Science & Technology Facilities Council
Rutherford Appleton Laboratory

The GENIE *

Neutrino Monte Carlo Generator

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

Costas Andreopoulos

GDR Neutrino – LPNHE Paris, April 28, 2009

Science & Technology Facilities Council

Outline

- GENIE Project overview / history
- **Physics in current production release**
- Improvements in upcoming releases
- *Interaction uncertainties / systematics – not to be covered in this talk*

The origins

GENIE evolved from primarily from ***neugen***
(G.Barr, E.Edgecock, H.Gallagher, A.Mann, G.Pearce et al.)

<u>Neugen developed for the Soudan2 expt.</u>

Soudan2:
A proton decay experiment in the ~80's

Back then:
νA a background!

Many models within GENIE have long development history and encapsulate significant expertise.

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 modern, Universal Neutrino MC

GENIE development at RAL, started ~2004

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 Project

Generates Events for Neutrino Interaction Experiments

A Neutrino Monte Carlo Generator (and extensive toolkit)

- ~120,000 lines
- Written in C++ following modern, OO design methodologies
- State of the art physics

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

Heavily re-developed for MINOS analyses

- Cross section model partially re-written / re-tuned.
- Hadronic simulations almost completely re-written.

Many year*FTE effort!

+

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GENIE Users

Primarily, the **current / near future medium energy (~1GeV) experiments**:

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

GENIE is already integrated with all of these experiments and being used for physics studies

NEUTRINO EXPT. SYNERGIES !!

On-going efforts to push validity range down to ~1 MeV (reactor, super-novae, SNS, ...)

- GENIE: (Nearly) universal generator
- An important tool for physics exploitation for the next decade+

Please find more information at **http://www.genie-mc.org**

Register at the mailing-list and don't hesitate asking questions!

The GENIE toolkit

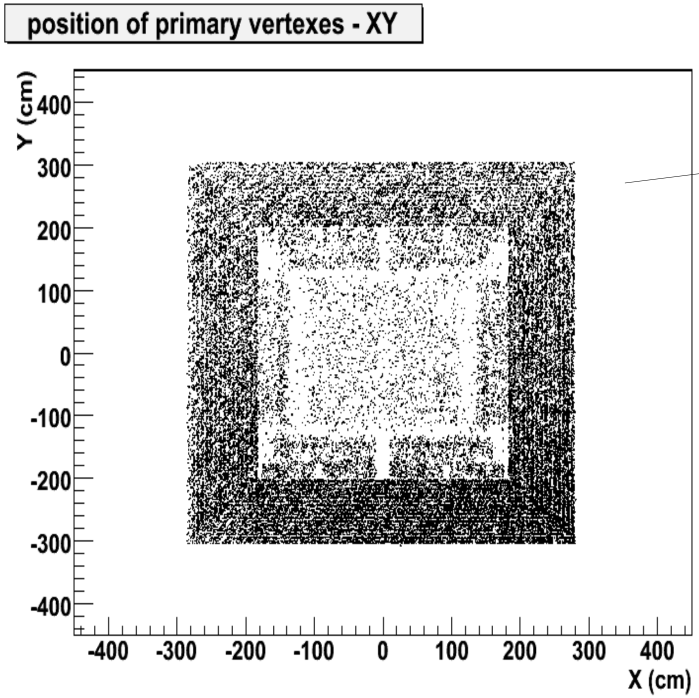
GENIE features an extensive toolkit, including tools for:

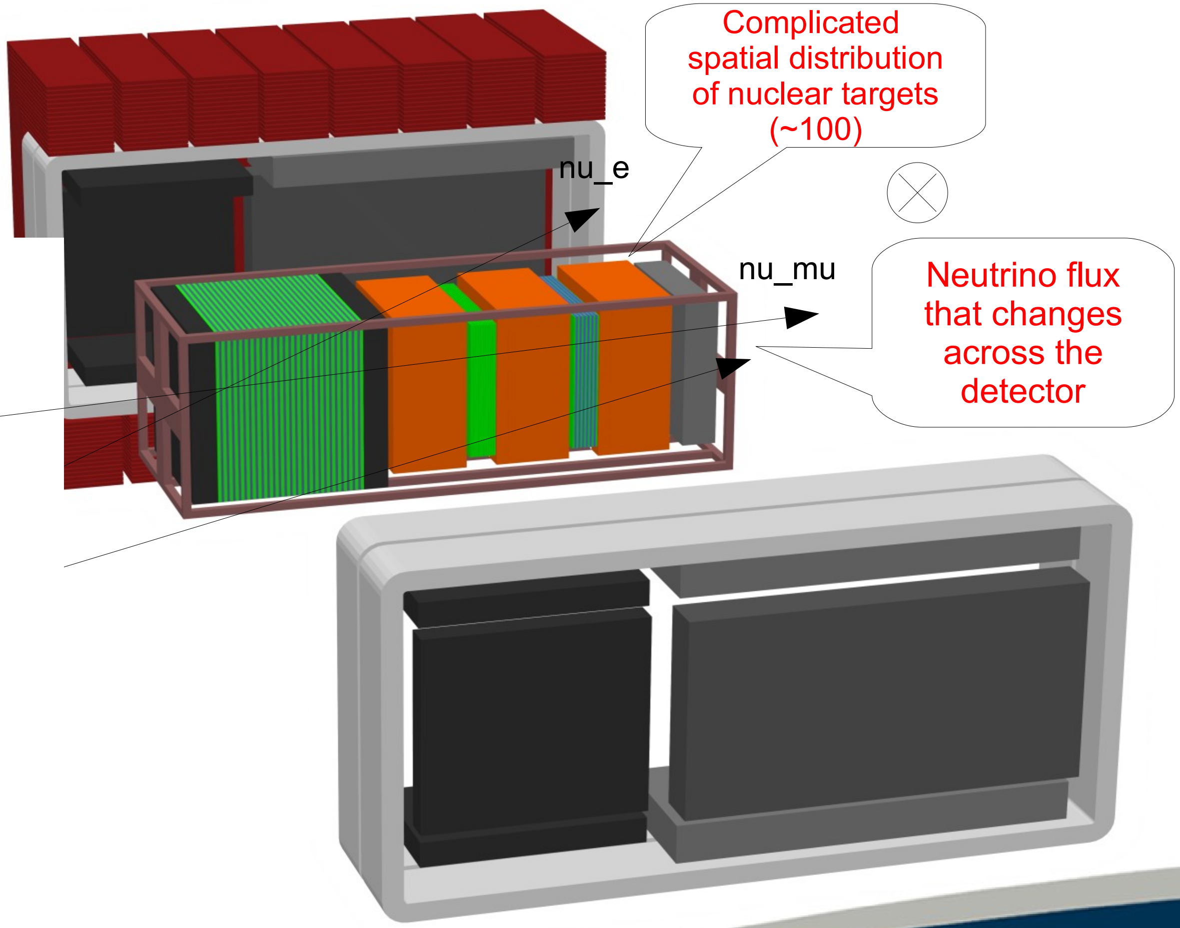
- Setting up realistic event generation jobs
- Propagating neutrino interaction uncertainties to physics analyses

Handling complex event generation cases

Event generation for realistic fluxes and detailed detector geometries using off-the-shelf components

Event generation:
A complicated convolution of flux (x) distribution of nuclear targets





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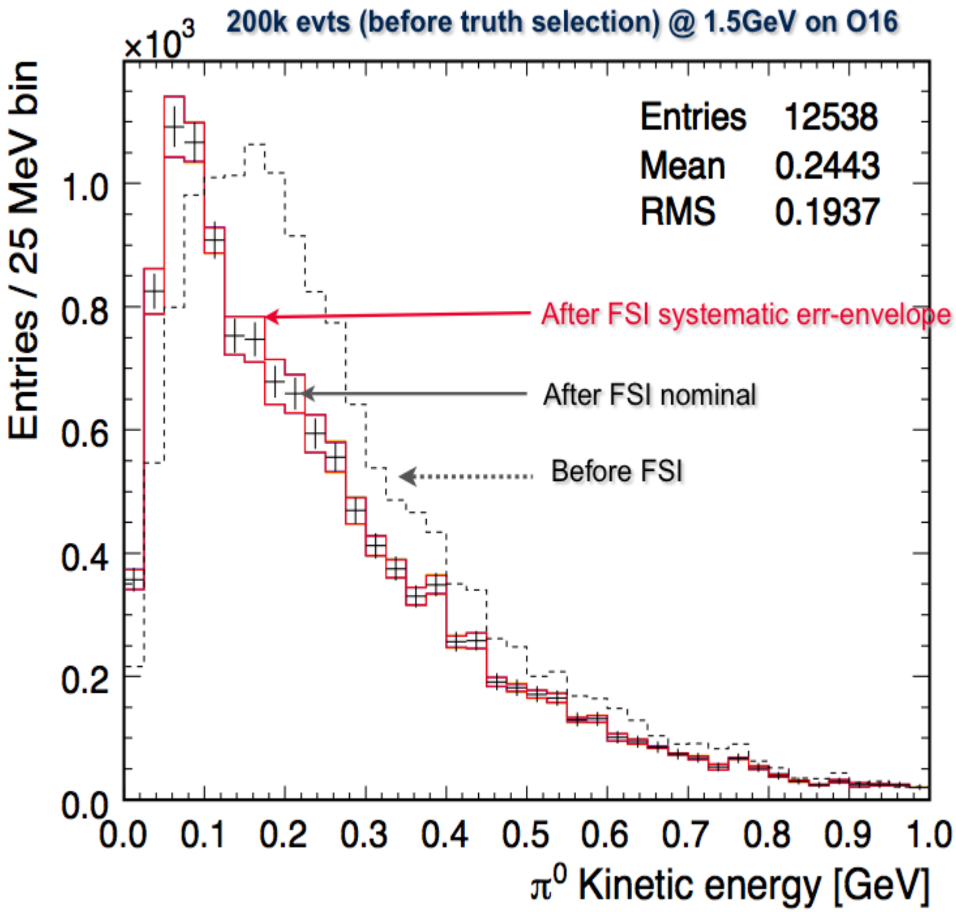
Event reweighing tools

For illustration:
NC1pi0 err envelope (Jim Dobson, CA, SD)



GENIE-based reweighing tools encapsulate significant expertise in quantifying neutrino interaction systematics *(minos, t2k)*

Physics in latest GENIE production release

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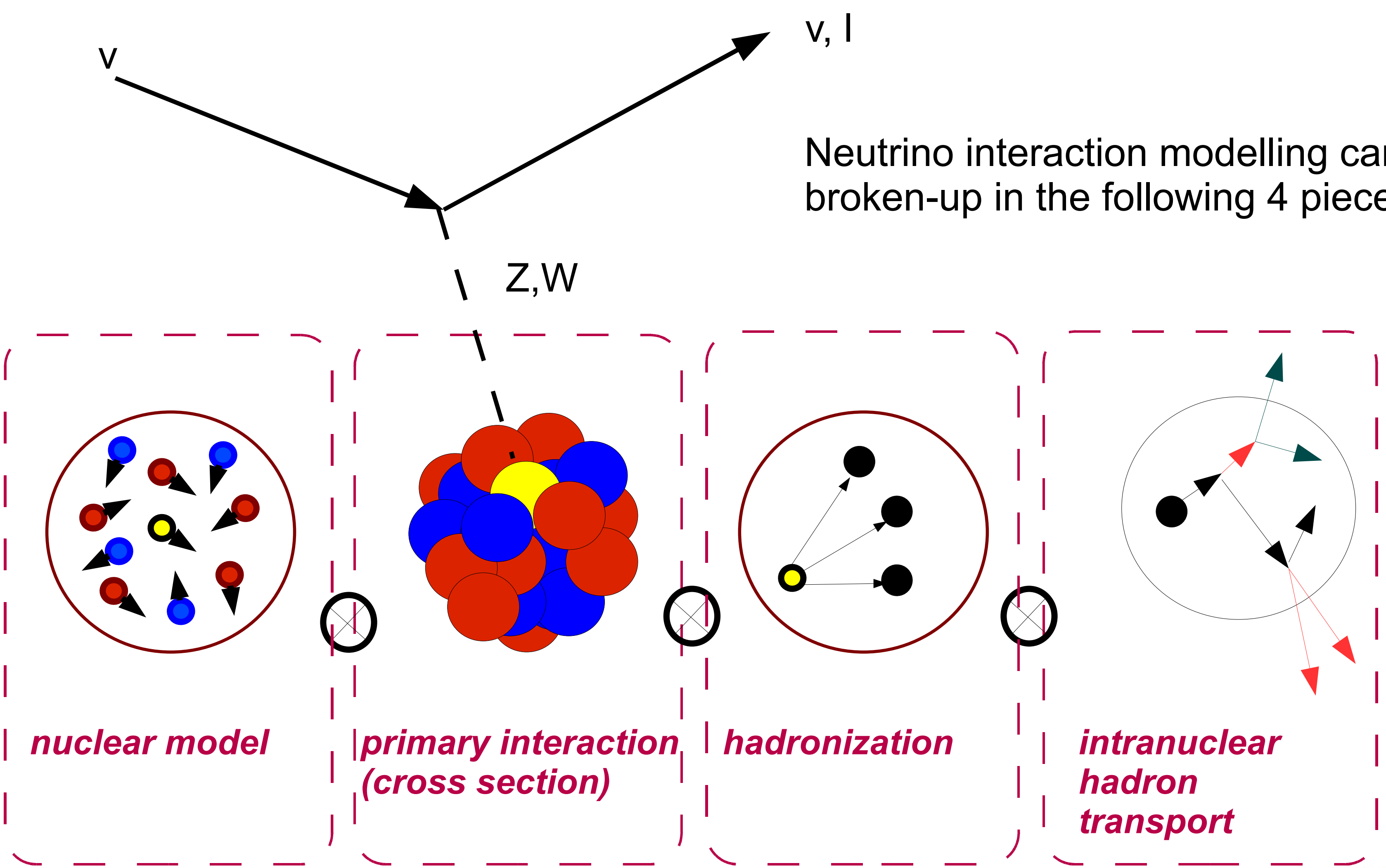
Neutrino Interaction Simulation `steps'



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

Note: A simplified picture

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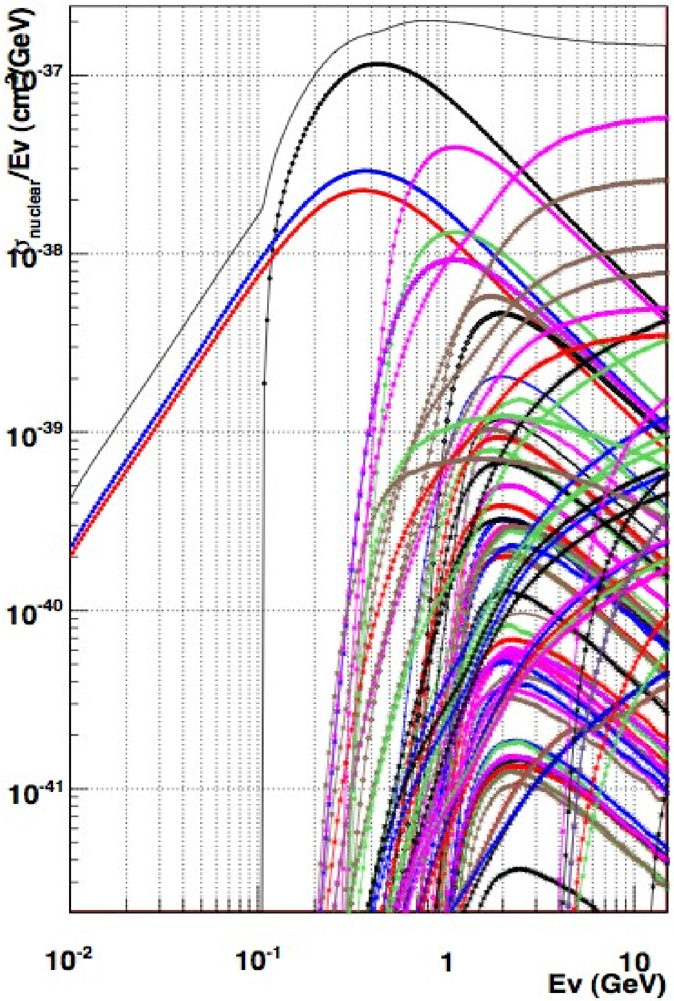
For illustration:
numu+O16 - All processes



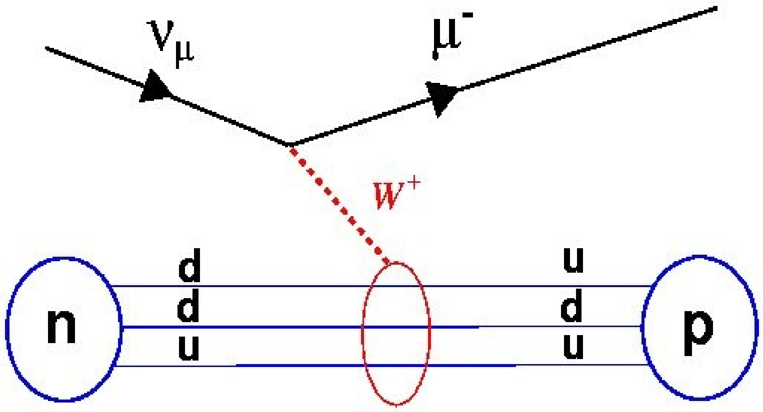
Cross section model in GENIE >>>

Current focus:

Ev from ~50 MeV to ~500 GeV

Quasi-elastic 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:

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

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

Quasi-elastic cross section

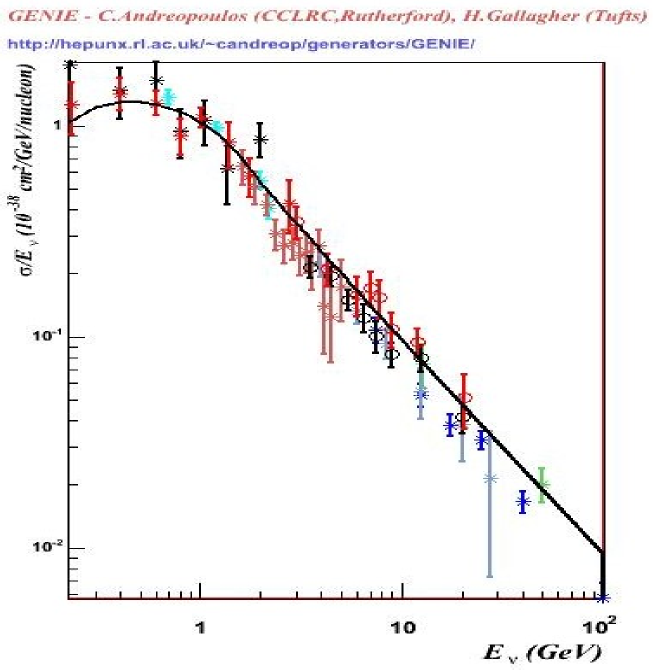
$$\frac{d\sigma^{\text{QES}}}{dQ^2} = \frac{G_F^2 \cos^2\theta_C M^2 \kappa^2}{2\pi E_\nu^2}\left[A\left(q^2\right) + \left(\frac{s-u}{4M^2}\right) B\left(q^2\right) + \left(\frac{s-u}{4M^2}\right)^2 C\left(q^2\right)\right]$$

A,B,C = *f* (FA, Fv1, Fv2)

vector form factors:
determined from e-N via CVC

dipole axial form factor:

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



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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

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

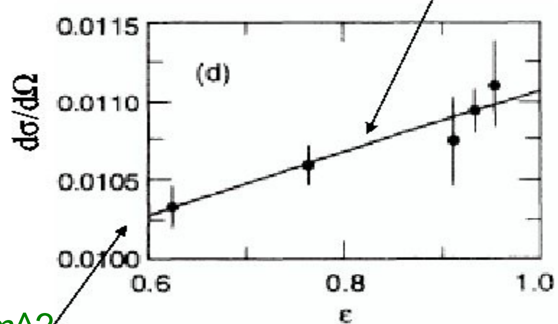
$$G_M^V(Q^2) = G_{mp}(Q^2) - G_{mn}(Q^2)$$

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*

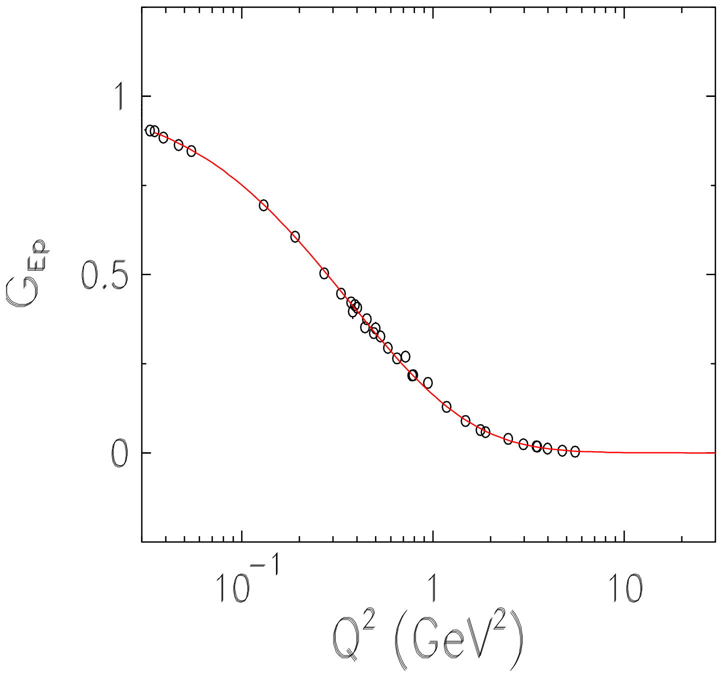
- ***Polarization measurements:***

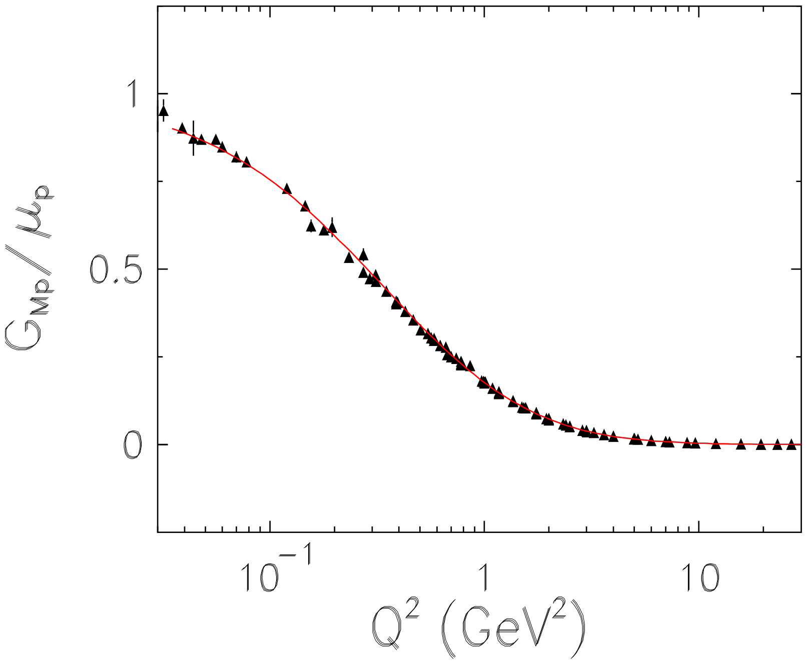
$$\frac{G_e}{G_m} = -\frac{P_t}{P_l} \frac{(E_e + E_{e'})}{2M} \tan\left(\frac{\theta_e}{2}\right)$$

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

Elastic nucleon form factors: Beyond the dipole ones

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





[R.Bradford et al, NuINT05]

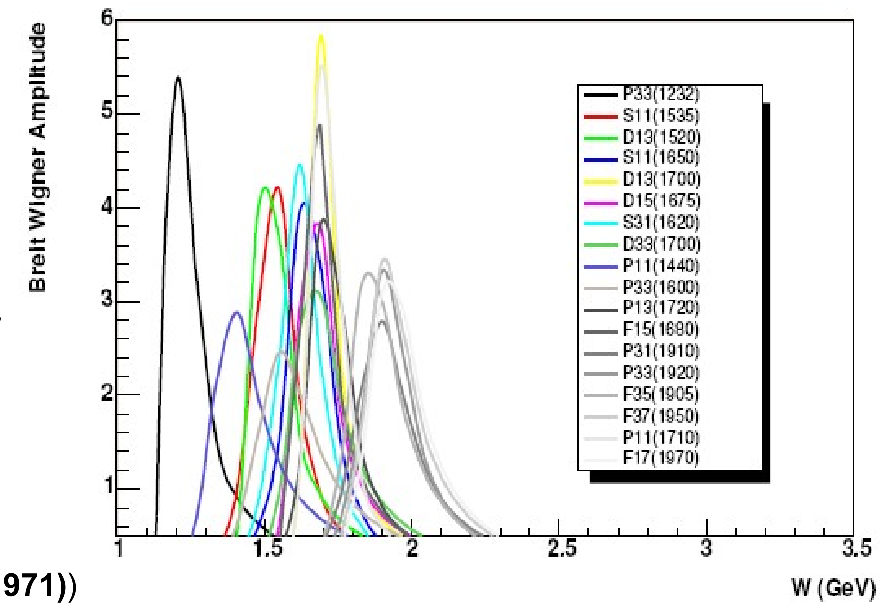
- GENIE includes all Sachs, BBA2003 and BBA2005 parameterizations
- BBA2005 is the default.

Resonance Neutrino-Production

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

- ~30% of the total CC xsec around ~ 1 GeV
- A number of resonances is considered
- Mostly single-pion final states; but a multitude of states are possible.

The most widely used model for resonance production
(*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

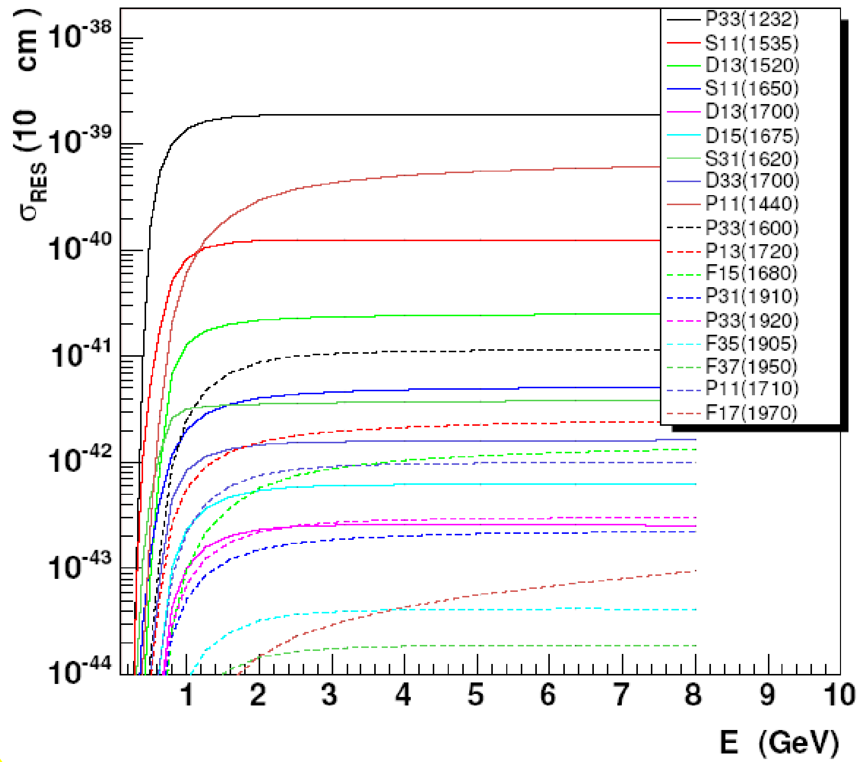
Axial & Vector transition form factors:
assuming dipole form Q^2 dependence

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

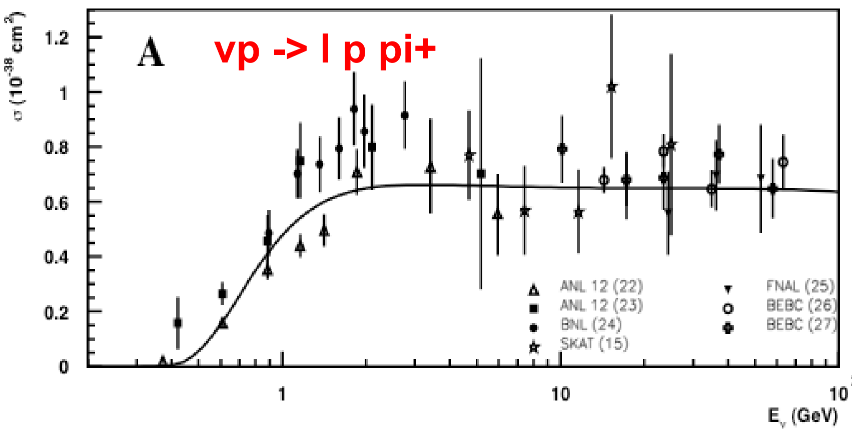
M_V=0.84 GeV/c^2, M_A~1 GeV/c^2 +/- 20%

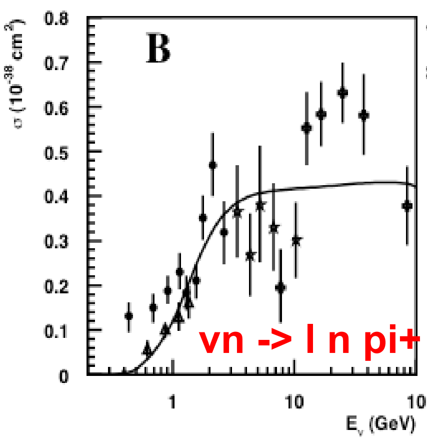
Resonance Neutrino-Production

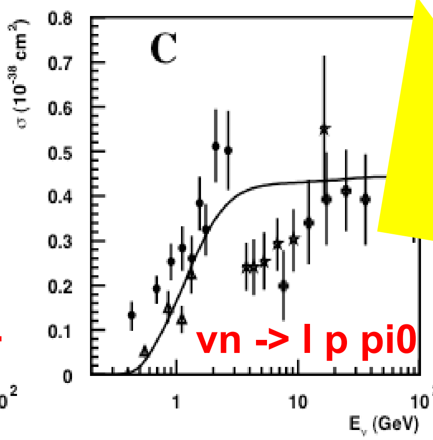
Resonance excitation cross sections
(as a function of energy / for muon neutrinos)



Single pion production cross sections



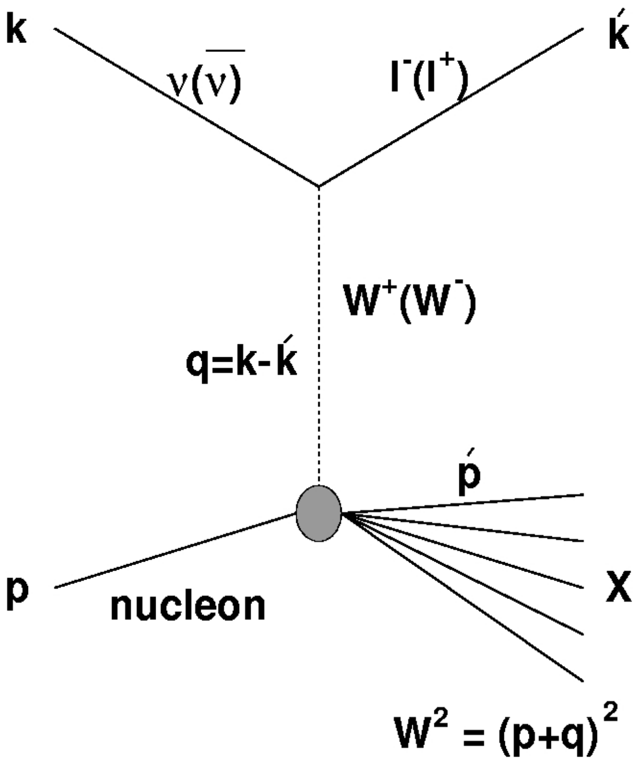


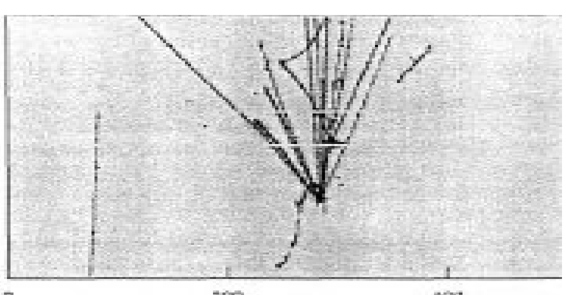


Include isospin amplitudes and 1pi BR to weight the contribution of each resonance to exclusive single pion reactions

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:

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

where:

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

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

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

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

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

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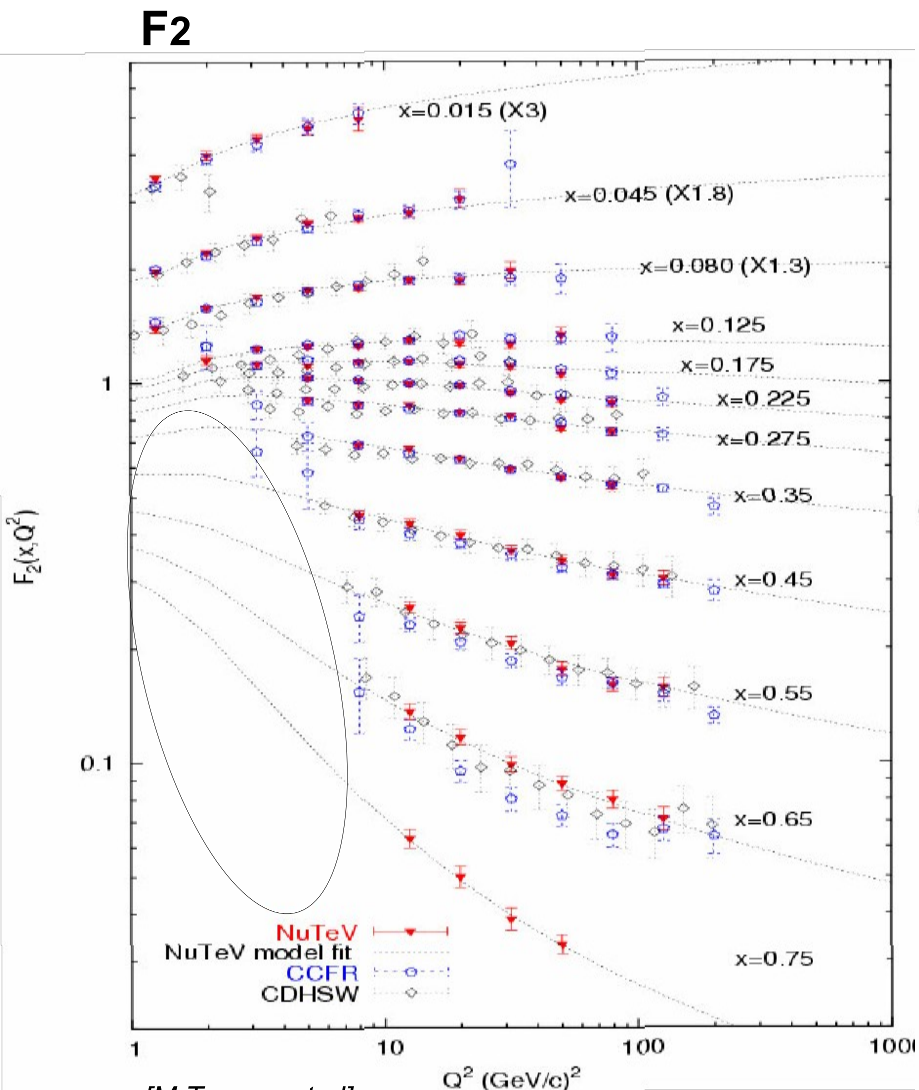
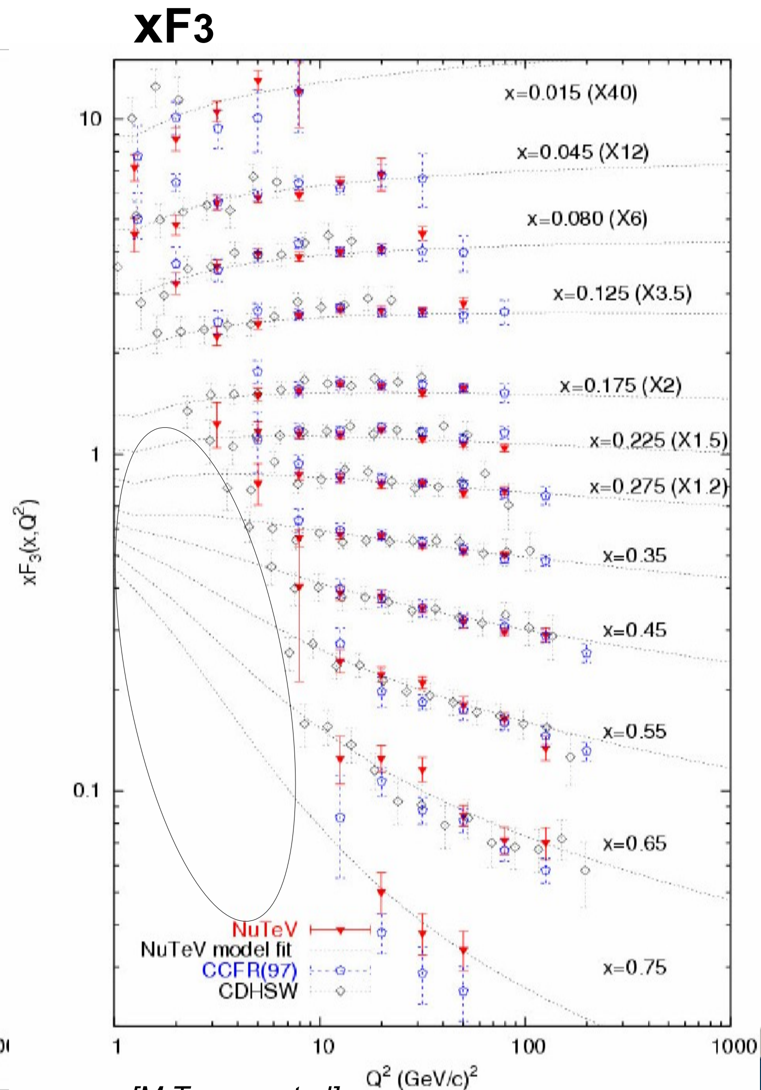
Deep Inelastic Scattering / Structure functions



[M.Tzanov et al]



[M.Tzanov et al]

Bodek / Yang model

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

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

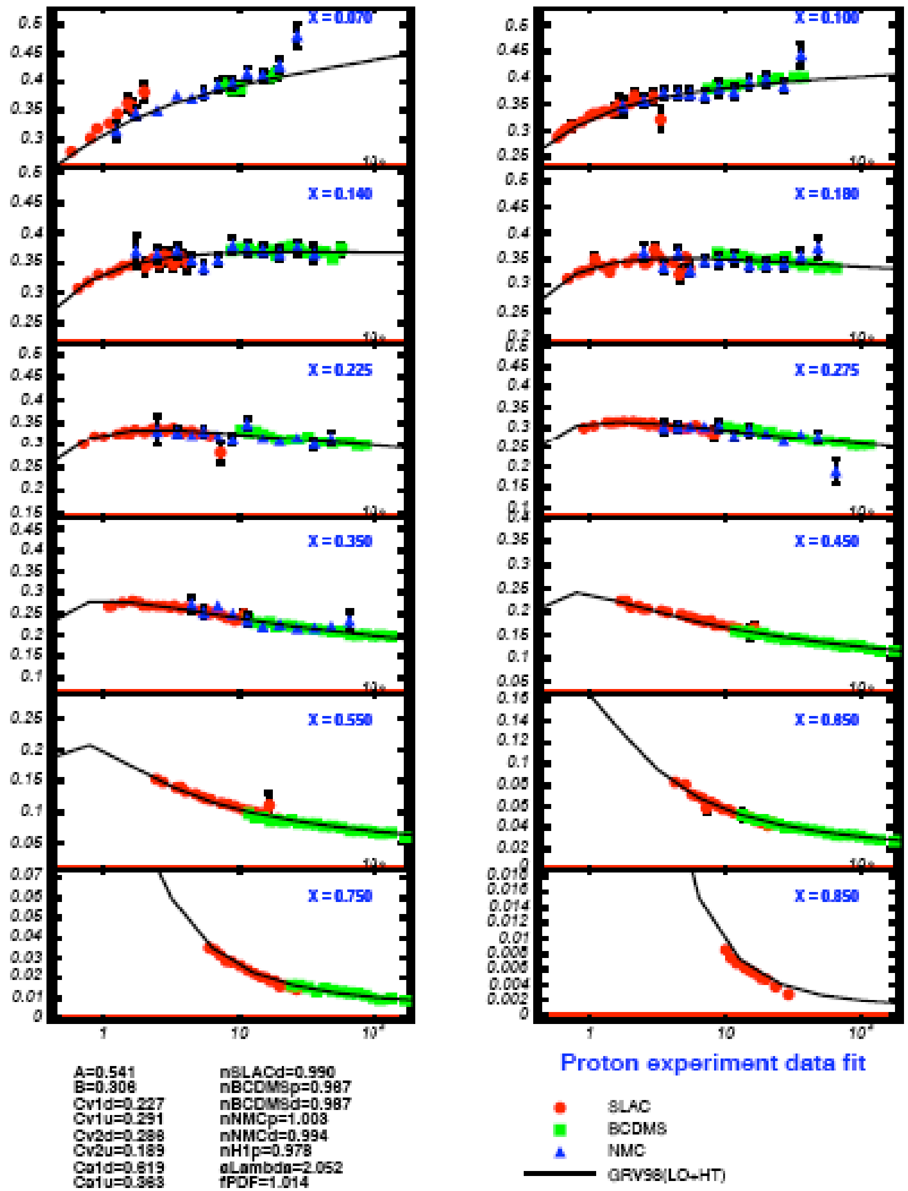
$$K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_s}$$

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

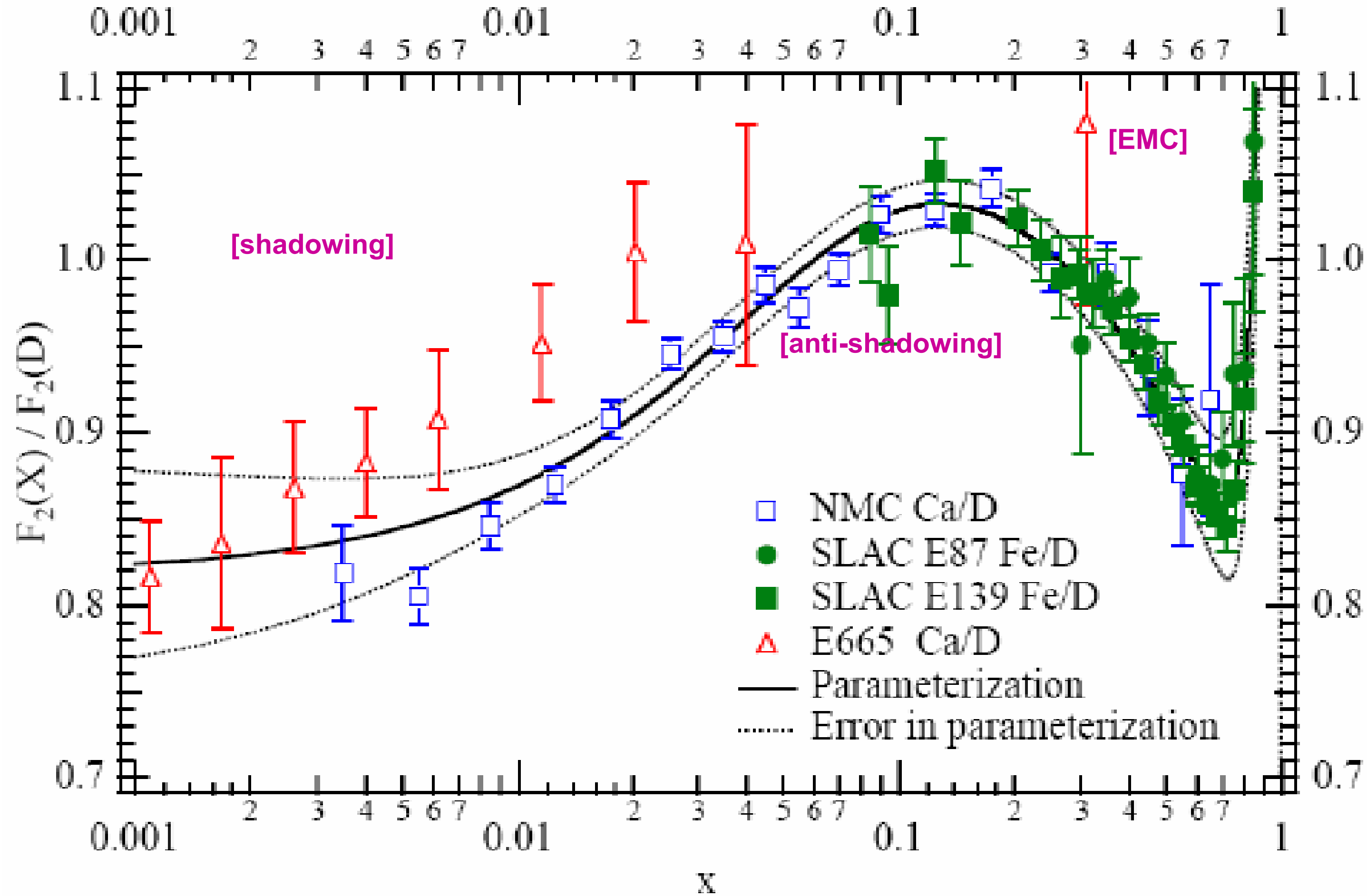
Fits based on GRV98LO and free nucleon charged lepton data

[hep-ph/0411202]

[Bodek & Yang]

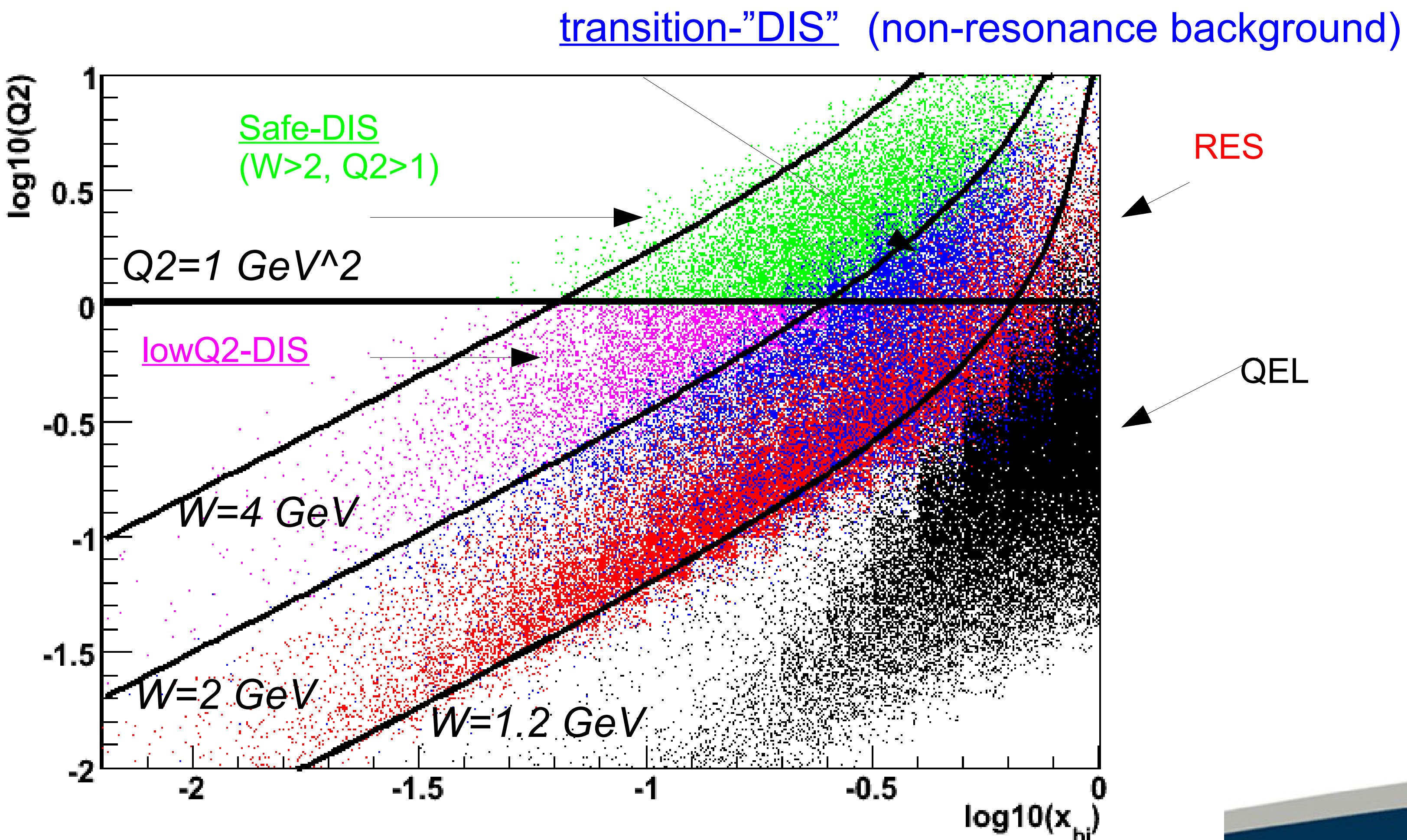


Deep Inelastic Scattering / Nuclear corrections



“Divide & conquer”

Kinematical coverage JPARC neutrino beam @ nd280 site



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Non-resonance bkg

Fraction of DIS 1pi and 2pi final states; with predicted kinematical (Q2,W) dependence

Added to resonance piece at W < 2 GeV

Fraction tuned to world's low multiplicity exclusive inelastic reaction data

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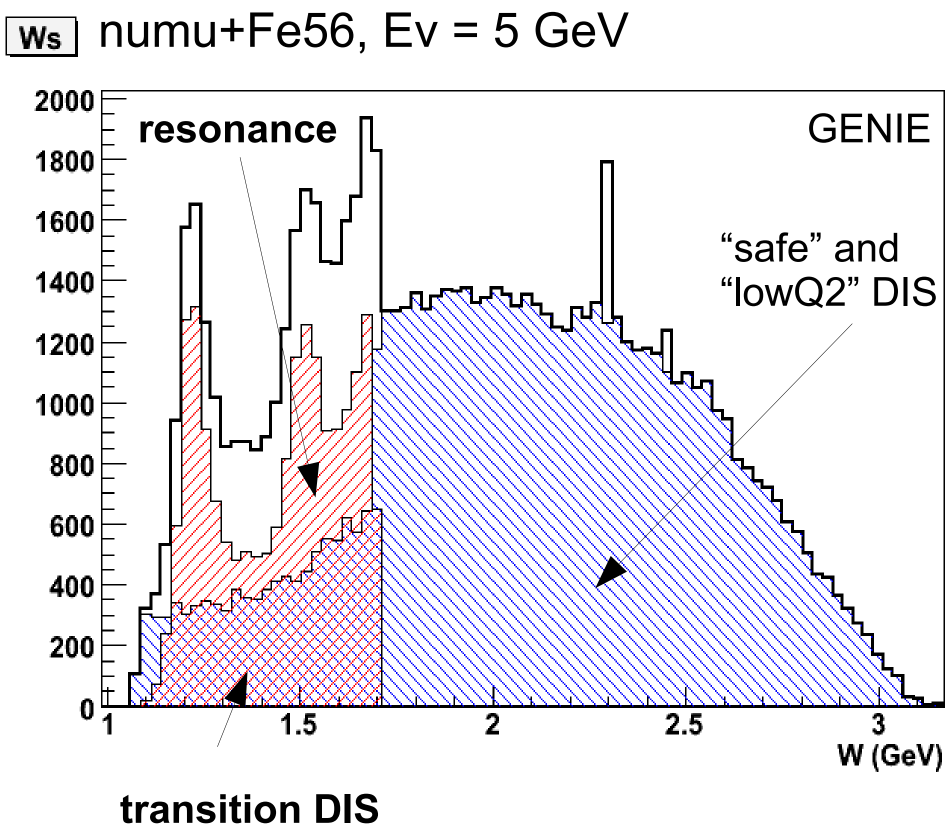
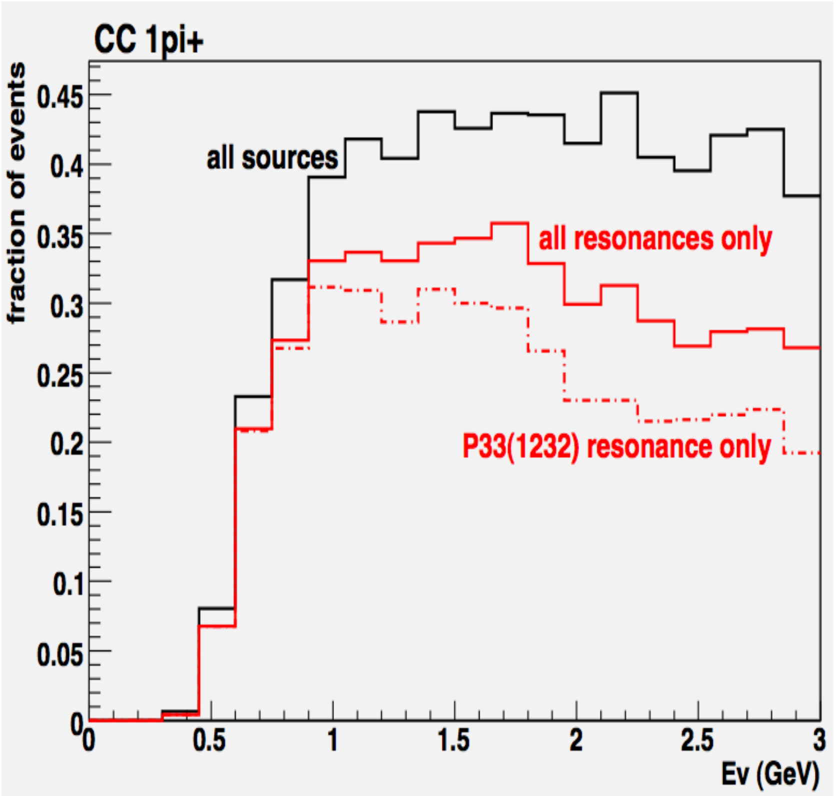
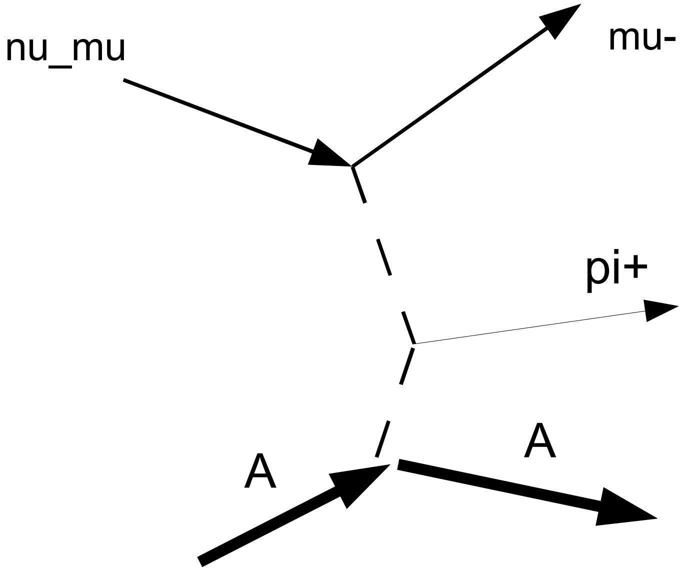
Putting everything together





Coherent meson 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.

For the time-being:

Ignore coherent production of vector mesons

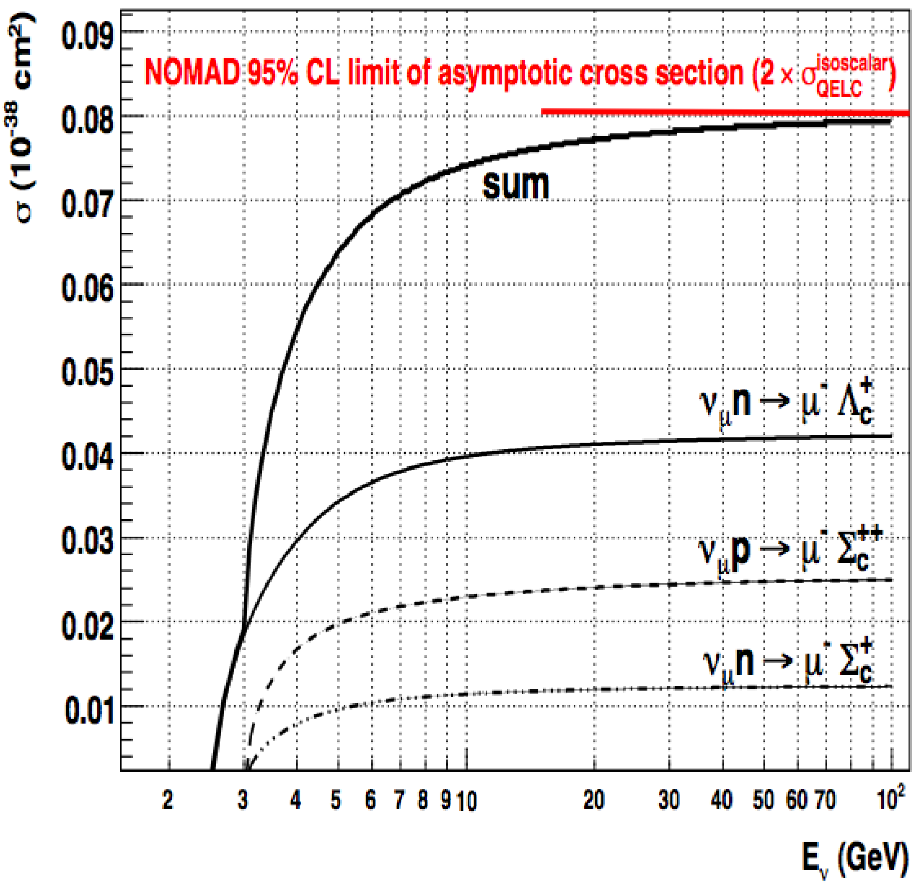
Ignore coherent production of photons

Ignore diffractive scattering

Charm production

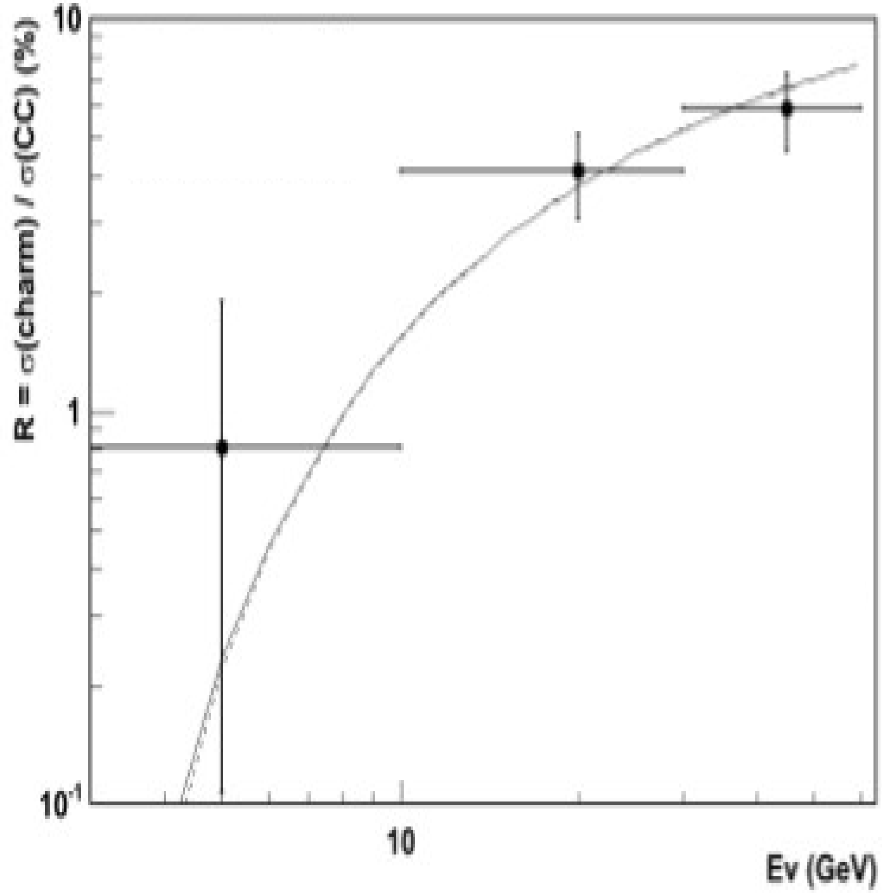
QEL

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



DIS

M.A.G.Aivazis, F.I.Olness and W.K.Tung

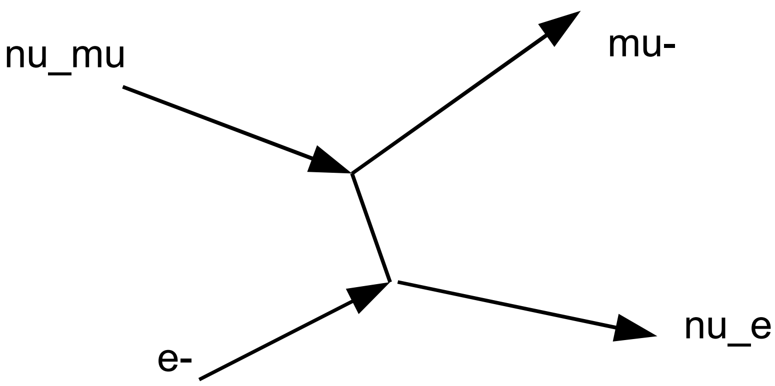


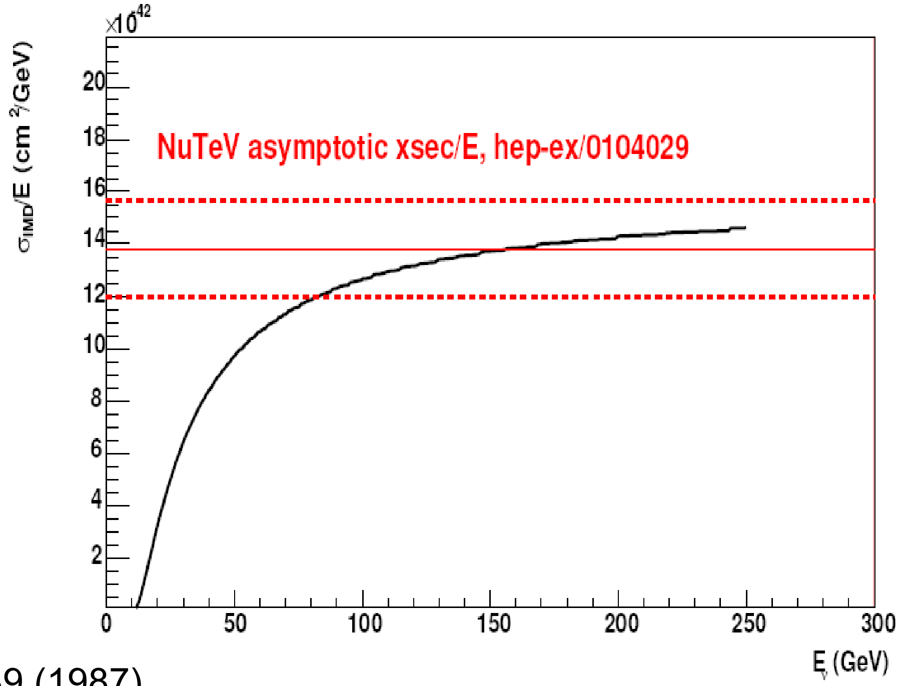
Neutrino-Electron scattering

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

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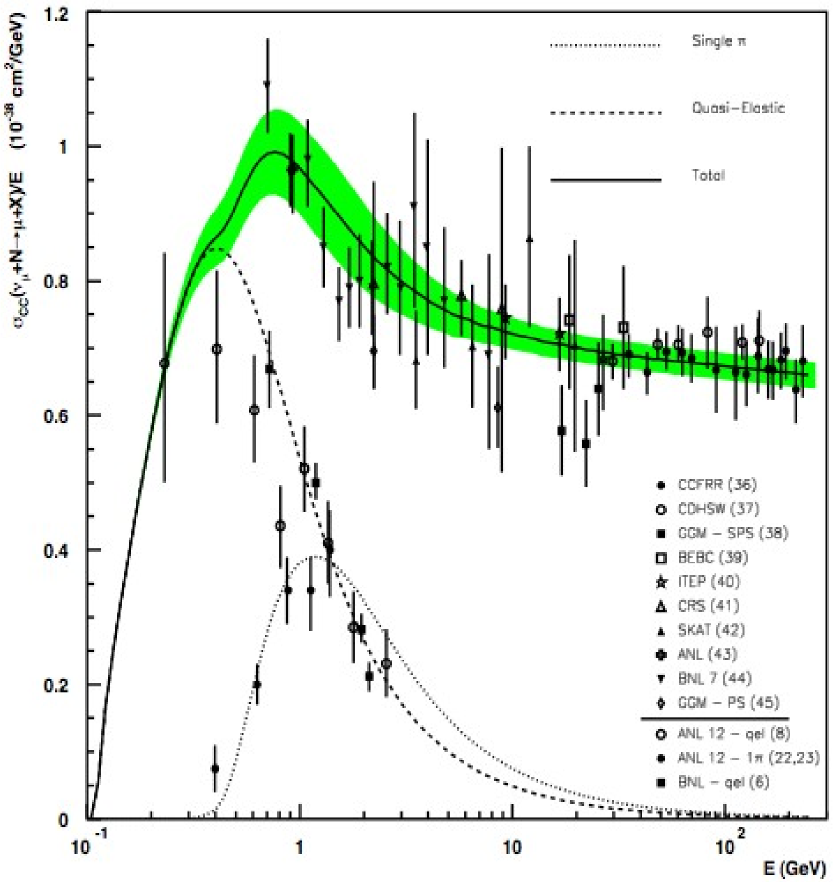
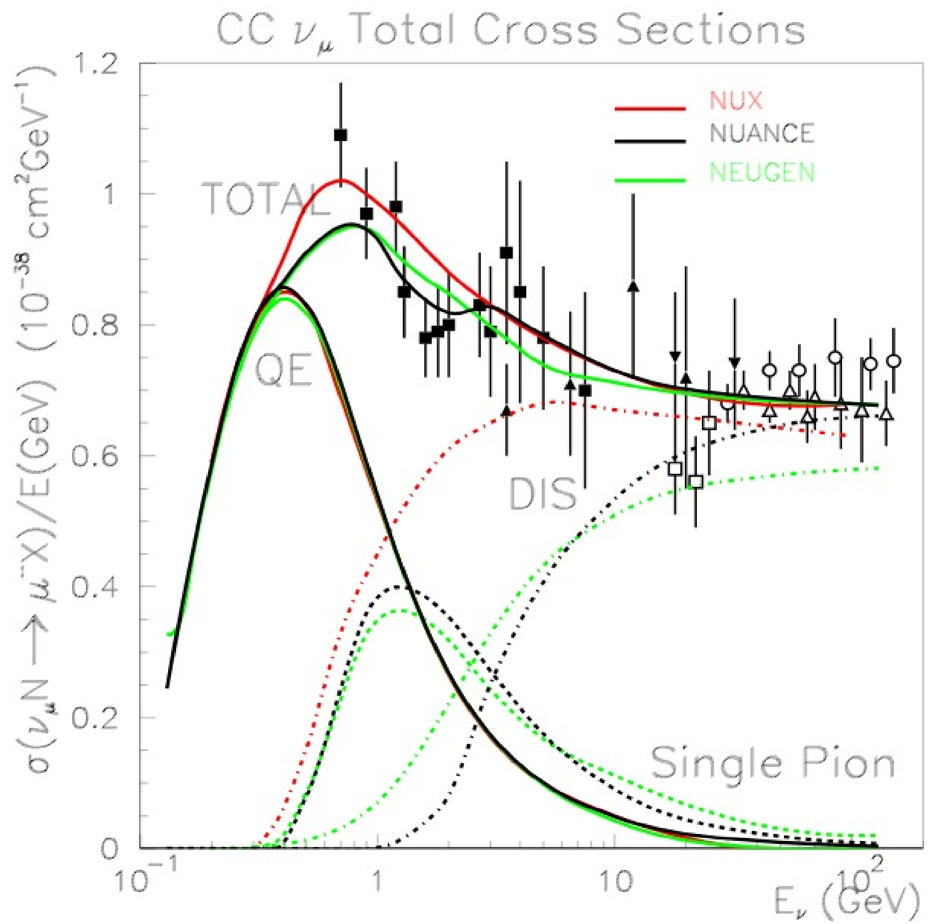
The GENIE cross section model

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



Sam Zeller. circa-2002 / Cross-generator comparisons



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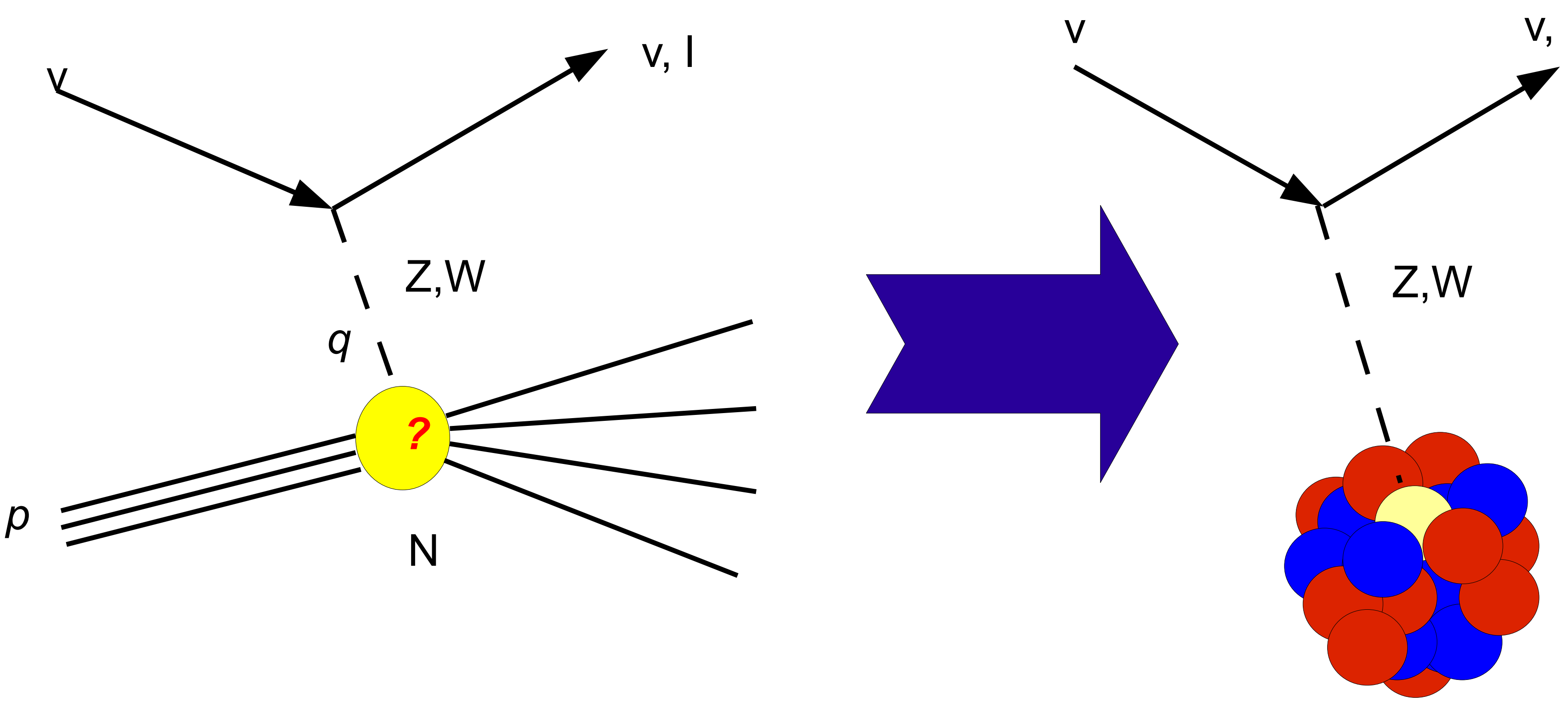
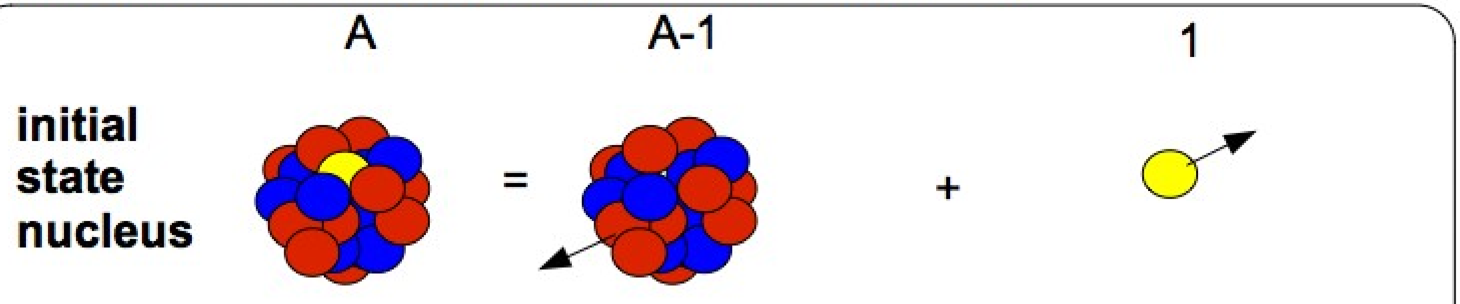
Free-nucleon cross section → Nuclear cross sections



Fermi Gas model in GENIE

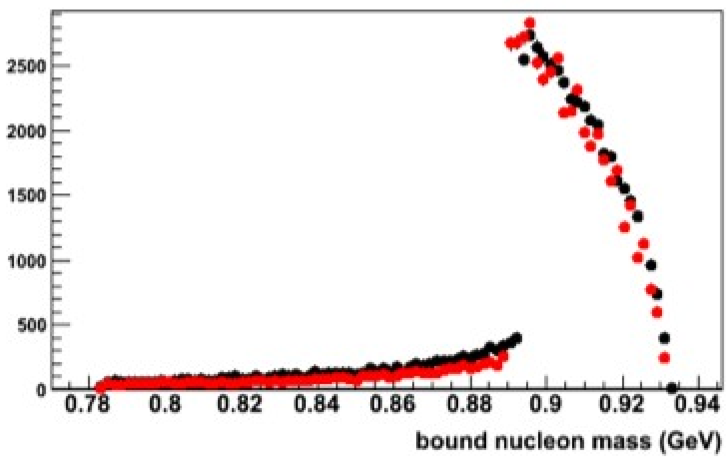


$p = -p_F$

$$E = \sqrt{M_{A-1}^2 + p_F^2}$$

$p = p_F$

$$E = M_A - \sqrt{M_{A-1}^2 + p_F^2}$$



Example;

Bound (off the shell) nucleon mass in Fe56

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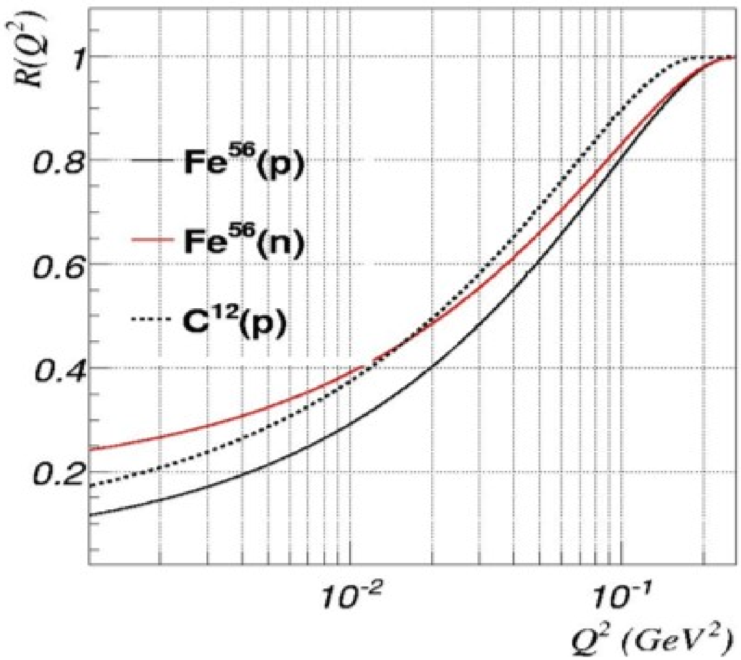
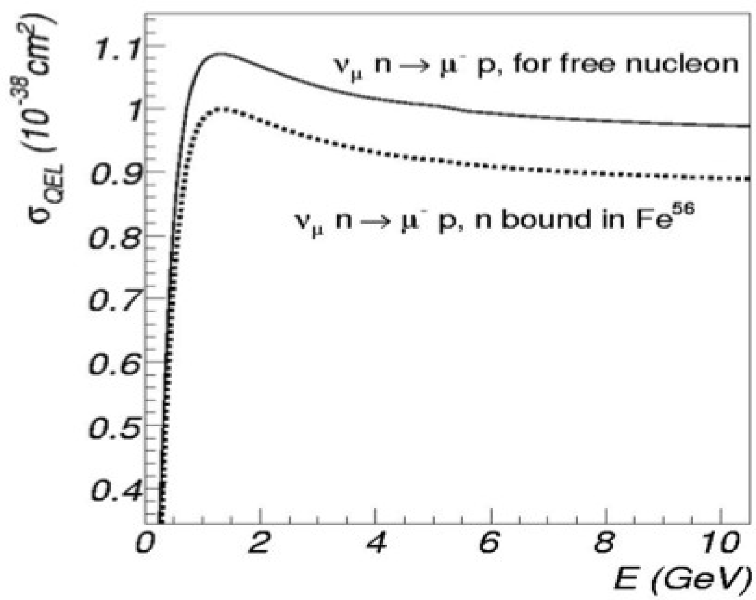
Quasi-elastic cross section for nuclear targets

Off-shell kinematics

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

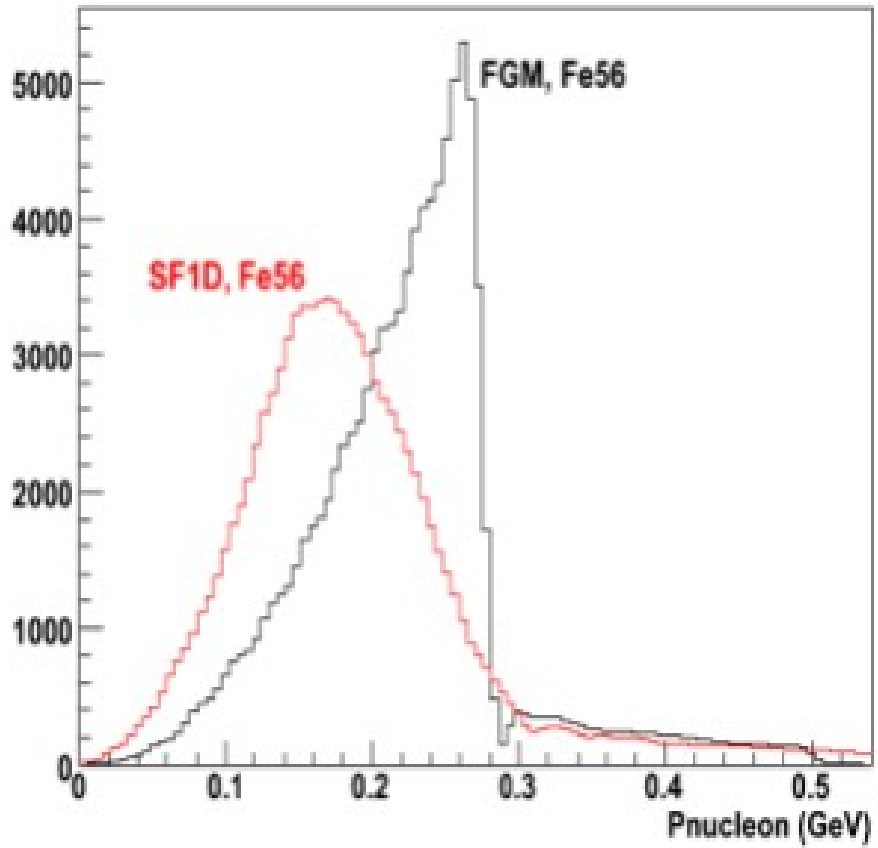


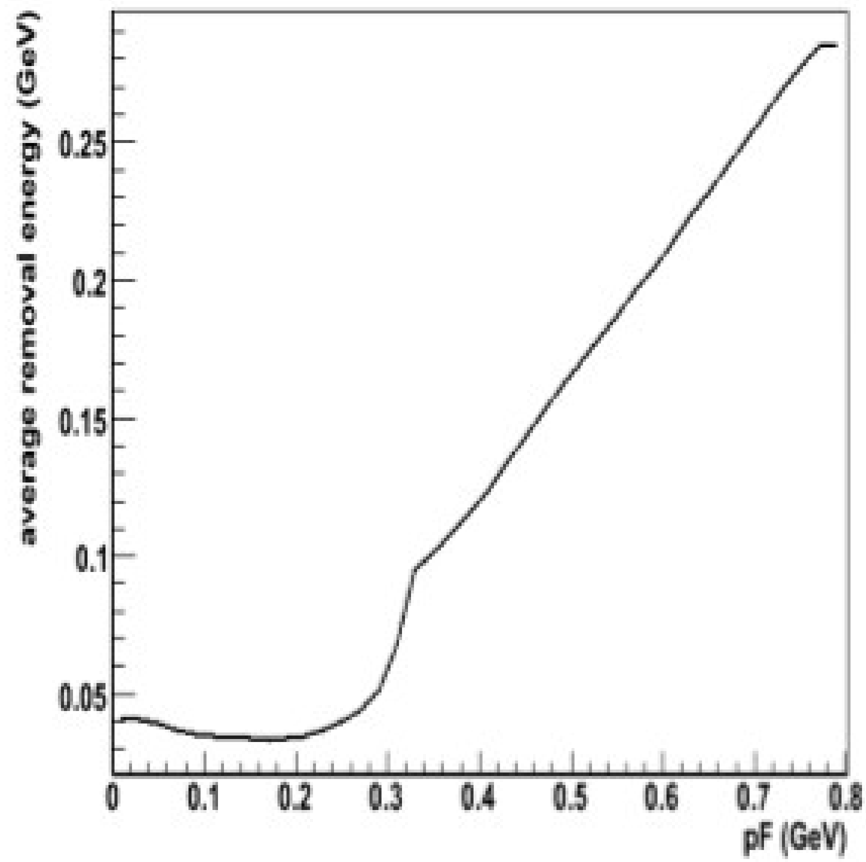


Moving to a spectral function implementation

Option currently available in GENIE

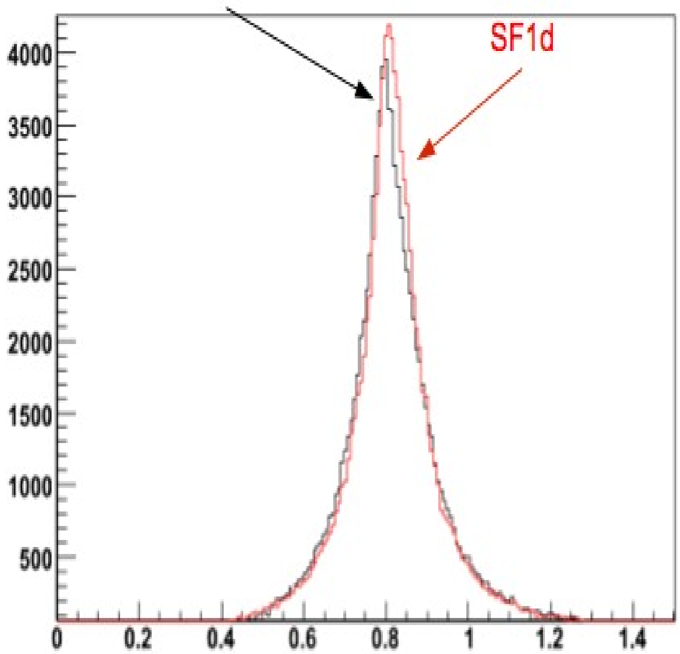
Switch to a S/F momentum profile and use the average binding energy at each momentum





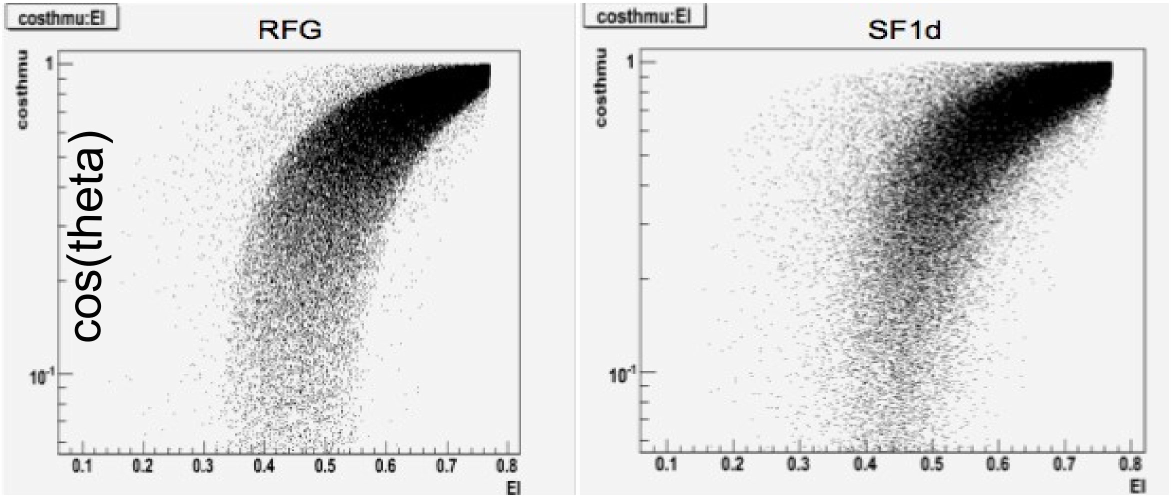
Moving to a spectral function implementation

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

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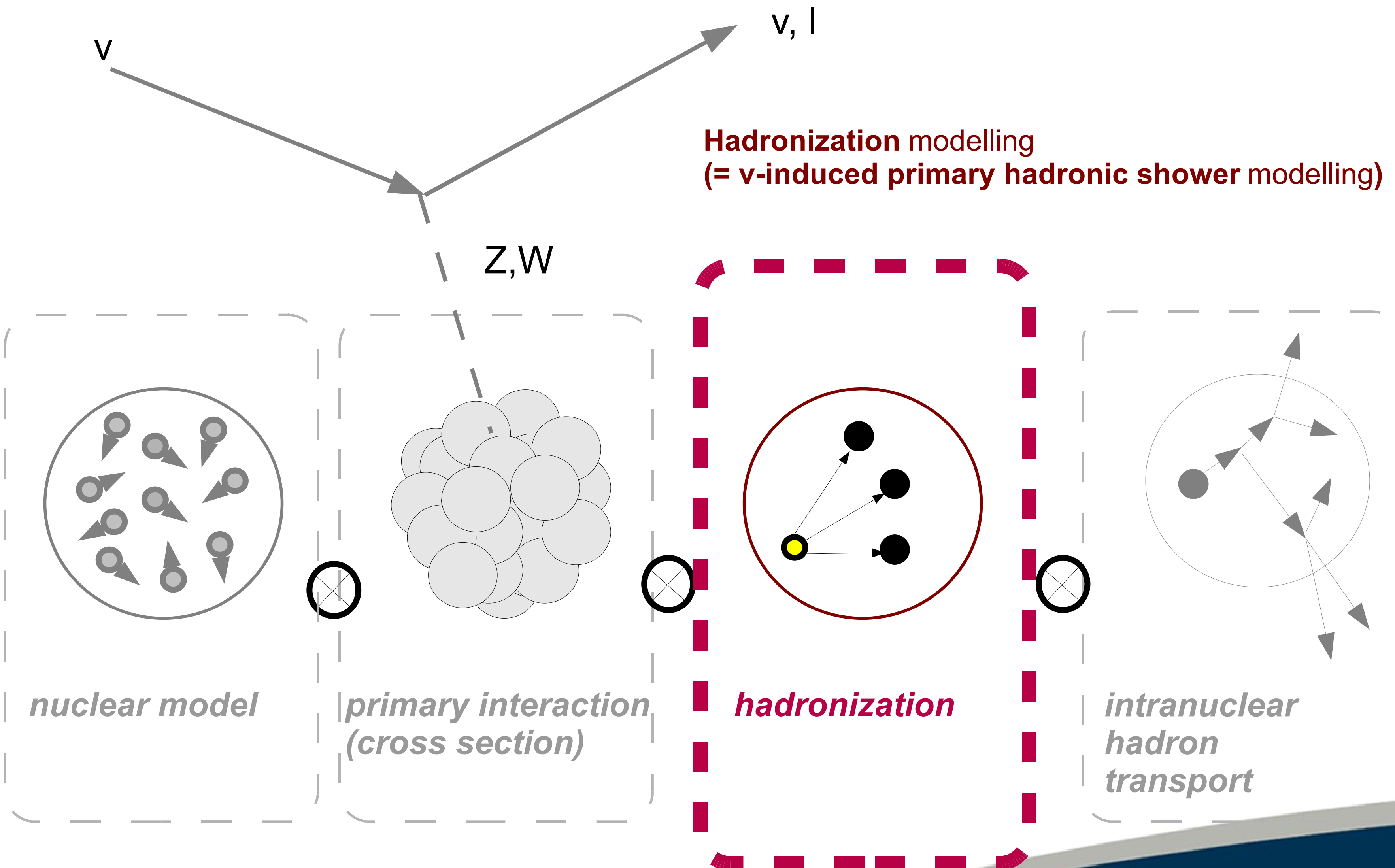
Hadronic simulations in GENIE
>>>

Hadronization modelling



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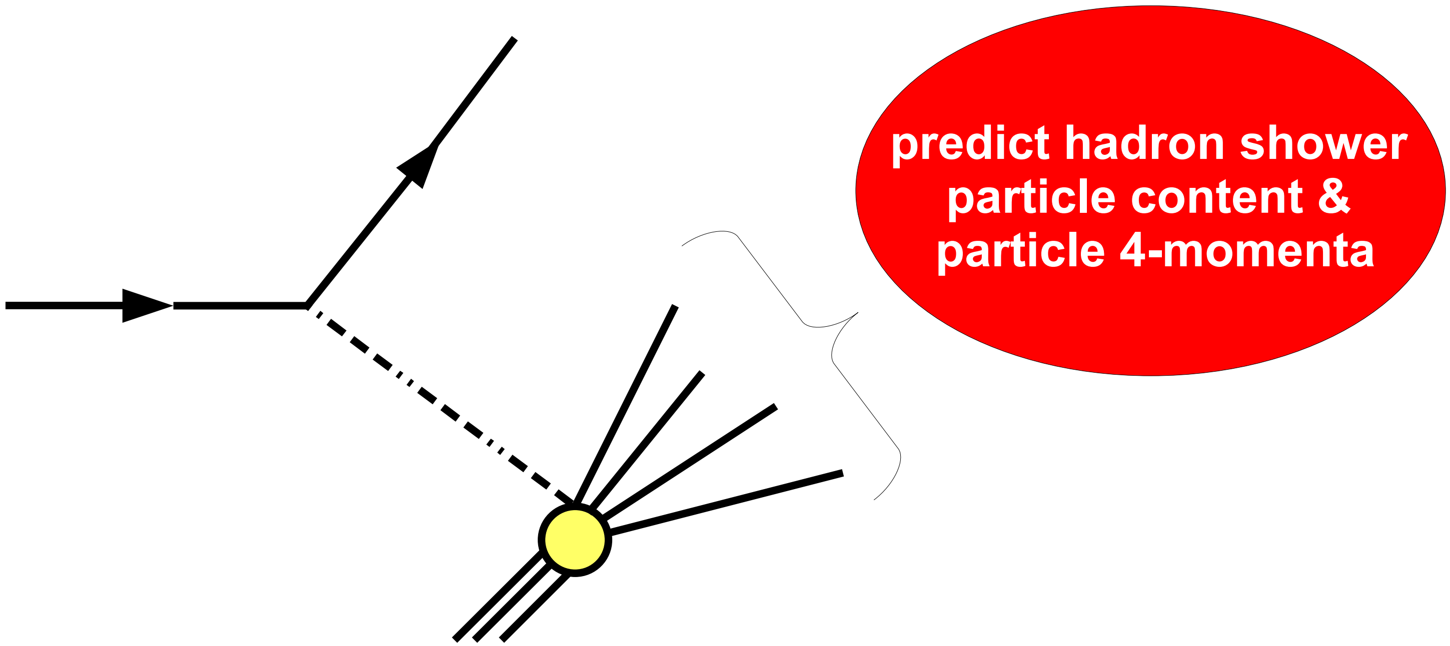
Hadronization modelling



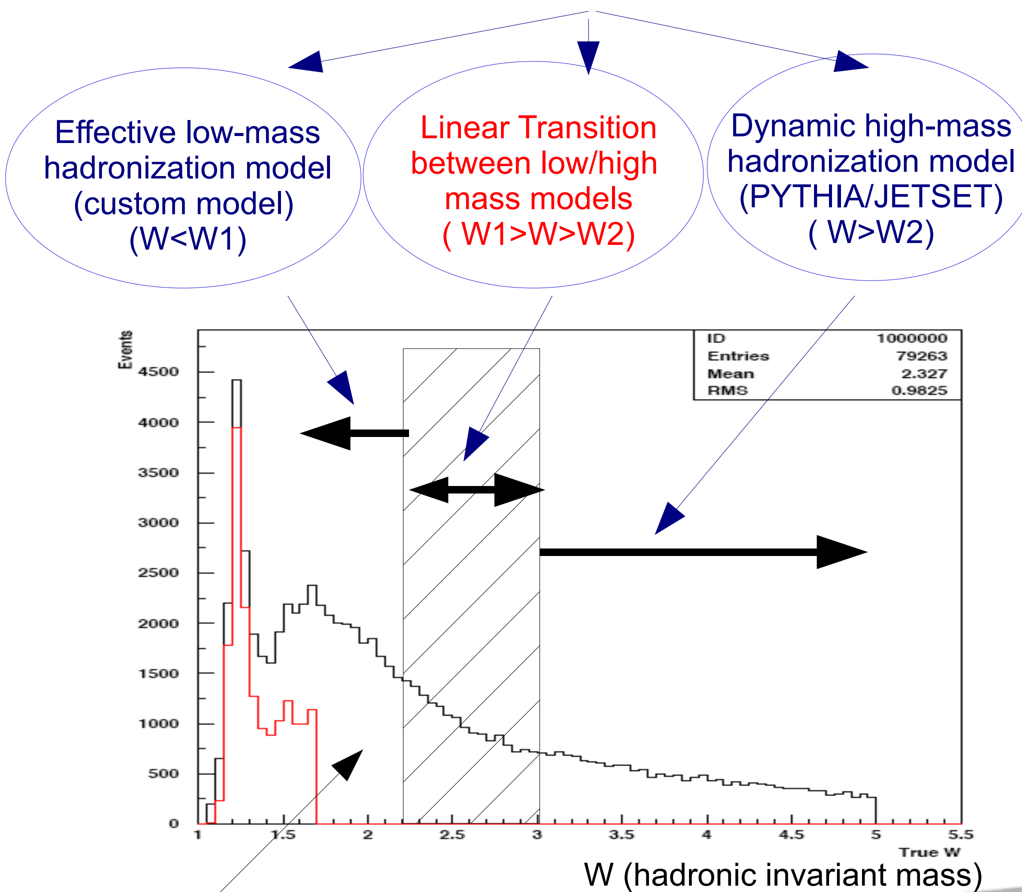
- Standard tools of the trade *(PYTHIA/JETSET, HERWIG)* don't work at the low hadronic invariant masses which are of interest to us

- 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

hep-ex/0904.4043

Andreopoulos-Gallagher-Keyahias-Yang (AGKY) model



At low hadronic invariant masses:

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

At high hadronic invariant masses:

- rich dynamics
- using JETSET model
- tuned energy cutoff, pT, s-sbar suppression

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

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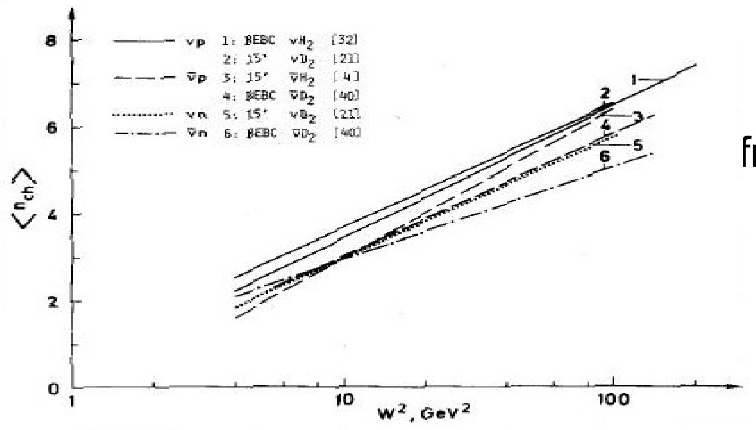
The GENIE hadronization / AGKY low-W model

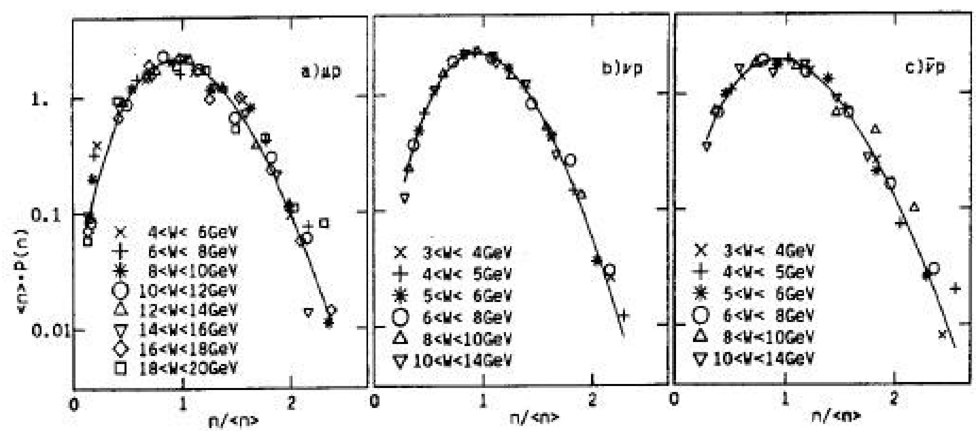


Get average multiplicity
from empirical parameterization

<n> = a + b * lnW^2

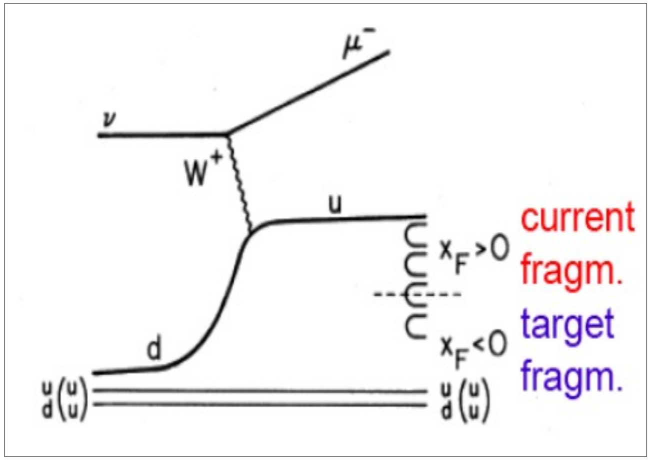
Generate the actual multiplicity
using the KNO scaling law:
<n>P(n) = f (n/<n>)

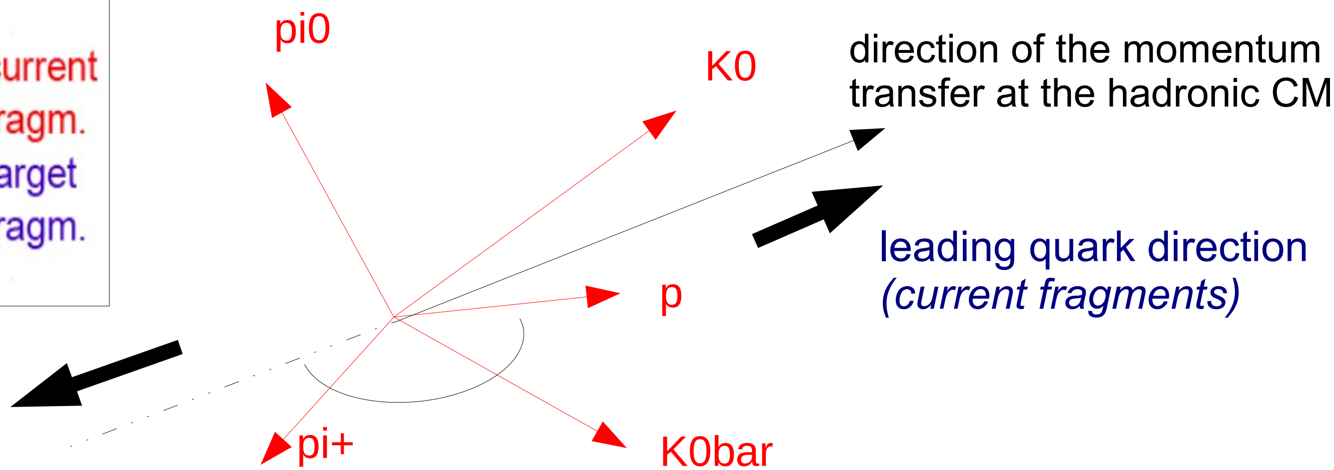
(taking into account that
<n_neutral> = 0.5 * <n_ch>



+ deriving particle spectrum *(skipping details here)*

The GENIE hadronization / AGKY low-W model





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

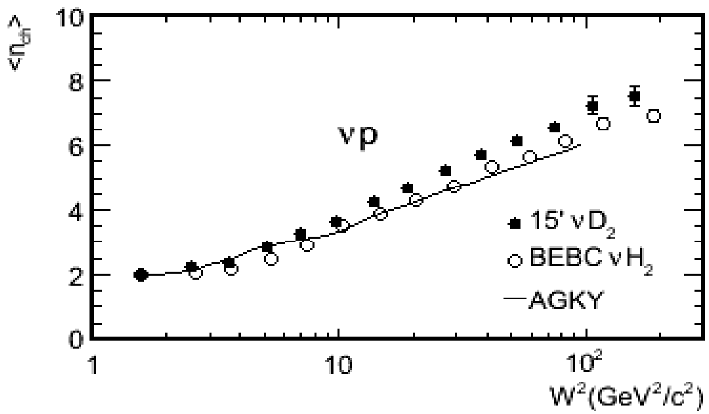
- Building in experimental data on nucleon pT and xF (= pL/pLmax =2*pL/W)
- PT limited phase space decay (reproducing experimental pion pT distribution)

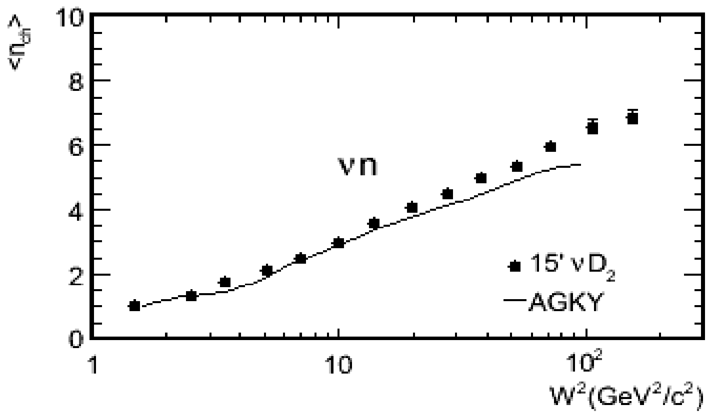
The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

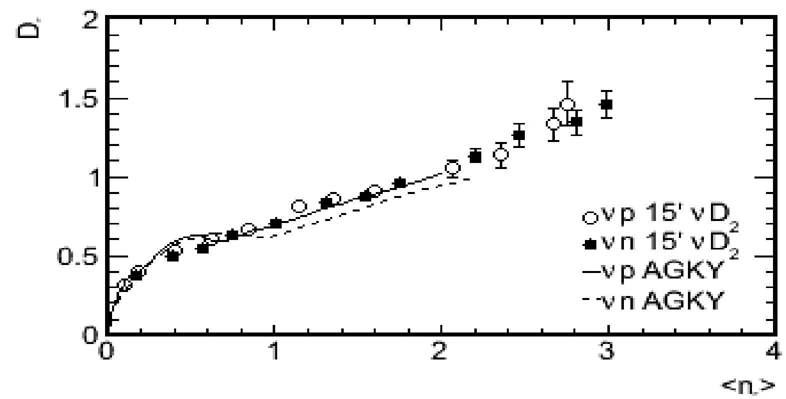
examples:

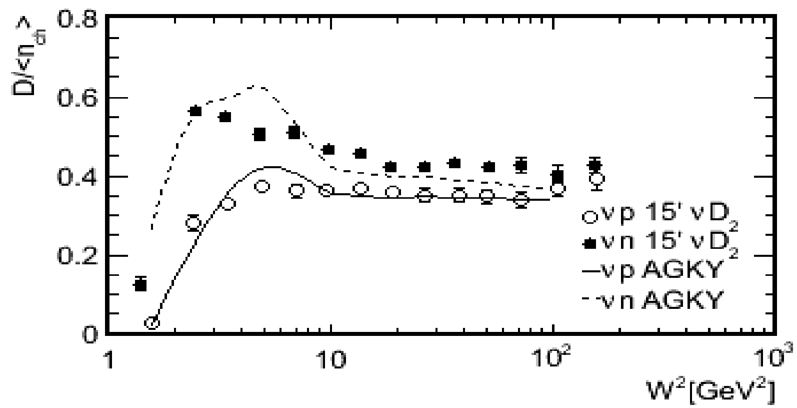
Charged pion multiplicities





Charged pion dispersion





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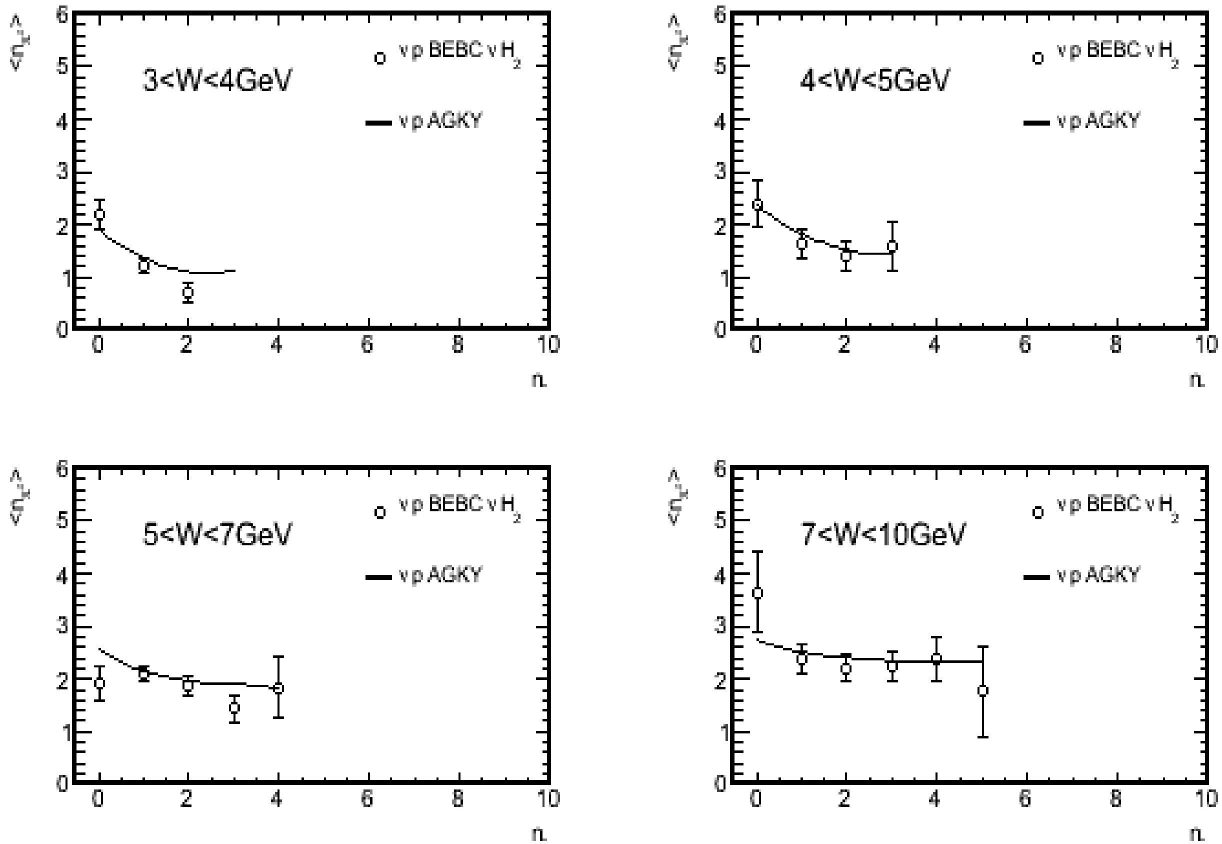
The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

Neutral / charged pion correlation



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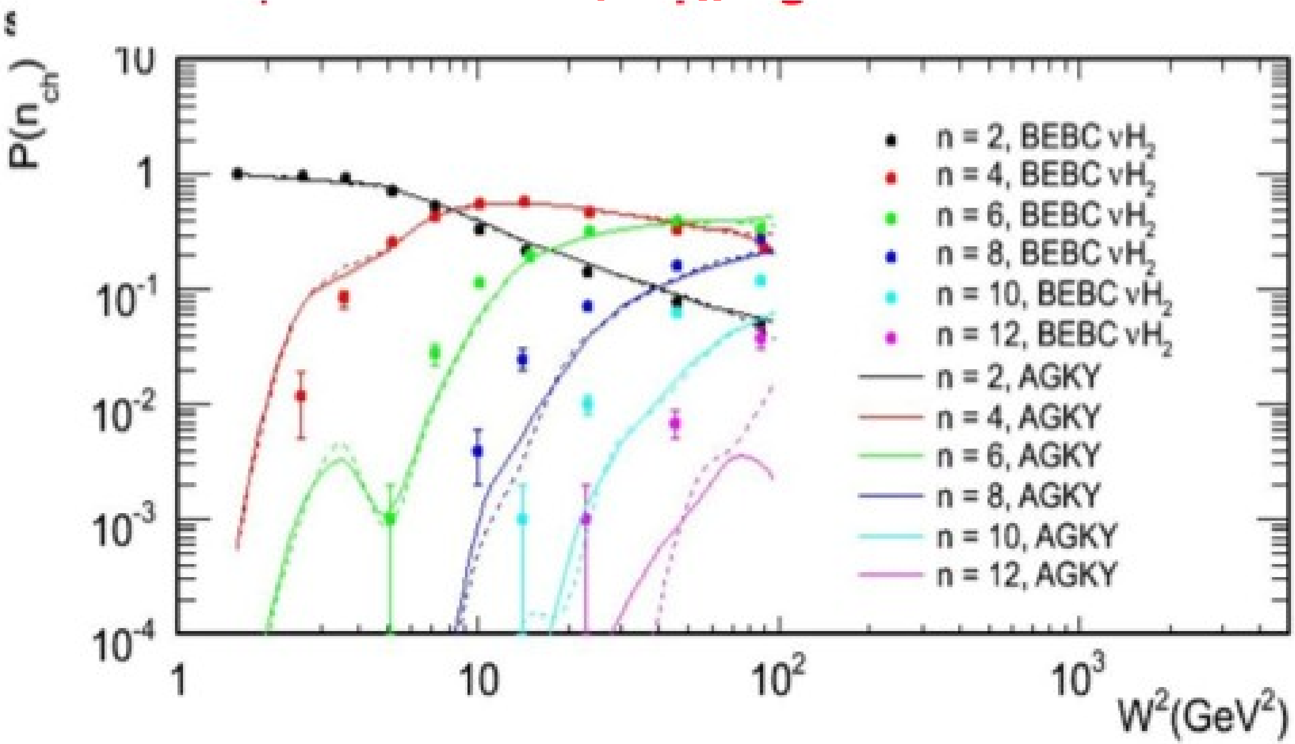
The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

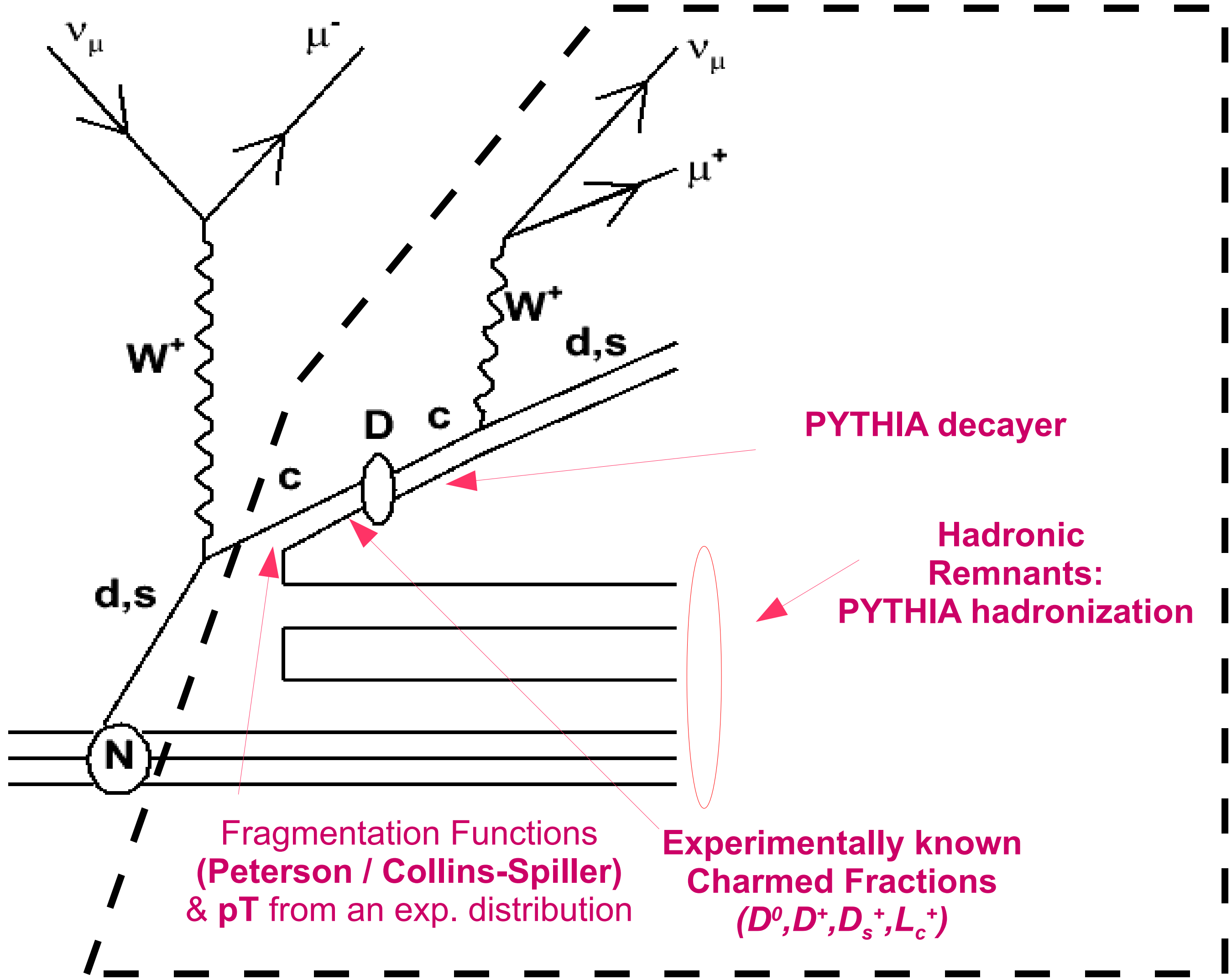
Normalized topological cross sections



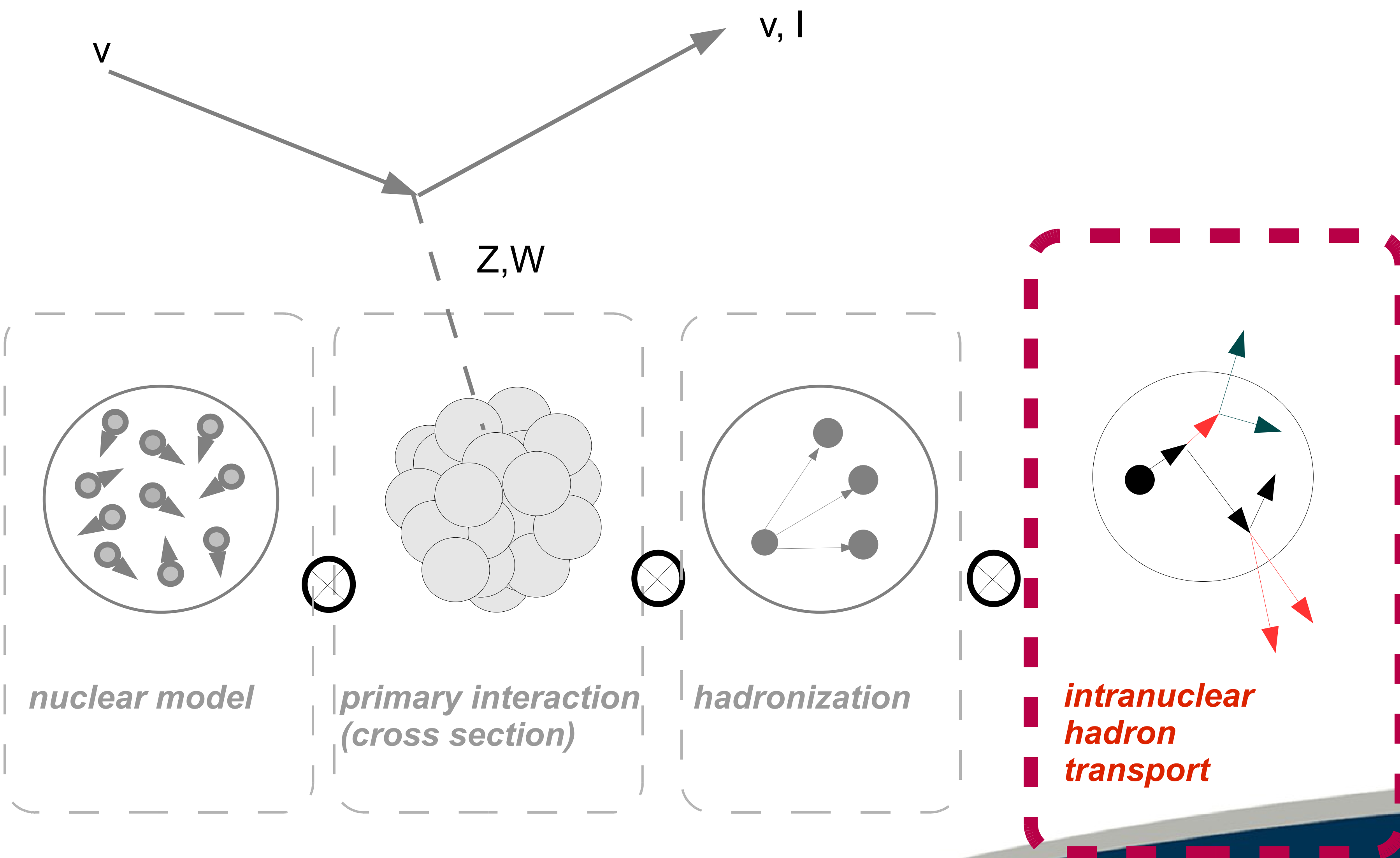
For more data/mc comparisons see hep-ex/0904.4043

The model and its shortcomings are very well understood.
Improvements in progress

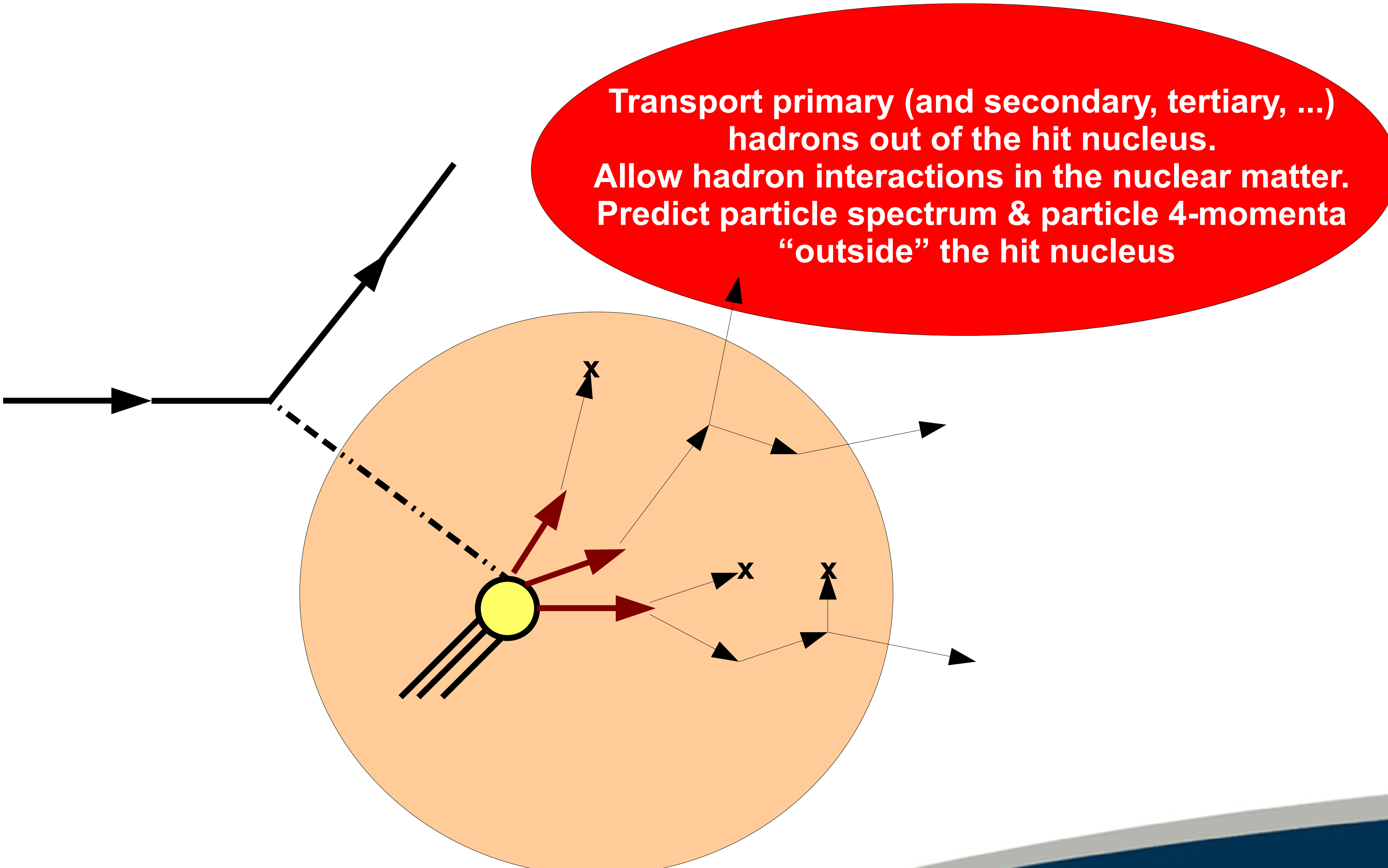
Special case: Hadronization model for DIS charm production



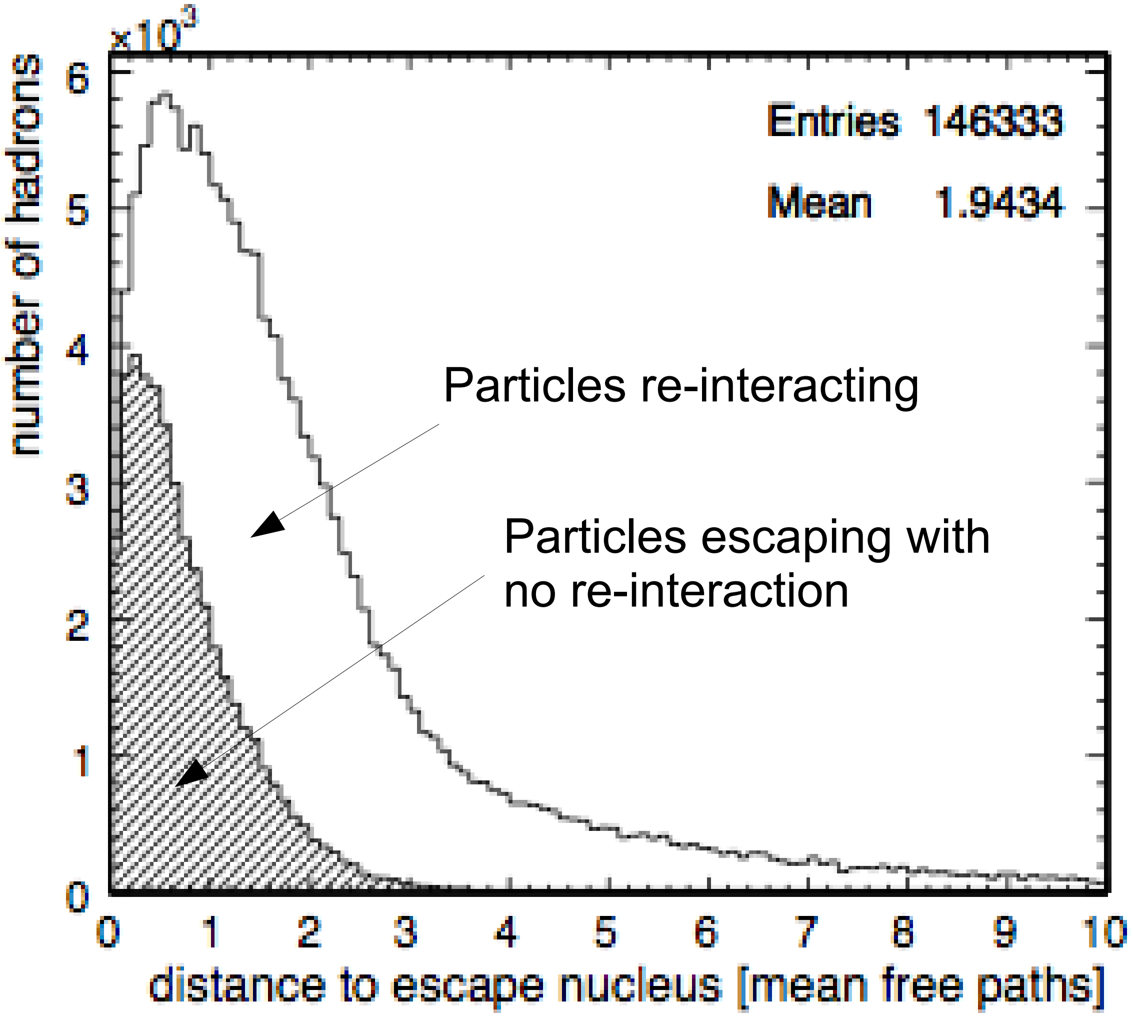
Intranuclear hadron transport



The GENIE hadron transport modelling



Intranuclear rescattering: At Ev ~1 GeV most hadrons re-interact



For illustration:

nu_mu + C12, Ev = 1 GeV

2/3 of hadrons re-interact

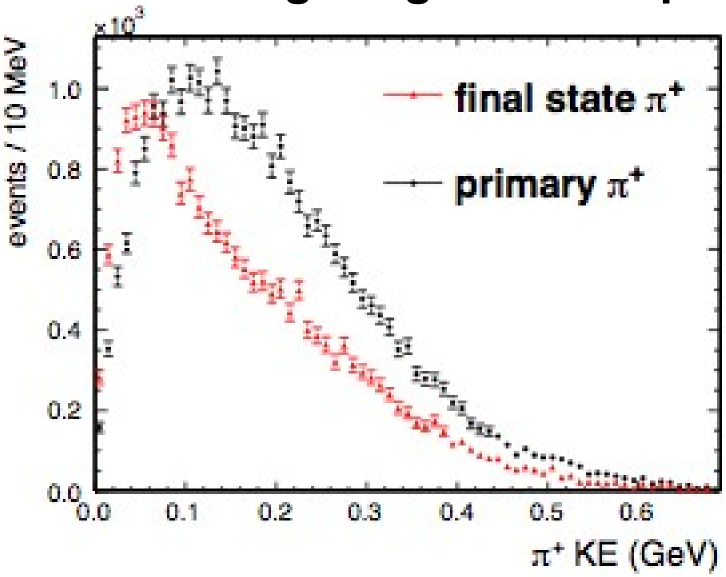
Re-scattering: Modifies the observed topologies

Intranuclear rescattering effects

Final-State	Primary Hadronic System									
	$0\pi X$	$1\pi^0 X$	$1\pi^+ X$	$1\pi^- X$	$2\pi^0 X$	$2\pi^+ X$	$2\pi^- X$	$\pi^0\pi^+ X$	$\pi^0\pi^- X$	$\pi^+\pi^- X$
$0\pi X$	**293446**	12710	22033	3038	113	51	5	350	57	193
$1\pi^0 X$	1744	**44643**	3836	491	1002	25	1	1622	307	59
$1\pi^+ X$	2590	1065	**82459**	23	14	660	0	1746	5	997
$1\pi^- X$	298	1127	1	**12090**	16	0	46	34	318	1001
$2\pi^0 X$	0	0	0	0	**2761**	2	0	260	40	7
$2\pi^+ X$	57	5	411	0	1	**1999**	0	136	0	12
$2\pi^- X$	0	0	0	1	0	0	**134**	0	31	0
$\pi^0\pi^+ X$	412	869	1128	232	109	106	0	**9837**	15	183
$\pi^0\pi^- X$	0	0	1	0	73	0	8	5	**1808**	154
$\pi^+\pi^- X$	799	7	10	65	0	0	0	139	20	**5643**

Example:
numu+O16;
nd280 spectrum

Re-scattering: Degrades the pion energies



Example:
numu+Fe56;
Ev = 1 GeV

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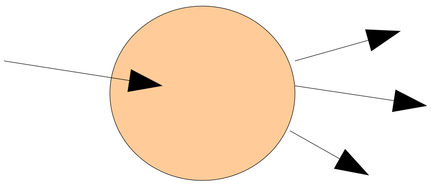
The GENIE hadron transport modelling

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

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

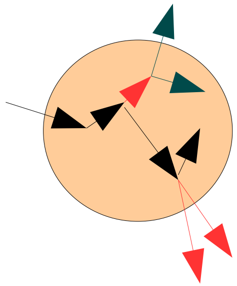
Intranuke / hA
(effective MC)



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

<u>available since 2.0.0</u>

Intranuke / hN
(true cascade MC)



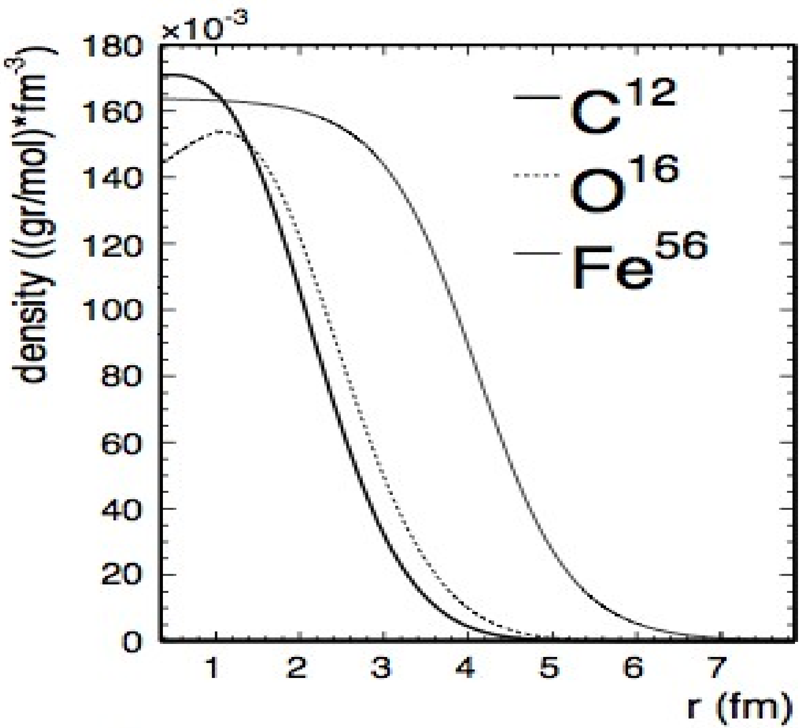
Builds everything up from hadron-nucleon xsecs

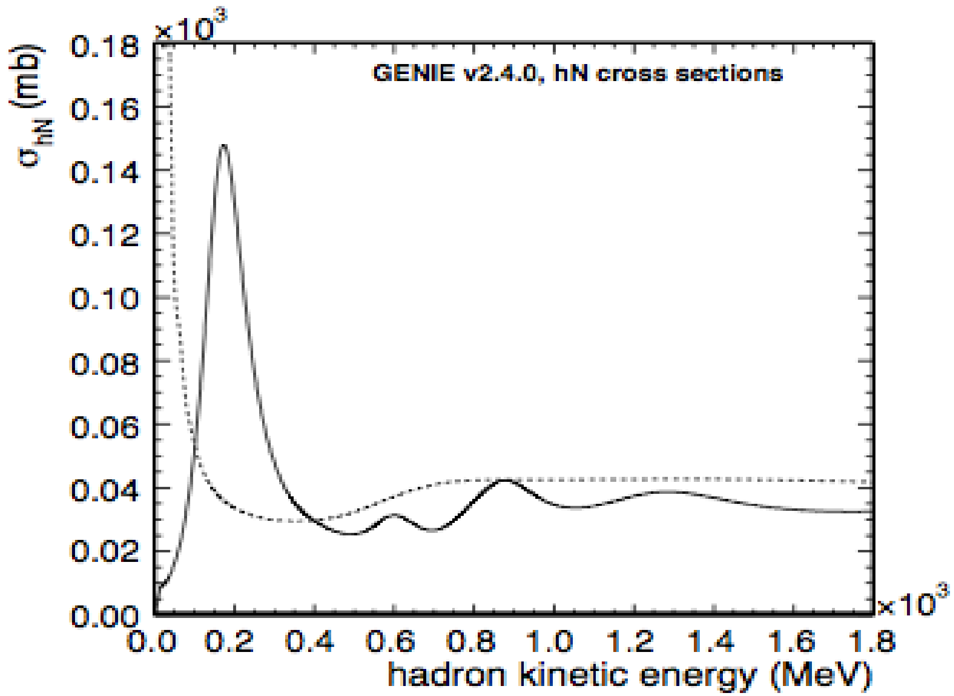
In advanced development stage
to become available soon

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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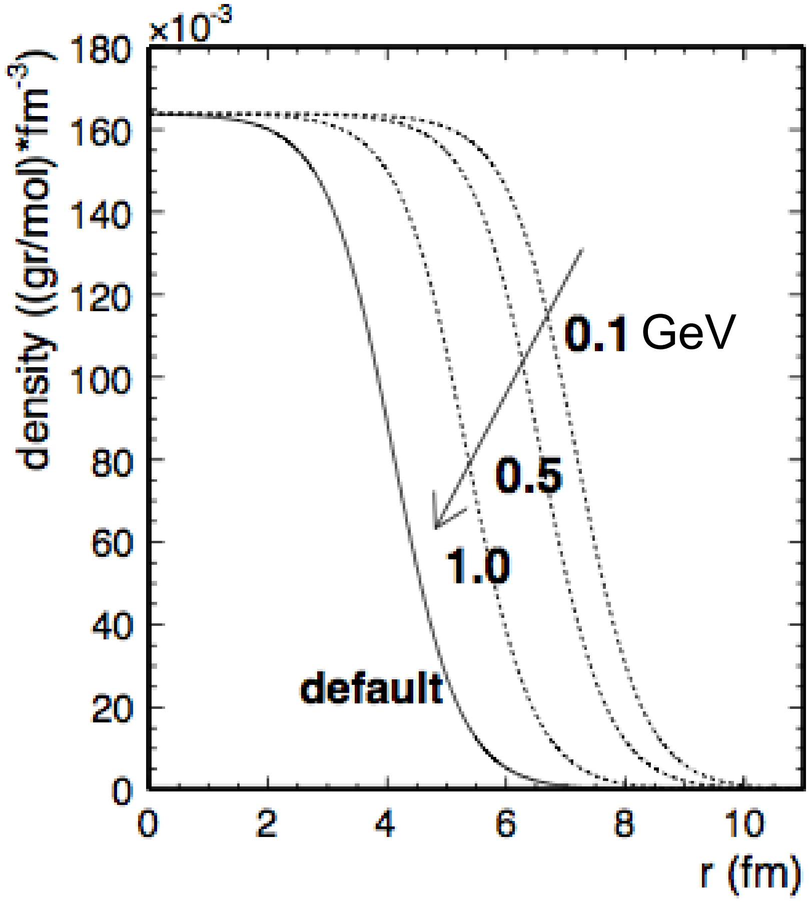
The GENIE hadron transport modelling (INTRANUKE/hA)

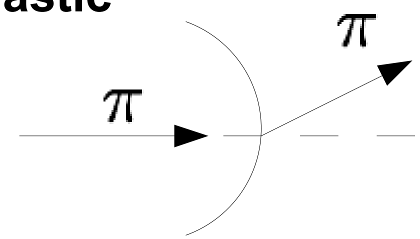


- Hadrons stepped by 0.05 fm at a time
- Hadrons traced till they reach
  r_max = N * R_nucl = N * R0 * A^(1/3)
  (R0 = 1.4, N = 3.0)
  so as to include the effects of the tails
  (Fe56: R_nucl=5.36fm, r_max=16.07fm)
- The nuclear density distribution is \`stretched' by n times the de Broglie wavelength of the tracked particle (n=1 for nucleons, n=0.5 for pions).

The GENIE hadron transport modelling (INTRANUKE/hA)

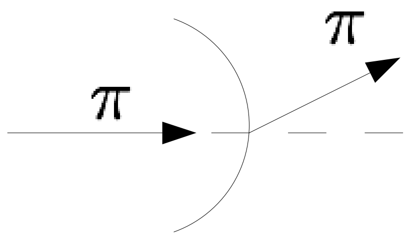
INTRANUKE/hA considers 5 types of 'hadron fates' (some may include many channels)

elastic



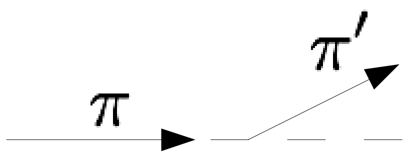
Pion deflected. Its kinetic energy stays the same.

inelastic

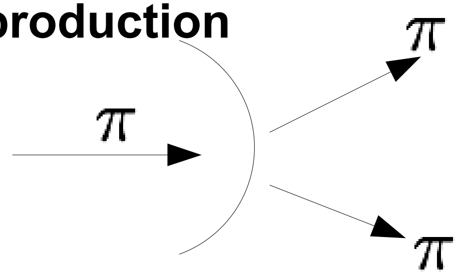


Pion deflected. Its kinetic energy is degraded.

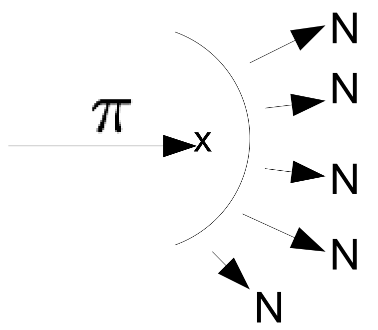
charge exchange



pion production



absorption

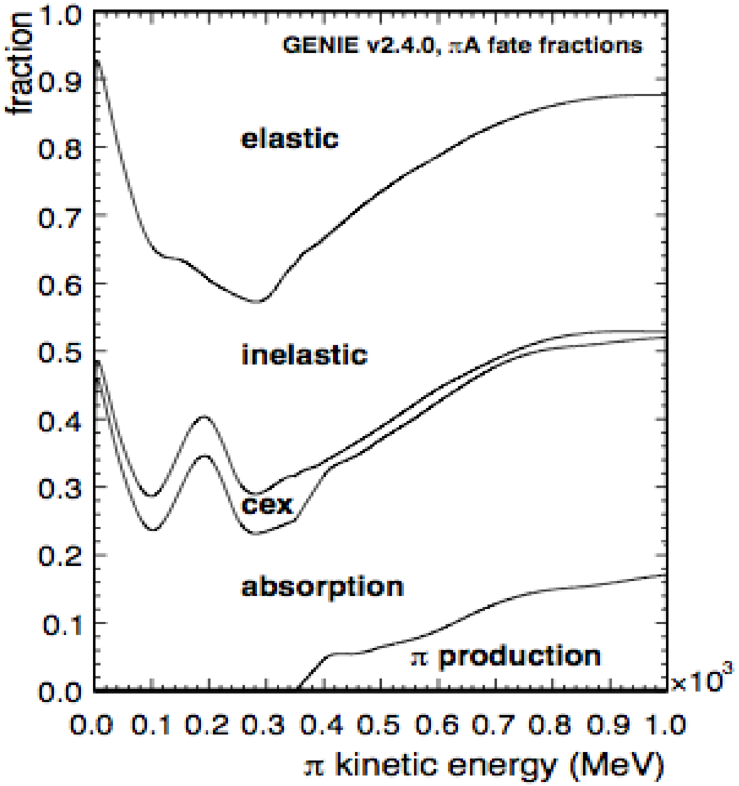


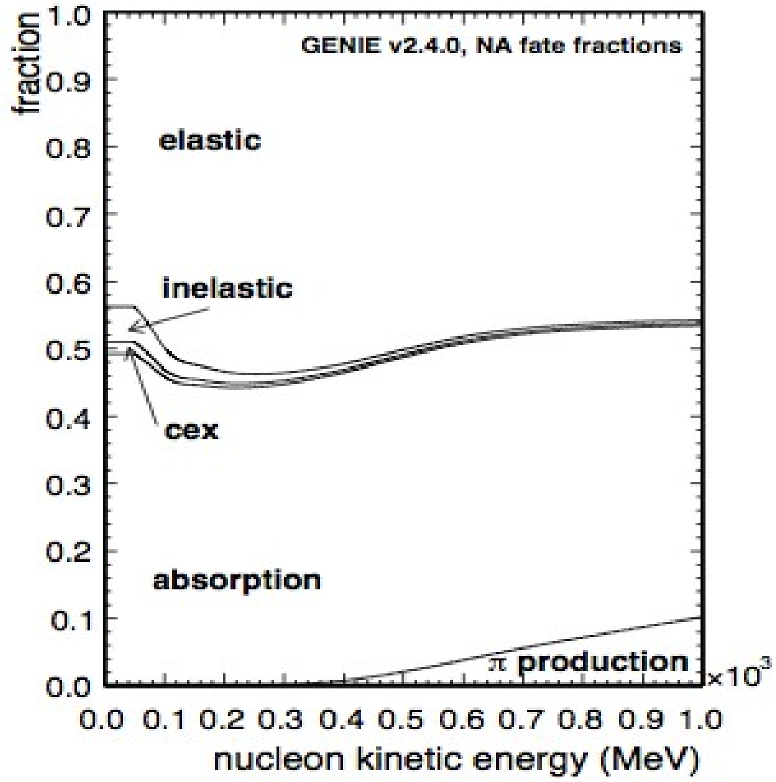
followed by emission of low energy nucleons

~ Similar fates for nucleons

The GENIE hadron transport modelling (INTRANUKE/hA)

Fractions taken mostly from data





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

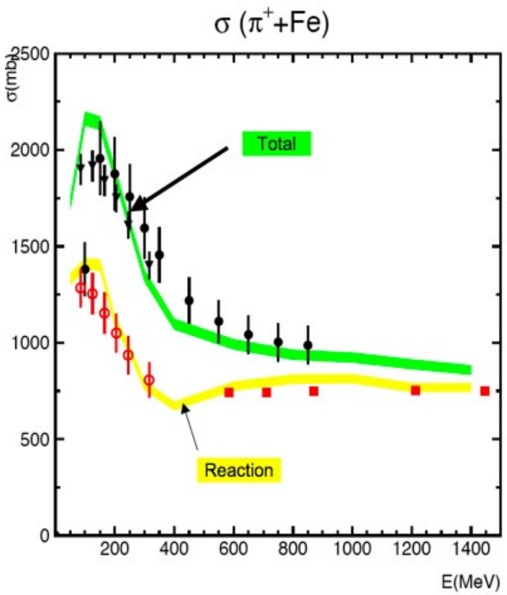
INTRANUKE/hA Data/MC comparisons

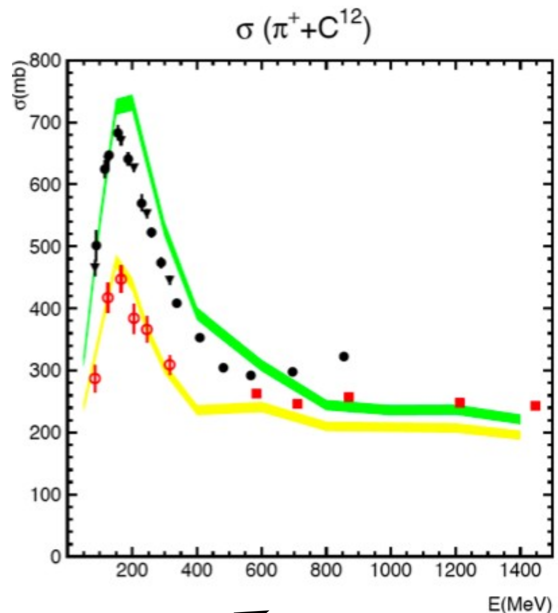
Much effort went into validation –
utilising experience from non-neutrino probes, mainly hadron+A reactions

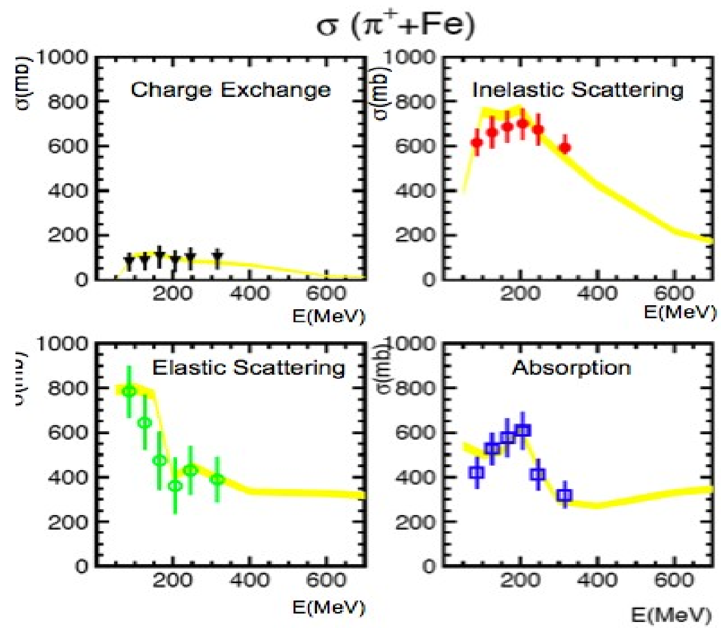
Lot of effort in tuning mean free path &
including the elastic contrib – difficult to model in context of INC

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.

Hadronization in nuclei: Formation zone

SKAT parameterization:

Hadron momentum

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

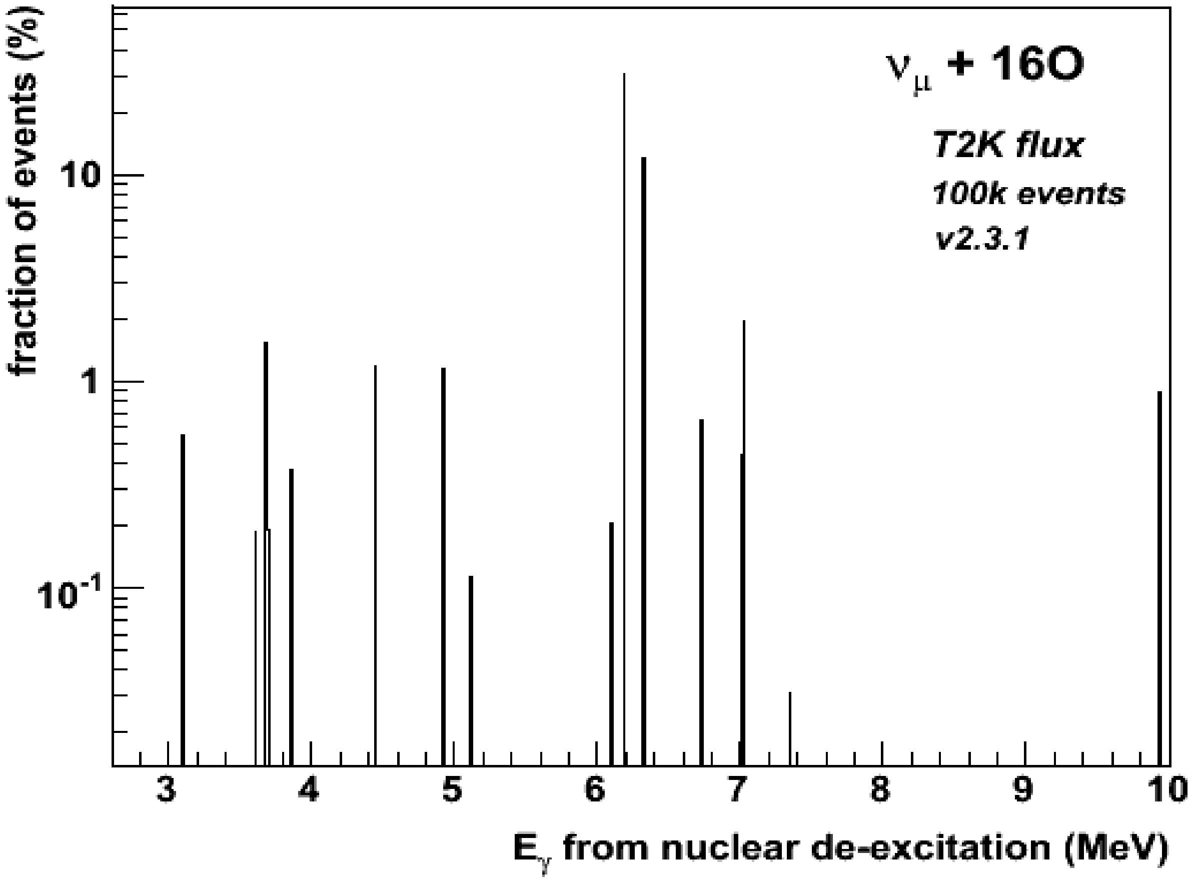
Transverse hadron momentum

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

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

(SKAT) model dependence

Nuclear excitations



Included in an ad-hoc way

Only for O16

To be added for C, Ar

Further physics improvements In upcoming releases

>>>

New intranuclear cascade

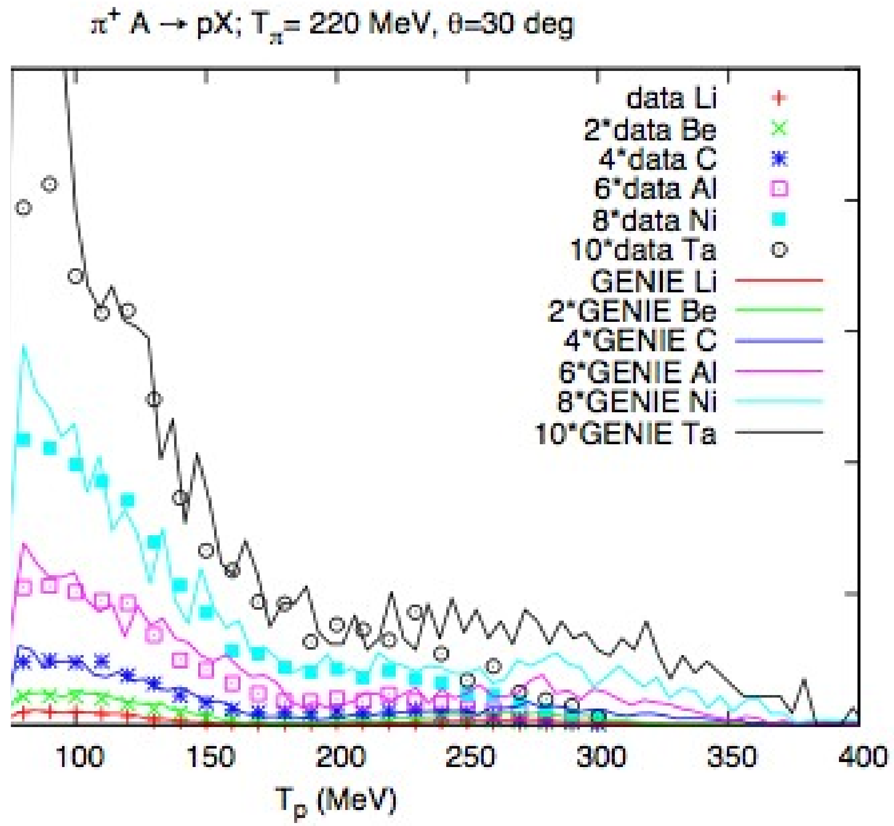
See Steve's talks
during the Ladek winter school

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

Improvements at B/Y structure funcions & R/S form factors.

Global cross section model retuning.

Improvements at AGKY

strange particle production

fwd/bkw asymmetry

Improvements at angular distributions of resonance decays

… … ...

Summary

Heavily validated, robust, comprehensive MC generator

Nearly universal!

Already provides high quality simulations for T2K, MINOS, MINERvA, NovA, others

Effort to extend validity range down to ~1 MeV (SNS, reactor, super-novae)