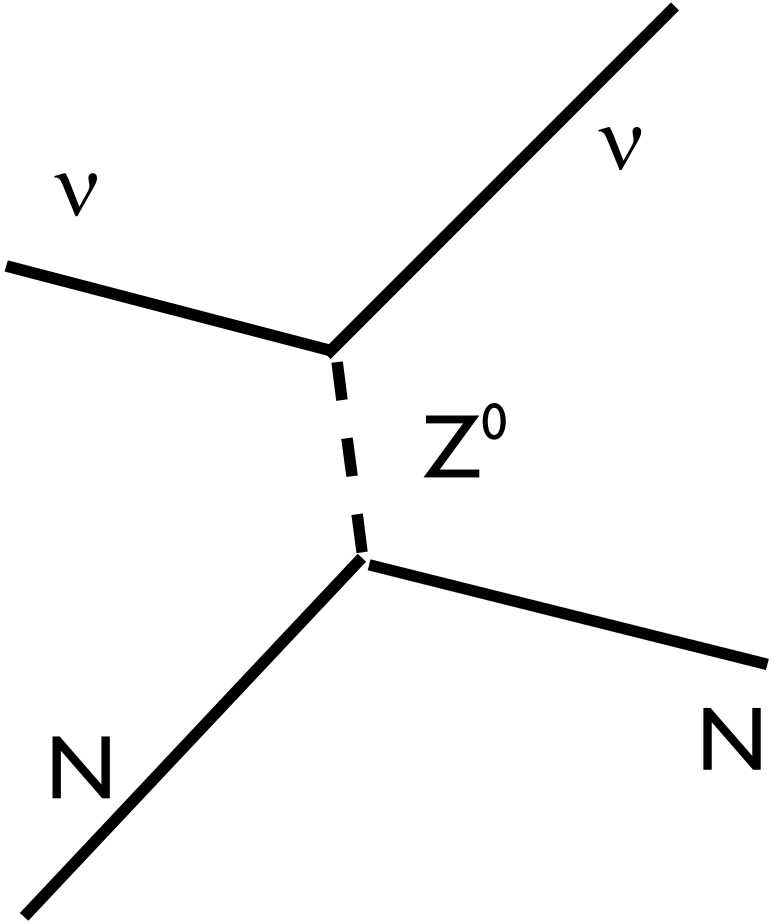
Neutrino Nucleon Elastic Scattering in MiniBooNE



Chris Cox
Indiana University

ν N $\rightarrow$ ν N: Motivation

Probe of the isoscalar structure of the nucleon e.g.

- contributions from strange quarks ($G^s_A \Rightarrow \Delta s$)
- axial mass (M_A)

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Nucleon Weak Current: $J_\mu = \langle N | F_1 \gamma_\mu + F_2 \sigma_{\mu\nu} q^\nu + G_A \gamma_\mu \gamma_5 | N \rangle$

Contributions from strange quarks enter as additions to form factors:

$F_1^s(Q^2)$, $F_2^s(Q^2)$, $G_A^s(Q^2)$ where $G_A^s(Q^2=0) = \Delta s$

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Complimentary to electron nucleon DIS and SIDIS measurements

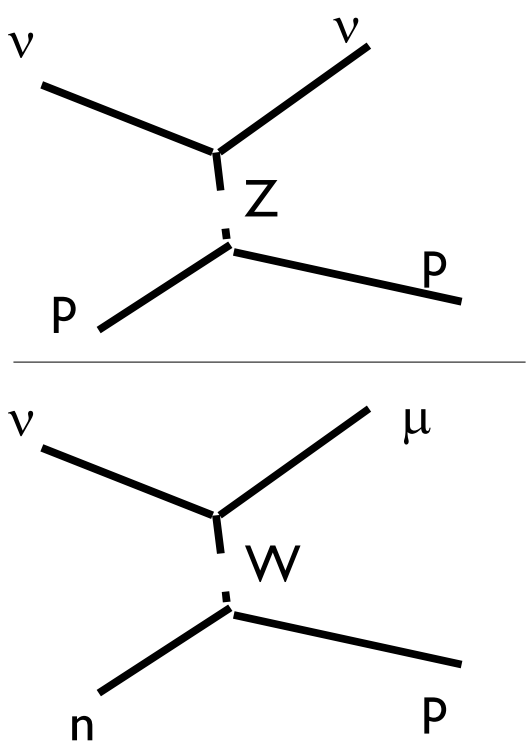
At low Q2, NCE cross section is most sensitive to axial term (unique to ν scattering)

$$\frac{d\sigma}{dQ^2} \propto (\pm G_A(Q^2) + G_A^s(Q^2))^2$$

$+$ for proton scattering
$-$ for neutron scattering

Extracting Δs from NC Elastic Scattering

An experiment like MiniBooNE would measure the ratio of NC elastic and CCQE interactions:



neutral current elastic (NCE)

charged current quasi-elastic (CCQE)

NCE depends on Δs

CCQE doesn't depend on Δs

A ratio reduces uncertainties from

- knowing absolute flux and other n systematics
- nuclear models and other form factors

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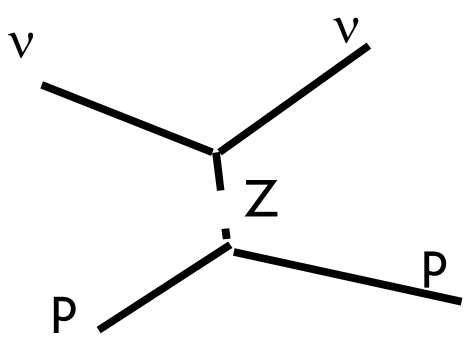

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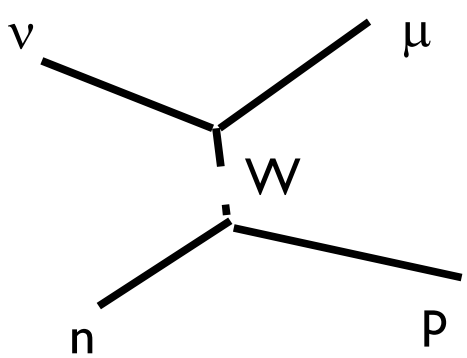

charged current quasi-elastic (CCQE)

$$\frac{d\sigma}{dQ^2} \propto (\pm G_A(Q^2) + G_A^s(Q^2))^2$$

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A ratio reduces uncertainties from

- knowing absolute flux and other

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- nuclear models and other form

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Requires ability to distinguish protons from neutrons, currently not possible in MiniBooNE

Extracting M_A from NC Elastic Scattering

M_A in NC Elastic is the same as CCQE.

$$G_A(Q^2) = \frac{g_A(0)}{(1+Q^2/M_A^2)^2}$$

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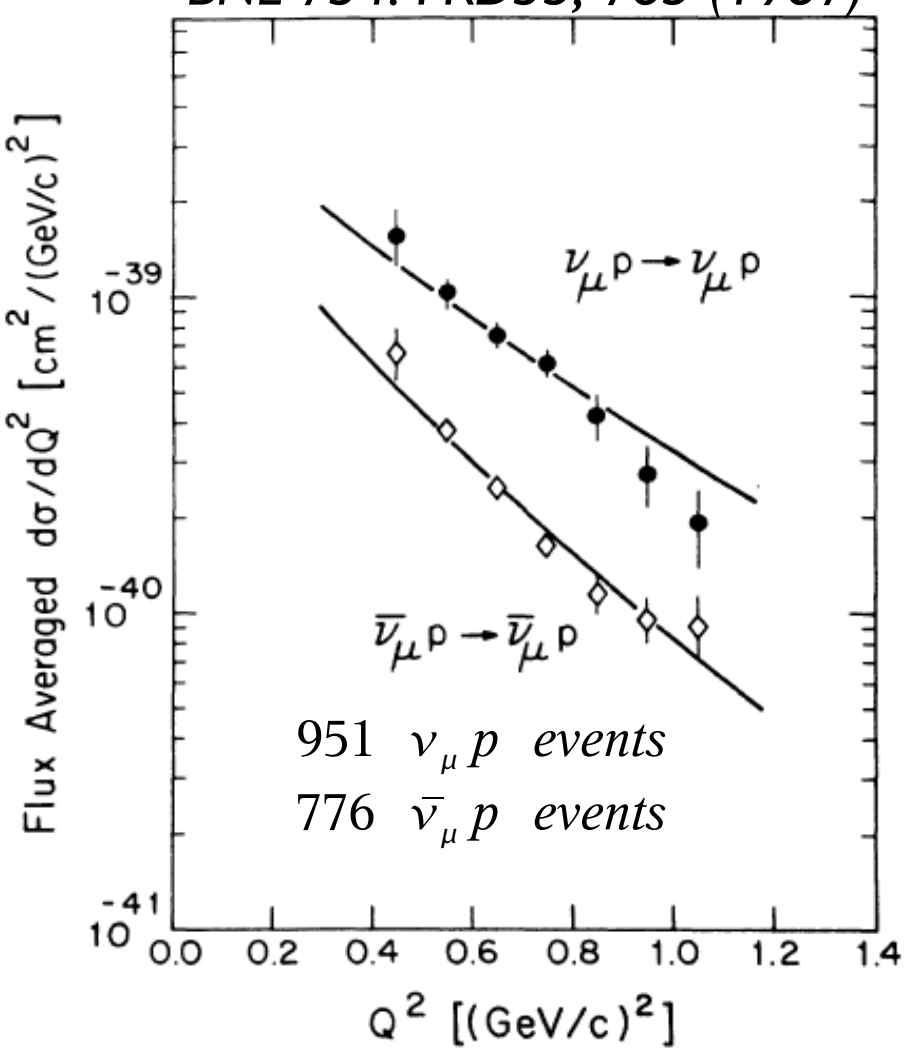
BNL 734: PRD35, 785 (1987)



BNL best fit MA = 1.06 ± 0.05 GeV/c²

world (1987) MA = 1.032 ± 0.036 GeV/c²

To measure M_A in MiniBooNE we need the differential cross section.

To measure the cross section, we need NC elastic events.

NC Elastics in MiniBooNE

MiniBooNE sees scintillation light from below threshold protons

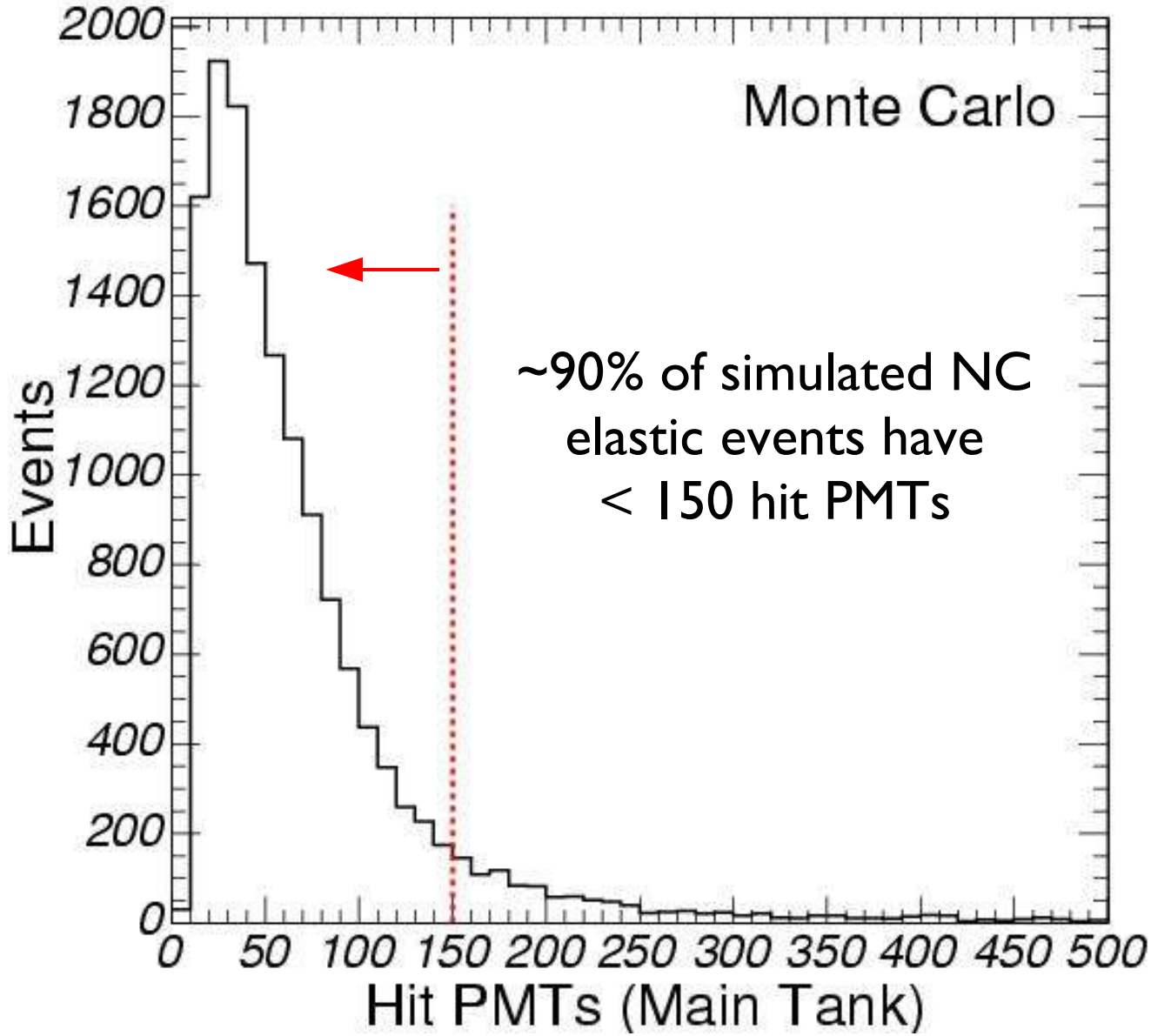
Mainly at low energy ⇒ focus at low light levels

NC elastic "pre-cuts:"

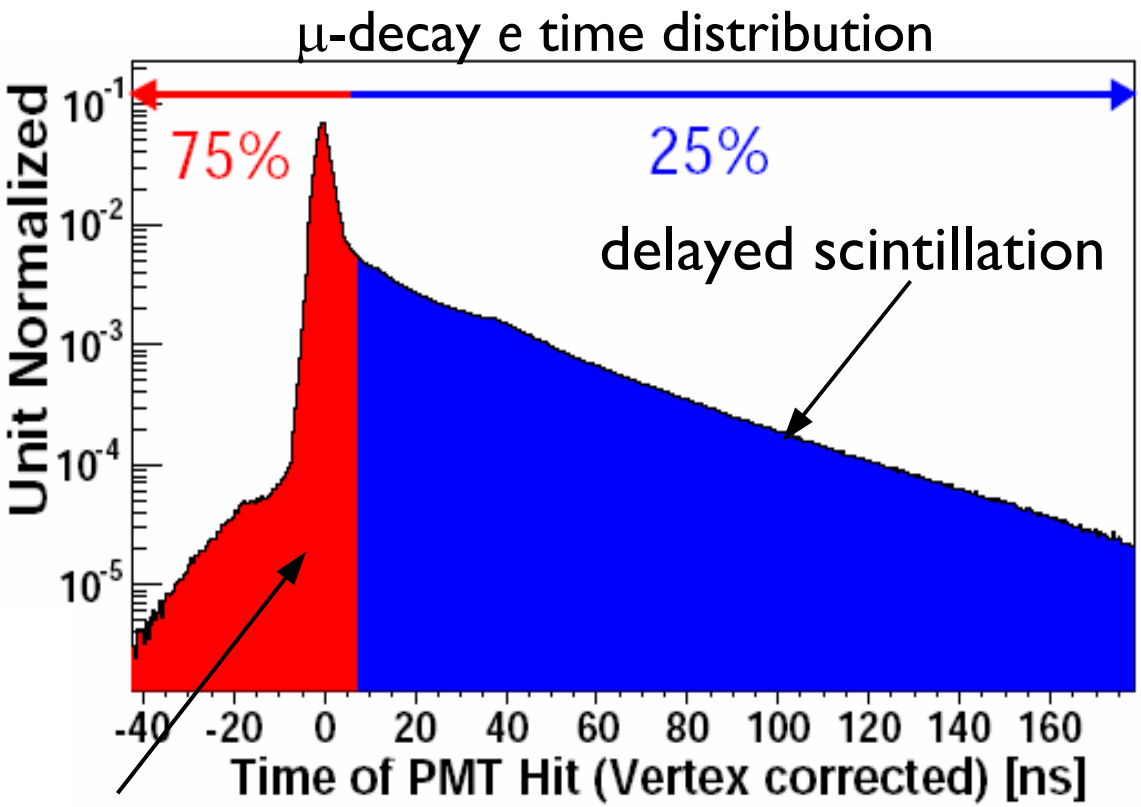
- veto cosmic rays
- no events with decays
- events in beam window
- # hit PMTs < 150

(to preserve blindness)

⇒ 80% pure sample of ν events generated inside the detector (only 3% are CCQE)



Prompt Cherenkov vs Late Scintillation



prompt Cherenkov

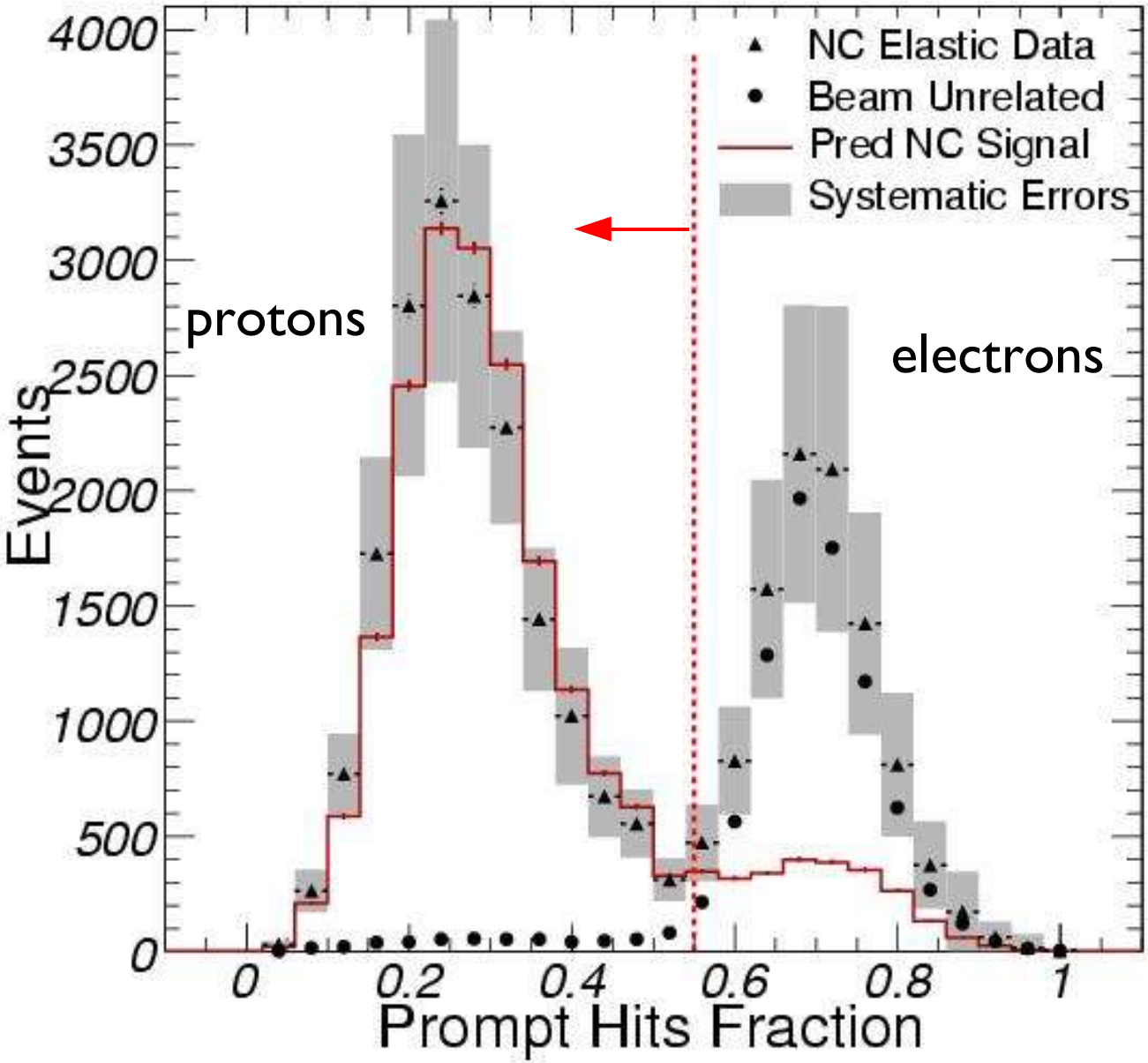
Scintillation light arrives later than Cherenkov light.

Most events in MiniBooNE have more prompt Cherenkov light than delayed scintillation.

NC elastic events (nucleons) have a larger fraction of scintillation ⇒ less prompt light

Prompt light fraction is useful as PID

Proton PID with Electrons from Muon Decay



The NC elastic data contains beam unrelated backgrounds: good test for prompt fraction as PID.

Compare to beam unrelated (random trigger) sample

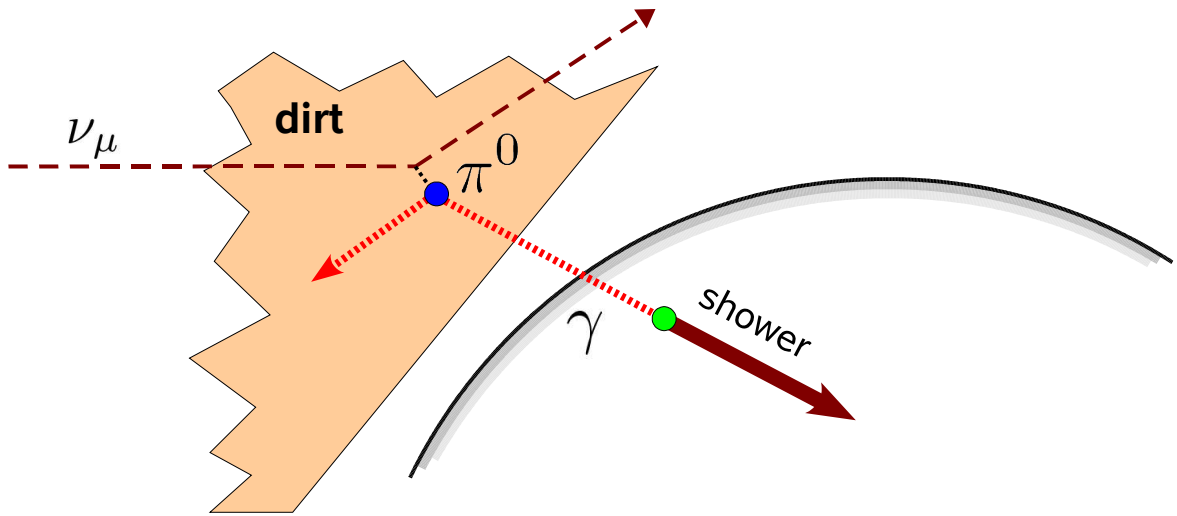
Beam Unrelated Backgrnds:

Total: 30%

NC-like: 3%

Some beam unrelated back-grounds have been included in the Monte Carlo.

Neutrino Interactions Outside The Tank ("Dirt" Backgrounds)



"Dirt" events: when particles from ν interactions outside the detector produce light inside the detector.

Mainly neutrons for NC.

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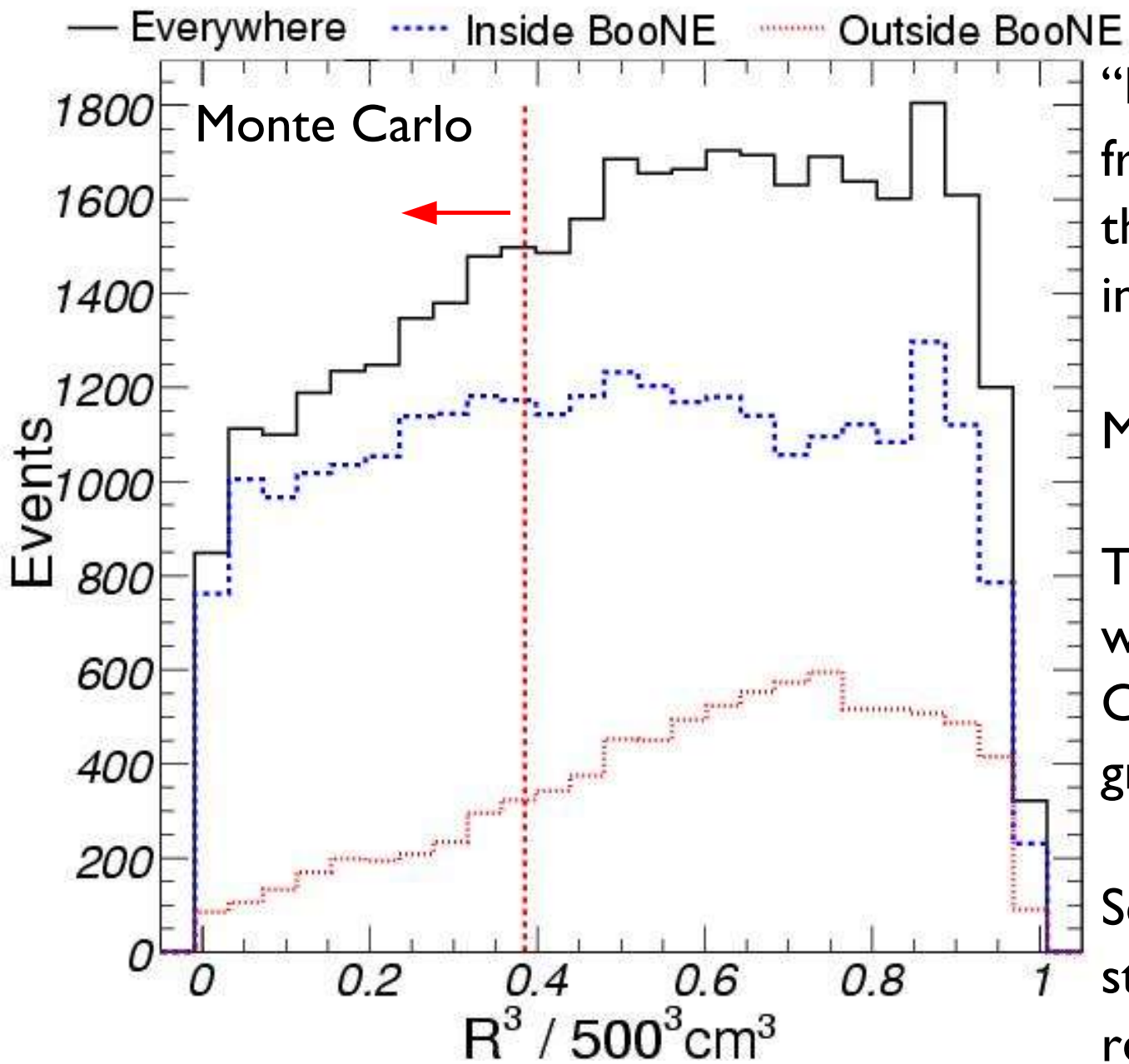

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Mainly neutrons for NC.

Template fits to data confirm within errors a 25% Monte Carlo predicted dirt background to NC elastic events.

Selecting events with reconstructed radius < 400 cm reduces dirt events to (16 ± 4)% of the data.

Neutrino Backgrounds Inside The Tank

Post PID and dirt removal,
the NC elastic composition:

- 84% NCEL
- 14% NC 1-pi
- 1% CCQE
- 1% multi-pi

The NC 1-pi channels:

- $\nu\, p \rightarrow \nu\, p\, \pi^{0}$
- $\nu\, p \rightarrow \nu\, n\, \pi^{+}$
- $\nu\, n \rightarrow \nu\, n\, \pi^{0}$
- $\nu\, n \rightarrow \nu\, n\, \pi^{-}$

In 80% of these (the ones in the NC elastic sample), there is no final state pion i.e. the pion is absorbed in the nucleus.

These look the identical to NC elastics.
They are an irreducible background.

NCEL Event Selection Summary

selection	purpose	effectiveness
• Veto PMT Hits < 6 • 1 Subevent • 4400 < Time (ns) < 6500 • Tank PMT Hits < 150	• remove cosmic rays • no decaying particles • events in beam time • low energies	• a neutrino-generated, inside-detector, MC 80% pure NC elastic sample
• Prompt Frac < 0.55	• assures protons	• beam unrelated backgrnds from 30% → 2%
• Recon R < 400	• reduces dirt bkgnds	• dirt backgrounds 25% → (16 ± 4) % of data

Calculating NCEL Cross Section

Goal: Measure a neutral current elastic cross section:

$$\sigma = \frac{(NC\ events - bkgd)/\epsilon_{NC}}{(\int \Phi_{\nu} * N_{POT} * N_{nucl})}$$

MiniBooNE predicts 5:4 ratio
NC p : NC n cross sections.

Currently there is no way to measure these separate protons and neutrons.

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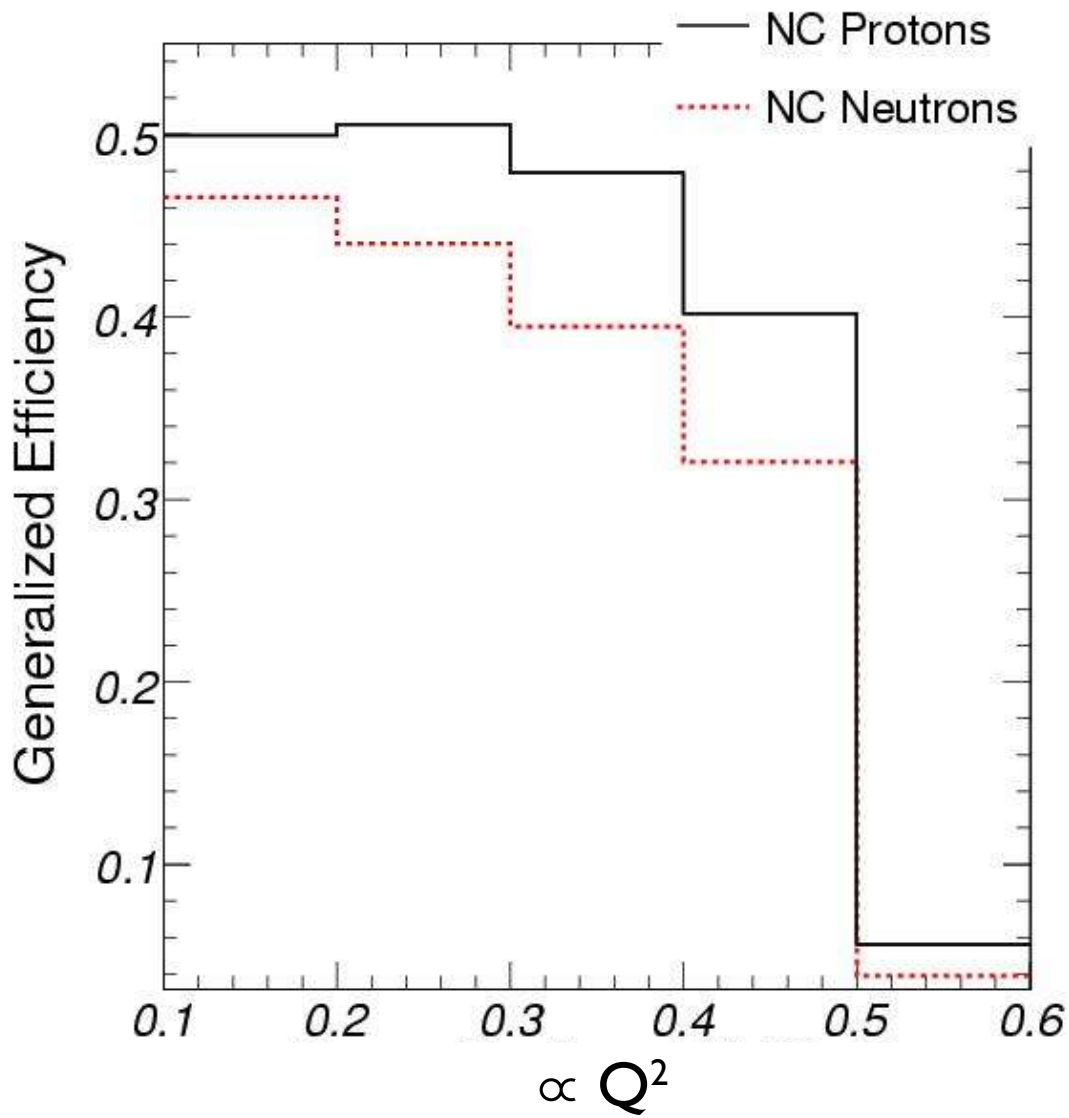
The efficiencies are similar ⇒ Calculate the cross section for NC n + NC p together

Handle systematics of p : n with Δs



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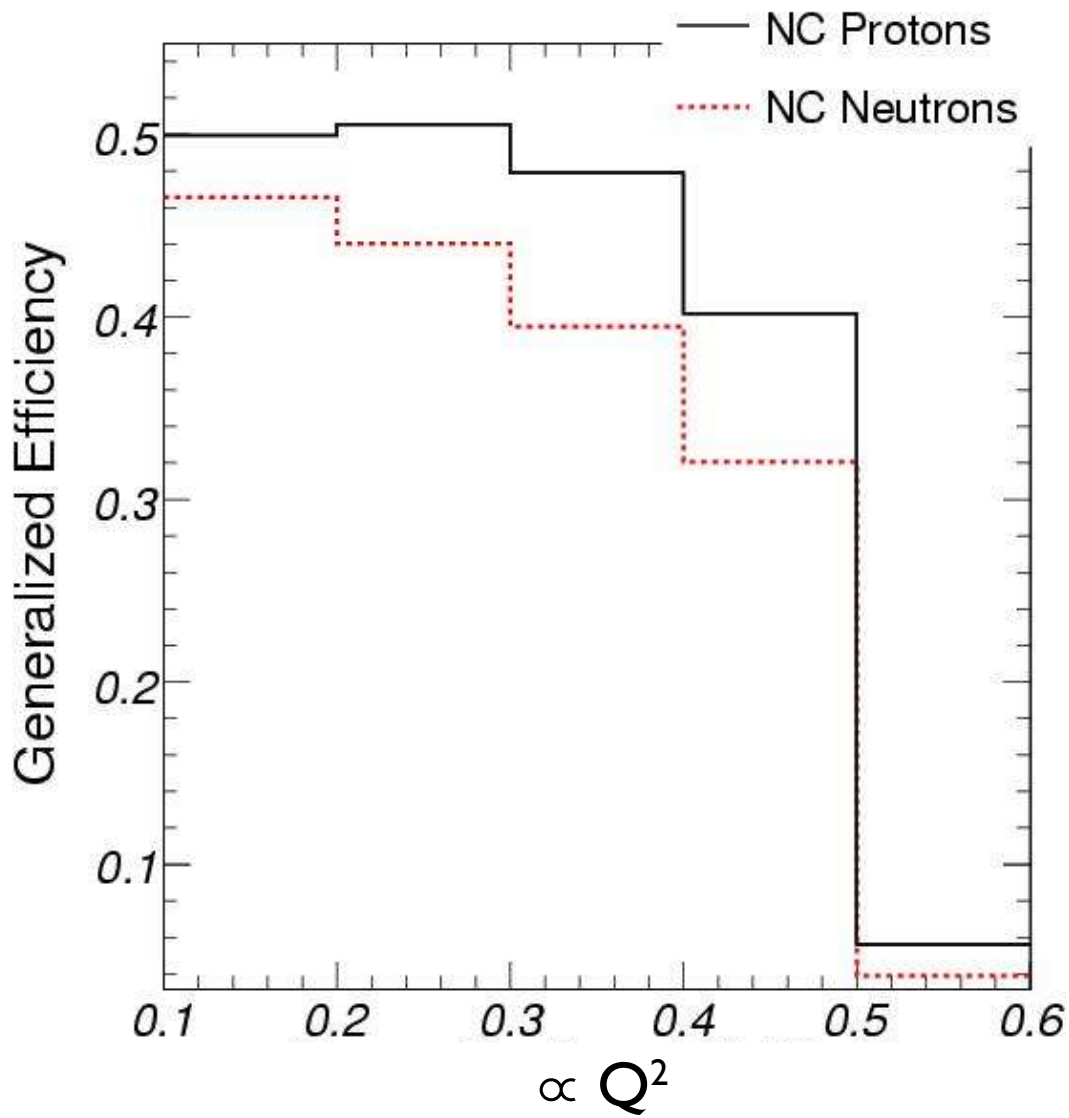
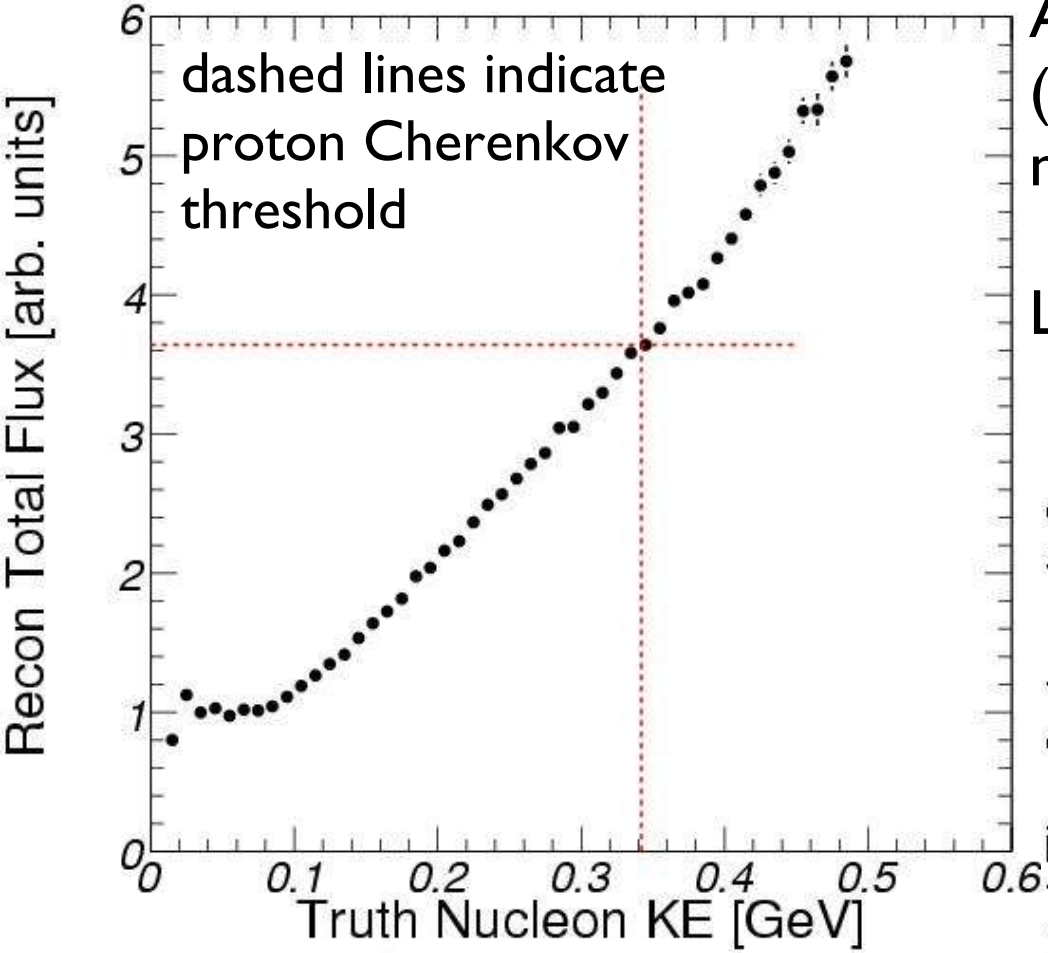


$Q^2 = 2\ m_N\ KE$ for NC elastic scattering ⇒ need KE

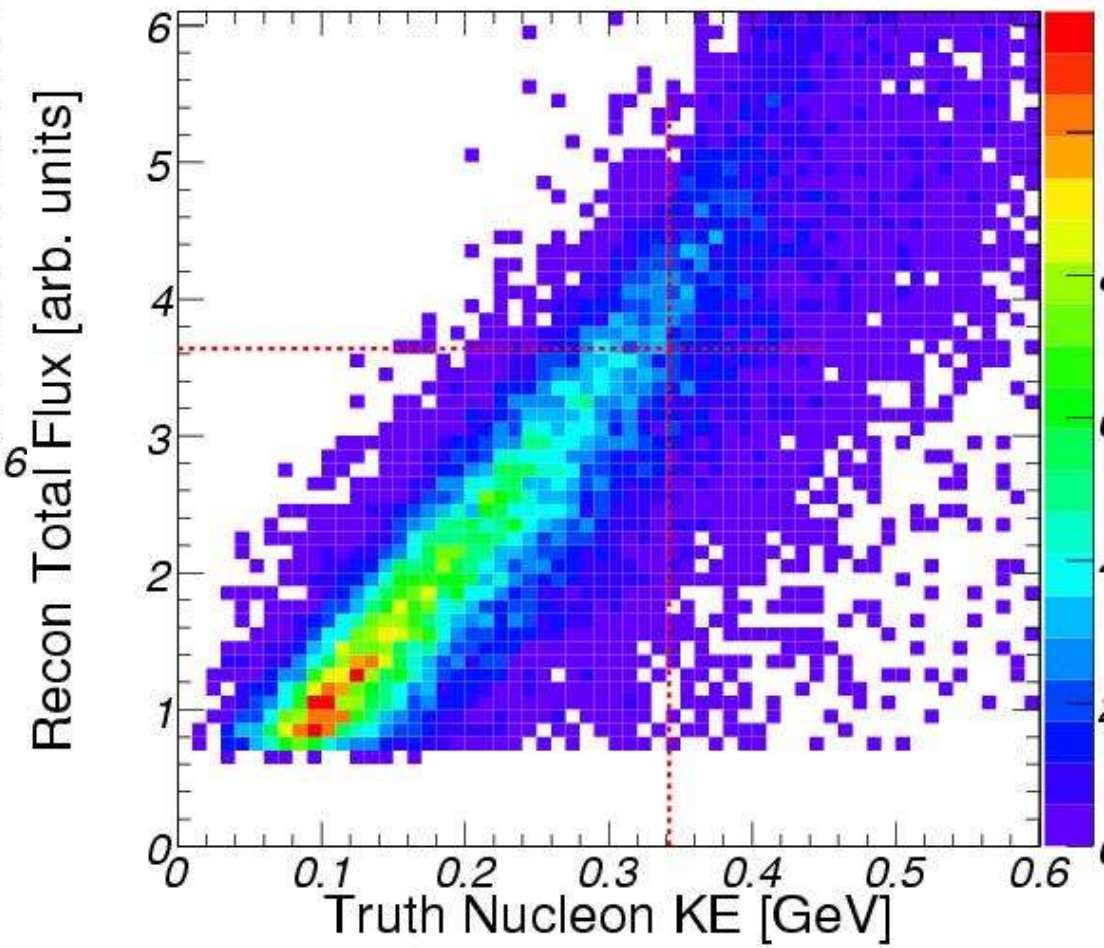
Kinetic Energy Calibration



A measurement of the total radiation flux (scintillation + Cherenkov) calibrates nucleon kinetic energy.

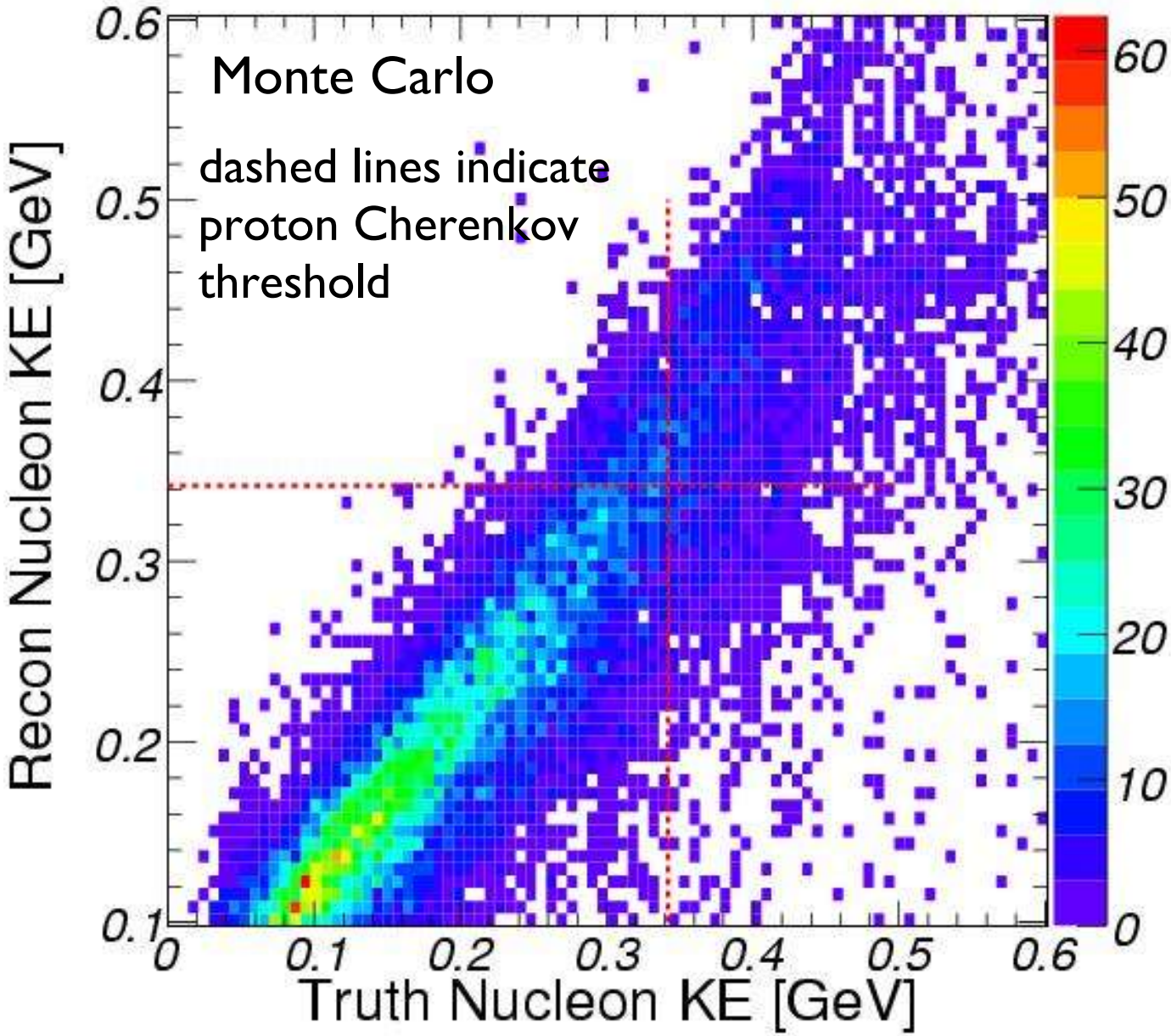
Low and high flux regions are fit to KE

same plot



Kinetic Energy Calibrated

Reconstructed total radiation flux becomes reconstructed nucleon kinetic energy.



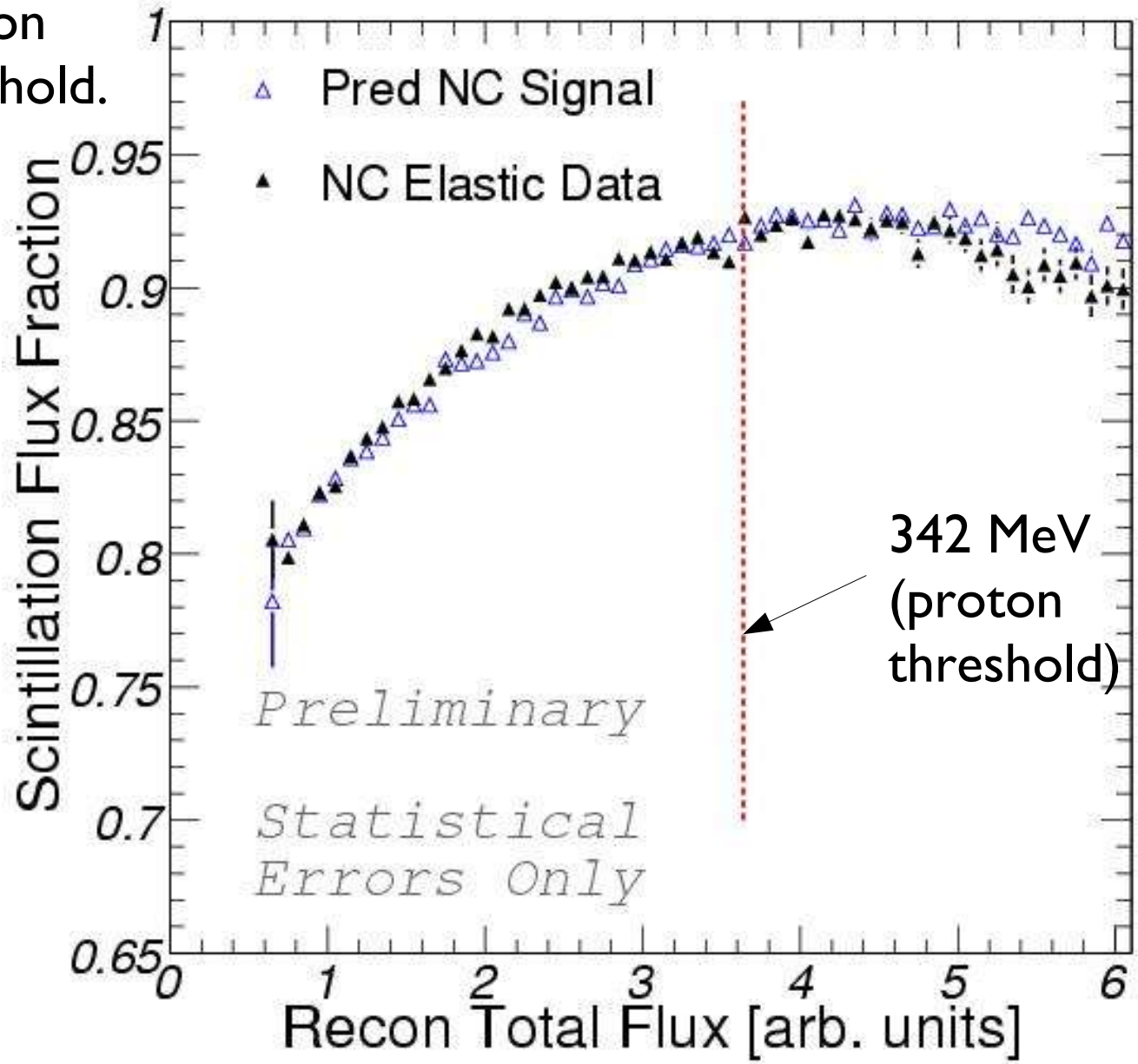
Kinetic Energy: Proton Threshold

Naively expect scintillation fraction = 1.0 until threshold.

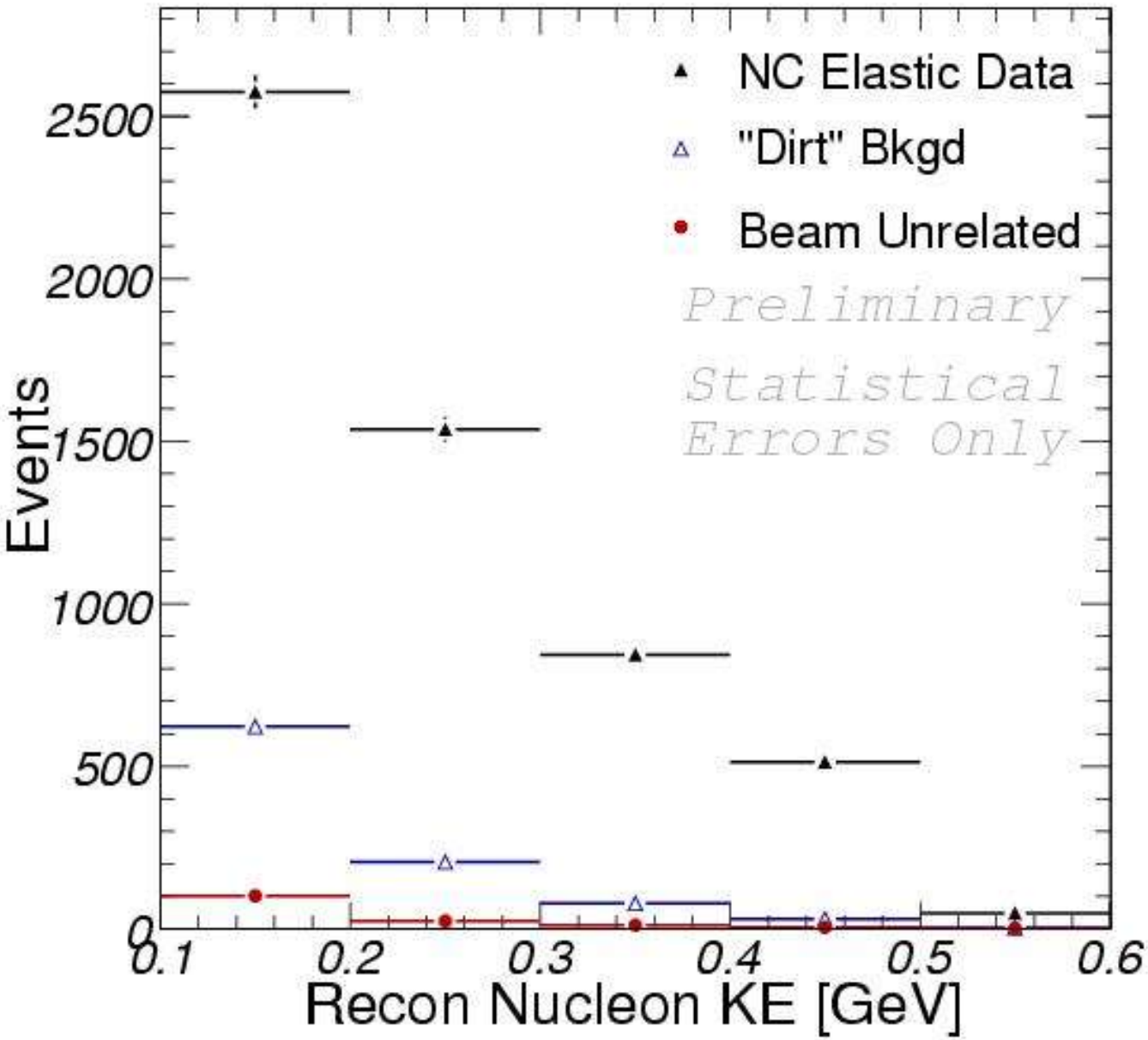
De-excitation γ's, other prompt light, and reconstruction effects give this distribution.

MC and data shape agree well. Threshold is the same in both.

No need to adjust energy scale.



Kinetic Energy Background Distributions I

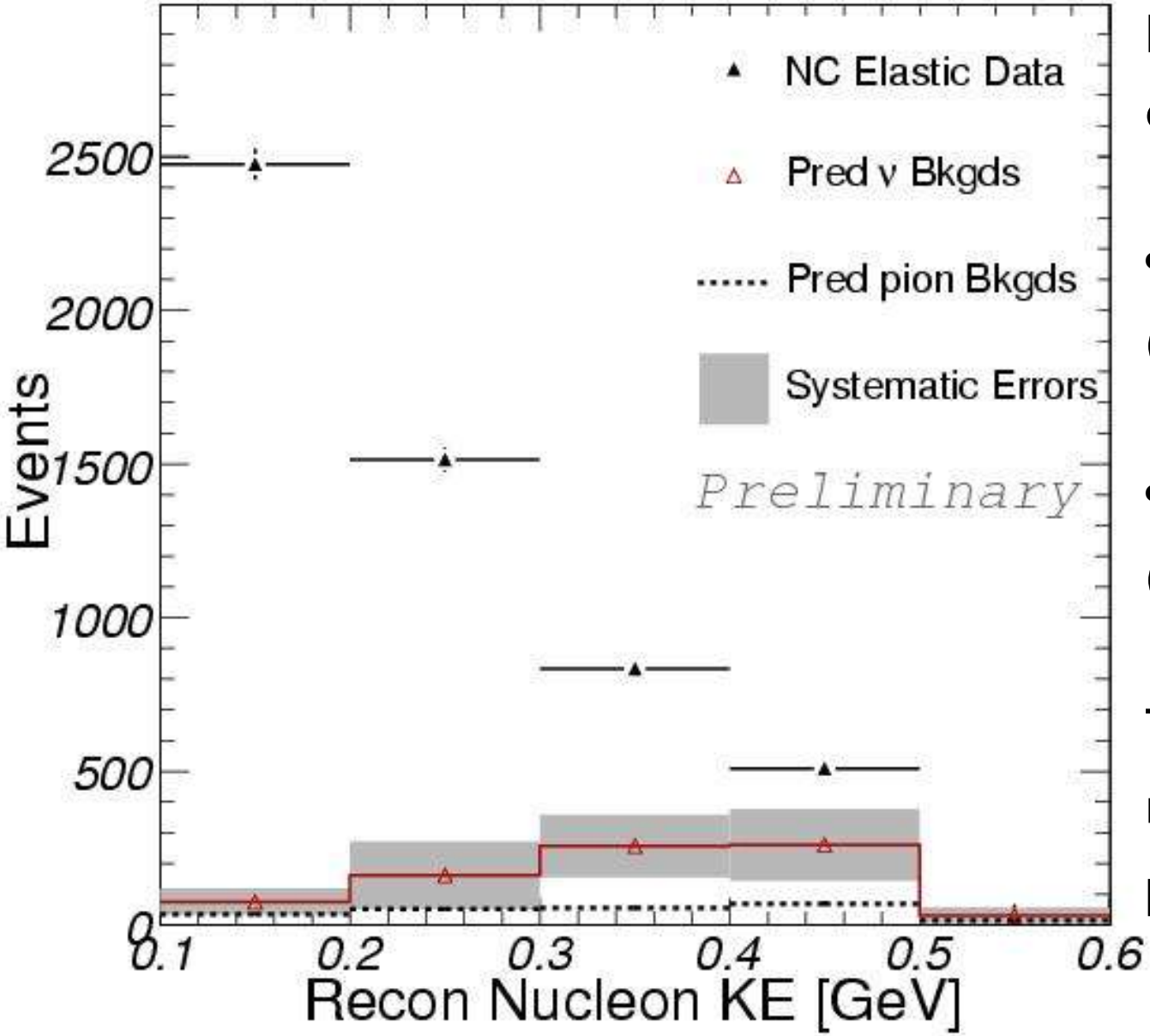


Post selection kinetic energy distributions:

- NC elastic data sample
- MC "dirt" prediction (absolutely normalized)
- Beam unrelated data (random trigger) sample

Future plots show NC data with beam unrelated backgrounds subtracted

Kinetic Energy Background Distributions II

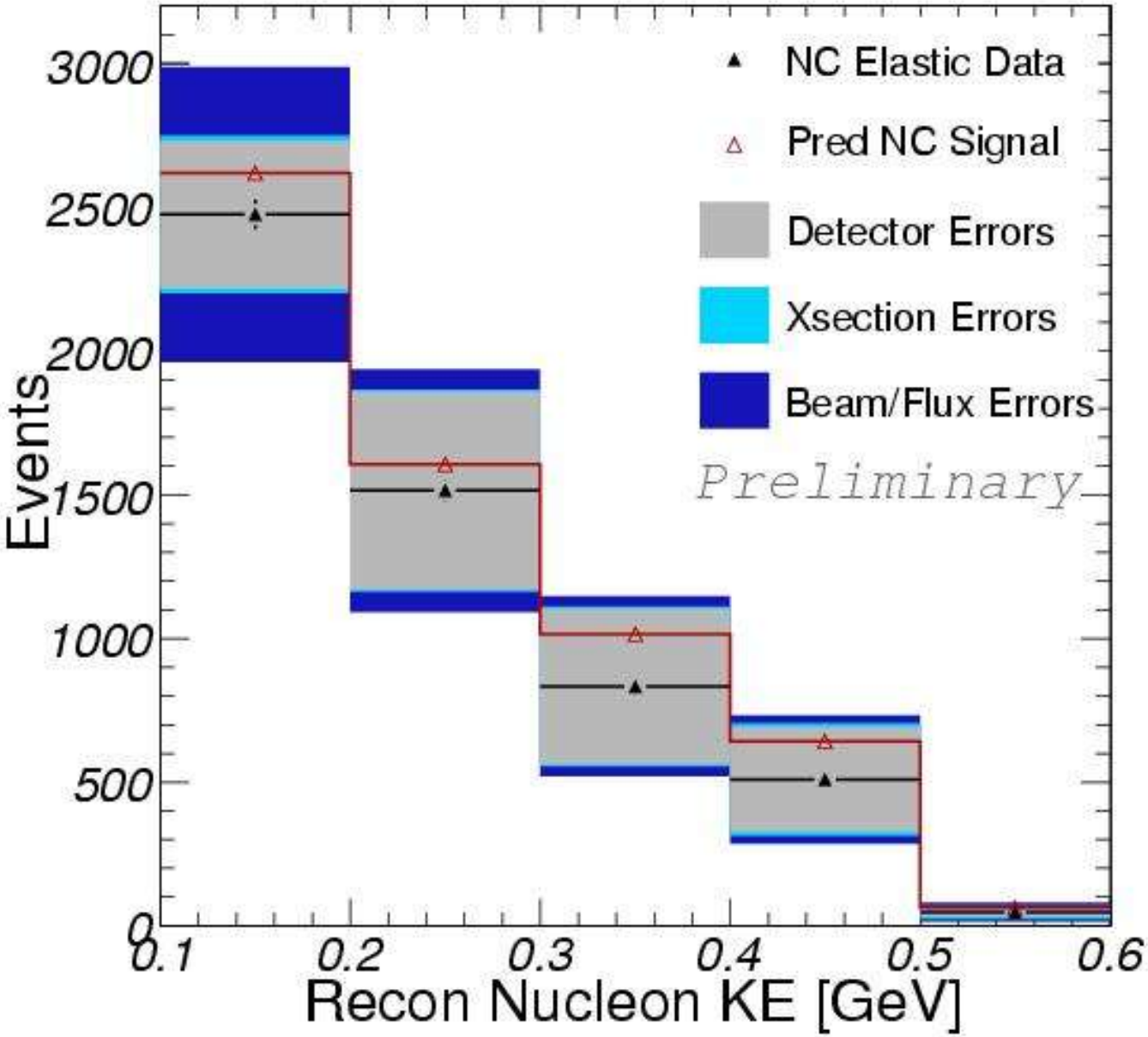


Post selection kinetic energy distributions:

- NC elastic data sample (unrelated bkgd subtracted)
- predicted ν backgrounds (absolutely normalized)

The dashed line is after removing the irreducible portion of the ν background

Kinetic Energy Signal Distributions



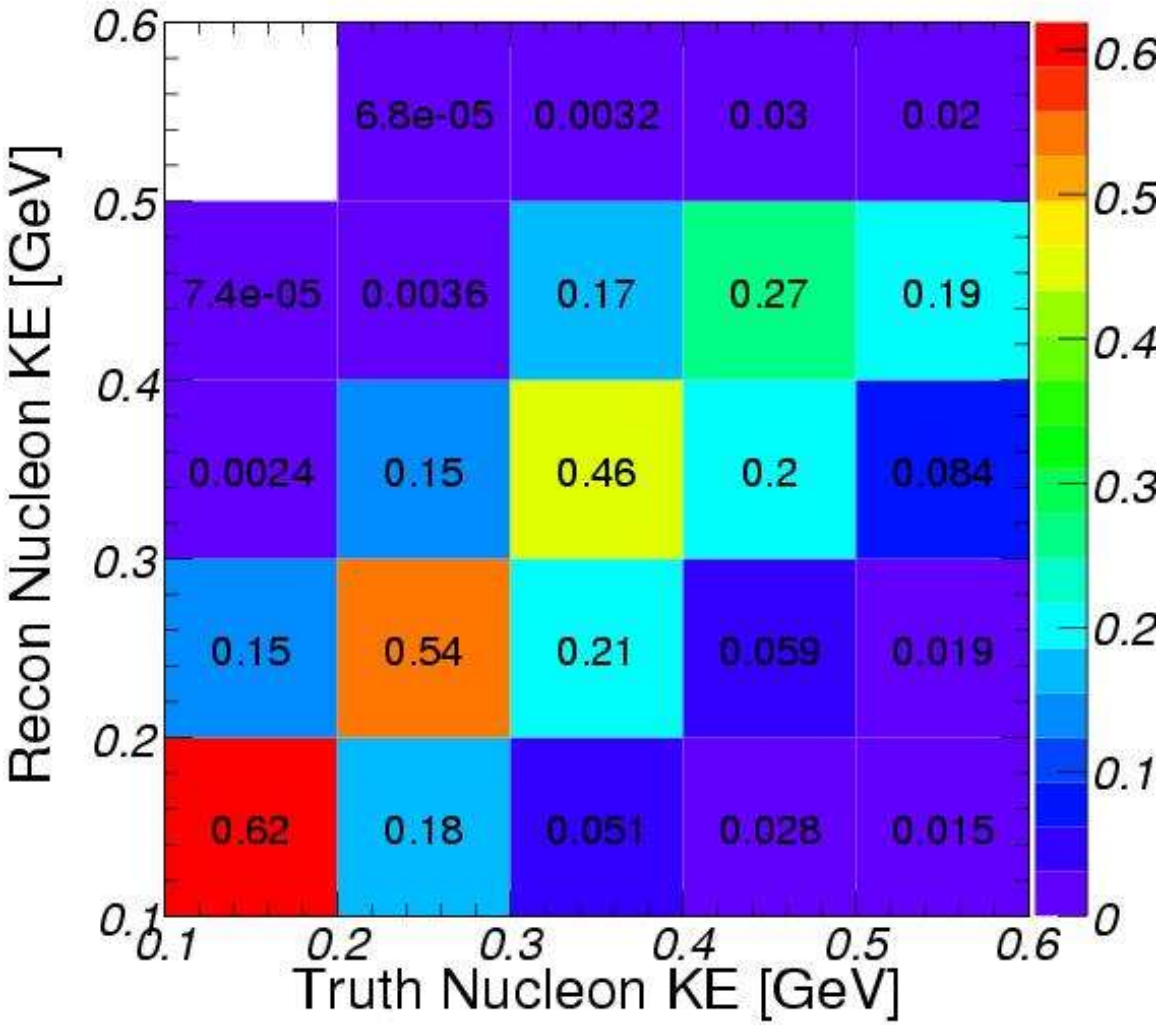
- NC elastic data sample (unrelated bkgd subtracted)

- pred NC "signal" includes all Monte Carlo "dirt" and ν bkgnds (absolutely normalized)

To fit M_A from the shape, this is good enough

But we want $\frac{d\sigma}{d\,KE}$

Unfolding Detector Effects: Bad Inversion



Standard problem:

$$\overrightarrow{KE}_{observed} = \epsilon \overrightarrow{KE}_{true} + \overrightarrow{KE}_{background}$$

How do you get the predicted KE from the observed KE

Naively: $\hat{\overrightarrow{KE}}_{true} = \epsilon^{-1} \overrightarrow{KE}_{signal}$

$$(\overrightarrow{KE}_{signal} = \overrightarrow{KE}_{observed} - \overrightarrow{KE}_{background})$$

This can be unstable, as here: too much smearing in the matrix

a known problem...

Unfolding Detector Effects: Correction Factors

Unfold using a correction factor

$$\hat{\overrightarrow{KE}}_{true} = \vec{C}\,\overrightarrow{KE}_{signal}$$

where each element in **C** is predicted from the Monte Carlo:

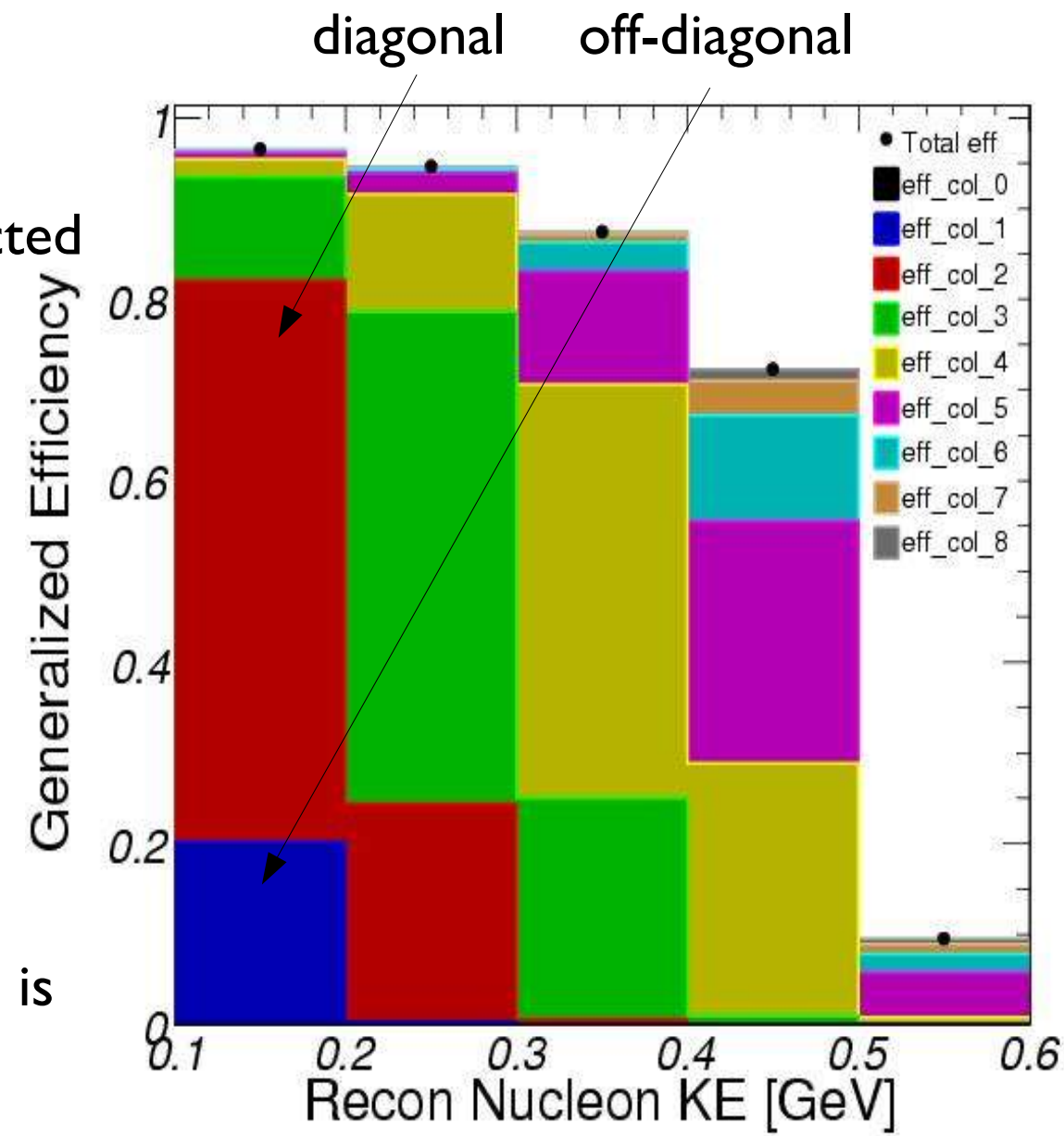
$$C_i = KE_i^{MC}{}_{predicted} / KE_i^{MC}{}_{reconstructed}$$

We can construct a generalized efficiency in terms of the error matrix

$$\epsilon_r = \frac{1}{C_r} = \frac{\overrightarrow{KE}_{r,obs}}{\overrightarrow{KE}_{r,true}} = \frac{\sum_g \overrightarrow{KE}_{g,true}\,\epsilon_{rg}}{\overrightarrow{KE}_{r,true}}$$

The estimated physics distribution is then:

$$KE_{g,physics} = KE_{r,observed} / \epsilon_r$$



Unfolding Detector Effects: Correcting

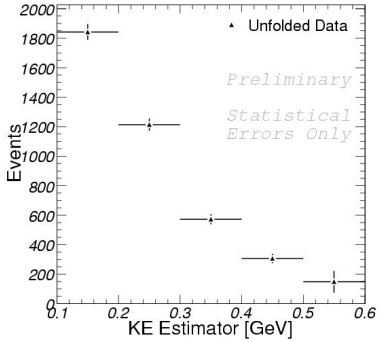
However this incurs a bias if MC doesn't have the same energy shape as the data:

$$bias_i = \left(\frac{KE_{i\ \ pred}^{MC}}{KE_{i\ \ recon}^{MC}} - \frac{\hat{KE}_{i\,,true}}{KE_{i\,,signal}} \right) * KE_{i\,,signal}$$

We can reduce the bias by correcting the MC to have a more data like distribution.

Unfolding Detector Effects: Procedure

UNFOLDED



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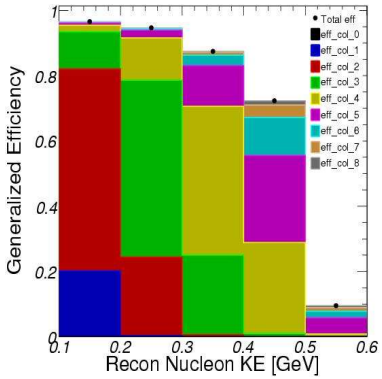

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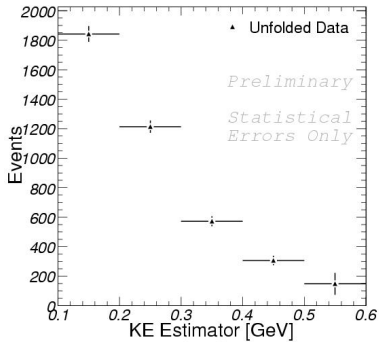

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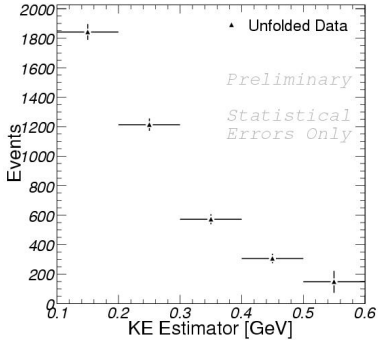

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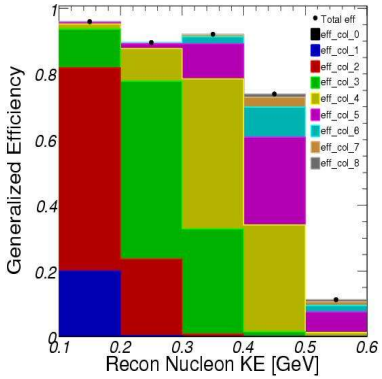

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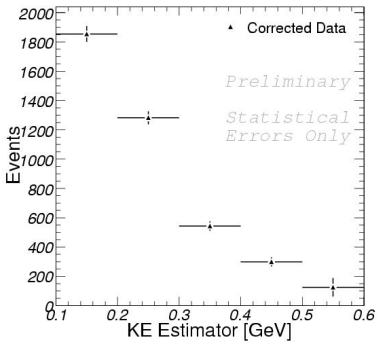

First Unfolding: Recon KE → KE estimator

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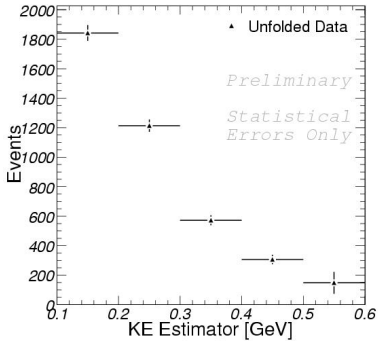

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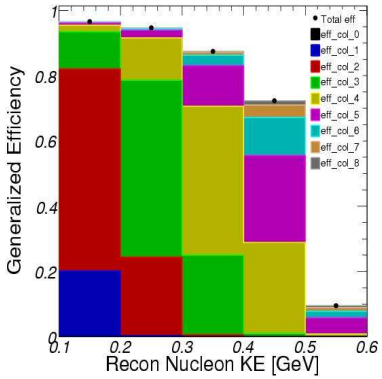

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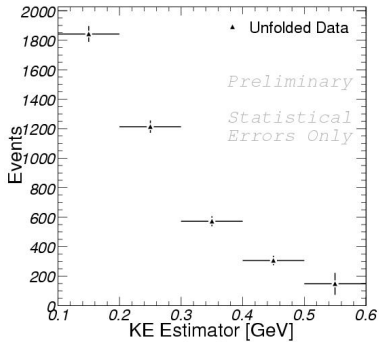

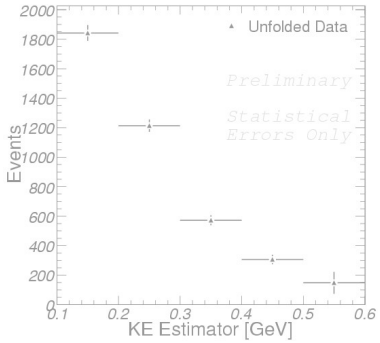

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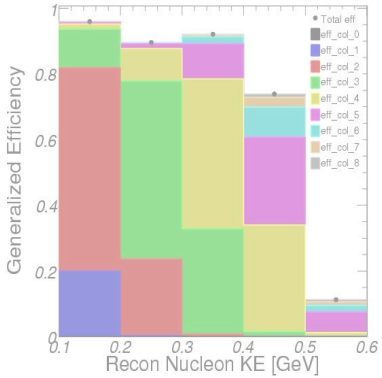

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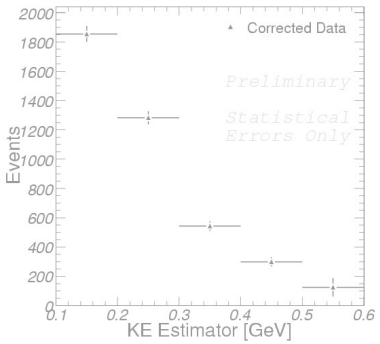

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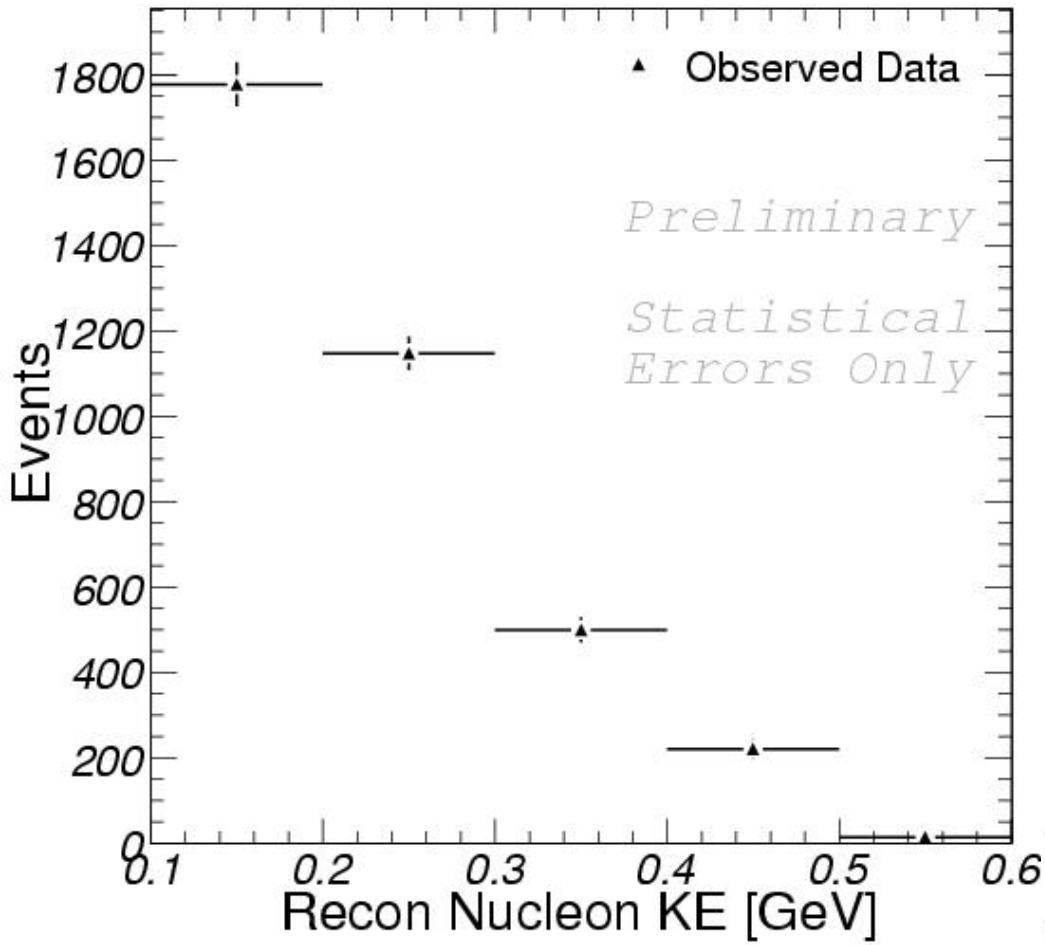
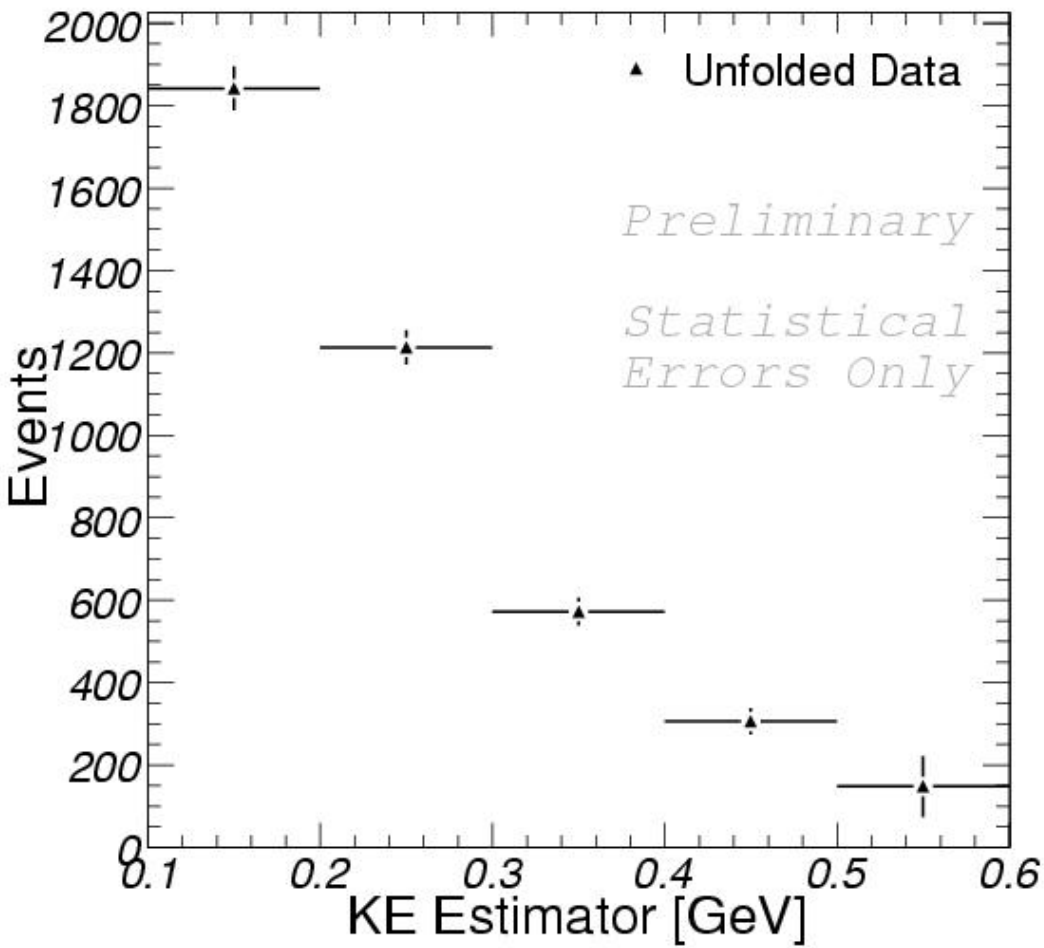


"Observed Data" is the NC elastic sample with all backgrounds subtracted.



Second Unfolding: Correcting the Bias

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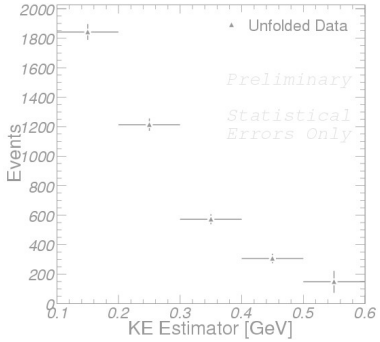

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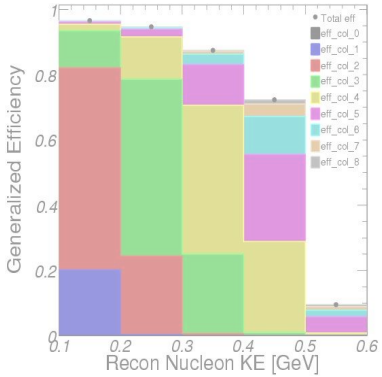

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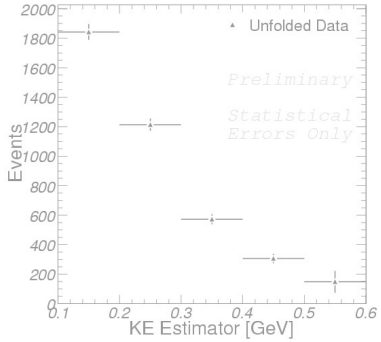

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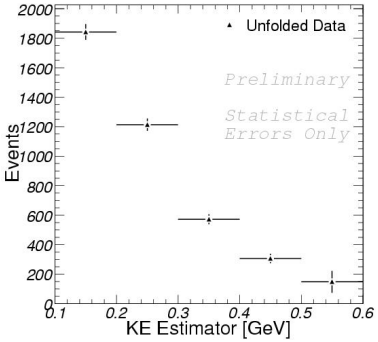

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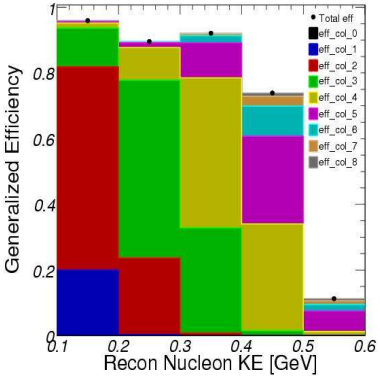

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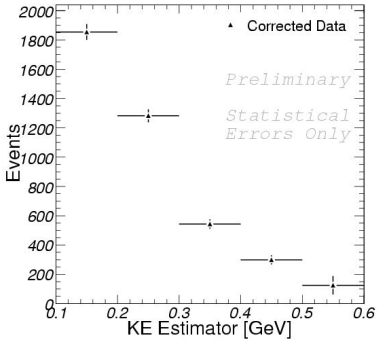
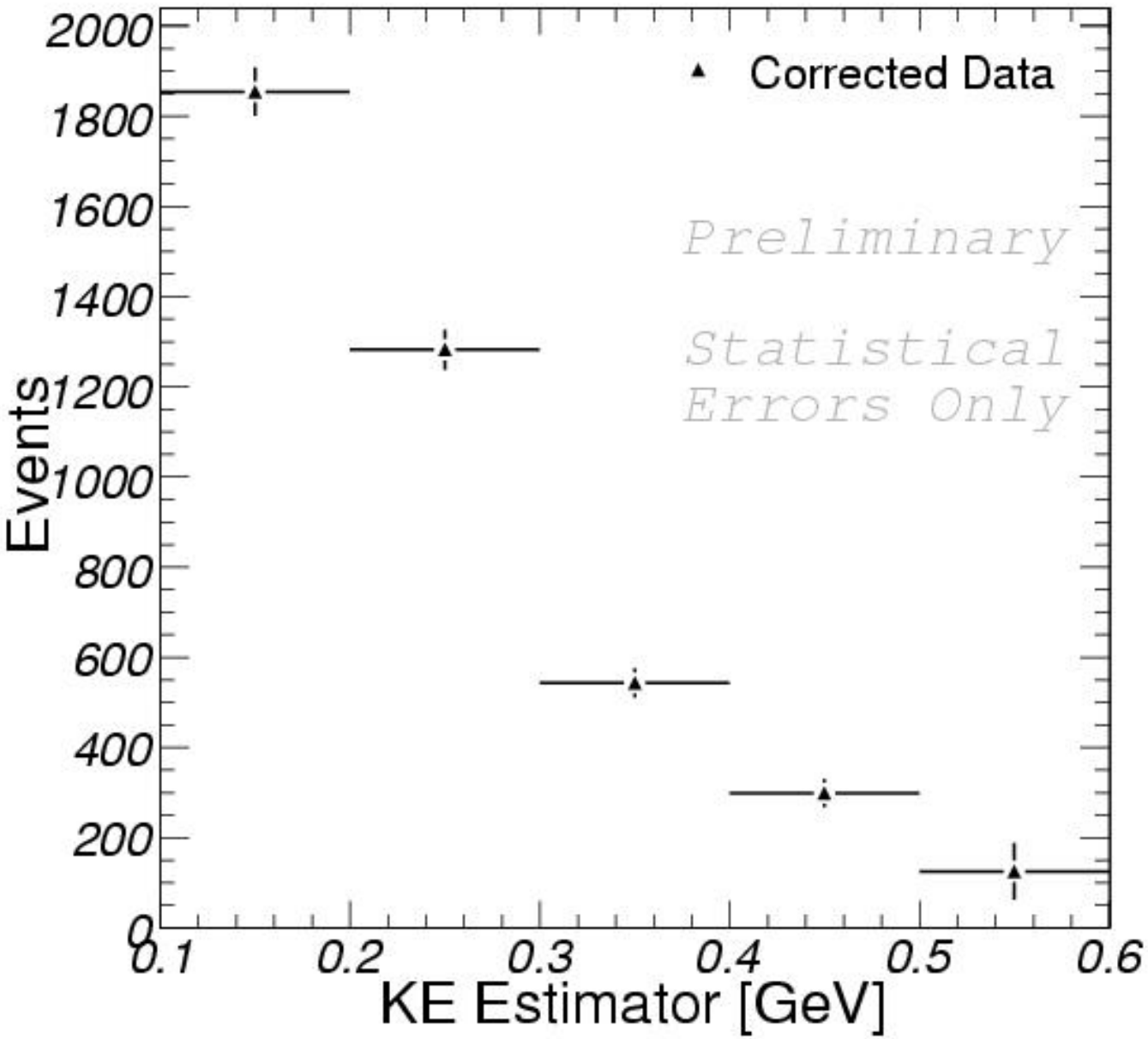


Second Unfolding: Correcting the Bias

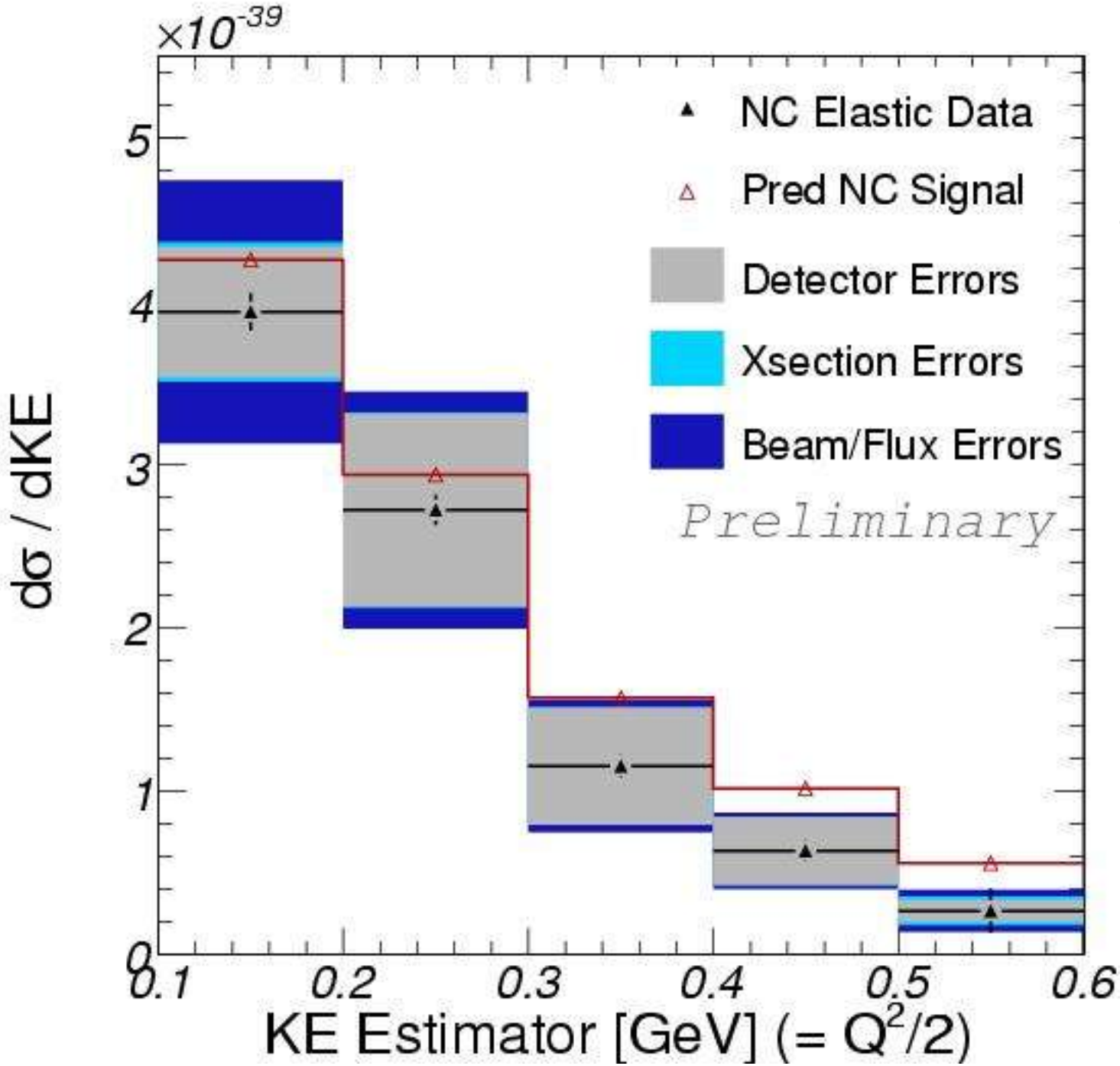


Correcting for the bias also changes little in most bins.

This is the numerator of the cross section:

$$\sigma = \frac{(NC\ events - bkgd)/\epsilon_{NC}}{(\int \Phi_\nu * N_{POT} * N_{nucl})}$$

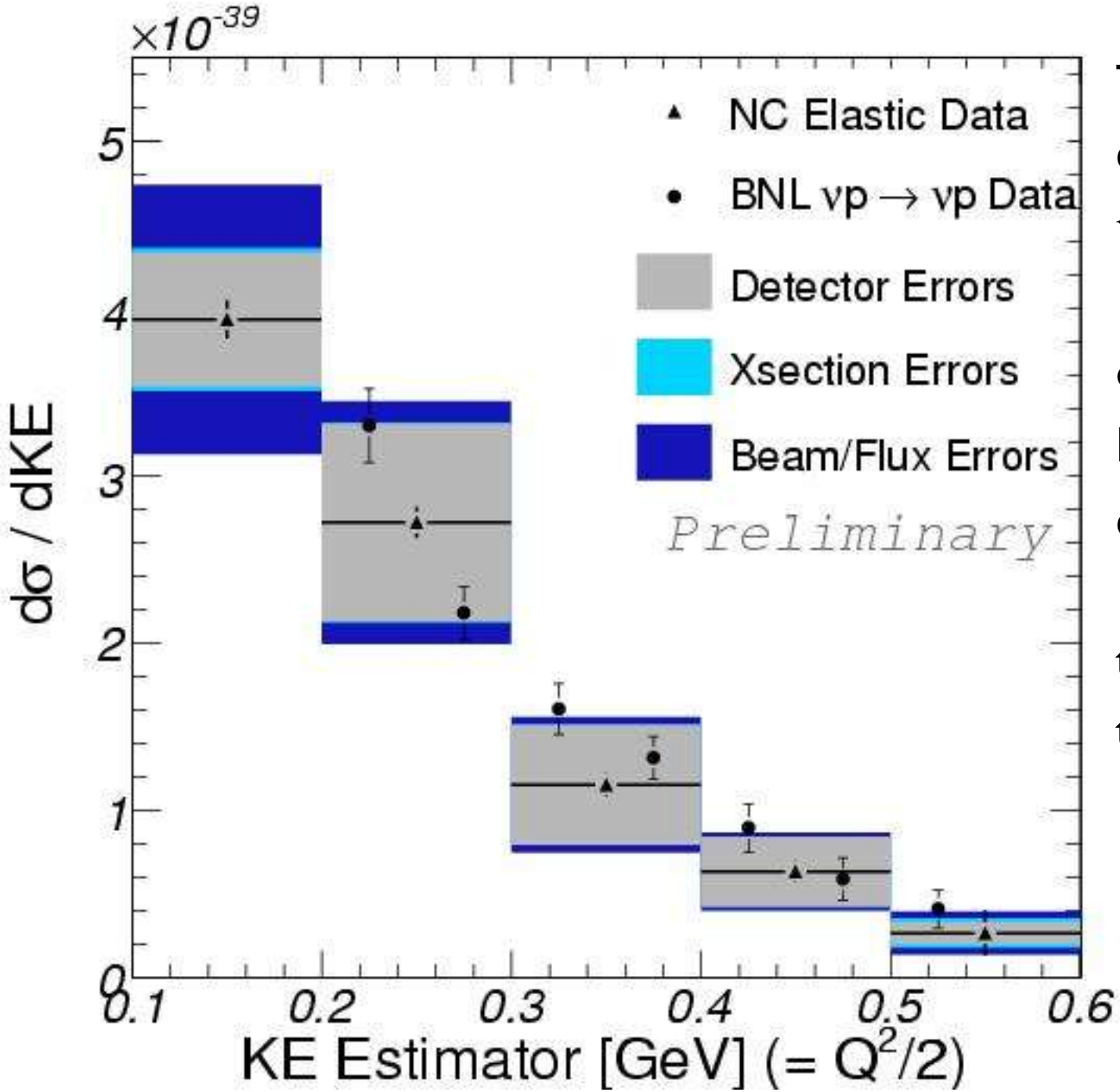
NC Elastic Differential Cross Section in MiniBooNE



MiniBooNE NC elastic data with systematic errors.

Monte Carlo prediction is absolutely (POT) normalized to the data.

NC Elastic Differential Cross Section in MiniBooNE & BNL 734



The same MiniBooNE cross section $\nu N \rightarrow \nu N$

overlaid by the BNL 734 $\nu p \rightarrow \nu p$ cross section

transformed from Q^2 to KE:

$(KE = Q^2 / 2m_p)$

Summary and Further Work

✔ A preliminary NC elastic differential cross section in KE.

→ Complete systematic error analysis

- complete dirt errors
- energy calibration
- nucleon tracking
- G_A^s errors

→ Fit the final cross section to extract M_A