



Science & Technology Facilities Council  
Rutherford Appleton Laboratory

# The GENIE \*

## Neutrino Monte Carlo Generator

**Costas Andreopoulos**

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

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 (νA 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:  $\nu A$  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)*

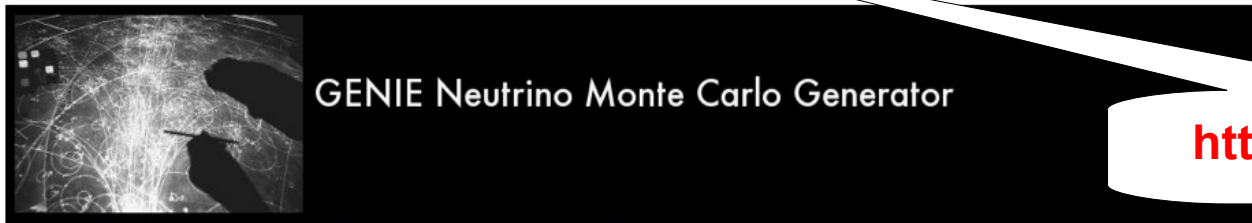
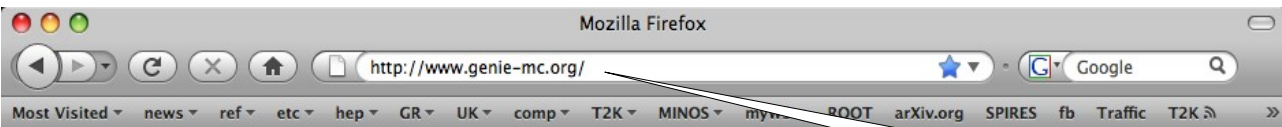


*Finding out more ...*

*Getting support ...*

*Staying in touch ...*





GENIE (*Generates Events for Neutrino Interaction Experiments*) is an Object-Oriented Neutrino MC Generator supported and developed by an [International collaboration of neutrino interaction experts](#) spanning all major neutrino experiments.

<http://www.genie-mc.org>

Mission statement

[GENIE collaboration](#)  
[Copyright notice](#)

[GENIE workshops](#)

[Users mailing list](#)  
[Devel mailing list](#)

[Downloads](#)  
[Release table](#)  
[Installation](#)  
[3rd Party software](#)  
[Supported platforms](#)  
[GENIE @ Grid](#)  
[CVS ChangeLogs](#)  
[LiveCD](#)

[Publications](#)  
[User manual \(20090128\)](#)  
[Doxygen doc.](#)

[NuValidator](#)

[T2K](#)  
 [MINOS](#)

**Next GENIE tutorial**

The next GENIE tutorial will take place at the [45th Karpacz Winter School in Theoretical Physics](#) ('Neutrino interactions: from theory to Monte Carlo simulations', Łańdek-Zdrój, Poland, February 2-7, 2009)

**User manual (Jan 16th, 2009)**

A 'user manual' is now available at the GENIE web site.

**Revision 2.4.2 (Dec. 20th, 2008)**

A 2.4 revision version was tagged on Sat. 20th December. The CVS tag for this version is 'R-2\_4\_2'. Contains a bug fix (Delta- pdg code) affecting the Delta- decays and, subsequently, the produced final states in anti-neutrino resonance production events. Includes code for mapping GENIE event types to NEUT ones and updated / extended 't2k\_tracker/event' file format for using GENIE events with the Super-K detector MC.

**Production release 2.4.0 (Jun. 8th, 2008)**

The production release 2.4.0 is now available. The CVS tag for this version is 'R-2\_4\_0'.

For more details see [here](#).

The next production release (2.6.0) is planned for Feb. 2009.



search

[www.genie-mc.org](http://www.genie-mc.org)

[Web feed: News](#)  
 [Web feed: Releases](#)  
 [Web feed: CVS Log](#)  
Please subscribe to these feeds.  
[What is a web feed?](#)

[Developers Blog](#)

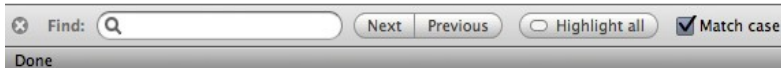
## Official GENIE web site

*You can find:*

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

For all enquiries please contact : [Dr. Costas Andreopoulos](#) (STFC, Rutherford Appleton Lab)

Last modified : 01/28/2009 15:06:37



**NEW**

The GENIE Neutrino Monte Carlo Generator

## USER MANUAL



by the GENIE collaboration<sup>1</sup>

January 28, 2009

<sup>1</sup>Corresponding Author: Costas Andreopoulos <costas.andreopoulos@stfc.ac.uk>

**Read the GENIE  
users manual**



news & media ▾ ref ▾ etc ▾ hep ▾ GR ▾ UK ▾ comp ▾ T2K ▾ MINOS ▾ myW3 ▾ ROOT Facebook >>

**JISCMail**

### List Archives

## Archives of NEUTRINO-MC-SUPPORT@JISCMail.AC.UK

*Universal Neutrino MC Generator User Support*

**Subscriber's Corner**  
[Server Archives](#)  
[List Archives](#)

**List Management**  
[List Moderation](#)  
[Server Management](#)

**Help**  
[Log off](#)





**Archive Search**

---

**CONTACTS:**  
[List Owner\(s\)](#)  
[JISCMail Helpline](#)

- ◆ [Search the archives](#)
- ◆ [Post to the list](#)
- ◆ [Join or leave the list \(or change settings\)](#)
- ◆ [Manage the list \(list owners only\)](#)
  
- ◆ [June 2008](#)
- ◆ [December 2007](#)
- ◆ [August 2007](#)
- ◆ [July 2007](#)

**JISCMail Tools**

-  [Files Area](#)
-  [Surveys](#)
-  [Discussion Room \(Help\)](#)
-  [Make a Meeting \(Help\)](#)

List Information	
Subscribers:	<a href="#">20</a>
Last Post:	<a href="#">25/06/2008 11:34</a>
Files:	0
Active Surveys:	0
Discussions:	0 in room

**Subscribe to the GENIE users mailing list !**

Find:  Next Previous Highlight all  Match case Phrase not found

Done

Google Reader (1000+)

http://www.google.com/reader/view/#stream/feed%2Fhttp%3A%2F%2Fhepunx.rl.ac.uk

news & media ref etc hep GR UK comp T2K MINOS myW3 ROOT Facebook Travel News T2K

Mail Calendar Documents Photos Reader Web more

candreop@googlemail.com | Online | Settings | My Account | Help | Sign out

Google Reader

All items Search

GENIE News Feed settings... Expanded view List view

Show: 7 new items - all items Mark all as read Refresh show details

☆ Fixed a serious memory leak. 12:52 PM (2 hours ago)

A serious memory leak in the internal caching system was fixed earlier today. Few other minor leaks found along the way have been fixed too. The leak was showing up in more complex event generation cases involving large numbers of possible initial states. The fix restores a very satisfactory pattern of memory usage, with a negligible increase in used memory past the initialization point. Changes have been committed to the development branch \_and\_ back-ported to 2.4.0 as well. A clean build is recommended.

☆ Add star Share Share with note Email Mark as read Edit tags: GENIE

☆ SuperK/MDC0 GENIE event sample generation at RAL Jun 19, 2008 (6 days ago)

Processing completed today. Will start shipping data tomorrow after the post-generation validation checks.

☆ Add star Share Share with note Email Mark as read Edit tags: GENIE

☆ More minor 2.4.0 back-ports Jun 19, 2008 (6 days ago)

Added option for conditional compilation of certain LOG() mesg in GJPARCnuFlux.cxx. Speeds up GenerateNext() by a factor of ~20. Backported the changes to 2.4.0 since the nd280/MDC0 processing has not started yet.

☆ Add star Share Share with note Email Mark as read Edit tags: GENIE

☆ Additional minor 2.4.0 back-ports Jun 17, 2008 5:08 PM

Added protection against round off errs at cross section spline evaluation (GEVGDriver.cxx) and demoted an err mesg to info mesg (Spline.cxx). The changes have been back-ported to 2.4.0 so as to be picked up by T2K MC production sites.

☆ Add star Share Share with note Email Mark as read Edit tags: GENIE

☆ Back-porting (2.4.0) new elements at GENIE pdg table Jun 13, 2008 7:56 PM

Previous item Next item 9 items

Find: LoadFromSpli Next Previous Highlight all Match case Phrase not found

Done

Subscribe to the  
GENIE RSS  
news feeds !

# *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.

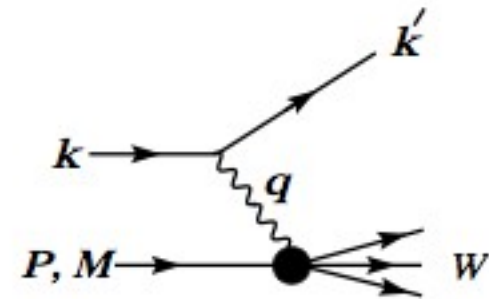
$Q^2 = -q^2 = 2(E E' - \vec{k} \cdot \vec{k}') - m_\ell^2 - m_{\ell'}^2$  where  $m_\ell(m_{\ell'})$  is the initial (final) lepton mass. If  $E E' \sin^2(\theta/2) \gg m_\ell^2, m_{\ell'}^2$ , then

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

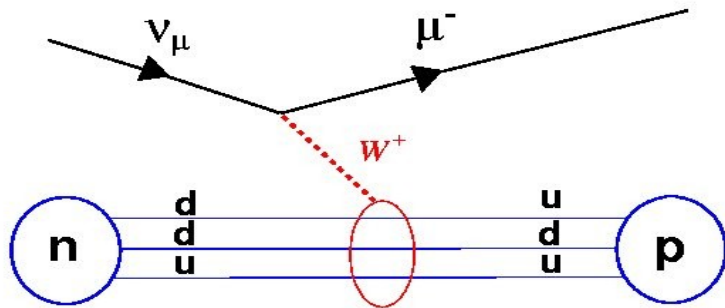
$x = \frac{Q^2}{2M\nu}$  where, in the parton model,  $x$  is the fraction of the nucleon's momentum carried by the struck quark.

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

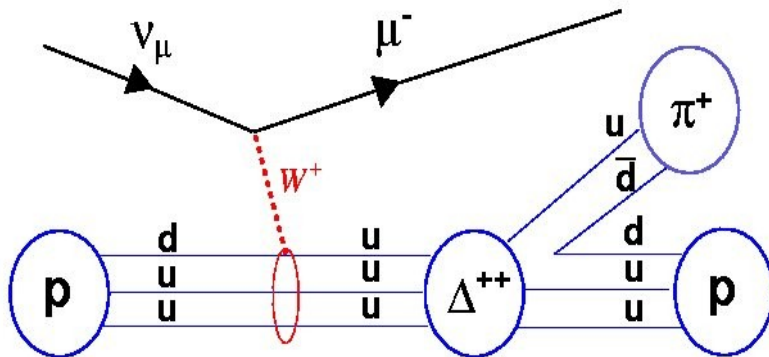
$W^2 = (P + q)^2 = M^2 + 2M\nu - Q^2$  is the mass squared of the system  $X$  recoiling against the scattered lepton.



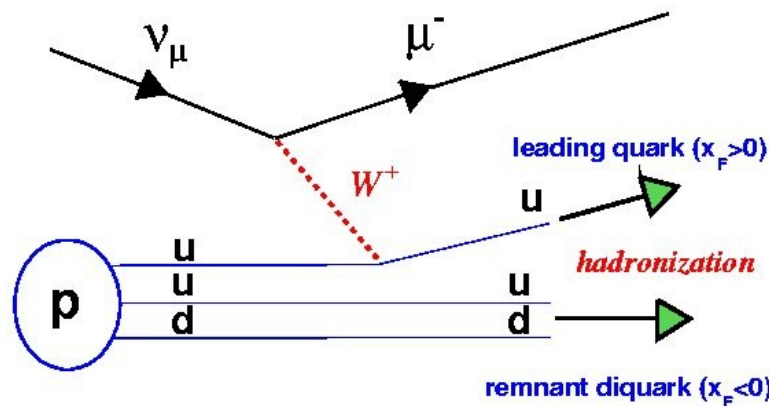
# Dominant interaction modes at $\sim 1$ GeV ( $\nu_\mu$ CC)



Quasi-Elastic Scattering (QEL)



Resonance production (RES)



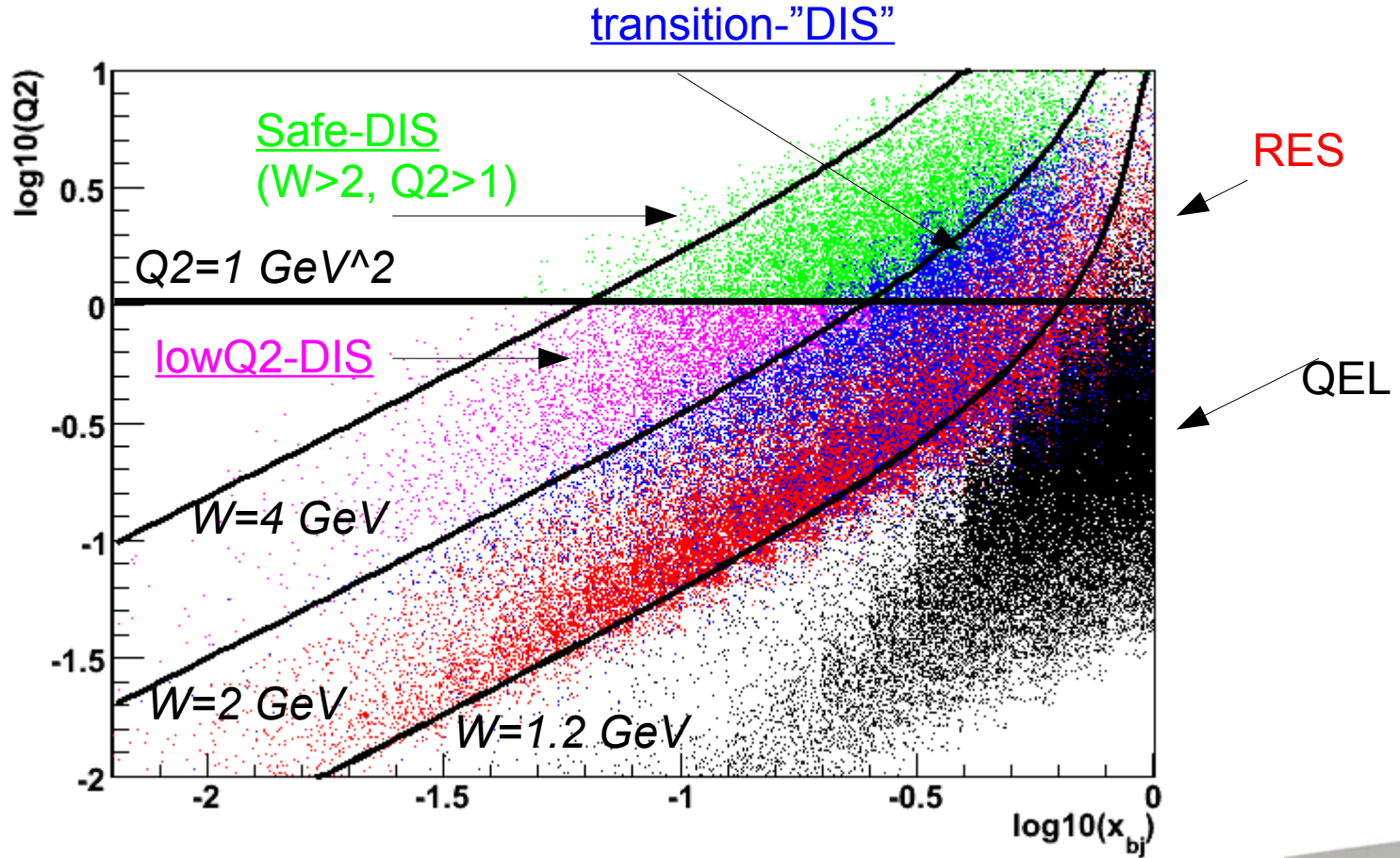
Deep-Inelastic Scattering (DIS)

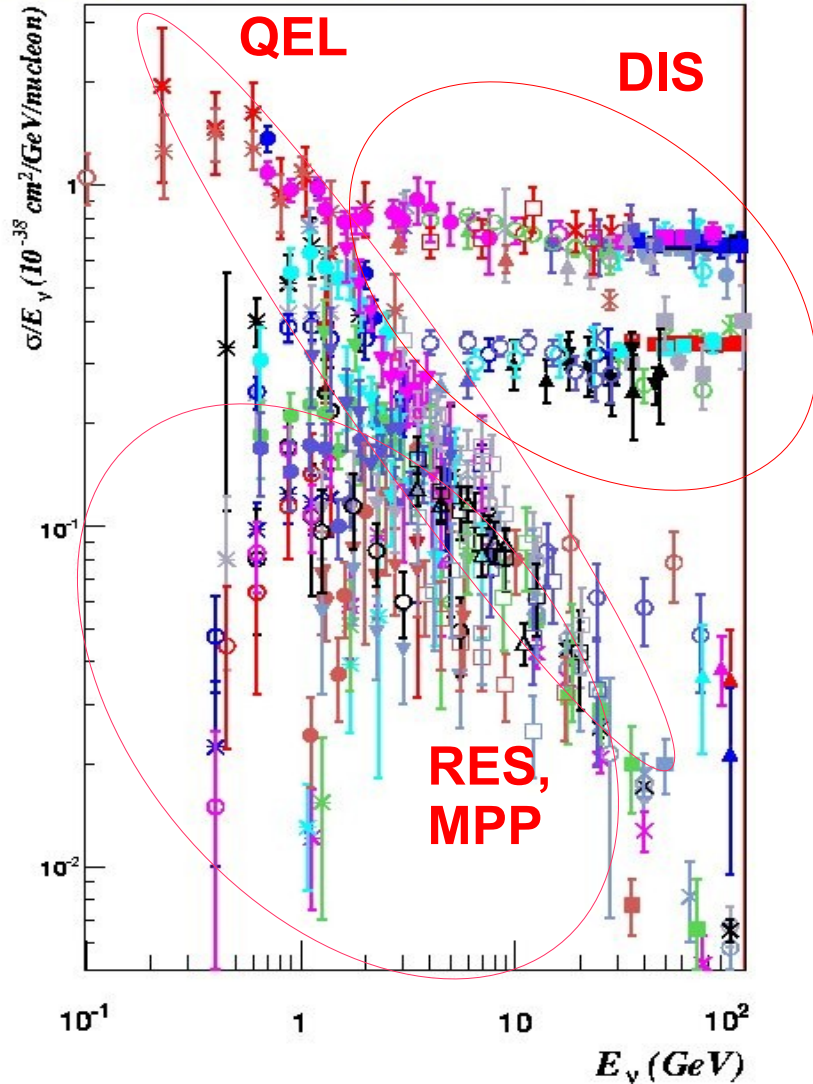
W  
↓



# Kinematical coverage

example shown for the JPARC neutrino beam @ nd280 site

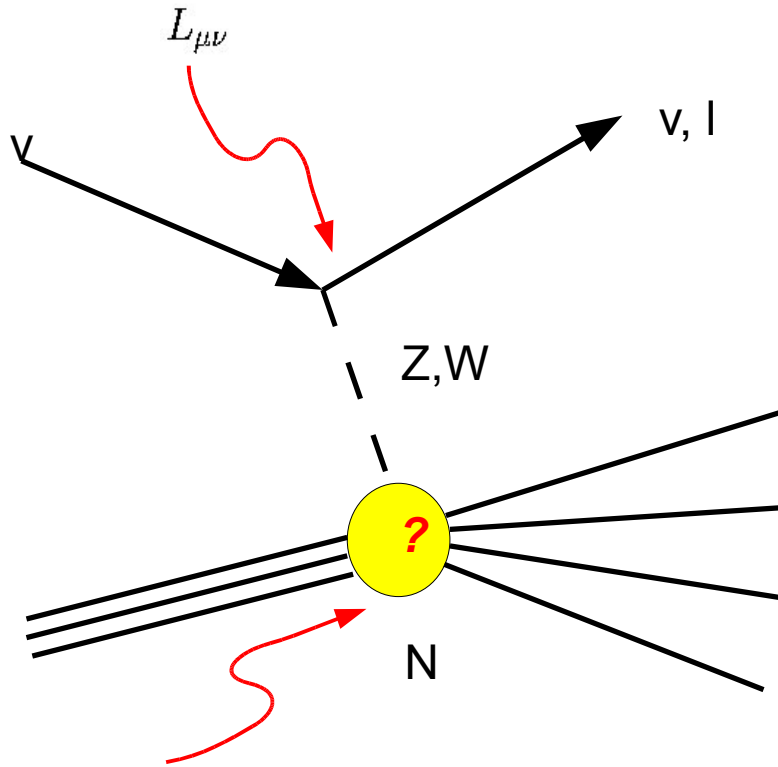




ANL_12FT	Campbell et al.	Phys. Rev. Lett. 30:335, 1973
ANL_12FT	Mann et al.	Phys. Rev. Lett. 31:844, 1973
ANL_12FT	Radecky et al.	Phys. Rev. D25:1161, 1982
ANL_12FT	Day et al.	Phys. Rev. D33:2714, 1983
ANL_12FT	Day et al.	Phys. Rev. D33:2714, 1983
ANL_12FT	Day et al.	Phys. Rev. D33:2714, 1983
ANL_12FT	Barish et al.	Phys. Lett. B66:291, 1976
ANL_12FT	Barish et al.	Phys. Rev. D16:3103, 1977
ANL_12FT	Barish et al.	Phys. Rev. D19:2521, 1979
ANL_12FT	Barish et al.	Phys. Rev. D19:2521, 1979
ANL_12FT	Barish et al.	Phys. Rev. D19:2521, 1979
ANL_12FT	Radecky et al.	Phys. Rev. D25:1161, 1982
ANL_12FT	Radecky et al.	Phys. Rev. D25:1161, 1982
BEC	Bosetti et al.	Phys. Lett. B70:273, 1977
BEC	Bosetti et al.	Phys. Lett. B70:273, 1977
BEC	Marage et al.	Z. Phys. C31:191, 1986
BEC	Marage et al.	Z. Phys. C43:523, 1989
BEC	Alasia et al.	Nud. Phys. B343:285, 1990
BEC	Alasia et al.	Nud. Phys. B343:285, 1990
BEC	Alasia et al.	Nud. Phys. B343:285, 1990
BEC	Colley et al.	Zell. Phys. C2:187, 1973
BEC	Colley et al.	Zell. Phys. C2:187, 1973
BEC	Allen et al.	Nud. Phys. B176:269, 1980
BEC	Bosetti et al.	Phys. Lett. B110:167, 1982
BEC	Bosetti et al.	Phys. Lett. B110:167, 1982
BEC	Parker et al.	Nud. Phys. B232:11, 1984
BEC	Parker et al.	Nud. Phys. B232:11, 1984
BEC	Allen et al.	Nud. Phys. B264:221, 1986
BNL_7FT	Baltay et al.	Phys. Rev. Lett. 44:916, 1980
BNL_7FT	Fanourakis et al.	Phys. Rev. D21:562, 1980
BNL_7FT	Fanourakis et al.	Phys. Rev. D21:562, 1980
BNL_7FT	Baker et al.	Phys. Rev. D23:2499, 1981
BNL_7FT	Baker et al.	Phys. Rev. D25:617, 1982
BNL_7FT	Kitagaki et al.	Phys. Rev. D34:2554, 1986
BNL_7FT	Kitagaki et al.	Phys. Rev. D34:2554, 1986
BNL_7FT	Kitagaki et al.	Phys. Rev. D34:2554, 1986
BNL_7FT	Kitagaki et al.	Phys. Rev. D34:2554, 1986
CCFR	Audino et al.	Zell. Phys. C43:11, 1990
CCFR	Audino et al.	Zell. Phys. C43:11, 1990
CCFR	Seligman	Nevis Report 292, 1996
CCFR	Seligman	Nevis Report 292, 1996
CCFR	Wu-Faiane et al.	Zell. Phys. C26:1, 1984
CDHS	Berge et al.	Zell. Phys. C35:443, 1987
CDHS	Berge et al.	Zell. Phys. C35:443, 1987
FNAL_15FT	Bel et al.	Phys. Rev. Lett. 41:1008, 1978
FNAL_15FT	Kitagaki et al.	Phys. Rev. Lett. 49:39, 1982
FNAL_15FT	Barish et al.	Phys. Lett. B91:161, 1980
FNAL_15FT	Kitagaki et al.	Phys. Rev. D28:436, 1983
FNAL_15FT	Taylor et al.	Phys. Rev. Lett. 51:739, 1983
FNAL_15FT	Asratyan et al.	Phys. Lett. B137:122, 1984
FNAL_15FT	Aderholz et al.	Phys. Rev. Lett. 63:2349, 1989
FNAL_15FT	Aderholz et al.	Phys. Rev. Lett. 63:2349, 1989
FNAL_15FT	Wilcox et al.	Phys. Rev. D47:2861, 1993
FNAL_15FT	Wilcox et al.	Phys. Rev. D47:2861, 1993
FNAL_15FT	Wilcox et al.	Phys. Rev. D47:2861, 1993
Gargamelle	Eichten et al.	Phys. Lett. 46B:274, 1973
Gargamelle	Eichten et al.	Phys. Lett. 46B:274, 1973
Gargamelle	Clampolillo et al.	Phys. Lett. 84B:281, 1979
Gargamelle	Enriquez et al.	Phys. Lett. B80:309, 1979
Gargamelle	Morin et al.	Phys. Lett. B104:235, 1981
Gargamelle	Morin et al.	Phys. Lett. B104:235, 1981
Gargamelle	Iskral et al.	Phys. Rev. Lett. 52:1096, 1984
Gargamelle	Iskral et al.	Phys. Rev. Lett. 52:1096, 1984
Gargamelle	Di Bonelli et al.	Nuovo Cimento A38:260, 1977
Gargamelle	Di Bonelli et al.	Nuovo Cimento A38:260, 1977
Gargamelle	Lerche et al.	Phys. Lett. B78:510, 1978
Gargamelle	Armenise et al.	Nud. Phys. B152:365, 1979
Gargamelle	Bolognese et al.	Phys. Lett. B81:393, 1979
Gargamelle	Bolognese et al.	Phys. Lett. B81:393, 1979
Gargamelle	Bolognese et al.	Phys. Lett. B81:393, 1979
Gargamelle	Bolognese et al.	Phys. Lett. B81:393, 1979
IHEP_ITEP	Asratyan et al.	Phys. Lett. B76:239, 1978
IHEP_ITEP	Asratyan et al.	Phys. Lett. B76:239, 1978
IHEP_ITEP	Voverko et al.	Sov. J. Nud. Phys. 30:527, 1983
IHEP_ITEP	Voverko et al.	Sov. J. Nud. Phys. 30:527, 1983
IHEP_ITEP	Voverko et al.	Sov. J. Nud. Phys. 30:527, 1983
IHEP_JINR	Anikeev et al.	Zell. Phys. C70:39, 1996
IHEP_JINR	Anikeev et al.	Zell. Phys. C70:39, 1996
LSND	Auerbach et al.	Phys. Rev. C66:15501, 2002
SERP_A1	Belkov et al.	Yad. Fiz. 35:59, 1982
SERP_A1	Belkov et al.	Z. Phys. A320:625, 1985
SERP_A1	Belkov et al.	Z. Phys. A320:625, 1985
SKAT	Baranov et al.	Phys. Rev. B81:255, 1979
SKAT	Grabasch et al.	Zell. Phys. C31:203, 1986
SKAT	Grabasch et al.	Zell. Phys. C31:203, 1986
SKAT	Grabasch et al.	Zell. Phys. C31:203, 1986
SKAT	Armosov et al.	Sov. J. Nud. Phys. 24:67, 1988
SKAT	Grabasch et al.	Zell. Phys. C41:527, 1988
SKAT	Grabasch et al.	Zell. Phys. C41:527, 1988
SKAT	Grabasch et al.	Zell. Phys. C41:527, 1988
SKAT	Brunner et al.	Zell. Phys. C45:551, 1990
SKAT	Brunner et al.	Zell. Phys. C45:551, 1990

# Historical World Data

# Neutrino scattering off free nucleons



process dynamics  
described by  
the invariant  
amplitude

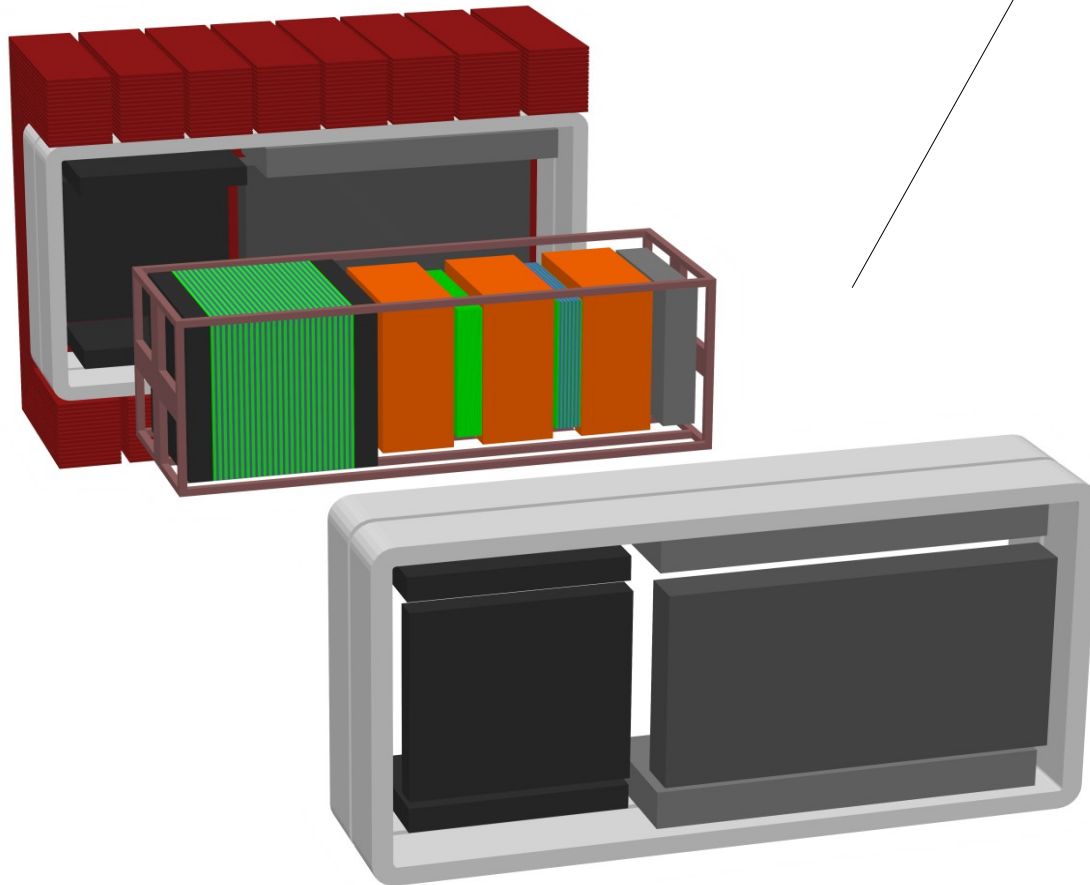
$$|M|^2 = L_{\mu\nu} W^{\mu\nu}$$

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

Complicated!!

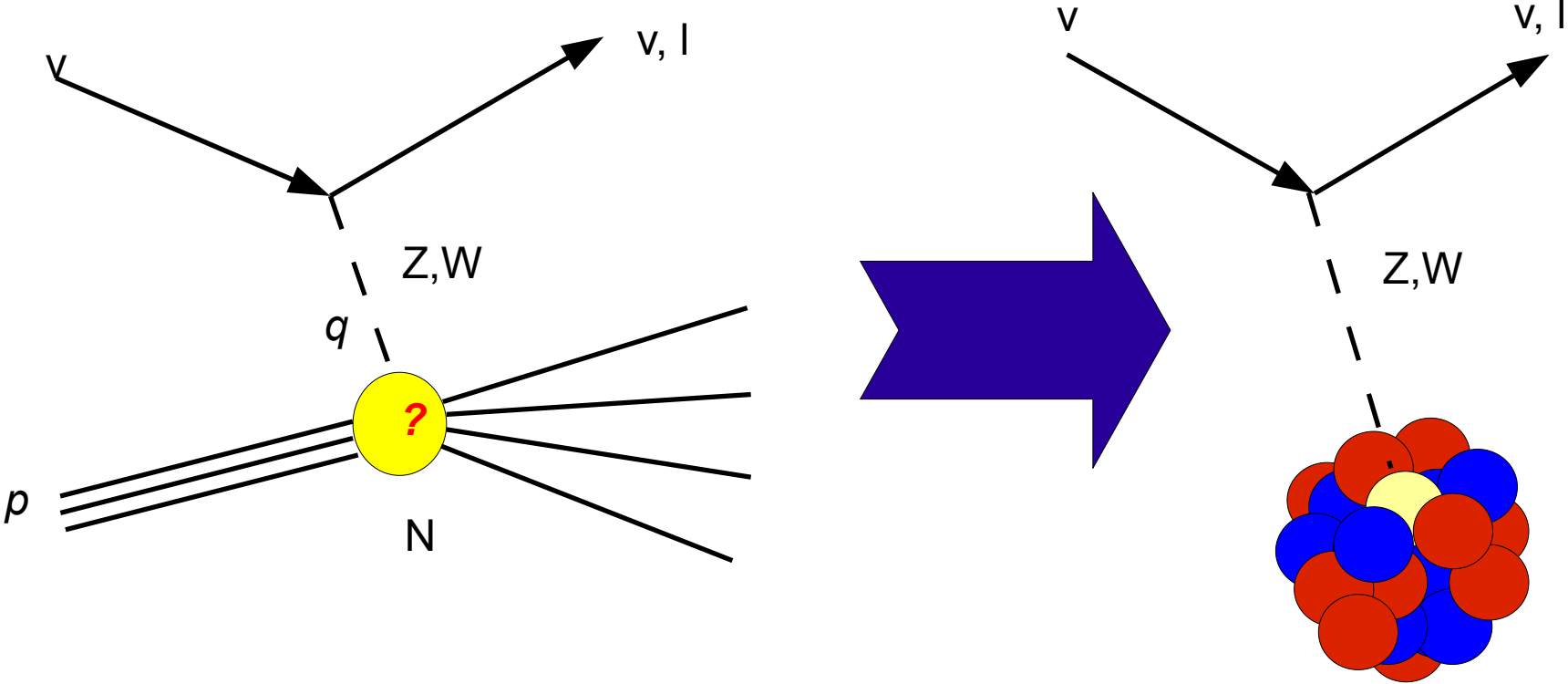
# We usually have to deal with nuclear targets

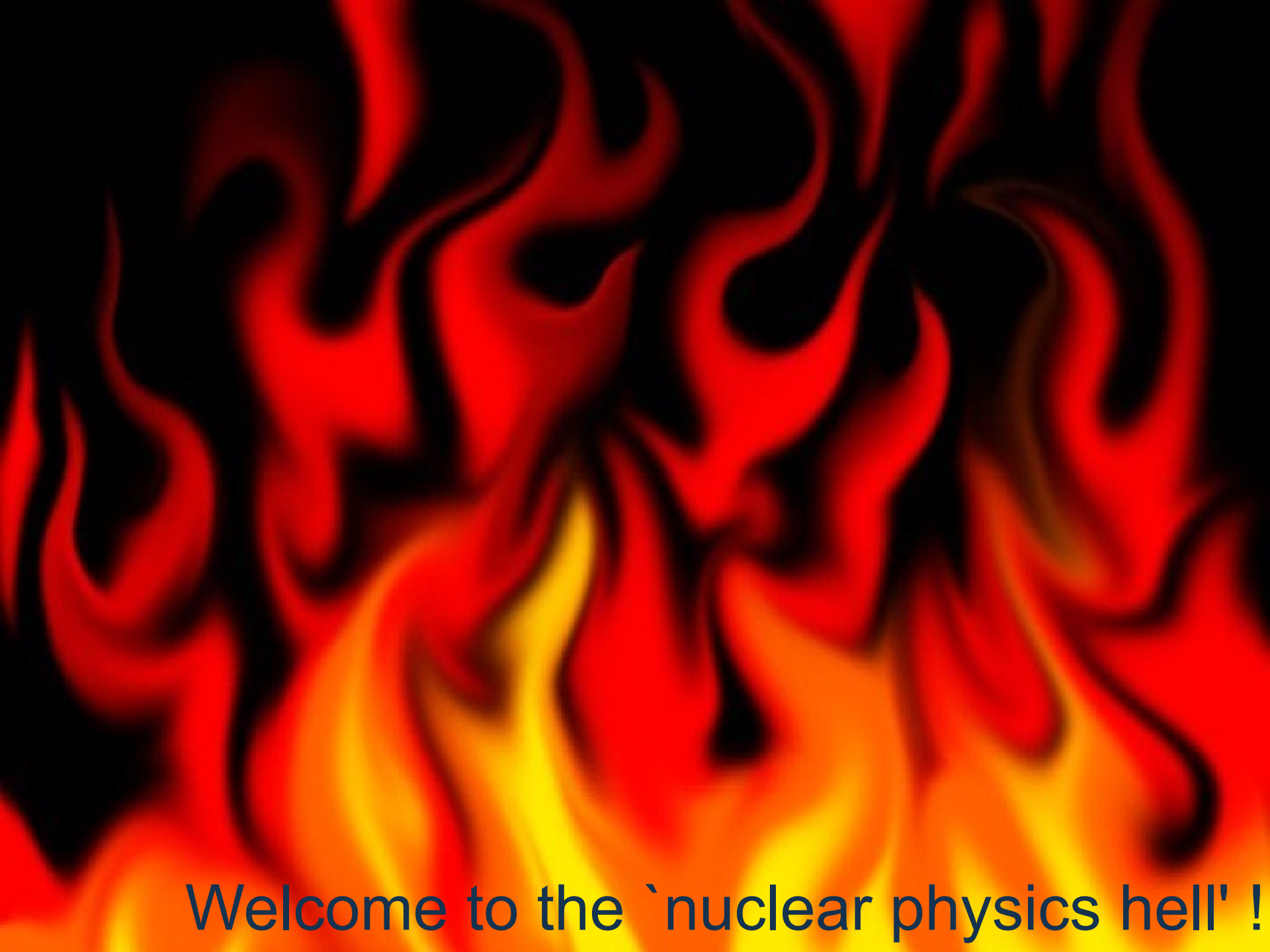
Example: nuclear targets in the nd280 geometry



- 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

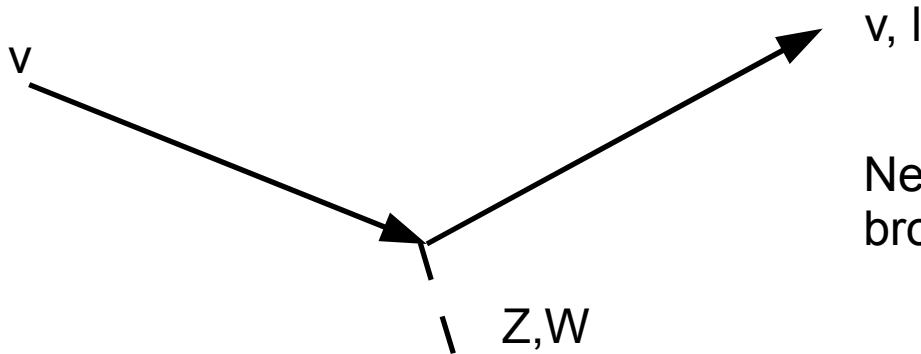
# Free-nucleon cross section $\rightarrow$ Nuclear cross sections



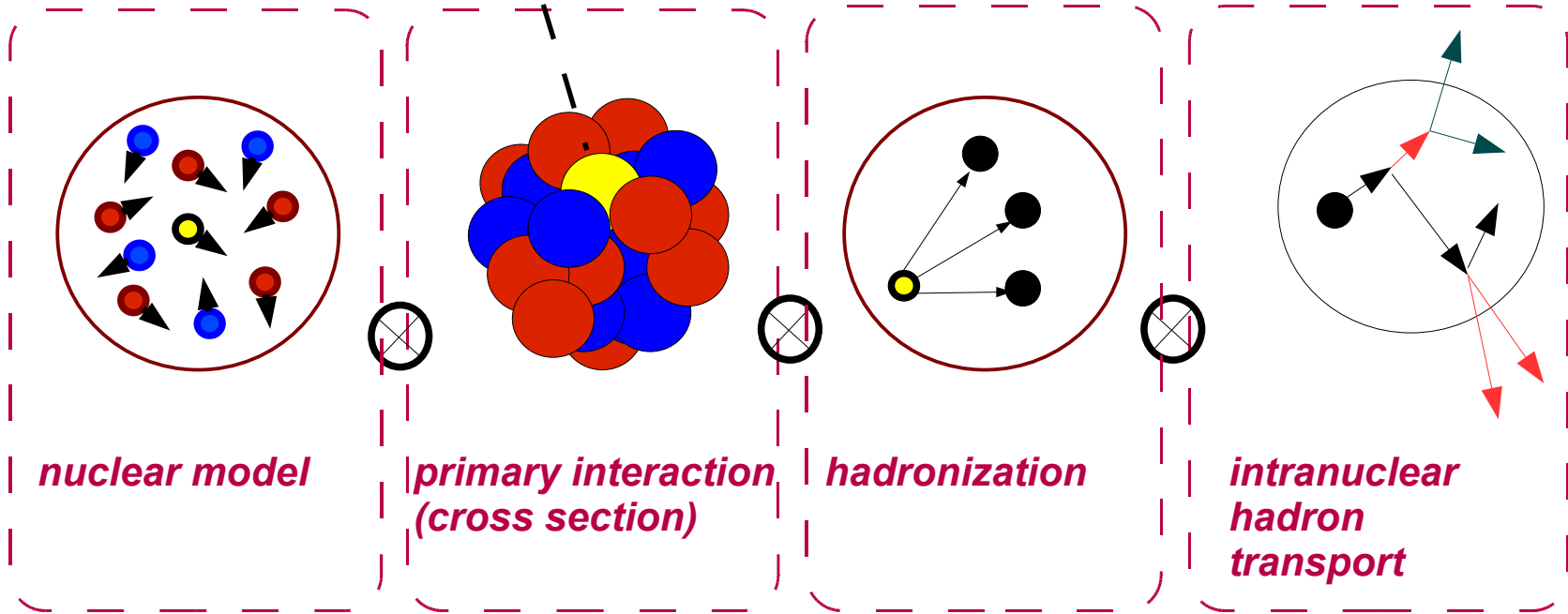


Welcome to the `nuclear physics hell' !

# 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

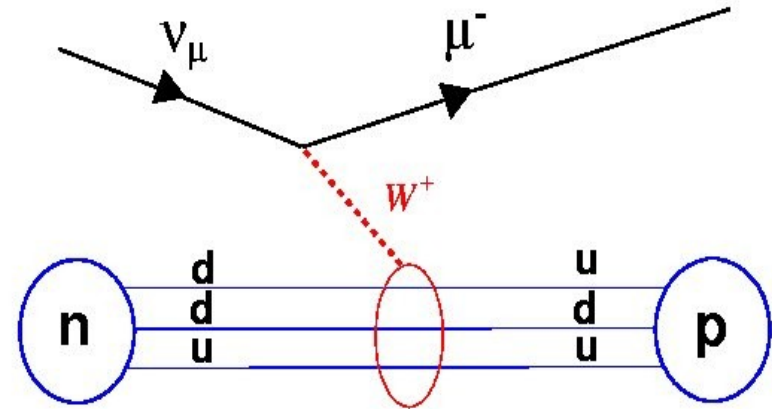
>>>





# 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

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

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

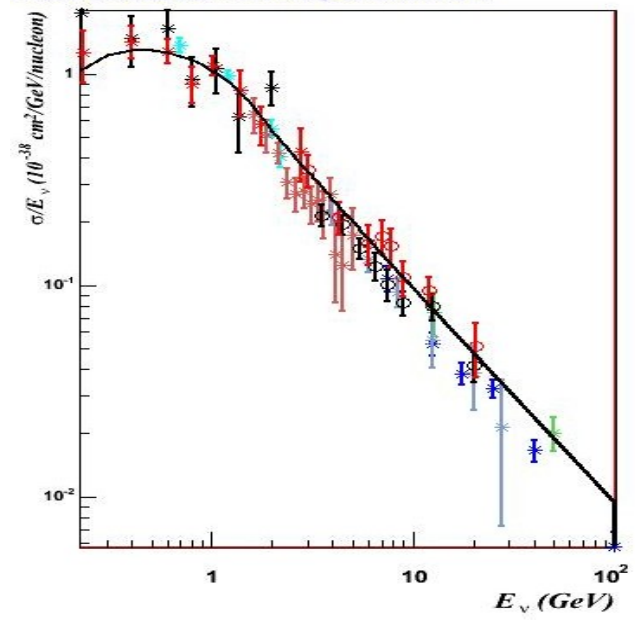
**vector form factors:**  
determined from e-N via CVC

**dipole axial form factor:**

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

GENIE - C.Andreopoulos (CCLRC,Rutherford), H.Gallagher (Tufts)

<http://hepunix.rl.ac.uk/~candreop/generators/GENIE/>



# 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  $G_{ve}$ ,  $G_{vm}$  from the elastic form factors

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

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

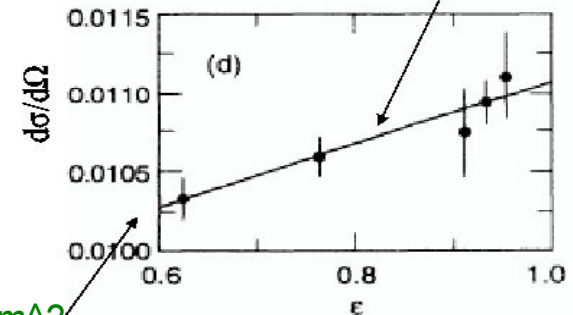
Elastic form factor measurements:

• **Rosenbluth separation:**

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

offset measures  $t * G_m^2$

slope measures  $G_e^2$



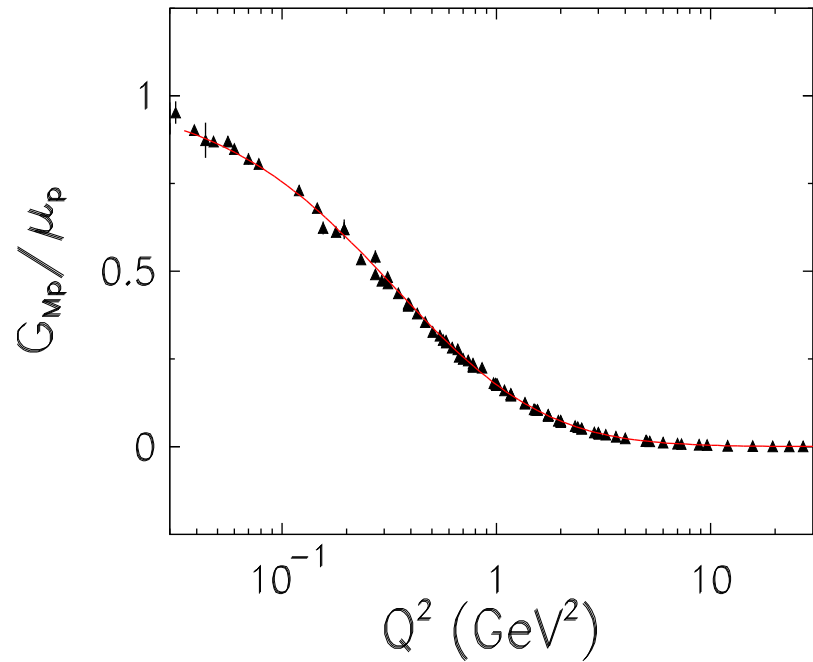
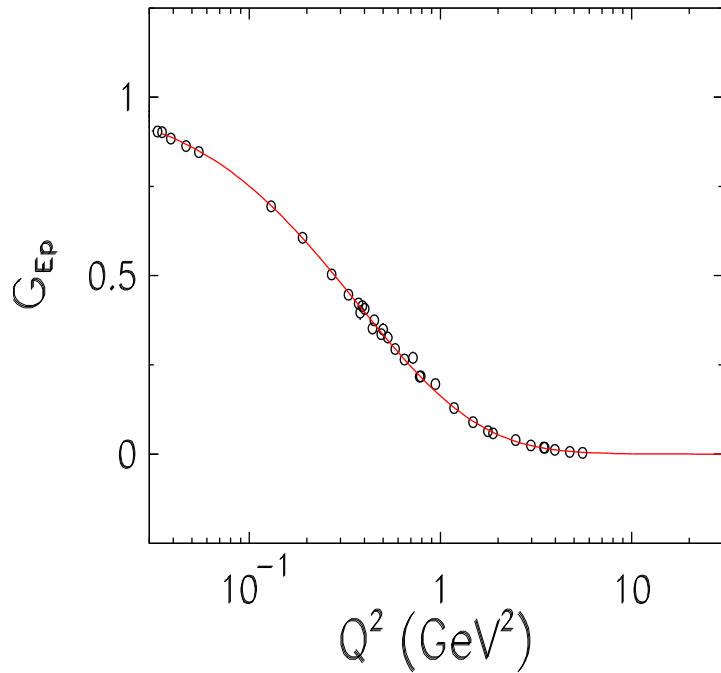
• **Polarization measurements:**

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

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

# Beyond the dipole form factors

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

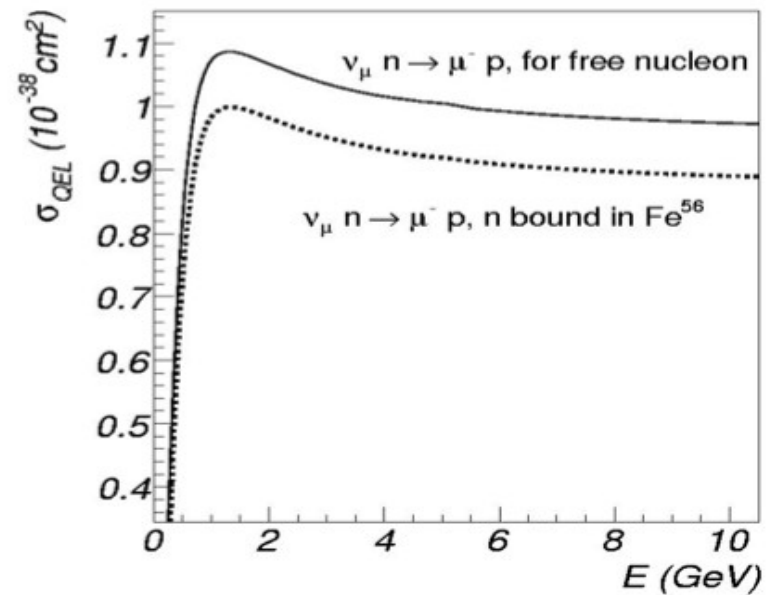
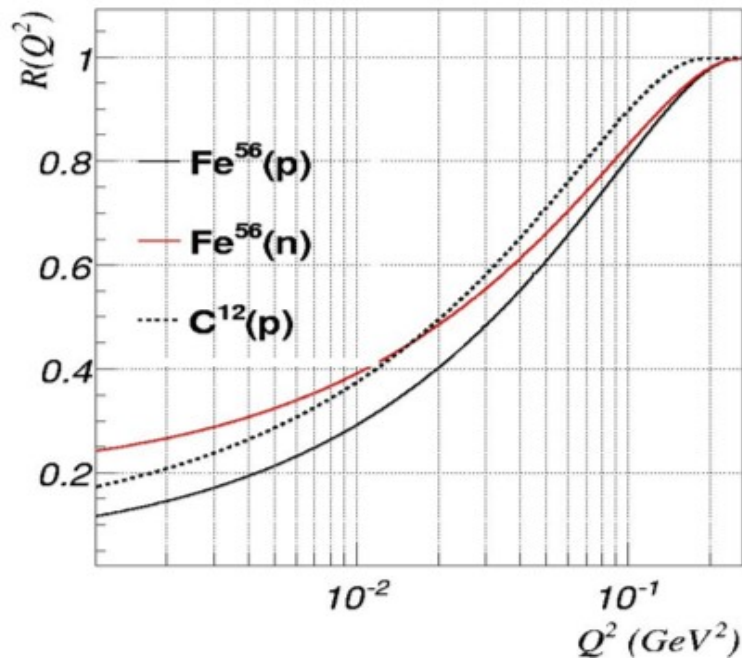


[R. Bradford et al, NuINT05]

# 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

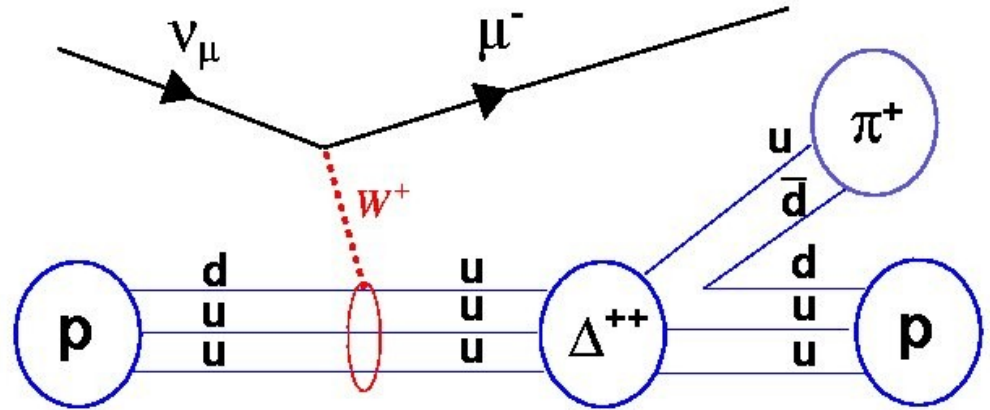
$$\nu + N \rightarrow l + Resonance$$

↳  $N + pion$   
(usually)

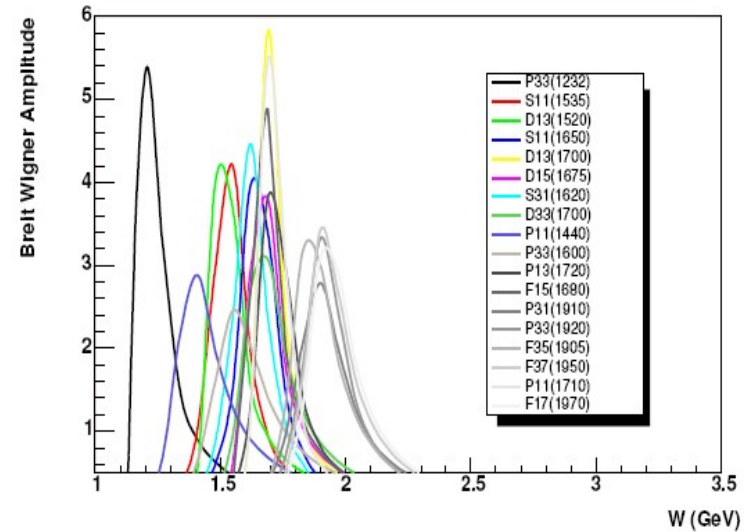
Very important channel(s)

~30% of the total CC xsec around ~ 1 GeV

Very complicated!

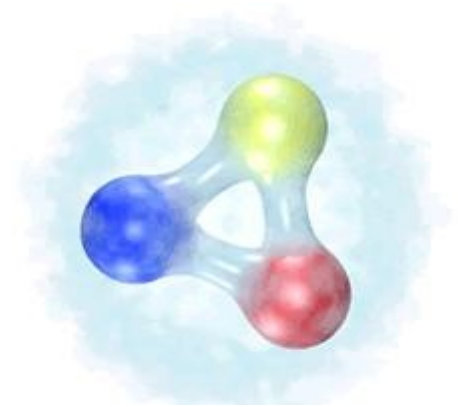


Resonance Mass (MeV)	$L(2I, 2J)$	PDG status	Breit-Wigner Width (MeV)	FKR $n$	BR $N^* \rightarrow N\pi$
$\Delta(1232)$	$F_{33}$	****	120	0	100%
$N(1535)$	$S_{11}$	****	150	2	45%
$N(1520)$	$D_{13}$	****	120	1	55%
$N(1650)$	$S_{11}$	****	150	1	73%
$N(1700)$	$D_{13}$	***	100	1	10%
$N(1675)$	$D_{13}$	****	150	1	45%
$\Delta(1700)$	$D_{33}$	****	300	1	15%
$N(1440)$	$F_{11}$	****	350	1	65%
$\Delta(1600)$	$F_{33}$	***	350	2	18%
$N(1720)$	$F_{13}$	****	150	2	15%
$N(1680)$	$F_{13}$	****	130	1	65%
$\Delta(1910)$	$F_{31}$	****	250	2	23%
$\Delta(1920)$	$F_{33}$	***	200	2	13%
$\Delta(1905)$	$F_{35}$	****	350	2	10%
$\Delta(1950)$	$F_{37}$	****	300	2	10%
$N(1710)$	$F_{11}$	***	100	2	38%



# Neutrino-production of resonances

The most widely used model for resonance neutrino 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  
 (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

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

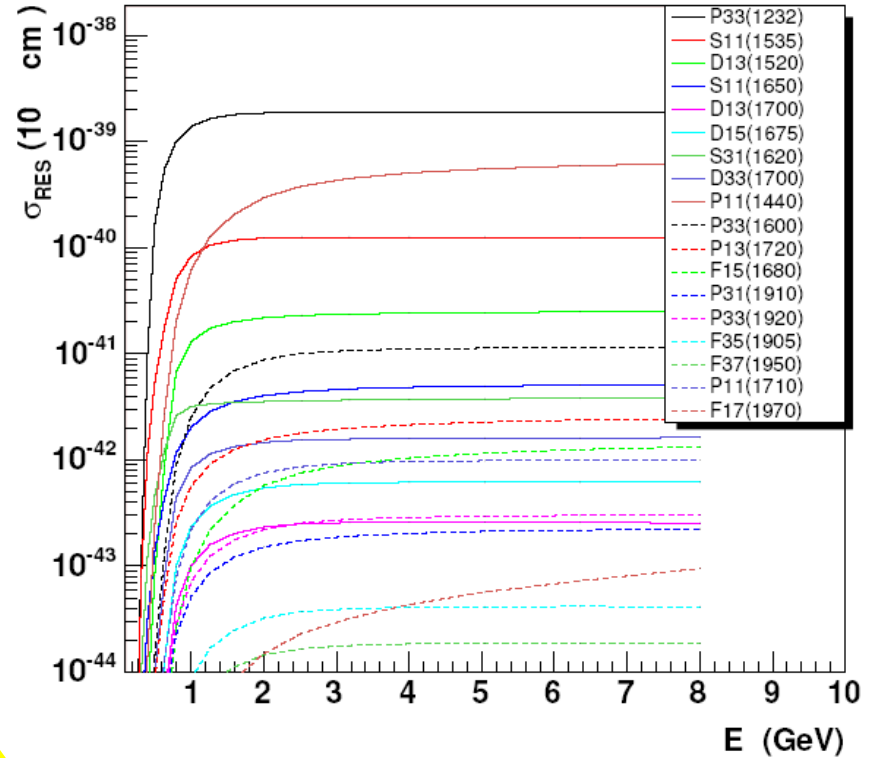
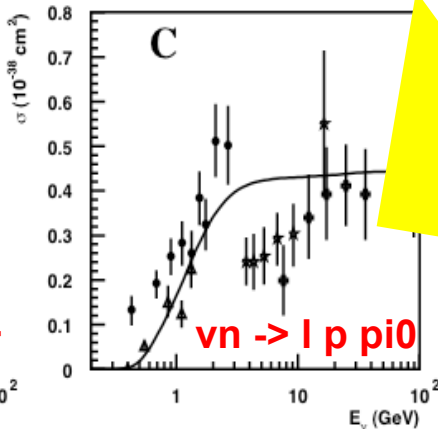
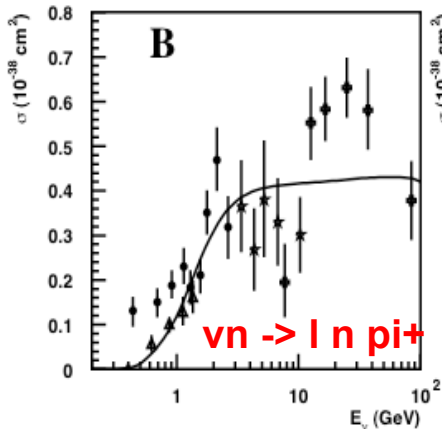
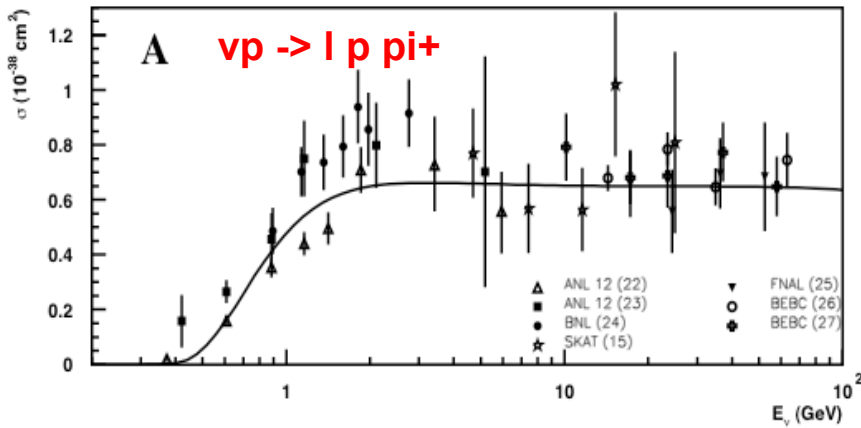
$$M_V = 0.84 \text{ GeV}/c^2, M_A$$



# Neutrino-production of resonances

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

## Single pion production cross sections

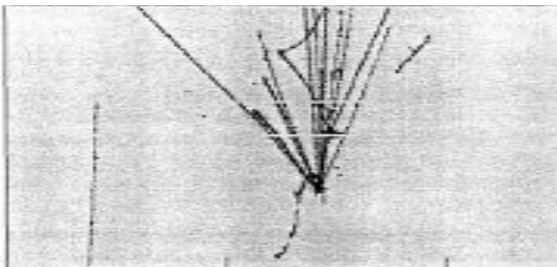
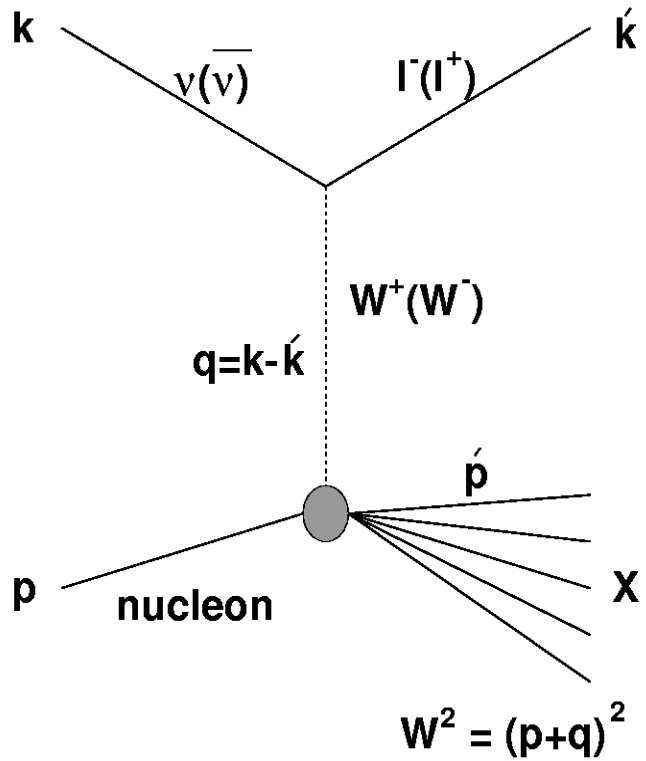


Include isospin amplitudes and 1pi BR  
to weight the contribution of each resonance  
to exclusive single pion reactions

Can add coherently  
For simplicity, many calculations add incoherently



# Deep Inelastic Scattering



LAr images, courtesy A. Currioni

Differential cross section in terms of 5 structure functions:

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

where:

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

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

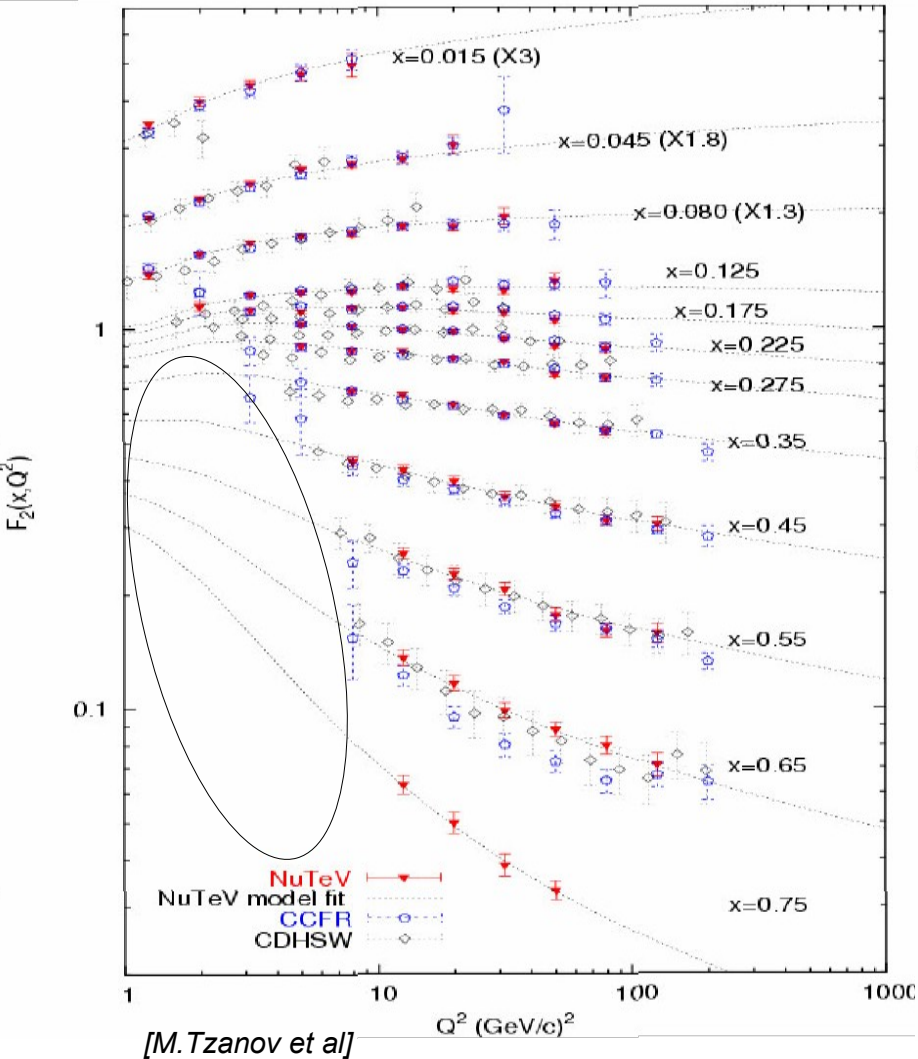
$$A_3 = \pm y \left[ x \left( 1 - \frac{y}{2} \right) - \frac{m_\mu^2}{4M_N E} \right],$$

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

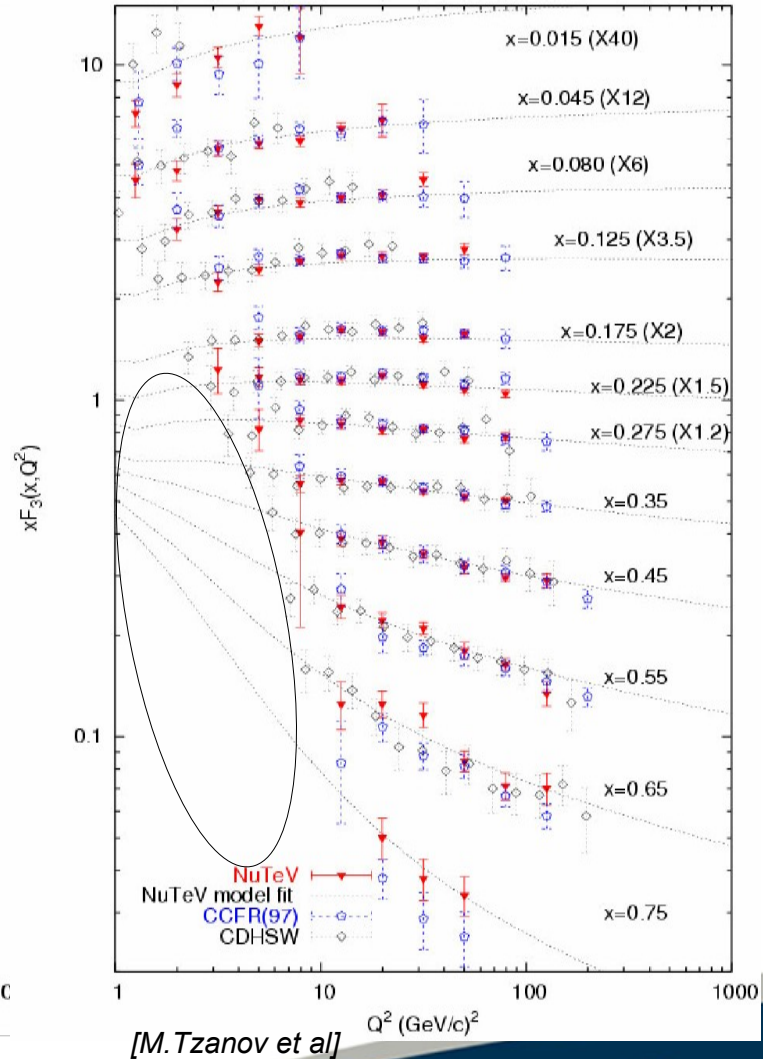
$$A_5 = -\frac{m_\mu^2}{M_N E}.$$

# Deep Inelastic Scattering / Structure functions

## F<sub>2</sub>



## xF<sub>3</sub>



# Bodek / Yang model

Based on LO cross section models with new scaling variable to account for higher twists and modified PDFs to describe low- $Q^2$  data

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

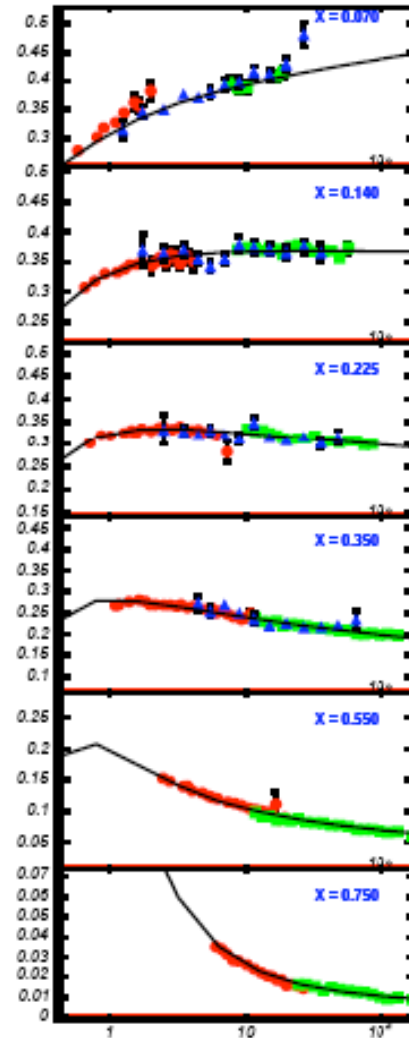
$$K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_s}$$

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

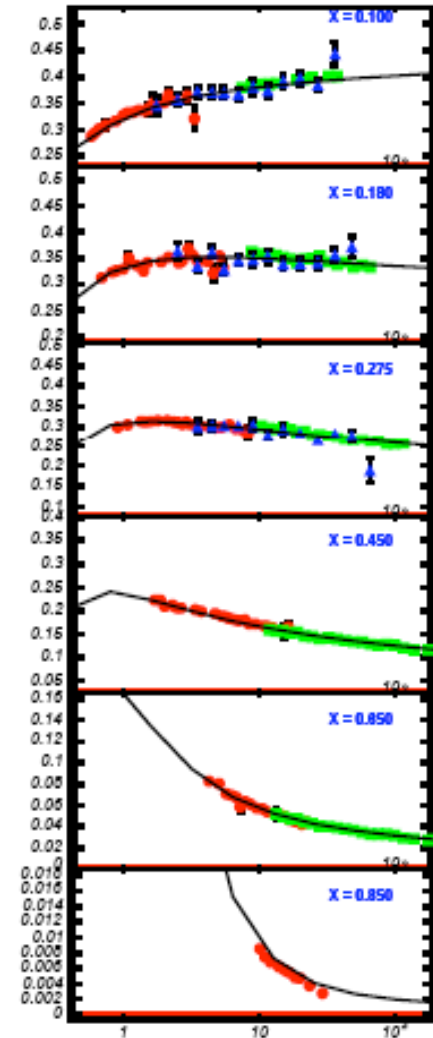
Fits based on GRV98LO and free nucleon charged lepton data

[[hep-ph/0411202](https://arxiv.org/abs/hep-ph/0411202)]

[Bodek & Yang]



A=0.541  
B=0.308  
Cv1d=0.227  
Cv1u=0.291  
Cv2d=0.288  
Cv2u=0.189  
Ca1d=0.819  
Ca1u=0.383  
nSLACd=0.990  
nBCDMSp=0.987  
nBCDMSd=0.987  
nNMCp=1.003  
nNMCd=0.994  
nH1p=0.978  
aLambda=2.052  
fPDF=1.014

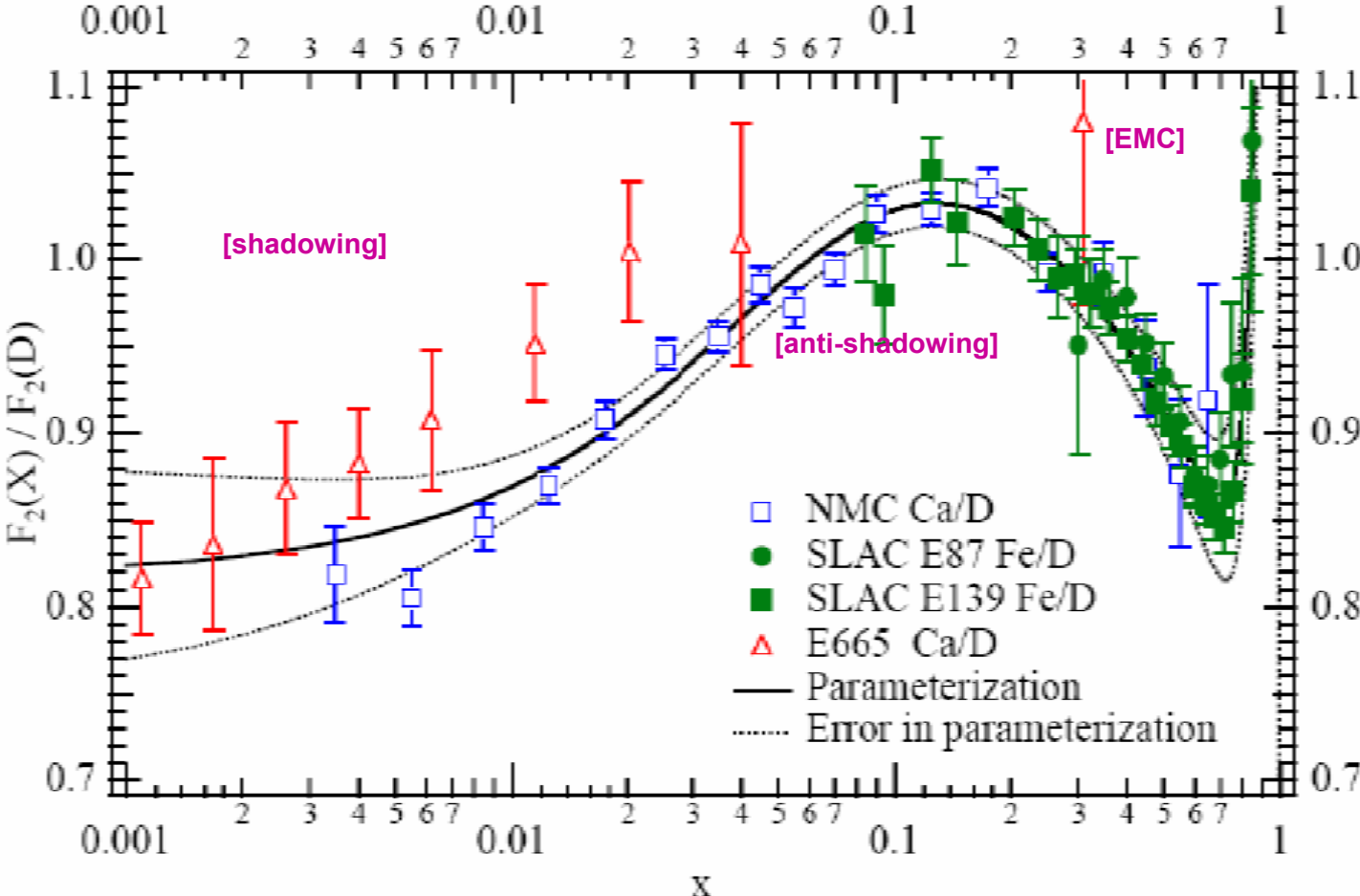


Proton experiment data fit

● SLAC  
■ BCDMS  
▲ NMC  
— GRV98(LO+HT)



# Deep Inelastic Scattering / Nuclear corrections



# Putting everything together

## total inclusive cross section

= sum of contributions from:

- *exclusive channels*
- *DIS*



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

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

# Putting everything together

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

where

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

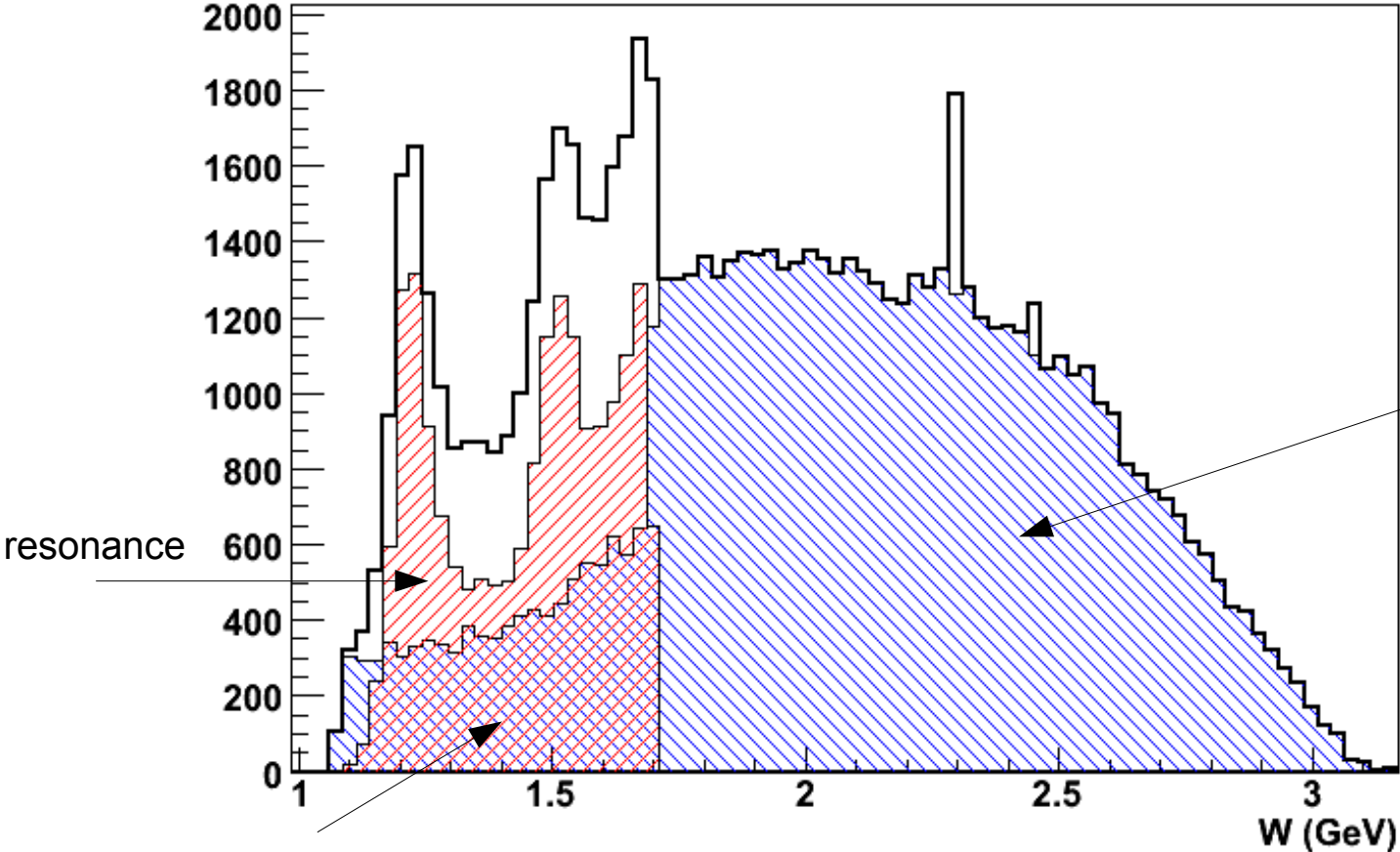
where the summation is over the 17 resonances in the Rein-Seghal model,  
and

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

# Putting everything together

numu, 5 GeV

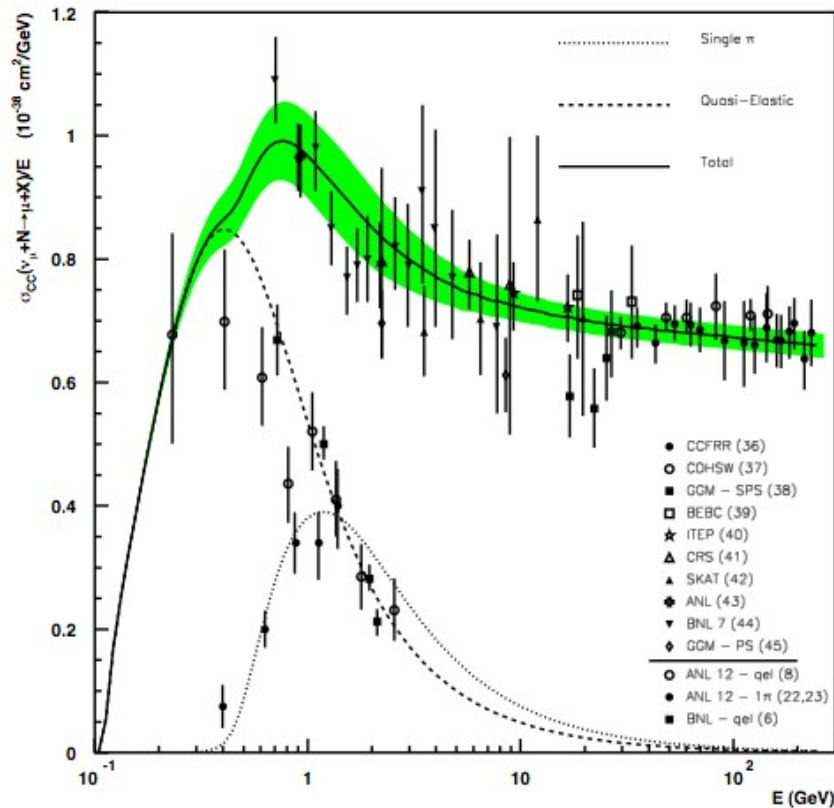
$W_s$



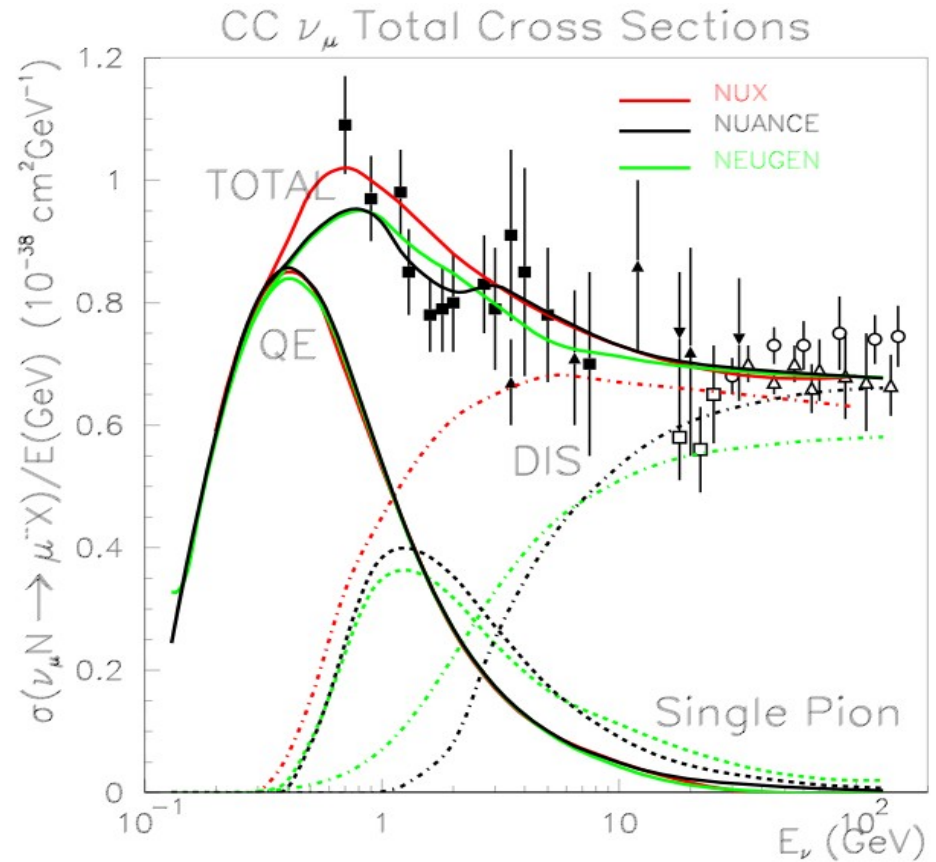
transition DIS

# The GENIE cross section model

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



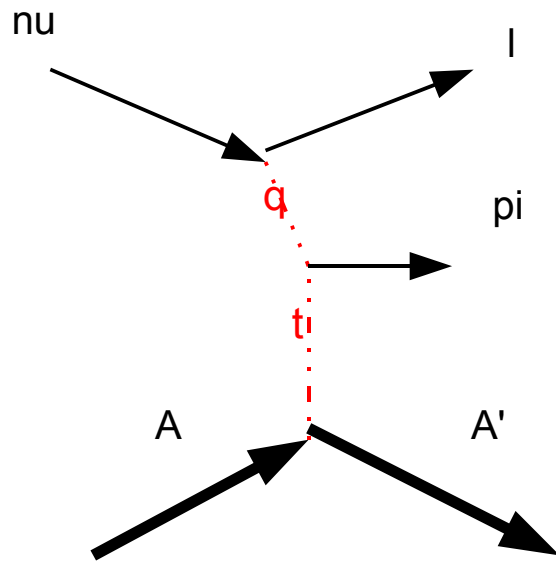
## Sam Zeller. circa-2002 / Cross-generator comparisons



- (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

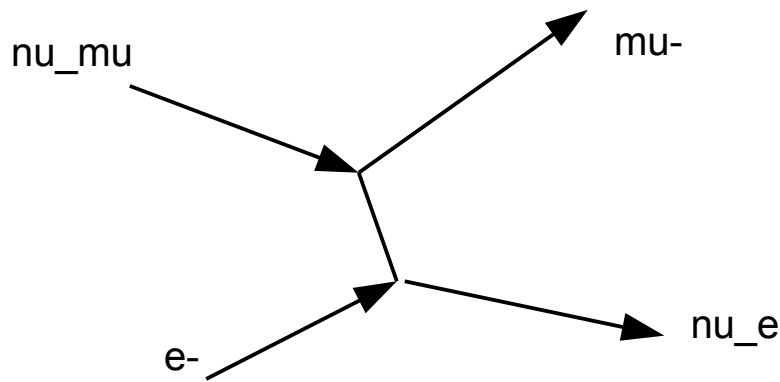
## *ve- elastic*

Fairly standard.

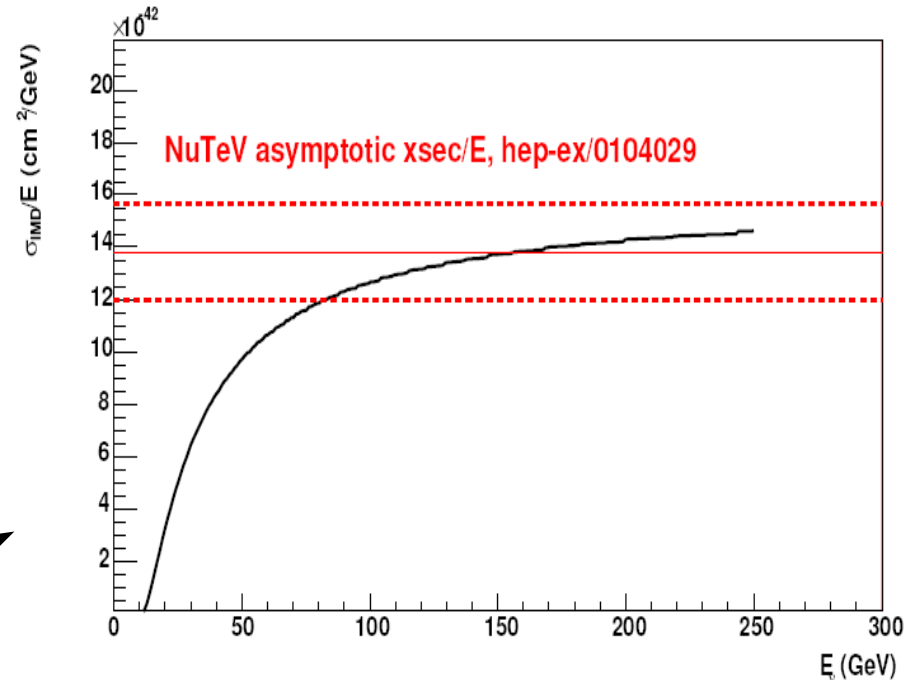
Cross sections implemented as in W.J.Marciano and Z.Parsa, J.Phys.G: Nucl.Part. Phys.29 (2003) 2629.

Radiative corrections currently neglected.

## *Inverse muon decay*

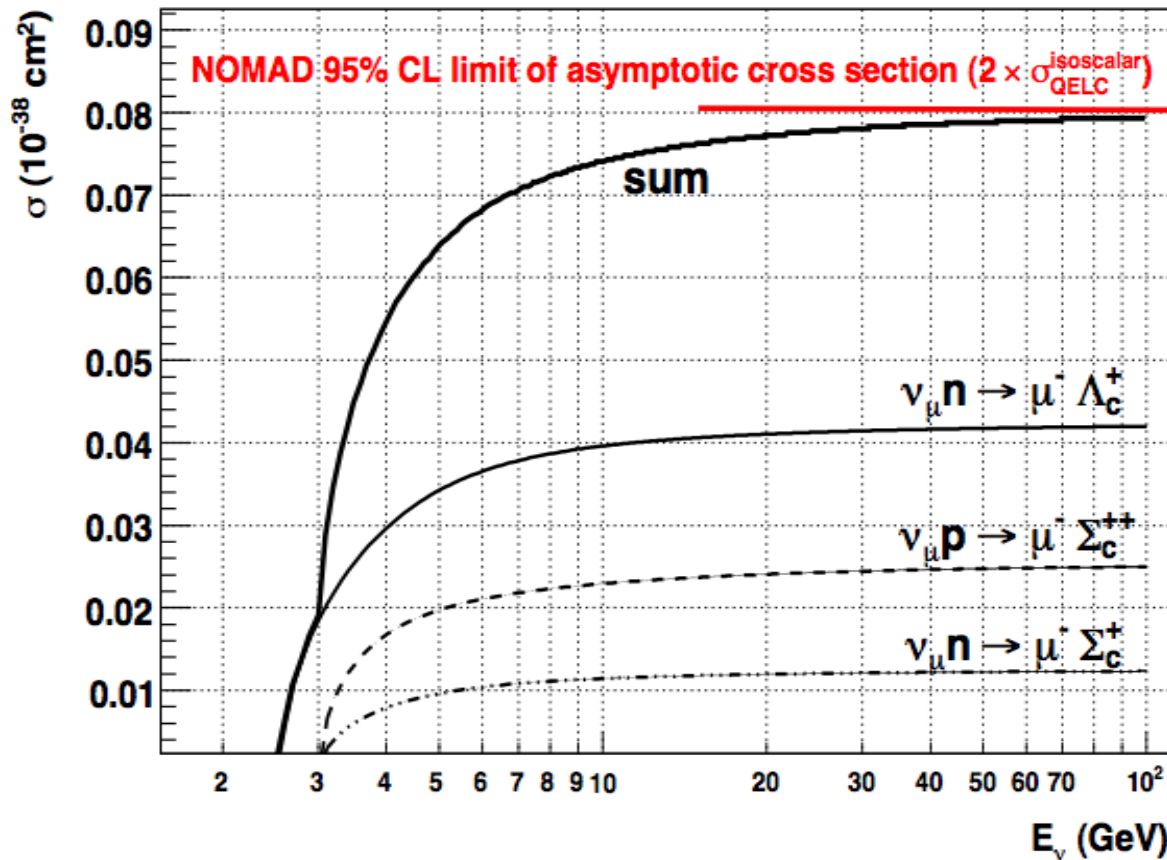


D.Yu.Bardin and V.A.Dokuchaeva,  
Nucl.Phys.B287:839 (1987),  
includes all 1-loop radiative corrections

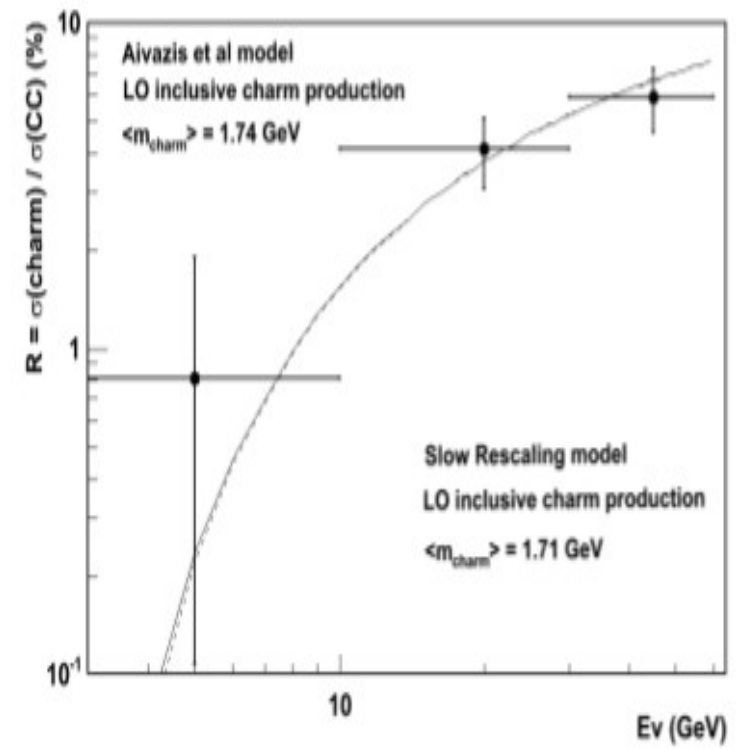
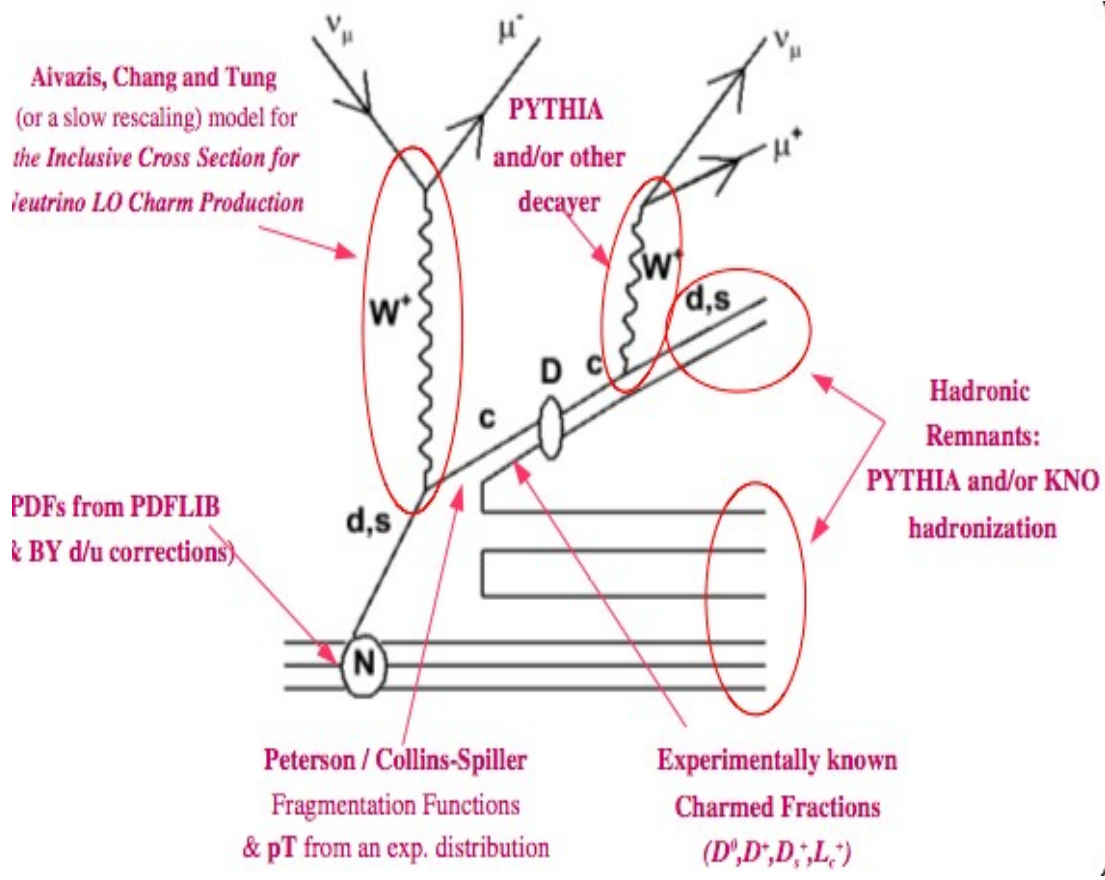


# QEL charm production

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



# DIS charm production

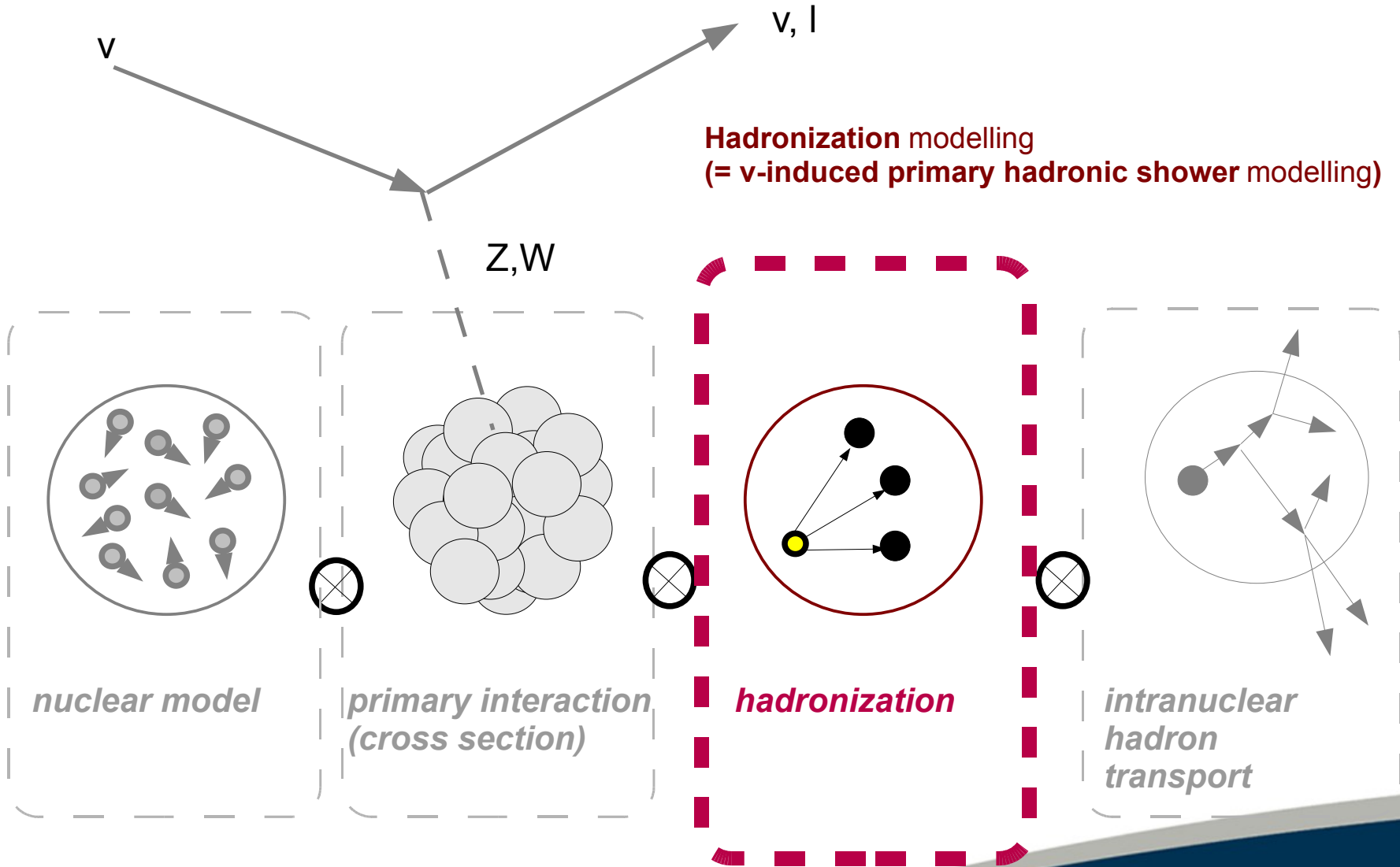


# Hadronic simulations within GENIE

>>>

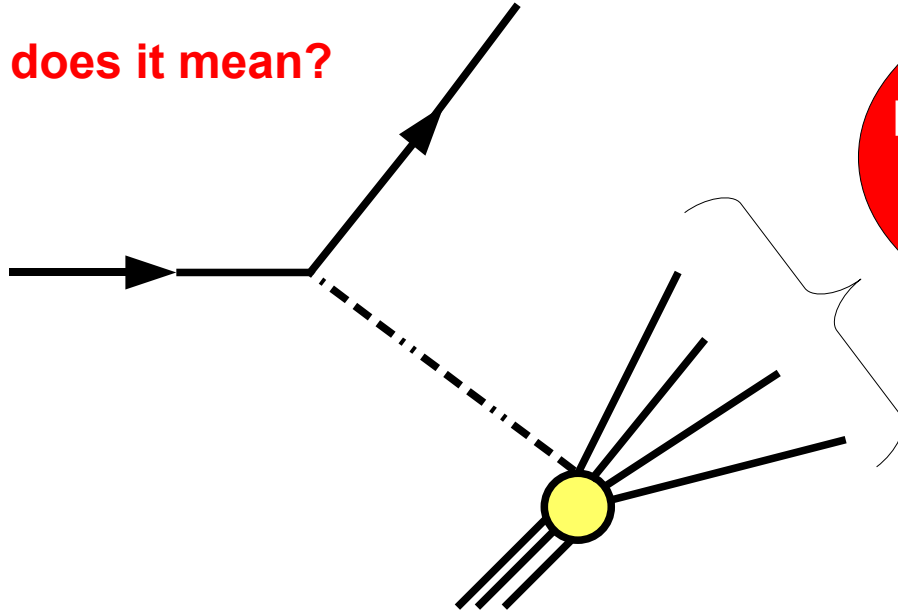


# Hadronization modelling



# Hadronization modelling

what does it mean?



predict hadron shower  
particle content &  
particle 4-momenta

- 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 /  $\pi^0$  fraction of the shower -> *nu*e backgrounds
    - Eg, CC/NC shower shapes -> CC/NC PIDs
  - Used to decompose inclusive  $\nu N \rightarrow IX$  to exclusive contributions
    - Eg, Contribution of 1  $\pi$  DIS channels in RES/DIS transition region



# The GENIE hadronization model

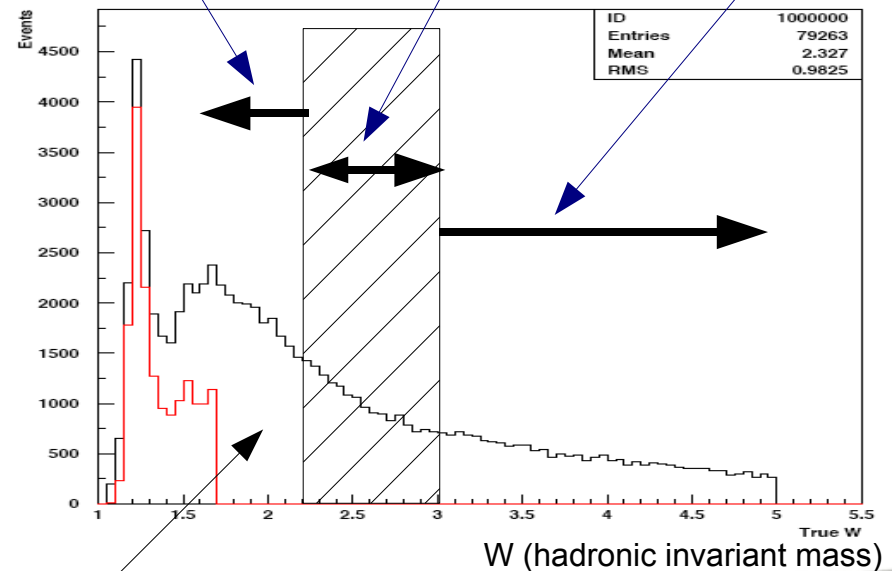
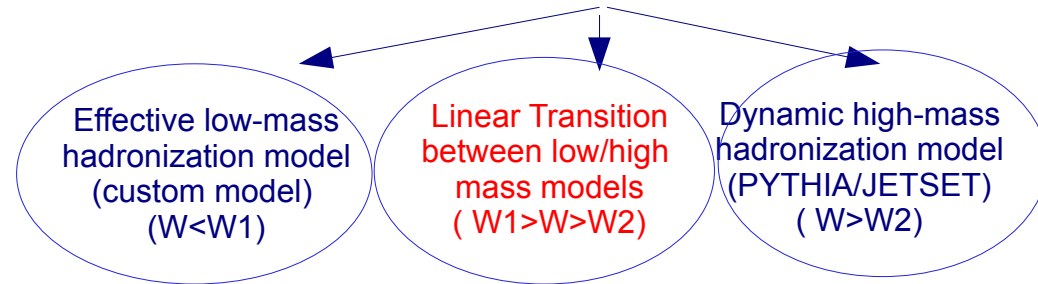
## Andreopoulos-Gallagher-Keyahias-Yang (AGKY) model

### 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. Etc...

### At high hadronic invariant masses:

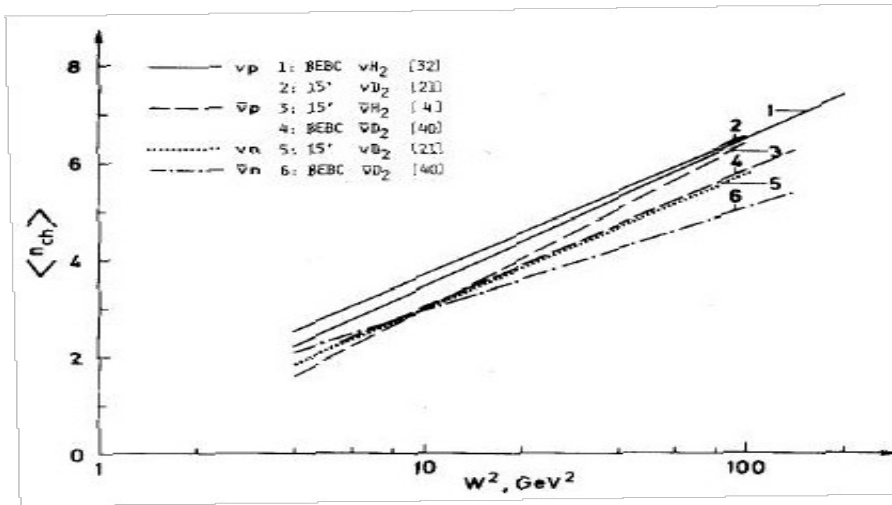
- rich dynamics
- using JETSET model
- tuned energy cutoff, pT, sbar suppression (as in NUX)
- not really relevant at t2k energies



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



# The GENIE hadronization / AGKY low-W model



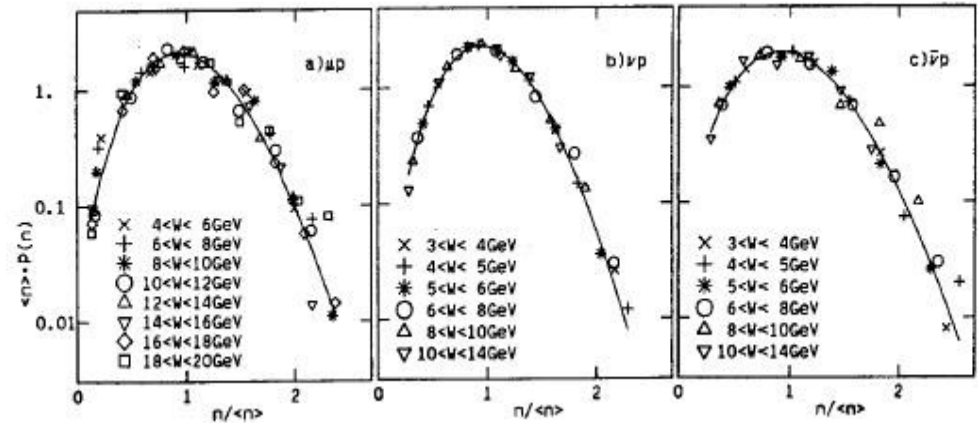
Get average multiplicity from empirical parameterizations

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

Generate the actual multiplicity using the KNO scaling law:

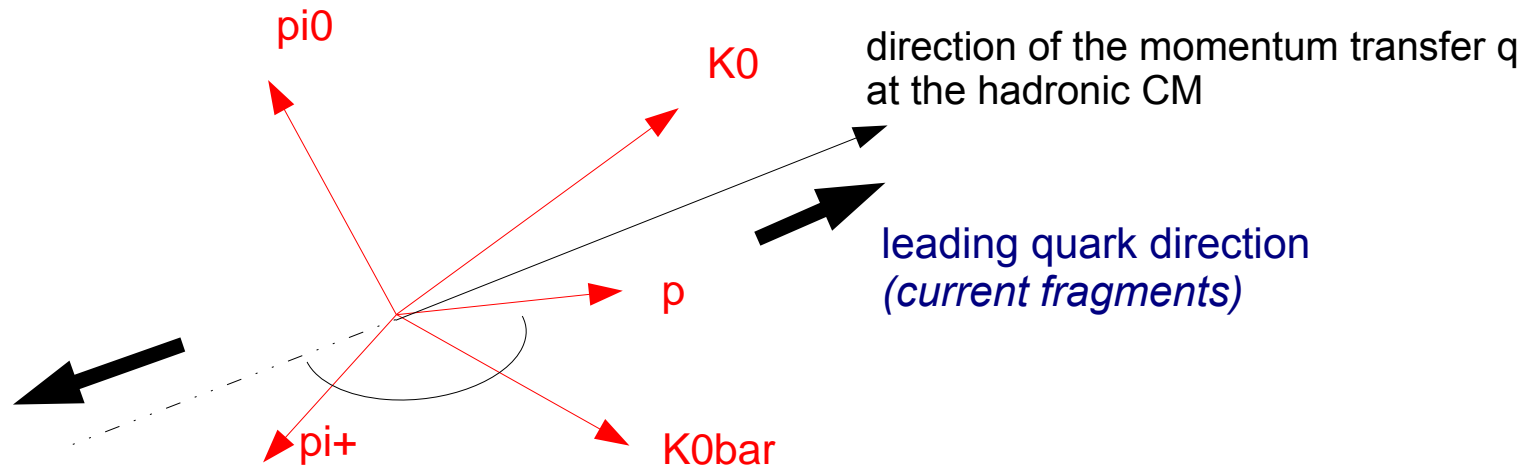
$$\langle n \rangle P(n) = f(n / \langle n \rangle)$$

(taken 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 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  $p_T$  and  $x_F$  ( $= p_L/p_{Lmax} = 2*p_L/W$ )

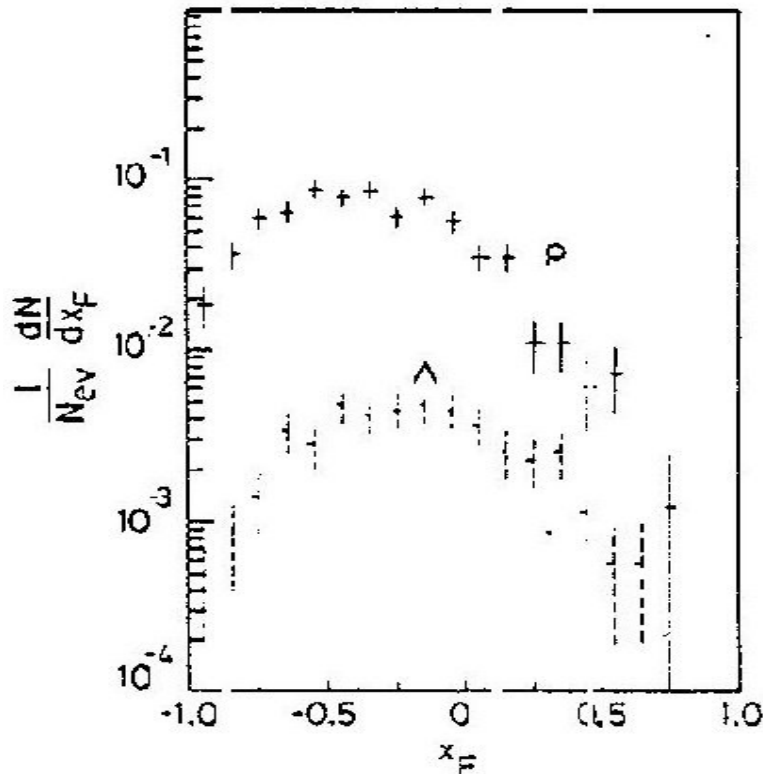
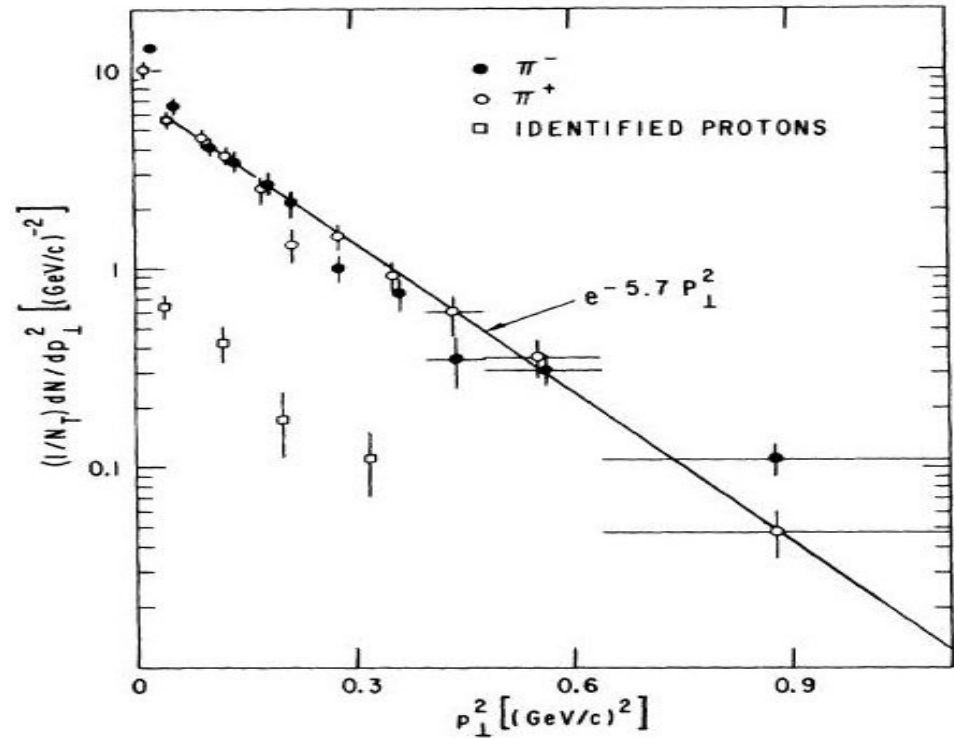


Fig. 11:  $x_F$  normalised distributions for protons ( $\times$  WA24 data) and lambda's ( $\Delta$  WA21 data, Bossetti et al, Nucl. Phys. 3194, 1 (1982)).



Cooper, Neutrino 82, proceedings

# The GENIE hadronization / AGKY low-W model

$$p4_{\text{meson `remnants'}} = p4_{\text{X}} - p4_{\text{nucleon from target fragments}}$$

## Meson 4-momenta:

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

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

pT-limited  
phase space decay

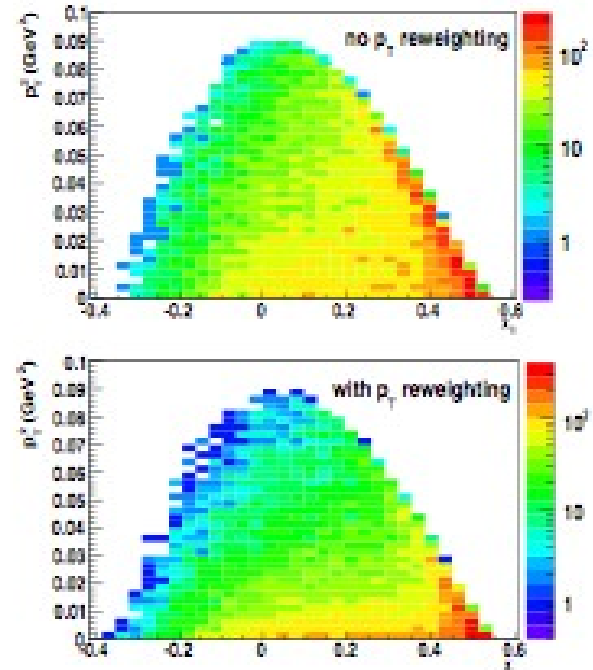


Figure 5. Pion  $x_F$  vs  $p_T^2$ , in the hadronic CM, for a  $(p, \pi^0, \pi^+)$  system decayed with invariant mass  $W = 1.6$  GeV, where, for convenience, the

# Formation zone

**SKAT parameterization:**

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

*Hadron momentum* (pointing to  $P$ )

*Transverse hadron momentum* (pointing to  $P_T$ )

$K=0, ct_0 = 0.342 \text{ fm}$

(SKAT) model dependence

**No intranuclear rescattering within formation zone**

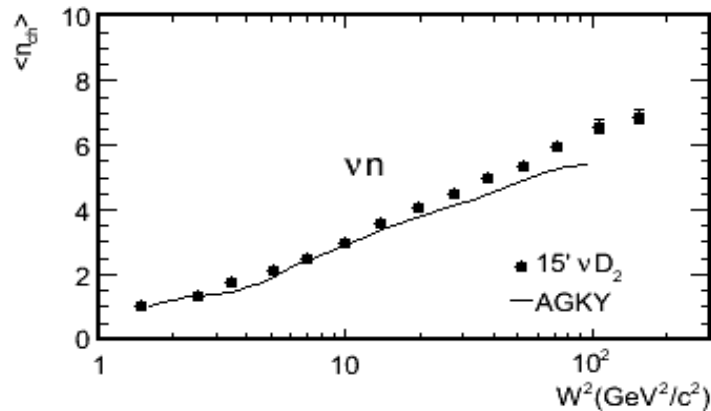
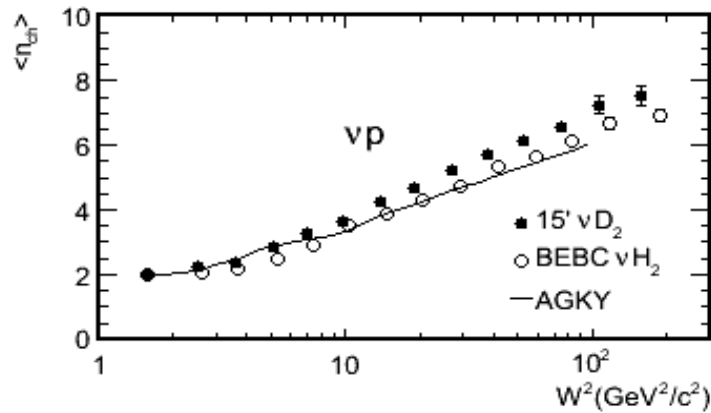
Used for hadrons generated by both the low-W KNO-based hadronization model and for the small fraction of events hadronized by JETSET (override JETSET positions)

# The GENIE hadronization model – Data/MC comparisons

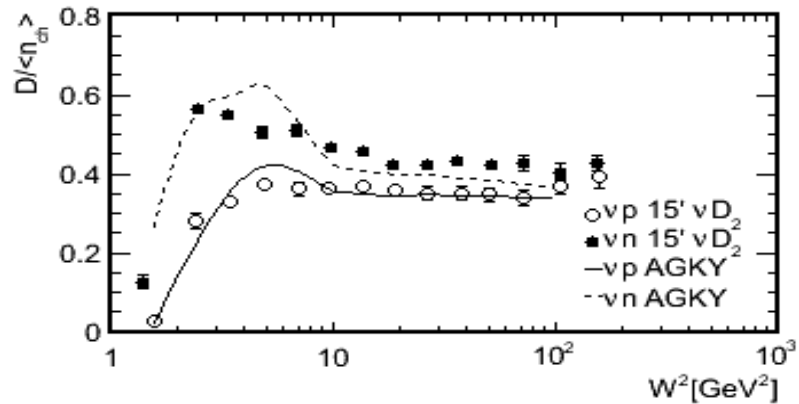
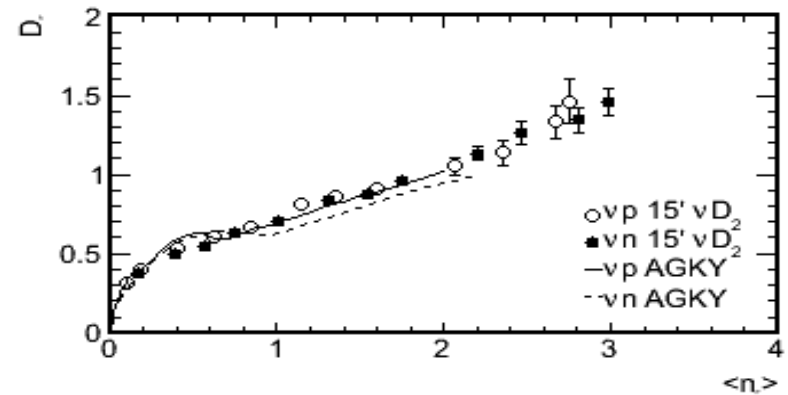
Model does very good job against a diverse host of data

examples:

## Charged pion multiplicities



## Charged pion dispersion

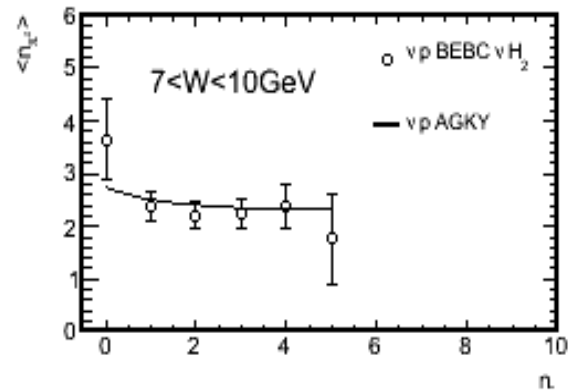
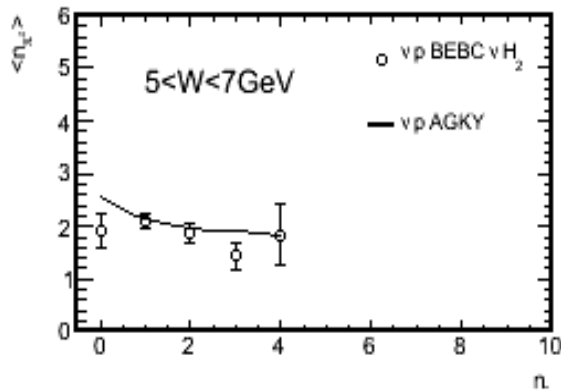
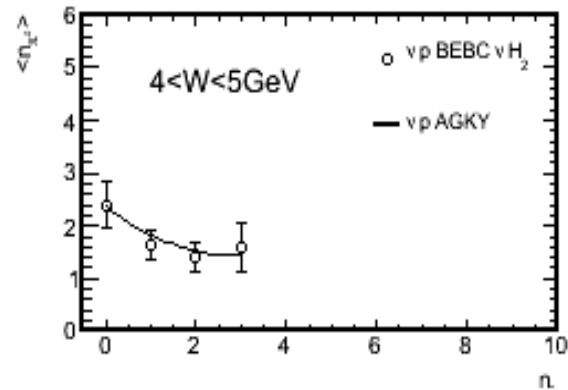
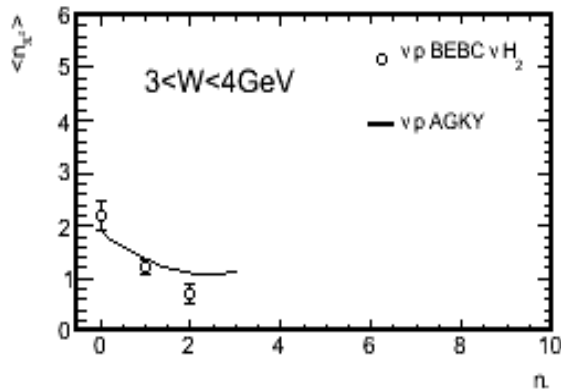


# The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

## Neutral / charged pion correlation

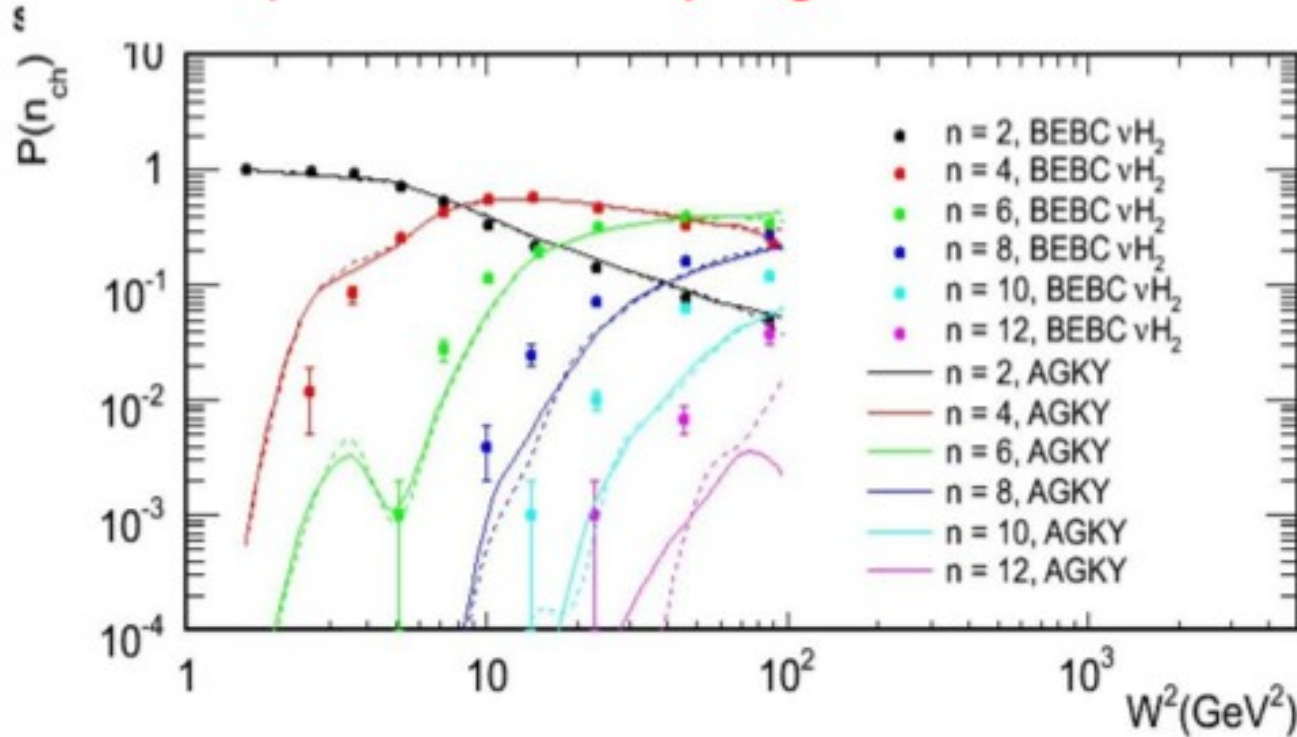


# The GENIE hadronization model – Data/MC comparisons

Model does very good job against a diverse host of data

example:

## Normalized topological cross sections

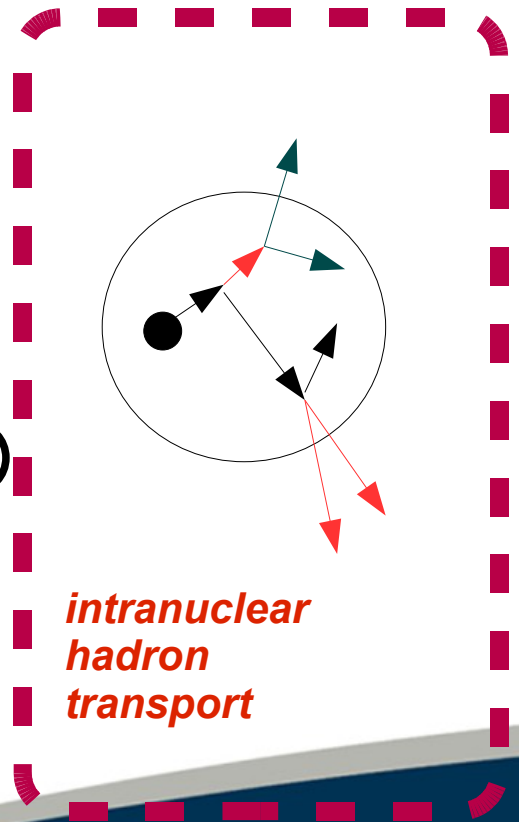
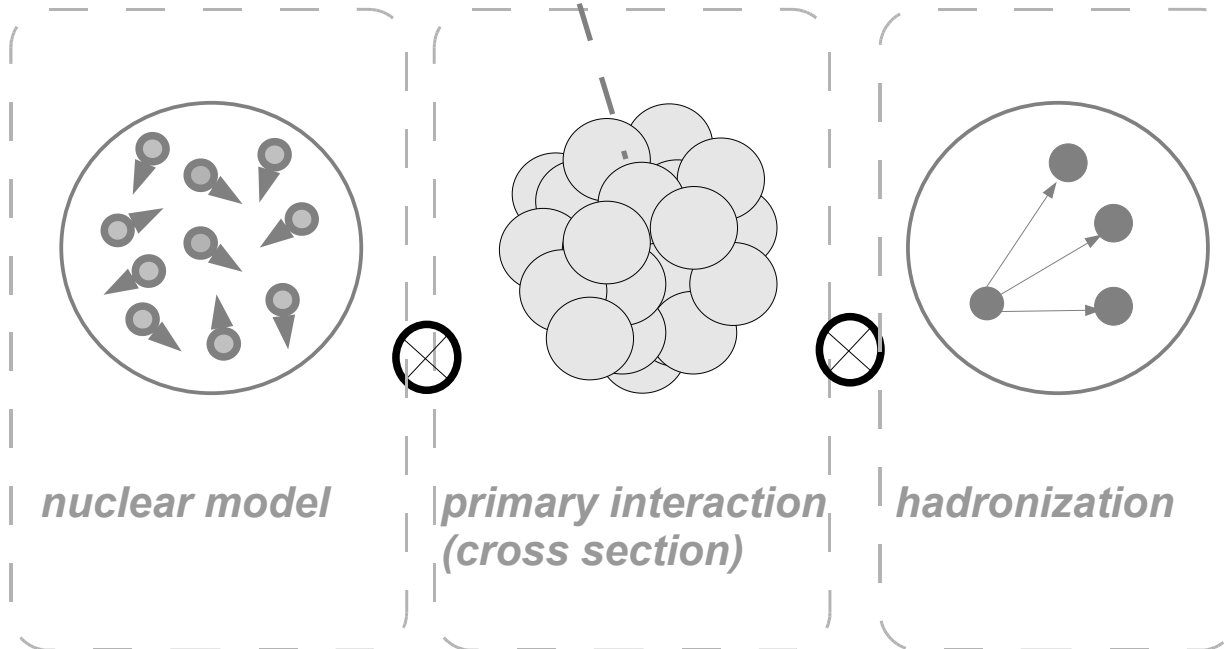
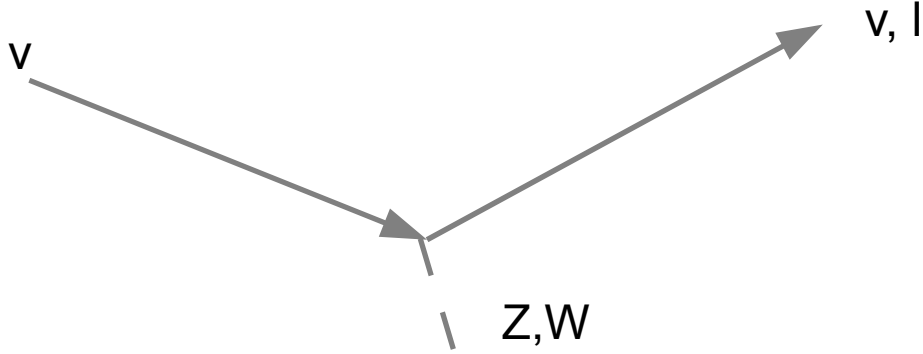


For more data/mc comparisons see GENIE-PUB/2007/002 and T.Yang's talk/proceedings at NuINT07

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



# Intranuclear hadron transport

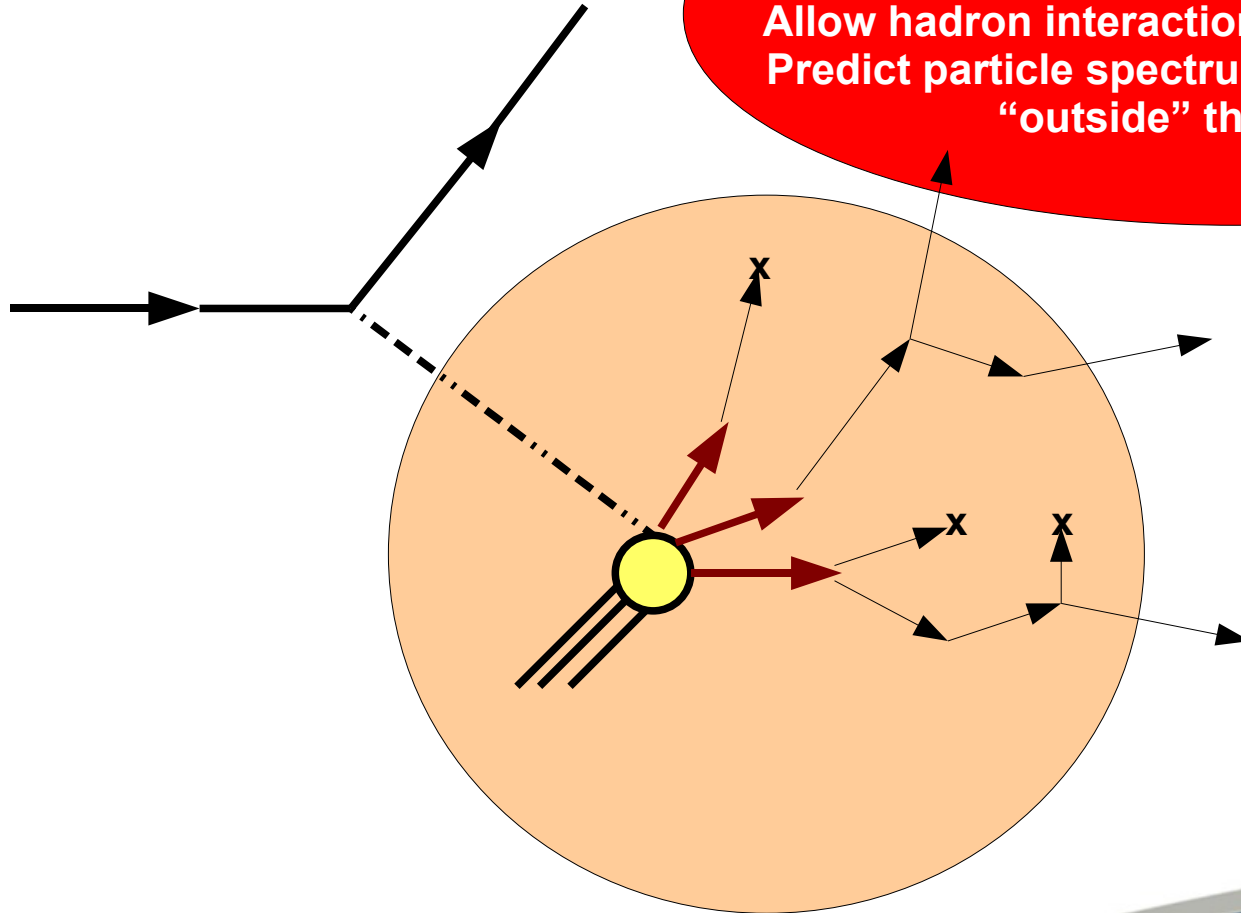


***intranuclear  
hadron  
transport***

# The GENIE hadron transport modelling

what does it mean?

Transport primary (and secondary, tertiary, ...) hadrons out of the hit nucleus. Allow hadron interactions in the nuclear matter. Predict particle spectrum & particle 4-momenta "outside" the hit nucleus

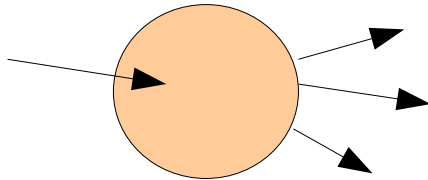


# The GENIE hadron transport modelling

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

Development of both is led by Steve Dytman

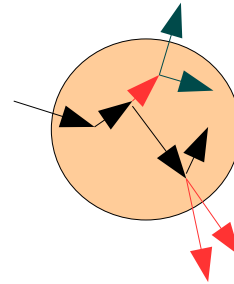
**Intranuke / hA**  
(effective MC)



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

available since 2.0.0

**Intranuke / hN**  
(true cascade MC)



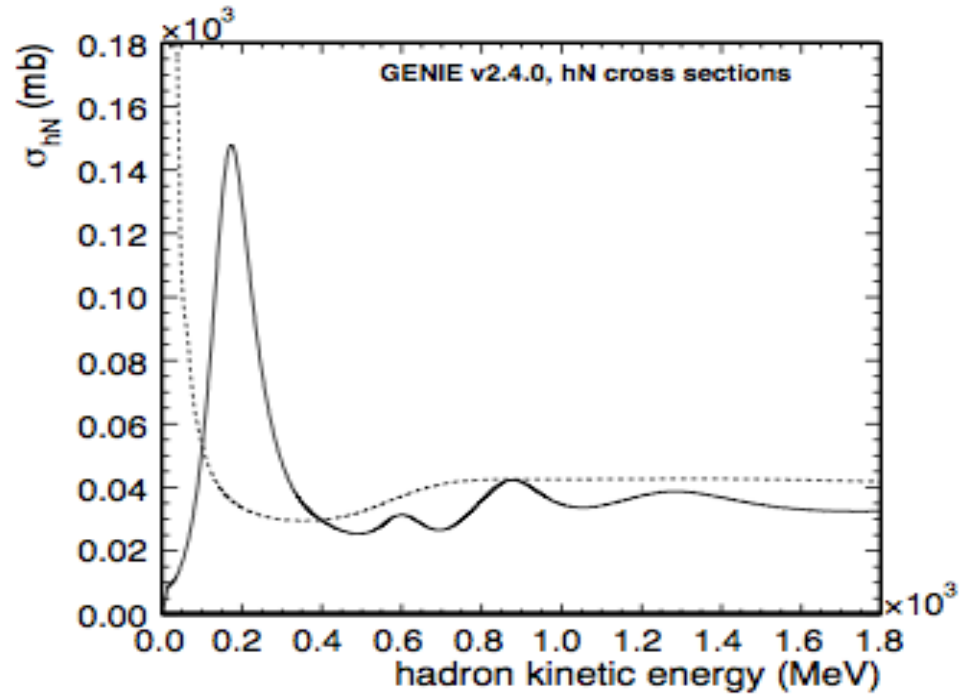
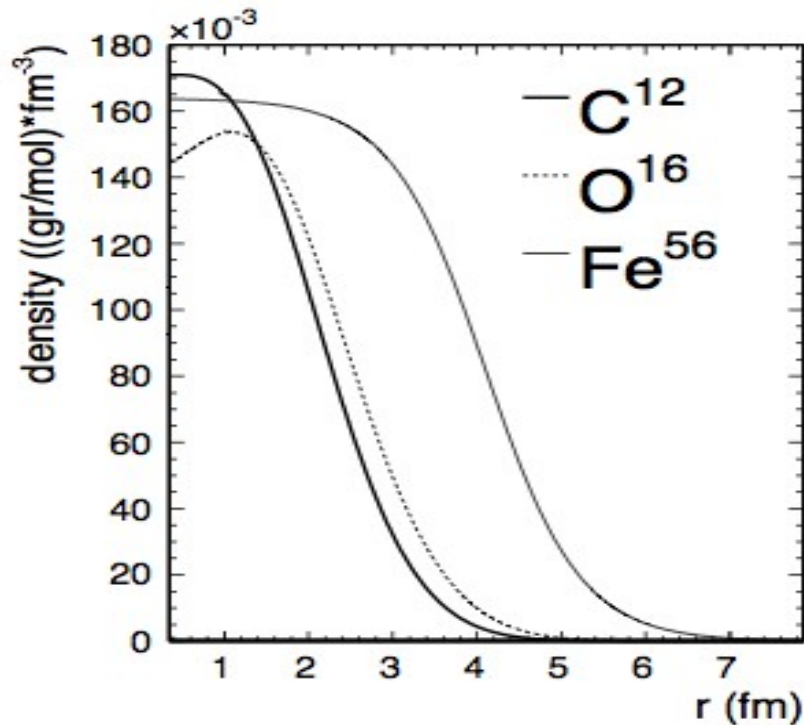
**Builds everything up from  
hadron-nucleon xsecs**

**In advanced development stage**  
to become available soon

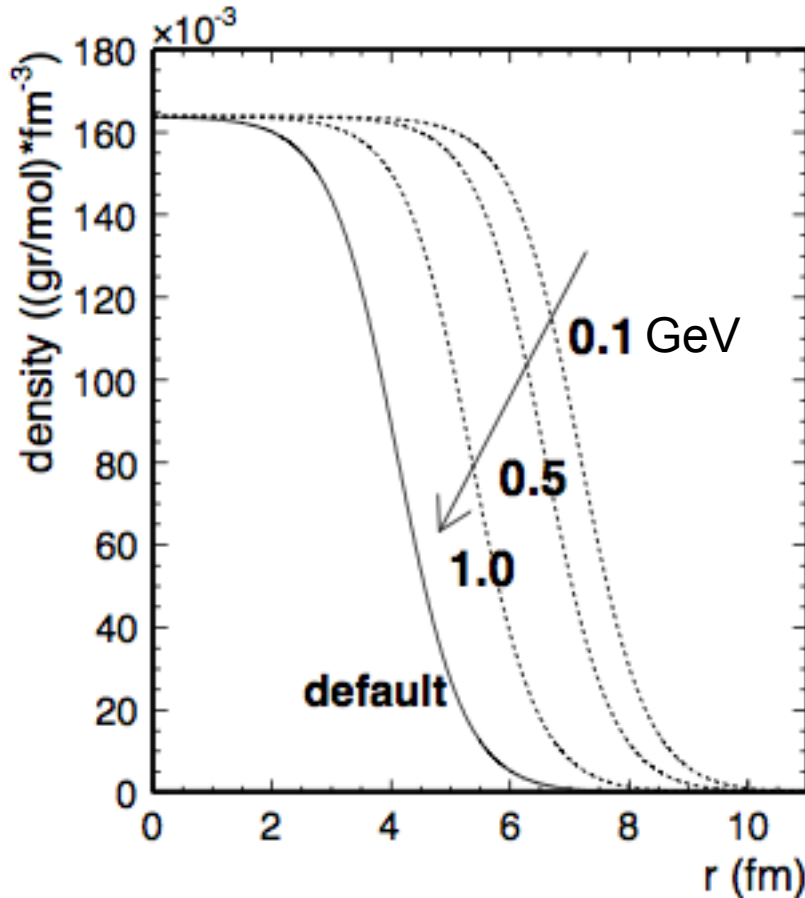
# The GENIE hadron transport modelling (INTRANUKE/hA)

Stepping primary hadrons within the target nucleus

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



# The GENIE hadron transport modelling (INTRANUKE/hA)

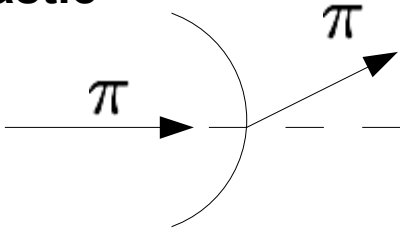


- Hadrons stepped by 0.05 fm at a time
- Hadrons traced till they reach  $r_{\text{max}} = N * R_{\text{nucl}} = N * R0 * A^{(1/3)}$  ( $R0 = 1.4$ ,  $N = 3.0$ ) so as to include the effects of the tails (Fe56:  $R_{\text{nucl}}=5.36\text{fm}$ ,  $r_{\text{max}}=16.07\text{fm}$ )
- The nuclear density 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)

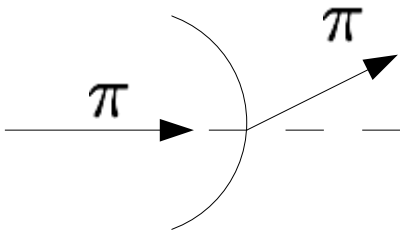
INTRANUKE/hA considers 5 types of 'hadron fates' (some may include many channels)

## elastic



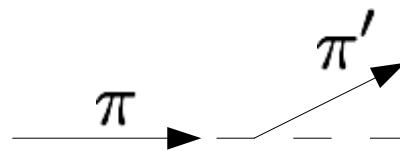
Pion deflected.  
Its kinetic energy stays the same.

## inelastic

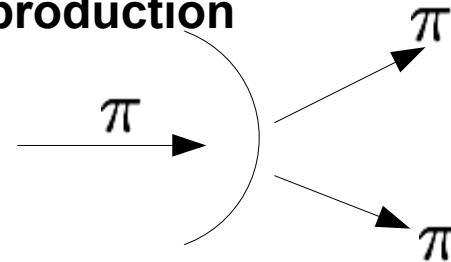


Pion deflected.  
Its kinetic energy is degraded.

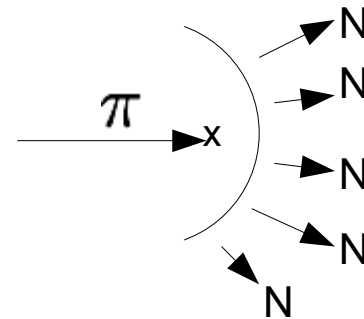
## charge exchange



## pion production



## absorption



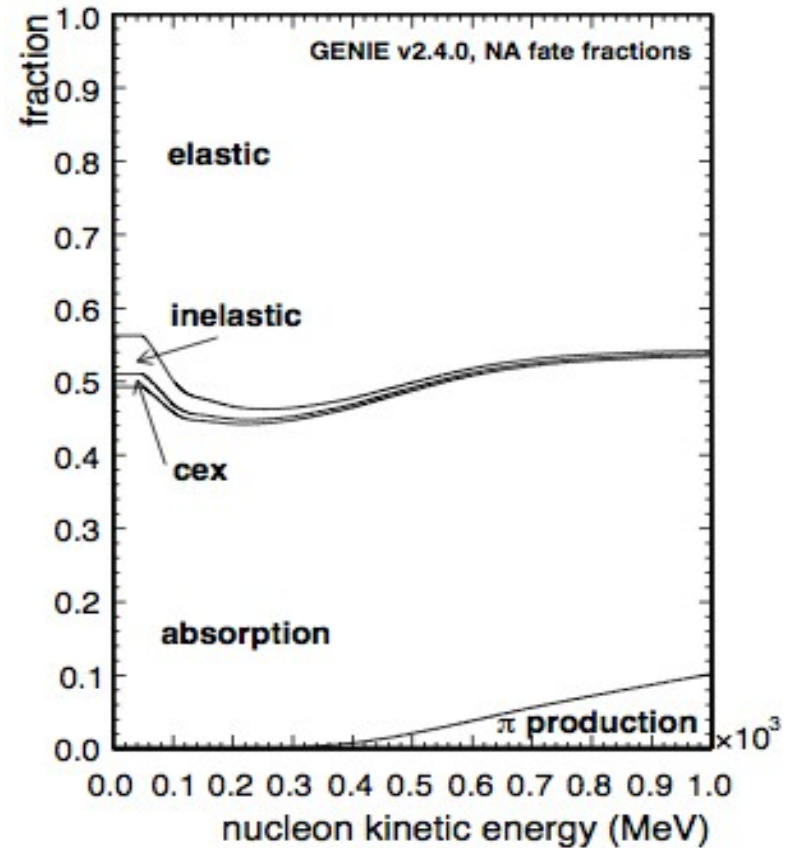
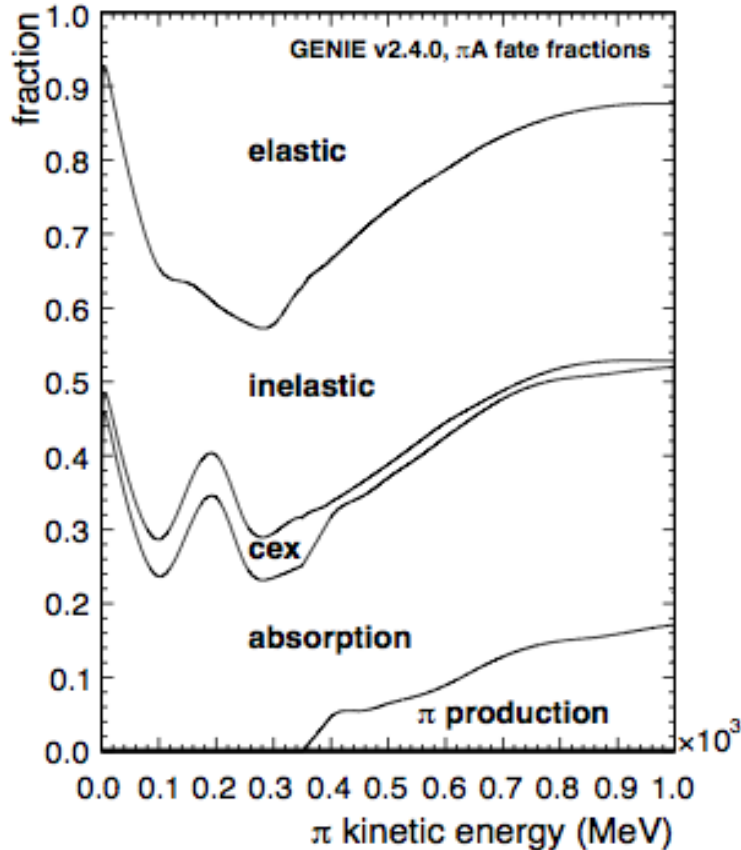
followed by  
emission  
of low energy  
nucleons

~ Similar fates for nucleons

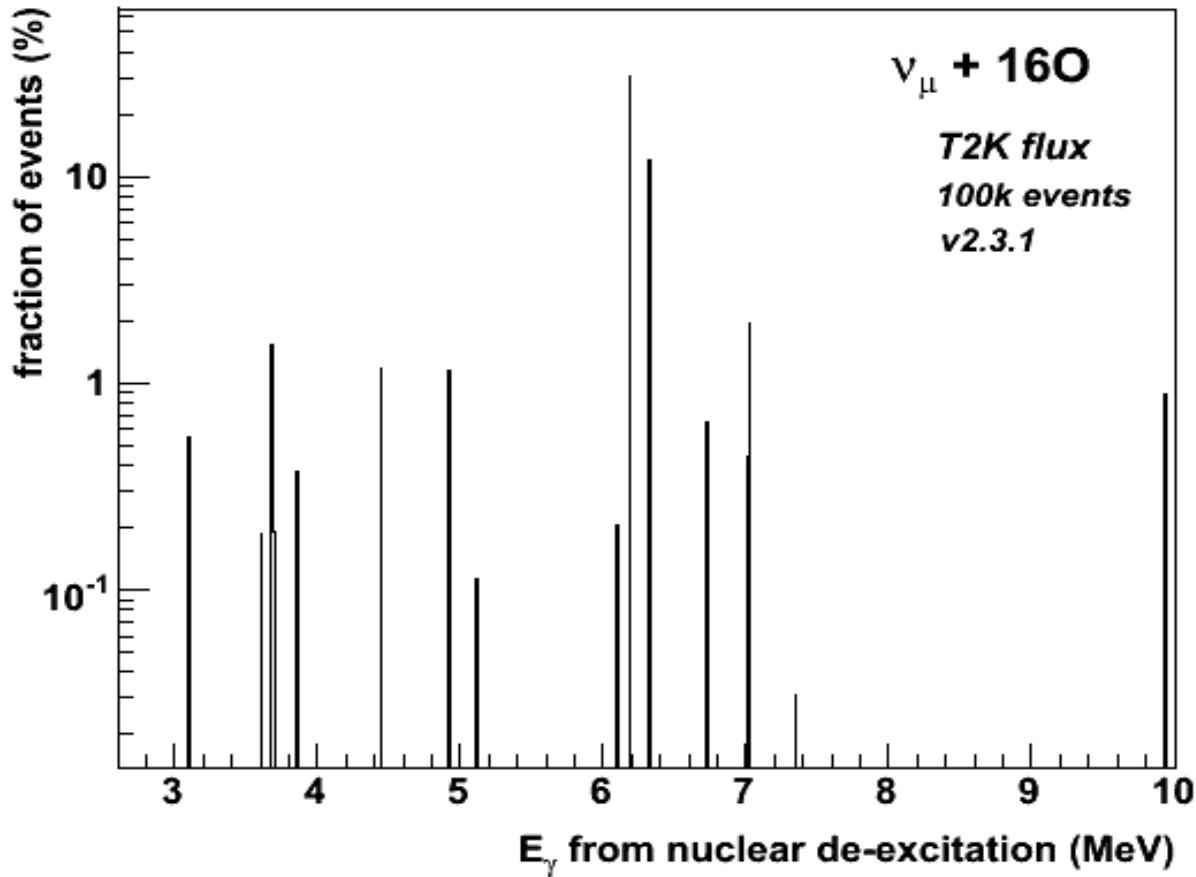


# The GENIE hadron transport modelling (INTRANUKE/hA)

Fractions taken mostly from data



# Nuclear excitations



Included in an ad-hoc way

Only for O16



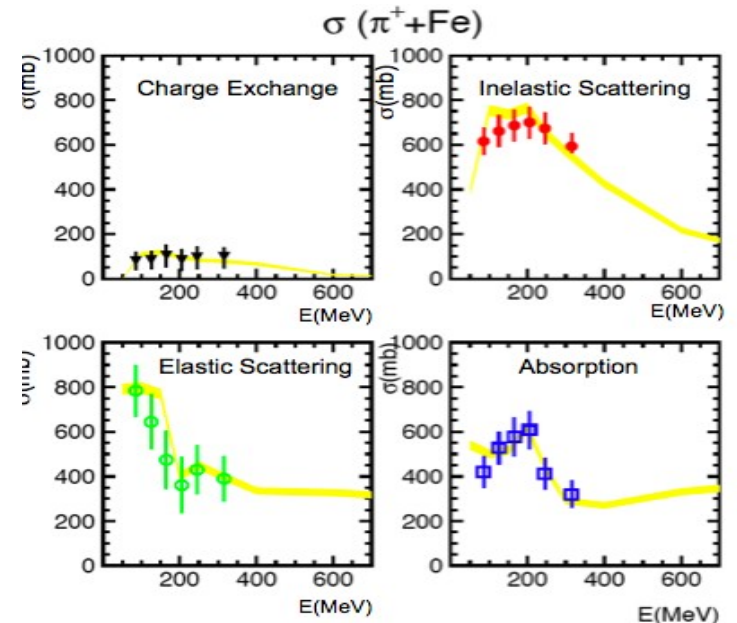
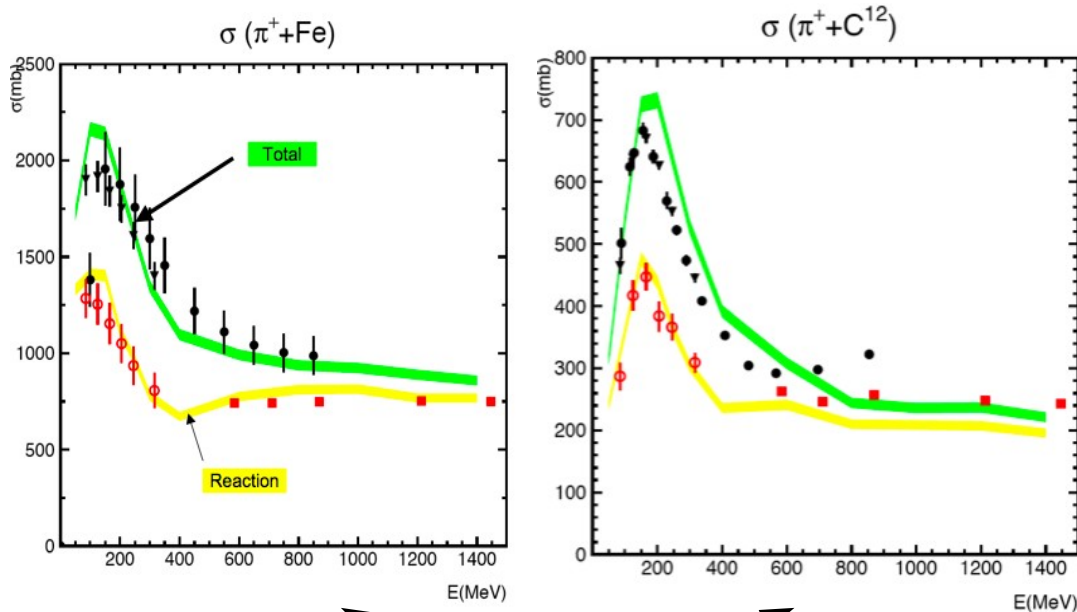
# INTRANUKE/hA Data/MC comparisons

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

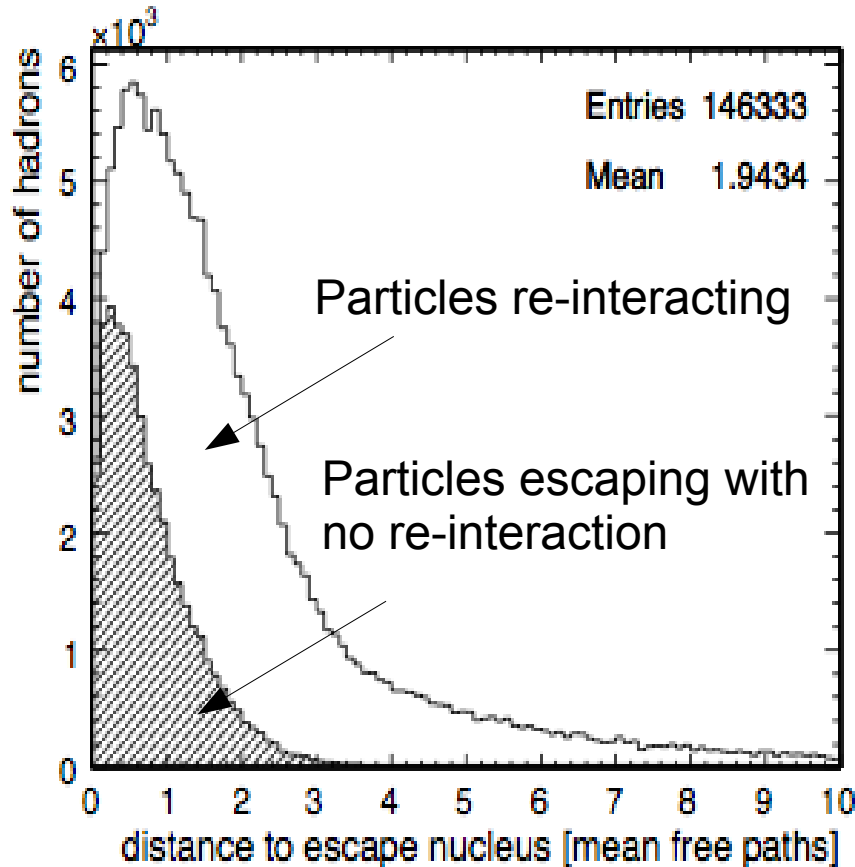
total = reaction + elastic  
reaction = cex + inel + absorption + pi prod

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



$\nu_\mu + \text{C12}$

1 GeV

Most particles (2/3) re-interact

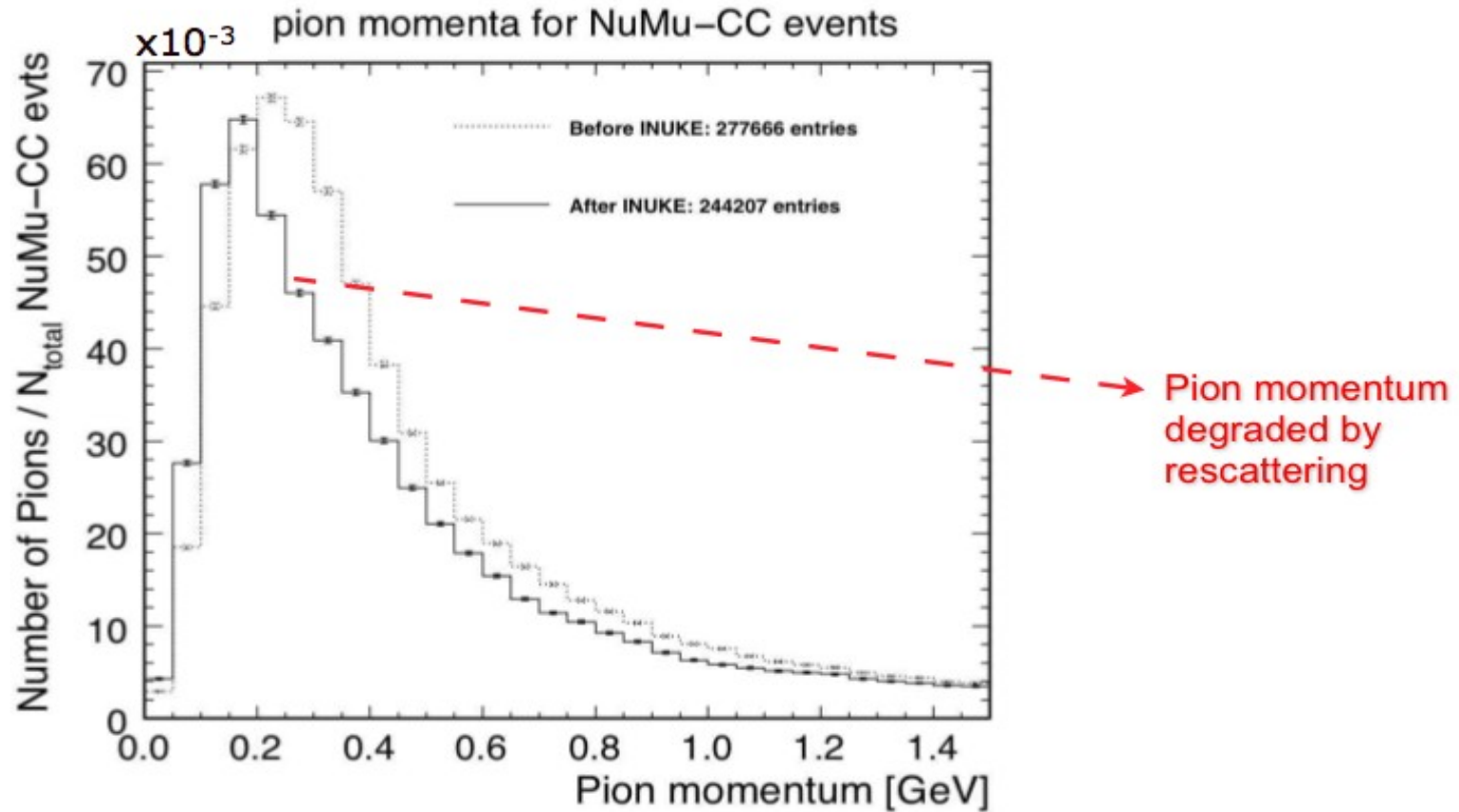
# Intranuclear rescattering effect

## 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



# 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...

## • 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

**Fairly standard  
at all v MCs**

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

**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**

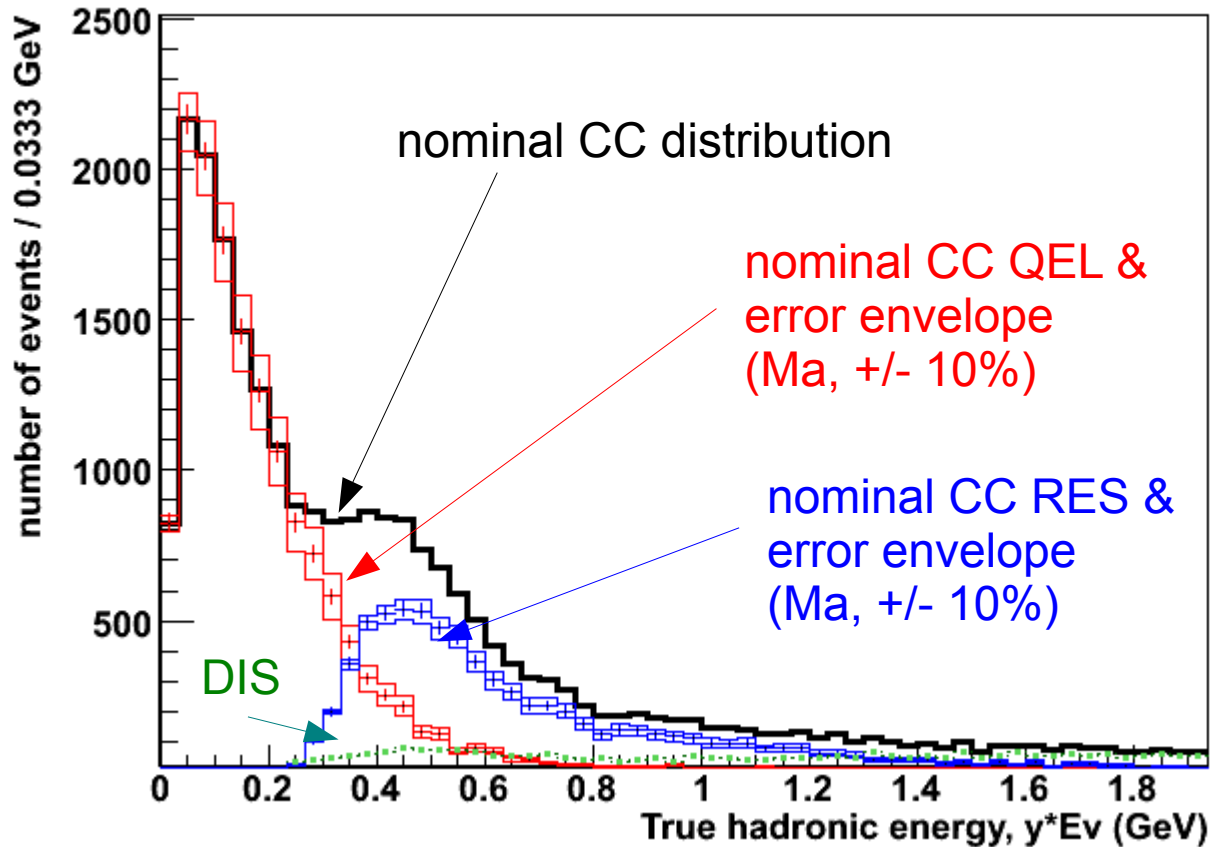
- *Nuclear model?*
- *Cascades?*
- *External (black-box) packages – eg JETSET, FLUKA*



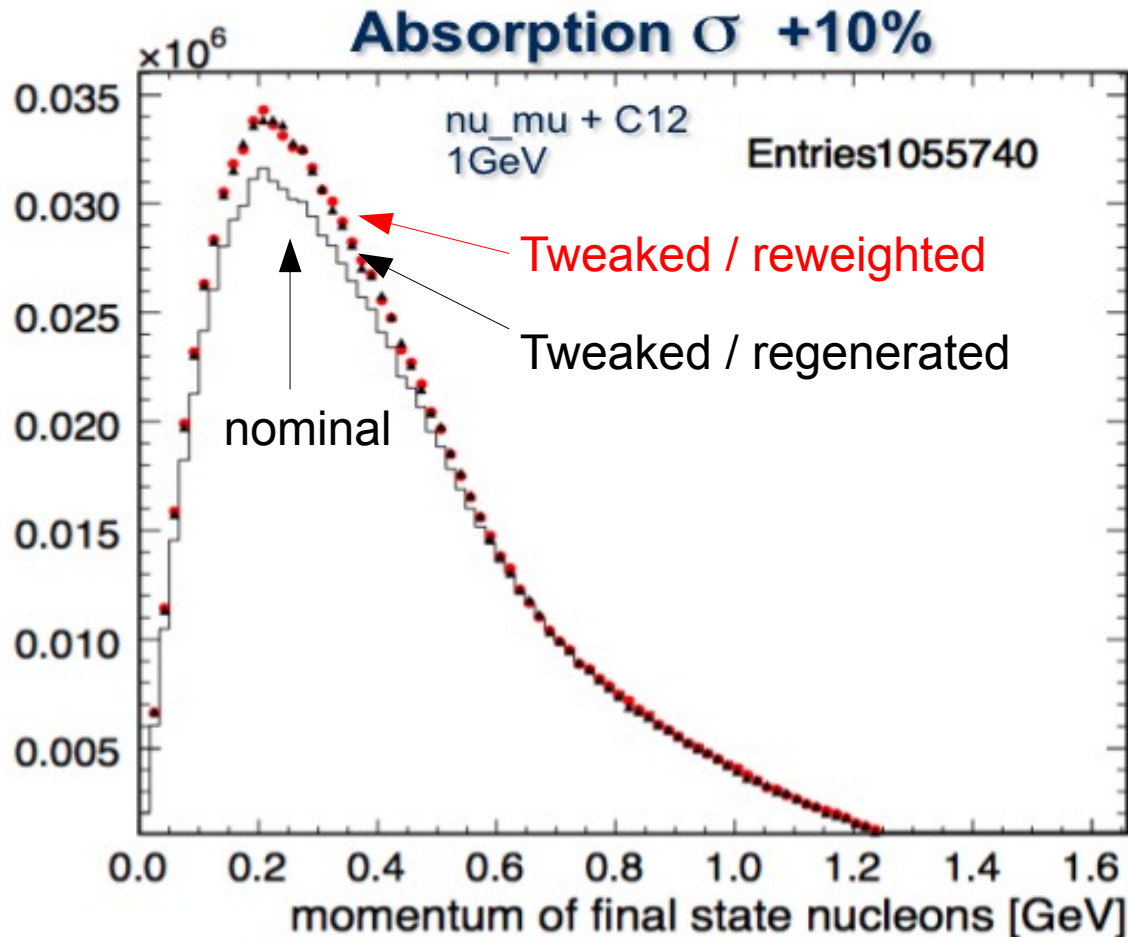
# Cross section reweighing: example

Example GENIE nd280 numu+O16

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



# Hadronic reweighting: example



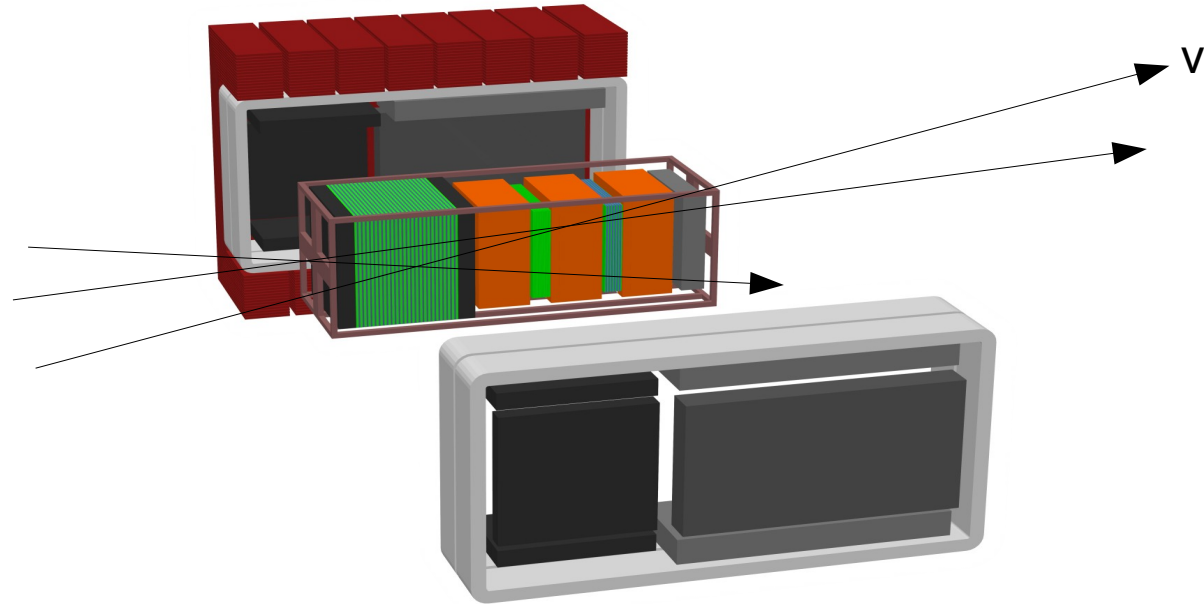
See Jim's talk for more details

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

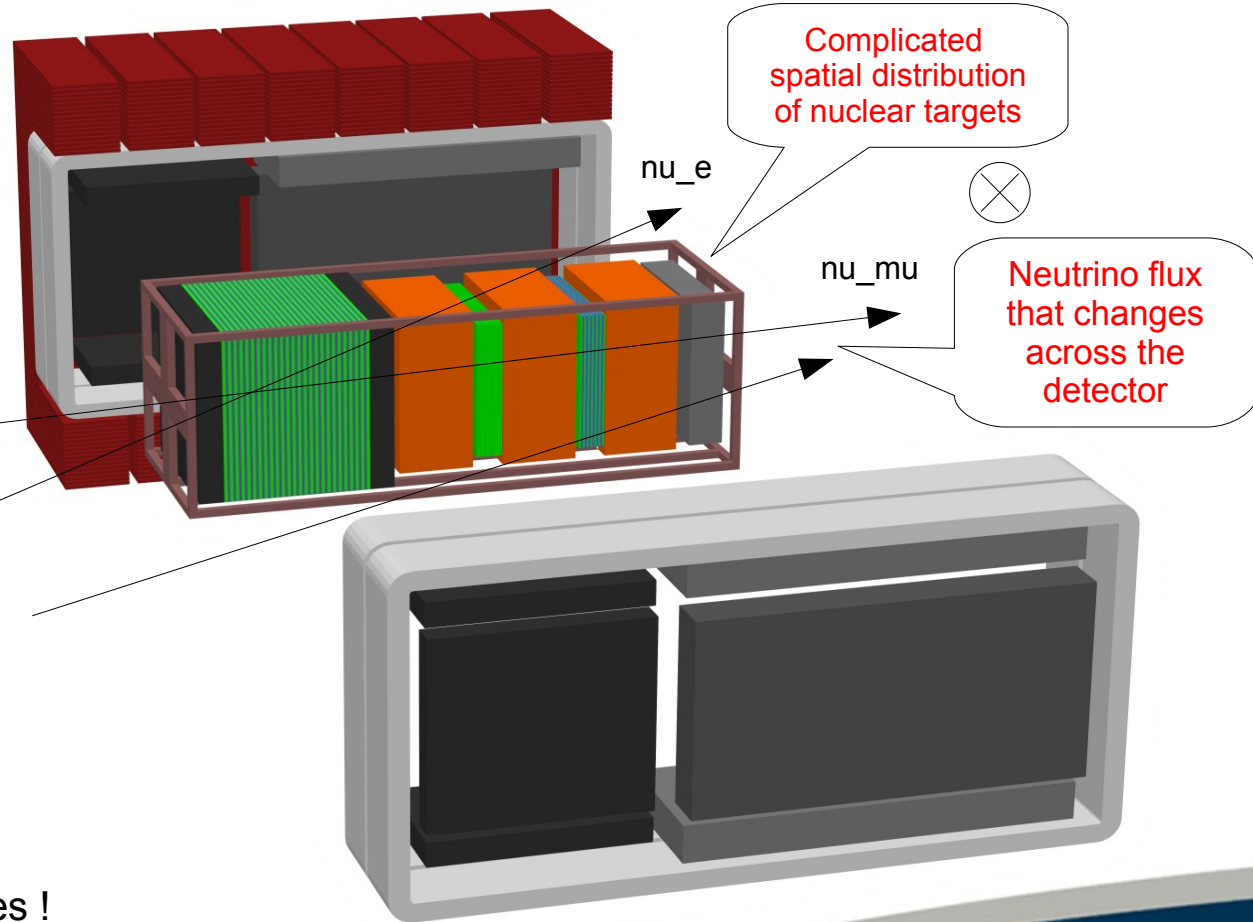
Neutrino generator's job is:  
**Generate an event**  
**once it is handed over**  
**an initial state**  
( $\nu + \text{target}$ , at a given energy)

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 !

Event generation:  
A complicated convolution of things:



# Neutrino fluxes and detector geometries

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

## fluxes

- *GJPARNuFlux*: 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 than 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**

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')

Probably ~ 1E+2  
different isotopes  
in nd280

Interaction  
probability

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

**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**

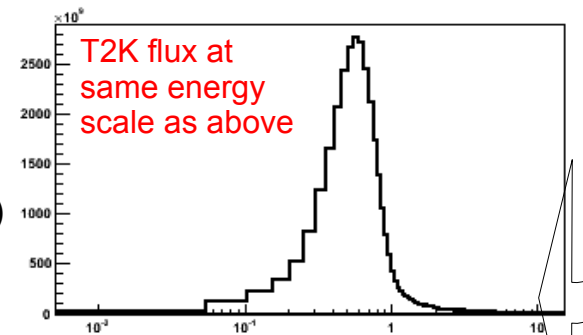
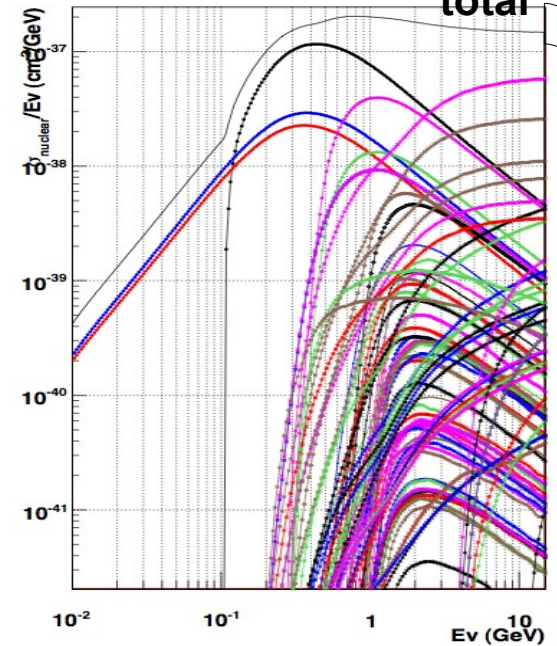
The probability scale is determined at an energy with low flux.



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

Irreducible.

numu+O16 cross sections -  
all processes



# 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...)



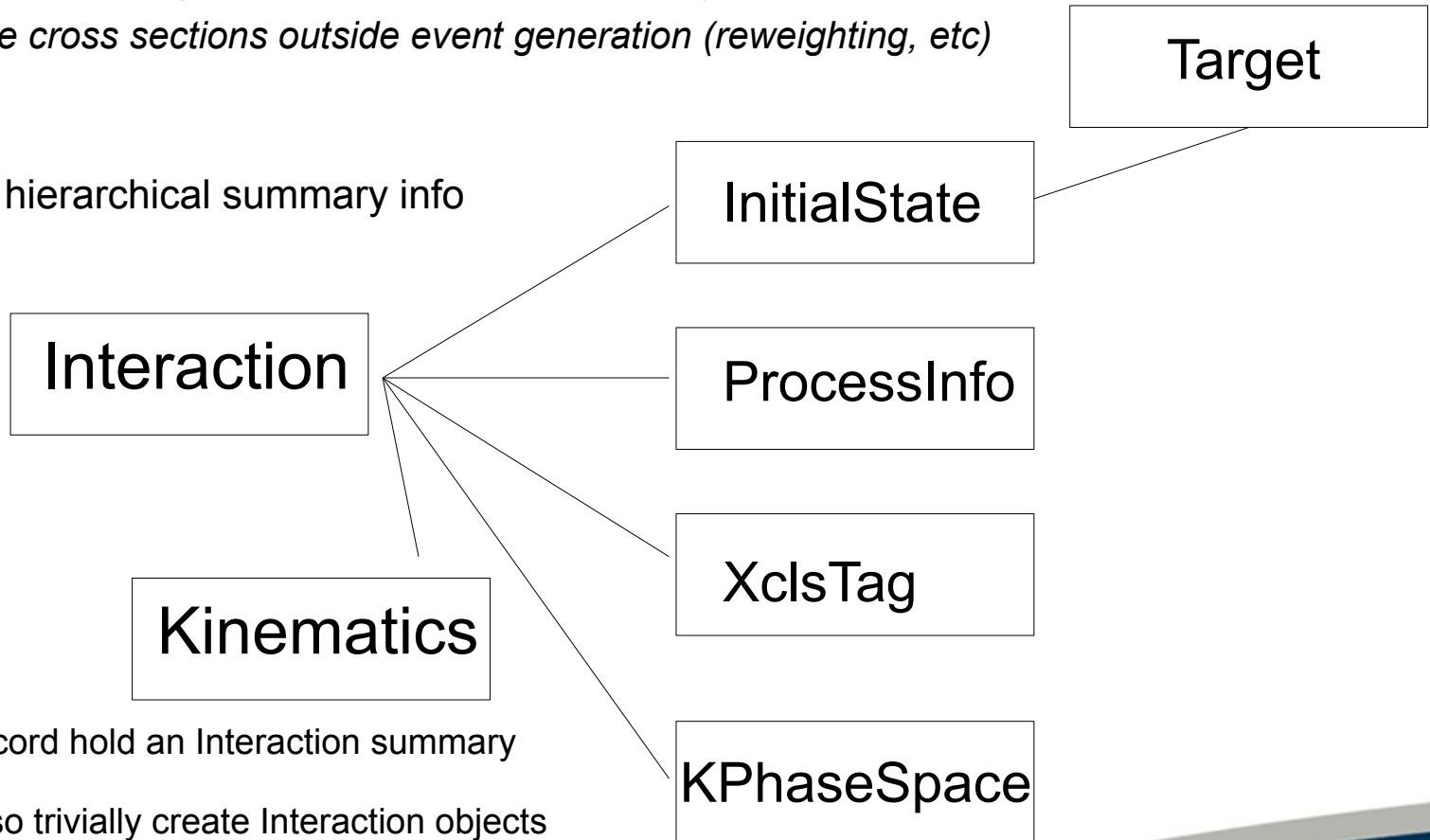
# Understanding GENIE events

The event record hold all info 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	<i>GHepStatus_t</i>	As int
Undefined	<i>kIStUndefined</i>	-1
Initial state	<i>kIStInitialState</i>	0
Stable final state	<i>kIStStableFinalState</i>	1
Intermediate state	<i>kIStIntermediateState</i>	2
Decayed state	<i>kIStDecayedState</i>	3
Nucleon target	<i>kIStNucleonTarget</i>	11
DIS pre-fragm. hadronic state	<i>kIStDISPreFragmHadronicState</i>	12
Resonant pre-decayed state	<i>kIStPreDecayResonantState</i>	13
Hadron in the nucleus	<i>kIStHadronInTheNucleus</i>	14
Remnant nucleus	<i>kIStFinalStateNuclearRemnant</i>	15

## Mother / daughter links



# Understanding GENIE events - 1<sup>st</sup> 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	15	2000000002	3	-1 -1				

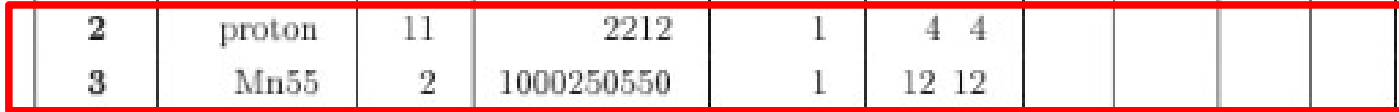




# Understanding GENIE events - 1<sup>st</sup> example

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

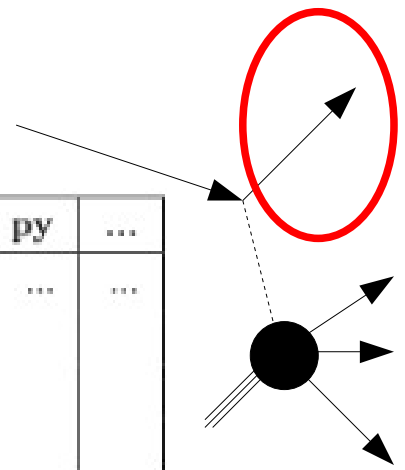
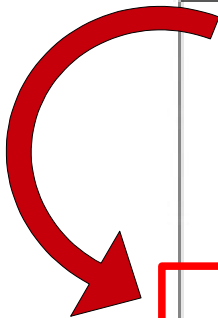
Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton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

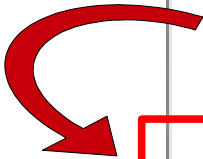
Incoming neutrino → final state primary lepton (eg. numu CC → mu-)

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 - 1<sup>st</sup> example

Hit proton excited to Delta++



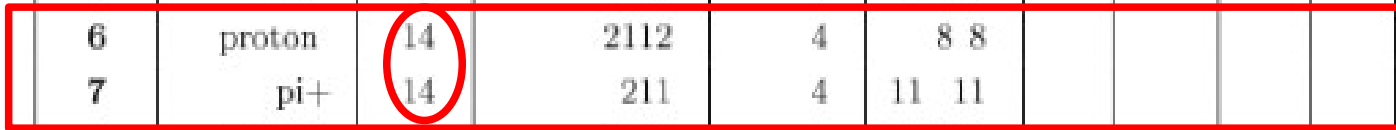
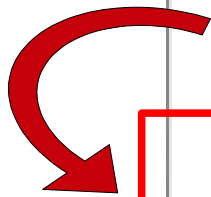
Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton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

Delta++ decays (selected decay channel: proton pi+)

Decay happened in nuclear environment → Decay products marked as 'hadrons in the nucleus (14)'

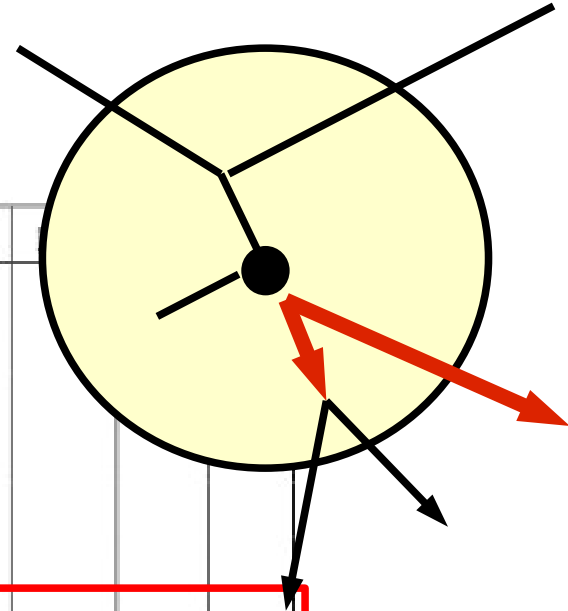
Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	5 5	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	proton	11	2212	1	4 4				
3	Mn55	2	1000250550	1	12 12				
4	Delta++	3	2224	2	6 7				
5	mu-	1	13	0	-1 -1				
6	proton	14	2112	4	8 8				
7	pi+	14	211	4	11 11				
8	proton	3	2212	6	9 10				
9	proton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



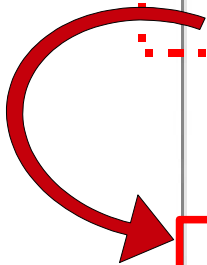
# Understanding GENIE events - 1<sup>st</sup> example

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 - 1<sup>st</sup> 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 - 1<sup>st</sup> 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 - 1<sup>st</sup> 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	15	2000000002	3	-1 -1				

# Understanding GENIE events - 2<sup>nd</sup> example

## A nu\_mu + Fe56 DIS event

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				

initial state



# Understanding GENIE events - 2<sup>nd</sup> example

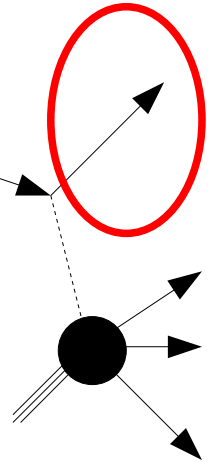
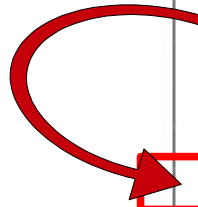
Fe56 = { hit nucleon } + { 'remnant' nucleus } = n + Fe55

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 - 2<sup>nd</sup> example

Final state primary lepton

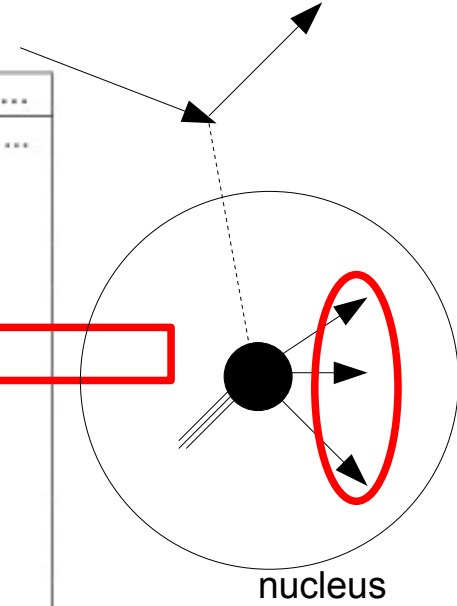
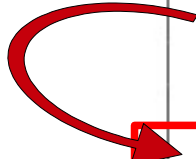
Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	...
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	8 8				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	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				



# Understanding GENIE events - 2<sup>nd</sup> example

$\nu_{\mu} + n \rightarrow \mu^{-} + X$  (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	15	2000000002	3	-1 -1				

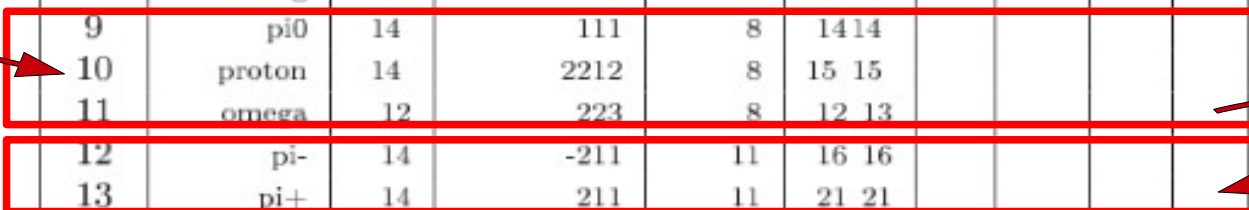
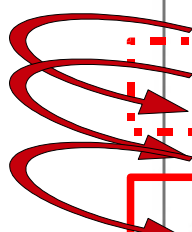


nucleus

# Understanding GENIE events - 2<sup>nd</sup> 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	HadrSvst	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				



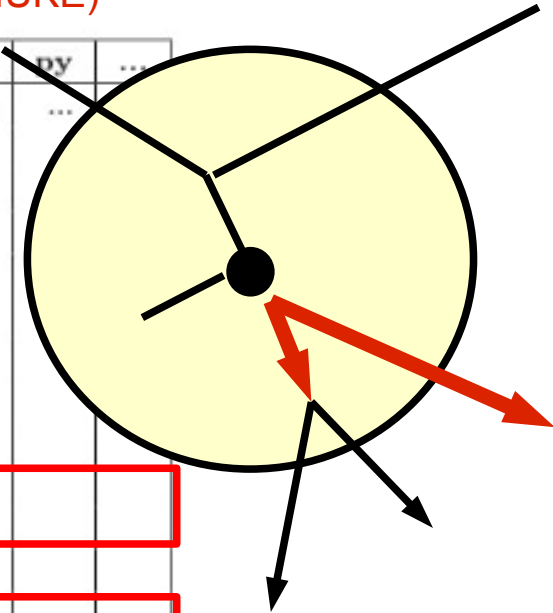
omega decay



# Understanding GENIE events - 2<sup>nd</sup> example

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

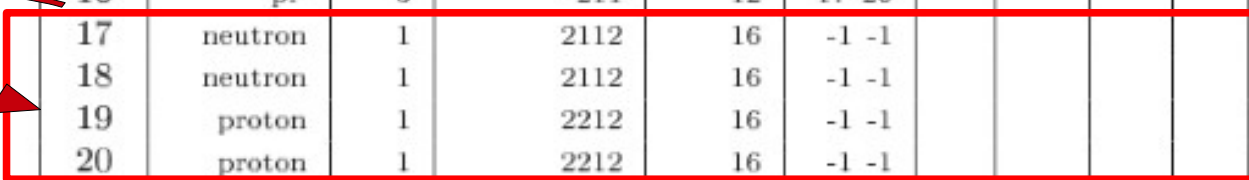
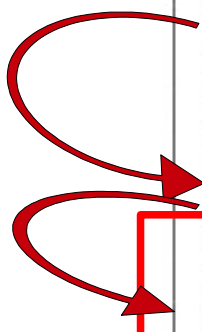
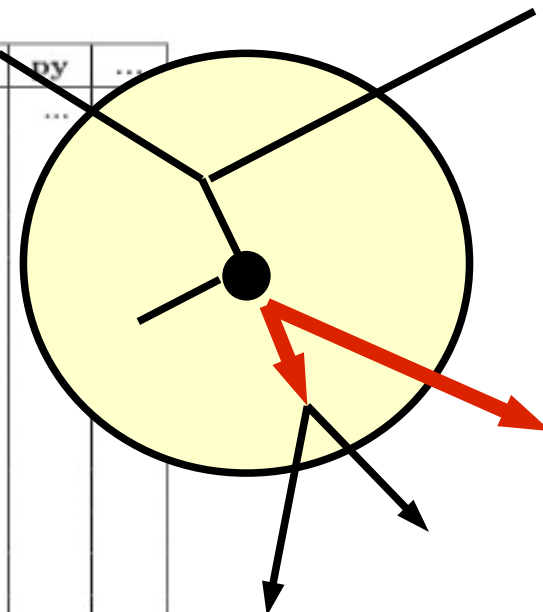
Idx	Name	ISt	PDG	Mom	Kids	E	px	py	...
0	nu_mu	0	14	-1	4 4	...	...	...	
1	Fe56	0	1000260560	-1	2 3				
2	neutron	11	2112	1	5 5				
3	Fe55	2	1000260550	1	22 22				
4	mu	1	13	0	-1 -1				
5	HadrSyst	12	2000000001	2	6 7				
6	u	12	2	5	88				
7	ud_1	12	2103	5	-1 -1				
8	string	12	92	6	9 11				
9	pi0	14	111	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 - 2<sup>nd</sup> 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	88				
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 - 2<sup>nd</sup> 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	15	2000000002	3	-1 -1				



# Understanding GENIE events - 2<sup>nd</sup> 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	15	2000000002	3	-1 -1				



# 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.

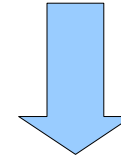
>>>

# Generating events – Step A: Selecting interaction

Example:  $\nu_{\mu} + \text{O16}$ : All processes

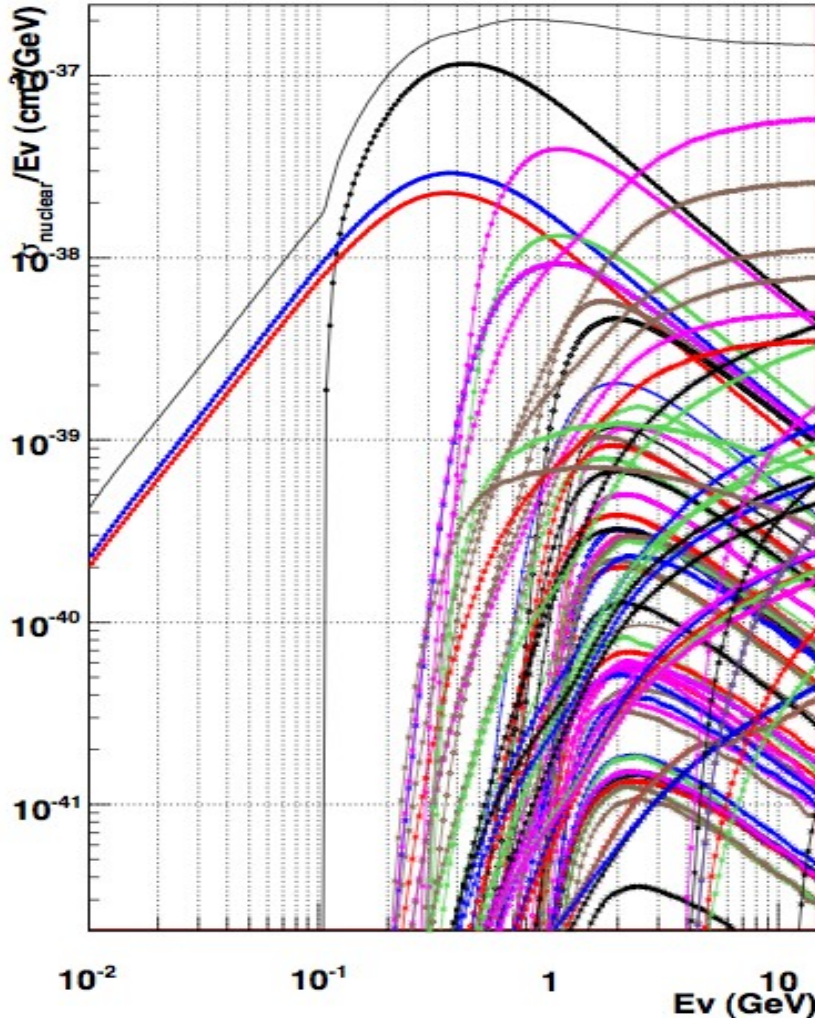
$\sim 1\text{E}+2$  'processes'

$\sim 1\text{E}+5$  diff. cross section evaluations  
per numerical integration



$\sim 1\text{E}+7$  differential cross section  
evaluations per target

Typically  $\sim 1\text{E}+2$  targets =>  
 $1\text{E}+9$  xsec calc just in order to start generation!



---

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

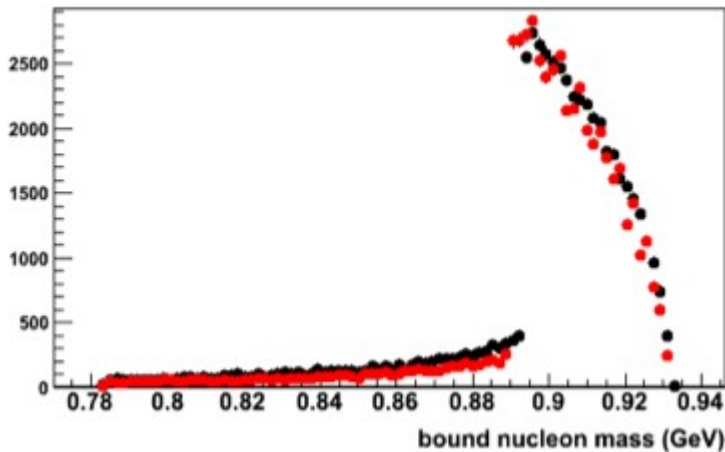
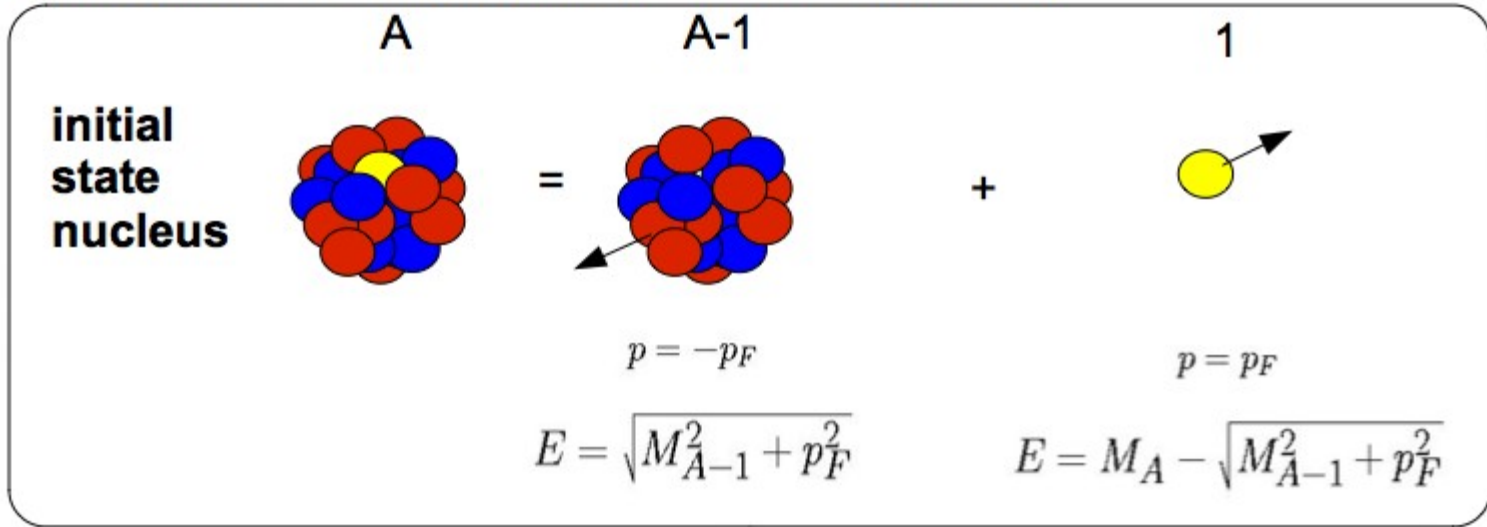
Adding initial state. Hit nucleon (if any) defined by selected interaction mode

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]:0000000000000000 | 1stSet: none |  
|-----
```

# Generating Fermi momentum

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



Example;  
Bound (off the shell) neutron mass in Fe56  
Off-shell kinematics handed a-la Bodek

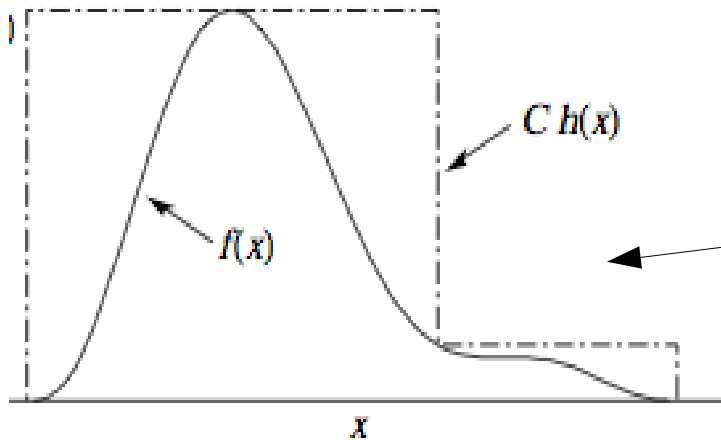
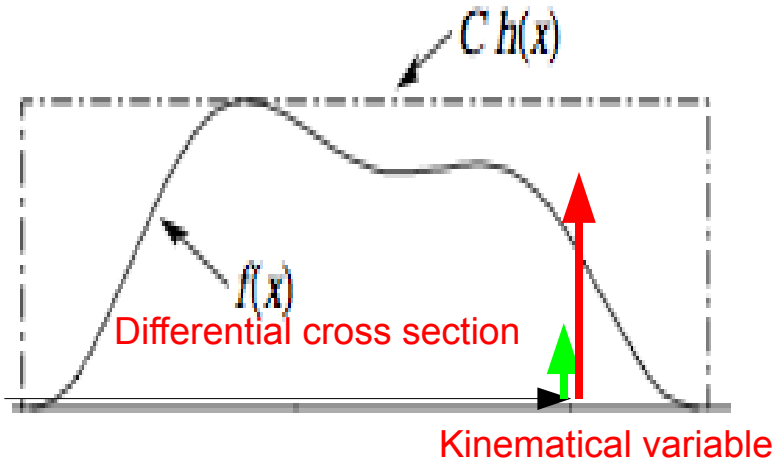
# Generating Fermi momentum

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]:0000000000000000 | 1stSet: none |  
-----
```

# Selecting kinematical variables

## Using the rejection method (typically in 2-D)



Need to scan the phase space 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:

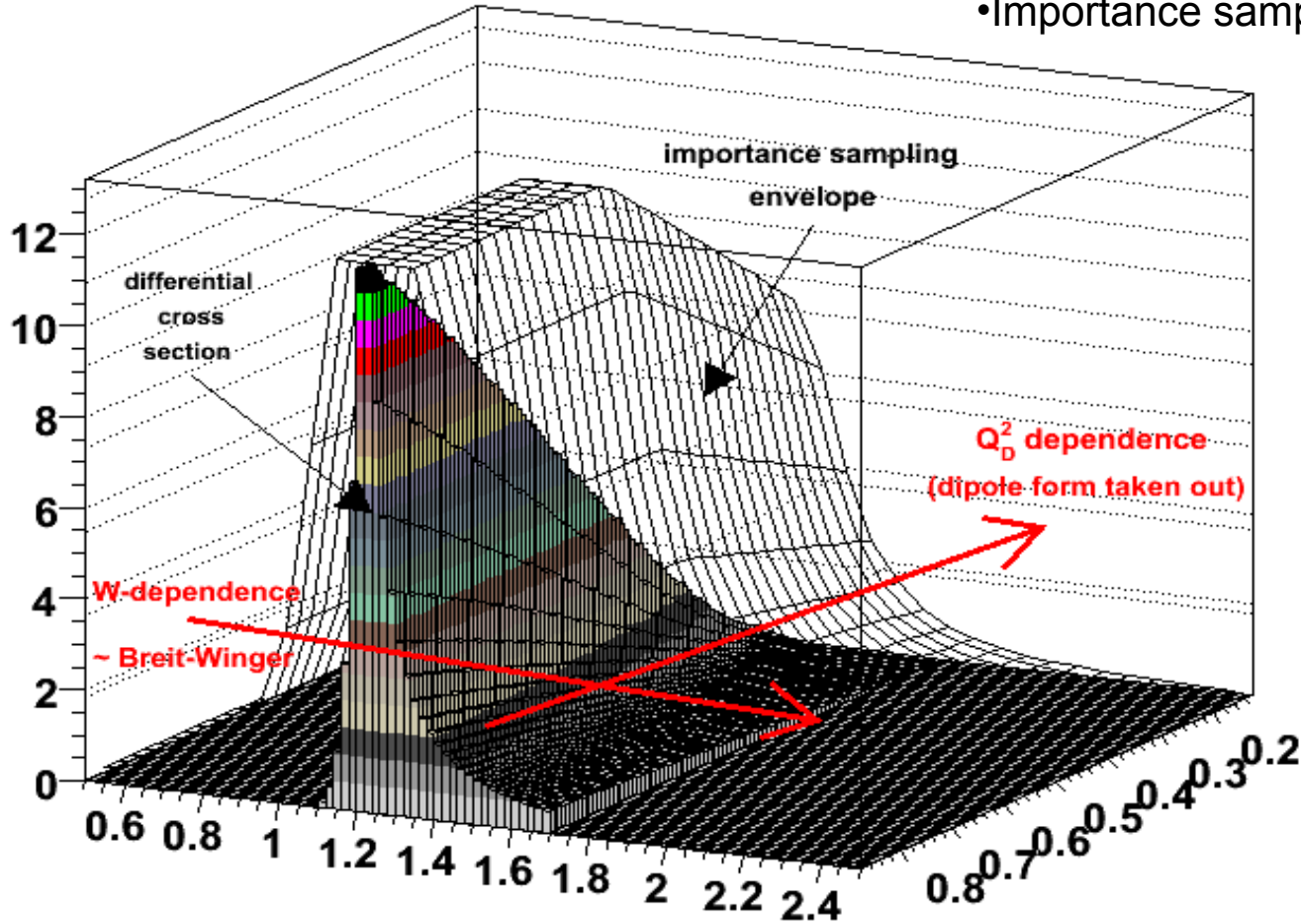
- Transformations to flatten-out cross section
- Importance sampling



# Selecting kinematical variables

RESEnvelope

- 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]:0000000000000000 | 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]:0000000000000000 | 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