Neutrino-Nucleon Neutral Current Elastic Interactions in MiniBooNE

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Outline

1. Neutral current elastic (NCE) events in MiniBooNE overview.
2. Analysis
3. Conclusion

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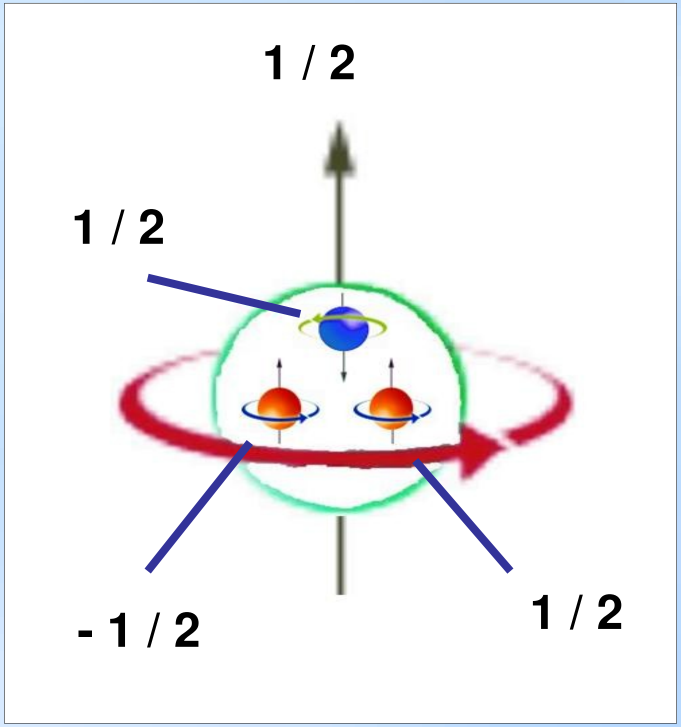
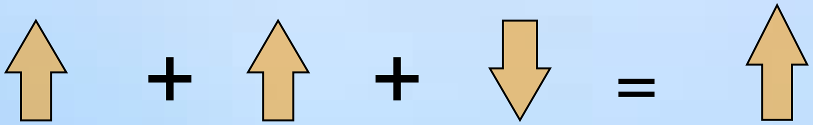
Spin of Proton



Sum of Spins of u u d Quarks = Spin of Proton



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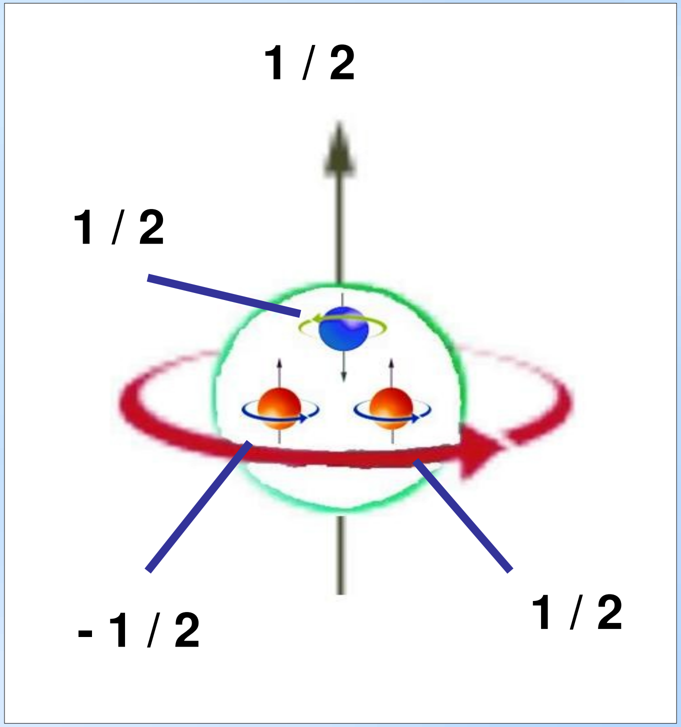

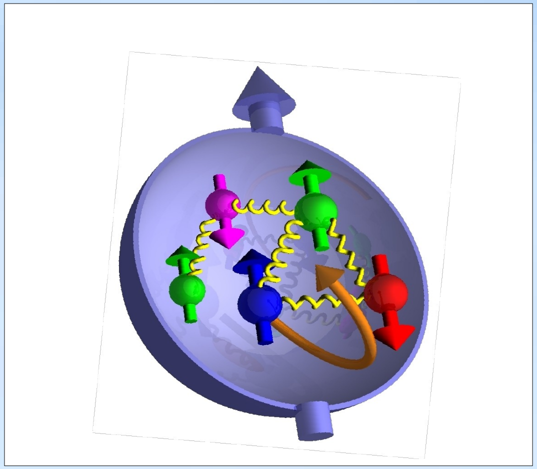

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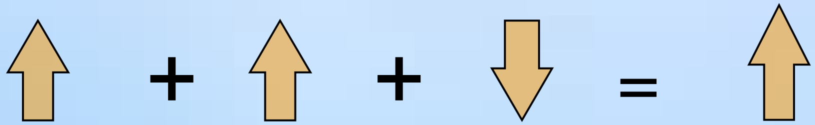


EMC Experiment (1988)

$$\frac{1}{2}(\Delta u+\Delta d+\Delta s)=\frac{1}{2}(0.14\pm0.03\pm0.1)$$

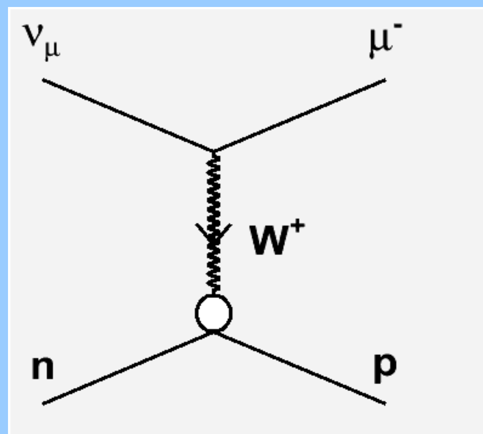
Hermes and COMPASS (2007)

$$\frac{1}{2}(\Delta u+\Delta d+\Delta s)=\frac{1}{2}(0.33\pm0.03\pm0.05)$$

Neutrino-nucleon (quasi)elastic scattering

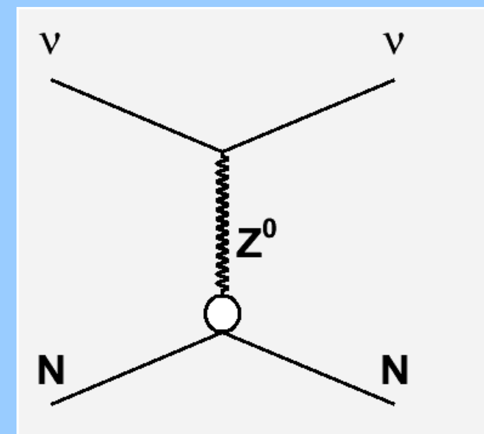
Charged current quasi-elastic (CCQE)

$$\nu_\mu n \to \mu^- p$$



Neutral current elastic (NCE)

$$\nu_\mu N \to \nu_\mu N$$

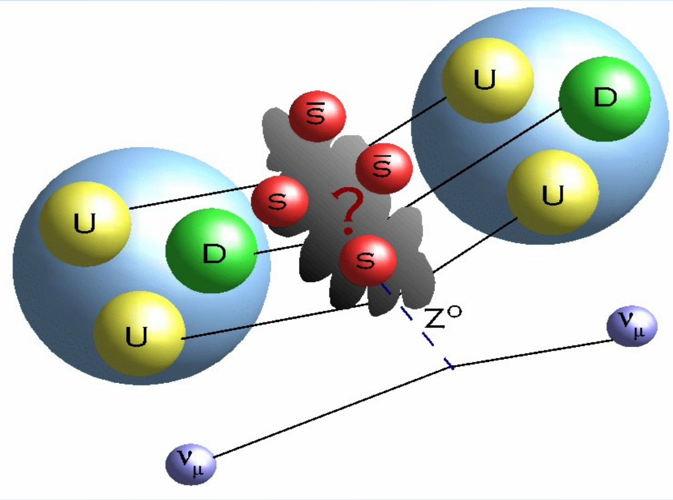


Weak interactions are mediated by either neutral (Z^0) or charged boson ($W^\pm$)

interactions via Z^0 are neutral current (NC), via $W^\pm$ are charged current

If there are no additional particles created in the interaction, then the scattering is called elastic (quasi-elastic).

Neutrino-Nucleon NC Elastic Scattering



- Fundamental NC probe of the nucleus.

- At low momentum transferred (Q^2) the cross-section is sensitive to the axial form factor, $d\sigma/dQ2 \sim F_A^2$

- Unlike CC quasielastic, sensitive to isoscalar component of nucleon (strange quarks)

- via isoscalar or "strange" axial-vector form factor, $G_A^s(Q^2)$

- and $\Delta s = G_A^s(Q^2 = 0)$

$$F_A(Q^2) = \left[\frac{G_A}{2} + \frac{G_A^s}{2}\right] = \frac{1}{2}\frac{\mp g_A + \Delta s}{(1+Q^2/M_A^2)^2}$$

- protons
+ neutrons

- Experimental sensitivity to isoscalar effects best via ratios:

- NCE(p)/NCE(n), NCE(p)/CCQE

as many systematics (flux, nuc. effects) should cancel.

- Another view:

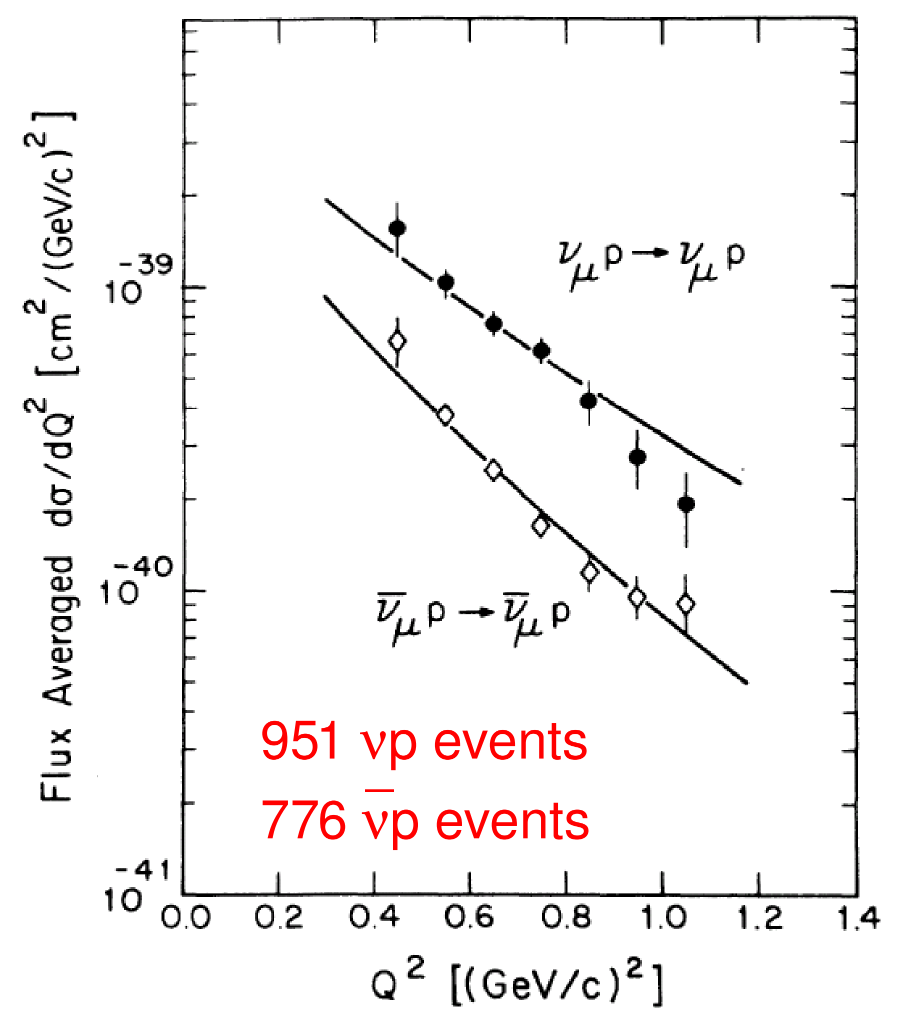
Does our knowledge of CCQE (usually measured via muon) completely predict NCE (measured via recoil nucleon) for nuclear targets?

Available world-wide neutrino NC Elastic data
BNL E734

BNL E734 used 170-ton high-resolution target detector, comprised of 112 modules, each of which had 16 liquid scintillator cells

The beam was 26 GeV protons incident on a production target

BNL E734: PRD 35, 785 (1987)



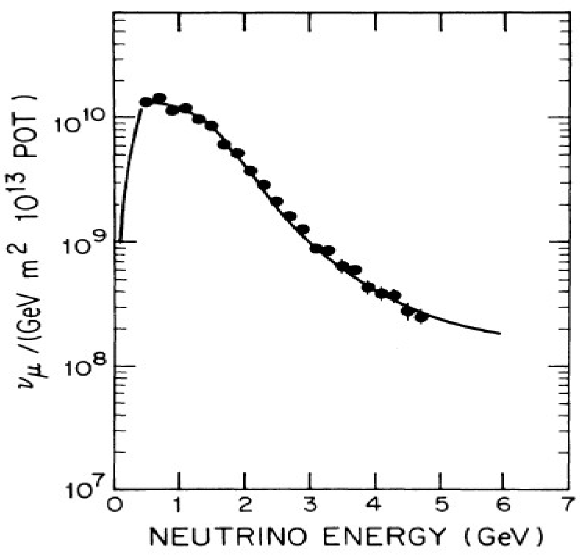


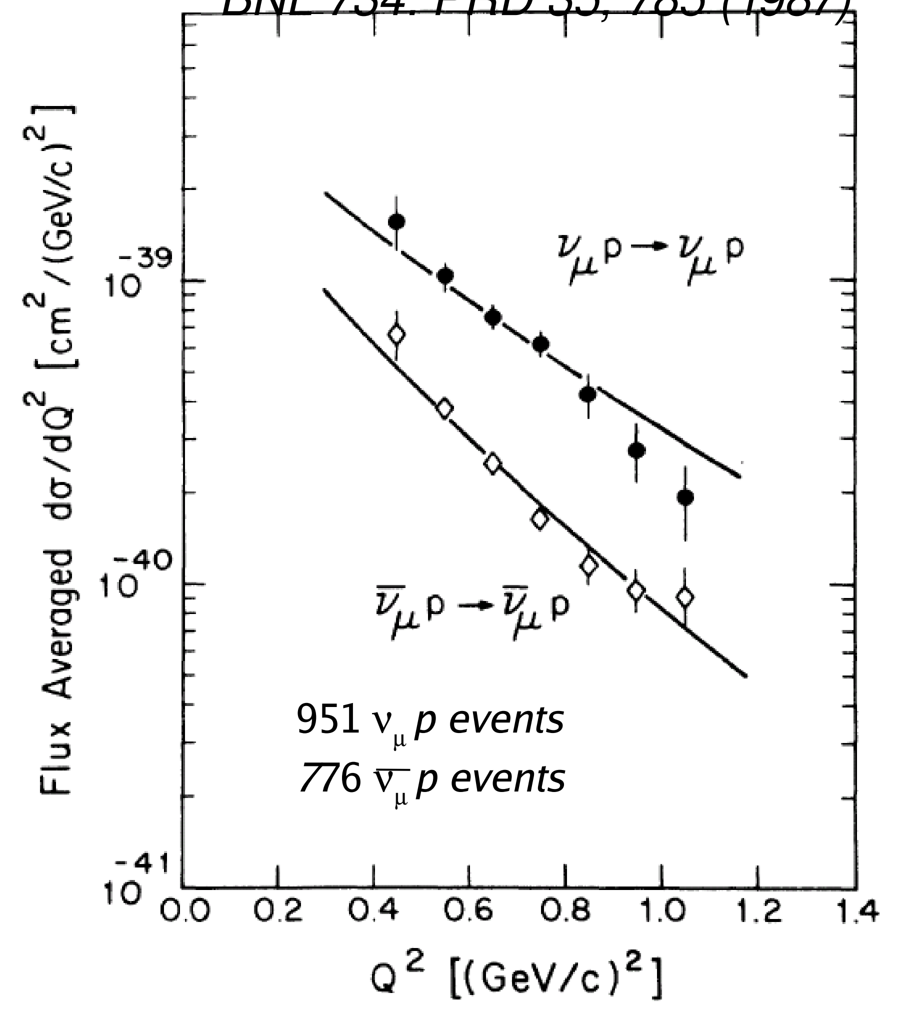
FIG. 2. The measured ν_μ flux. The error bars represent data from the reaction $\nu_\mu n \rightarrow \mu^- p$. The solid curve is a Monte Carlo beam flux calculation. Details of the flux measurement and Monte Carlo calculations are given in Ref. 19.

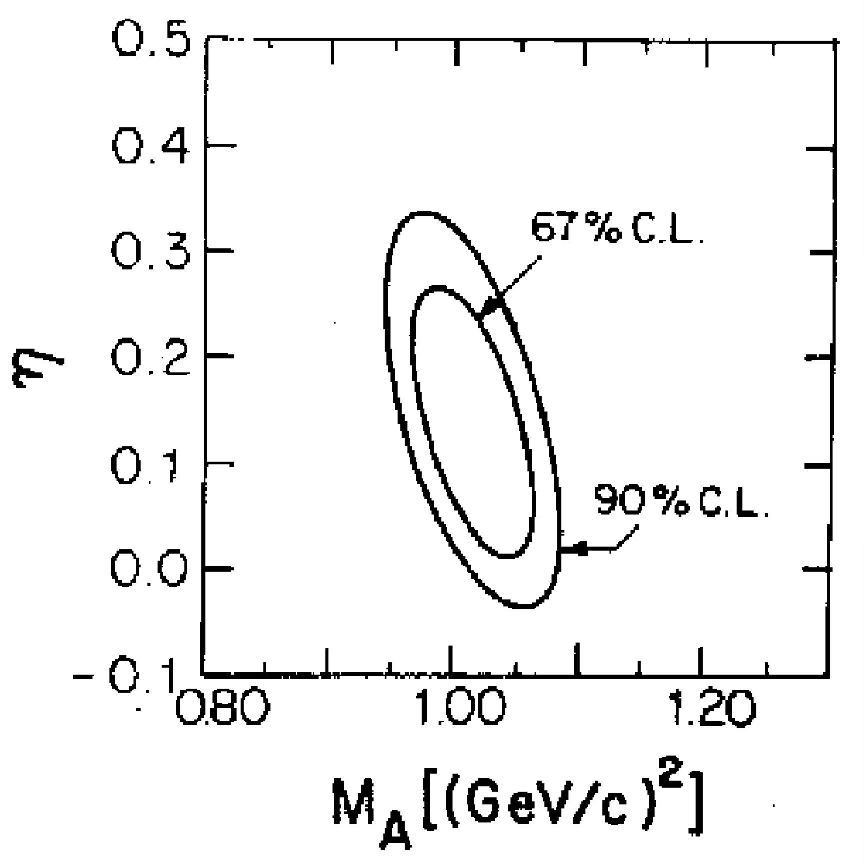
Measurements of Δs(=-η) from neutrino experiments

$$F_A(Q^2) = 0.5 \frac{\mp g_A + \Delta s}{(1+Q^2/M_A^2)^2}$$

The best data to date are from BNL 734(1987):

BNL 734: PRD 35, 785 (1987)





MiniBooNE experiment setup

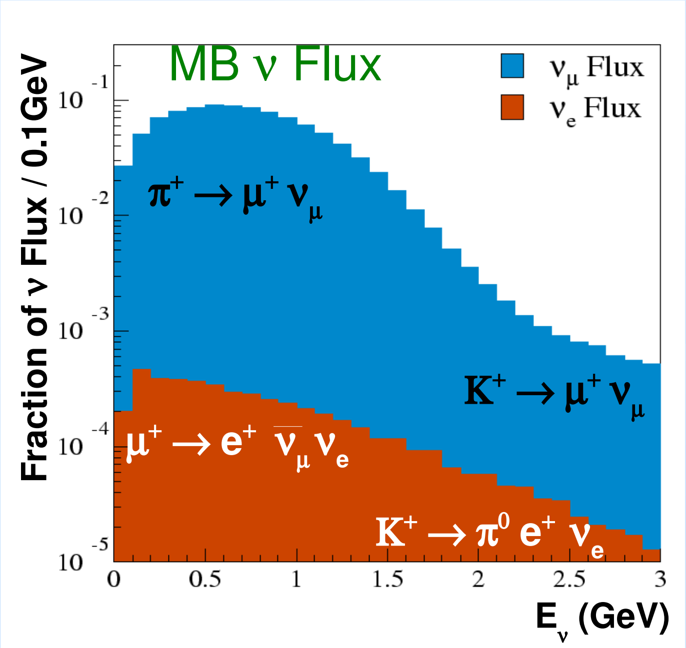
- Proton beam from 8 GeV from the booster accelerator

- Delivered to a beryllium target producing mesons

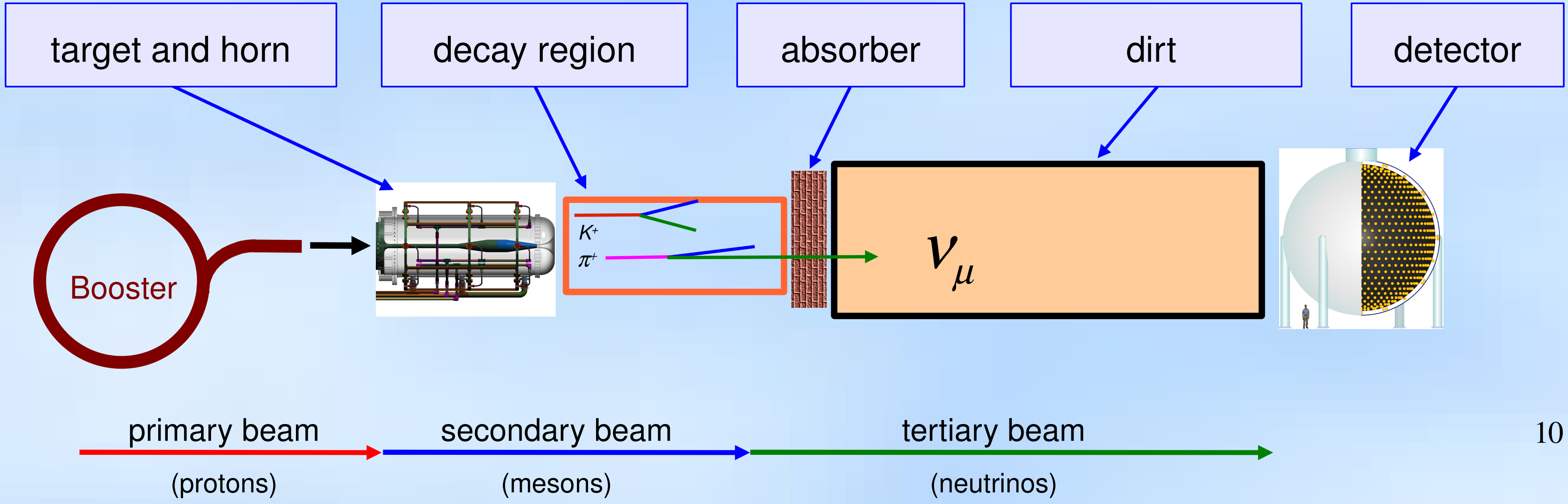
- Which go through the magnetic horn, focusing positively charged particles and defocusing negative

- Mesons decay producing a pure muon neutrino beam

- 541 meters away from the target is the MB detector

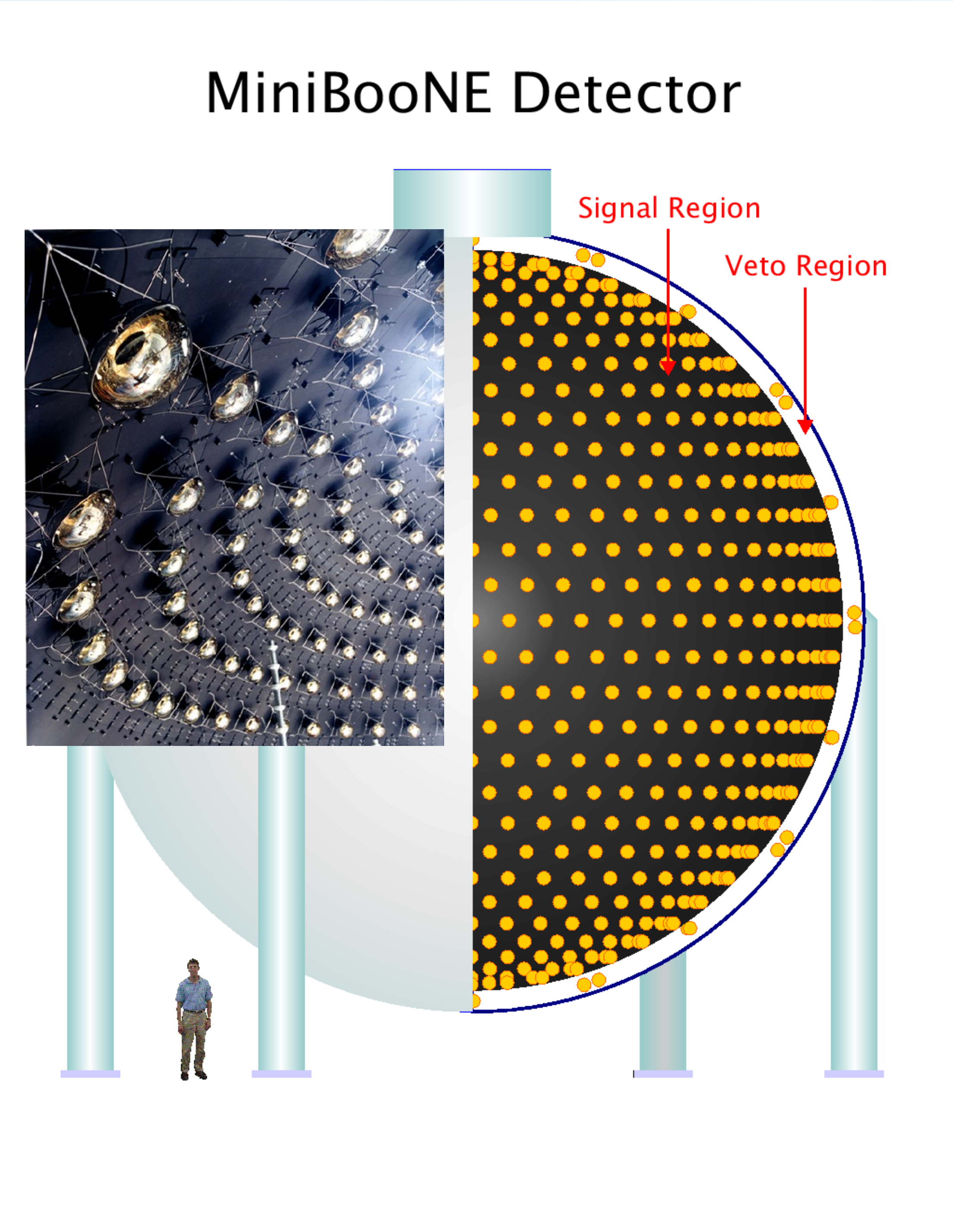


Phys. Rev. D. 79, 072002 (2009)

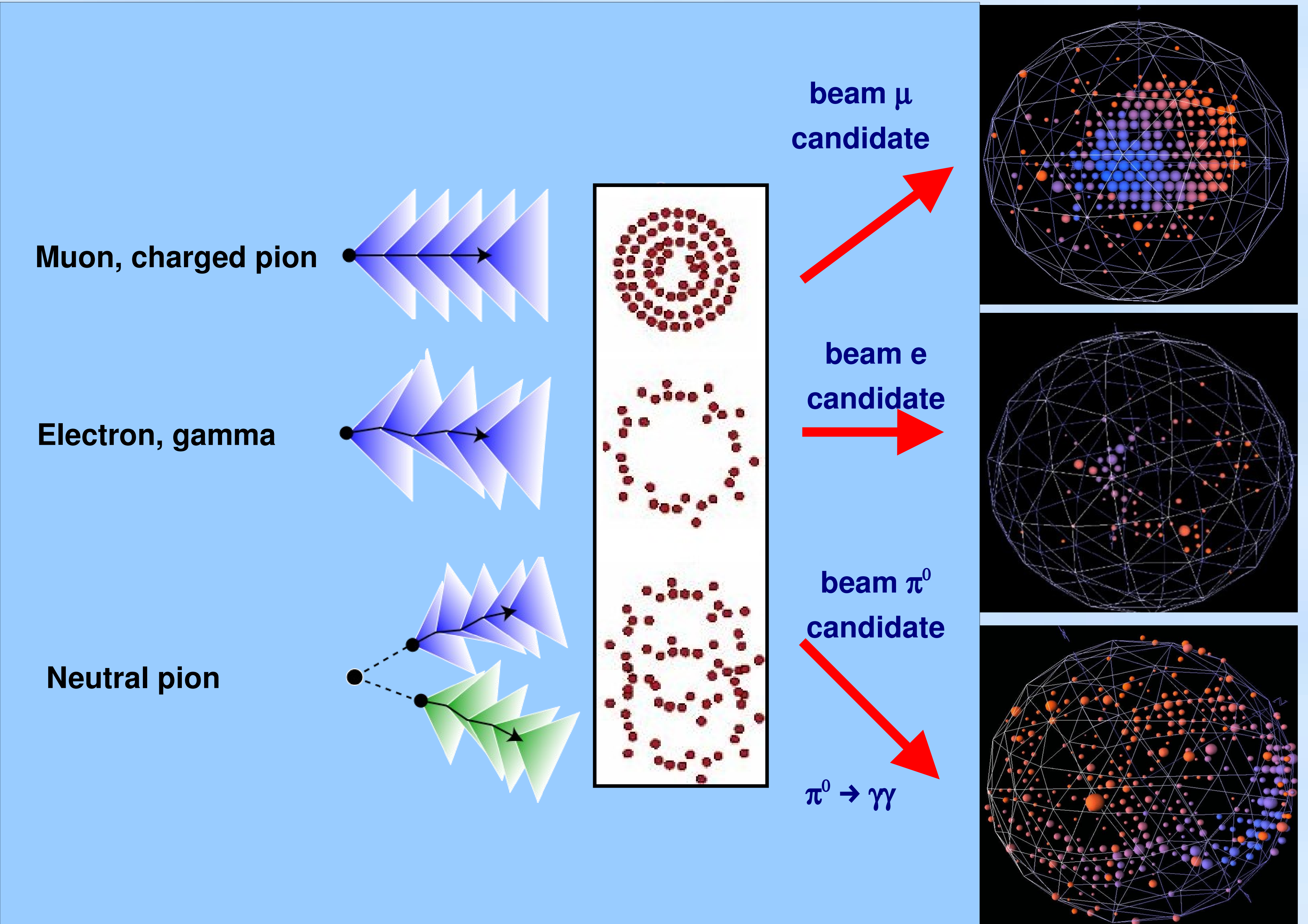


MiniBooNE detector

- 12 meter diameter sphere
- 800 tons mineral oil (CH_2)
- Cerenkov detector with cerenkov/scintillation = 3/1 for electrons
- 3 m overburden
- includes 35 cm "veto region"
- viewed by 1280 8"PMTs (10% coverage) + 240 veto
- Simulated with a GEANT3 Monte Carlo program tuned with external/internal calibration data



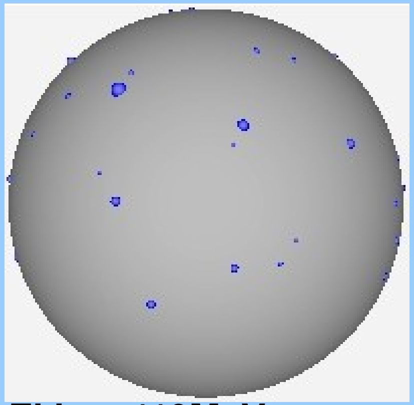
Particles seen in the MiniBooNE detector



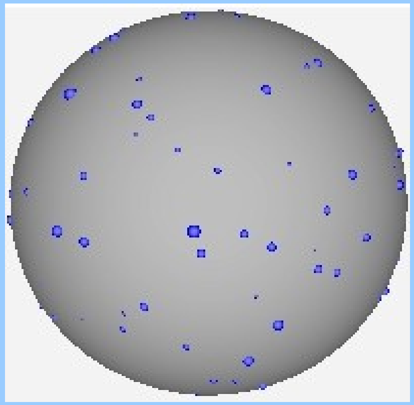
Protons in the MiniBooNE detector

Protons have mass 938 MeV, thus the Cerenkov threshold is 350 MeV in mineral oil (compared to 0.2 MeV for electron and 40 MeV for muon)

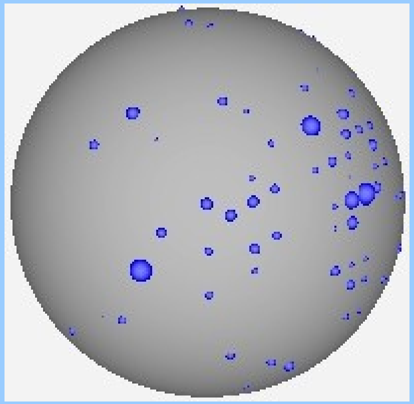
About 80% of the time protons from NC elastic are below 350 MeV



Ekin = 110MeV



Ekin = 290MeV



Ekin = 220MeV, on the outside

Protons in the MiniBooNE detector

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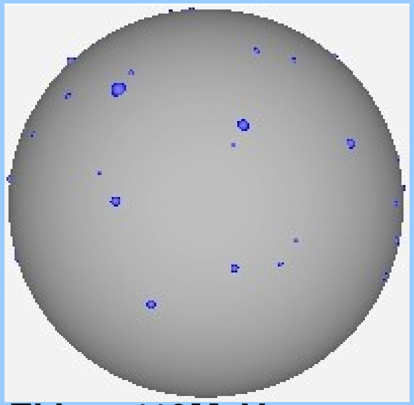

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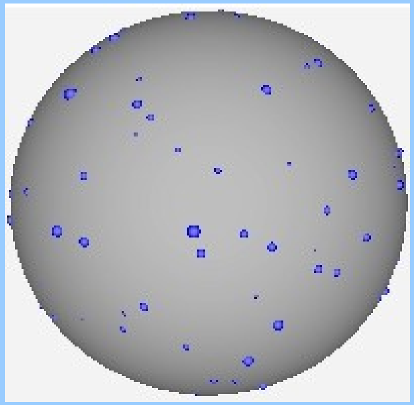

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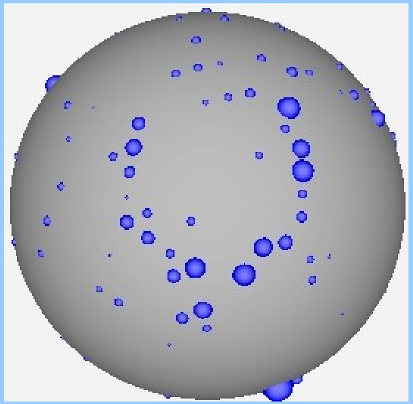
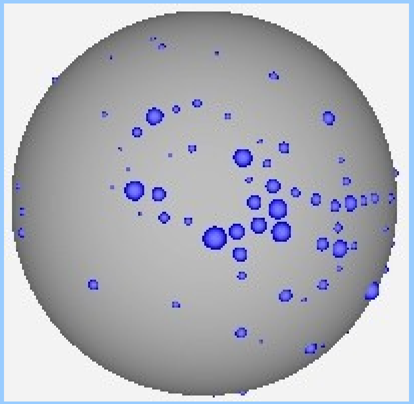
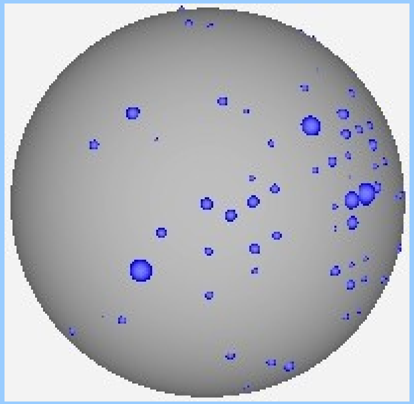


Ekin = 700MeV



Ekin = 450MeV

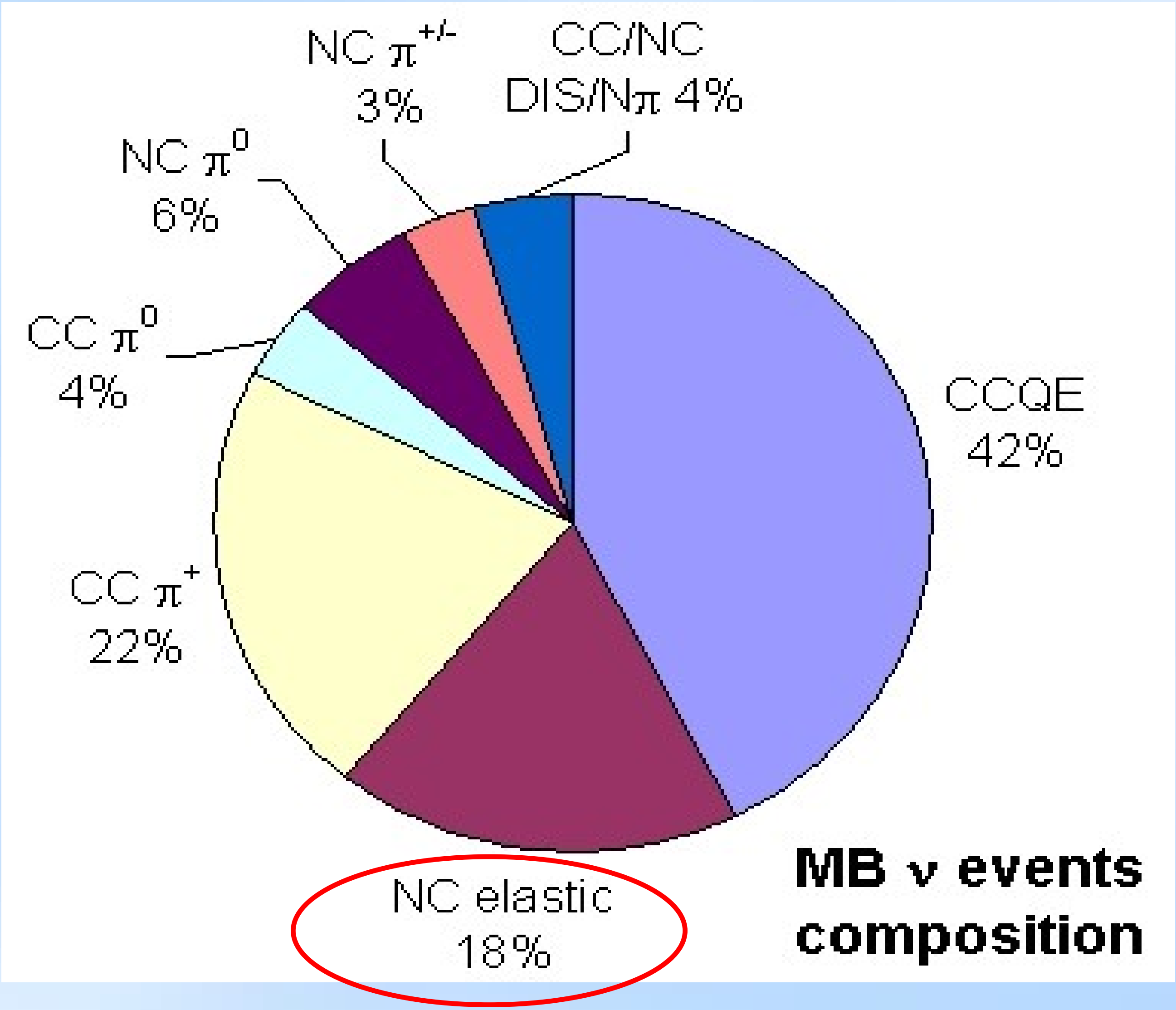


Ekin = 220MeV, on the outside

Protons above 350 MeV produce Cerenkov cone with weaker strength and narrower opening Cerenkov angle than other particles

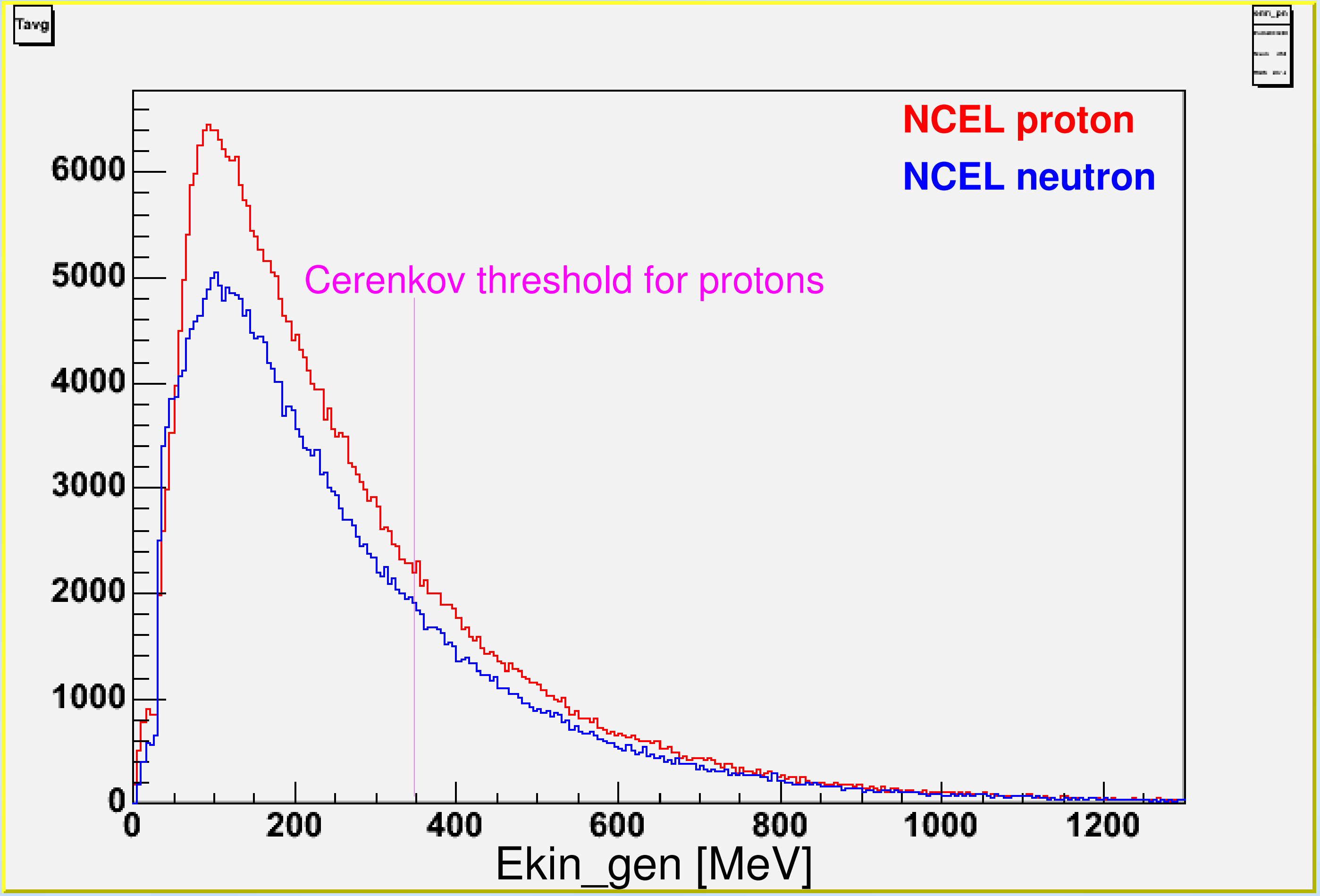
$$\cos\theta_{cer} = \frac{1}{\beta n}$$

MiniBooNE Event Composition



NC elastic is the third biggest sample of neutrino interactions in MiniBooNE

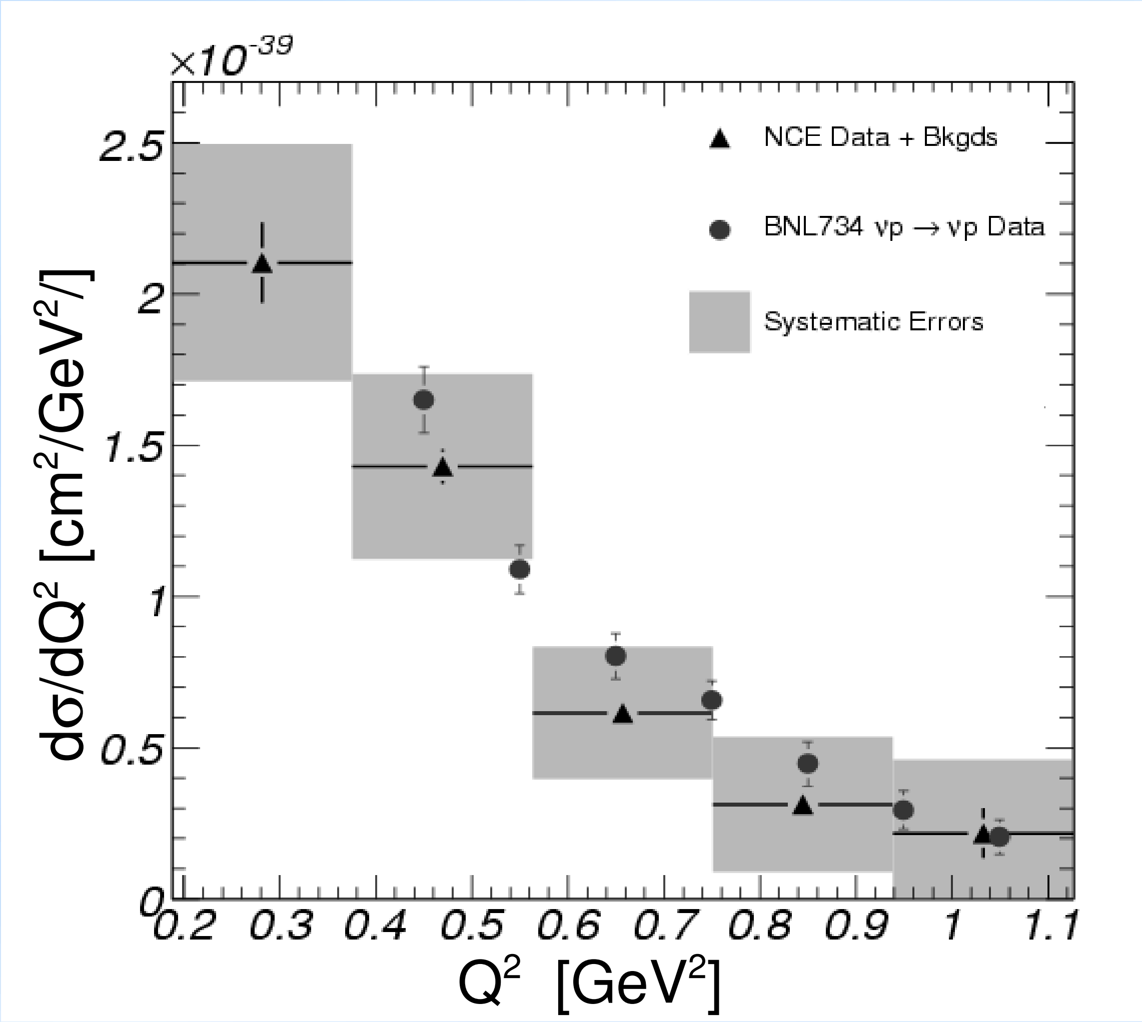
Kinetic energy of nucleons in the NCEL events



Most of the events are below Cerenkov threshold, where cannot separate NCEL protons from NCEL neutrons, **so we measure the total NCEL cross-section.**

But there may be some interesting physics results above protons Cerenkov threshold – we may be able to measure proton/neutron NCEL channel separately.

BNL E734 νp Elastic (1987) Data and MiniBooNE Preliminary NC Elastic Flux-averaged Differential Cross-Section using 10% MiniBooNE data



An early analysis, limited by oscillations analysis blindness requirement

Ph.D. Thesis, Chris Cox, Indiana University

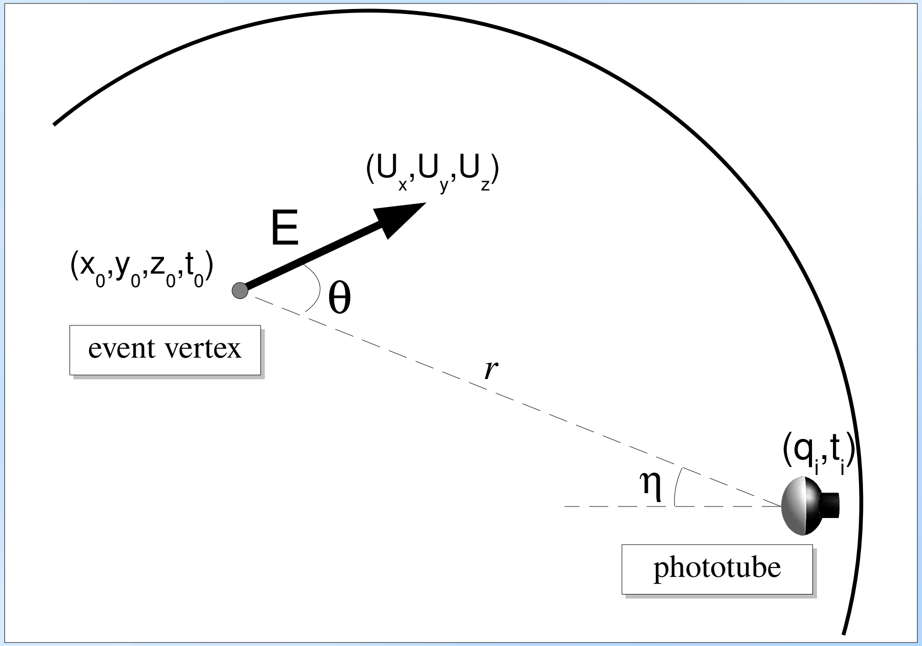
Outline

1. Neutral current elastic (NCE) events in MiniBooNE overview.
2. **Analysis**
   Reconstruction

3. Results and conclusion

Proton Fitter

In the early analysis the electron hypothesis fitter was used for the NC elastic events reconstruction.



- Proton fitter features reconstruction of events assuming the event is a proton

- Cerenkov angle profile, Cerenkov and scintillation light fluxes and time likelihoods for proton events have been determined from MC

- Point-like event is assumed

- Reconstruction is done by maximizing Charge and Time likelihood functions

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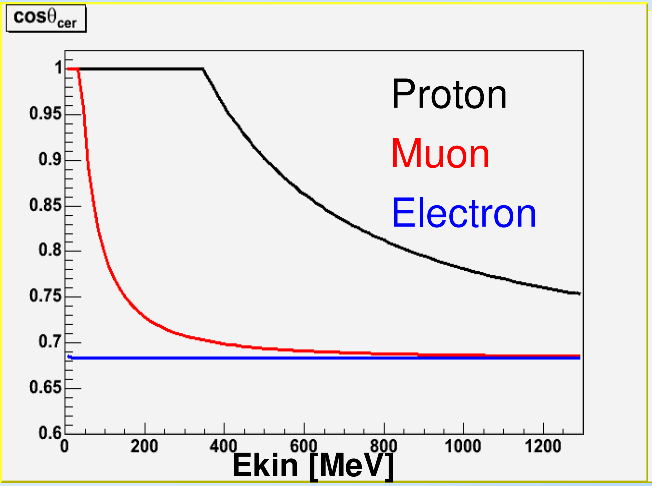

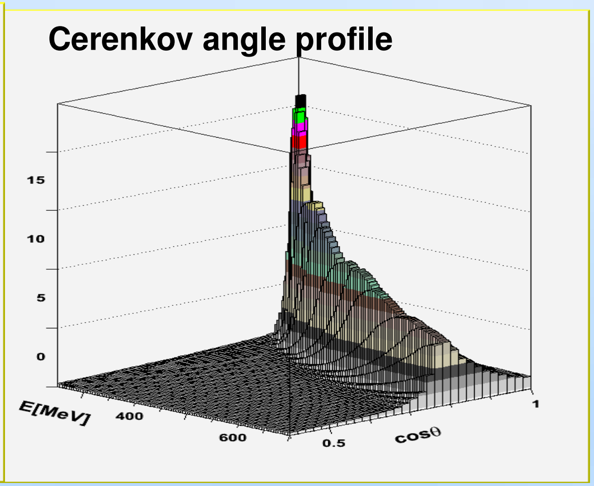

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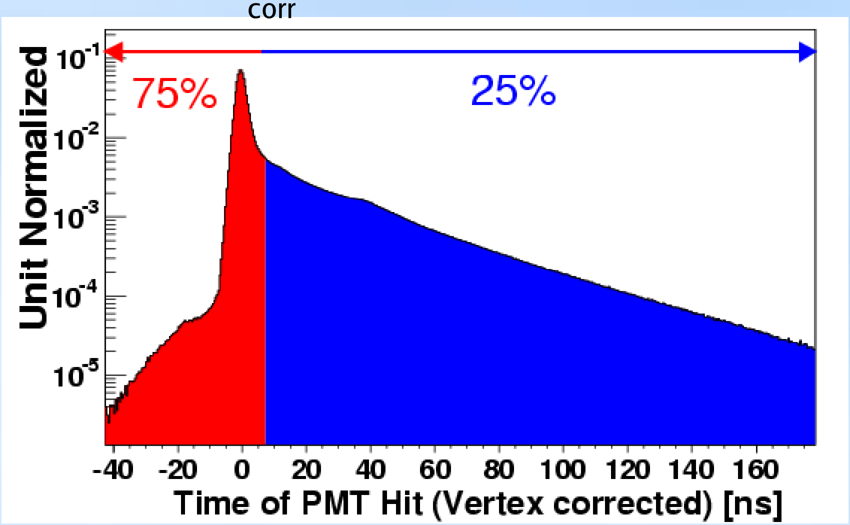
t_{corr} distribution



- Point-like event is assumed
- Reconstruction is done by maximizing Charge and Time likelihood functions

Proton Fitter

In the early analysis we have used the electron hypothesis fitter for the NC elastic events reconstruction.

With the proton hypothesis fitter we have improved the kinematics reconstruction :

1. Position resolution: 1.3m → 0.7m for protons

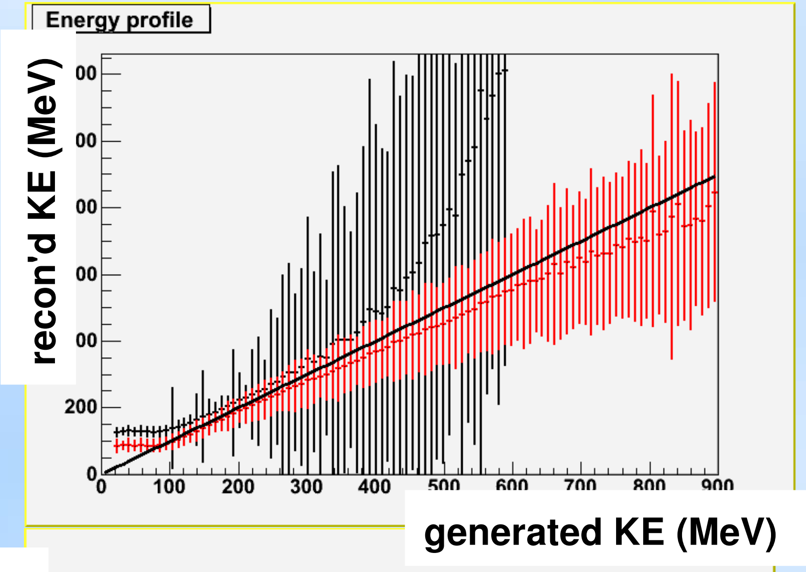
2. Energy reconstruction:

   substantial improvement at higher E

   MC protons reconstructed with

   -proton fitter

   -electron fitter



3. Direction:

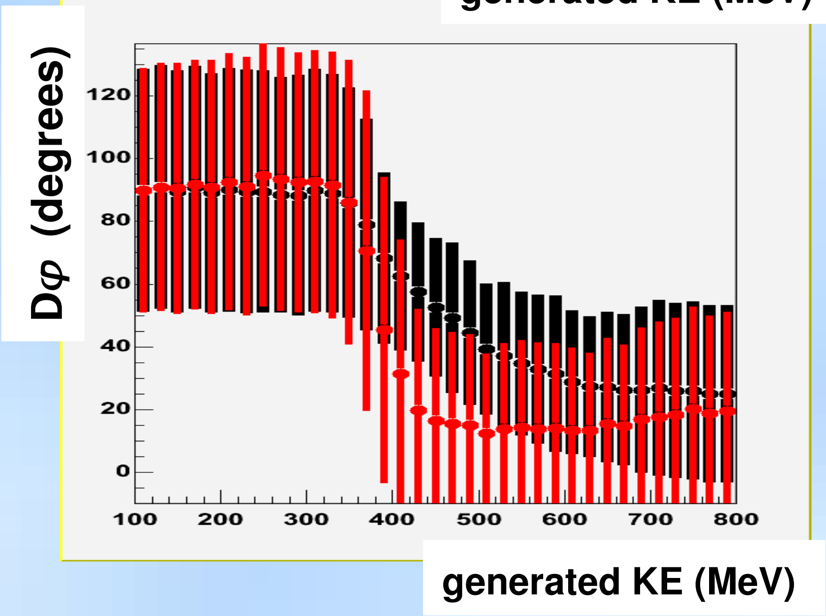
   improvement above Cerenkov threshold

   MC protons reconstructed with

   -proton fitter

   -electron fitter

   $\Delta\phi$ = true - reconstructed angle



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1. Neutral current elastic (NCE) events in MiniBooNE overview.

2. Analysis

Events selection

3. Conclusion

NC elastic event selection:

1 subevent	- Removes decaying particles (μ or π)
Veto PMT hits < 6	- Removes cosmic rays, external (dirt) events
Beam time window	- Neutrino induced events
Tank PMT hits > 24	- Reconstructible events
Reconstructed energy < 650 MeV	- Signal is of low-energy
Time likelihood ratio between proton and electron hypotheses	- proton-like events (removes beam-unrelated Michel electrons)
Fiducial volume = { **R<4.2m if $Ekin_{rec}$<200MeV**; **R<5.0m if $Ekin_{rec}$>200MeV** }	- Removes dirt events, assures reconstructable events

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Beam time

Tank PMT h

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proton and d Michel electrons)

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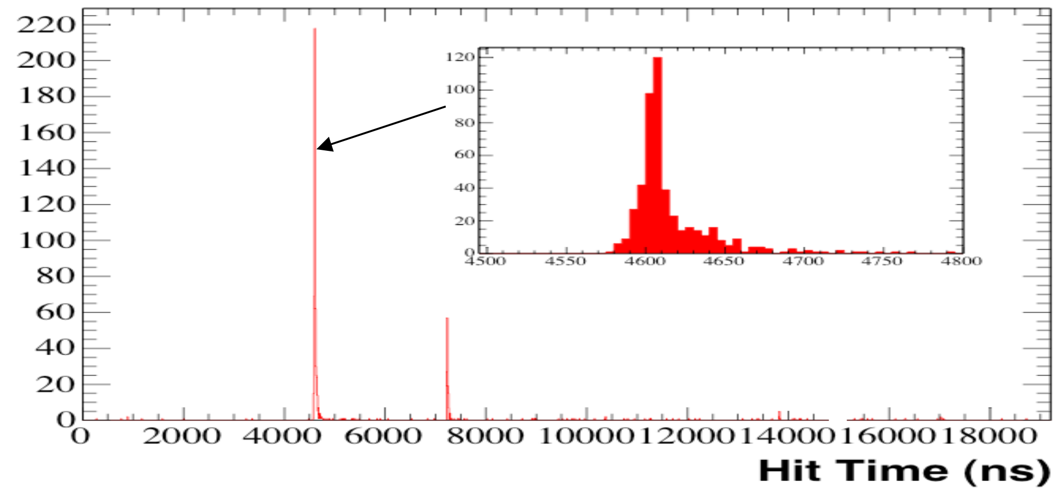
Fiducial vol

Decaying μ event



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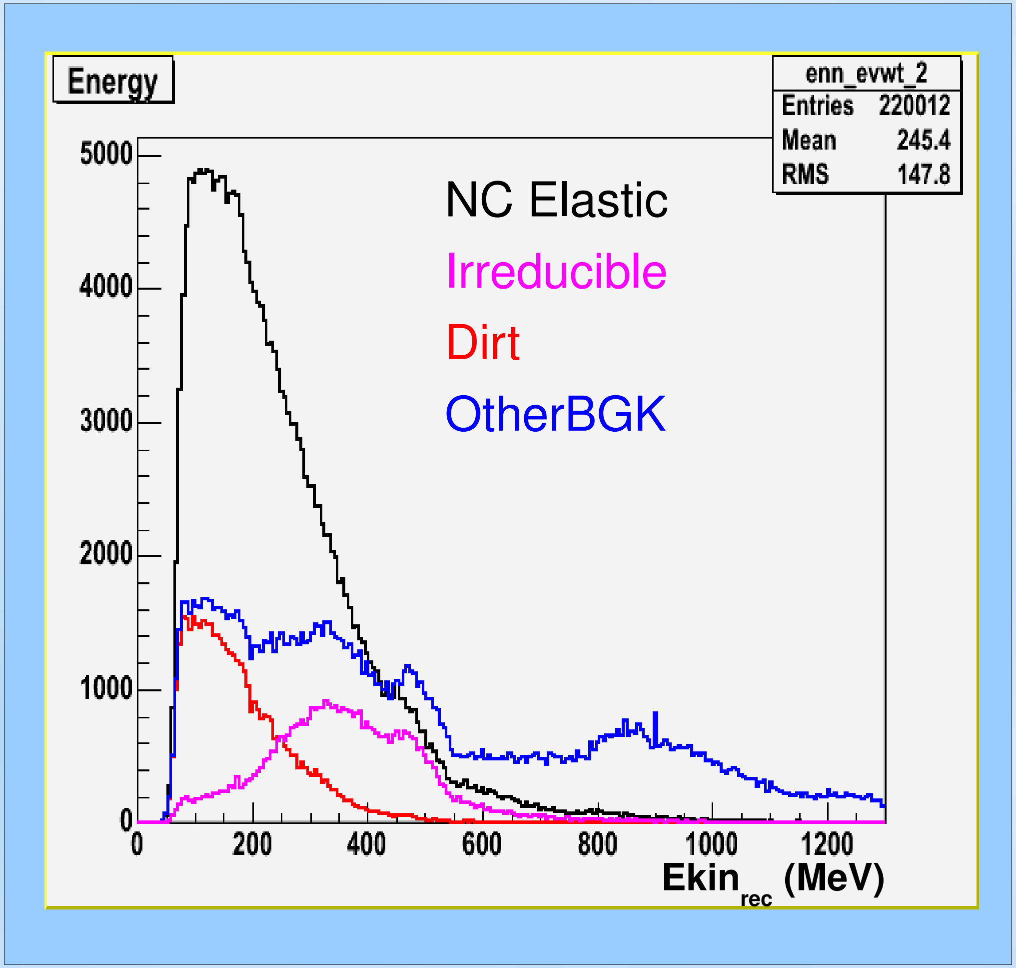

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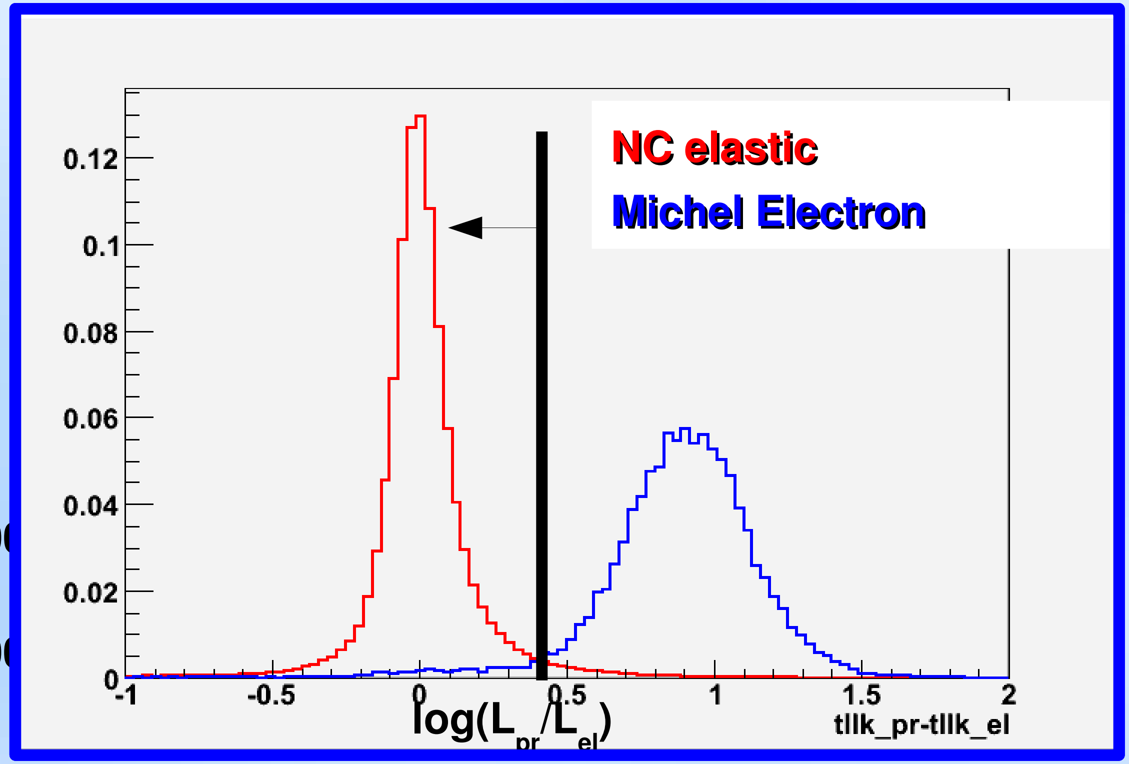

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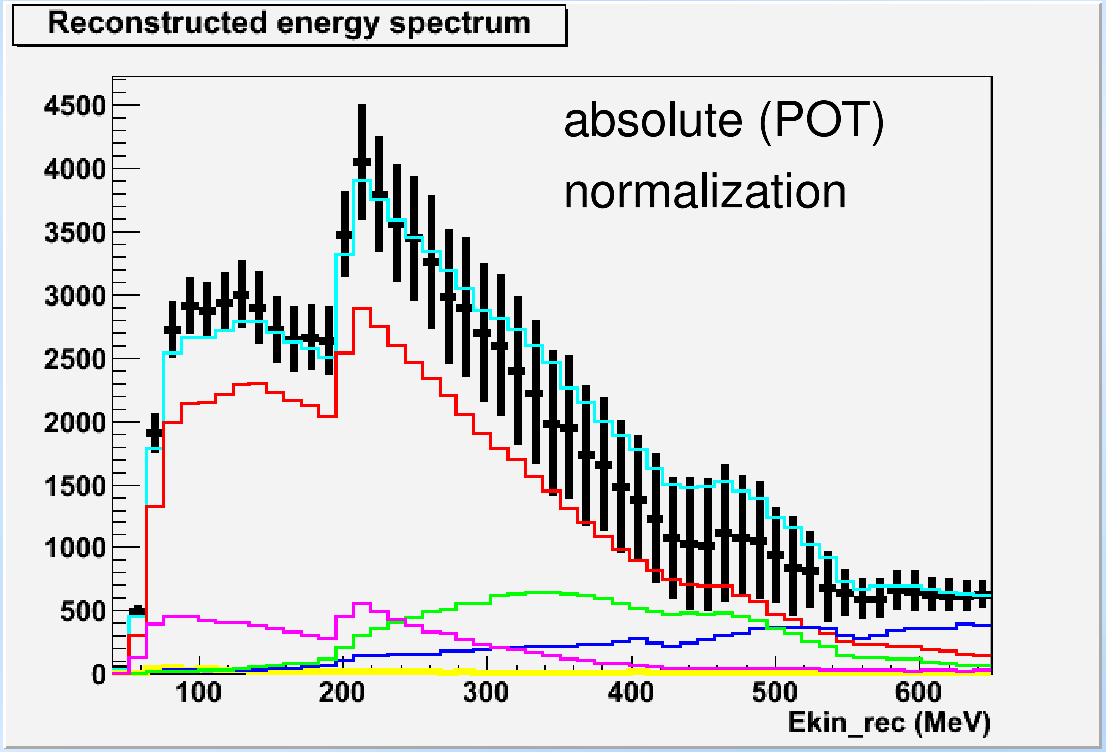
NC elastic events:



Data with total error

Total Monte Carlo

NC elastic (RFG, M_A=1.23 GeV)

Dirt

Irreducible

Beam unrelated

Other

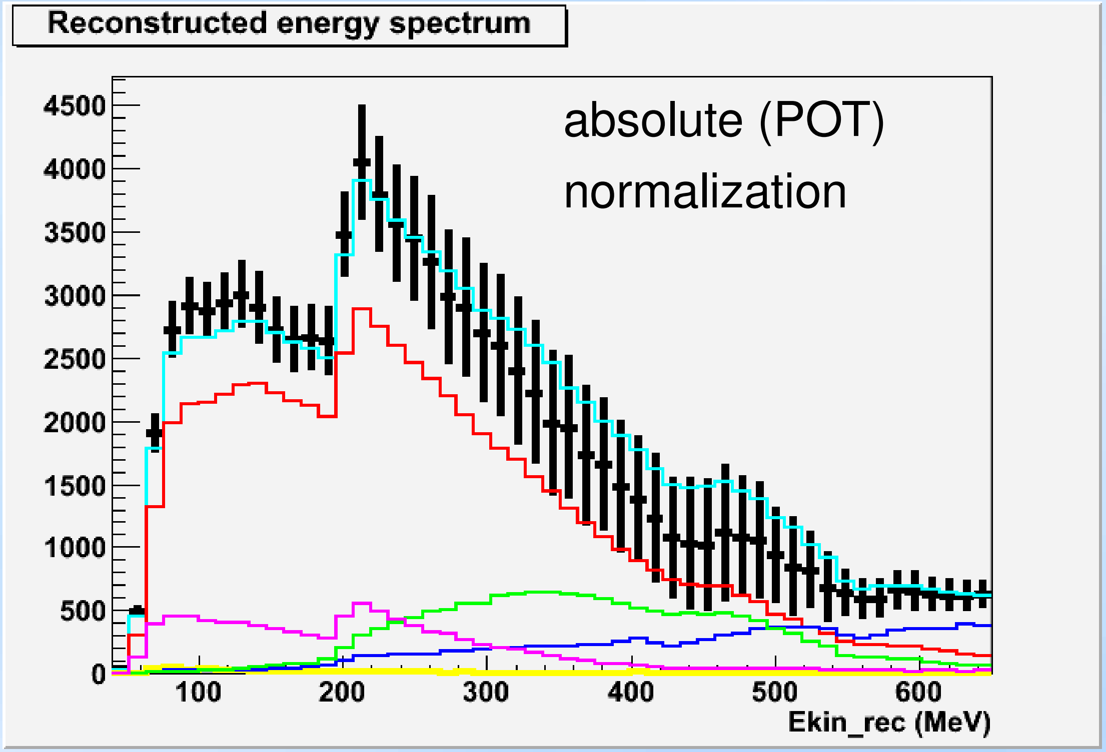
94.5K data events from

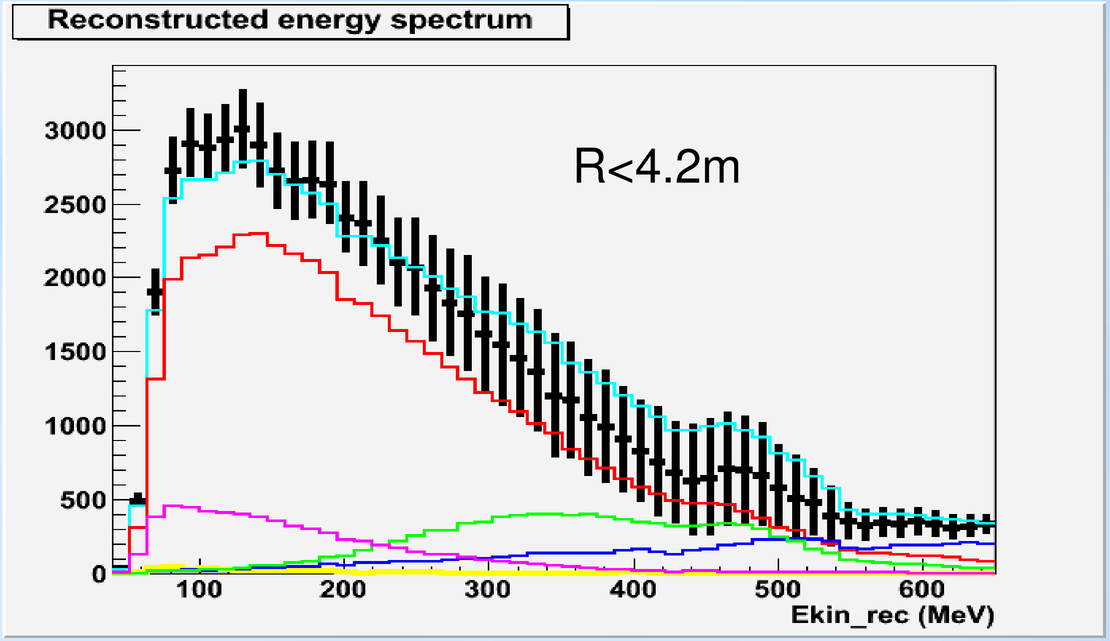
6.46 10^{20} POT

NCel efficiency = 26%

NCel purity = 65%

NC elastic events:





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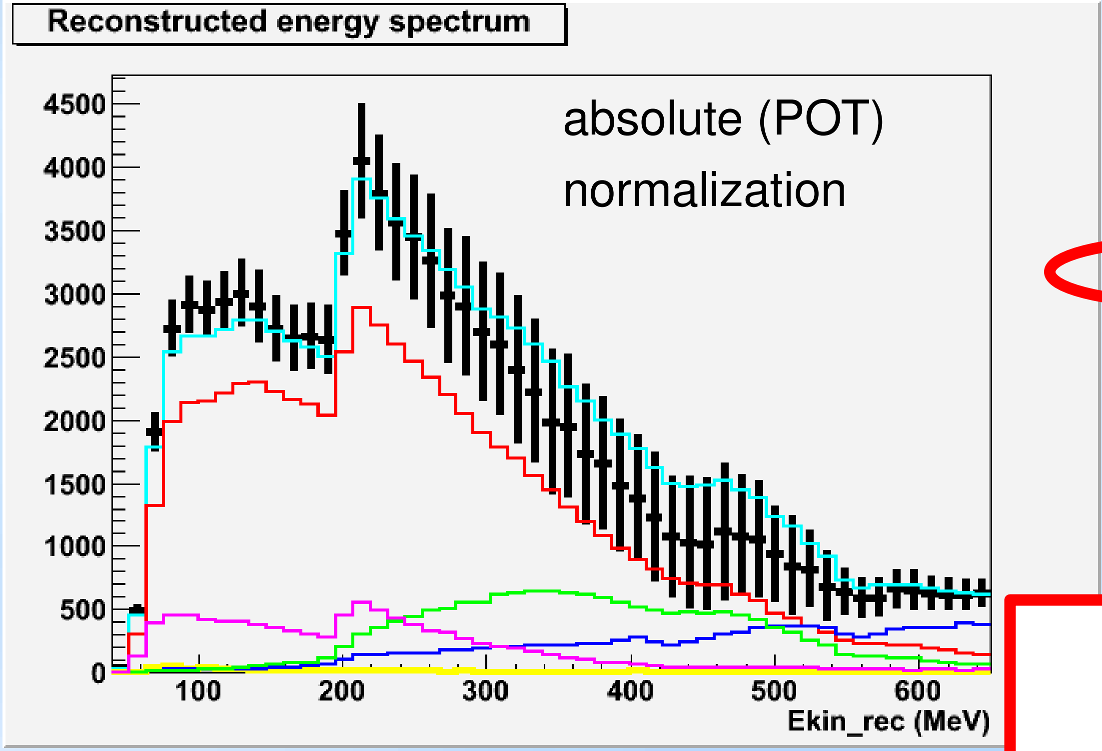

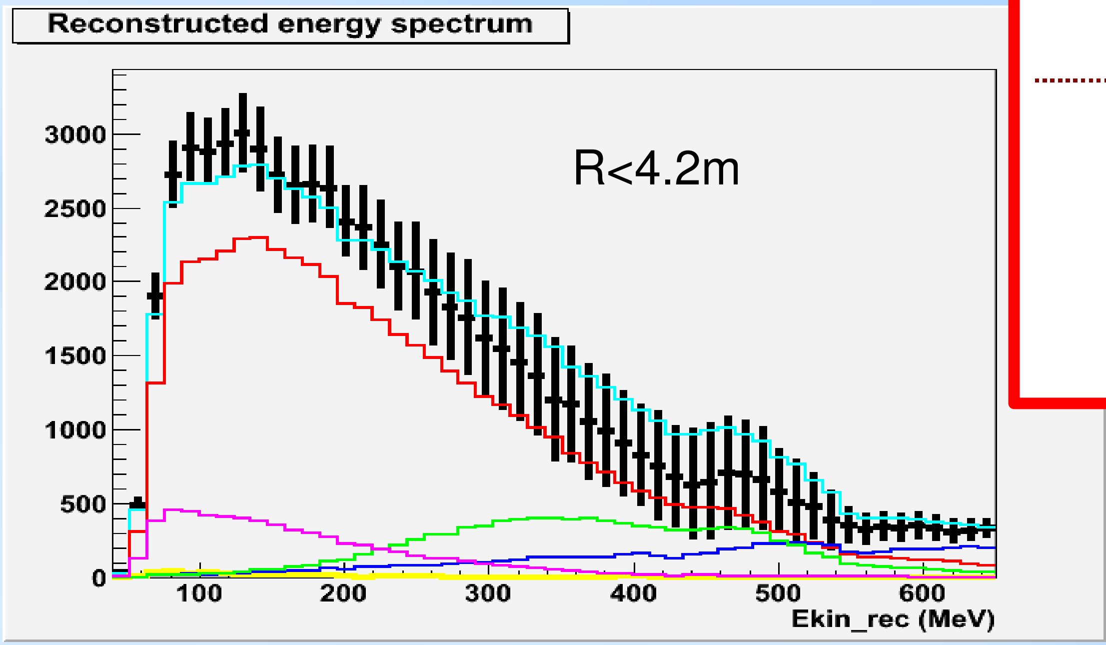

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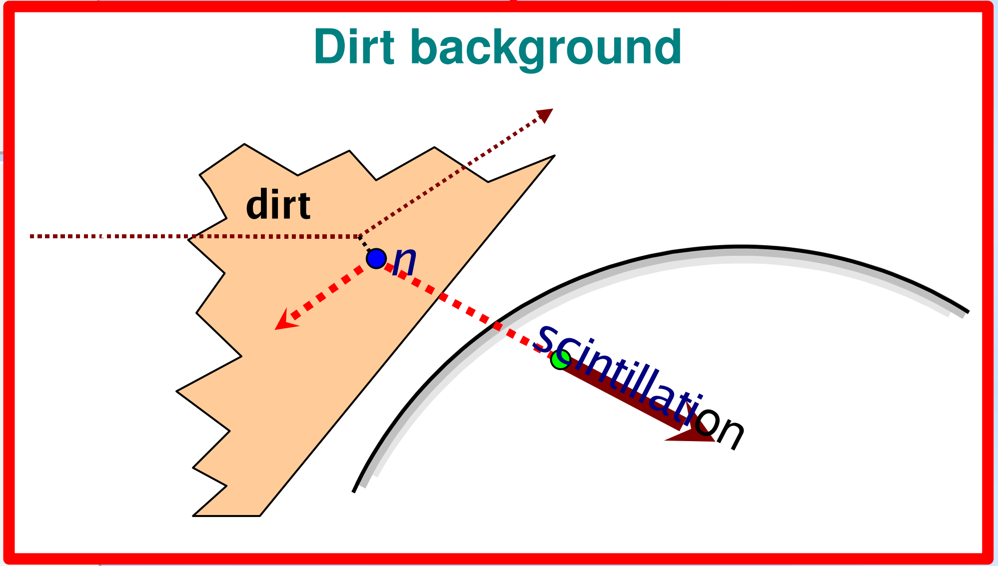
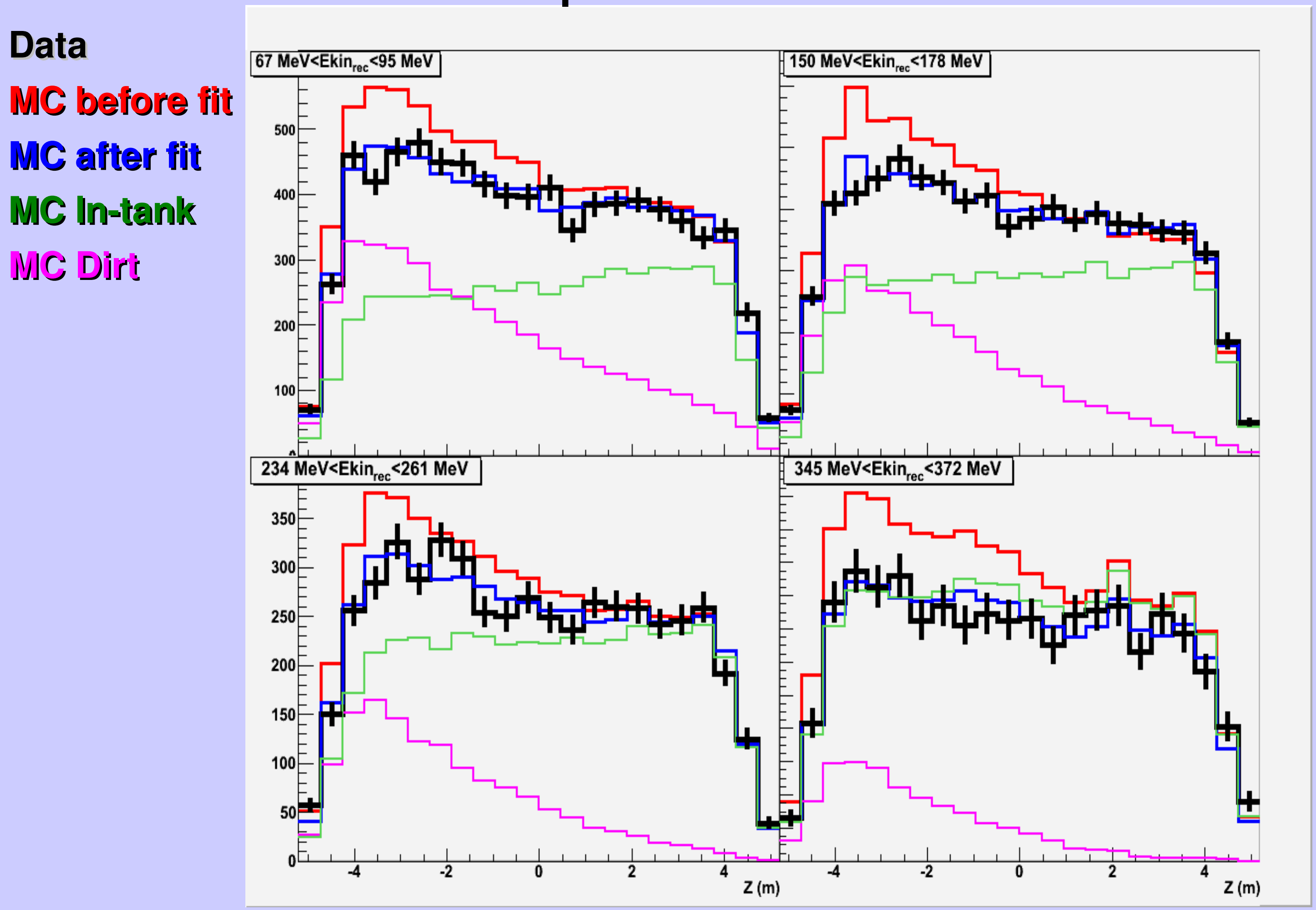


Low energy background

Dirt background measurement

We have measure the dirt event energy spectrum by looking at the ***dirt-enriched samples*** and fitting **Z**, **R** and **Energy** distributions.

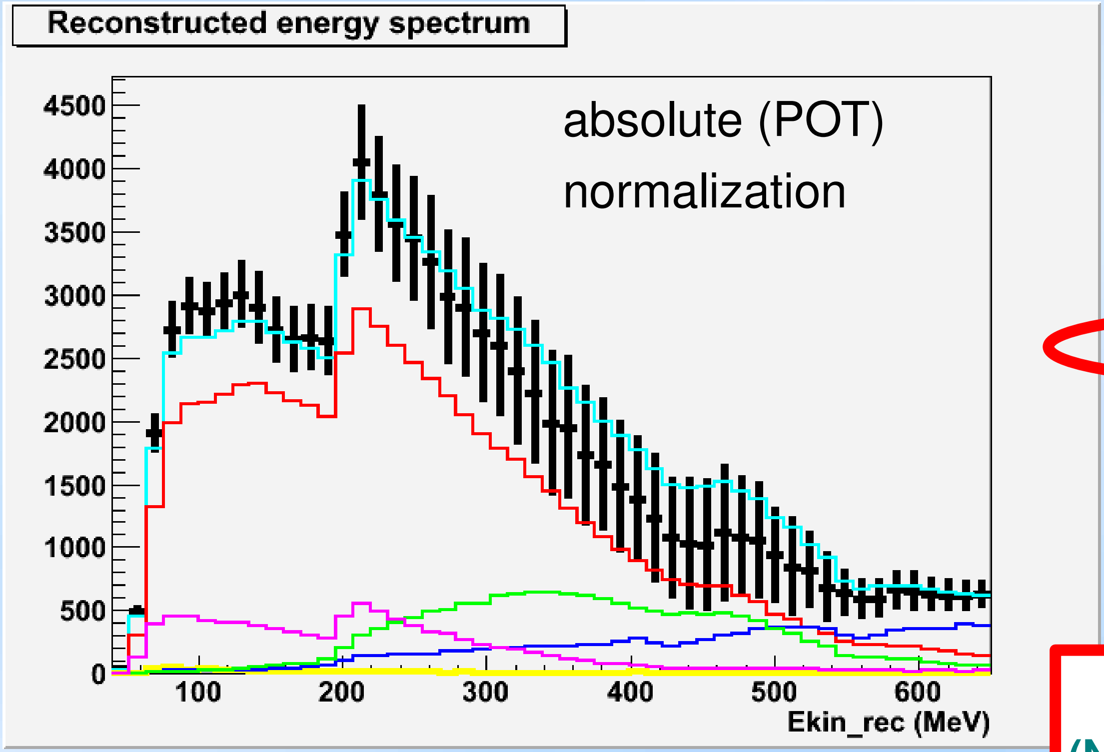
Z fit example. Events with 3.8m<R<5.0m



The three fits agree with each other, and MC/Data in Z and R distributions agreement is good after the fit.

We constrain dirt backgrounds to 10% error from MiniBooNE data.

NC elastic events:



Data with total error

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94.5K data events from 6.46 10^{20} POT

NCEL fraction	**65%**
Dirt background fraction	**10%**
Irreducible background fraction	**15%**

Irreducible background

(NC π channels with no pion in the final state)

$$\nu\, p \rightarrow \nu\, p\, \not{\pi}^0$$

$$\nu\, p \rightarrow \nu\, n\, \not{\pi}^+$$

$$\nu\, n \rightarrow \nu\, n\, \not{\pi}^0$$

$$\nu\, n \rightarrow \nu\, p\, \not{\pi}^-$$

intermediate energy background

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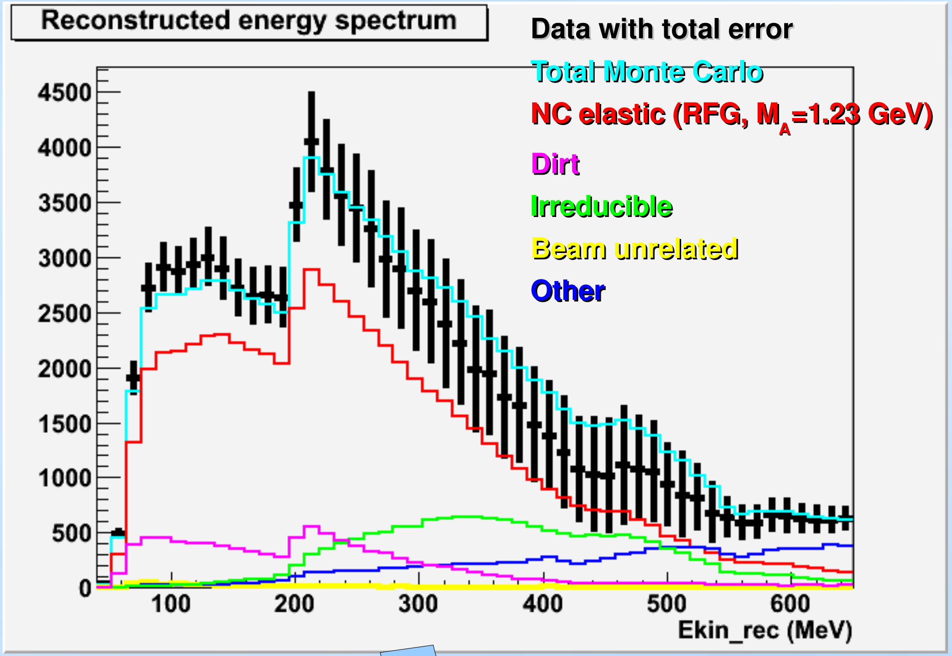
2. Analysis

Cross-section results

3. Conclusion

Calculating cross-section



Subtract backgrounds

NCE signal

Apply unsmearing procedure

(take into account the detector efficiency, energy resolution, and reconstruction bias)

NCE event rate

Multiply by appropriate number

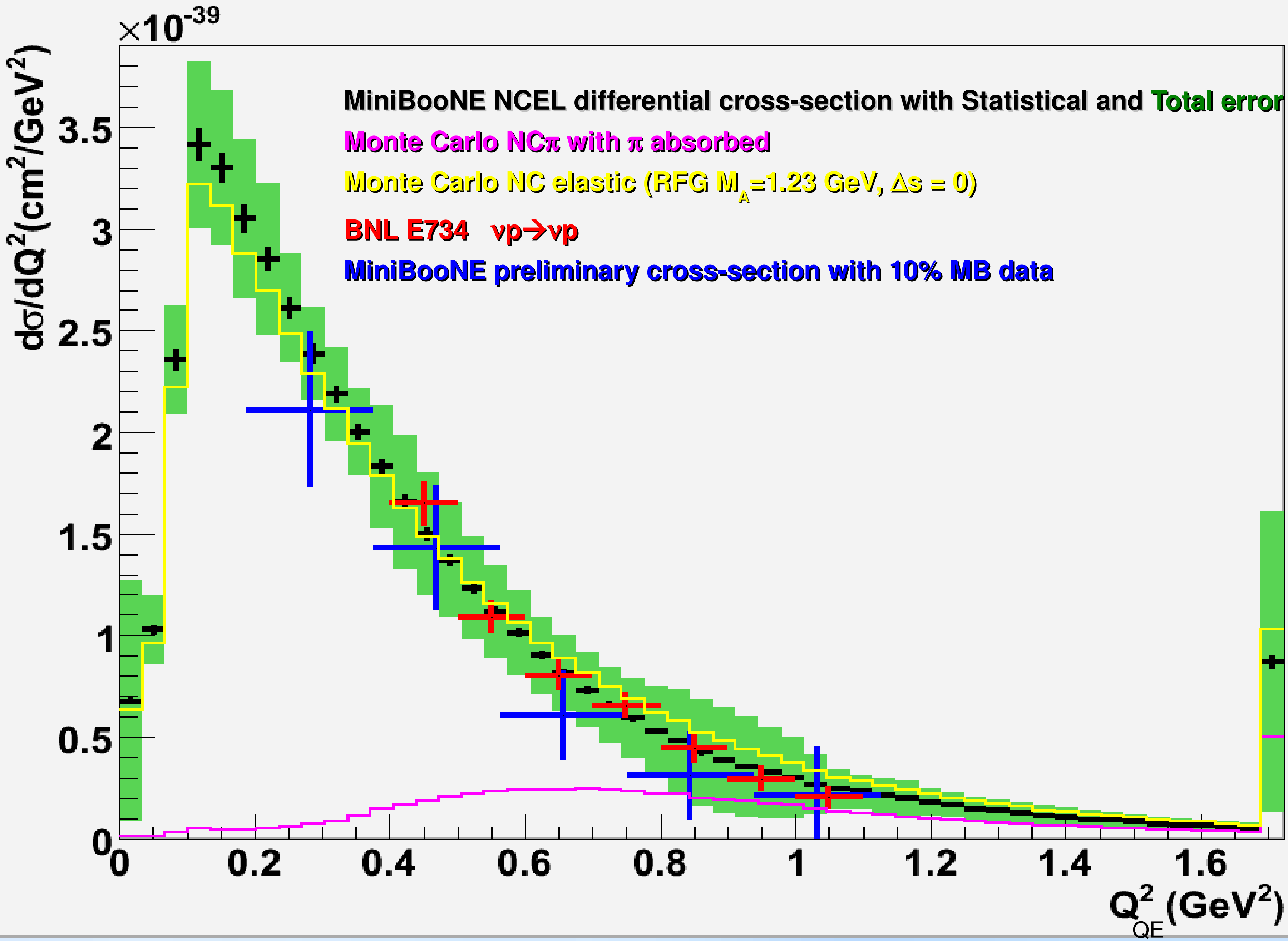
(Flux, number of nucleons etc)

$d\sigma/dQ^2$

Statistical and systematic NCE cross-section errors

Error type	%
Statistical	3.1
Discriminator threshold	1.1
QT PMT response	2.0
Dirt	1.4
POT	1.7
π^0 production	0.1
Additional hadronic error (photonuclear effect etc)	0.2
Cross-section	3.4
Horn uncertainties	4.7
K^0 production	0.1
K^+ production	0.5
π^- production	0.3
π^+ production	4.1
Optical model	12.3
Unfolding (unsmearing)	7.5
TOTAL	**18.9**

Results: Flux-averaged MiniBooNE NC elastic differential cross-section



Note: “Q^2_{QE}” = $2m_pT_p$

Outline

1. Neutral current elastic (NCE) events in MiniBooNE overview.

2. Analysis

Axial vector mass fit

3. Conclusion

Axial vector mass M_A

M_A is a parameter in the nucleon axial form factor with the dipole approximation. For CCQE

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

Historical value,

M_A=1.026±0.021GeV

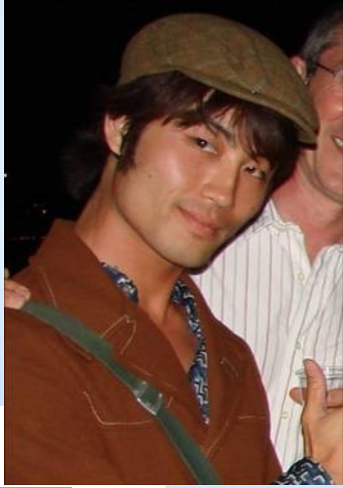
is set largely by deuterium-based bubble chamber experiments.

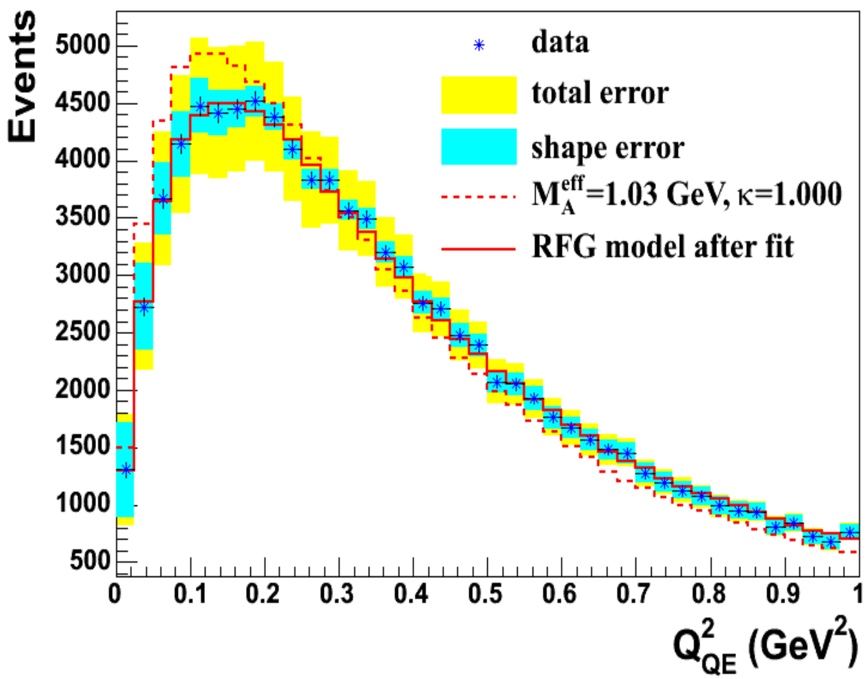
However recent M_A measurements from CCQE on Carbon ...

Axial vector mass M_A

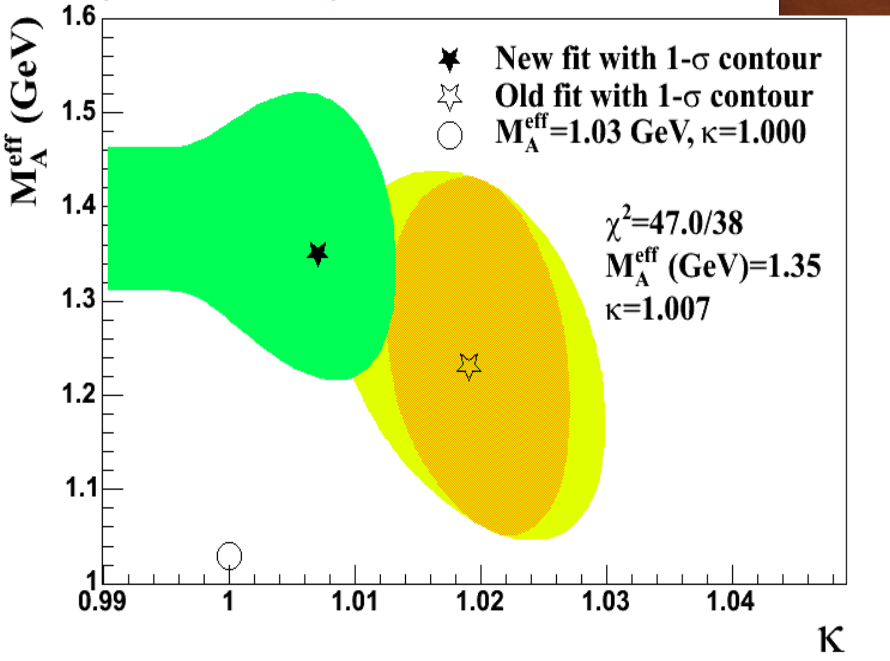
M_A/κ fits from MiniBooNE CCQE shows significantly higher M_A

(analysis is done by Teppei Katori, Ph.D)





Fit parameter space



M_A = 1.35±0.17

κ = 1.007±0.007

These higher M_A values are confirmed by K2K (twice), MINOS and SciBooNE

Can we test it with NC elastic?

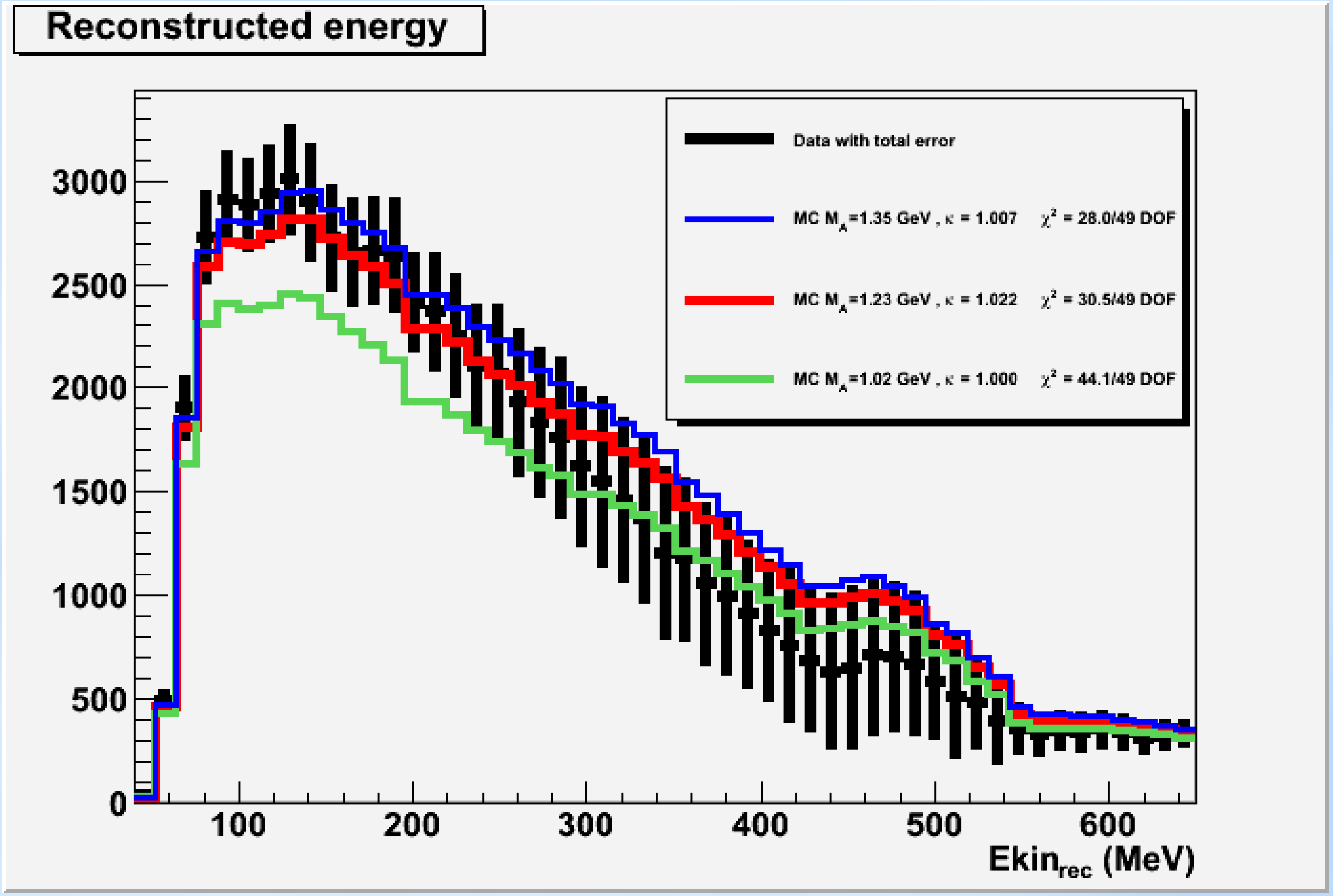
Axial vector mass M_A

For NCE, the axial form factor:

$$F_A(Q^2) = 0.5 \frac{\mp g_A + \Delta s}{(1+Q^2/M_A^2)^2}$$

\- for protons
\+ for neutrons

RFG model comparisons in reconstructed energy spectrum



NuInt09 MiniBooNE CCQE measurement

NuInt07 MiniBooNE CCQE measurement

World-averaged values before MiniBooNE

Monte Carlo with values of M_A 1.23 GeV and 1.35 GeV gives a better fit to the data, than 1.02 GeV, especially at low energies.

Outline

1. Neutral current elastic (NCE) events in MiniBooNE overview.

2. Analysis

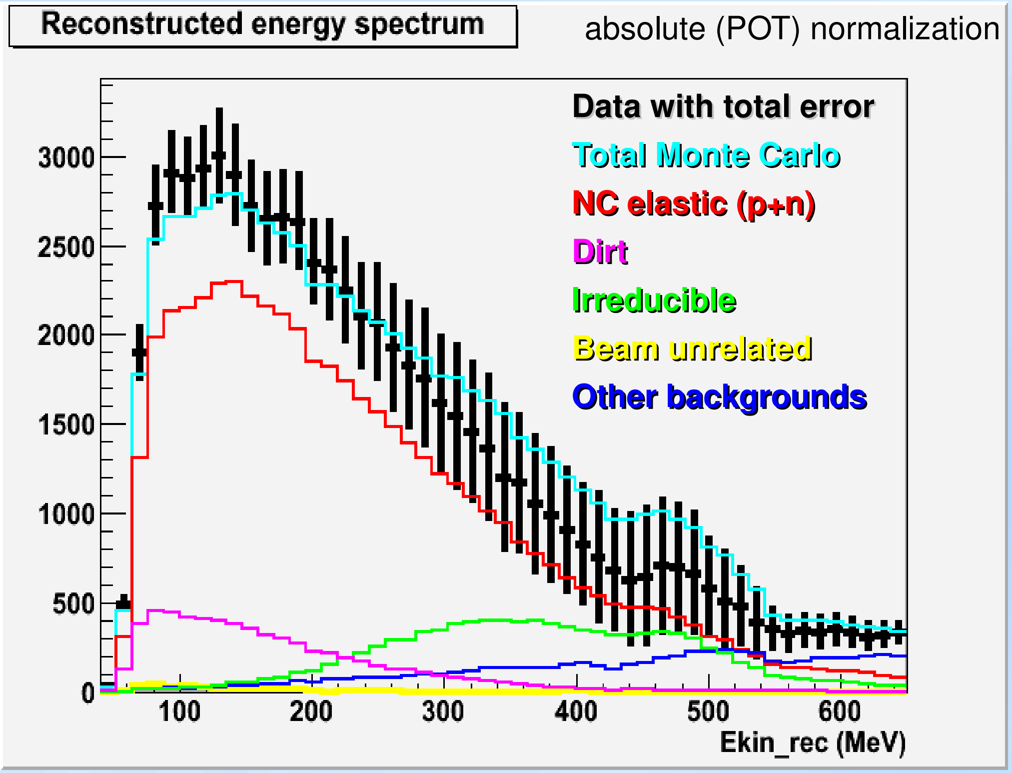
Δs measurement using high energy (above proton Cerenkov threshold) sample

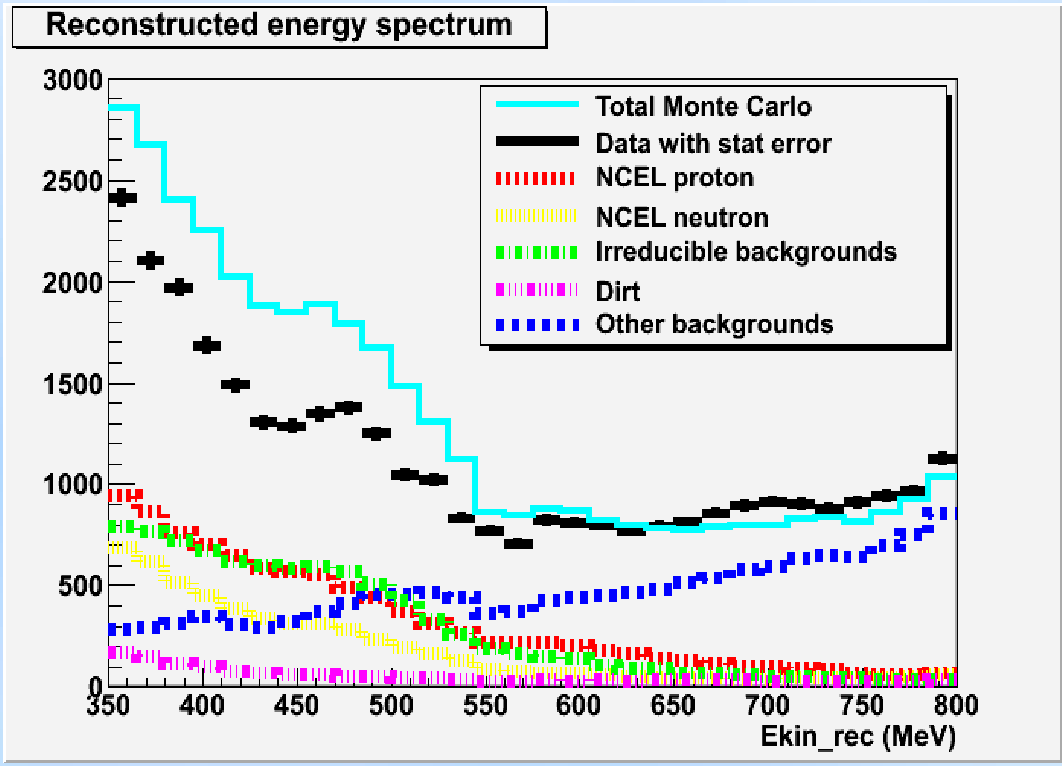
3. Conclusion

NCE proton-enhanced sample

In order to investigate G_A^s (Δs), need a proton-enhanced NCE sample..

Start with the high energy NCE reconstructed spectrum (after NCE cuts are applied):

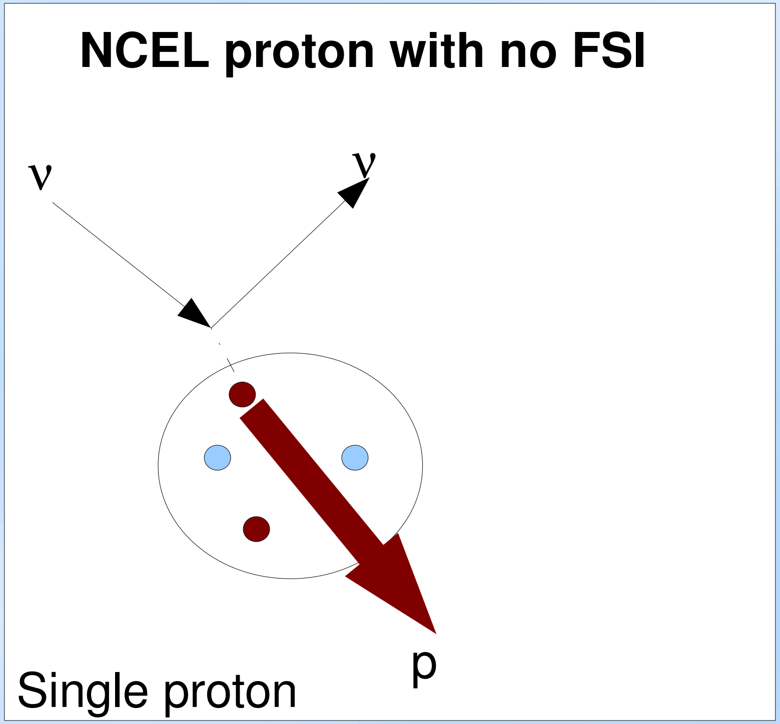


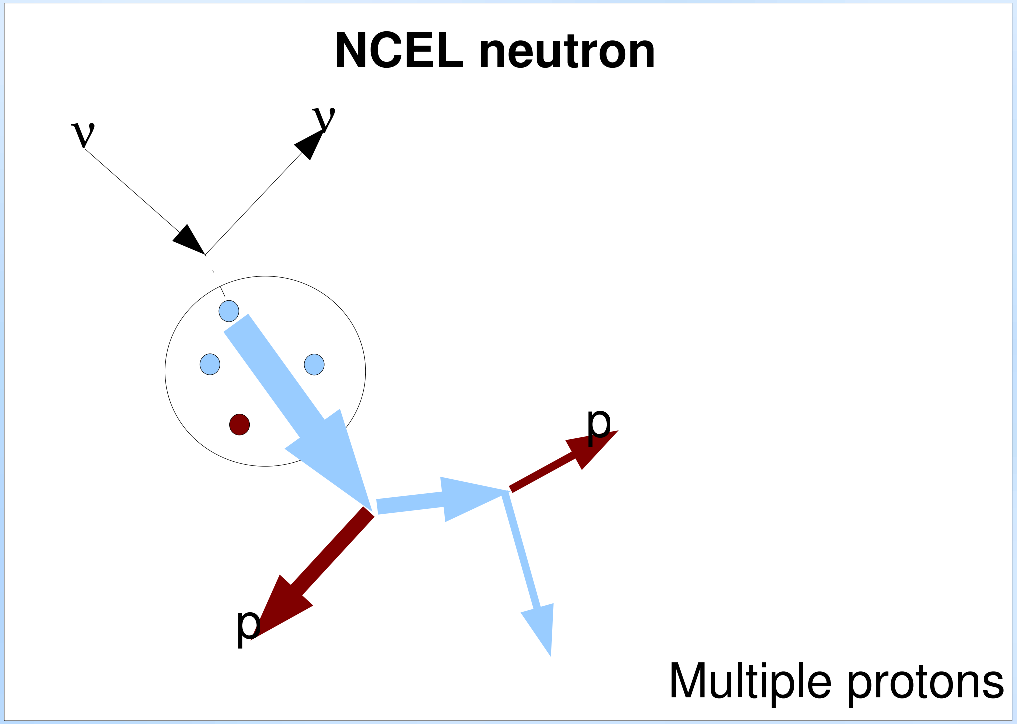


As one can see, much background. Signal (NCEL proton) is not strong.

NCE proton-enhanced sample

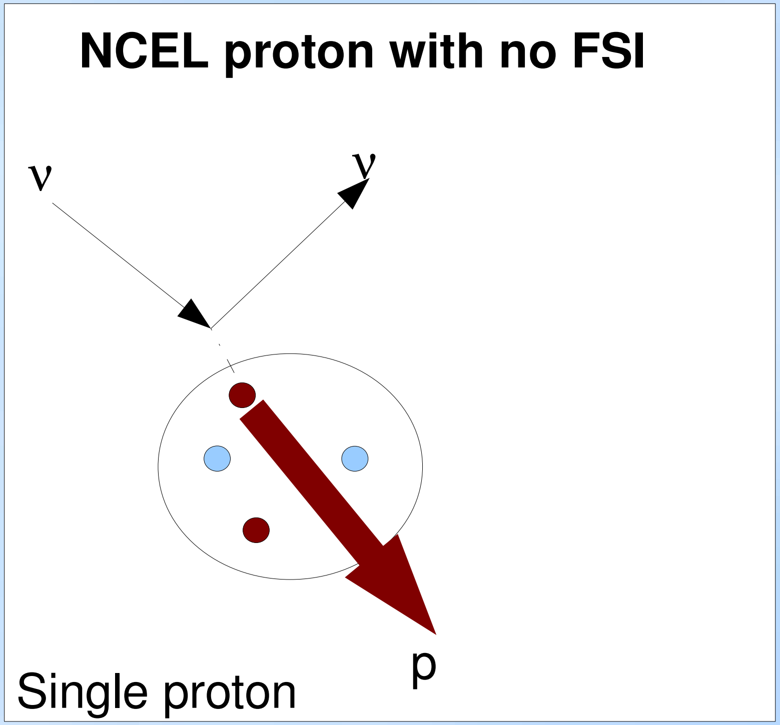
NCE proton particle identification

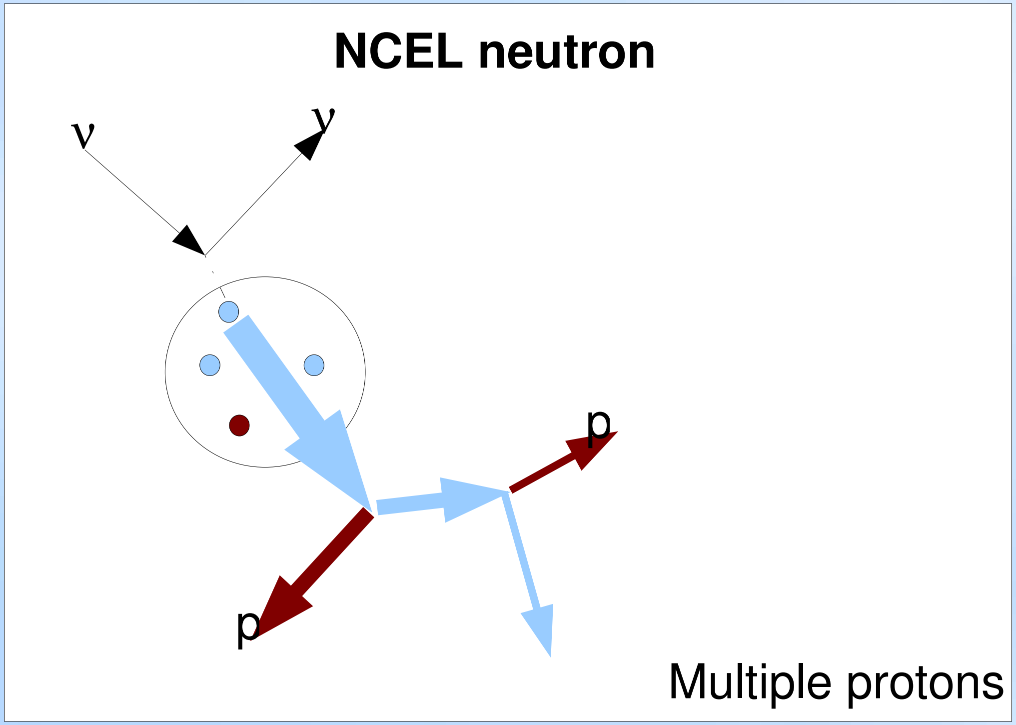


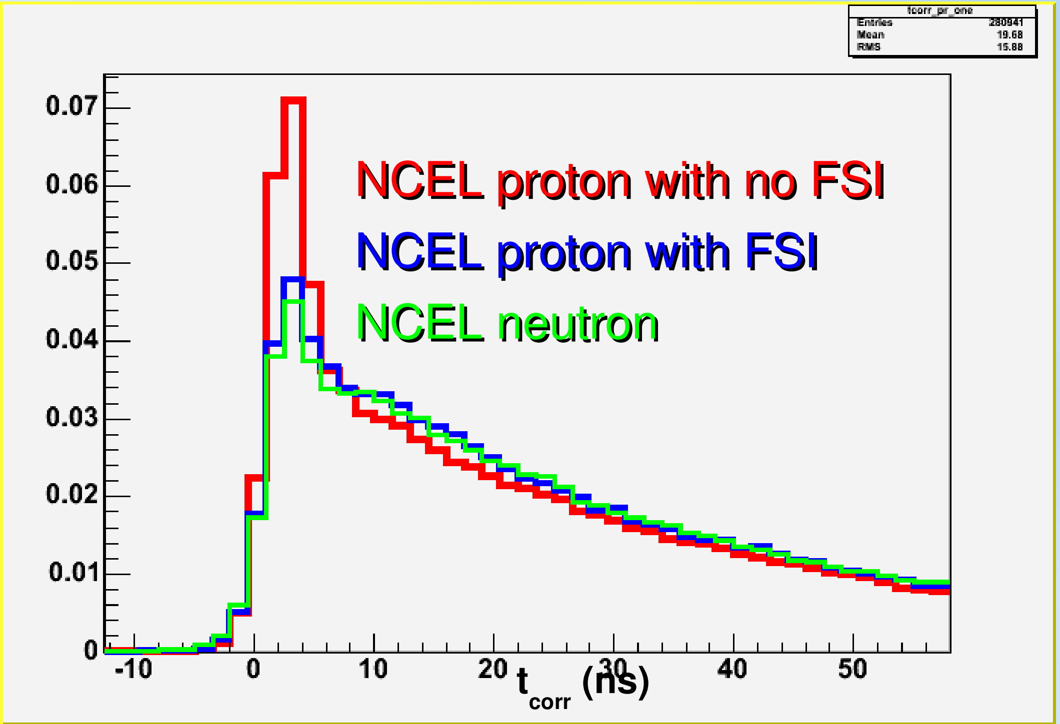


Single proton events should have more Cerenkov light fraction than multiple proton events (such as NCEL proton with FSI, NCEL neutron and Irreducible backgrounds)

NCE proton particle identification

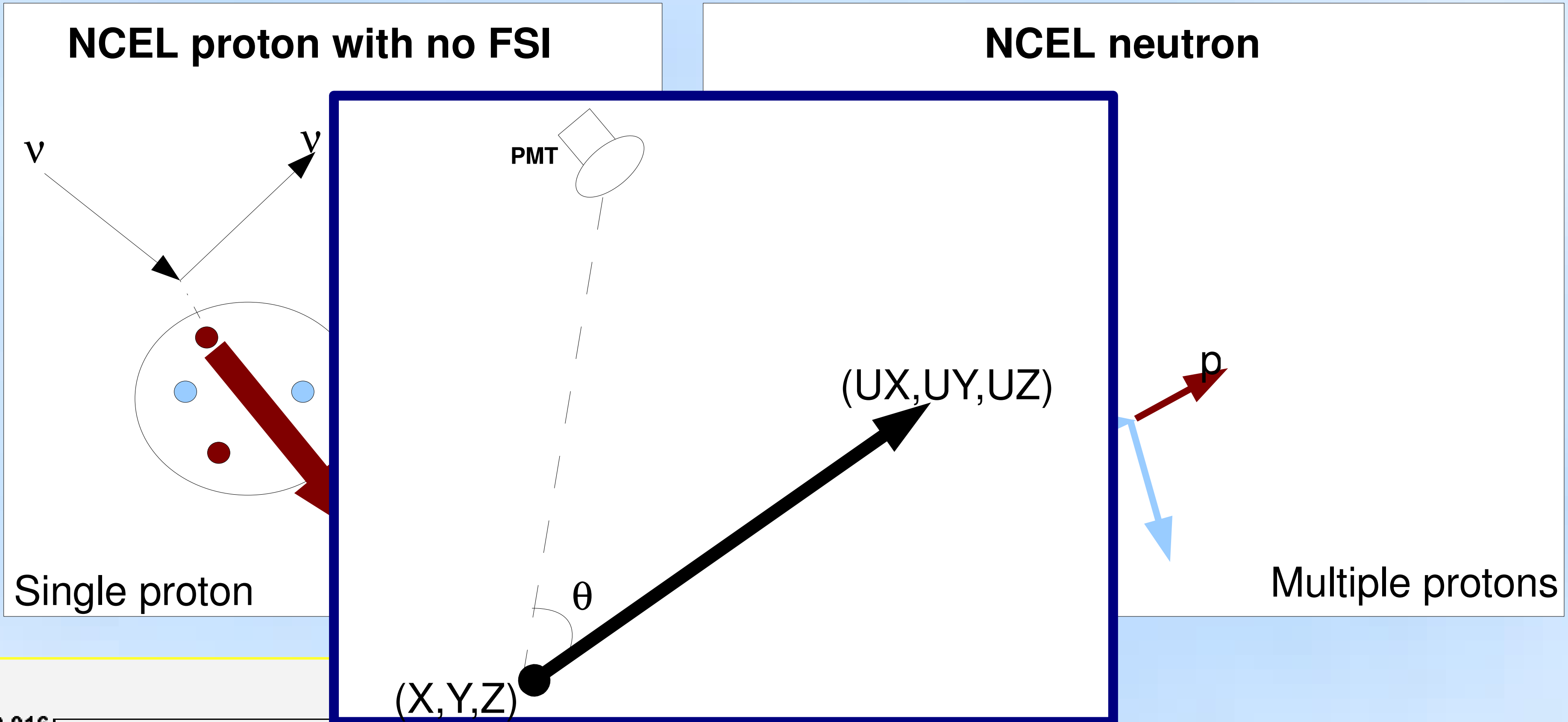


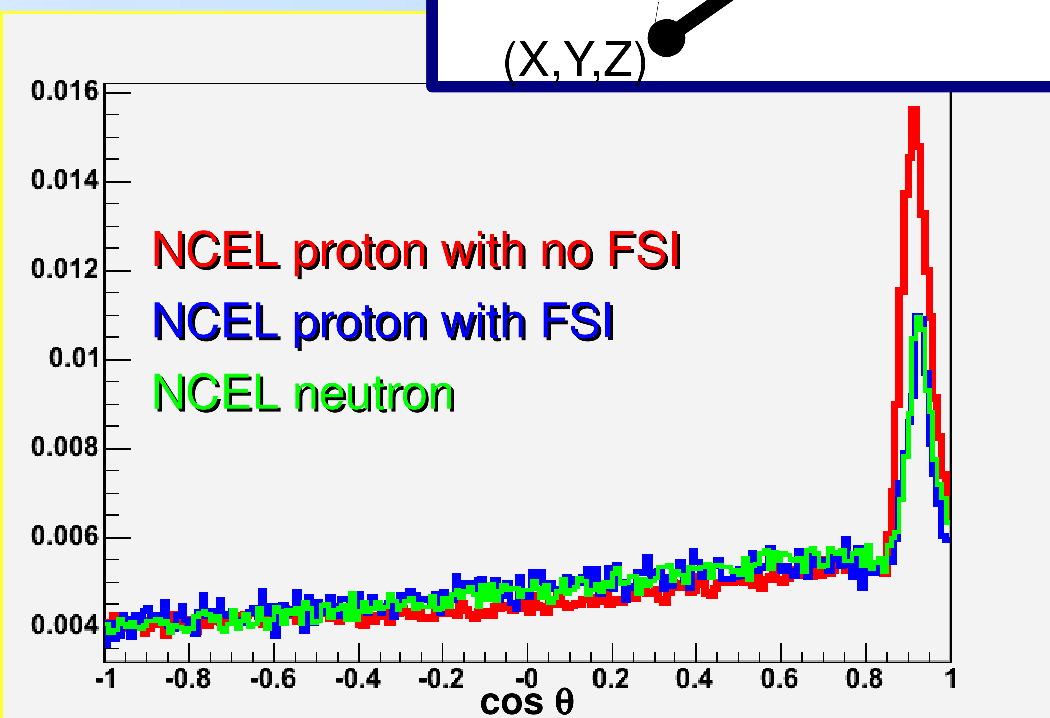




Single proton events have more prompt light

NCE proton particle identification





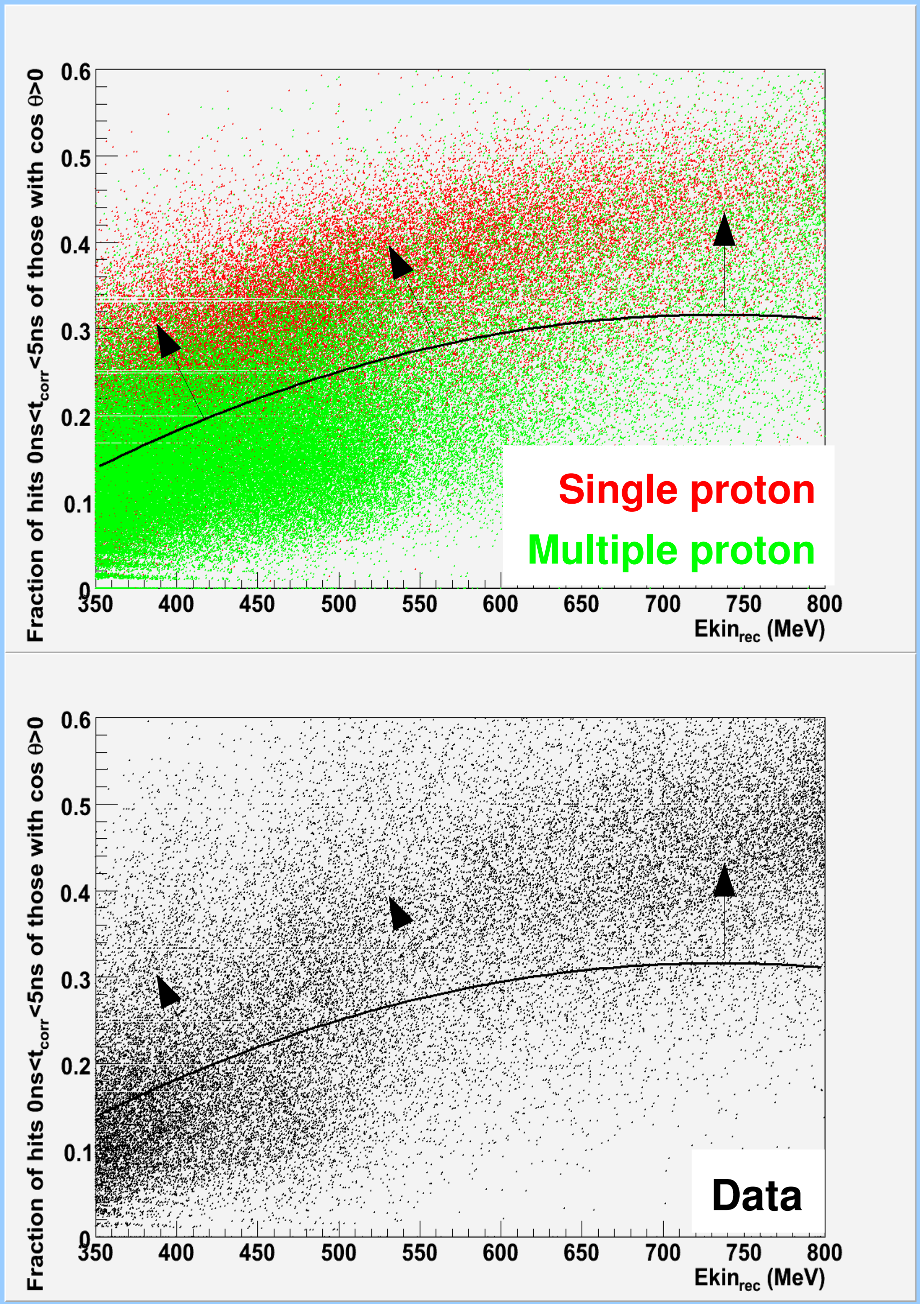
Single proton events have more directional light

Two additional PID cuts

(arrows indicate side of the cut is kept in the analysis)

p/n Cut

Fraction of prompt hits among PMTs that have cosθ > 0

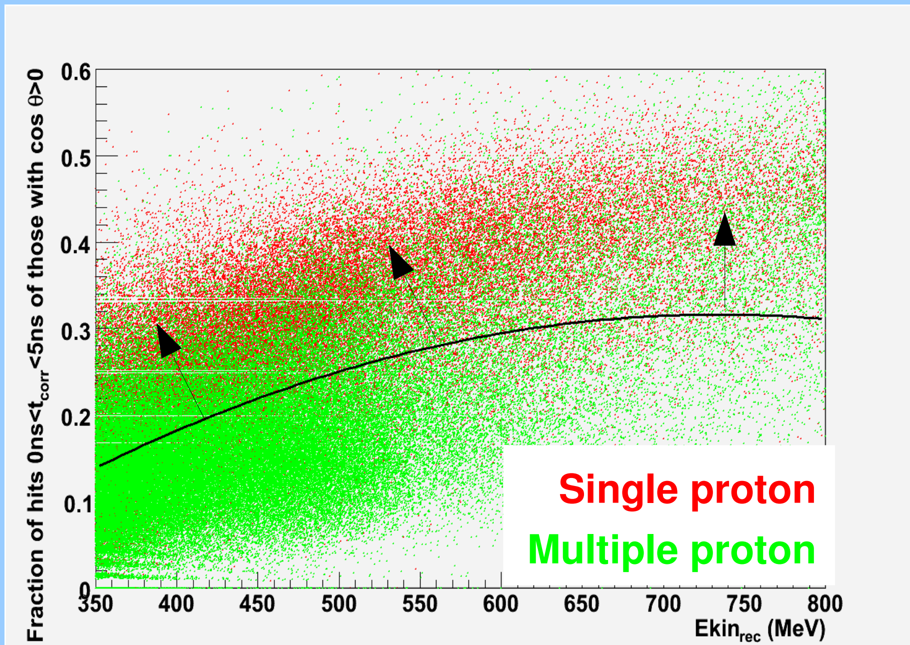


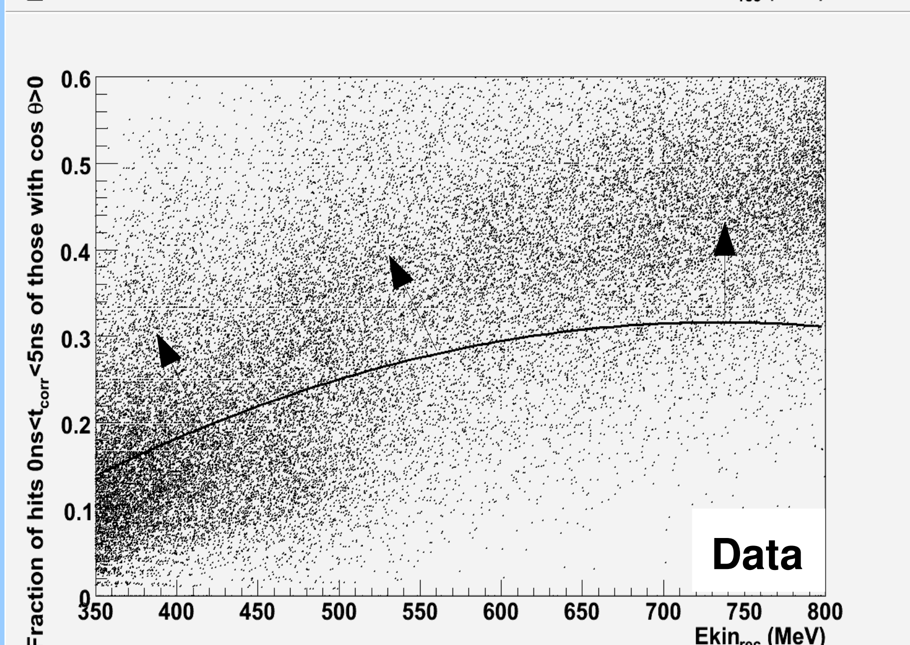
Two additional PID cuts

(arrows indicate side of the cut is kept in the analysis)

p/n Cut

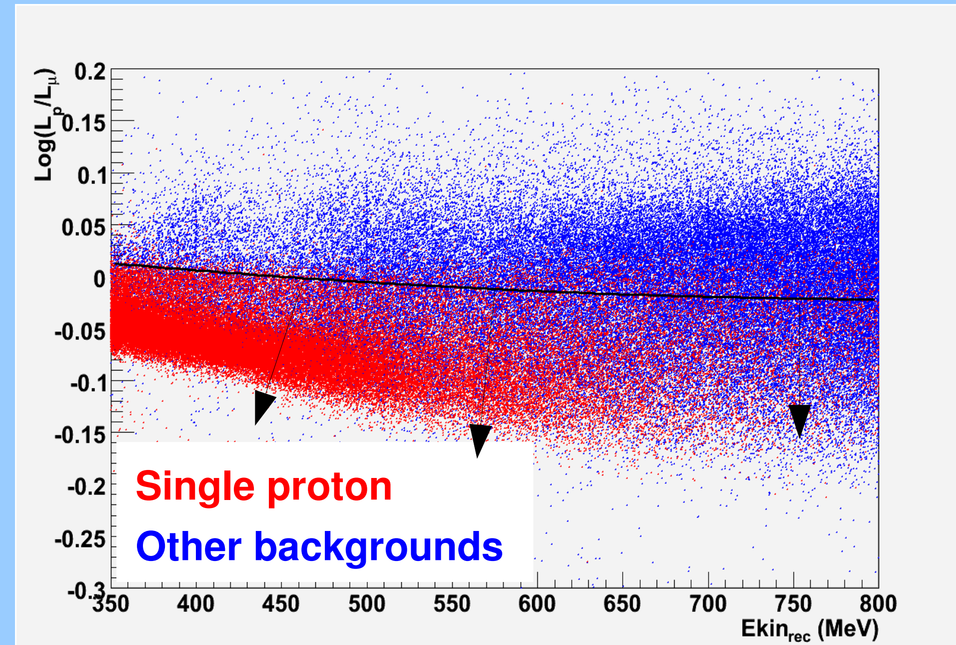
Fraction of prompt hits among PMTs that have cosθ > 0

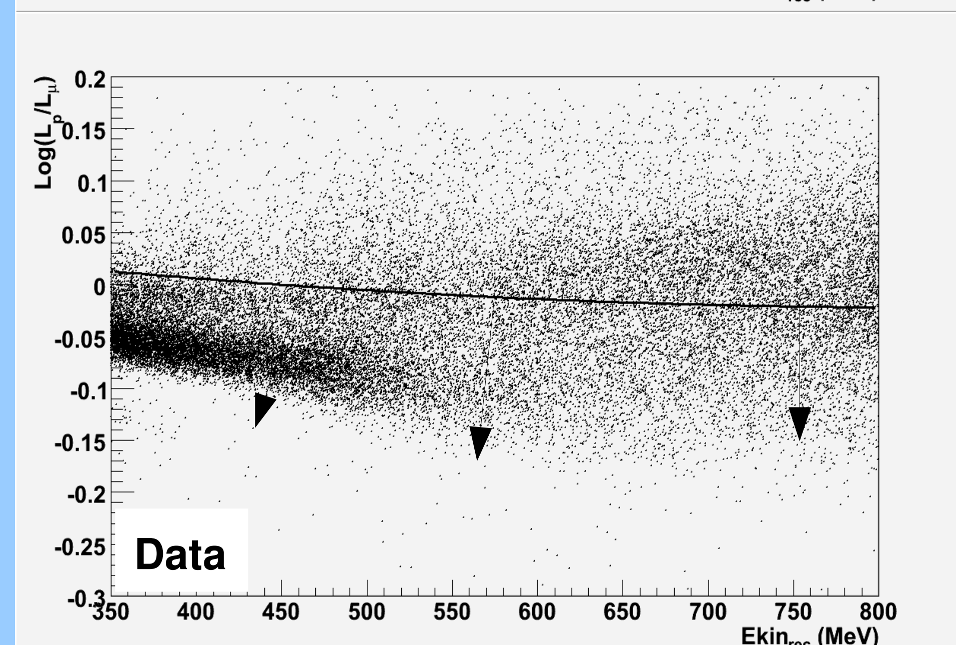




p/μ Cut

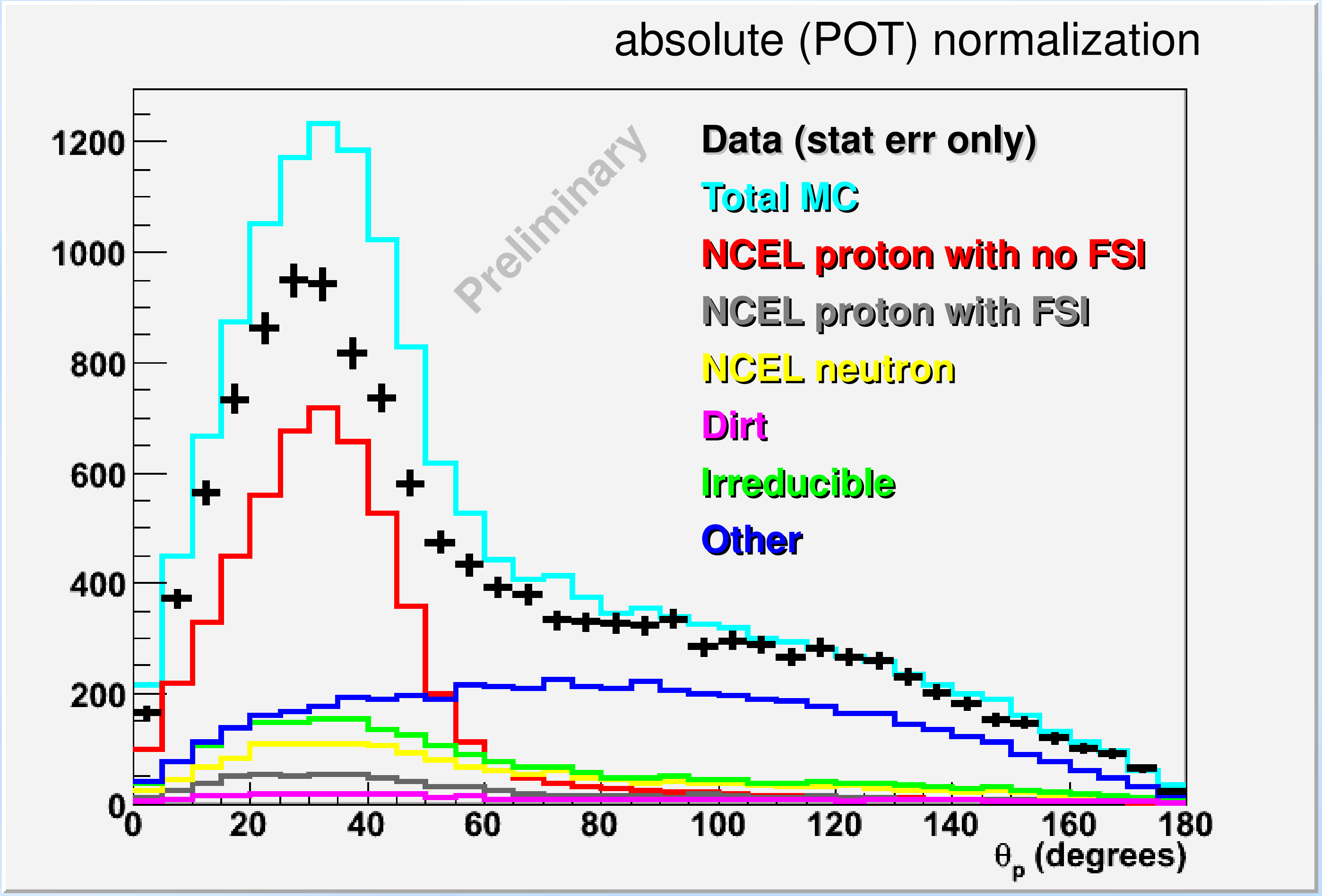
Likelihood ratio between proton and muon hypothesis





NC elastic proton-enhanced sample

Reconstructed proton angle with respect to the beam direction

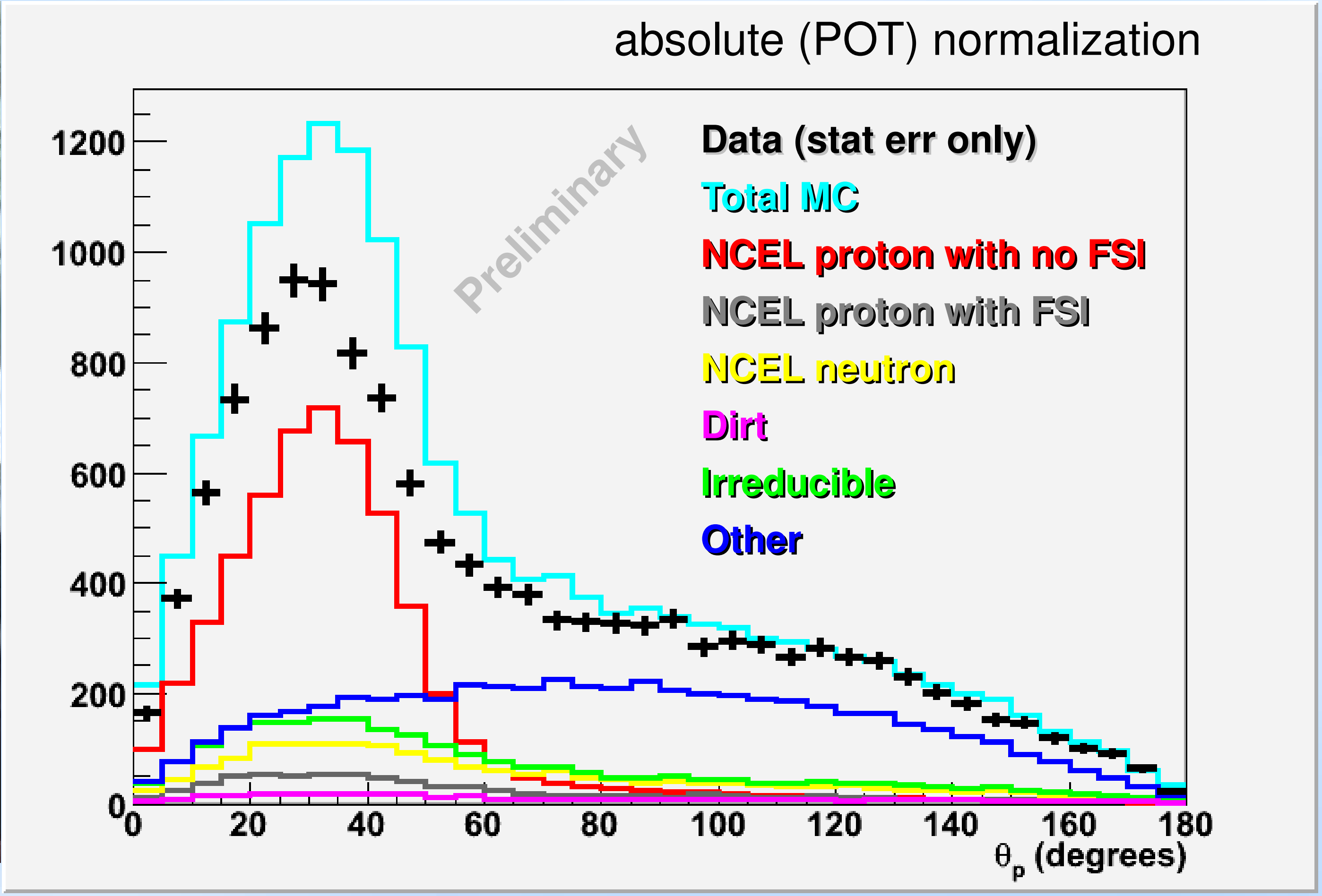


For the NCEL proton-enriched sample we make one more cut, $\theta_p < 60^o$

NC elastic proton-enhanced sample

Reconstructed proton angle with respect to the beam direction

Sam Zeller

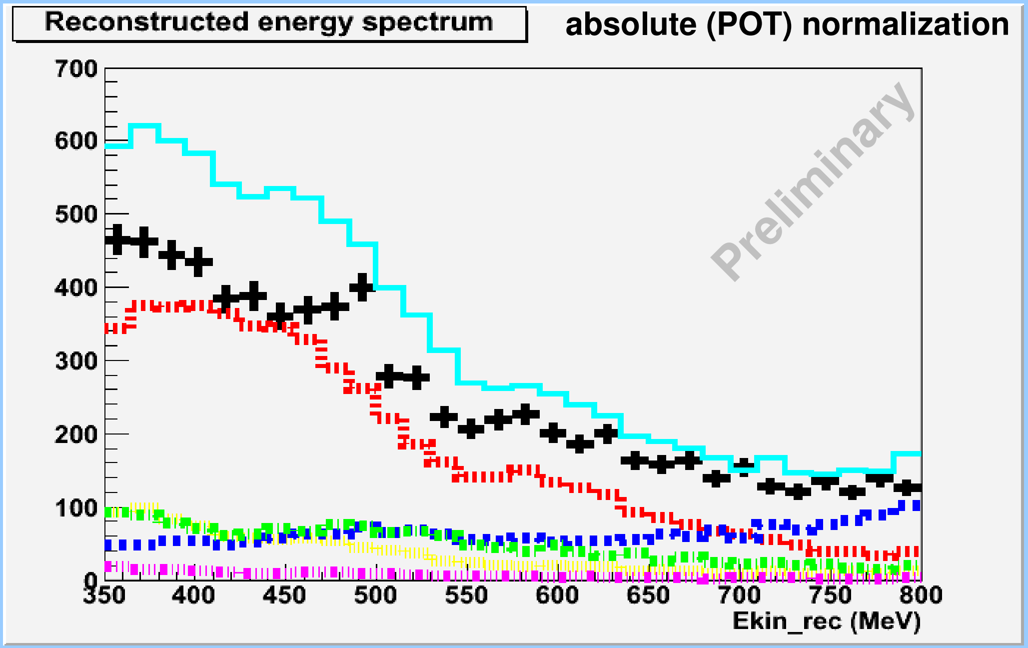


For the NCEL proton-enriched sample we make one more cut, $\theta_p < 60^{\circ}$

2 samples of NC elastic events

After NCE + p/μ + p/n + θ_p<60° ,

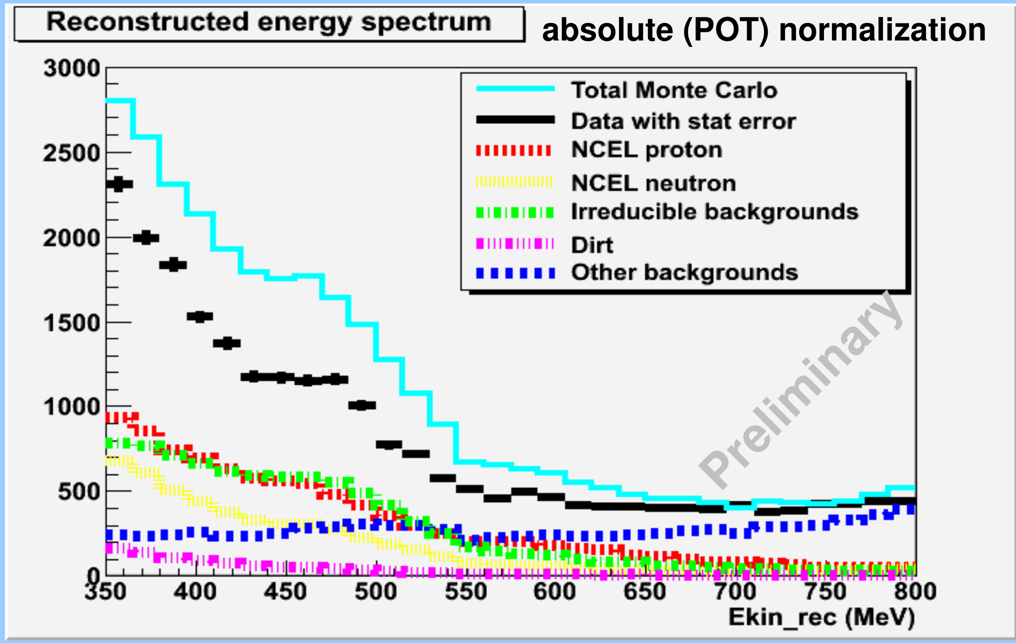
we get the **NCE p-enriched** sample:



NCE p fraction is 55%

After NCEL + p/μ,

we get the **NCE (p+n)** sample:



NCE (p+n) fraction is 45%

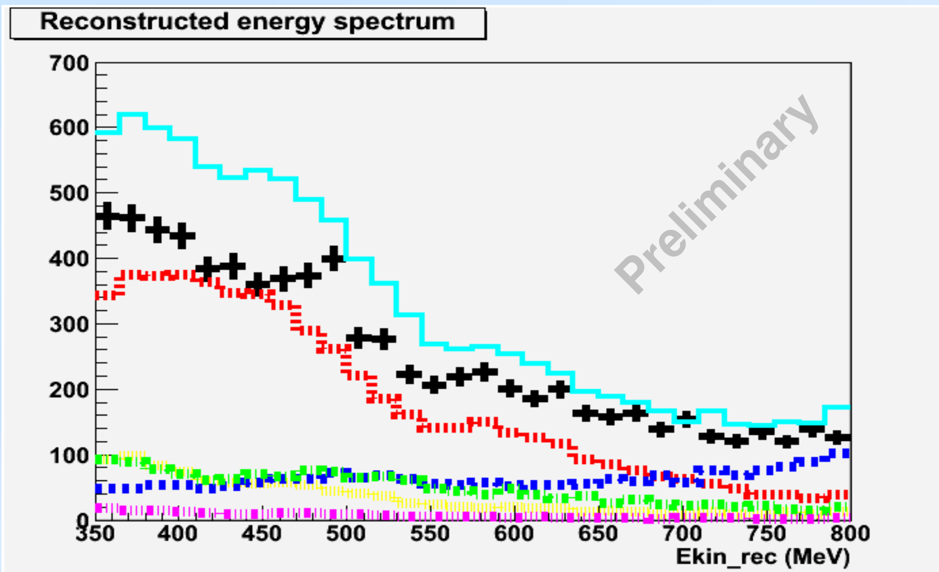
We can form a ratio in order to cancel systematics...

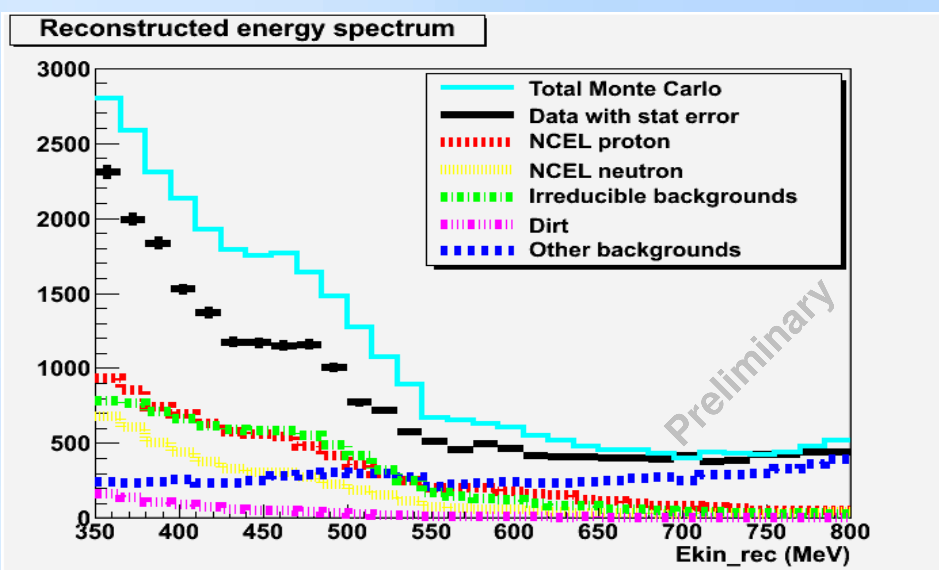
NC elastic ratio

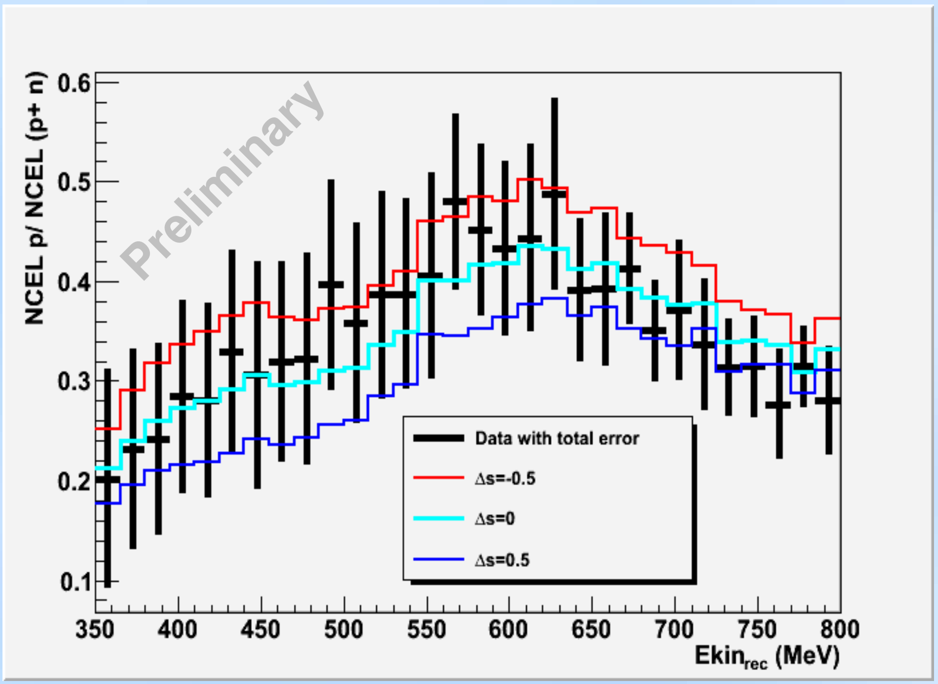
NCEL p / NCEL (p+n),

where the numerator – the NCEL proton-enriched sample,

the denominator has standard NCEL cuts, thus NCEL (p+n) sample







$\Delta s = 0.0 \pm 0.3$ (preliminary)

Conclusion

1. MiniBooNE has collected the world largest sample of neutrino NCE interactions (~94.5K NCE candidates) with high purity (65%). Currently it also has the largest sample of antineutrino NCE, which are waiting to be analyzed.

2. Measured flux-averaged NCE (p+n) cross-section.

3. A test of measured from CCQE M_A/κ on MiniBooNE NCE has been performed. Higher (~1.2-1.3 GeV) values of M_A are preferred.

4. Using the high energy NCE proton-enriched sample we have measured the ratio NCE p /NCE (n+p) in order to reduce systematics. From the ratio measurement, the strange quark contribution in the nucleon has been extracted, $\Delta s = 0.0 \pm 0.3$ (preliminary)

BACKUPS

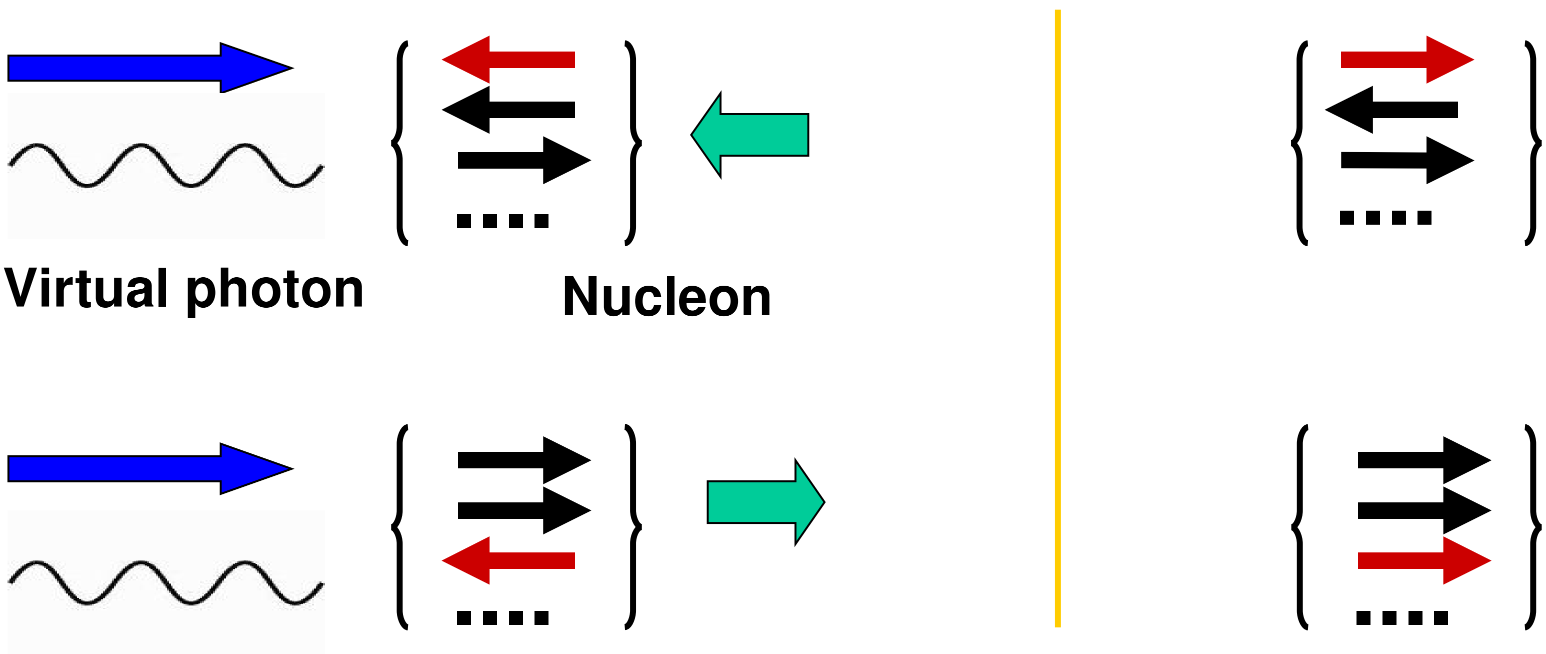
How was it measured?

Quark Helicity Distributions, Flavor Separation

Double-spin asymmetry

$$e + N \rightarrow e' + X$$

Polarized beam and polarized target

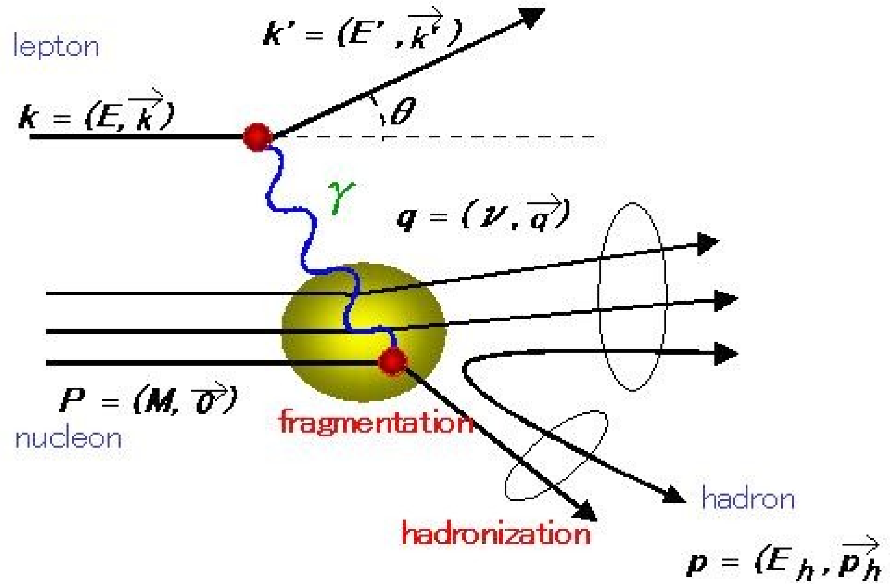


$$A_1(x,z) = \frac{\sigma_{\rightleftarrows}(x) - \sigma_{\rightrightarrows}(x)}{\sigma_{\rightleftarrows}(x) + \sigma_{\rightrightarrows}(x)}$$

Asymmetry, Polarized Quarks

$$\sigma_h(x,z) \propto \sum_q e_q^2\, q(x)\; D_q^h(z)$$

(quark distribution) x
(fragmentation function)



$$A_1(x,z) = \frac{\sigma_{\rightleftarrows}(x) - \sigma_{\rightrightarrows}(x)}{\sigma_{\rightleftarrows}(x) + \sigma_{\rightrightarrows}(x)}$$

$q(x) = q^{\leftarrow}(x) + q^{\rightarrow}(x)$ **Quark Density Distribution**

$\Delta q(x) = q^{\leftarrow}(x) - q^{\rightarrow}(x)$ **Quark Helicity Distribution**

Neutral current elastic cross-section on a free nucleon

$$\frac{d\sigma}{dQ^2}=\frac{G_F^2 Q^2}{2\pi E_\nu^2}\left(A(Q^2)+B(Q^2)W+C(Q^2)W^2\right)$$, where

$$W=\frac{4E_\nu}{M_N}-\frac{Q^2}{M_N^2} \qquad \tau=\frac{Q^2}{4\mathrm{M}_N}$$

$$A(Q^2)=\frac{1}{4}[(F_A^Z)^2(1+\tau)-((F_1^Z)^2-\tau(F_2^Z)^2)(1-\tau)+4\tau F_1^Z F_2^Z]$$

$$B(Q^2)=-\frac{1}{4}F_A^Z(F_1^Z+F_2^Z)$$

$$C(Q^2)=\frac{M_N^2}{16\mathrm{Q}^2}[(F_A^Z)^2+(F_1^Z)^2+\tau(F_2^Z)^2]$$

At low Q^2,

$$\frac{d\sigma}{dQ^2} \sim (F_A^Z(0))^2 + (F_1^Z(0))^2 + O(Q^2)$$

Under CVC

$$F_i^Z(Q^2) = (\frac{1}{2} - \sin^2\theta_W)[F_i^{EM,p} - F_i^{EM,n}]\tau_3 - \sin^2\theta_W [F_i^{EM,p} + F_i^{EM,n}] - \frac{1}{2} F_i^s$$

$$F_A^Z(Q^2) = \frac{\tau_3}{2} F_A - \frac{1}{2} F_A^s$$, where τ_3 is +1 for protons and -1 for neutrons

At $Q^2=0$

$$F_1^{Z,p}(0) = \frac{1}{2} - 2\sin^2\theta_W \approx 0$$

$$F_1^{Z,n}(0) = -\frac{1}{2}$$

$$F_A(0) = g_A$$

$$F_A^s(0) = \Delta s$$

$$\frac{d\sigma_{\nu p}}{dQ^2} \sim g_A^2 - 2\Delta s + (\Delta s)^2$$

$$\frac{d\sigma_{\nu n}}{dQ^2} \sim 1 + g_A^2 + 2\Delta s + (\Delta s)^2$$

In MiniBooNE we measure

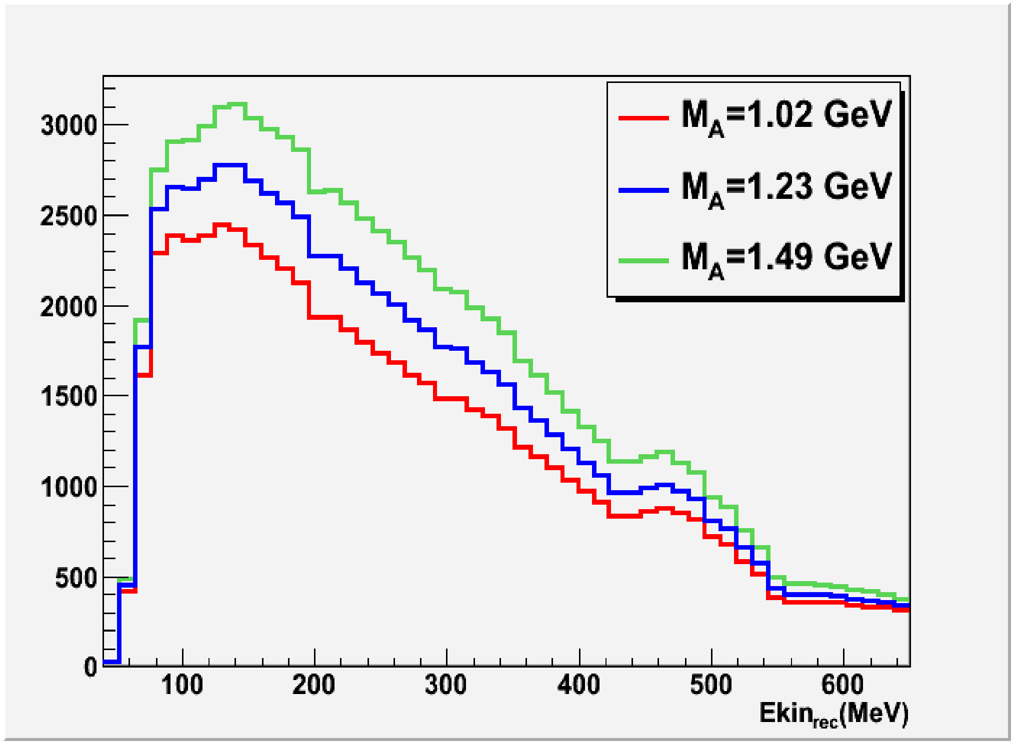
$$\frac{d\sigma_{NCE}}{dQ^2}=\frac{1}{7}\frac{d\sigma_{\nu p,H}}{dQ^2}+\frac{3}{7}\frac{d\sigma_{\nu p,C}}{dQ^2}+\frac{3}{7}\frac{d\sigma_{\nu n,C}}{dQ^2}$$

$$\approx\frac{1}{2}\frac{d\sigma_{\nu p}}{dQ^2}+\frac{1}{2}\frac{d\sigma_{\nu n}}{dQ^2}$$

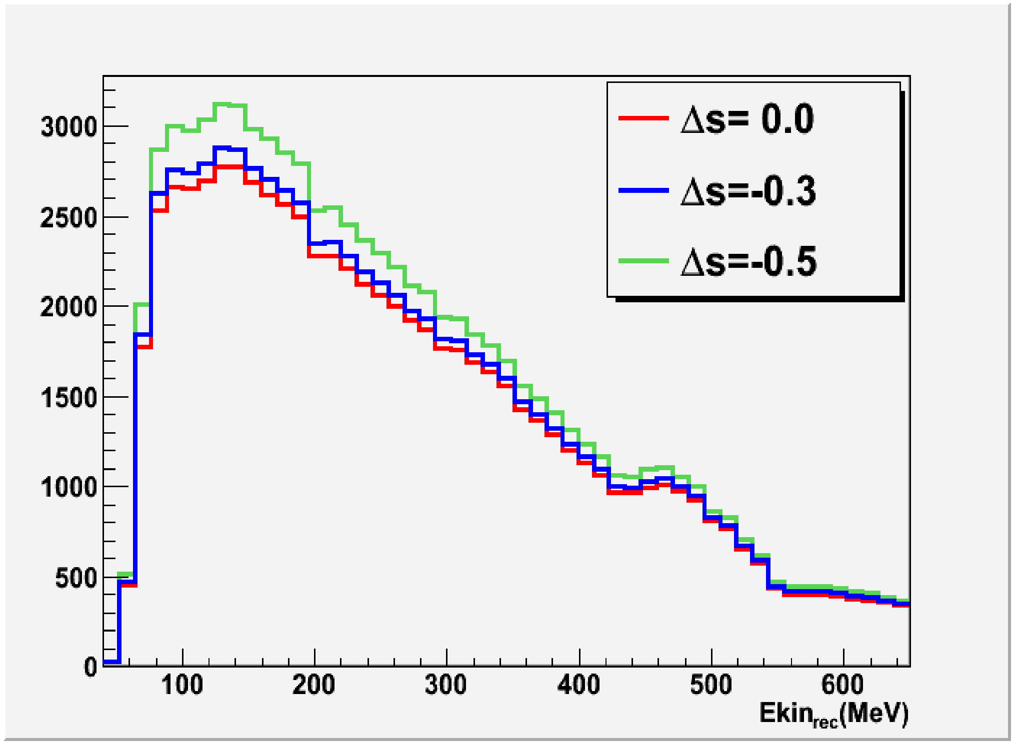
$$\sim\frac{1}{2}+g_A^2+(\Delta s)^2$$

Thus, at small values of Δs, the cross-section doesn't depend on it in the first order

Different M_A



Different Δs

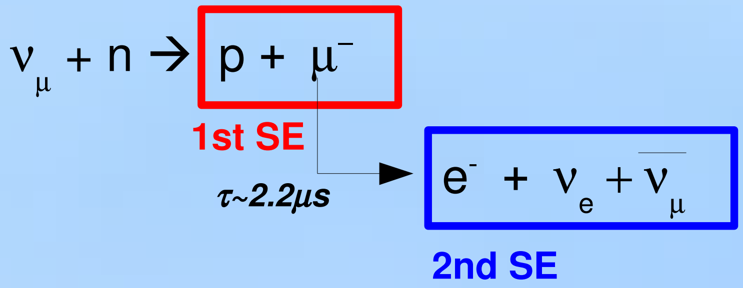


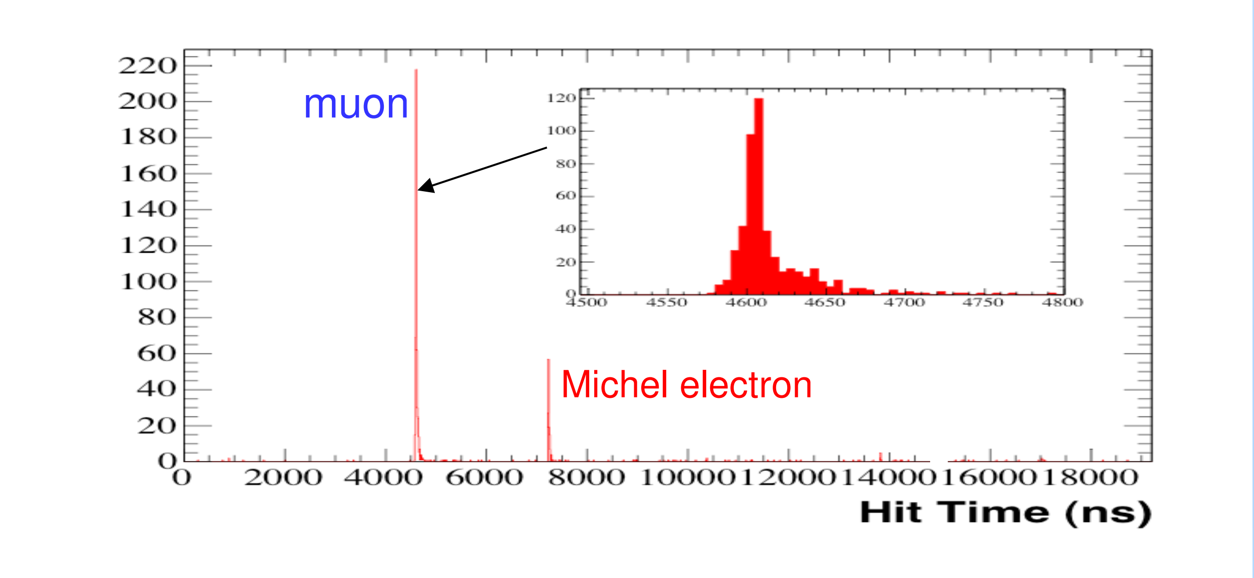
From 0.0 to -0.3, Δs doesn't change the energy spectrum, but after that gives a significant contribution at low energy < 250 MeV

Subevents

Both charged pions and muons decay within the DAQ time window, producing "subevents" - separate events in the same DAQ time window, each of which consist of at least 10 PMT hits and ~100 ns long

1. Charge current quasi-elastic (CCQE)





Typically CCQE has 2 subevents: neutrino interaction and a muon decay

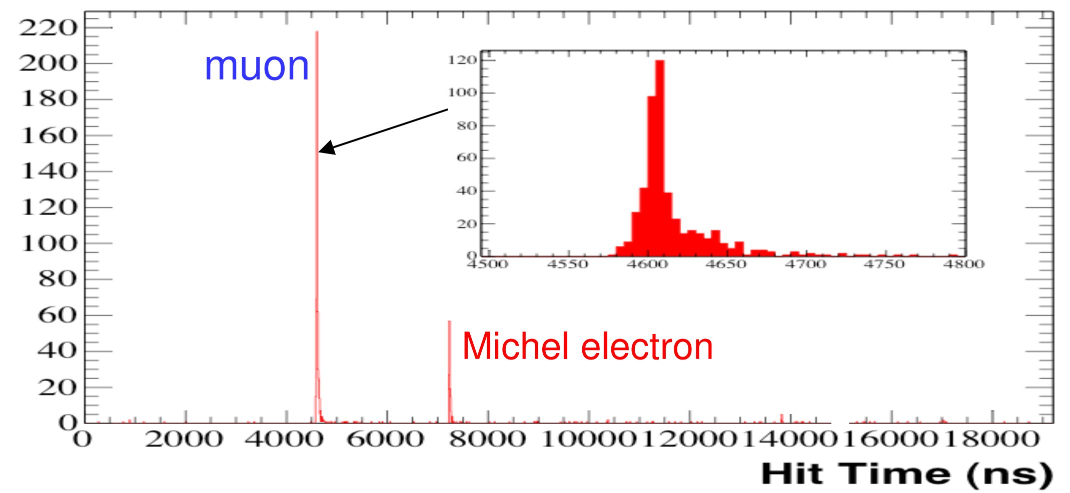
Subevents

Both charged pions and muons decay within the DAQ time window, producing "subevents" - separate events in the same DAQ time window, each of which consist of at least 10 PMT hits and ~100 ns long

1. Charge current quasi-elastic (CCQE)

$\nu_\mu + n \rightarrow p + \mu^-$ (1st SE)

$\tau \sim 2.2\mu s$: $\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu$ (2nd SE)



2. Charge current π^+ (CCpi+)

$\nu_\mu + N \rightarrow \pi^+ + \mu^- + N$ (1st SE)

$\tau \sim 21ns$: $\pi^+ \rightarrow \nu_\mu + \mu^+$ (1st SE)

$\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu$ (2nd SE)

$\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ (3rd SE)

Typically CCPi+ has 3 subevents: neutrino interaction with pion decay and two muon decays

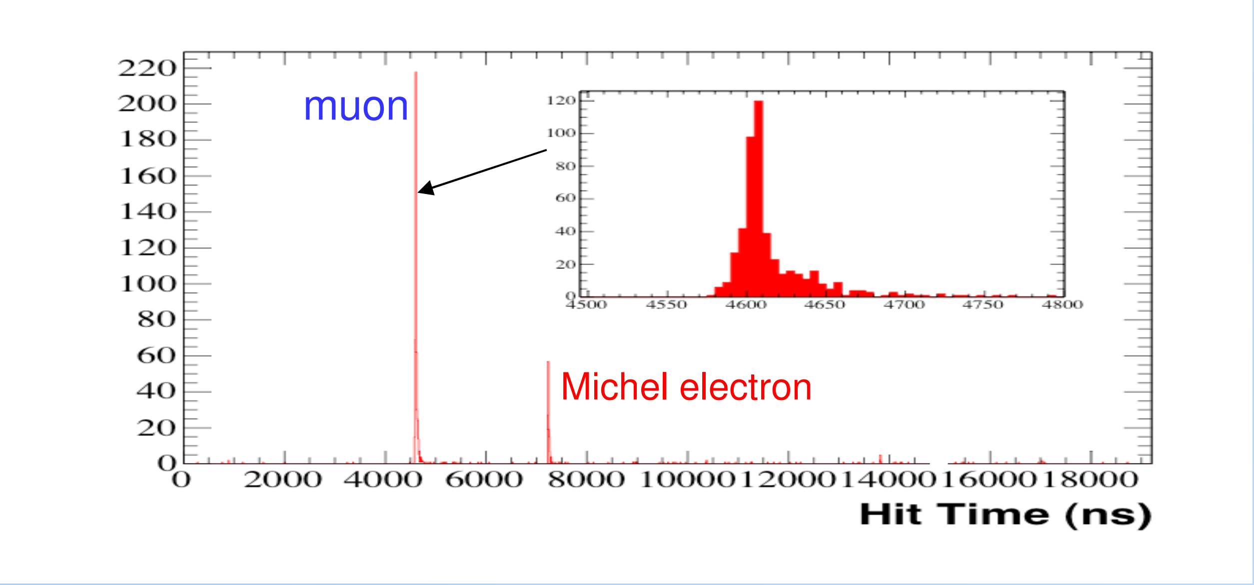
Subevents

Both charged pions and muons decay within the DAQ time window, producing "subevents" - separate events in the same DAQ time window, each of which consist of at least 10 PMT hits and ~100 ns long

1. Charge current quasi-elastic (CCQE)

$\nu_\mu + n \rightarrow p + \mu^-$ (1st SE)

$\tau \sim 2.2\mu s$: $\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu$ (2nd SE)



2. Charge current π^+ (CCpi+)

$\nu_\mu + N \rightarrow \pi^+ + \mu^- + N$ (1st SE)

$\tau \sim 21ns$: $\pi^+ \rightarrow \nu_\mu + \mu^+$

$\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_\mu$ (2nd SE)

$\mu^+ \rightarrow e^+ + \bar{\nu}_e + \nu_\mu$ (3rd SE)

3. Neutral current elastic

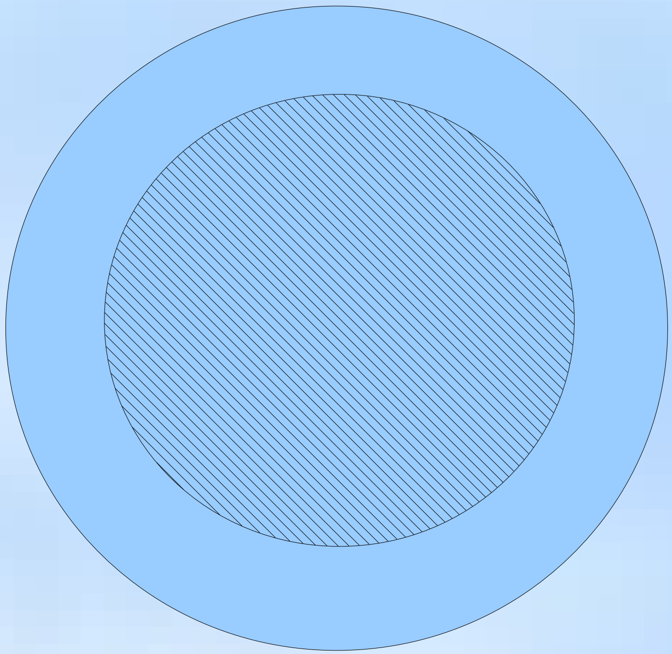
$\nu_\mu + N \rightarrow \nu_\mu + N$ (1 SE)

NC elastic usually has only 1 subevent

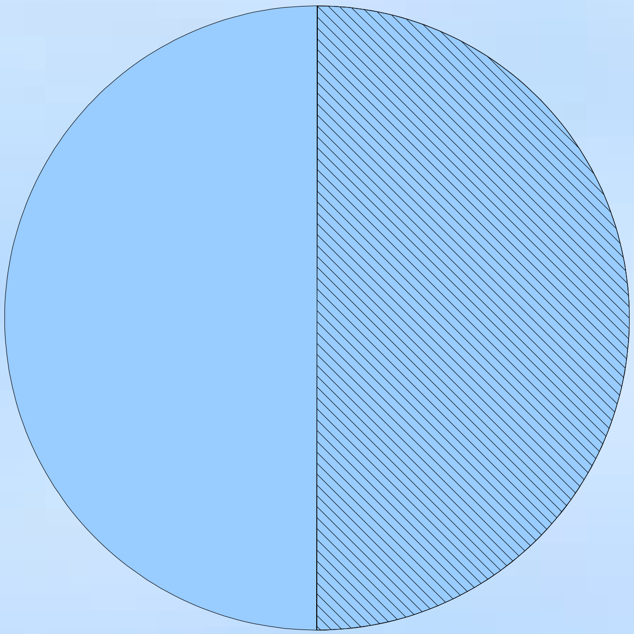
Dirt background measurement

Dirt-enriched samples

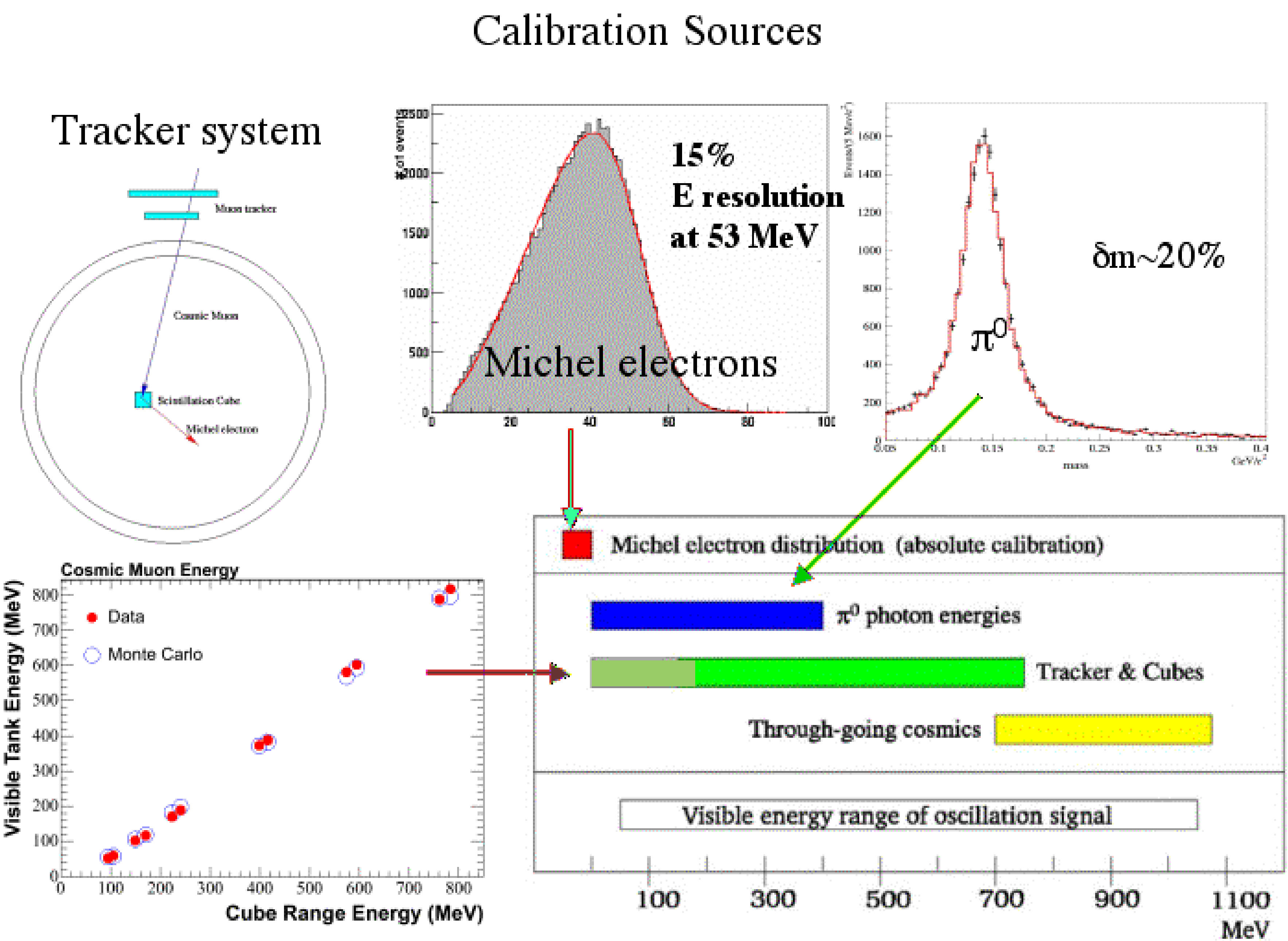
Cut on the radius (looking at the outer shells)



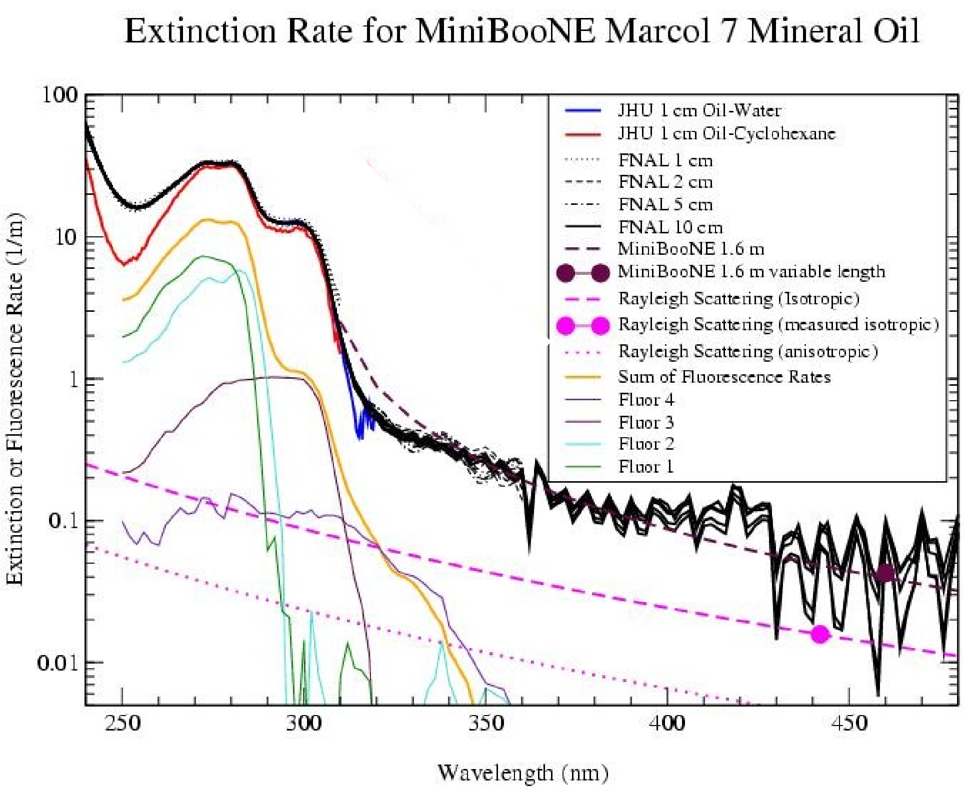
Cut on the Z (looking at upstream part)

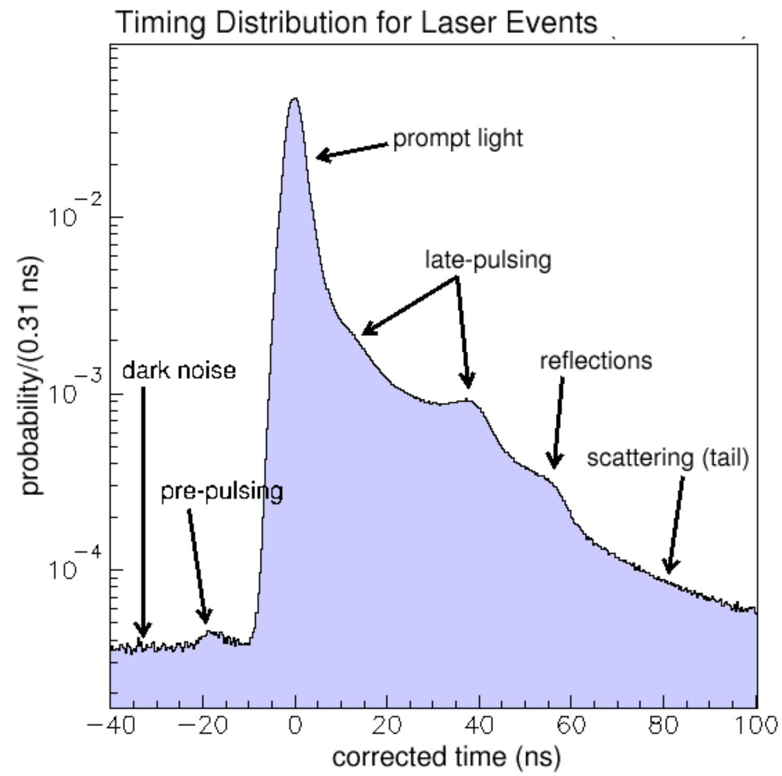


Calibration sources span various energies



Light propagation in the detector





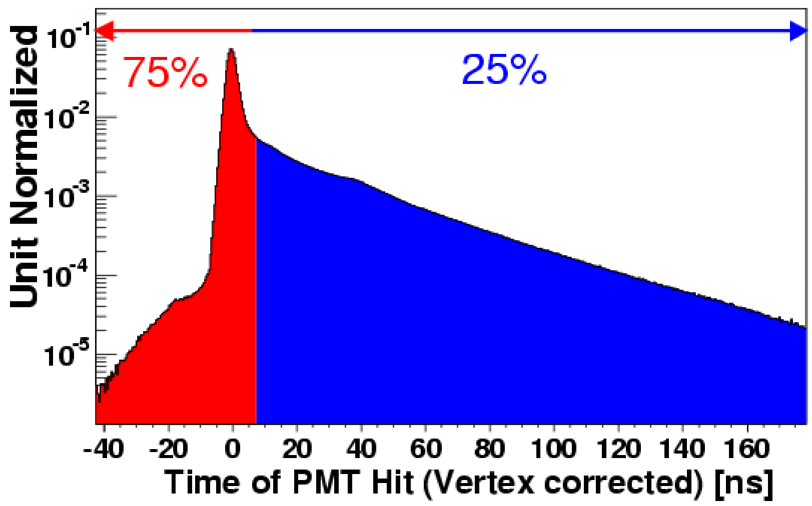
Optical model is very complex

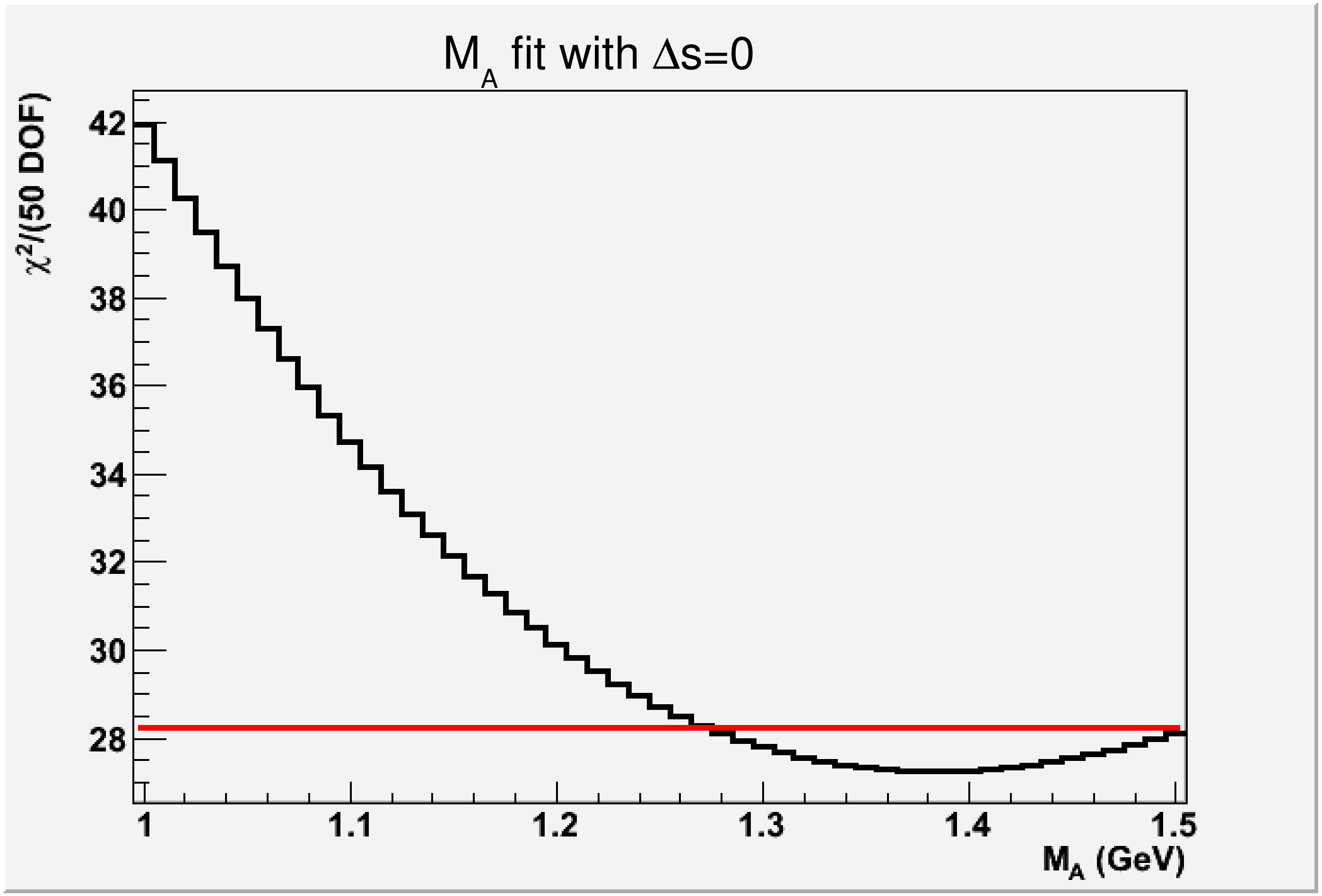
- Cerenkov, scintillation, fluorescence
- PMT Q/t response
- Scattering, reflection, prepulses

Overall, about 40 non-trivial parameters

Started with benchtop measurements, refined via *in situ* tuning.
  Data/MC agreement critical (esp. for Boosted Decision Tree)

Michel electron t distribution

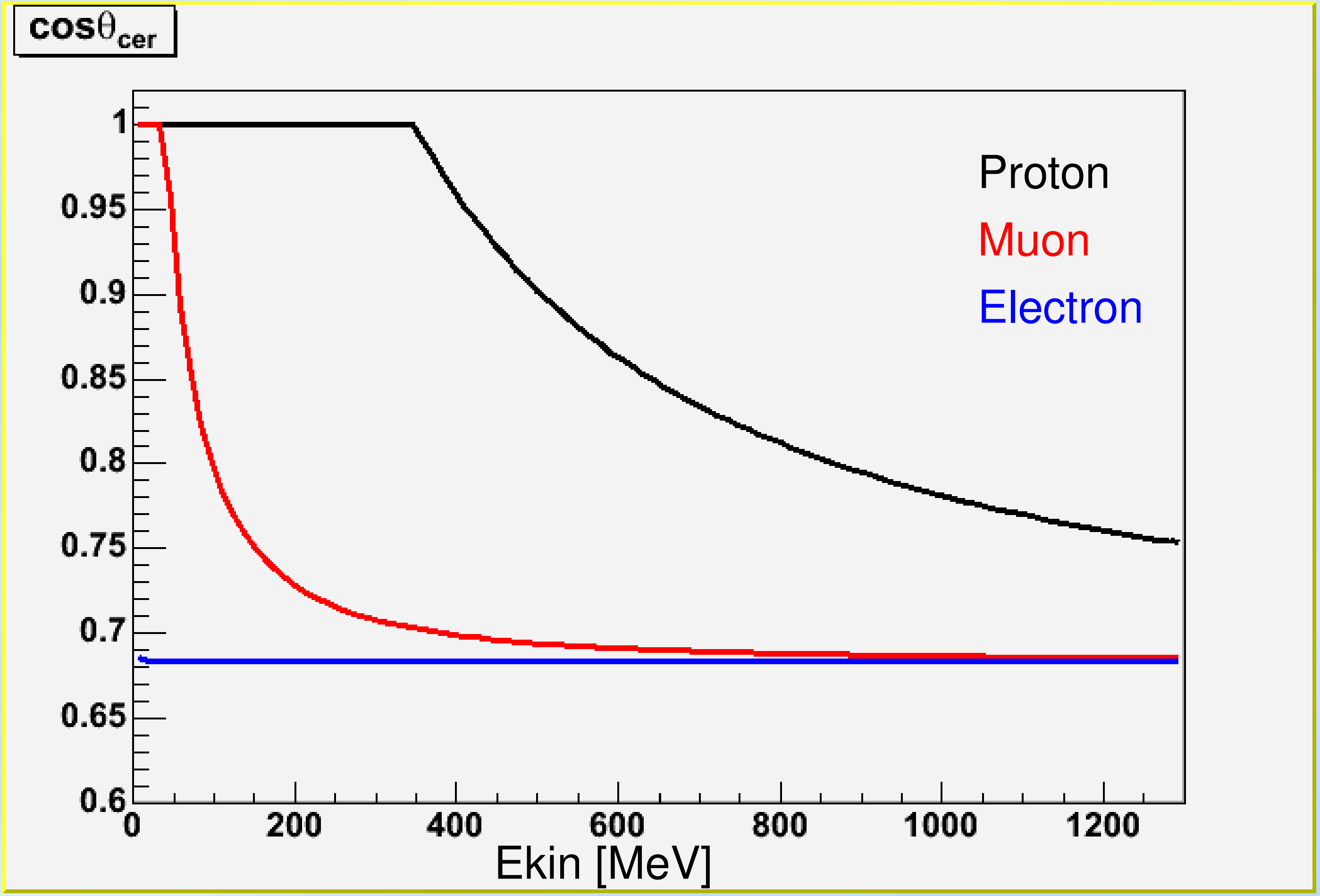




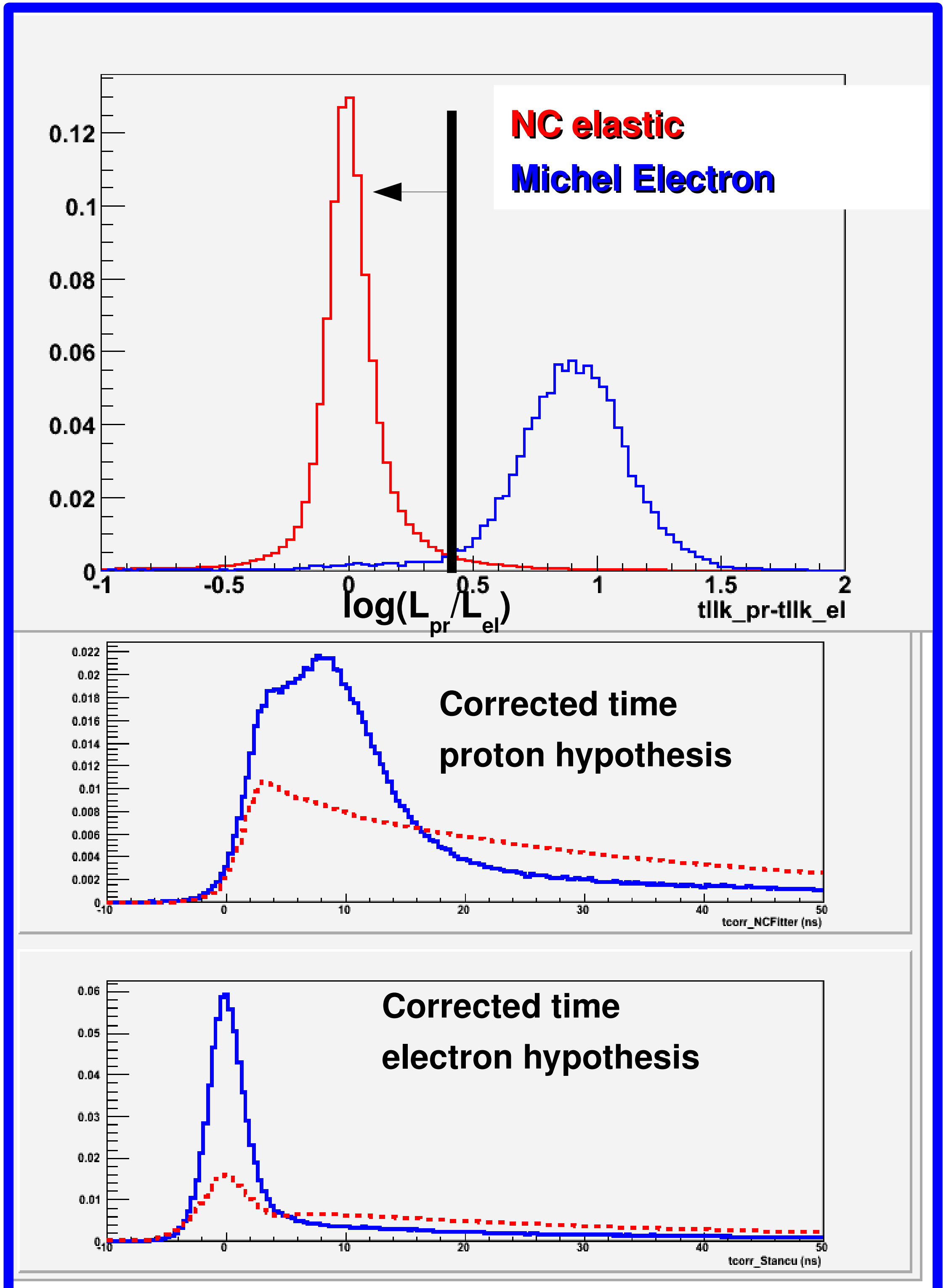
$M_A = 1.38 \pm 0.1$ GeV

Cerenkov angle

$$\cos\theta_{cer} = \frac{1}{\beta n}$$

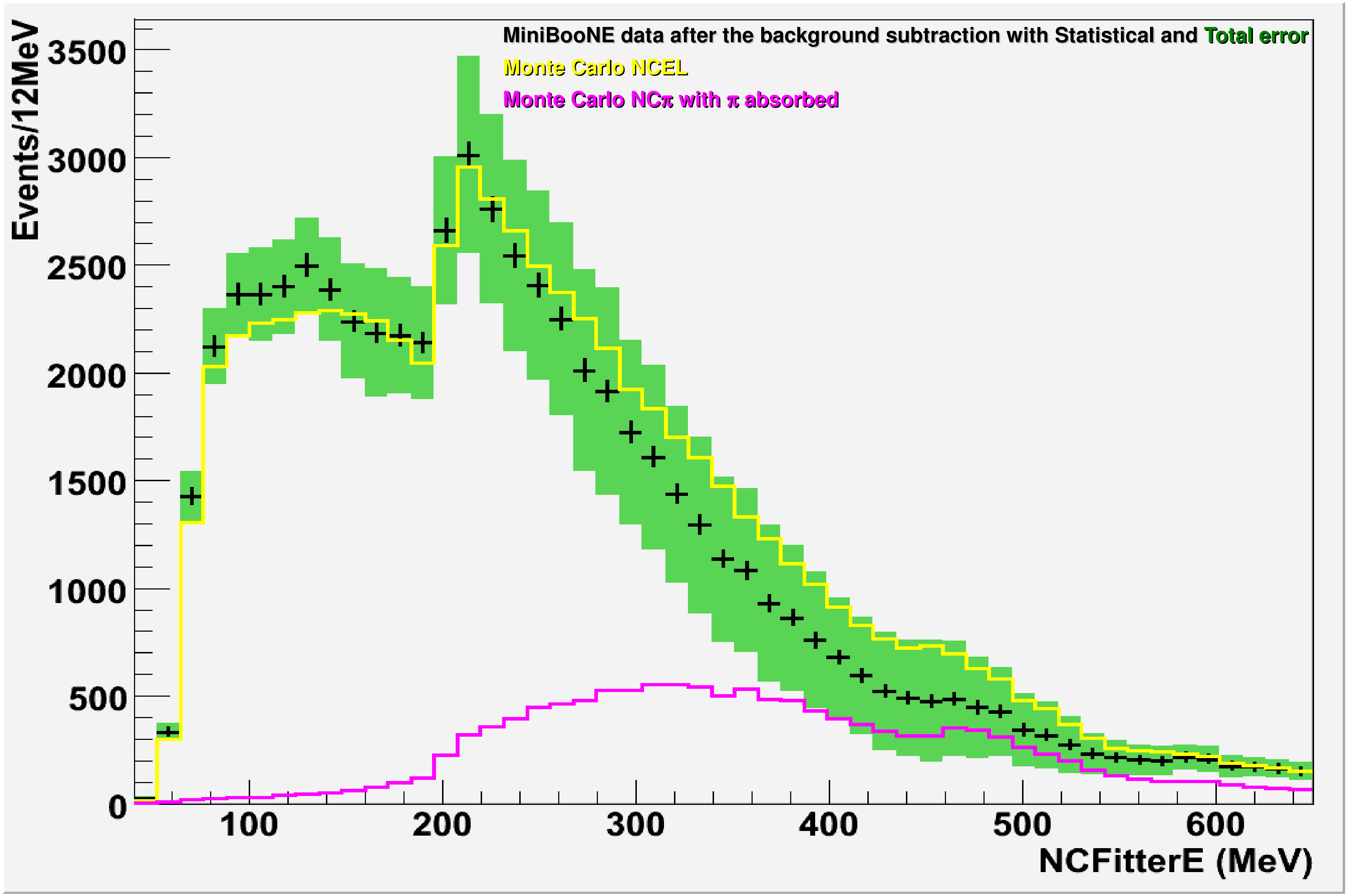


Protons have much different Cerenkov profile... need to have a proton hypothesis reconstruction

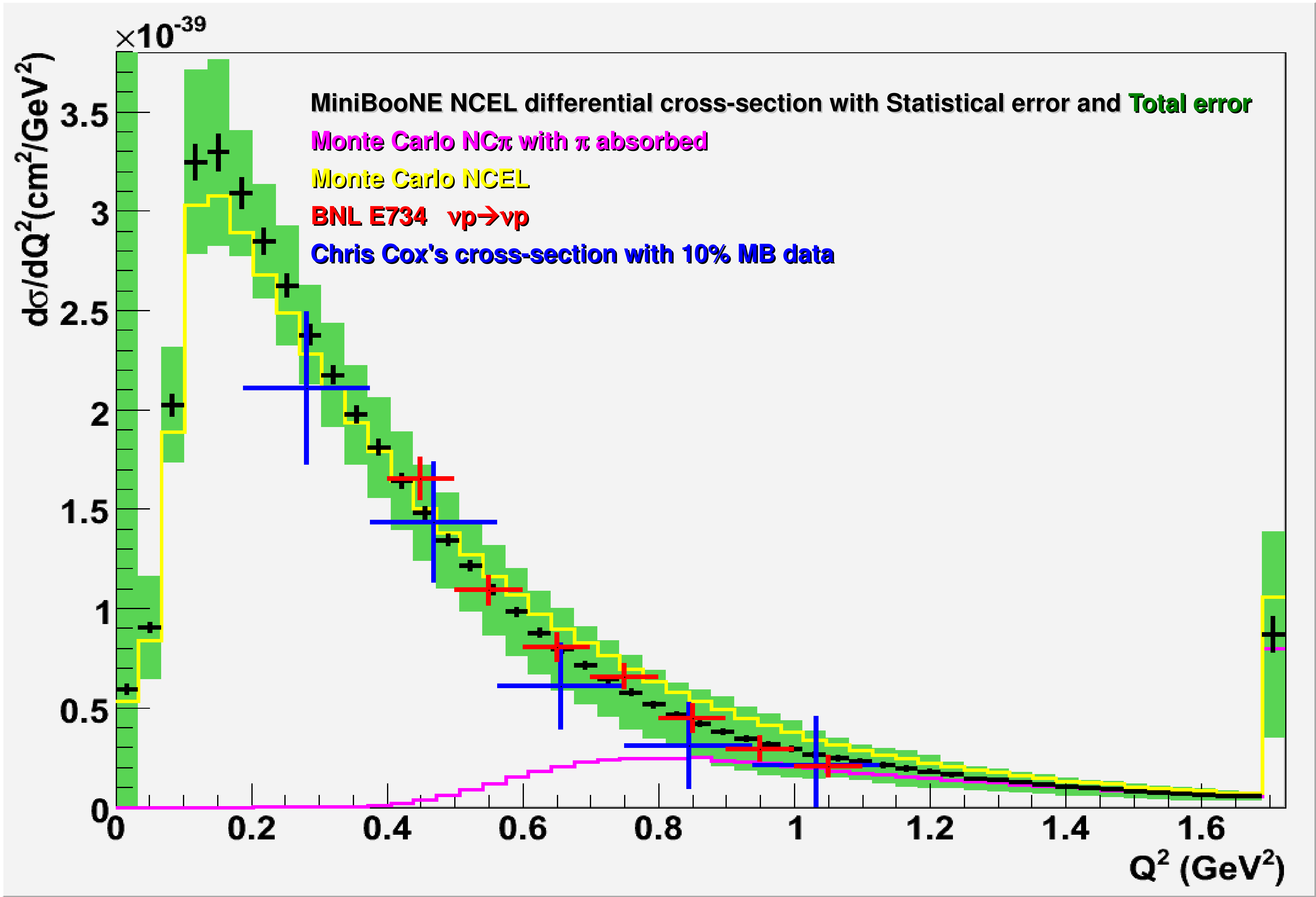


NC elastic
Michel Electron
log(L_pr/L_el)
tllk_pr-tllk_el
Corrected time
proton hypothesis
tcorr_NCFitter (ns)
Corrected time
electron hypothesis
tcorr_Stancu (ns)

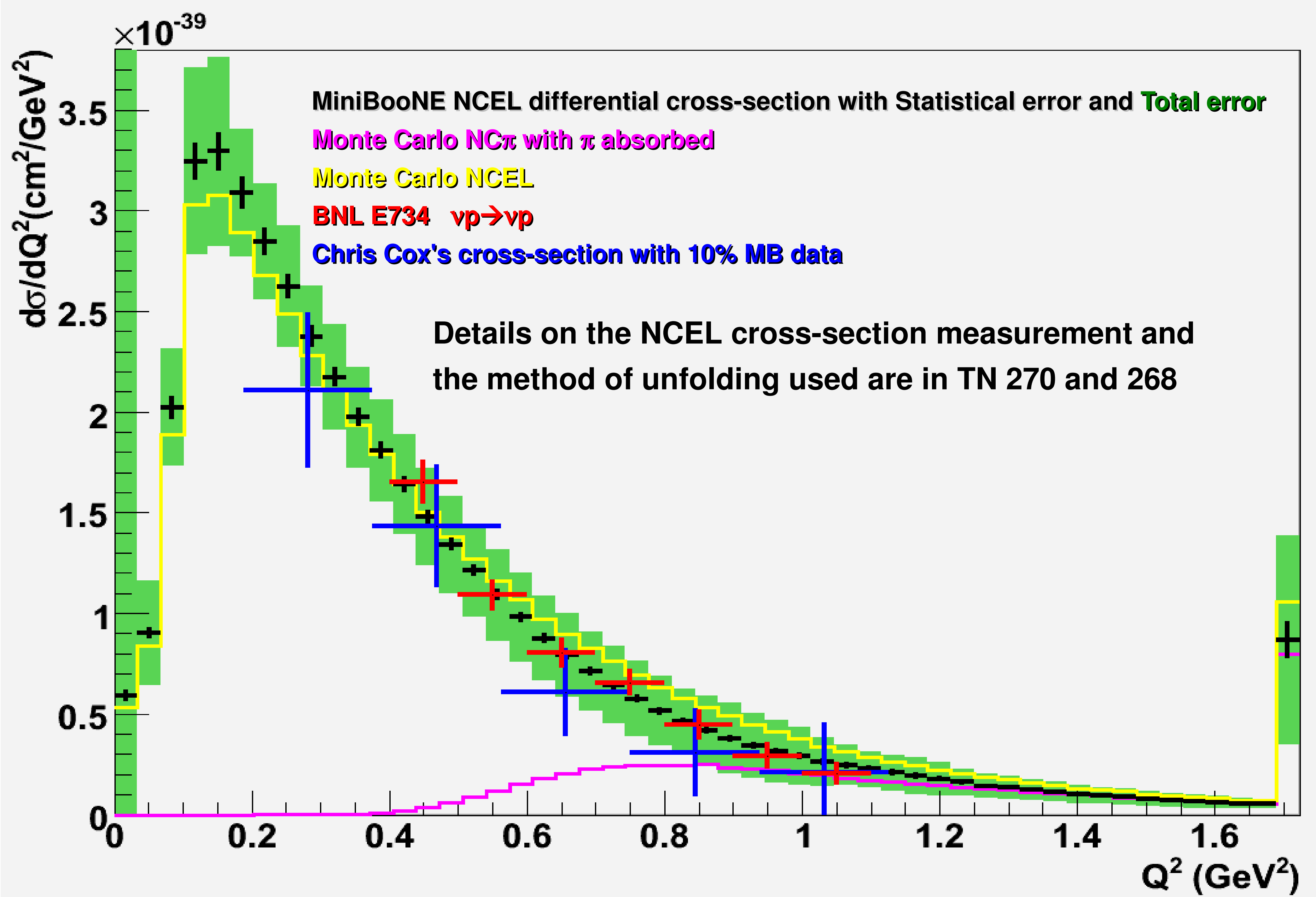
Reconstructed energy spectrum



MiniBooNE NCEL differential cross-section



MiniBooNE NCEL differential cross-section



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Nucleon structure

Nucleon structure is parameterized in the nucleon weak current:

$$J_\mu = \left\langle N(p') \middle| F_1(Q^2)\gamma_\mu + F_2(Q^2)\sigma_{\mu\nu}q^\nu + G_A(Q^2)\gamma_\mu\gamma_5 \middle| N(p) \right\rangle$$

F_1, F_2, and G_A are the nucleon form factors

Q^2 is the momentum transferred to the nucleon in the interaction

$$Q^2 = -(p' - p)^2$$

Nucleon structure

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F_1, F_2, and G_A are the nucleon form factors

Q^2 is the momentum transferred to the nucleon in the interaction

$$Q^2 = -(p'-p)^2$$

In neutral current scattering, contributions from strange quarks are additions
to form factors $F^s_1(Q^2)$, $F^s_2(Q^2)$, $G^s_A(Q^2)$ where $G^s_A(Q^2=0) = \Delta s$

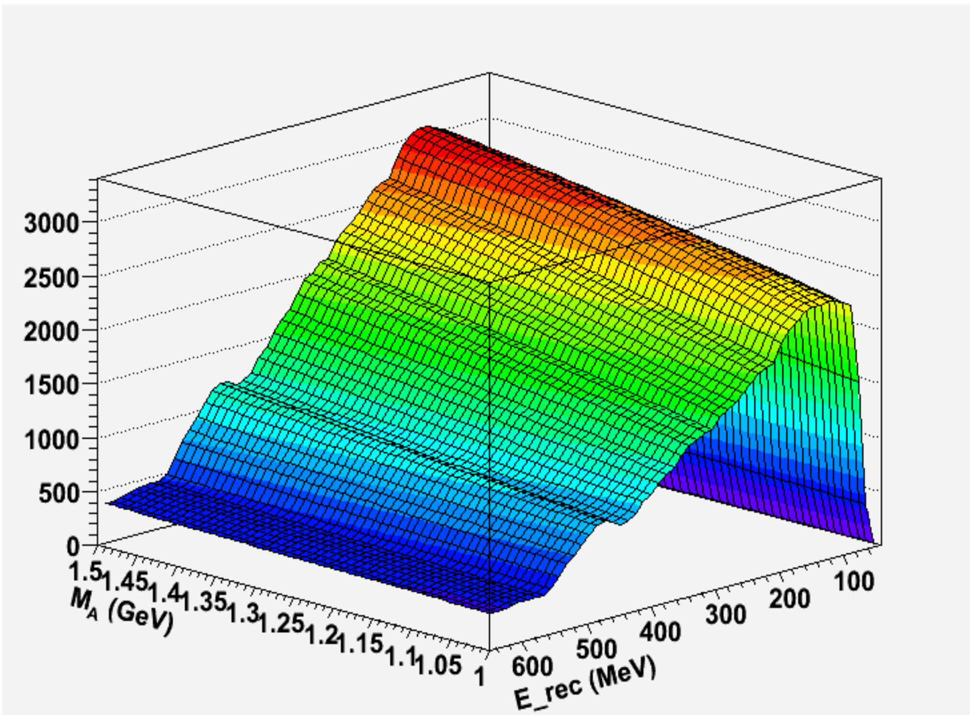
The NCEL cross section is very sensitive to the axial form factor G_A at low Q^2

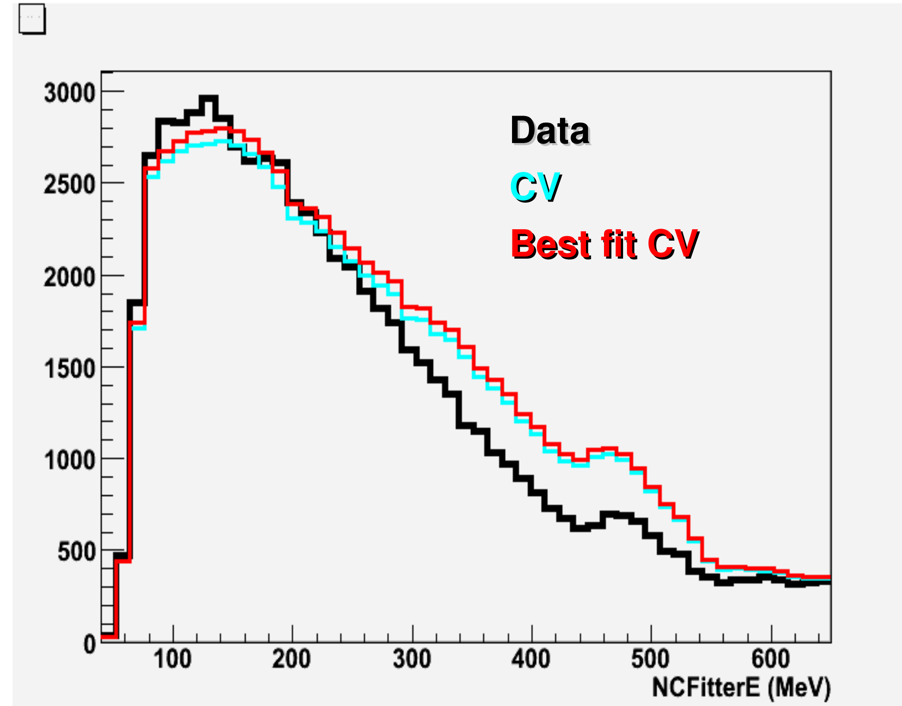
$$\frac{d\sigma}{dQ^2} \propto (\pm G_A(Q^2) + G^s_A(Q^2))^2$$

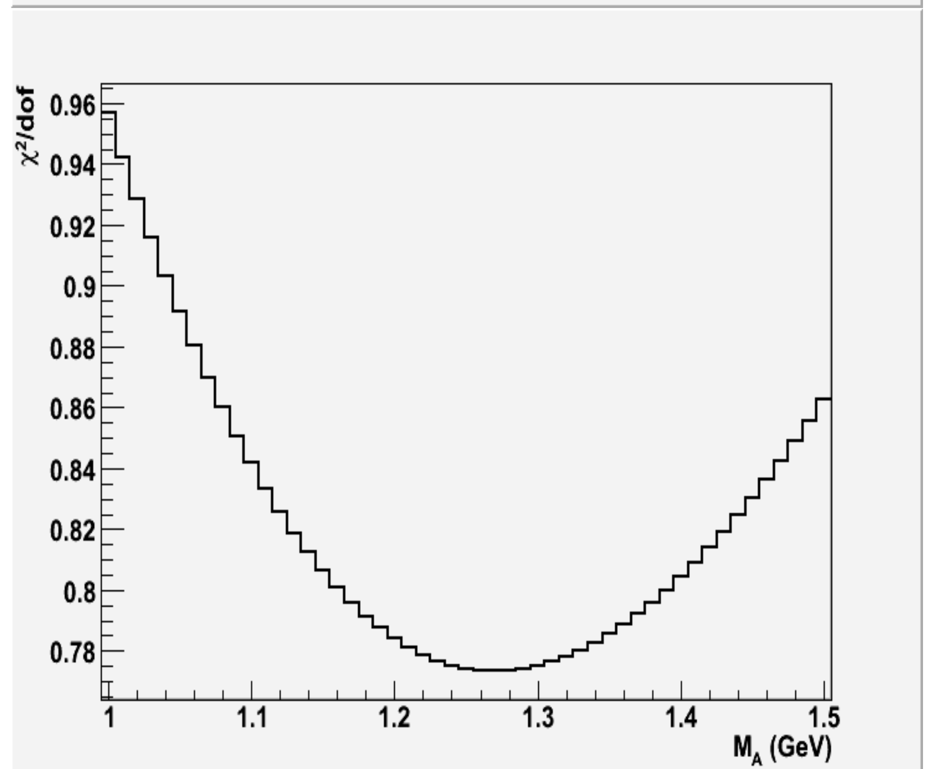
+ for proton scattering
– for neutron scattering

M_A fits of the NCEL cross-section

$$G_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)^2} \quad , g_A = 1.267$$







$M_A = 1.27 \pm 0.09$ GeV

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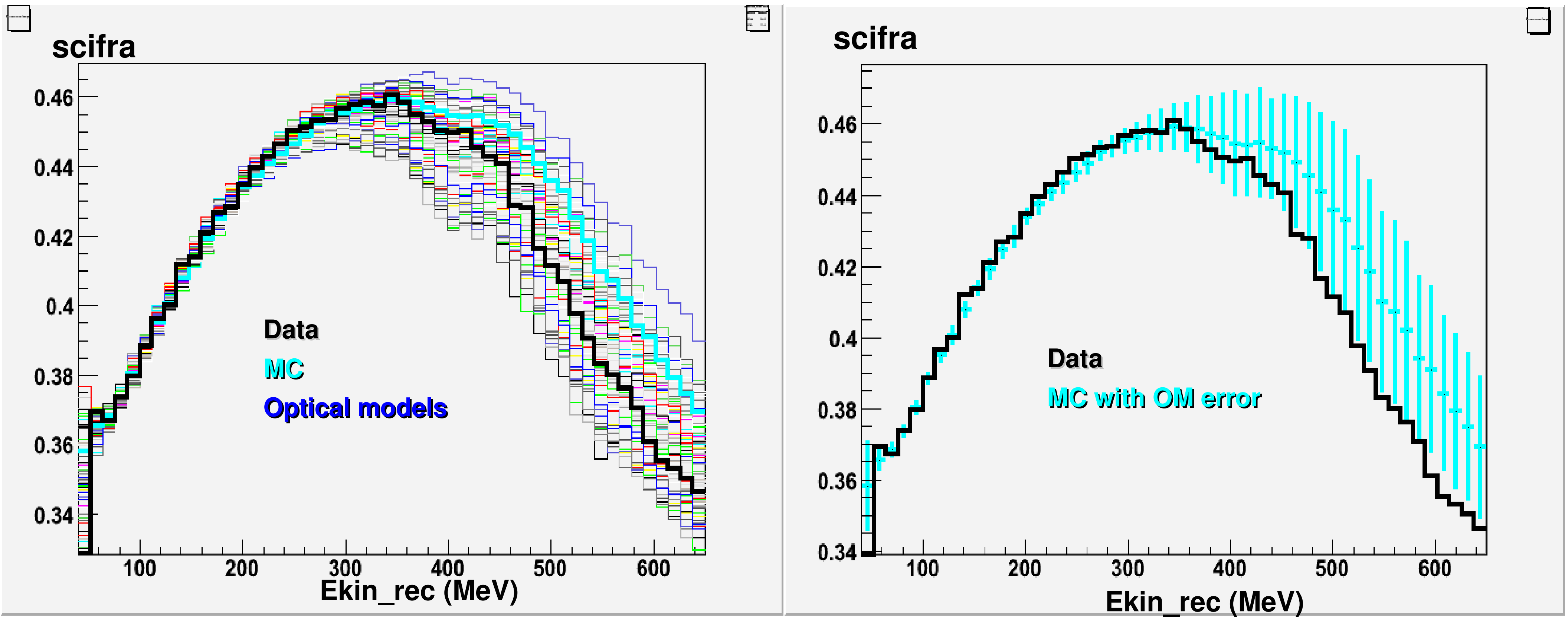
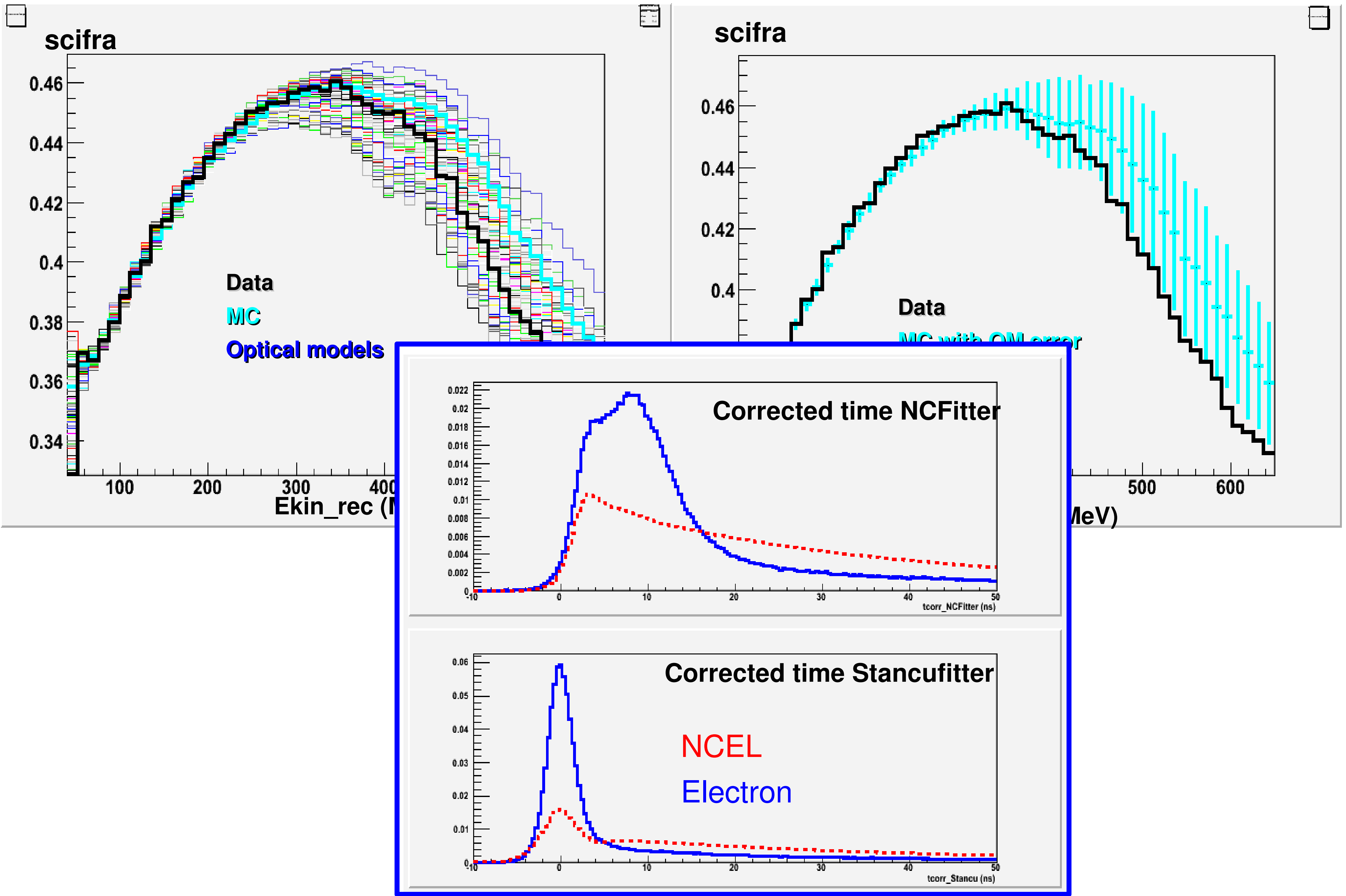
Scintillation fraction (in the electron fitter) vs NCFitterE



Scintillation fraction (in the electron fitter) vs NCFitterE



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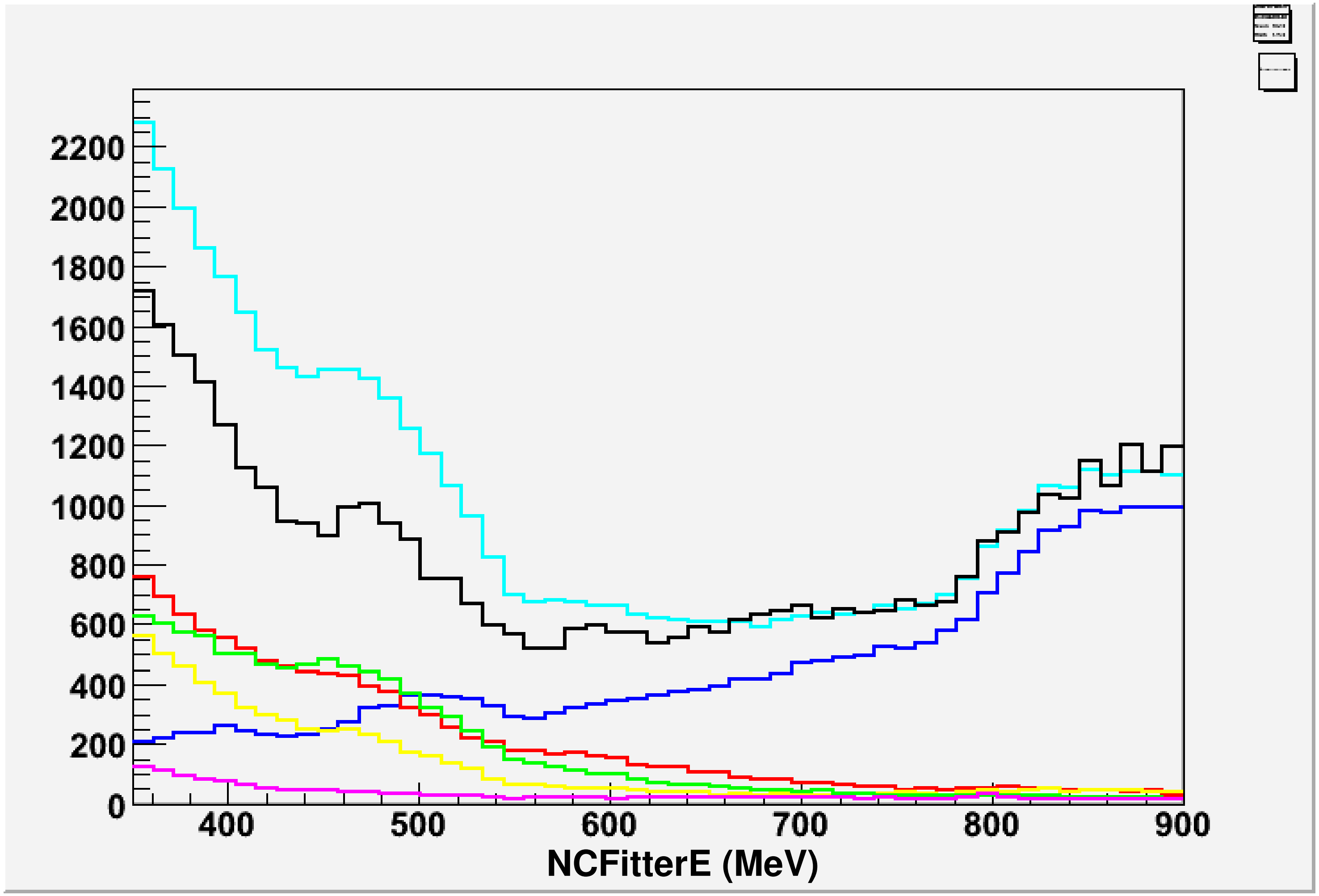
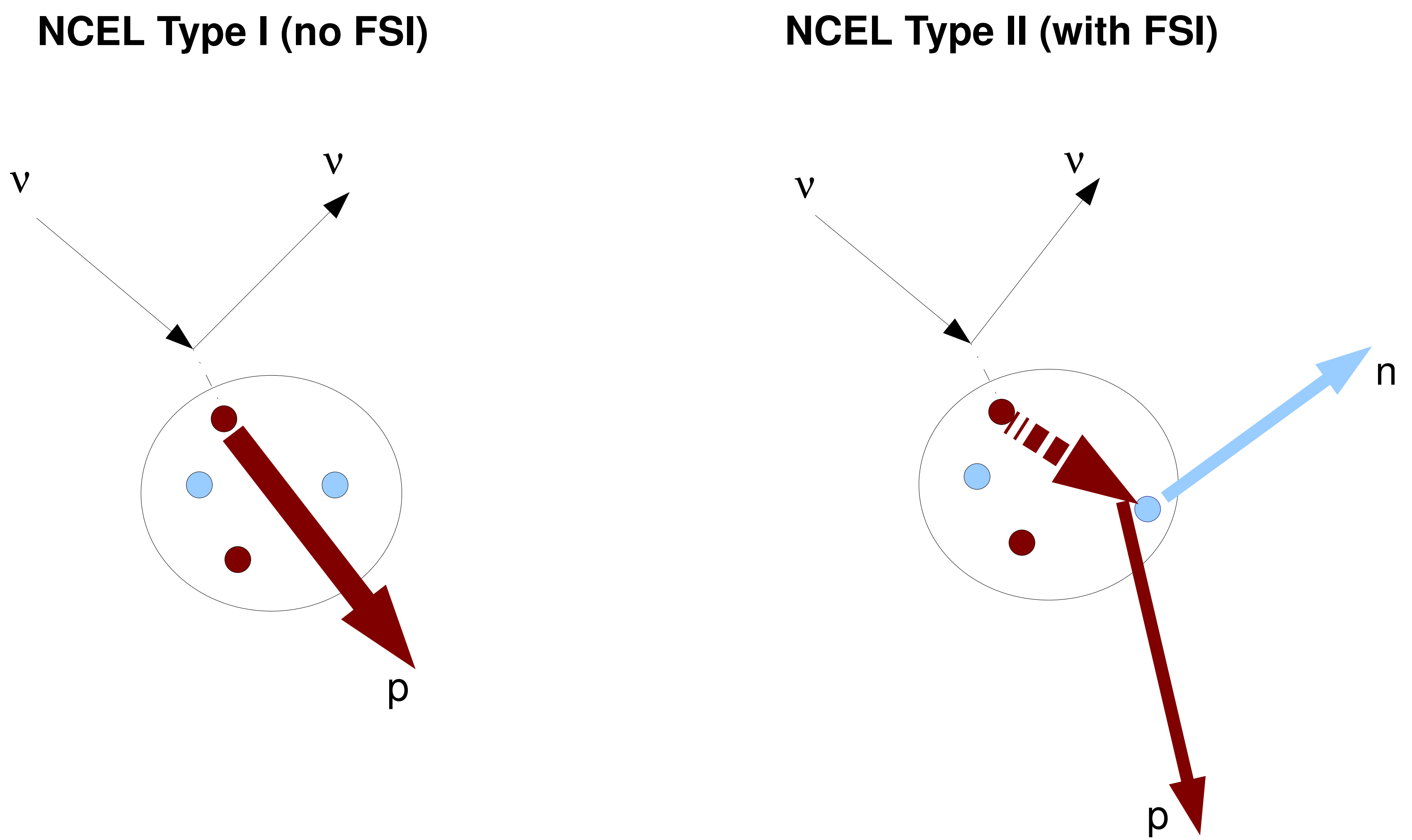
We start with the high energy NCEL reconstructed spectrum (after NCEL cuts are applied):



As one can see, there are lots of backgrounds. Signal (NCEL proton) is not strong.

Cuts: 1SE+ Vhits<6 + R<5.0m + beamtimewindow + tllkdiff<0.42 + 350MeV<E<900MeV

What exactly are we going to identify?



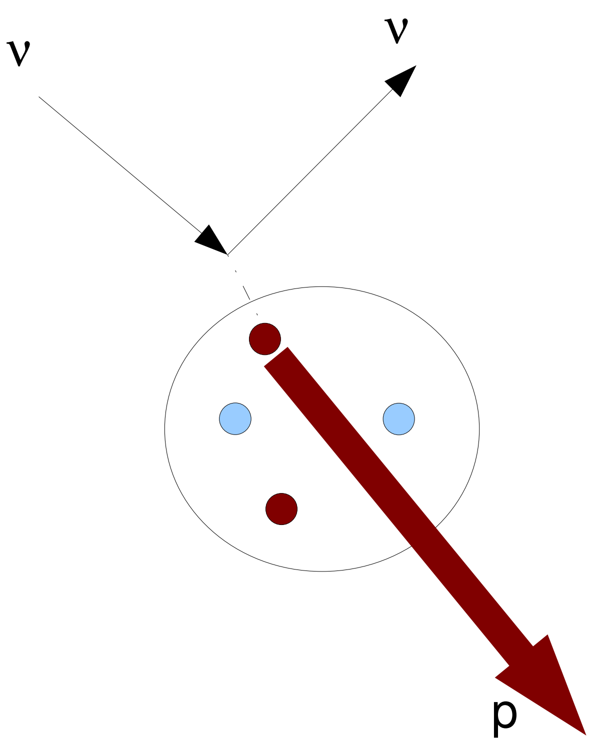
The FSI probability on ^{12}C is 26%

The FSI probability on H is 0%

The FSI probability on CH_2 is 22%

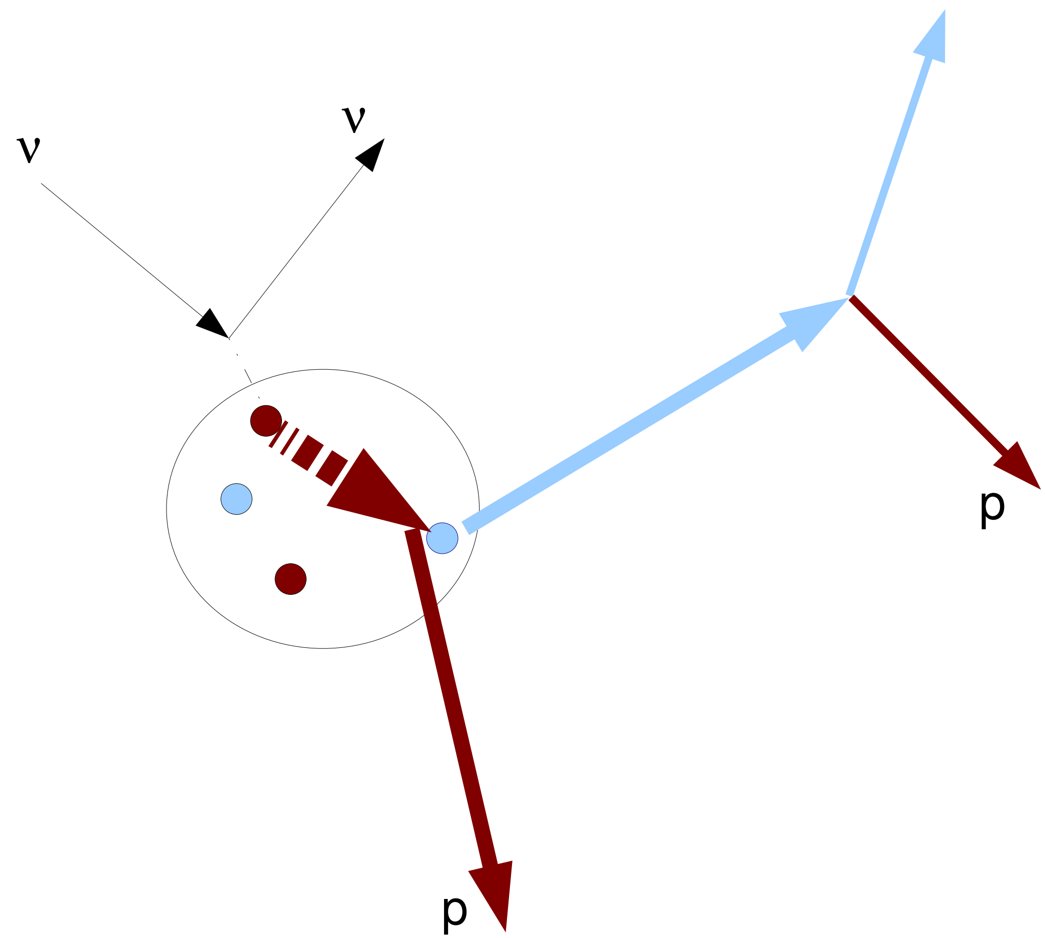
NCEL protons (νp→νp)

Type I



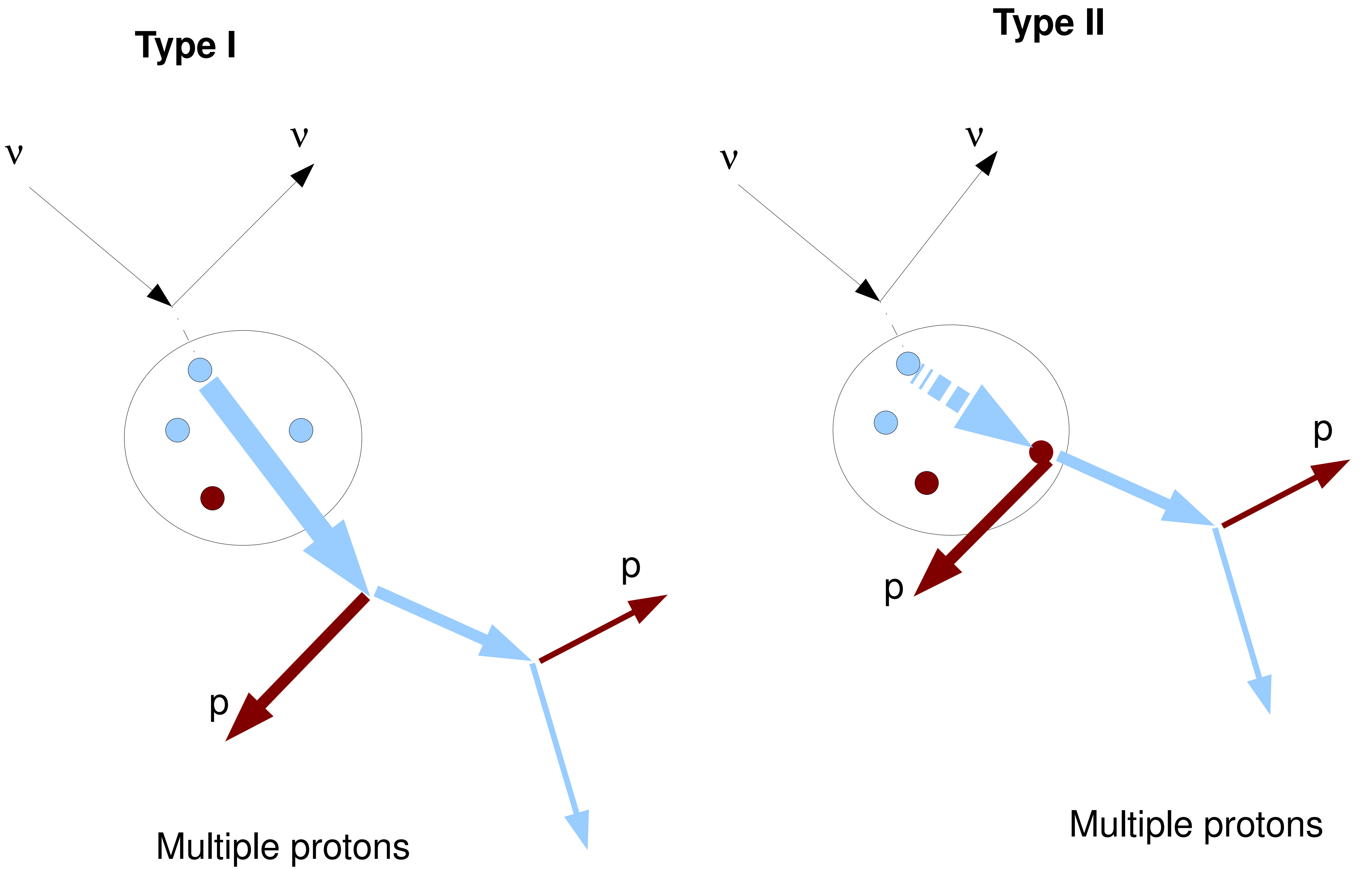
1 proton

Type II



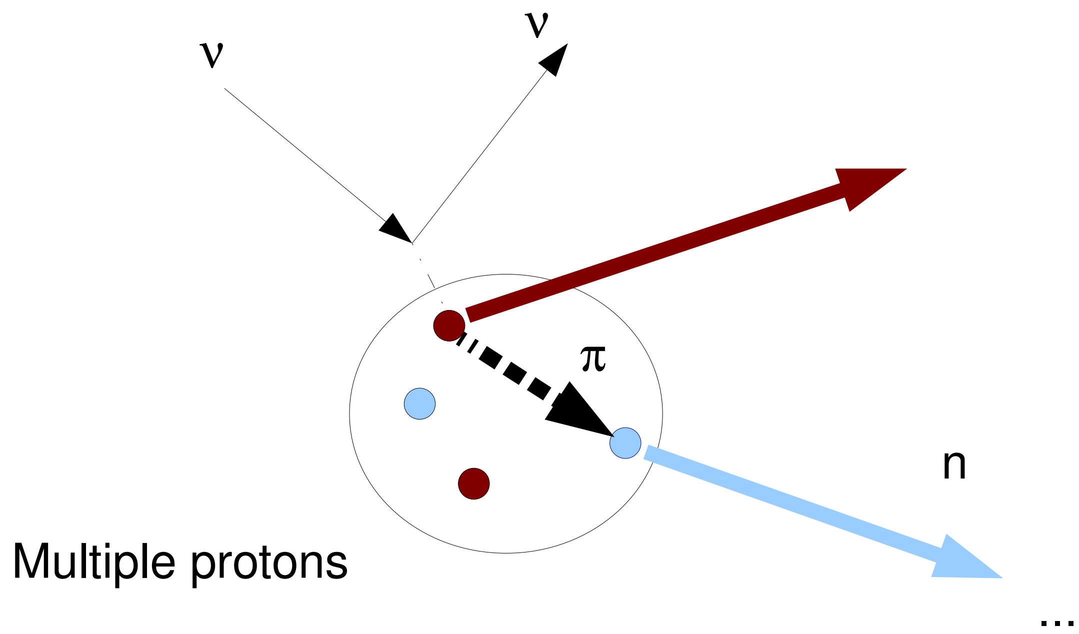
Multiple protons

NCEL neutrons ($\nu n \rightarrow \nu n$)



Both types for NCEL neutron are equivalent

Irreducible background (NC π with no π in the final state)

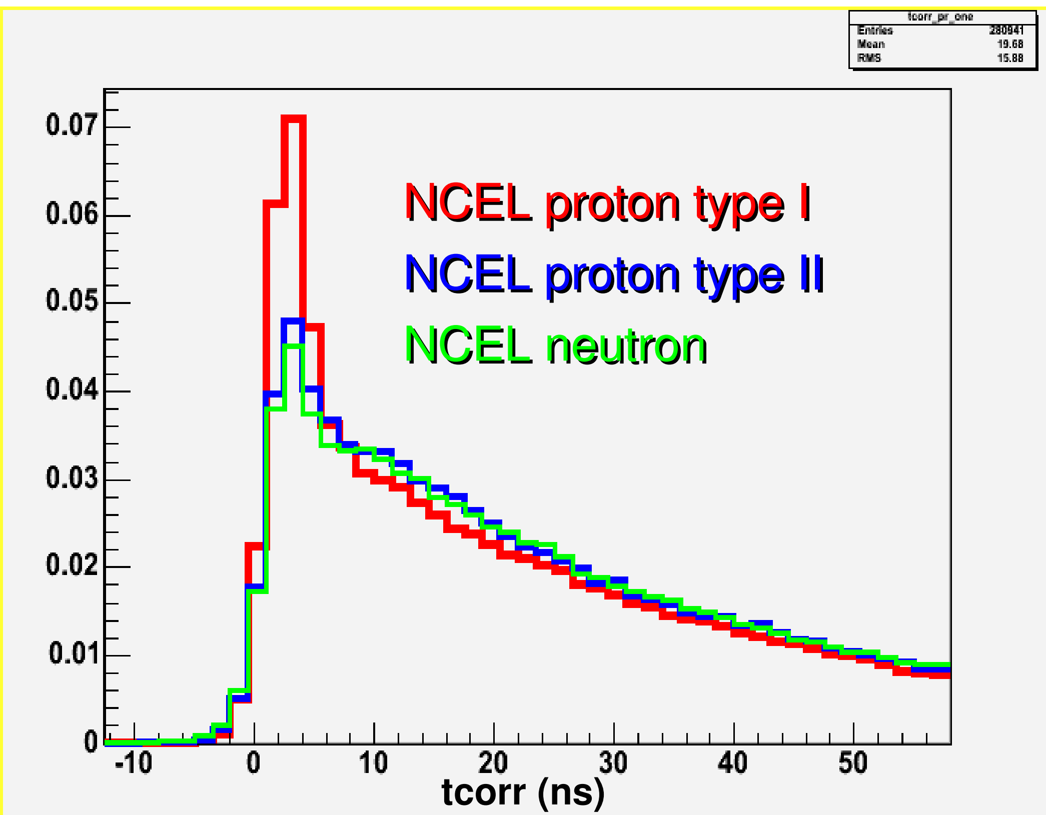


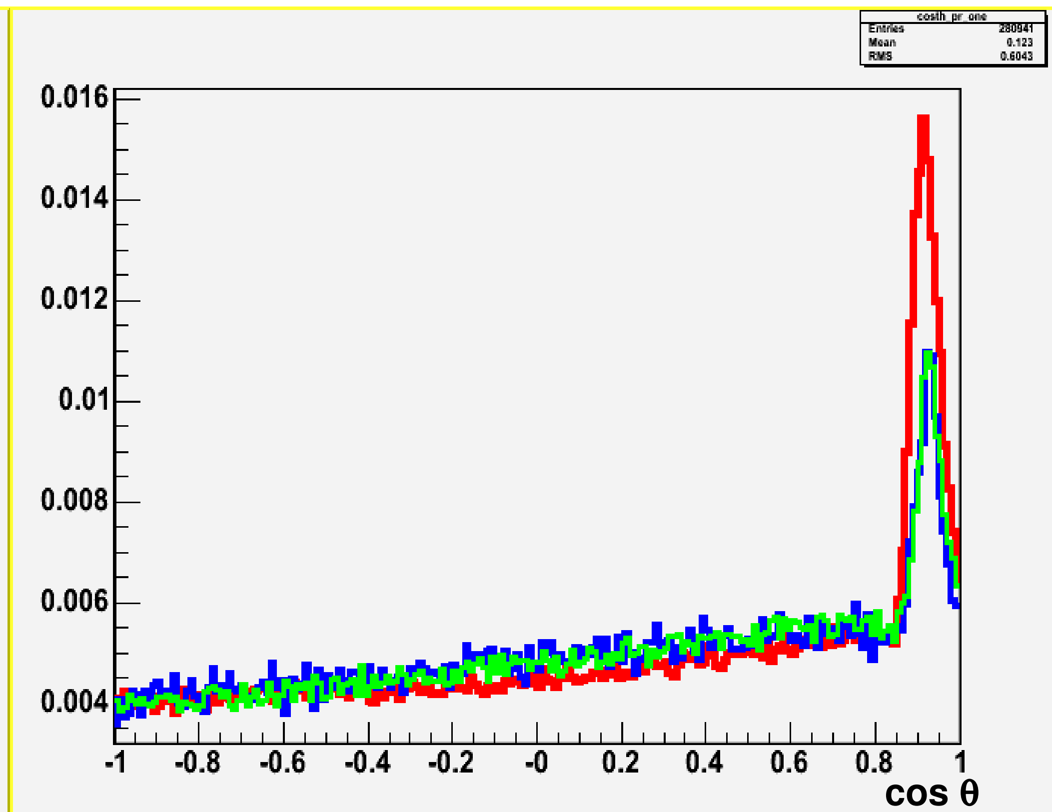
Equivalent to NCEL neutron

High energy NCEL proton sample

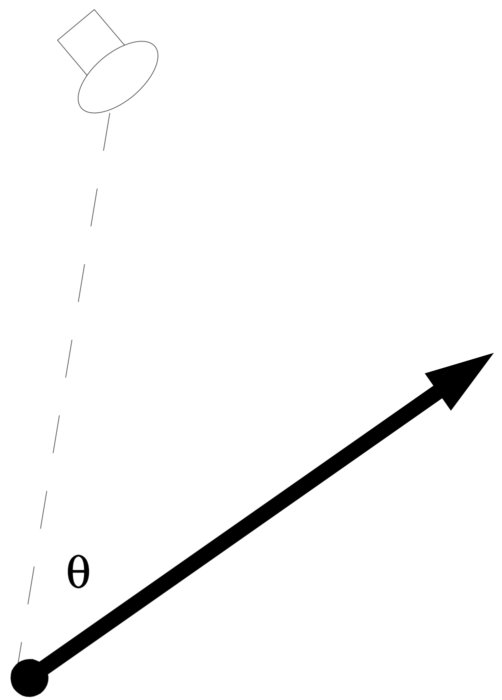
NCEL proton type I	Single proton
NCEL proton type II	Multiple protons
NCEL neutron type I	Multiple protons
NCEL neutron type II	Multiple protons
Irreducibles	Multiple protons

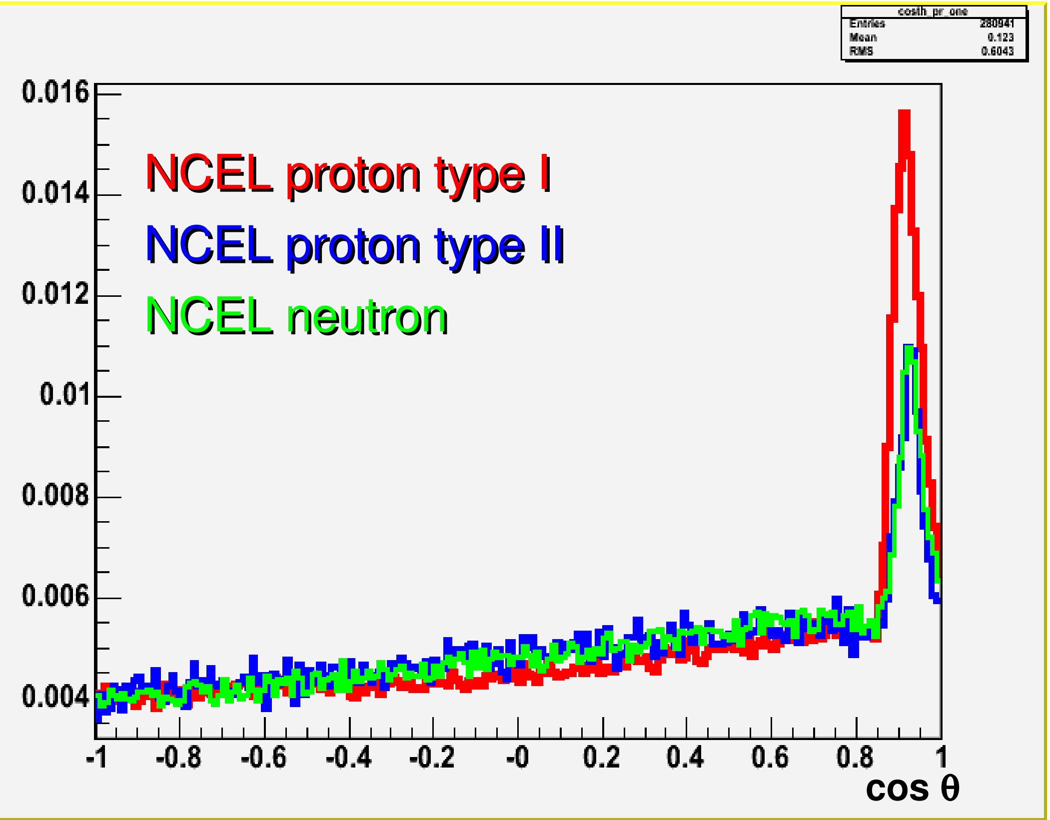
At high Q^2 (above 0.7 GeV^2) for the same amount of charge, single proton events have more Cerenkov light, than multiple proton events.





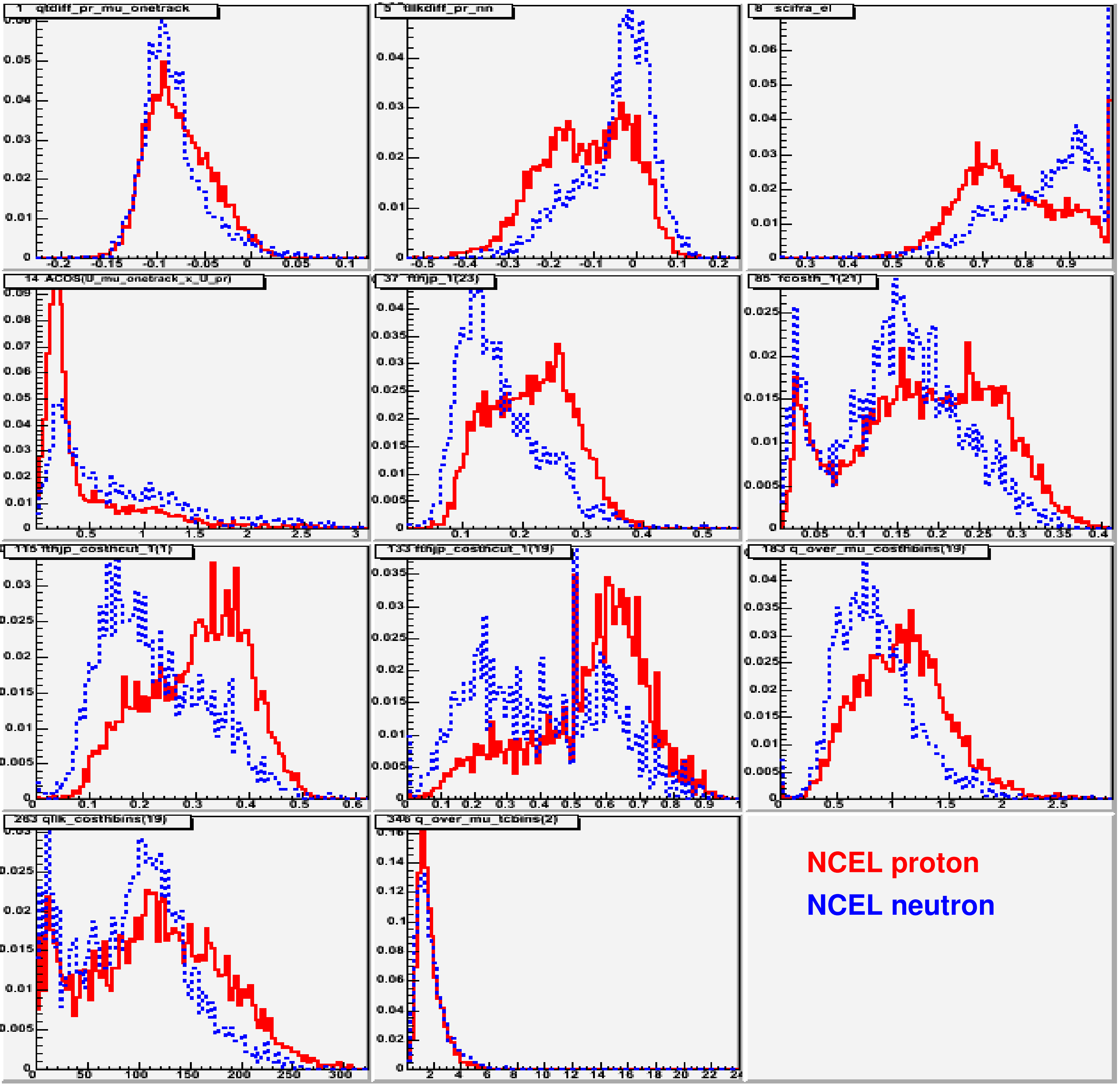
High energy NCEL proton sample





High energy NCEL proton sample

Particle-id variables (input for Boosting)



Trained Boosting based on these variables to separate :

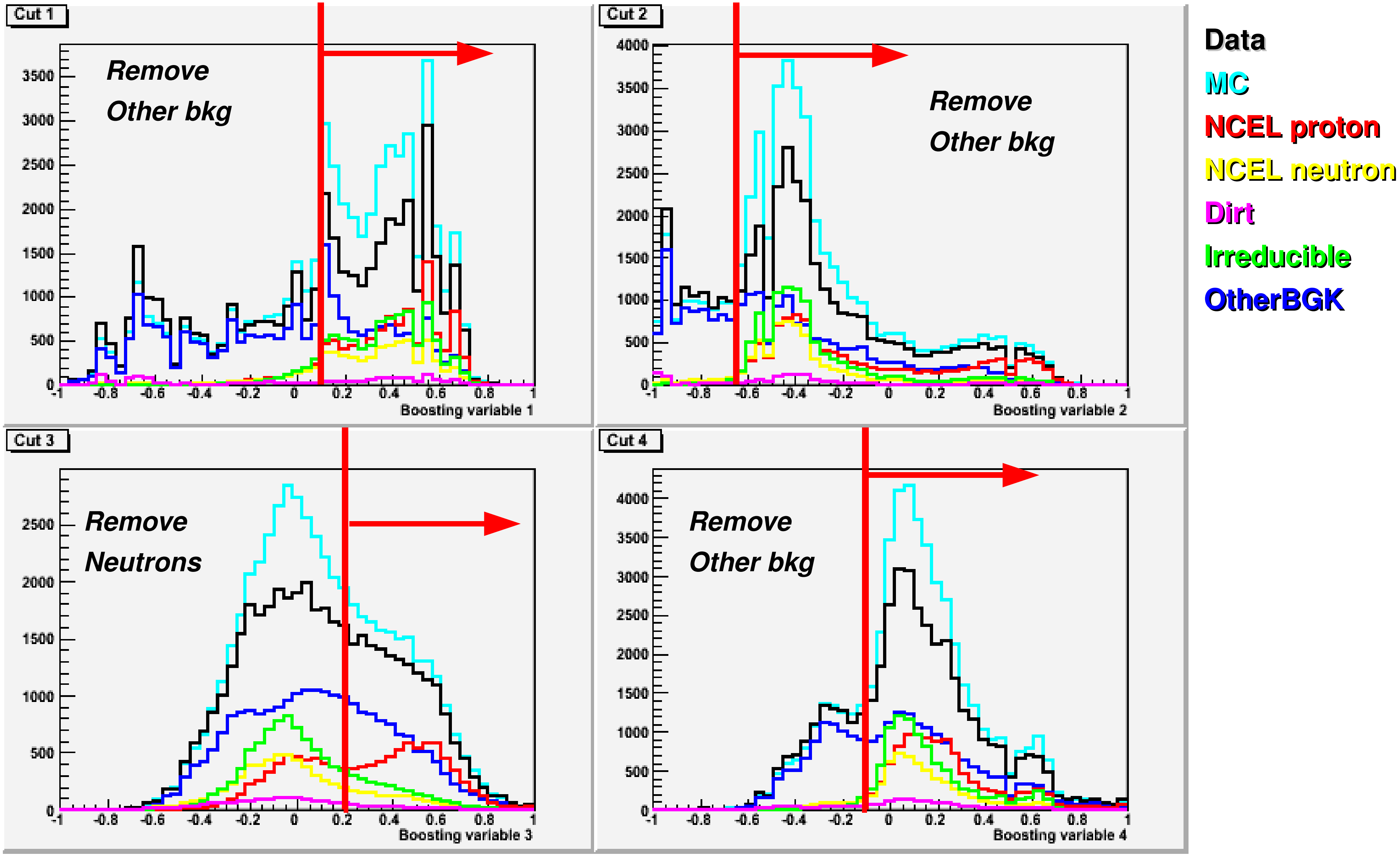
NCEL proton/NCEL neutron

and

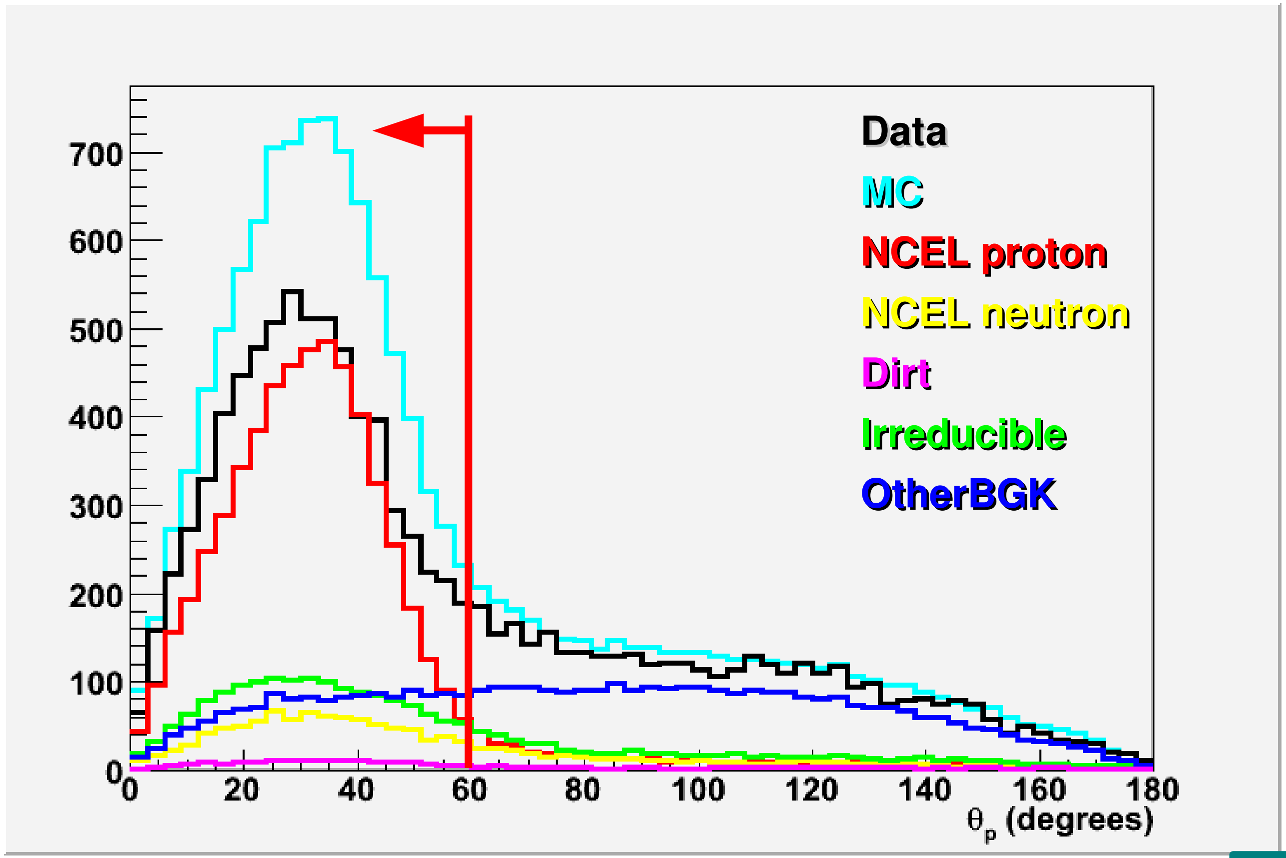
NCEL proton/Other Bkg

High energy NCEL proton sample

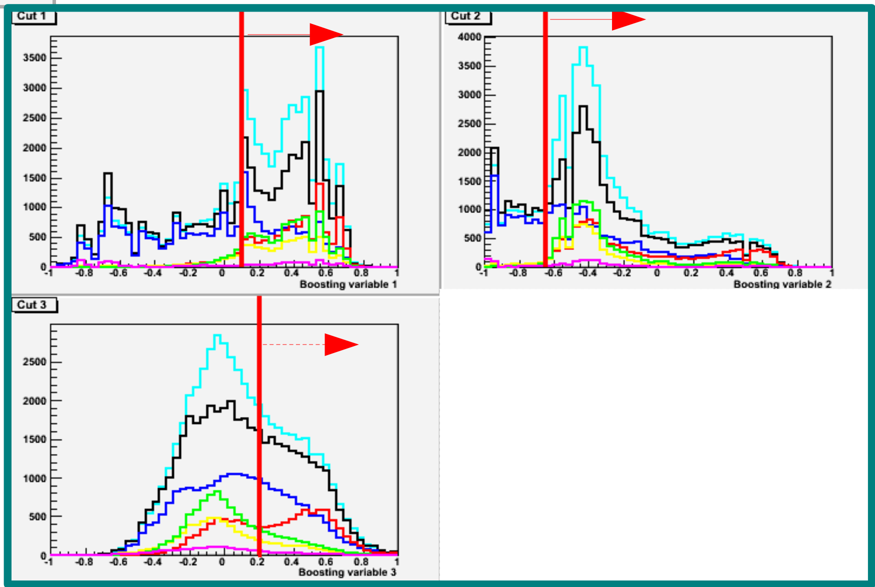
additional PID cuts:



Proton angle with respect to Z axis (arccos UZ)

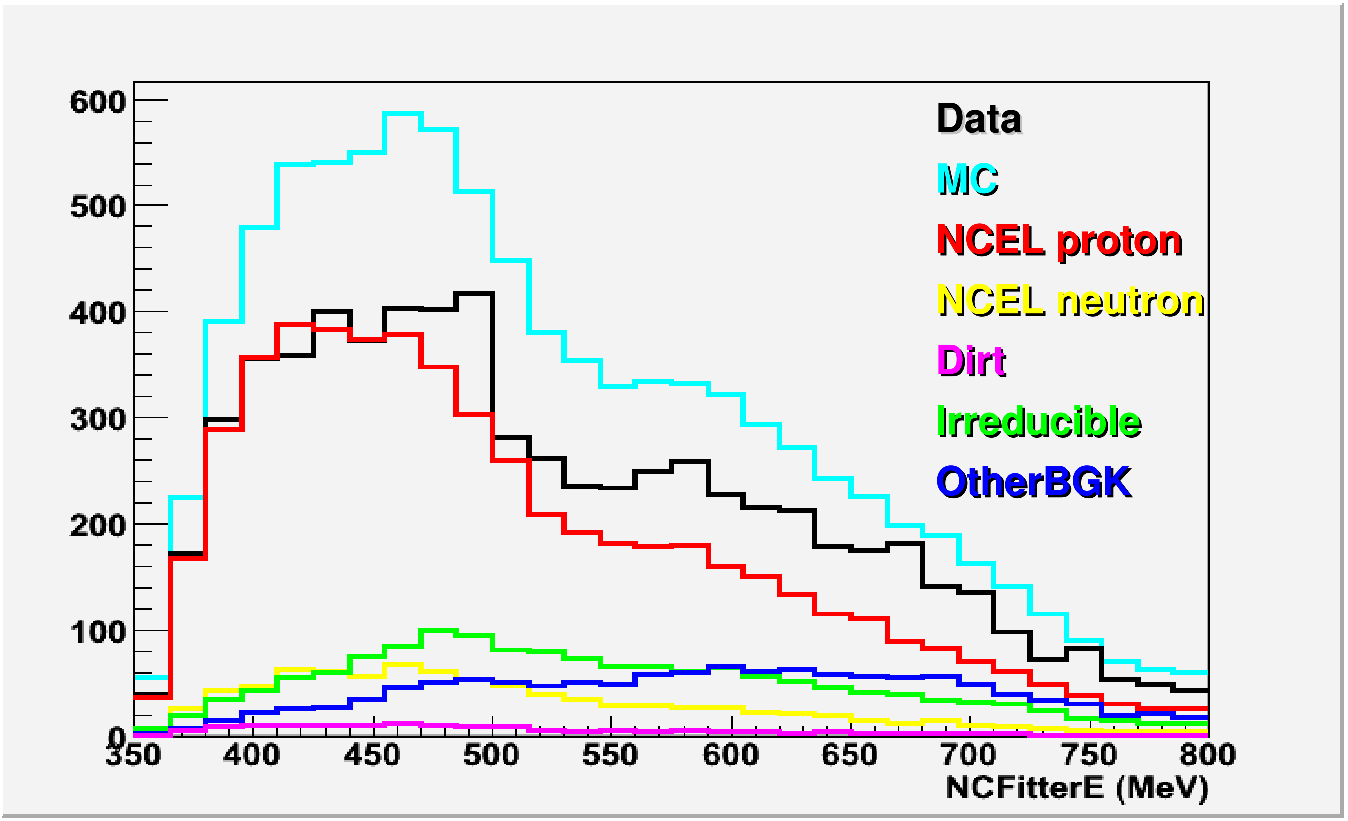


NCEL cuts + NCFitterE>350MeV +

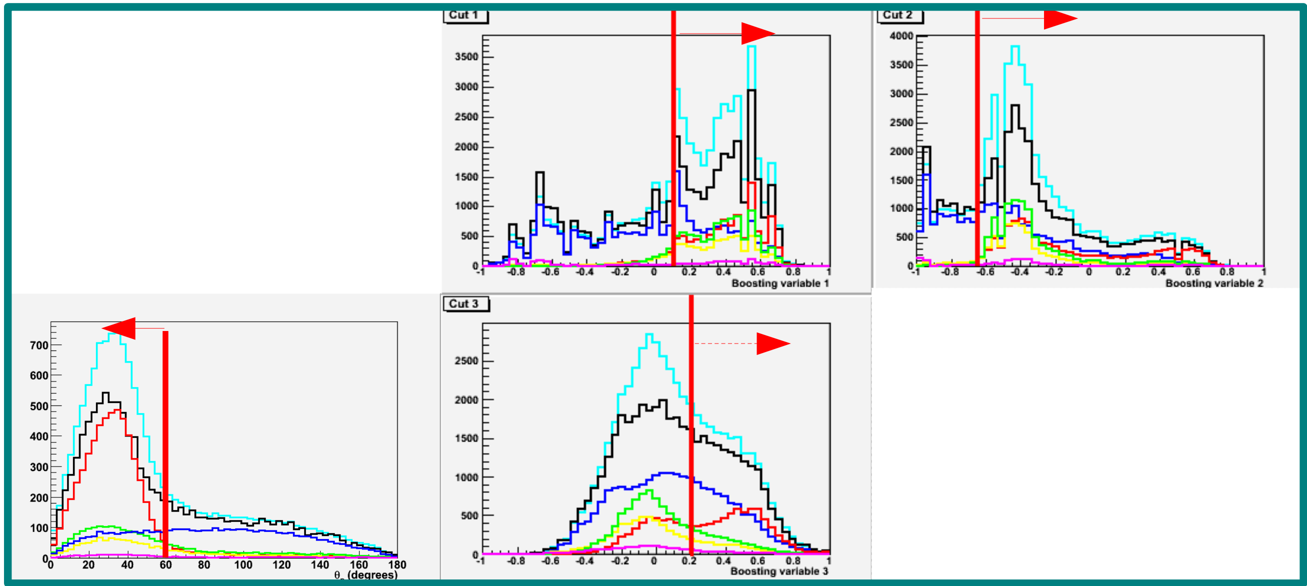


High energy NCEL proton sample

Reconstructed energy after NCEL proton cuts are applied



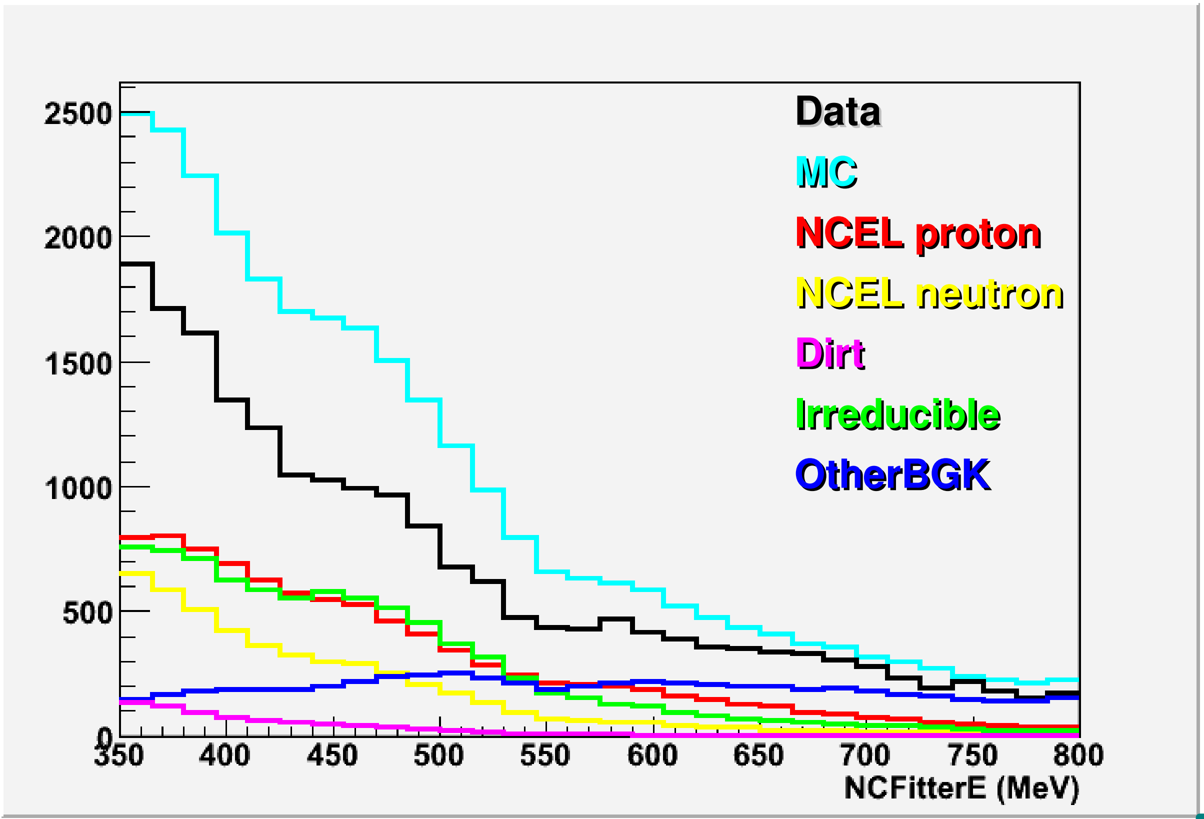
NCEL cuts + NCFitterE>350MeV +



Data has 6605 events

NCEL proton/MC = 0.58

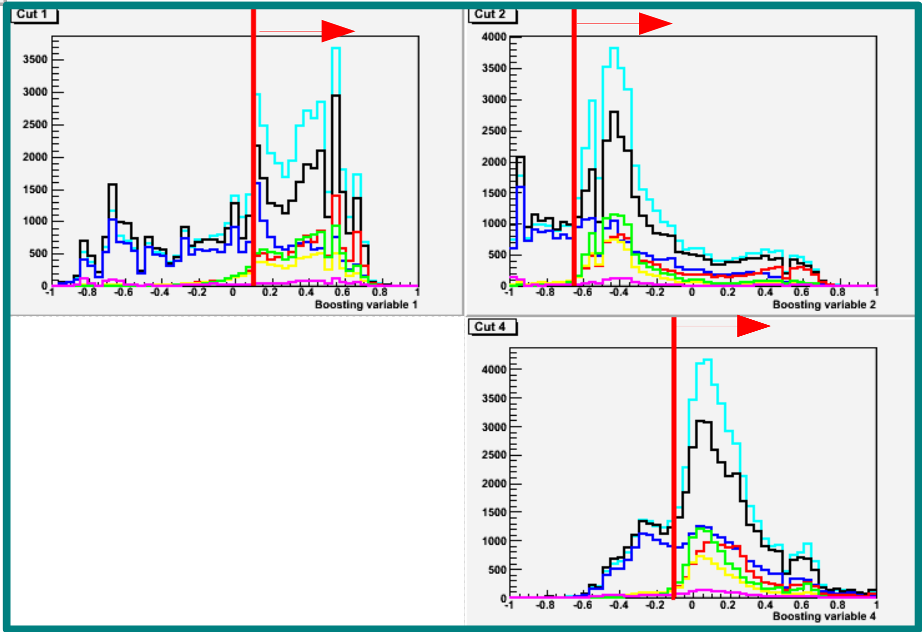
Reconstructed energy after NCEL (proton+neutron) cuts are applied



Data has 19704 events

(NCEL proton+NCEL neutron)/MC = 0.47

NCEL cuts + NCFitterE>350MeV +



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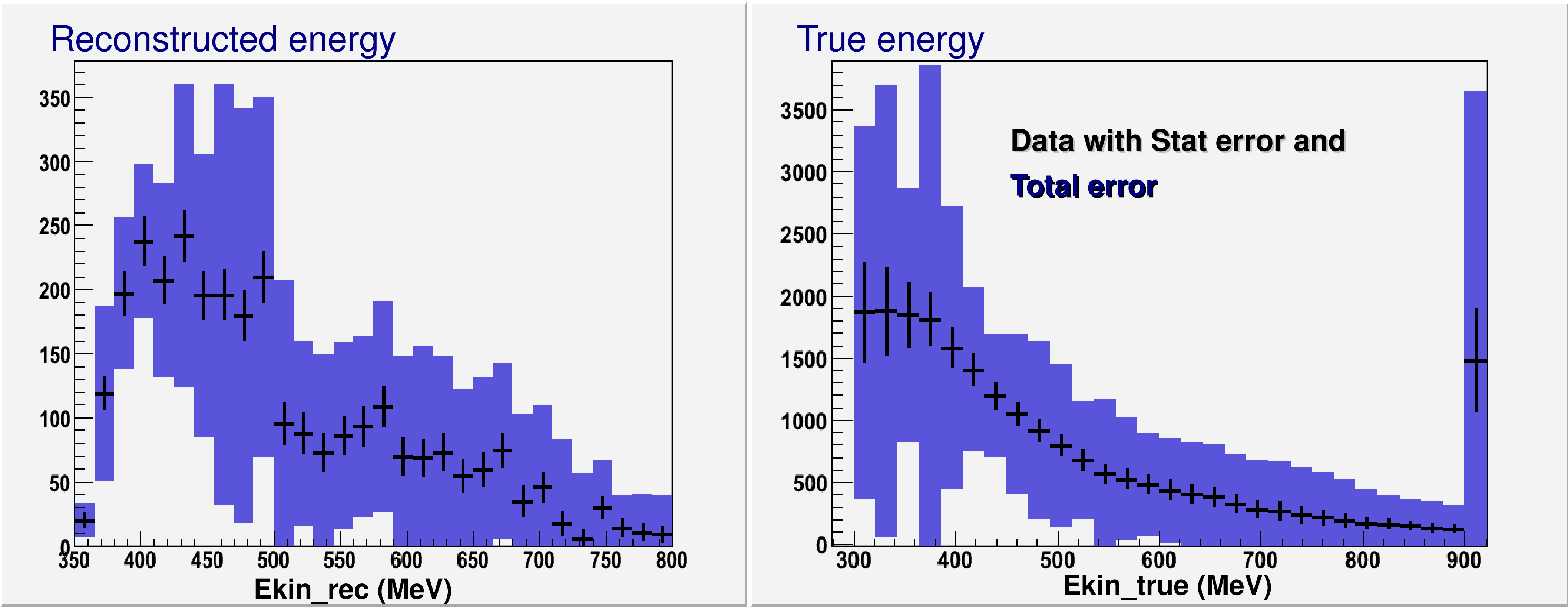
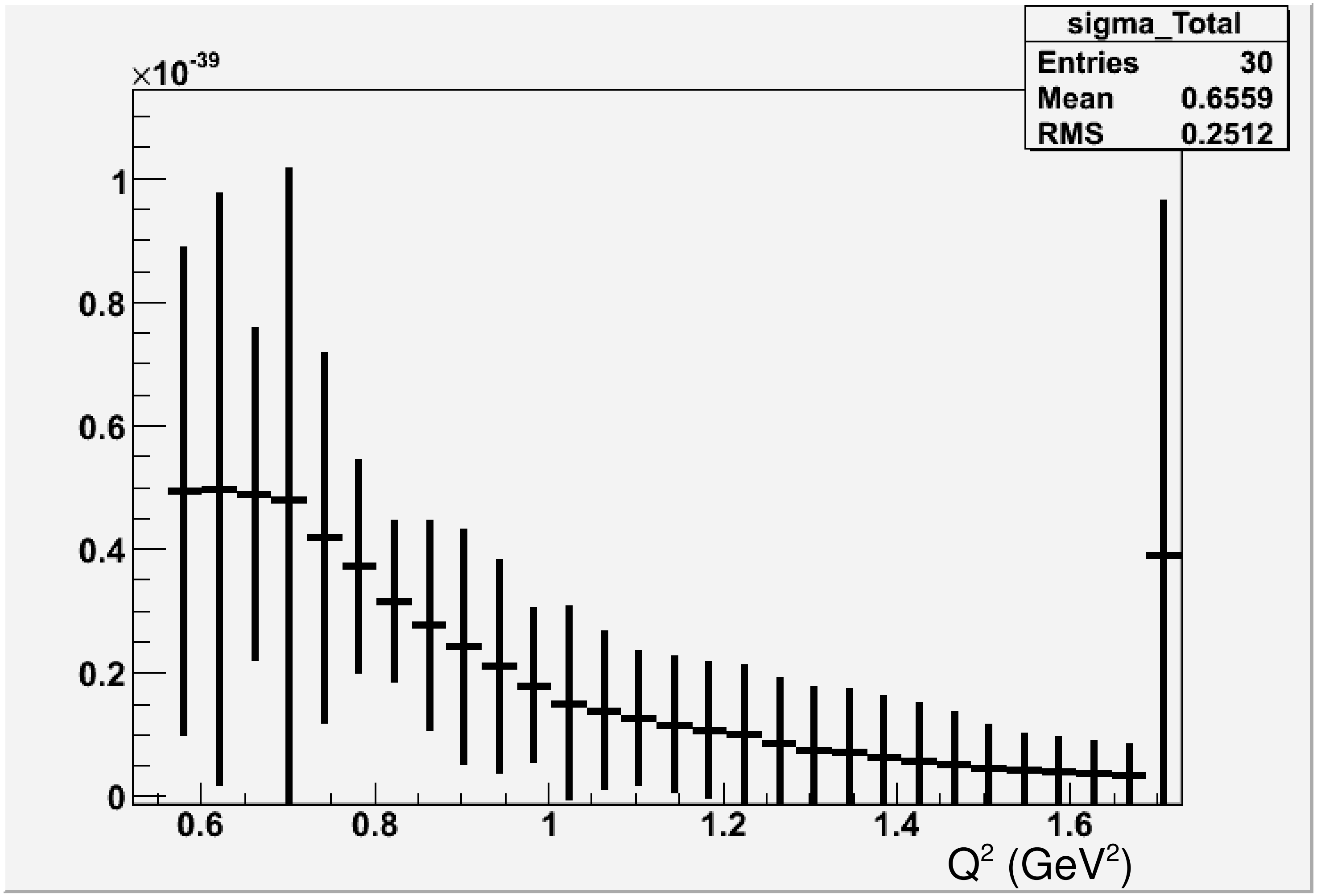
Preliminary high energy NCEL proton cross-section



Measured NCEL proton cross-section



The errors seems to be too large.

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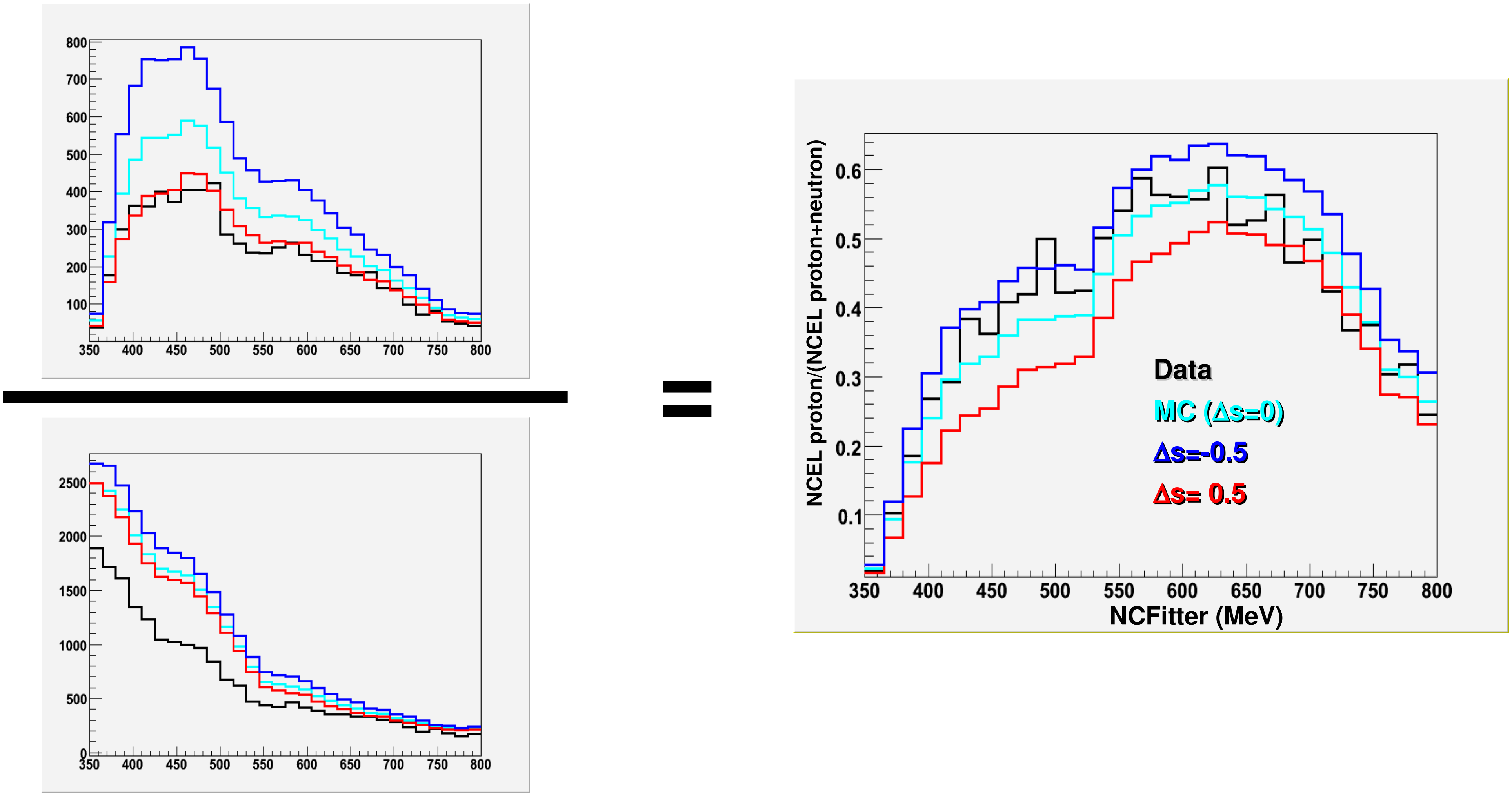
Preliminary Δs fits from the ratio of (NCEL proton-enriched)/(NCEL-like) at high energy

Measuring NCEL proton/ (NCEL proton + neutron) ratio

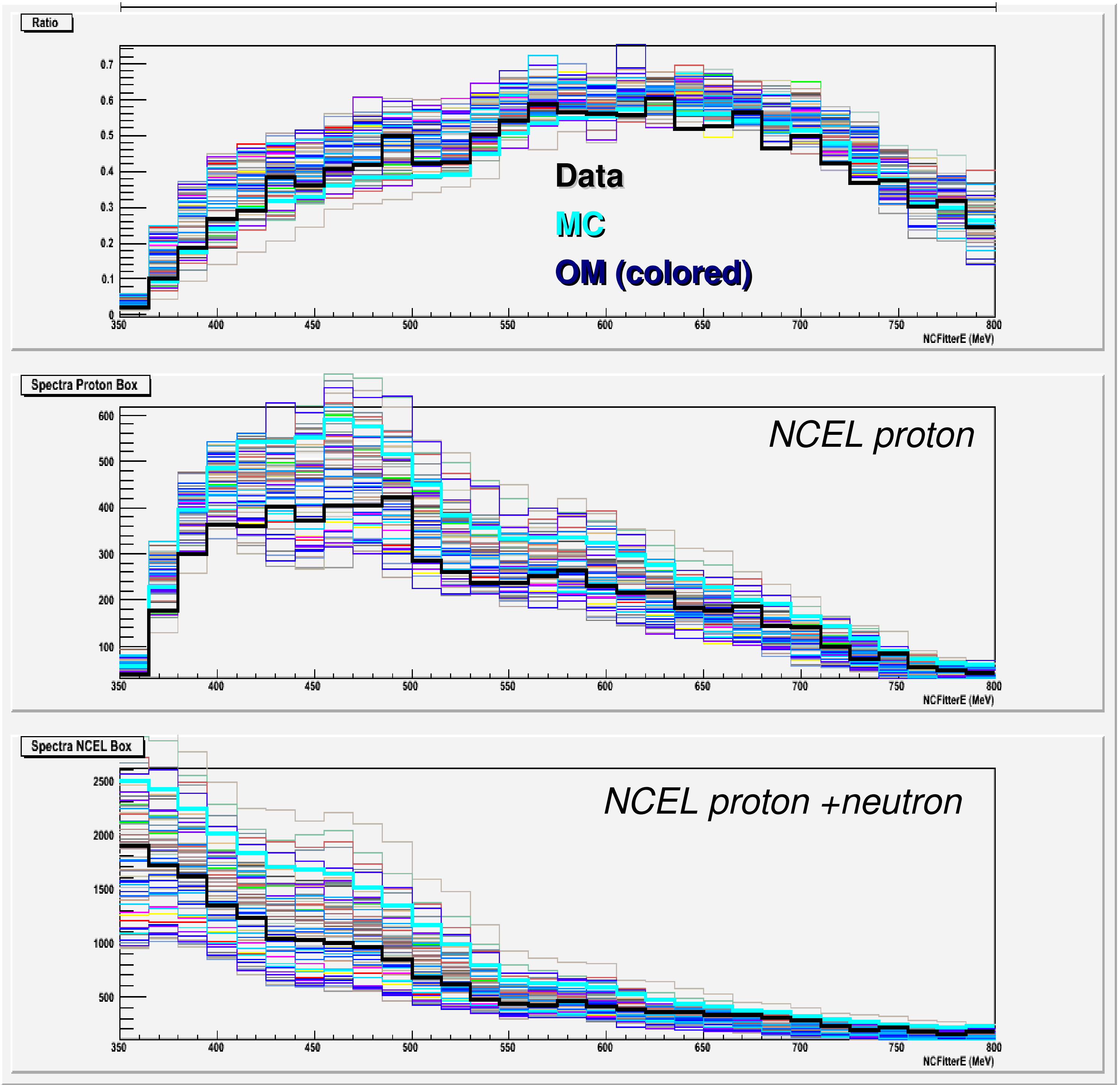
For numerator using NCEL proton cuts, for denominator – NCEL proton + neutron cuts, calculate the ratio.

Look at the reconstructed energies only. No unfolding involved.

No background subtraction.



Δs fits from NCEL proton/NCEL (proton+neutron) ratio



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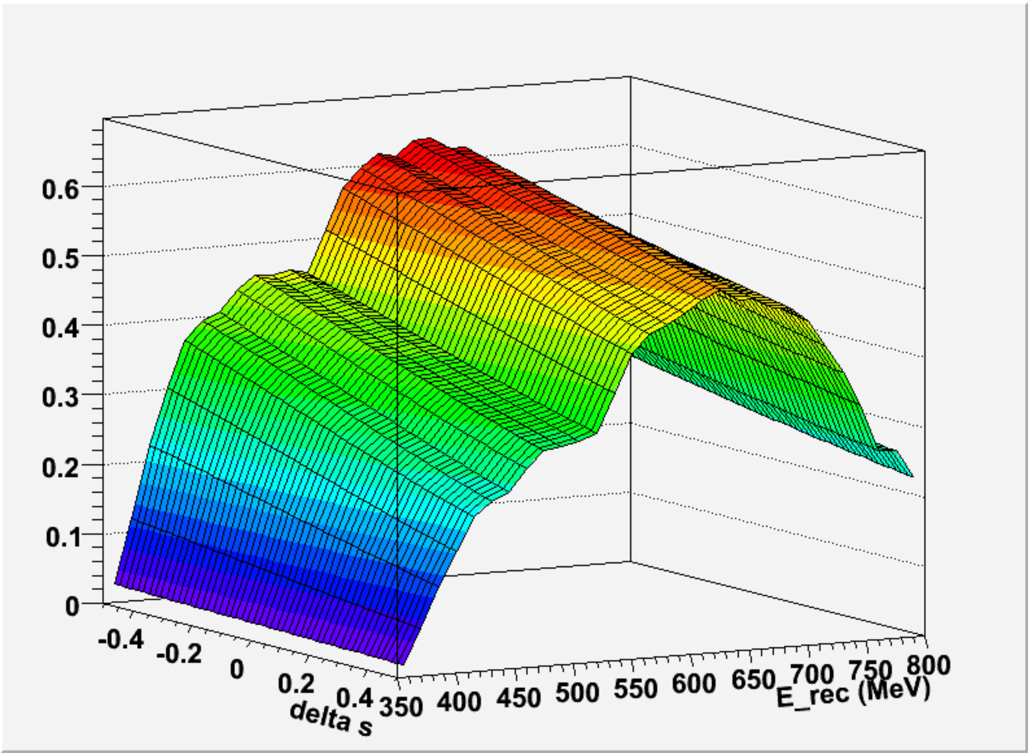
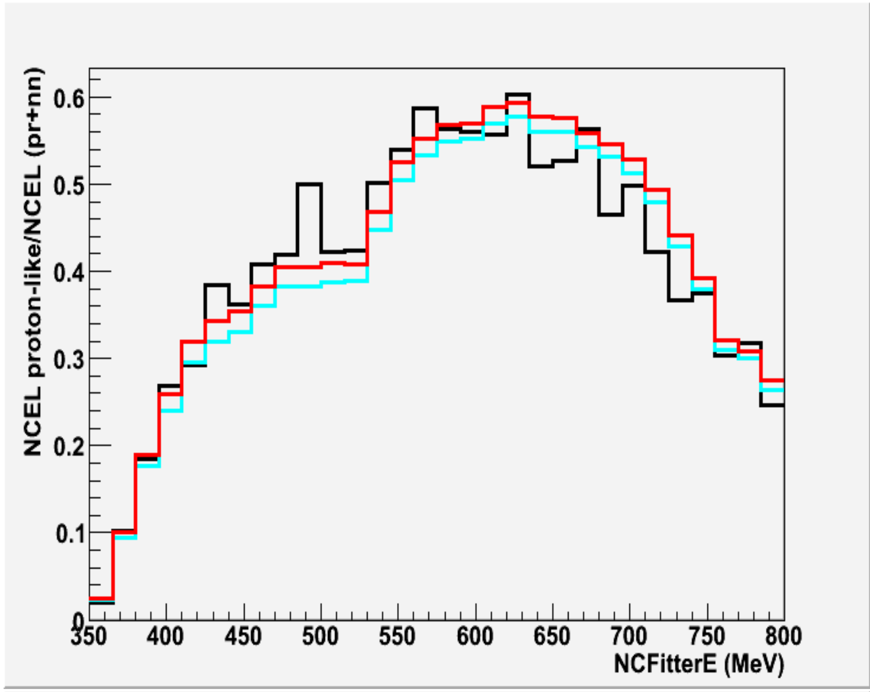
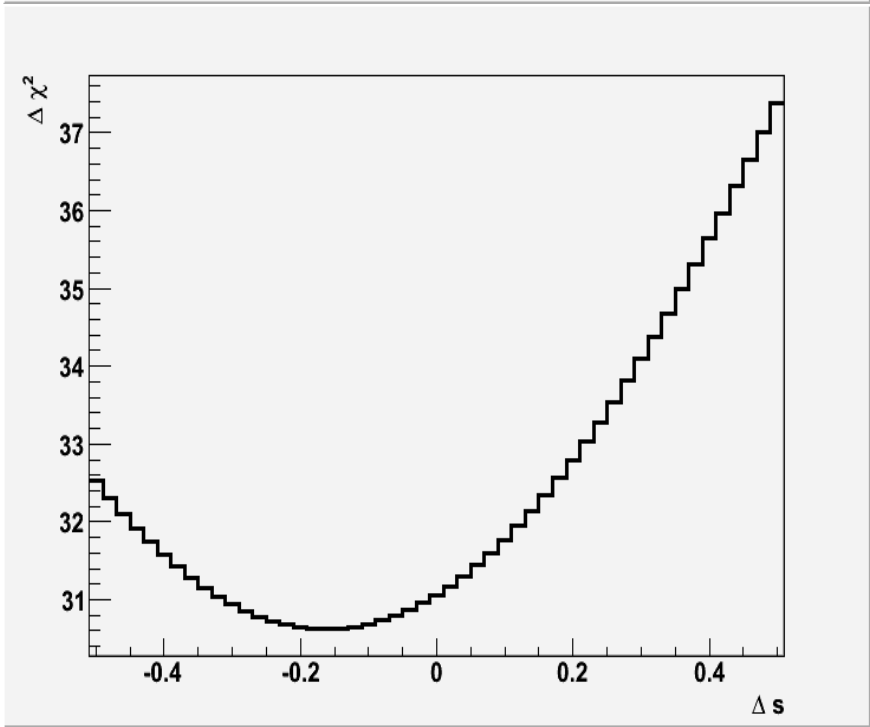




$\Delta s = -0.16 \pm 0.24$

$\Delta\chi^2 = 0.61/\text{d.o.f}$



Conclusions

1. A proton reconstruction package was developed, and used in the NCEL analysis.

2. We have measured the spectrum of dirt backgrounds in the NCEL event sample from dirt-enriched samples of events. This reduced the systematic errors due to dirt.

3. The NCEL differential cross-section has been measured and systematic errors were taken into account.

4. Fits to M_A from the NCEL differential cross-section were done. Absolute normalization was used in this fits. The results are consistent with MiniBooNE M_A from CCQE.

4. We looked at a possible proton energy scaling. Although we found a possibility of ~10%wrong energy scaling, it is covered with systematical uncertainties in the optical model.

5. High energy (above proton Cerenkov threshold) NCEL sample was studied. We were able to identify a pure sample of NCEL protons at those energies and measured the differential cross-section. However the errors for the cross-section are too large.

6. The Δs fits from the ratio of NCEL proton/NCEL (proton+neutron) were done. The results are shown to the collaboration.

Conclusions 2

7. Technical notes 268 (on the method of unfolding used for NCEL analysis) and 270 (on the NCEL differential cross-section measurement) are on the website and are being reviewed.

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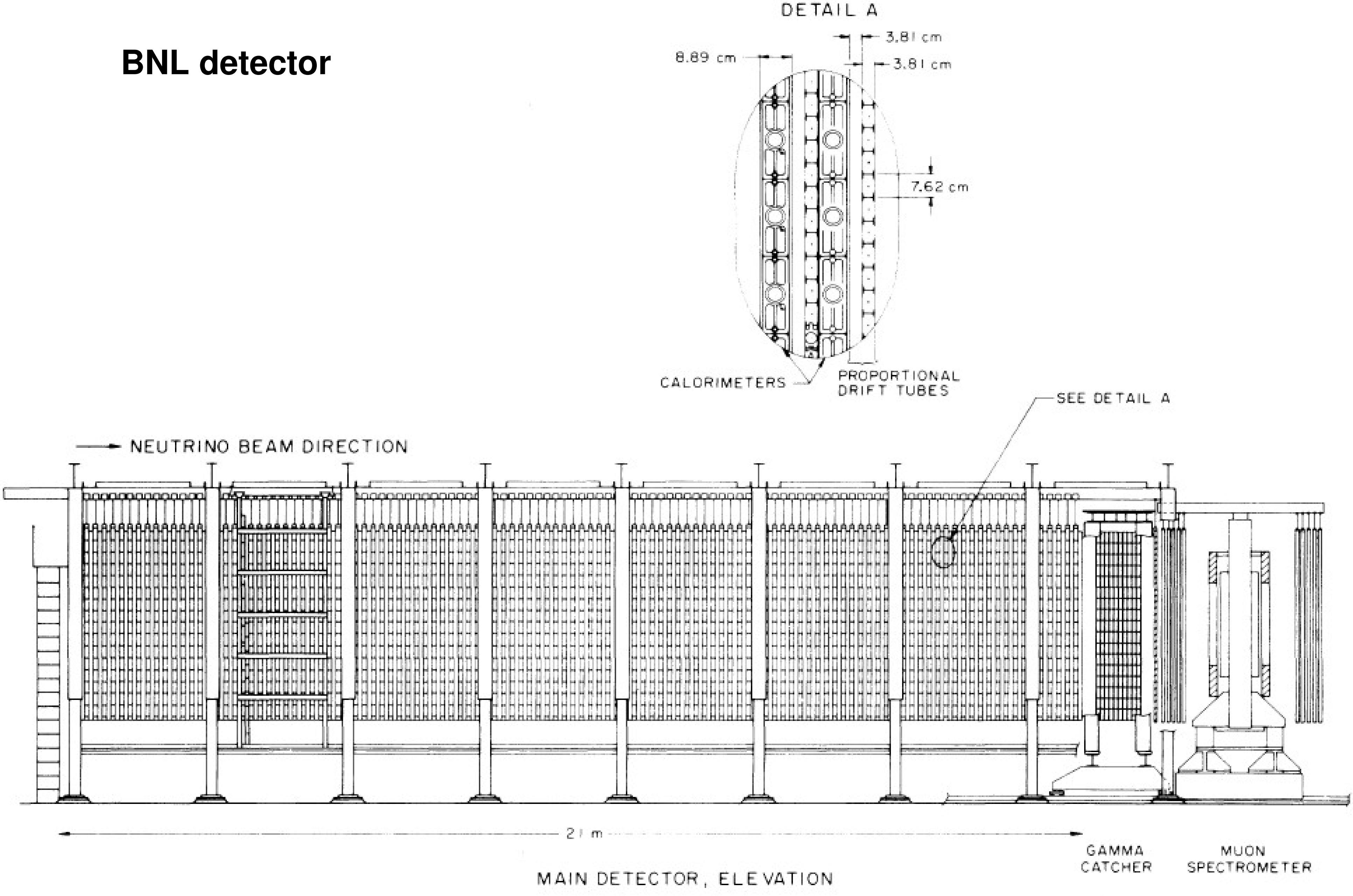
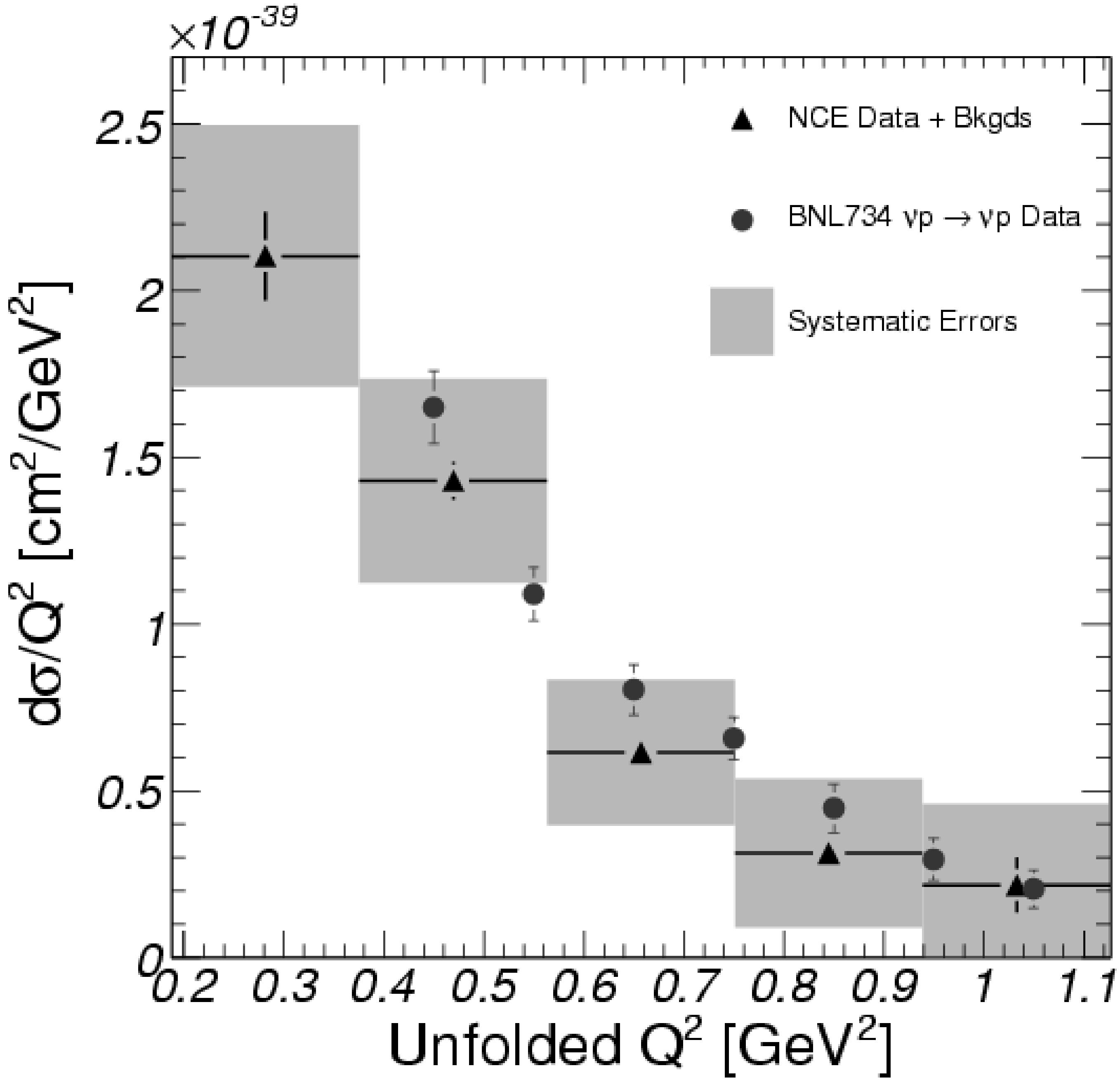
Many thanks to: Ion, Sam, Rex and Teppei for ideas, guidance, help in the analysis and letters of recommendation.

BNL detector



A schematic drawing of the BNL—Brown—KEK—Osaka—Pennsylvania—Stony Brook neutrino detector.

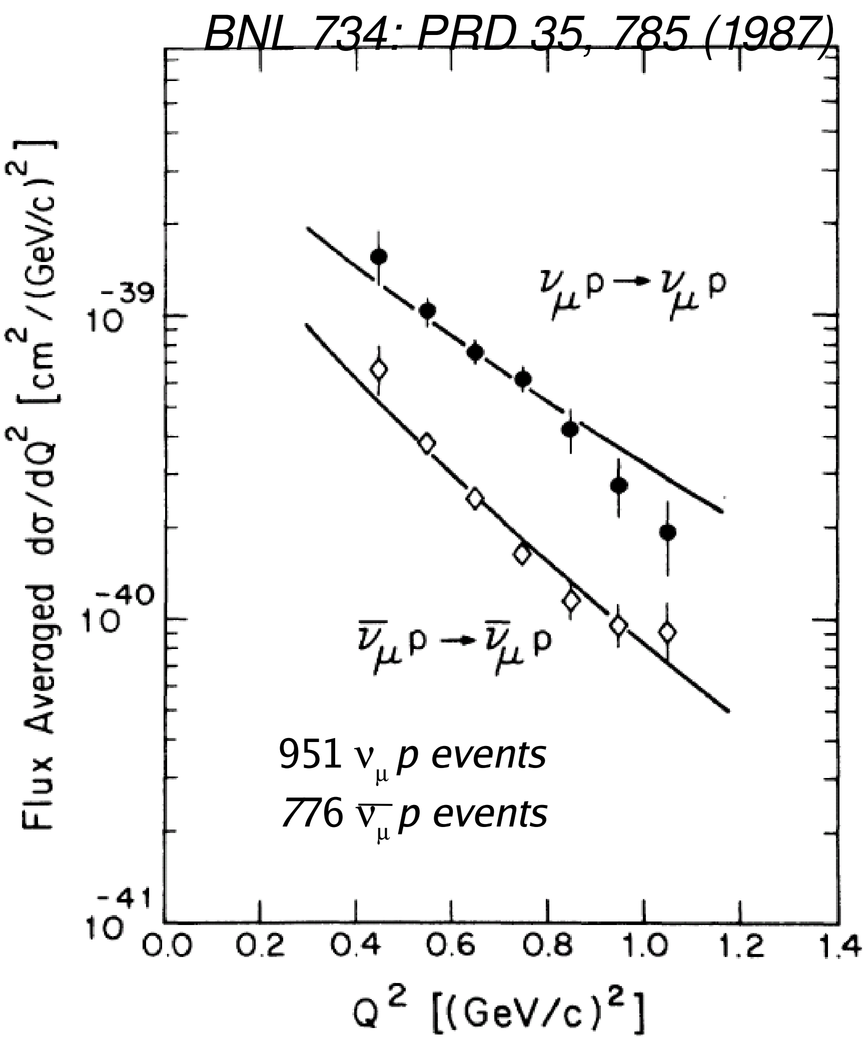
BNL E734 νp elastic (1987) data
w/ Chris Cox's NCEL Differential Cross-Section using 10% MiniBooNE data

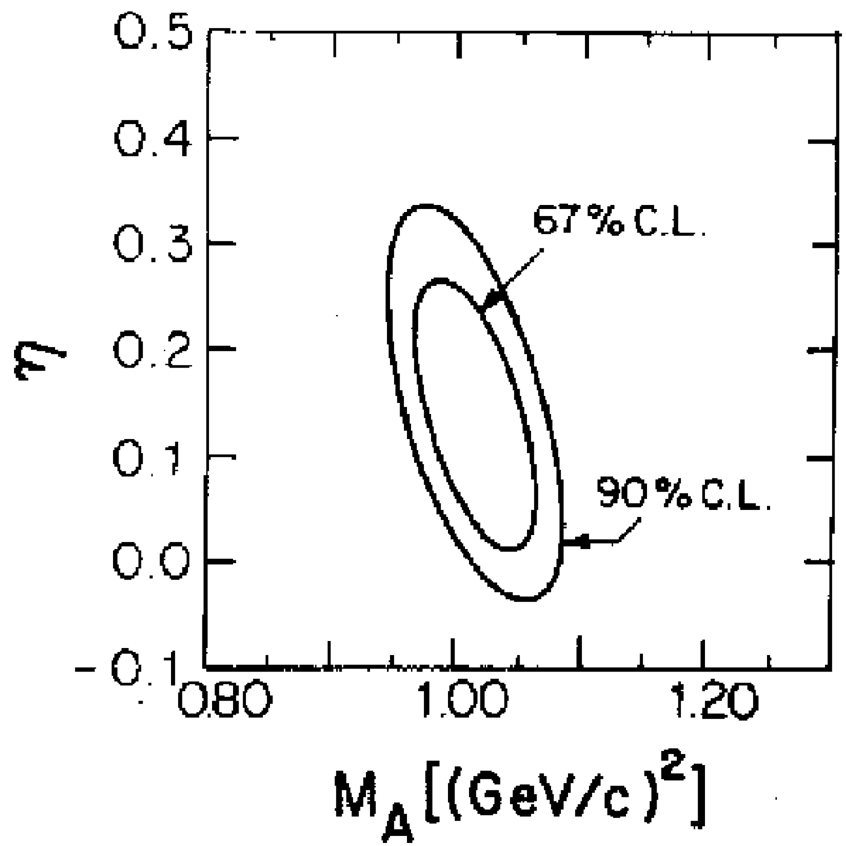


Measurements of Δs(=-η) from neutrino experiments

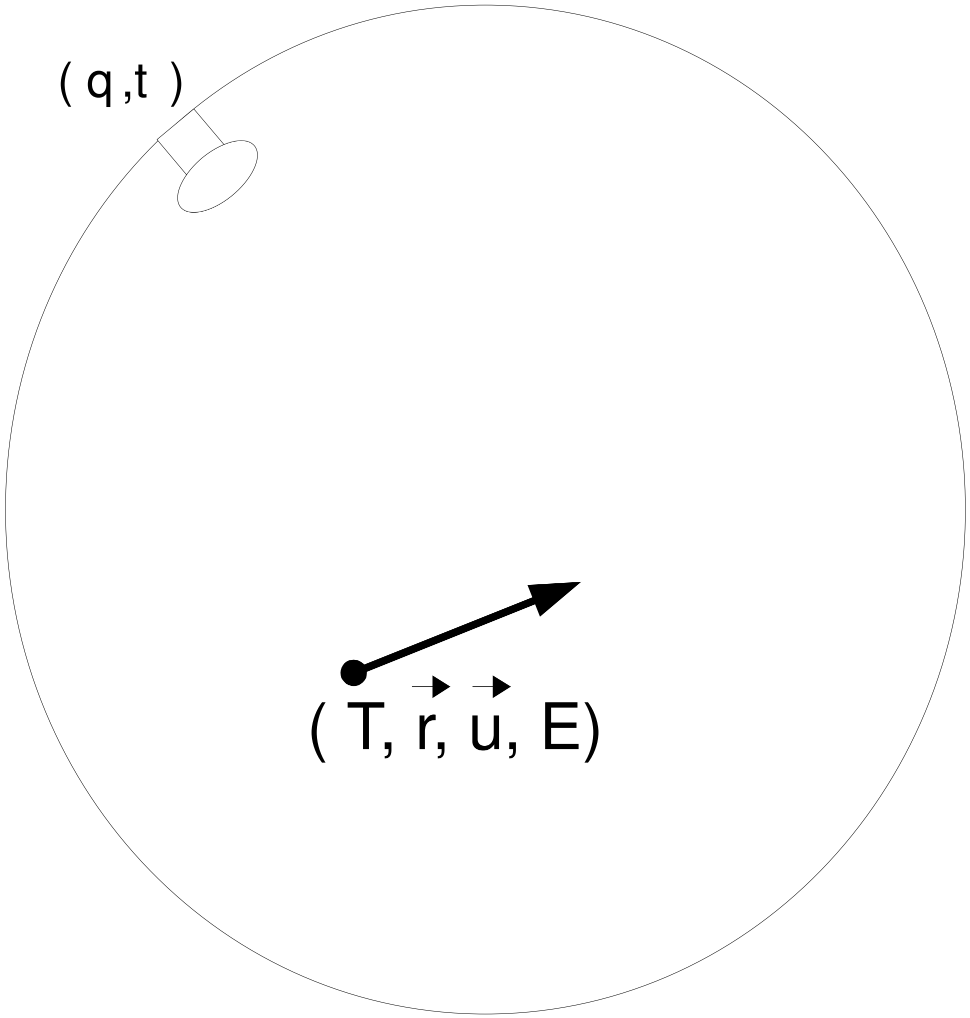
$$G_A^s(Q^2) = 0.5\frac{\Delta s}{1+Q^2/M_A}$$

The best data to date are from BNL 734(1987):





Reconstruction of the NCEL events

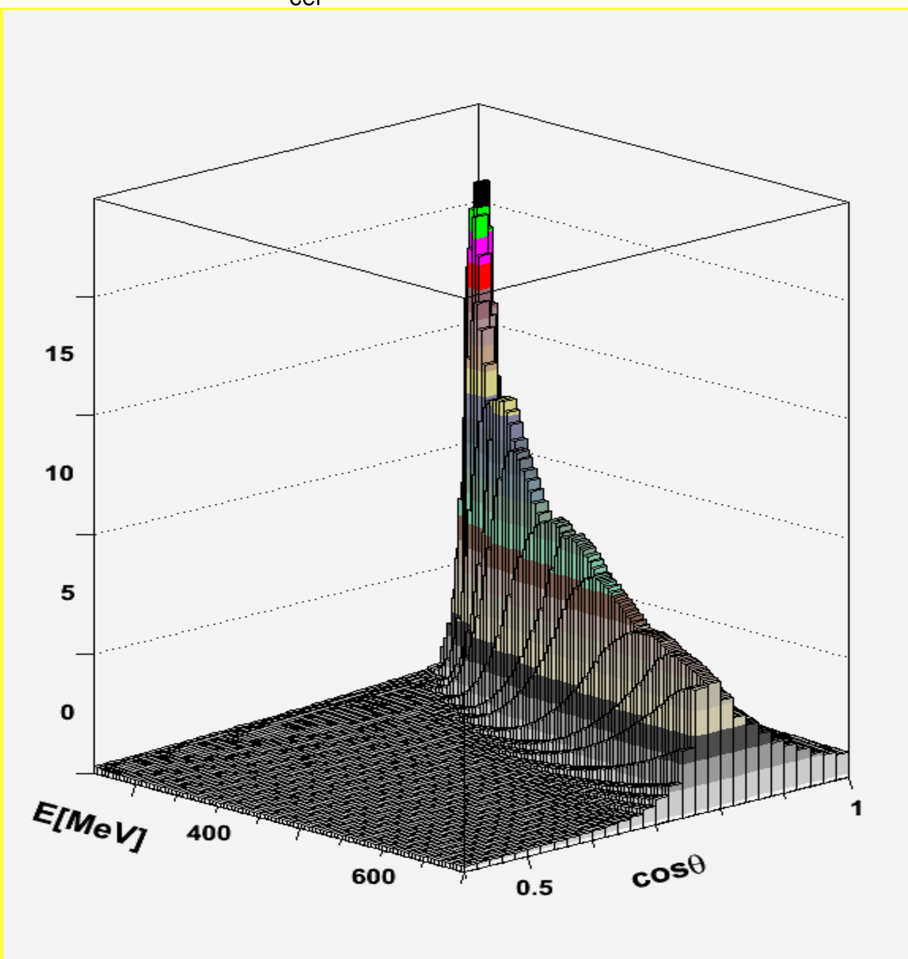


NCFItter features reconstruction of events assuming the event is a proton.

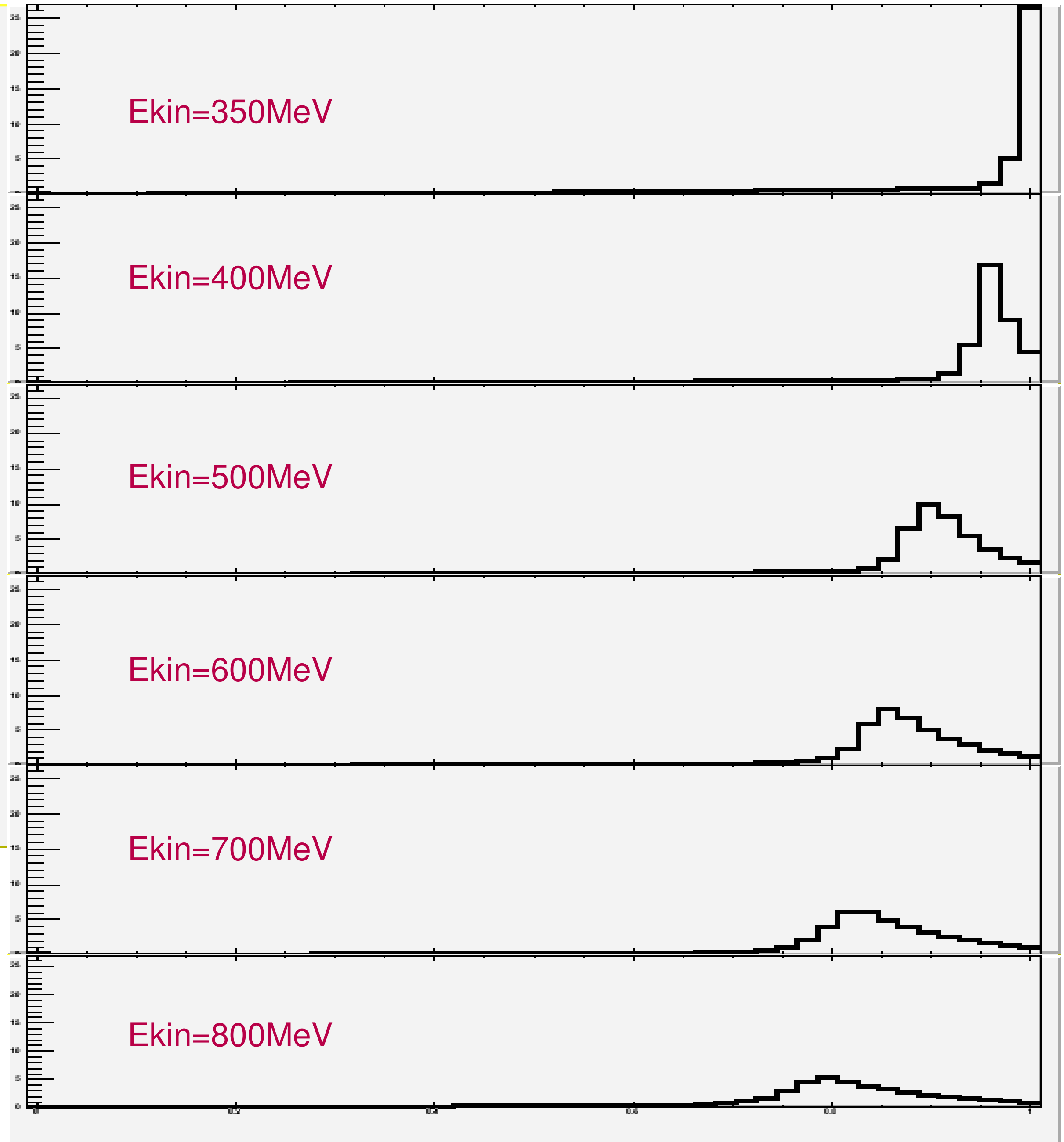
It is done by minimizing the likelihood functions – Charge and Time likelihoods, parameters of which were measured from Monte Carlo events.

F(cosθ_{cer},E) for protons

F(cosθ_{cer}) 2-dimensional plot



F(cosθ_{cer}) for different energies

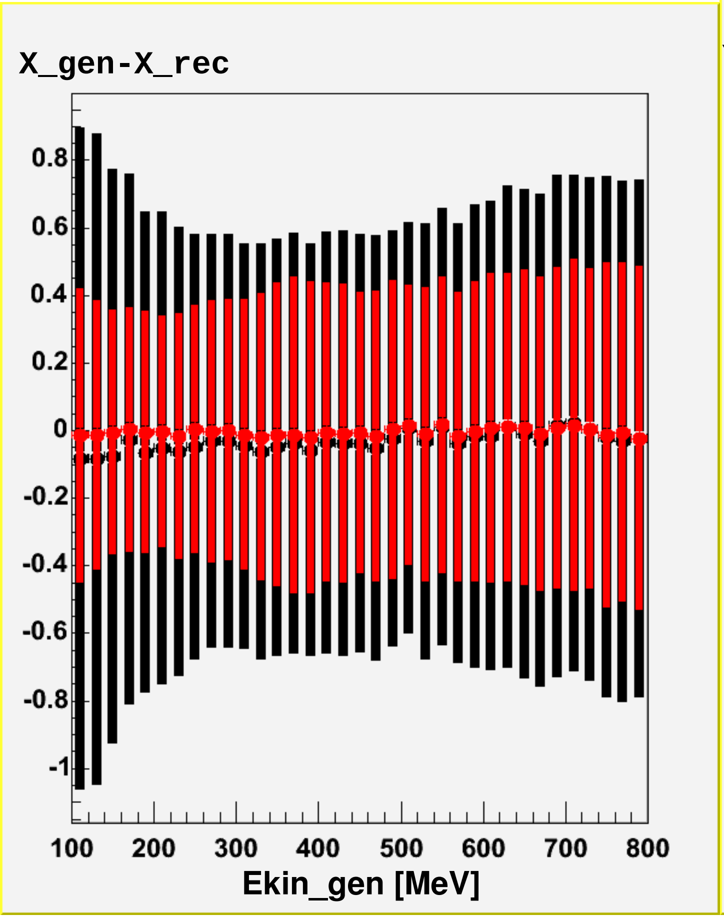


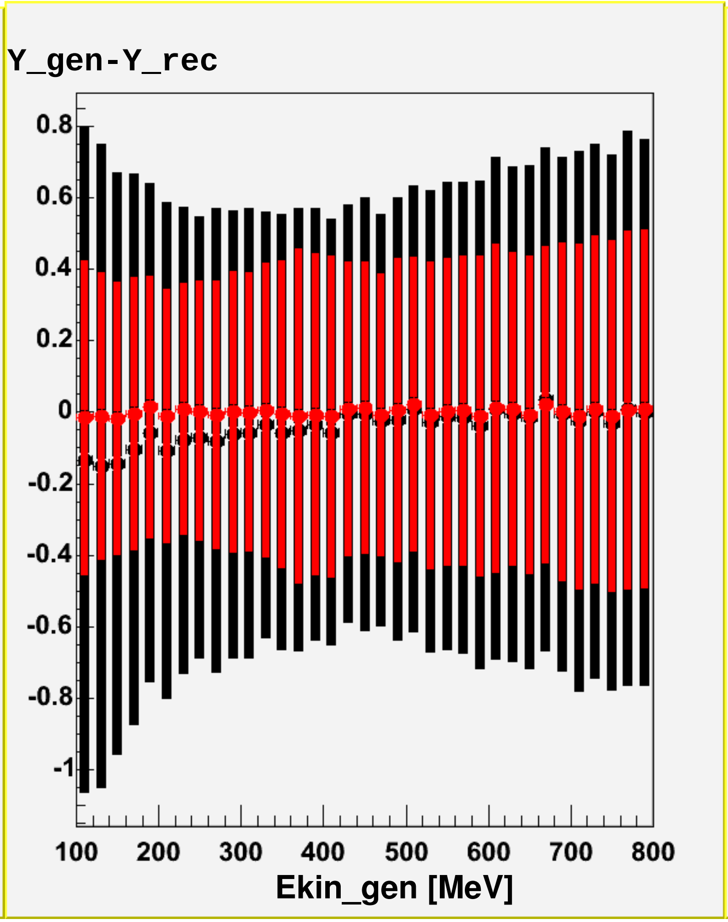
Reconstruction performance

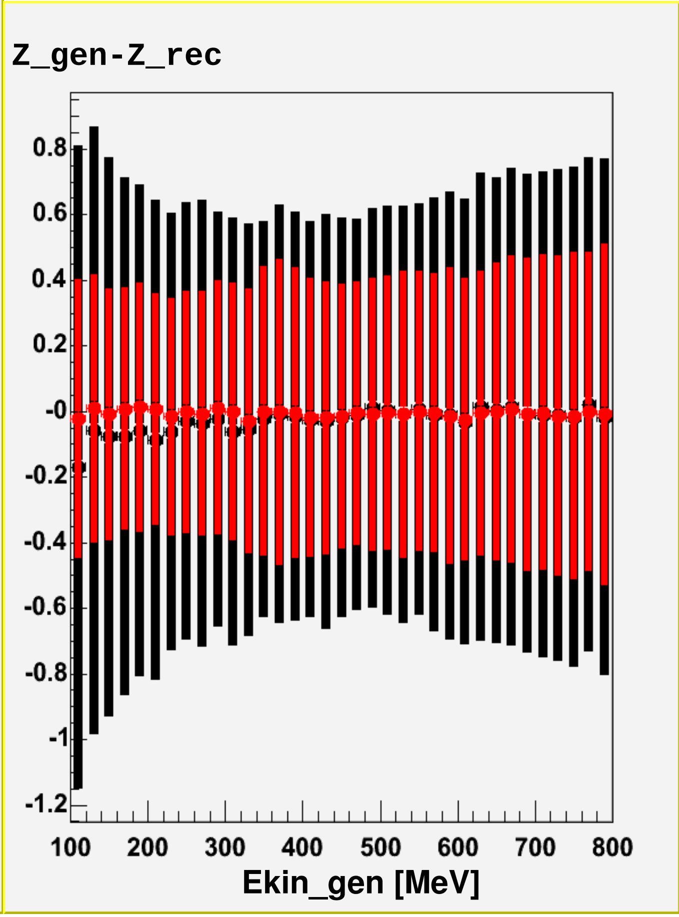
NCFitter vs StancuFitter (electron fitter)

Position resolution

Accuracy: 1.29m → 0.74m







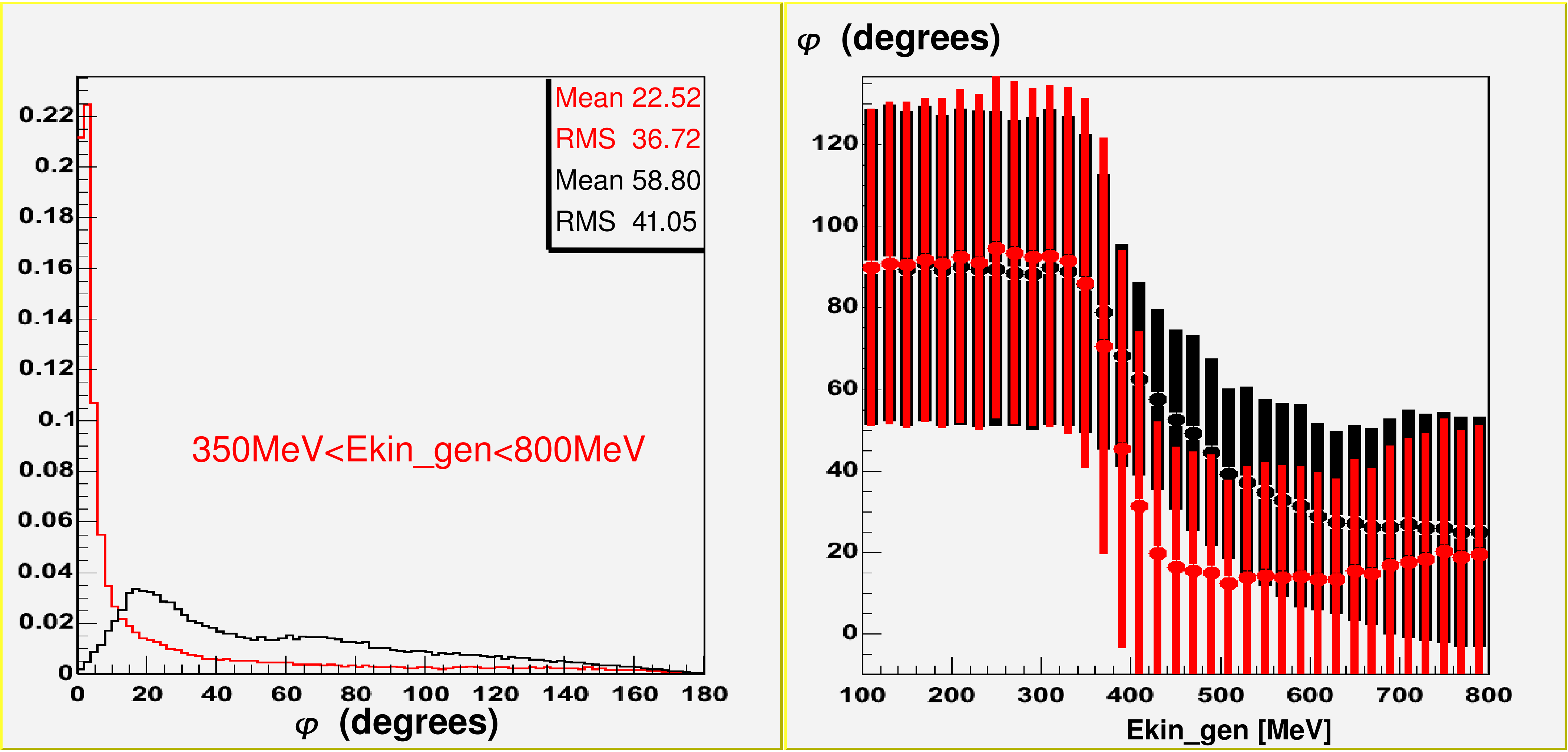
Protons 100MeV<Ekin_gen<800MeV Cuts: VHits<6 + THits>24 + NCFitterR<4.5m

Reconstruction performance

NCFitter vs StancuFitter (electron fitter)

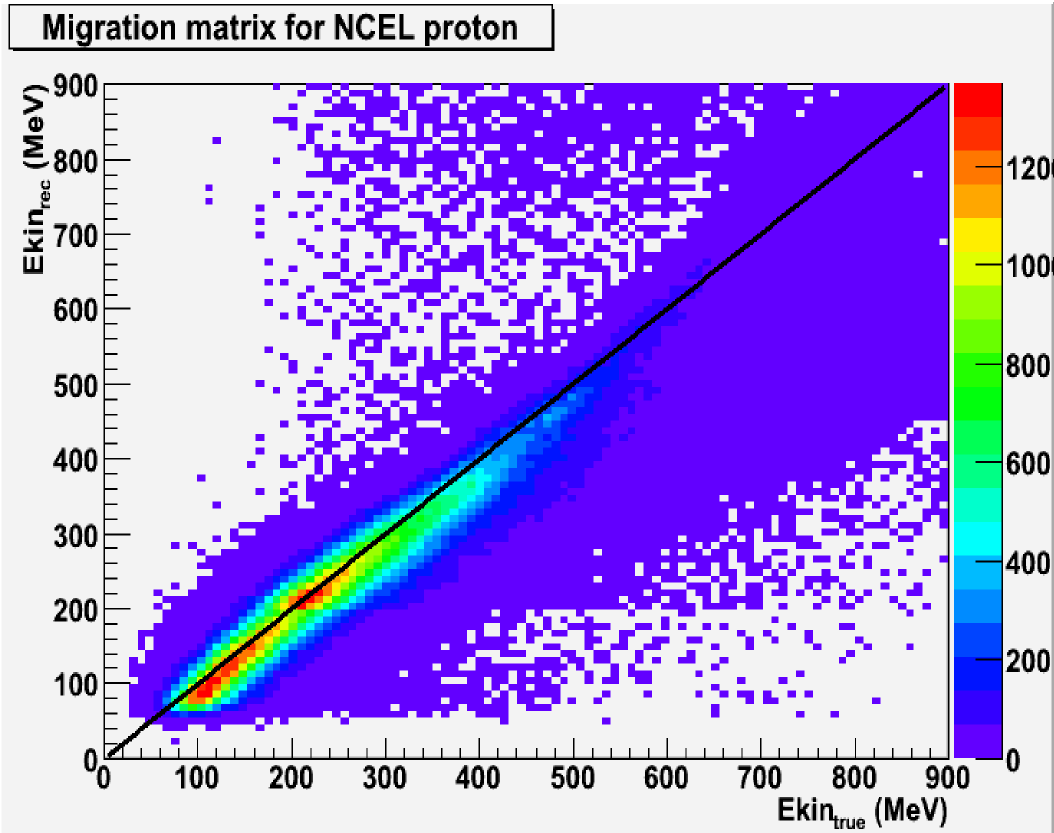
Direction resolution

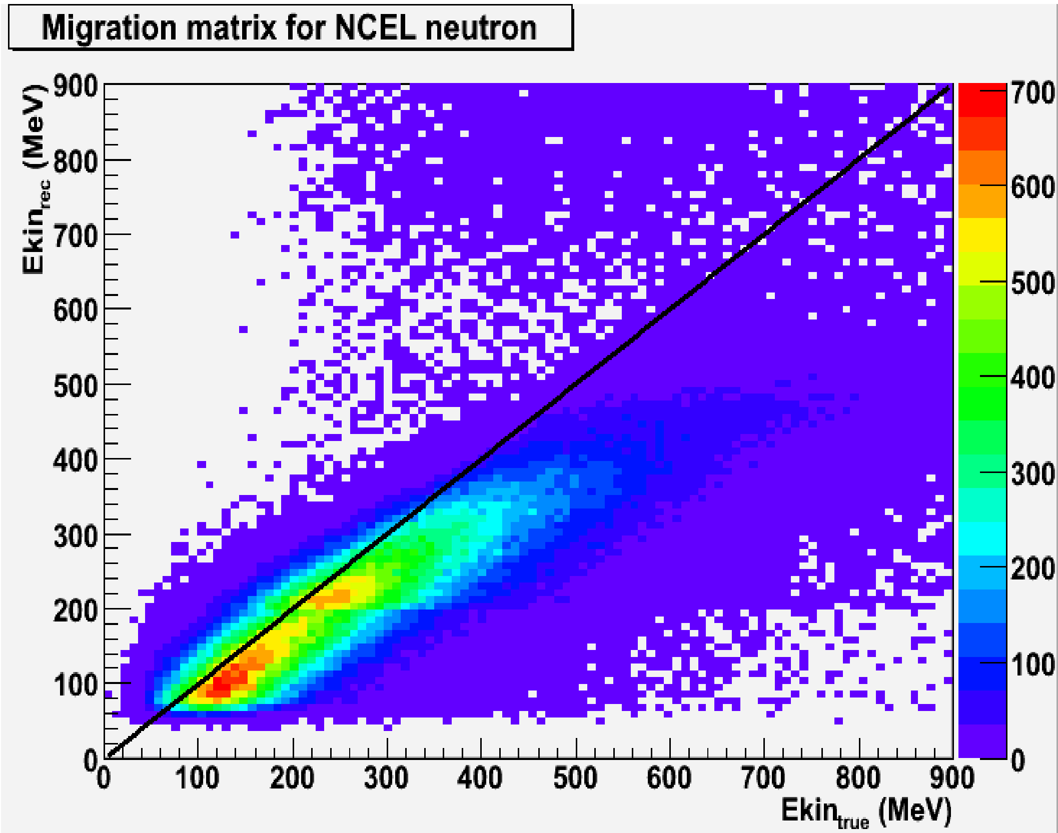
φ = angle between true and reconstructed directions



Protons 100MeV<Ekin_gen<800MeV   Cuts: VHits<6 + THits>24 + NCFitterR<4.5m

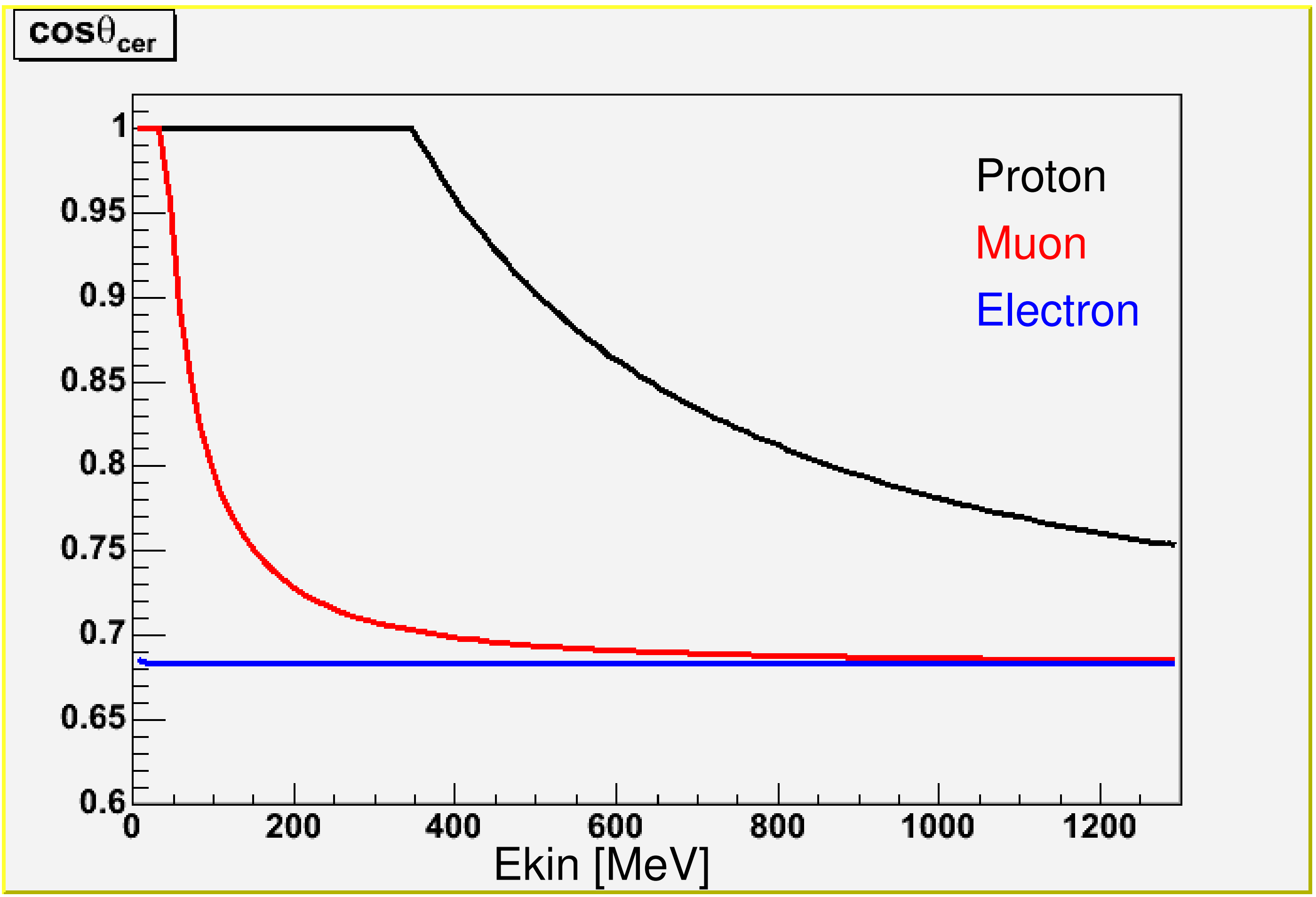
Energy reconstruction





Cerenkov angle

$$\cos\theta_{cer} = \frac{1}{\beta n}$$



Cerenkov profile for protons is much different, than muon or electron,
thus in order to reconstruct protons, we had to develop a special fitter (NCFitter)

Reconstruction performance

NCFitter vs StancuFitter (electron fitter)

Position resolution

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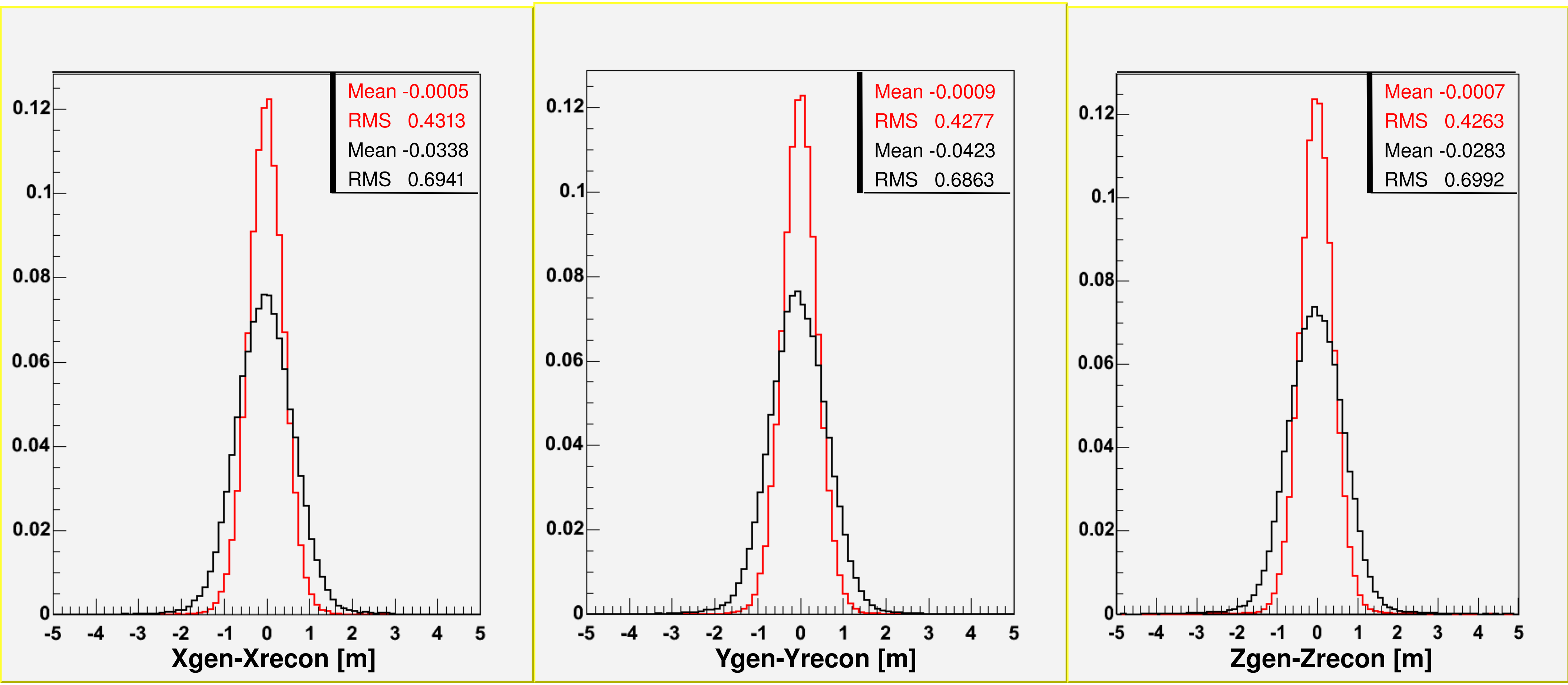


Protons 100MeV<Ekin_gen<800MeV   Cuts: VHits<6 + THits>24 + NCFitterR<4.5m

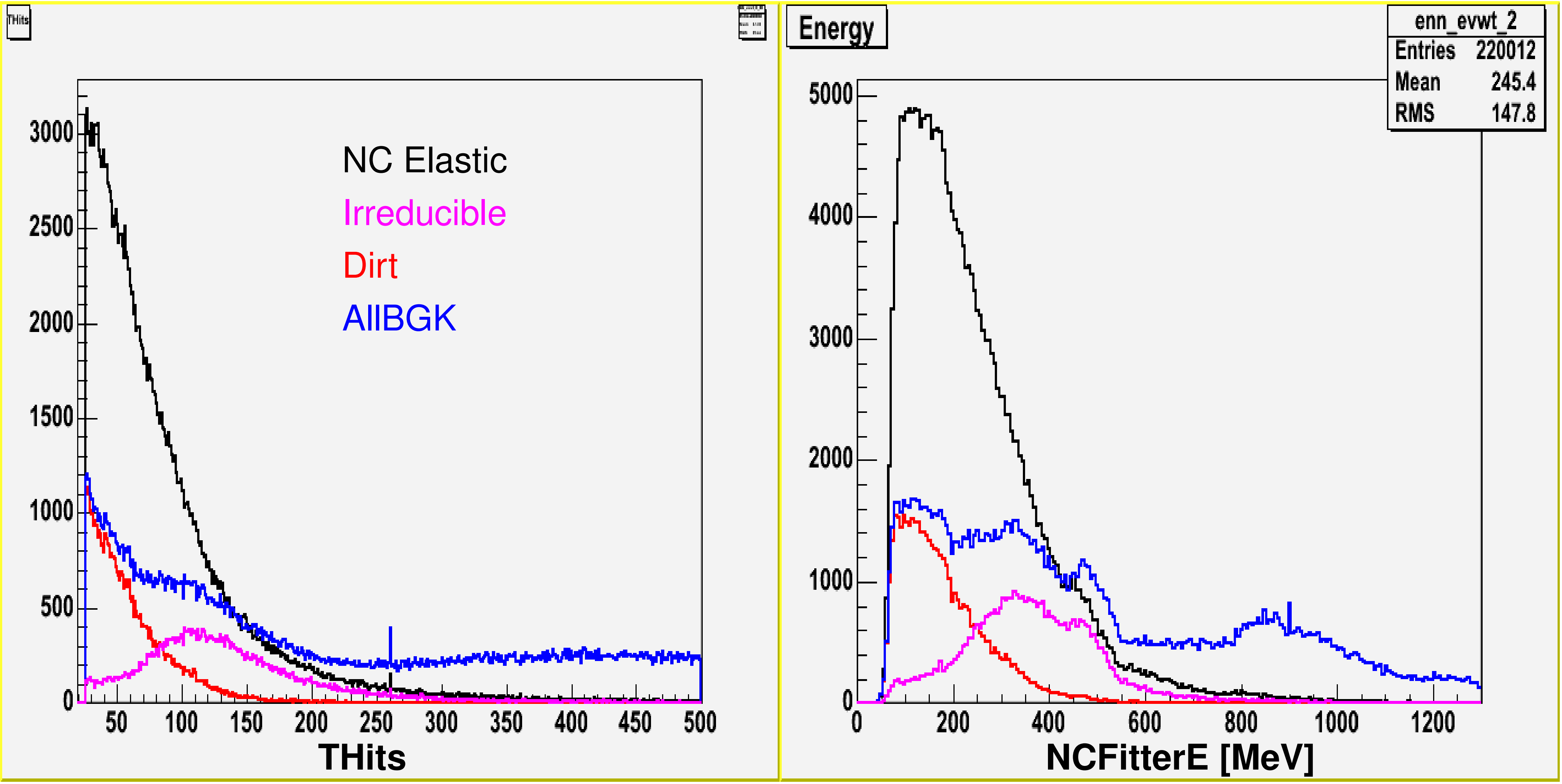
Selection cuts for NC Elastic

Selection	Purpose	Fraction of events, %						NCEL eff, %	Total events*, 10^3
		NCEL	Dirt	Irr	CCQE	BU	Other		
No cuts (>0SE)		0.6	1.7	0.1	1.9	94.1	1.7	100.0	33910.0
Veto PMTs<6	Remove cosmic rays	3.7	2.6	0.6	7.0	79.8	6.4	95.3	10853.0
1 Subevent	No decaying particles	7.1	5.1	1.1	2.4	80.8	3.5	80.8	1942.5
4400<Time<6500	Events in beam time	26.6	19.1	4.2	9.1	27.9	13.1	80.8	516.1
Tank PMTs>24	Reconstructible events	29.2	16.7	5.5	12.2	18.9	17.6	65.5	380.5
NCFitterE<650	Ensures low energy	38.7	20.1	7.4	1.9	26.7	5.2	59.5	261.3
tllkdiff<0.52	Assures protons	56.6	21.4	11.0	2.5	1.6	6.9	59.1	177.5
CUTR**	Reduces dirt	61.8	12.6	14.7	2.1	1.2	7.6	33.8	93.0

*Total number of events for official MiniBooNE neutrino data for 6.46 10^{20} POT

**CUTR={R<4.2m if Ekin_rec<200MeV, R<5.0m if Ekin_rec>200MeV}

Reconstructed energy and THits distribution for may06cocktail+dirt with CUTS



We can see that Dirt events are mostly at low energies. So, the idea is to use a tighter cut on NCFitterR at low energies(E<200) and probably, we'll just use NCFitterR<5 at high energies (E>300)

CUTS: 1 subevent + THits>24 + VHits<6 + 4400<ProtonT<6500 + fthjp<.55 + NCFitterR<4.5

Constraining Dirt events in NCEL sample

Constraining Dirt in NCEL

First method is based on fitting reconstructed Z and R distributions for each reconstructed energy bin

2 additional dirt-enriched samples (3 overall):

1. NCEL *1 subevent + THits>24 + VHits<6 + 4400<T<6500 + tllkdiff<0.42 +* ***NCFitterE<650 + CUTR***

Dirtfra=12.6%

2. dirtZ *1 subevent + THits>24 + VHits<6 + 4400<T<6500 + tllkdiff<0.42 +* ***NCFitterE<315 + 3.8<NCFitterR<5.2***

Dirtfra=31.5%

3. dirtR *1 subevent + THits>24 + VHits<6 + 4400<T<6500 + tllkdiff<0.42 +* ***NCFitterE<315 + NCFitterZ<0***

Dirtfra=36.6%

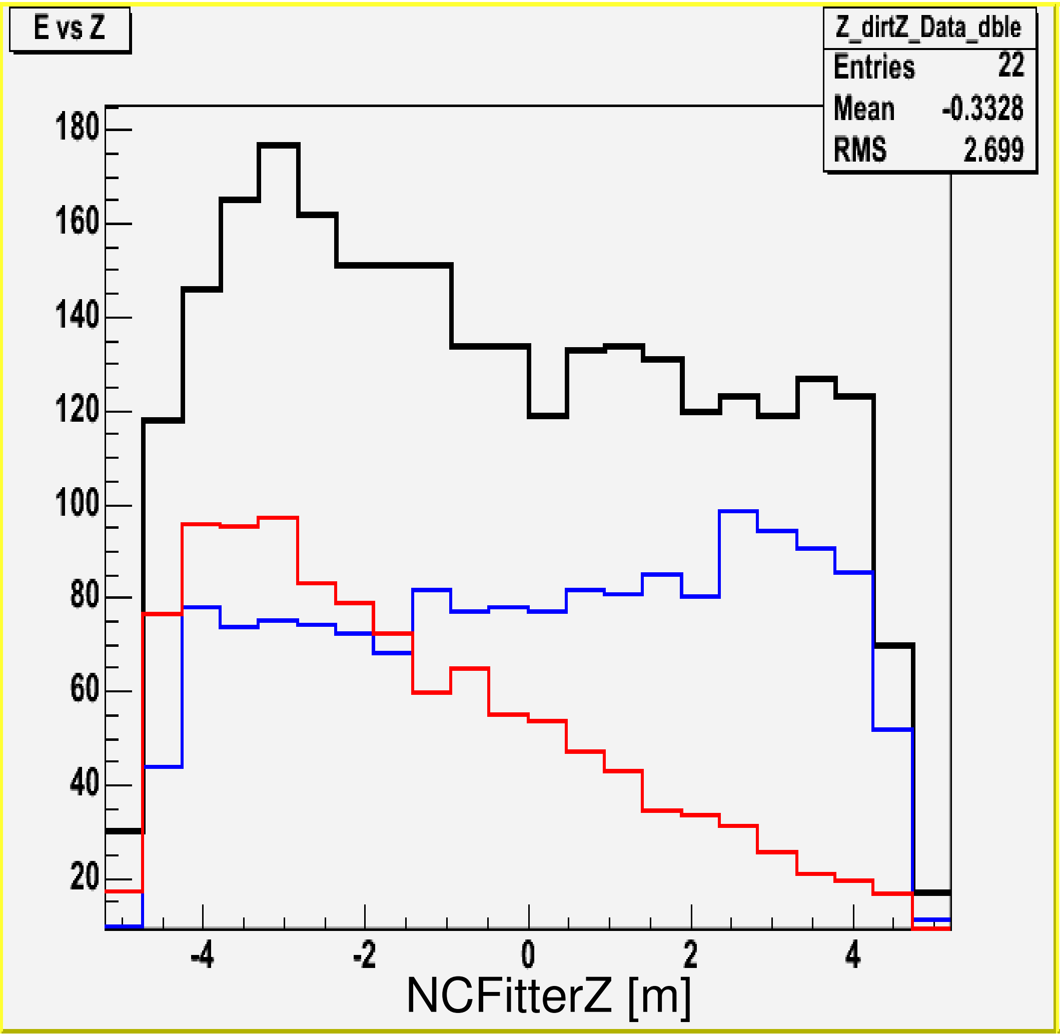
dirtZ sample is used in the Z-distribution fit. DirtR is used in R-distribution fit.

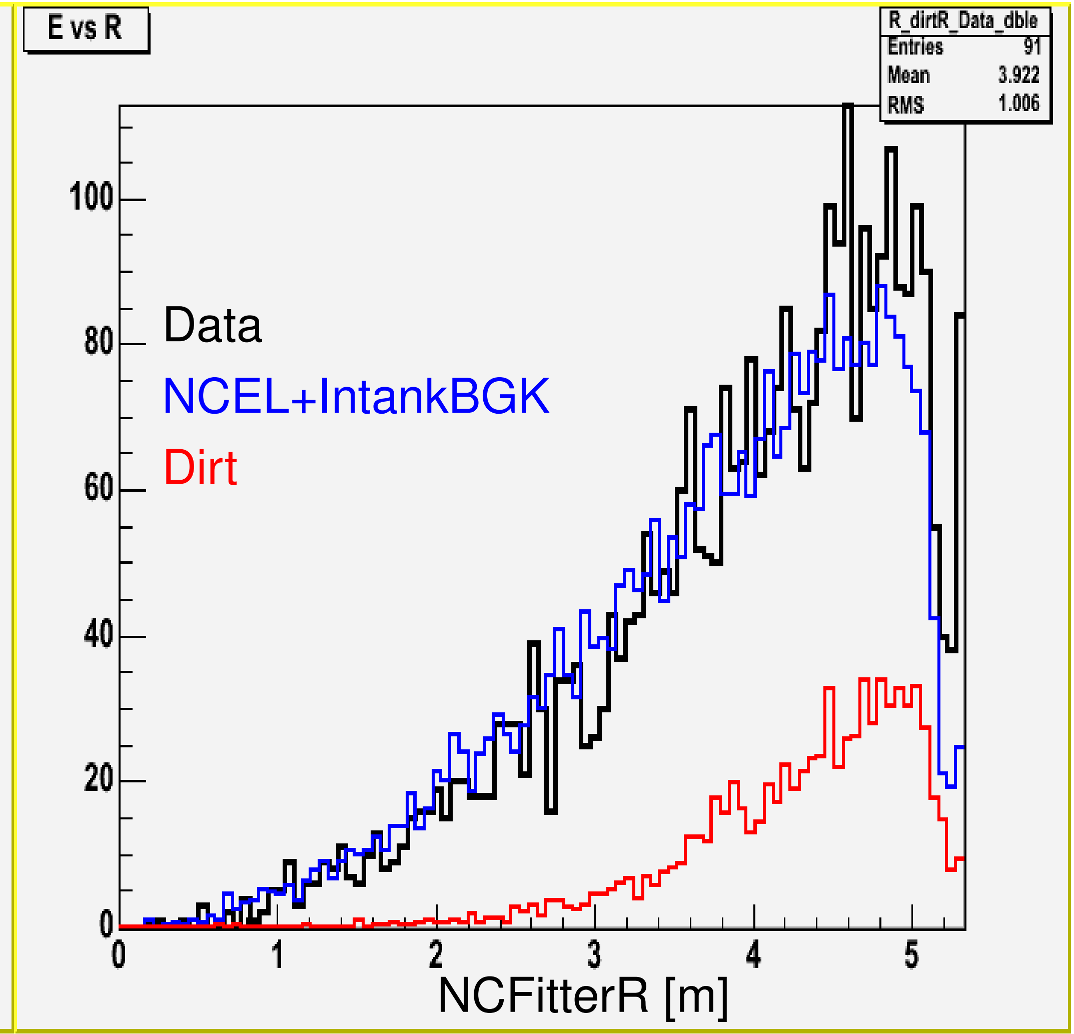
where CUTR={NCFitterR<4.2m if NCFitterE<200MeV, NCFitterR<5.0m if NCFitterE>200MeV}

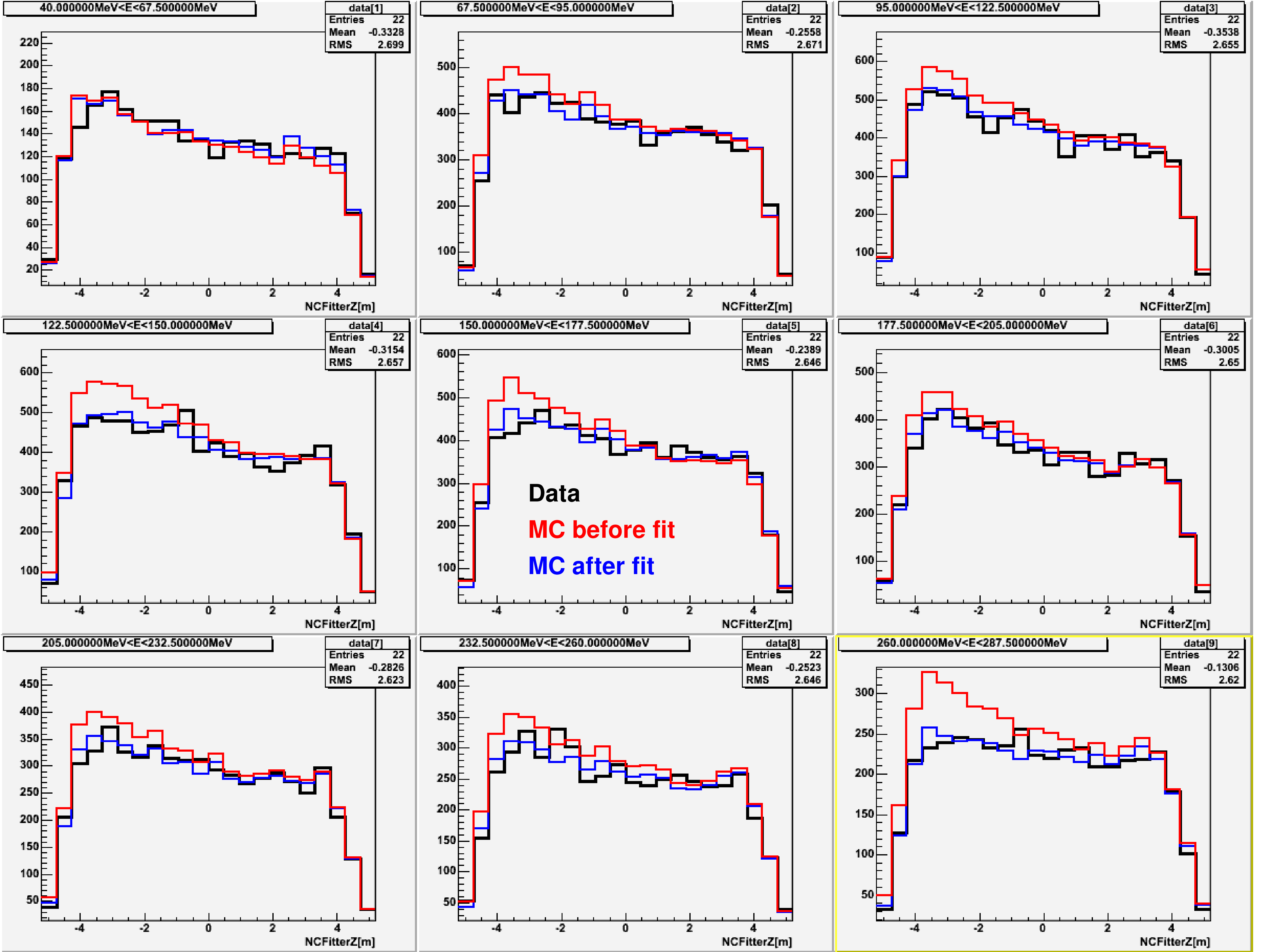
First method of constraining Dirt

Based on fitting reconstructed Z and R distributions for each reconstructed energy bin

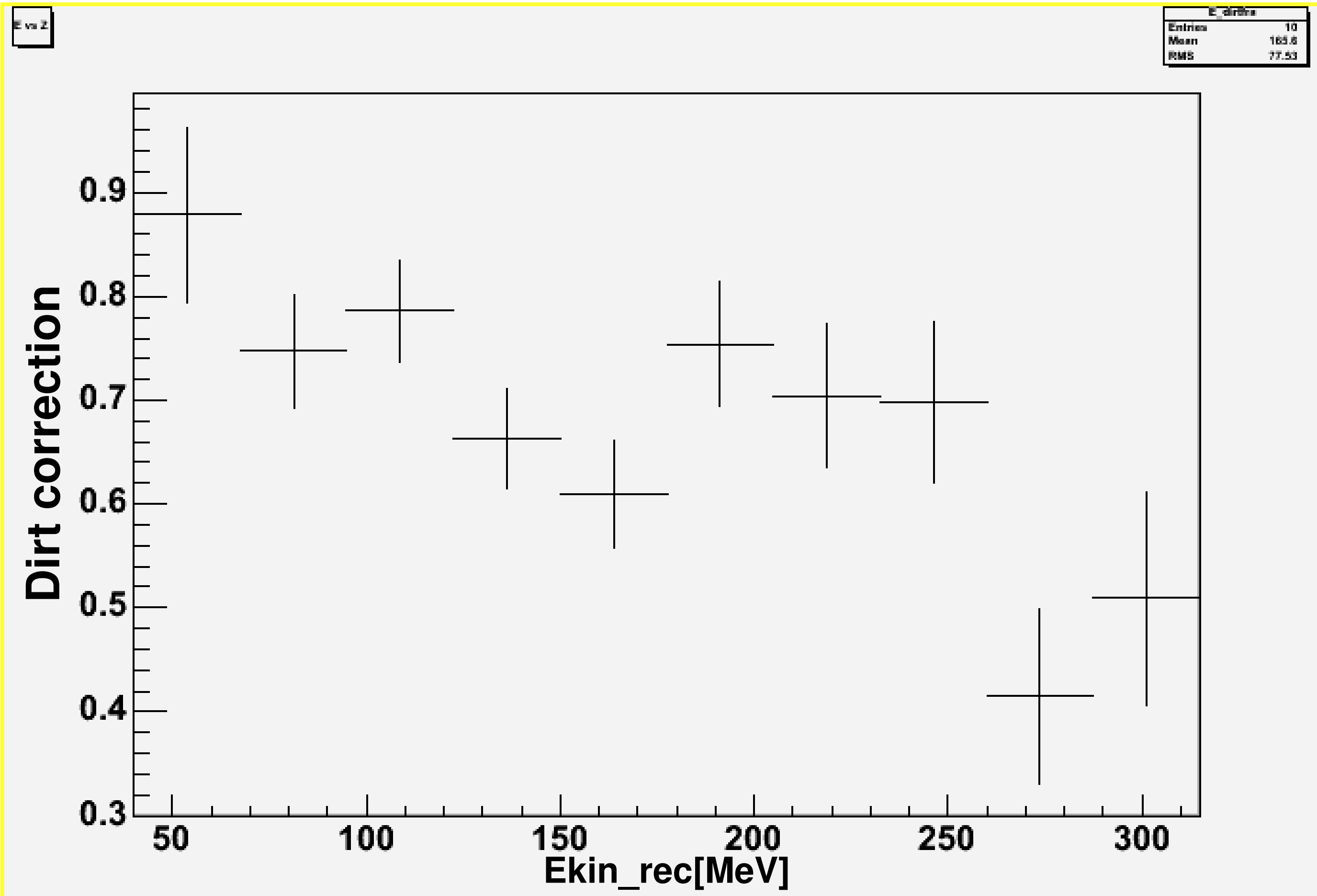
Clearly, for the dirt-enriched samples, we can fit dirt fraction from data in both Z and R distributions



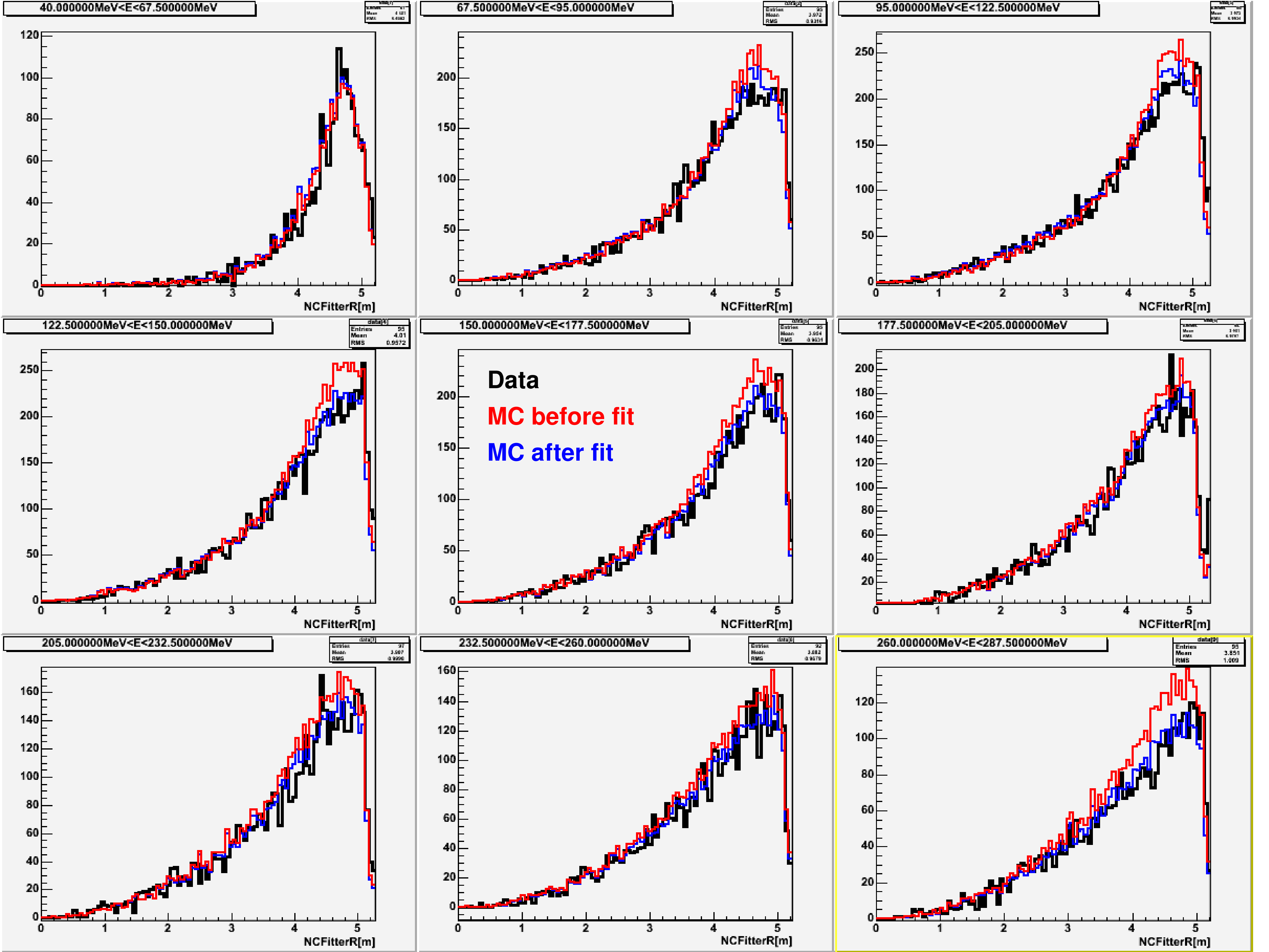



40.000000MeV<E<67.500000MeV
data[1]
Entries 22
Mean -0.3328
RMS 2.699
67.500000MeV<E<95.000000MeV
data[2]
Entries 22
Mean -0.2558
RMS 2.671
95.000000MeV<E<122.500000MeV
data[3]
Entries 22
Mean -0.3538
RMS 2.655
122.500000MeV<E<150.000000MeV
data[4]
Entries 22
Mean -0.3154
RMS 2.657
150.000000MeV<E<177.500000MeV
data[5]
Entries 22
Mean -0.2389
RMS 2.646
177.500000MeV<E<205.000000MeV
data[6]
Entries 22
Mean -0.3005
RMS 2.65
205.000000MeV<E<232.500000MeV
data[7]
Entries 22
Mean -0.2826
RMS 2.623
232.500000MeV<E<260.000000MeV
data[8]
Entries 22
Mean -0.2523
RMS 2.646
260.000000MeV<E<287.500000MeV
data[9]
Entries 22
Mean -0.1306
RMS 2.62
Data
MC before fit
MC after fit
NCFitterZ[m]

Dirt energy correction from Z fit

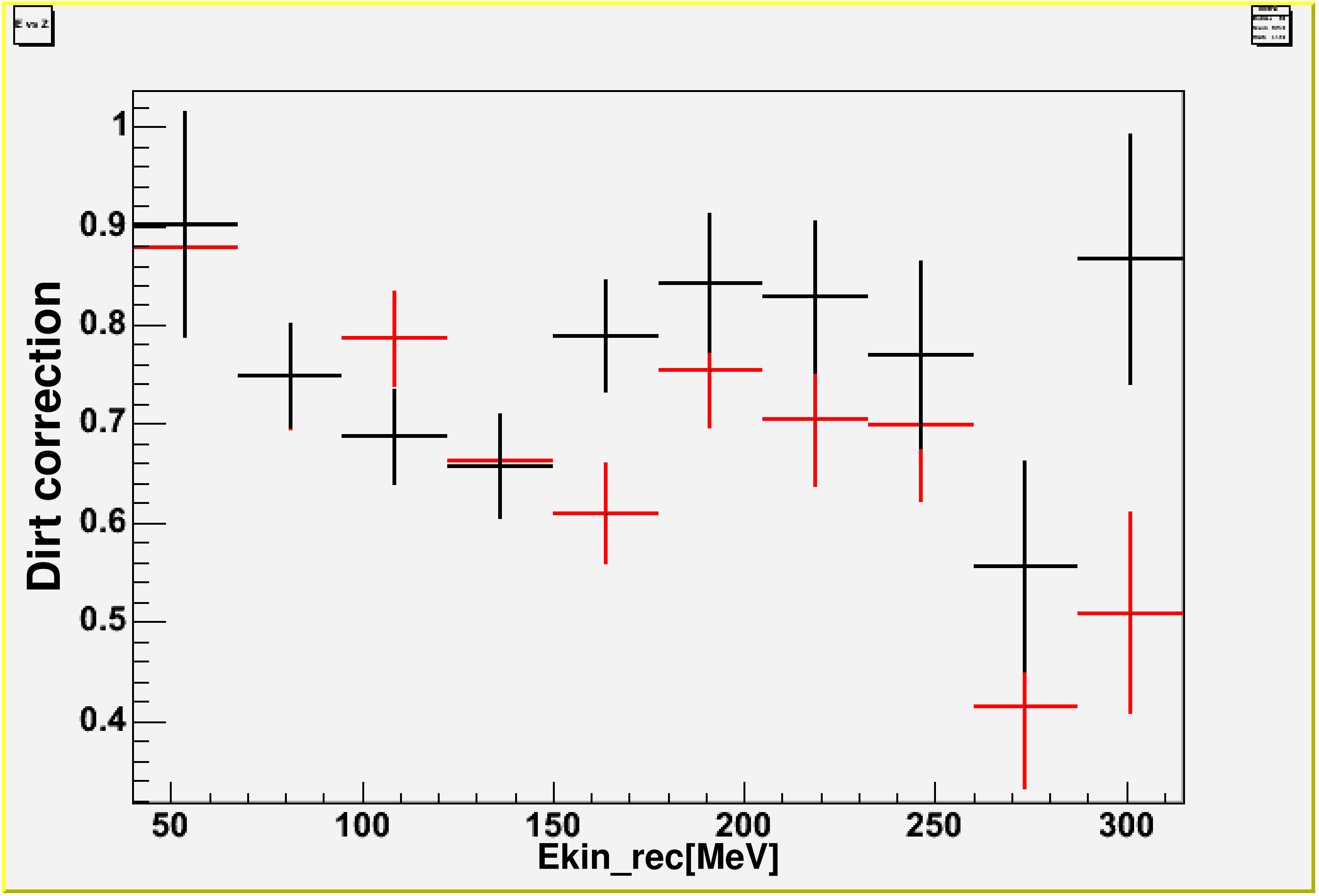


MC' = correction * MC



40.000000MeV<E<67.500000MeV
67.500000MeV<E<95.000000MeV
95.000000MeV<E<122.500000MeV
122.500000MeV<E<150.000000MeV
150.000000MeV<E<177.500000MeV
177.500000MeV<E<205.000000MeV
205.000000MeV<E<232.500000MeV
232.500000MeV<E<260.000000MeV
260.000000MeV<E<287.500000MeV
Data
MC before fit
MC after fit
NCFitterR[m]

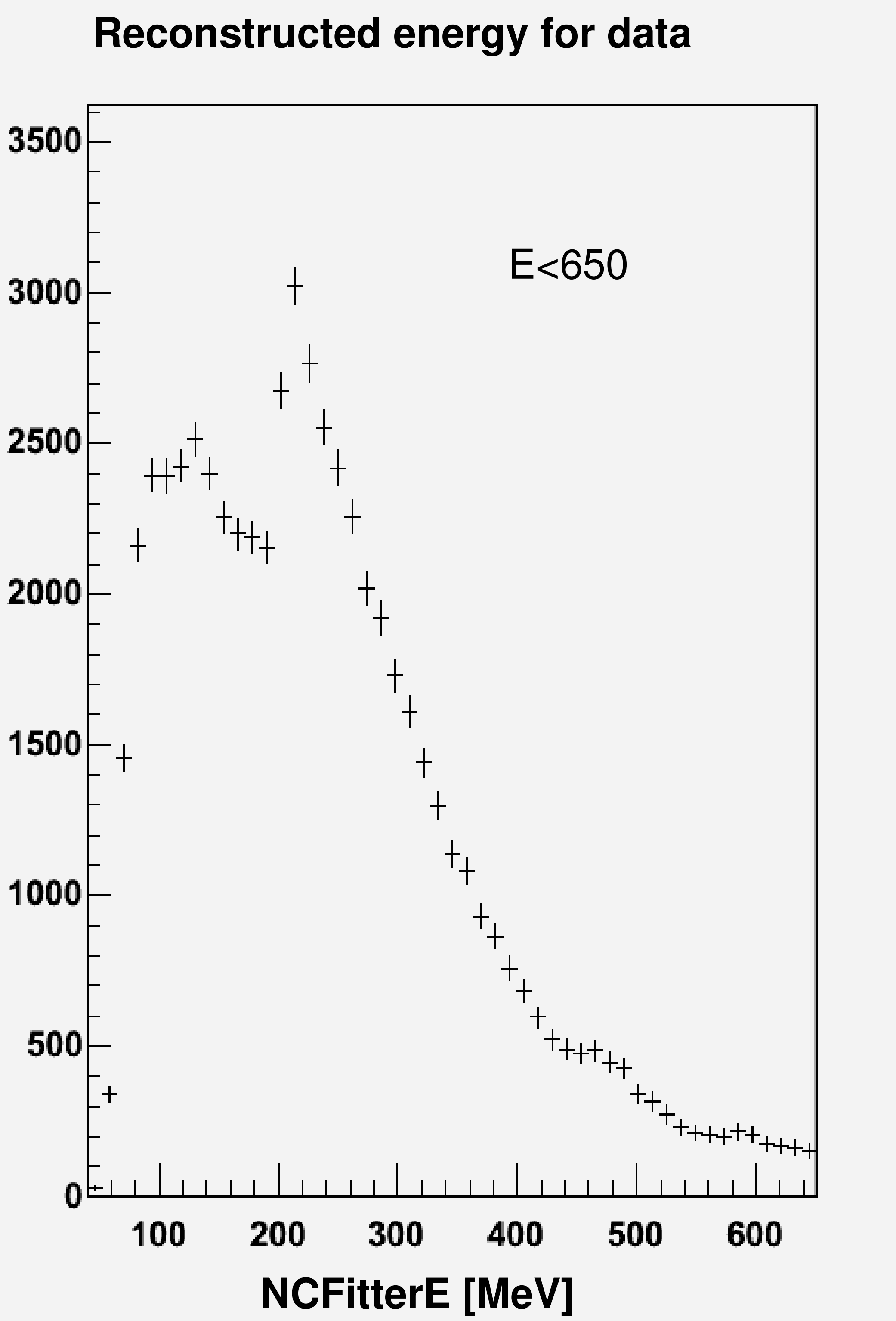
Dirt energy correction



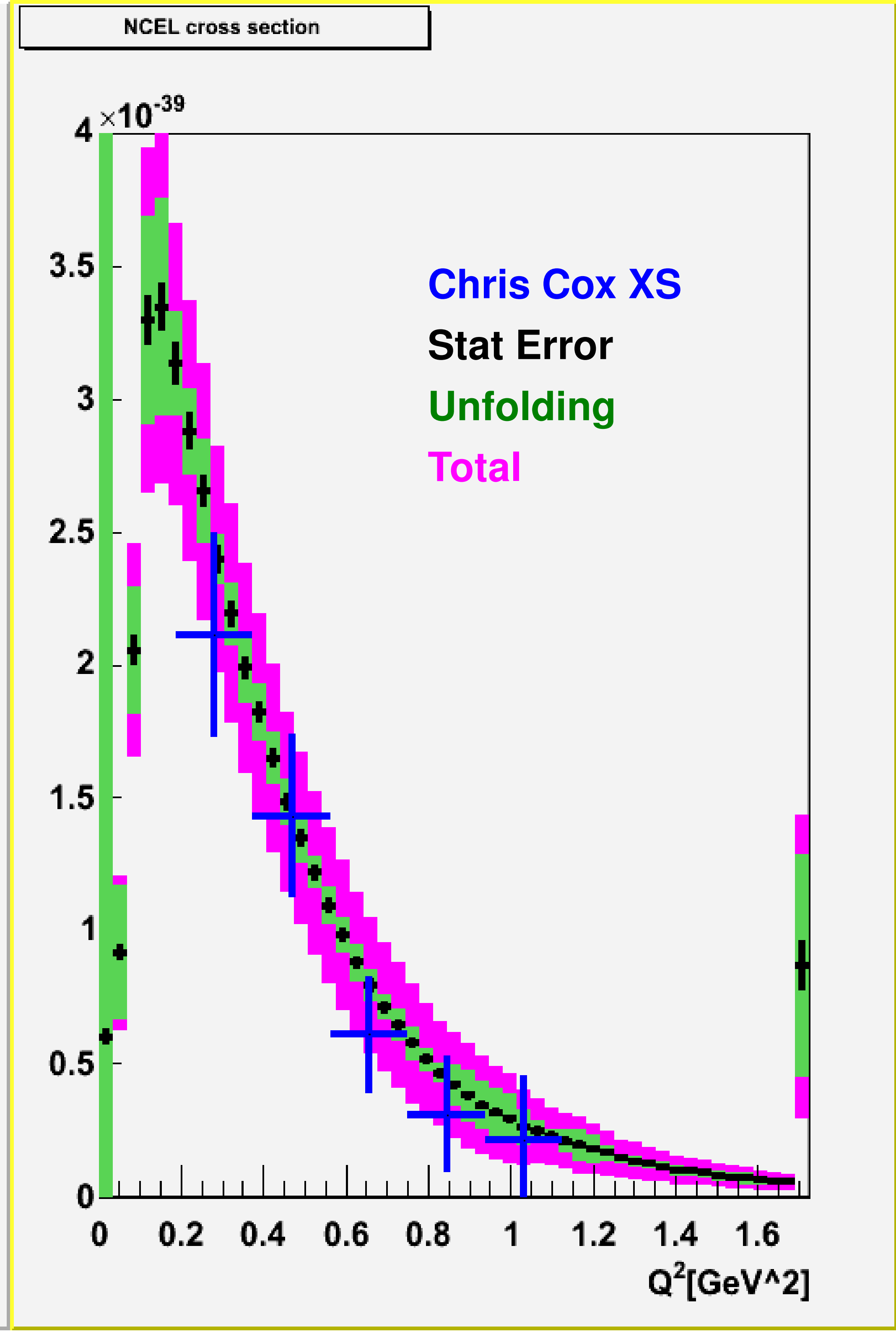
From Z fit

From R fit

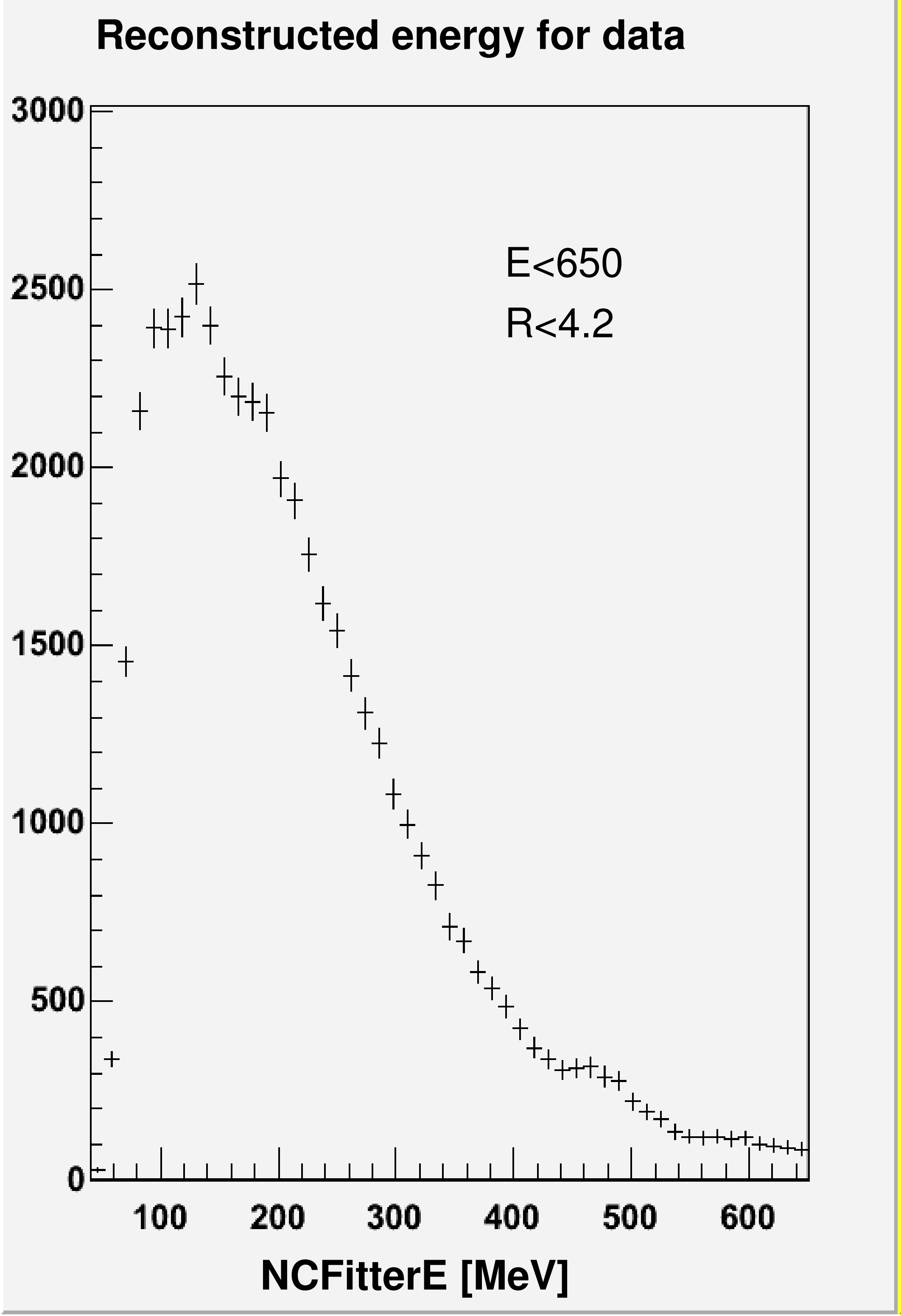
MC' = correction * MC

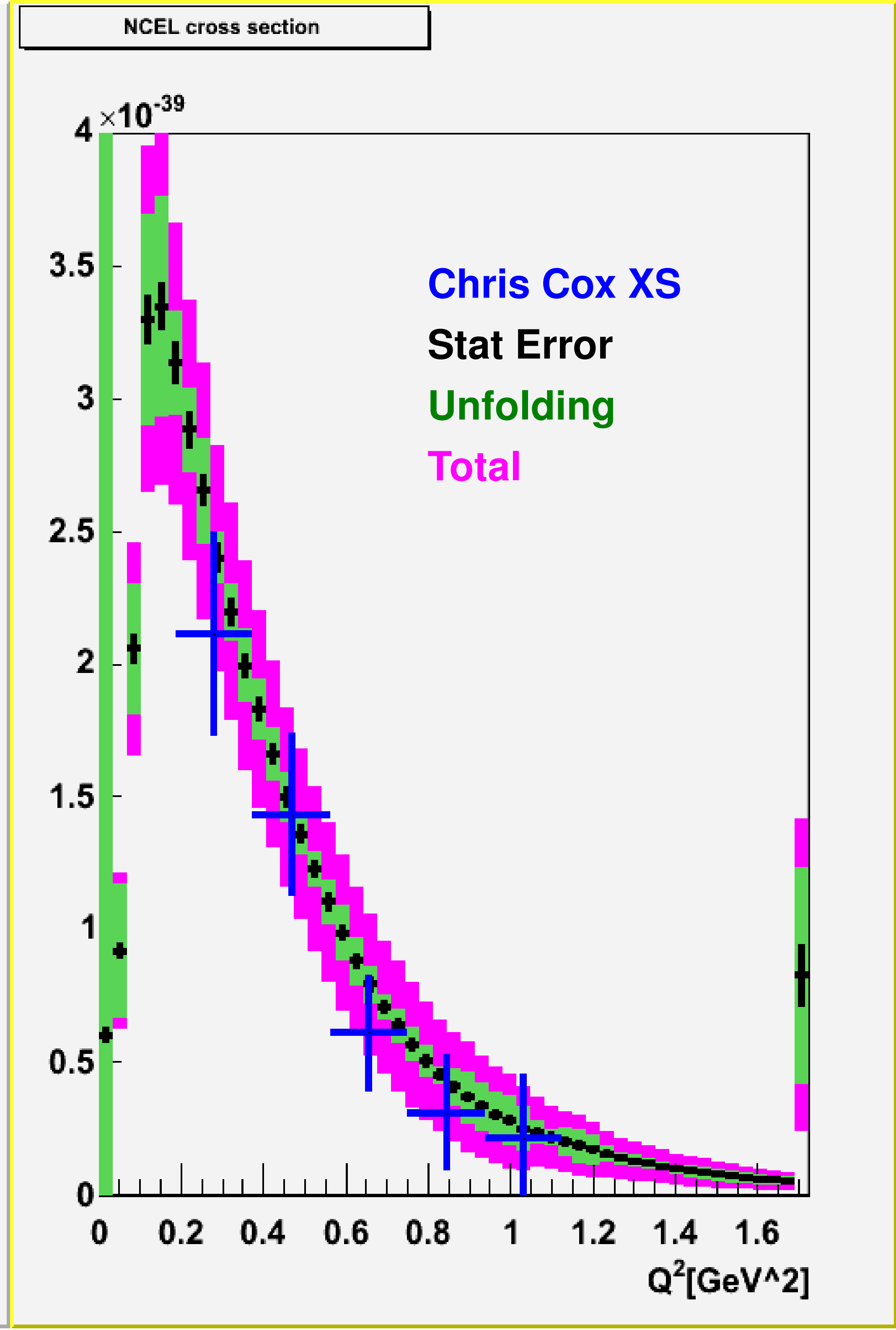


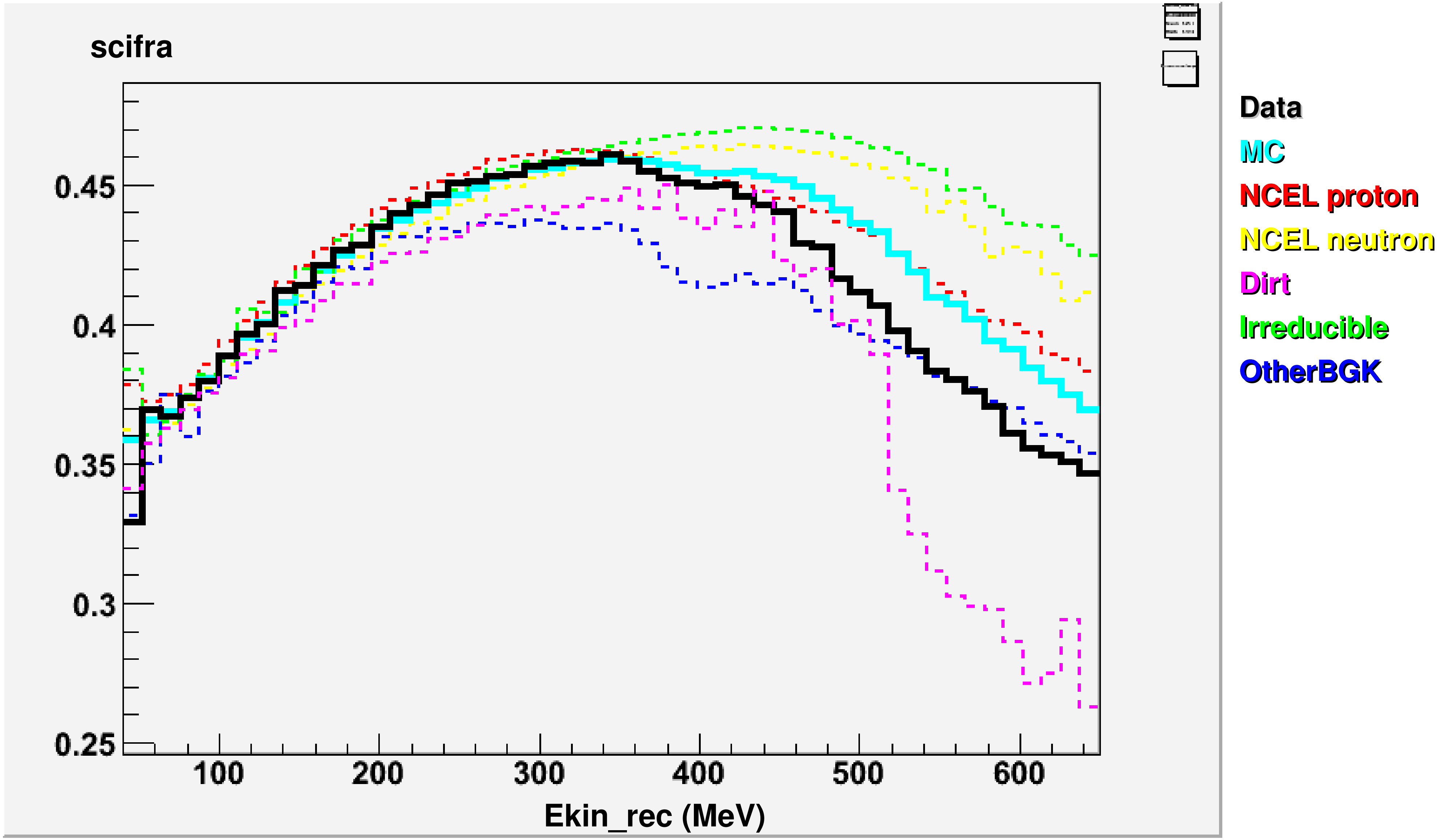
Reconstructed energy for data
E<650
3500
3000
2500
2000
1500
1000
500
0
100
200
300
400
500
600
NCFitterE [MeV]



NCEL cross section
×10^-39
4
3.5
3
2.5
2
1.5
1
0.5
0
Chris Cox XS
Stat Error
Unfolding
Total
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Q^2[GeV^2]


Reconstructed energy for data
E<650
R<4.2
3000
2500
2000
1500
1000
500
0
100
200
300
400
500
600
NCFitterE [MeV]

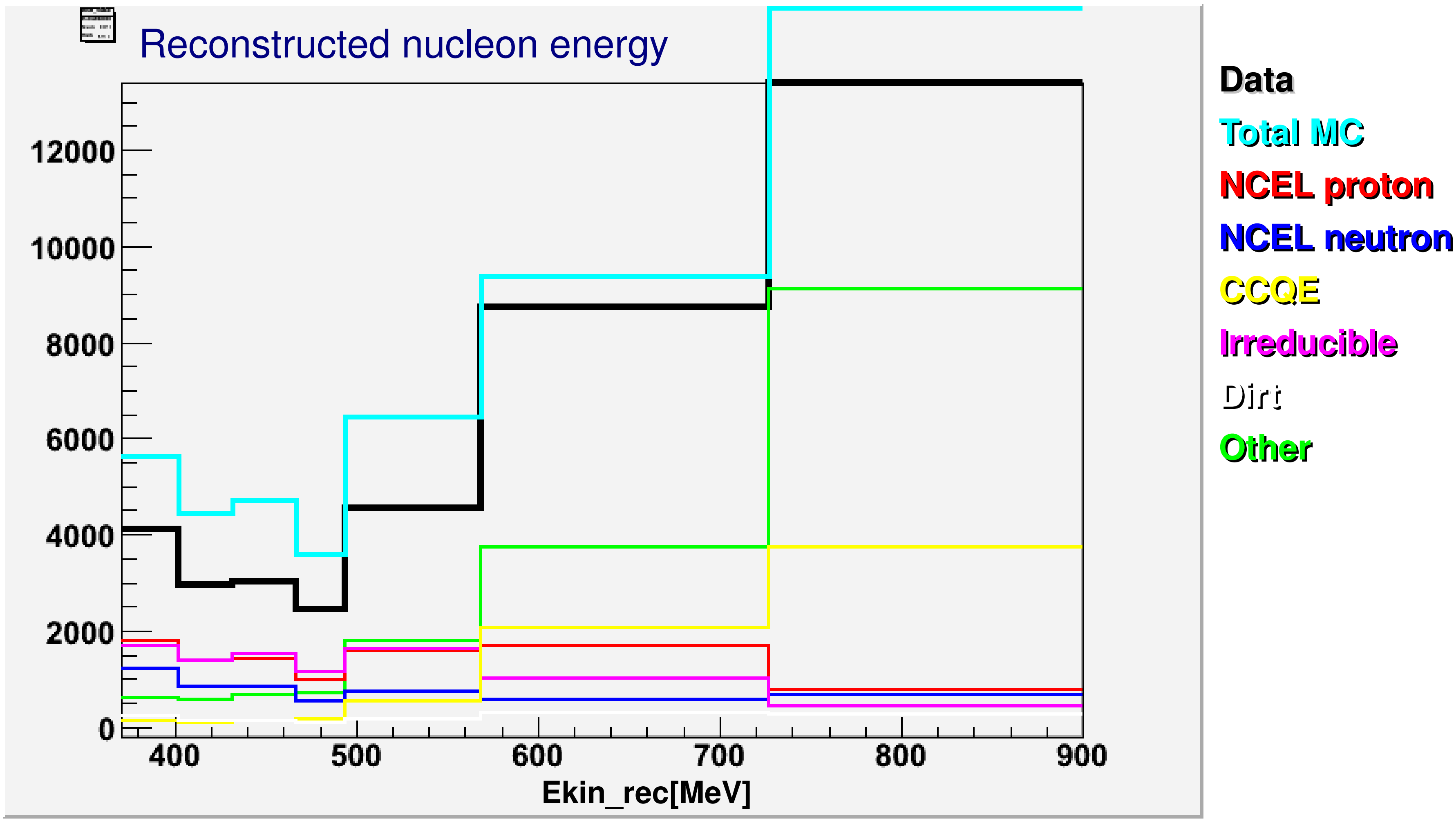

NCEL cross section
×10^-39
4
3.5
3
2.5
2
1.5
1
0.5
0
Chris Cox XS
Stat Error
Unfolding
Total
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Q^2[GeV^2]



scifra
0.45
0.4
0.35
0.3
0.25
100
200
300
400
500
600
Ekin_rec (MeV)
Data
MC
NCEL proton
NCEL neutron
Dirt
Irreducible
OtherBGK

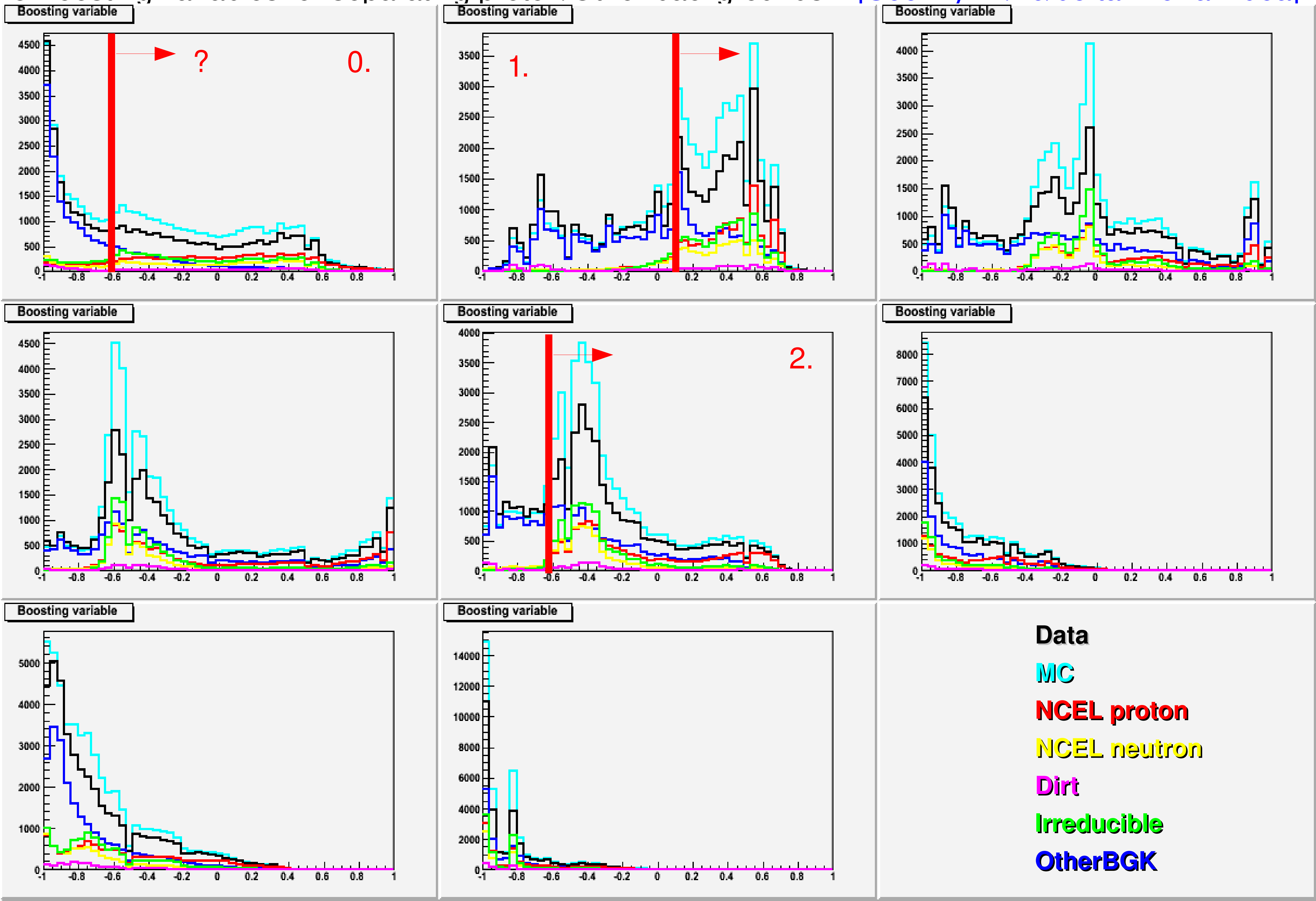
7 new bins of energy.

The same plot as on the previous slide but with new bins and only above Cerenkov threshold for protons:

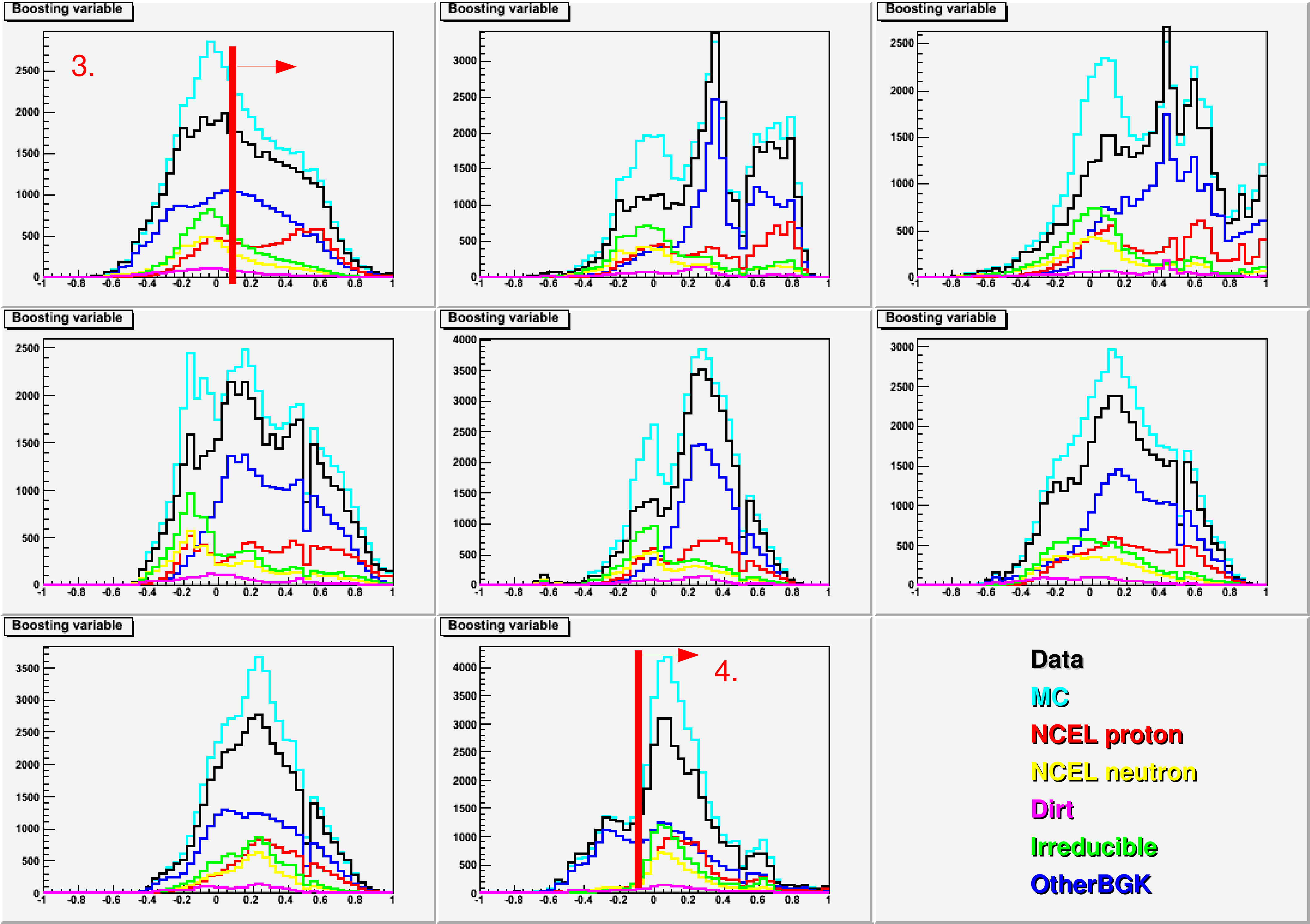


Boosting PID variables (by training on the may06 cocktail with 11 variables – NO UZ)

8 Boosting variables for separating proton/Other backgrounds. [See my 12/16/08 talk for an idea]

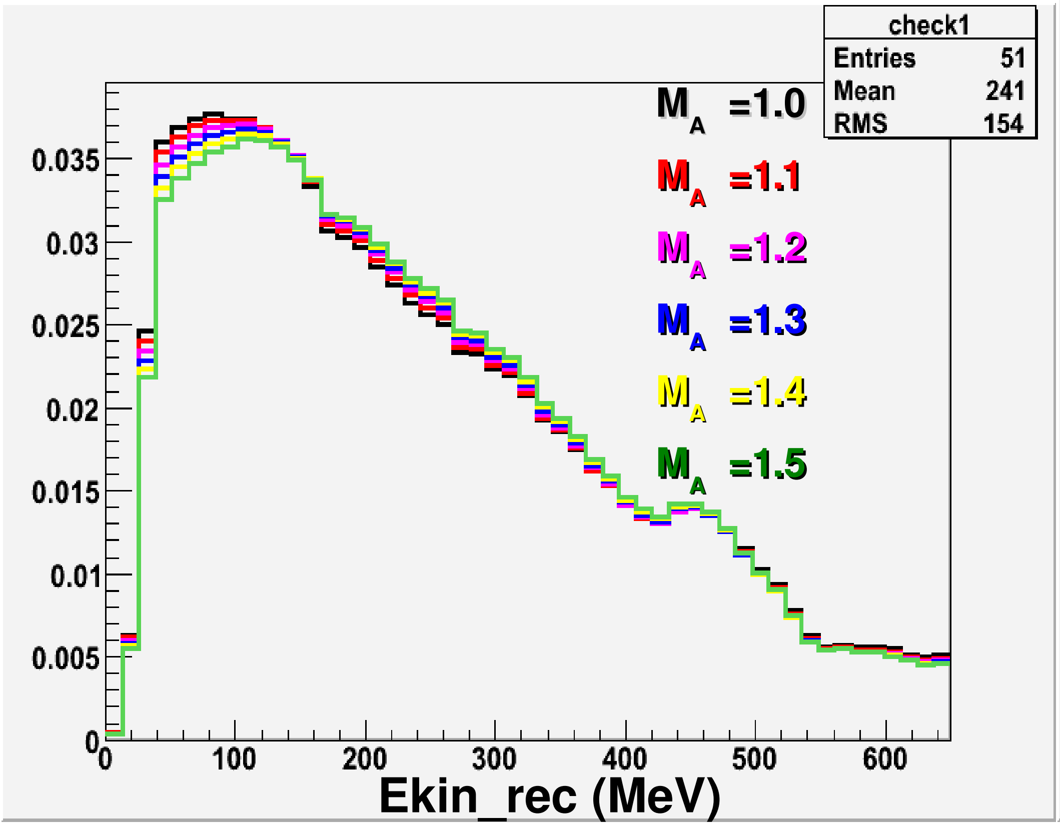


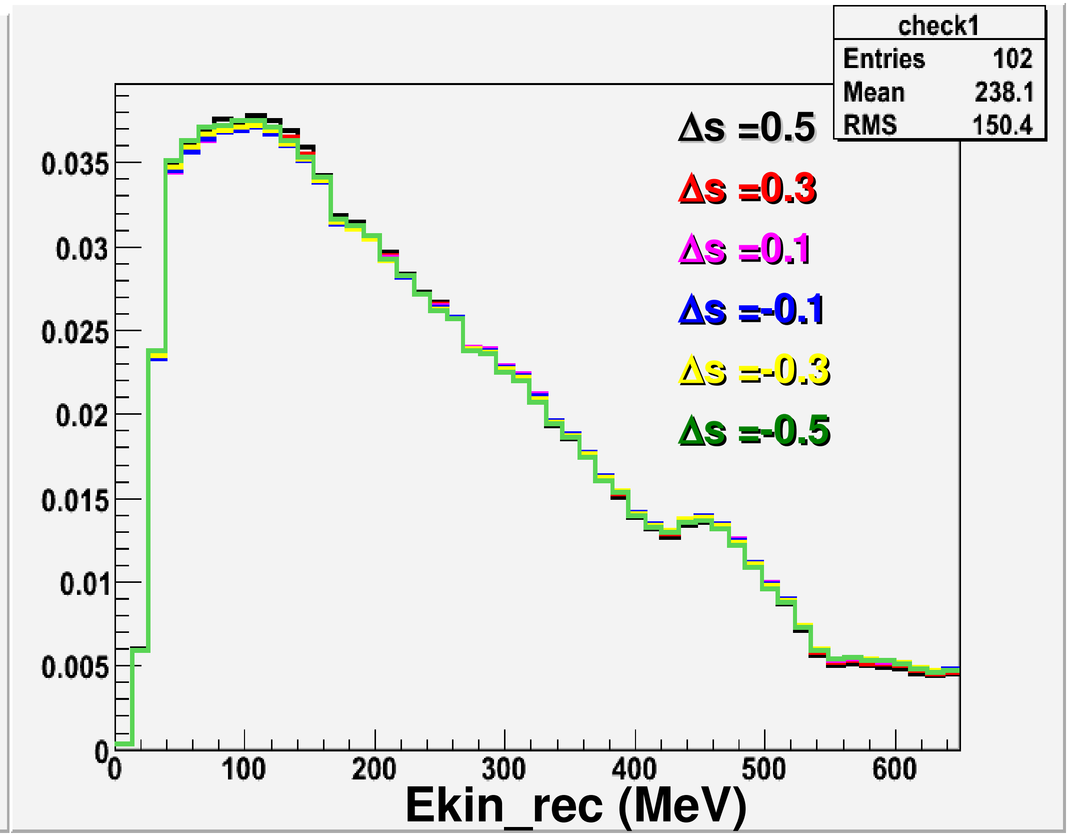
And 8 Boosting variables for separating proton/neutron.



MC shapes for different M_A

MC shapes for different Δs



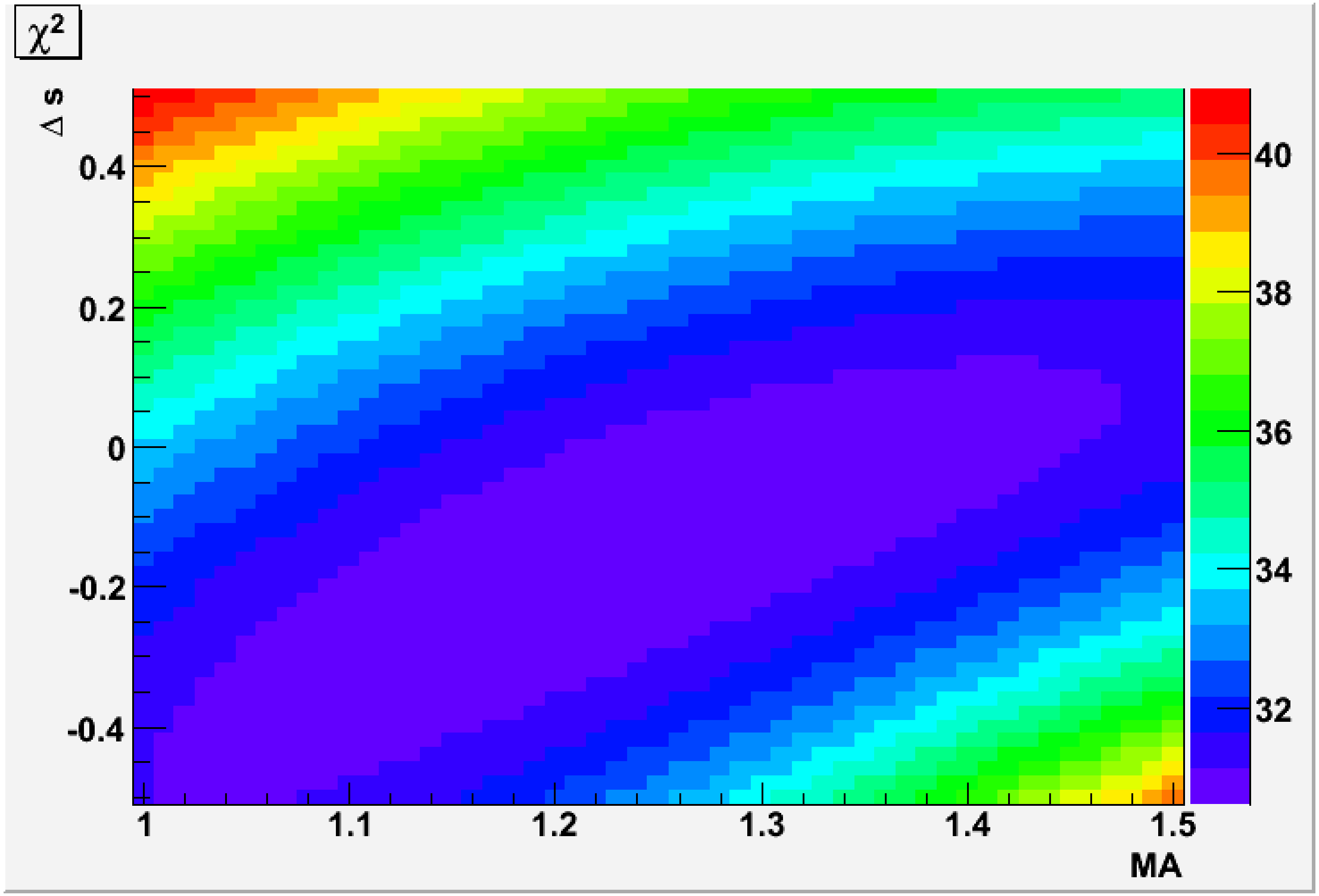


M_A does change the shape a little, mostly at low energy E<300MeV or so (backgrounds start to dominate)

As we can see, Δs doesn't change the spectrum much

But overall, there is not much shape difference for different MA/Δs

After all systematic errors, this is the chi2 that I get for the ratio.



The chi2 that I obtained previously for NCEL cross-section (for 0 MeV<Ekin<650 MeV)