Science & Technology Facilities Council
Rutherford Appleton Laboratory

The GENIE *

Neutrino Monte Carlo Generator

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

Costas Andreopoulos

45th Karpacz Winter School in Theoretical Physics

Neutrino interactions: from theory to Monte Carlo simulations

Feb 03, 2009

Science & Technology Facilities Council

Outline

- General information on GENIE

- **Neutrino Interaction Physics**
  - This introductory talk is geared towards:
    - » *Covering the basics for younger students*
    - » *Giving a glimpse of the `more involved' stuff (vA hadronics)*

- Understanding GENIE capabilities

- Understanding GENIE events

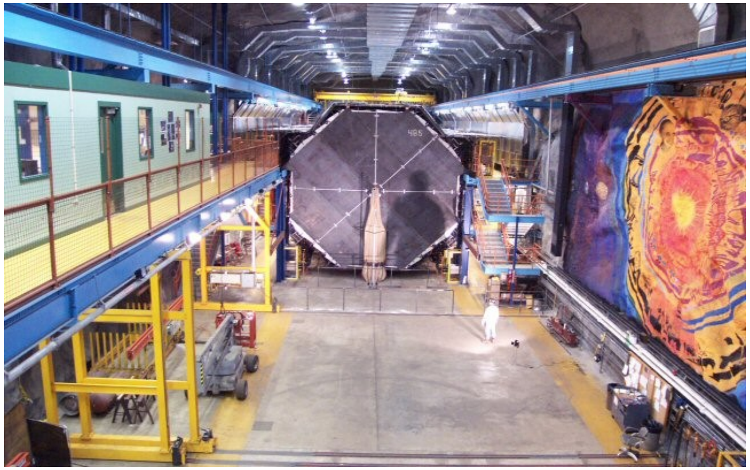
More technical discussions at the `how to run GENE' session and during the hands-on tasks

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: νA 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

What is GENIE?

Generates Events for Neutrino Interaction Experiments

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 openness and synergies between experiments

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

Who is using GENIE now?

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

- T2K
  - nd280
  - SK
  - ingrid
- MINOS
- NovA
- MINERvA
- 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.

Could trivially extend GENIE in new kinematical regimes (reactor expts. / neutrino telescopes)
if there is avail. manpower from these communities.

Who develops GENIE ?

Mostly experimentalists !

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

The physics in the current version was shaped primarily from the work of

Costas Andreopoulos *(Rutherford Lab. – MINOS/T2K)*
Steve Dytman *(Pittsburgh U. - MINOS/MINERvA/T2K)*
Hugh Gallagher *(Tufts U. - MINOS/MINERvA/NOvA)*
Donna Naples *(Pittsburgh U. - MINOS/MINERvA/T2K)*

The project never really attracted theorists (is it the C++ ?)

New theoretical work (*sitting idle in arXiv*) could have been used for MC generation of major experiments and for systematic error evaluation

`Physics MC' by experimentalists ?

It has its advantages !!

Focusing on simulating what we actually measure

- Many effective models / Building-in many pieces of data
    - *Reliable*
    - *Simple (understood by data-analysers / reweight-able)*

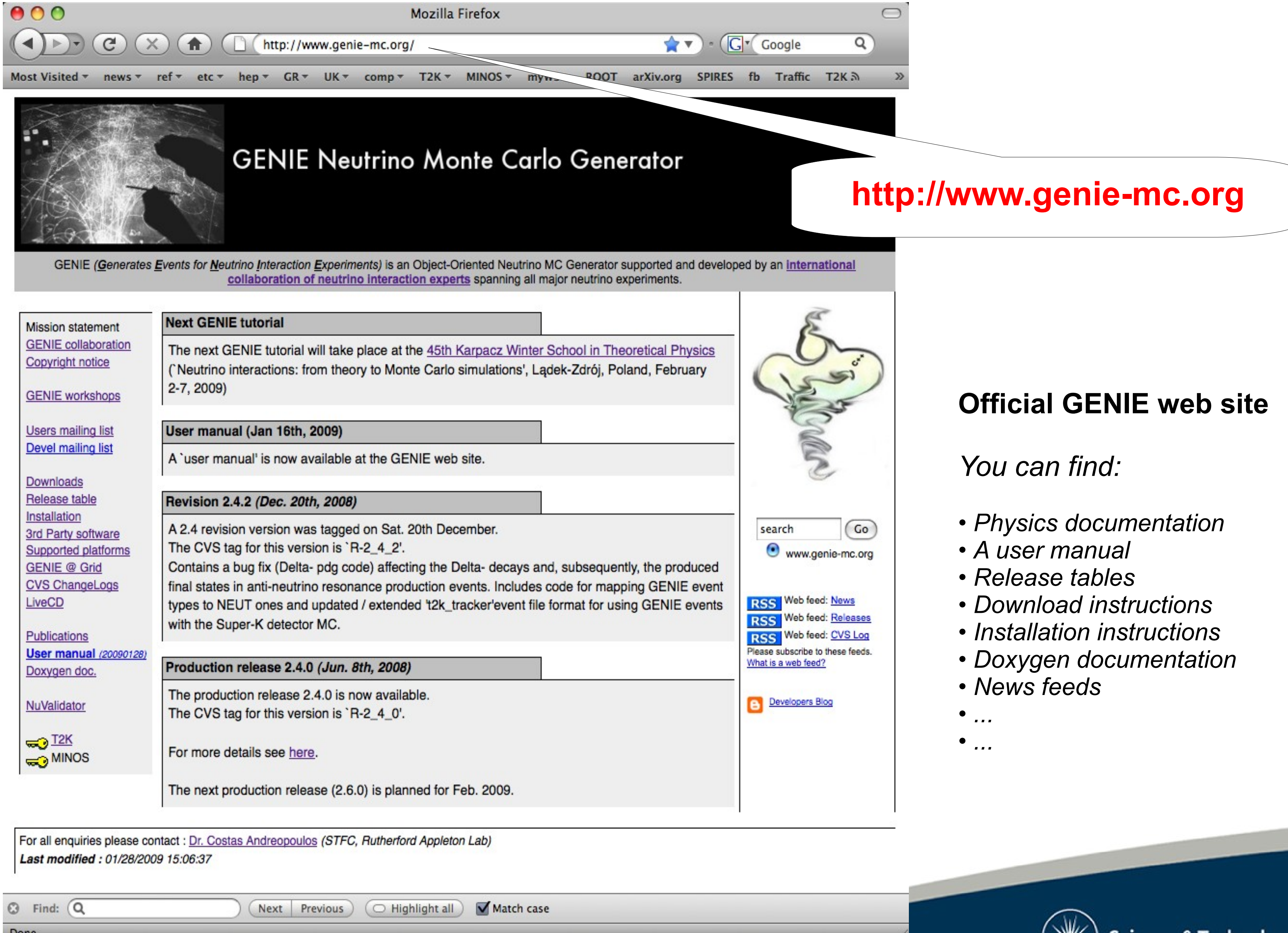
Focusing on understanding what is important for our oscillation studies

- *Generator uncertainties*
- *Providing tools to propagate uncertainties into physics analyses (reweighing, see Jim's talk at the workshop)*

Finding out more …

Getting support …

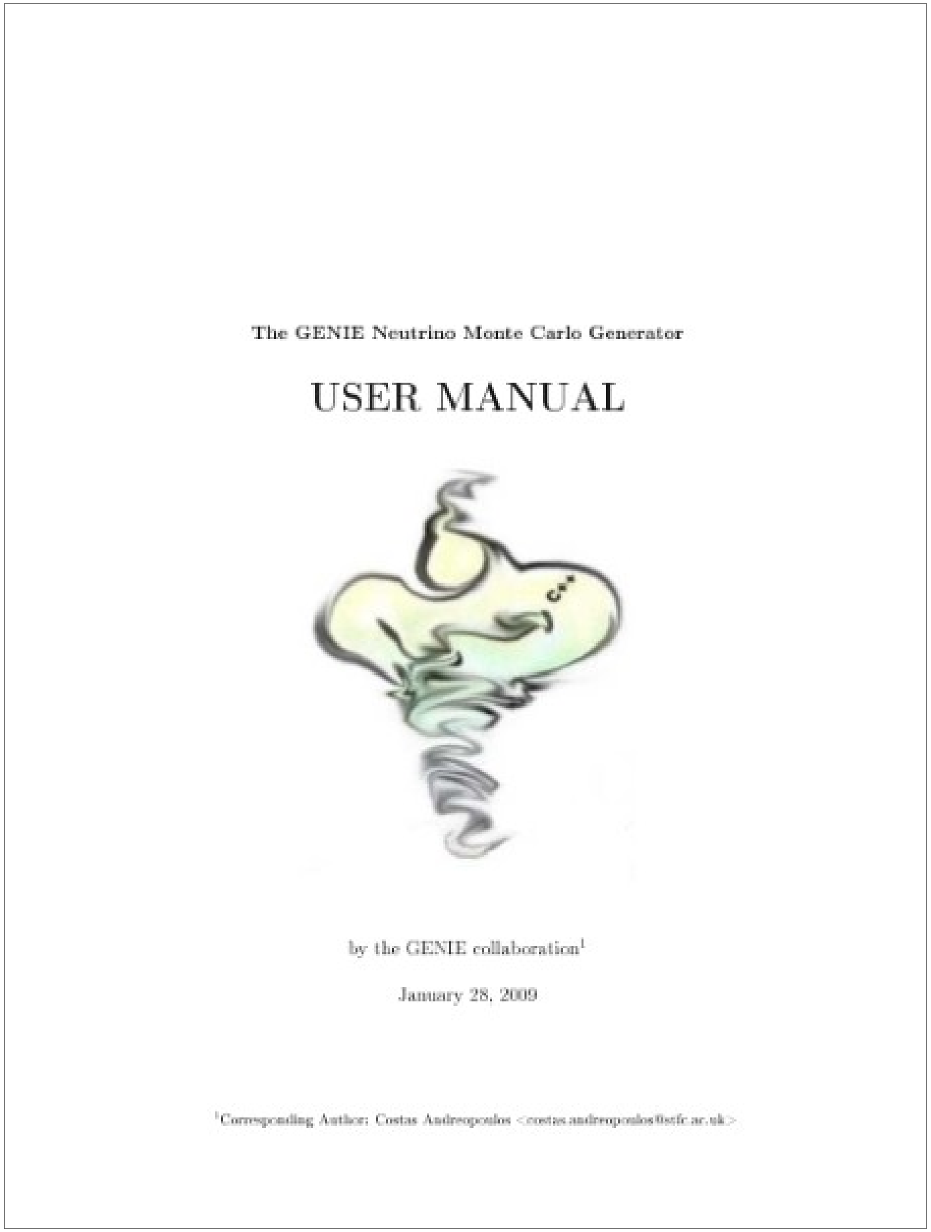
Staying in touch …



Official GENIE web site

You can find:

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



The GENIE Neutrino Monte Carlo Generator

USER MANUAL

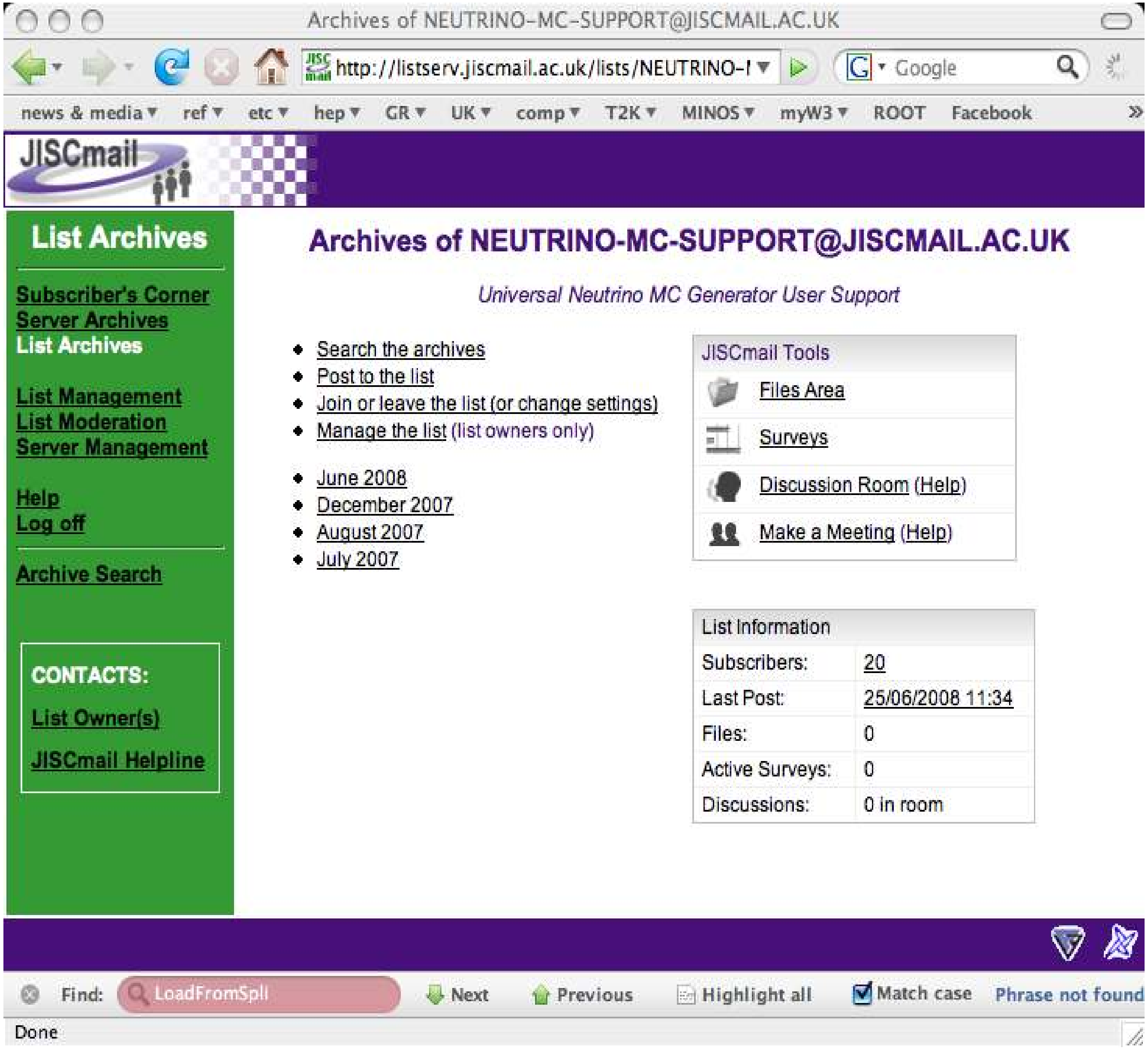
by the GENIE collaboration[1]

January 28, 2009

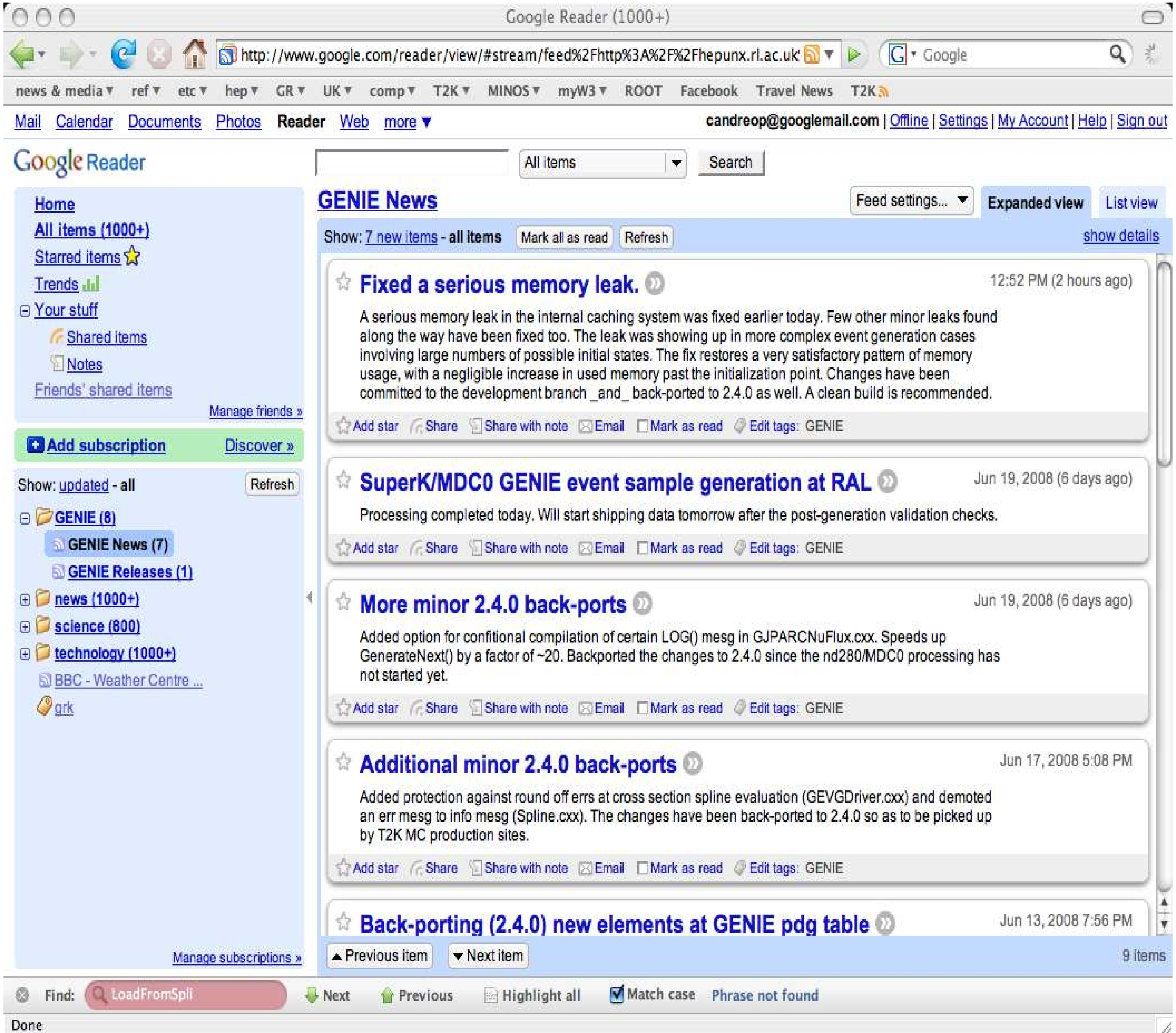
[1]Corresponding Author: Costas Andreopoulos <costas.andreopoulos@stfc.ac.uk>

NEW

Read the GENIE users manual



Subscribe to the GENIE users mailing list !



Subscribe to the GENIE RSS news feeds !

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Neutrino Interactions
>>>

Kinematical variables

$\nu = \frac{q \cdot P}{M} = E - E'$ is the lepton's energy loss in the nucleon rest frame (in earlier literature sometimes $\nu = q \cdot P$). Here, E and E' are the initial and final lepton energies in the nucleon rest frame.

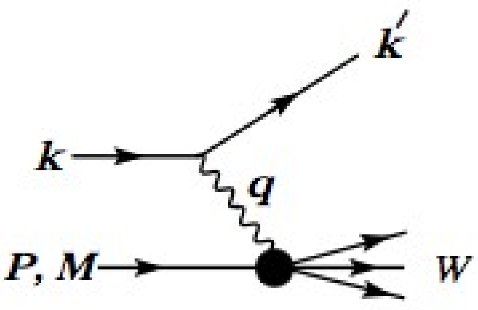
$Q^2 = -q^2 = 2(EE' - \vec{k} \cdot \vec{k}') - m_\ell^2 - m_{\ell'}^2$, where $m_\ell (m_{\ell'})$ is the initial (final) lepton mass. If $EE' \sin^2(\theta/2) \gg m_\ell^2, m_{\ell'}^2$, then

$\approx 4EE' \sin^2(\theta/2)$, where θ is the lepton's scattering angle with respect to the lepton beam direction.

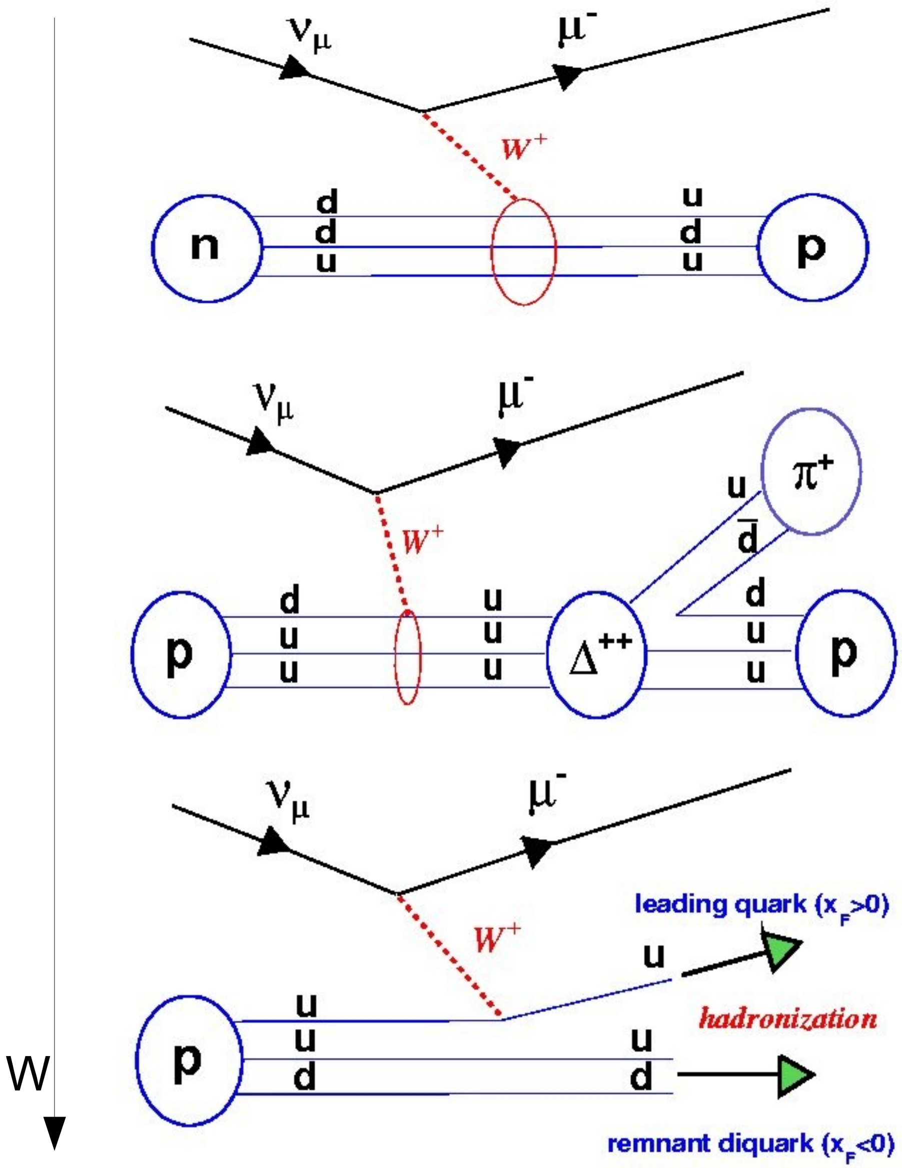
$x = \frac{Q^2}{2M\nu}$ where, in the parton model, x is the fraction of the nucleon's momentum carried by the struck quark.

$y = \frac{q \cdot P}{k \cdot P} = \frac{\nu}{E}$ is the fraction of the lepton's energy lost in the nucleon rest frame.

$W^2 = (P + q)^2 = M^2 + 2M\nu - Q^2$ is the mass squared of the system X recoiling against the scattered lepton.



Dominant interaction modes at ~1 GeV *(nu_mu CC)*



Quasi-Elastic Scattering (QEL)

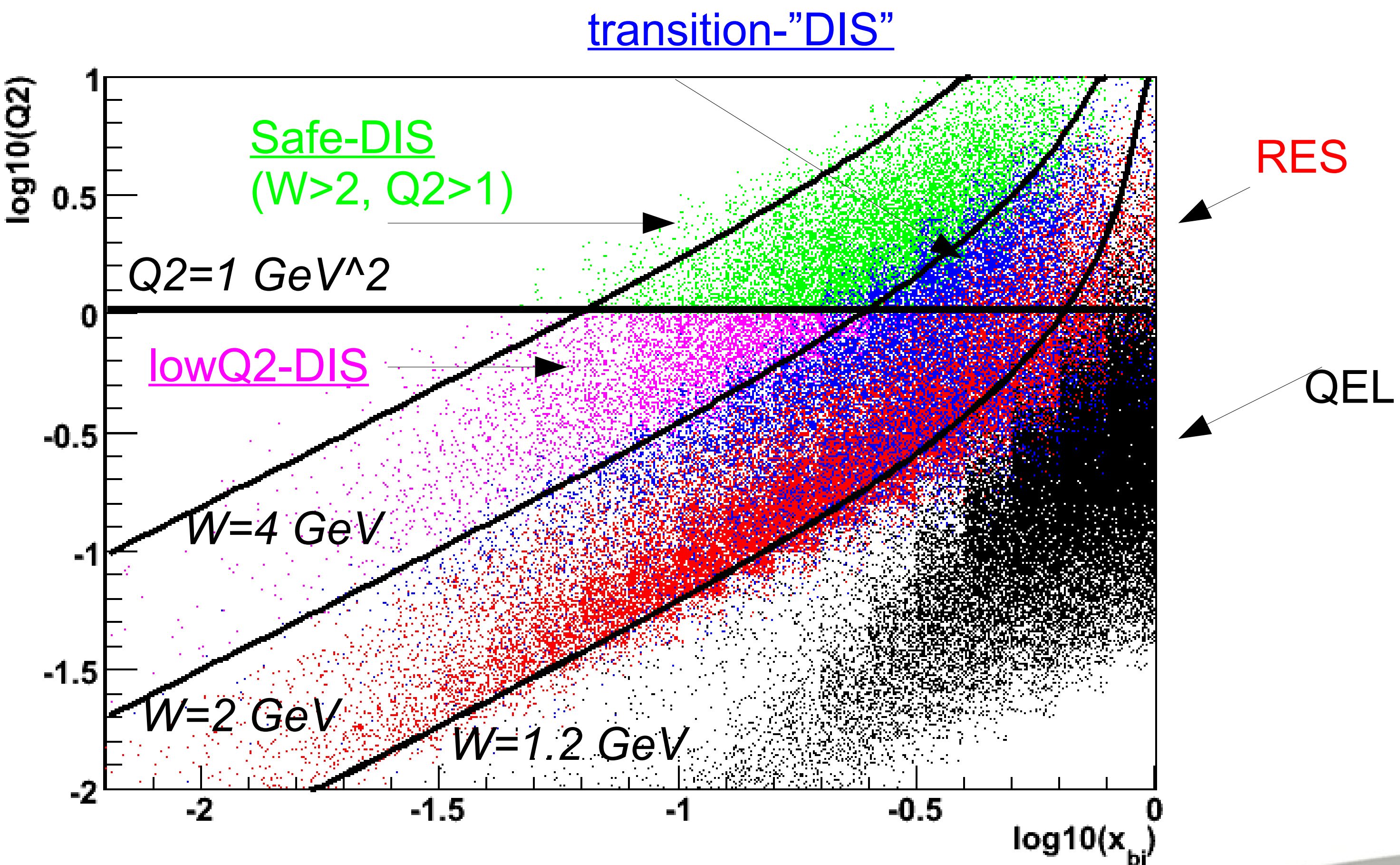
Resonance production (RES)

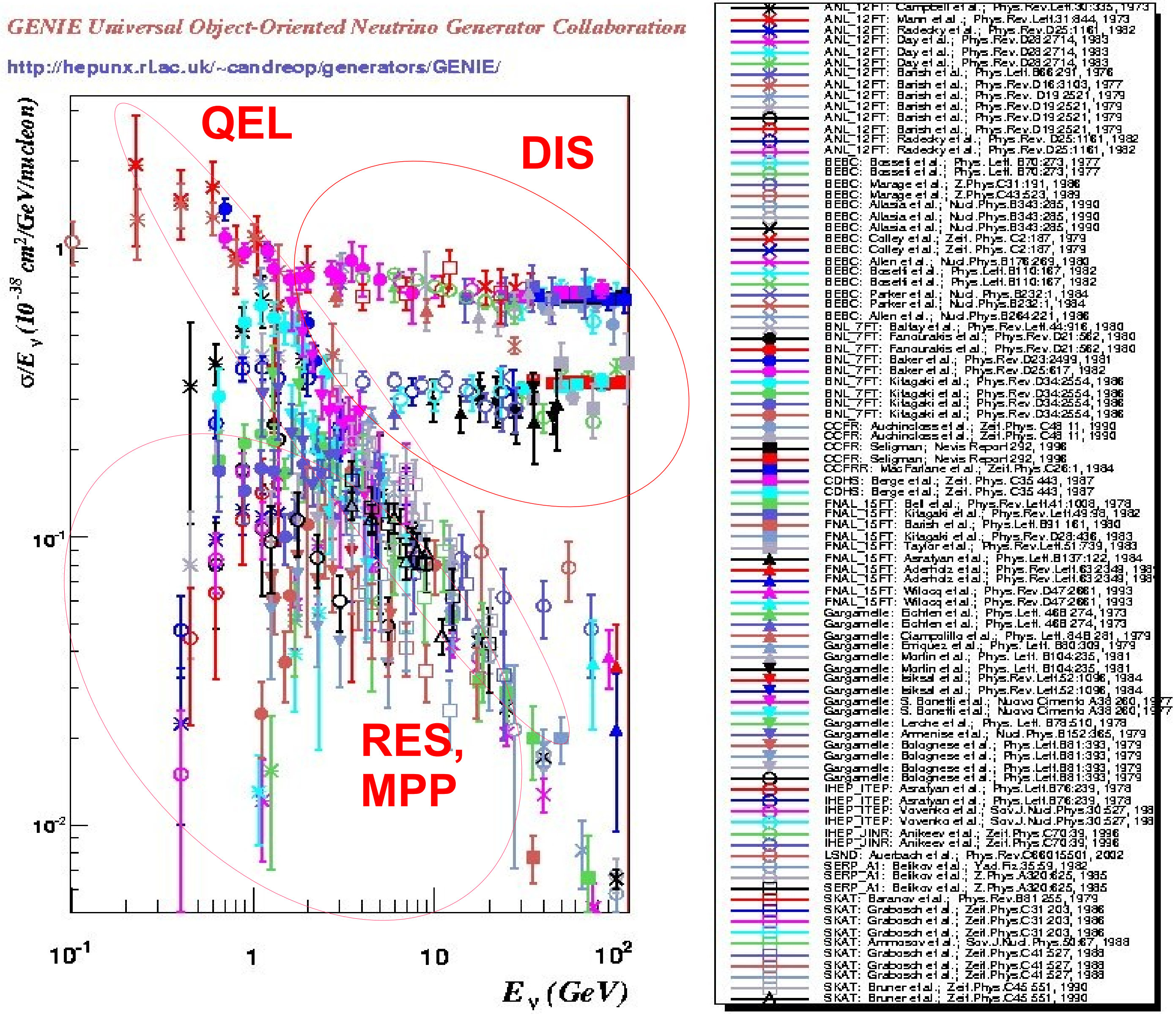
Deep-Inelastic Scattering (DIS)

Costas Andreopoulos, *Rutherford Appleton Lab.*

Kinematical coverage

example shown for the JPARC neutrino beam @ nd280 site





Historical World Data

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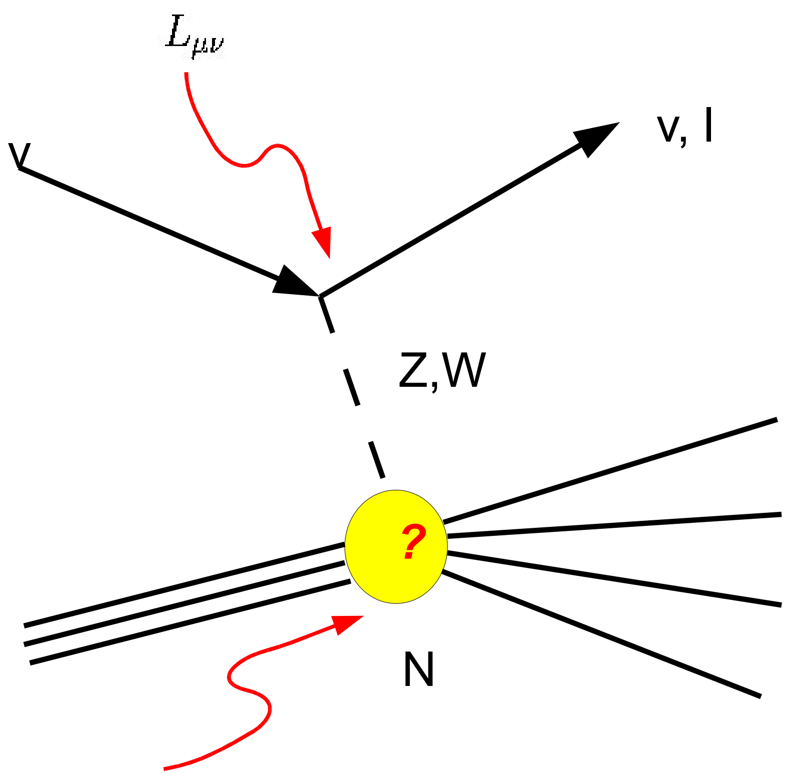
Neutrino scattering off free nucleons



process dynamics described by the invariant amplitude

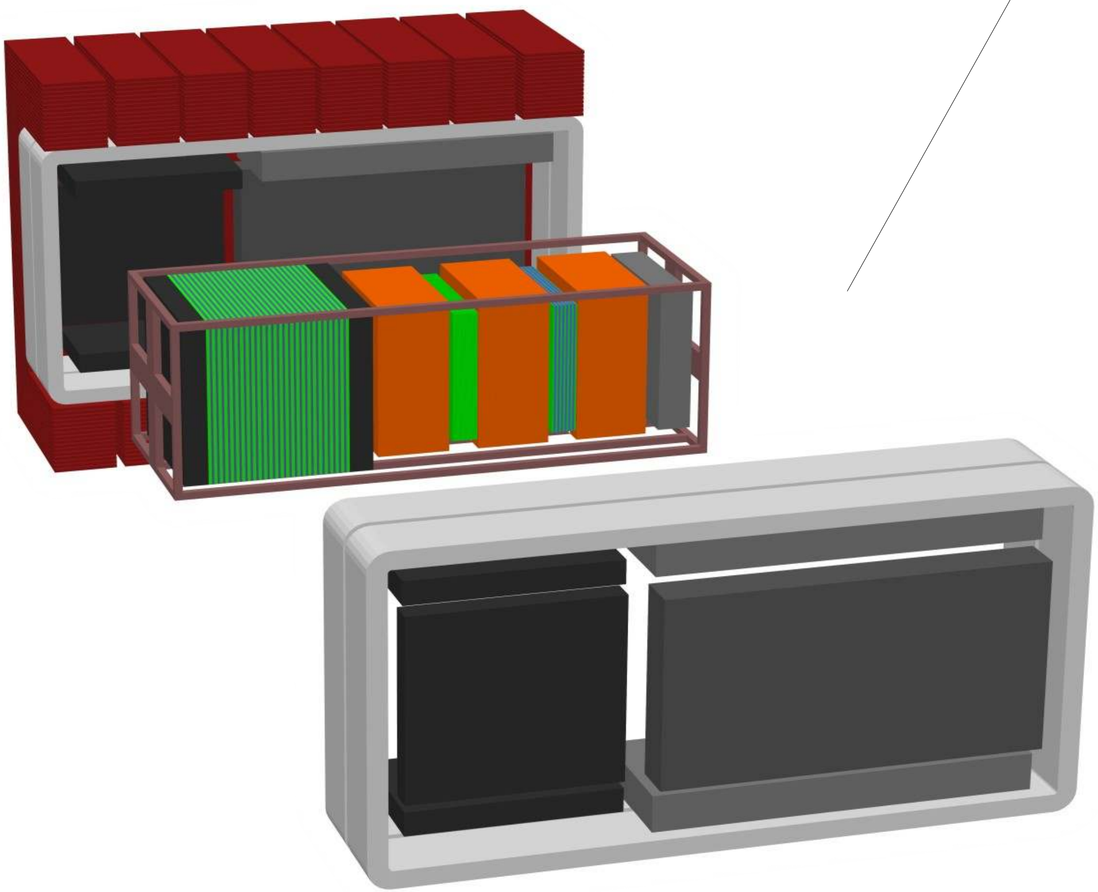
$$|M|^2 = L_{\mu\nu} W^{\mu\nu}$$

$$W_{\mu\nu} = W_1 \delta_{\mu\nu} + W_2 p_\mu p_\nu + W_3 \epsilon_{\mu\nu\alpha\beta} p^\alpha p^\beta + W_4 q_\mu q_\nu + W_5 (p_\mu q_\nu + p_\nu q_\mu) + W_6 (p_\mu q_\nu - p_\nu q_\mu)$$

Complicated!!

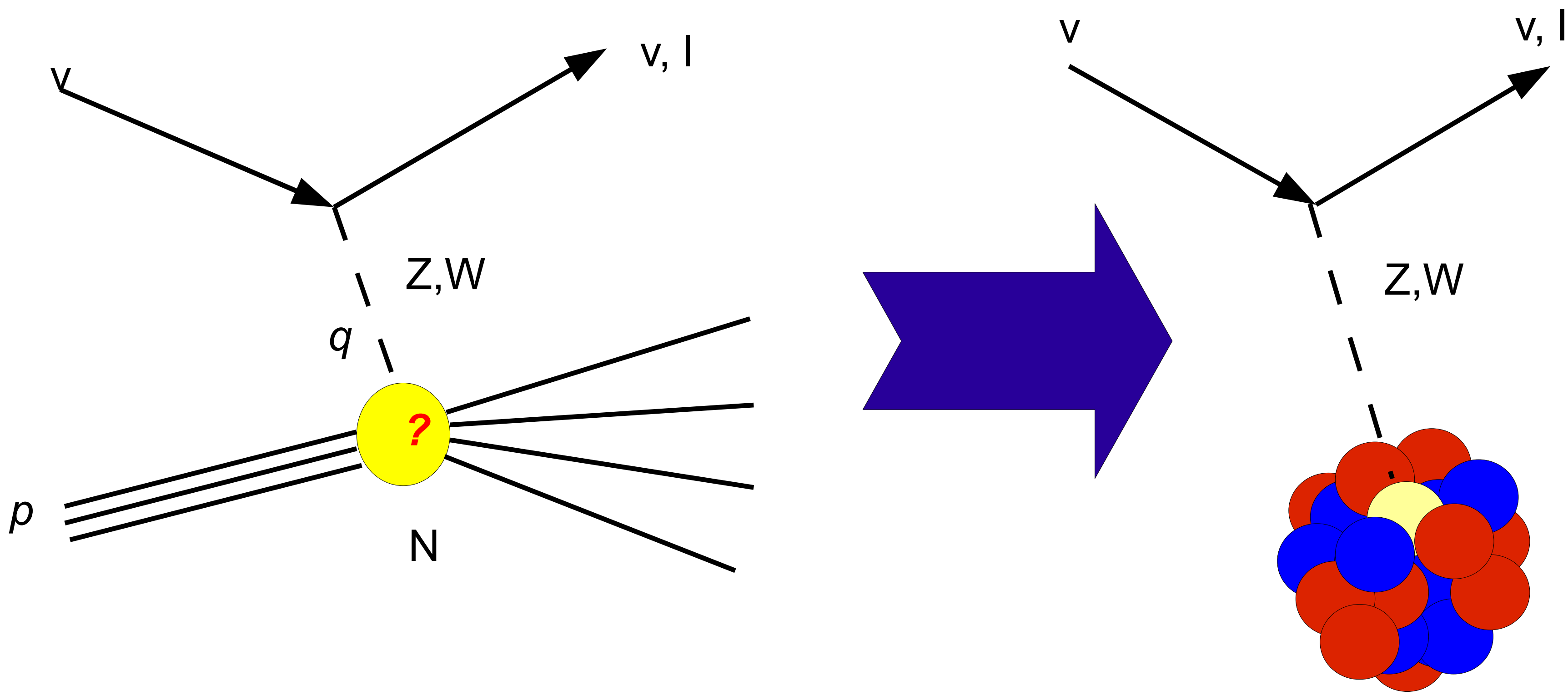
We usually have to deal with nuclear targets

Example: nuclear targets in the nd280 geometry



H2,
B10, B11,
C12, C13,
N14, N15,
O16, O17, O18,
Na23,
Al27,
Si28, Si29, Si30,
Cl35, Cl37,
Ar36, Ar38, Ar40,
Fe54, Fe56, Fe57, Fe58
Cu63, Cu65,
Zn64, Zn66, Zn67, Zn68, Zn70,
Co69,
Pb204, Pb206, Pb207, Pb208

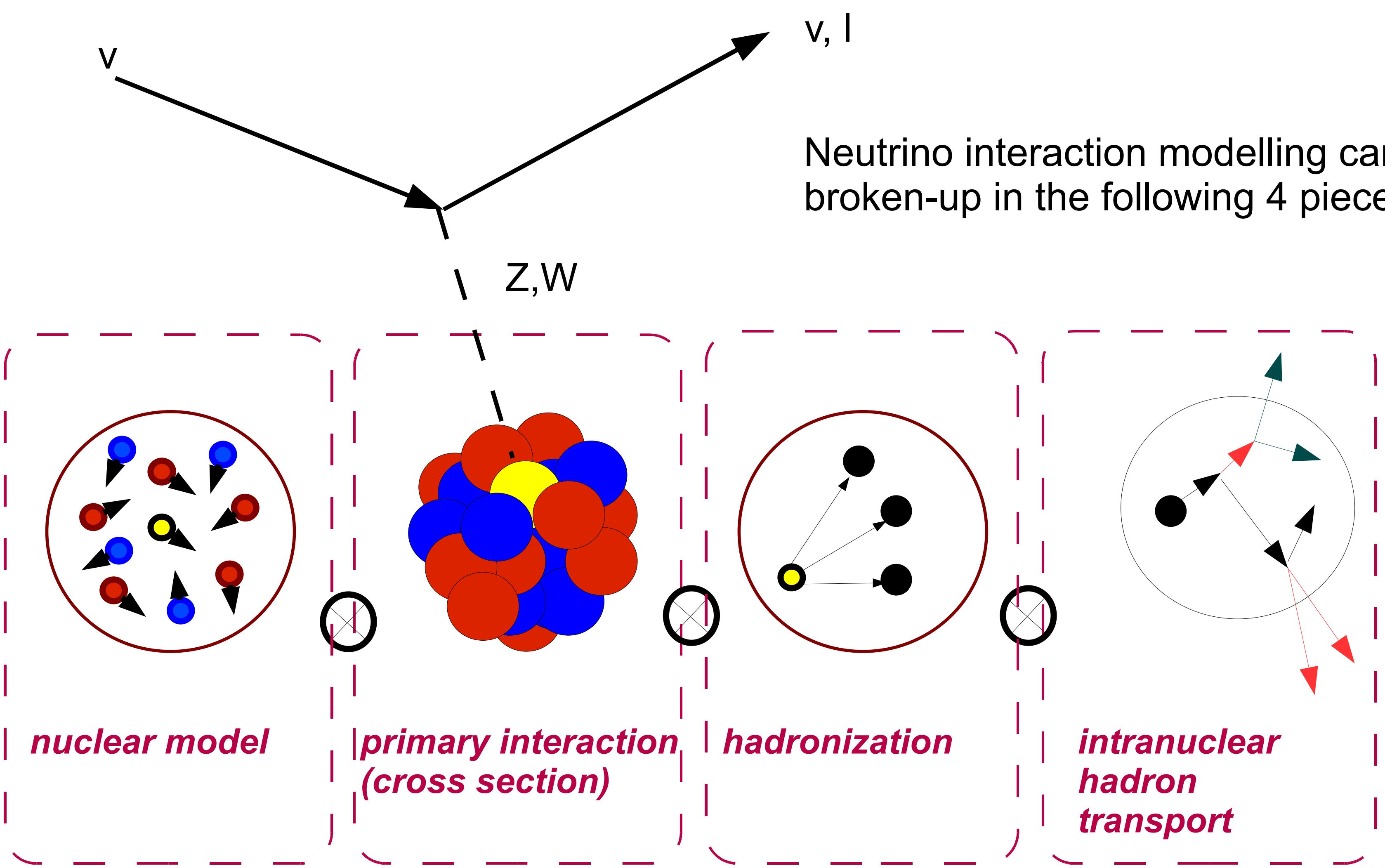
Free-nucleon cross section → Nuclear cross sections



Welcome to the `nuclear physics hell' !

Neutrino Interaction Simulation `steps'

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



Note: A simplified picture

Calculating Neutrino Interaction Cross Sections within GENIE
>>>

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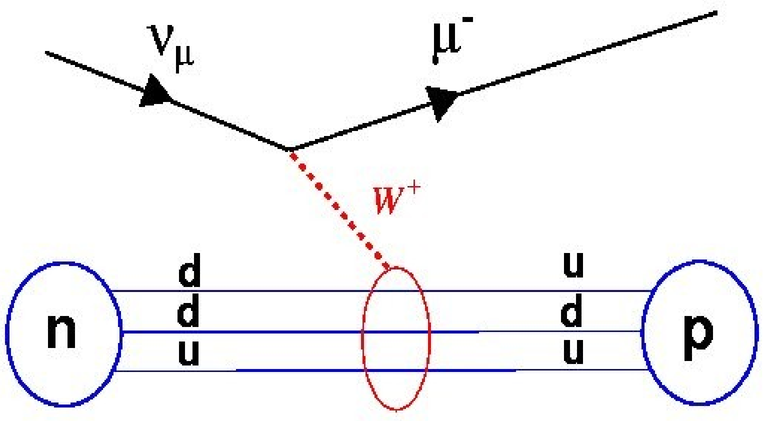
QEL scattering

- Critical for current accelerator LBL oscillation experiments
- *> ~50% of total CC cross section at ~1 GeV*



Full kinematical reconstruction just by looking at the leptonic system:

$$E_\nu = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu cos\theta_\mu}$$

$$Q^2 = -2E_\nu(E_\mu - p_\mu cos\theta_\mu) + m_\mu^2$$

QEL cross section

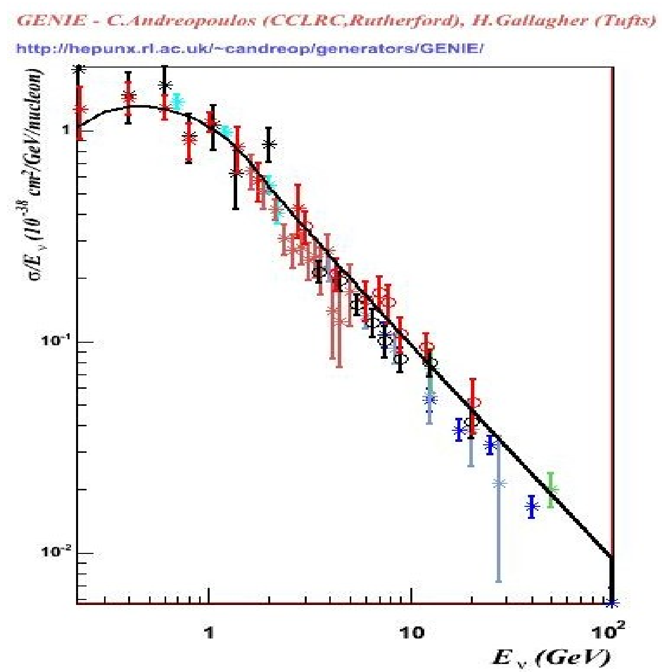
$$\frac{d\sigma^{QES}}{dQ^2} = \frac{G_F^2 \cos^2\theta_C M^2 \kappa^2}{2\pi E_\nu^2}\left[A(q^2) + \left(\frac{s-u}{4M^2}\right)B(q^2) + \left(\frac{s-u}{4M^2}\right)^2 C(q^2)\right]$$

A,B,C = f(F_A, F_{v1}, F_{v2})

vector form factors:
determined from e-N via CVC

dipole axial form factor:

$$F_A = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$



Elastic nucleon form factors

vN QEL xsec expressed in terms of vector & axial form factors

$$F_V^1(Q^2) = \frac{G_E^V(Q^2) - \tau G_M^V(Q^2)}{1-\tau}$$

$$\xi F_V^2(Q^2) = \frac{G_M^V(Q^2) - G_E^V(Q^2)}{1-\tau}$$

CVC allows us to determine Gve, Gvm from the elastic form factors

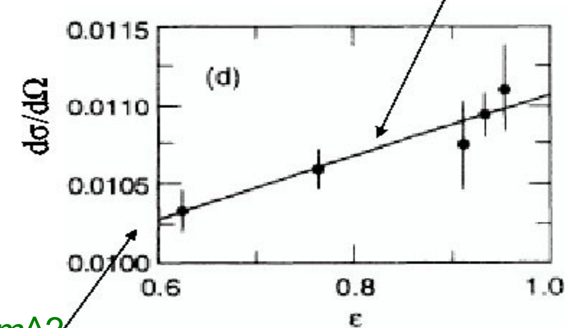
$$G_E^V(Q^2) = G_{ep}(Q^2) - G_{en}(Q^2),$$
$$G_M^V(Q^2) = G_{mp}(Q^2) - G_{mn}(Q^2)$$

Elastic form factor measurements:

- ***Rosenbluth separation:***

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 E_e' \cos^2\frac{\theta_e}{2}}{4E_e^3 \sin^4\frac{\theta_e}{2}}\left[G_e^2 + \frac{\tau}{\varepsilon}G_m^2\right]\left(\frac{1}{1+\tau}\right)$$

slope measures Ge^2



*offset measures t * Gm^2*

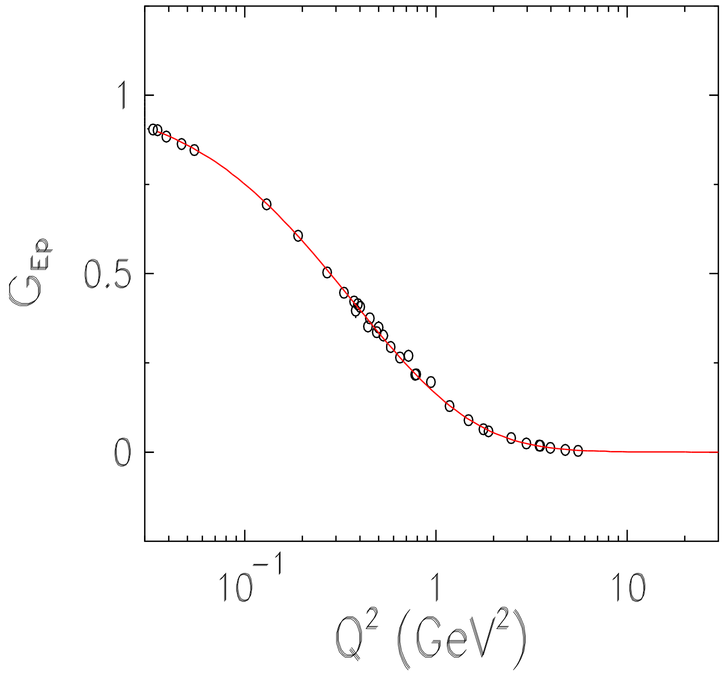
- ***Polarization measurements:***

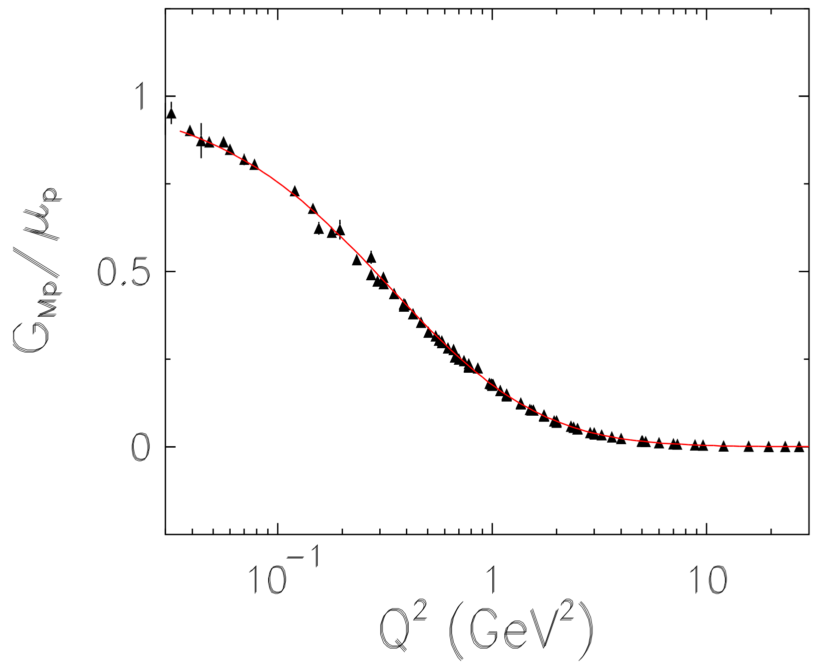
$$\frac{G_e}{G_m} = -\frac{P_t}{P_l}\frac{(E_e + E_{e'})}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

- The 2 methods do not agree
- Polarization measurements seen as more reliable

Beyond the dipole form factors

<u>BBA</u> fit based mostly on polarisation data (eg Budd / Bodek / Arrington. See hep-ex/0308005)



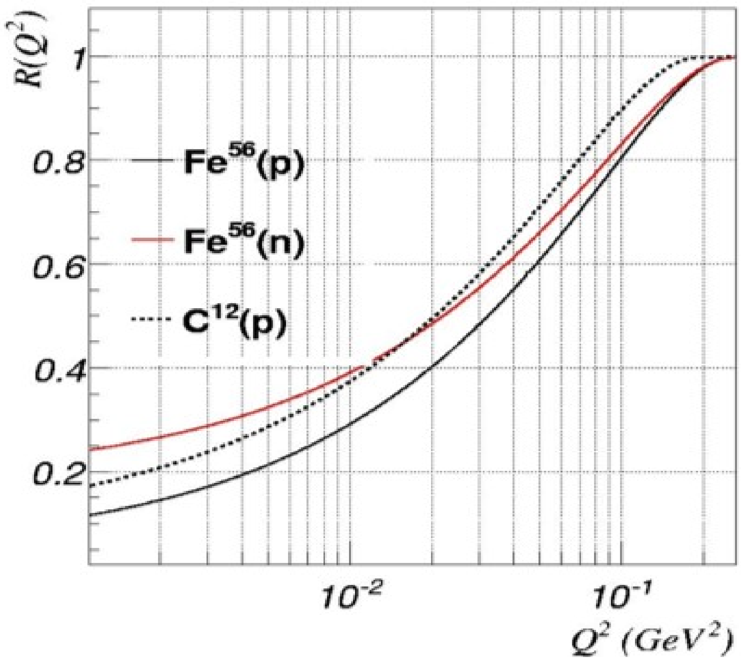


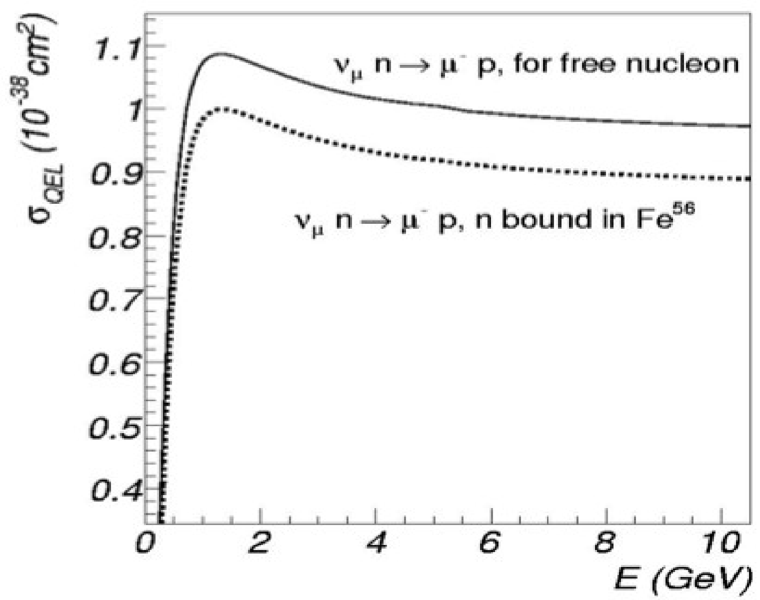
[R.Bradford et al, NuINT05]

QEL cross section for nuclear targets

Off-shell kinematics

A suppression factor R(Q^2), derived from an analytical calculation of the Pauli blocking effect, is included.

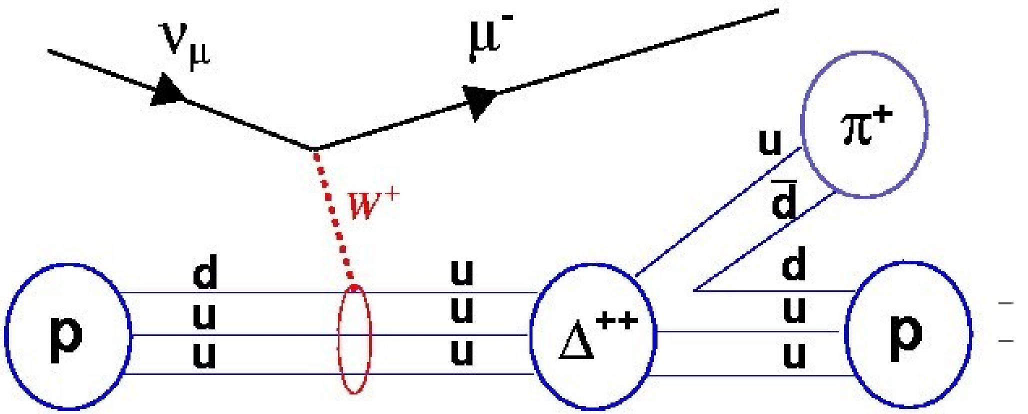




Neutrino-production of resonances

$$\nu + N \rightarrow l + Resonance$$

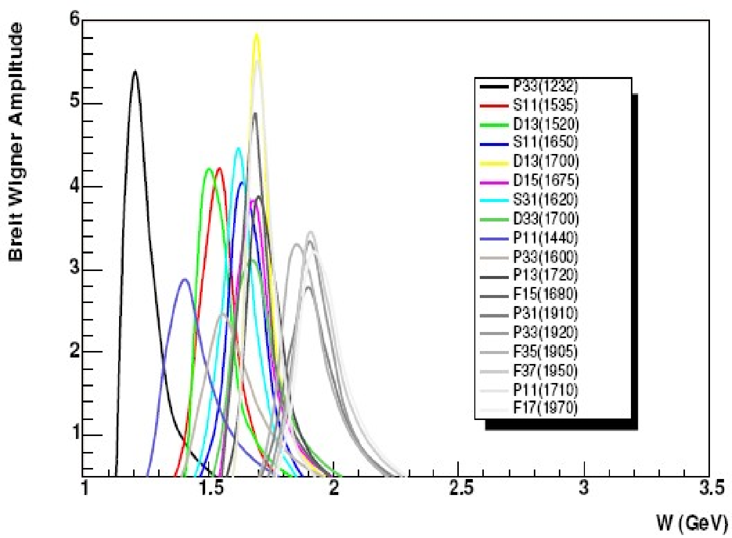
↳ *N + pion*
(usually)



Very important channel(s)
~30% of the total CC xsec around ~ 1 GeV

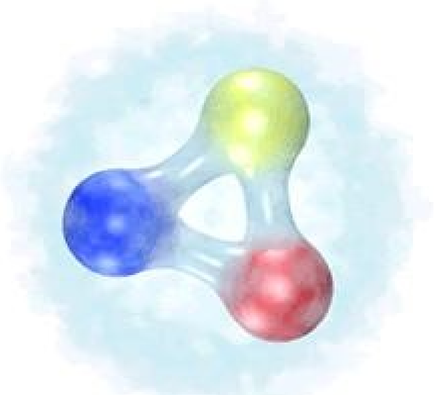
Very complicated!

Resonance Mass (MeV)	L(2I,2J)	PDG status	Breit – Wigner Width (MeV)	FKR n	BR $N^* \rightarrow N\pi$
$\Delta(1232)$	P_{33}	****	120	0	100%
N(1535)	S_{11}	****	150	2	45%
N(1520)	D_{13}	****	120	1	55%
N(1650)	S_{11}	****	150	1	73%
N(1700)	D_{13}	***	100	1	10%
N(1675)	D_{15}	****	150	1	45%
$\Delta(1700)$	D_{33}	****	300	1	15%
N(1440)	P_{11}	****	350	1	65%
$\Delta(1600)$	P_{33}	***	350	2	18%
N(1720)	P_{13}	****	150	2	15%
N(1680)	P_{15}	****	130	1	65%
$\Delta(1910)$	P_{31}	****	250	2	23%
$\Delta(1920)$	P_{33}	***	200	2	13%
$\Delta(1905)$	F_{35}	****	350	2	10%
$\Delta(1950)$	F37	****	300	2	10%
N(1710)	P_{11}	***	100	2	38%



Neutrino-production of resonances

The most widely used model for resonance neutrinoproduction
(*D.Rein, L.M Sehgal*, **Ann.Phys.133, 79 (1981)**)
uses the FKR dynamical model
(*R.P.Feynman, M.Kislinger, F.Ravndall*, **Phys.Rev.D 3, 2706 (1971)**)
to describe excited states of a 3 quark bound system.



kinematical factors

$$\frac{d^2\sigma}{dW\,dq^2} \propto u^2\sigma_L(q^2,W) + v^2\sigma_R(q^2,W) + 2uv\sigma_S(q^2,W)$$

Helicity Cross Sections *(L,R,S)*
They depend on the details of the FKR model
(and "maybe" a snapshot of the PDG resonance tables as they were in early '70's ?)

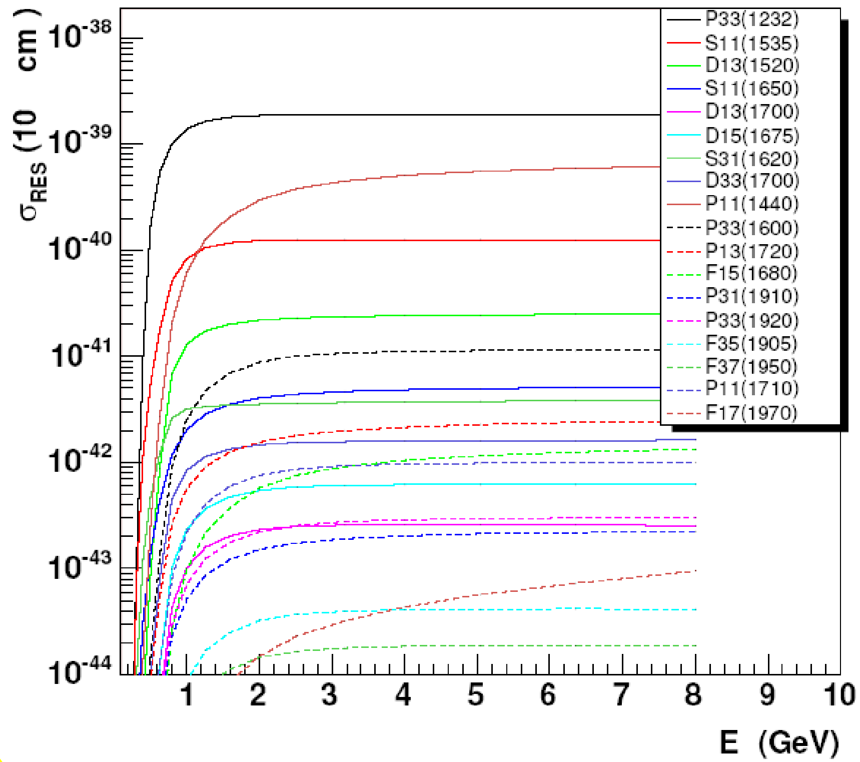
Axial & Vector transition form factors:
assuming dipole form Q^2 dependence

$$G^{V,A}(Q^2) = \left(1+\frac{Q^2}{4M^2}\right)^{1/2-n}\left(1+\frac{Q^2}{M_{V,A}^2}\right)^{-2}$$

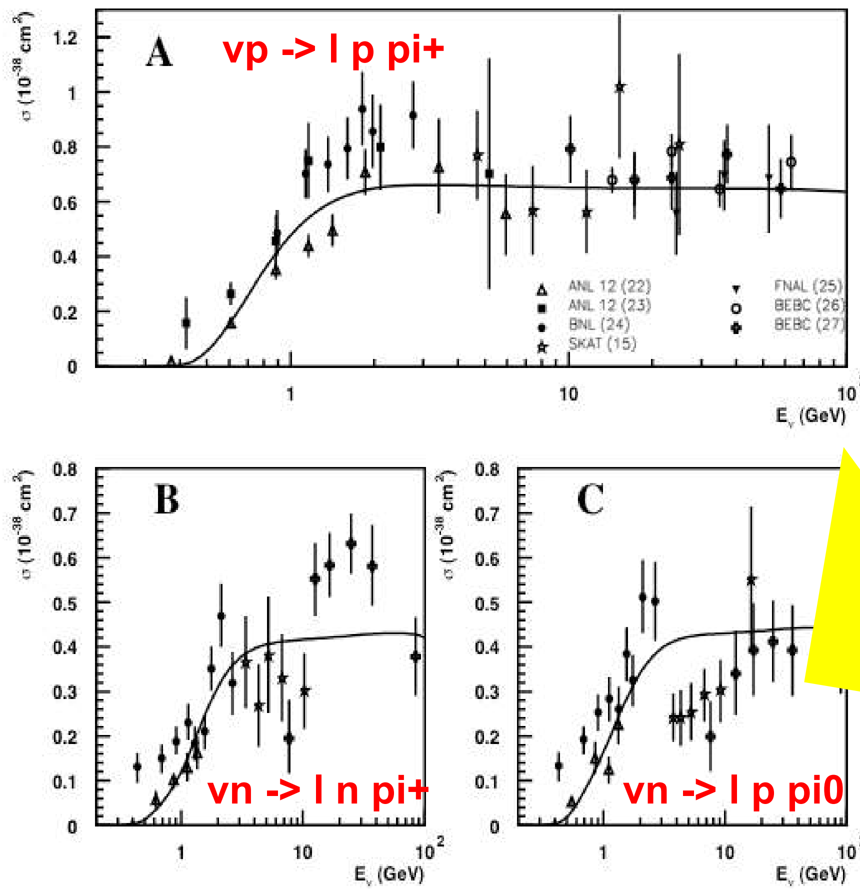
M_V=0.84 GeV/c^2, M_A

Neutrino-production of resonances

Resonance excitation cross sections
(as a function of energy / for muon neutrinos)



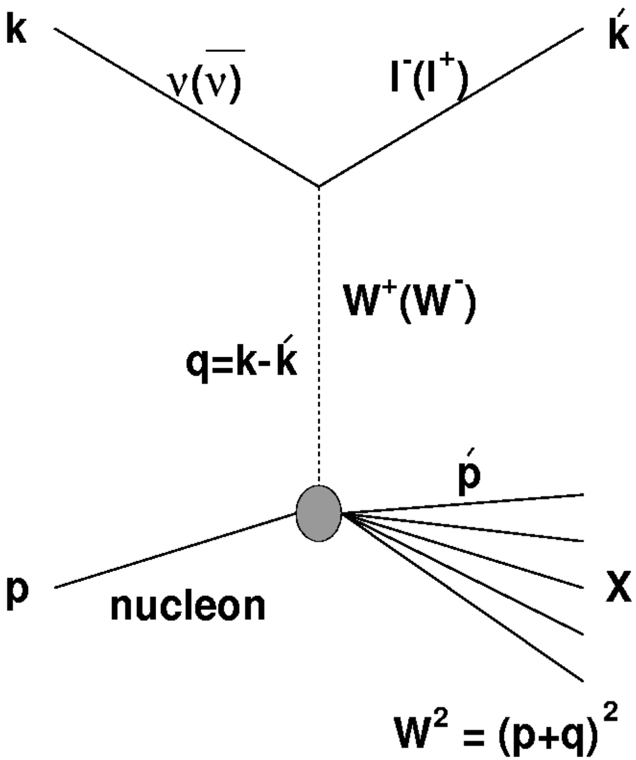
Single pion production cross sections

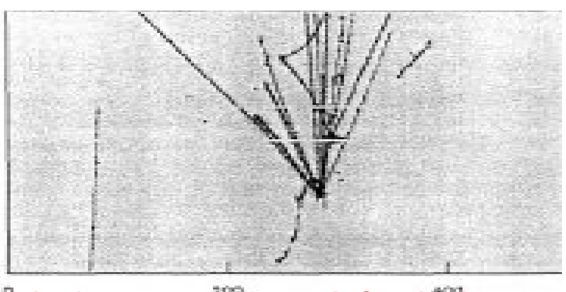


Include isospin amplitudes and 1pi BR to weight the contribution of each resonance to exclusive single pion reactions

Can add coherently
For simplicity, many calculations add incoherently

Deep Inelastic Scattering





LAr images, courtesy A.Curioni

Differential cross section in terms of 5 structure functions:

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M_N E}{\pi(1+Q^2/M_W^2)^2} \sum_{i=1}^{5} A_i\,(x,y,E)\,F_i\,(x,Q^2)$$

where:

$$A_1 = y\left(xy + \frac{m_\mu^2}{2M_N E}\right),$$

$$A_2 = 1 - \left(1 + \frac{M_N x}{2E}\right) y - \frac{m_\mu^2}{4E^2},$$

$$A_3 = \pm y\left[x\left(1 - \frac{y}{2}\right) - \frac{m_\mu^2}{4M_N E}\right],$$

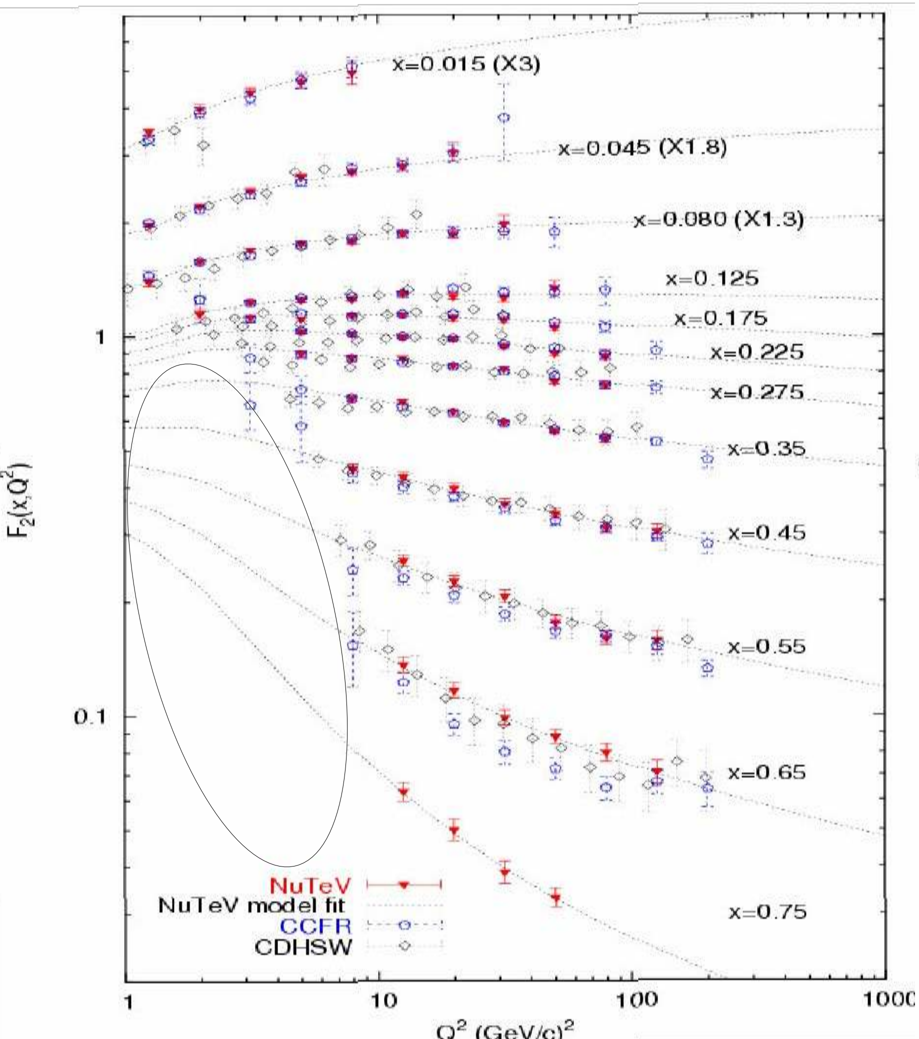
$$A_4 = \frac{m_\mu^2}{2M_N E}\left(y + \frac{m_\mu^2}{2M_N E x}\right),$$

$$A_5 = -\frac{m_\mu^2}{M_N E}.$$

Costas Andreopoulos, *Rutherford Appleton Lab.*

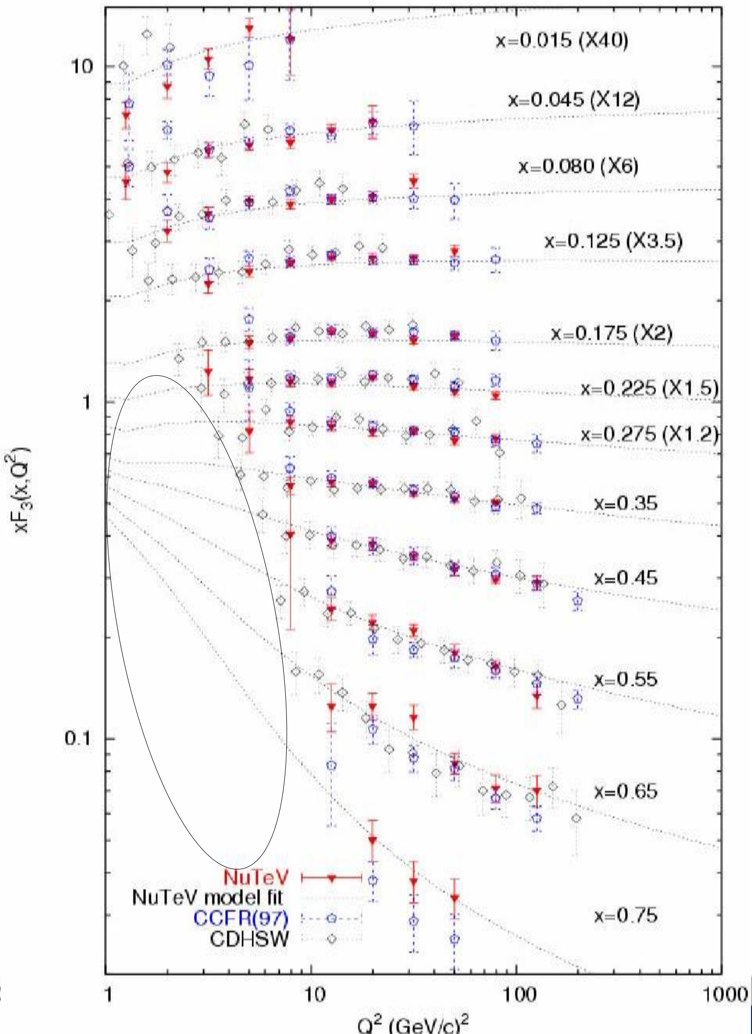
Deep Inelastic Scattering / Structure functions

F2



[M.Tzanov et al]

xF3



[M.Tzanov et al]

Bodek / Yang model

Based on LO cross section models with new scaling variable to account for higher twists and modified PDFs to describe low-Q2 data

$$\xi_w = \frac{2x(Q^2 + {M_f}^2 + B)}{Q^2[1 + \sqrt{1 + (2Mx)^2/Q^2}] + 2Ax}$$

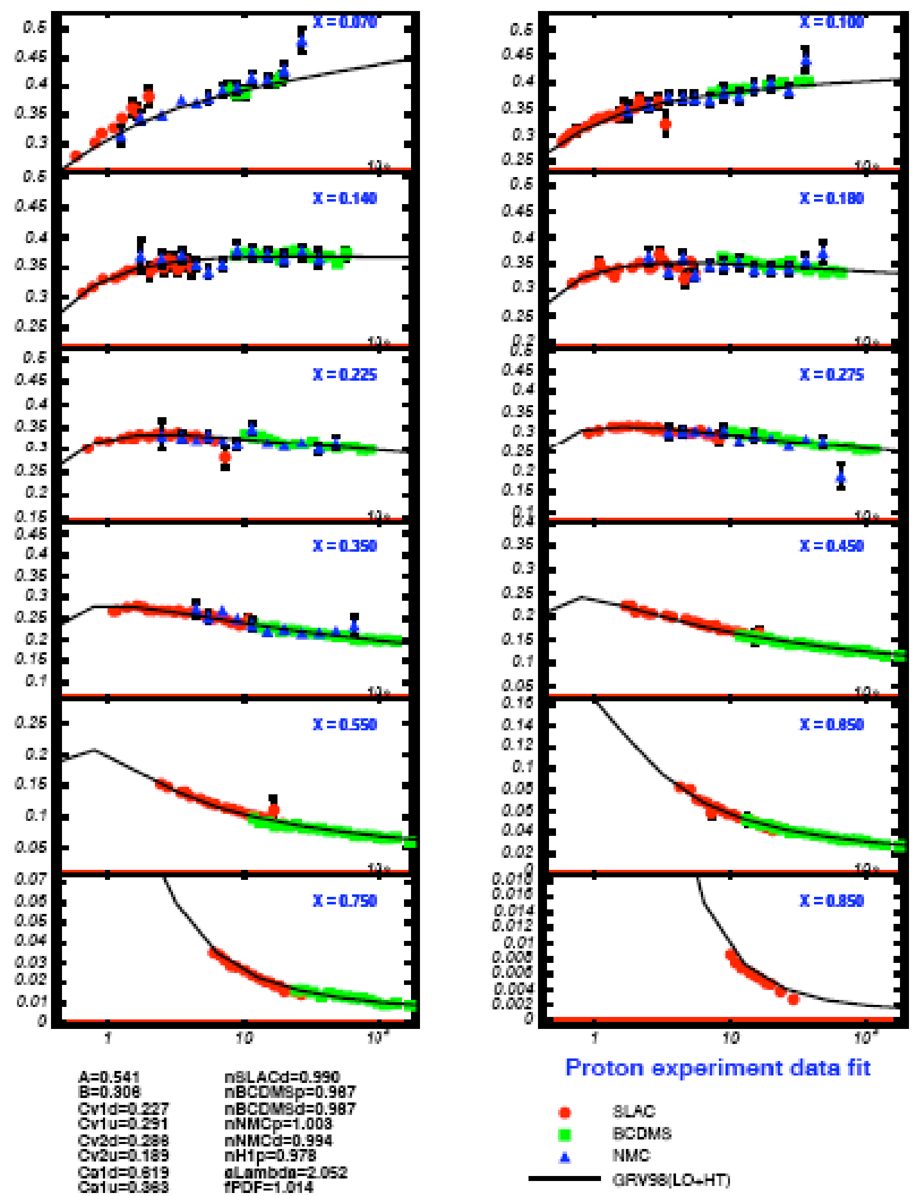
$$K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_s}$$

$$K_{valence}(Q^2) = [1 - G_D^2(Q^2)] \times \left(\frac{Q^2 + C_{v2}}{Q^2 + C_{v1}}\right)$$

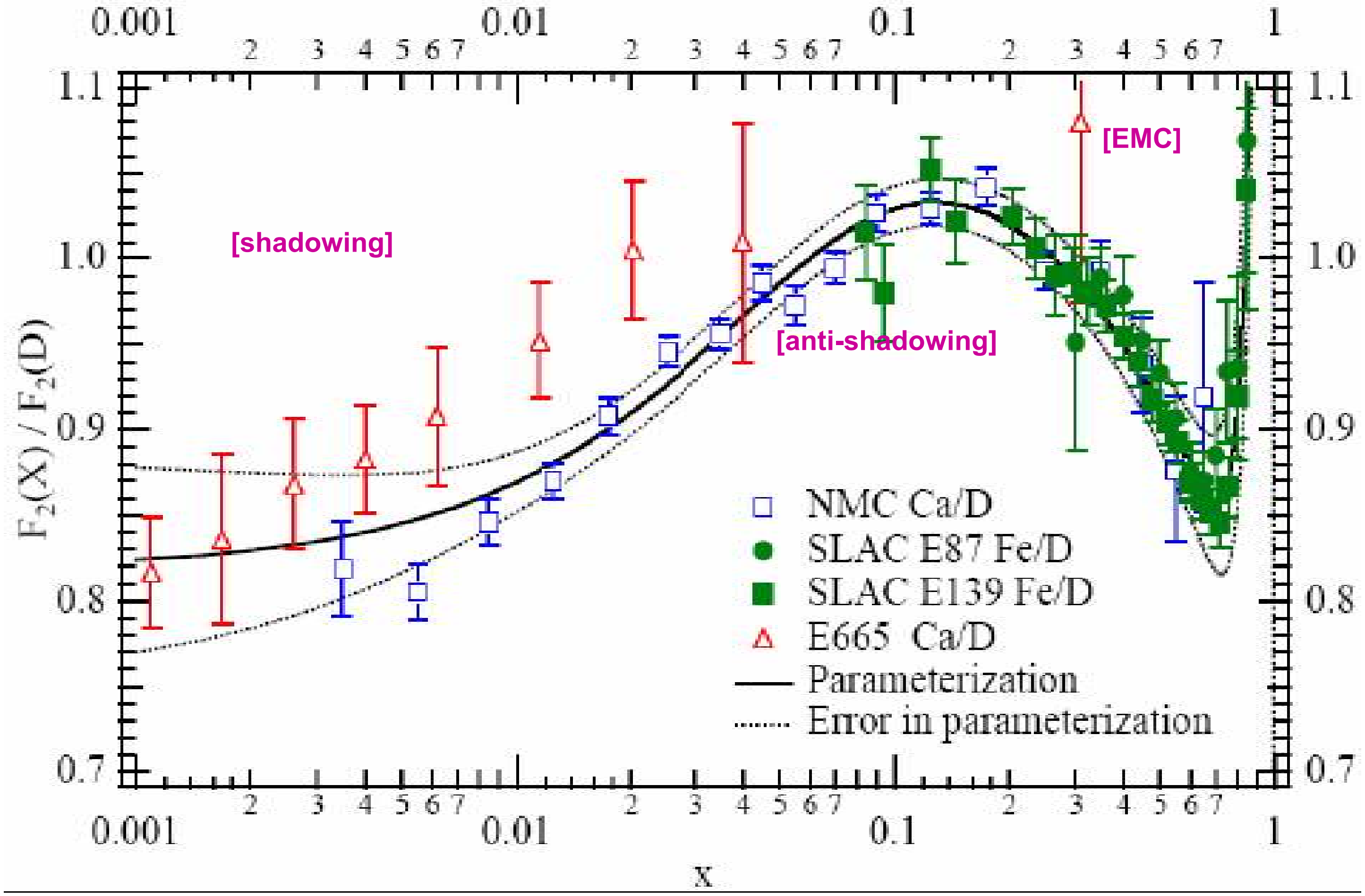
Fits based on GRV98LO and free nucleon charged lepton data

[hep-ph/0411202]

[Bodek & Yang]



Deep Inelastic Scattering / Nuclear corrections



Putting everything together

total inclusive cross section
= sum of contributions from:

- *exclusive channels*
- *DIS*

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

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

Putting everything together

$$\frac{d\sigma}{d\theta dE'} = \frac{d\sigma}{d\theta dE'}^{RES} + \frac{d\sigma}{d\theta dE'}^{DIS}$$

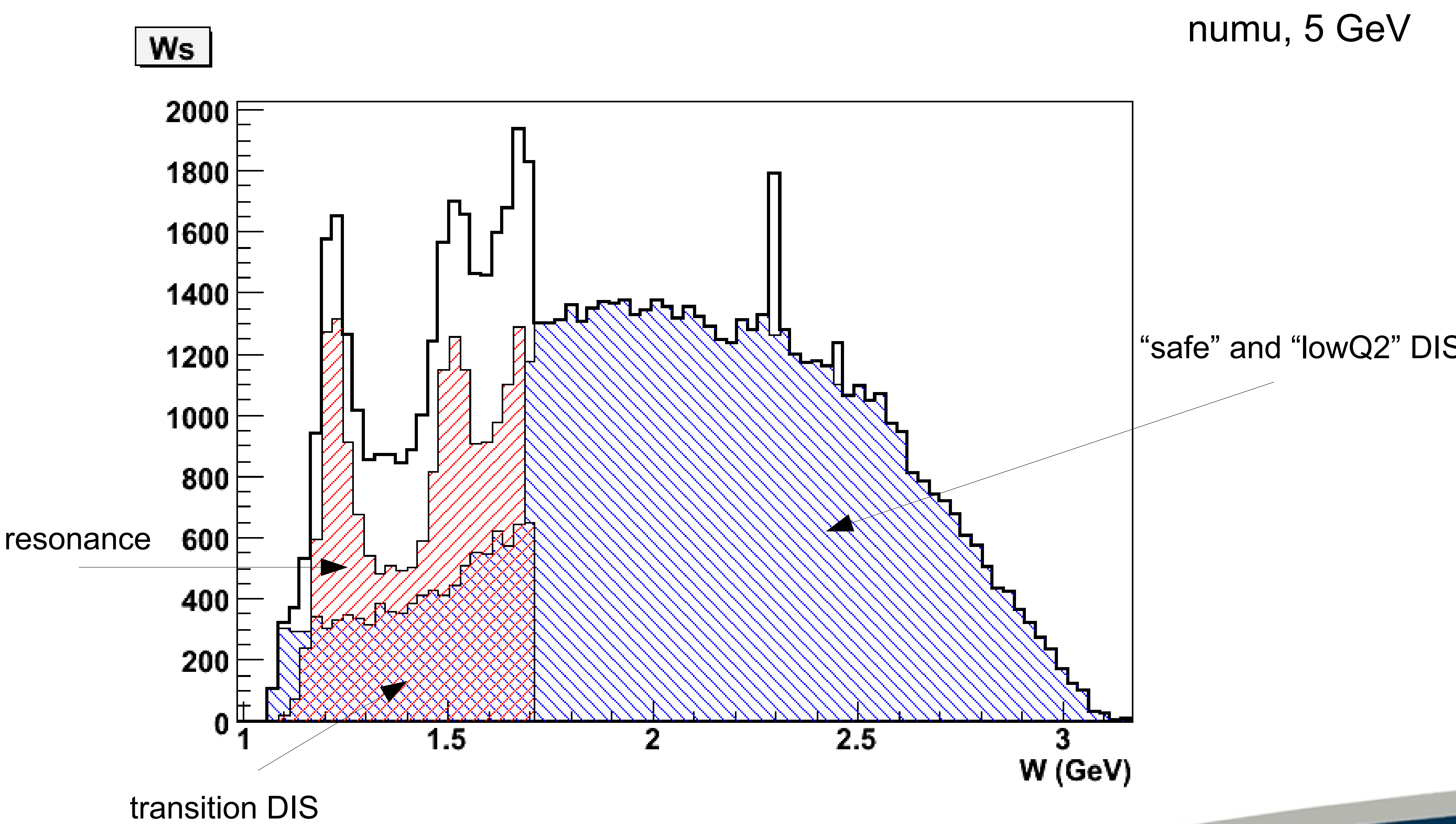
where

$$\frac{d\sigma}{d\theta dE'}^{RES} = \sum_{i=1}^{17} \frac{d\sigma}{d\theta dE'}_i^{RS} \Theta(Wcut - W)$$

where the summation is over the 17 resonances in the Rein-Seghal model.
and

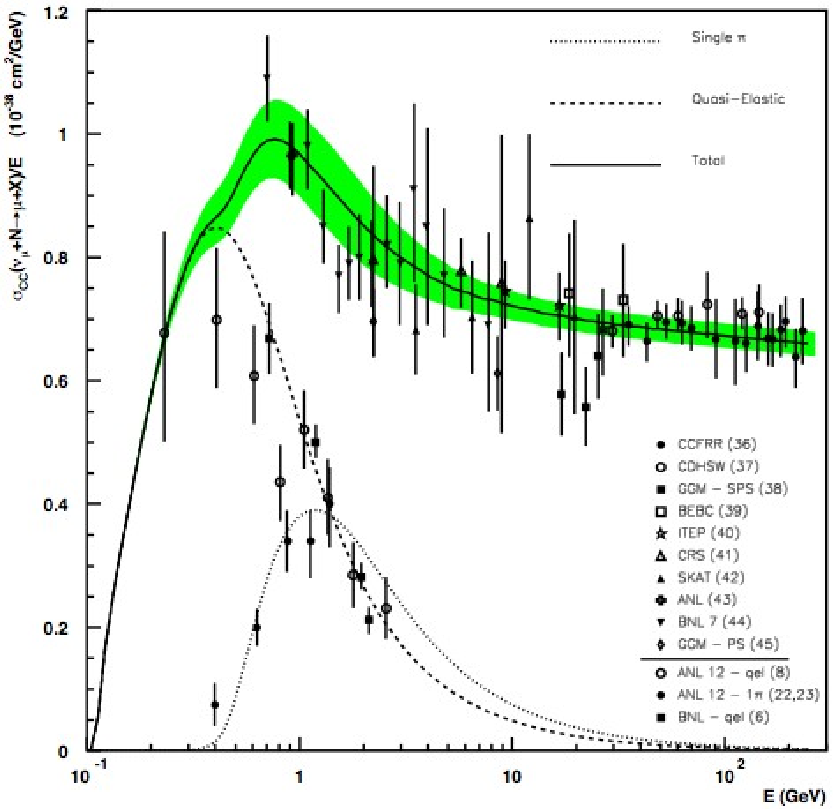
$$\frac{d\sigma}{d\theta dE'}^{DIS} = \frac{d\sigma}{d\theta dE'}^{DIS-BY} \Theta(W - Wcut) + \frac{d\sigma}{d\theta dE'}^{DIS-BY} \Theta(Wcut - W) \sum_k f_k$$

Putting everything together

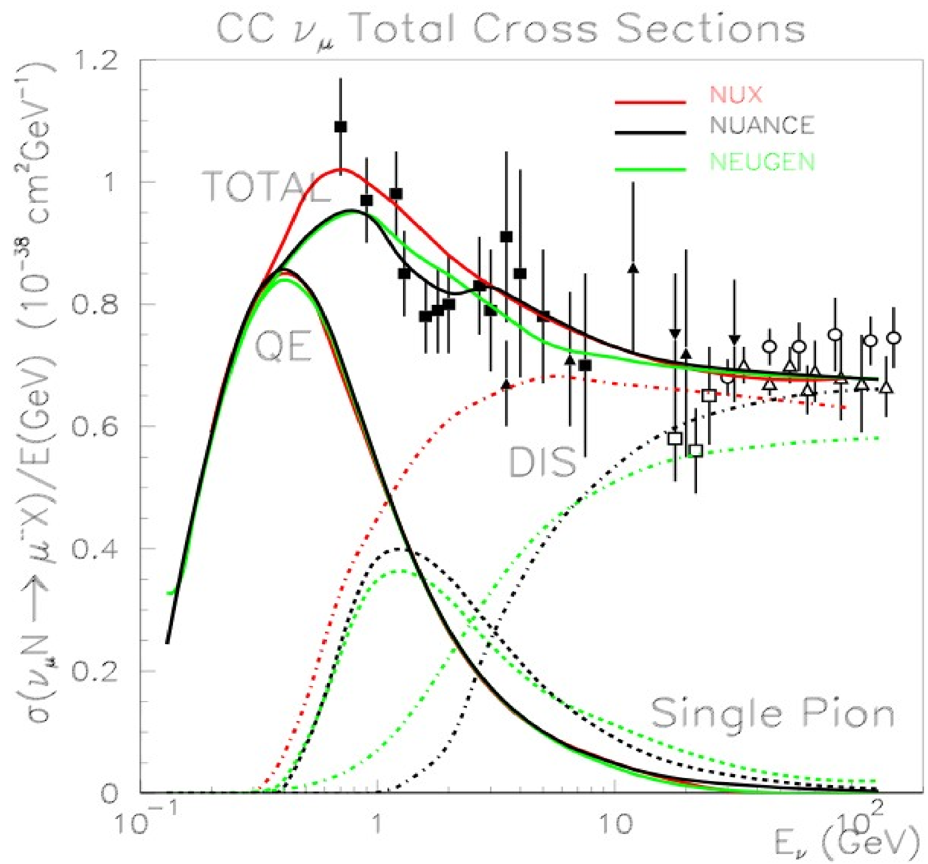


The GENIE cross section model

2.5.1 free nucleon cross section prediction vs B/C data & estimated uncertainty

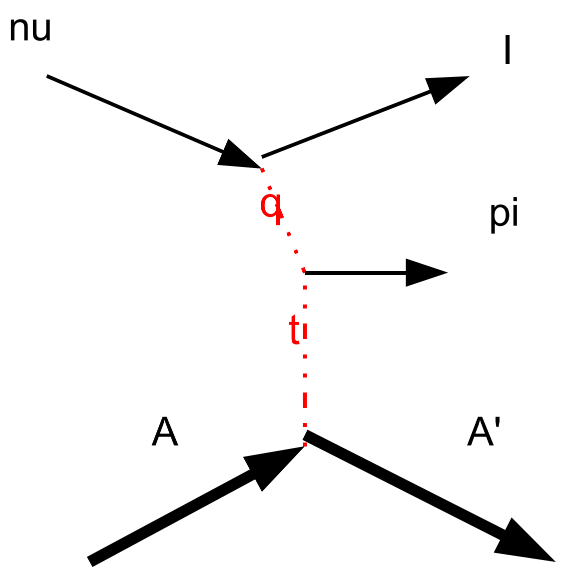


Sam Zeller. circa-2002 / Cross-generator comparisons



- (Incl. & low multiplicity excl.) free-nucleon cross section differences between generators not significant
- Within uncertainty band
- **Understanding the uncertainty on a prediction is more important than any given prediction.**

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.

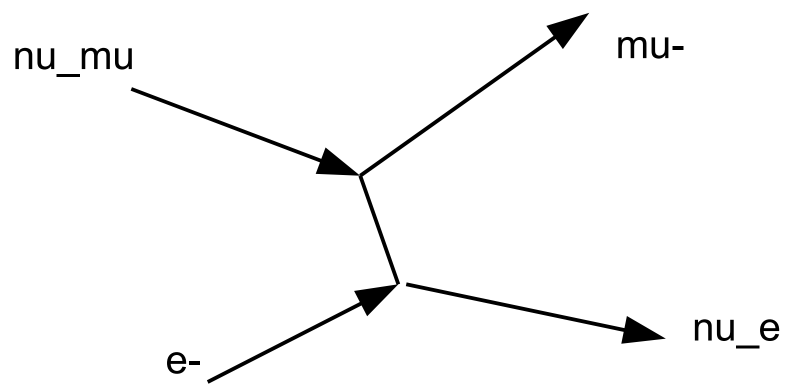
Coherent elastic

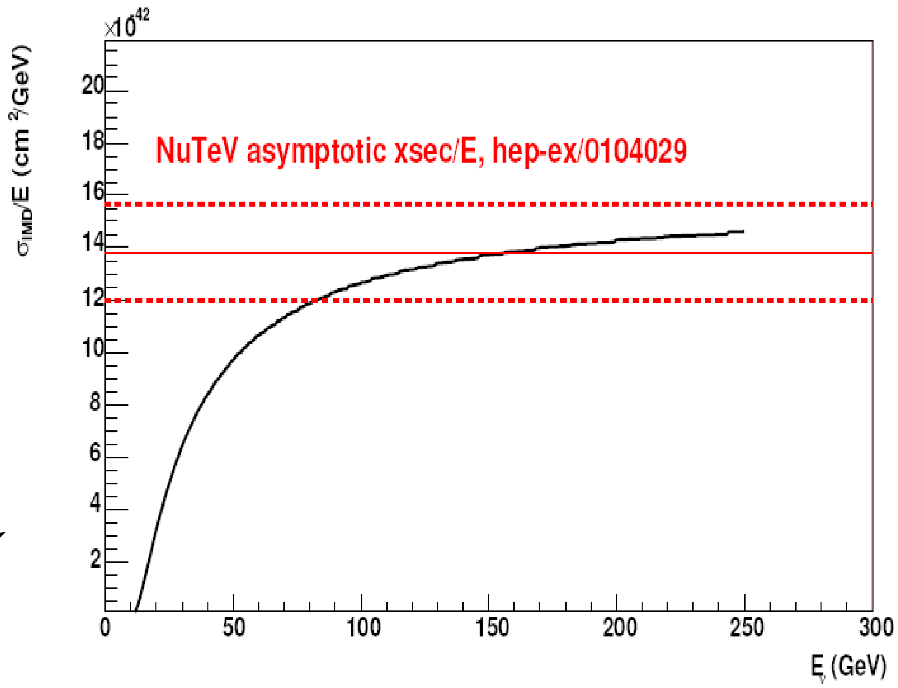
In progress – not implemented yet

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



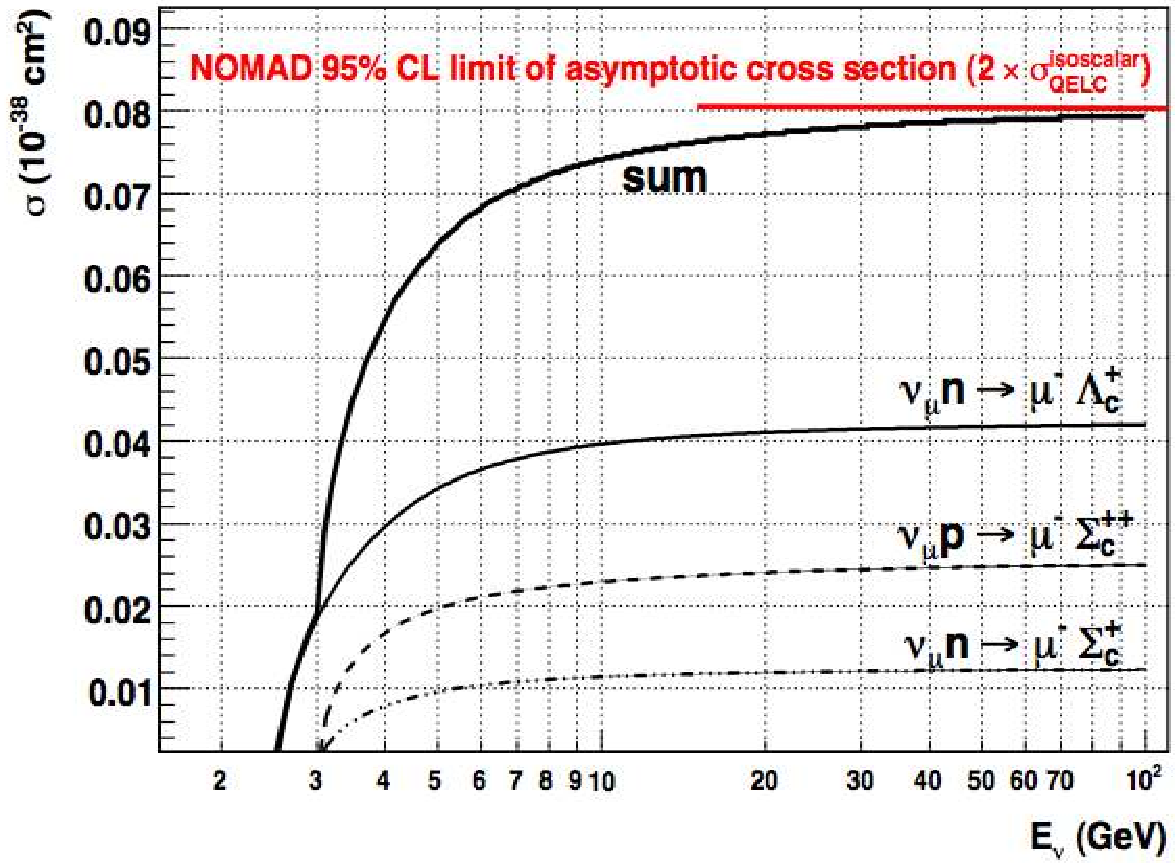


D.Yu.Bardin and V.A.Dokuchaeva, Nucl.Phys.B287:839 (1987), includes all 1-loop radiative corrections

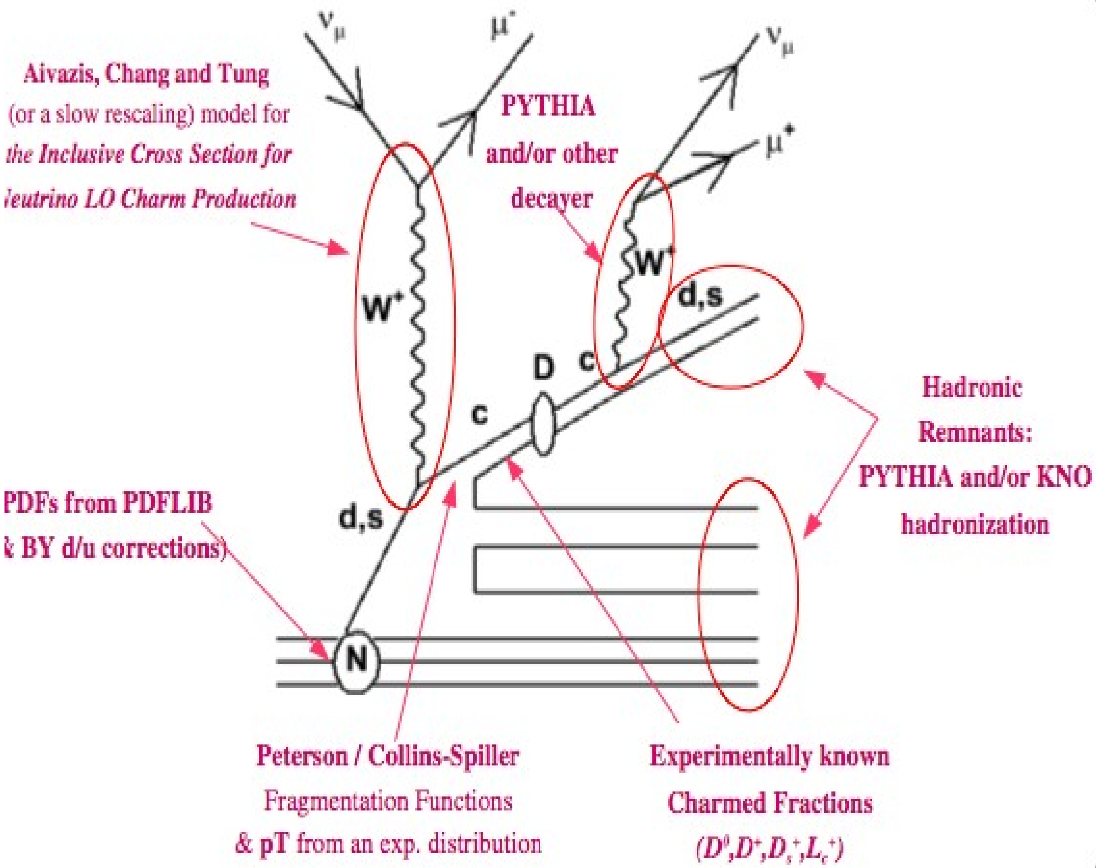
QEL charm production

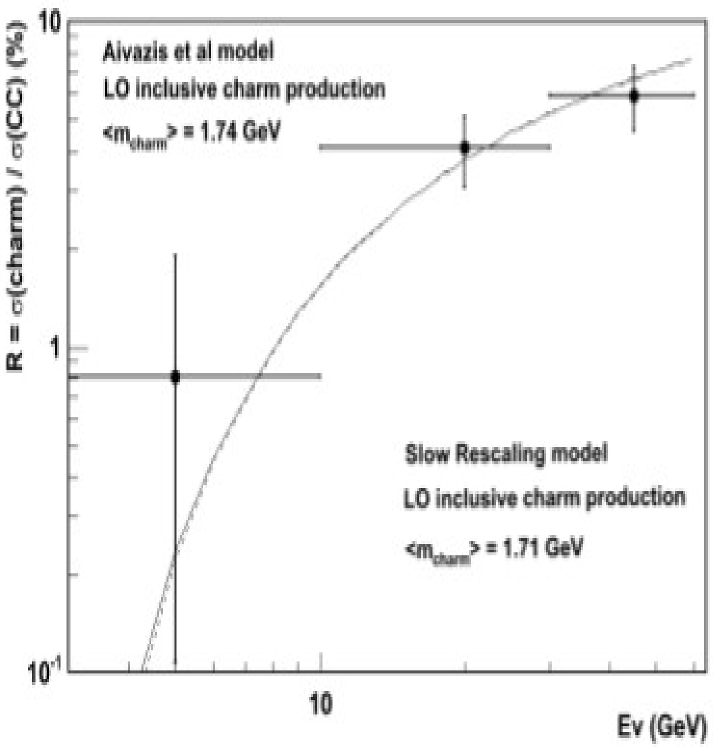
$$\nu + n \rightarrow l^- + \Lambda_c^+(2285)$$
$$\nu + n \rightarrow l^- + \Sigma_c^+(2455)$$
$$\nu + p \rightarrow l^- + \Sigma_c^{++}(2455)$$

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



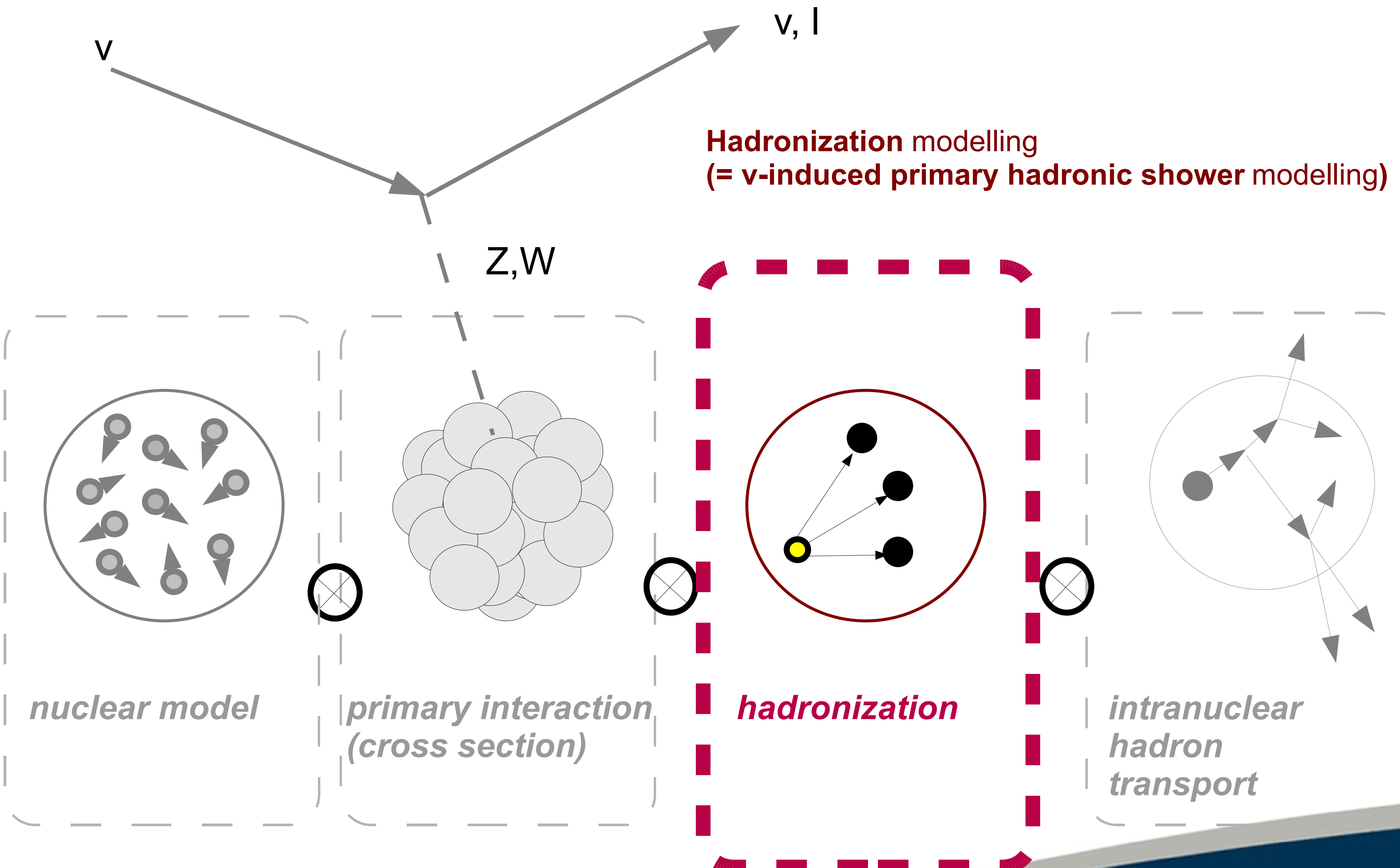
DIS charm production





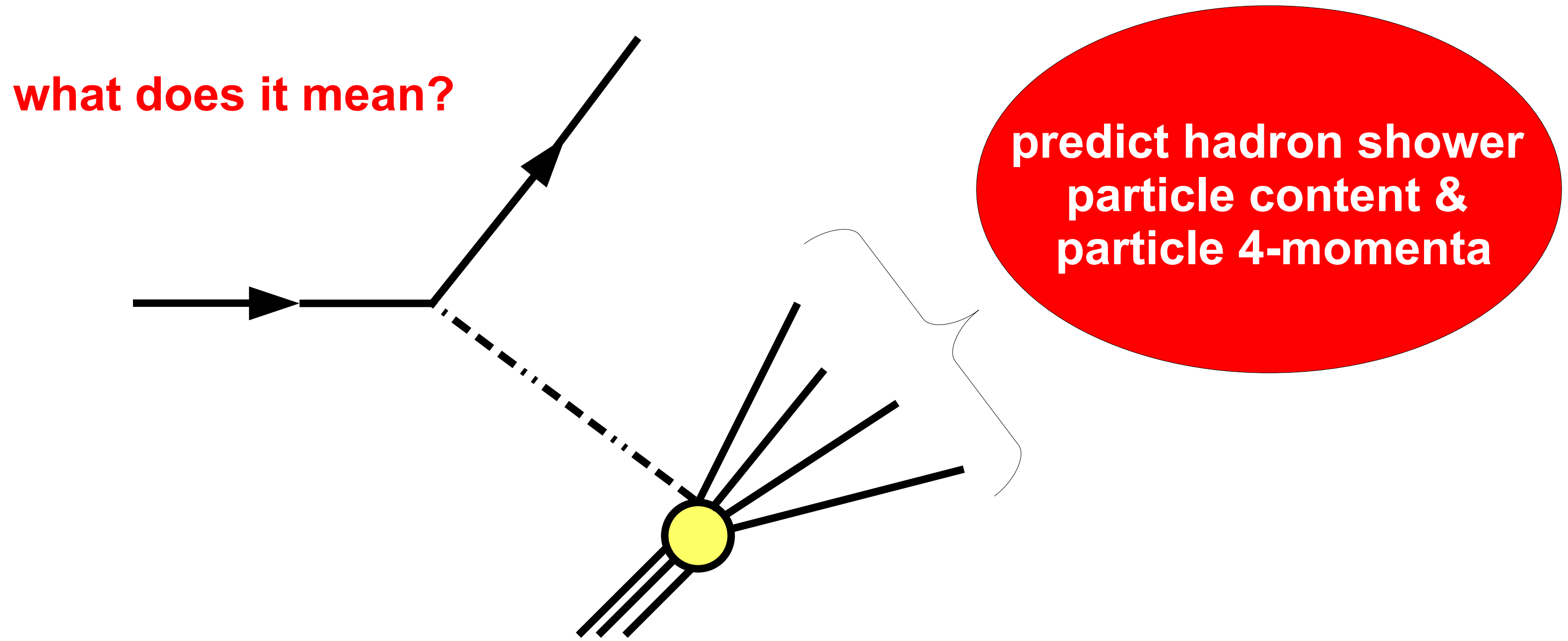
Hadronic simulations within GENIE
>>>

Hadronization modelling



Costas Andreopoulos, *Rutherford Appleton Lab.*

Hadronization modelling

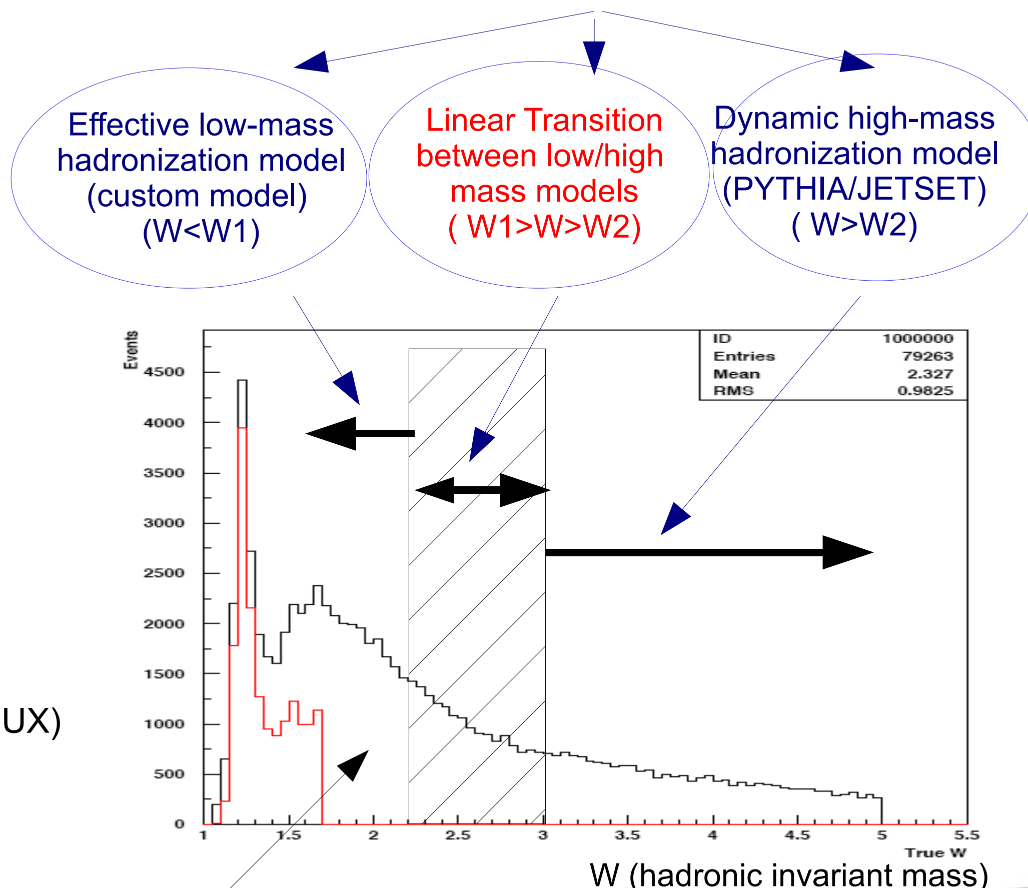


- Standard tools of the trade *(PYTHIA/JETSET, HERWIG)* don't work at the low hadronic invarant masses which are of interest to us

- 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->IX 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



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

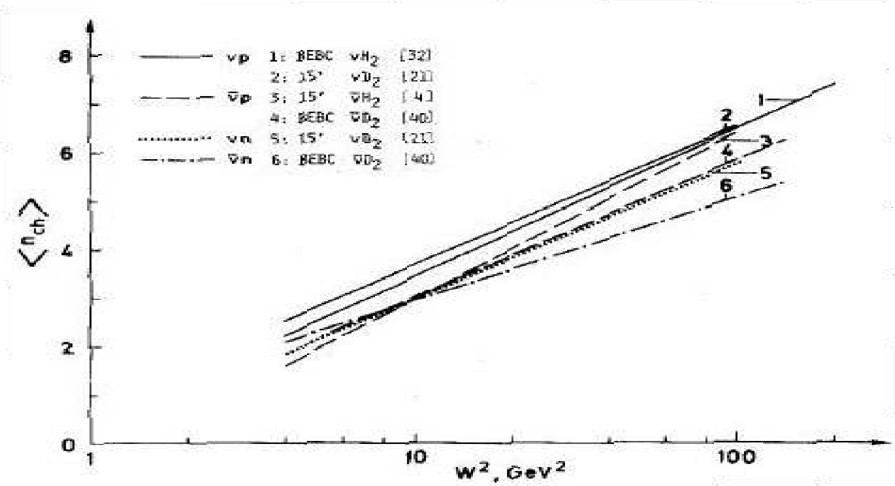
- severe kinematical constraints – limit dynamics
- effective model using KNO scaling and data-driven modelling of average multiplicities, forward/backward asymmetries, pT-dep. Etc...

<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



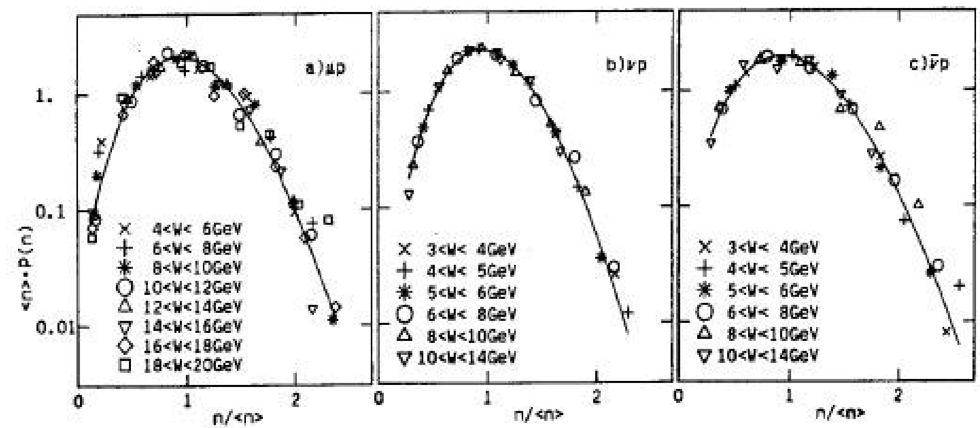
Get average multiplicity
from empirical parameterizations

$$\langle n \rangle = a + b * \ln W^2$$

Generate the actual multiplicity
using the KNO scaling law:

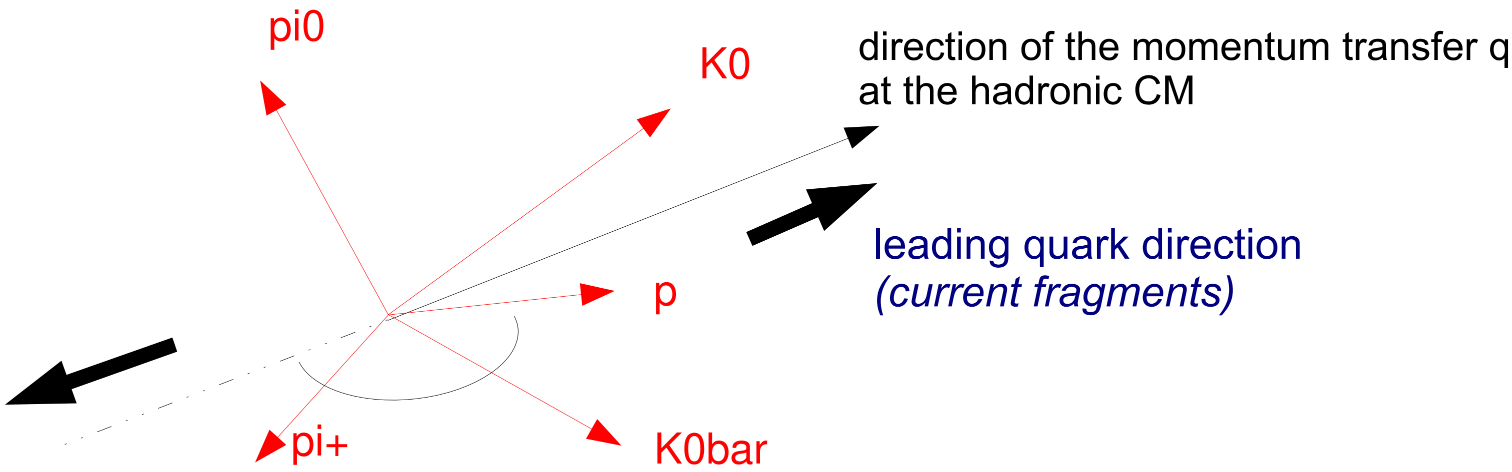
$$\langle n \rangle P(n) = f\,(n/\langle n \rangle)$$

(takin into account that
$\langle n\_neutral \rangle = 0.5 * \langle n\_ch \rangle$)



Simple arguments (charge, isospin conservation) 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)

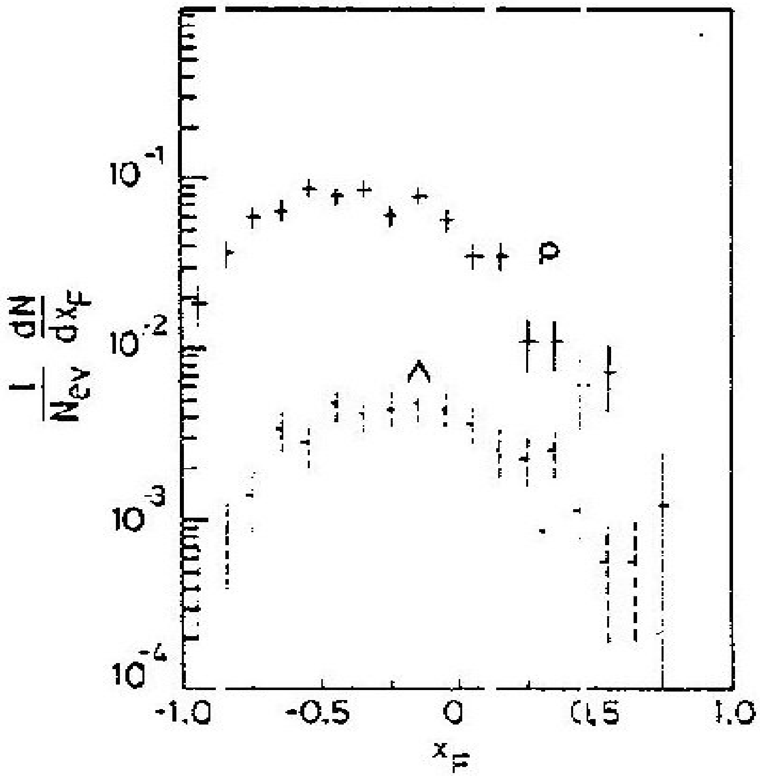
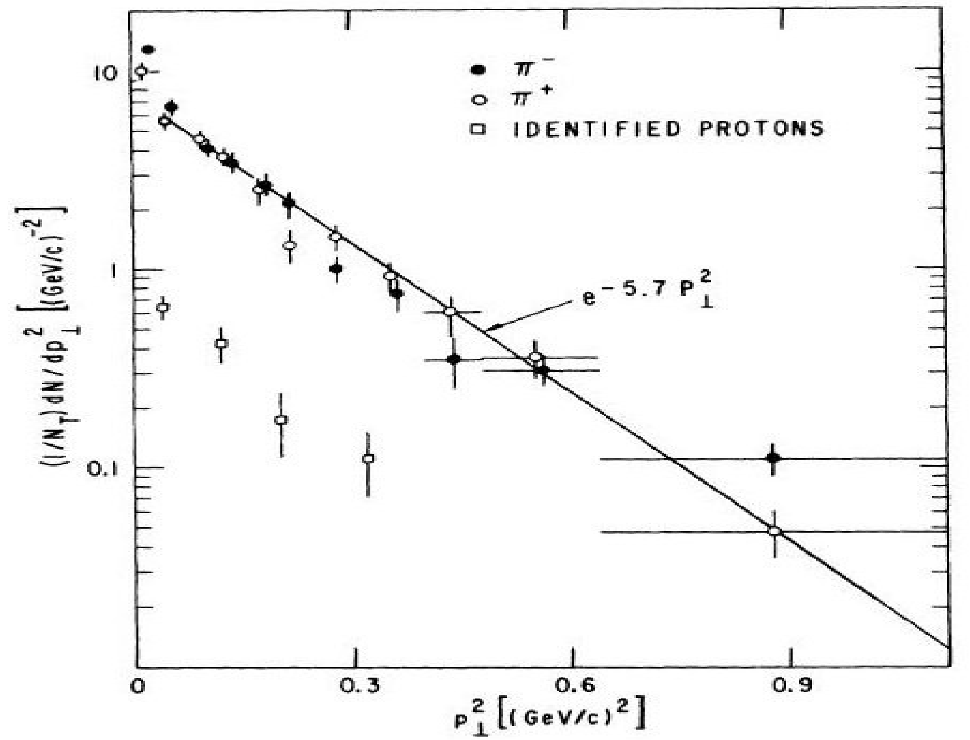


Fig. 11: x_F normalised distributions for protons (ν WA24 data) and lambda's (WA21 data, Bossetti et al, Nucl. Phys. B194, 1 (1982)).



Cooper, Neutrino 82, proceedings

Science & Technology Facilities Council

The GENIE hadronization / AGKY low-W model

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

pT-limited
phase space decay

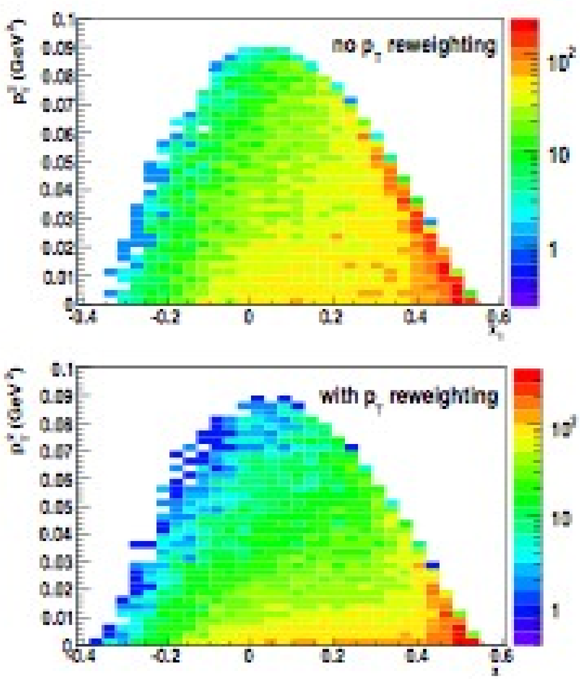


Figure 5. Pion x_F vs p_T^2, in the hadronic CM, for a (p, π^0, π^+) system decayed with invariant mass W = 1.6 GeV, where, for convenience, the

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.

Science & Technology Facilities Council

Formation zone

SKAT parameterization:

Hadron momentum

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

Transverse hadron momentum

K=0, ct0 = 0.342 fm

(SKAT) model dependence

No intranuclear rescattering within formation zone

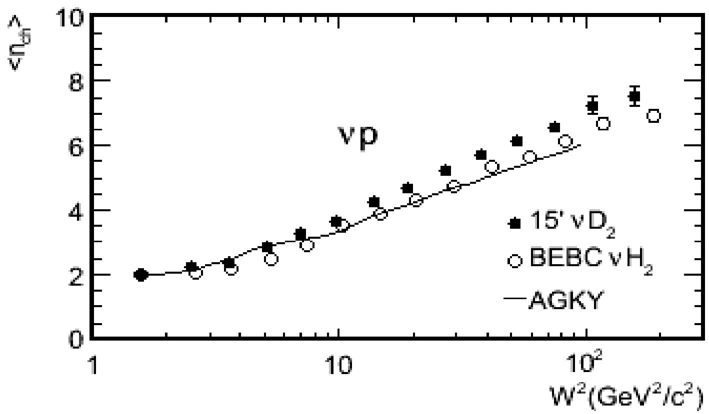
Used for hadrons generated by both the low-W KNO-based hadronization model
<u>and</u> for the small fraction of events hadronized by JETSET (override JETSET positions)

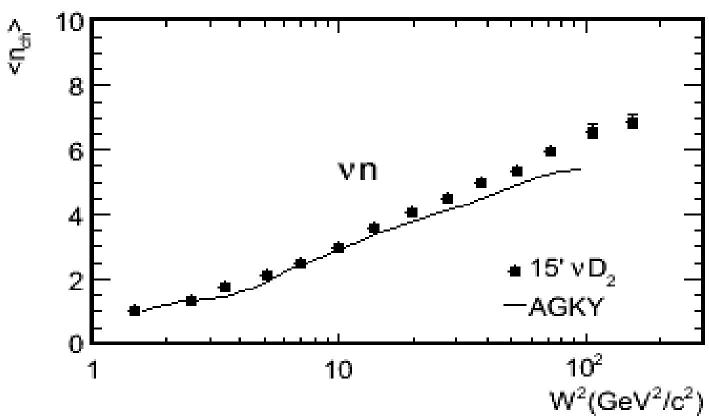
The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

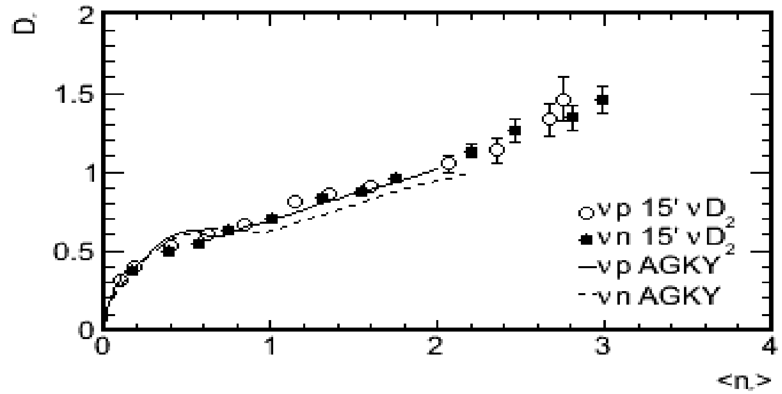
examples:

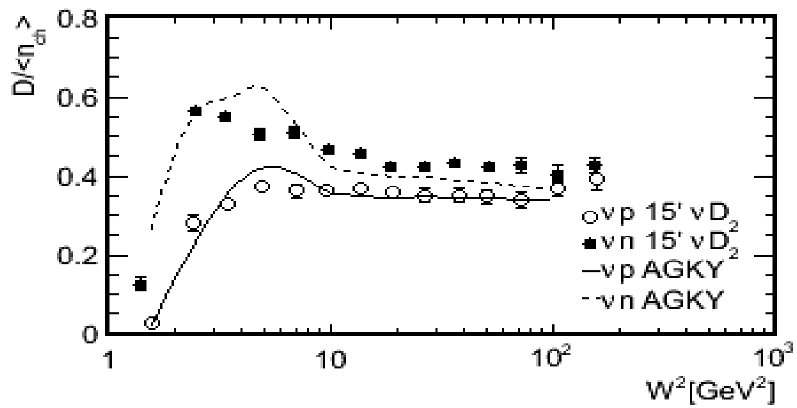
Charged pion multiplicities





Charged pion dispersion



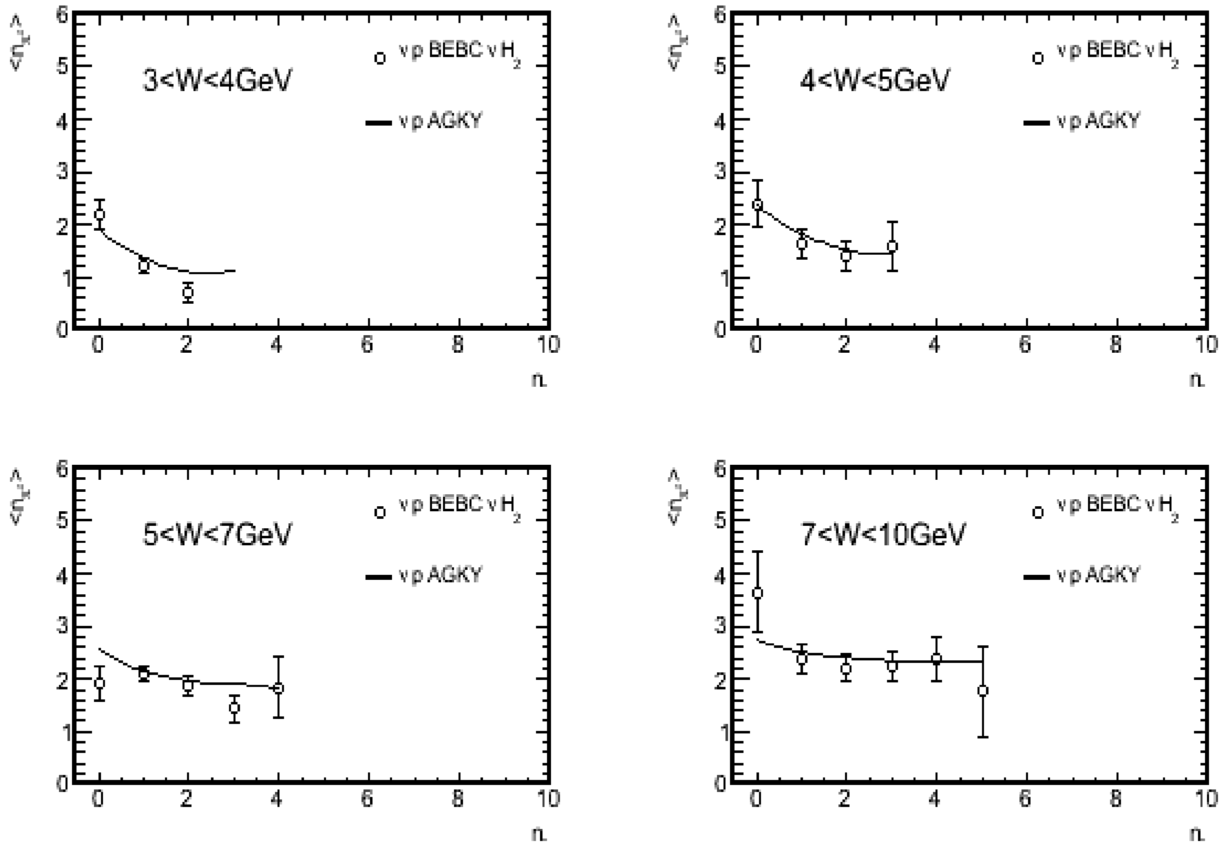


The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

Neutral / charged pion correlation

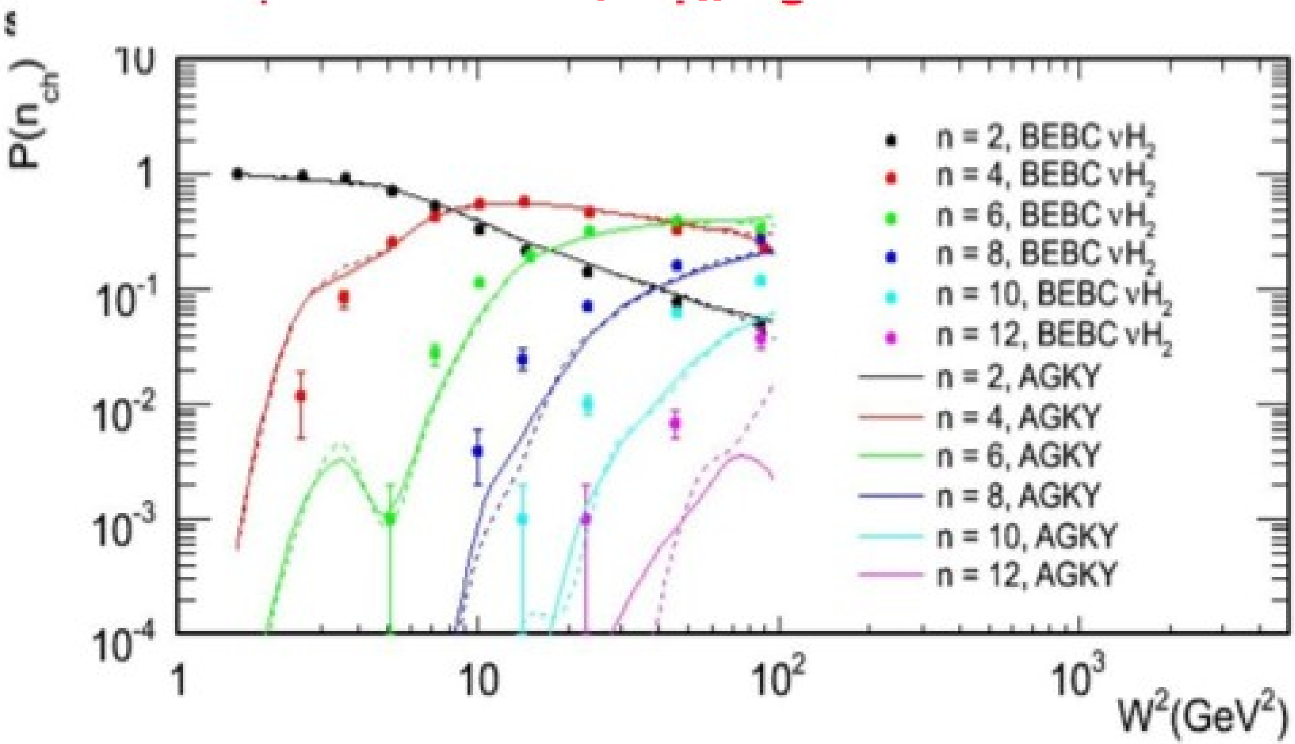


The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

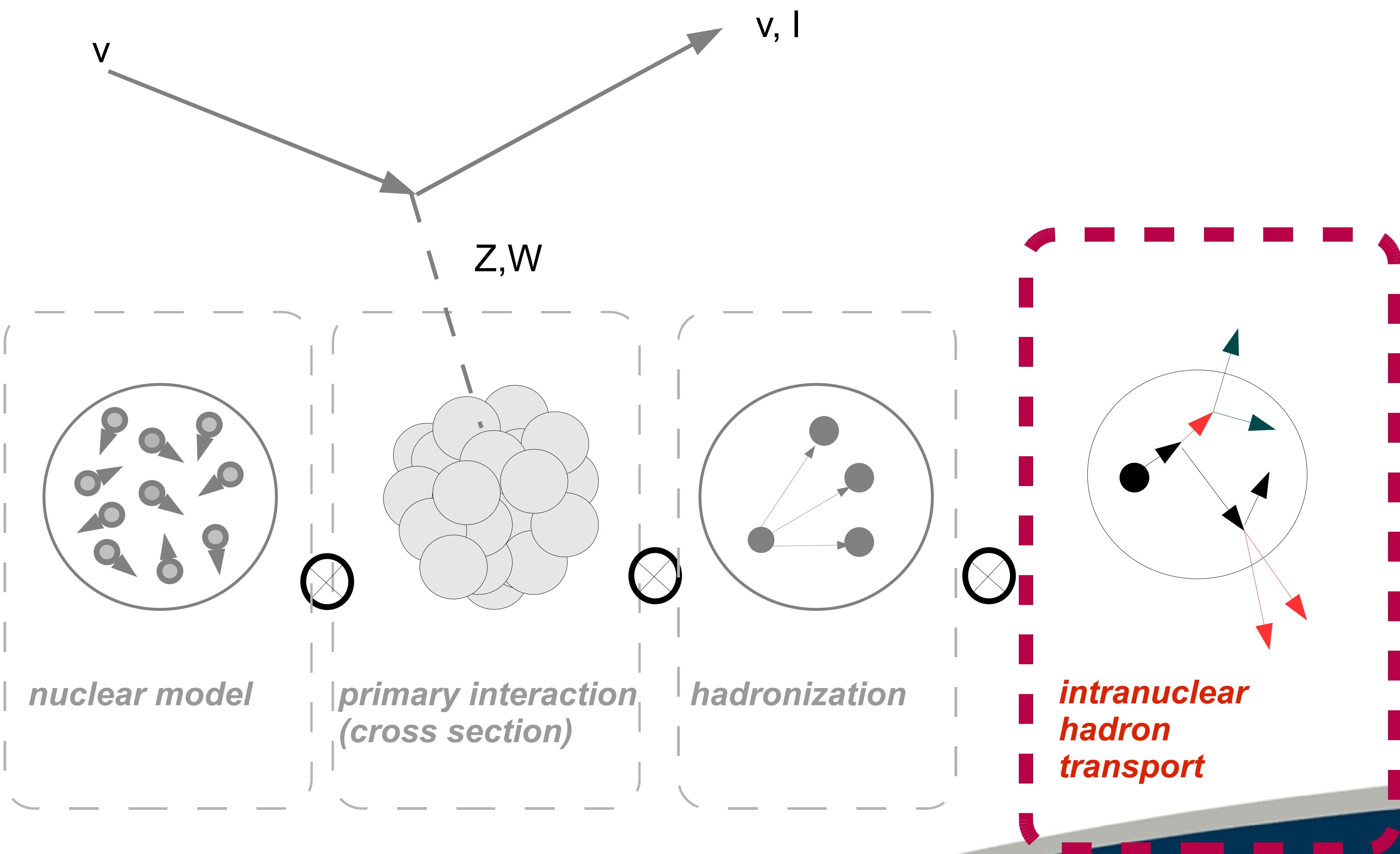
Normalized topological cross sections



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

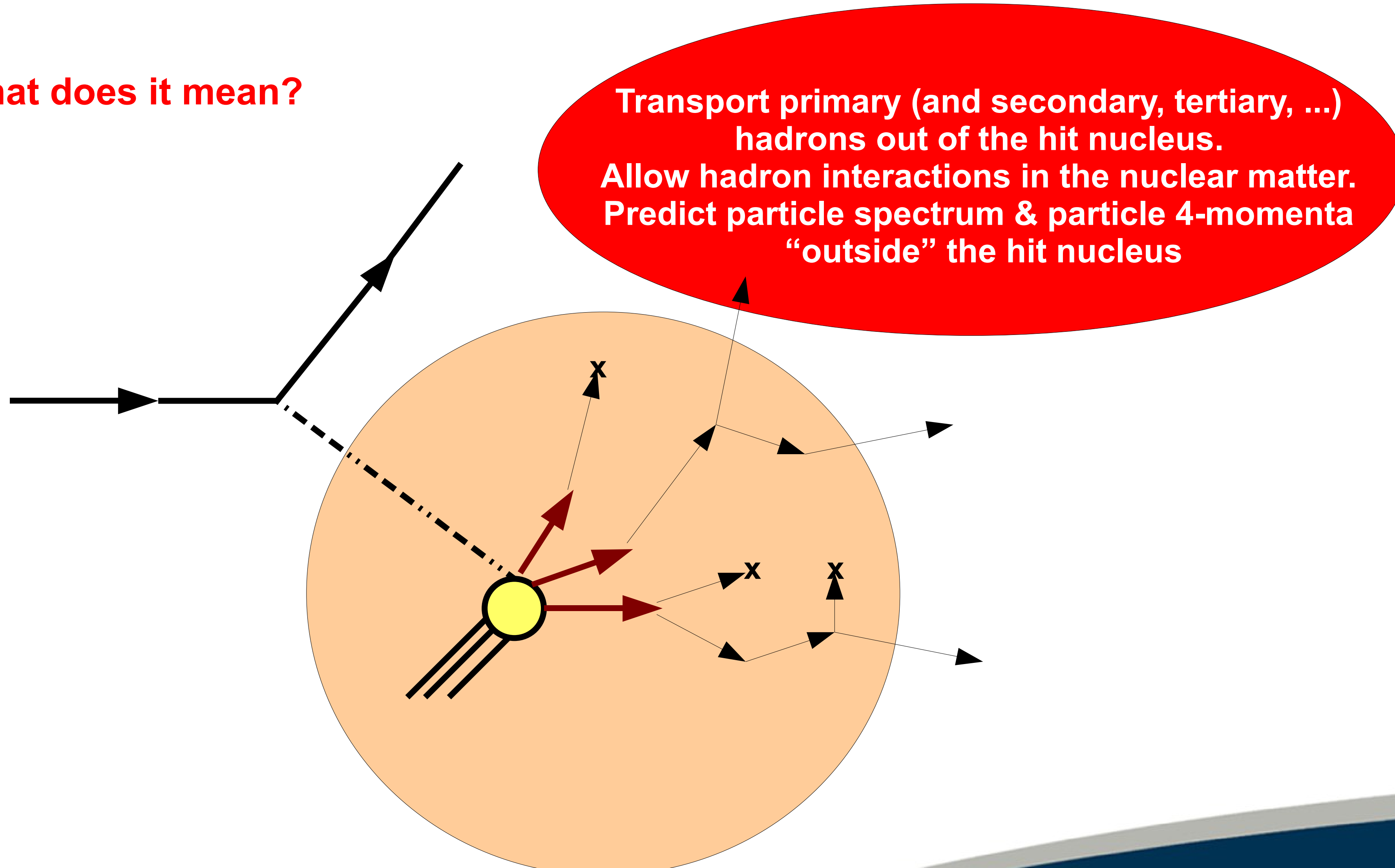
Intranuclear hadron transport



Costas Andreopoulos, *Rutherford Appleton Lab.*

The GENIE hadron transport modelling

what does it mean?

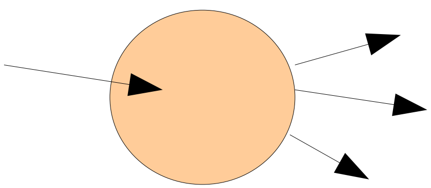


The GENIE hadron transport modelling

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

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

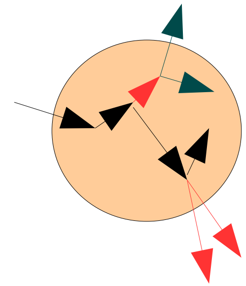
Intranuke / hA
(effective MC)



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

<u>available since 2.0.0</u>

Intranuke / hN
(true cascade MC)



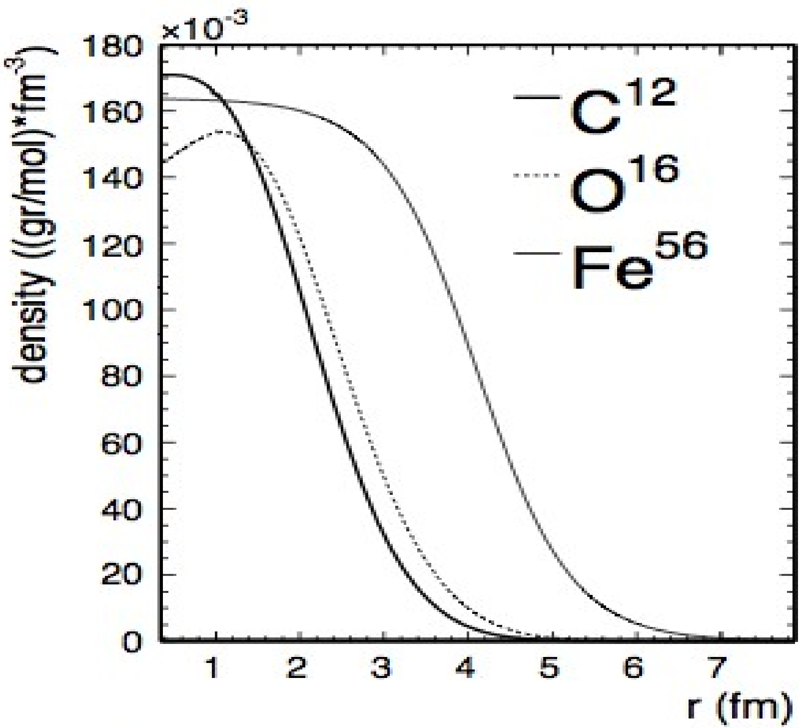
Builds everything up from hadron-nucleon xsecs

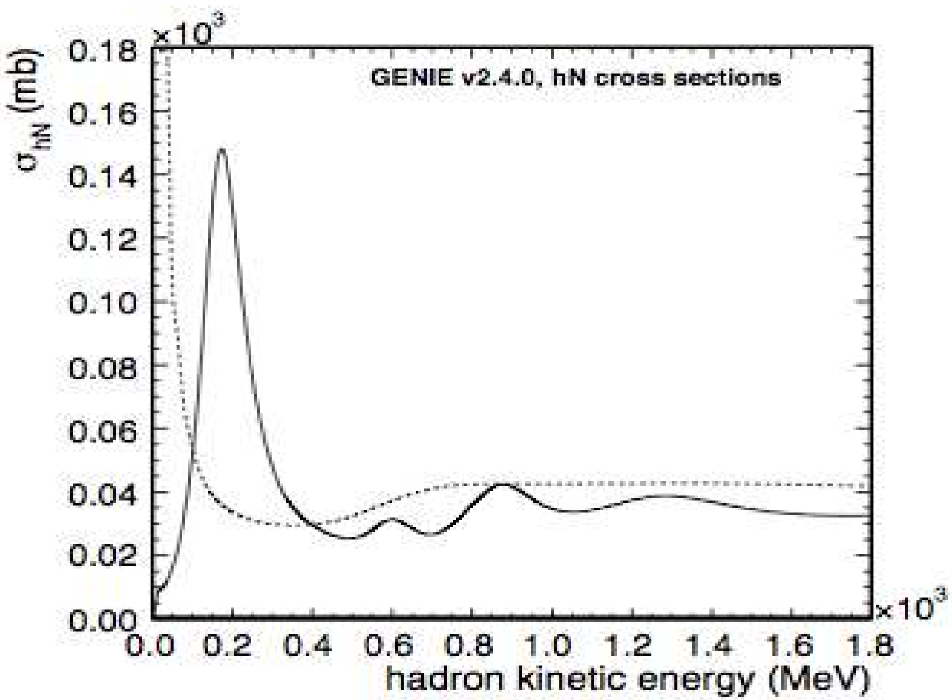
In advanced development stage
to become available soon

The GENIE hadron transport modelling (INTRANUKE/hA)

Stepping primary hadrons within the target nucleus

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





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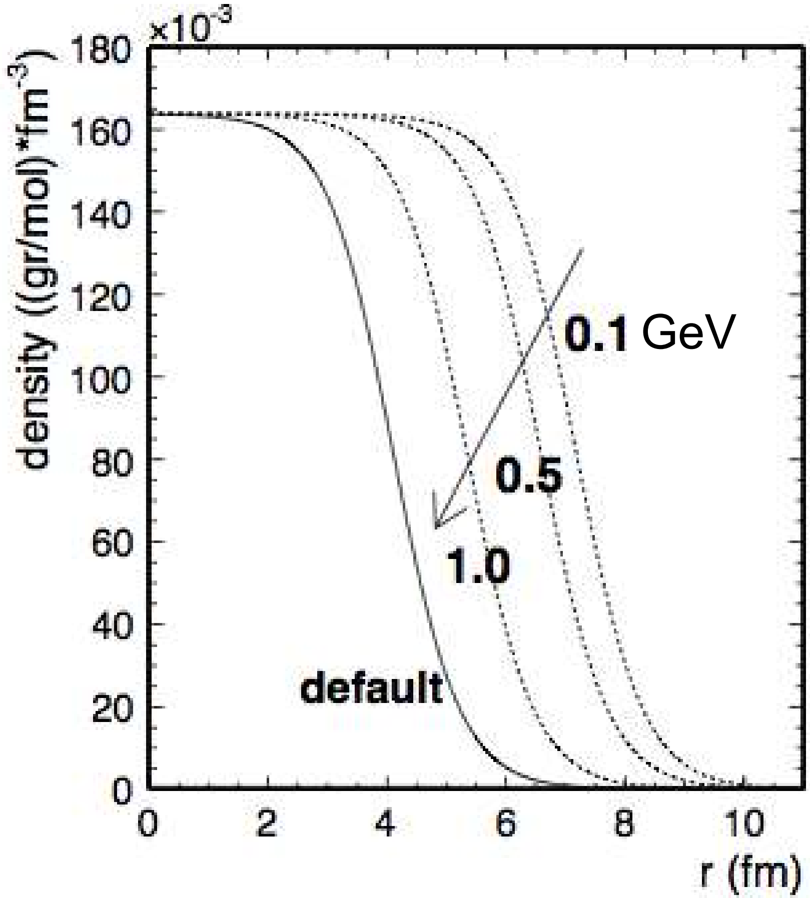
The GENIE hadron transport modelling (INTRANUKE/hA)



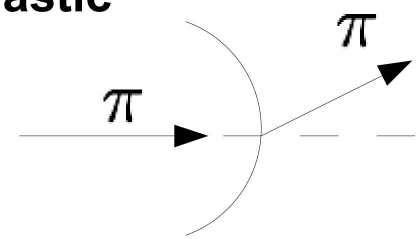
- Hadrons stepped by 0.05 fm at a time
-
- Hadrons traced till they reach
  r_max = N * R_nucl = N * R0 * A^(1/3)
  (R0 = 1.4, N = 3.0)
  so as to include the effects of the tails
  (Fe56: R_nucl=5.36fm, r_max=16.07fm)

- 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).

The GENIE hadron transport modelling (INTRANUKE/hA)

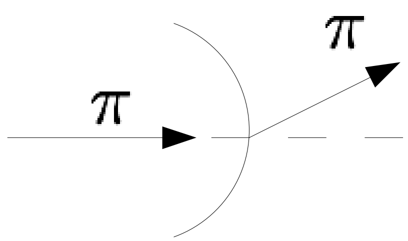
INTRANUKE/hA considers 5 types of 'hadron fates' (some may include many channels)

elastic



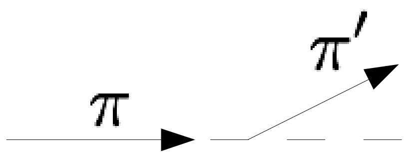
Pion deflected.
Its kinetic energy stays the same.

inelastic

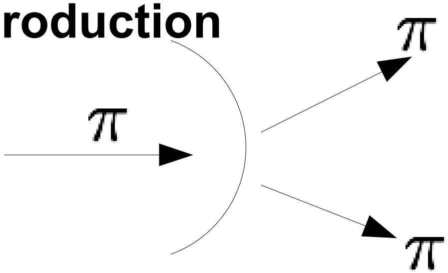


Pion deflected.
Its kinetic energy is degraded.

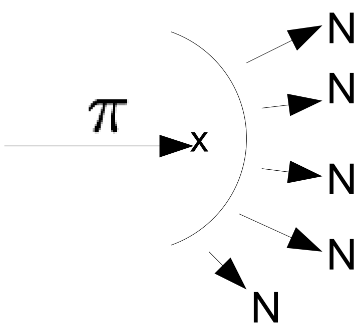
charge exchange



pion production



absorption

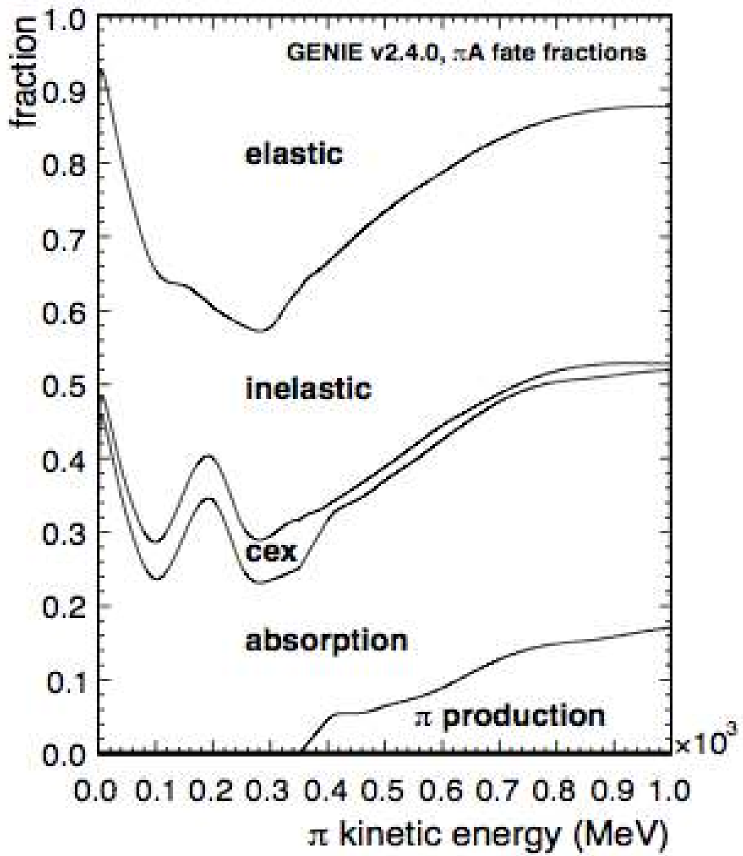


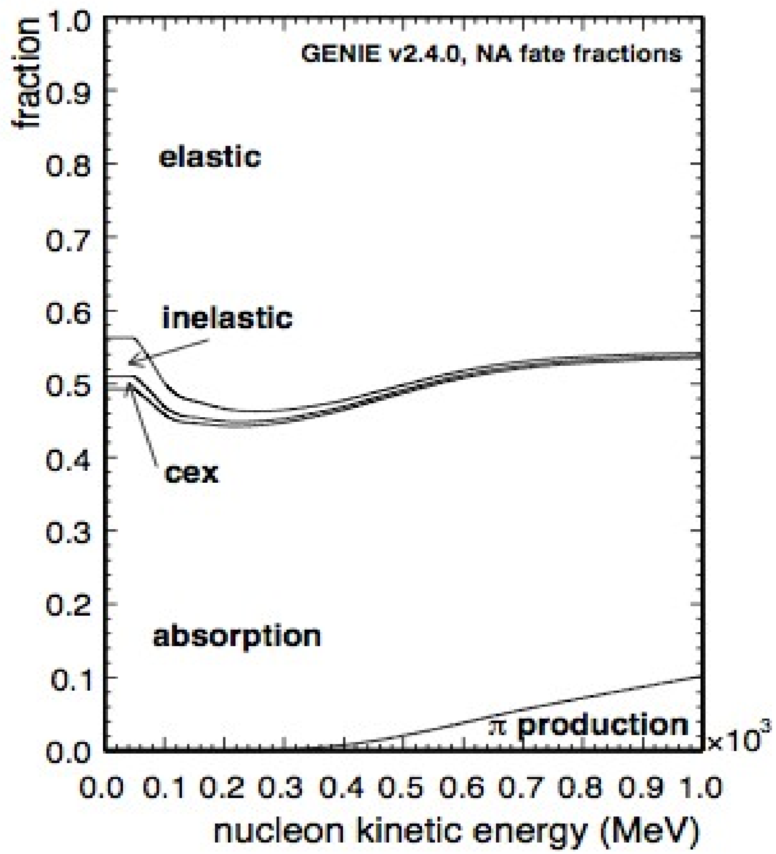
followed by emission of low energy nucleons

~ Similar fates for nucleons

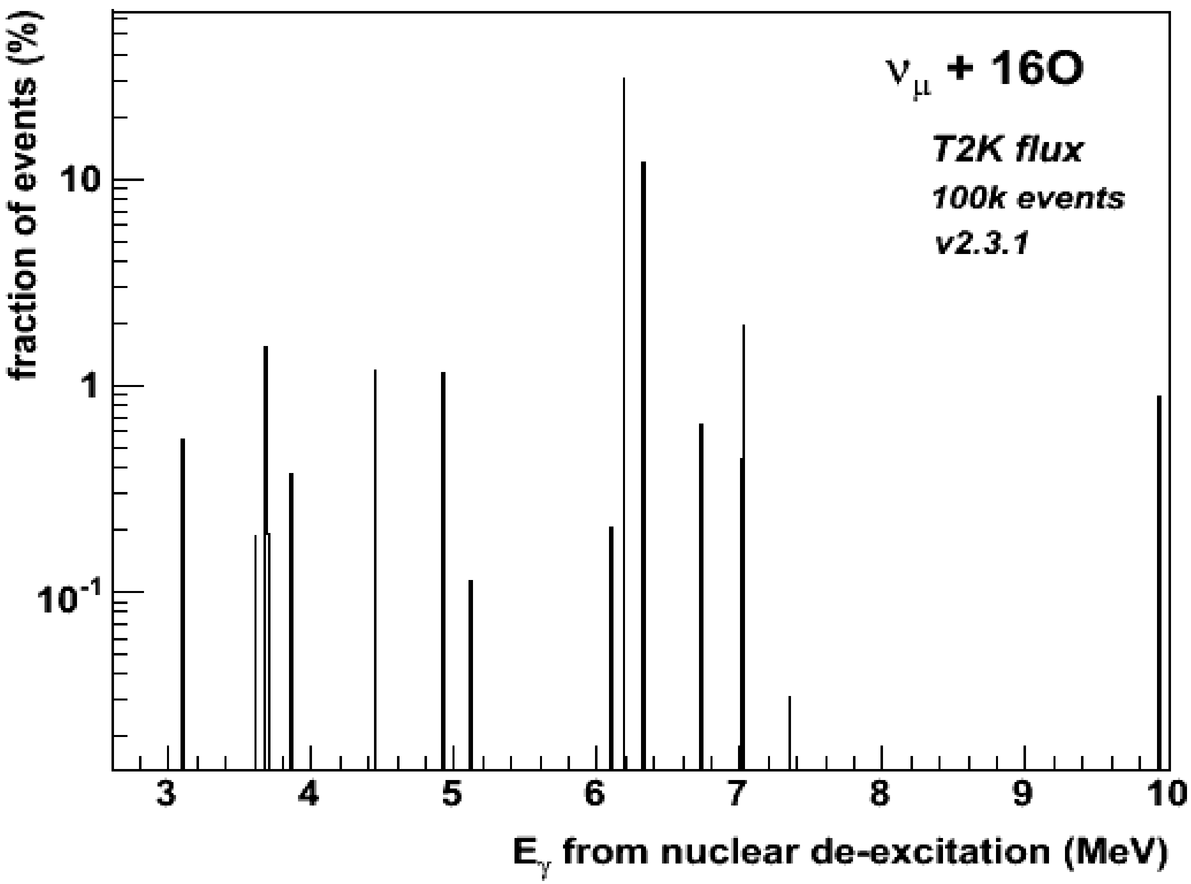
The GENIE hadron transport modelling (INTRANUKE/hA)

Fractions taken mostly from data





Nuclear excitations



Included in an ad-hoc way

Only for O16

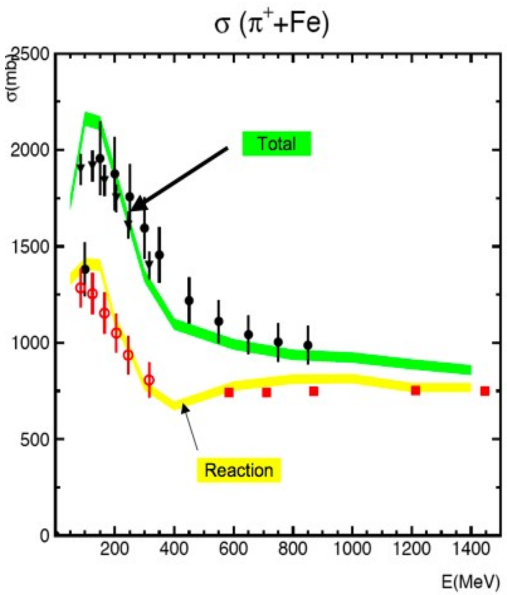
INTRANUKE/hA Data/MC comparisons

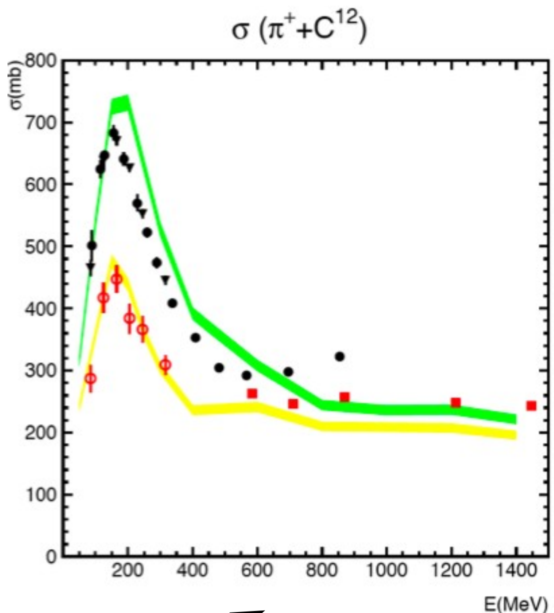
Much effort went into validation –
utilizing experience from non-neutrino probes, mainly hadron+A reactions

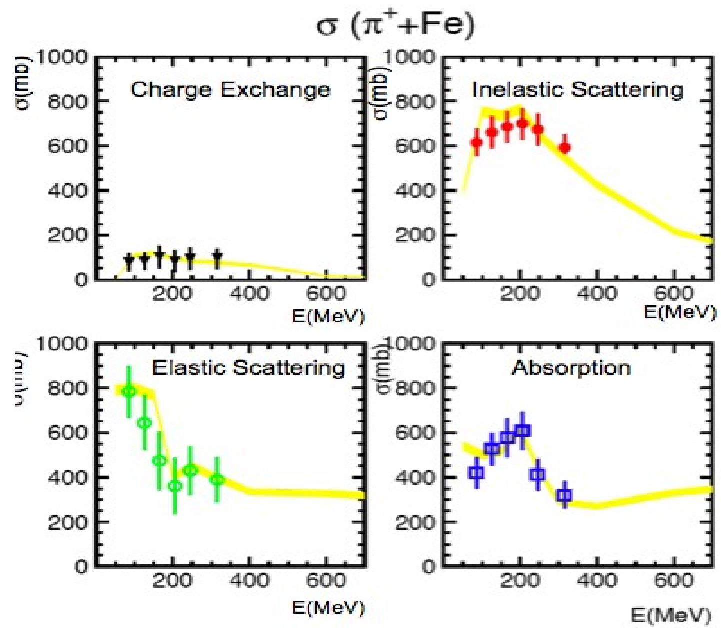
Lot of effort in tuning mean free path &
including the elastic contrib – difficult to model in context of INC

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

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

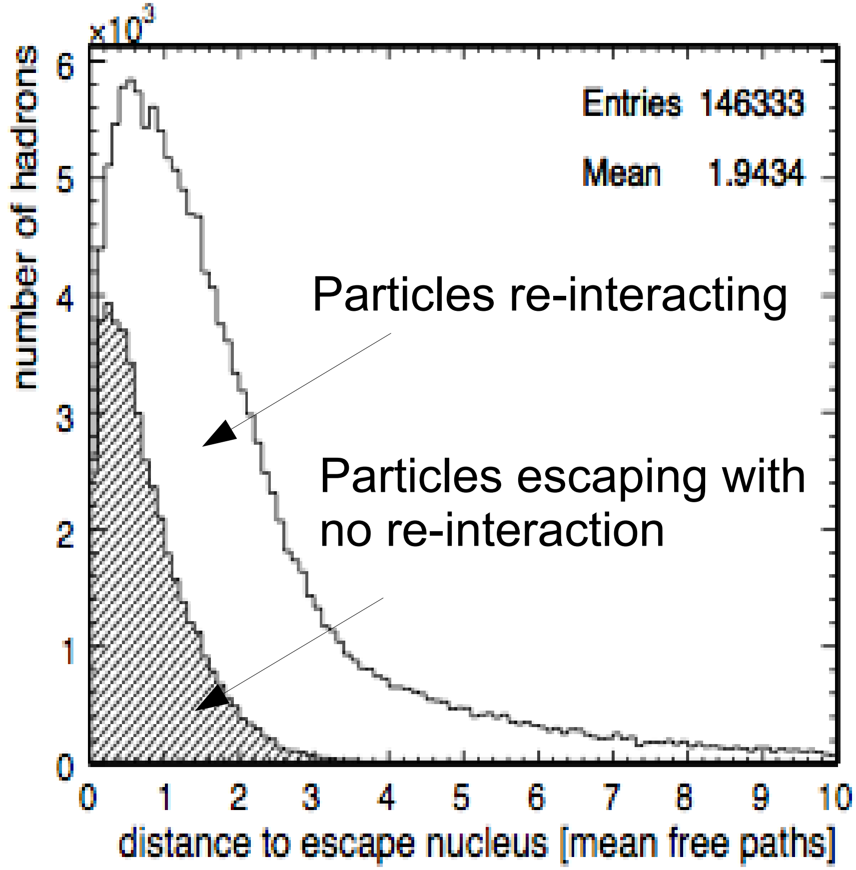






`MC experiments': throw hadrons into nuclei,
'measure cross sections' and compare with data.

Intranuclear rescattering effect



nu_mu + C12

1 GeV

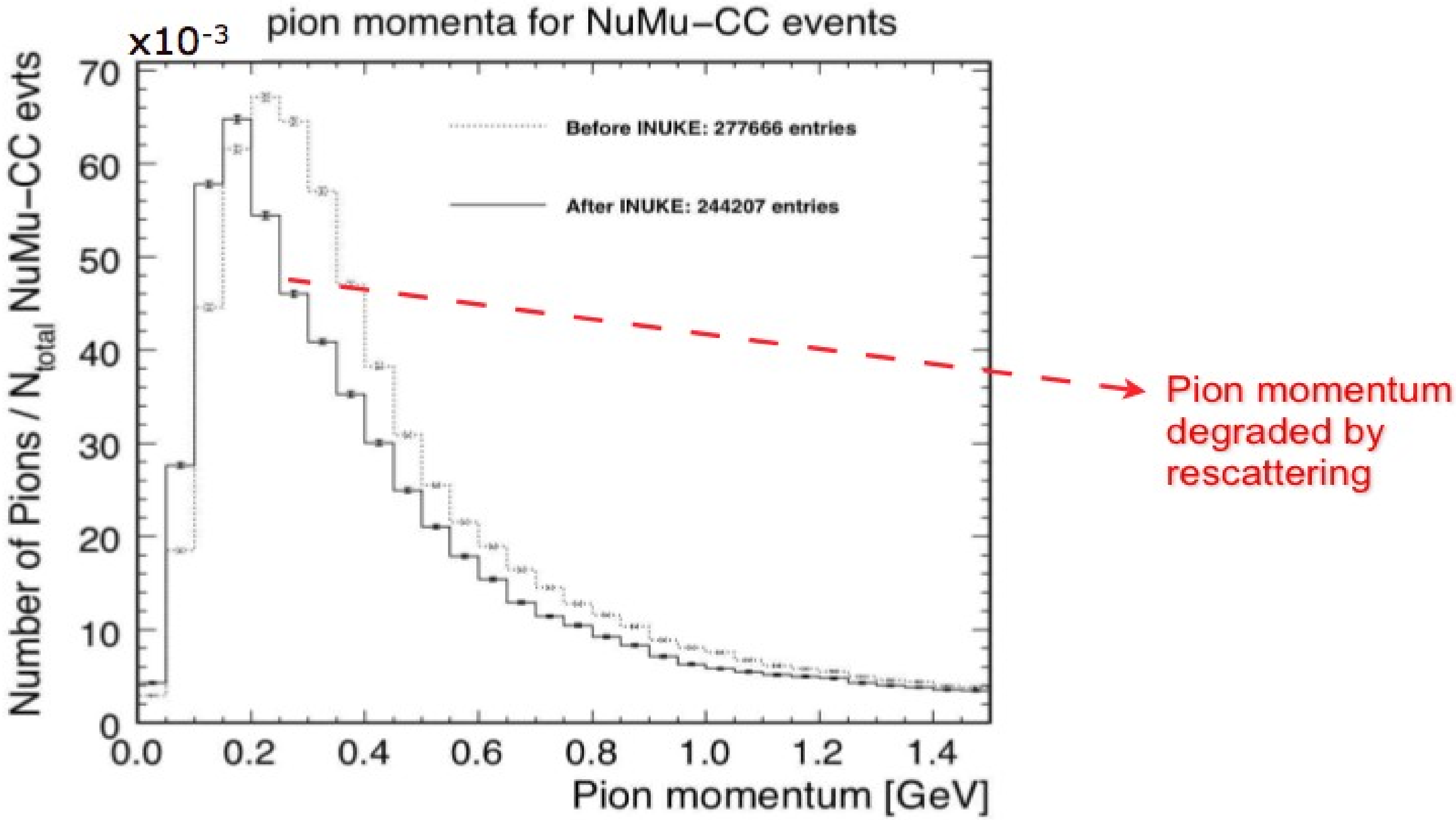
Most particles (2/3) re-interact

Intranuclear rescattering effect

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

Intranuclear rescattering effect



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

GENIE capabilities
>>>

The GENIE Tool-kit

Many tools are included in GENIE.
Of particular importance to experimentalists is the ability to :

Handle interaction modelling uncertainties using event reweighting

- can propagate a host of uncertainties and generate err envelopes for any observable
- can fit interaction models to near detector data / tune MC

Generate events for realistic detector geometries & neutrino fluxes

- **Off-the shelf components for very complex event generation cases**
  - *Flux changing across the detector*
  - *Complex geometries, multiple target materials*
  - *Beam-related backgrounds by interactions in non-active materials (cavern walls, etc)*

- **Important for high statistics experiments**

We can have concrete examples at the practical sessions

Event Reweighting >>>

Event reweighting

Use one sample to emulate another...

Can be used to propagate vA uncertainties to analyses, bug-fix precious large samples

2 popular use-cases

- **Reweight from a fixed set of {models/configuration} A to another fixed set B**

  eg reweight a generated sample to an improved / bug-fixed release

- **Given a set of models, reweight for changes in the configuration**

  eg, given QEL model, propagate effect of Ma uncertainty

What can be reweighed ?

- **Quite easily / generically**
  - *The cross section model*

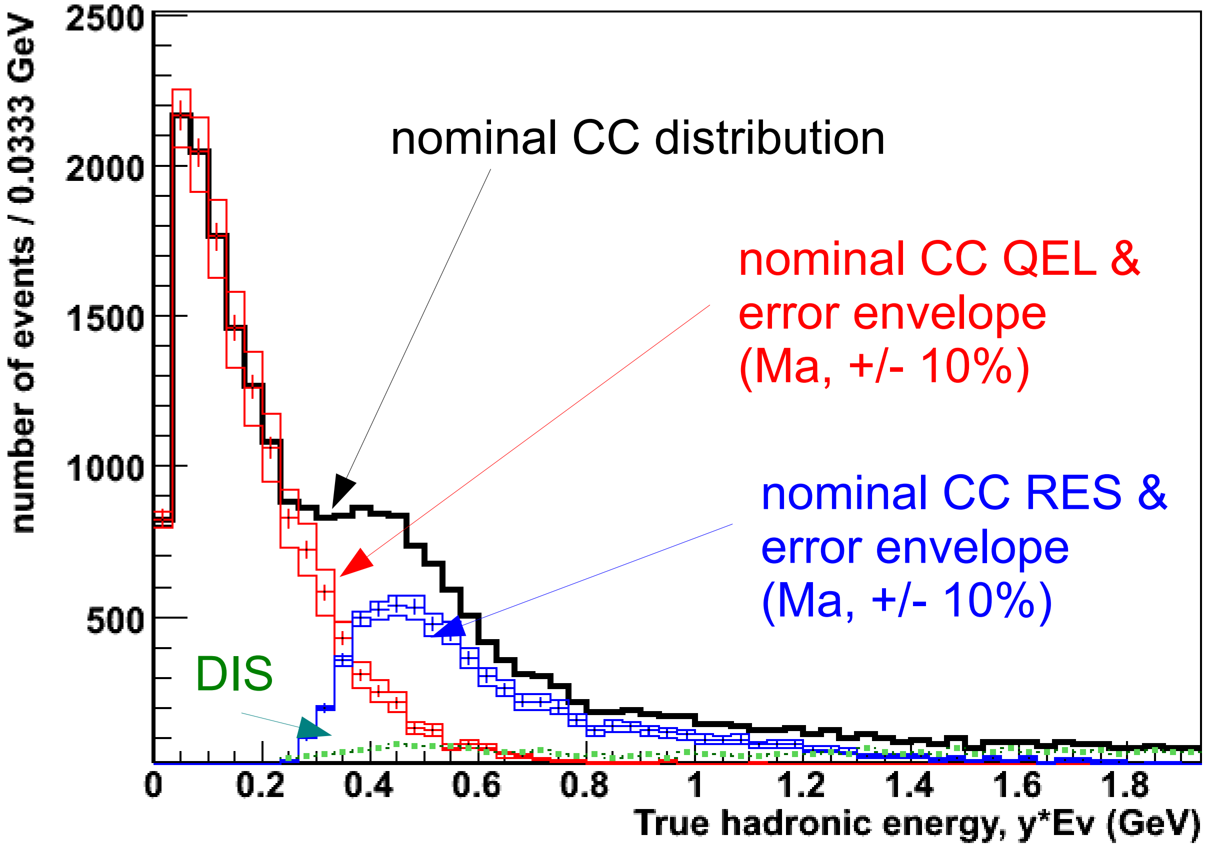
- **Less easily / generically but perfectly doable**
  - *Many aspects of the hadronization model*
  - *Many aspects of the Intranuclear hadron transport model*

- **Not easily or not at all doable**
  - *Nuclear model?*
  - *Cascades?*
  - *External (black-box) packages – eg JETSET, FLUKA*

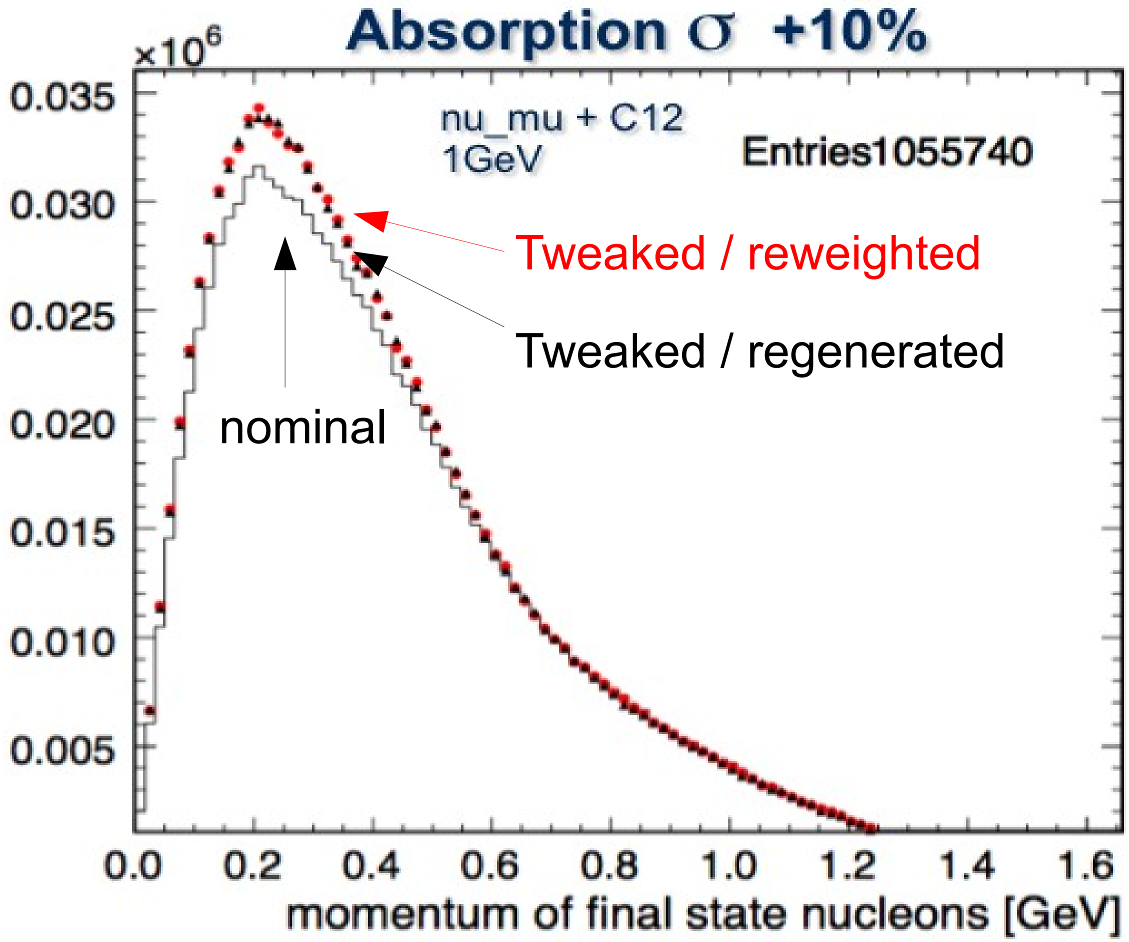
Cross section reweighing: example

Example GENIE nd280 numu+O16

Tweaked Ma-QEL and Ma-RES by +/- 10%



Hadronic reweighing: example

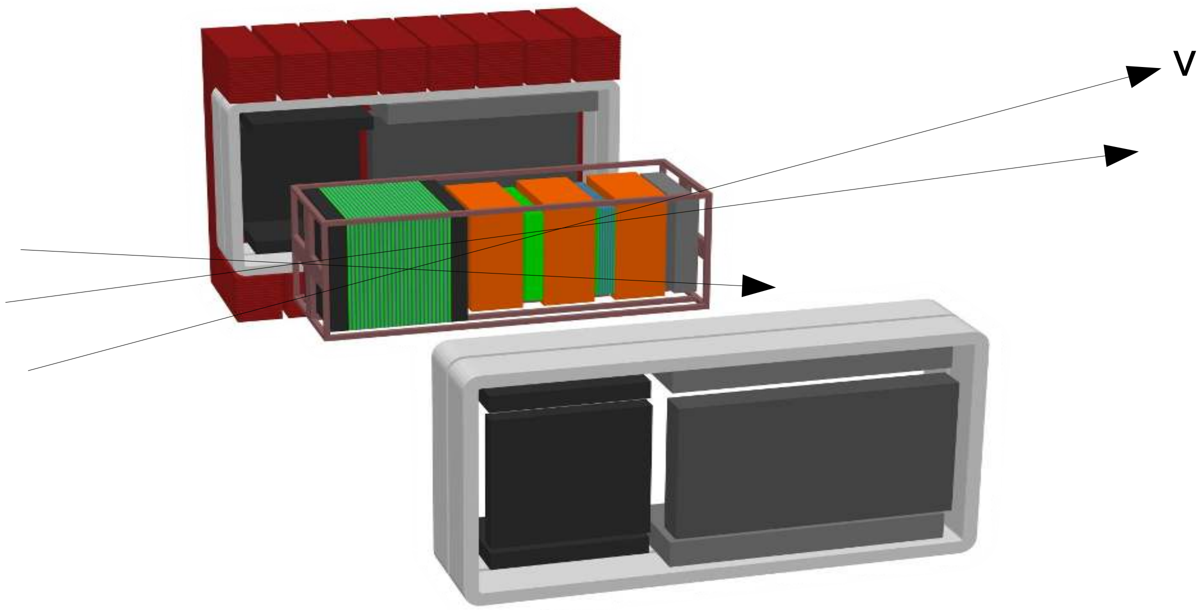


See Jim's talk for more details

A GENIE reweighting package (cross sections + INTRANUKE) available for T2K

Not fully available with standalone GENIE just yet

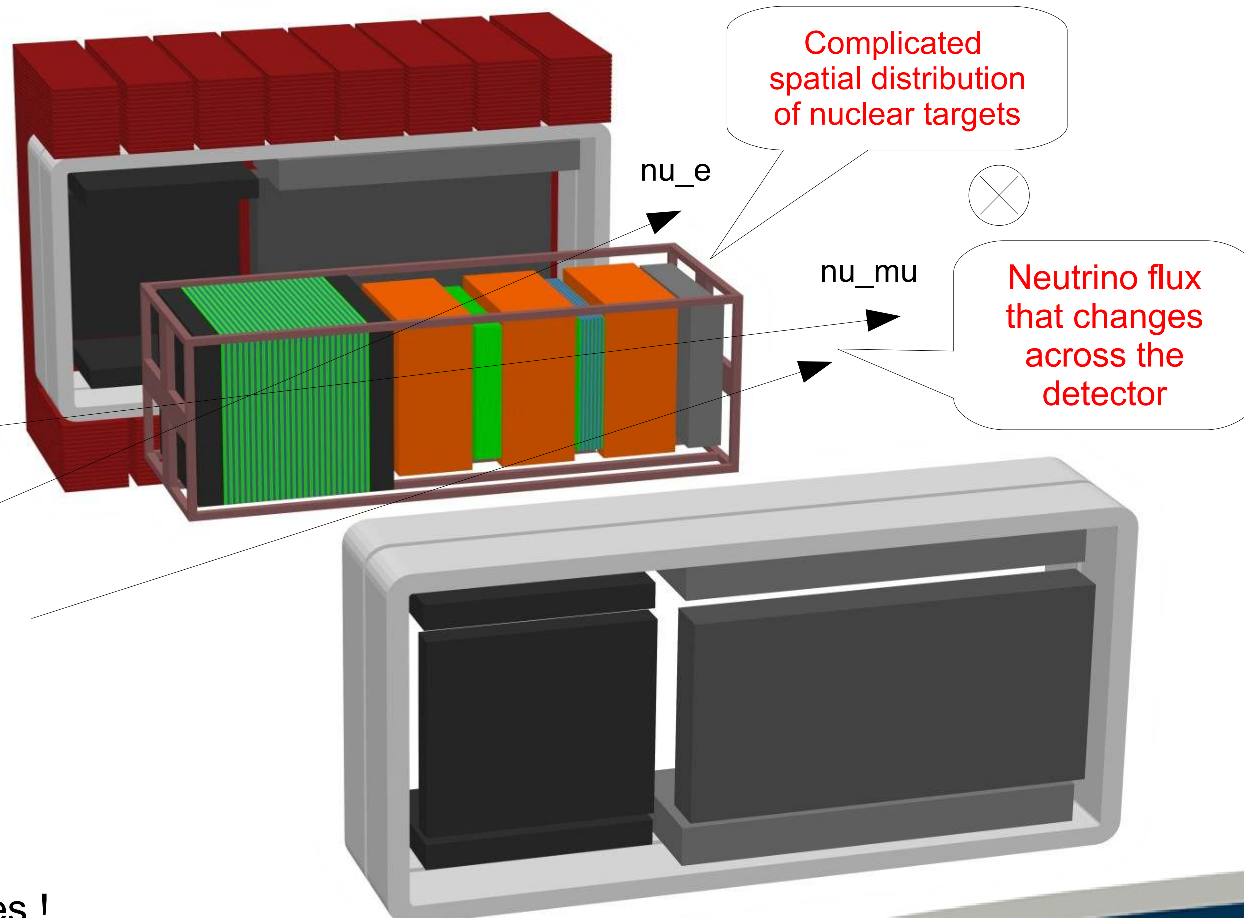
Using realistic detector geometries & beam simulation outputs >>>



Using fluxes / geometries

Event generation:
A complicated convolution of things:

Neutrino generator's job is:
Generate an event
once it is handed over
an initial state
(nu + target, at a given energy)



The **problem** here is
how to select that initial state
(and take into account its energy and spatial dependence)

Eg in MINOS:
6 neutrino flavours X
~60 (!) isotopes in detector geom =
360 possible initial states

BTW, the generator
should handle all these initial states !

Neutrino fluxes and detector geometries

A number of concrete flux and geometry drivers are included. More can be trivially added

fluxes

- *GJPARCNuFlux*: An interface to the JPARC neutrino beam simulation [8] used at SK, nd280, and INGRID.
- *GNuMIFlux*: An interface to the NuMI beam simulations [9] used at MINOS, NOvA, MINERvA and ArgoNEUT.
- *GBartolAtmoFlux*: A driver for the Bartol atmospheric flux by G. Barr, T.K. Gaisser, P. Lipari, S. Robbins and T. Stanev (cite)
- *GFlukaAtmo3DFlux*: A driver for the FLUKA-based 3-D atmospheric neutrino flux by A. Ferrari, P. Sala, G. Battistoni and T. Montaruli [?]
- *GCylindTH1Flux*: A generic flux driver, describing a cylindrical neutrino flux of arbitrary 3-D direction and radius. The radial dependence of the neutrino flux is configurable (default: uniform per unit area). The flux driver may be used for describing a number of different neutrino species whose (relatively normalised) energy spectra are specified as ROOT 1-D histograms. This driver is being used whenever an energy spectrum is an adequate description of the neutrino flux.
- *GMonoEnergeticFlux*: A trivial flux driver throwing mono-energetic flux neutrinos along the +z direction. More that one neutrino species can be included, each with its own weight. The driver is being used in simulating a single initial state at a fixed energy mainly for probing, comparing and validating neutrino interaction models.

geometry

- ROOT/Geant4-based geometries
- Simple target mix, eg. "*40%O16 + 20%C12 + 40%H1*"

Expt.-specific event generation drivers

Using these off-the-self components to build expt-specific event generation drivers

A driver that handles the JPARC beam-line experiments was added in v2.4.0

- *Handles the JNUBEAM flux simulation outputs*
- *Handles the SuperK, nd280, Ingrid, 2km, detector geometries / target mix...*

A driver that handles the NuMI beam-line experiment is being added in v2.5.1

- *Handles the GNUMI flux simulation outputs*
- *Handles the MINOS, MINERvA, … , … detector geometries*

Selecting initial states

GENIE uses the input flux driver to **throw flux neutrinos**

For **each flux neutrino**, GENIE computes **interaction probabilities** **for each isotope**

Probably ~ 1E+2 different isotopes in nd280

Remember,
for each (flux neutrino + isotope) pair:

Total interaction cross section
for given neutrino + isotope,
at given E
(get this from generator's own cross section 'libraries')

Interaction probability

$$P \sim \frac{\sigma L \varrho}{A}$$

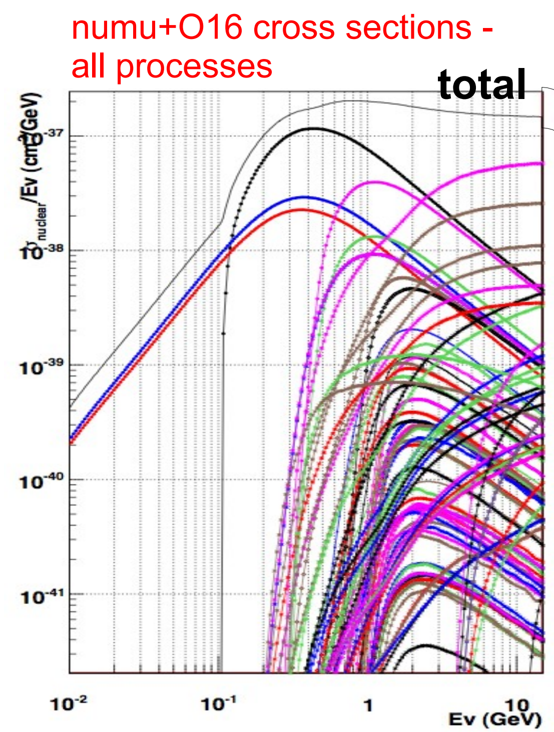
Path length X density
for given isotope,
along the current flux neutrino direction
integrated across the detector
(get this from a "geometry driver")

Selection of initial state is based on these interaction probabilities

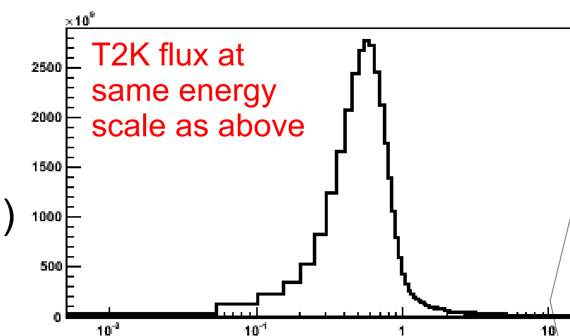
Selecting initial states:
The no-interaction probability

Obviously, **interaction probabilities are very small numbers**

Of course the generator doesn't have to throw zillions of flux neutrinos to get an interaction.
Probabilities are scaled-up to reduce the number of trials



Probability scale is the maximum interaction probability
(i.e. Probability at maximum energy --so, max cross section-- and for the maximum possible path length)
summed over initial states



The probability scale is determined at an energy with low flux.

Significant selection inefficiency
(rejecting ~500 flux neutrinos / interaction for nd280 configuration)

Irreducible.

Understanding GENIE events

I will show you a couple of actual GENIE events

and describe what is going on there

>>>

Understanding GENIE events

Stored in `GHEP' event trees (GHEP: a customized StdHep-like event record)

GHepParticles :

- *Holds info about generated particles*
  (4-momentum, 4-position in nucleus coord syst, charge, mass, name, polarization, ...)

- *Generated particles can be initial / intermediate / final-state particles or generator book-keeping actions (pseudo-particles)*

GhepRecord:

- A TClonesArray of GHepParticles

- Holds info with event-wide scope
  (weights, flags, vertex in detector coord syst, …)

- Also contains an "summary information" for the generated interactions
  (to be described in a second...)

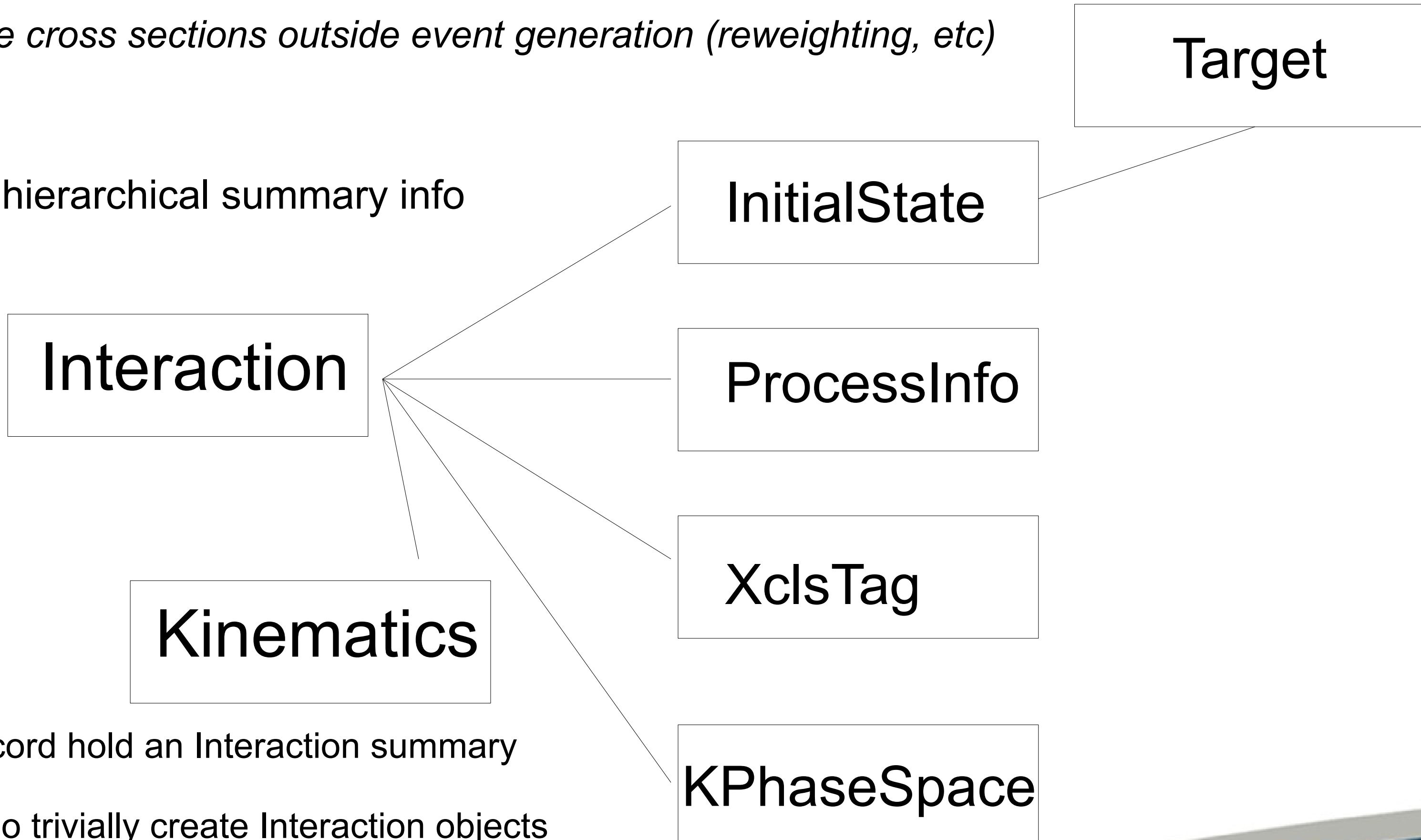
Understanding GENIE events

The event record hold <u>all info</u> about an event

... but you do not want to pass events to cross section algorithms

Eg. want to use cross sections outside event generation (reweighting, etc)

Interaction = hierarchical summary info



Every event record hold an Interaction summary

But you can also trivially create Interaction objects yourself & use them to query cross section algorithms and other models.
We will learn how to do that later.

Check out **http://doxygen.genie-mc.org** –

Familiarise yourselves with the classes in the **GHEP** and **Interaction** packages

Also browse the GENIE user manual –

especially the `Analysing GENIE outputs' chapter

You are expected to have that done before the practical sessions

Understanding GENIE events

PDG codes

Standard codes for all particles
PDG-2006 codes for ions (10LZZZAAAI), eg Fe56: 1000260560

Status codes

Description	*GHepStatus_t*	As *int*
Undefined	*kIStUndefined*	-1
Initial state	*kIStInitialState*	0
Stable final state	*kIstStableFinalState*	1
Intermediate state	*kIStIntermediateState*	2
Decayed state	*kIStDecayedState*	3
Nucleon target	*kIStNucleonTarget*	11
DIS pre-fragm. hadronic state	*kIStDISPreFragmHadronicState*	12
Resonant pre-decayed state	*kIStPreDecayResonantState*	13
Hadron in the nucleus	*kIStHadronInTheNucleus*	14
Remnant nucleus	*kIStFinalStateNuclearRemnant*	15

Mother / daughter links

Understanding GENIE events - 1st example

A nu_mu + Fe56 resonance event

initial state

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob		2000000002	3	-1 -1				

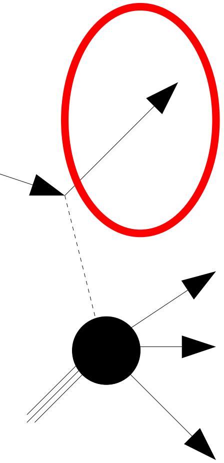
Understanding GENIE events - 1st example

Fe56 = { hit nucleon } + { `remnant' nucleus } = p + Mn55

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob	15	2000000002	3	-1 -1				

Understanding GENIE events - 1st example

Incoming neutrino → final state primary lepton (eg. numu CC → mu-)



Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob	15	2000000002	3	-1 -1				

Understanding GENIE events - 1st example

Hit proton excited to Delta++

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob	15	2000000002	3	-1 -1				

Understanding GENIE events - 1st example

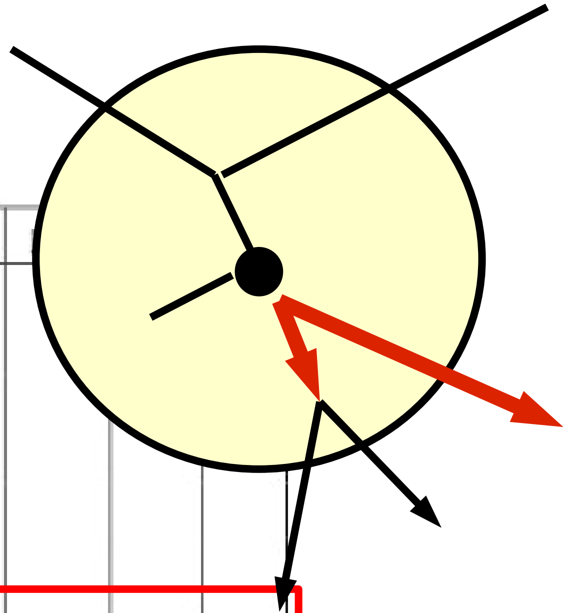
Delta++ decays (selected decay channel: proton pi+)
Decay happened in nuclear environment → Decay products marked as `hadrons in the nucleus (14)'

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob	15	2000000002	3	-1 -1				

Understanding GENIE events - 1st example

GENIE sees particles marked `hadrons in the nucleus (14)'
Begin **intra-nuclear hadron transport**

Idx	Name	ISt	PDG	Mom	Kids	E
0	nu_mu	0	14	-1	5 5	...
1	Fe56	0	1000260560	-1	2 3	
2	proton	11	2212	1	4 4	
3	Mn55	2	1000250550	1	12 12	
4	Delta++	3	2224	2	6 7	
5	mu-	1	13	0	-1 -1	
6	proton	14	2112	4	8 8	
7	pi+	14	211	4	11 11	
8	proton	3	2212	6	9 10	
9	proton	1	2212	8	-1 -1	
10	proton	1	2212	8	-1 -1	
11	pi+	1	211	7	-1 -1	
12	HadrBlob	15	2000000002	3	-1 -1	



Understanding GENIE events - 1st example

Multi-nucleon knock-out

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob	15	2000000002	3	-1 -1				

Understanding GENIE events - 1st example

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob	15	2000000002	3	-1 -1				

Understanding GENIE events - 1st example

Nuclear remnant

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob	15	2000000002	3	-1 -1				

Understanding GENIE events - 1st example

(Neutrino generator) Final state particles

To be passed-on to detector (eg Geant4-based) simulation

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton	1	2212	8	-1 -1				
10	proton	1	2212	8	-1 -1				
11	pi+	1	211	7	-1 -1				
12	HadrBlob		2000000002	3	-1 -1				

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Understanding GENIE events - 2nd example

<u>A **nu_mu + Fe56 DIS** event</u>

initial state

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob		2000000002	3	-1 -1				

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Understanding GENIE events - 2nd example

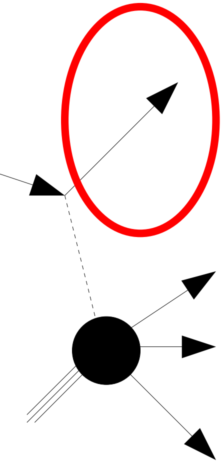
Fe56 = { hit nucleon } + { `remnant' nucleus } = n + Fe55

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob	15	2000000002	3	-1 -1				

Understanding GENIE events - 2nd example

Final state primary lepton

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob	15	2000000002	3	-1 -1				



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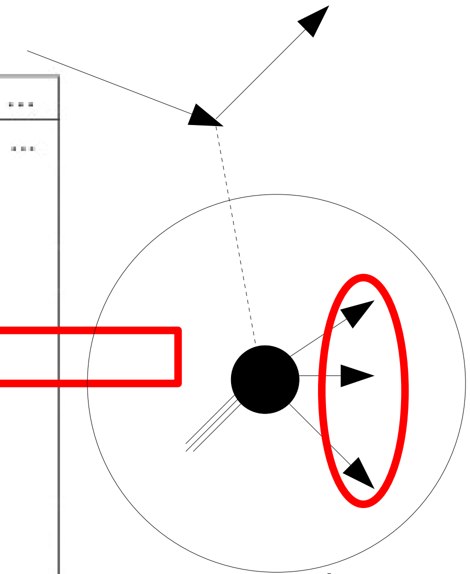
Understanding GENIE events - 2nd example

nu_mu + n → mu- + **X** (X: pre-fragmented hadronic system)

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob	[illegible]	2000000002	3	-1 -1				



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Understanding GENIE events - 2^{nd} example

Hadronization

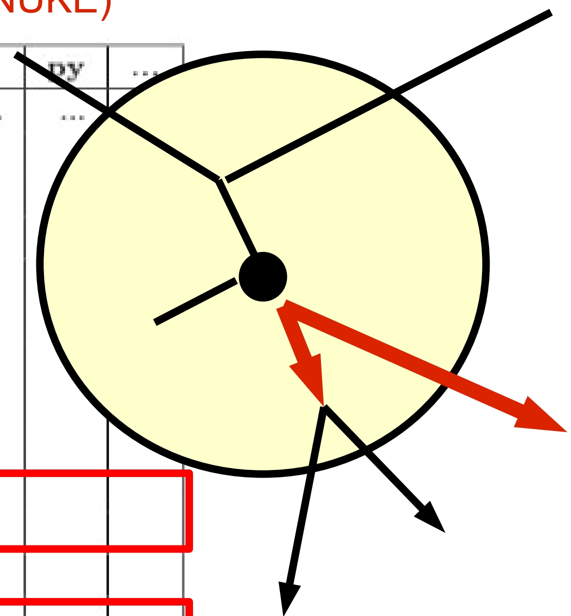
Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob		2000000002	3	-1 -1				

\omega decay

Understanding GENIE events - 2nd example

Particles to be tracked by GENIE intranuclear hadron transport (INTRANUKE)

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob		2000000002	3	-1 -1				



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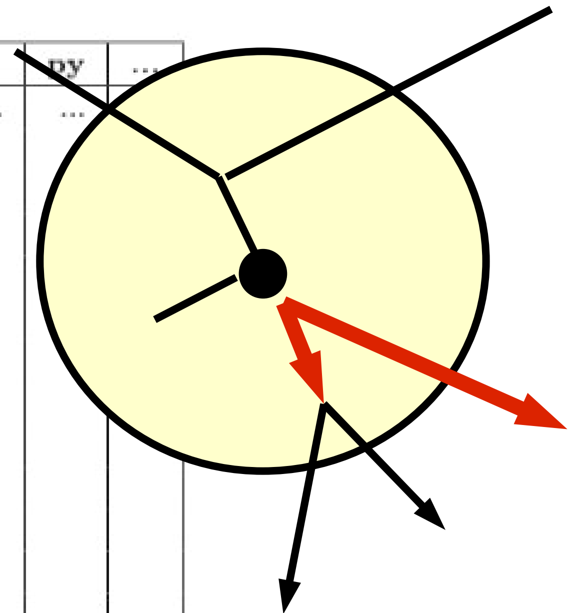
Understanding GENIE events - 2nd example

A pi- re-scattering (absorption followed by nucleon emission)

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob		2000000002	3	-1 -1				



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Understanding GENIE events - 2nd example

Nuclear remnant

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob		2000000002	3	-1 -1				

Understanding GENIE events - 2nd example

(Neutrino generator) Final state particles (= Geant4 primaries)

Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	8	14 14				
10	proton	14	2212	8	15 15				
11	omega	12	223	8	12 13				
12	pi-	14	-211	11	16 16				
13	pi+	14	211	11	21 21				
14	pi0	1	111	9	-1 -1				
15	proton	1	2212	10	-1 -1				
16	pi-	3	-211	12	17 20				
17	neutron	1	2112	16	-1 -1				
18	neutron	1	2112	16	-1 -1				
19	proton	1	2212	16	-1 -1				
20	proton	1	2212	16	-1 -1				
21	pi+	1	211	13	-1 -1				
22	HadrBlob		2000000002	3	-1 -1				

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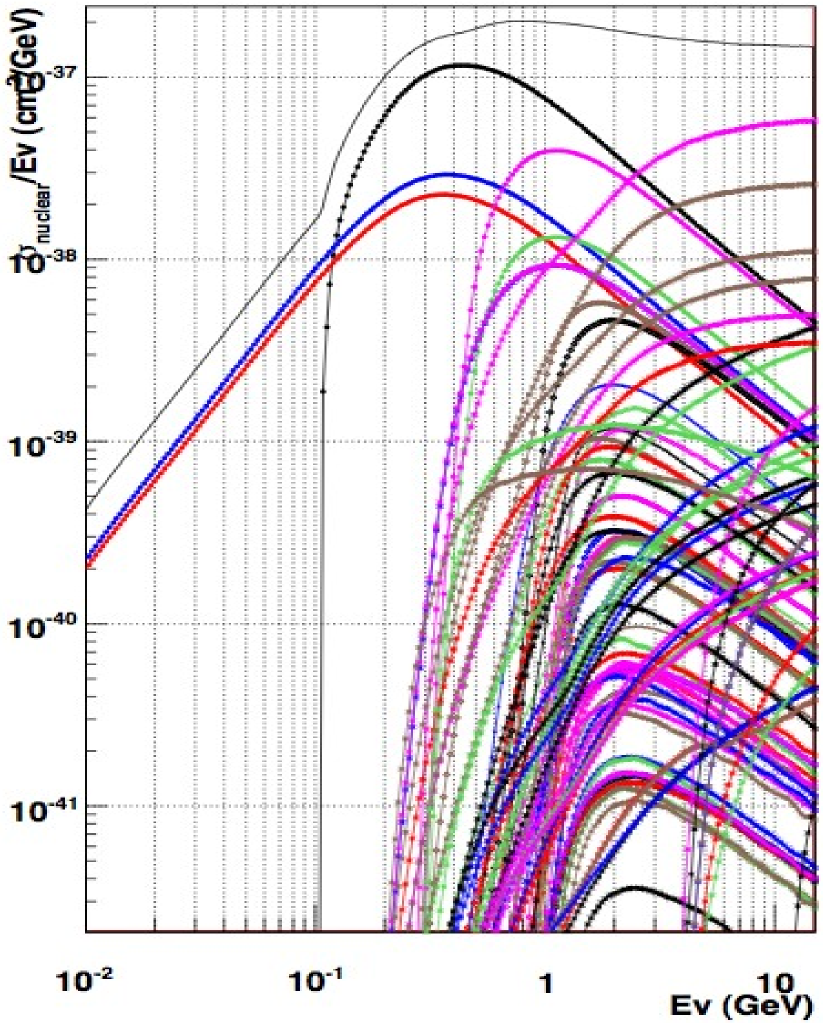
Generating events

Now, rather than describing a fully generated event,
will present you with a typical event `as it gets generated'.

Will describe the basic generation steps & some MC issues.

>>>

Generating events –
Step A: Selecting interaction



Example: **nu_mu + O16:** All processes

~1E+2 `processes'
~1E+5 diff. cross section evaluations per numerical integration

~1E+7 differential cross section evaluations per target

Typically ~1E+2 targets =>
<u>1E+9 xsec calc just in order to start generation!</u>

Impossible to calculate at generation time
Cross sections pre-computed and interpolated
Will learn more at the `hands-on' sessions

As soon as an interaction is selected an `Interaction' summary object gets filled-in And attached to an empty event record

Adding initial state

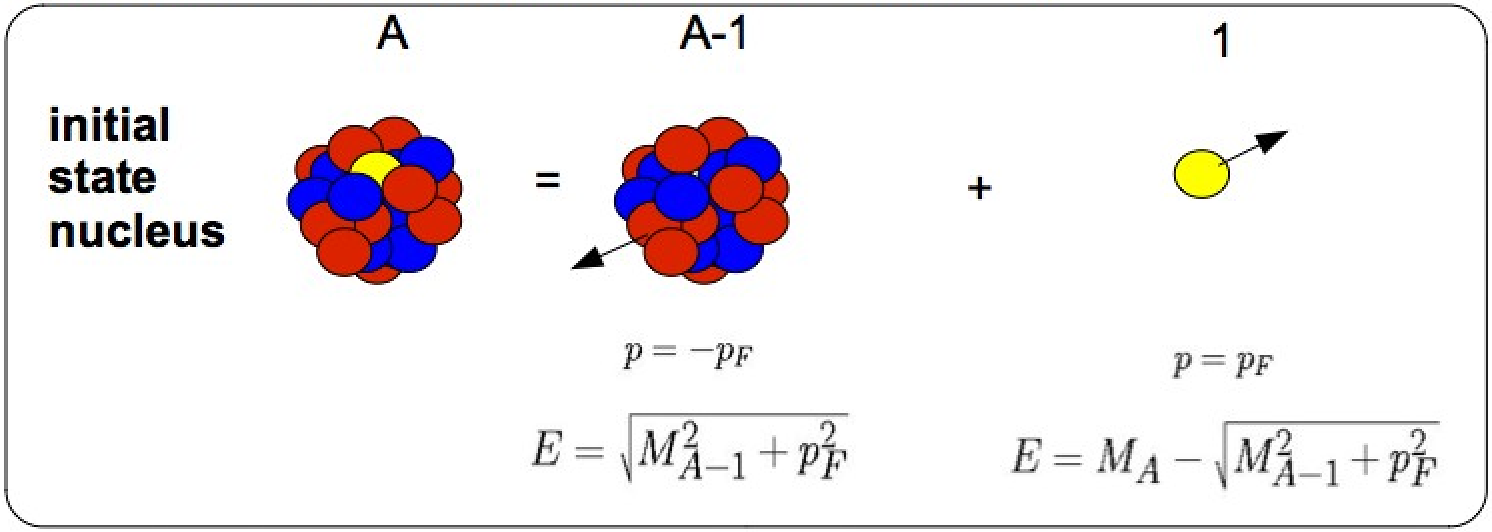
Adding initial state. Hit nucleon (if any) defined by selected interaction mode

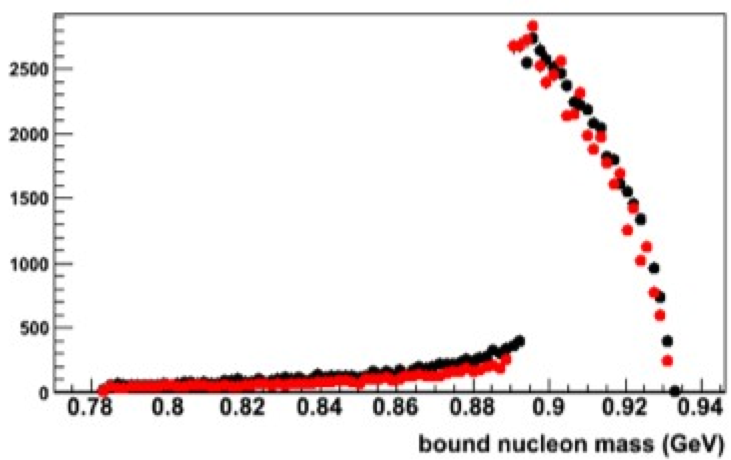
Hit nucleon originally on mass-shell, no 3-momentum

```
|--------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [shown using $GHEPPRINTLEVEL = 1]                                               |
|--------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |  Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|--------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 |  -1 |  -1 |  -1 |  -1 |   0.000 |   0.000 |   3.000 |   3.000 |   0.000 |
|   1 |          Fe56 |   0 | 1000260560 |  -1 |  -1 |   2 |   2 |   0.000 |   0.000 |   0.000 |  52.103 |  52.103 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |  -1 |  -1 |   0.000 |   0.000 |   0.000 |   0.940 |   0.940 |
|--------------------------------------------------------------------------------------------------------|
|      Fin-Init:|     |            |          |           |   0.000 |   0.000 |  -3.000 | -55.103 |         |
|--------------------------------------------------------------------------------------------------------|
|      Vertex:  |      nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =           0 s) |
|--------------------------------------------------------------------------------------------------------|
|      FLAGS:   | UnPhys: [OFF] | ErrBits[16->0]:00000000000000000 | 1stSet:                           none|
|--------------------------------------------------------------------------------------------------------|
```

Generating Fermi momentum

Select nucleon momemtum (goes off the mass shell). Recoil 'nuclear spectator'.





Example;

Bound (off the shell) neutron mass in Fe56

Off-shell kinematics handed a-la Bodek

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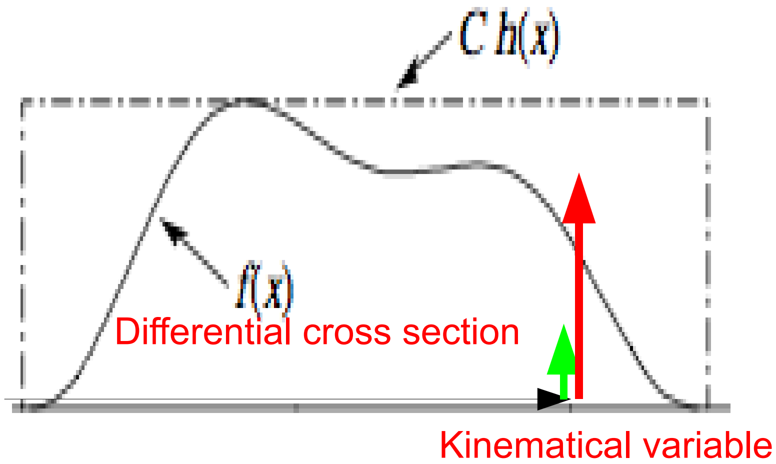
Generating Fermi momentum

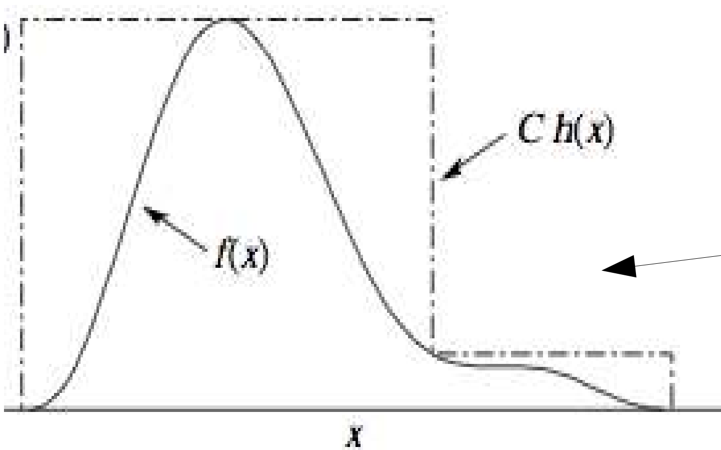
Hit nucleon now appears with fermi momentum and off the mass-shell.

```
|----------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [shown using $GHEPPRINTLEVEL = 1]                                     |
|----------------------------------------------------------------------------------------------|
| Idx |        Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|----------------------------------------------------------------------------------------------|
|   0 |       nu_mu |   0 |         14 |  -1 |  -1 |  -1 |  -1 |   0.000 |   0.000 |   3.000 |   3.000 |   0.000 |
|   1 |        Fe56 |   0 | 1000260560 |  -1 |  -1 |   2 |   2 |   0.000 |   0.000 |   0.000 |  52.103 |  52.103 |
|   2 |     neutron |  11 |       2112 |   1 |  -1 |  -1 |  -1 |   0.163 |  -0.041 |   0.185 |   0.931 | **0.940 | M = 0.897
|----------------------------------------------------------------------------------------------|
|      Fin-Init:|     |            |           |           |   0.000 |   0.000 |  -3.000 | -55.103 |         |
|----------------------------------------------------------------------------------------------|
|      Vertex:  |      nu_mu @ (x =    0.00000 m, y =    0.00000 m, z =    0.00000 m, t =         0 s)  |
|----------------------------------------------------------------------------------------------|
|      FLAGS:   | UnPhys: [OFF] | ErrBits[16->0]:00000000000000000 | 1stSet:                  none|
|----------------------------------------------------------------------------------------------|
```

Selecting kinematical variables

Using the rejection method
(typically in 2-D)





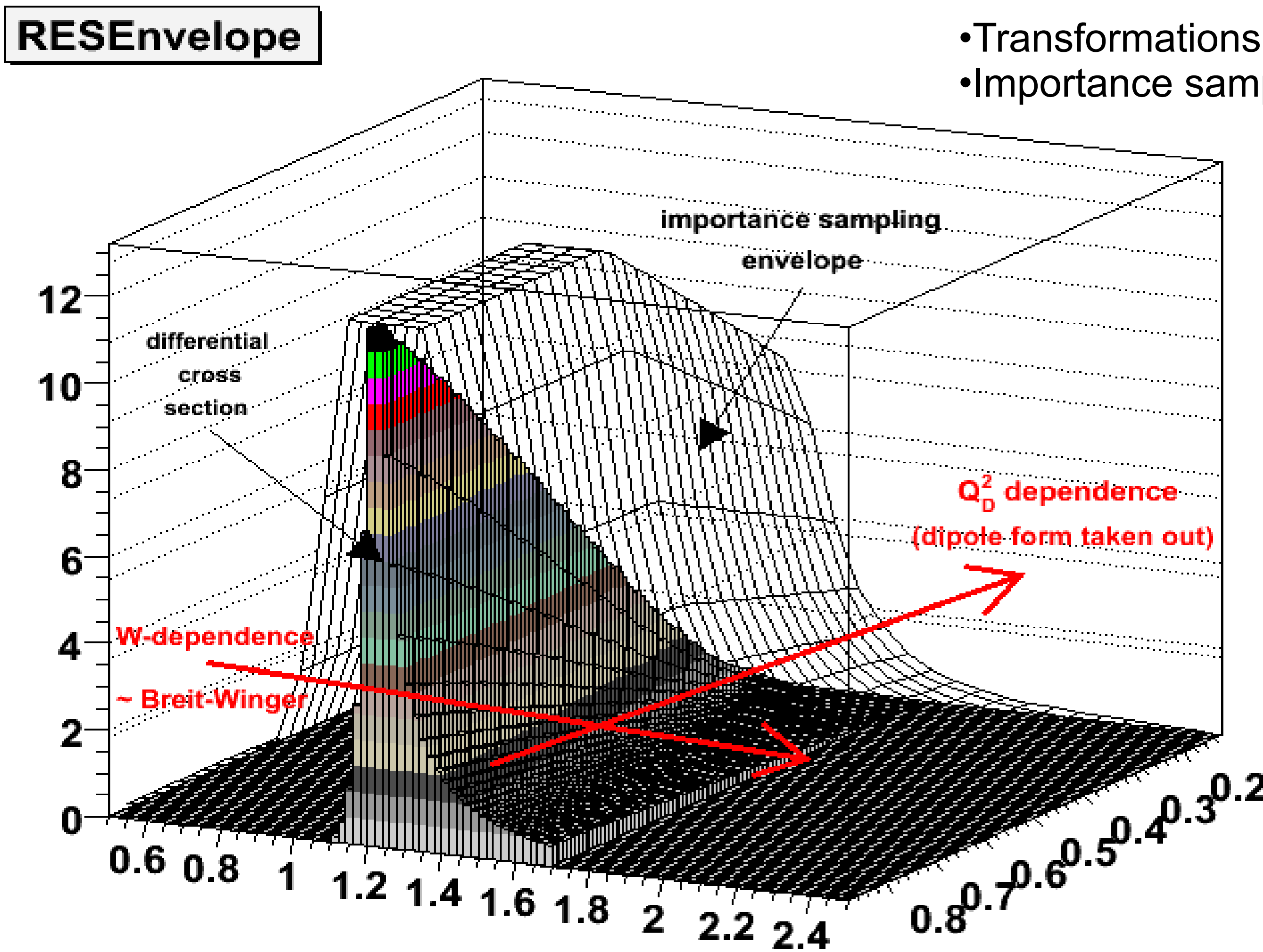
Need to <u>scan the phase space</u> for the max differential cross section

- Computationally expensive
- Maximum cross section cached
    - Event generation speed improves with time

Inefficiency proportional to the fraction of the volume above the cross section surface:

•Transformations to flatten-out cross section
•Importance sampling

Selecting kinematical variables



- Transformations to flatten-out cross section
- Importance sampling

Generating final state primary lepton

```
|-----------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [shown using $GHEPPRINTLEVEL = 1]                                                         |
|-----------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|-----------------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 |  -1 |  -1 |   3 |   3 |   0.000 |   0.000 |   3.000 |   3.000 |   0.000 |
|   1 |          Fe56 |   0 | 1000260560 |  -1 |  -1 |   2 |   2 |   0.000 |   0.000 |   0.000 |  52.103 |  52.103 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |  -1 |  -1 |   0.163 |  -0.041 |   0.185 |   0.931 | **0.940 | M = 0.897
|   3 |           mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |  -0.200 |   0.075 |   1.184 |   1.208 |   0.106 | P = (0.166,-0.062,-0.984)
|-----------------------------------------------------------------------------------------------------------------|
|       Fin-Init:|     |            |           |           |  -0.200 |   0.075 |  -1.816 | -53.895 |         |
|-----------------------------------------------------------------------------------------------------------------|
|       Vertex:  |       nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =              0 s) |
|-----------------------------------------------------------------------------------------------------------------|
|       FLAGS:   | UnPhys: [OFF] | ErrBits[16->0]:00000000000000000 | 1stSet:                                 none|
|-----------------------------------------------------------------------------------------------------------------|
```

Adding primary hadronic system / decay

```
|-------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [shown using $GHEPPRINTLEVEL = 1]                                                    |
|-------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m |
|-------------------------------------------------------------------------------------------------------------|
|   0 |         nu_mu |   0 |         14 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 |   3.000 |   3.000 |   0.000 |
|   1 |          Fe56 |   0 | 1000260560 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  52.103 |  52.103 |
|   2 |       neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |   0.163 |  -0.041 |   0.185 |   0.931 | **0.940 | M = 0.897
|   3 |          Fe55 |   1 | 1000260550 |   1 |  -1 |  -1 |  -1 |  -0.163 |   0.041 |  -0.185 |  51.172 |  51.172 |
|   4 |           mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |  -0.200 |   0.075 |   1.184 |   1.208 |   0.106 | P = (0.166,-0.062,-0.984)
|   5 |      HadrSyst |  12 | 2000000001 |   2 |  -1 |   6 |   7 |   0.362 |  -0.116 |   2.001 |   2.723 | **0.000 | M = 1.808
|   6 |        proton |  14 |       2212 |   5 |  -1 |  -1 |  -1 |   0.049 |  -0.516 |   0.603 |   1.230 |   0.938 |
|   7 |           pi0 |  14 |        111 |   5 |  -1 |  -1 |  -1 |   0.314 |   0.400 |   1.398 |   1.494 |   0.135 |
|-------------------------------------------------------------------------------------------------------------|
|       Fin-Init:|     |            |           |           |  -0.362 |   0.116 |  -2.001 |  -2.723 |         |
|-------------------------------------------------------------------------------------------------------------|
|       Vertex:  |       nu_mu @ (x =     0.00000 m, y =     0.00000 m, z =     0.00000 m, t =             0 s)  |
|-------------------------------------------------------------------------------------------------------------|
|       FLAGS:   | UnPhys: [OFF] | ErrBits[16->0]:0000000000000000 | 1stSet:                                 none|
|-------------------------------------------------------------------------------------------------------------|
```

Transport primary hadrons

Simulate re-interactions, de-excitations.
Subtract binding energies as nucleons leave nucleus

```
|------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [shown using $GHEPPRINTLEVEL = 1]                                                          |
|------------------------------------------------------------------------------------------------------------------|
| Idx |       Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |       m  |
|------------------------------------------------------------------------------------------------------------------|
|   0 |      nu_mu |   0 |         14 |  -1 |  -1 |   4 |   4 |   0.000 |   0.000 |   3.000 |   3.000 |   0.000 |
|   1 |       Fe56 |   0 | 1000260560 |  -1 |  -1 |   2 |   3 |   0.000 |   0.000 |   0.000 |  52.103 |  52.103 |
|   2 |    neutron |  11 |       2112 |   1 |  -1 |   5 |   5 |   0.163 |  -0.041 |   0.185 |   0.931 | **0.940 | M = 0.897
|   3 |       Fe55 |   2 | 1000260550 |   1 |  -1 |  10 |  10 |  -0.163 |   0.041 |  -0.185 |  51.172 |  51.172 |
|   4 |        mu- |   1 |         13 |   0 |  -1 |  -1 |  -1 |  -0.200 |   0.075 |   1.184 |   1.208 |   0.106 | P = (0.166,-0.062,-0.984)
|   5 |   HadrSyst |  12 | 2000000001 |   2 |  -1 |   6 |   7 |   0.362 |  -0.116 |   2.001 |   2.723 | **0.000 | M = 1.808
|   6 |     proton |  14 |       2212 |   5 |  -1 |   8 |   8 |   0.049 |  -0.516 |   0.603 |   1.230 |   0.938 |
|   7 |        pi0 |  14 |        111 |   5 |  -1 |   9 |   9 |   0.314 |   0.400 |   1.398 |   1.494 |   0.135 |
|   8 |     proton |   1 |       2212 |   6 |  -1 |  -1 |  -1 |   0.049 |  -0.516 |   0.603 |   1.230 |   0.938 |
|   9 |        pi0 |   1 |        111 |   7 |  -1 |  -1 |  -1 |   0.227 |   0.384 |   1.419 |   1.494 |   0.135 |
|  10 |   HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |  -0.076 |   0.057 |  -0.206 |  51.172 | **0.000 | M = 51.172
|------------------------------------------------------------------------------------------------------------------|
|        Fin-Init:|     |            |           |           |   0.000 |  -0.000 |   0.000 |   0.000 |          |
|------------------------------------------------------------------------------------------------------------------|
|        Vertex:  |        nu_mu @ (x =      0.00000 m, y =      0.00000 m, z =      0.00000 m, t =            0 s) |
|------------------------------------------------------------------------------------------------------------------|
|        FLAGS:   | UnPhys: [OFF] | ErrBits[16->0]:00000000000000000 | 1stSet:                                  none|
|------------------------------------------------------------------------------------------------------------------|
```

I hope you got a clear idea of the basic physics

and can now understand the `GENIE events'

More details on how to run GENIE to follow

Please browse the GENIE manual before-hand