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Overview of Progress in vN Simulation Codes

Costas Andreopoulos

5th International Workshop on vN Interactions (NuINT07), May 30th - June 3rd, Fermilab

Goals / Outline

Outline
Use cases
MC Goals
Challenges
Avail. Data
Goals Revisited
Uncertainties
ReWeighting
Generators
Comparisons
Developments
Trends
Highlights
Future
Summary

Give overview of neutrino MC Generators:

- *What they do ? ('generating events' does not tell the full story...)*
- *How do they get used by experiments?*
- *Which are the tools of the trade?*
- *Which are the main issues?*
- *What were the recent developments?*
- *Where do we need to be?*

I will try to give a comprehensive picture
(from the experimentalist's point of view)

Thanks to S.Zeller, Y.Hayato, H.Gallagher, S.Dytman, T.Yang, J.Sobczyk, J.Lagoda for the information they sent me

...but MINOS will be my primary pool of examples.

Neutrino Physicist's Swiss Army Knife

Neutrino MC Generators are polymorphic tools

- Front-end for fast νA event generation
- Back-end to full Neutrino Experiment MC Simulation chain
- Cross-section libraries
- Event Re-Weighting Engines
- Data-bases of world νA xsection measurements, eA, hA xsections, ...
- Tools for model tuning / fitting
- Tools for analysing MC samples
- More than νA generators: eA, hA generators ...
- ...

Neutrino Generator Goals

Describe all the vA physics correctly / accurately...

- *Starting from first principles / dynamical models...*
- *Having minimal dependence on input data...*

It is standard model physics after all...

Neutrino Generator Goals

Describe all the vA physics correctly / accurately...
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- *Having minimal dependence on input data...*

It is standard model physics after all...

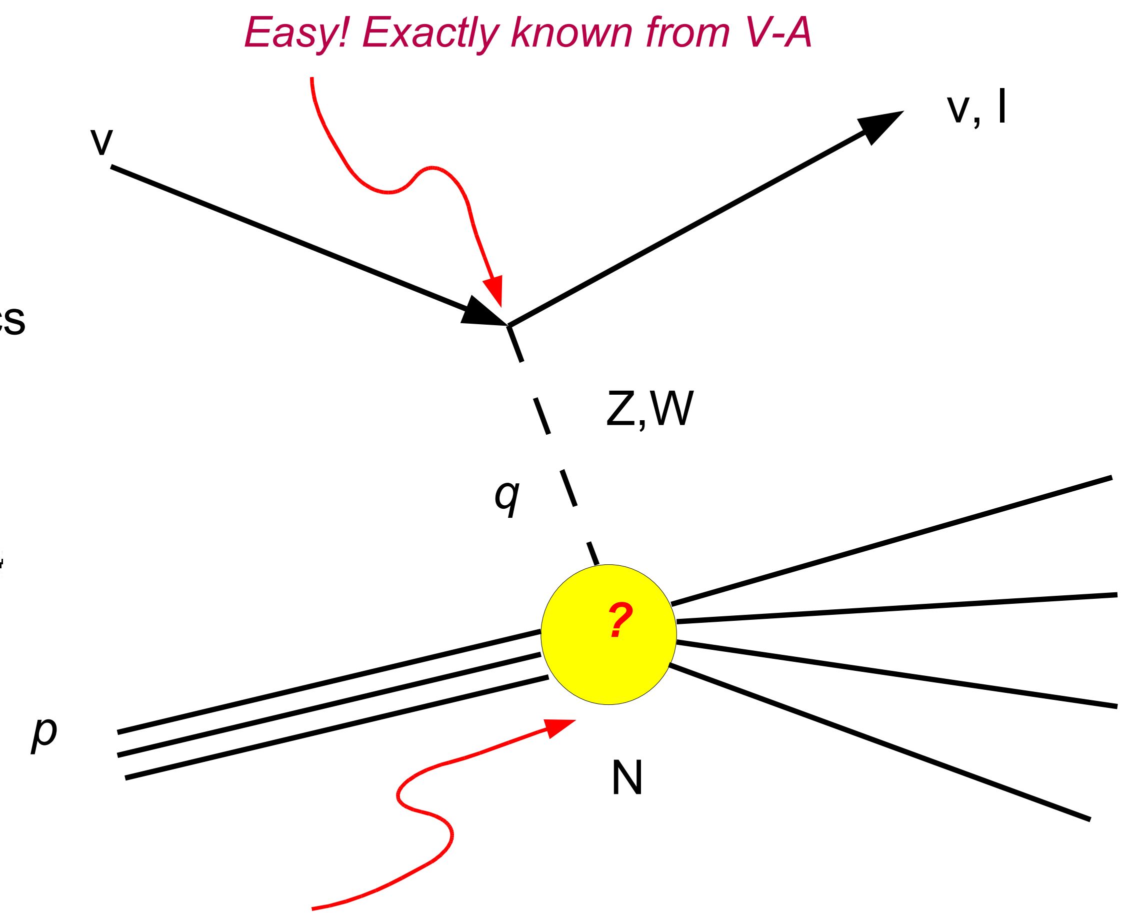
Problem of sheer complexity!

Can not reproduce nature although basic physics laws are known...

ν Interaction Simulations: Challenges

process dynamics described by the invariant amplitude

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

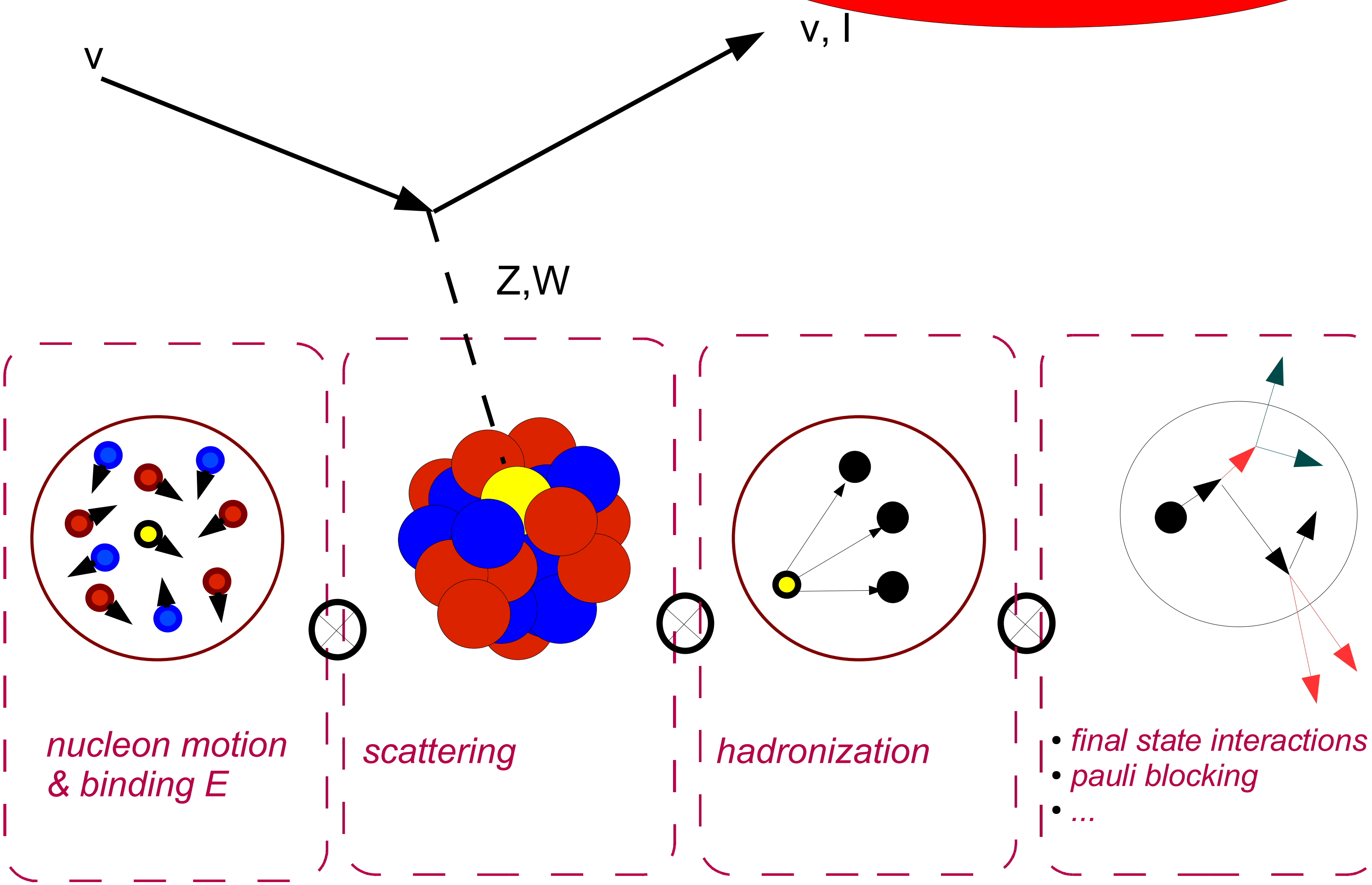


$$W_{\mu\nu} = W_1 \delta_{\mu\nu} + W_2 p_\mu p_\nu + W_3 \epsilon_{\mu\nu\alpha\beta} p^\alpha p^\beta + W_4 q_\mu q_\nu + W_5 (p_\mu q_\nu + p_\nu q_\mu) + W_6 (p_\mu q_\nu - p_\nu q_\mu)$$

Complicated! Parametrize from data.

ν Interaction Simulations: Challenges

There is more to it than just the νN cross sections!



- Too complex!
- Effective models firmly attached to a large body of data is probably the best bet

So everything boils down to ...

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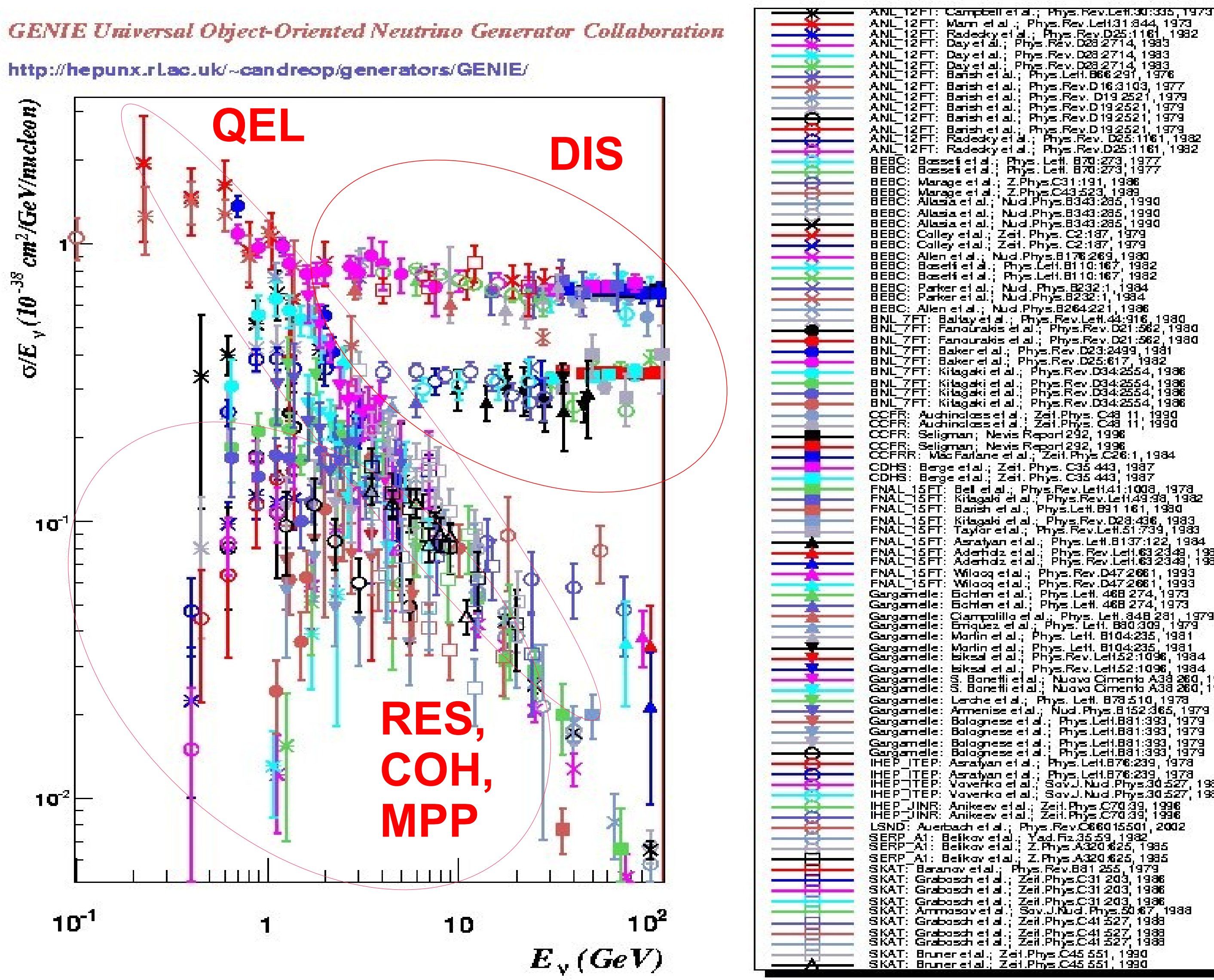
... not having enough constraints from the available data

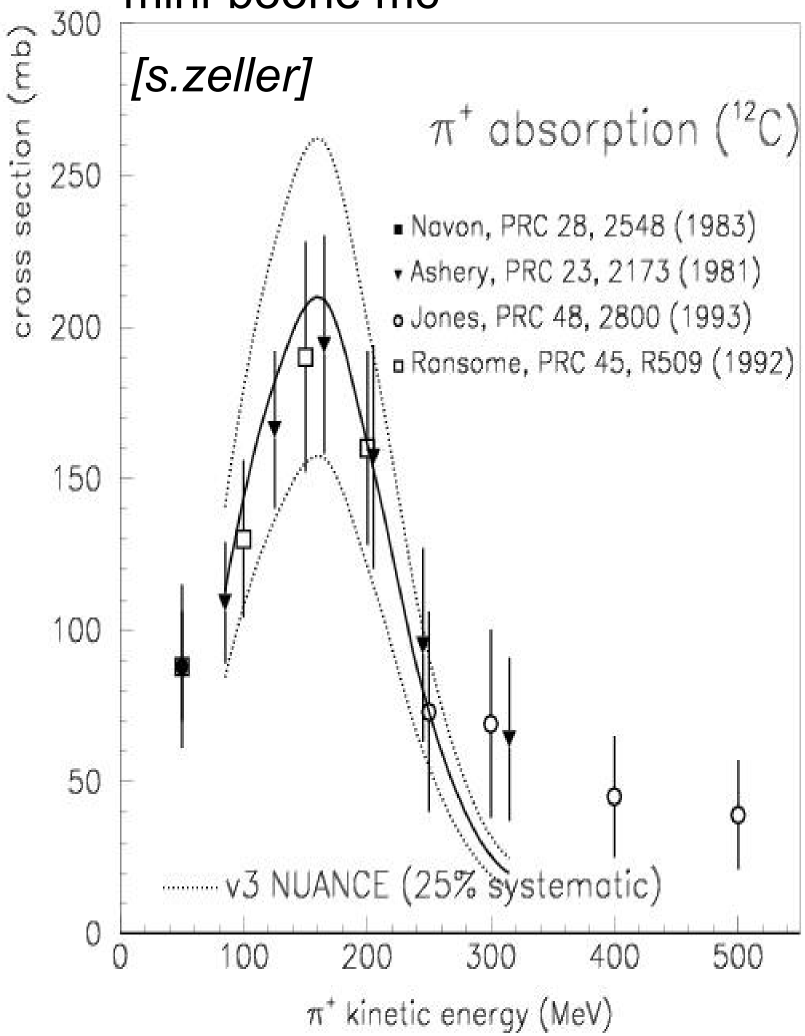
- Data are sparse – with large errors
- Particularly **x-section data for exclusive inelastic channels are very poor!**



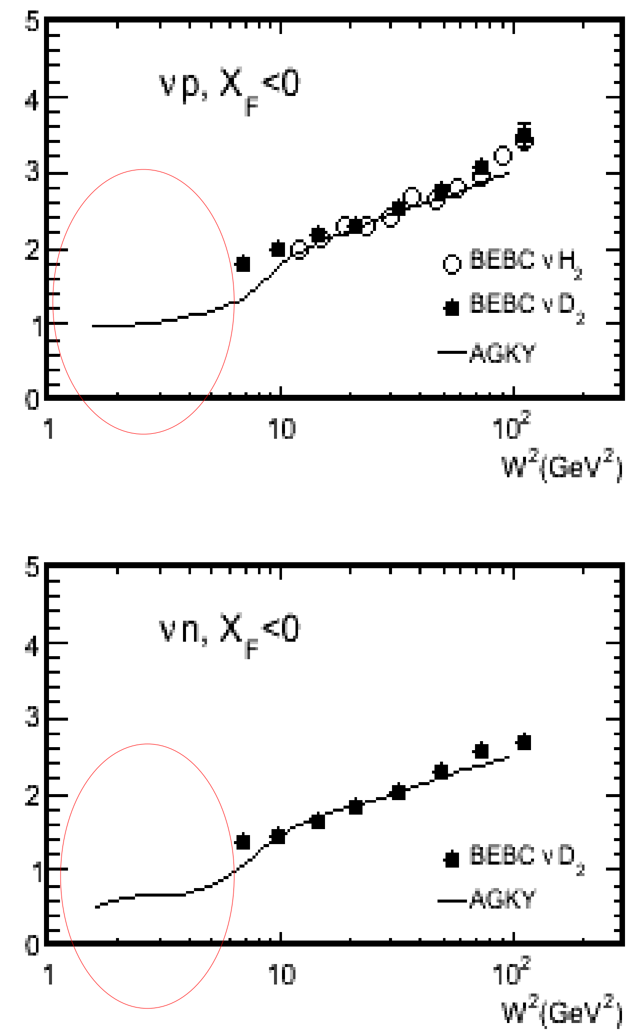
Again, there is more to it than just neutrino x-sections

- *Poor data on low-E hadron+nucleus interactions*
- *Poor data on low-W neutrino-induced hadronic shower characteristics*

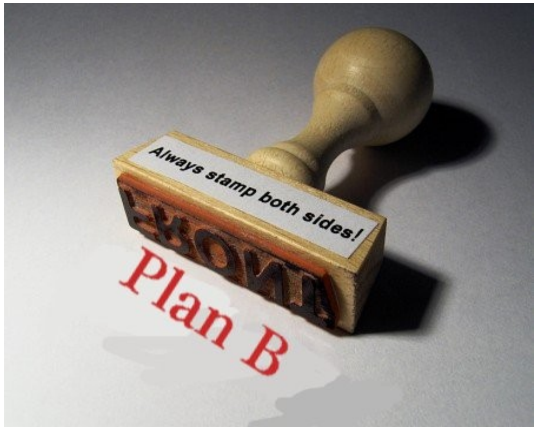
mini-boone mc



minos mc



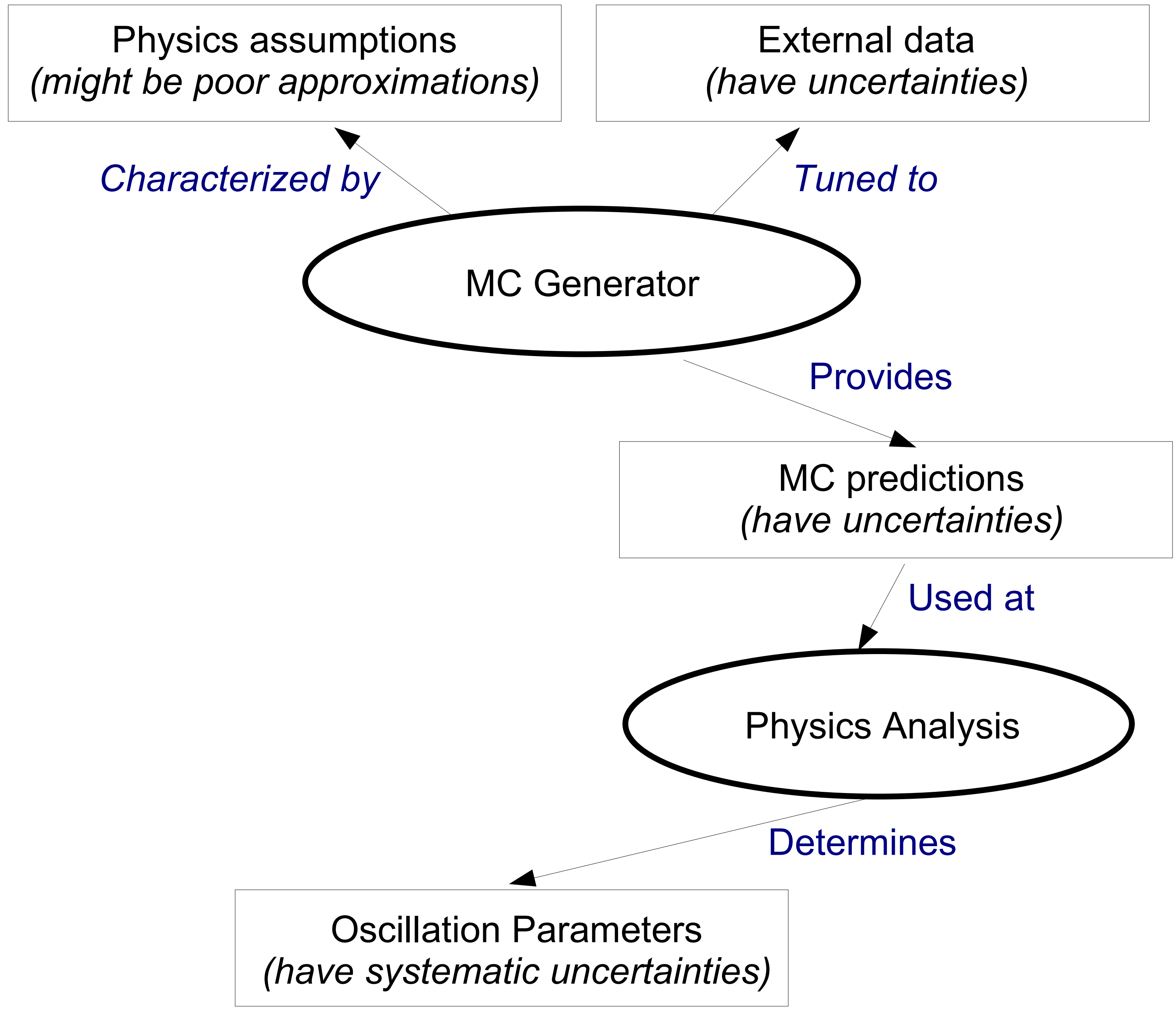
Neutrino Generator Goals



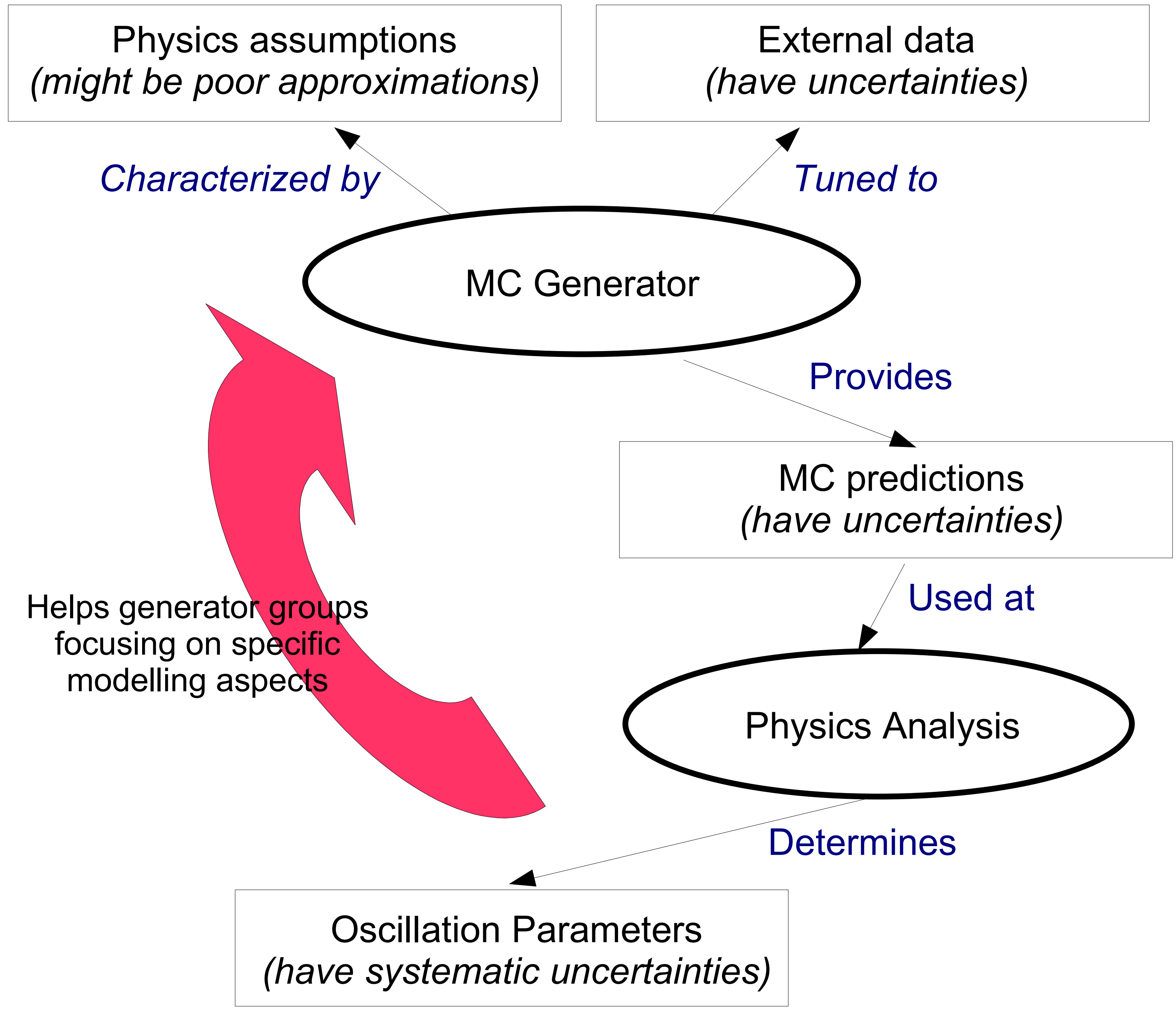
Goals Revisited !

- **Describe all the vA physics accurately enough for v oscillation experiments**
  - Focus development on what is really important for the oscillation measurement
    - Depends on the measurement / detector technology
    - Requires close interaction with analysis groups
- **Do data archaeology ! Unearth, check, build into the simulations**
- **Maintain "Intellectual honesty"**
  - Easy to get data / mc agreement in an ad-hoc way
    - Difficult to do so using 'physics motivated arguments' & 'external data'
- **Understand the underlying model uncertainties**
  - Propagates as systematic uncertainties to oscillation measurements
- ...

Generator Uncertainties propagate...



Closing the loop: Analysis Feedback



Example of such an interaction: MINOS

- Comprehensive free nucleon cross section modelling / tuning to world data
- Quantifying neutrino interaction model systematics

1st published MINOS disappearance analysis

Issues with data / mc agreement on hadron shower related quantities
Concerns for uncertainties in light of recent measurements
(Are they too conservative? Or they ought to be bigger?)

- Fine-tunings to the free nucleon cross section model
- Almost complete re-write of the hadronic multiparticle production model
- Almost complete re-write of the intranuclear hadron transport model
- Re-evaluating sources of systematic uncertainties

At the same time analysis groups prepare tools which allow them to reweight the hadronization & hadron transport models

NOW

2nd published MINOS disappearance analysis

Residual long-standing ND data / mc discrepancies

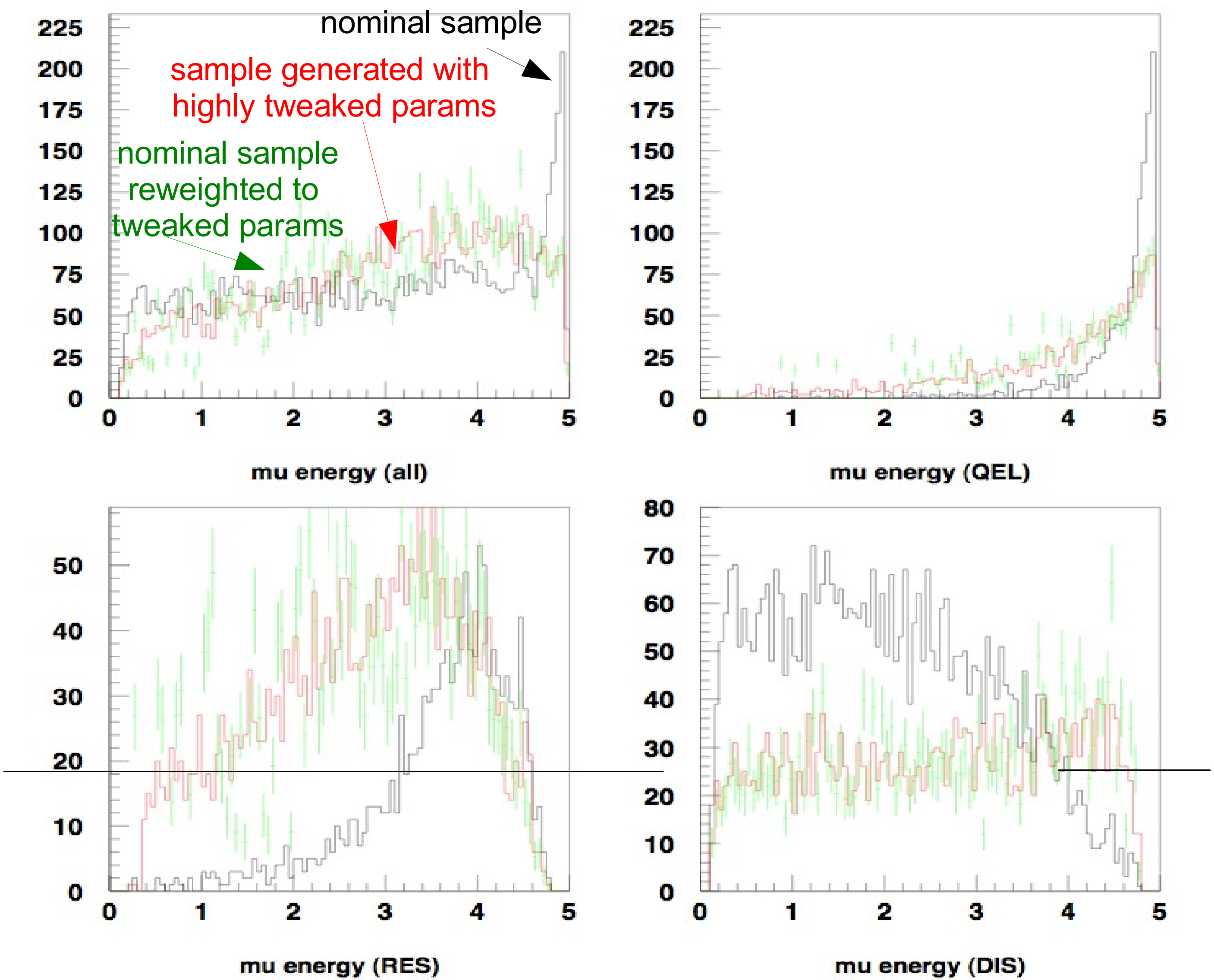
- Fine-tunings to the hadronic multiparticle production model
- Alternative intranuclear hadron transport models
- Nuclear model upgrade

t

Generator as an Event Re-Weighting tool

Ability to reweight samples is important!

Equivalence between reweighted sample & sample generated with tweaked params



[source: H.Gallagher]

Why is Re-Weighting important?

Marginalization
Can integrate out 'nuisance' parameters

Fit
Can determine how to tweak interaction model to better fit own data

'Emulate' samples generated with tweaked model parameters

MC generation is CPU intensive

MINOS MC run at Caltech farm: ~75 dual ~2.8 Ghz CPUs
=> 0.7E+19 POT/week
=> **14 weeks / 1E+20 POTsample**

[source: Kregg Arms, MINOS MC WG]

*However, **event re-weighting is <u>not a silver bullet</u>**.*
- *Can reweight continuous processes that can be parametrized*
- *Can not use the same scheme to handle processes that have discrete levels*
  - *a event is pauli-blocked or not*
  - *a hadron re-interacts or does not re-interact*
  - *...*

Neutrino Simulation Codes

Which are the tools of the trade?

There are quite a few...

- **Developed within certain experiments**
  - Usually publicly available
  - **Comprehensive**
    - Model all (important) processes
      - *at the full kinematic range accessible to the experiment*
      - *may not do a great job everywhere but they do something*
  - **Validated against the experiments own data**
    - *Maybe (explicitly ot implicitly) tuned to experiments own (unpublished) data*

- **Developed by theory groups**
  - Usually not public
  - Usually not comprehensive – there are few exceptions (see later)
  - Typically not utilized by experiments

- **Lately joint efforts by cross-experiment (& theory) groups**
  - Effort towards a universal / canonical neutrino MC (?)

Neutrino Simulation Codes -- Comments

A 'neutrino community' irregularity:
- *Imagine if each LEP, Tevatron & LHC experiment had its own generator...*
- *Imagine if none of these experiments was using PYTHIA & HERWIG...*

We have to bridge this gap!

- **Developed within certain experiments**
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Neutrino Simulation Codes -- Comments

In my opinion this is undesirable
Generators *(to be of any use outside a particular experiment)* must not be fine-tuned.

Assumptions / tuning is 'forgotten' and generator is used at another context...
Non-trivial systematics!!!
Does your generator corrects for some other experiment's mis-calibration or flux uncertainty?

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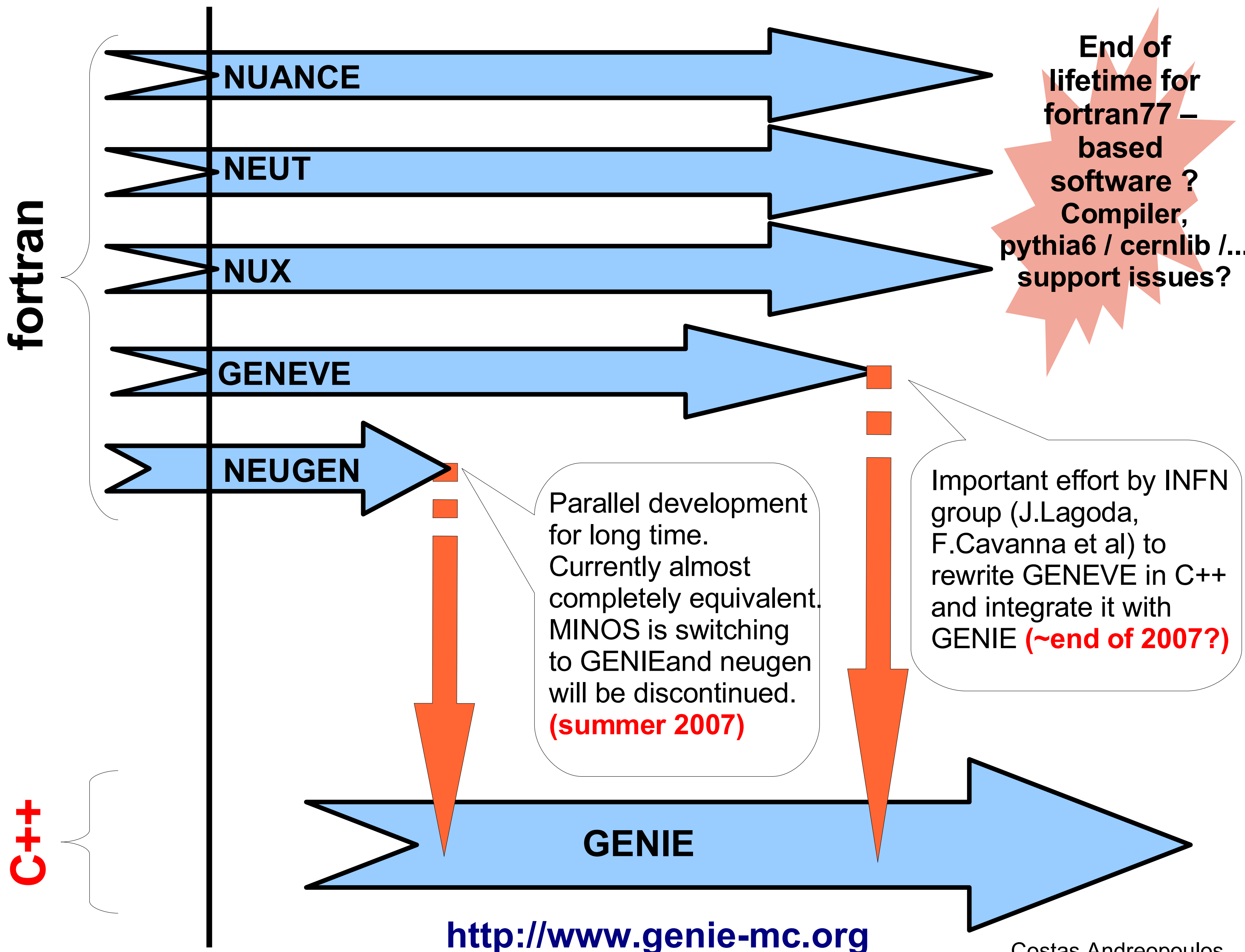
Generators developed within experiments

t ~= - "infinity"

(context: ν oscillations not established yet, fortran 77 is the language of the future...)



Generators developed by theory groups

Usually not publicly available & not comprehensive.
I know of 2 taking a more comprehensive approach :

- **Wroclaw Neutrino Generator (NuWro)** / *developed in C++*
  Jaroslaw Nowak, Cezary Juszczak, Jan Sobczyk et al.
  (will be described later)

- **Giessen Transport MC (GiBUU)** / *developed in fortran2003*
  Ulrich Mosel, Tina Leitner et al.
  - **Unified transport framework for:**
    - Heavy ion reactions
    - Pion-induced reactions
    - Low and high energy photon and electron-induced reactions
    - **Neutrino-induced reactions**
  - **Probabilistic coupled-channel** description of **hadron-nucleus scattering**.

Prof. U.Mosel is giving a talk at NuINT07

Very high threshold for experiments to adopt a new neutrino generator

- *especially a 'totally' external one*
- *_no_ manpower for interfaces / high-statistics sample generation / validation*

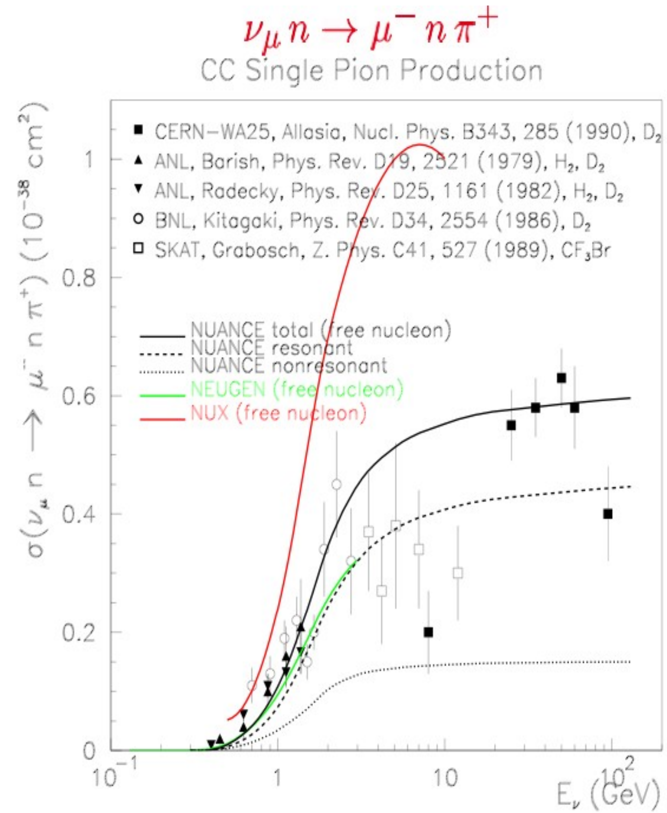
Generators developed by theory groups are rarely utilized in experiments...
However, these MCs contain some rather unique components - not in mainstream MCs

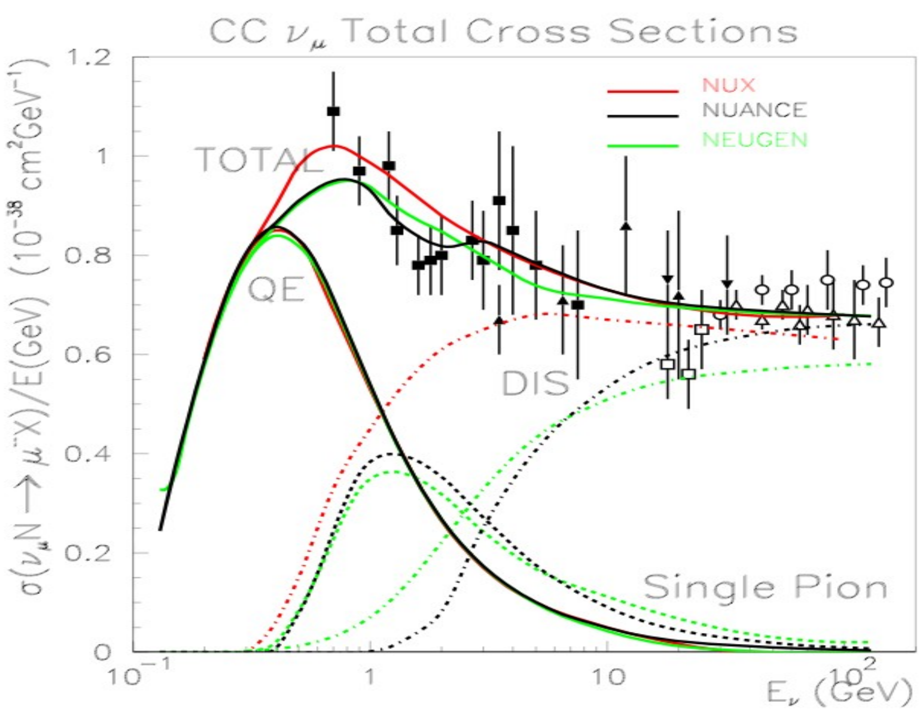
- ***extracting PYTHIA fragmentation functions down to inelastic threshold (NuWro)***
- ***hadron transport code (GiBUU)***

Generators @ NuINT01/02

At NuINT02, **S.Zeller** did the first cross-generator comparisons

- Common theoretical inputs
  - ↪ Llewellyn Smith for free nucleon QE cross section
  - ↪ Rein and Sehgal resonance cross sections
  - ↪ standard DIS formula for high W, Q^2
- But non–trivial differences
  - ↪ implementation of Fermi gas model for QE
  - ↪ treatment of nuclear effects (charge exchange, π absorption, rescattering, nuclear de–excitatio
  - ↪ hadronization of final hadronic state
  - ↪ joining of resonance and DIS regions





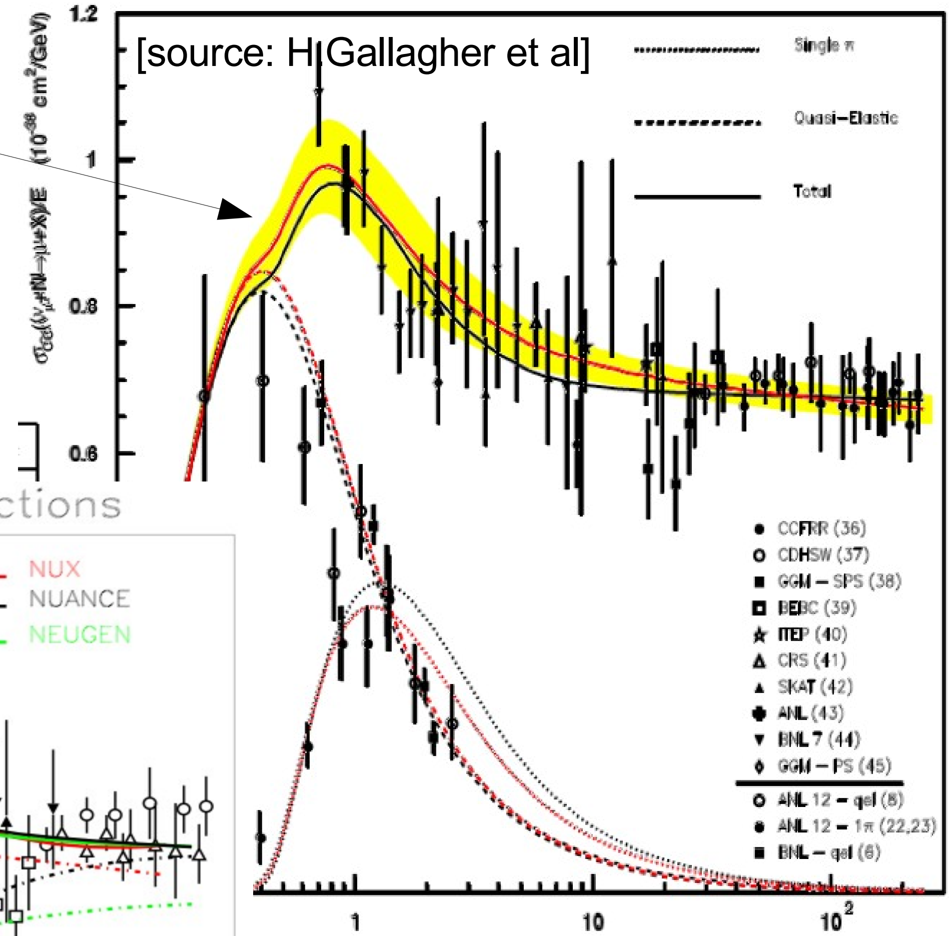
Conclusions

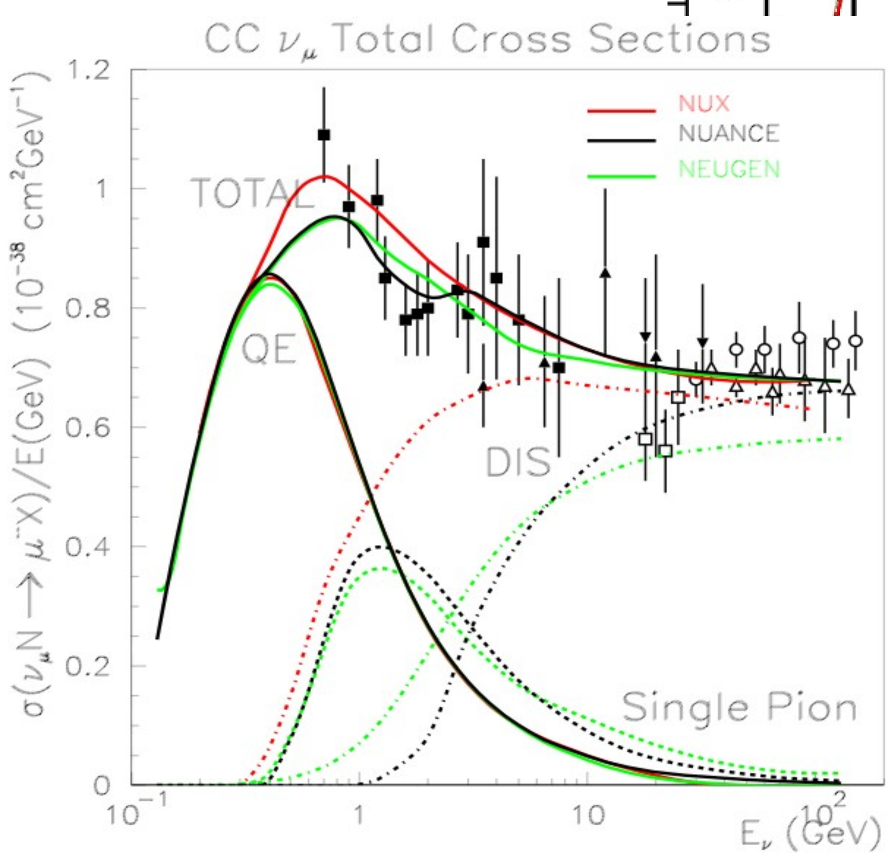
- Reasonably good agreement between the various Monte Carlos (and experimental data)
  - ↪ Better for CC than for NC
- Various Monte Carlo cross section predictions agree at least as well as the data agrees with itself

Generators @ NuINT01/02

MINOS MC model for 1st (red) and 2nd (black) CC analysis & estimated uncertainty.

Prediction changes ~ as much as prediction from different generators differs...

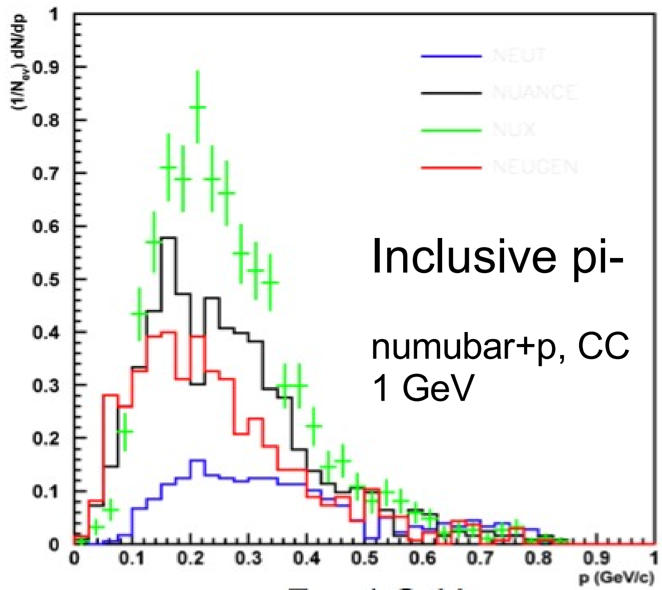


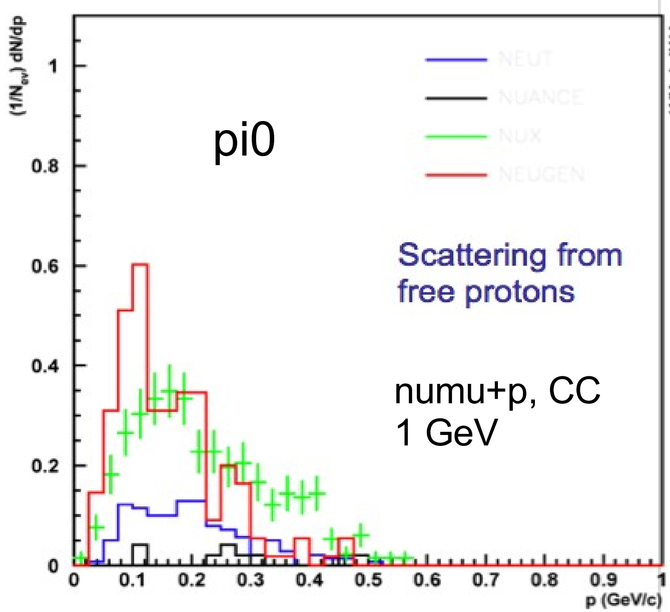


Actual prediction matters less than size of error envelope

Generators @ NuINT04

At NuINT-04 **H.Gallagher** compared samples from all generators focusing mainly at the hadronic system simulation





Conclusions

Different resonance models and methods for combining DIS/resonance result in quite different kinematic distributions: Largest differences in the low invariant mass region

Q^2, x dependence of cross sections at higher energies shows significant differences →due to choice of scaling variables??

Intranuclear scattering models are surprisingly similar. Largest differences in inclusive distributions were the result of different free particle hadronization models, particularly at low energy.

NC predictions for "experiment-like" π^0 sample consistent to 50%

Generators today

So what where the developments in each generator?

NUANCE (by MiniBooNE)

[source: S.Zeller]

Nuance development partly driven by mini-boone

- **added nuclear density for carbon**
  public release of NUANCE now has ability to set different targets
- **tuned pion absorption and CEx rates based on external pion-carbon data**
  shown this at previous NuInts
- **added Delta radiative decays**
- **added de-excitation photons for carbon**
  verified this with our NC elastic scattering data sample
- **installed non-isotropic decay of Delta resonance as per Rein-Sehgal paper**
- **adjusted coherent cross section**
  based on MB data measurement in NC pi0 sample / Jon Link will show this at NuInt07
- **adjusted pi0 momentum spectrum**
  applied in analysis code - not nuance / Jon Link will show this at NuInt07
- **adjusted QE model parameters (Ma, Pauli blocking)**
  based on fits to MiniBooNE QE data / Teppei Katori will show this at NuInt07

NEUT

[source: Y.Hayato]

- Use Smith-Moniz for the cross-section of quasi-elastic scattering
- Implement Bodek-Yang corrections for DIS
- Implement nucleon final state interactions (rescattering in 16O)

Plans:

- **Support Carbon. Also, support Iron to some extent.**
- **Make code available**.
- Implement recent models if applicable to SK, T2K and SciBooNE.

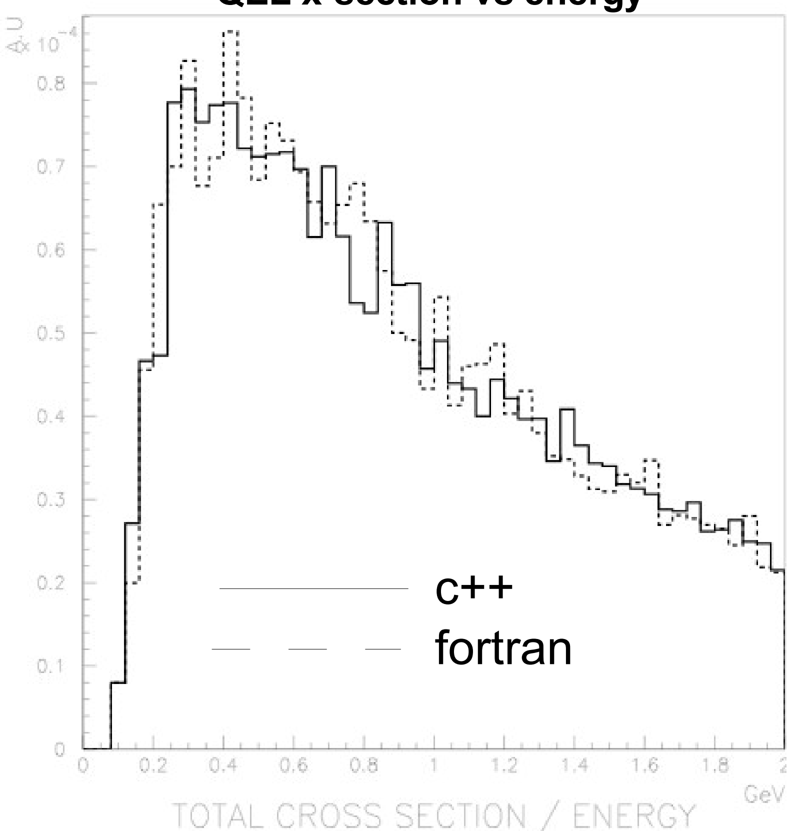
Gaku Mitsuka is giving a talk on NEUT

GENEVE

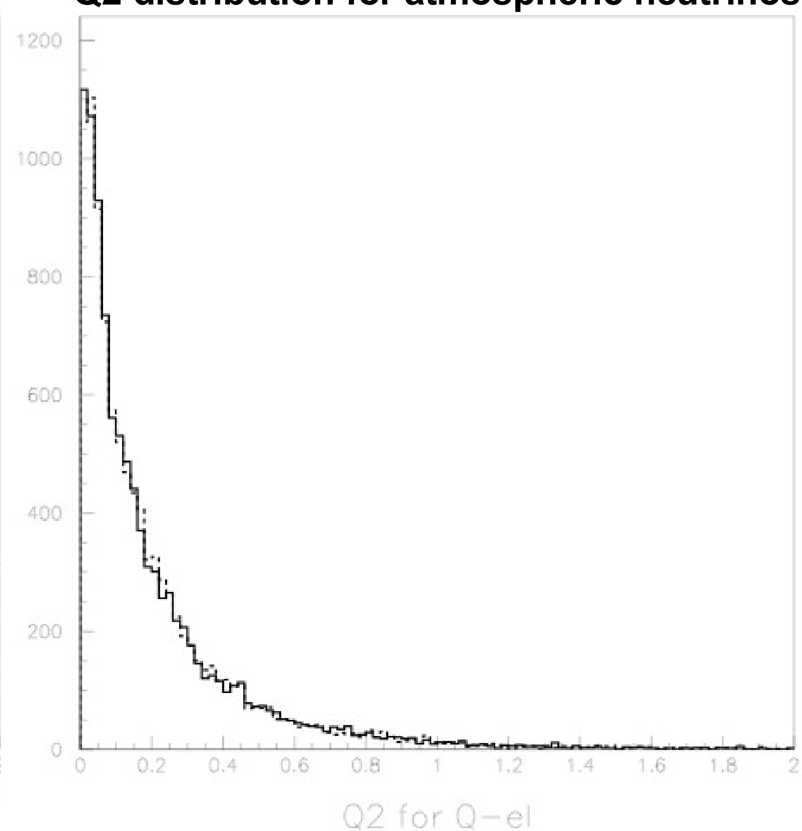
[source: J.Lagoda]

- Original code by F.Cananna, O.Palamara et al. was translated to C++ by Justyna Lagoda
- We would be looking for ways to **integrate GENEVE into GENIE** later this summer
- **Complete equivalence** has been achieved between the C++ and fortran versions

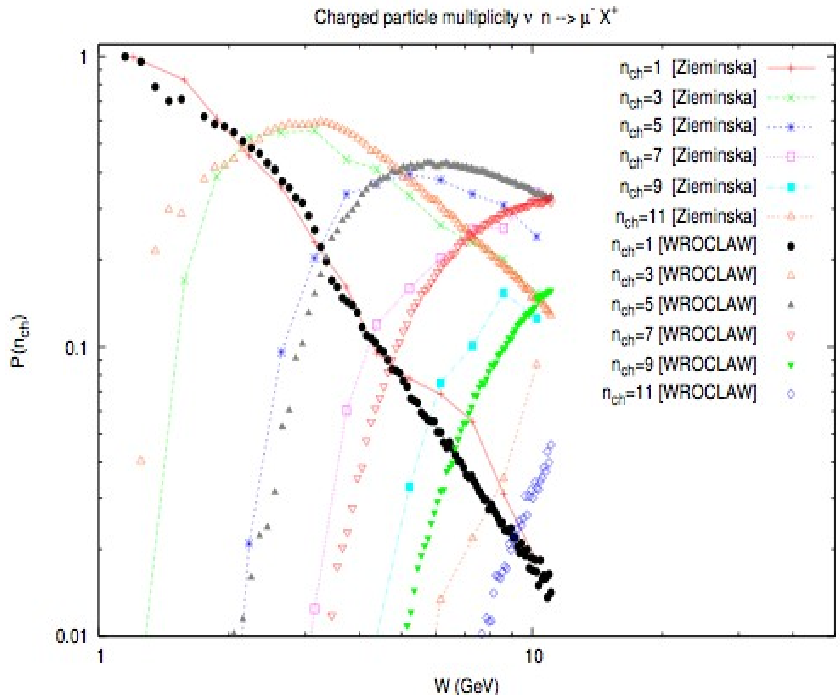
QEL x-section vs energy

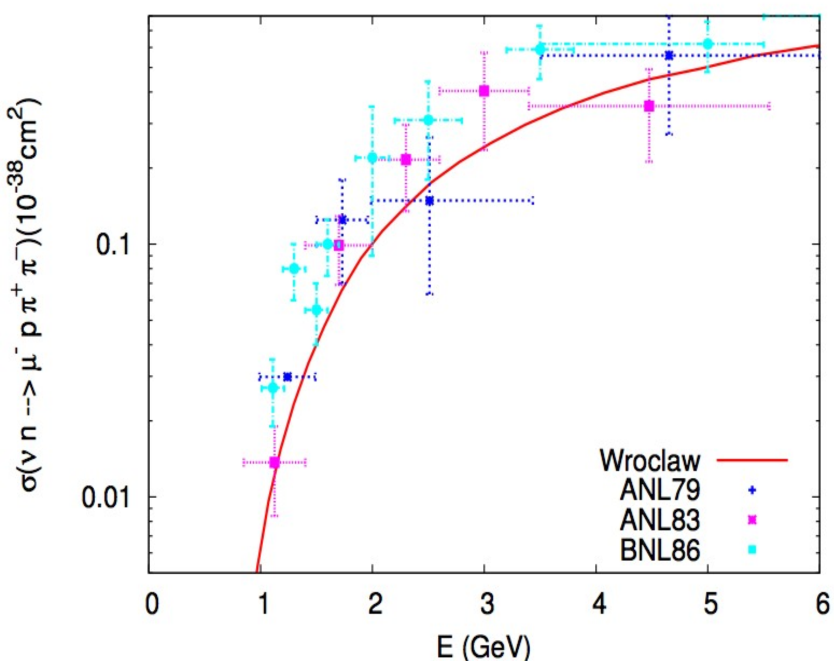


Q2 distribution for atmospheric neutrinos



Wroclaw Generator (NuWro)





[source: J.Sobczyk]

- Dynamics: QEL, Delta production, DIS.
- **Final states are produced by the PYTHIA fragmentation routines.**
- **The PYTHIA is adapted to produce final states below W=2GeV.**
- **The Rein-Sehgal model IS NOT used.**
- Linear RES/DIS trans. in W=(1.4, 1.6) GeV
- More inelastic channels -> PYTHIA
- The non-resonant background is simulated as a fraction of the DIS contribution.
- Nuclear effects: Fermi gas, LDA, effective momentum dependent potential.

Plans:

- Internuclear cascade
- Spectral functions in the "effective approach" proposed in A.Ankowski, J.Sobczyk, Phys.Rev. C74 (2006) 054316.

Neugen3 & GENIE

- **Comprehensive cross section modeling / tuning to world data**
  - Implemented Bodek-Yang model
  - Moved to BBA2005 elastic form factors
  - Updated COH model *(new Rein-Sehgal paper, modified PCAC)*
  - Adopted global tuning of Kuzmin et al.
  - Retuned DIS contributions to RES region
- **Almost complete re-write of the hadronization model**
- **Almost complete re-write of the hadron transport model**

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GENIE Status

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Parallel development of physics models with neugen3 while the GENIE framework & tools were developed

- GENIE/neugen almost completely equivalent now
  - *Final validation during first half of summer 2007*
  - *Neugen will be retired*

- MINOS will be adopting GENIE for physics MC production

- GENIE also interfaced / tested by SciBooNE, Minerva, T2K
  Using it at T2K Software Vertical Slice Test (?)

- Active further development
  - *Nuclear model upgrade (end of summer 2007)*
  - *More hadron transport models (INTRANUKE hN, interface to GiBUU ?, ...)*
  - *Hadronization model fine-tunings*
  - *Integrate GENEVE-specific models*
  - *...*

M.Kim is presenting a GENIE poster, focusing on Pittsburgh Univ. group (S.Dytman et al) efforts on hadron transport modelling

Common trends...

Generators still look largely the same...

FGM + QEL (Llewellyn-Smith), RES (mostly Rein-Sehgal), DIS (Bodek-Yang)

Work to ensure past efforts live on at the c++ world

Much work on what S.Zeller had described as 'non-trivial differences'

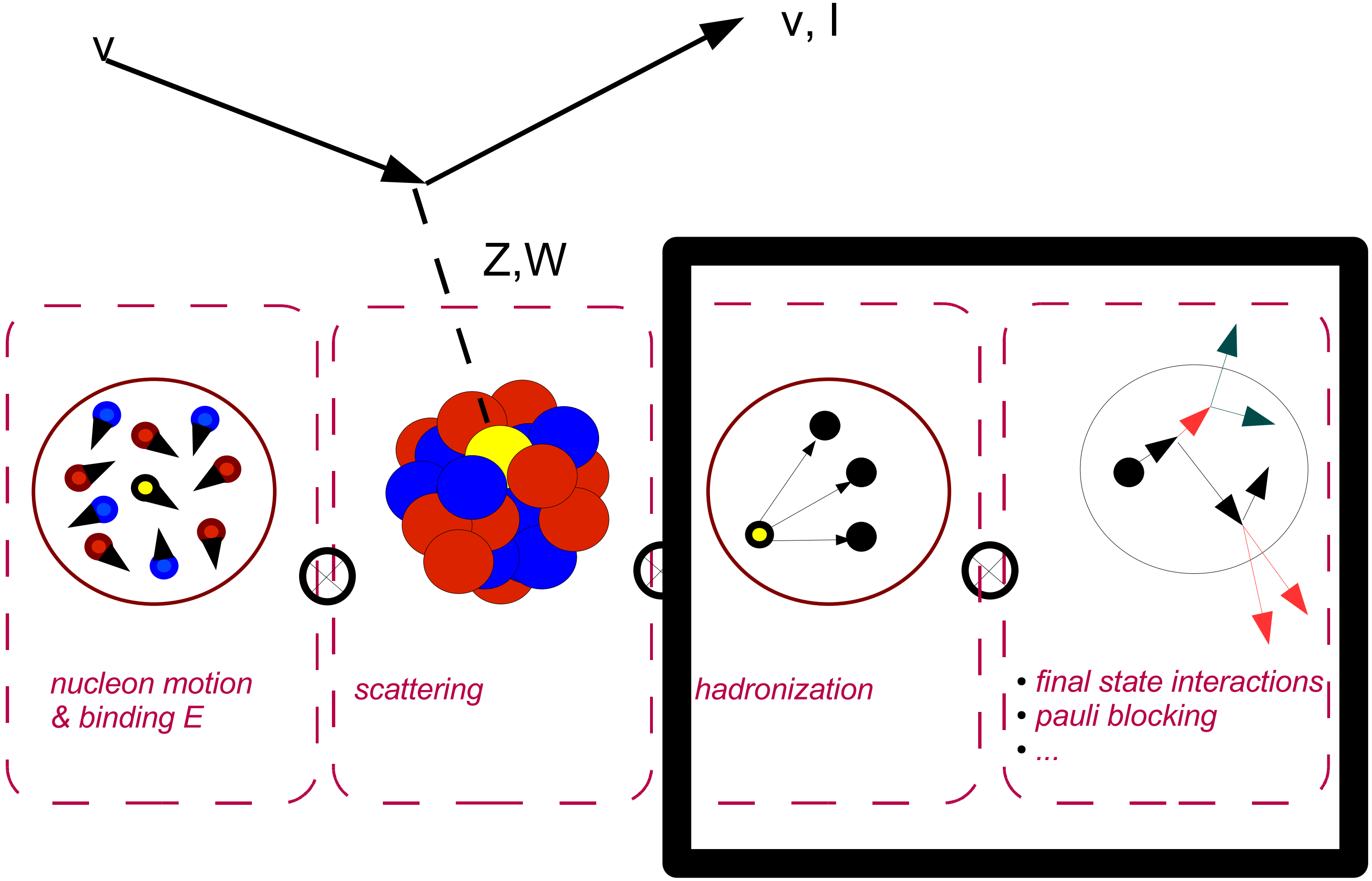
Mainly at
- hadronization modeling
- hadron transport modeling

Presumably, differences 'even less trivial' now...
Another cross-generator check is now due!

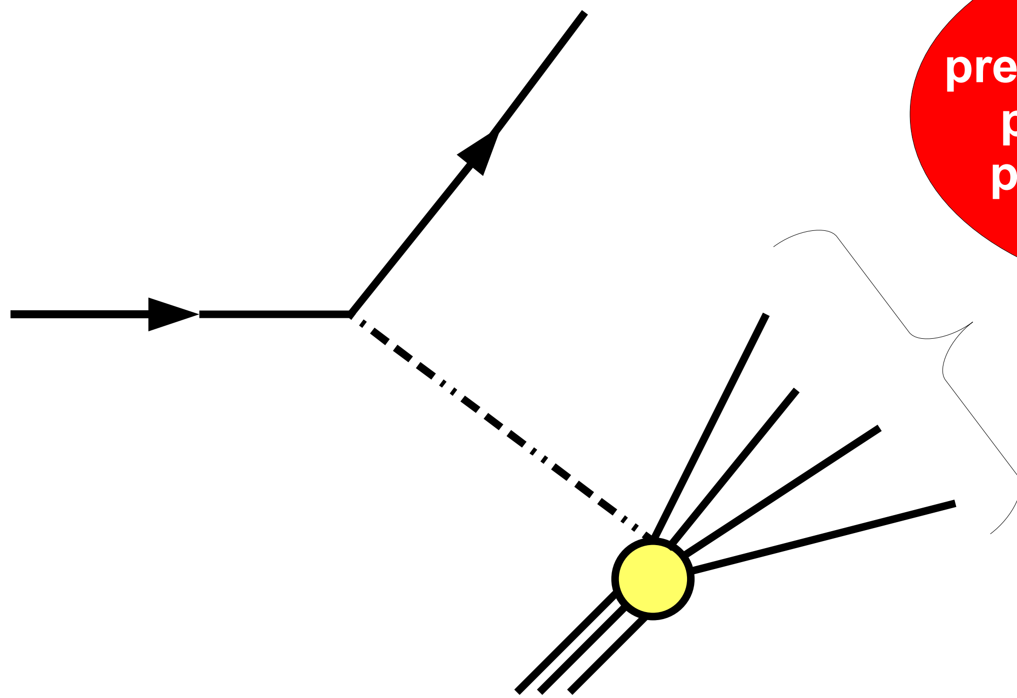
Generators state again the willing to move beyond FGM

Work in progress in at least two : GENIE & NuWro

Much of the recent progress in modelling the νA hadronic system



Hadronic Multiparticle Production model



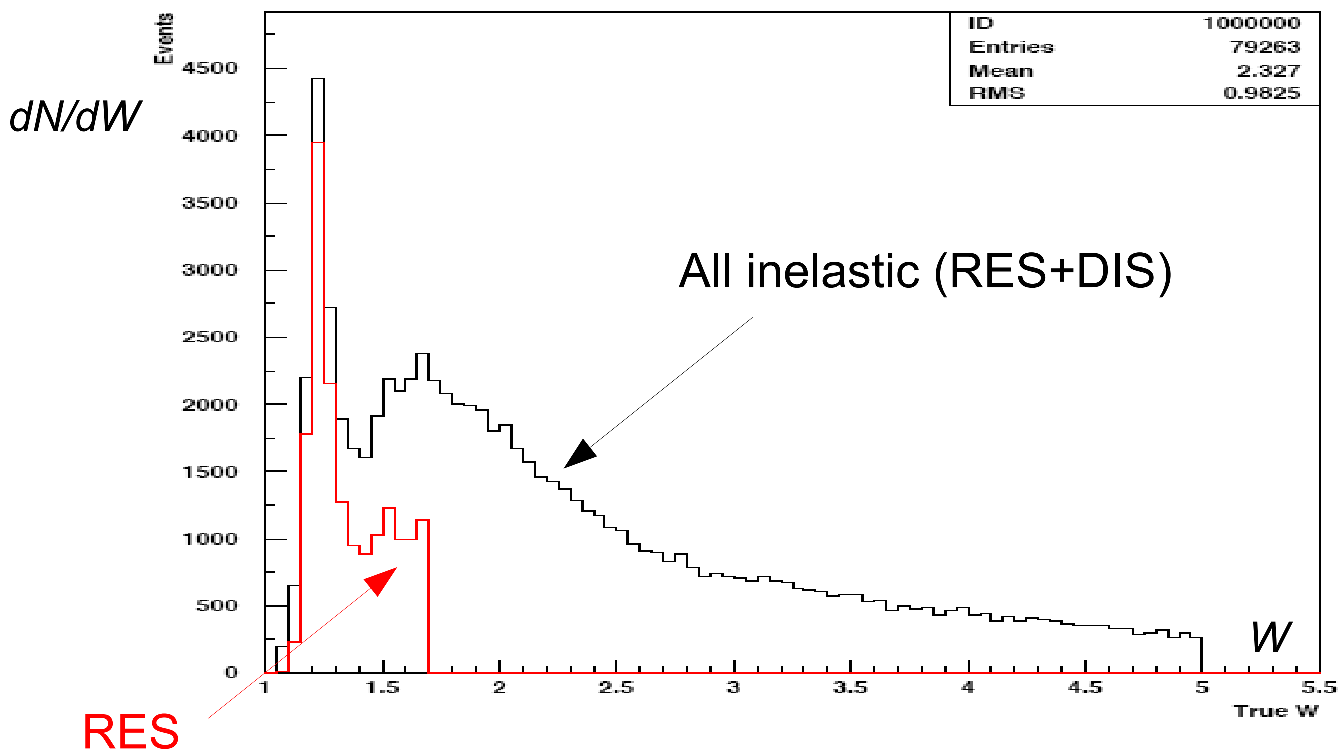
predict hadron shower particle content & particle 4-momenta

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

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

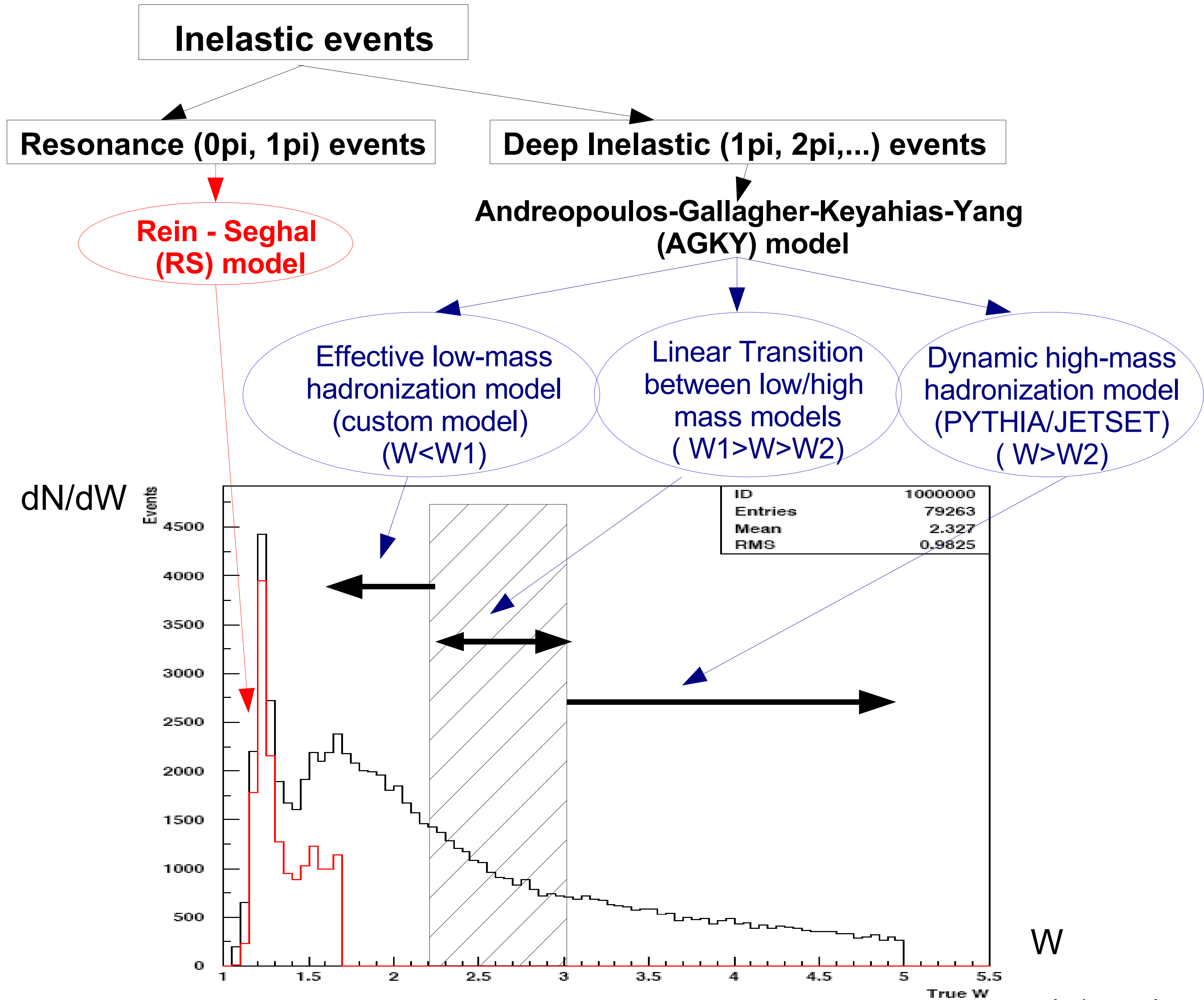
Hadronic Multiparticle Production model

- **Particularly important for MINOS in the NuMI beam**
- Sees a 'wide range' of hadronic invariant masses (W)
- Needs to employ a host of hadronization models to cover the accessible W space
- MINOS data ideal for testing hadronization models from inelastic threshold up to the high-W DIS regime



T.Yang is giving a talk on the AGKY hadronization mode

MINOS 'Suite' of Hadronization



AGKY : Improving of hadron shower characteristics

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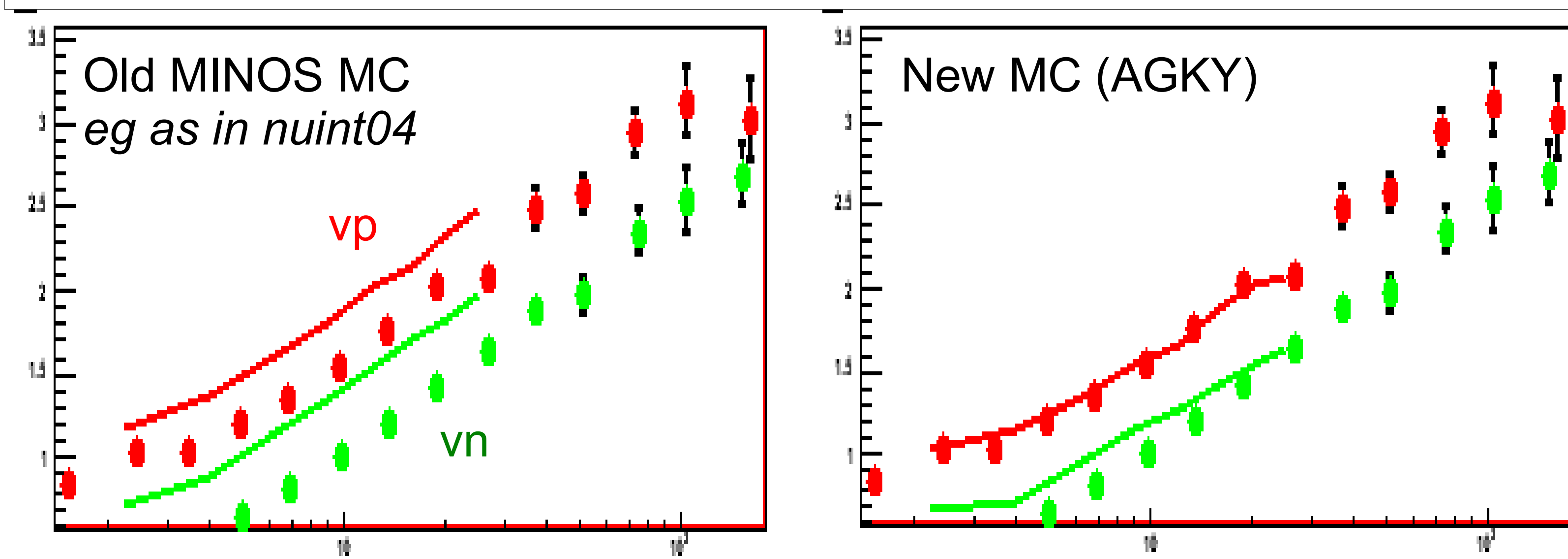
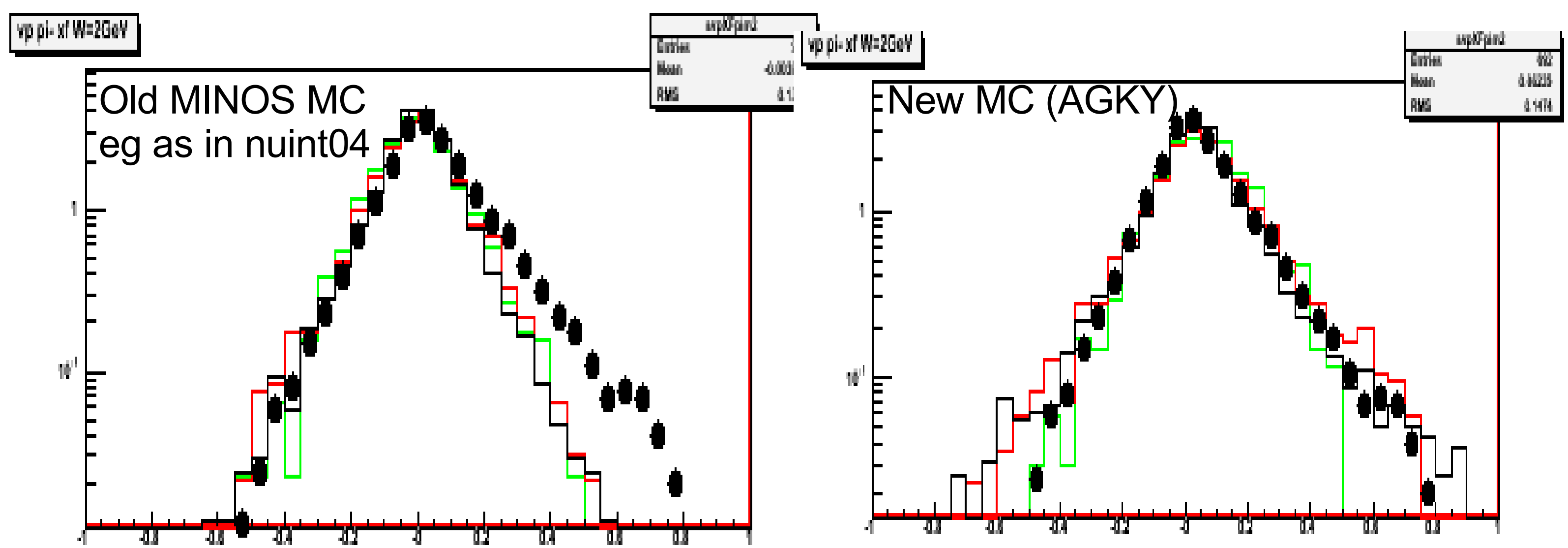
Backward – hemisphere average hadronic multiplicity vs W^2

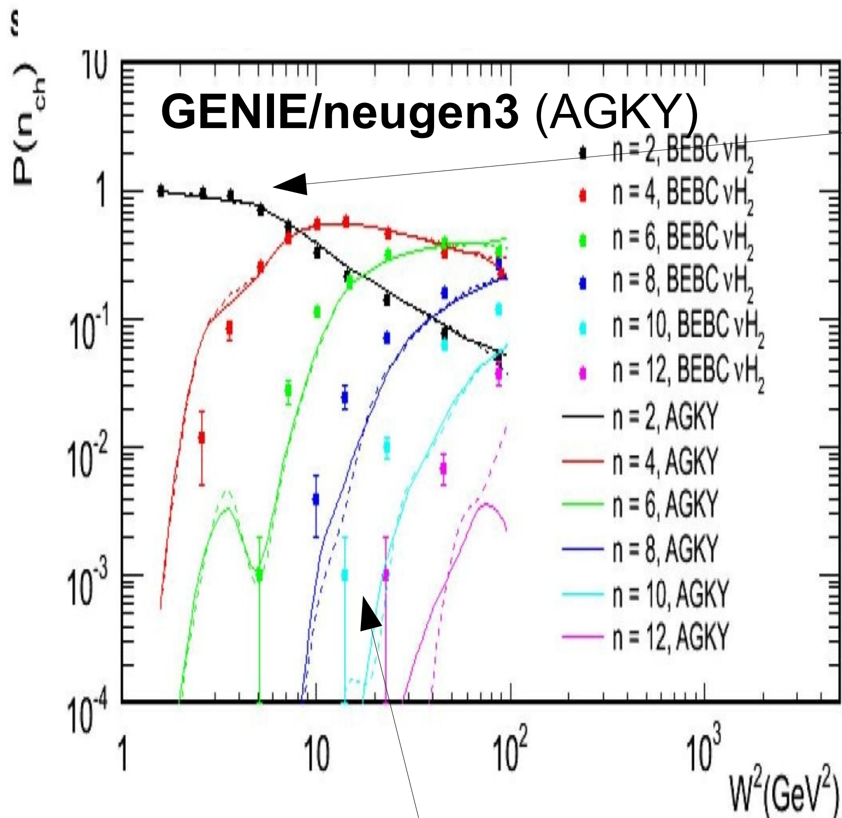


Feynman x distribution for pions

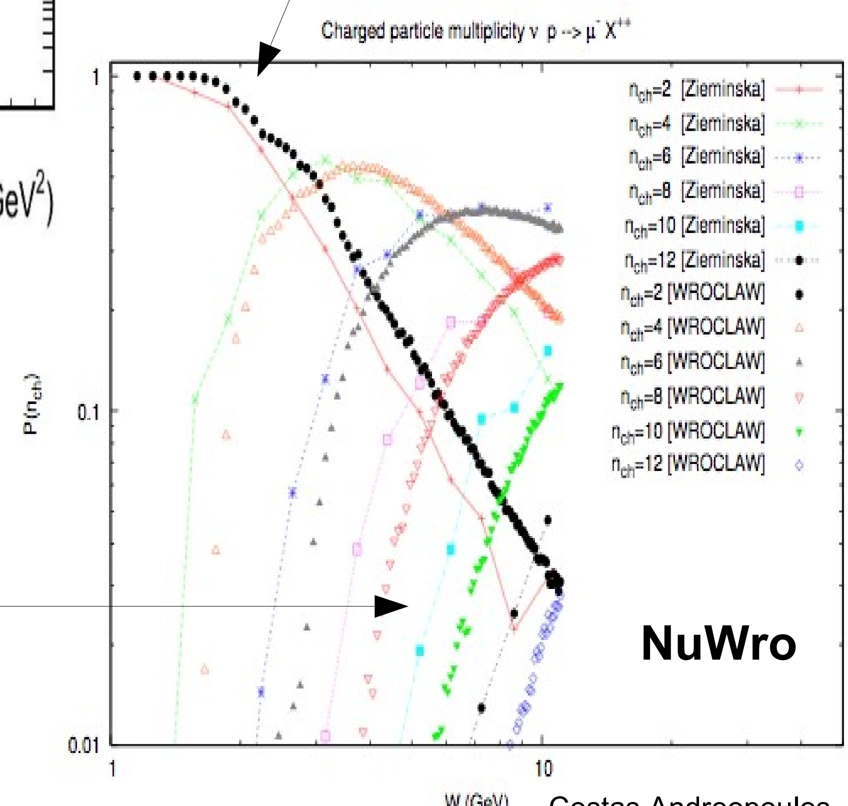


Extensive data/mc comparisons at T.Yang's talk

AGKY vs NuWro



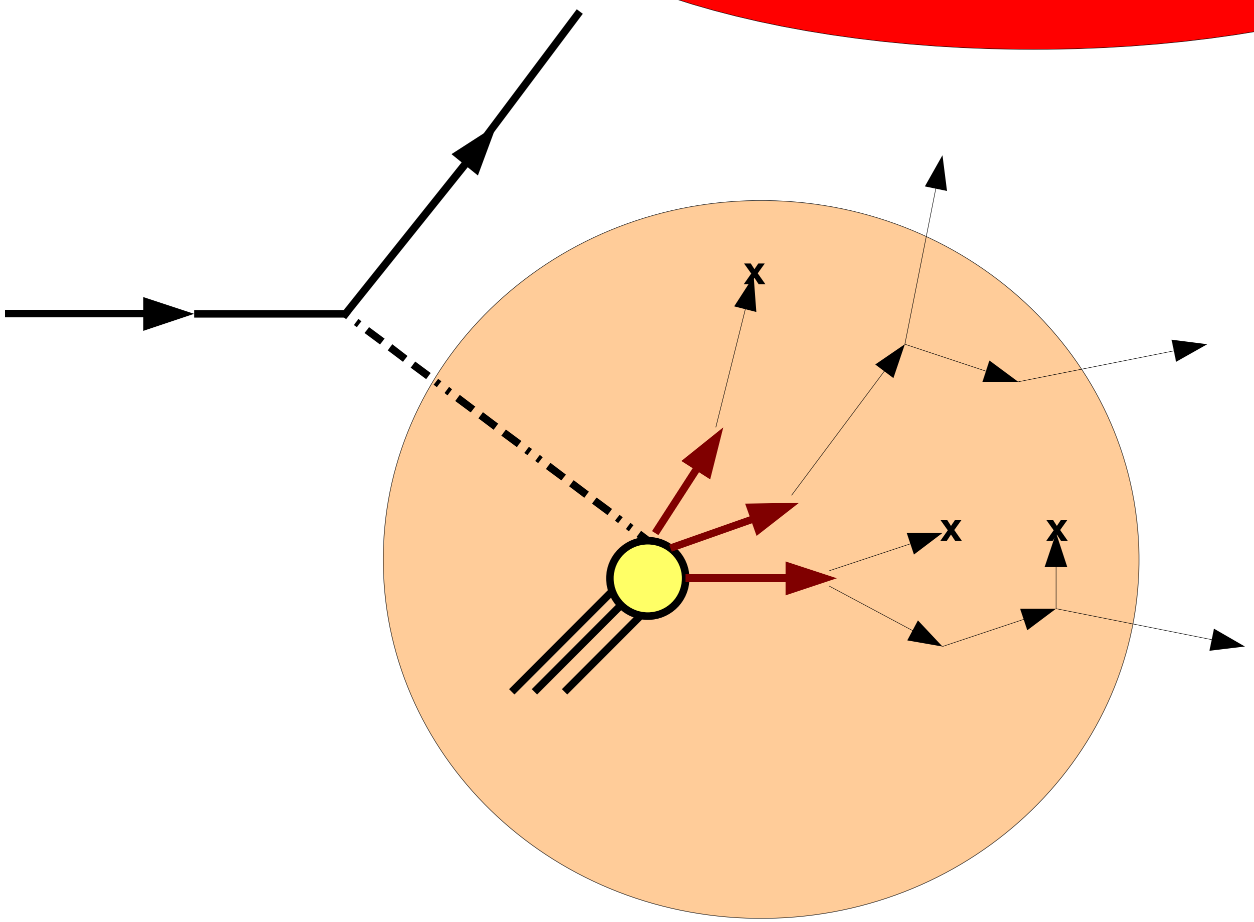
AGKY effective model better than PYTHIA at low-W



NuWro drives PYTHIA better at high-W?

Intranuclear Hadron Transport

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



Intranuclear Hadron Transport

Is worth noting:

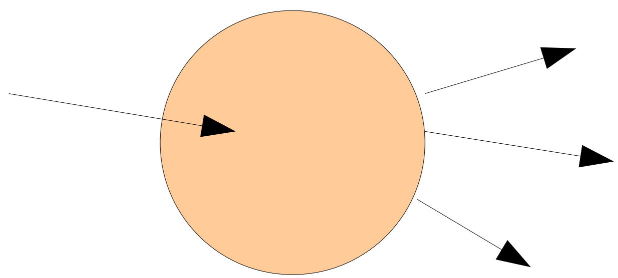
- **Plenty of hadron transport codes exist!**
- Many common inputs but -in some cases- **orthogonal approaches**
- Many generic – others tuned to specific nuclear targets.
- Need to be able to run them all

- **BUU *(Boltzmann-Uehling-Uhlenbeck)* – based transport MCs**
  - *GiBUU*
  - *...?*
- **Cascade MCs**
  - *FLUKA*
  - *GENIE/neugen INTRANUKE hN-model*
  - *NEUT's INC model*
  - *NUANCE INC model*
  - *...?*
- **“Effective” MCs**
  - *GENIE/neugen INTRANUKE hA-model*
  - *...?*

GENIE/neugen INTRANUKE

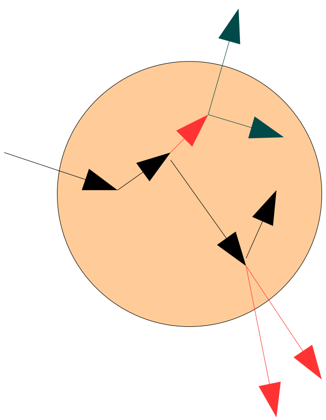
Development led by Prof. **Steve Dytman** et al.

Intranuke / hA
(effective MC)



Anchored to a large body of experimental hadron+nucleus data

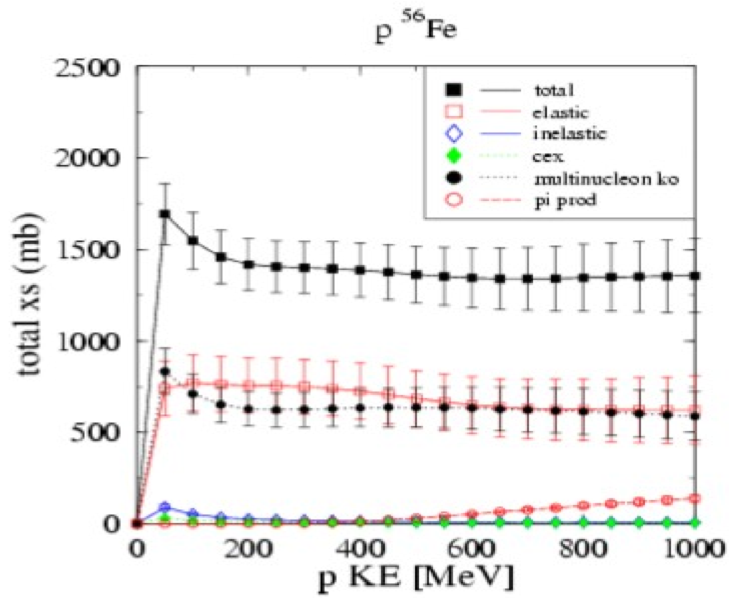
Intranuke / hN
(cascade MC)



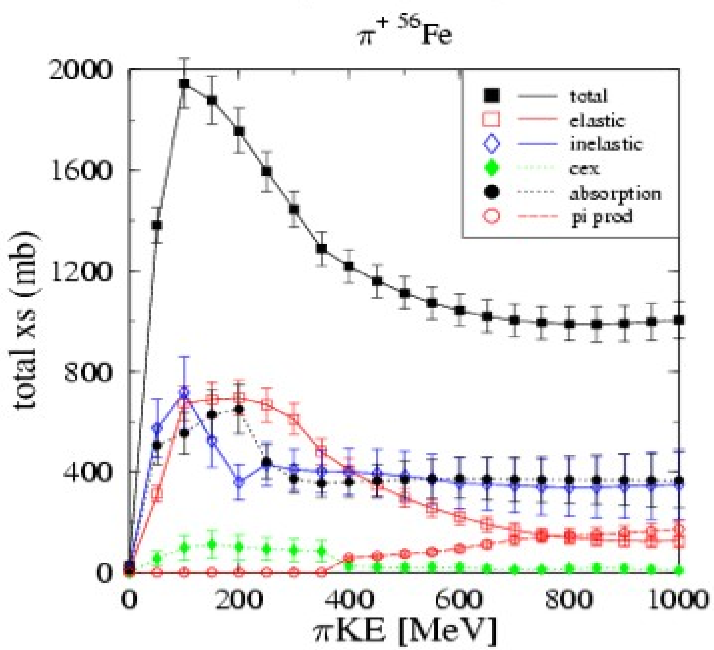
(work in progress)

INTRANUKE / hA

Rescattering channels implemented at GENIE / neugen3 INTRANUKE– eg for Fe56



Elastic	p ^{56}Fe→p ^{56}Fe
Charge exchange	p ^{56}Fe→n ^{56}Co
Inelastic	p ^{56}Fe→p´ ^{56}Fe
Breakup	p ^{56}Fe→pn ^{55}Fe
	p ^{56}Fe→pp ^{55}Mn
	p ^{56}Fe→ppn ^{54}Mn
	p ^{56}Fe→pnn ^{54}Fe
Breakup-generic	p ^{56}Fe→pppnn ^{52}Cr
Pion production	p ^{56}Fe→π^+ n ^{56}Fe
	p ^{56}Fe→π^+ π^0 n ^{56}Fe



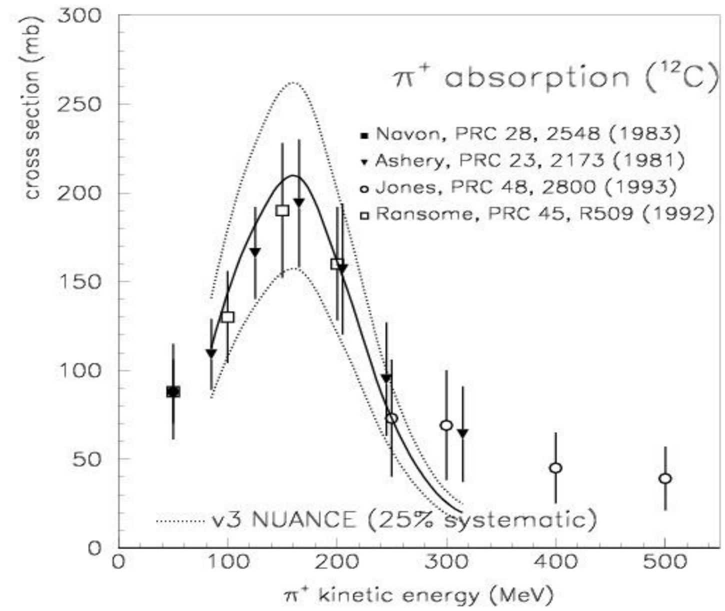
Elastic	π^+ ^{56}Fe→ π^+ ^{56}Fe
Charge exchange	π^+ ^{56}Fe→ π^0 ^{56}Cr
Inelastic	π^+ ^{56}Fe→ $\pi^{+\prime}$ N ^{56}Fe
Absorption	π^+ ^{56}Fe→ **pn** ^{54}Fe
	π^+ ^{56}Fe→ **pp** ^{54}Mn
	π^+ ^{56}Fe→ **ppn** ^{53}Mn
	π^+ ^{56}Fe→ pnn ^{53}Fe
Abs-generic	π^+ ^{56}Fe→ ppnn ^{52}Mn
Pion production	π^+ ^{56}Fe→ $\pi^+\pi^0$ ^{56}Fe

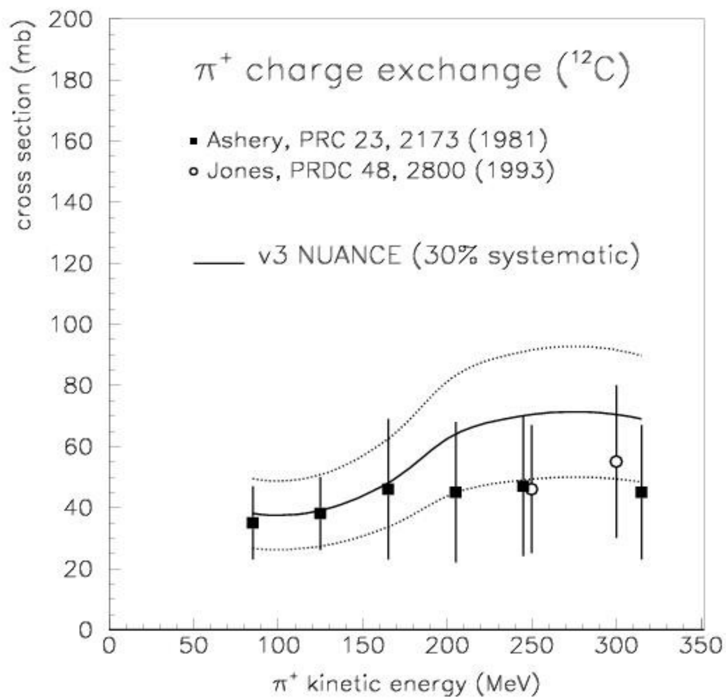
Nuance INC

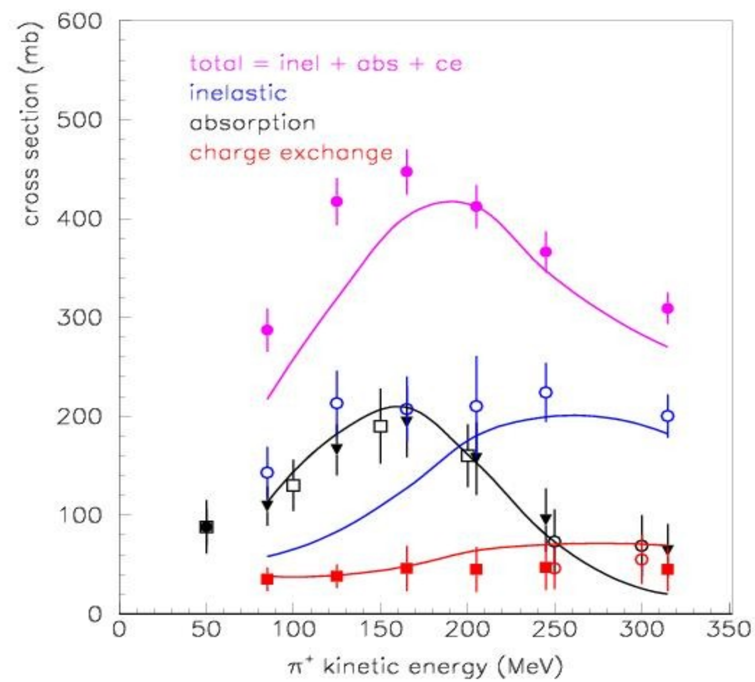
[source: S.Zeller]

Tuned pion absorption and CEx rates based on external pion-carbon data

(shown this at previous NuInts)







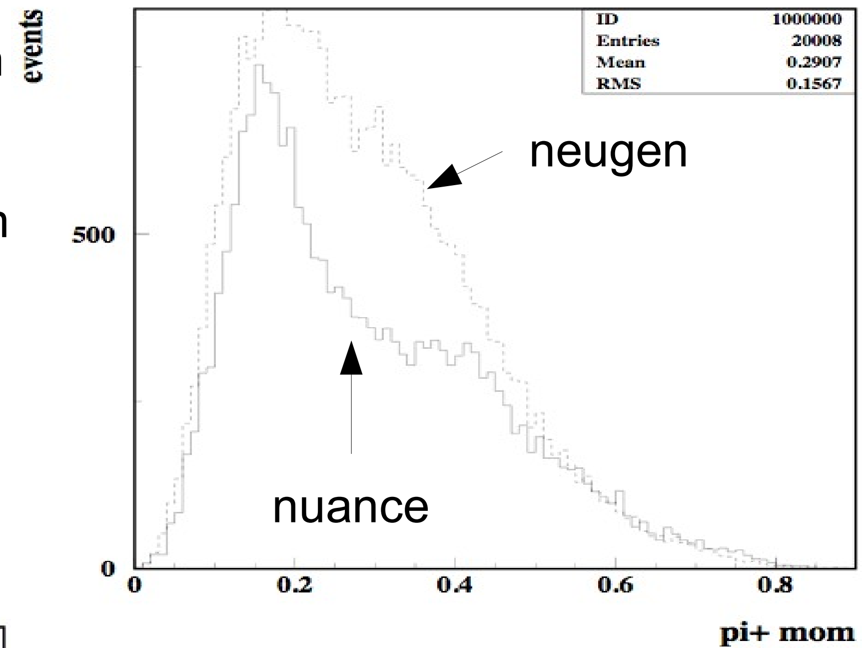
Nuance INC vs INTRANUKE hA

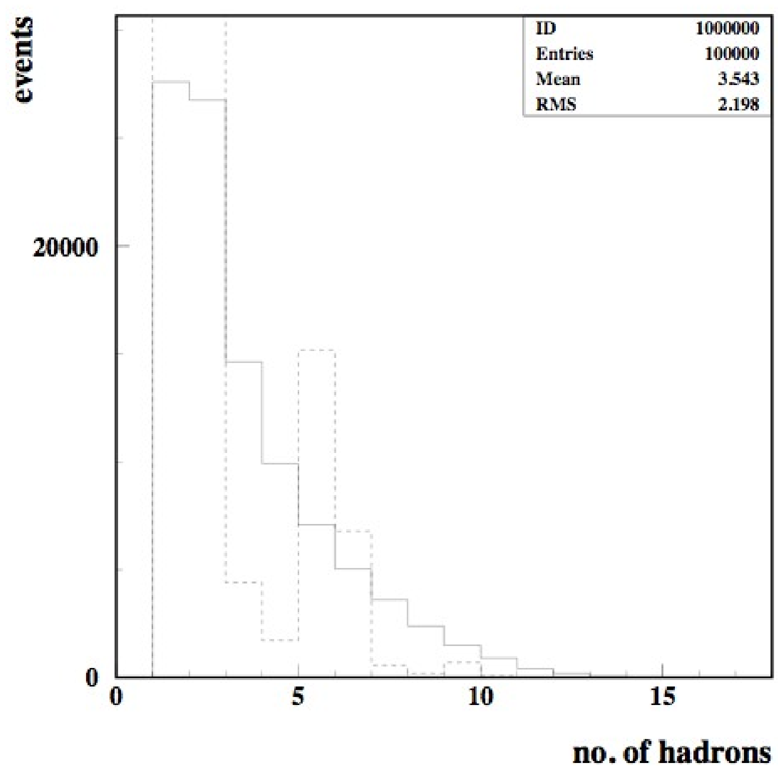
Comparison prepared by S.Dytman at the last minute before NuINT07

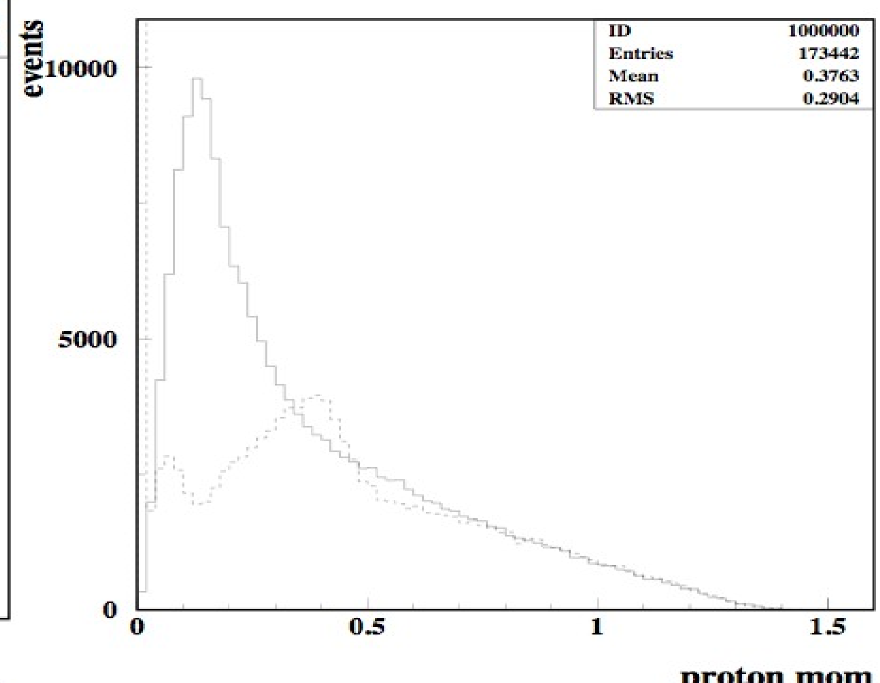
Details of the hadonic system seem to be very different

Preliminary / Investigating...

(numu+O16, 5 GeV?)







What do we need?

Data

- Results by **K2K**, **MiniBooNE** stirred the waters
- Eagerly awaiting for results from **SciBooNE**, **Minerva**, **nd280,...**
- **No much progress can be expected before that...**

Guidance from theory

- Help understanding uncertainties (NC, anti-neutrinos, hadronic system characteristics)
- Helping out with nuclear model upgrade
- Contribute code (GiBUU / NuWro - interfaces)

Collaboration between MC authors

- Move faster towards a "universal / canonical" neutrino MC

Summary

- **Important improvements / generator tunings over the past 2-3 years**
  - **At the most 'tricky' areas of neutrino interaction modelling**
    - *Hadronization modeling*
    - *Hadron Transport modeling*

- Situation calls for another extensive cross-generator comparison
  - *Partly within the T2K/UK Physics Work Package – over the summer*
  - *I will be in contact with other MC authors*
  - *Summarize the results at the proceedings*