# Neutrino-Nucleon Neutral Current Elastic Scattering at SciBooNE

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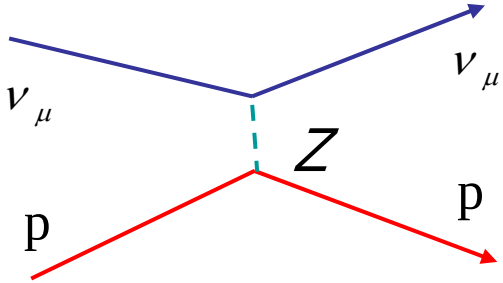
# Introduction

# Neutral Current Elastic Scattering

Neutral Current (NC) elastic scattering

$\nu N \rightarrow \nu N$




$$\frac{d\sigma}{dQ^2} = \frac{M_N^2 G_F^2}{8\pi E_\nu^2}\left[A(Q^2) \pm B(Q^2)\frac{s-u}{M_N^2} + C(Q^2)\frac{(s-u)^2}{M_N^4}\right]$$

+ for neutrino
- for antineutrino

$$C(Q^2) = \frac{1}{4}\left[G_A^2 + F_1^2 + F_2^2\frac{Q^2}{4M_N^2}\right]$$

contrbution from strange quark

$$G_A = \left[-\frac{G_A^{ud}(Q^2)}{2}\tau_z + \frac{G_1^s(Q^2)}{2}\right]$$

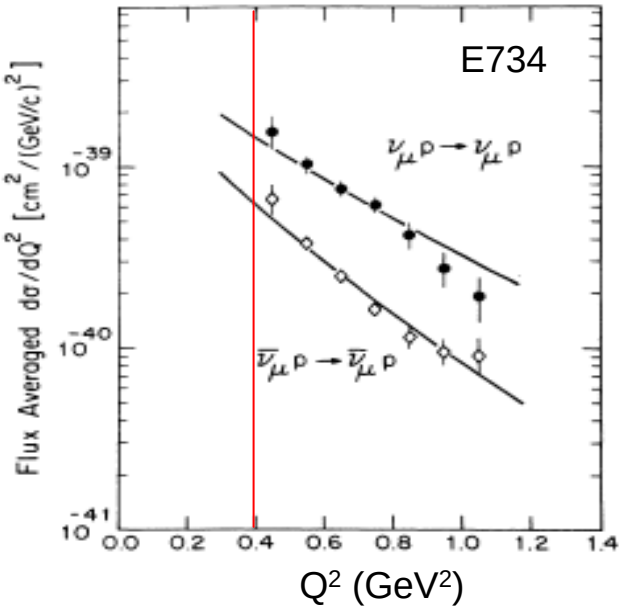
$$s-u = 4M_N E_\nu - Q^2$$

## Motivation:

precise measurement of neutral current (NC) elastic scattering cross section

- no experimental data of NC elastic below $Q^2$=0.4GeV$^2$ are published. We aim at measurement in the smaller $Q^2$ region with the largest statistics.

Phys. Rev. D35, 3 (1987)




- access to the axial vector form factor of the nucleon
(Strange component is accessed using $\nu p \rightarrow \nu p$ events.)

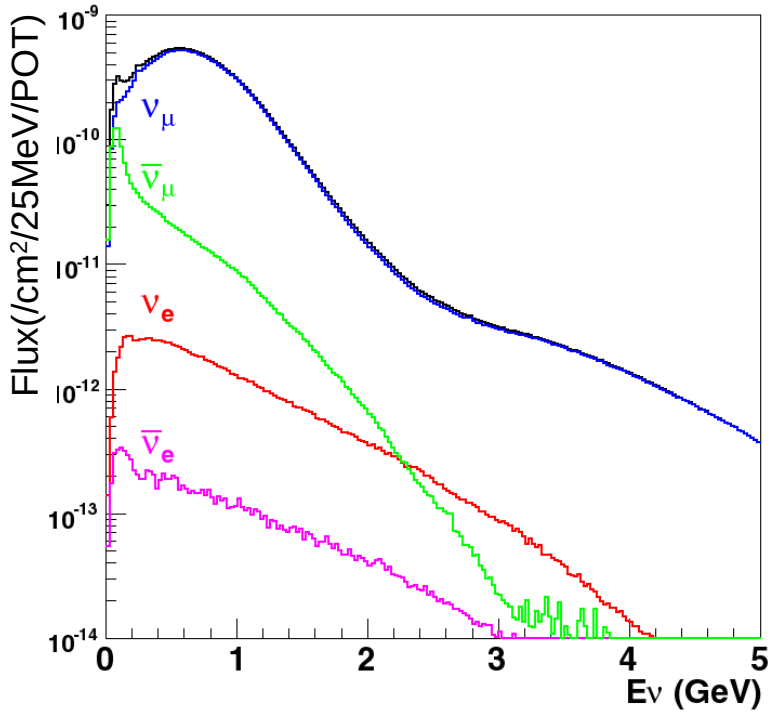
# Simulations at SciBooNE

## Neutrino Flux

Neutrino beam flux is predicted by GEANT4 based beam simulation.

Experimental data (HARP) are used for hadron production and re-interactions on the beryllium target.

A.A. Aguilar-Arevalo, *et al*., “The Neutrino Flux Prediction at MiniBooNE”, Phys.Rev.D**79** 072002 (2009), arXiv:0806.1449 [hep-ex].



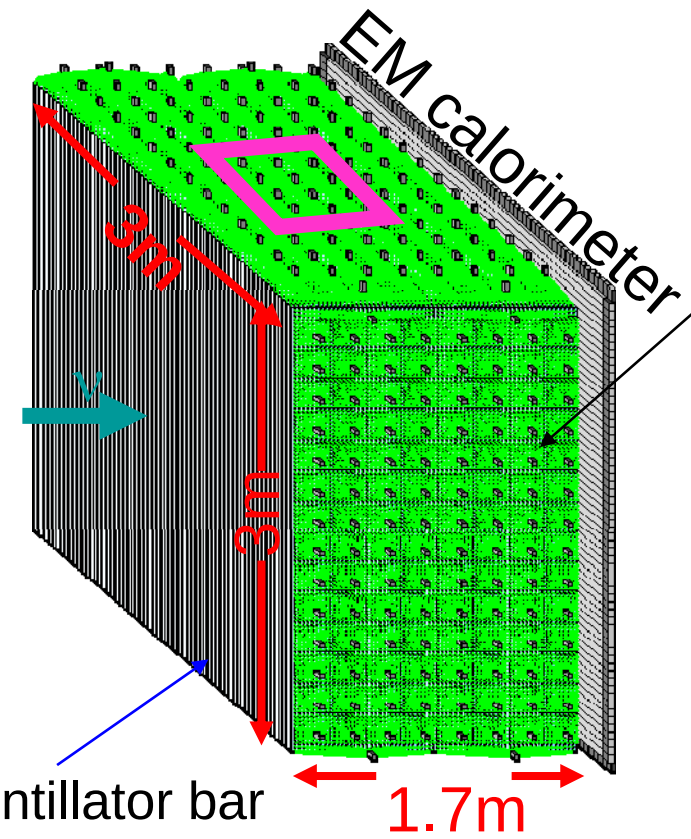

## Neutrino Interactions

NEUT is used for this analysis.

$M_A$=1.1 GeV/$c^2$ is used.

Nuclear effect such as Fermi motion and nucleon scattering in nucleus are taken into account.

# SciBar Detector




multi-anode PMT & wavelength shifting fiber

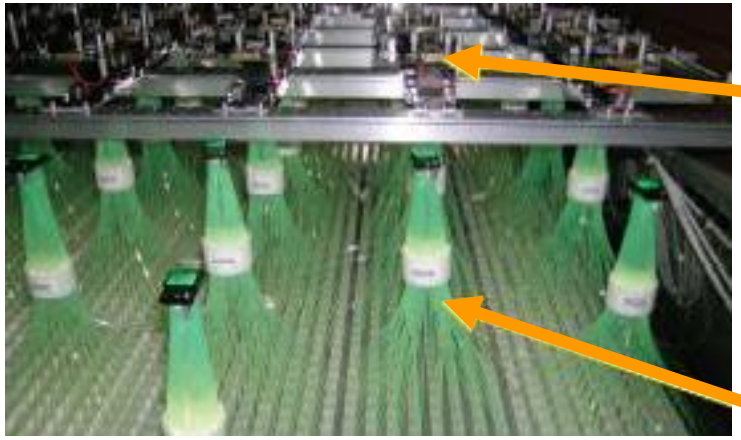
**Weight 15 tons**
**(Fiducial mass ~10 tons)**

**Number of channels 14,336**

**Number of PMTs 224**
**(64 anodes for each PMT)**

**Hit finding efficiency >99%**

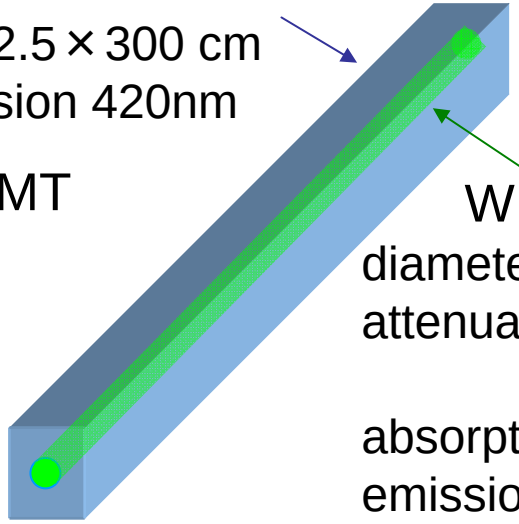
**Identify tracks > 8 cm**



multi-anode PMT

wavelength shifting fiber (WLS fiber)

scintillator bar
1.3 × 2.5 × 300 cm
emission 420nm

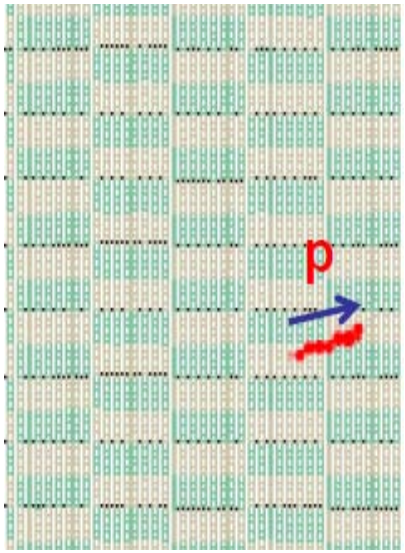


WLS fiber
diameter: 1.5mm
attenuation length: ~3.5m
absorption: 430nm
emission: 476nm

# Analysis for Neutrino-Nucleon Neutral Current Elastic Scattering

# Analysis for Neutral Current Elastic Scattering

Typical Neutral Current elastic scattering event




requirement to the event:
- single track
- contained in SciBar
- proton-like track

If nuclear effects are not considered, $T_N$ can be converted to $Q^2$ by

$$Q^2 = 2m_N T_N$$

Goal: differential cross section per nucleon as a function of nucleon kinetic energy ($d\sigma/T_N$)

Data

total $\nu$ events
$9.9 \times 10^{19}$ POT

Event Selection

after the selection
$8.4 \times 10^3$ events
in data

Purity Correction

remove
backgrounds

Detector Unfolding
Detection Efficiency Correction

Differential Cross Section as a function of nucleon kinetic energy ($d\sigma/T_N$)

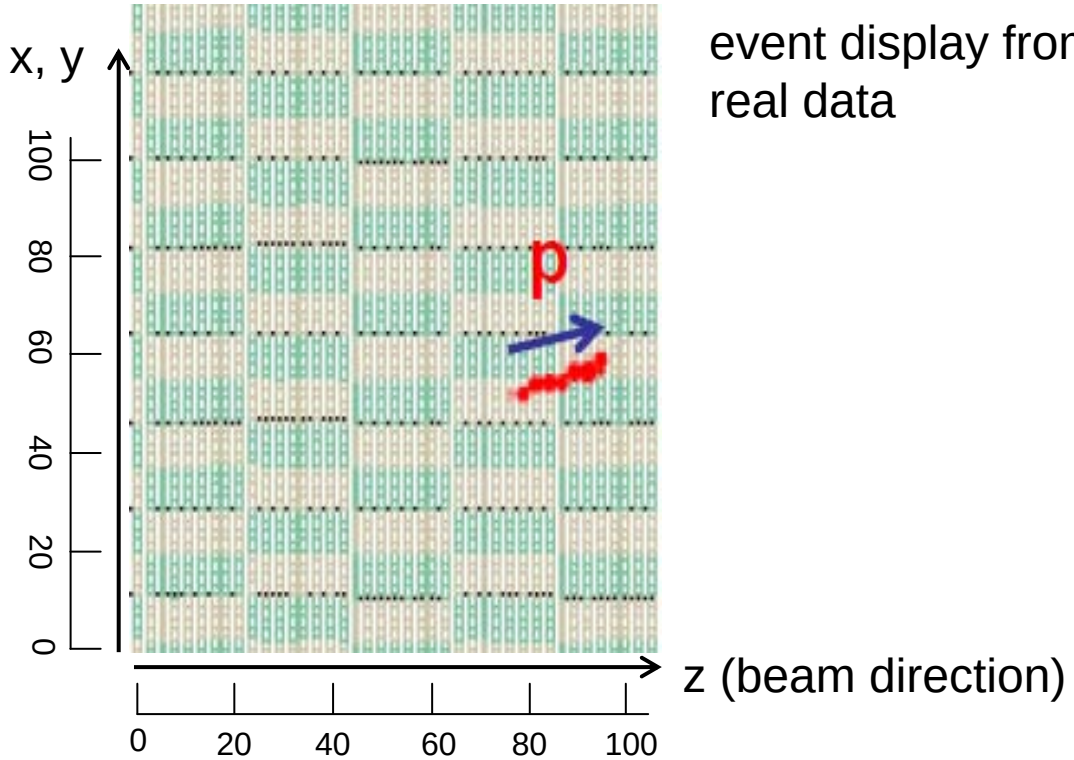
$T_N$: kinetic energy of nucleon

# Selection of Neutral Current Elastic Scattering

## Typical Neutral Current elastic scattering event

single track

large dE/dx

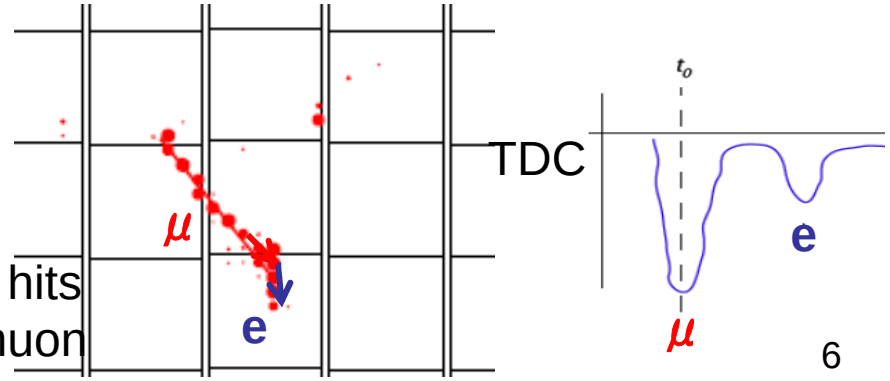



event display from real data

event selection:

1. SciBar contained track
2. single track
3. proton identification
   3-1. decay particle rejection
   3-2. *dE/dx* cut

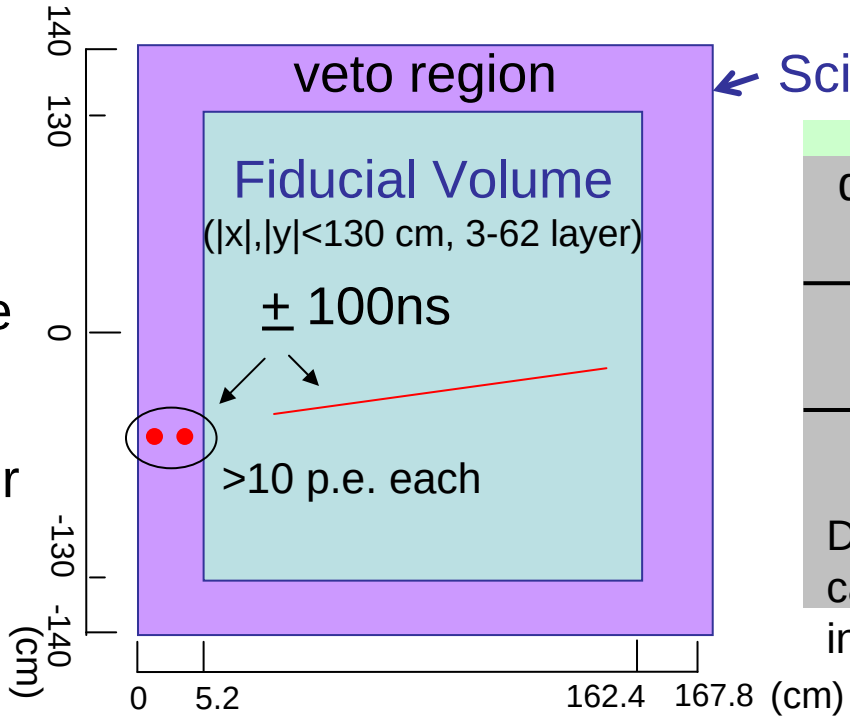
TDC multiple hits from decay muon

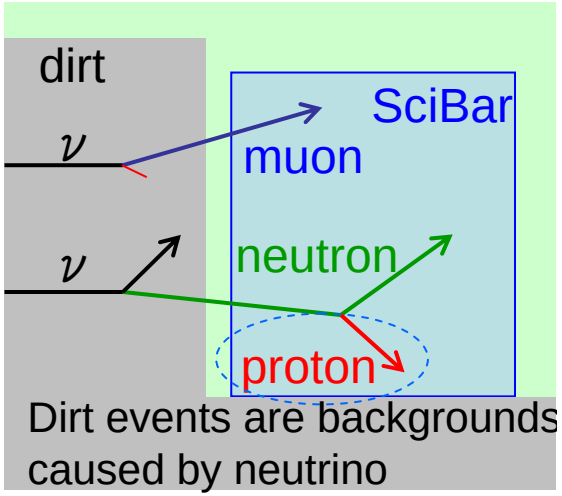


# Event Selection 1 & 2.
# – SciBar Contained and Single Track

It removes particles which come from outside (such as dirt) and escape from inside SciBar.

require a cluster of 2 or more hits with >10 photoelectrons to avoid noise hits

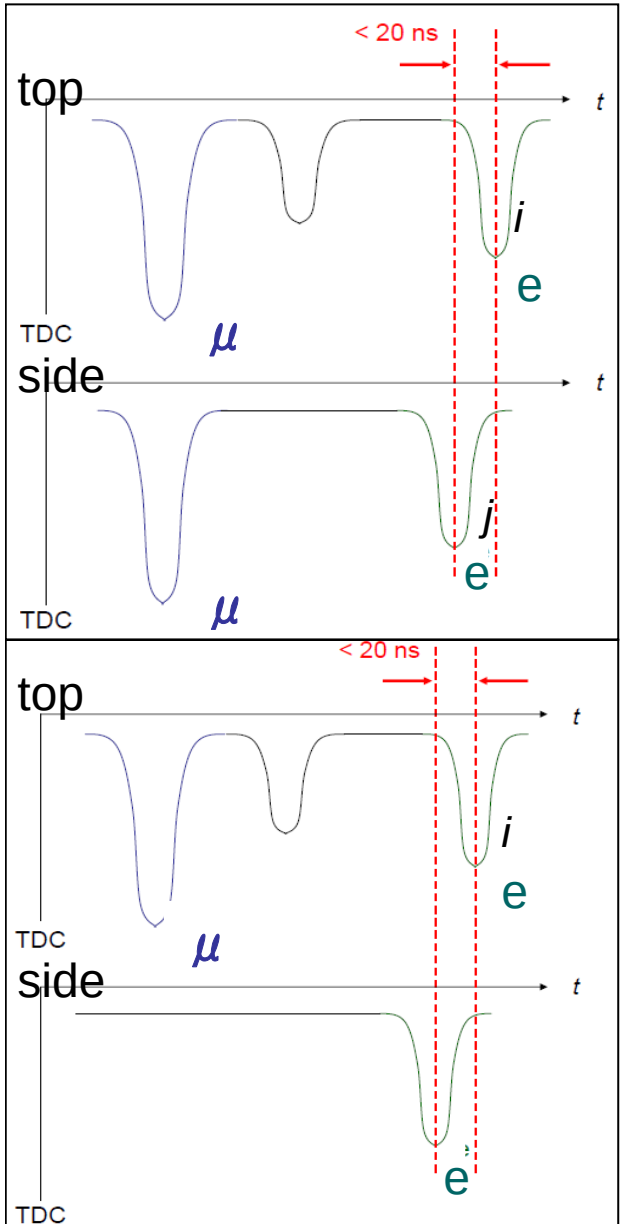



Dirt events are backgrounds caused by neutrino interactions inside dirt.

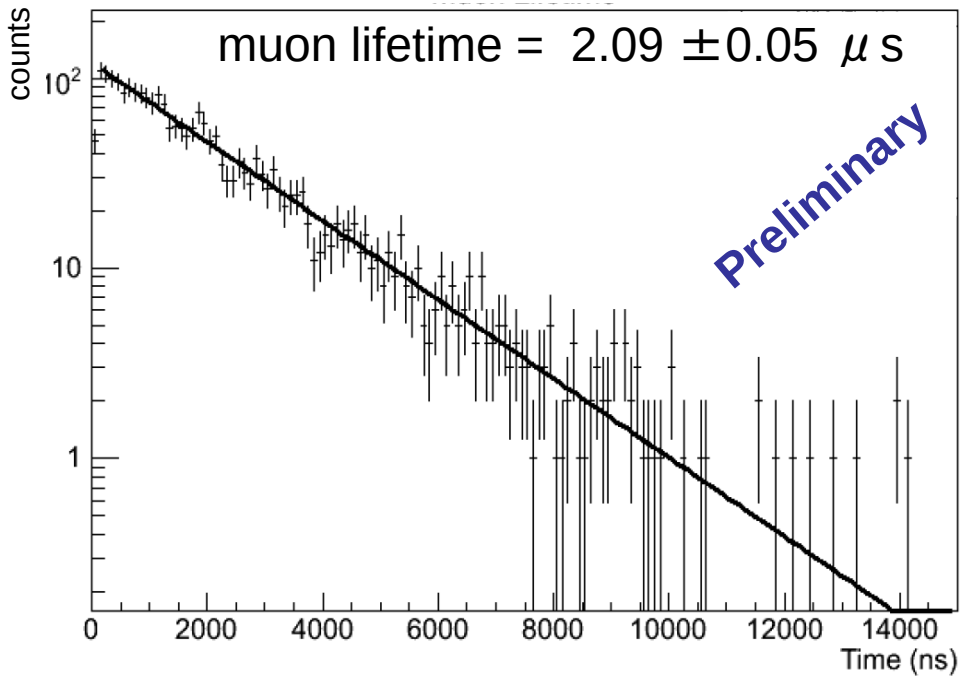
- Events with cluster of >20 photoelectron are removed.
- Edges of track are contained in Fiducial Volume
- one track in each view (top and side)

# Event Selection 3-1. - Decay Particle Rejection

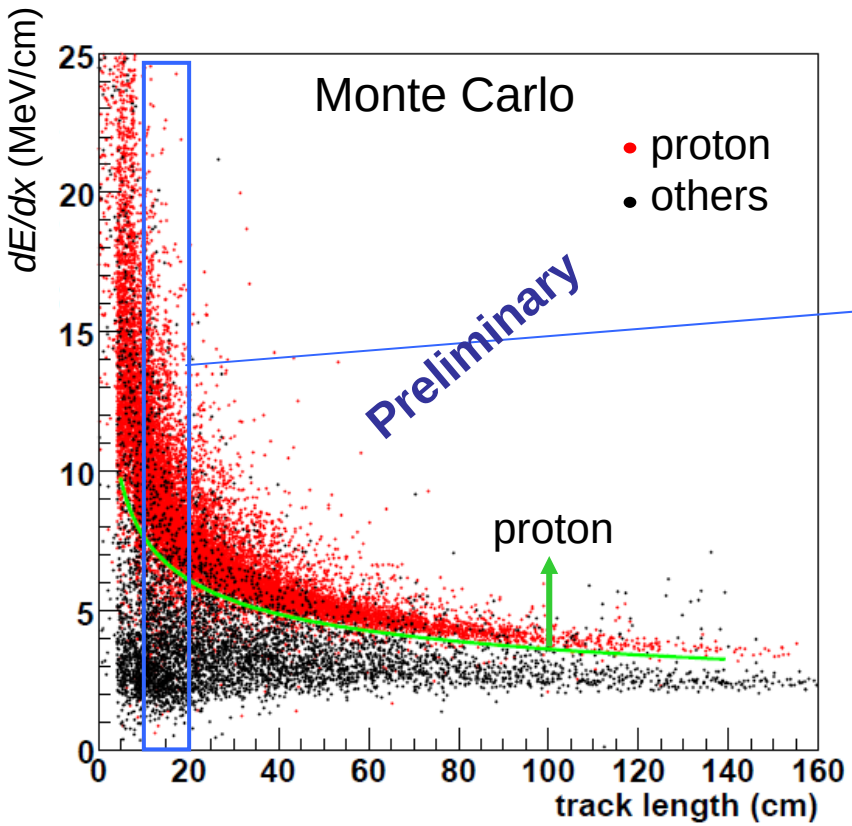


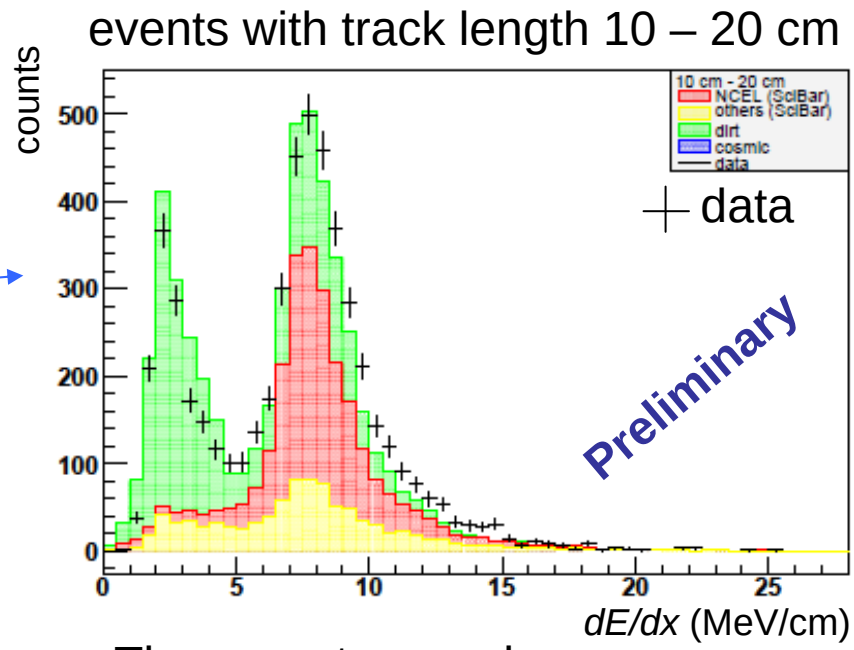

-use multi-hit TDCs at end edges of track
-If ith and jth multi-hit TDCs on top and side are closer than threshold (20ns), this event is tagged as Michel decay.
-If the time of ith (i≥2)TDC hit in one view matches with the time of 1st hit in another view, this event is tagged as Michel decay.

Muon lifetime is measured using decay muon sample.



# Event Selection 3-2. - *dE/dx* cut




There are two peaks.
One is from protons, the other is from muons, pions and electrons.

"others" means all non-proton particle in SciBar (e.g. muon, pion, electron)

fractions of particles after all cuts

| | SciBar | dirt |
|---|---|---|
| proton | 5391 | 1814 |
| e+/e- | 41 | 64 |
| mu+/mu- | 62 | 4 |
| pi+/pi- | 94 | 19 |

# Event Selection Summary

POT normalized

| event selection | data | MC (signal)** | MC (B. G.)** | purity (%)*** |
|---|---|---|---|---|
| veto | 1262476 | 27962 | 96341 | 22.5 |
| timing cut $0 \le t \le 2\ \mu s$ | 123501 | 27962 | 96341 | 22.5 |
| 1 track | 18325 | 5200 | 16415 | 24.7 |
| decay particle rejection | 13917 | 5017 | 7739 | 39.3 |
| $dE/dx$ cut | 8441 | 4340 | 3335 | 56.5 |

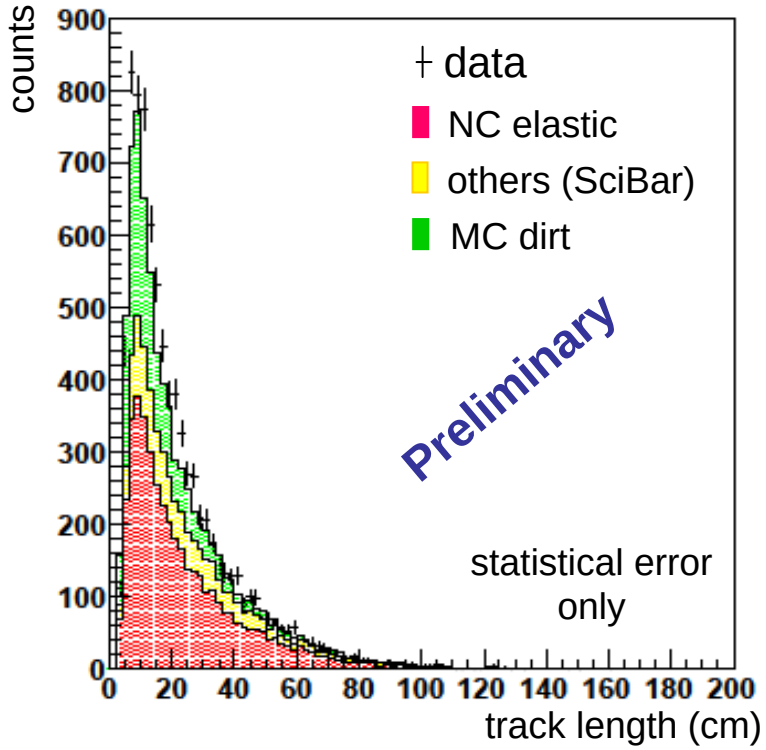
*total numbers of neutrino beam trigger

**MC (signal) includes NC(p) and NC(n). MC (B.G.) includes all non-NC elastic interactions in SciBar and dirt backgrounds.

***purity:
(MC(signal)) / (MC(signal)+B.G.)

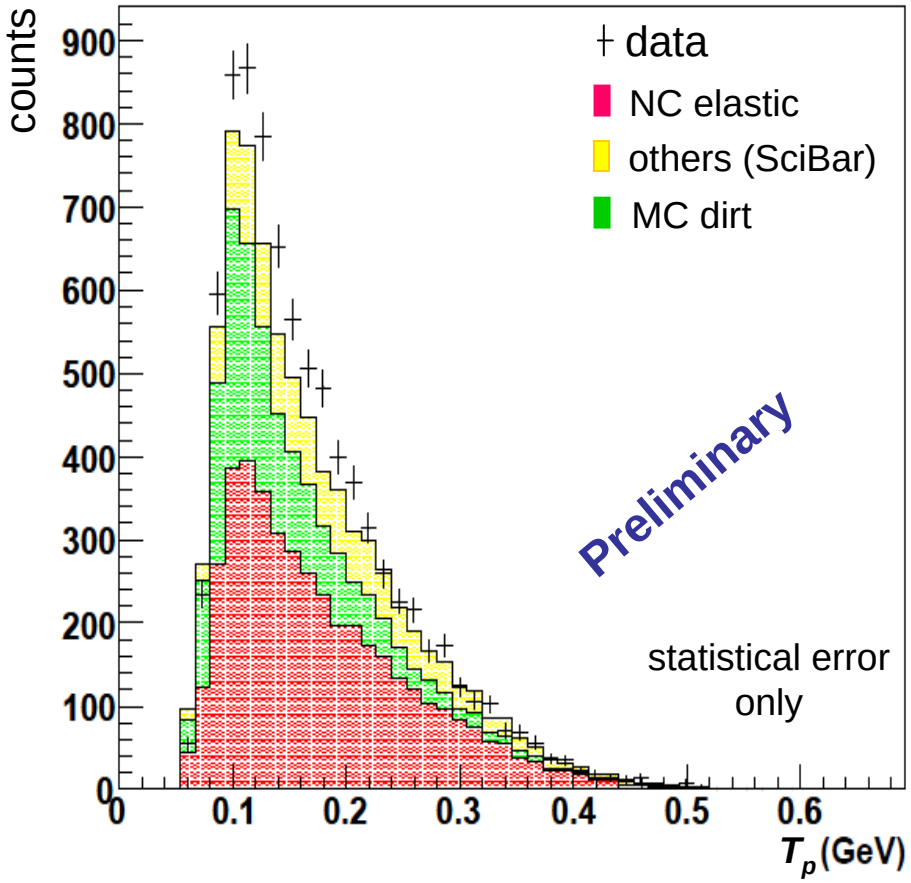
MC indicates that the data contains quite some amount of backgrounds.

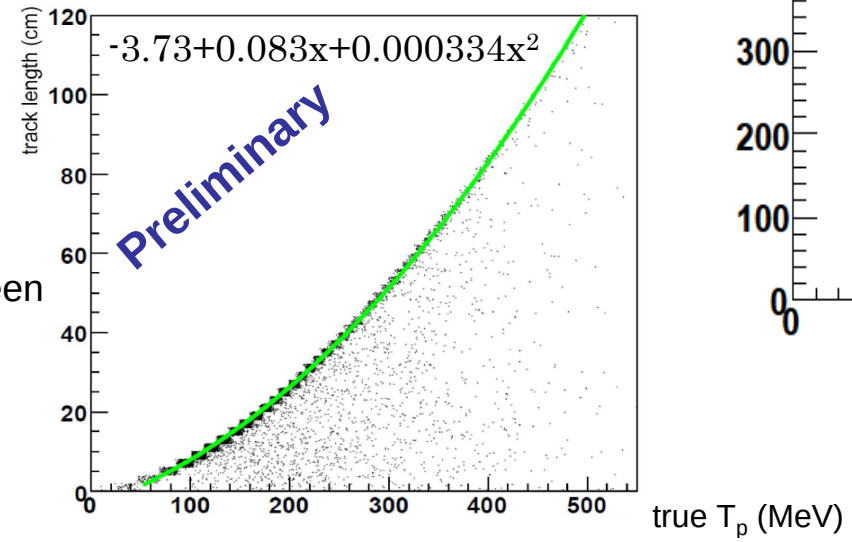
# Track Length & $T_p$ Distribution




NC elastic sample

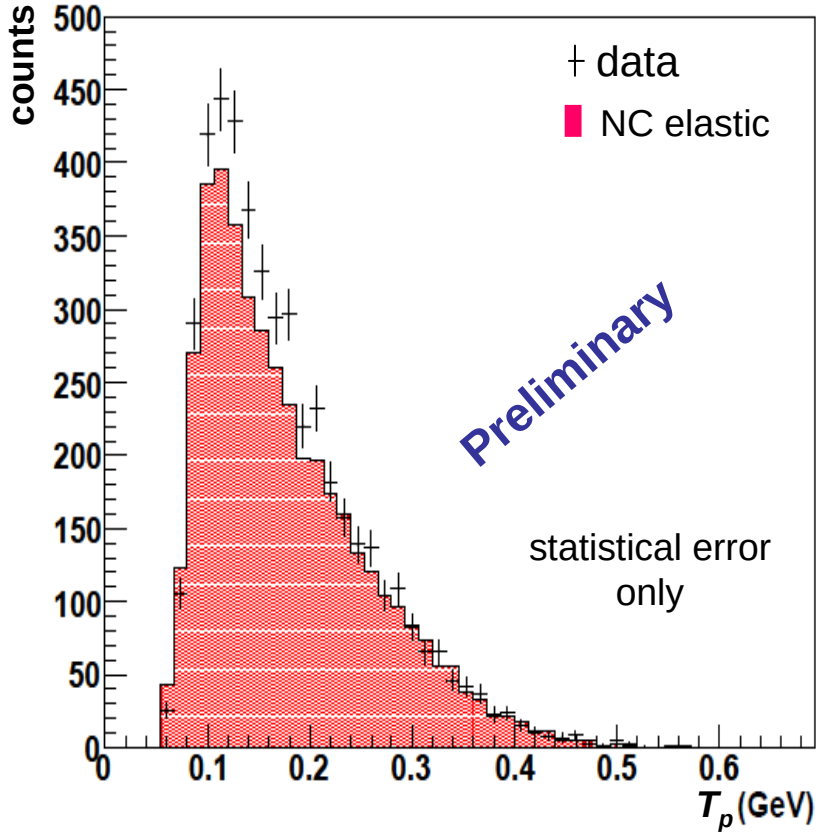
Using the track length distribution and the relationship between $T_p$ and the track length, $T_p$ distribution is obtained.




Relationship between $T_p$ and the track length is checked using MC.
Green curve is the result of fit.

# Purity Correction : $T_p$ Distribution



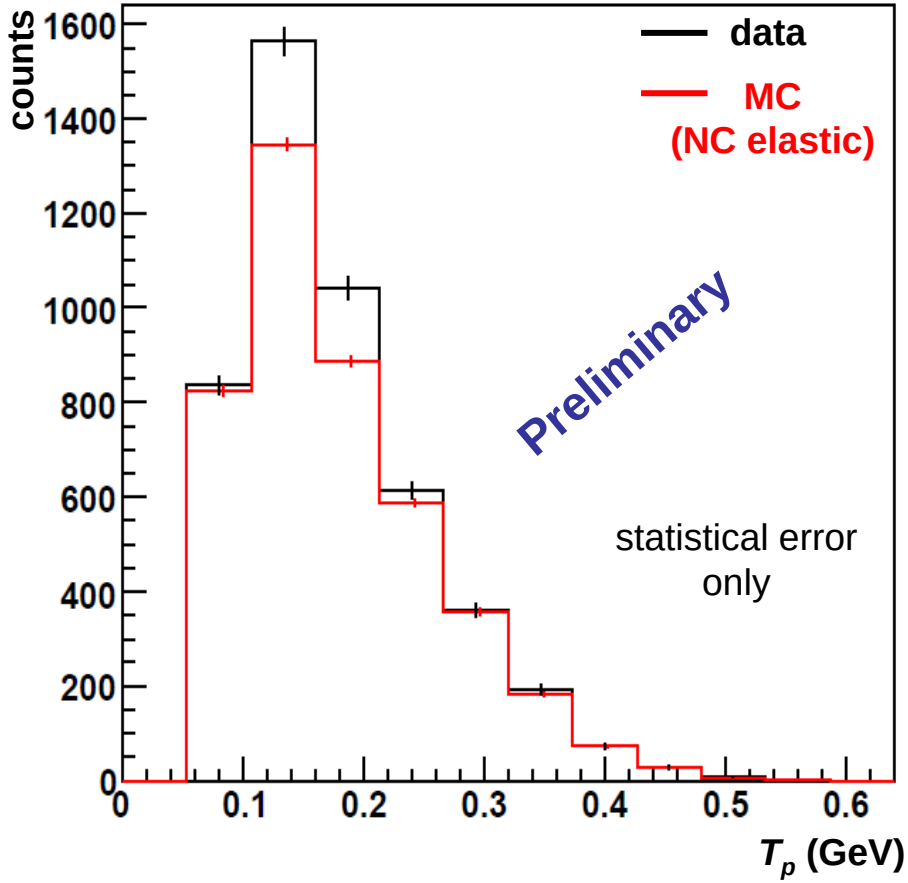

Data is corrected by

$$\text{data} \times \frac{\text{signal}}{\text{signal+B.G.}}$$

B.G. includes all non-NC elastic in SciBar and all the dirt events.

# $T_p$ Distribution

purity corrected $T_p$ distribution



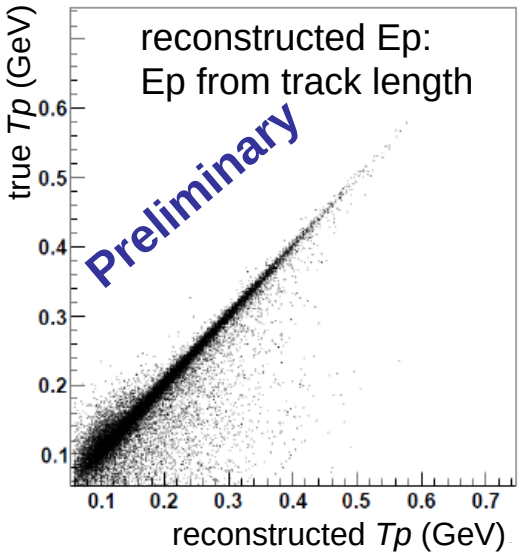

Same plot as previous page but bin size is changed.
Bin width corresponds to $Q^2$=0.1 $(GeV/c)^2$.

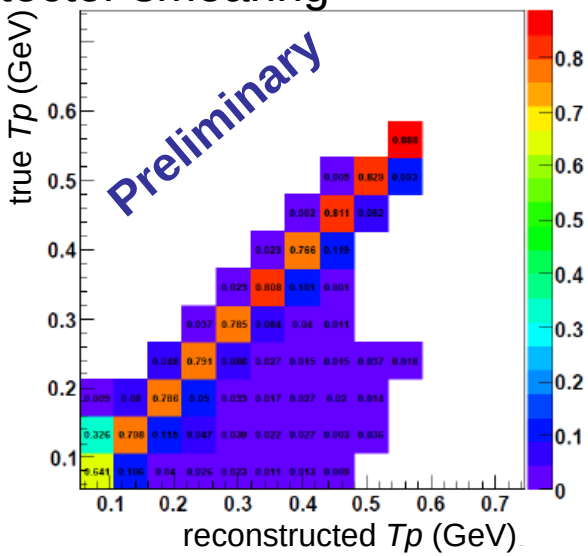
$(Q^2 = 2m_p T_p)$

# Detector Unfolding

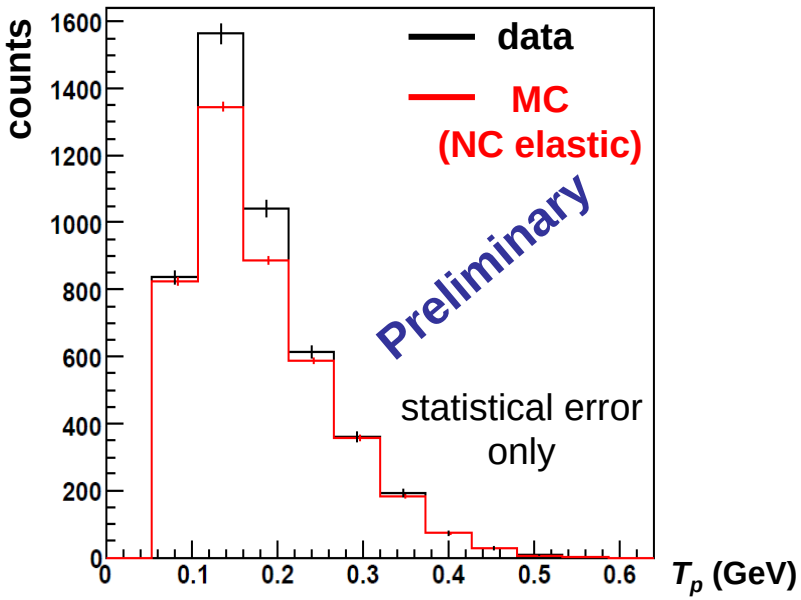
Using Monte Carlo Simulation

correction for detector smearing

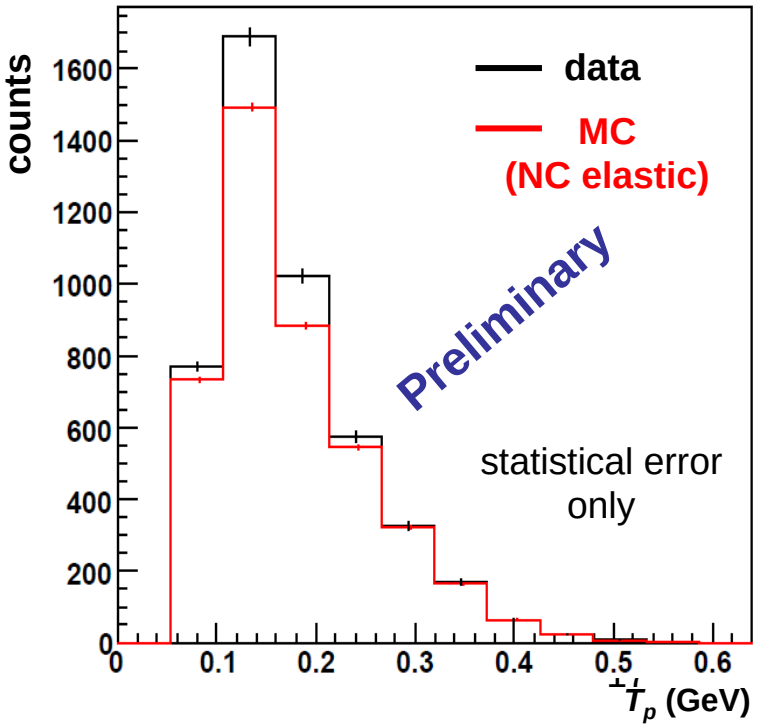



before corrections



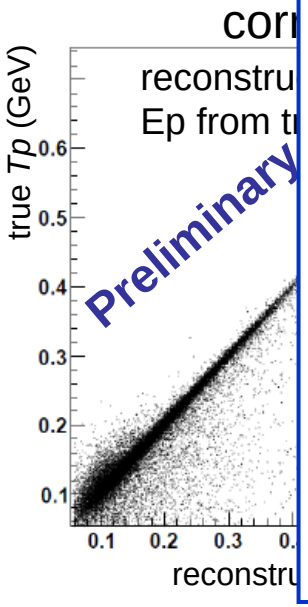

detector unfolded



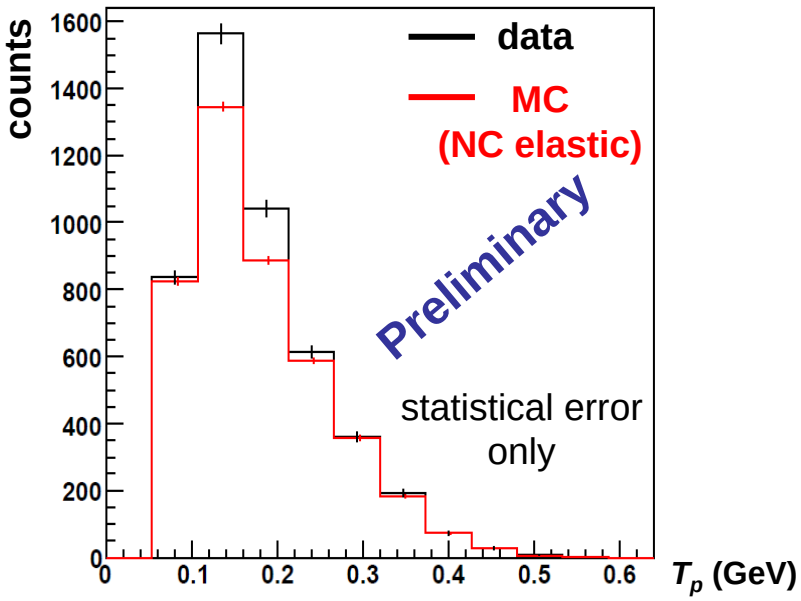
# Detector Unfolding

data excess in low Ep region
In this region, there are large contamination from the dirt events.
To get "clean" sample, cut is applied.

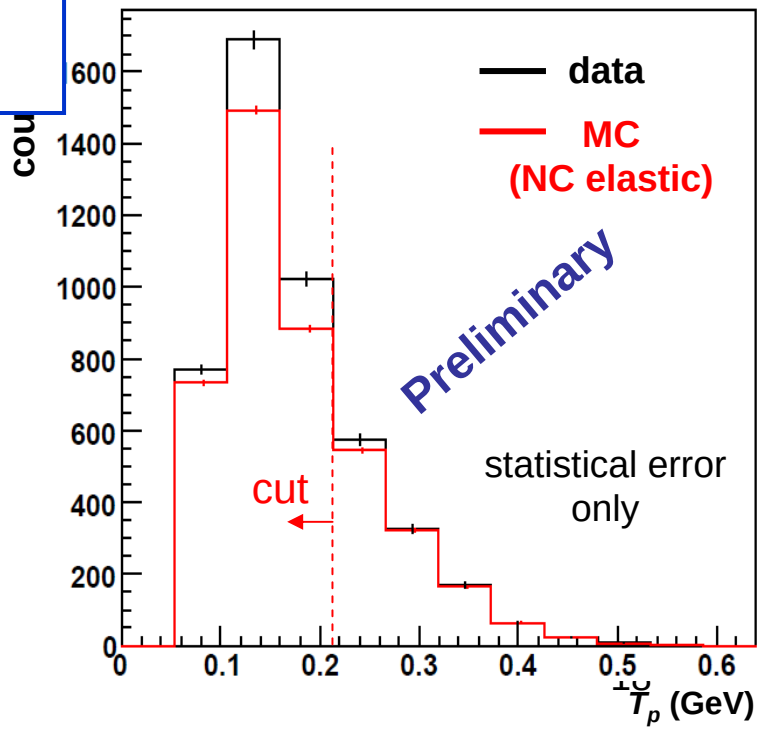
Low energy region is under study.
possible reson:
- wrong MC prediction for kinematics
- dirt background prediction
- track reconstruction
- other backgrounds




before corrections




detector unfolded

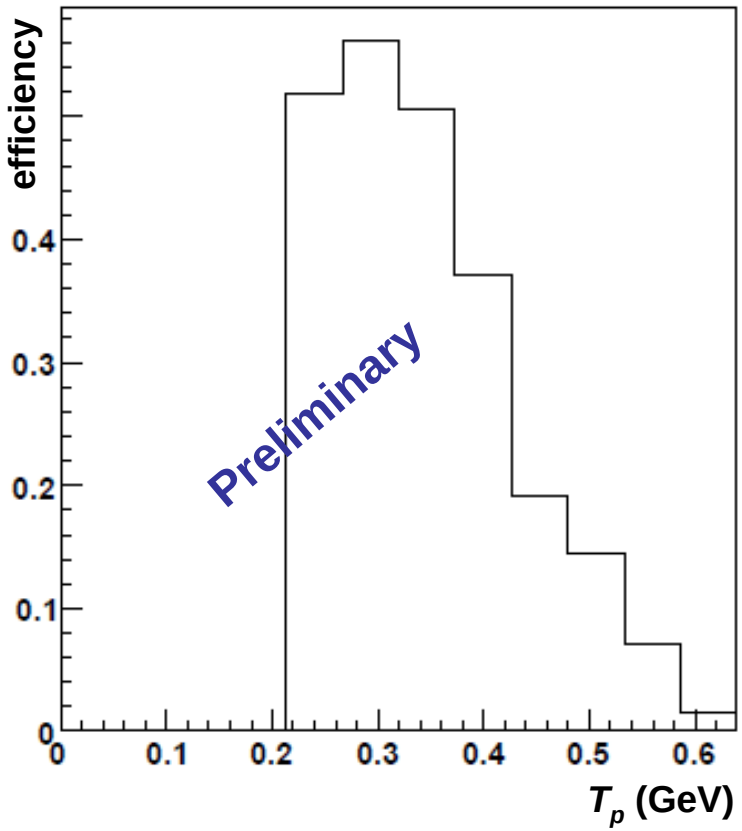


# Detection Efficiency Correction

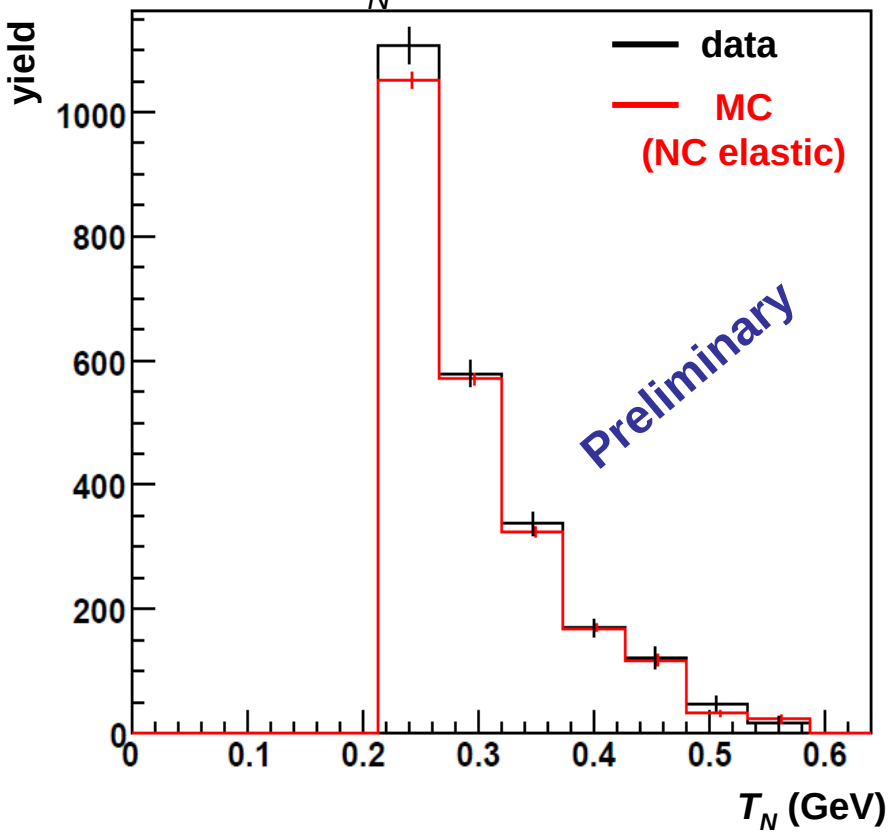
energy cut applied

$T_p$ efficiency

(only $Tp$>0.2 is shown)




detection efficiency corrected $T_N$ distribution




$n_N$: number of events in NC(p)+NC(n) data

$\varepsilon_N$: efficiency for NC(p)+NC(n)

$$\varepsilon_N = \frac{\text{NC(p) + NC(n)}}{\text{all SciBar MC events}}$$

$$\text{yield} = \frac{n_N}{\varepsilon_N}$$

$T_p$ from NC(n) events with visible proton track can be transferred to $T_n$.

# Result

# Differential Cross Section $d\sigma/dT_N$

$$\frac{d\sigma_i}{dT_N} = \frac{Y_i/(\Delta T_N)}{N_{POT} N_{target} \int \phi_\nu(E_\nu) dE_\nu}$$

$Y_i$: yield in $i$ th bin

$\Delta T_N$: width of $T_N$ bin

$N_{POT}$: number of proton on target

$N_{target}$: number of nucleon target

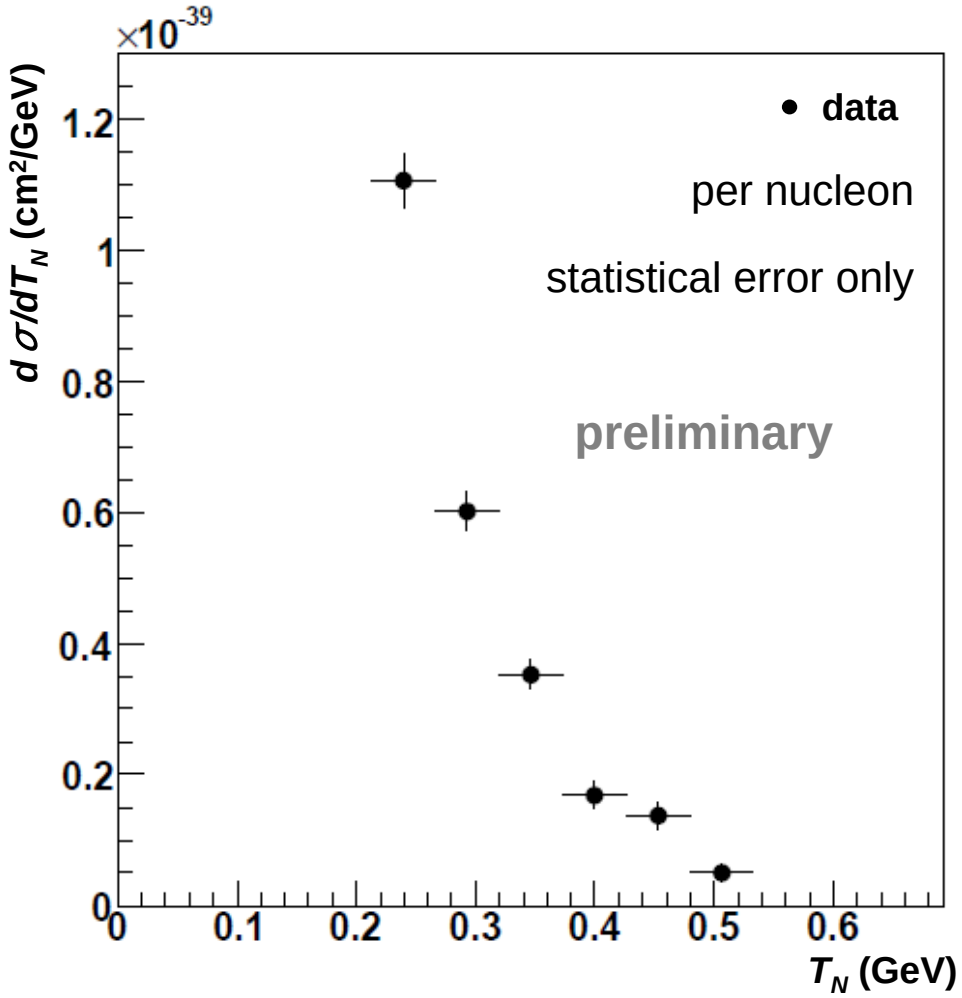
$\Phi_\nu(E_\nu)$: neutrino beam flux / POT

$N_{POT}$ = 9.90e19 POT

integrated flux:

$\int \phi_\nu(E_\nu) dE_\nu$ = 1.91e-8 (1/(cm$^2$·POT))

Number of neutrinos: 1.89e12 (1/cm$^2$)

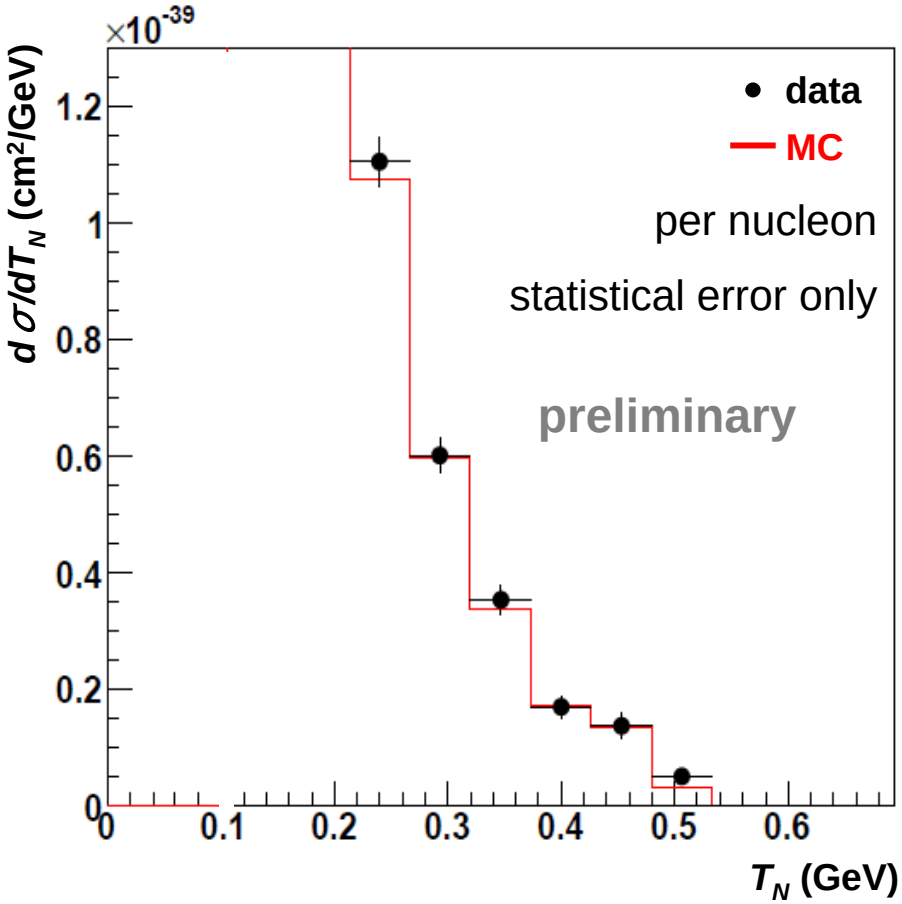


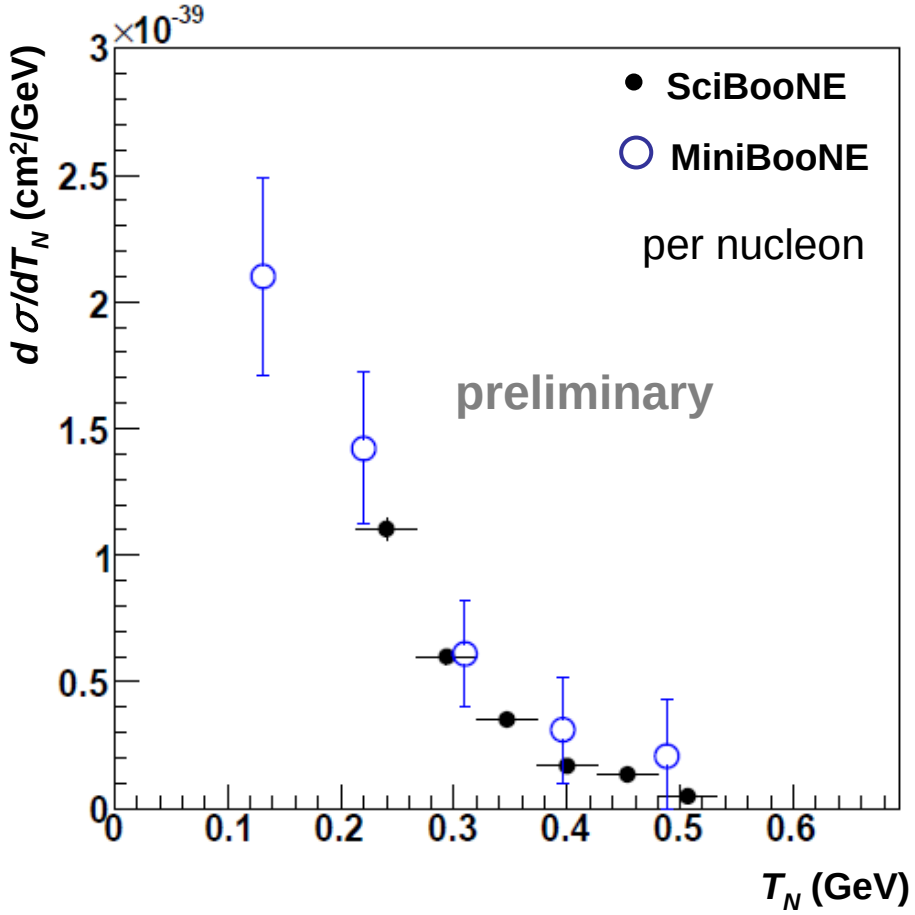

flux prediction

A.A. Aguilar-Arevalo, *et al.*, "The Neutrino Flux Prediction at MiniBooNE", Phys.Rev.D**79** 072002 (2009), arXiv:0806.1449 [hep-ex].

# Differential Cross Section $d\sigma/dT_N$

## comparison with MC and MiniBooNE




SciBooNE data includes statistical error only
MiniBooNE Data includes statistical and systematic error

# Summary

- Differential cross section for neutral current (NC) elastic scattering as a function of nucleon kinetic energy $d\sigma/dT_N$ is evaluated with small statistical error.

- Currently data with $T_N$ region larger than 0.2 GeV is used. Disagreement between Data and MC with small $T_N$ region is under study.

- Result of NC elastic scattering at SciBooNE is compared to Monte Carlo prediction and MiniBooNE result. Both comparisons show good agreement.

# Further Study

- After study for data with small $T_N$ region, include these data to evaluate $d\sigma/dT_N$ with smaller $T_N$ region.

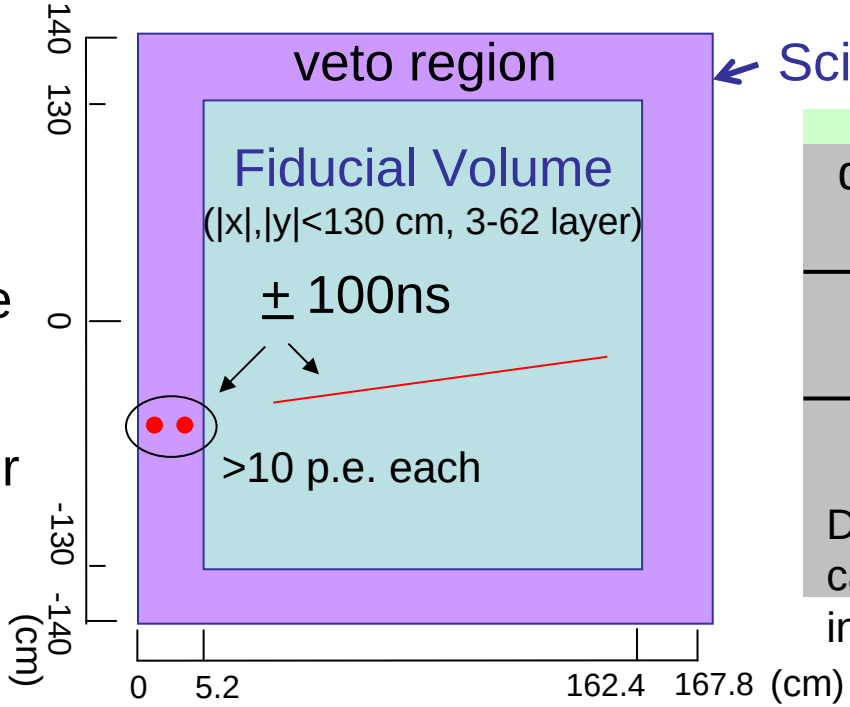
- Systematic uncertainty will be evaluated.

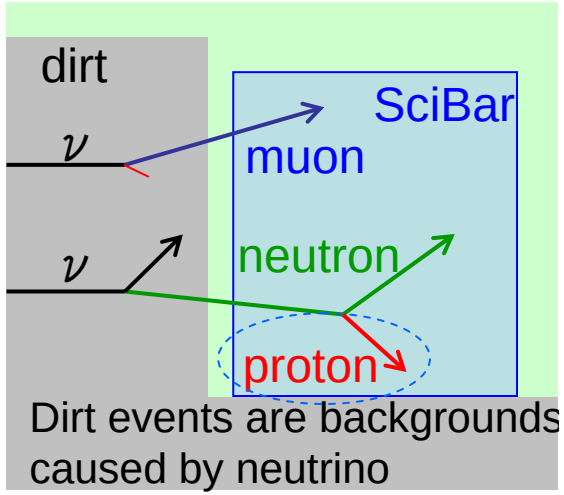
backup

# Event Selection 1. – SciBar Contained Track

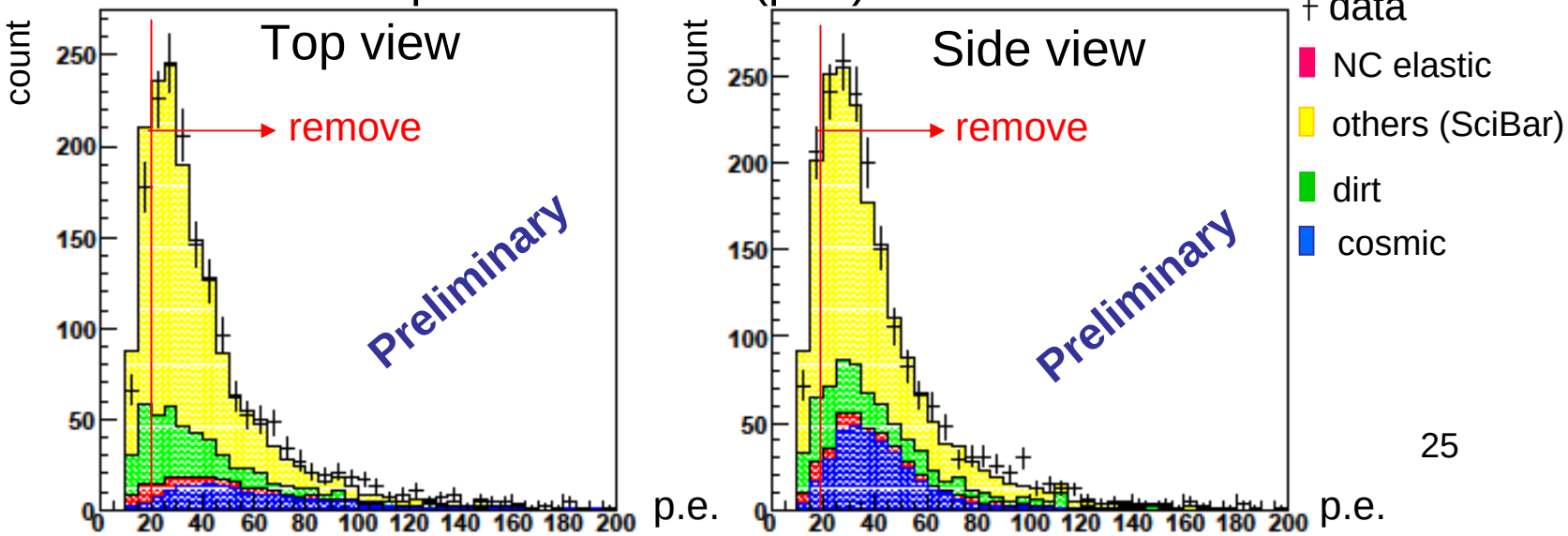
It removes particles which come from outside (such as dirt) and escape from inside SciBar.

require a cluster of 2 or more hits with >10 photoelectrons to avoid noise hits



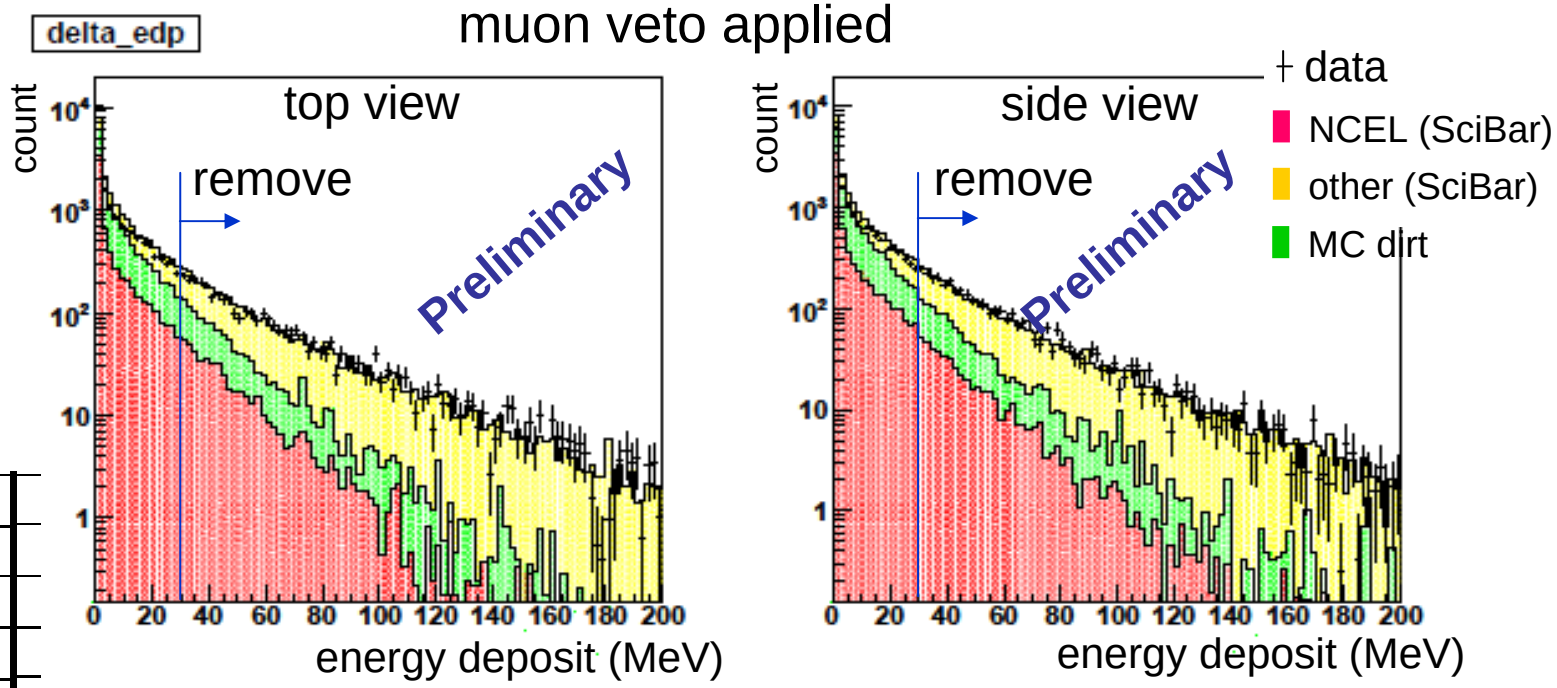

total photoelectrons (p.e.) of clusters

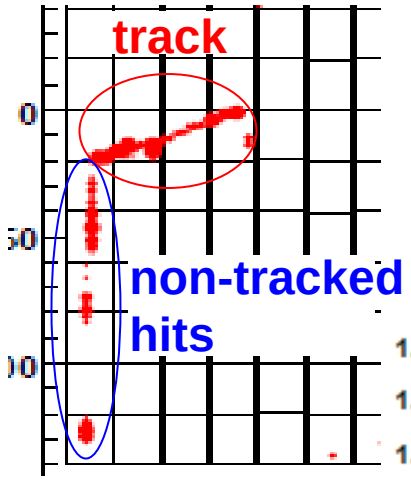


# Check of Misidentification of Single Track

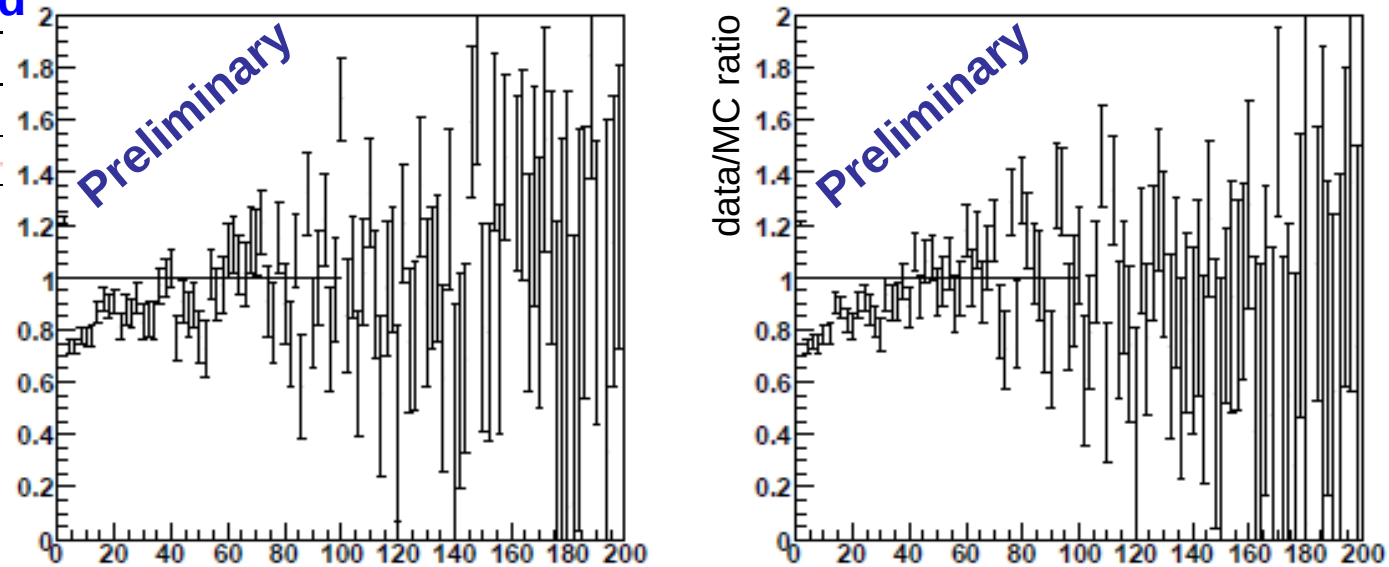
muon veto applied

non-track hits:
>10 p.e.
(above MIP
considering
attenuation)



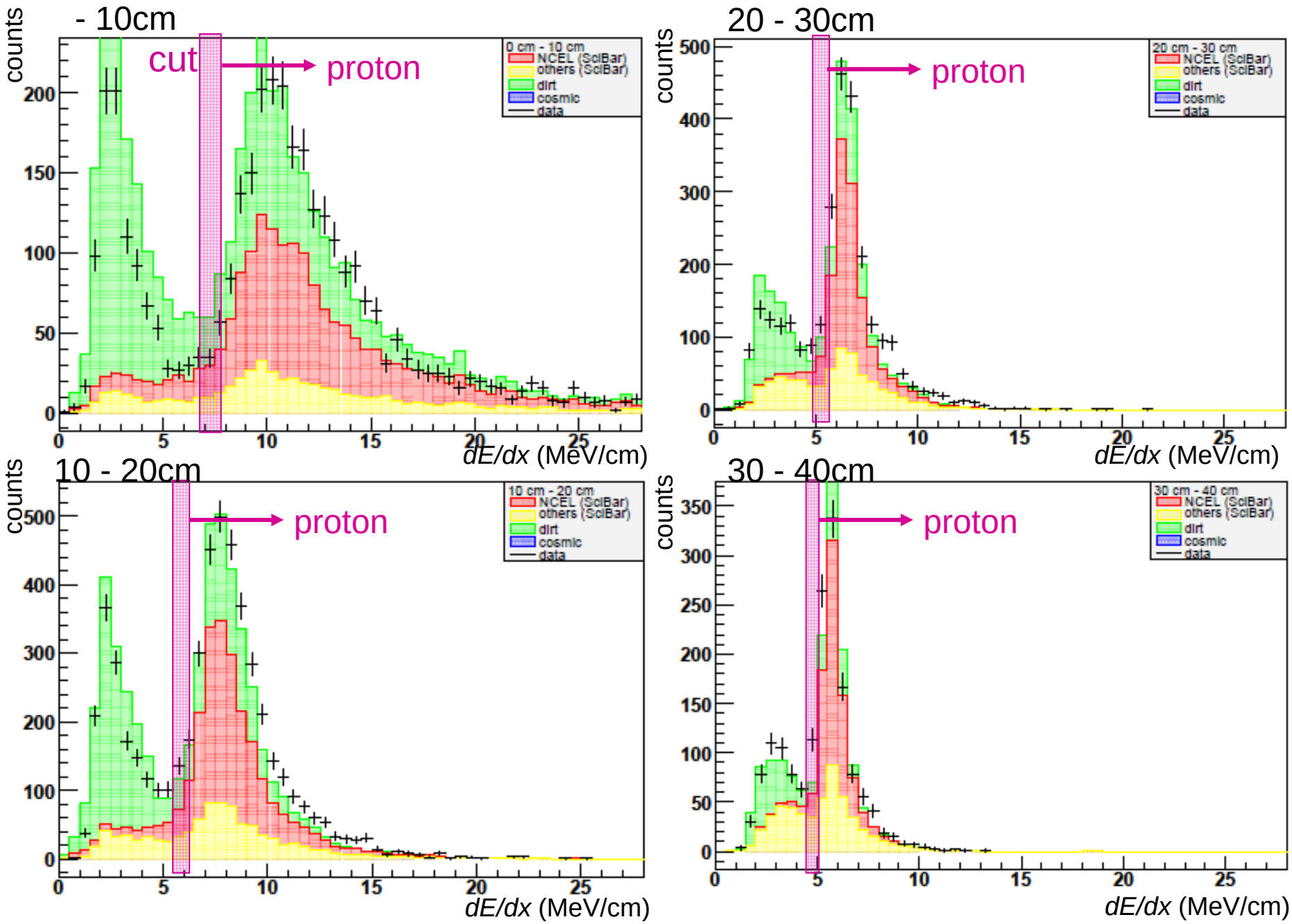

MC simulation




normalized by
MRD match

# cosmic events subracted *dE/dx* Distributions

normalized by MRD
matced sample

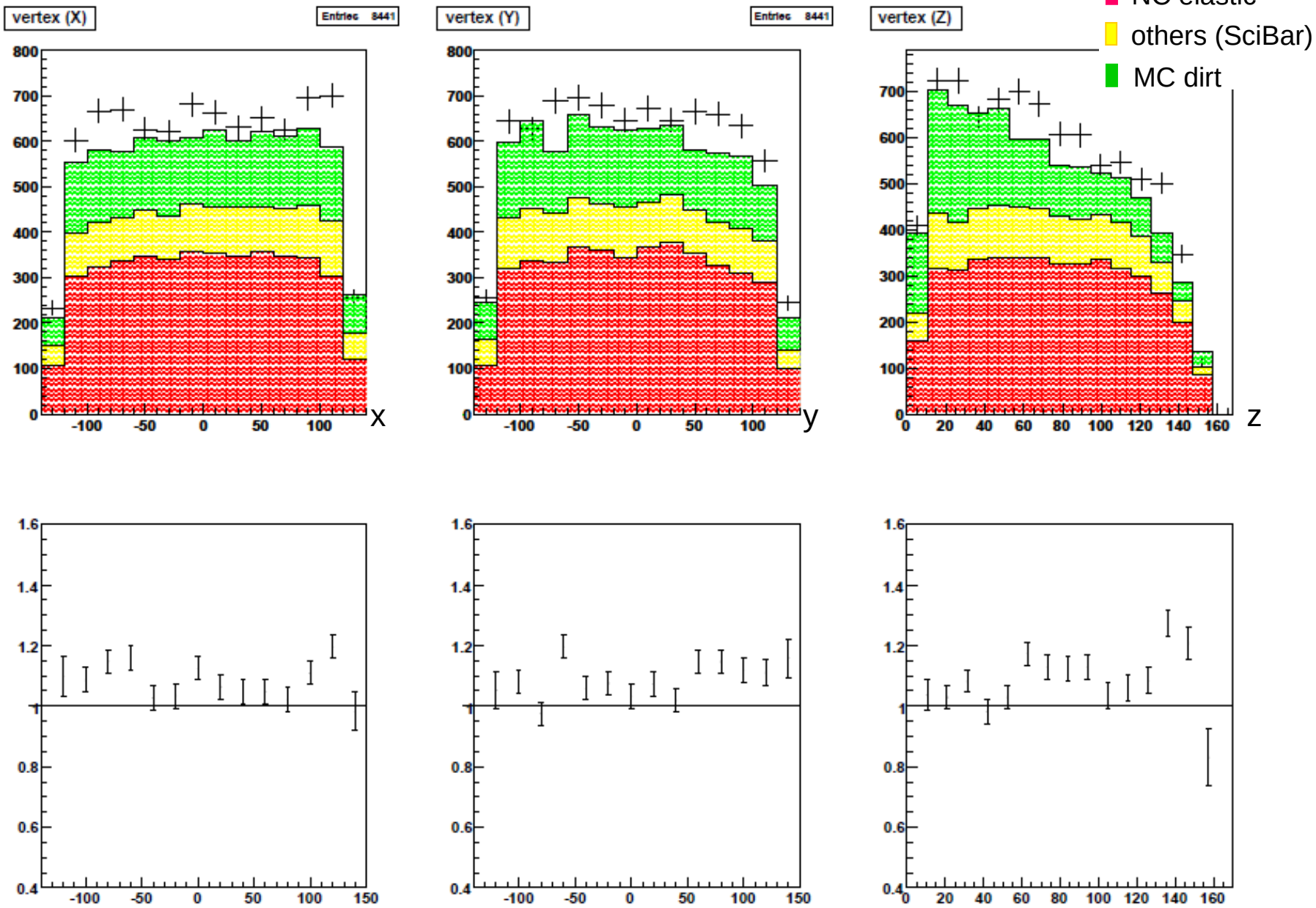


# Vertex Distributions

final sample
(cosmic subtracted)

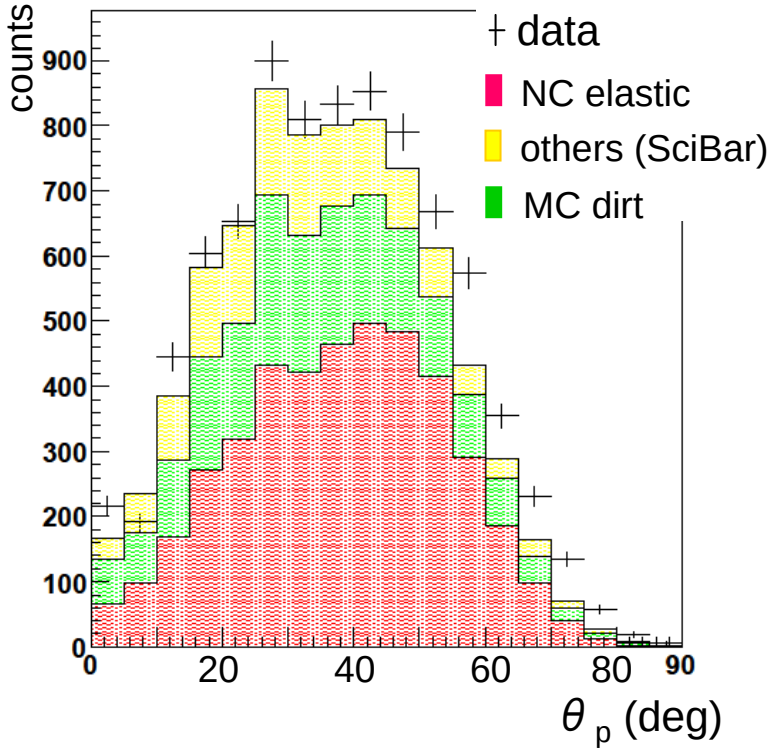
0 ≤t ≤2 μ s

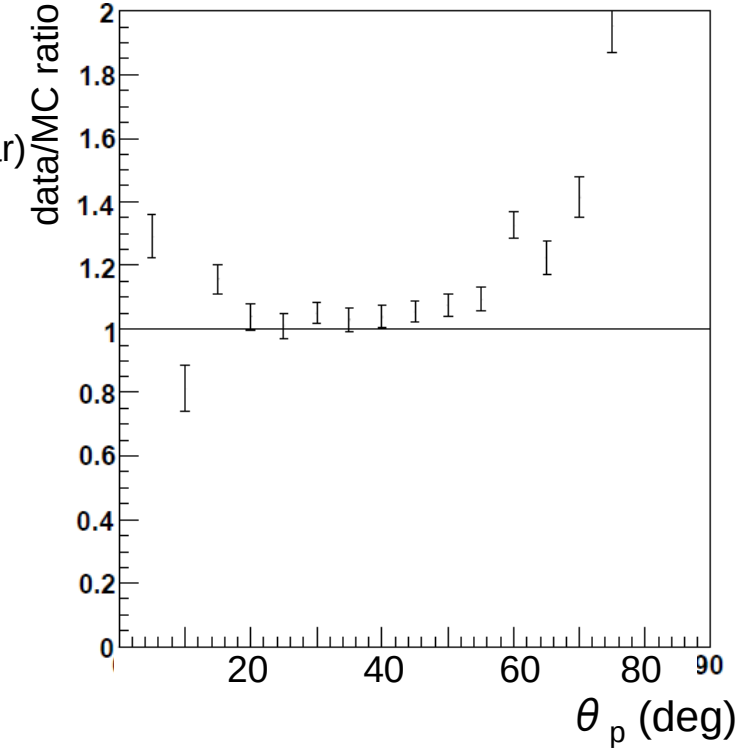
+ data
NC elastic
others (SciBar)
MC dirt

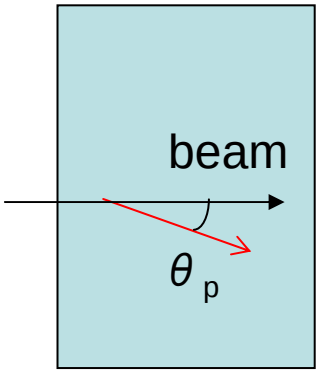


# Angular Distribution

NC elastic sample



# Fractions of NC(p) and NC(n)

NC elastic sample

| data | NC(p)+NC(n) | B.G. | purity |
|---|---|---|---|
| 8441 | 4340 | 3335 | 56.5% |

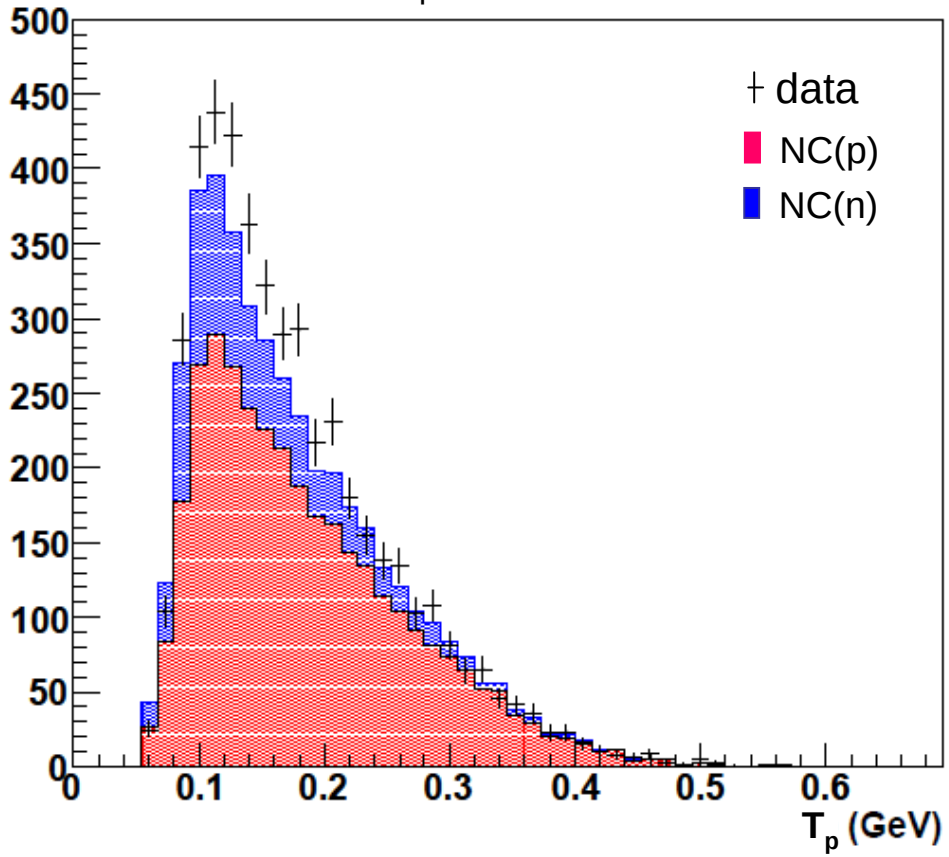
events

NC(p): 3422
NC(n): 918

78.8% of the NC elastic sample is NC(p) events.

4773 events in data after B.G. subtraction

$E_p$ distribution

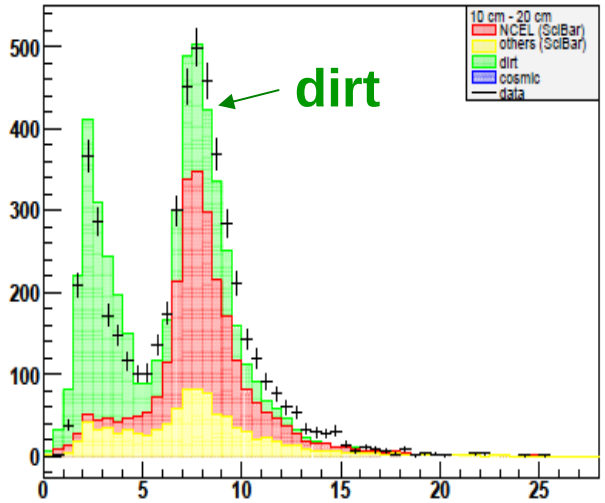


# Study of Dirt Background

- Dirt events are backgrounds caused by neutrino interactions inside dirt.

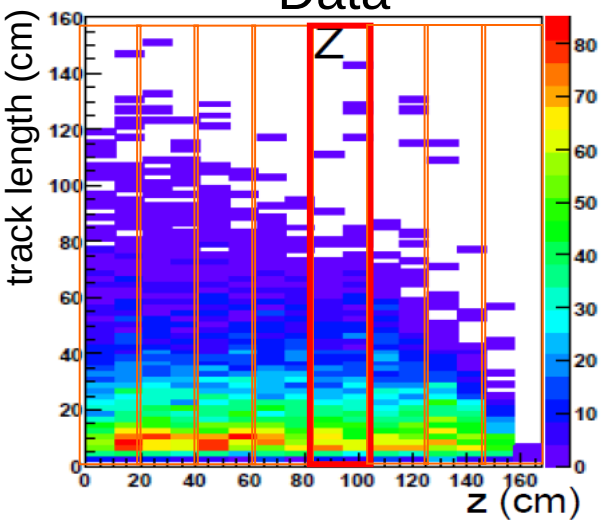
- dirt events → estimate from z v.s. length distribution

・Divide z into 8 bins.
・Subtract number of events in downstream bin from upstream bin.
・Compare data with MC (SciBar+dirt) for each z bin.

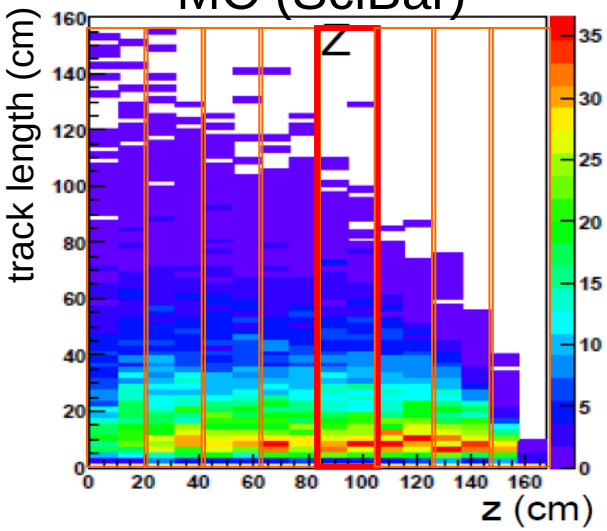



~90% of dirt B.G. is from protons recoiled by neutron.

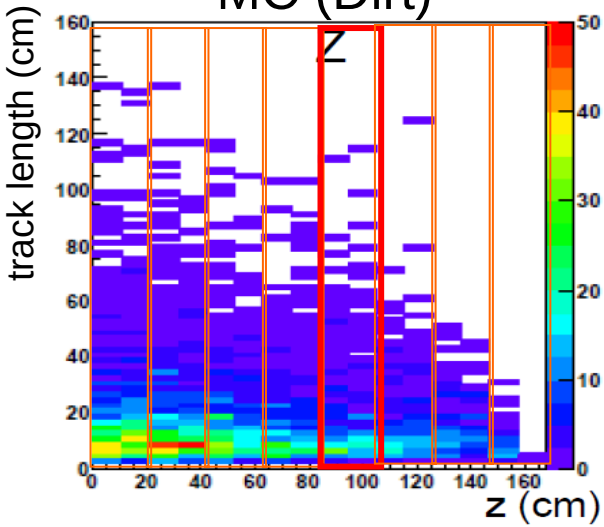
Data




MC (SciBar)

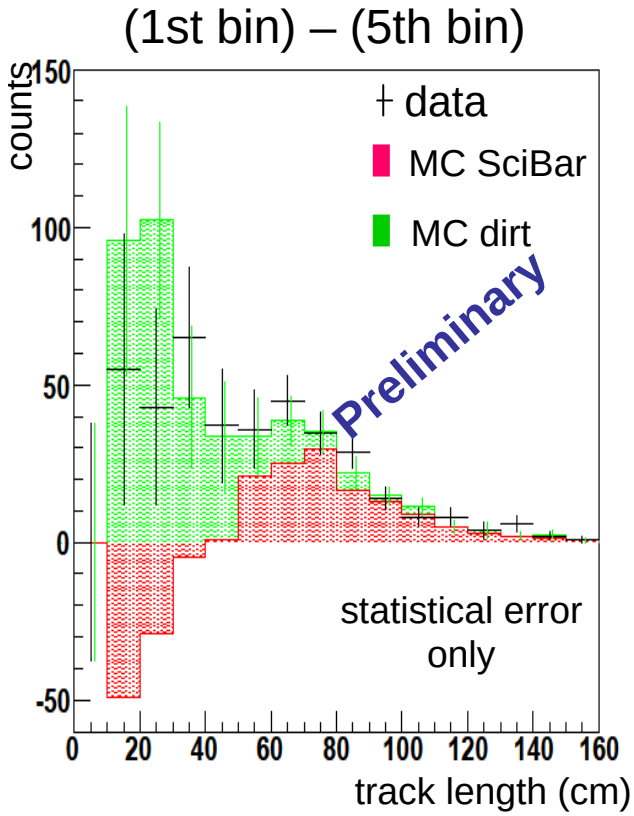


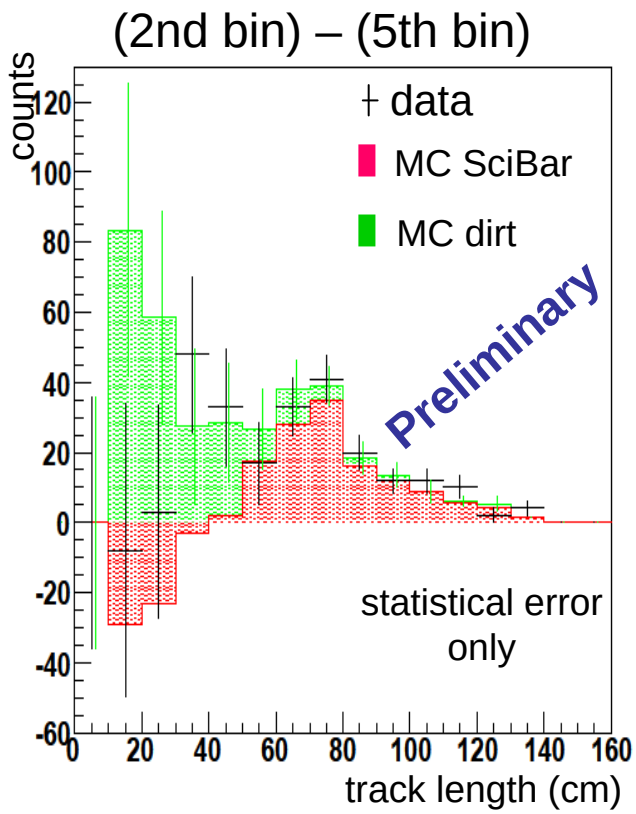

MC (Dirt)

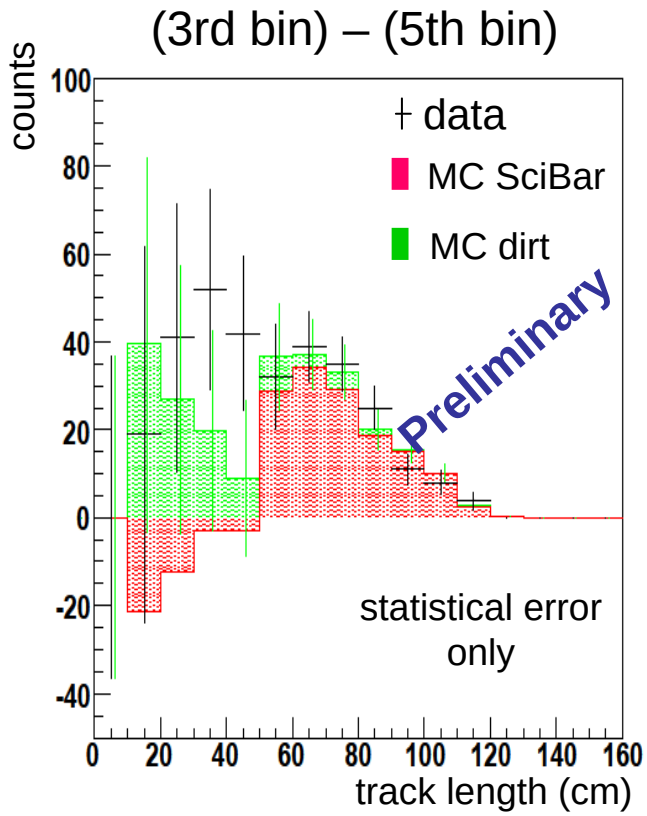


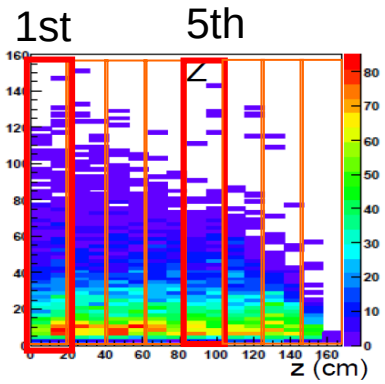

I took 5th bin as reference, and compared with upstream bins.

# Study of Dirt Background




Study of dirt is under way.

Particles which have roots in dirt events and make NC elastic scattering-like track in SciBar.

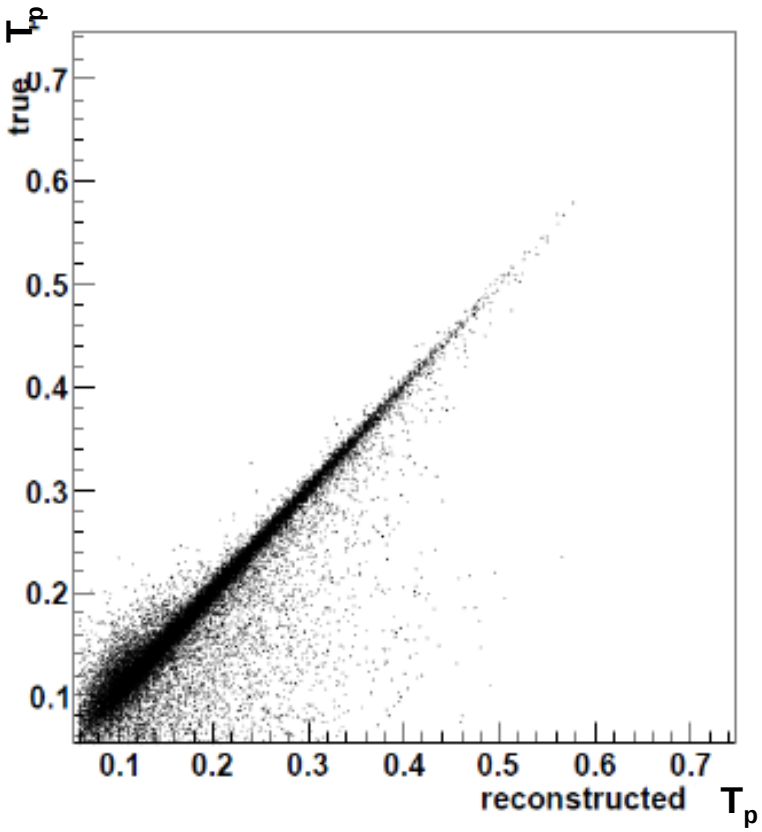
| particle | number of events |
|---|---|
| proton | 1814 |
| electron | 64 |
| muon | 4 |
| pion | 19 |
| total | 1901 |

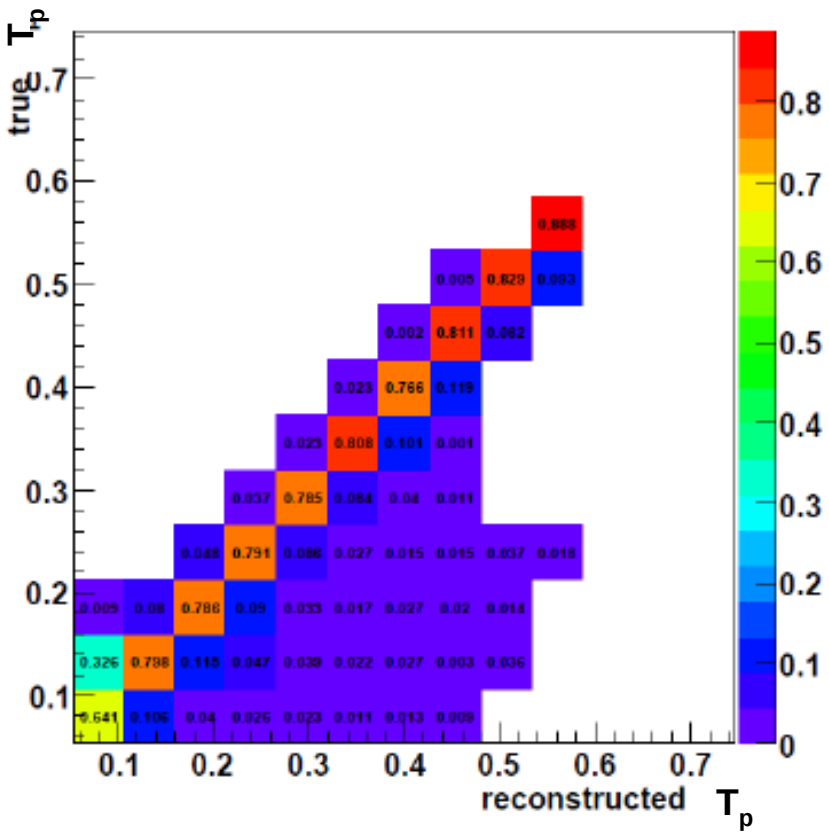
Fractions of the neutrino interactions in the dirt which make a proton track in SciBar.

| interaction | fraction (%) |
|---|---|
| NC elastic ($\nu p \to \nu p$) | 3 |
| NC elastic ($\nu n \to \nu n$) | 30 |
| NC pion production | 13 |
| CC elastic ($\nu n \to \mu^- p$) | 16 |
| CC pion production | 27 |

# Detector Unfolding Matrix

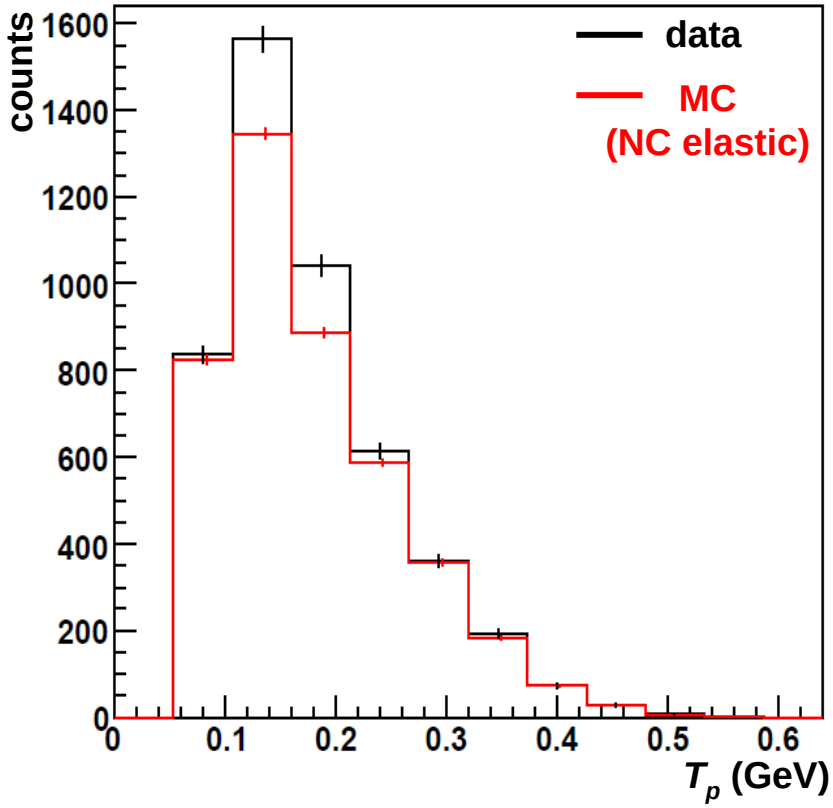
rec Tp: reconstructed Tp from reconstructed
proton track length



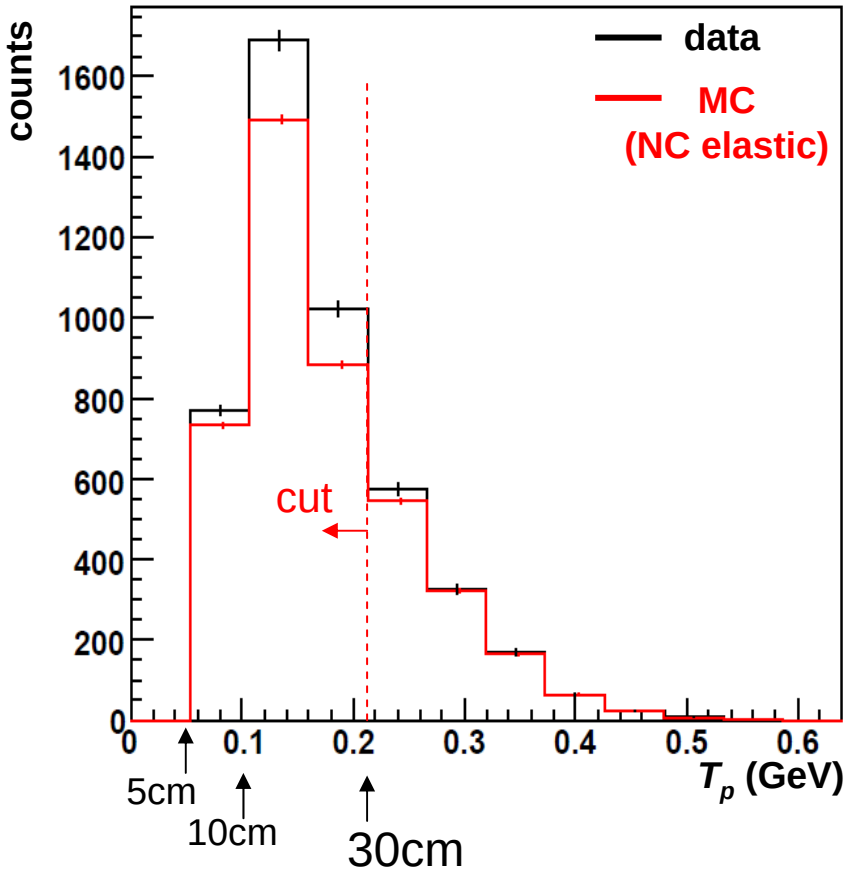



# Detector Unfolded $T_p$ Distribution

purity corrected $T_p$ distribution

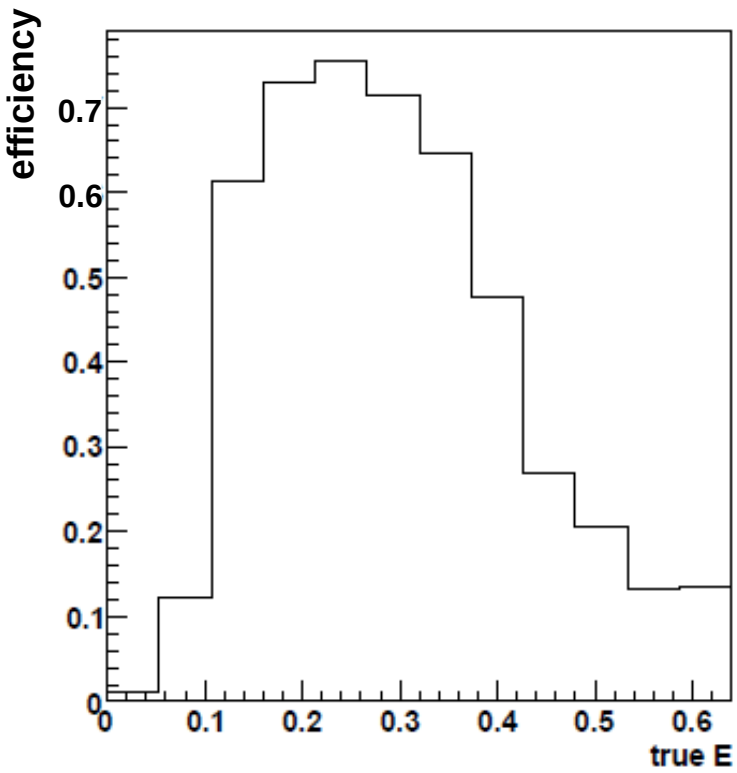



detector unfolded $T_p$ distribution



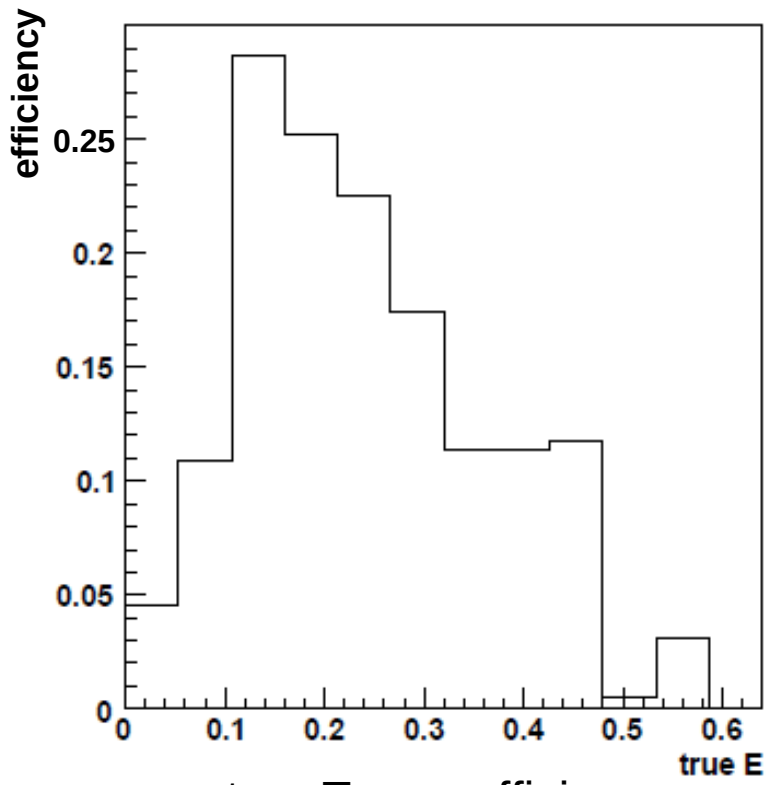
# Detection Efficiencies for NC(p) and NC(n)

detection efficiency for NC(p)




true $T_p$ v.s. efficiency

detection efficiency for NC(n)




true $T_n$ v.s. efficiency

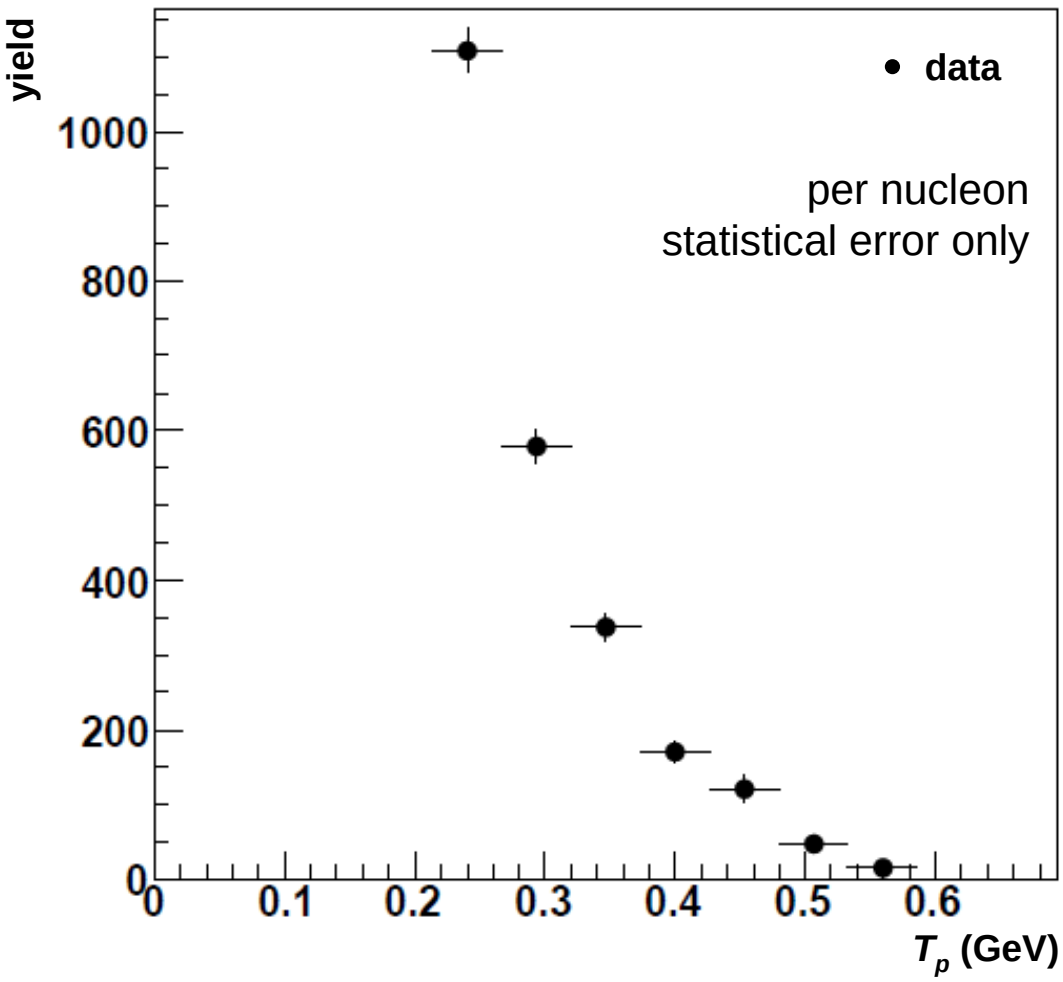
$$\text{efficiency} = \frac{\text{detected NC(p)}}{\text{all NC(p) in SciBar}}$$

$$\text{efficiency} = \frac{\text{detected NC(n)}}{\text{all NC(n) in SciBar}}$$



"detected": proton recoiled by neutron is observed

# $\nu N$ NC Elastic Scattering Yield as a function of $T_p$




CH target

# Differential Cross Section $d\sigma/dT_N$

(log scale)

$$\frac{d\sigma_i}{dT_N} = \frac{Y_i/(\Delta T_N)}{N_{POT} N_{target} \int \phi_\nu(E_\nu) dE_\nu}$$

$Y_i$: yield in $i$ th bin

$\Delta T_N$: width of $T_N$ bin

$N_{POT}$: number of proton on target

$N_{target}$: number of nucleon target

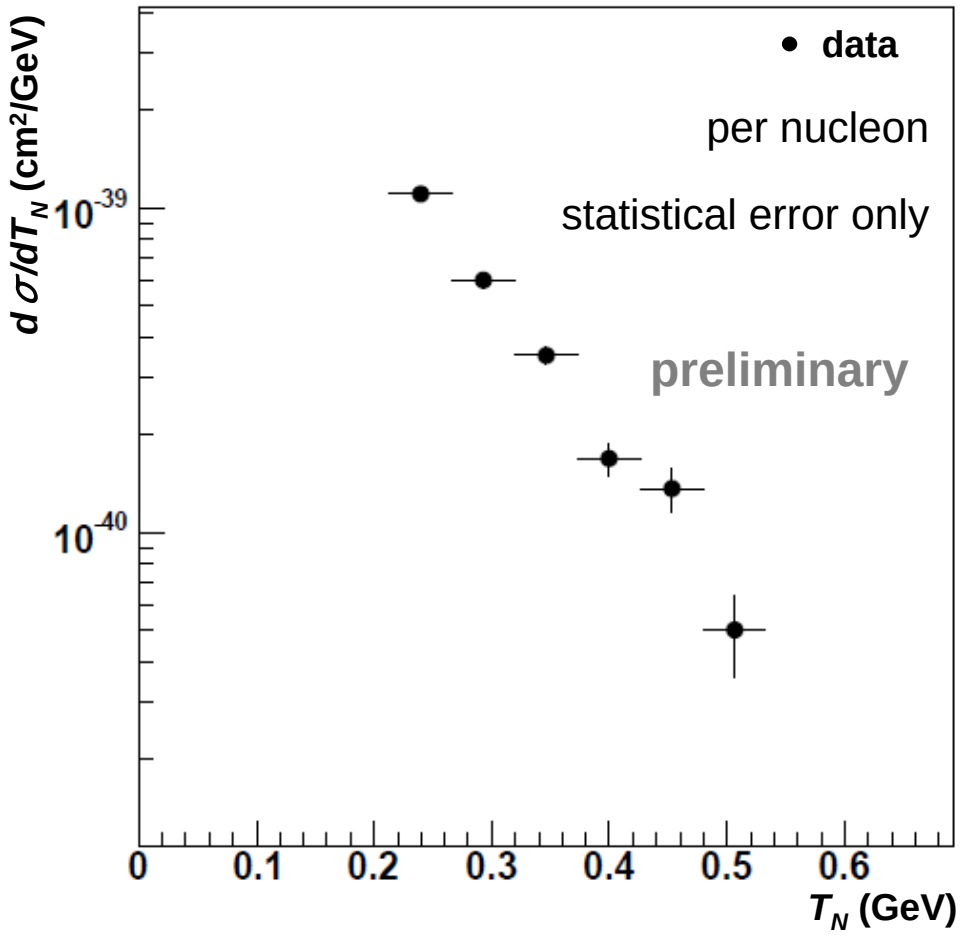
$\Phi_\nu(E_\nu)$: neutrino beam flux / POT

$N_{POT}$ = 9.90e19 POT

integrated flux:

$\int \phi_\nu(E_\nu) dE_\nu$ = 1.91e-8 (1/(cm$^2$·POT))

Number of neutrinos: 1.89e12 (1/cm$^2$)

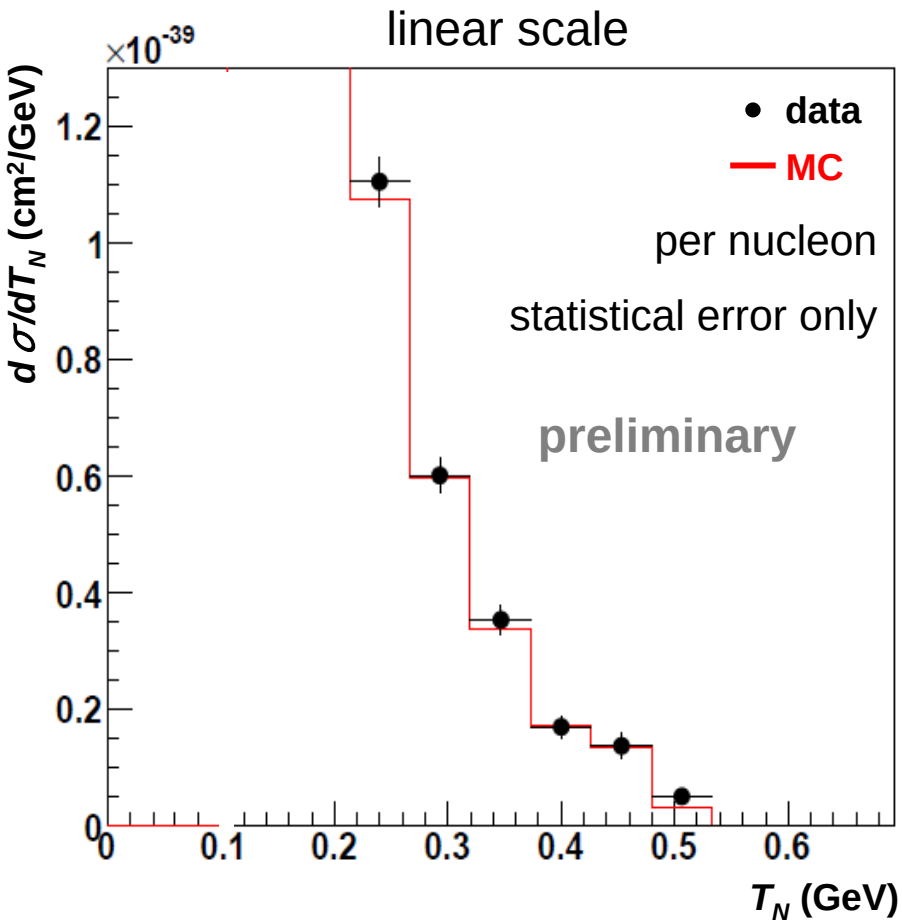


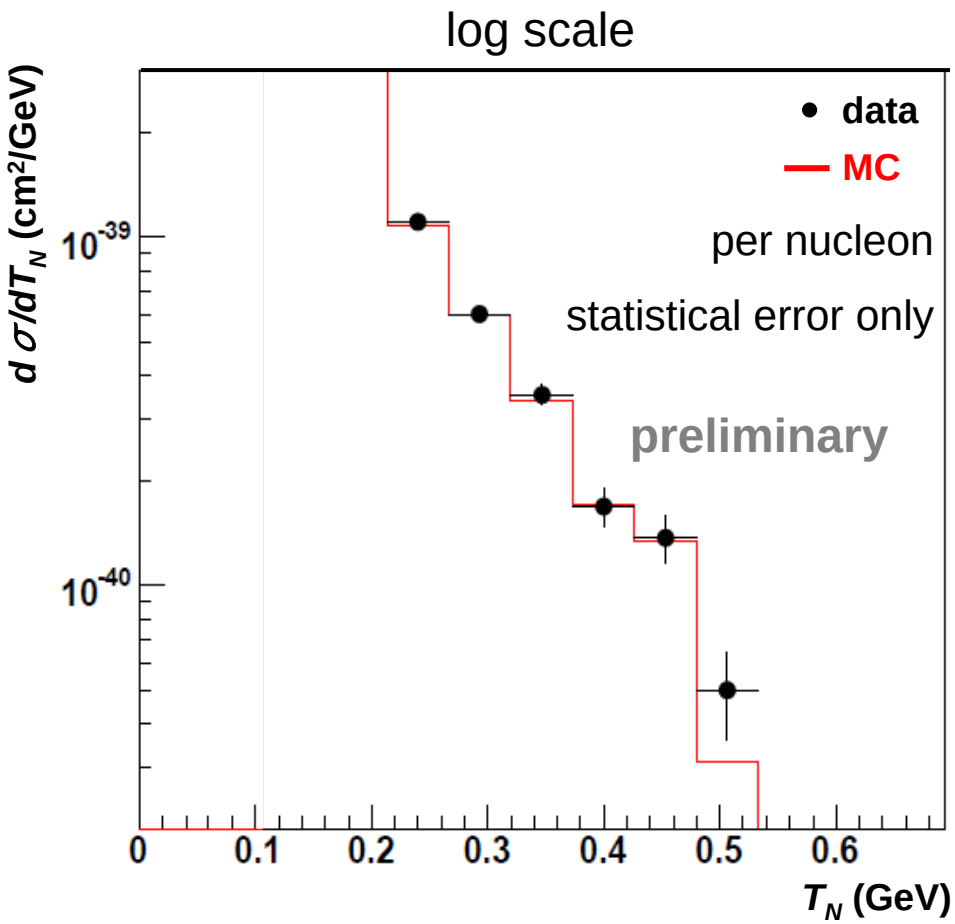

flux prediction

A.A. Aguilar-Arevalo, *et al.*, "The Neutrino Flux Prediction at MiniBooNE", Phys.Rev.D**79** 072002 (2009), arXiv:0806.1449 [hep-ex].

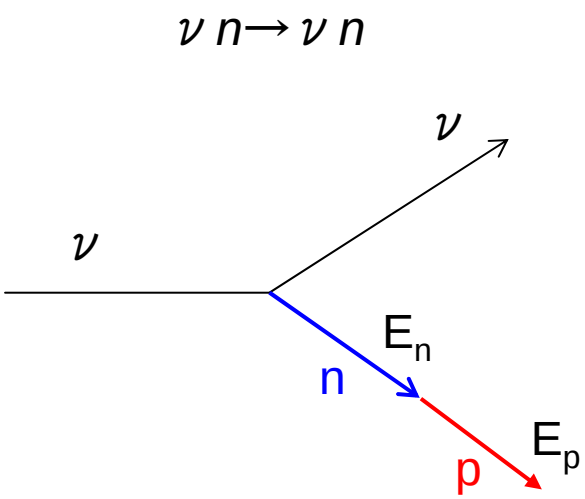
# Differential Cross Section $d\sigma/dT_N$

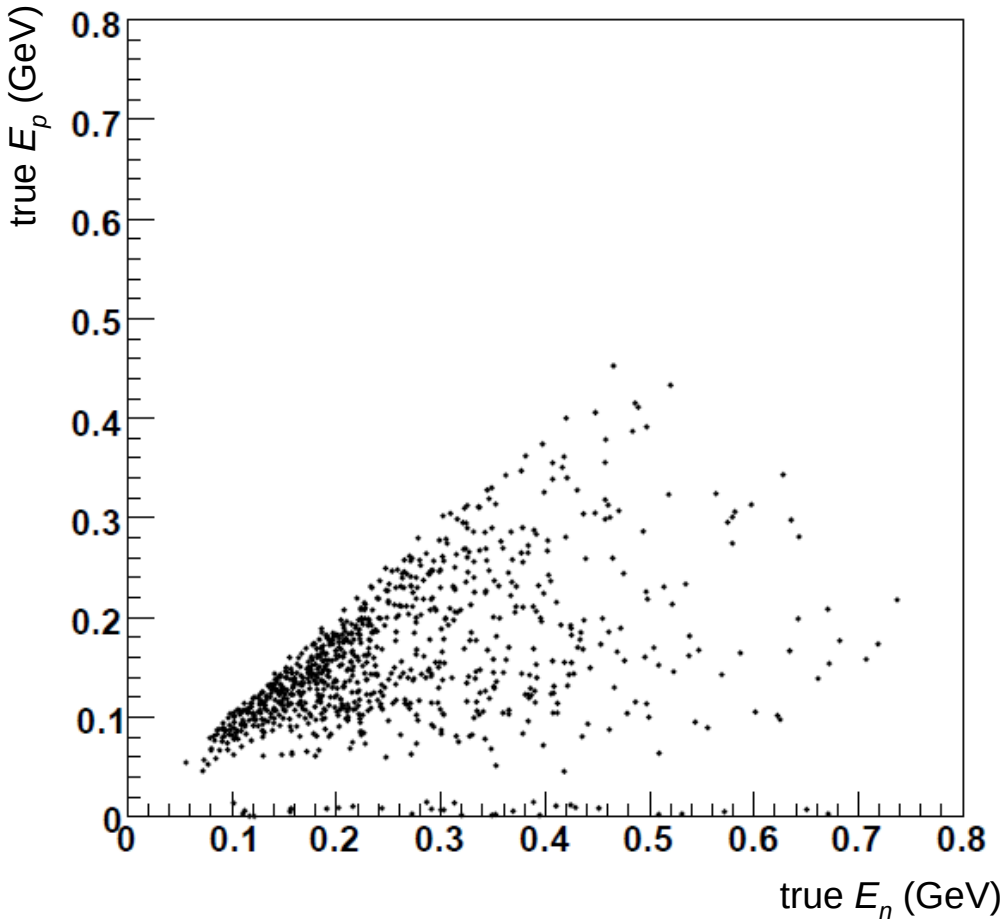
## comparison with MC



# $T_n$ v.s. $T_p$ in $\nu\, n \rightarrow \nu\, n$



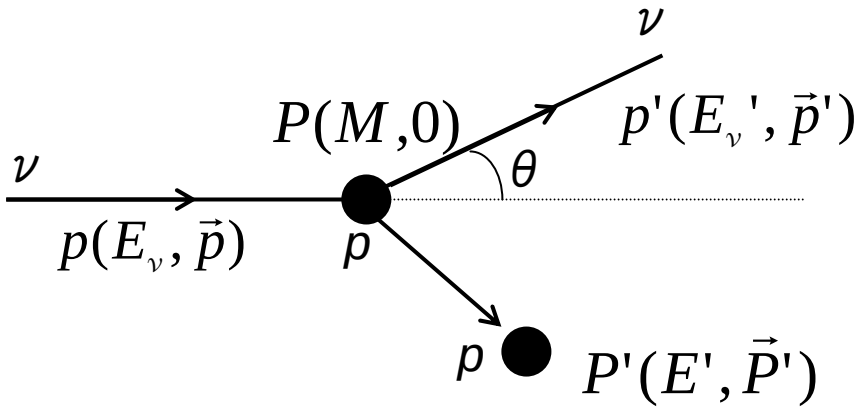




$\nu\, n \rightarrow \nu\, n$ in NC elastic sample are used for this plot.

# Kinematics of Neutral Current Elastic Scattering

$$\nu\, p \rightarrow \nu\, p$$

$E_\nu$=0.7 GeV




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

$m_p$=938MeV

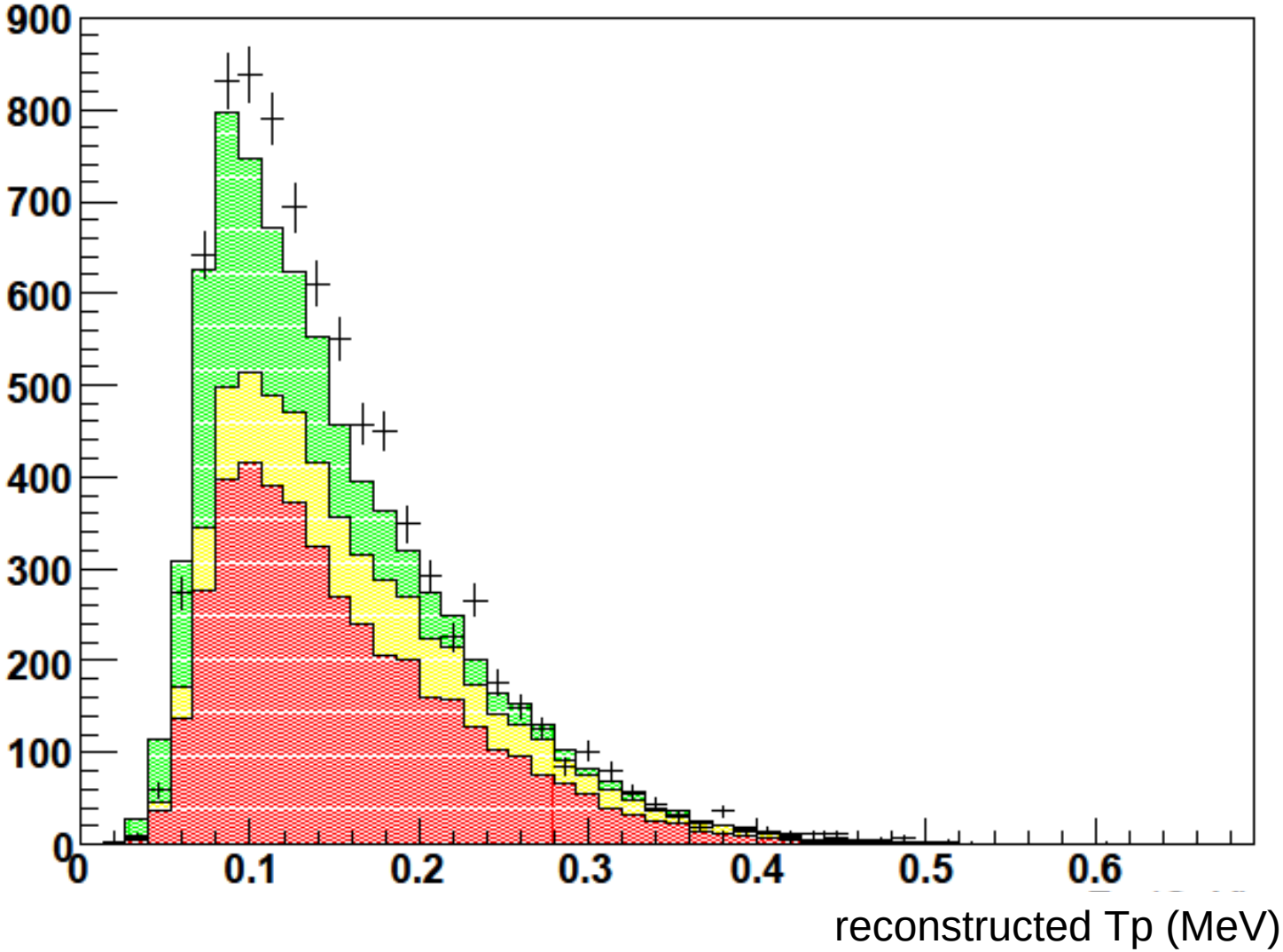
$$\boxed{Q^2 = 2m_p E_{kin}}$$

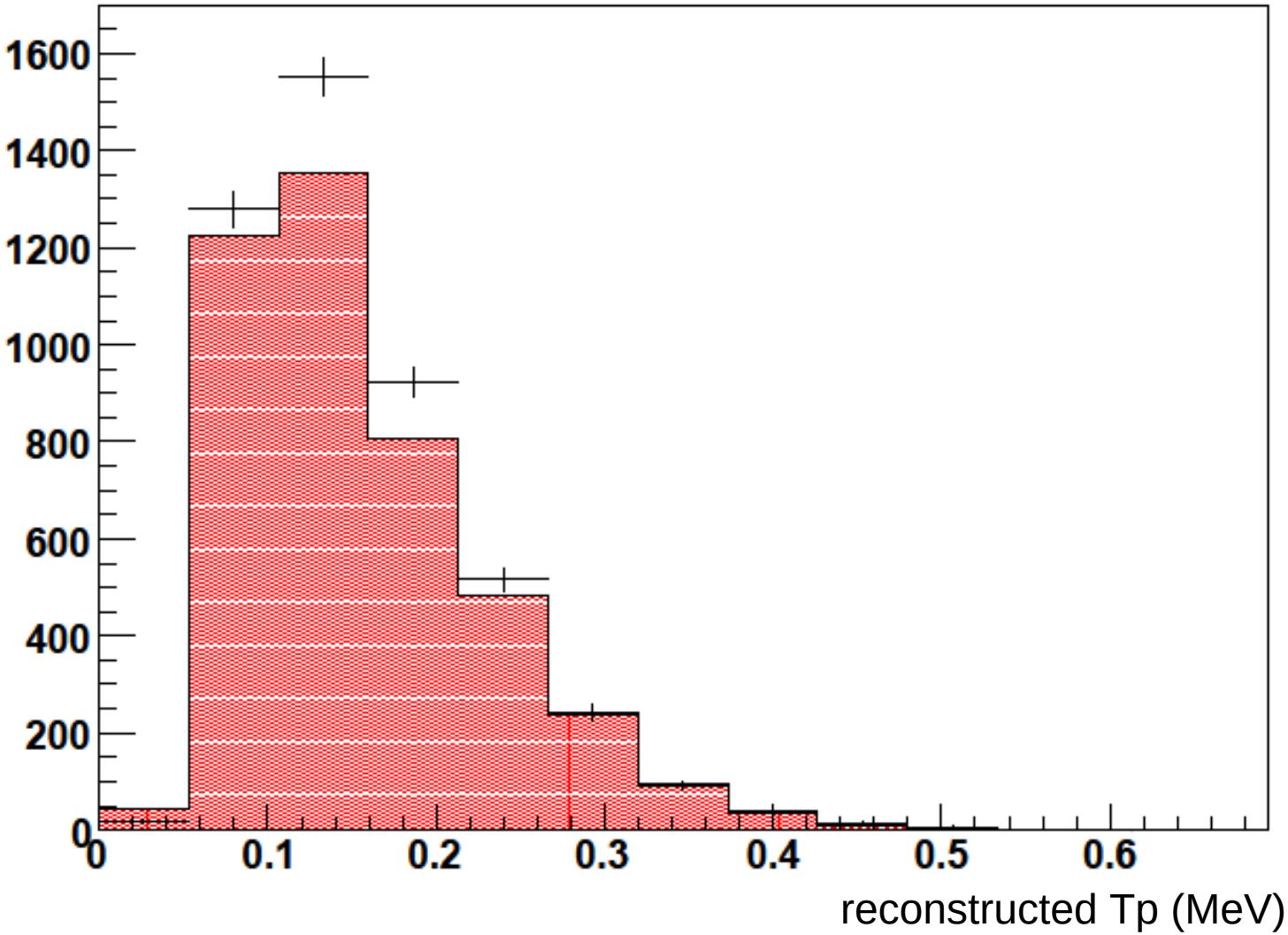
(with no approximation)

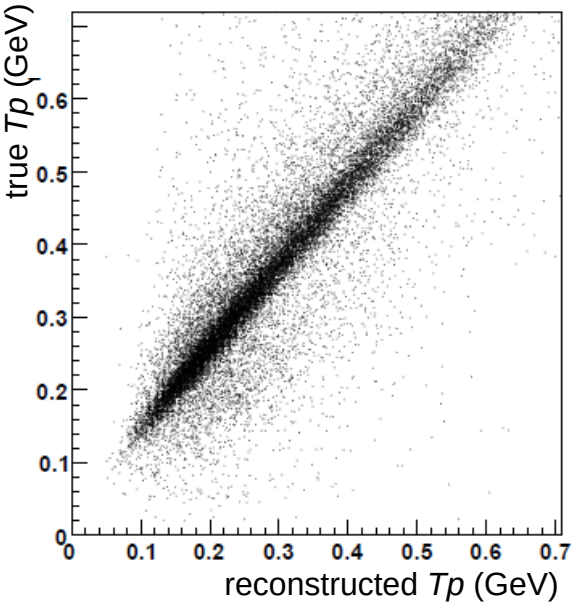
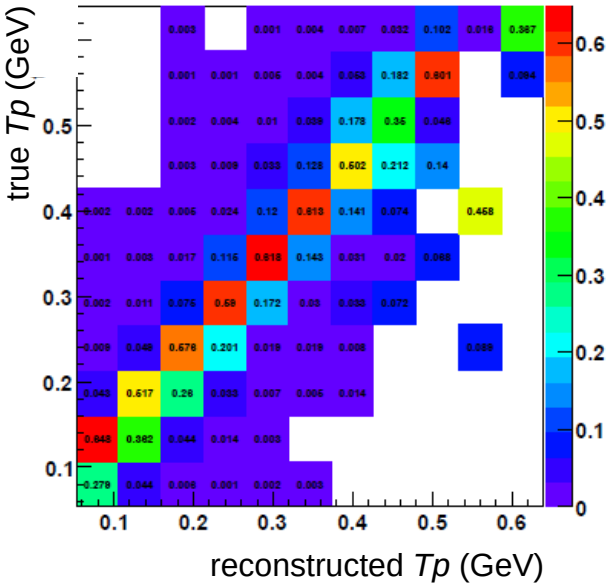
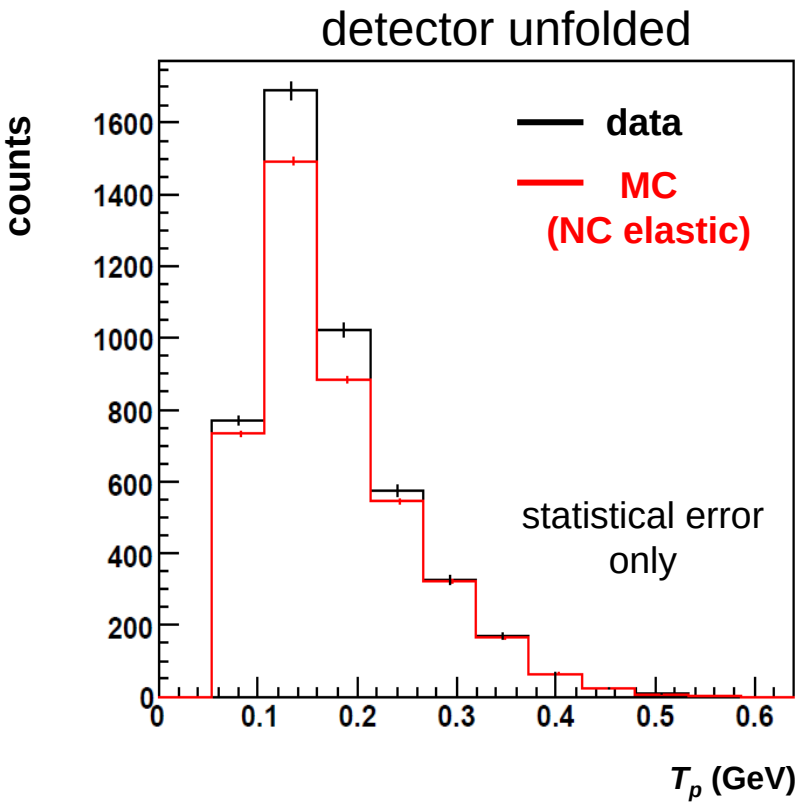
$E_{kin}$: kinetic energy of recoil proton

$E_{kin}$ is reconstructed using track length reconstructed by SciBar.

$Q^2$ can be determined without knowing incident energy nor scattering angle.


900
800
700
600
500
400
300
200
100
0
0
0.1
0.2
0.3
0.4
0.5
0.6
reconstructed Tp (MeV)


1600
1400
1200
1000
800
600
400
200
0
0
0.1
0.2
0.3
0.4
0.5
0.6
reconstructed Tp (MeV)

# Detector Unfolding

using reconstructed Tp