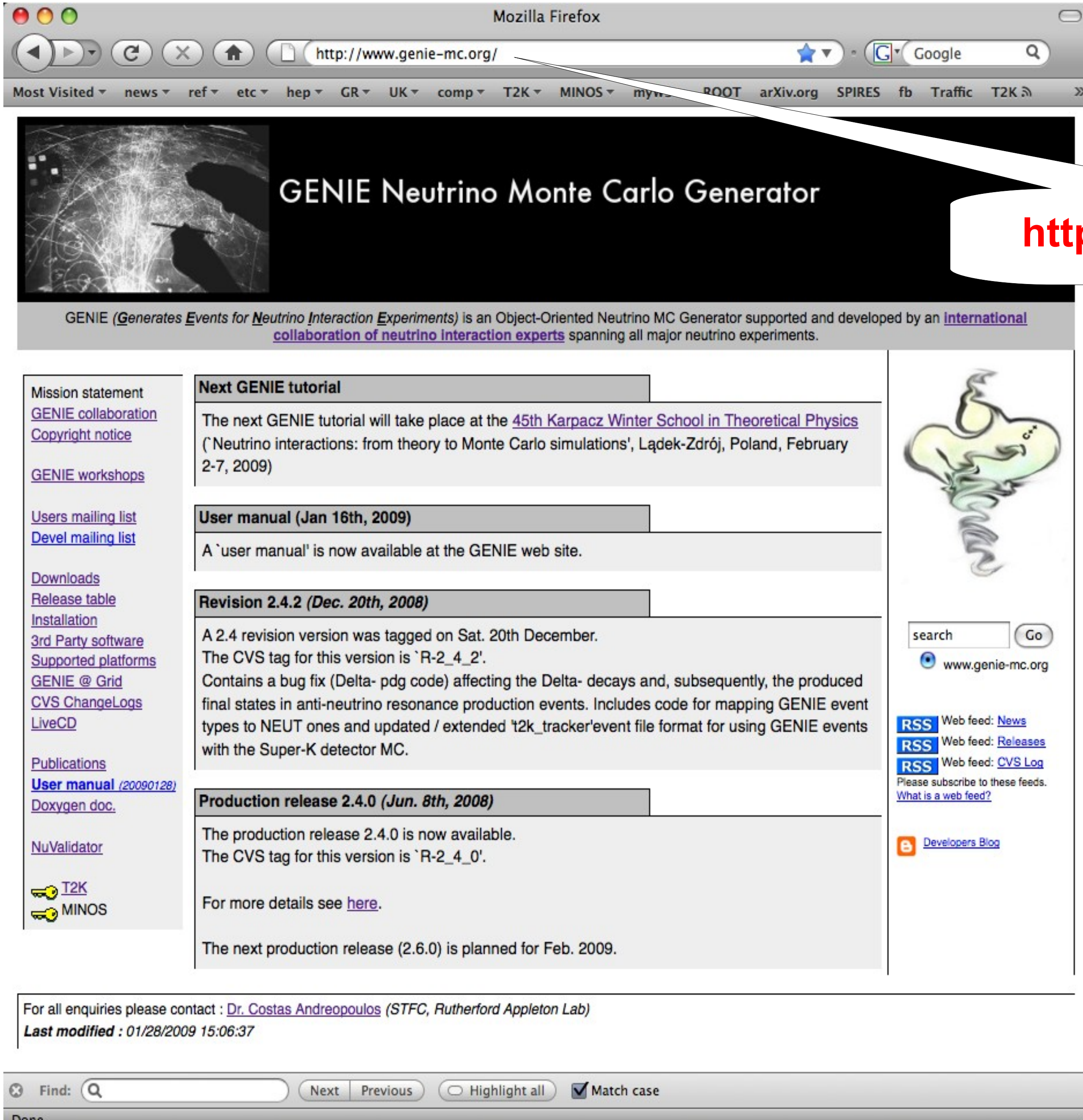
Primary clients are the current / near future medium energy experiments:

- T2K
  - nd280
  - SuperK
  - ingrid
- MINOS
- NovA
- MINERvA
- ArgoNEUT
- MicroBooNE
- EU LAr R&D projects
- ...

After ~4 yrs of development (from scratch)
now have a nearly universal neutrino physics MC
(an important tool for physics exploitation for the next decade++)

NEUTRINO EXPT. SYNERGIES !!

GENIE already interfaced to most of these expts & used in physics MC prod.



http://www.genie-mc.org

Official GENIE web site

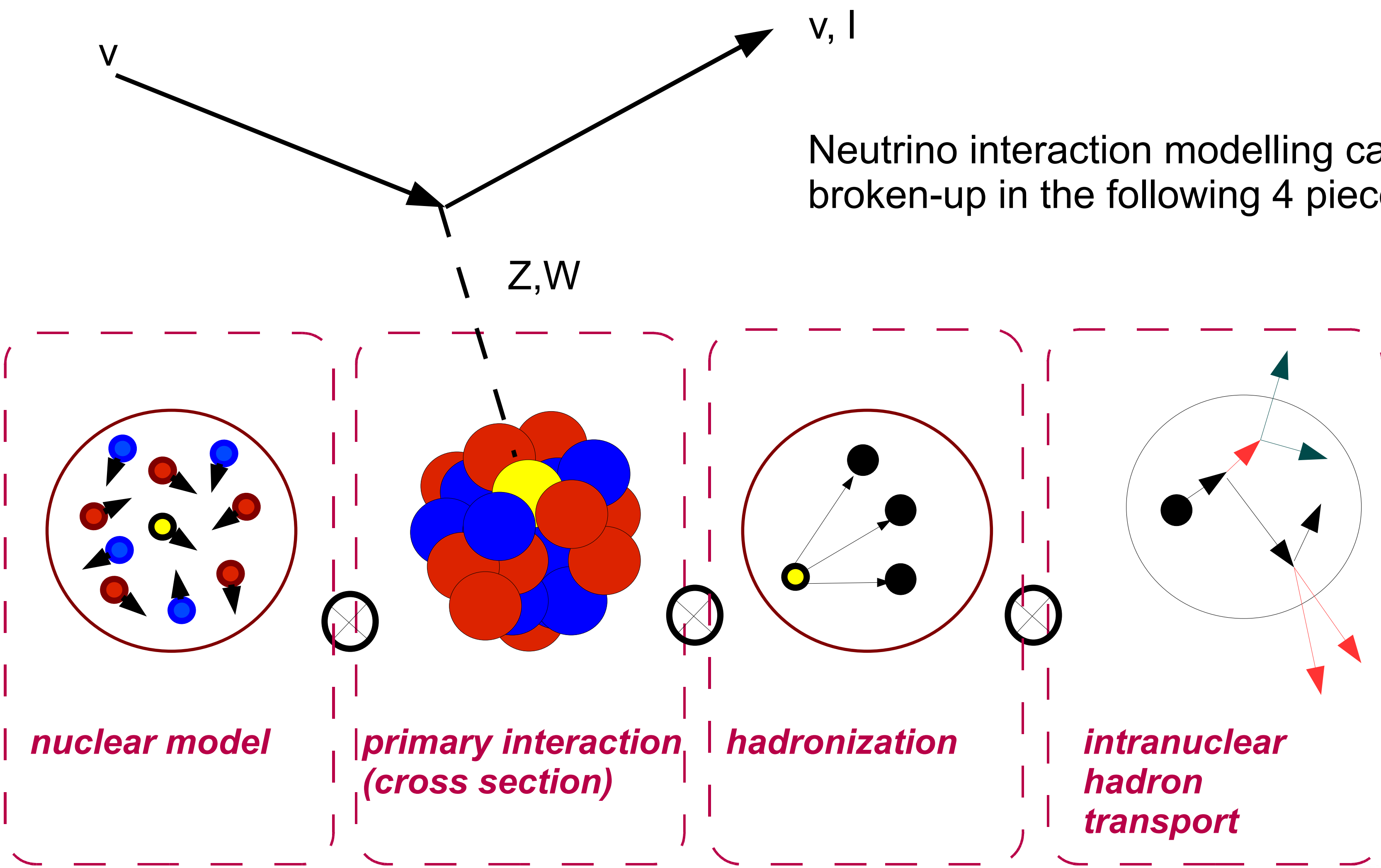
You can find:

- *Physics documentation*
- *A user manual*
- *Release tables*
- *Download instructions*
- *Installation instructions*
- *Doxygen documentation*
- *News feeds*
- *...*
- *...*

Physics in GENIE v2.4.*

Neutrino Interaction Simulation `steps'

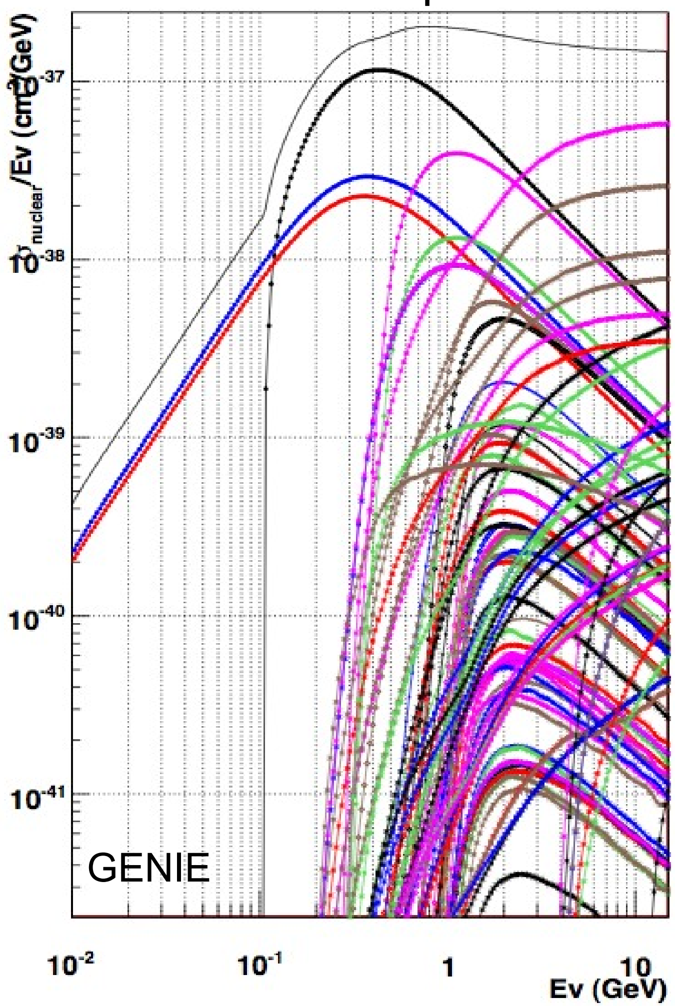
Neutrino interaction modelling can be broken-up in the following 4 pieces :



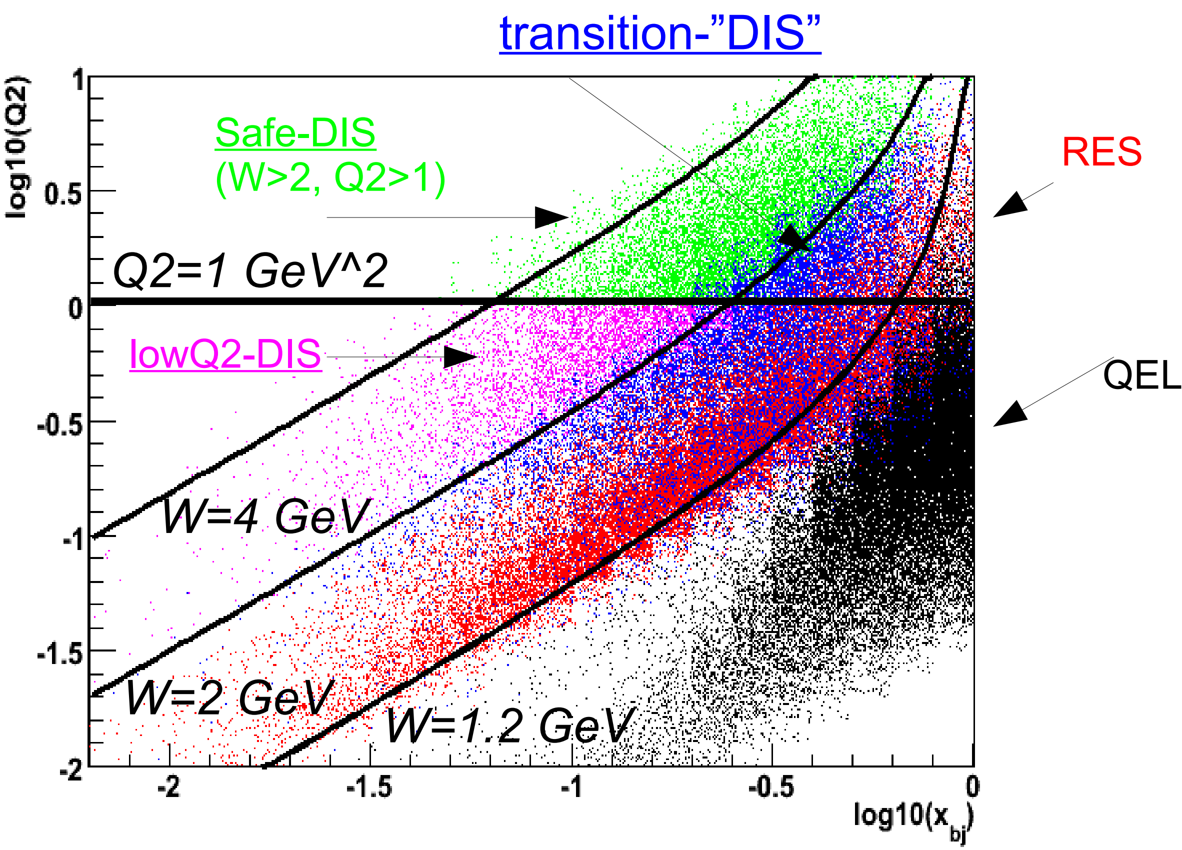
Note: A simplified picture

“Divide & conquer”

numu+O16 - All processes



Kinematical coverage
JPARC neutrino beam @ nd280 site



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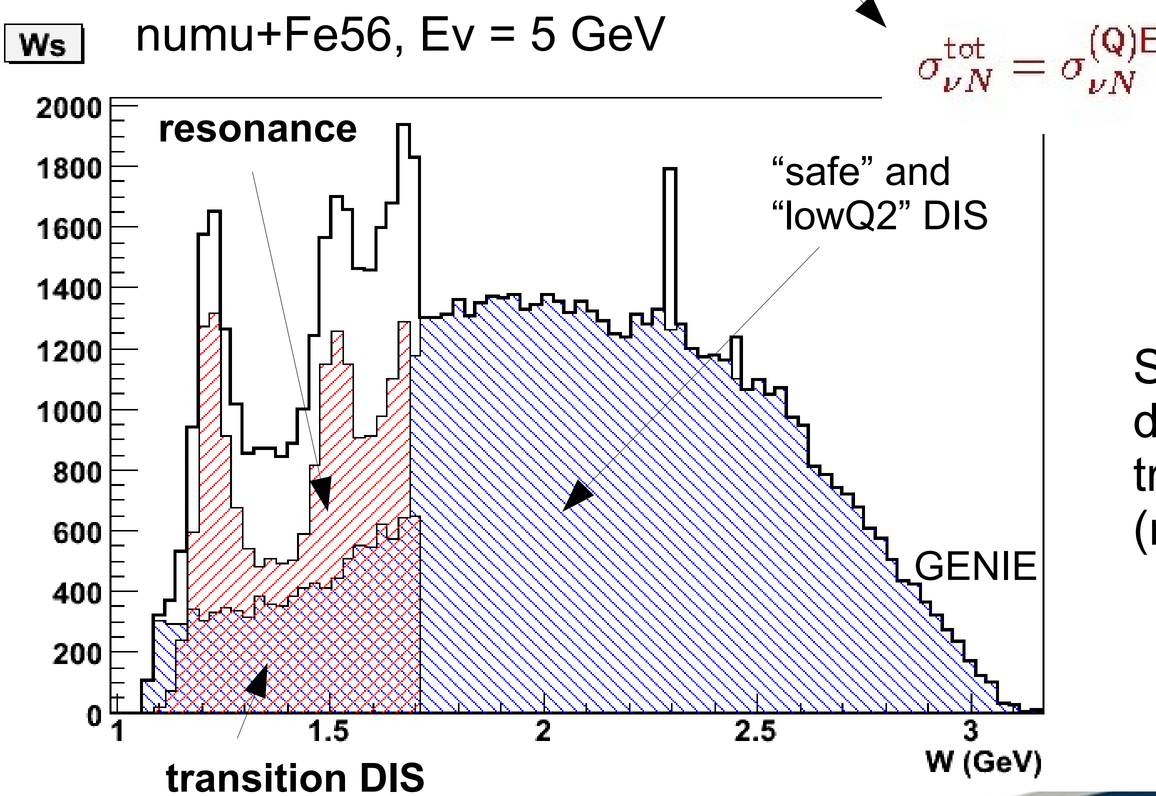
Putting everything together

Naumov, Max Born symposium (2007)

$$\sigma_{\nu N}^{\text{tot}} = \sigma_{\nu N}^{\text{(Q)ES}} \oplus \boxed{\sigma_{\nu N}^{1\pi} \oplus \sigma_{\nu N}^{2\pi} \oplus \ldots \oplus \sigma_{\nu N}^{1K} \oplus \ldots} \oplus \sigma_{\nu N}^{\text{DIS}}.$$

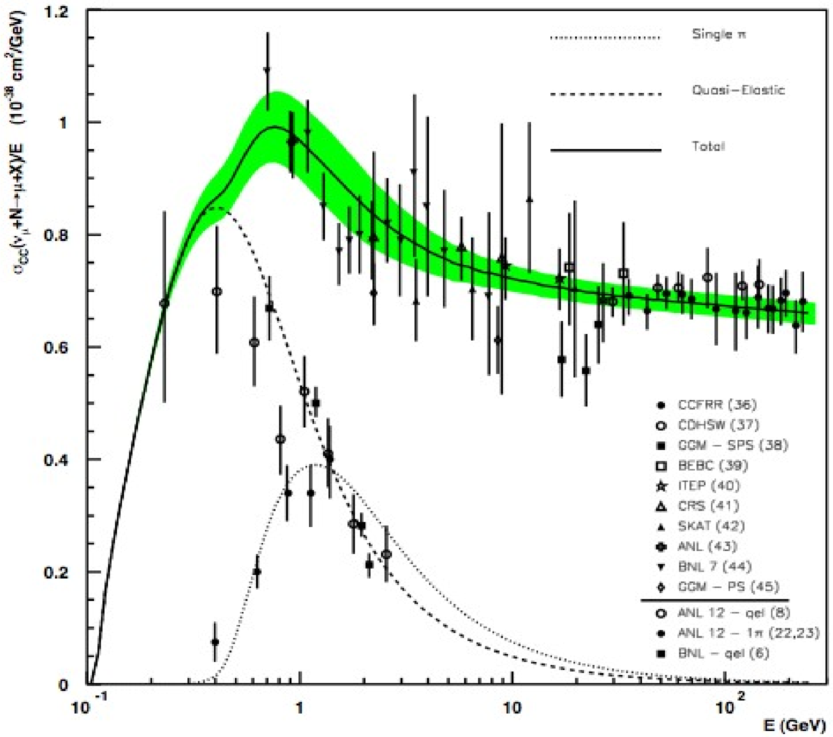
$$\sigma_{\nu N}^{\text{tot}} = \sigma_{\nu N}^{\text{(Q)ES}} \oplus \sigma_{\nu N}^{\text{RES}} \oplus \sigma_{\nu N}^{\text{DIS}}$$



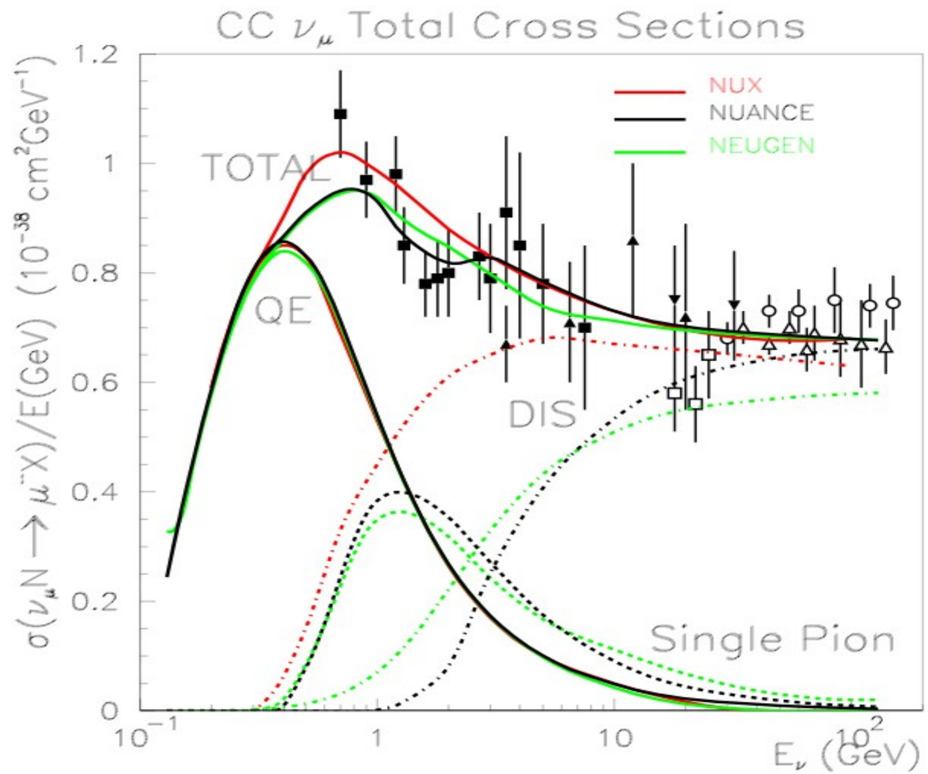
See Hugh's talk on the details of modelling the transition region (non-resonance background)

The GENIE cross section model

v2.5.1 free nucleon cross section prediction vs B/C data & <u>estimated uncertainty</u>



Sam Zeller. circa-2002 / Cross-generator comparisons



- QEL: Llewellyn-Smith with BBBA05 elastic f/f
- RES: Rein-Sehgal / incoherent / 16 resonances up to W=2GeV
- Non-resonance background
- COH pi production: Rein-Sehgal / includes updated PCAC
- DIS: latest Bodek-Yang
  - Including parametrization of the longitudinal structure function FL
  - Including NuTeV parameterization of nuclear effects

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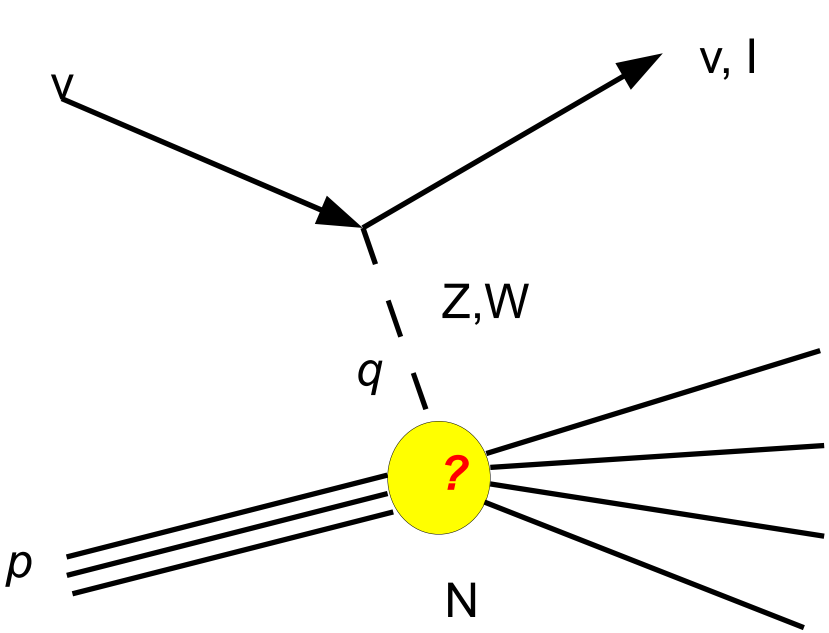
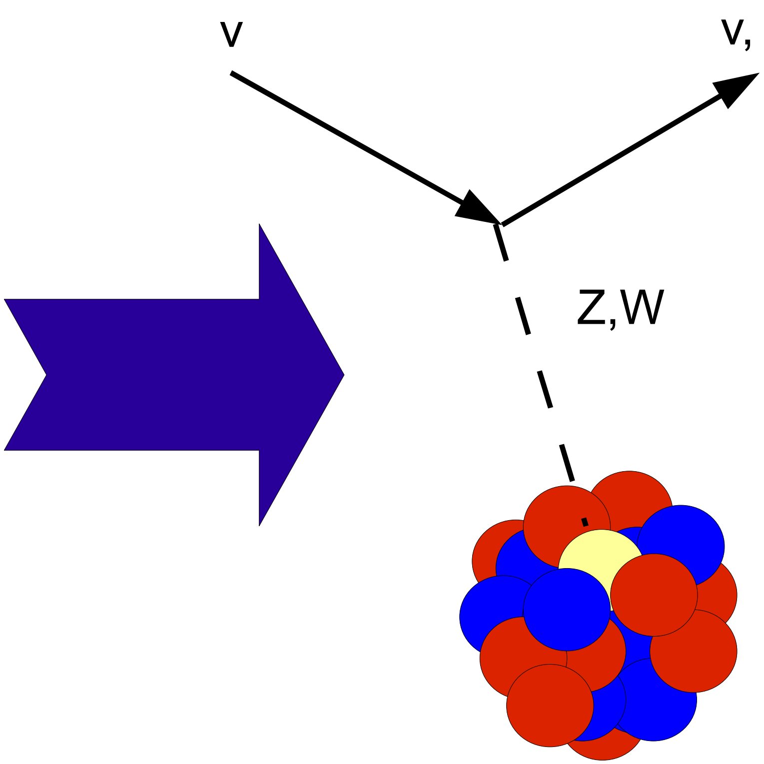
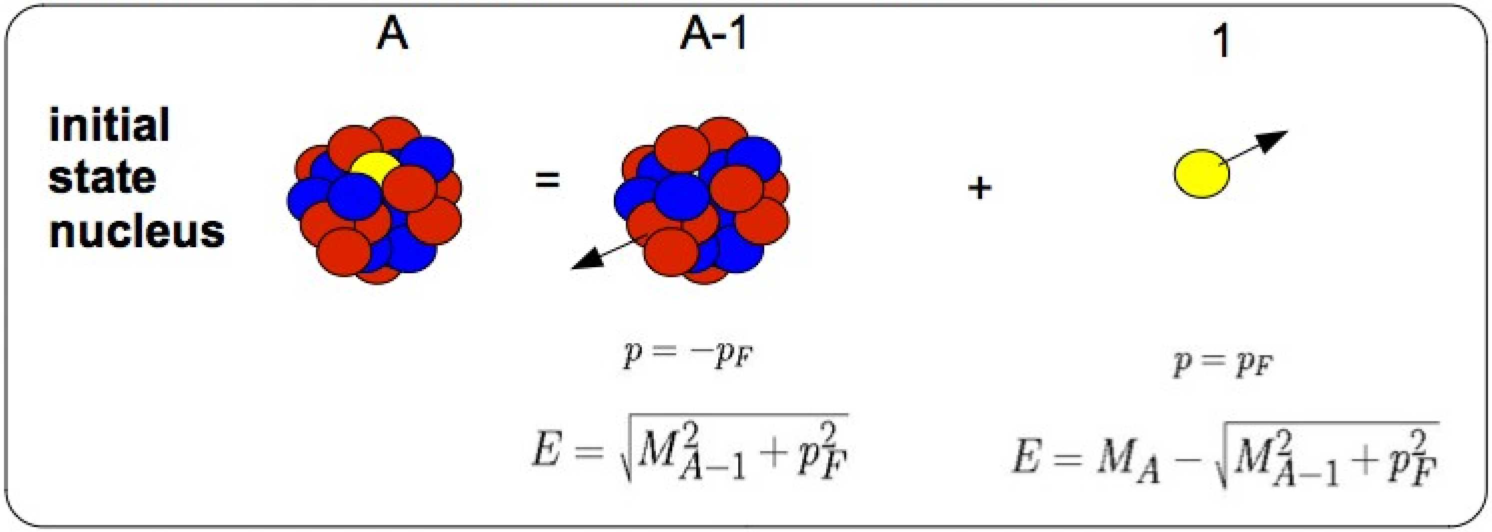
Free-nucleon cross section → Nuclear cross sections

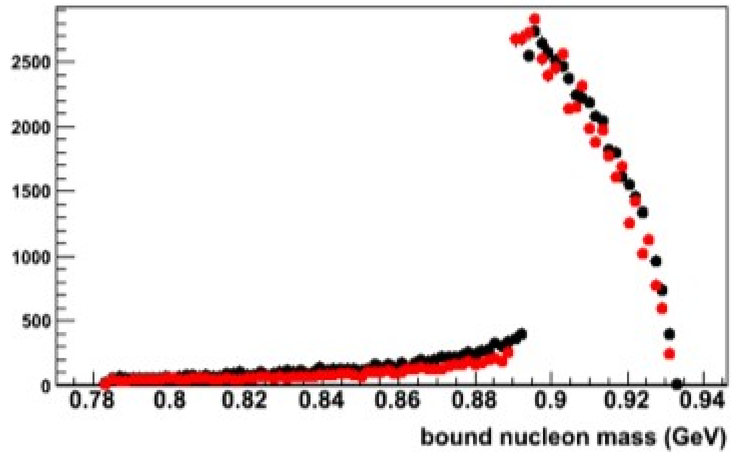




Fermi Gas model in GENIE

Curr





Example;

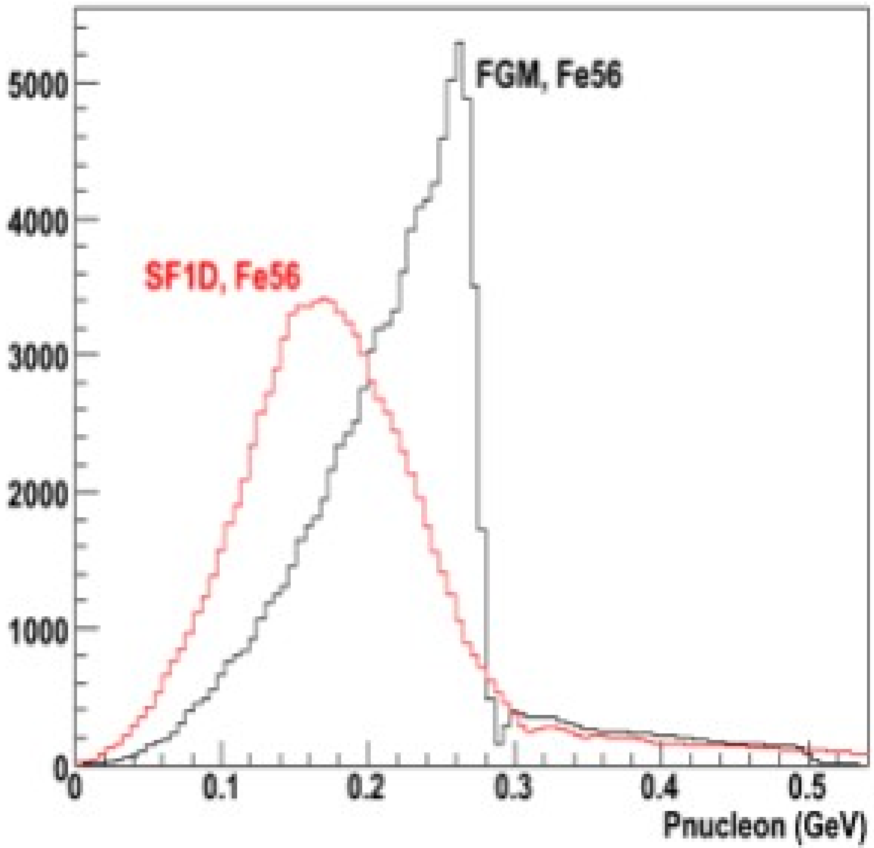
Bound (off the shell) nucleon mass in Fe56

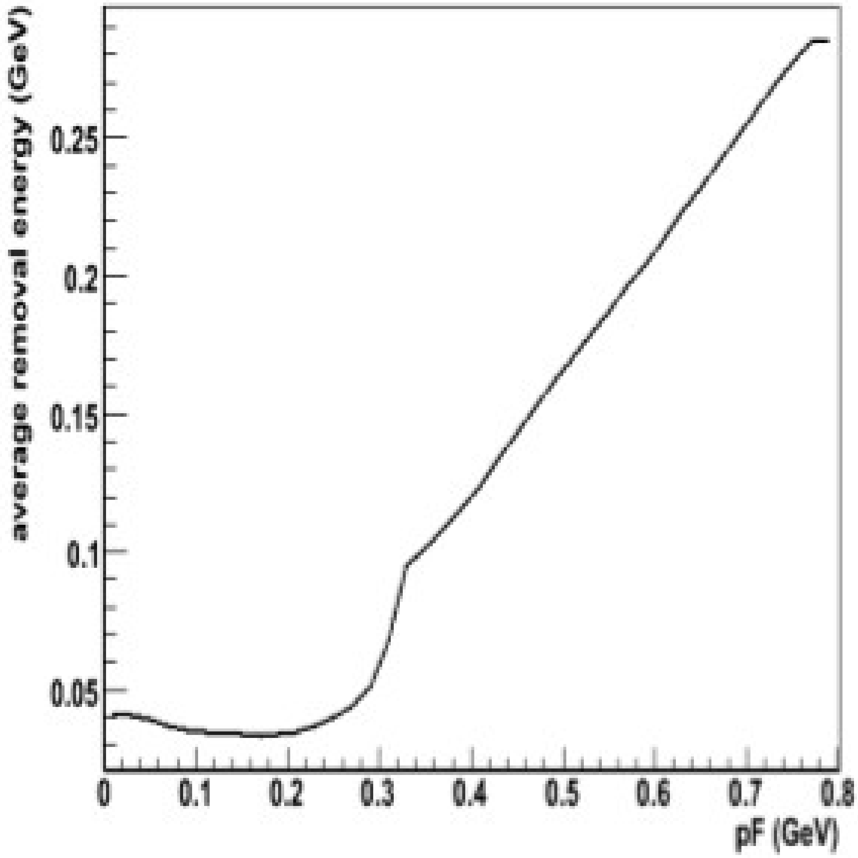
Off-shell kinematics handed a-la Bodek

Moving to a spectral function implementation

Option currently available in GENIE

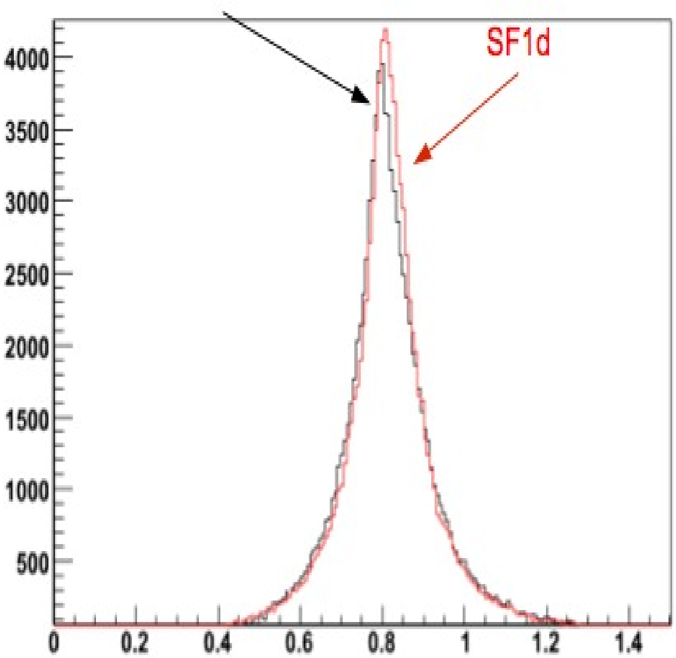
Switch to a S/F momentum profile and use the average binding energy at each momenum





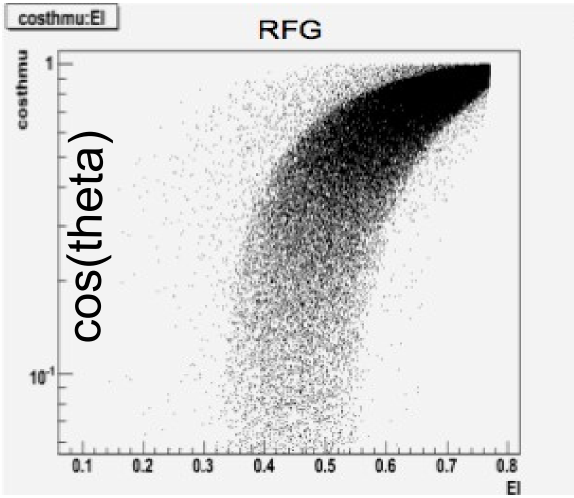
Moving to a spectral function implementation

Measurable effect to observable distributions

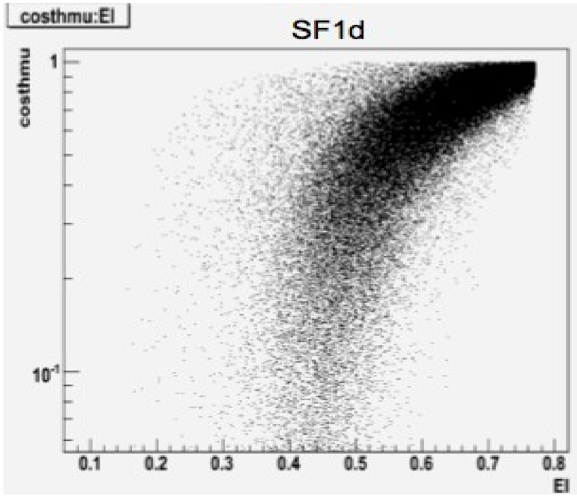


Reconstructed energy shifts
of the order of few x 10 MeV

Distorts final state lepton kinematics



Emu



Emu

numu+C12, Ev=800MeV

Moving to a spectral function implementation

This workshop has catalysed the process

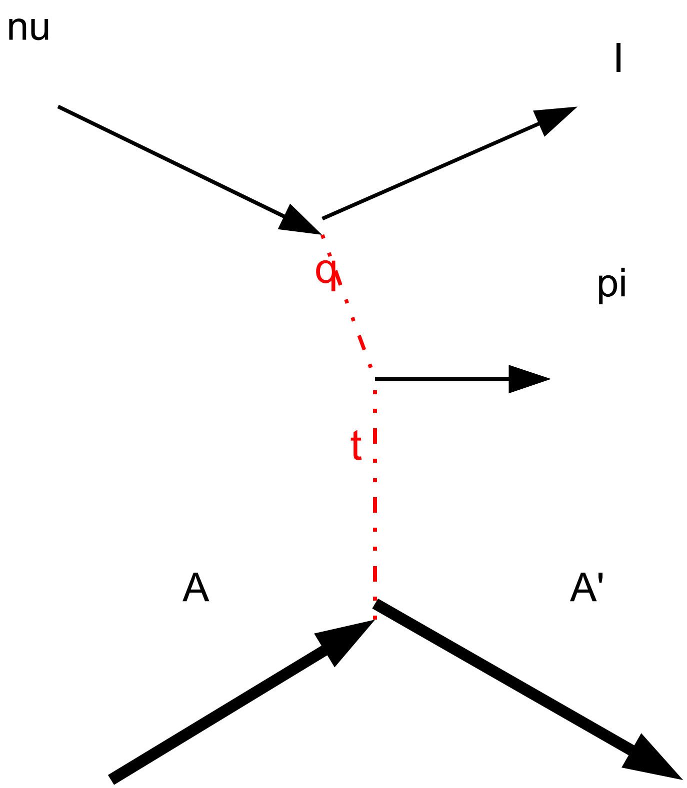
- Enlightening talks by Omar Benhar during the school

- Analytical S/F's for C,O,Ca,Ar,Fe available by Artur Ankowski

- Figuring out how to do inclusive e- scattering in GENIE (for model validation)

More 'rare' processes included in GENIE >>>

Coherent pion production



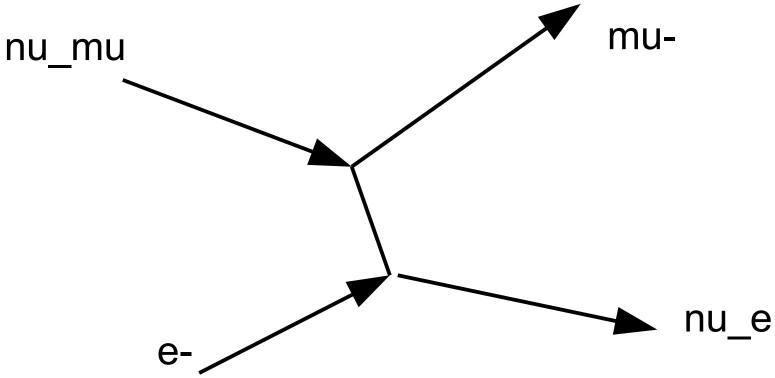
Cross section computed as in
Rein, Sehgal, hep-ph/0606185

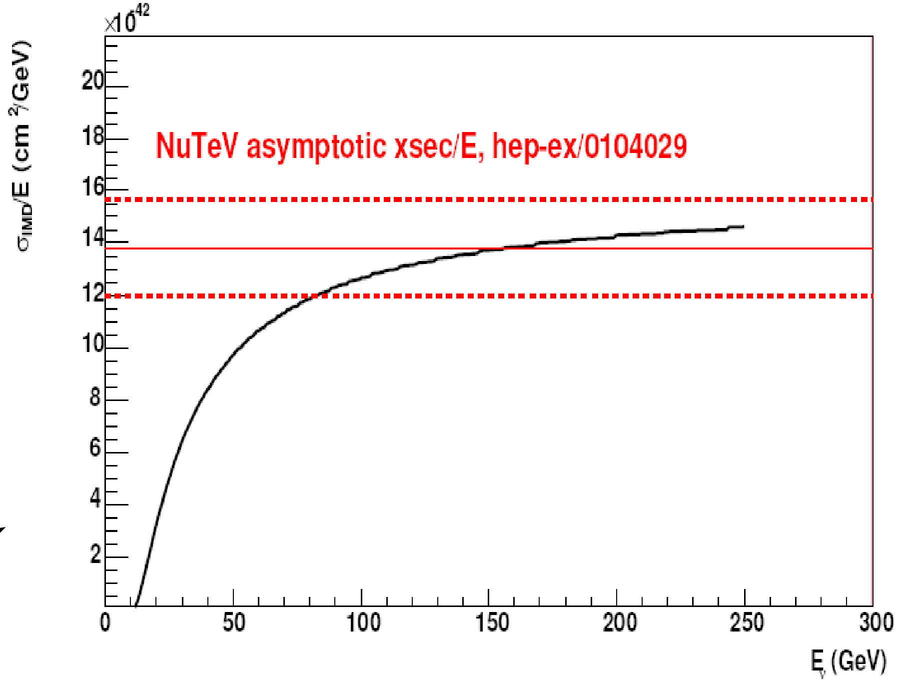
Including the PCAC formula with the non-vanishing muon mass causing destructive interference between AV and PS amplitudes.

νe- elastic

Fairly standard.
Cross sections implemented as in W.J.Marciano and Z.Parsa, J.Phys.G: Nucl.Part. Phys.29 (2003) 2629.
Radiative corrections currently neglected.

Inverse muon decay

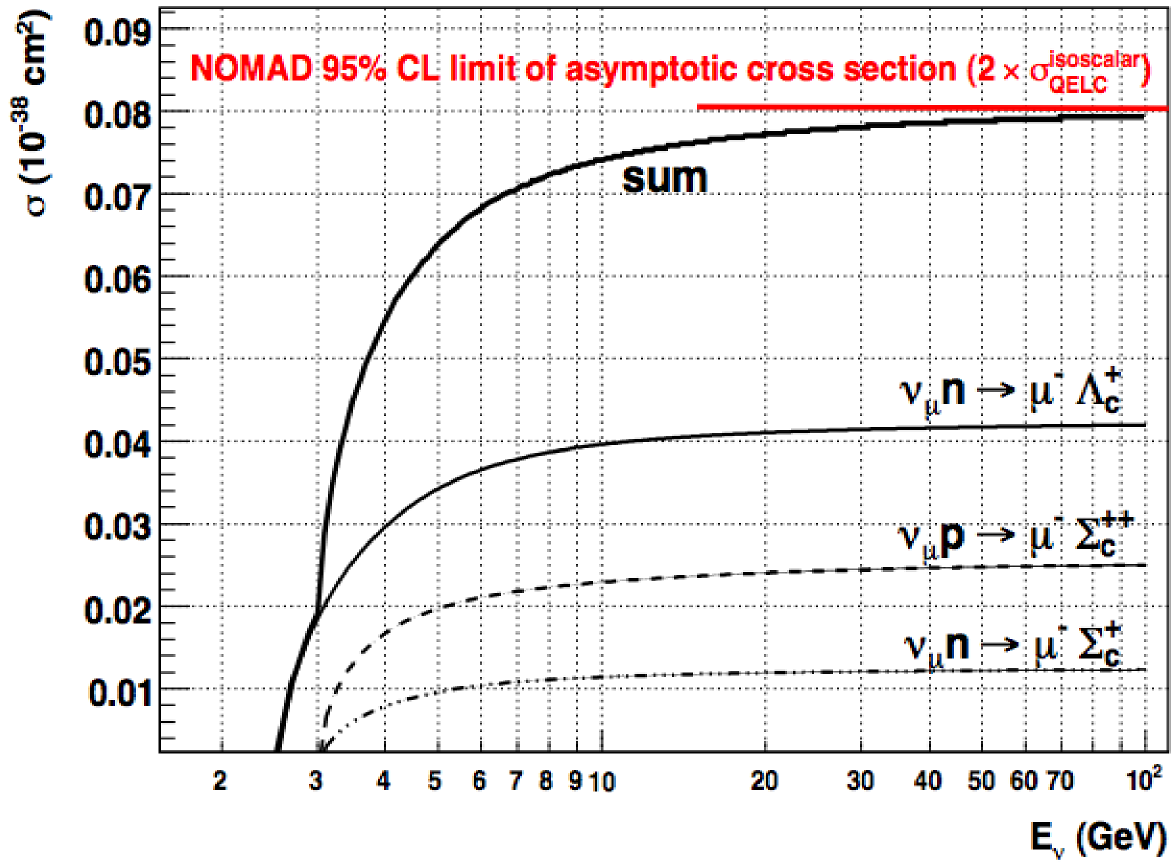




D.Yu.Bardin and V.A.Dokuchaeva, Nucl.Phys.B287:839 (1987), includes all 1-loop radiative corrections

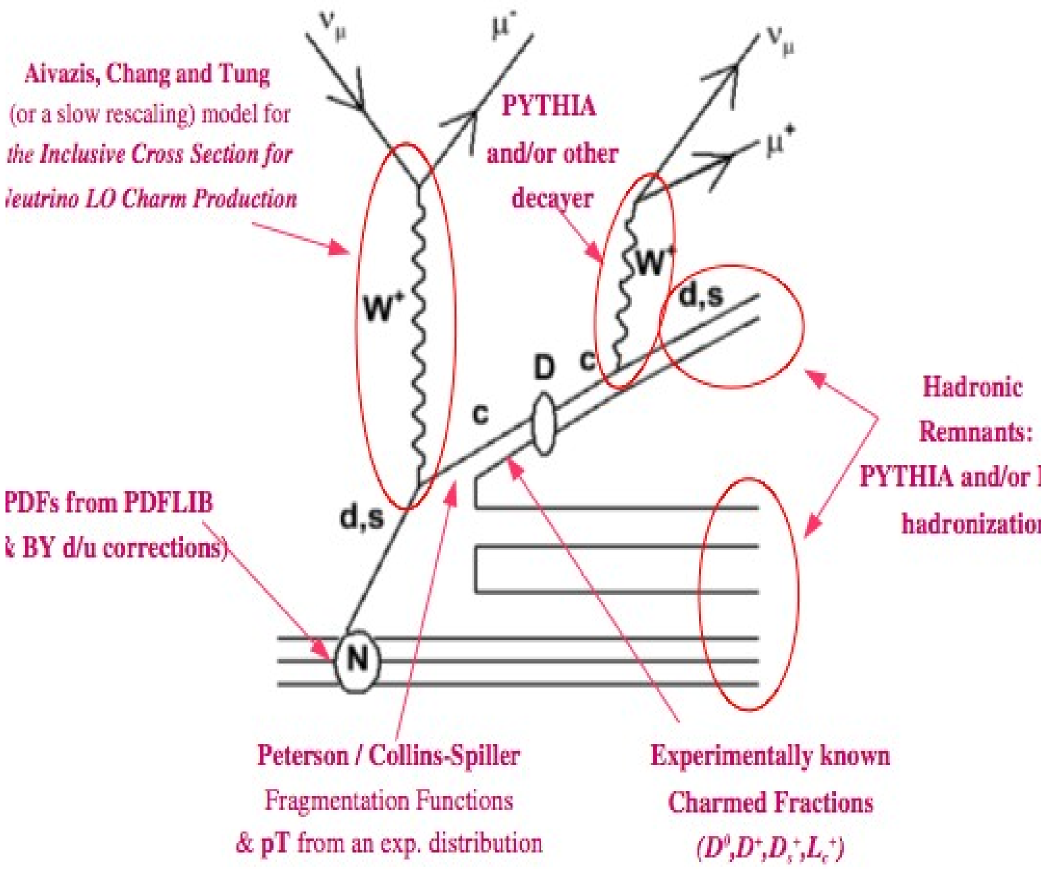
QEL charm production

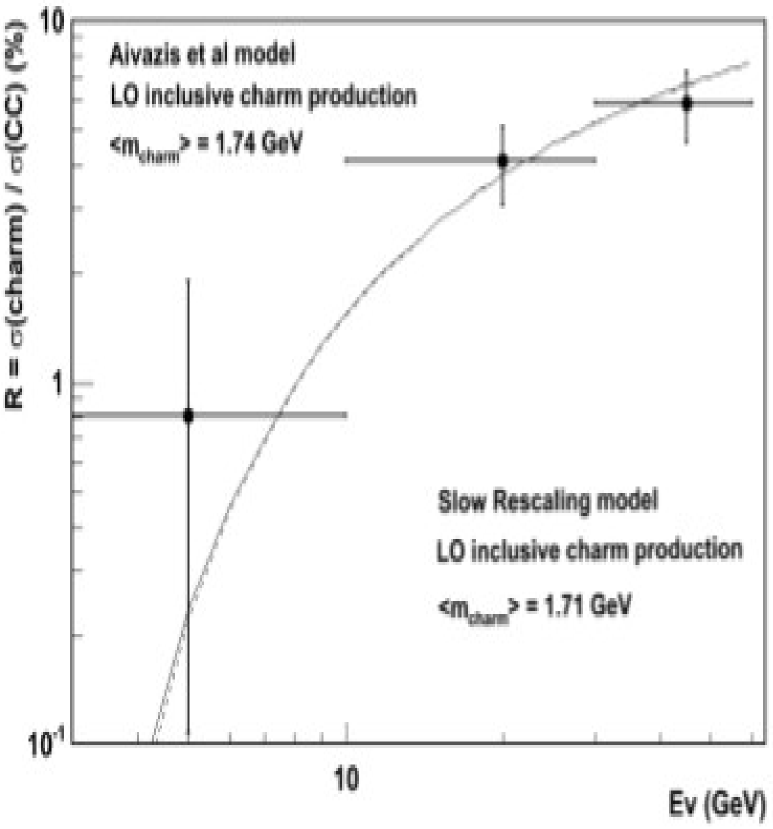
S.G.Kovalenko, Sov.J.Nucl.Phys.52:934 (1990)
re-scaled to NOMAD limit



$$\nu + n \rightarrow l^- + \Lambda_c^+(2285)$$
$$\nu + n \rightarrow l^- + \Sigma_c^+(2455)$$
$$\nu + p \rightarrow l^- + \Sigma_c^{++}(2455)$$

DIS charm production





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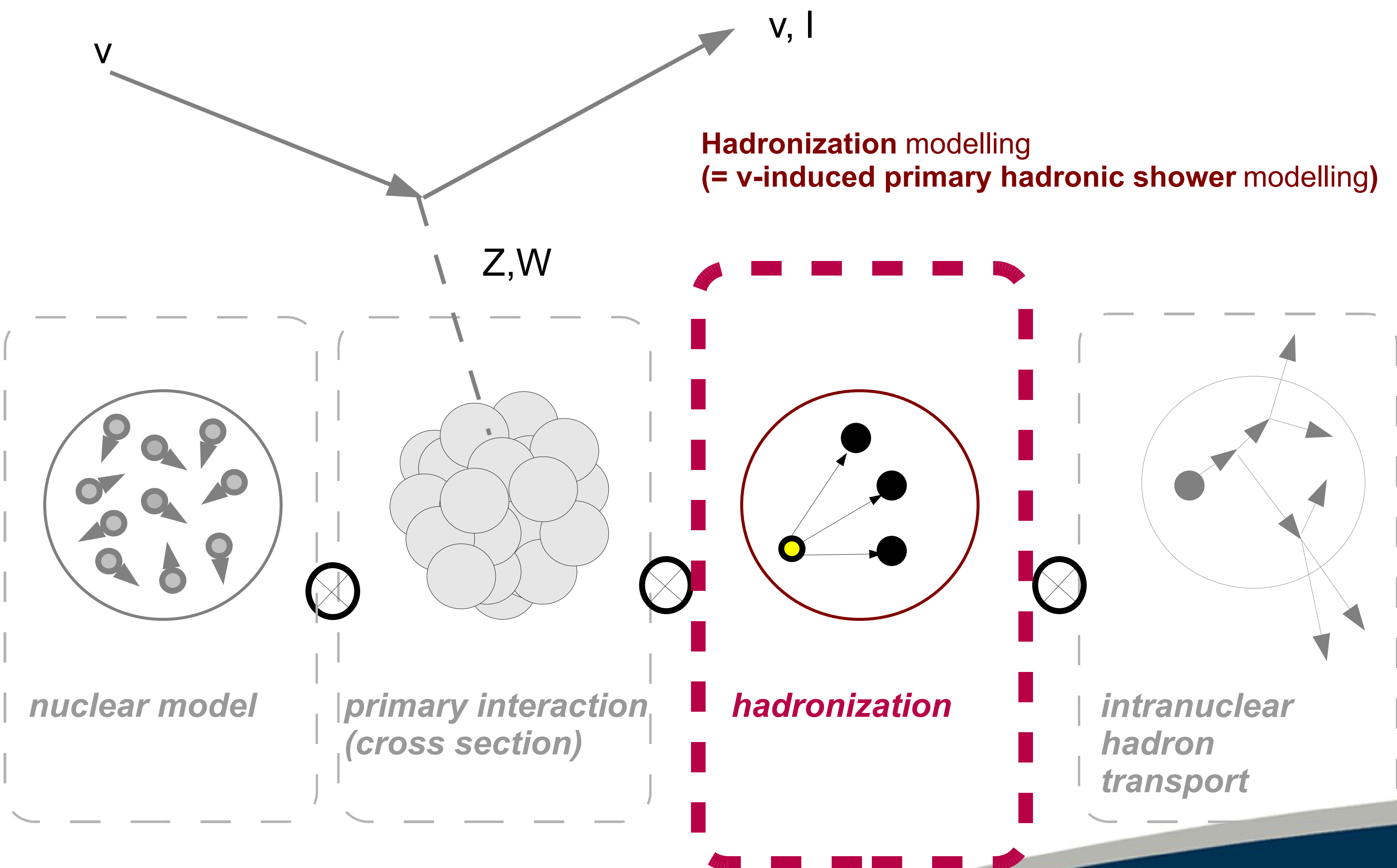
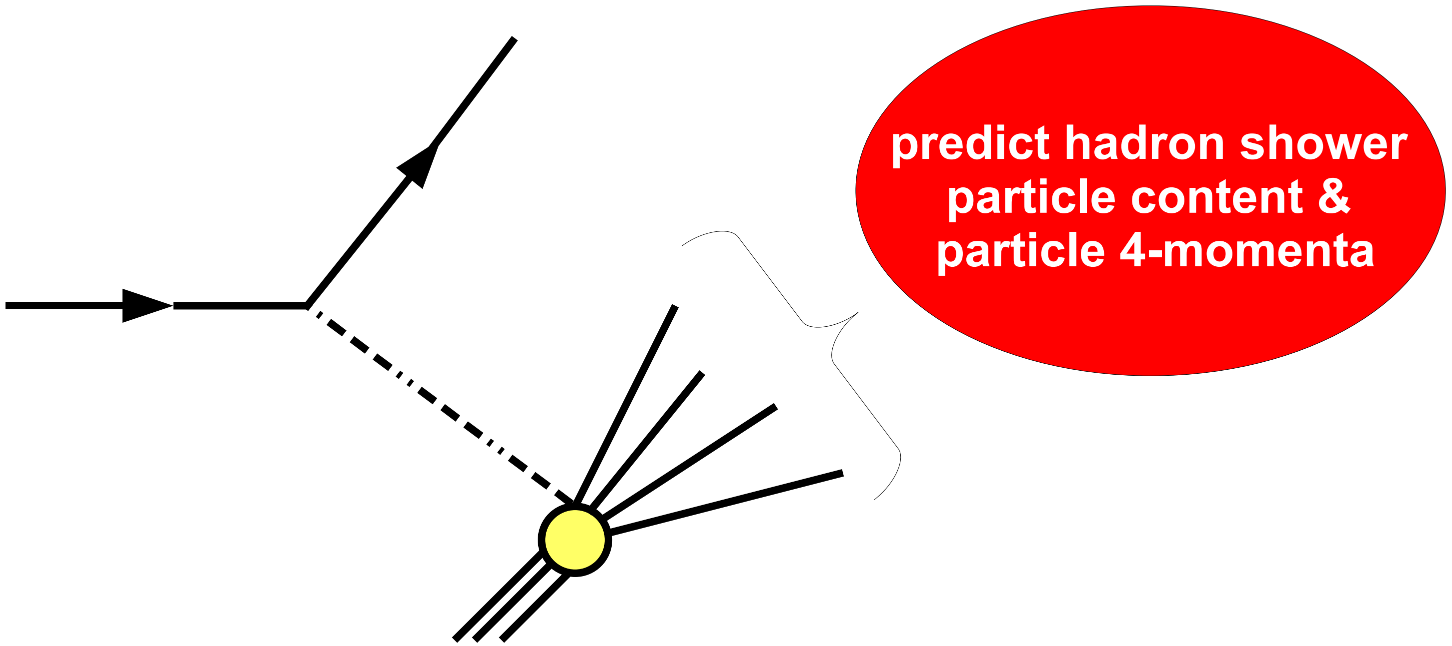
Hadronic simulations in GENIE
>>>

Hadronization modelling

Hadronization modelling
(= ν-induced primary hadronic shower modelling**)**



Hadronization modelling

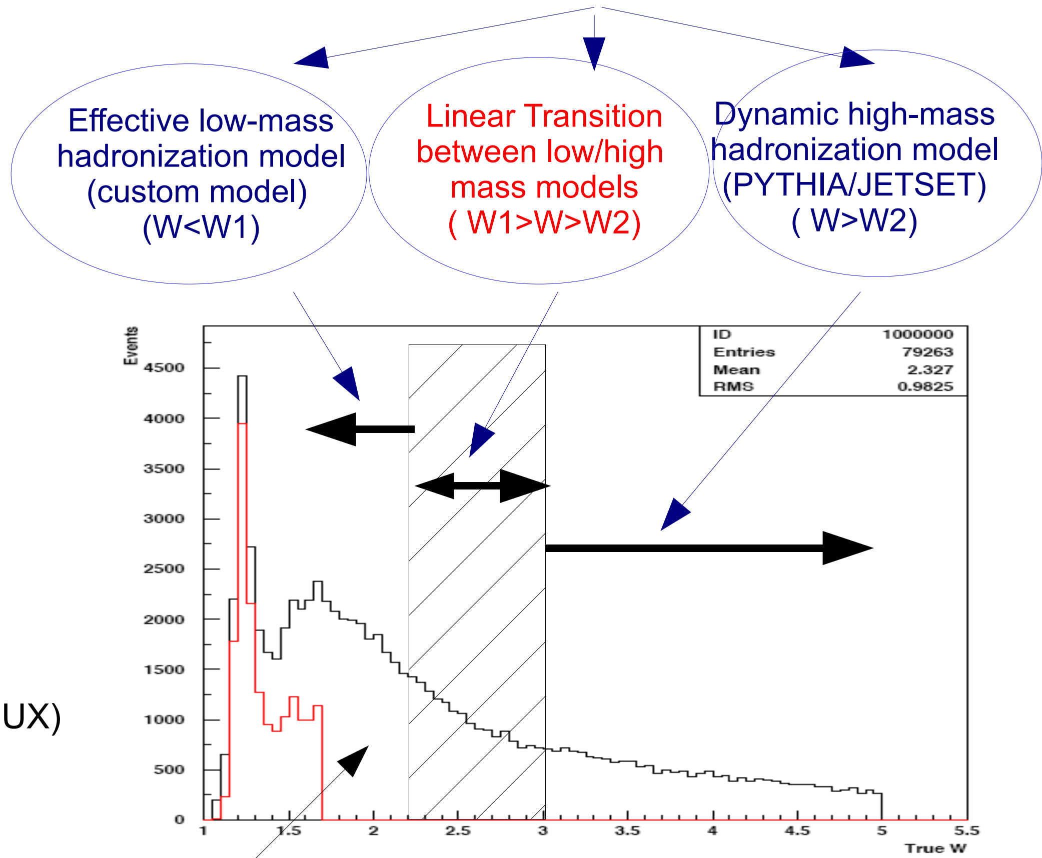


- Standard tools of the trade *(PYTHIA/JETSET, HERWIG)* don't work at the low hadronic invarant masses which are of interest to us

- Important to get that right
  - Determines shower shapes & particle content
    - *Eg, electromagnetic (pi0) fraction of the shower -> nue backgrounds*
    - *Eg, CC/NC shower shapes -> CC/NC PIDs*
  - Used to decompose inclusive vN->lX to exclusive contributions
    - *Eg, Contribution of 1 pi DIS channels in RES/DIS transition region*

The GENIE hadronization model

Andreopoulos-Gallagher-Keyahias-Yang (AGKY) model



W (hadronic invariant mass)

<u>At low hadronic invariant masses:</u>

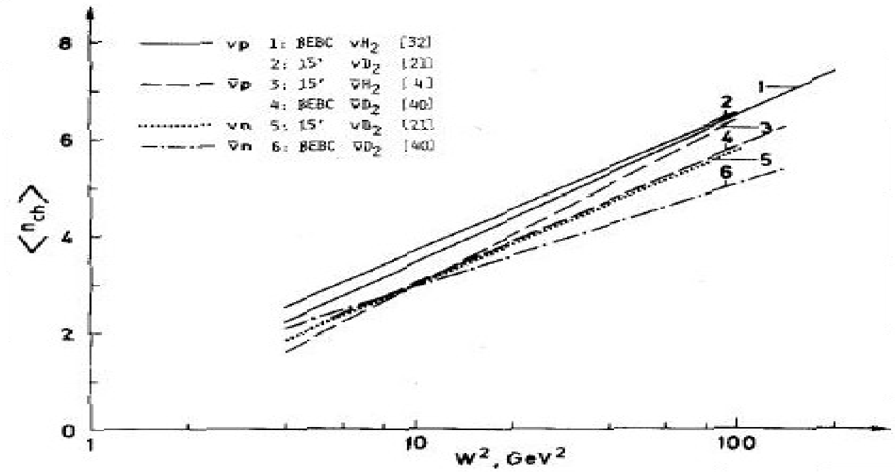
- severe kinematical constraints – limit dynamics
- effective model using KNO scaling and data-driven modelling of average multiplicities, forward/backward asymmetries, pT-dep. Etc...

<u>At high hadronic invariant masses:</u>

- rich dynamics
- using JETSET model
- tuned energy cutoff, pT, ssbar suppression (as in NUX)
- not really relevant at t2k energies

Minos kinematical coverage at PH2LE beam
(spans a large area of kinematical phase space space -
t2k much more limited)

The GENIE hadronization / AGKY low-W model



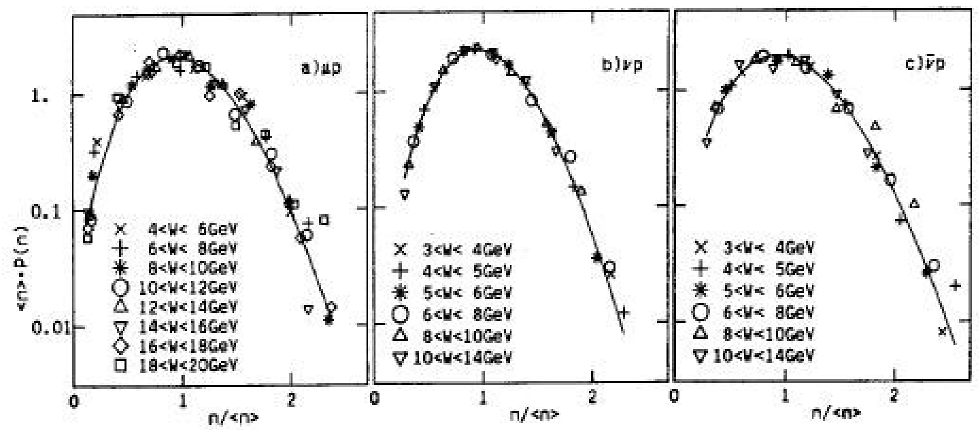
Get average multiplicity
from empirical parameterization

<n> = a + b * lnW^2

Generate the actual multiplicity
using the KNO scaling law:

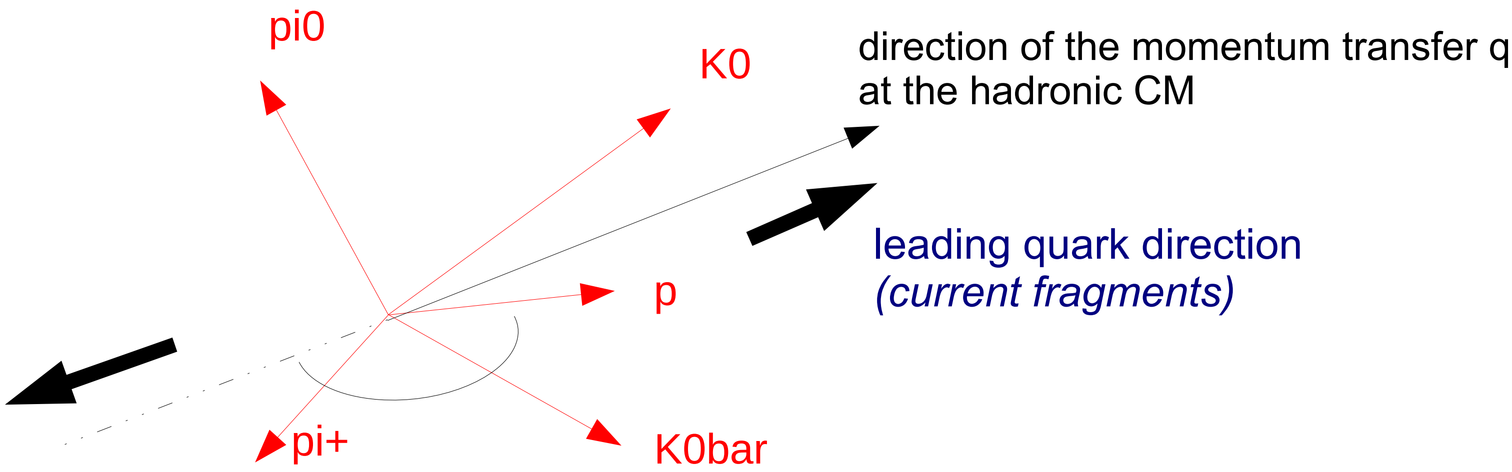
<n>P(n) = f (n/<n>)

(taking into account that
<n_neutral> = 0.5 * <n_ch>)



Simple arguments (charge conservation, quark model) to derive particle spectrum

The GENIE hadronization / AGKY low-W model



At the hadronic CM, **the nucleon direction be should be correlated with the diquark direction** *(opposite to the direction of the momentum transfer q)*

The GENIE hadronization / AGKY low-W model

Building in experimental data on nucleon pT and xF (= pL/pLmax =2*pL/W)

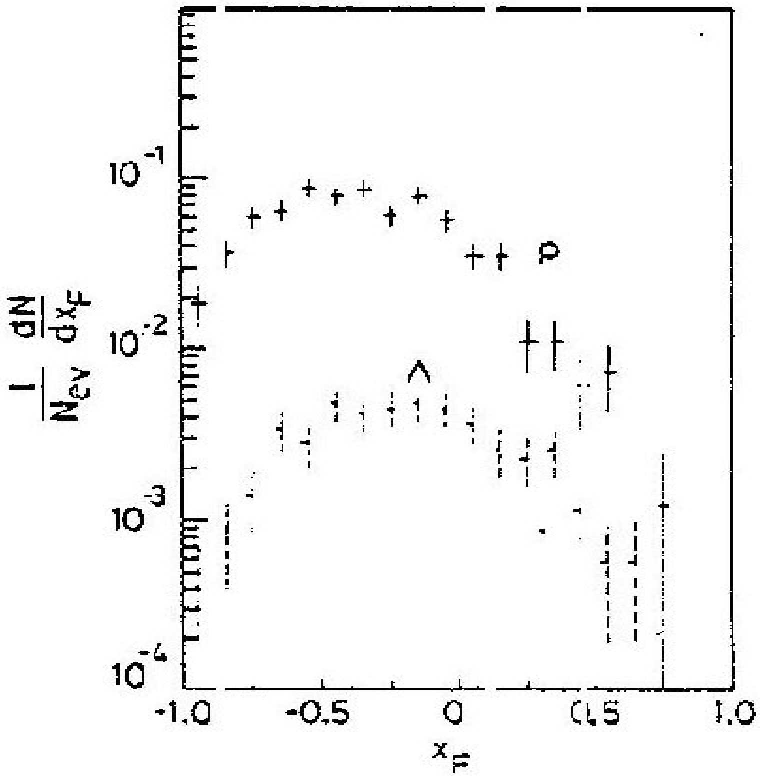
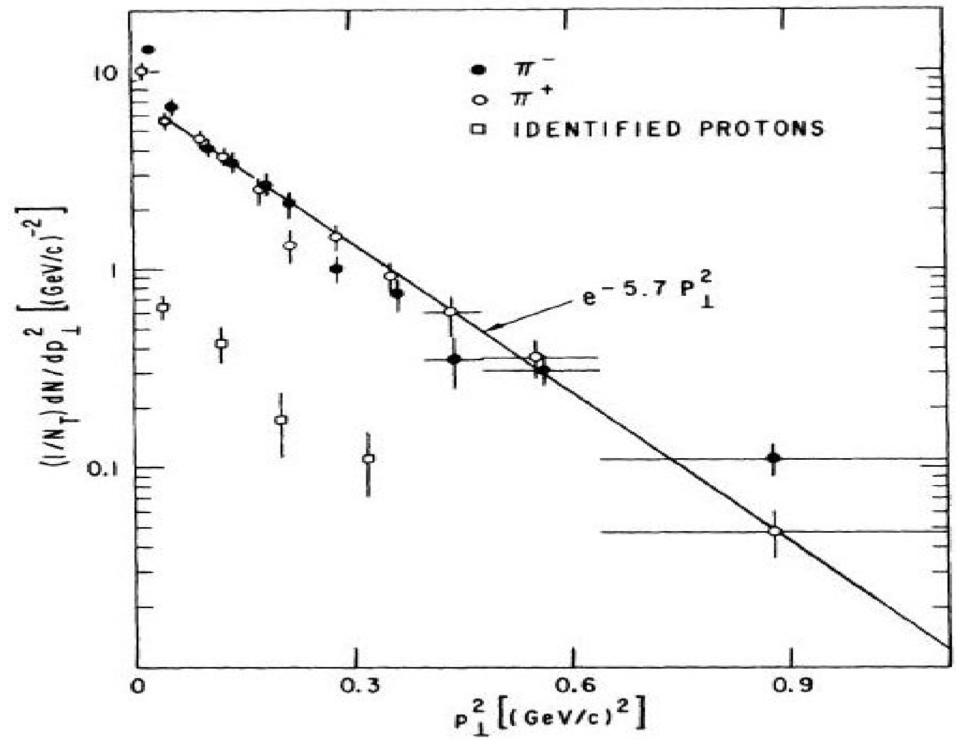
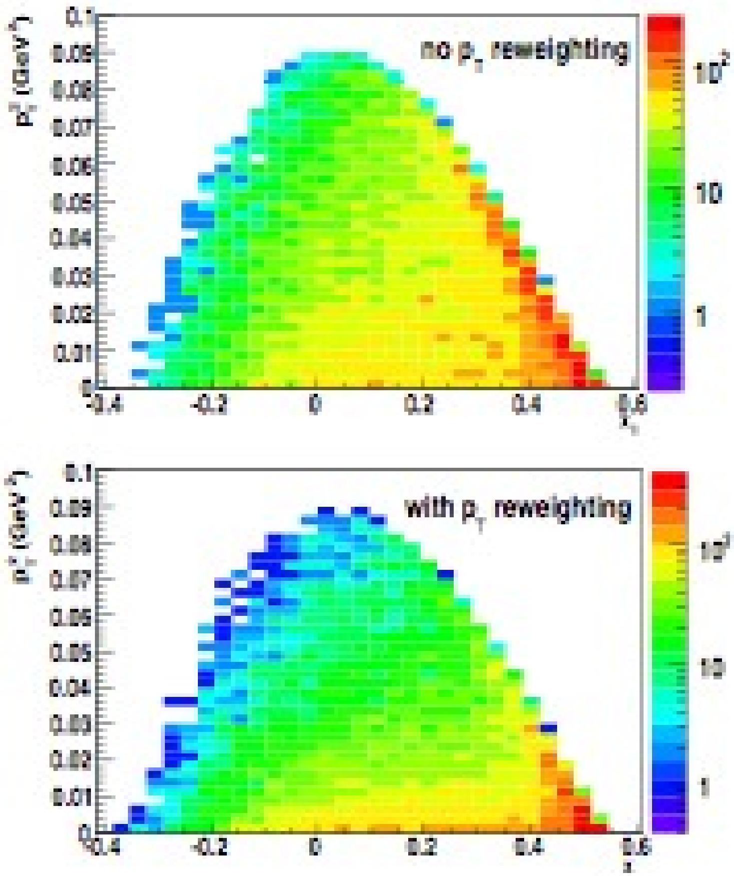


Fig. 11: x_F normalised distributions for protons (ν WA24 data) and lambda's (WA21 data, Bossetti et al, Nucl. Phys. B194, 1 (1982)).



Cooper, Neutrino 82, proceedings

The GENIE hadronization / AGKY low-W model



pT-limited
phase space decay

Figure 5. Pion x_F vs p_T^2, in the hadronic CM, for a (p, π^0, π^+) system decayed with invariant mass W = 1.6 GeV, where, for convenience, the

p4_{meson `remnants'} =
p4_{X} –
p4_{nucleon from target fragments}

Meson 4-momenta:

Boosting to the remnant hadronic system CM and performing a phase space decay.

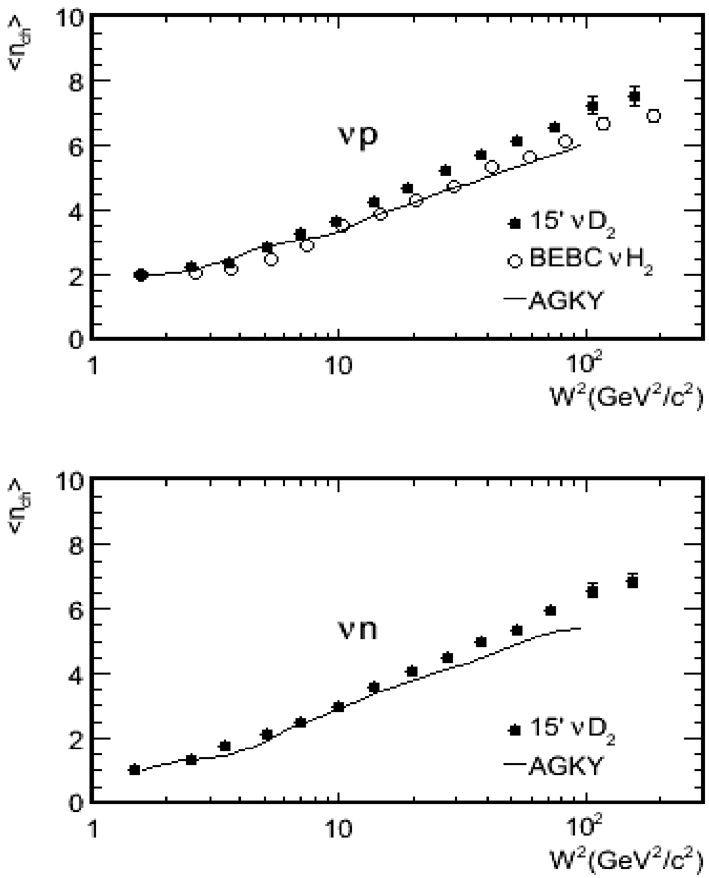
A pT-limited decay to match experimental pion PT distribution.

The GENIE hadronization model – Data/MC comparisons

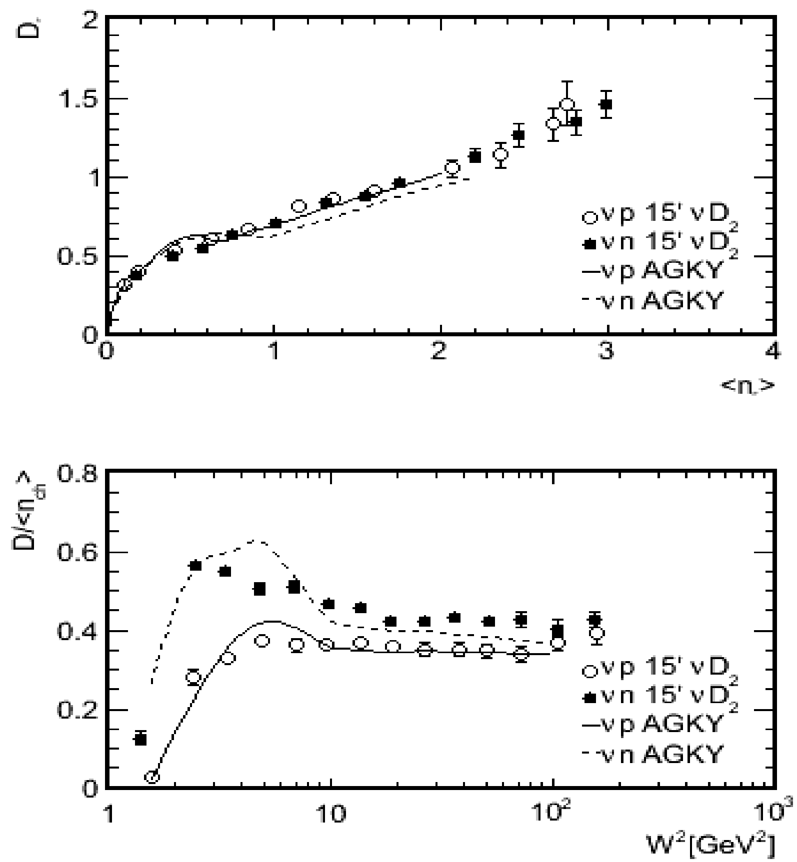
Model does very good job against a diverse host of data

examples:

Charged pion multiplicities



Charged pion dispersion

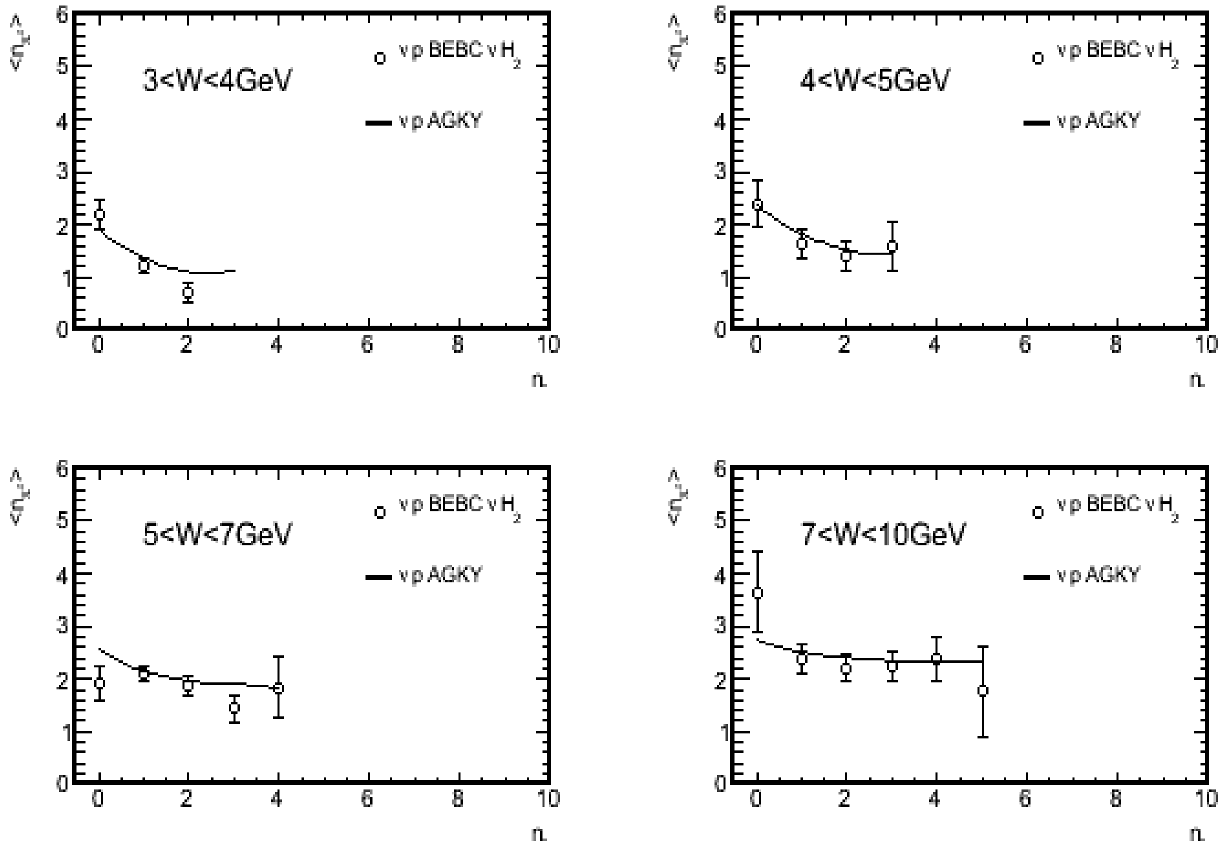


The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

Neutral / charged pion correlation

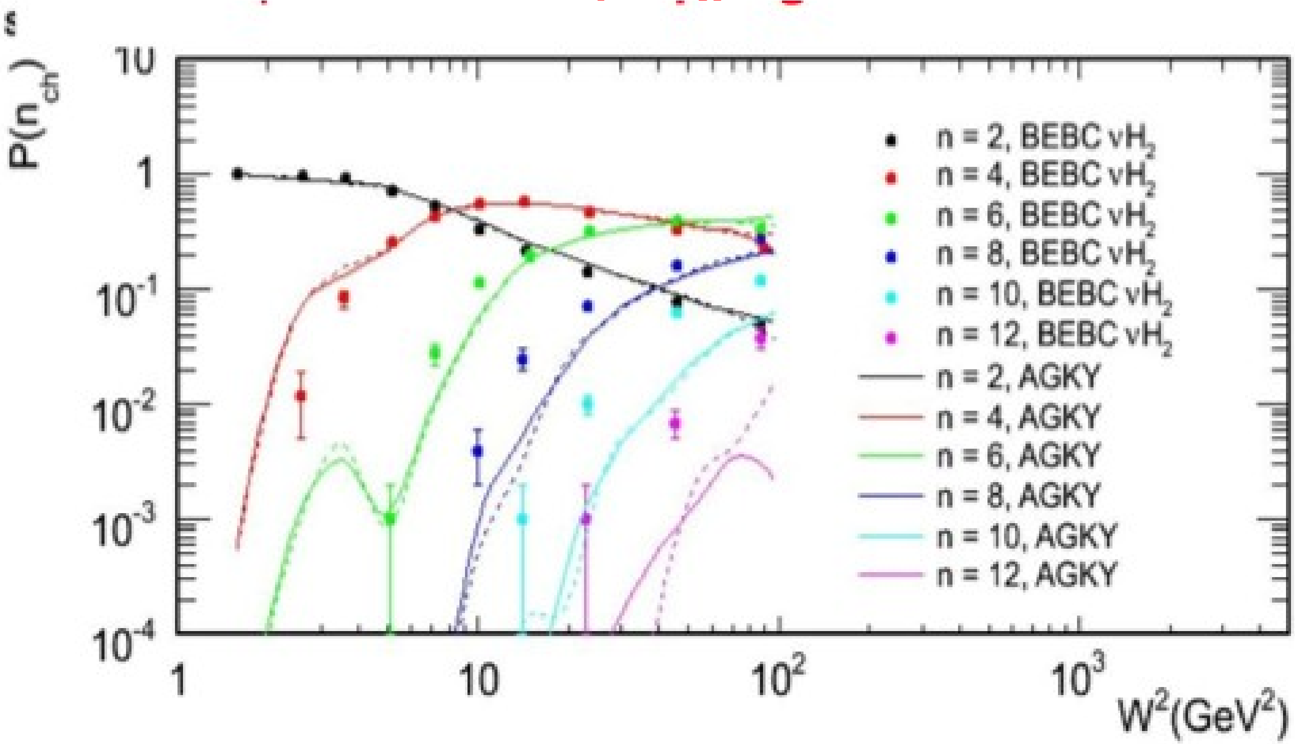


The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

Normalized topological cross sections



For more data/mc comparisons see GENIE-PUB/2007/002 and T.Yang's talk/proceedings at NuINT07

The model and its shortcomings are very well understood.
Improvements for low multiplicity (n=2) hadronic systems under way

Hadronization in nuclei: Formation zone

SKAT parameterization:

Hadron momentum

$$fzone = \frac{P \times ct_0 \times m}{m^2 + K \times P_T^2}$$

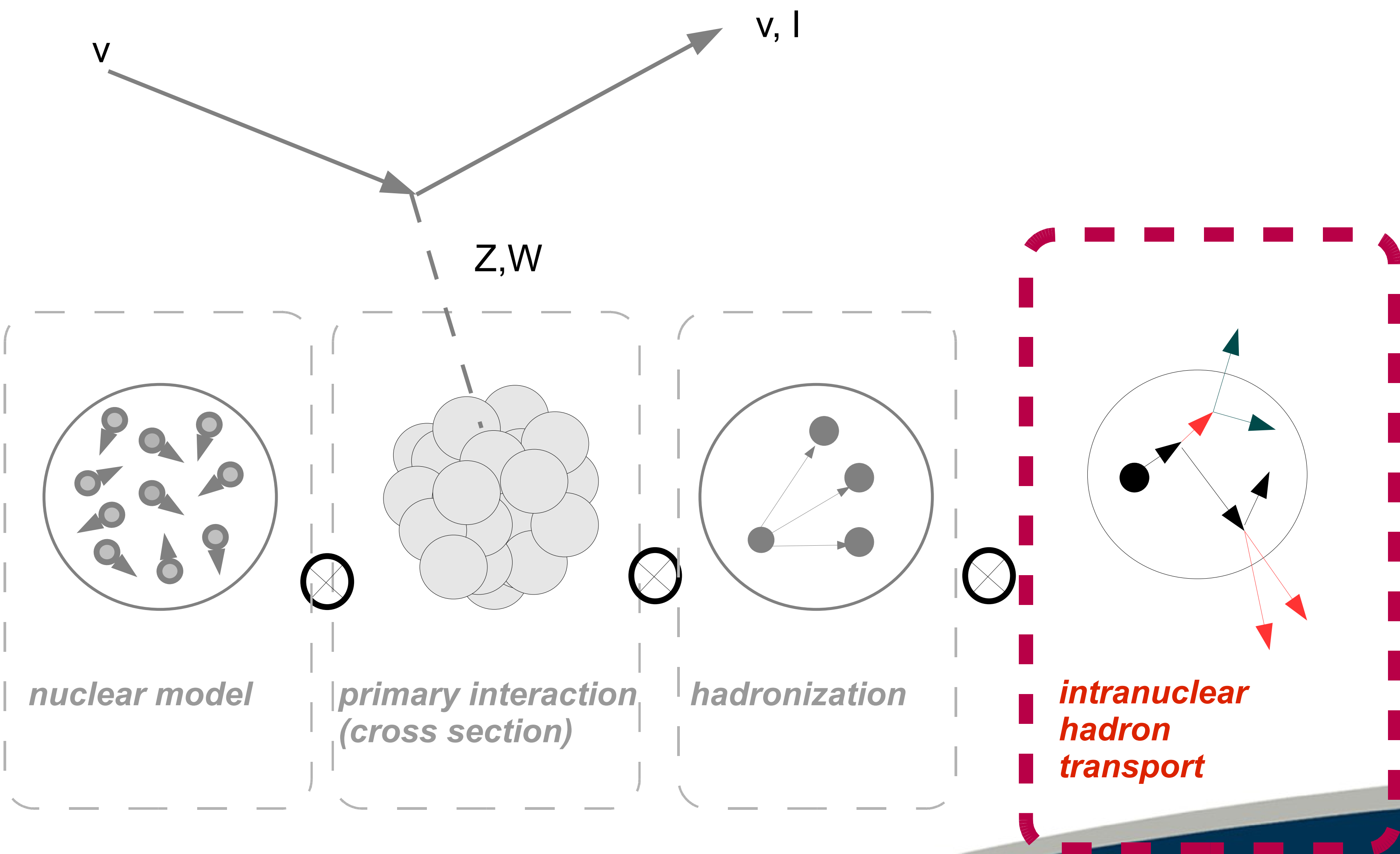
Transverse hadron momentum

In v2.4.: K=0, ct0 = 0.342 fm*

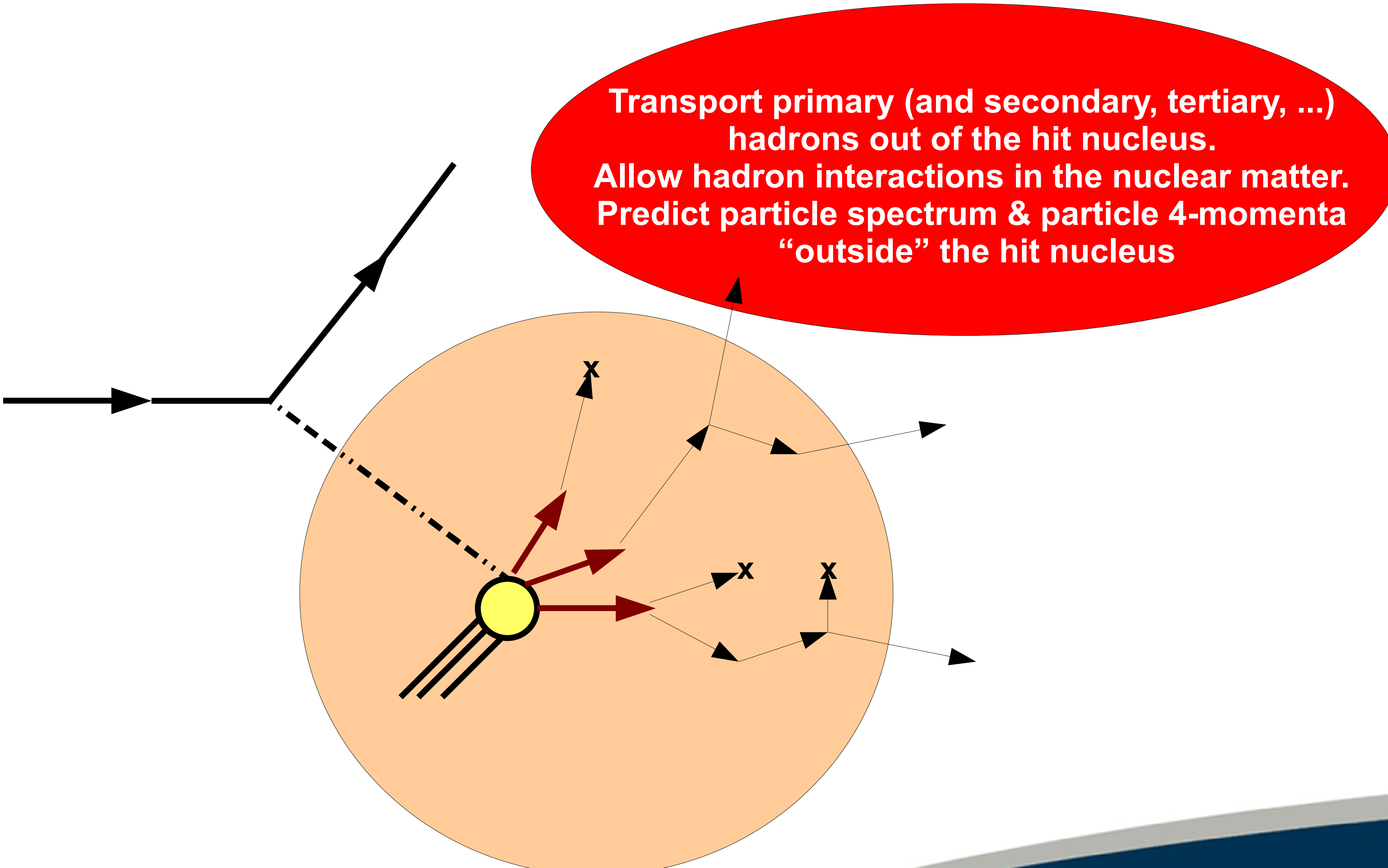
<u>No intranuclear rescattering within formation zone</u>

(SKAT) model dependence

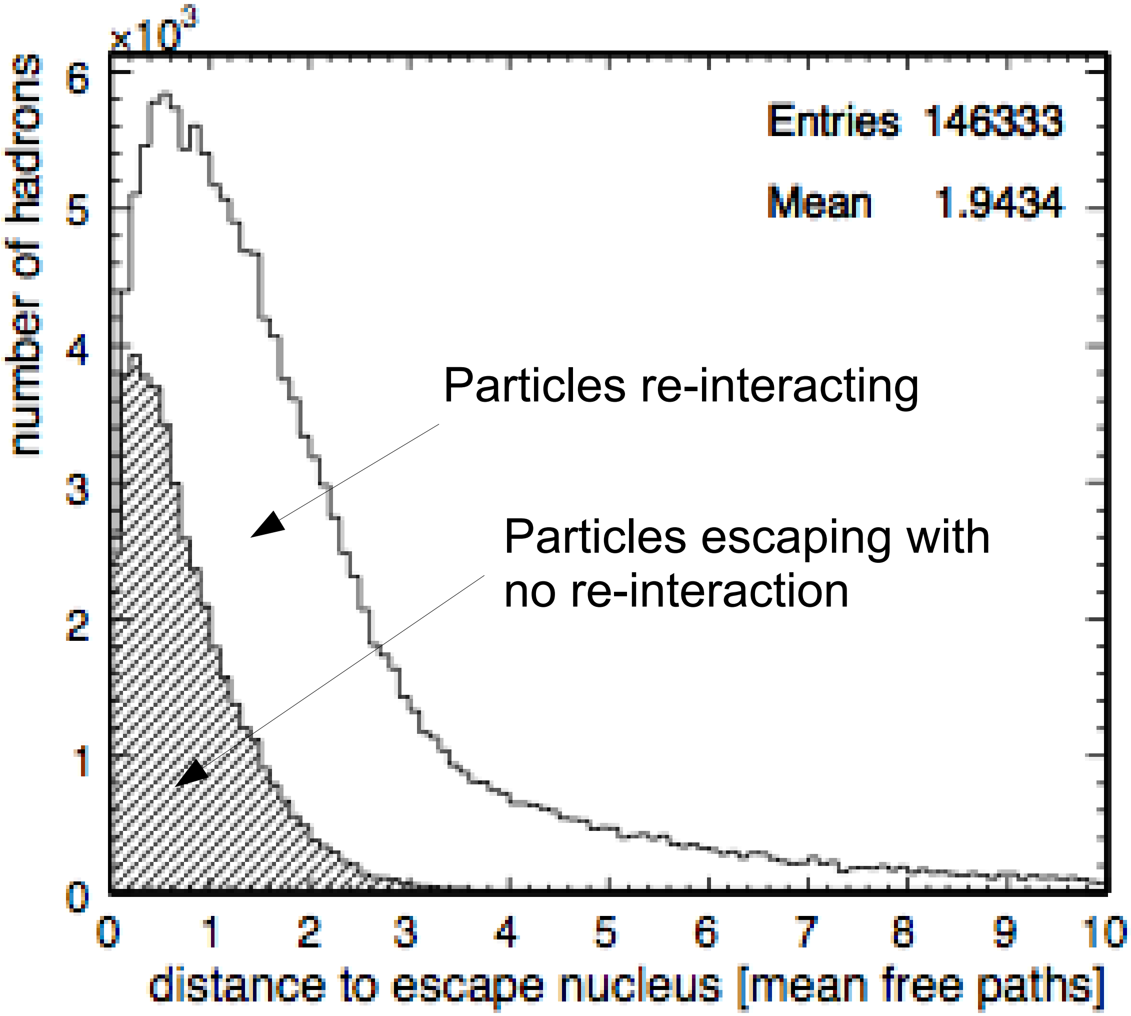
Intranuclear hadron transport



The GENIE hadron transport modelling

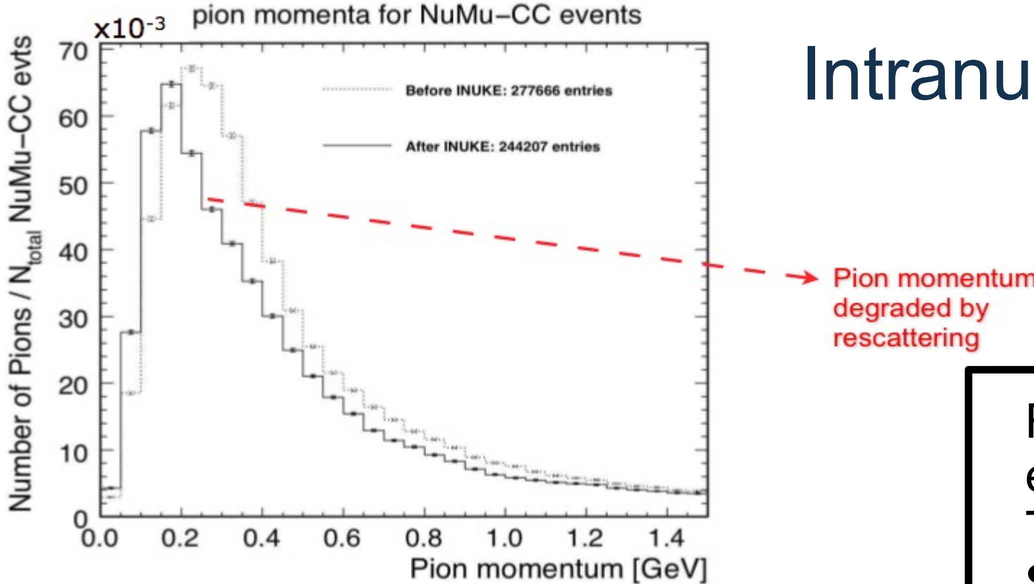


Intranuclear rescattering



nu_mu + C12
Ev = 1 GeV

Most particles (2/3) re-interact



Intranuclear rescattering effects

[shown for an nd280 event sample]

Reweighting tool to provide error estimates for these predictions. To be used for physics analysis. **See next talk.**

Severe effect on observed topologies

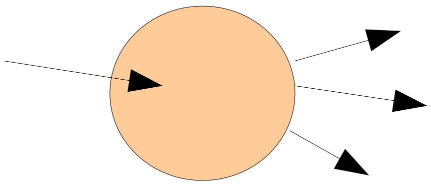
Topology after	Topology before										
	$0\pi X$	$\pi^0 X$	$\pi^+ X$	$\pi^- X$	$\pi^0\pi^+ X$	$\pi^0\pi^- X$	$\pi^+\pi^- X$	$2\pi^0 X$	$2\pi^+ X$	$2\pi^- X$	$\geq 3\pi X$
$0\pi X$	6053177	291116	520783	72611	9949	1843	6236	3037	2073	195	2390
$\pi^0 X$	26265	902112	87831	11465	42229	7916	1746	23933	616	49	10371
$\pi^+ X$	42820	26243	1655899	481	41826	157	24599	483	16408	0	12490
$\pi^- X$	4502	24564	15	243424	700	7874	24536	435	0	1253	6633
$\pi^0\pi^+ X$	9948	21378	28679	5758	194323	594	5082	2770	2877	24	41100
$\pi^0\pi^- X$	0	44	2	1	93	35773	3630	1690	0	198	17552
$\pi^+\pi^- X$	16804	183	146	1846	3058	584	108396	38	0	3	40218
$2\pi^0 X$	0	0	0	0	6002	1171	113	54246	52	0	21323
$2\pi^+ X$	1225	128	9496	19	3533	1	298	24	37812	0	18160
$2\pi^- X$	0	0	0	13	0	584	0	20	0	2833	2891
$\geq 3\pi X$	5352	6480	11459	2221	13563	2661	8282	4133	2416	126	566980
Total	6160093	1272248	2314310	337839	315276	59158	182918	90809	62254	4681	740108

The GENIE hadron transport modelling

Currently **have 2 alternative models** (using different techniques) –

Development of both is **<u>led by Steve Dytman</u>**

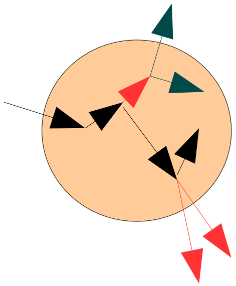
Intranuke / hA
(effective MC)



Anchored to a large body of experimental data
(including hadron+nucleus data)

<u>available since 2.0.0</u>

Intranuke / hN
(true cascade MC)



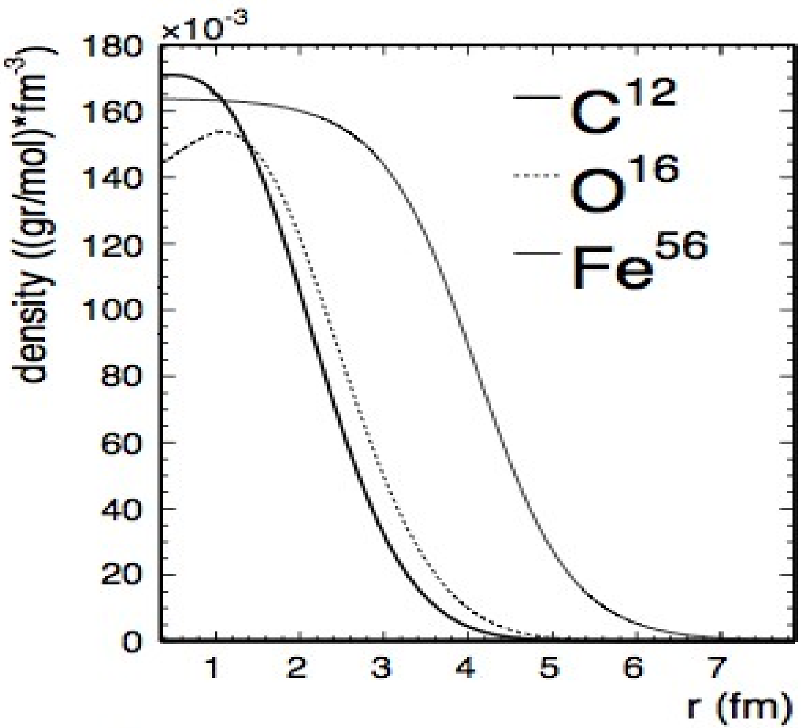
Builds everything up from hadron-nucleon xsecs

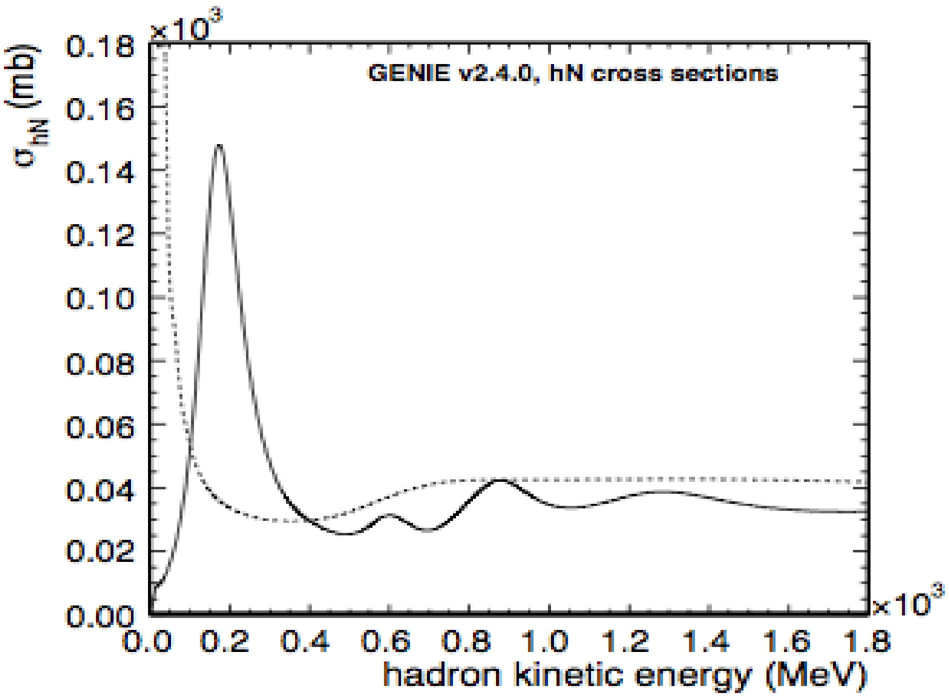
In advanced development stage
to become available soon

The GENIE hadron transport modelling (INTRANUKE/hA)

Stepping primary hadrons within the target nucleus

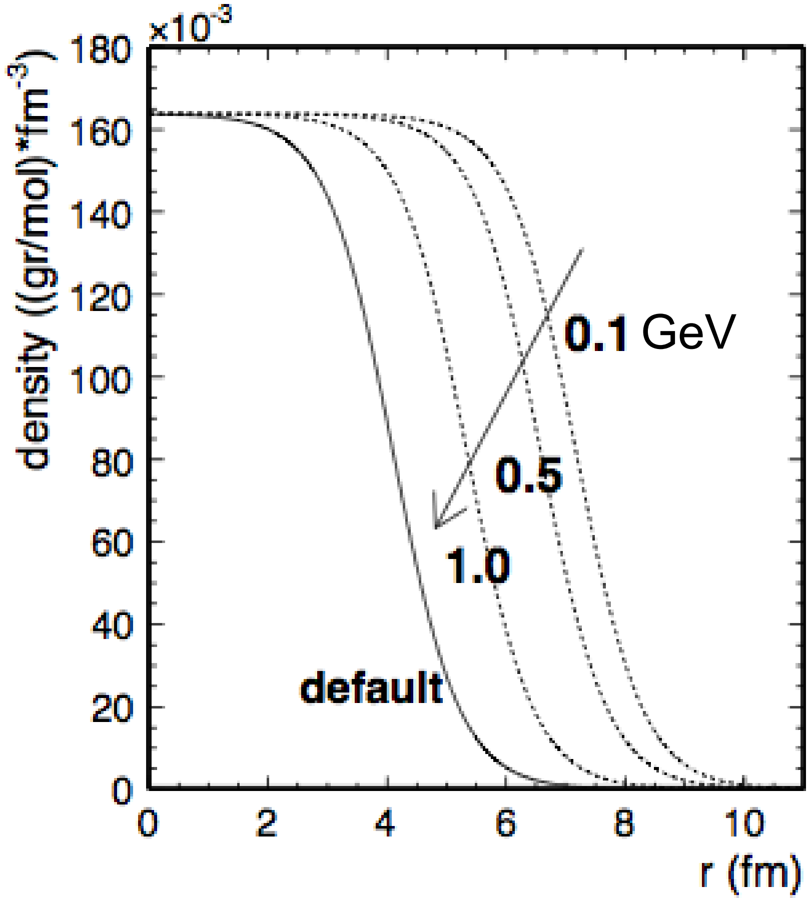
$$P^h_{rescat} = 1 - P^h_{surv} = 1 - \int e^{-r/\lambda(\vec{r},h,E_h)} dr$$





Science & Technology Facilities Council

The GENIE hadron transport modelling (INTRANUKE/hA)



- Hadrons stepped by 0.05 fm at a time
-
- Hadrons traced till they reach
  r_max = N * R_nucl = N * R0 * A^(1/3)
  (R0 = 1.4, N = 3.0)
  so as to include the effects of the tails
  (Fe56: R_nucl=5.36fm, r_max=16.07fm)

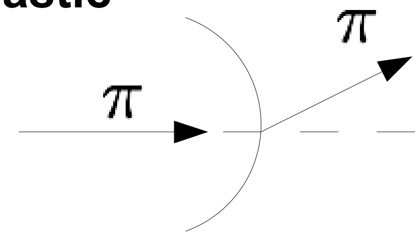
- The nuclear density distribution is `stretched' by n times the de Broglie wavelength of the tracked particle (n=1 for nucleons, n=0.5 for pions).

Science & Technology Facilities Council

The GENIE hadron transport modelling (INTRANUKE/hA)

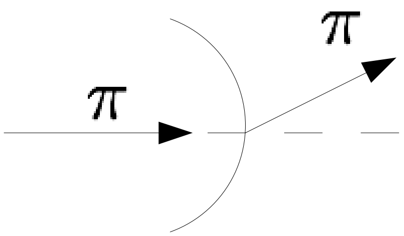
INTRANUKE/hA considers 5 types of 'hadron fates' (some may include many channels)

elastic



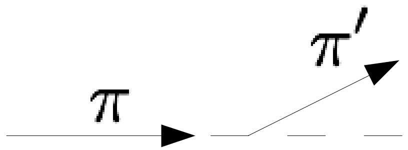
Pion deflected.
Its kinetic
energy stays
the same.

inelastic

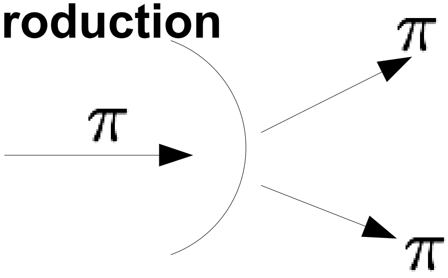


Pion deflected.
Its kinetic
energy is
degraded.

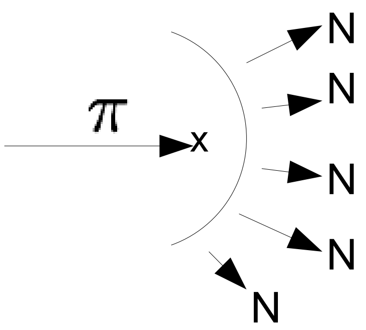
charge exchange



pion production



absorption

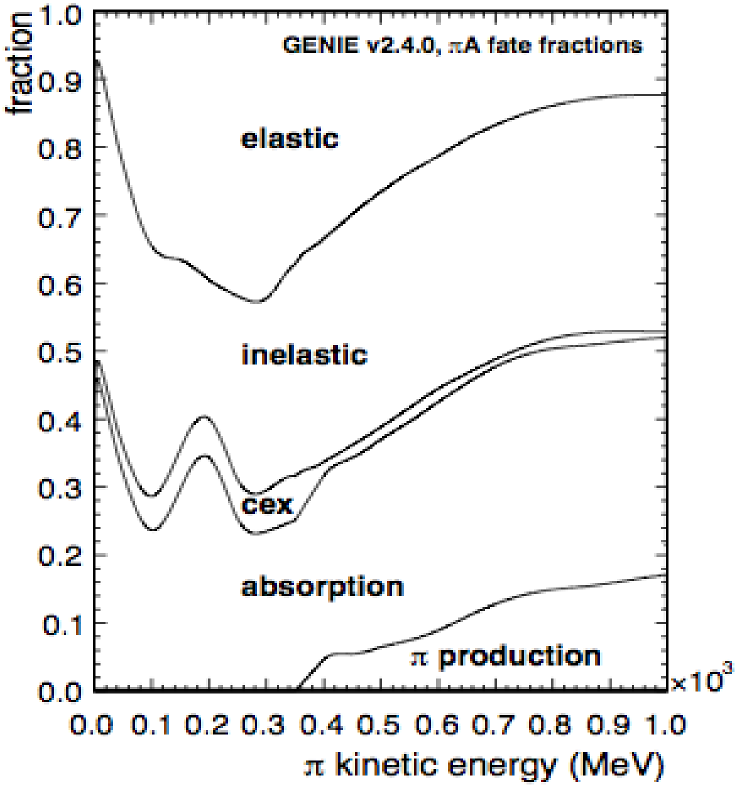


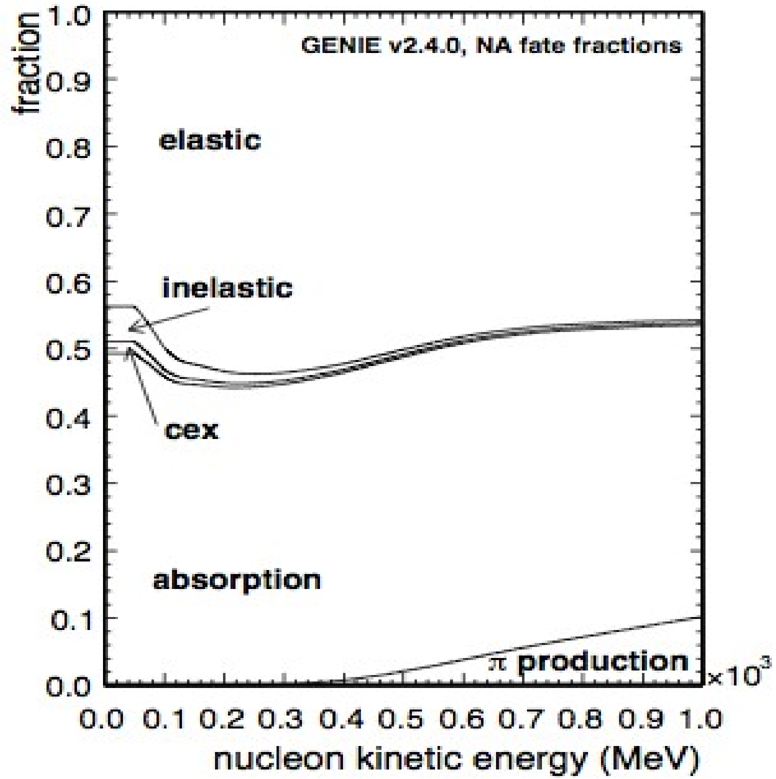
followed by
emission
of low energy
nucleons

~ Similar fates for nucleons

The GENIE hadron transport modelling (INTRANUKE/hA)

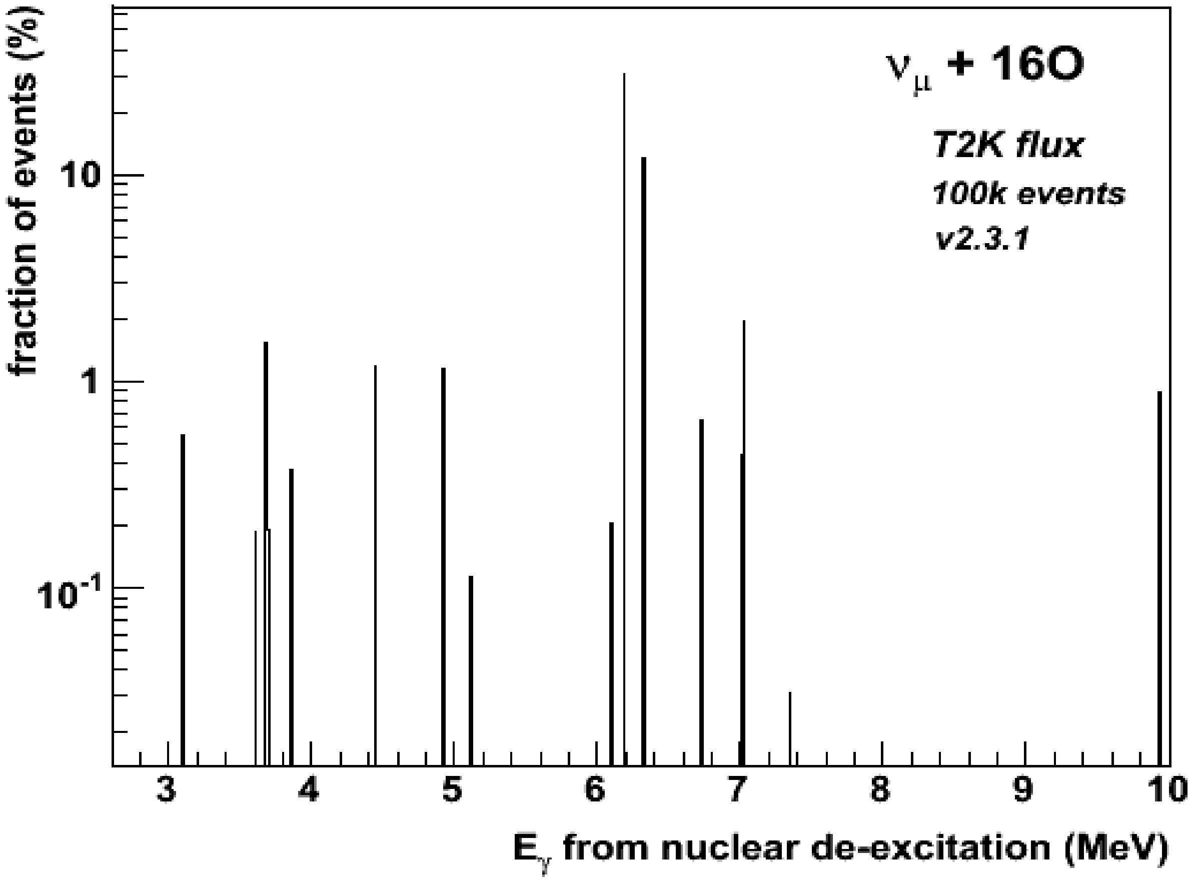
Fractions taken mostly from data





Final state hadron 4-momenta generated using built-in expt distributions and phase space decays.

Nuclear excitations



Included in an ad-hoc way

Only for O16

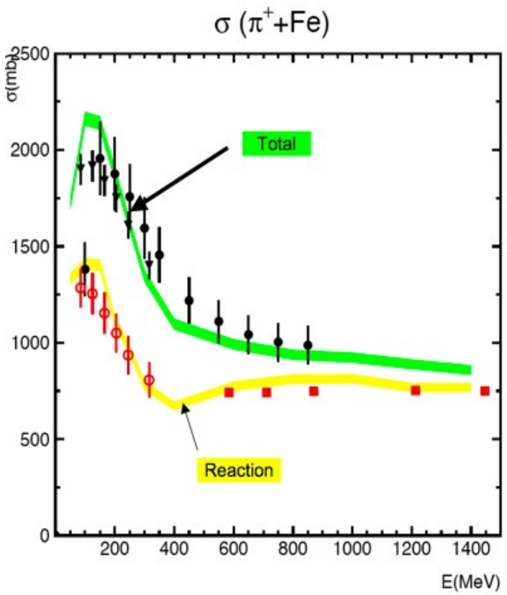
INTRANUKE/hA Data/MC comparisons

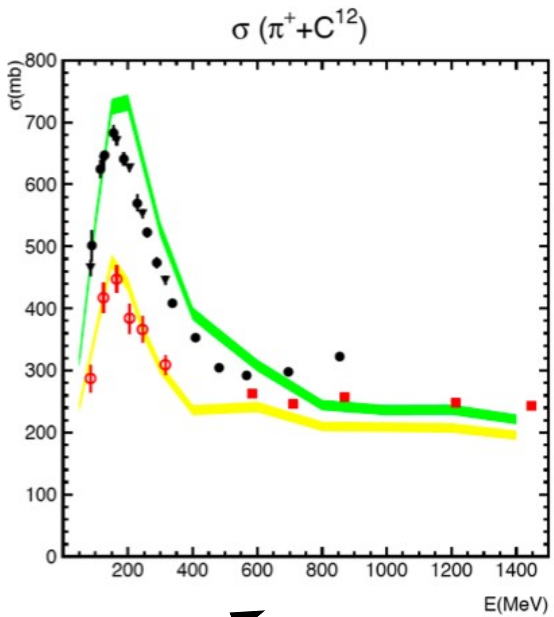
Much effort went into validation –
utilising experience from non-neutrino probes, mainly hadron+A reactions

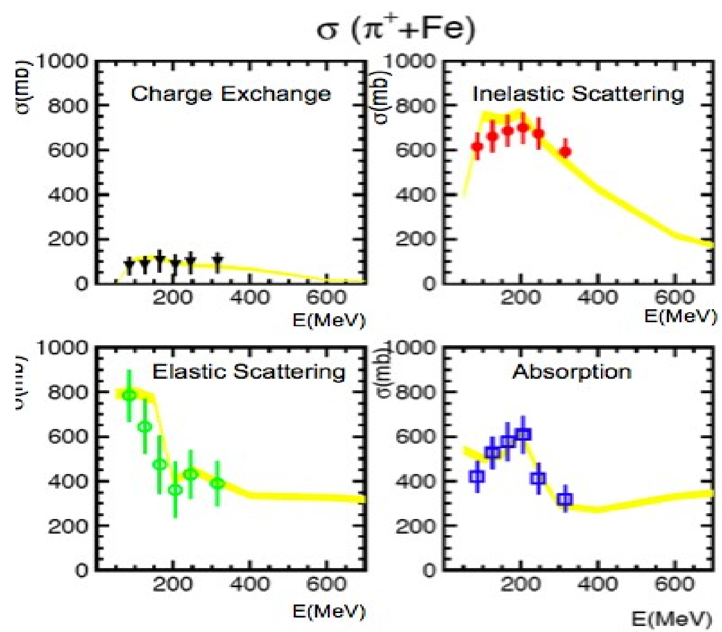
Lot of effort in tuning mean free path &
including the elastic contrib – difficult to model in context of INC

Then, components modelled directly from data – requires total xsec to be modelled correctly first

total = reaction + elastic
reaction = cex + inel + absorption + pi prod







`MC experiments': throw hadrons into nuclei,
'measure cross sections' and compare with data.

Costas Andreopoulos, *Rutherford Appleton Lab.*

GENIE models – A summary

- **Cross section model**
  - QEL: Llewellyn-Smith with any of Sachs/BBA03/BBA05 elastic f/f
  - RES: Rein-Sehgal
  - COH pi production: Rein-Sehgal / includes updated PCAC
  - DIS: latest Bodek-Yang
    - Including parametrization of the longitudinal structure function FL
    - Including NuTeV parameterization of nuclear effects
  - Many other more rare channels: DIS & QEL charm / ve- elastic / inv.mu-decay/...
- **Nuclear model**
  - Fermi Gas model
  - Including high momentum tail due to N-N correlations modelled from eN data
  - "Standard" FG prescription for off-shell kinematics...

Fairly standard at all ν MCs

Careful implementation as MINOS spans a huge kinematical region (E ~ <1 to >100 GeV)

- **Transition region cross section modelling**
  - Non resonance background modelled from DIS & AGKY hadronization
  - Tuned to the world exclusive multi-pion cross section data
- **Neutrino-induced primary hadronic shower modelling**
  - AGKY
  - Effective KNO-based hadronization at low-W
  - Switching gradually to PYTHIA/JETSET at high-W
  - SKAT-type formation zone parametrization
- **Intranuclear hadron transport**
  - INTRANUKE/hA model
  - Anchored to a set of hadron+Fe56
  - Scaled to all nuclei

Unique to GENIE

Costas Andreopoulos, *Rutherford Appleton Lab.*

GENIE includes an extensive toolkit >>>

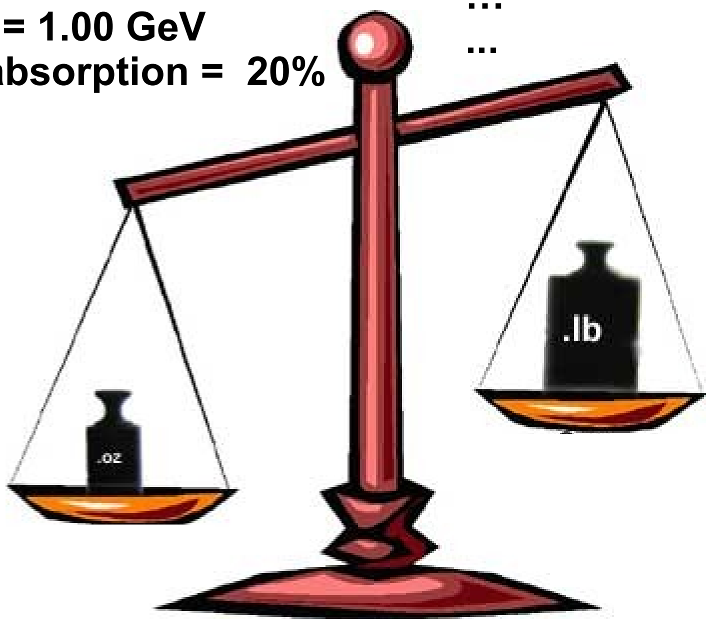
Facilitate experiments in

- Propagating νA uncertainties in physics measurements
- Generate realistic MC for complex experimental situations

Event Reweighting >>>

Ma = 1.20 GeV
pi absorption = 40%
…
...

Ma = 1.00 GeV
pi absorption = 20%
…
...

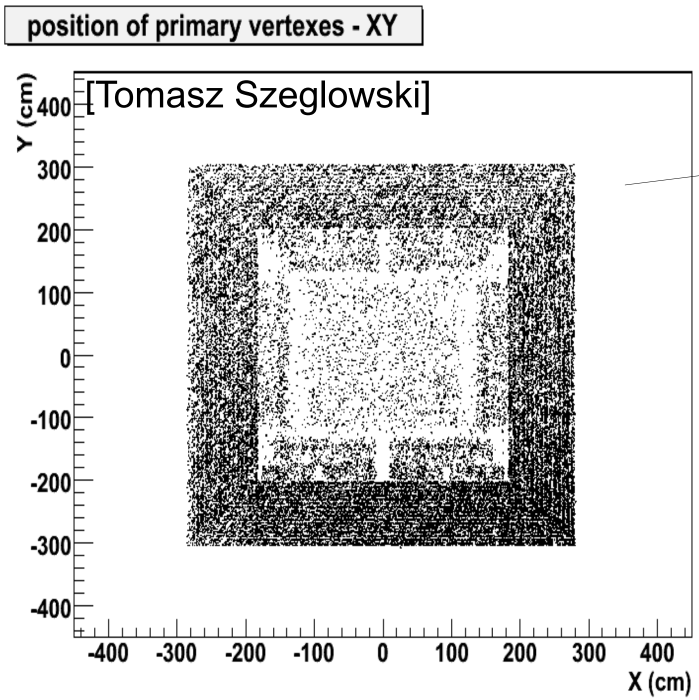


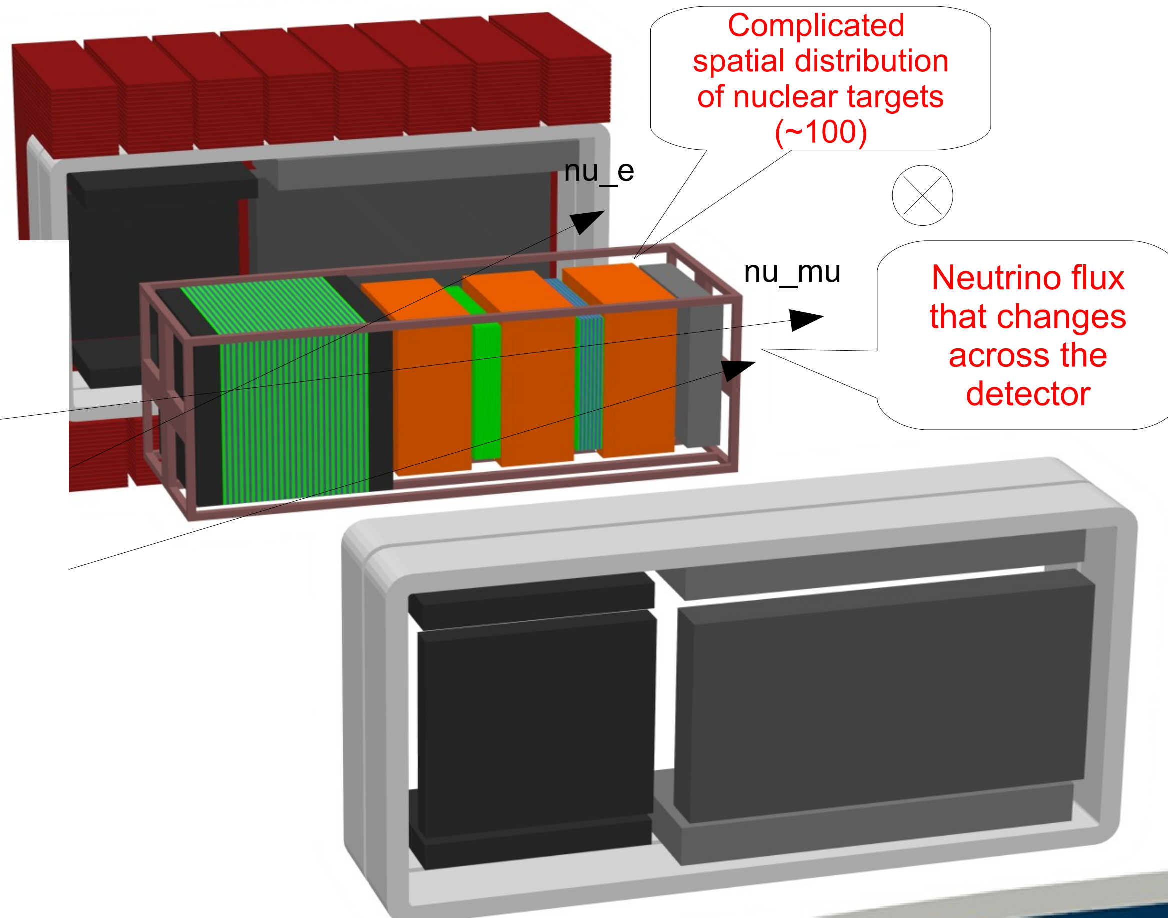
See next talk
by Jim Dobson (Imperial)

Handling complex event generation cases

Using off-the-shelf components

Event generation:
A complicated convolution of things:





Costas Andreopoulos, *Rutherford Appleton Lab.*

Improvements in upcoming releases

Much faster geometry navigation code.

Support for event generation in user-defined `fiducial volume' not necessarily corresponding to any actual geometry volume.

Including specialised drivers for NuMI beam-line experiments
(as we already did for the JPARC expts)

Further physics improvements In upcoming releases >>>

Many important changes are in the pipeline

New intranuclear cascade

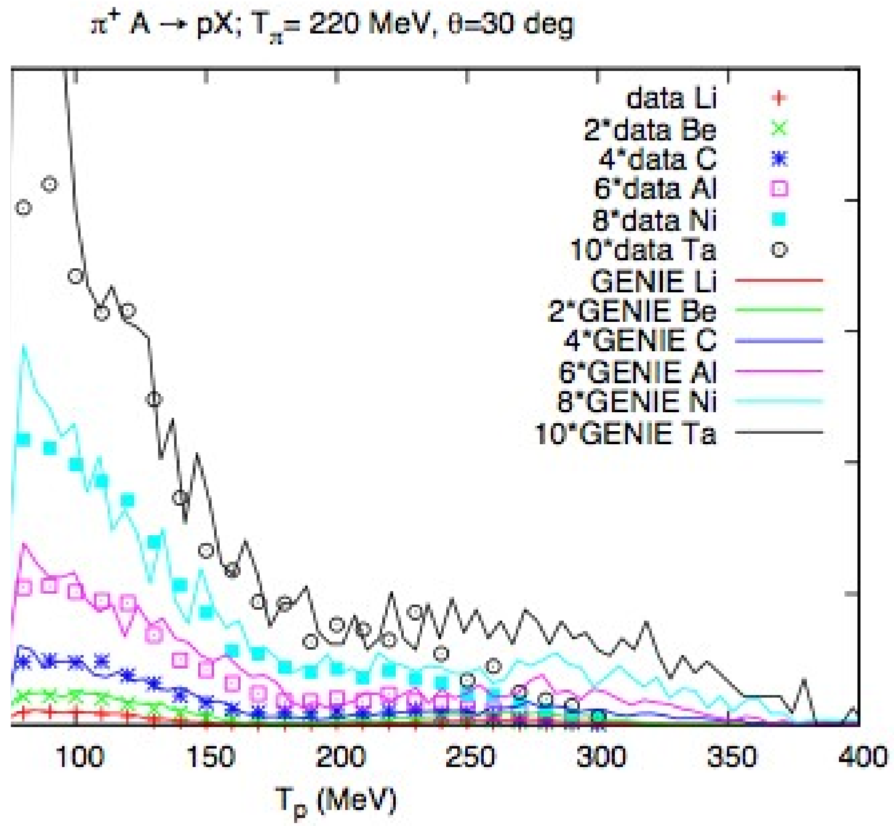
See Steve's talks during the school

New hN model successful in describing a broad set of features.

Some issues to resolve.

Development ~80% done.

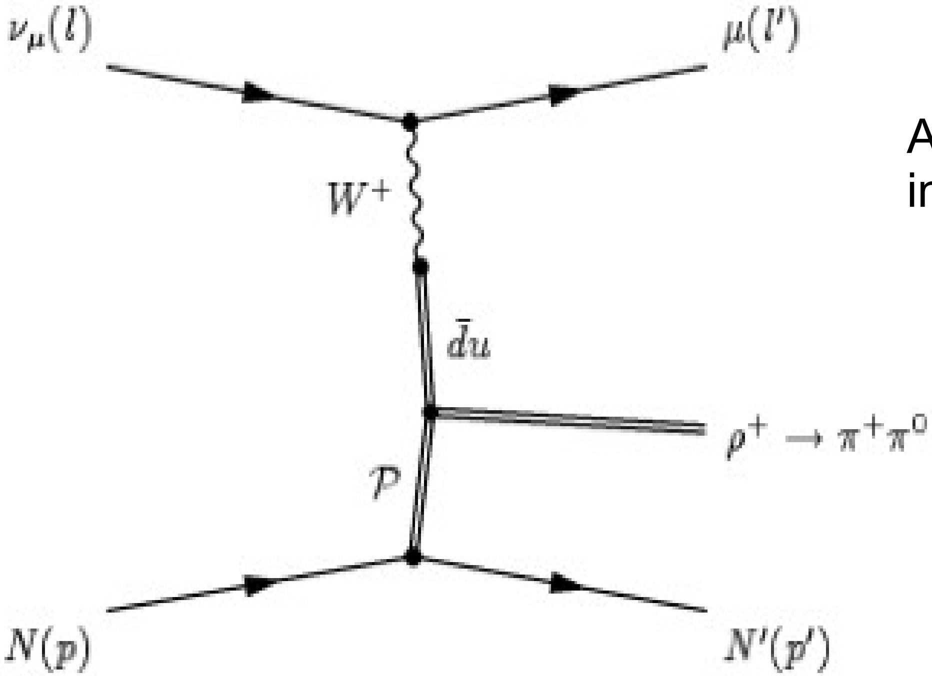
hN can feed-back to the faster & reweightable hA model



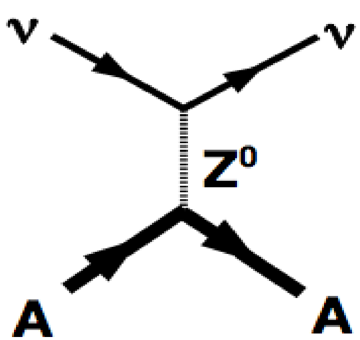
Updated nuclear model

Full spectral function implementation – using de Forest kinematic prescription
Using C,O,Ca,Ar,Fe S/F parameterizations by Artur Ankowski

New reaction channels

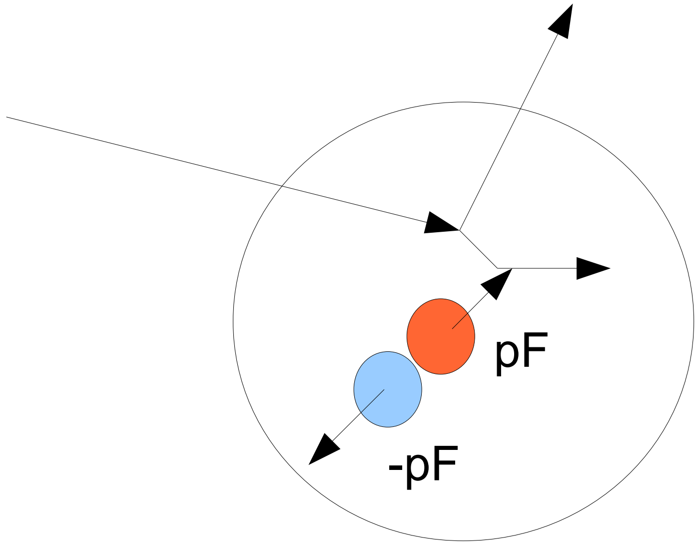


Adding coherent diffractive scattering in v2.6.0

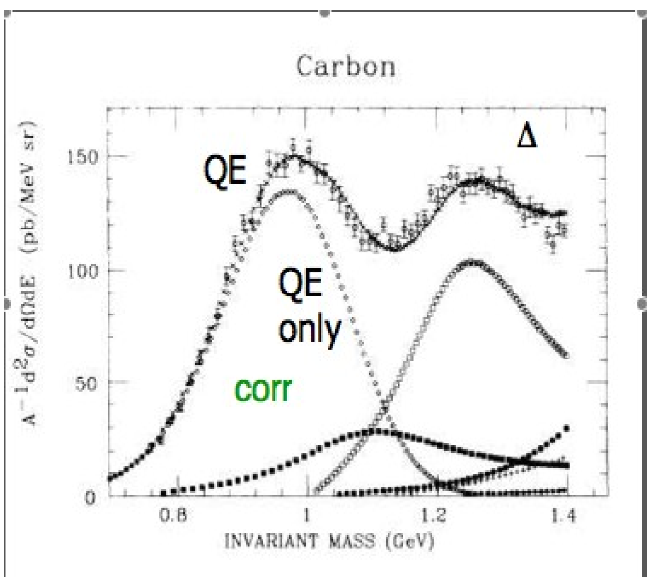


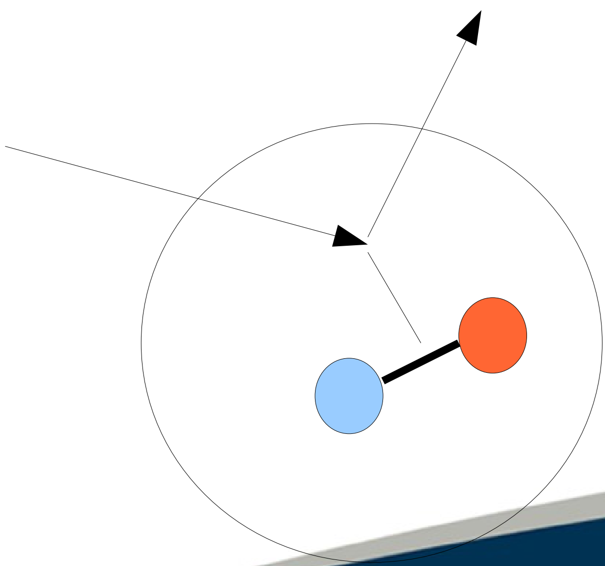
Adding coherent elastic scattering in v2.8.0

Short and long range correlations



20%
- 18% np
- 1% nn
- 1% pp





Near future improvements cont'd

Some changes to the B/Y structure funcions & R/S form factors.
Global cross section model retuning.

Improvements at AGKY strange particle production

Improvements at AGKY fwd/bwd asymmetry

Improvements at angular distributions of resonance decays

… … ...

Summary

Heavily validated and robust comprehensive MC generator

Nearly universal!

Provides high quality simulations for T2K, MINOS, MINERvA, NOvA

Roadmap to v3.0.0

Advancing simulations beyond current level
(S/F nuclear model, state-of-the art hadronization & cascade models,
comprehensive list of simulated processes, short/long range correlations, ...)

For: Final MINOS analyses, first T2K analyses, first MINERvA analyses, ...