Propagating Interaction Uncertainties via Event Reweighting

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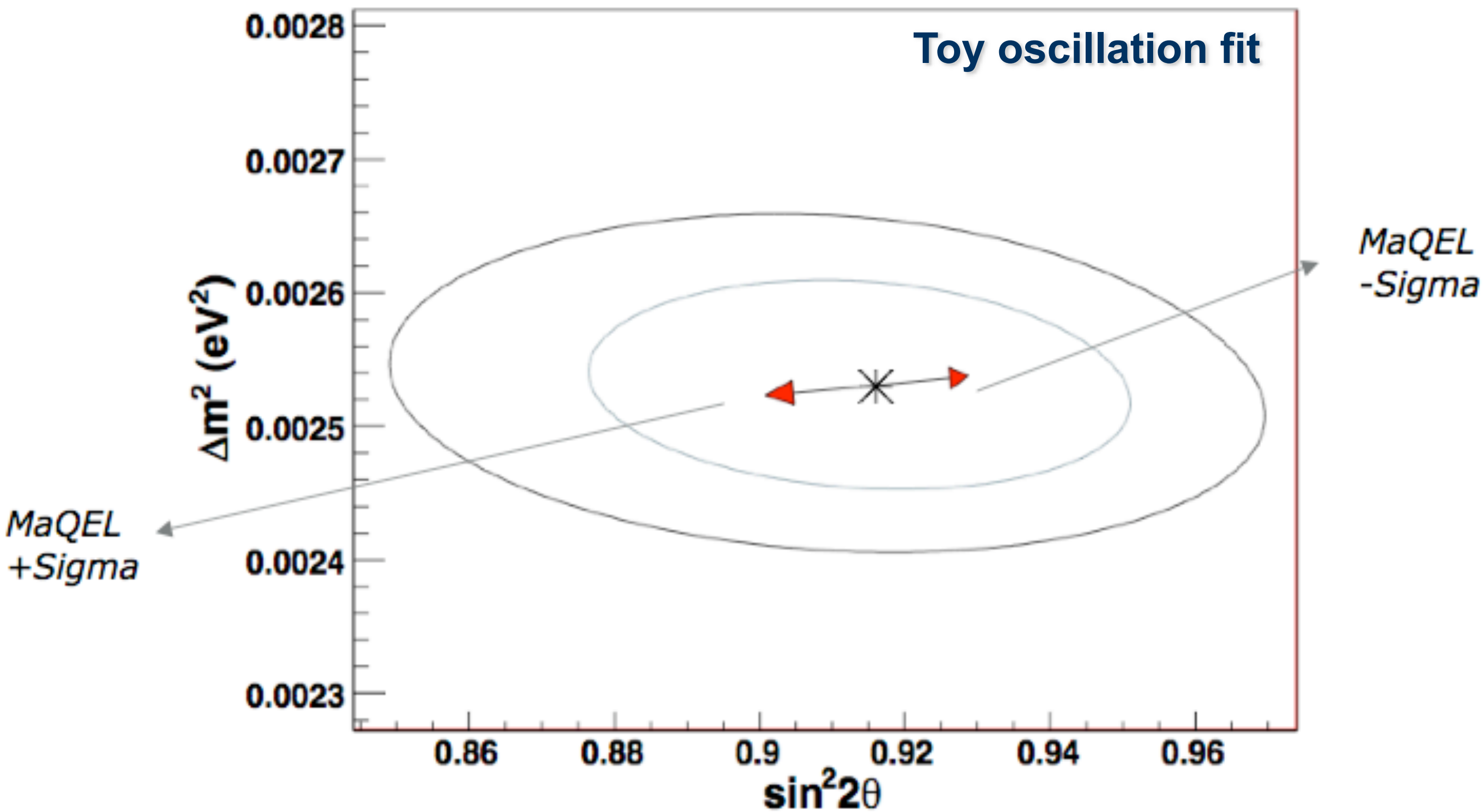
Outline of talk

- Motivations
  - Intranuclear rescattering
    - » reweighting scheme
    - » validation
    - » example
  - Neutrino cross sections
    - » reweighting scheme
    - »validation
    - » example
- Performance and applications

Motivations

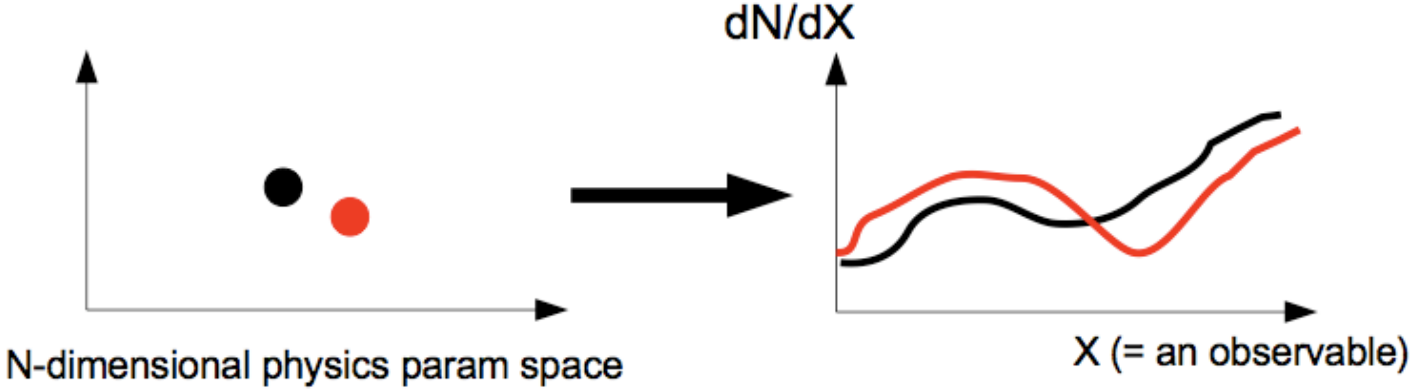
Quantify the effect of interaction uncertainties in physics measurements.



Toy 2 flavour oscillation fit showing shift in best fit for $\sin^2 2\theta$ and Δm^2 due to variation in $\mathrm{Ma\text{-}QEL}$ of $\pm 1\sigma$.

Motivations

Want to see effect of different input MC model parameters on observable.



Without running full MC again (**GENIE MDC0 sample** @ Liverpool 5E+21 POT ~ 200 CPUs * 3 weeks).

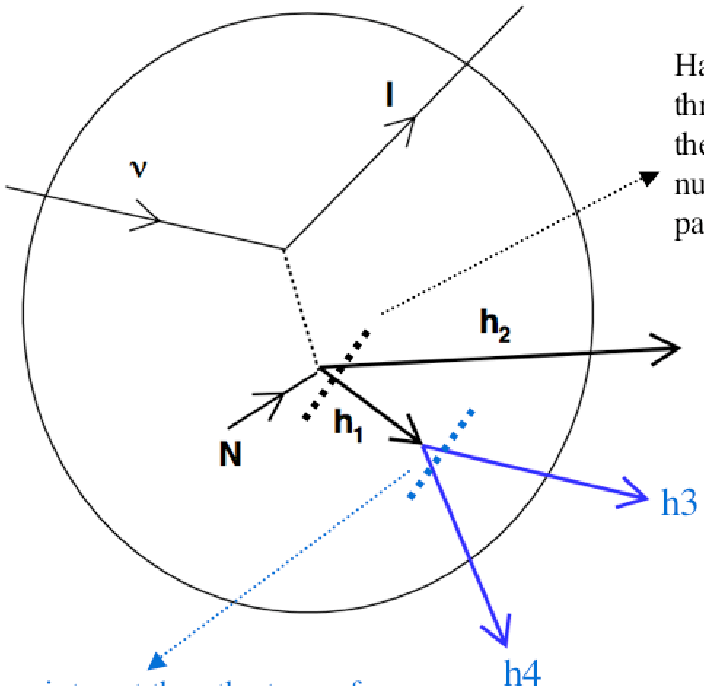
Event reweighting provides a shortcut. Use original MC data set but for every event generate a weight that reflects the change in probability due to changing some physics input parameter.

Limited to processes for which probability can be calculated without resorting to MC methods.

Intranuclear Hadron Transport Reweighting

Unlike typical cascade models GENIE's INTRANUKE/hA is an effective model.
And so it is possible to calculate probabilities without resorting to MC methods.

Intranuclear Hadron Transport Model (INTRANUKE/hA)



Hadrons h1 and h2 are stepped through the nucleus. Whether they interact depends on the nuclear density and mean free path.

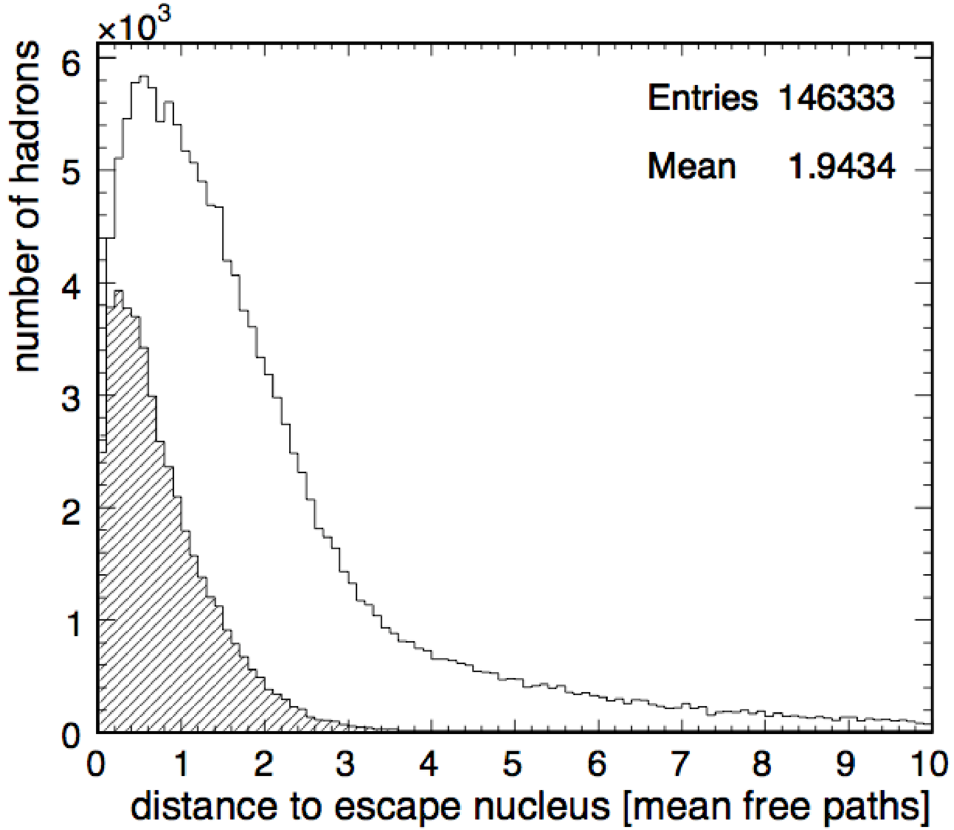
If they interact then the type of reaction is chosen according to hadron nucleus inclusive cross section tables.

- Hadrons produced inside the nucleus are stepped out (0.05fm steps).
- For each step interaction prob is calculated. MC method to see whether it interacts.
- If it interacts then its fate is decided based on hA cross section data.
- The hadron is stepped until either it interacts or it gets to 3xNuclear radius (~3fm for C12), in which case it escapes.

Reweighting code has to calculate exactly the same rescattering probability.

Most Hadrons Re-interact

At few GeV energies **most hadrons re-interact**.



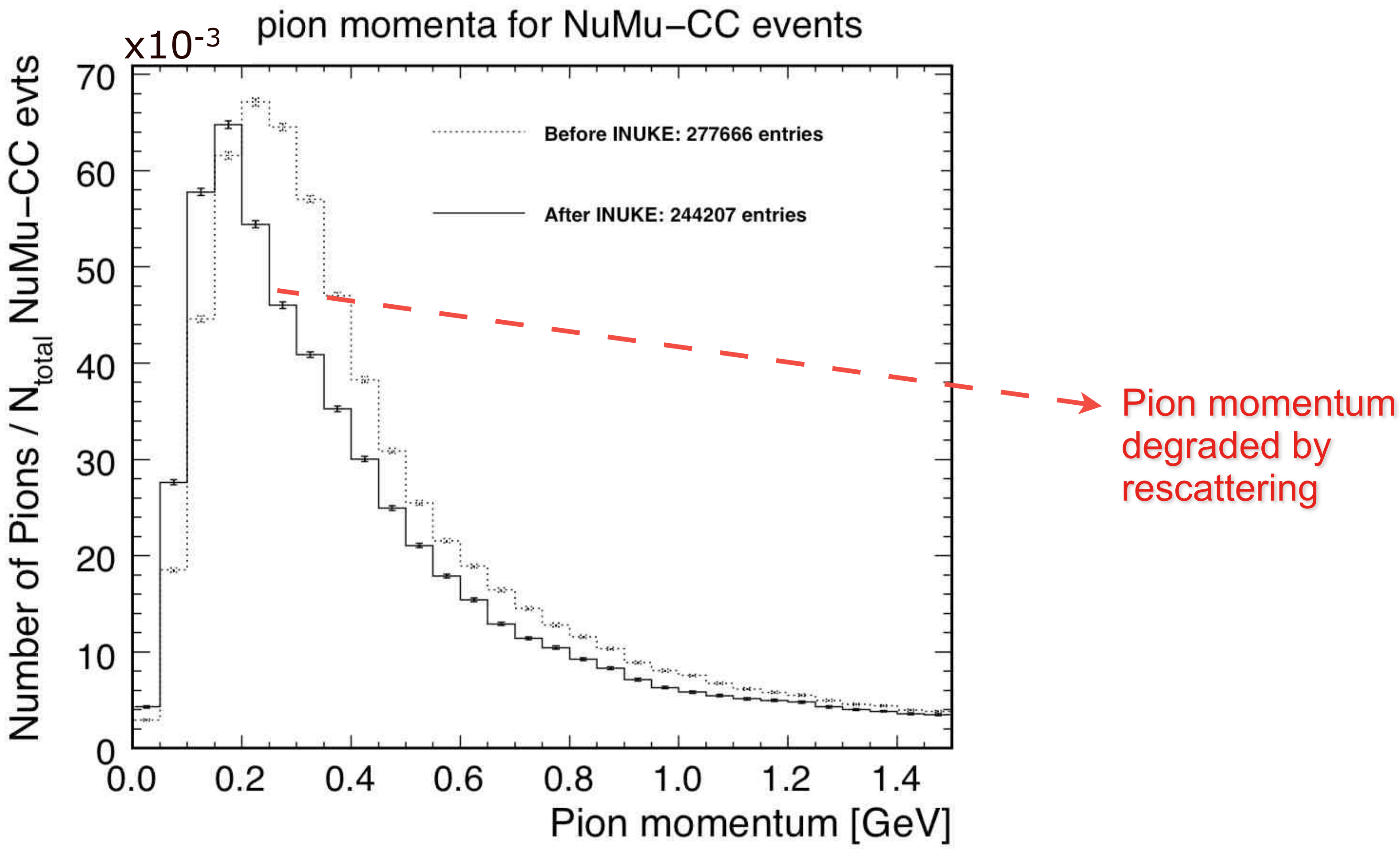
Distance to escape nucleus in mean free paths. Hatched region shows fraction of events (~1/3) that escaped. 100k events on C12.

Effect of Intranuclear Rescattering

No pions in initial state → 1pi+ in final state.

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

Effect on Pion Momenta



Intranuclear Reweighting Schemes

We consider two types of parameters:

- Ones that control the **total reinteraction rate**:
  - Mean free path

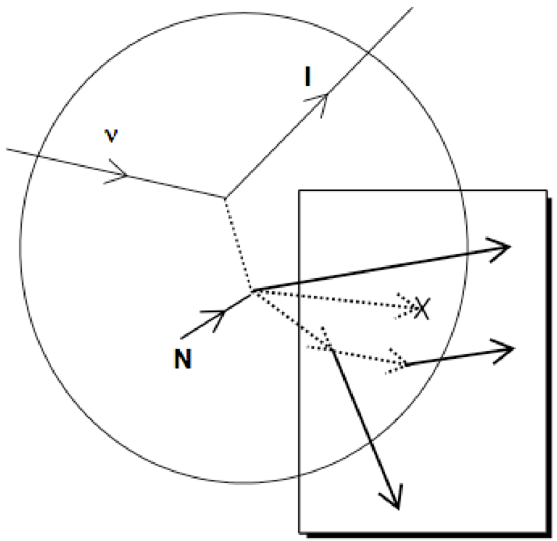
- Ones that control the **relative fractions of various rescatterring modes (fates)**:
  - Probability for charge exchange
  - Probability for pion production
  - Probability for absorption followed by nuclear breakup
  - Probability for elastic scattering
  - Probability for inelastic scattering

Separately for nucleons and pions.

Intranuclear Hadron Transport Tweaking Parameters

Physics Param.	Short description	*T2KReWeight* knob (*T2KSyst_t* variable)	Default value	Error ($1\ \sigma$)
x^N_{mfp}	Tweaks the nucleon mean free path	kSystINuke_MFPTwk_N	0.0	1.0
x^N_{cex}	Tweaks the nucleon charge exchange prob.	kSystINuke_CExTwk_N	0.0	1.0
x^N_{el}	Tweaks the nucleon elastic reaction prob.	kSystINuke_ElTwk_N	0.0	1.0
x^N_{inel}	Tweaks the nucleon inelastic reaction prob.	kSystINuke_InelTwk_N	0.0	1.0
x^N_{abs}	Tweaks the nucleon absorption prob.	kSystINuke_AbsTwk_N	0.0	1.0
x^N_{π}	Tweaks the nucleon π-production prob.	kSystINuke_PiProdTwk_N	0.0	1.0
x^{π}_{mfp}	Tweaks the π mean free path	kSystINuke_MFPTwk_pi	0.0	1.0
x^{π}_{cex}	Tweaks the π charge exchange prob.	kSystINuke_CExTwk_pi	0.0	1.0
x^{π}_{el}	Tweaks the π elastic reaction prob.	kSystINuke_ElTwk_pi	0.0	1.0
x^{π}_{inel}	Tweaks the π inelastic reaction prob.	kSystINuke_InelTwk_pi	0.0	1.0
x^{π}_{abs}	Tweaks the π absorption prob.	kSystINuke_AbsTwk_pi	0.0	1.0
x^{π}_{π}	Tweaks the π π-production prob.	kSystINuke_PiProdTwk_pi	0.0	1.0

Unitarity Constraints



Intranuke schemes should, by construction, maintain unitarity.

Qualitatively this can be seen by considering an observer who is blind to the hadronic system in the box.

To them the outgoing primary lepton distribution should remain unchanged.

We require that the sum of weights is equal to the number of events N_{tot} as

$$N'_{tot} = \sum_{j=1}^{j=N_{tot}} w_j^{evt}$$

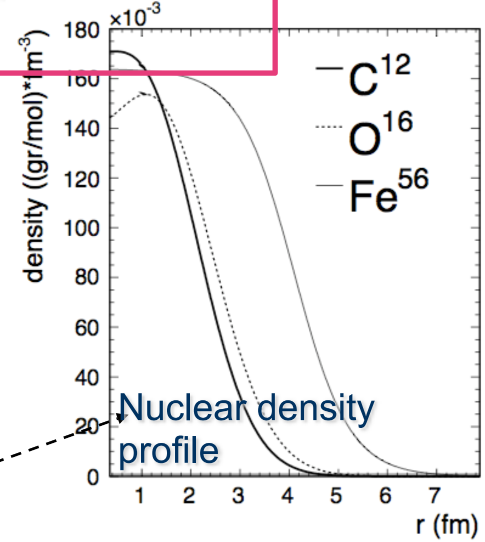
So look at distribution of weights for a given sample and expect a mean weight of 1.

See internal note for more detailed explanation on the unitarity constraints.

Prescription for calculating weights

Calculating Weight to Account for Change in Mean Free Path

Critical to match physics in original model with that used to calculate new probabilities.

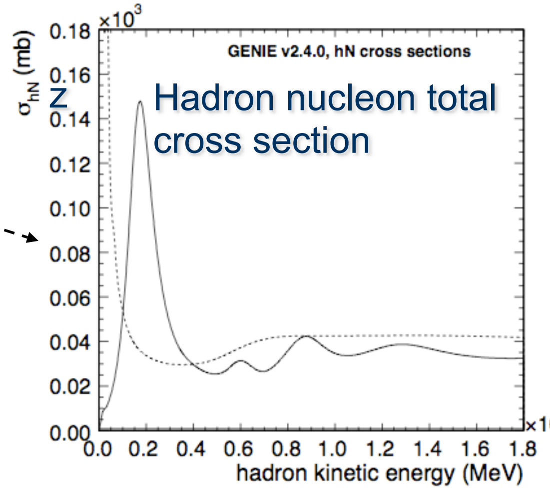


To do this need to access same data as original MC.

The probability that a hadron will rescatter given by,

$$\lambda^h = 1/(\rho_{nucl}(r) * \sigma^{hN}(E_h))$$

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



Calculating Weights for Change in Hadron Fate XSections

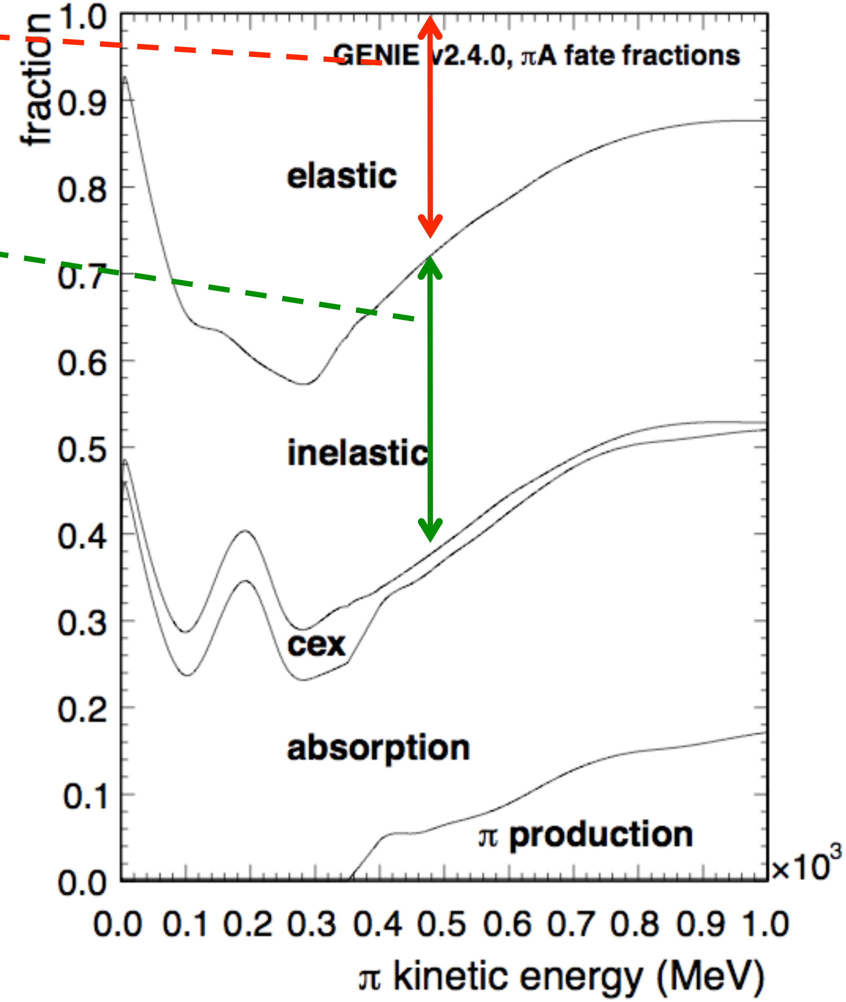
Elastic (**Elas**):
Momentum change with no energy change.

Inelastic (**Inel**):
Momentum and energy change.

Charge Exchange (**CEx**):
p + A -> A' + n
pi+ + A -> A' + pi0
etc…

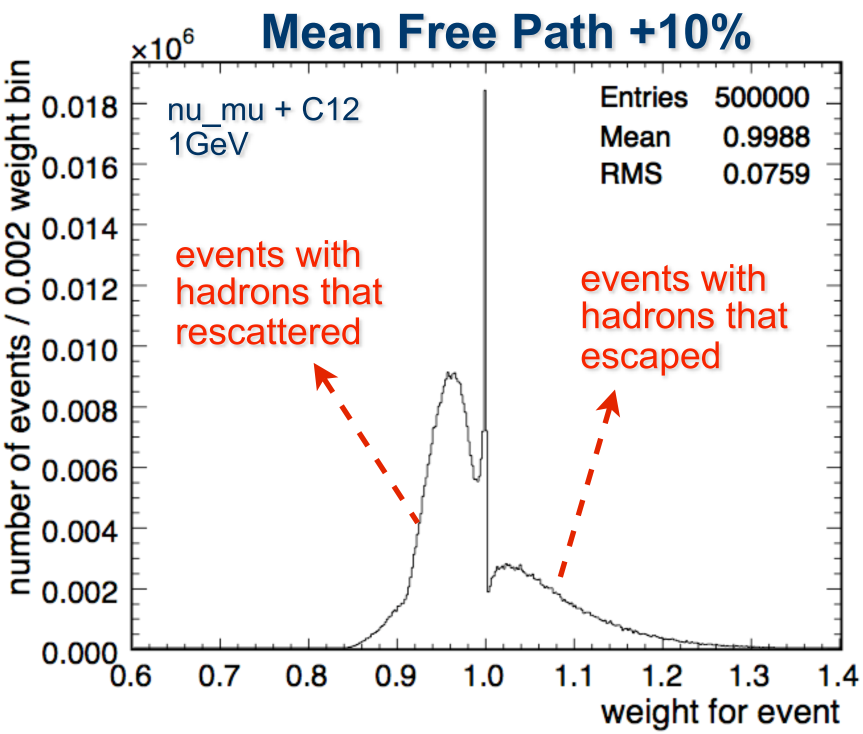
Absorption followed by nuclear breakup (**Abs**):
pi /N + A --> A' + np/pp/npp/nnp/nnpp

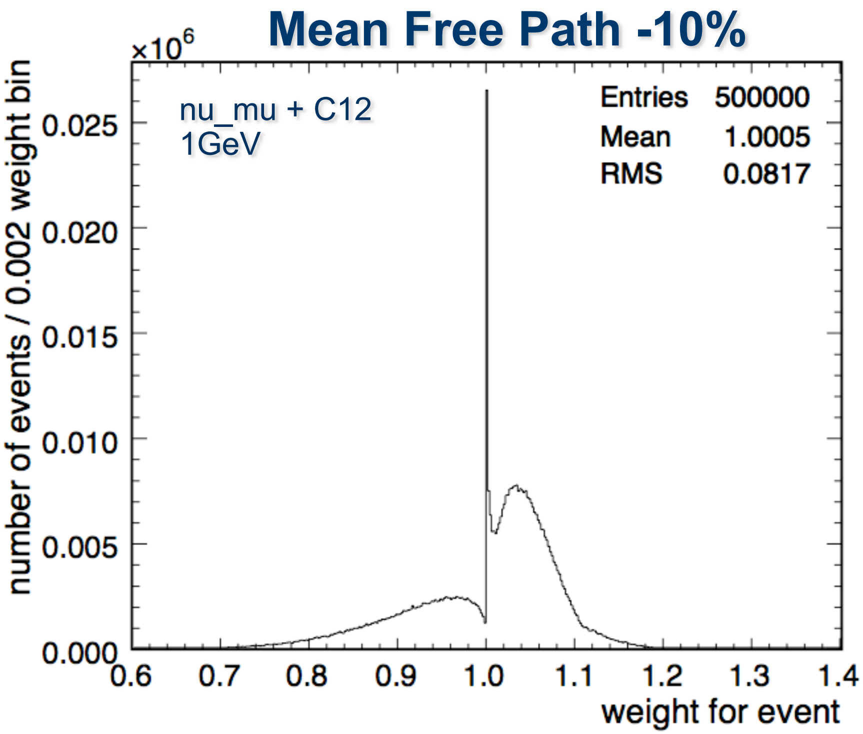
Pion production (**PiProd**):
pi + A -> A' + n + pi+ + pi0
N + A -> A' + n + pi+
N + A -> A' + n + pi+ + pi0



Intranuke Reweighting Validation

Weight Distributions: Rescattering Rate Scheme



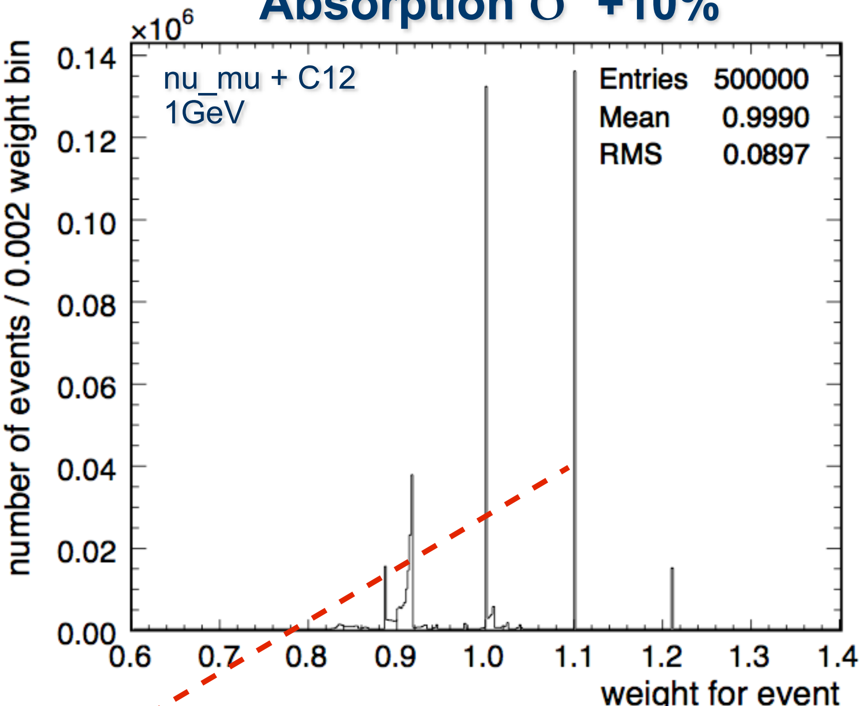


- **Most hadrons interact (~2/3)** --> Expected asymmetry in weight distributions.

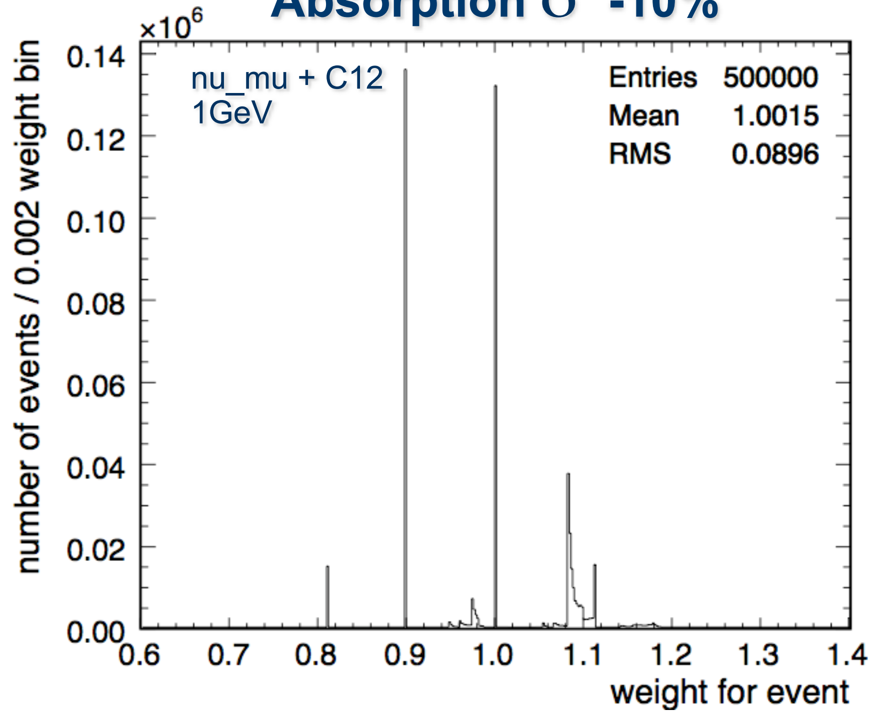
- Unity is conserved to ~ 1 part in 1000 despite this asymmetry.

Weight Distributions: Fates Scheme

Absorption σ +10%



Absorption σ -10%



$$w = \frac{\sigma'_{abs}}{\sigma_{abs}} = \frac{\sigma_{abs}+10\%}{\sigma_{abs}} = 1.1$$

Discrete peaks and continuous distributions as expected.
Also unity is conserved to ~ 1 part in 1000.

Ultimate Test Procedure

nominal sample

Tweak physics parameter X

REWEIGHT

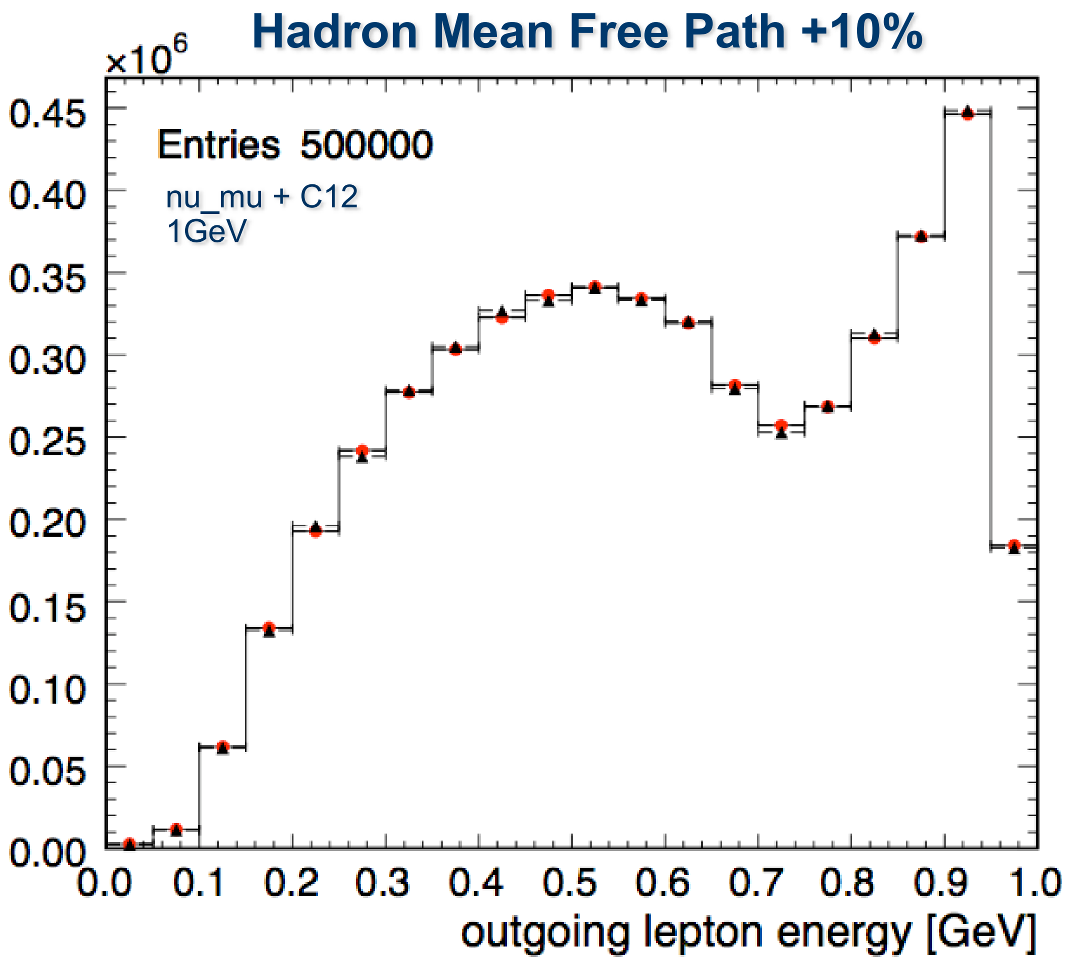
reweighted sample

Do they match?

sample **regenerated** with tweaked physics parameter X

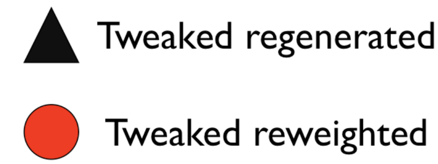
Ultimate test is comparing reweighted and regenerated. If this works then scheme is validated.

Lepton Spectra Remains Unchanged (As Expected)



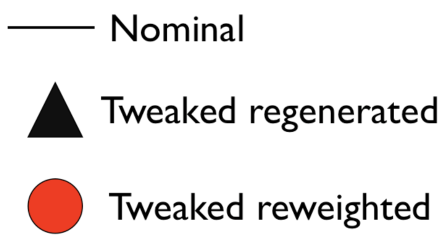
As expected all three distributions are the same.

Legend:



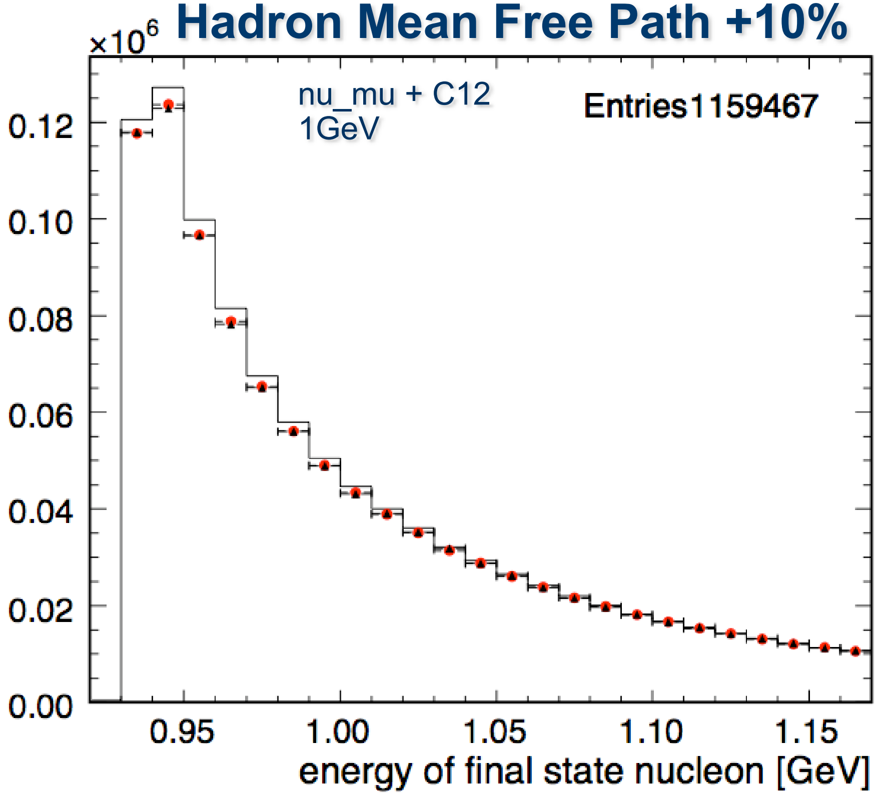
Typical Hadronic System Properties

Legend:

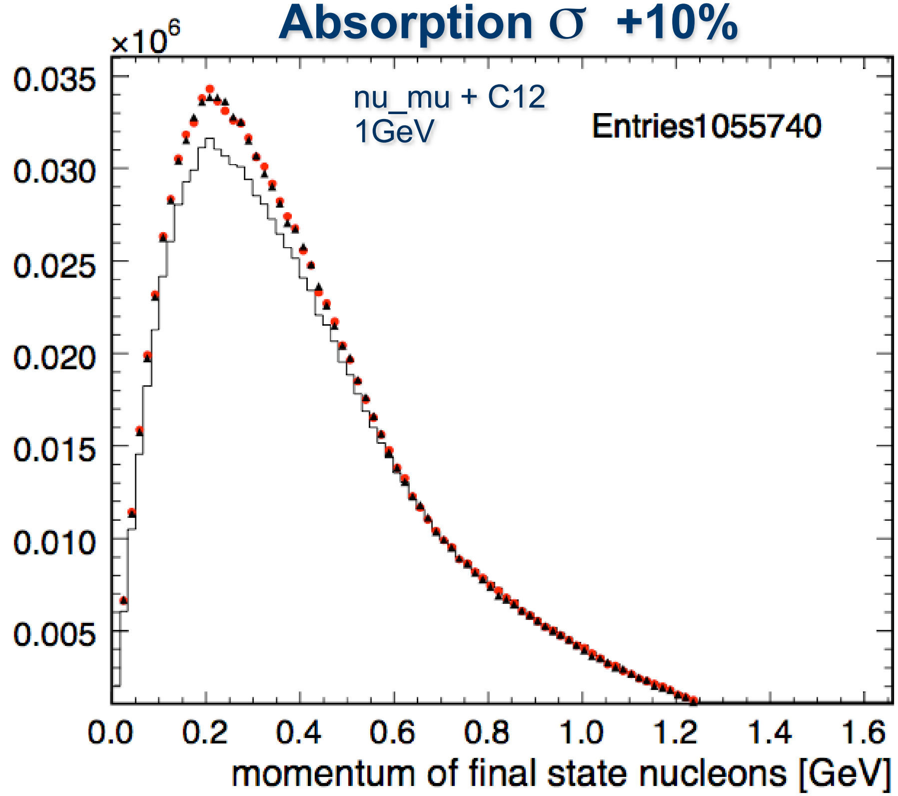


Both plots show very good agreement between reweighted and regenerated.

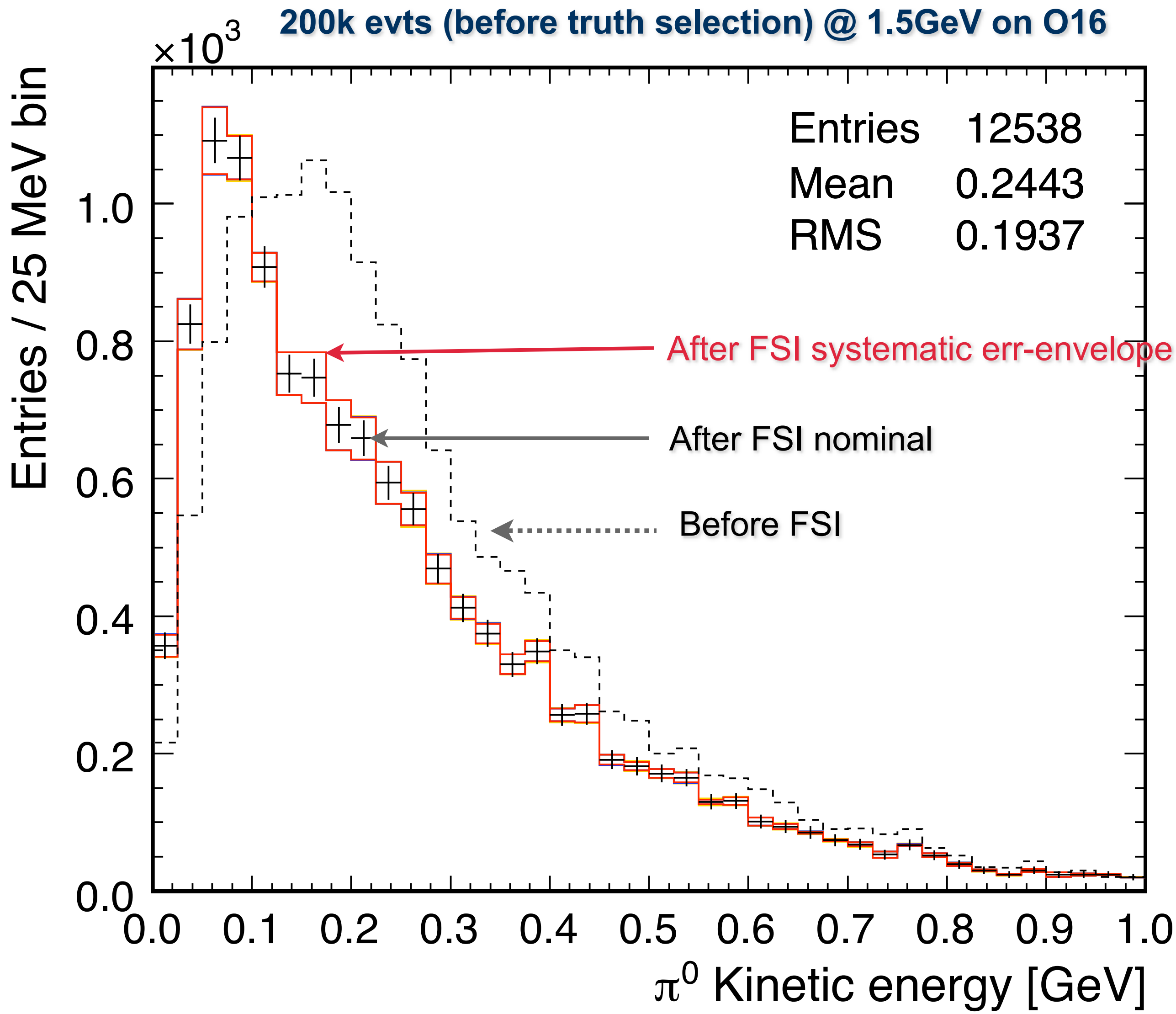
Hadron Mean Free Path +10%



Absorption σ +10%



Example: NC 1π^0 topology error envelope



Select single π^0 topology:
- 14,783 before FSI
- 12,538 after FSI

Scan intranuke/hA phase space:
- Treat Pion and Nucl fates independently.
- Treat mfp parameter separately.
- Add above three in quadrature.

(~170 parameter configs)

Cross Section Reweighting

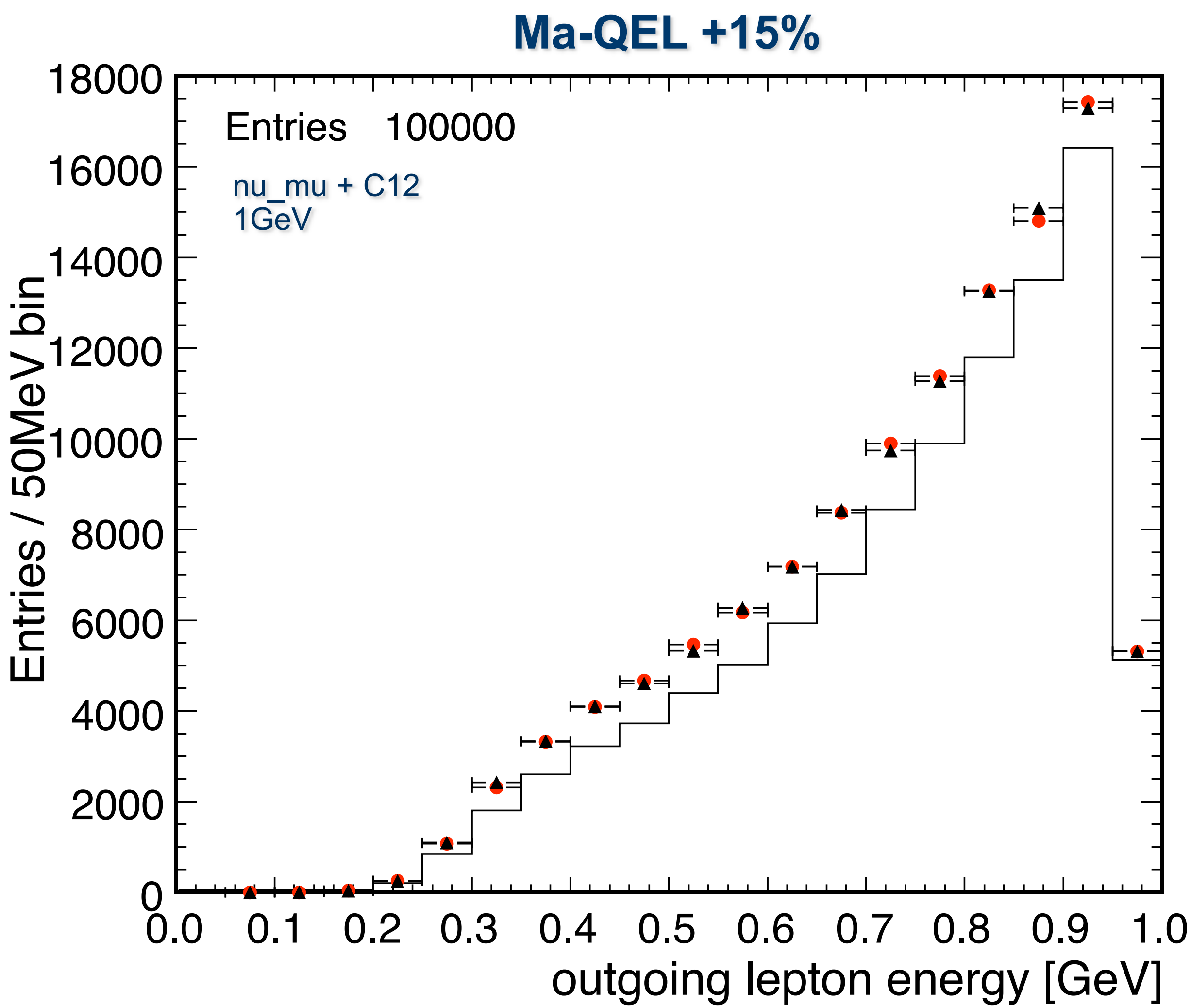
$$weight = (d^n\sigma'/dK^n)/(d^n\sigma/dK^n)$$

tweaked default

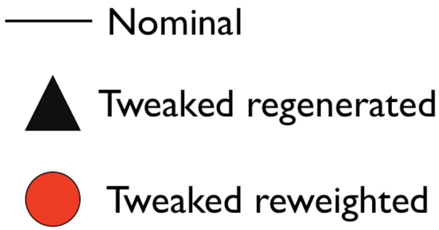
Cross Section Tweaking Parameters

Physics Param.	Short description	*T2KReWeight* knob (*T2KSyst_t* variable)	Default value	Error (1 σ)
M_A^{QEL}	QEL axial mass	kSystNuXSec_MaQEL	0.990 GeV	$\sim$ 15%
M_V^{QEL}	QEL vector mass	kSystNuXSec_MvQEL	0.840 GeV	$\sim$ 5%
M_A^{RES}	RES axial mass	kSystNuXSec_MaRES	1.120 GeV	$\sim$ 20%
M_V^{RES}	RES vector mass	kSystNuXSec_MvRES	0.840 GeV	$\sim$ 5%
$R^{bkg}_{\nu p;CC1\pi}$	Controls the non-RES bkg for νp $CC1\pi$	kSystNuXSec_RvpCC1pi	0.1	$\sim$ 50%
$R^{bkg}_{\nu p;CC2\pi}$	Controls the non-RES bkg for νp $CC2\pi$	kSystNuXSec_RvpCC2pi	1.0	$\sim$ 50%
$R^{bkg}_{\nu p;NC1\pi}$	Controls the non-RES bkg for νp $NC1\pi$	kSystNuXSec_RvpNC1pi	0.1	$\sim$ 50%
⋮	⋮ 16 non-RES parameters in total	⋮	⋮	⋮
$R^{bkg}_{\bar{\nu} n;NC2\pi}$	Controls the non-RES bkg for $\bar{\nu} n$ $NC2\pi$	kSystNuXSec_RvbarnNC2pi	1.0	$\sim$ 50%

Cross Section Validation

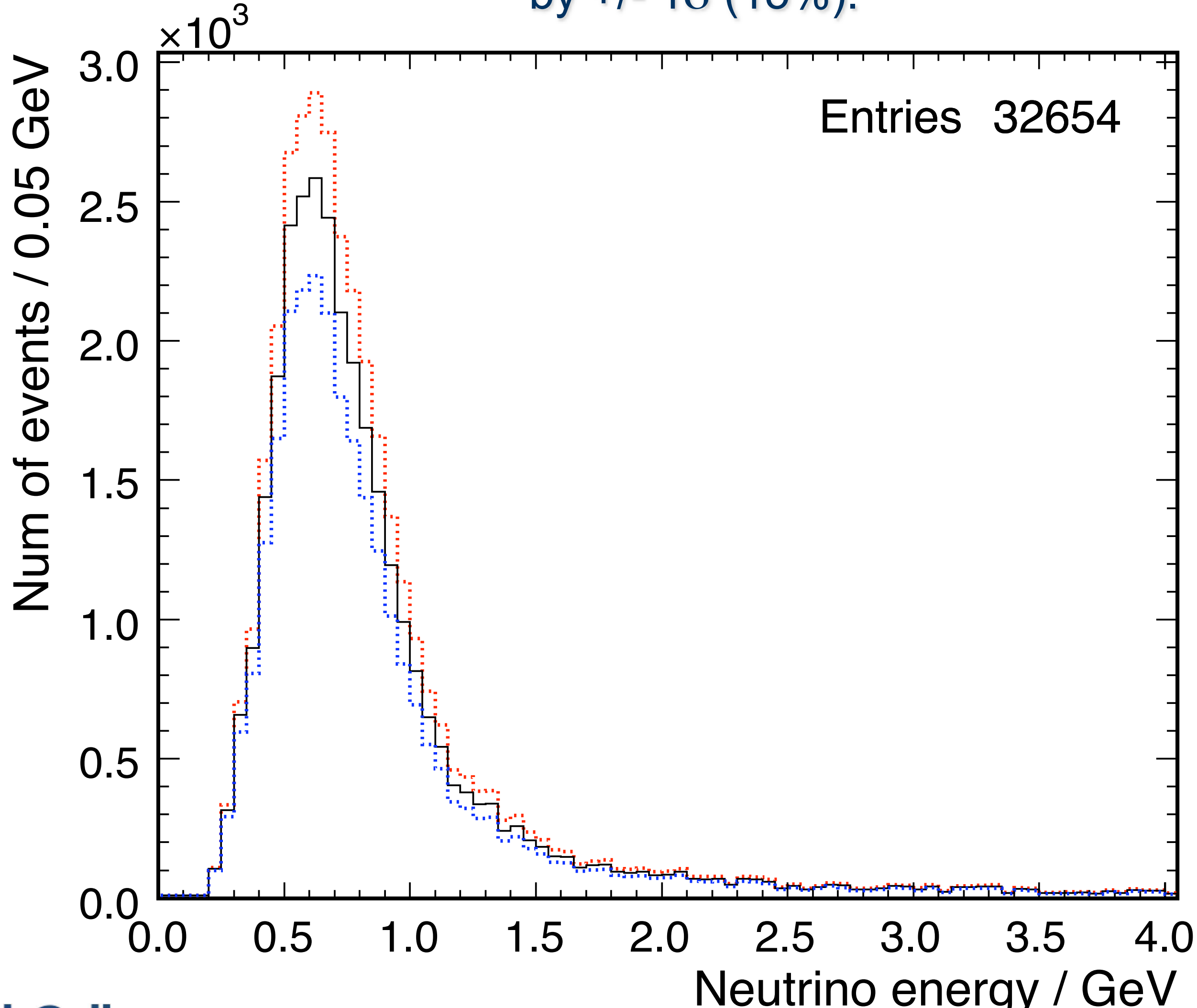


Legend:



Example XSec Error Envelope

An error envelope generated for numuCC sample where MaQEL has been tweaked by +/- 1σ (15%).



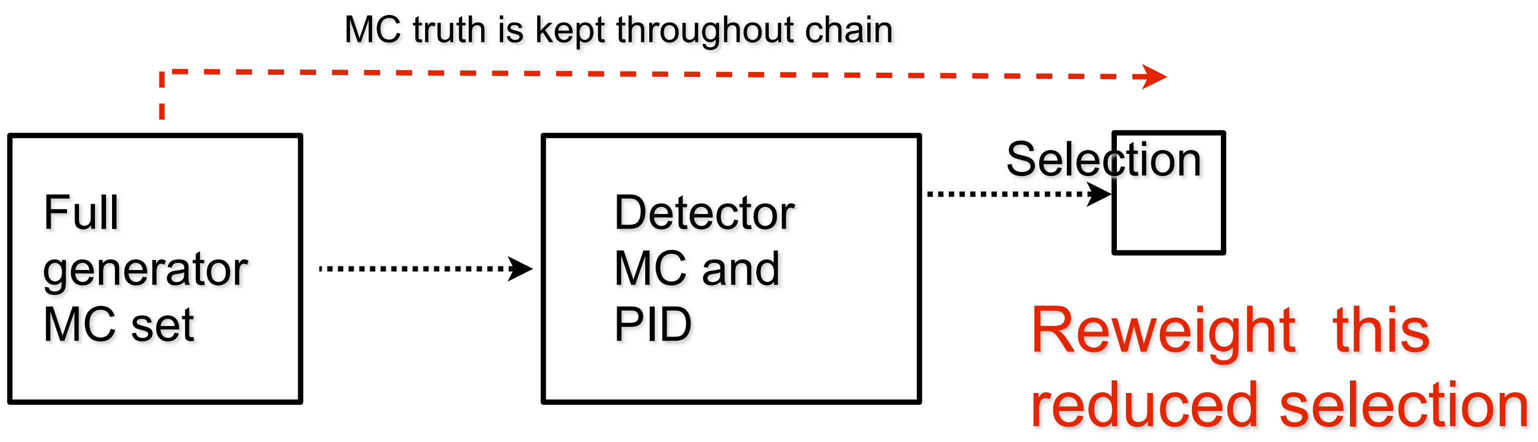
Summary

Performance

- Whole point was to be faster than regenerating MC.

- Reweighting is between 10 and 100 times faster (even more for certain params)

- Main advantage is that reweight selections of full MC data set further down the MC chain.



Summary

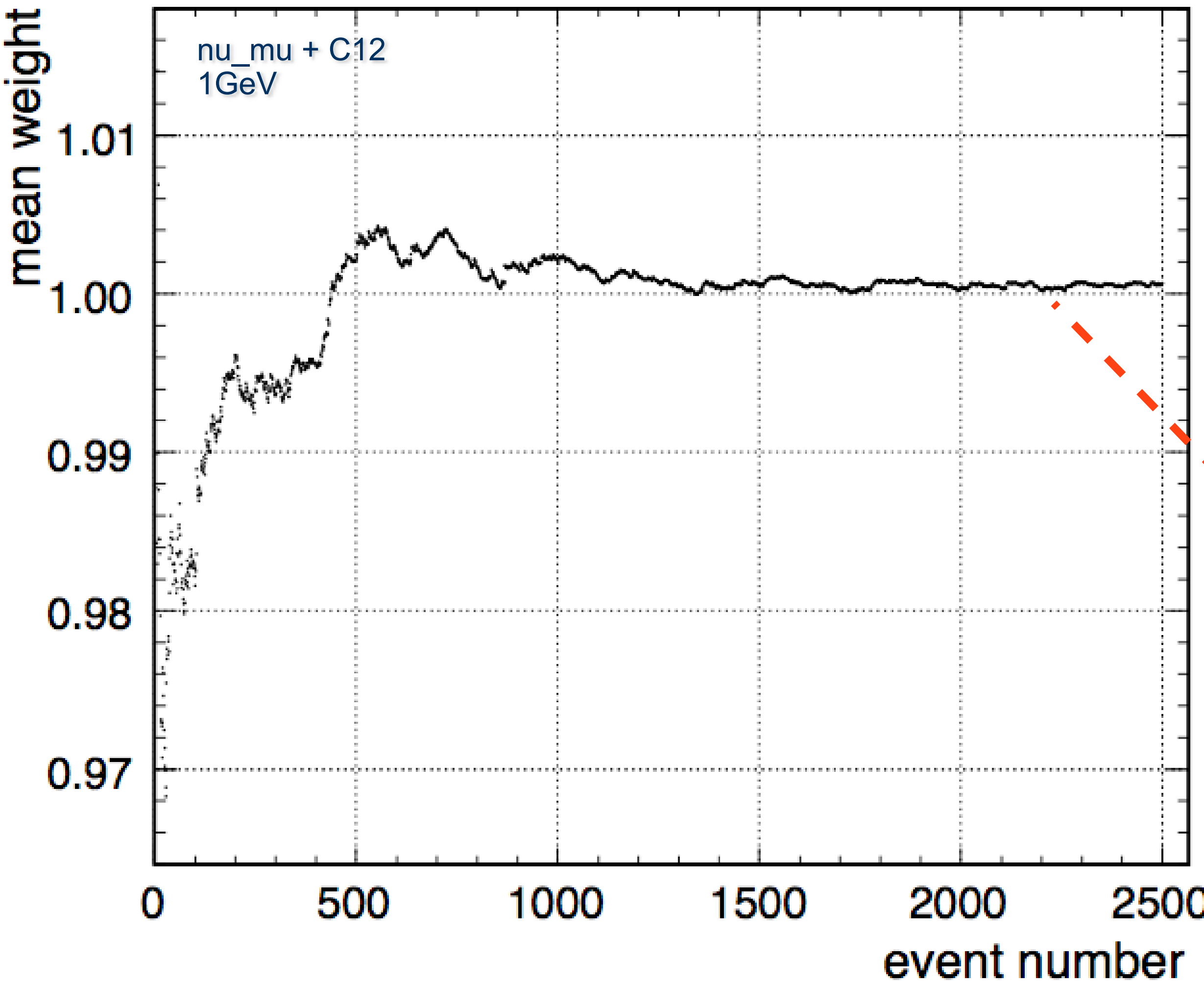
• Reweighting schemes developed and validated for neutrino interaction and hadron transport (Intranuke/hA).

• Examples of different applications were shown.

There is a detailed internal note that will be released shortly and in the future the code will be made available at: http://www.genie-mc.org/

Backup slides

Convergence on Unity



Mean weight as function of event number. This is for mfp tweaking dials at +10%.

Converges on 1 after ~2000 events.

Tweaking Knobs

When tweaking a parameter do so in terms of the error associated with that parameter. For example take the mean free path.

$$\lambda' = \lambda \times (1 + x^N_{mfp} \frac{\delta(\lambda)}{\lambda})$$

To tweak the nucleon mean free path to + 1 standard deviation would set

$$x^N_{mfp} = 1$$

Rescattering Rate Tweaking Dial.

Tweaking the mean free path dial. Get weights,

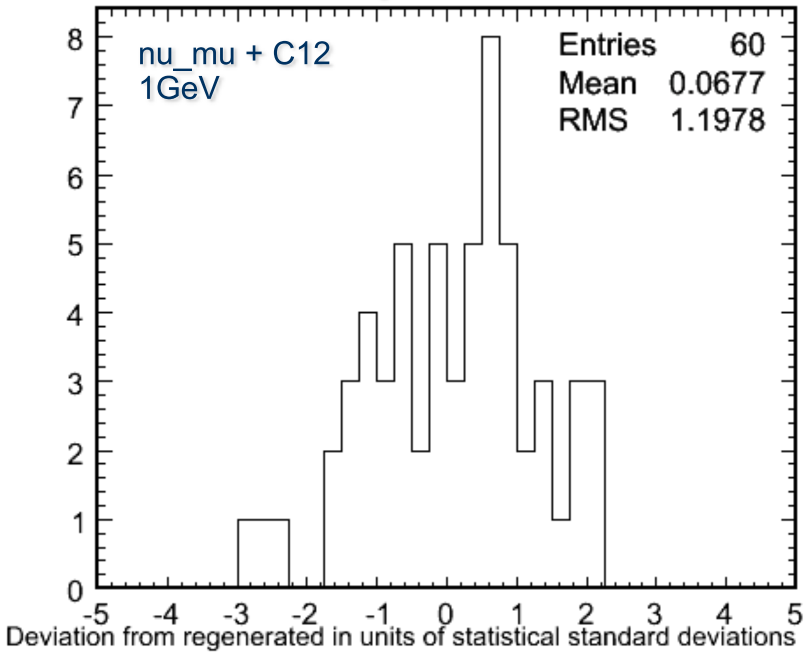
$$w_{surv} = \frac{P'_{surv}}{P_{surv}} \quad \text{and} \quad w_{rescat} = \frac{1 - P'_{surv}}{1 - P_{surv}}$$

Qualitative behavior of rescattering rate reweighting.

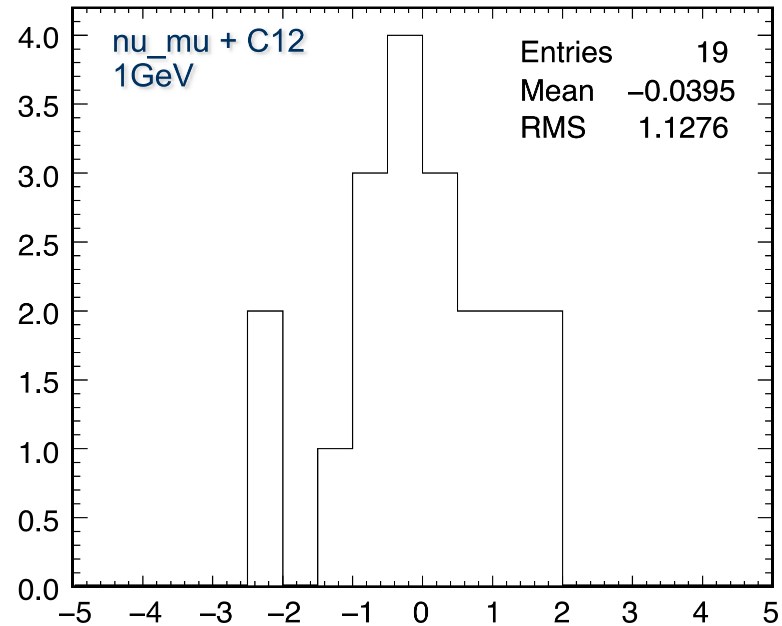
Mean Free Path Change	Interaction Probability Change	Weight (hadrons that interact)	Weight (hadrons that don't interact)
$\Uparrow$	$\Downarrow$	$\Downarrow$	$\Uparrow$
$\Downarrow$	$\Uparrow$	$\Uparrow$	$\Downarrow$

Comparing Regenerated and Reweighted

Absorption σ +10%



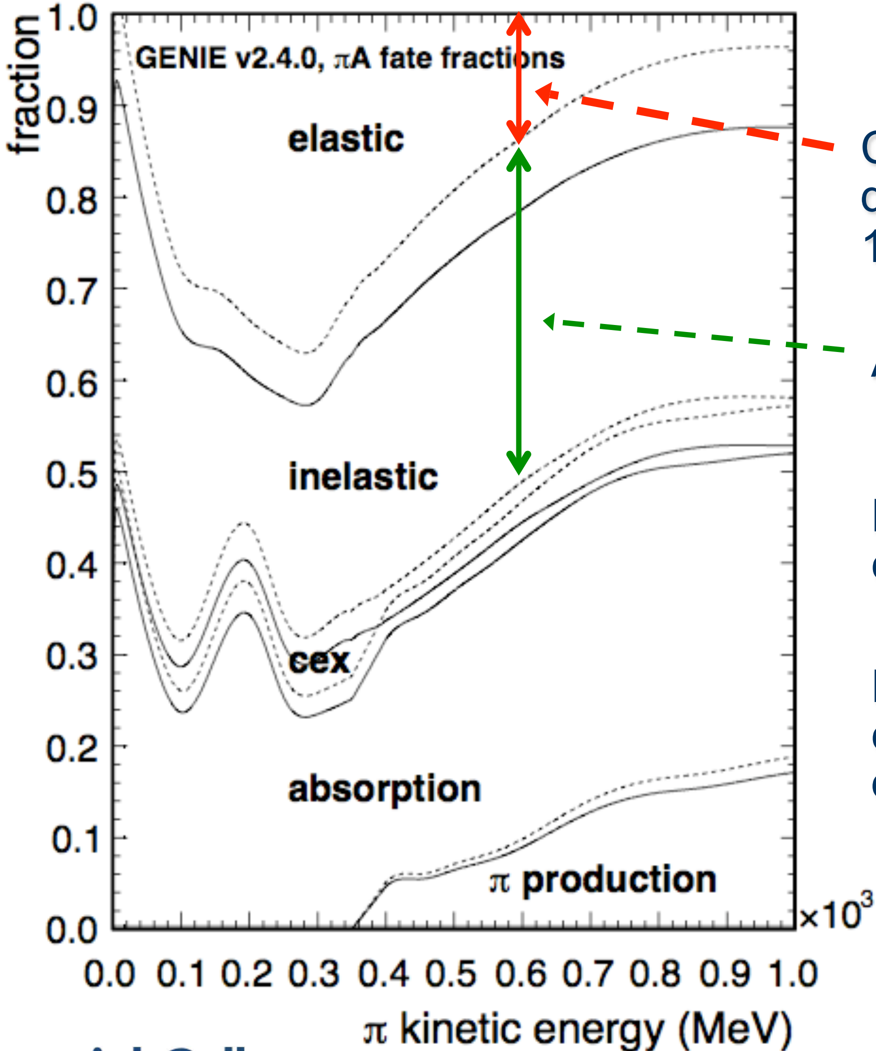
Ma-QEL +15%



Histograms showing difference between regenerated and reweighted samples in units of 1 standard deviation. ~60% of entries are between +/- 1 standard deviation.

Weight Depends on Fate of Hadron

Example: Increase Inel, CeX, Abs and PiProd by 10%.



Cushion term (in this case **Elas**) has to decrease to maintain unity. This decrease is not 10% it is a function on energy.

All other terms have increased by 10%.

Hadron that reinteracted by one of the 4-non cushion term channels would get weight = 1.1

Hadron that reinteracted via the cushion term channel would get a spread of weights dependent on energy.

Uncertainties Taken from Data

Uncertainties for the various fate reweighting scheme will be taken from data. At present all set to nominal 10%.