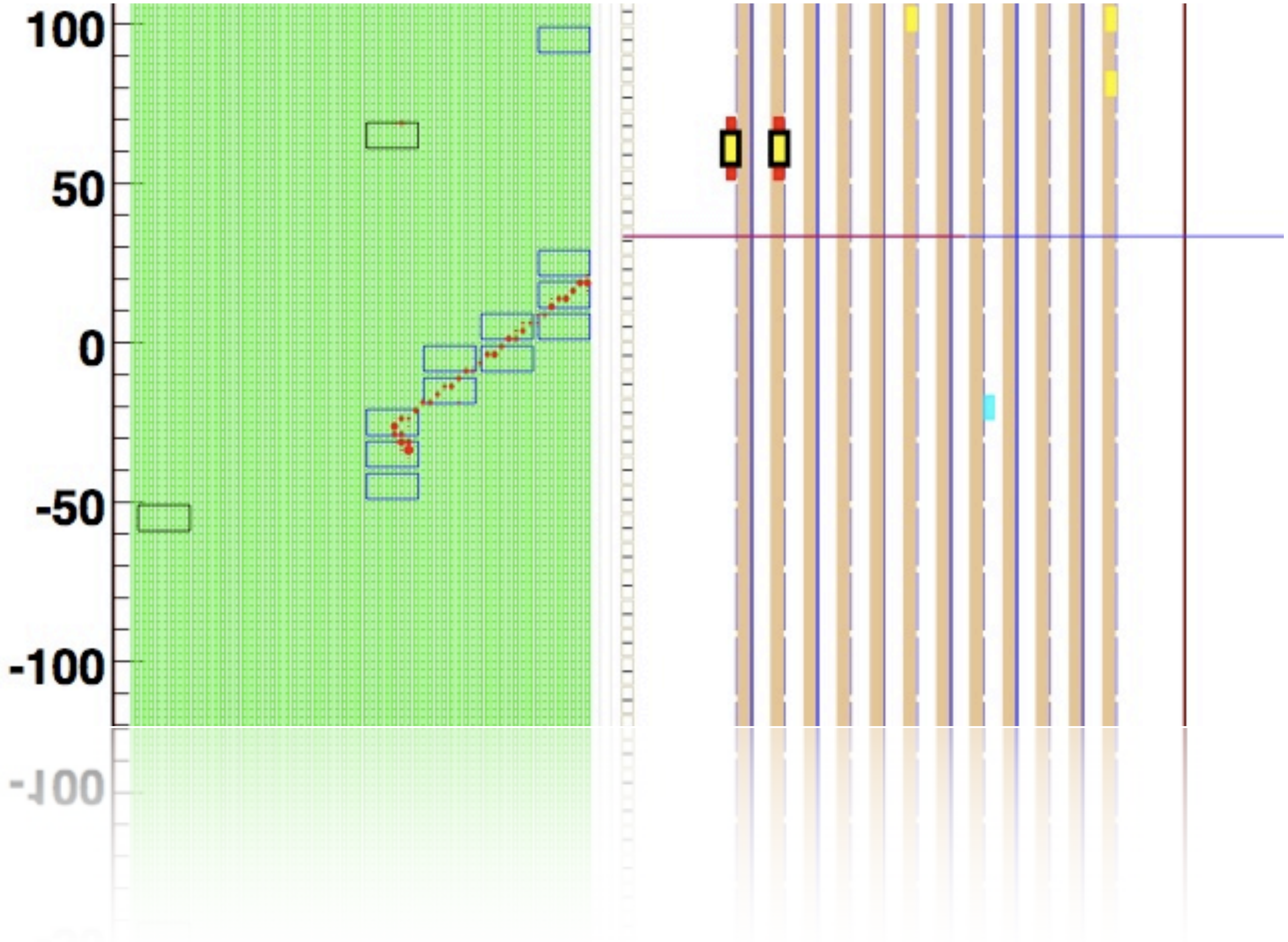


Lecture 2. CCQE

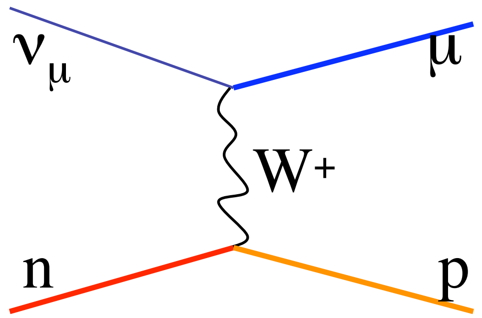
Lecture 2: CCQE

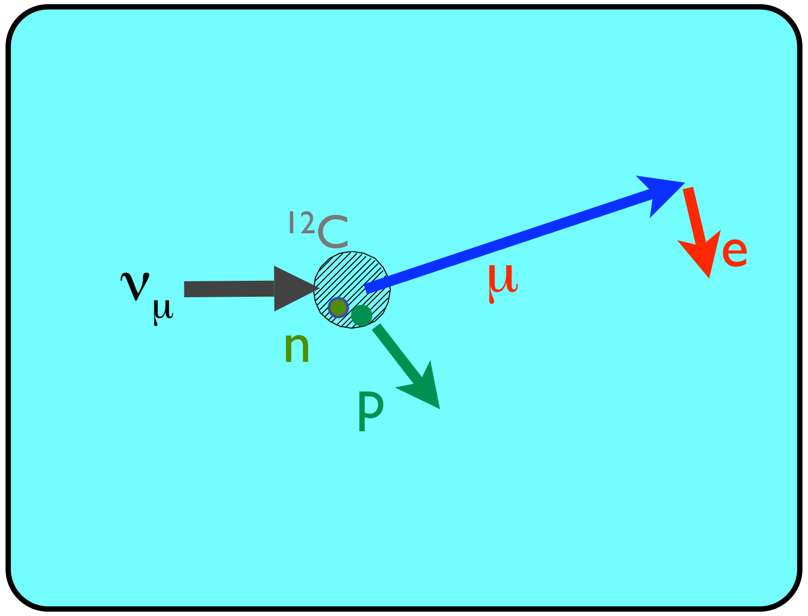
- Introduction
- Event kinematics and topology
- Experimental Searches
  - Event Selections
  - Efficiencies and Systematics
  - Extracted parameters
- Upcoming measurements

K2K
(SciFi & SciBar),
MiniBooNE,
SciBooNE

CCQE Intro

- Terminology:
  - Charged current quasi-elastic
- Simple reaction kinematics
- Dominant reaction at 1 GeV





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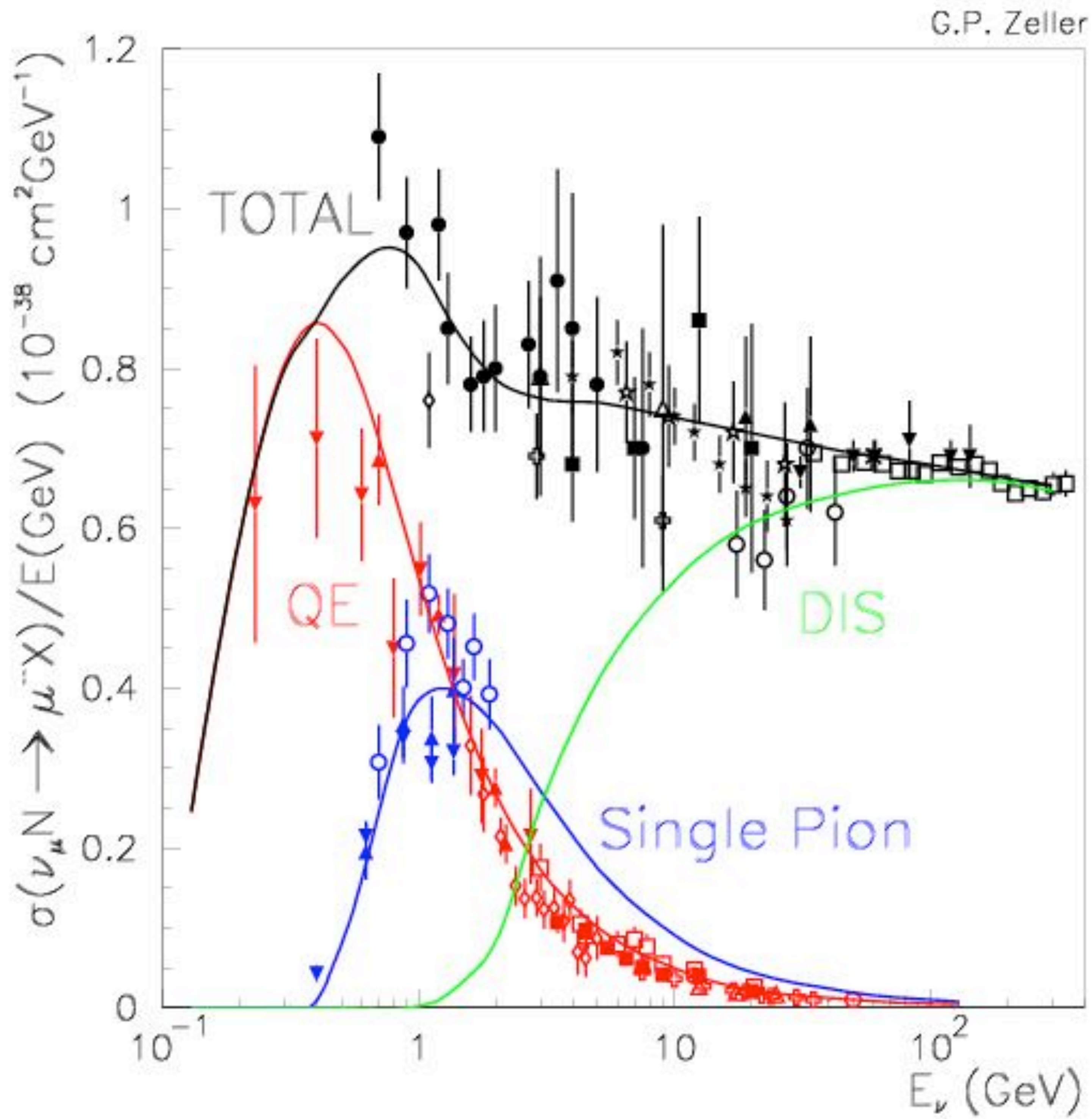
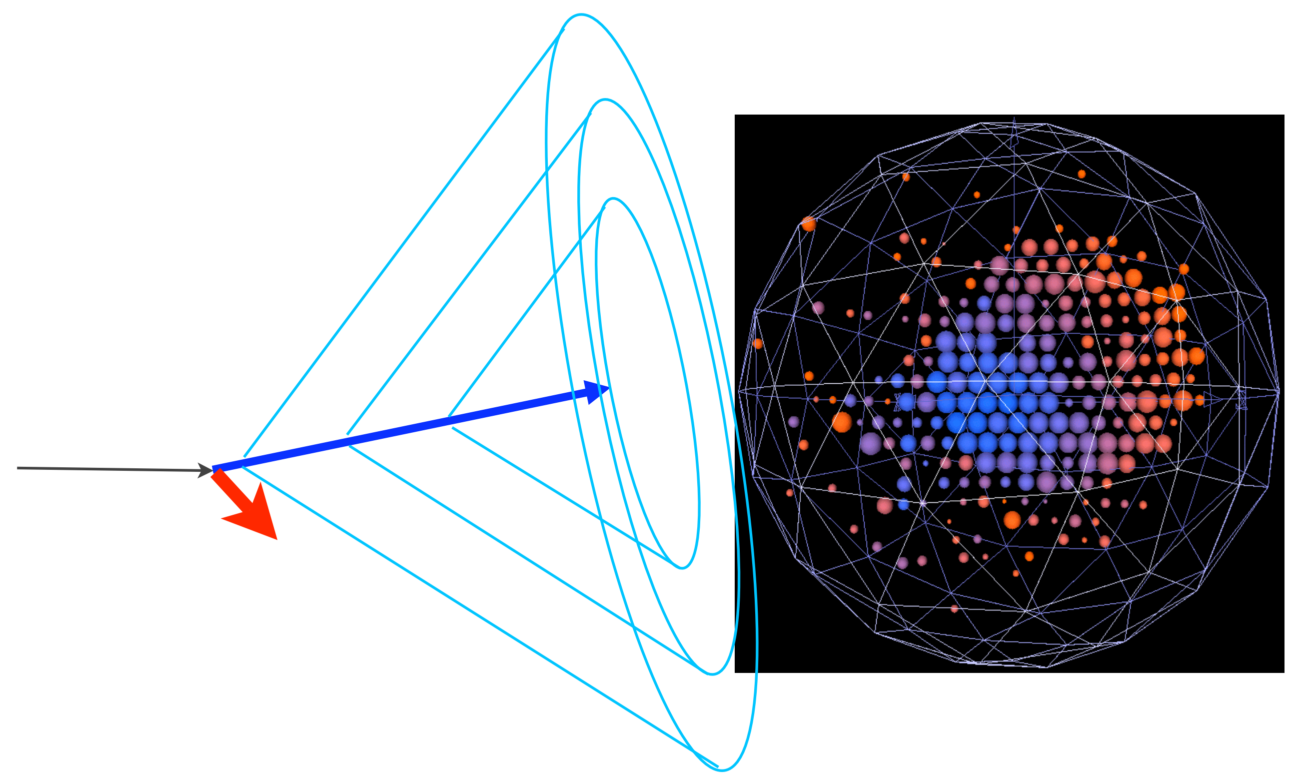


CCQE Intro

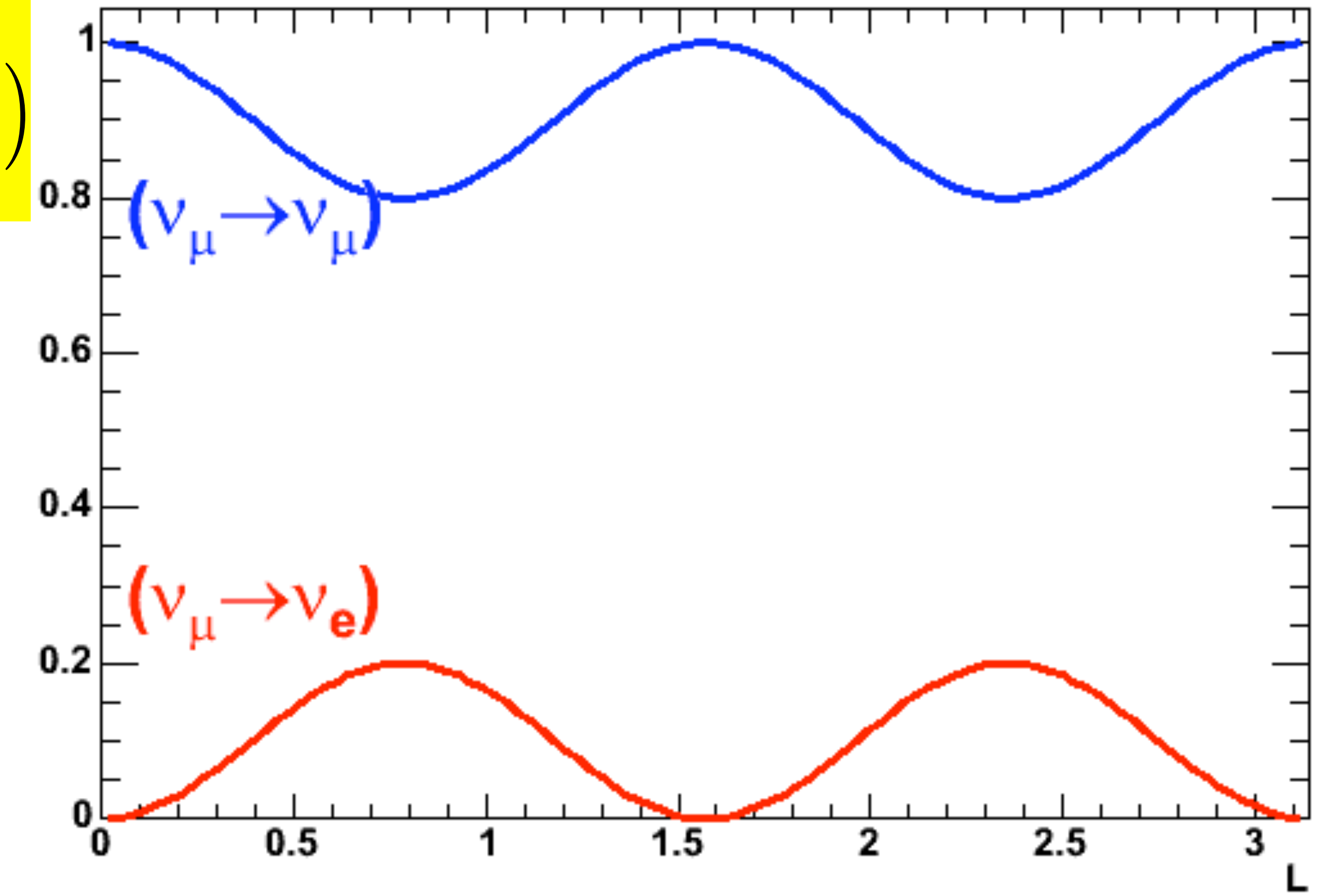
$$E_\nu^{QE} = \frac{1}{2}\frac{2M_pE_\mu - m_\mu^2}{M_p - E_\mu + \sqrt{(E_\mu^2 - m_\mu^2)}\cos\theta_\mu}$$

- Determine flux (in near detector)
- Reconstruct neutrino energy using outgoing lepton
- Energy reconstruction is important for neutrino oscillation measurements



$$P_{osc}(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$



- 2 fundamental parameters
  - $\Delta m^2 \leftrightarrow$ period
  - $\theta_{12} \leftrightarrow$ magnitude
- 2 experimental parameters
  - L = distance travelled
  - E = neutrino energy
- Choose L&E to target ranges of Δm^2 and θ
- Neutrinos disappear and appear

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{12}\frac{L}{E})$$

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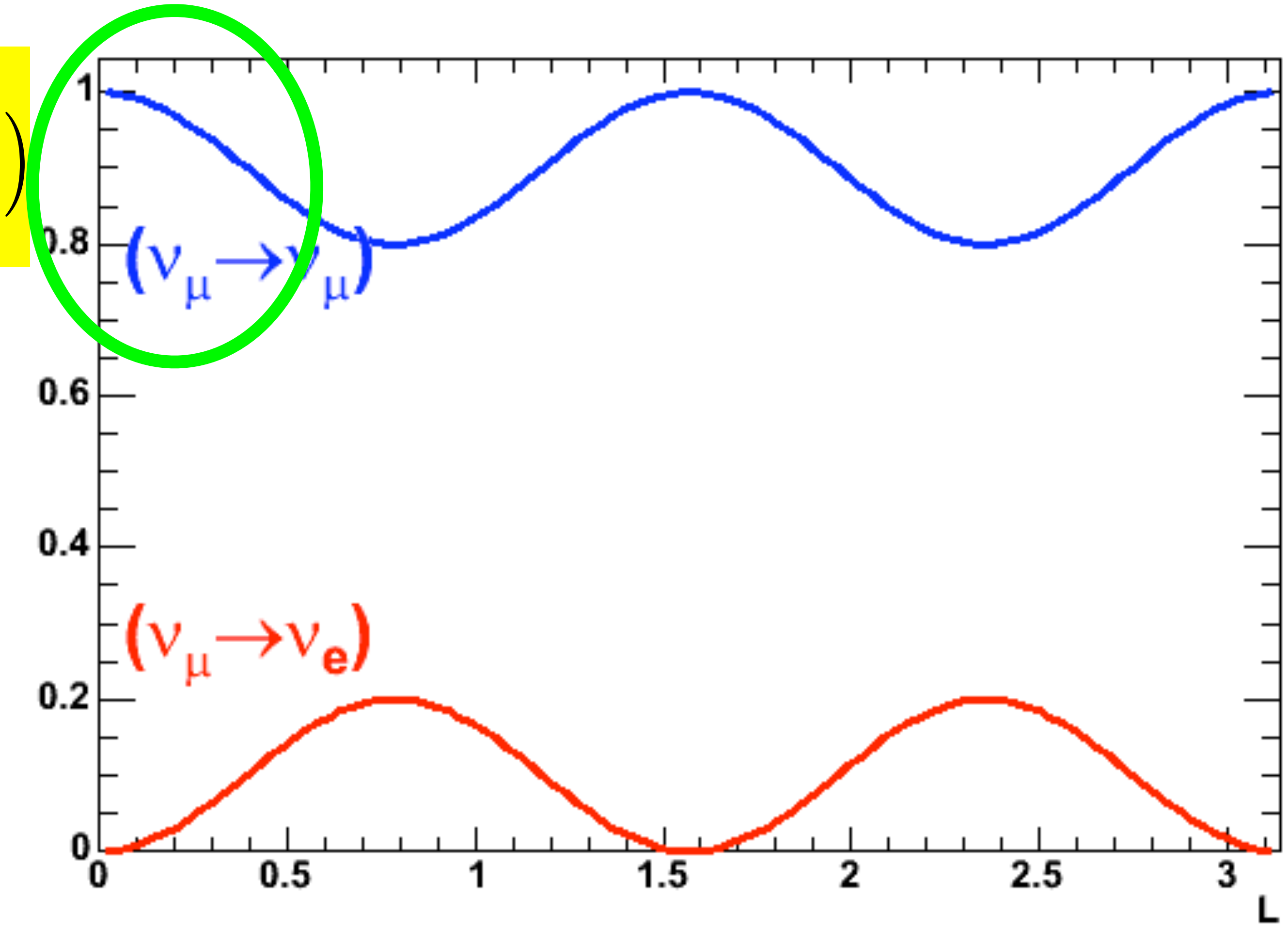

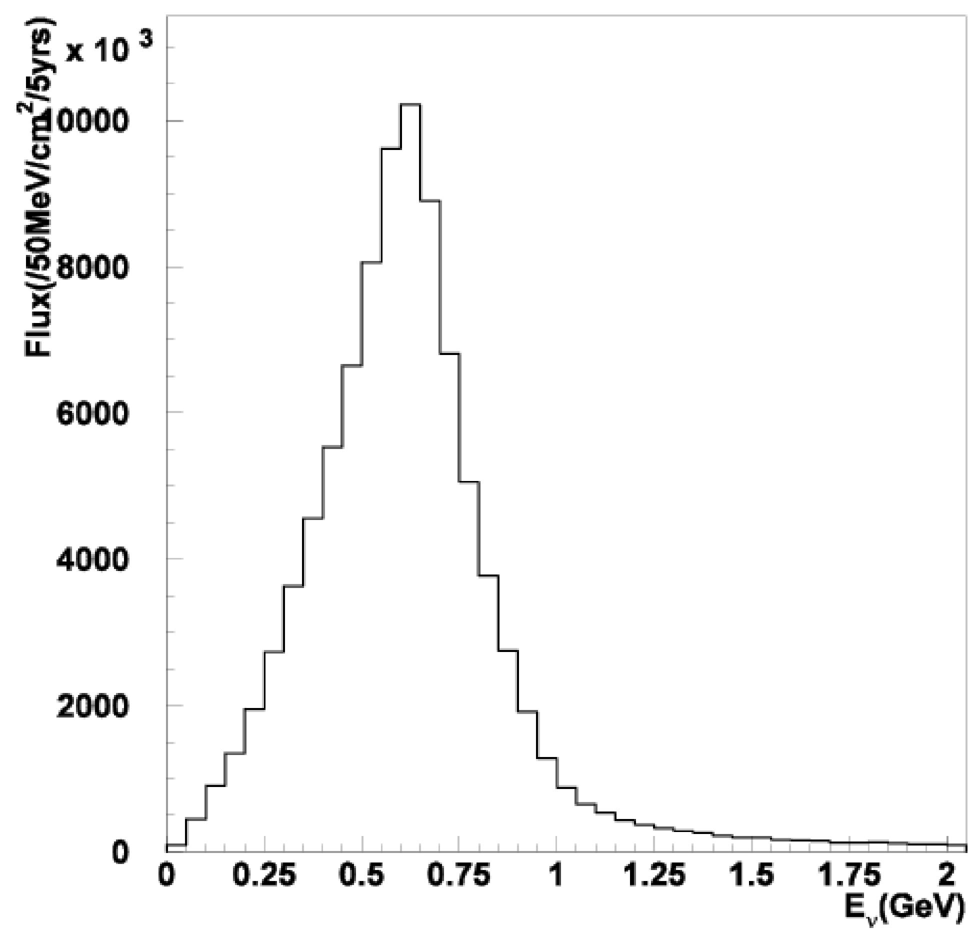

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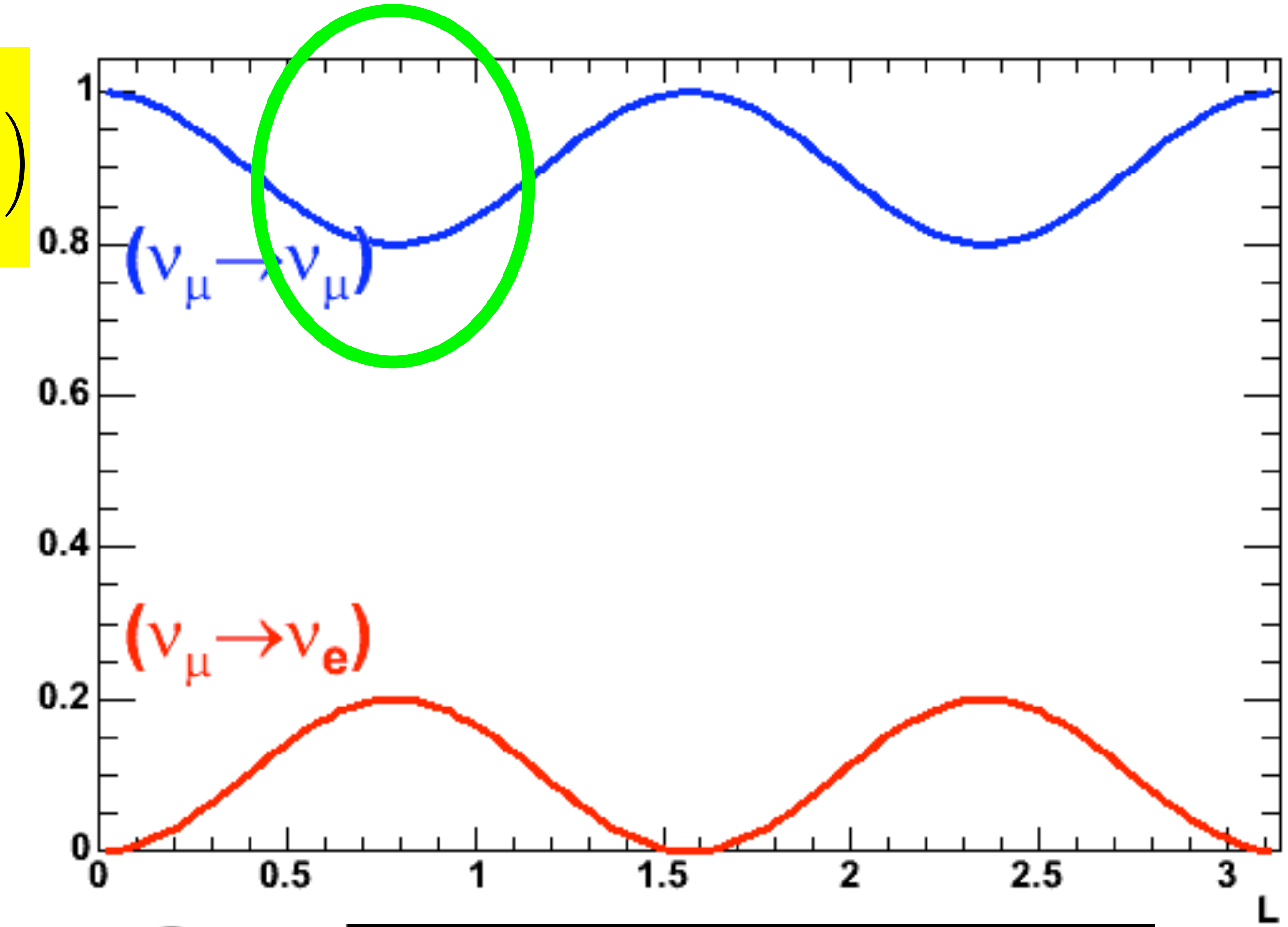

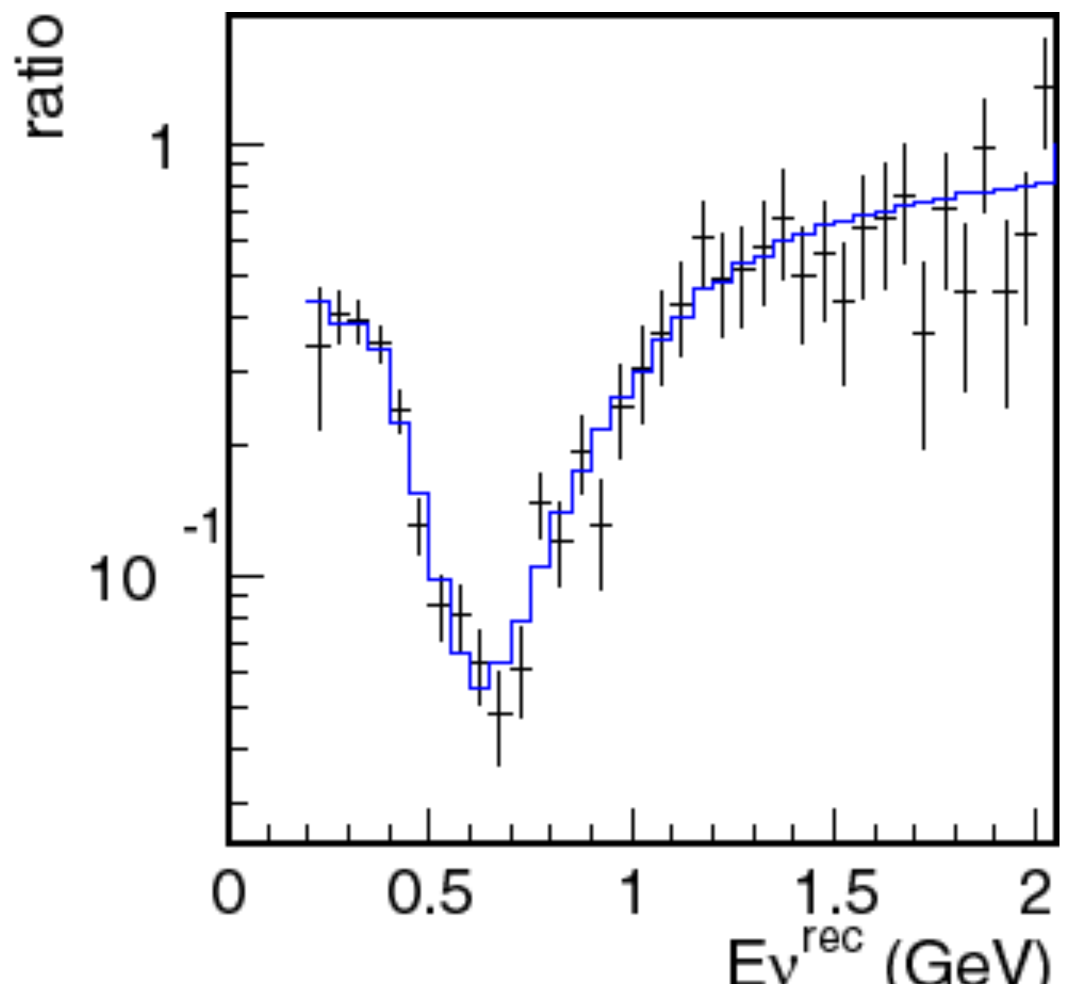

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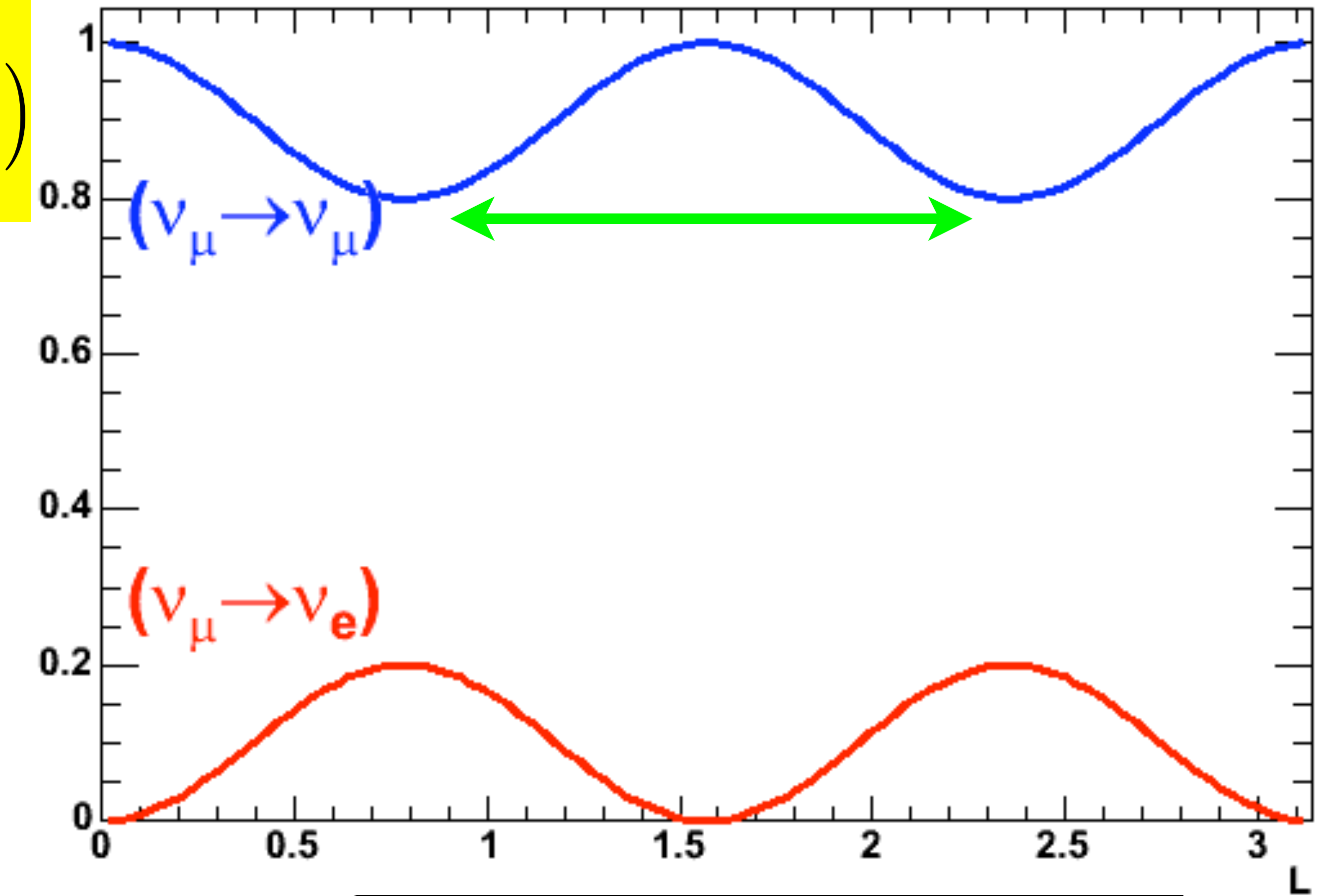

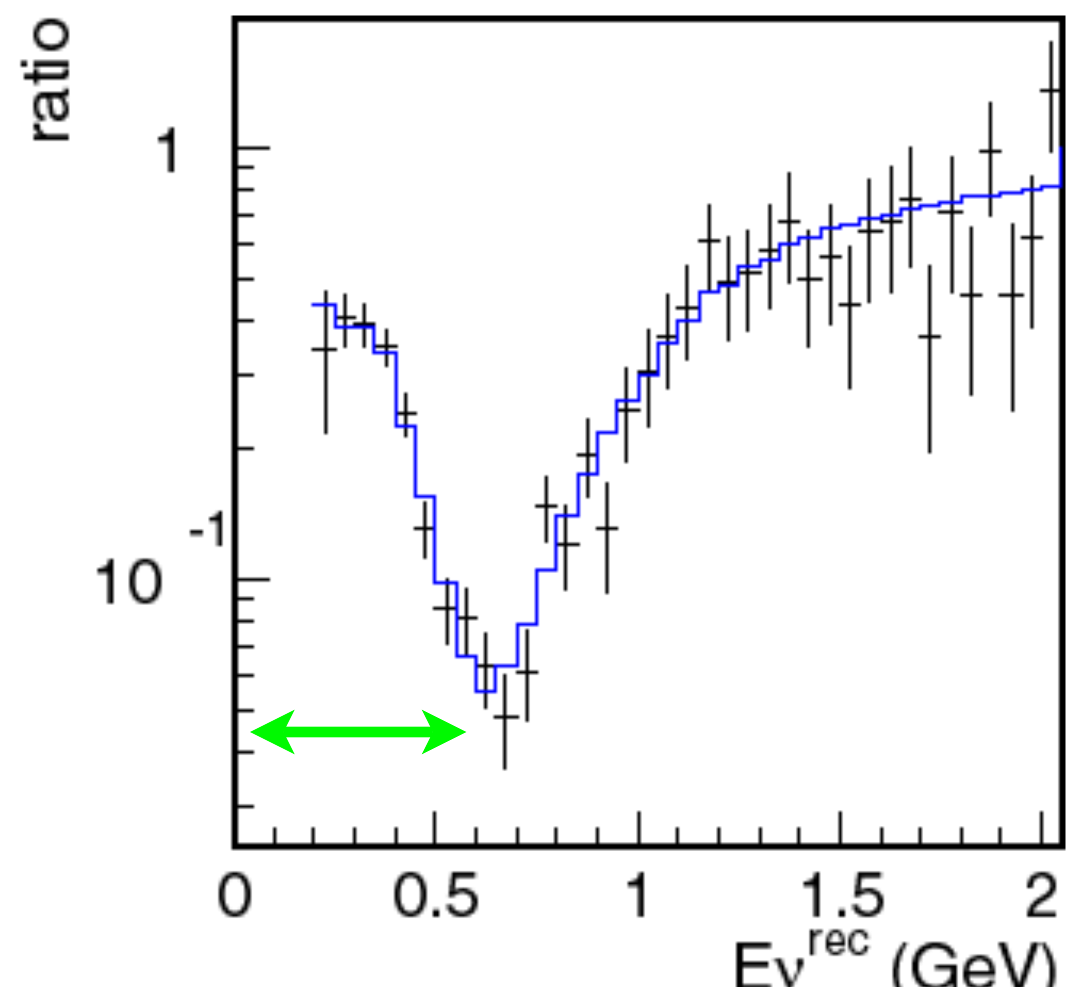

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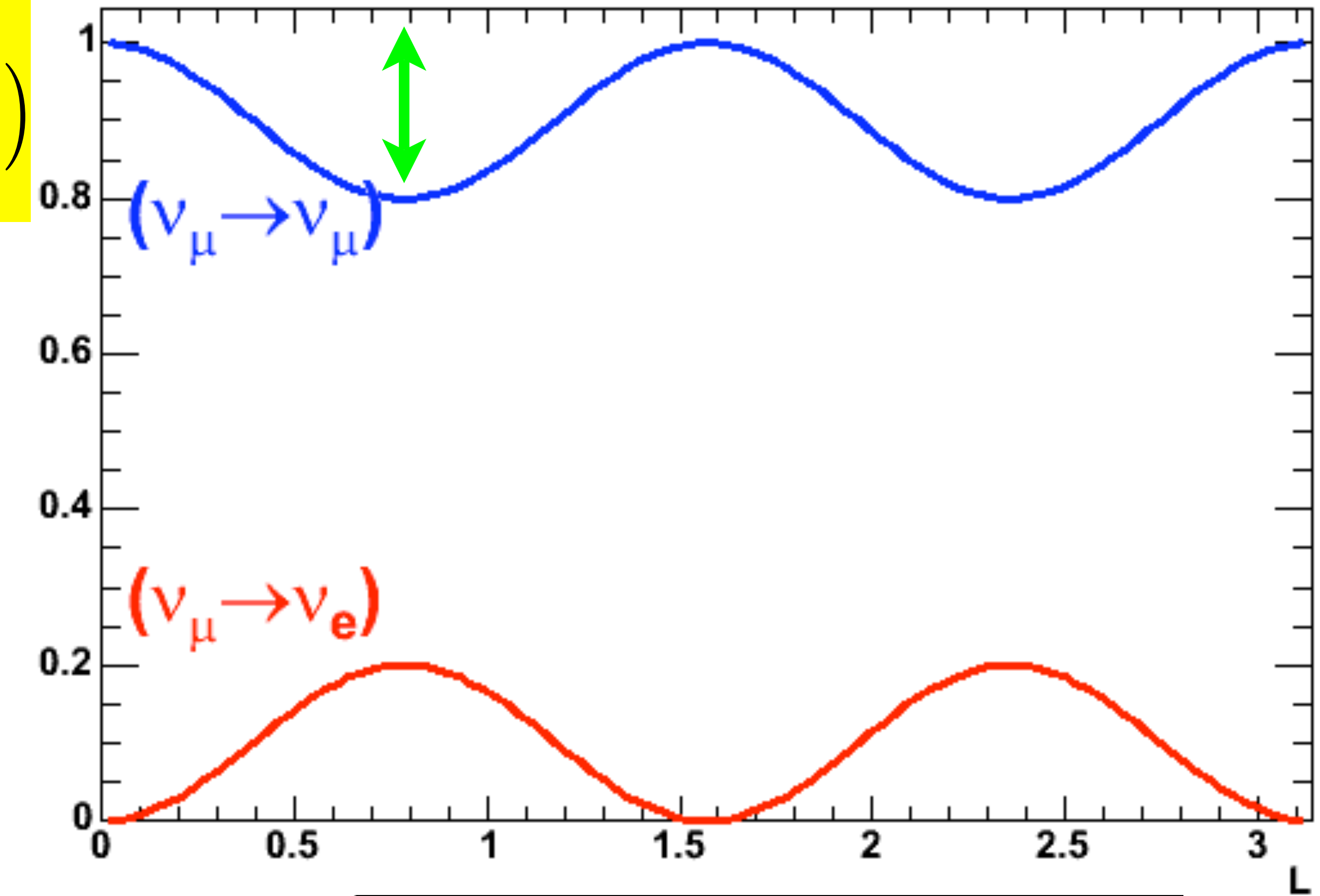

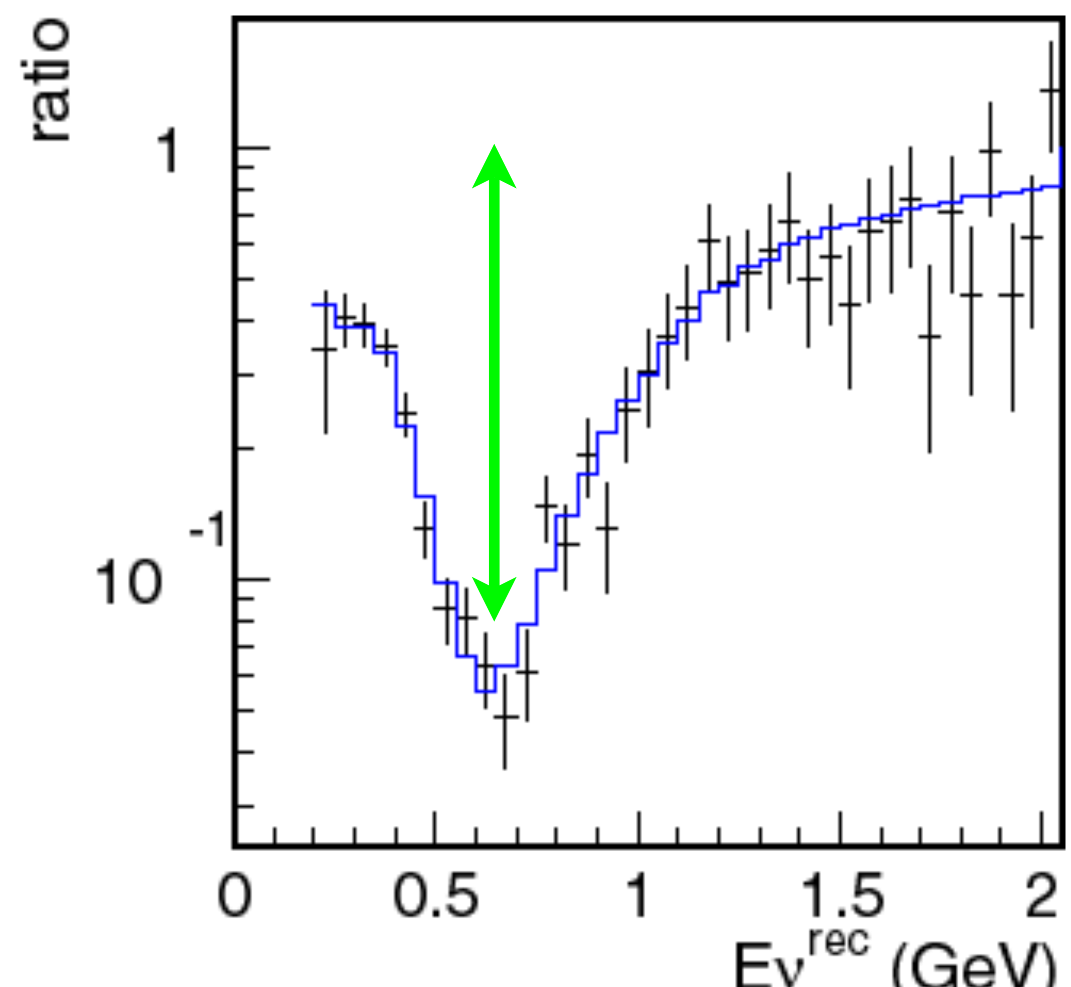

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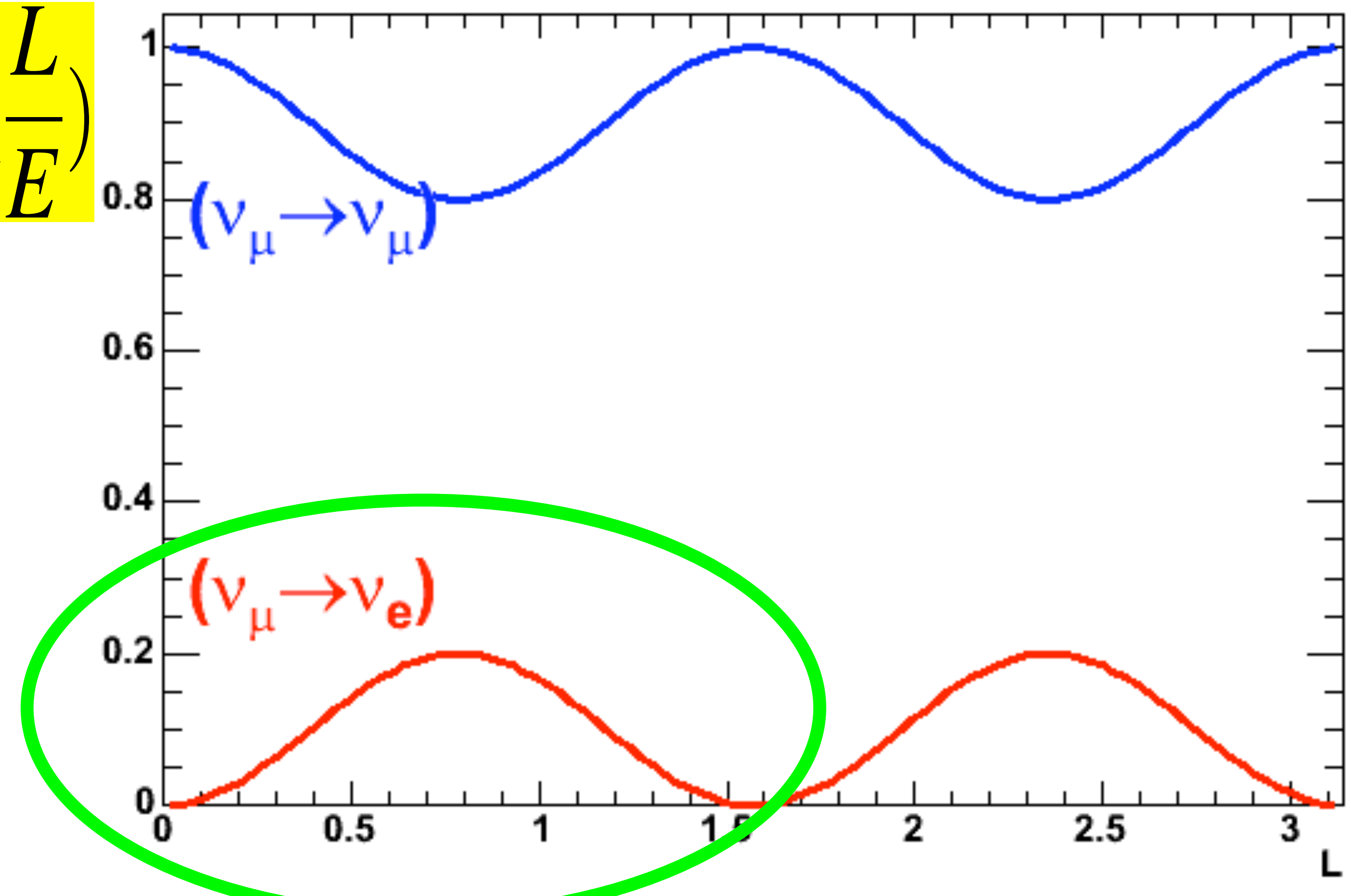
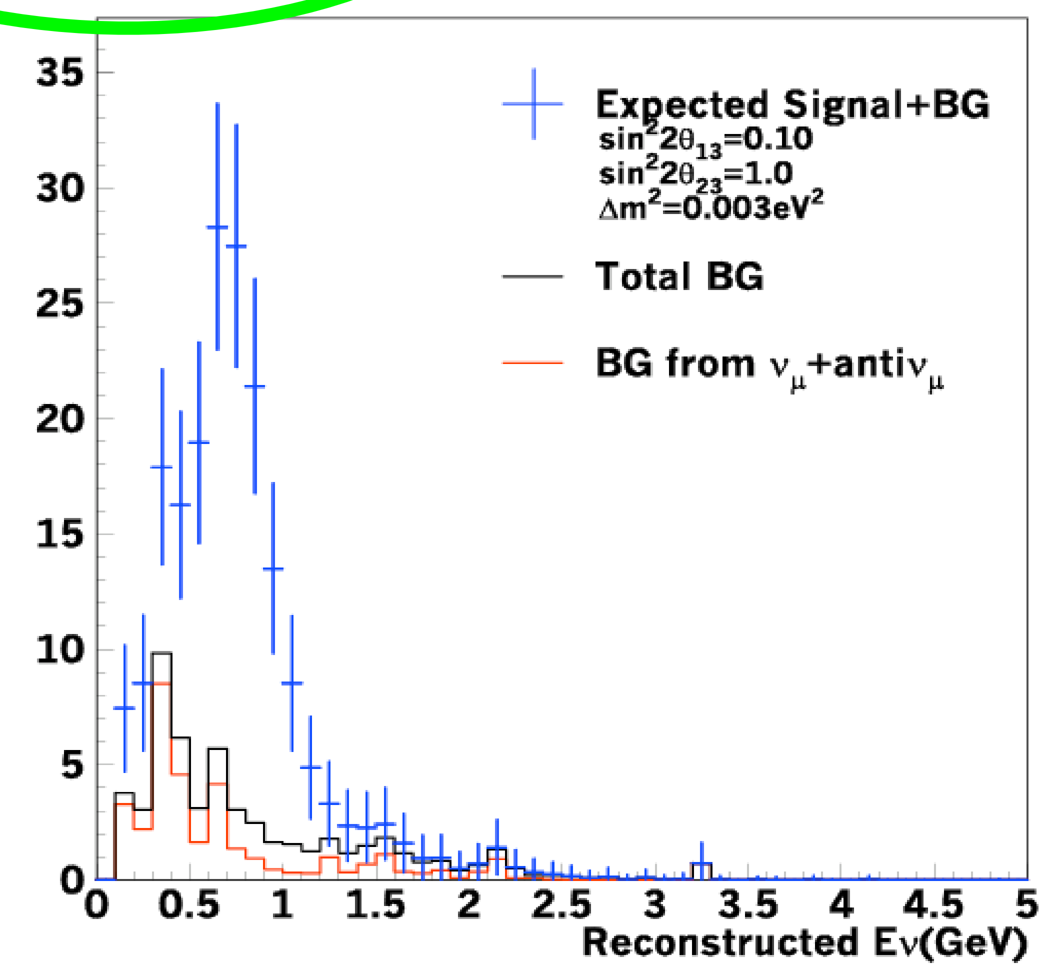
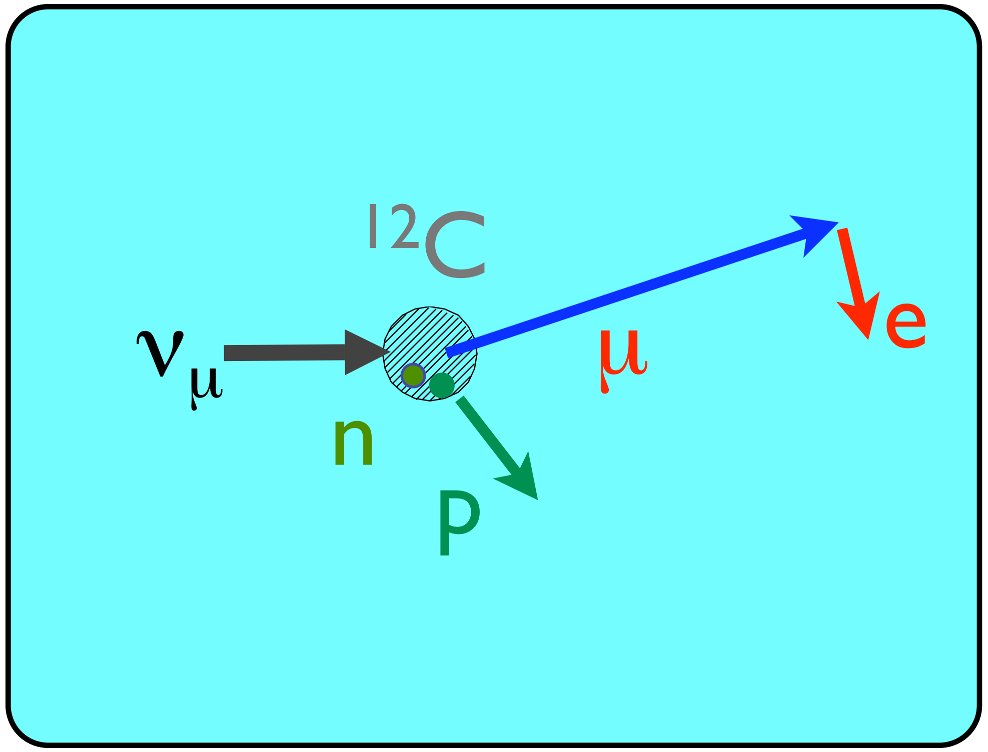




CCQE Topology

- Final state particles in detector:
  - Outgoing lepton
    - Key to measurement
    - Muons can be tagged with penetration, PID or decay electron
  - Recoil nucleon
    - Usually below Cherenkov threshold
  - Recoil nucleus
    - Effectively invisible



Main background comes from CC1π+ with unobserved pion

Axial Form Factor

- Recall CCQE cross section written in Llellwyn Smith formalism:

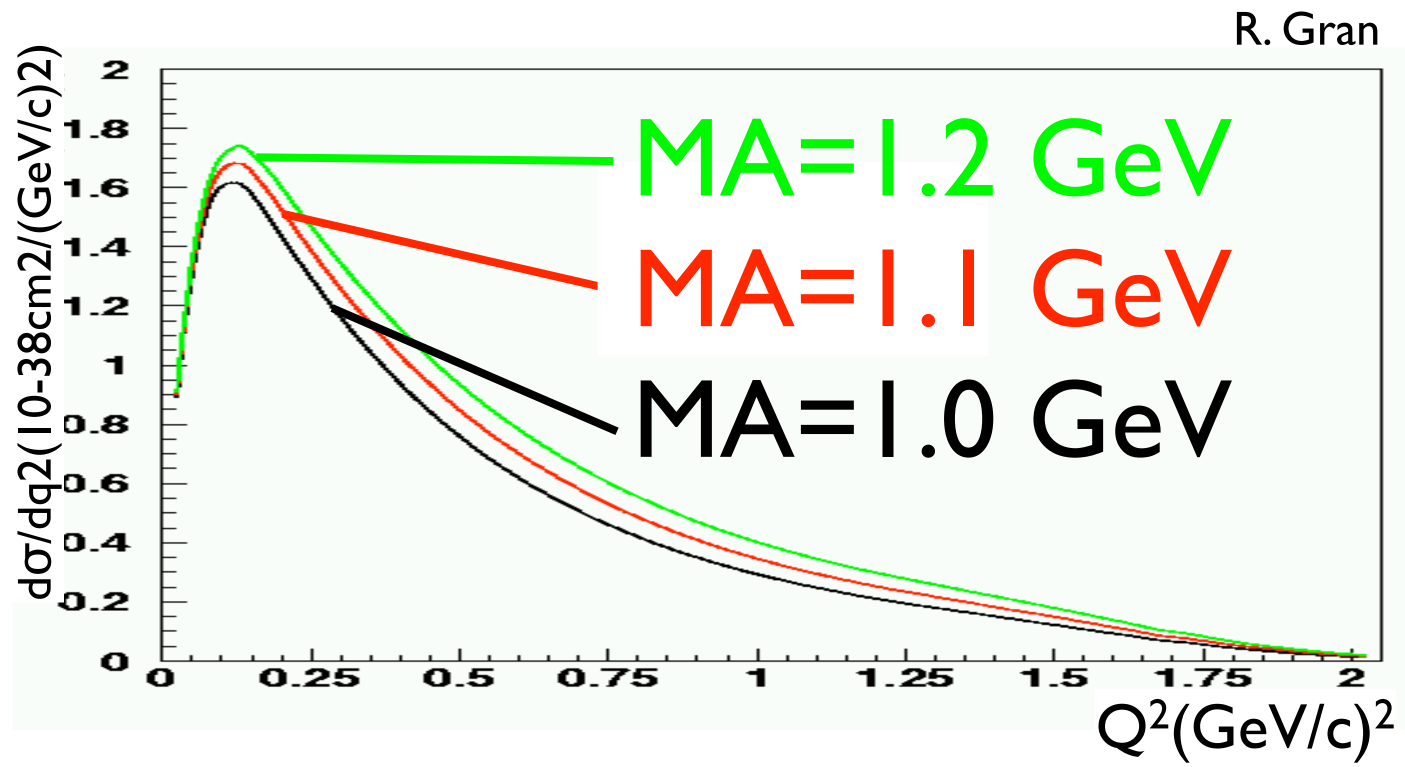
$$< N'|J_\mu|N > \; = \; \overline{u}(N')\left[\gamma_\mu F_V^1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu \xi F_V^2(q^2)}{2M} + \gamma_5\gamma_\mu F_A(q^2)\right] u(N)$$

- Axial form factor usually parameterized as a dipole function:

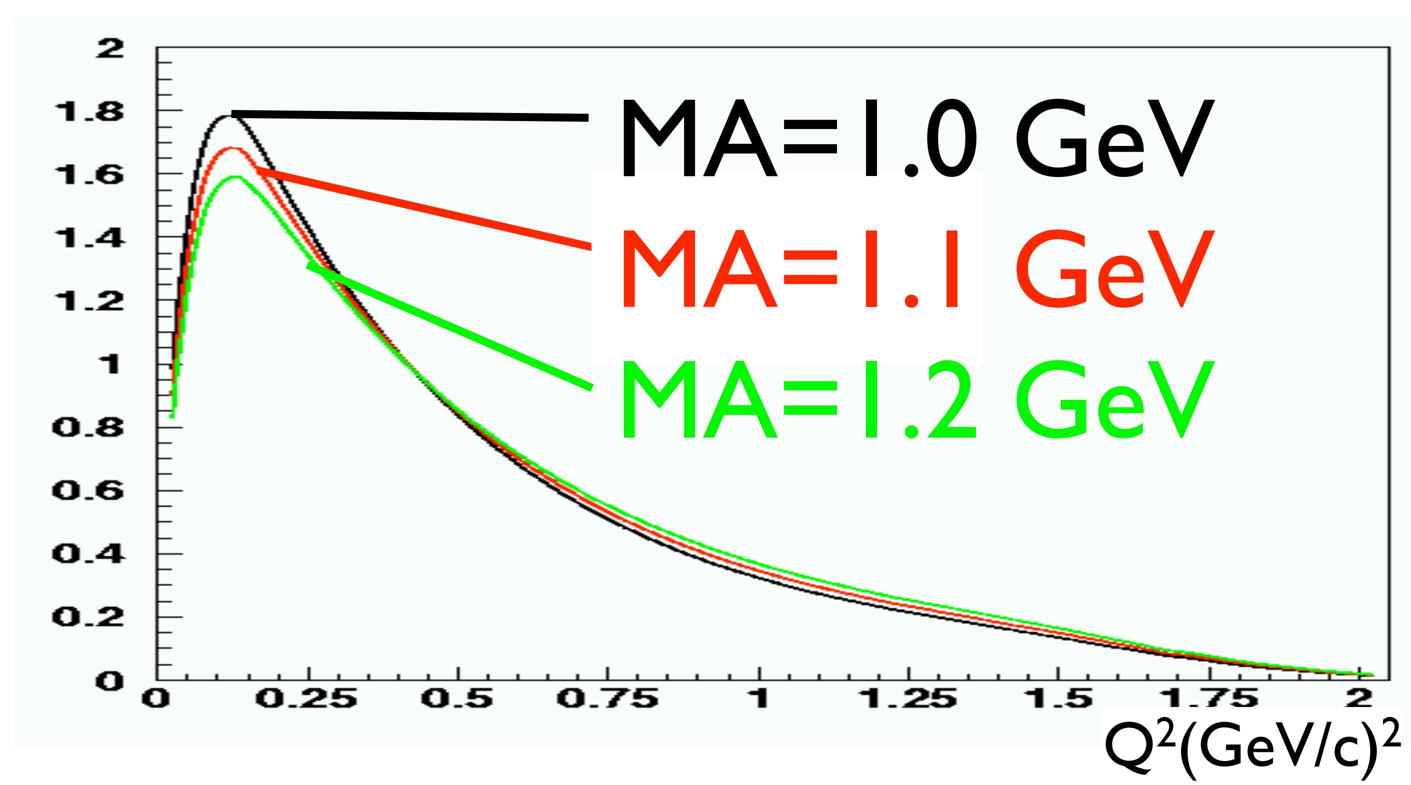
$$F_A(Q^2) = \frac{g_A}{(1+Q^2/M_A{}^2)^2}$$

Importance of M_A

Absolute Cross-section (includes normalization)



Shape only



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Basic Data Reduction

Raw Data Sample

Timing and fiducial volume cuts ↓

Neutrino Data Sample

Number of muons ↓

Charged, Neutral Current

Number of tracks ↓

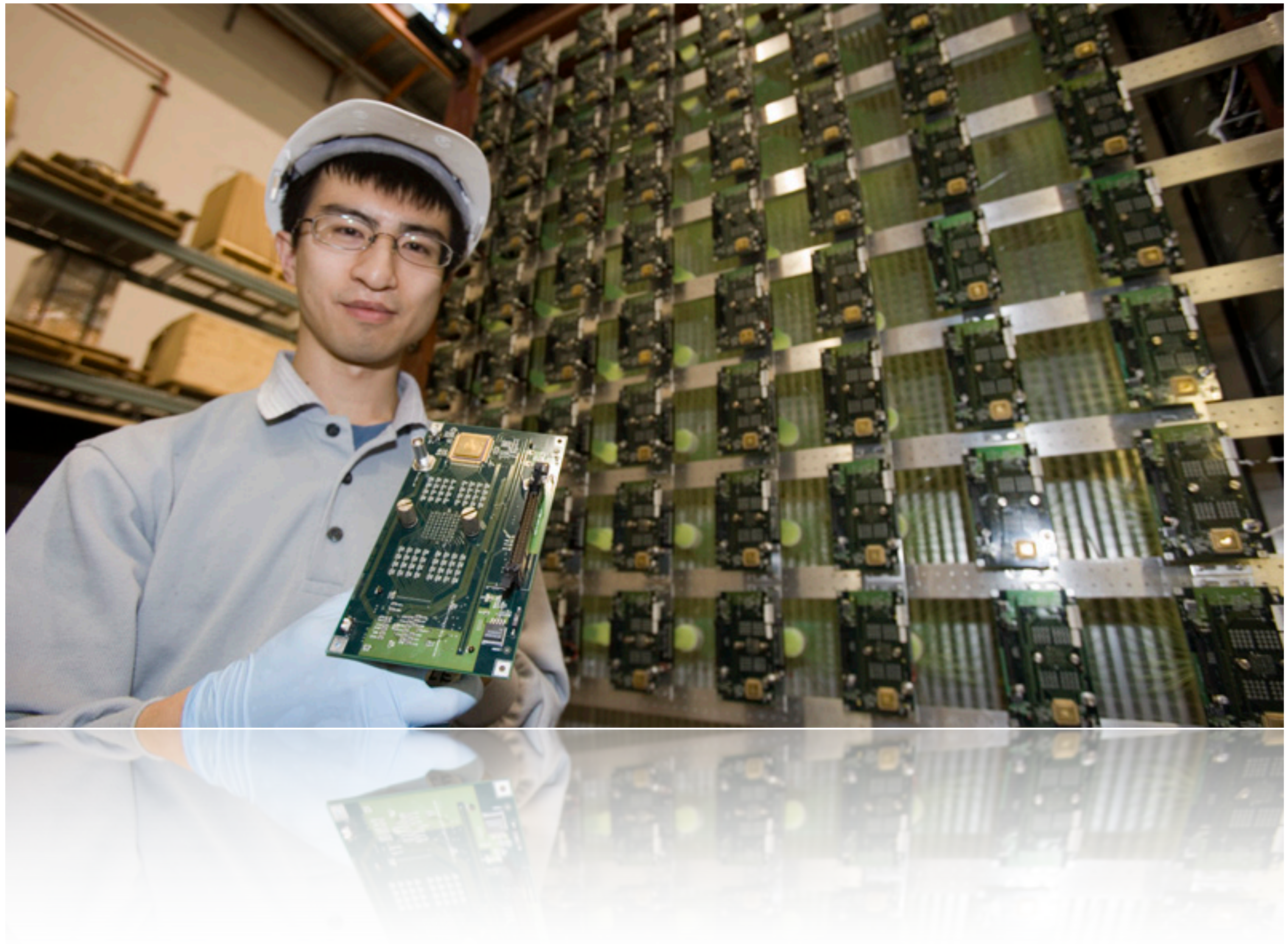
1,2, multi tracks

Particle identification ↓

MIP, shower, proton

Energy deposit around the vertex ↓

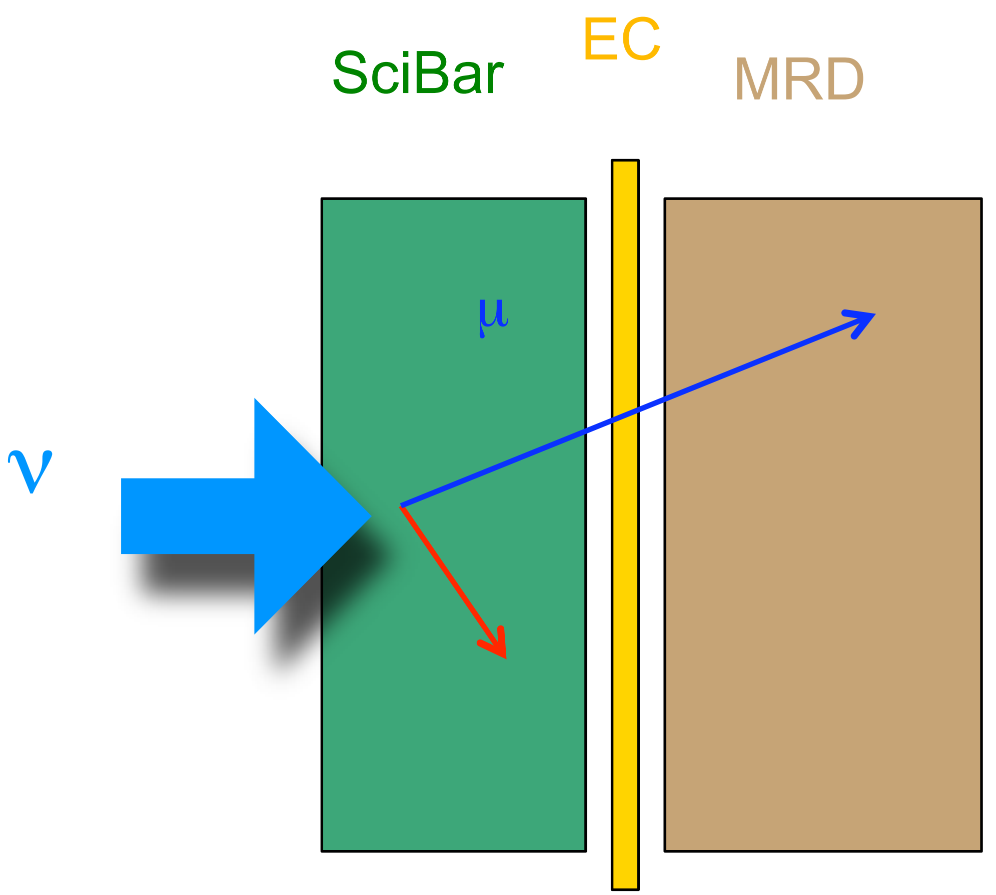
untracked particles?

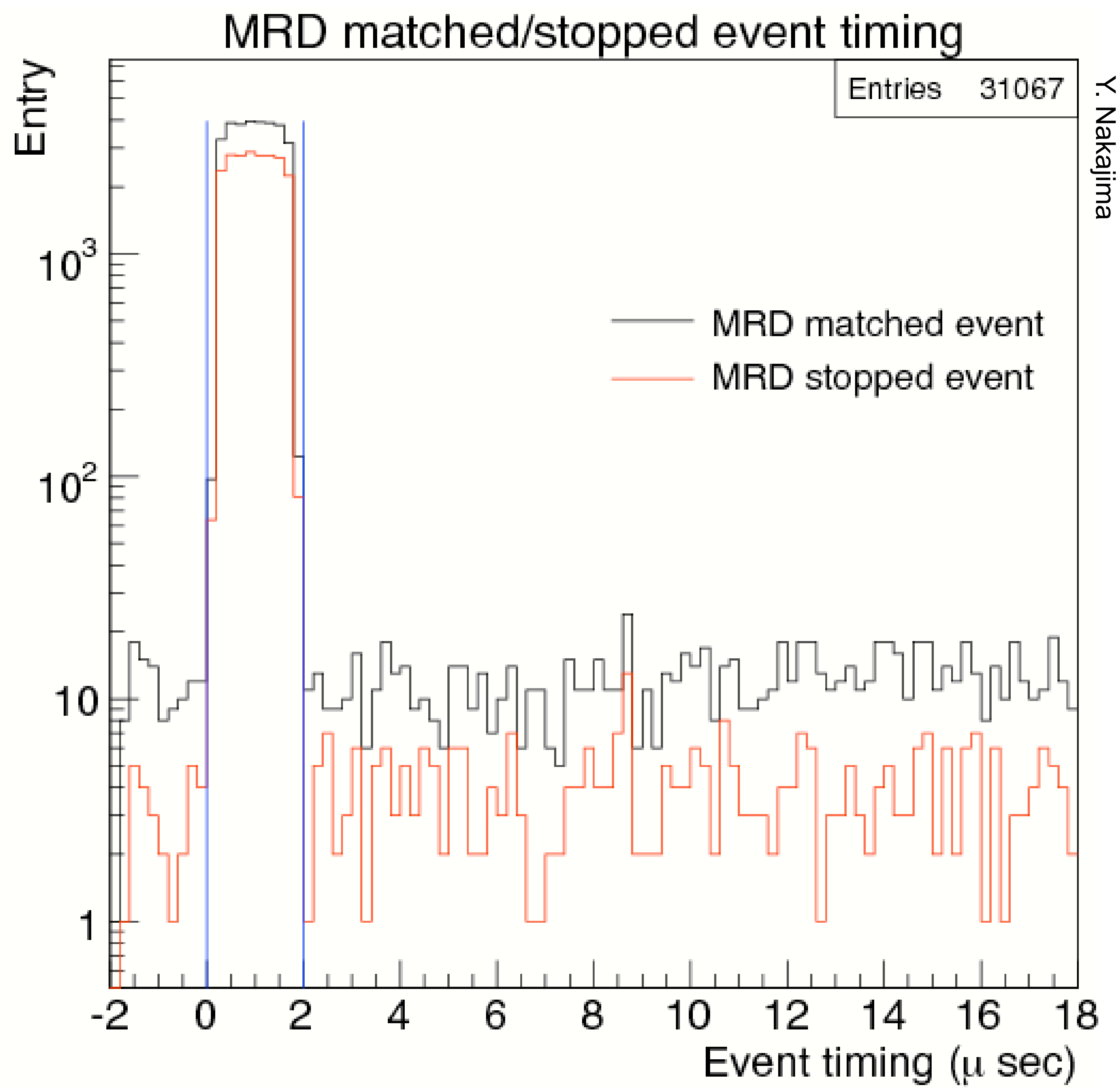


SciBooNE CCQE

CC Inclusive

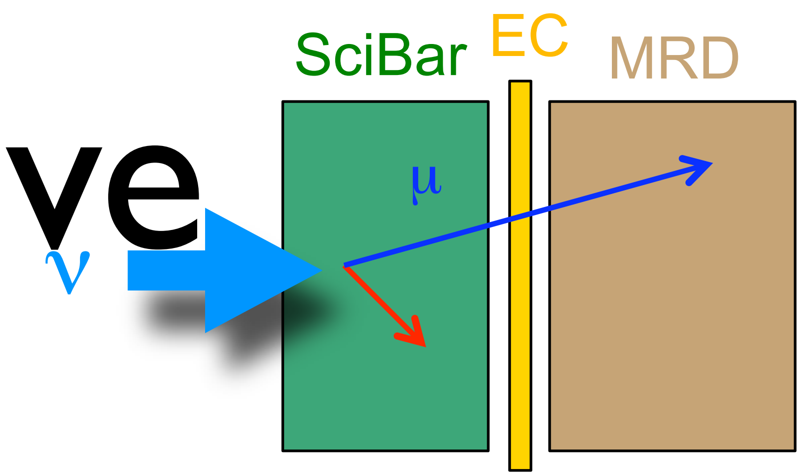
- μ's easily identified if penetrate MRD
- 96% pure CC
- 21,431 stopped ν events





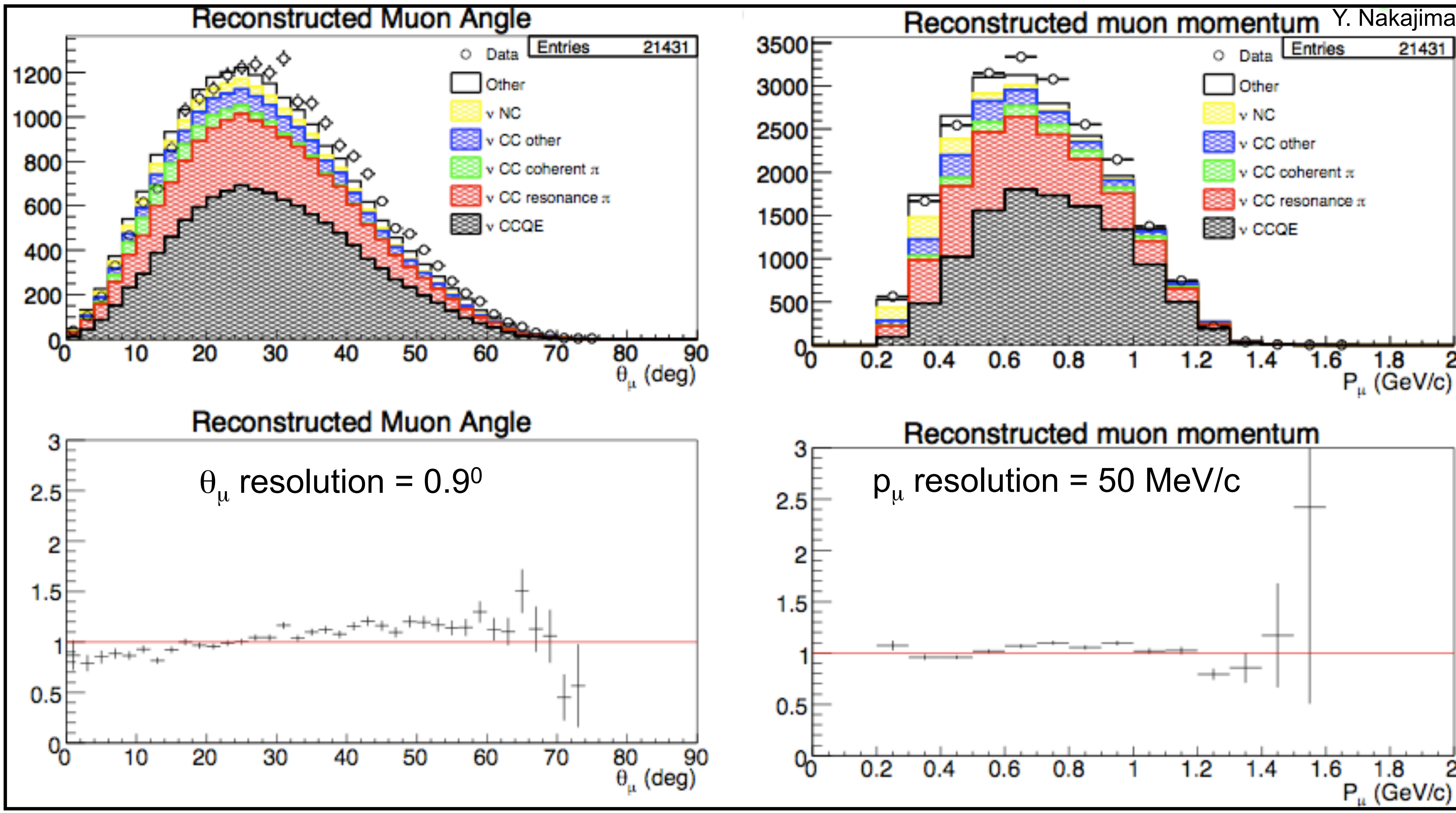
- *Normalisation set by*
- *MRD-matched events*

CC Inclusive



MRD stopped events

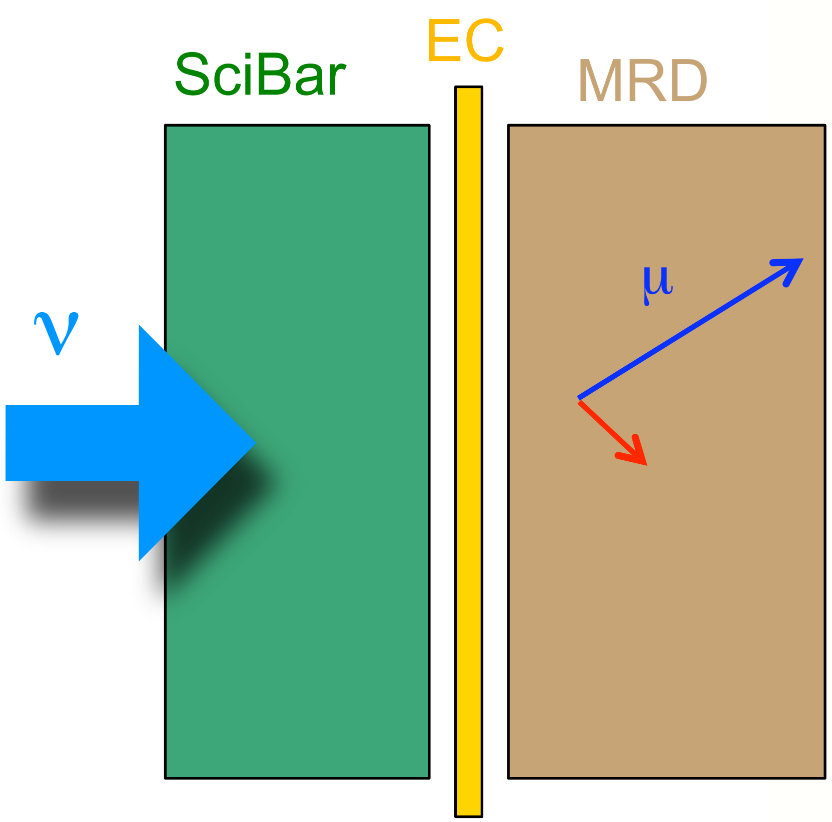
Normalised to MRD matched events

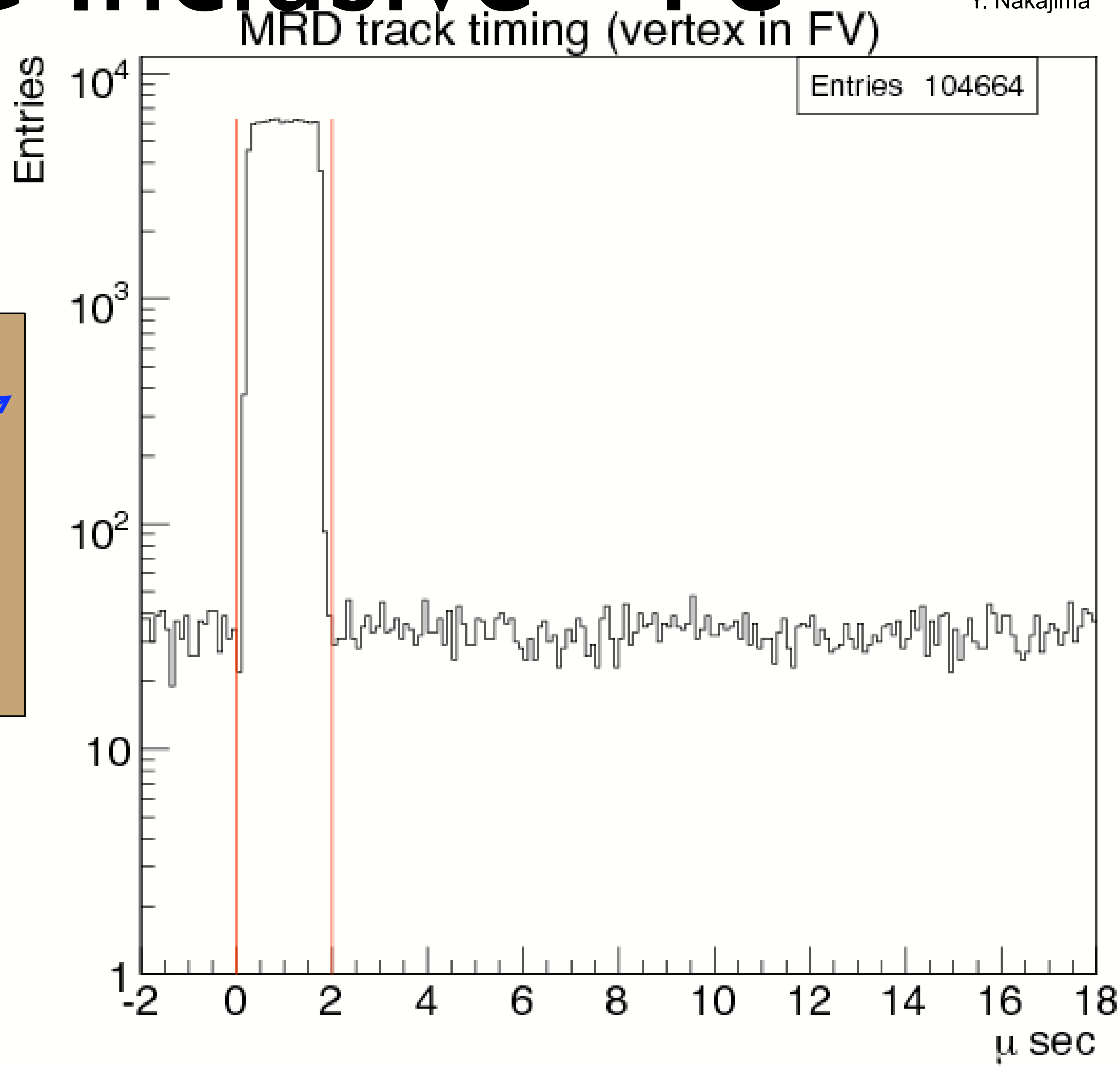


Angular discrepancy is not detector effect →physics?

CC Inclusive - Fe

Y. Nakajima





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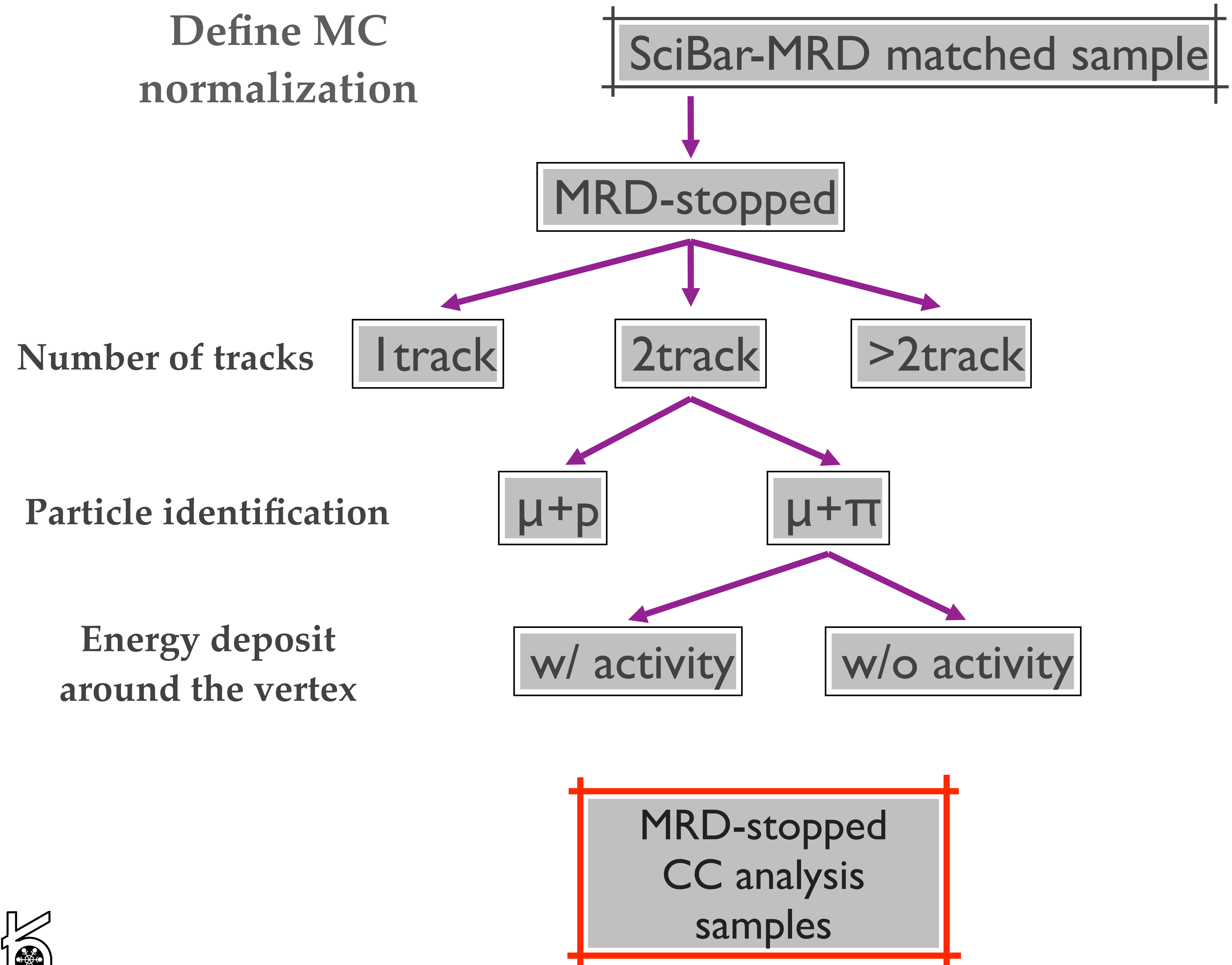
CC event classification



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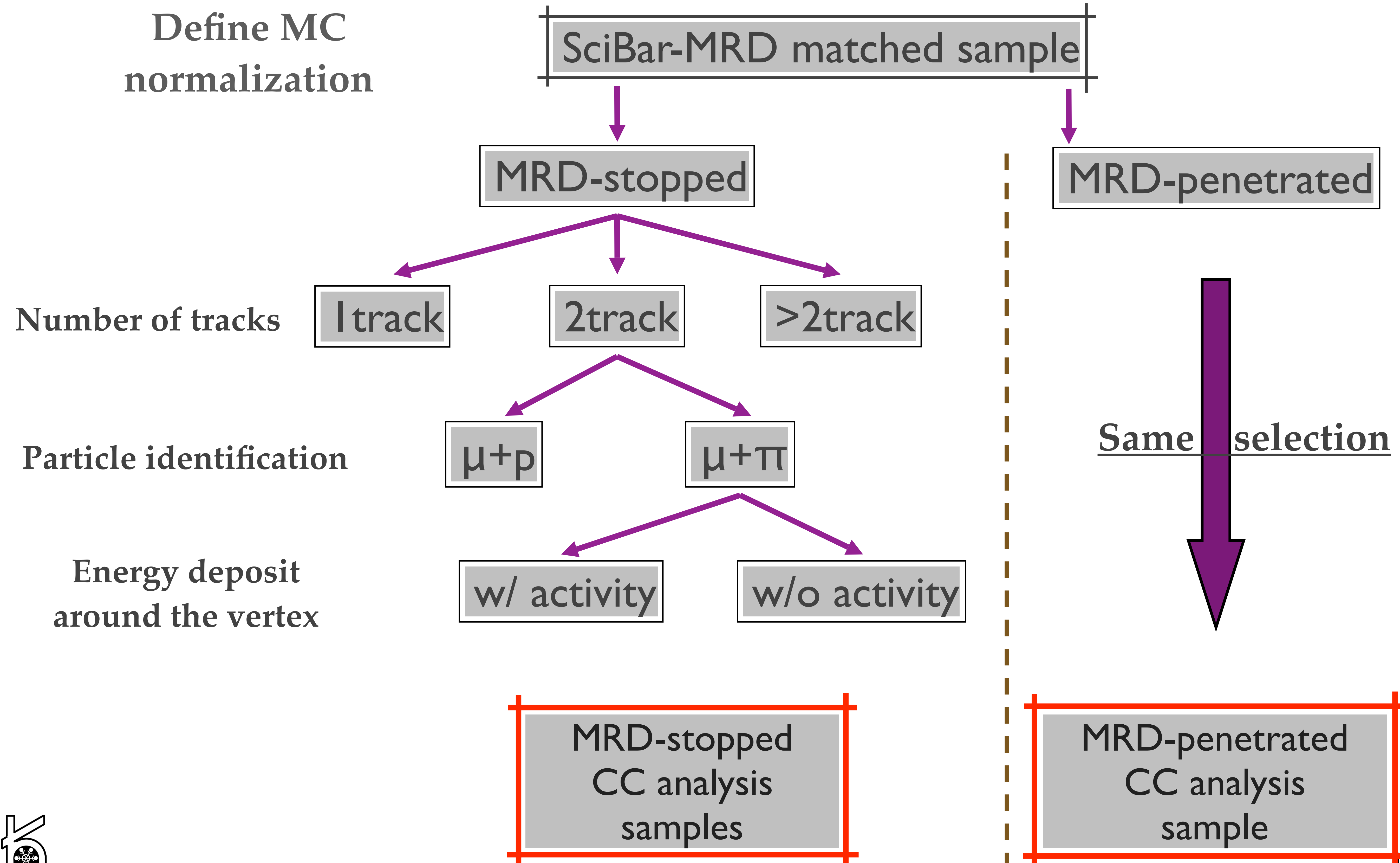
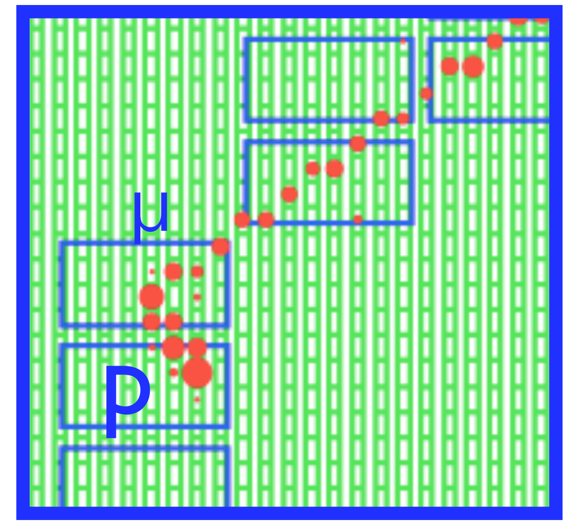
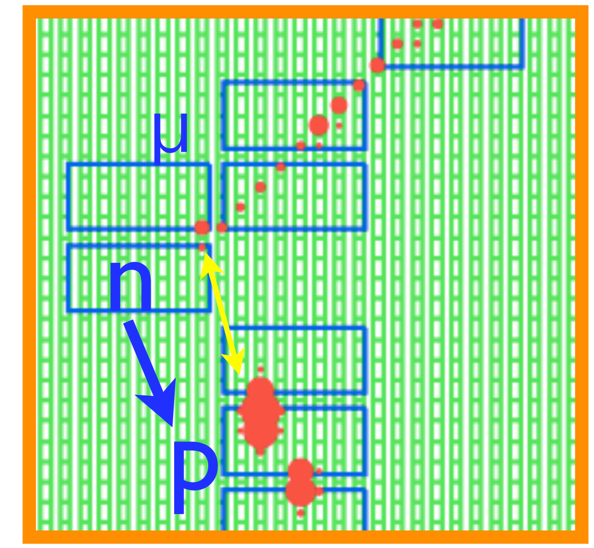
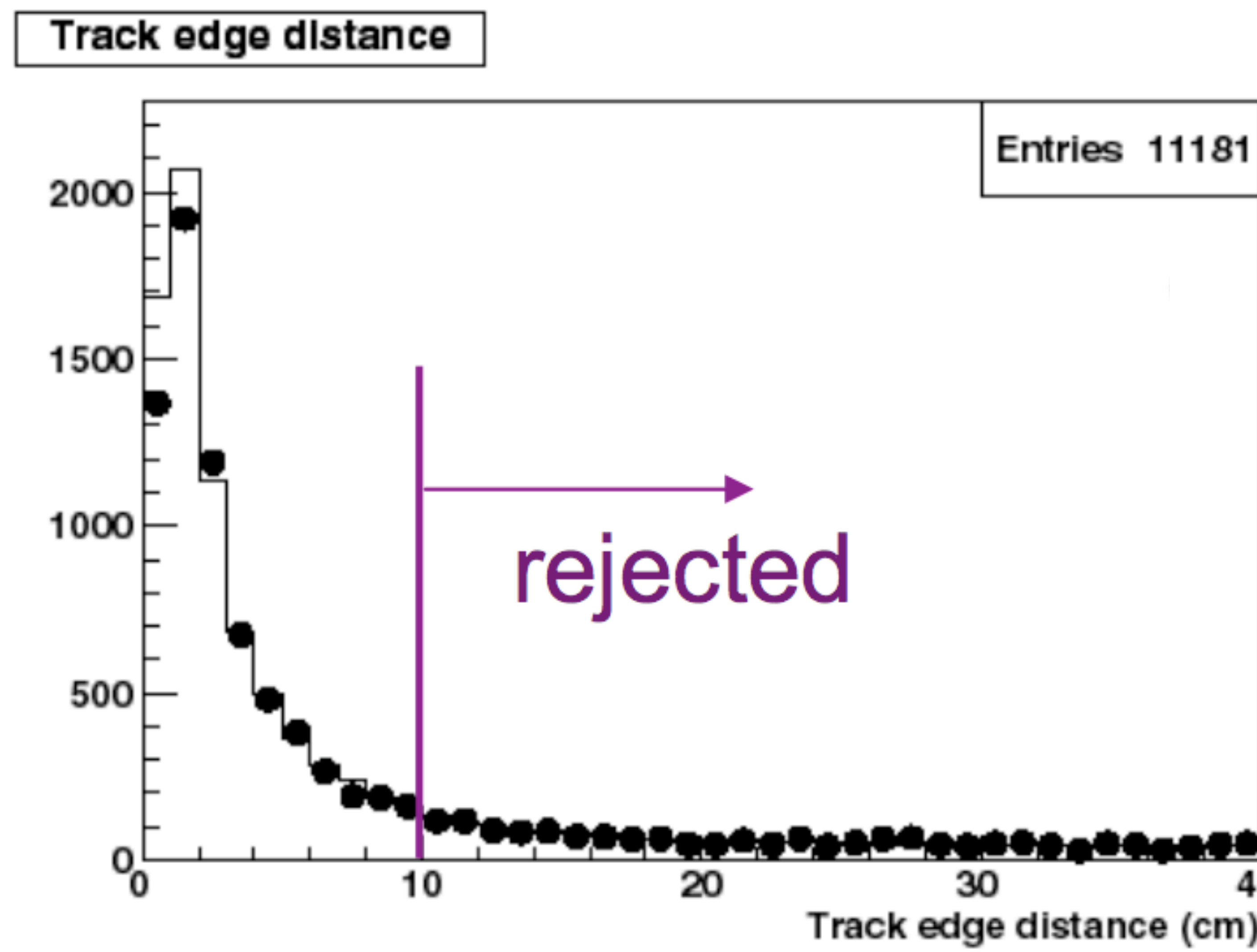


SciBar Cuts





- Additional track parameters used to distinguish interaction signatures
  - Vertex separation
  - 2nd track angle
    - $\Delta\theta_p$



SciBar Cuts

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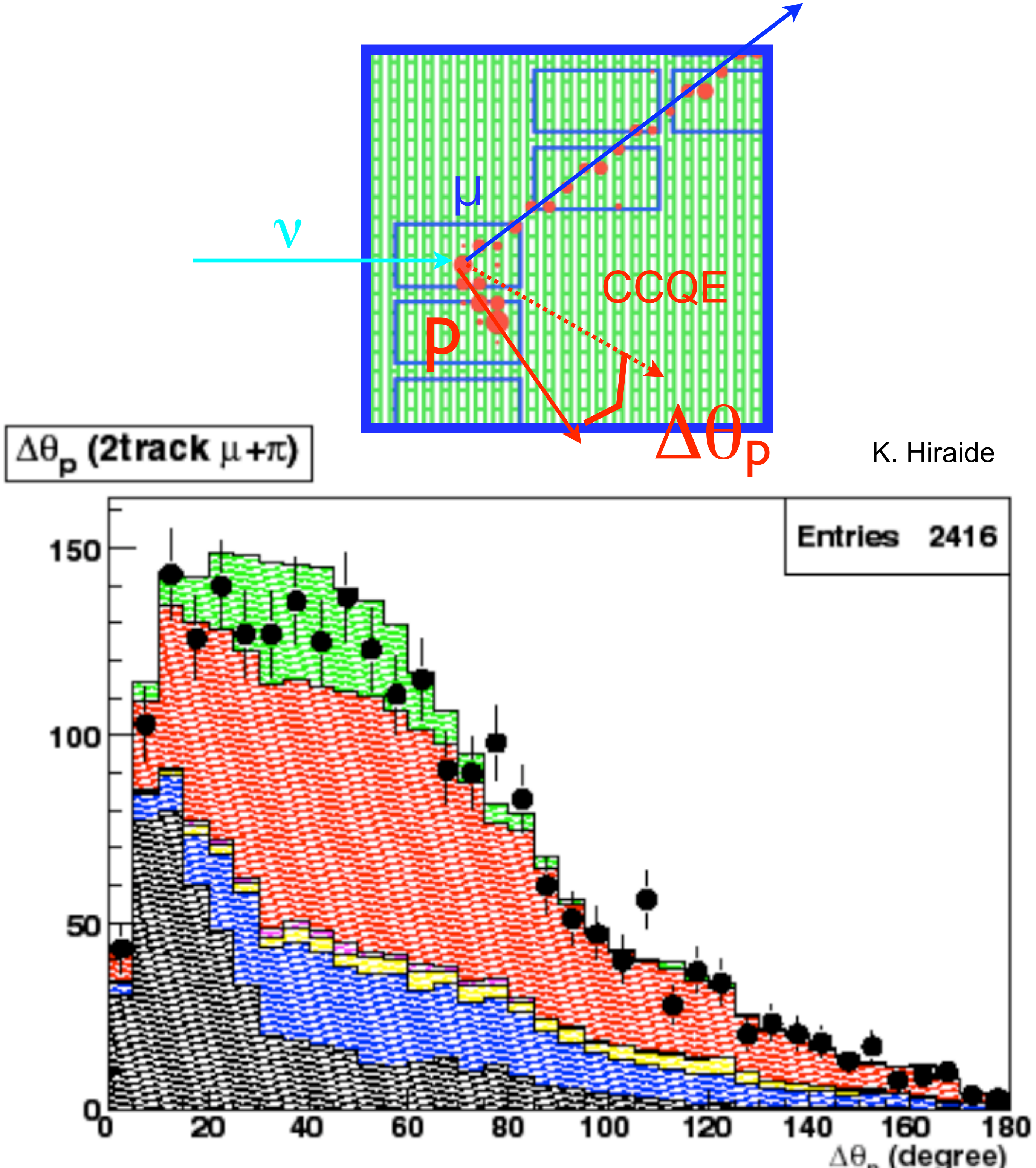
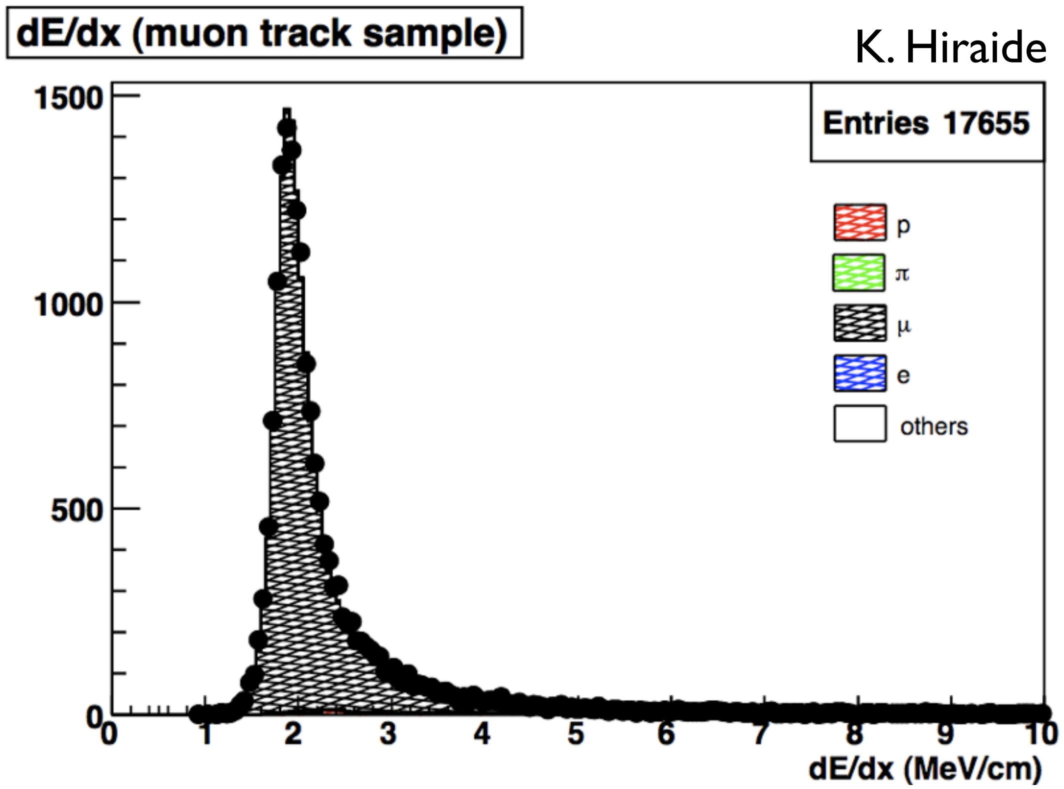
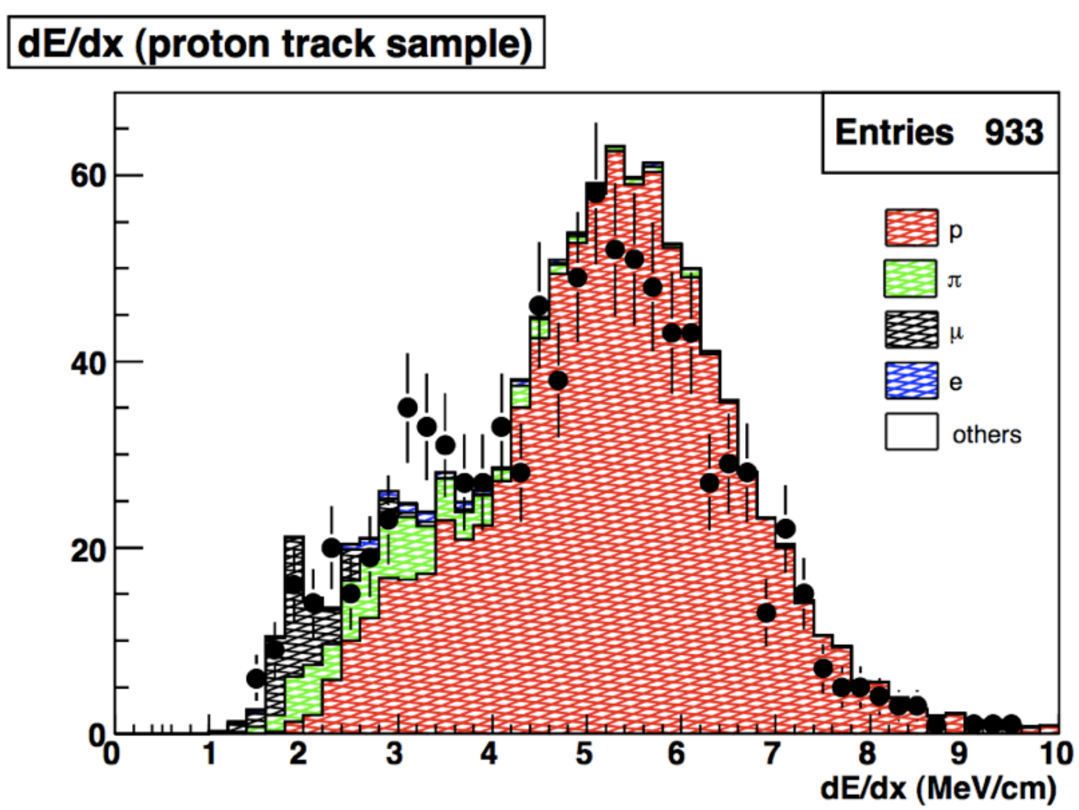
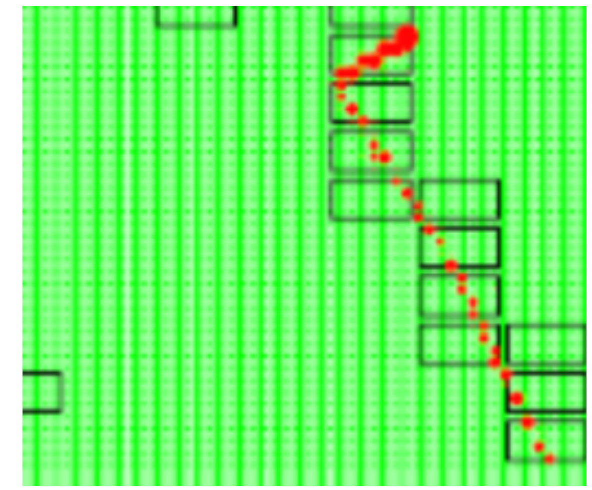


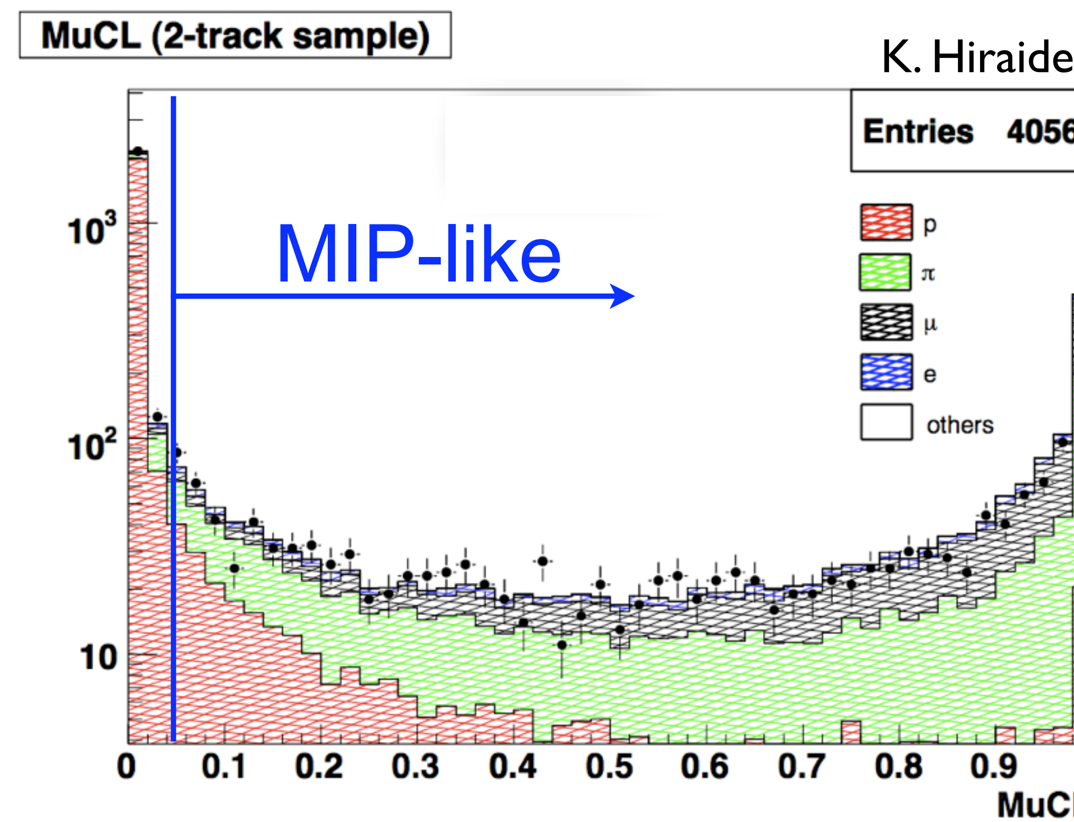
SciBar PID





Energy deposit used as PID





Cut at MuCL>0.05 for 2nd tracks:
84% π+ efficiency
~90% p rejection

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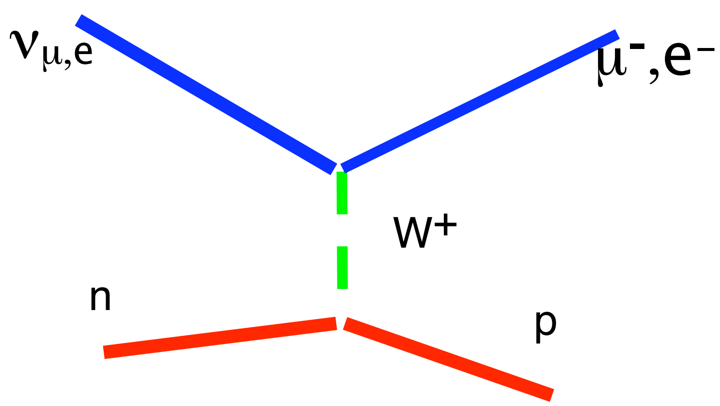
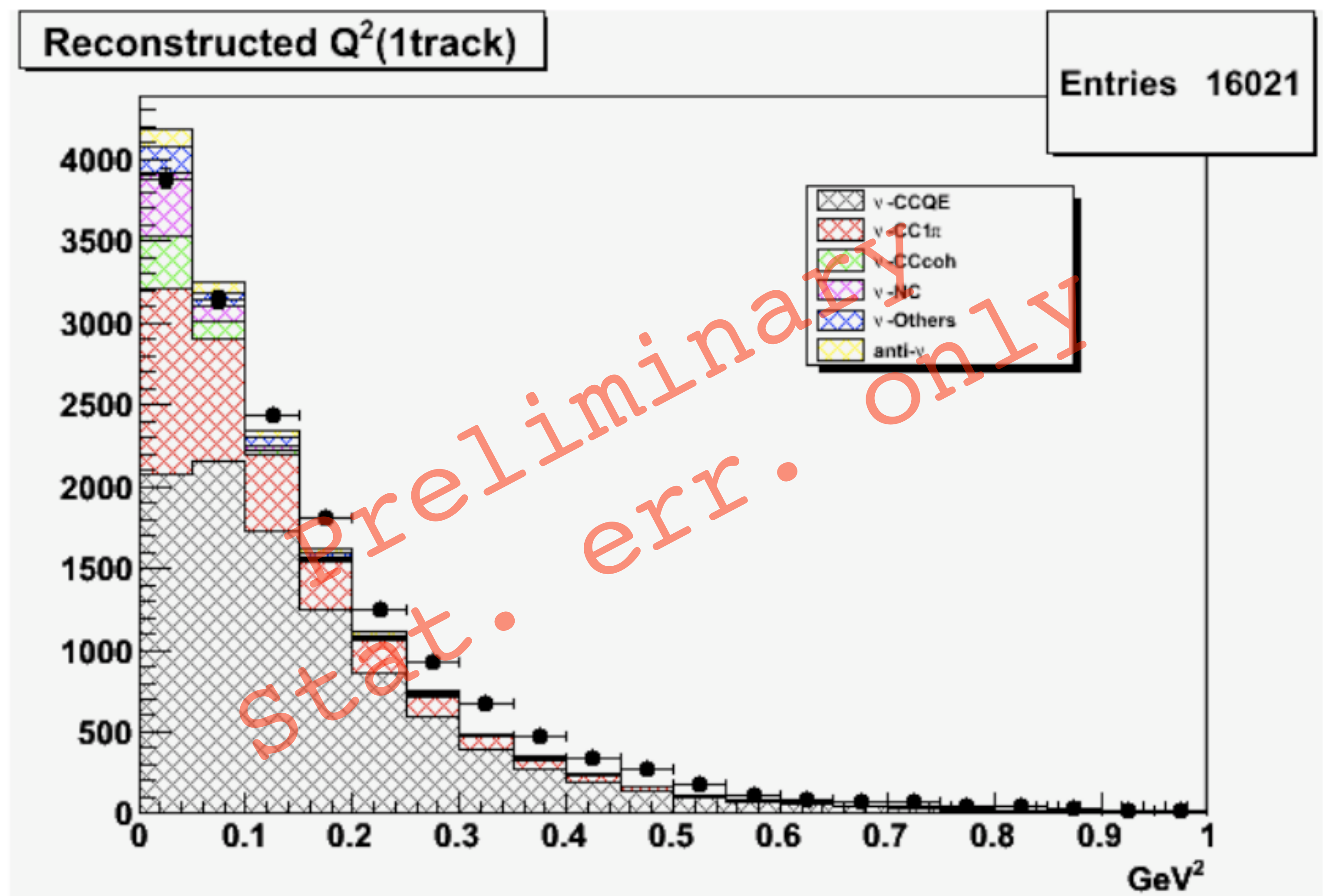
CCQE - 1 track

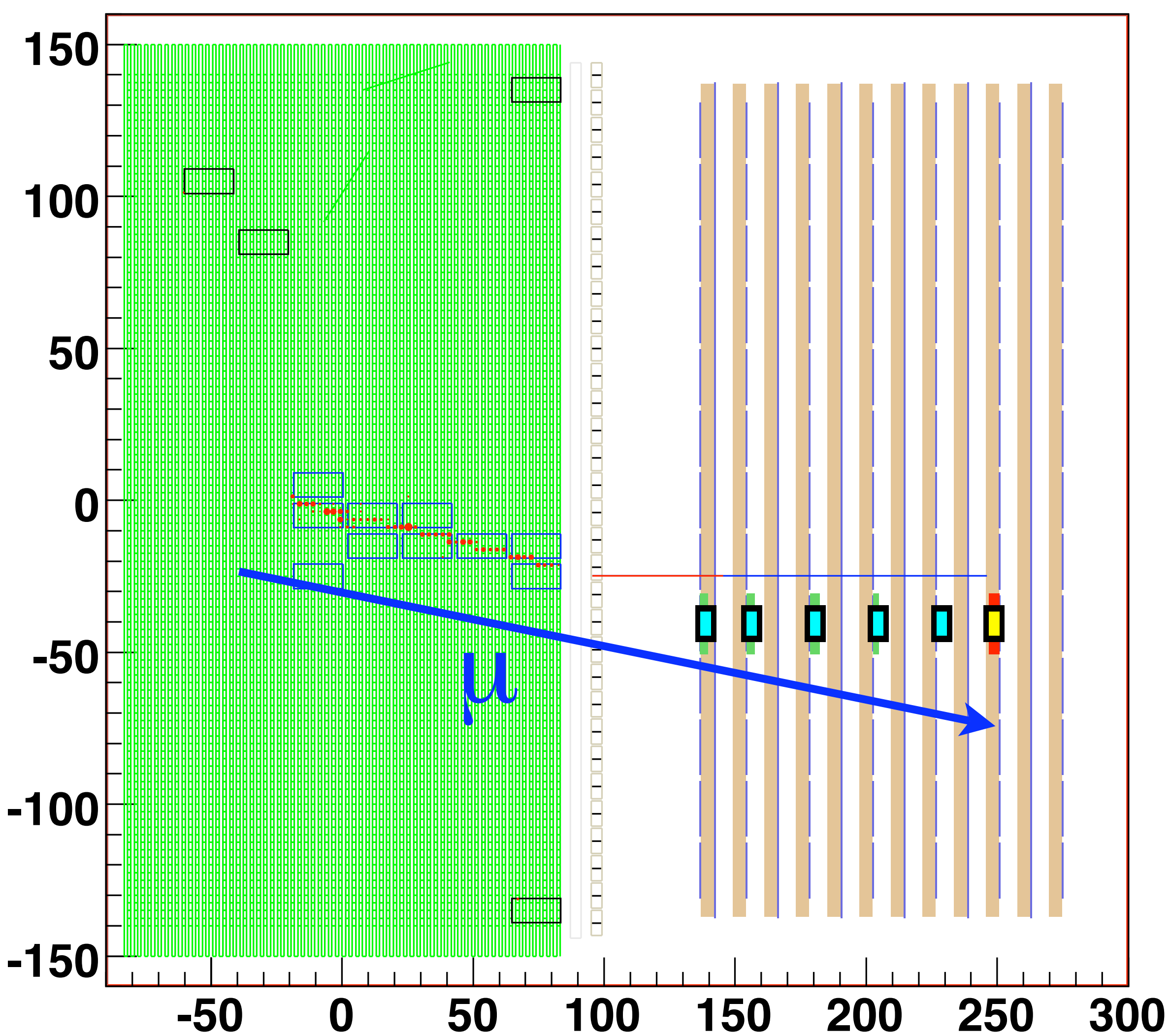


$$Q^2_{rec} = 2E_\nu^{rec}(E_\mu - p_\mu\cos\theta_\mu) - m_\mu^2$$

J. Alcaraz-Aunion



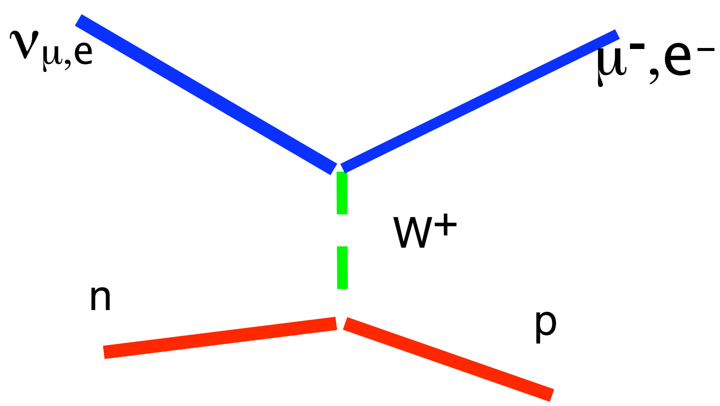
SciBooNE data



1 track events 67% pure CCQE

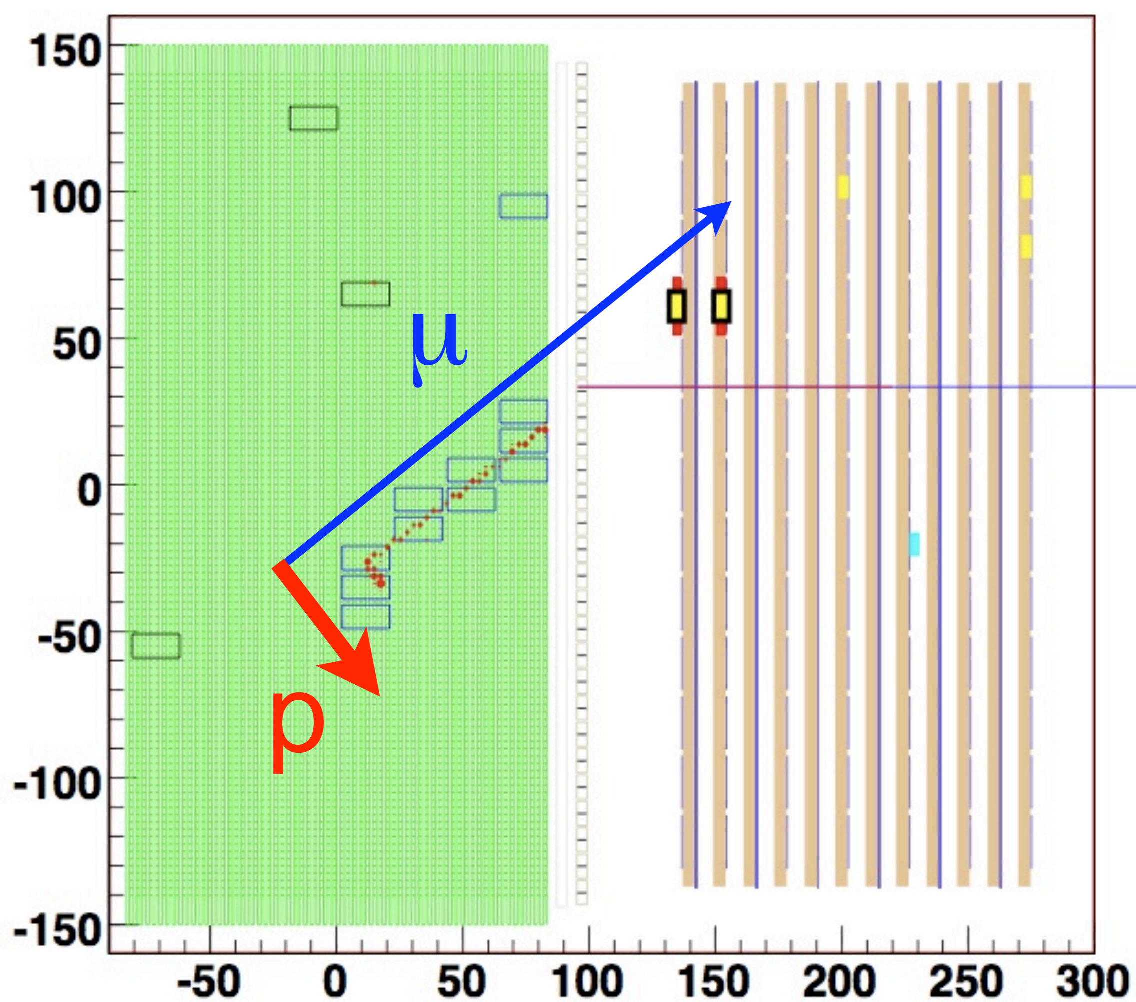
using NEUT (M_A=1.1 GeV)

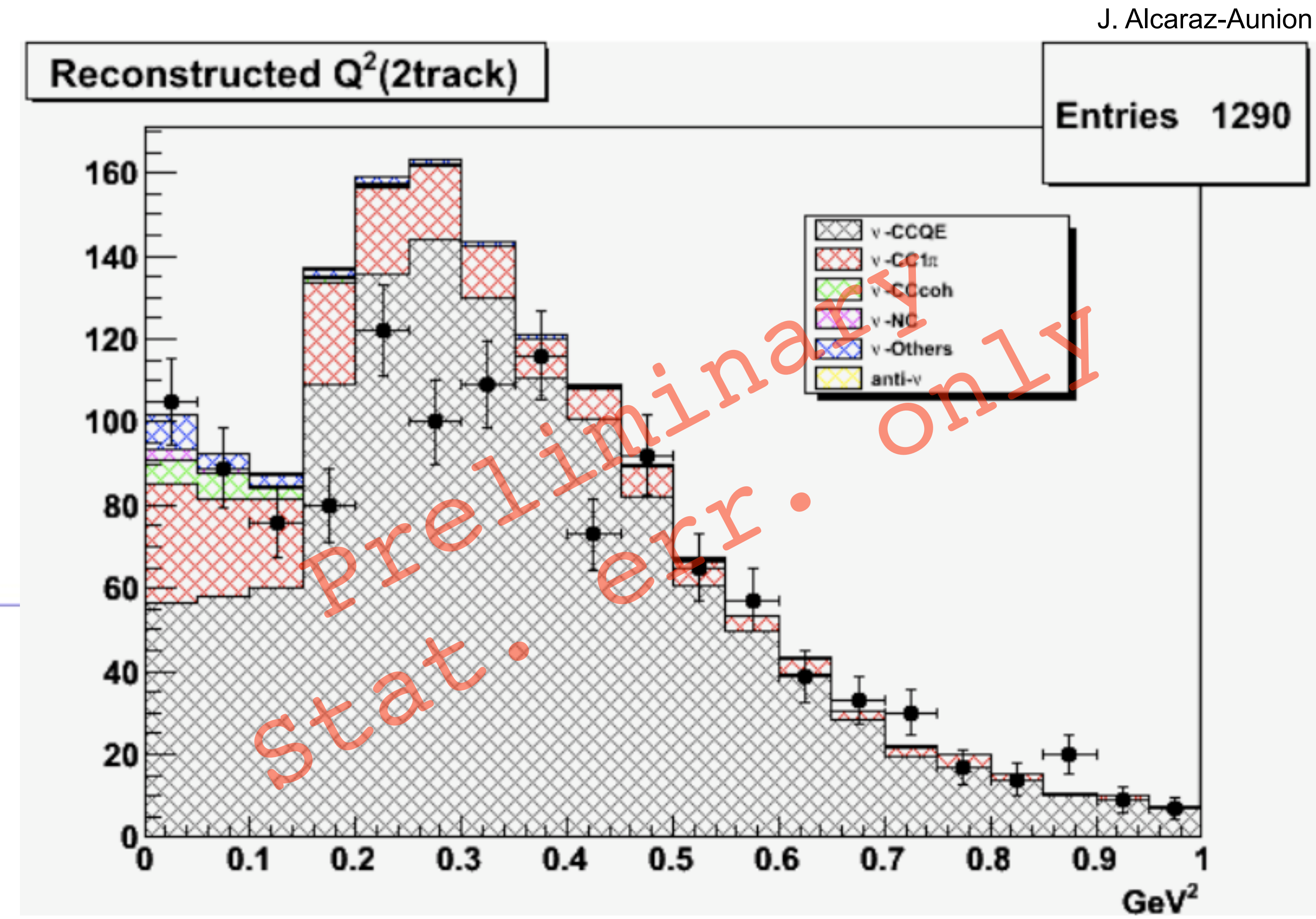
CCQE - 2 track



$$Q^2_{rec} = 2E_\nu^{rec}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

SciBooNE data



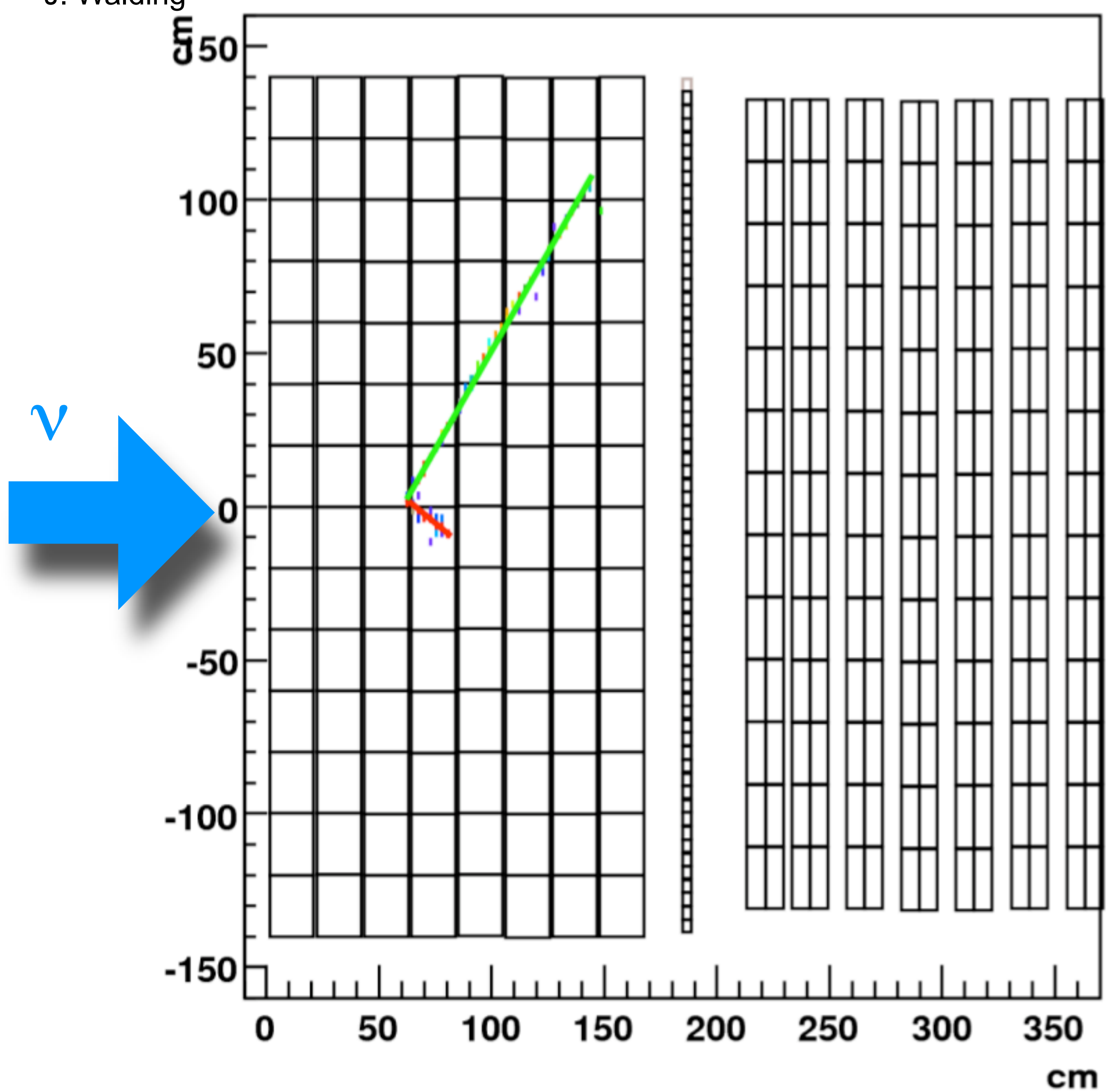


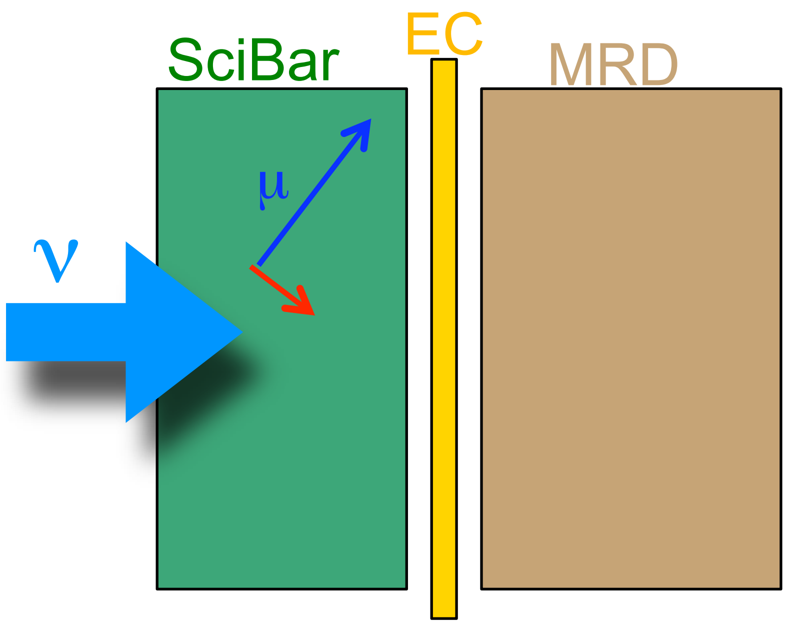
2 track events 81% pure CCQE
(μ + proton using PID)

using NEUT (M_A=1.1 GeV)

CCQE - SciBar only

J. Walding



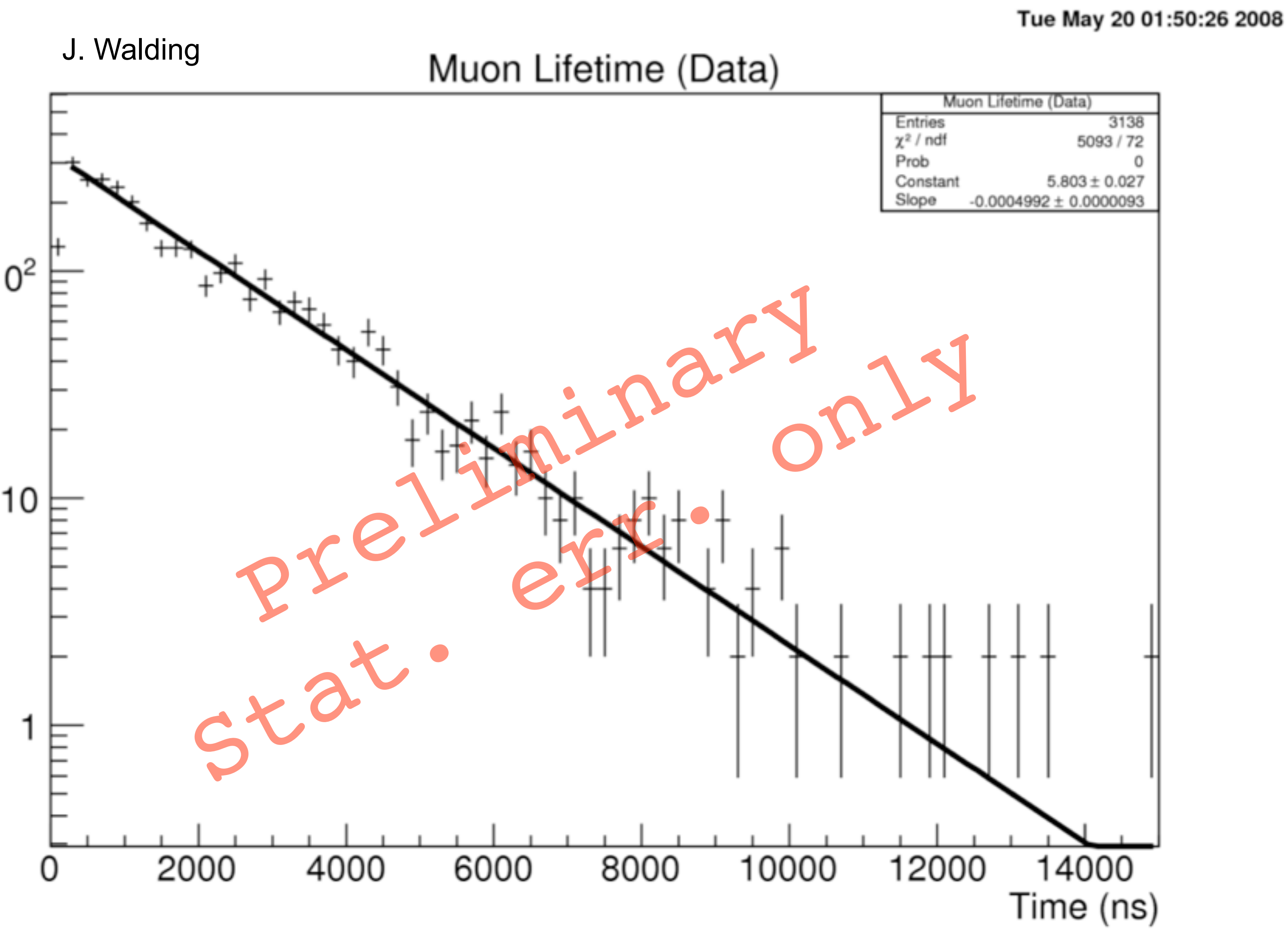


- Events can remain in SciBar only
  - Look for muon decay to tag the muon tracks

Different kinematic regions

Different systematics on p_μ measurement

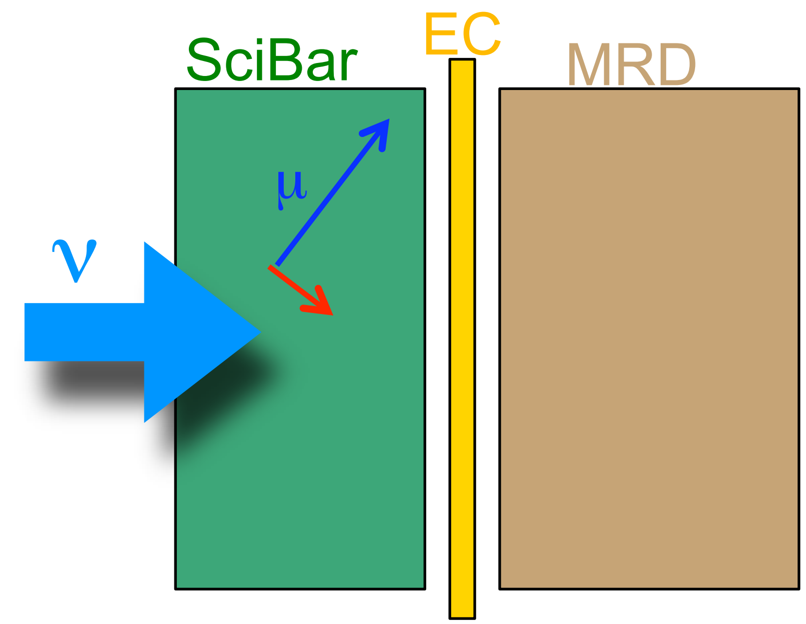
CCQE - SciBar only



τ_μ = 2.003 ± 0.047 (stat) μs

expected = 2.026 ± 0.001 μs

Suzuki, et al., PR**C35**, 2122 1987



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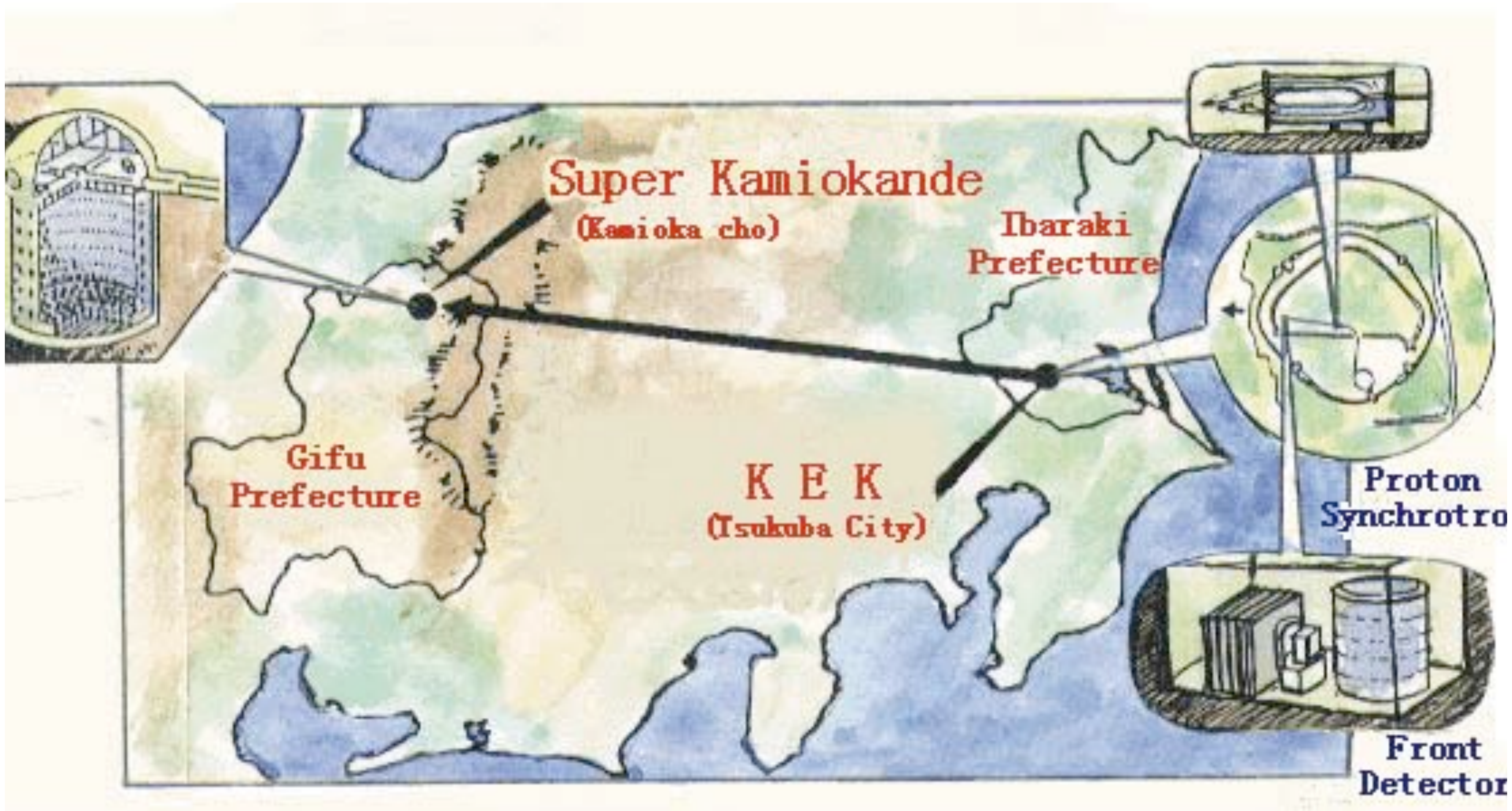
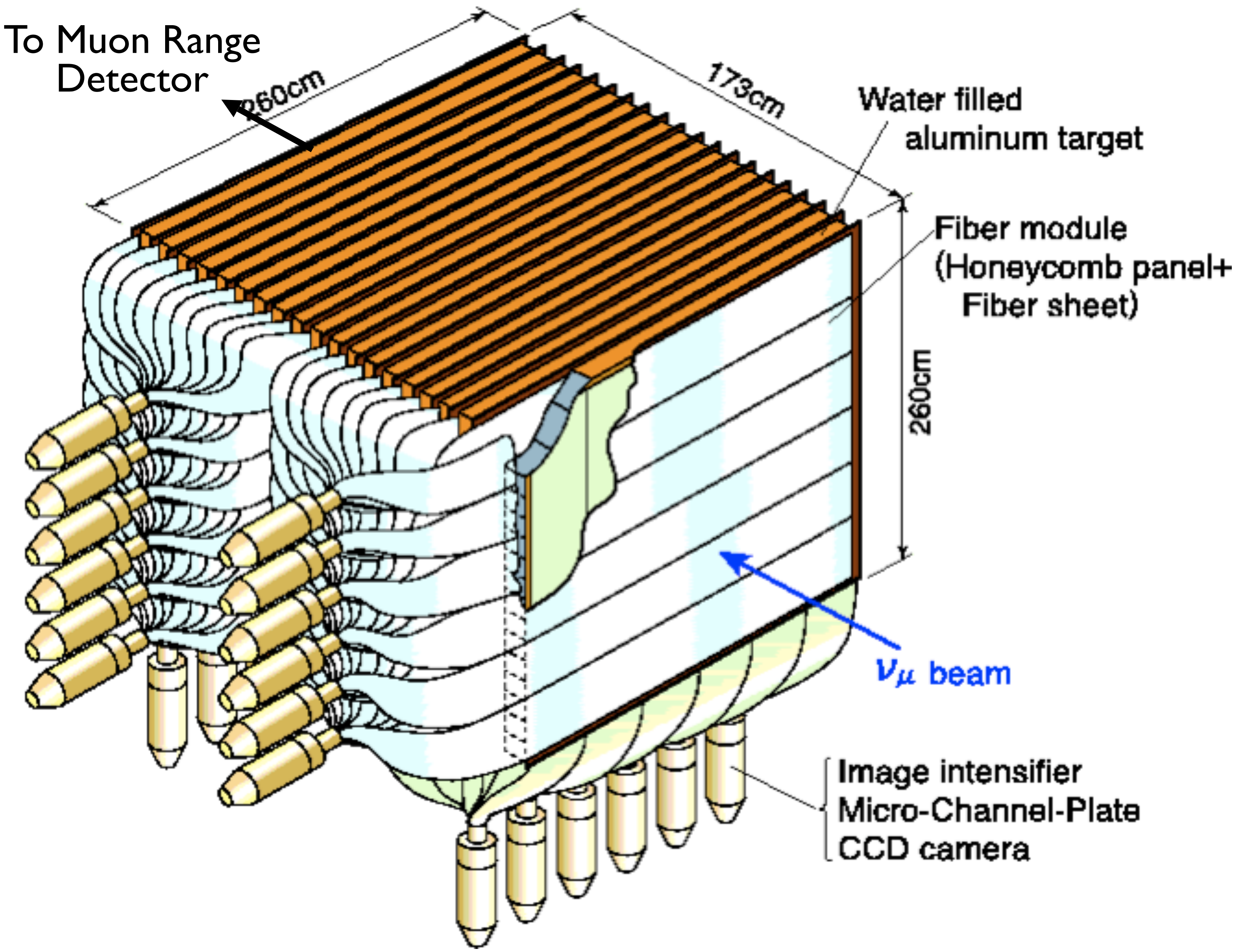

Super Kamiokande
(Kamioka cho)
Ibaraki
Prefecture
Gifu
Prefecture
K E K
(Tsukuba City)
Proton
Synchrotro
Front
Detector

K2K CCQE

SciFi CCQE

Muon in the Muon Range Detector must have p_{muon} > 600 MeV/c

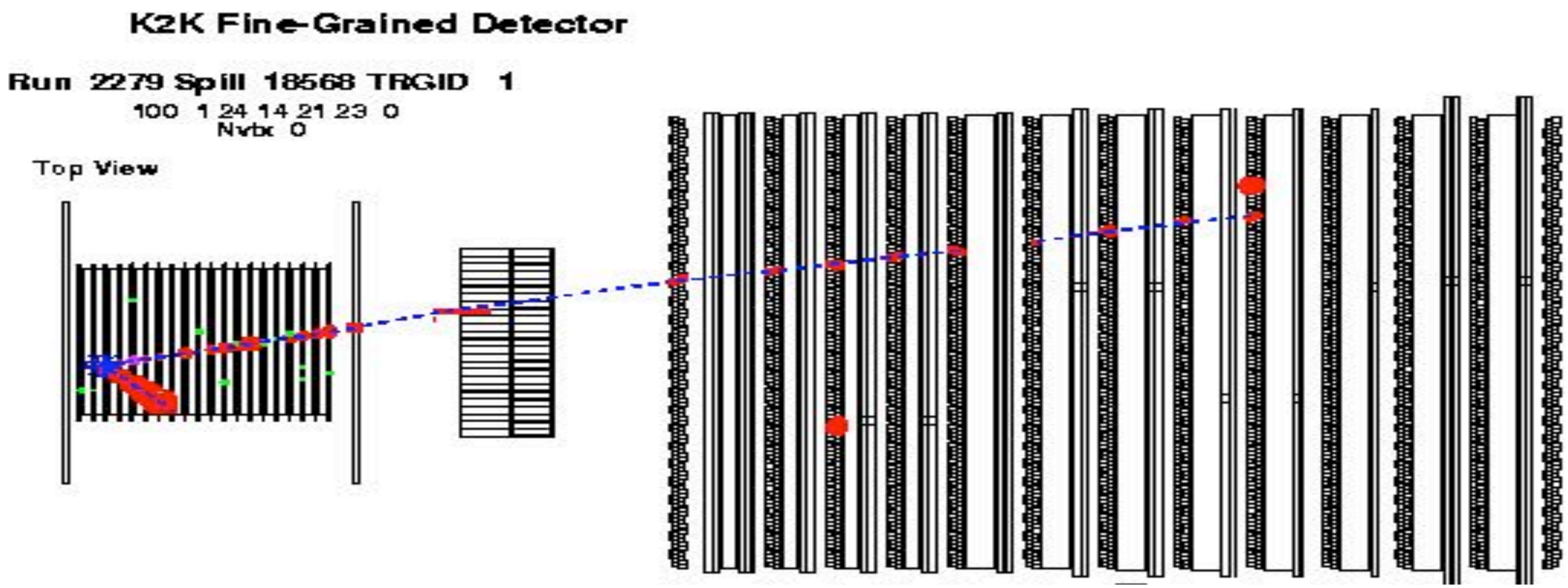
Recoil proton threshold is three layers in SciFi p_{proton} > ~ 600 MeV/c

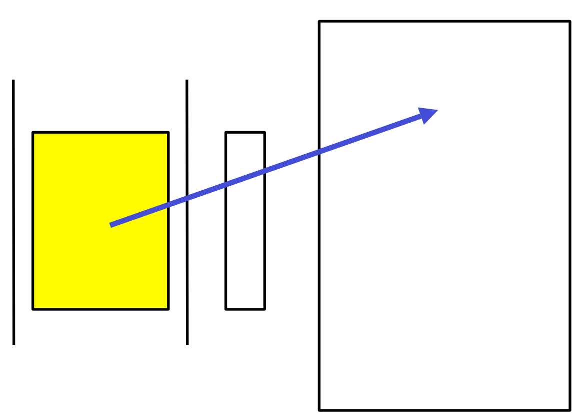


1-track events with muon only
2-track events with muon plus either proton or pion

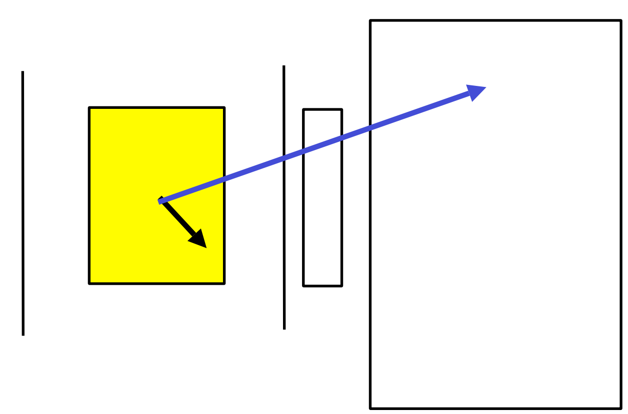
Event Selection

Typical two-track event showing the muon and second track





1 track event



2 track event

Neutrino interaction on H_2O target (+ 20% Aluminum)

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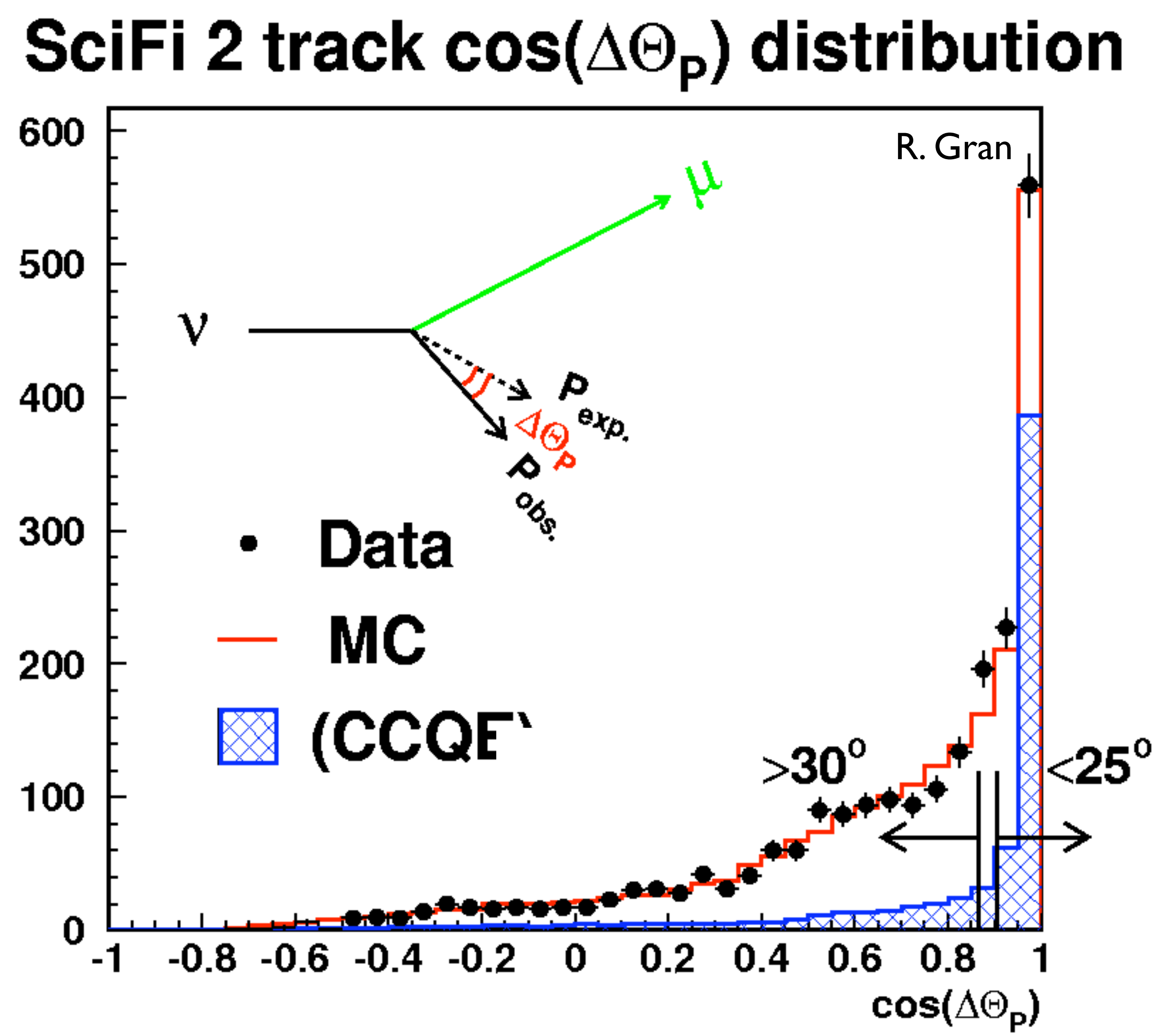
2 track events

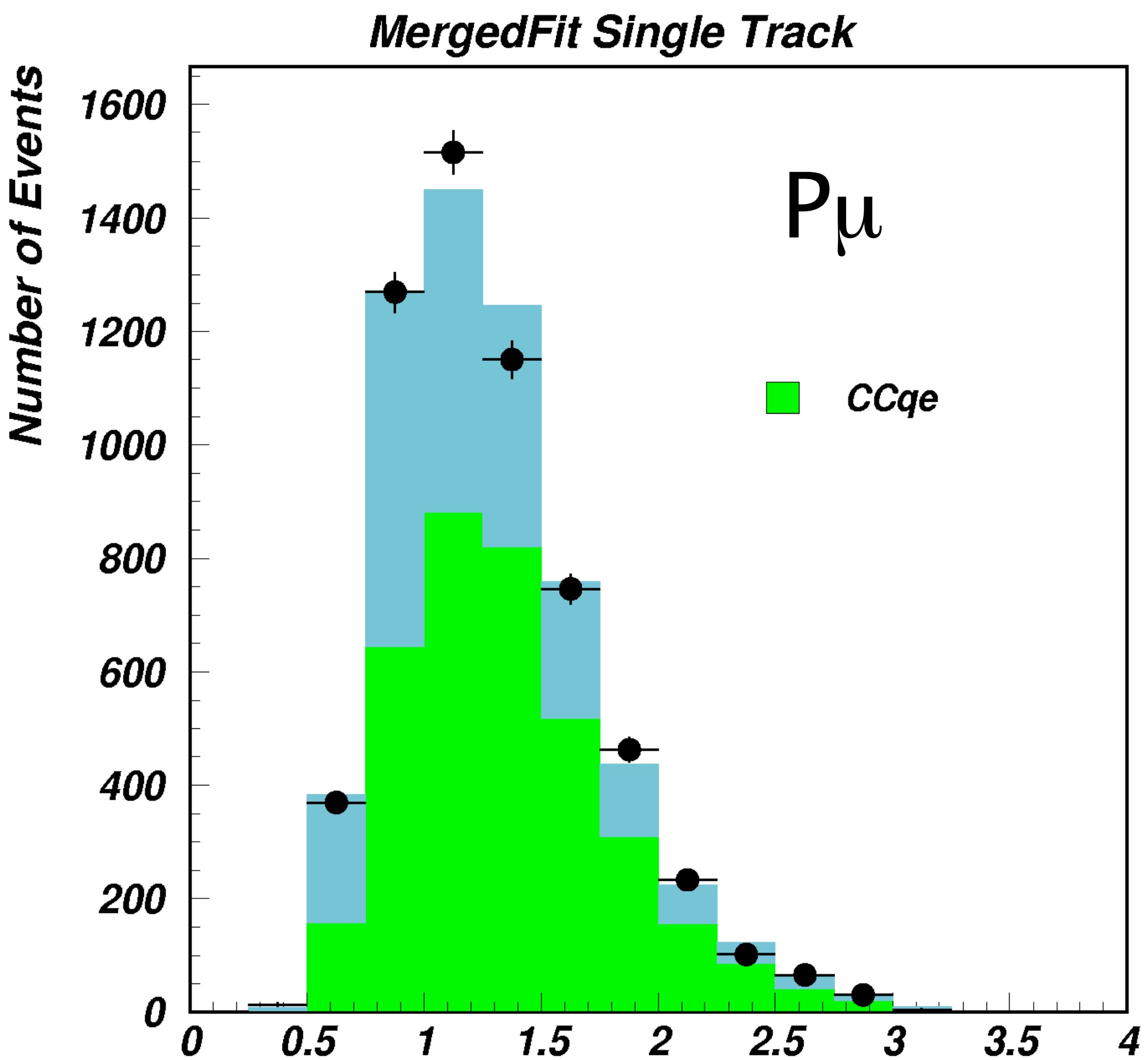
use the location of proton track
to separate events
into three subsamples:

1-track (no proton) 60% QE
2-track QE enhanced 60% QE
2-track nQE 85% nonQE, 15% QE
(NEUT)

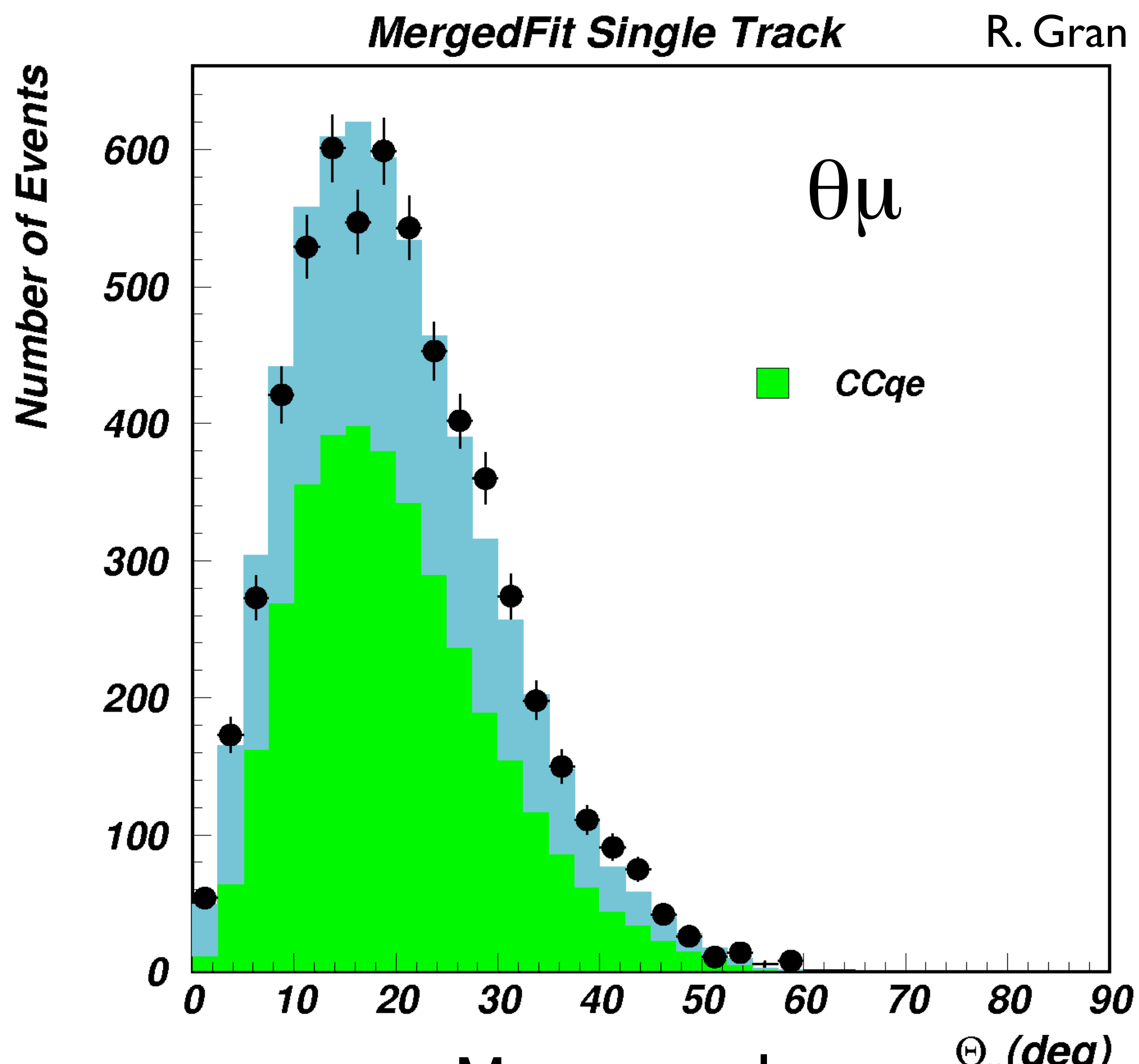


Basic Distributions, P_μ, θ_μ for Scifi Detector

Overall agreement is good



Muon momentum

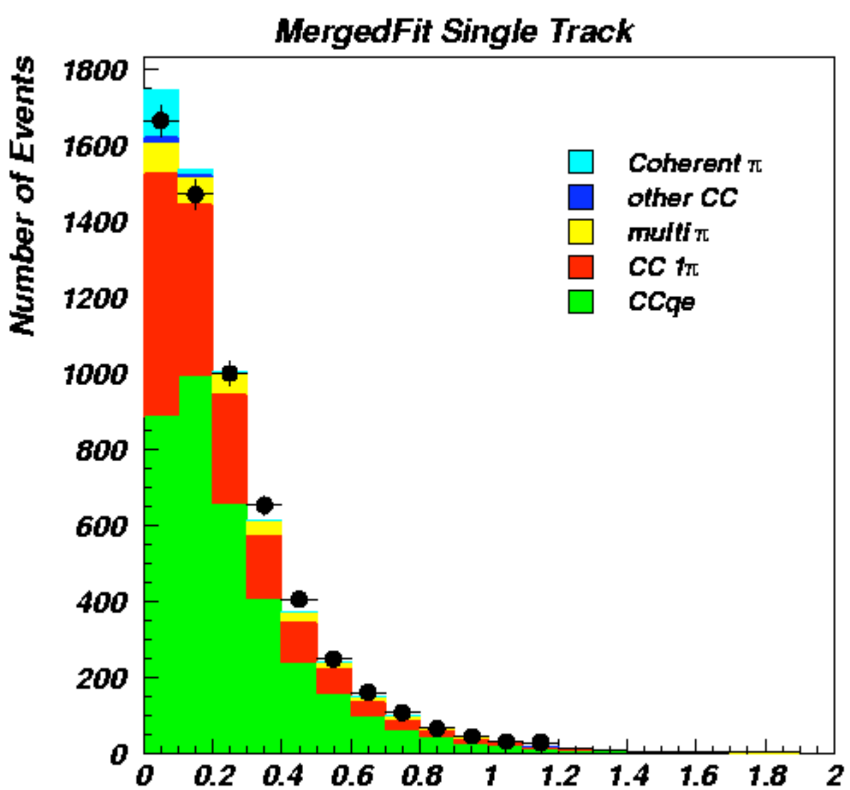


Muon angle

One-track events (60% QE, NEUT)

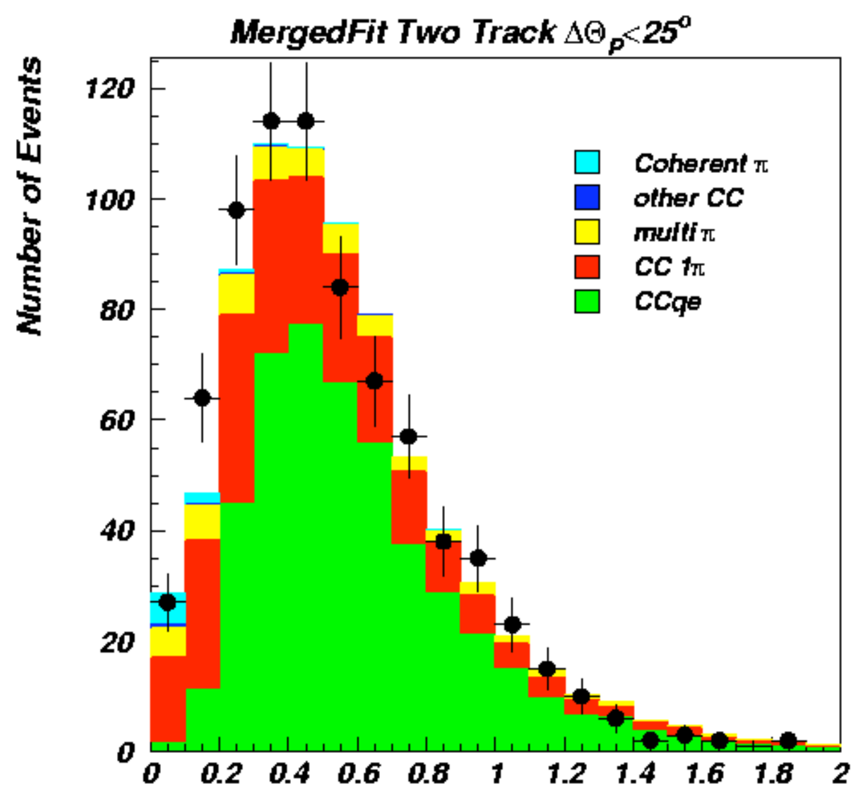
Reconstructed Q^2 distribution in SciFi detector

1 track sample



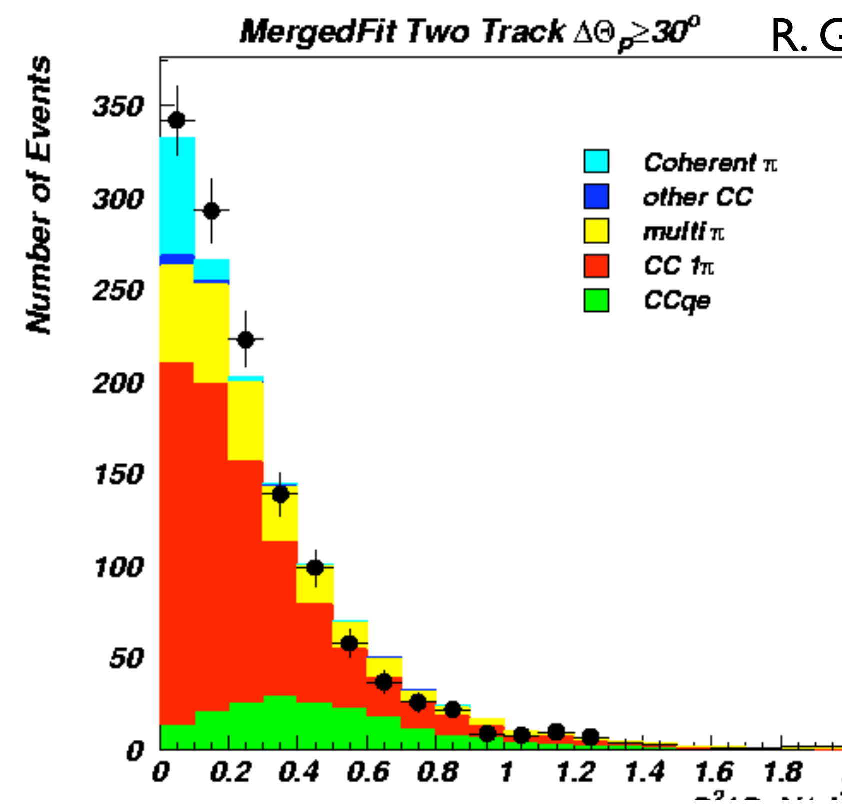
Q^2 (GeV/c)^2

2 track QE enhanced



Q^2 (GeV/c)^2

2 track non-QE



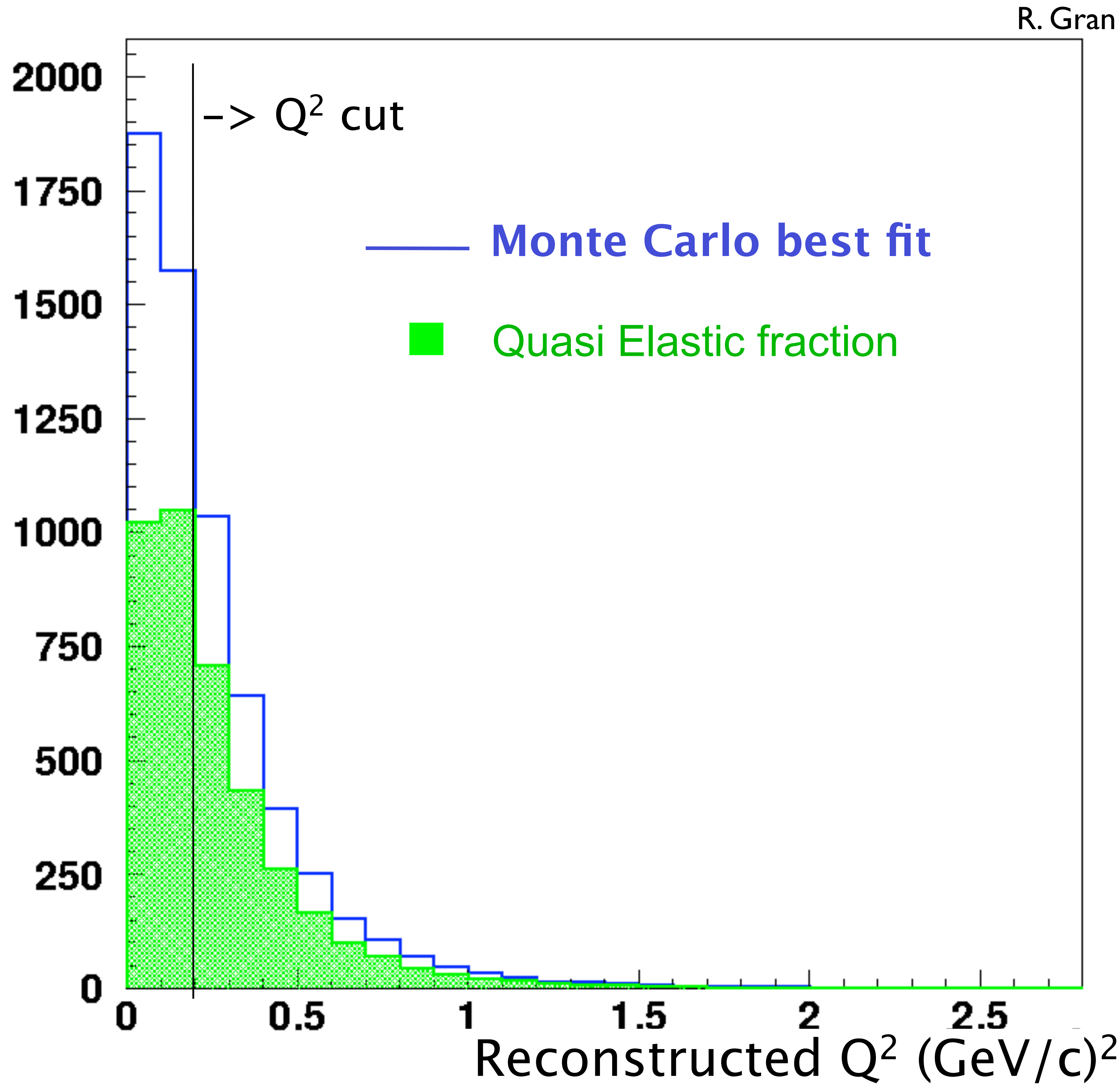
R. Gran

Q^2 (GeV/c)^2

Fit only $Q^2 > 0.2$ region

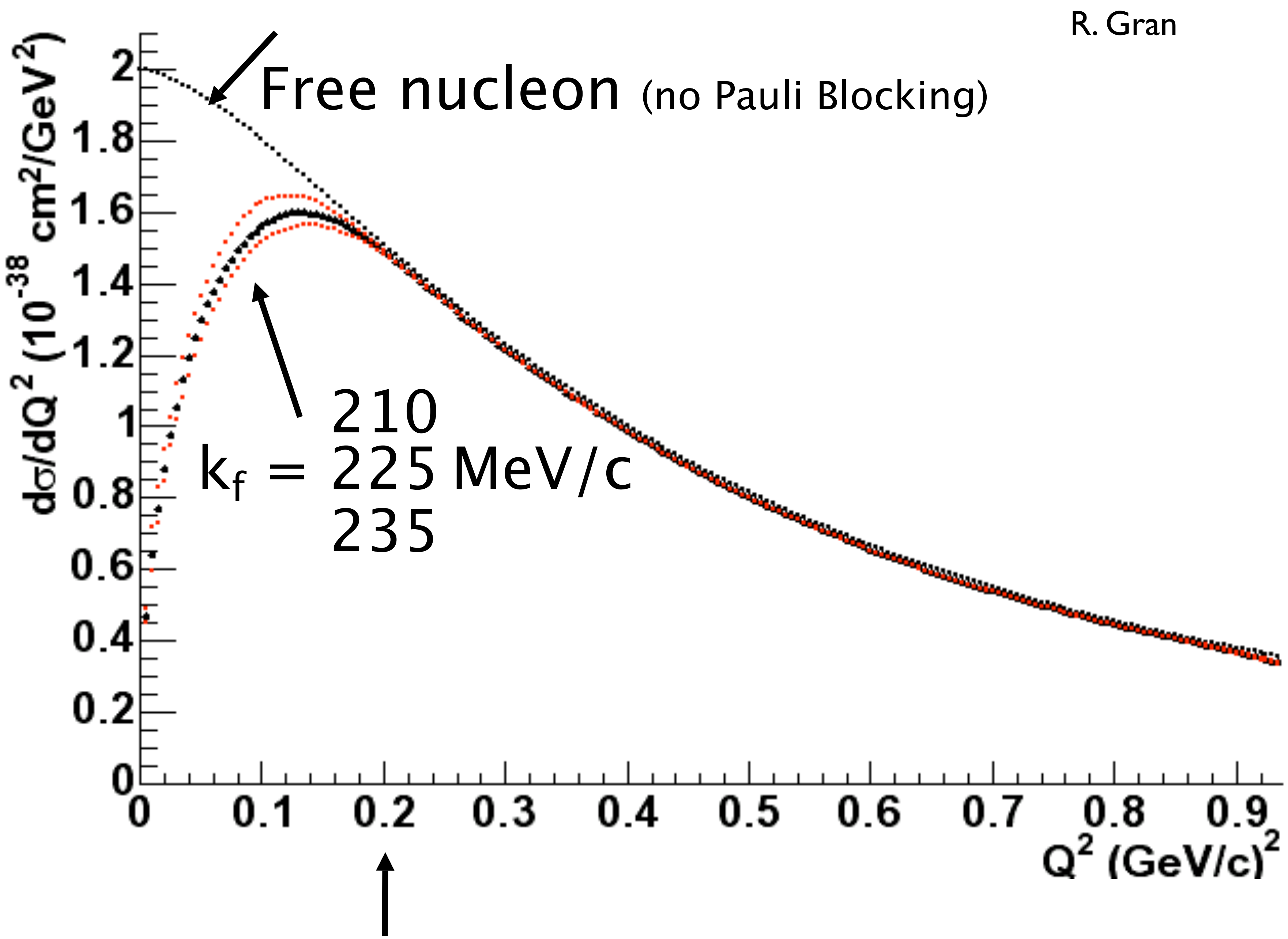
Most significant uncertainties due to Pauli blocking and choice of nuclear model, coherent pion, correction to DIS

QE signal
and inelastic background
are treated the same way



Uncertainty in QE cross section due to Pauli Blocking

in the $Q^2 < 0.2$ region
a Fermi-gas model with different Fermi-momenta k_f



We Cut here

K2K SciFi M_A fit

Fit the 1track, 2track (QE), and 2track (nonQE) simultaneously

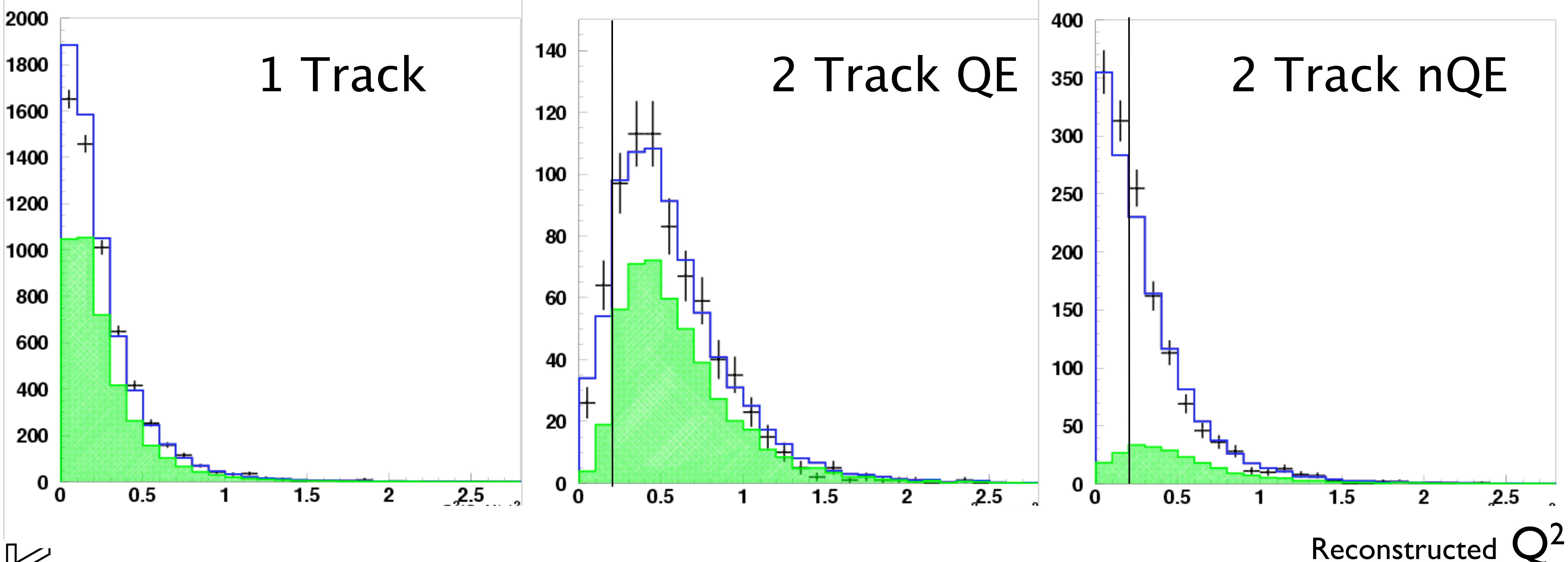
K2K-I: 8114 events total 4310 Q2>0.2 in fit

K2K-IIa: 5967 events total 2525 Q2>0.2 in fit

$$M_A = 1.20 \pm 0.03 \text{ stat} \pm 0.12 \text{ syst}$$

Bodek/Yang DIS correction and Marteau Coherent Pi cross-section

R. Gran



Systematic Errors

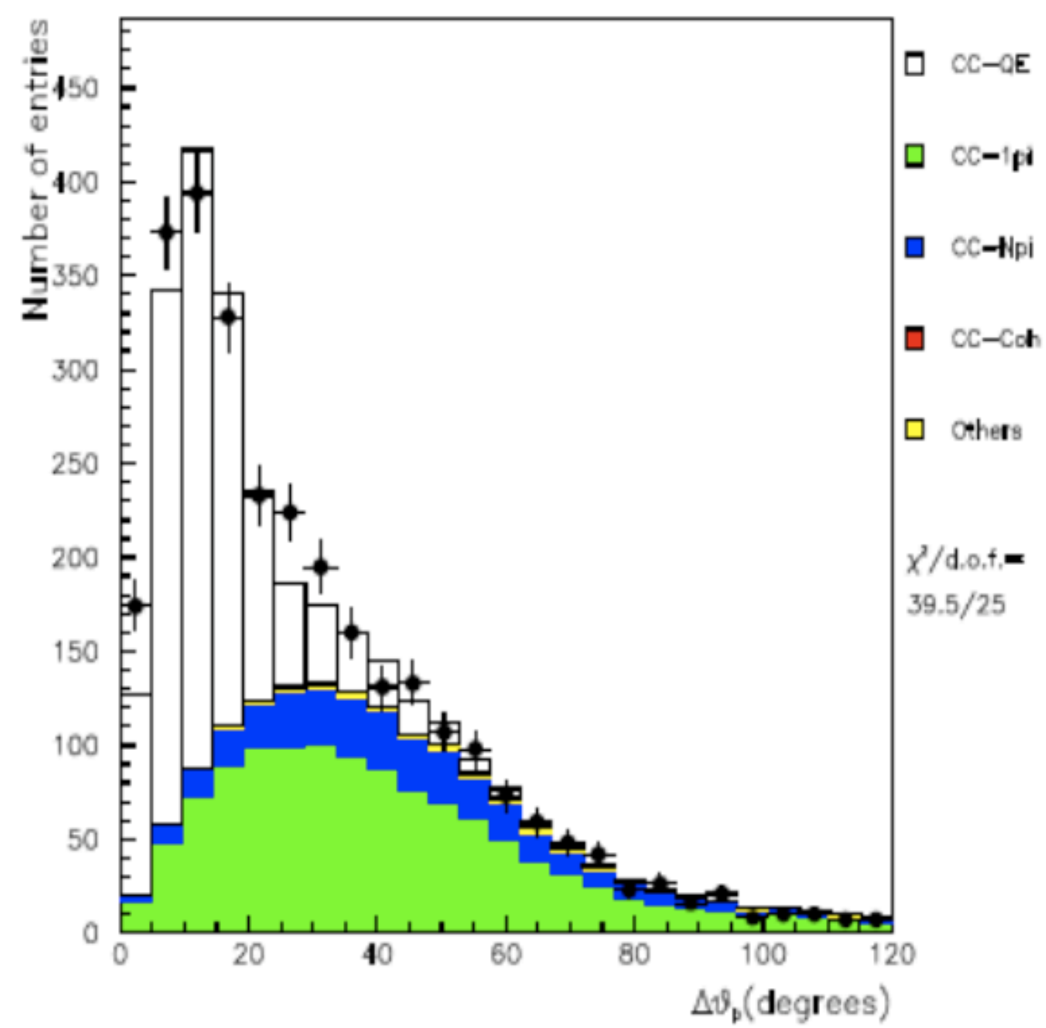
Source	Uncertainty
Energy scale	0.08
LG density	0.02
Escale/LC correlation	0.04
Escale-MA correlation	0.03
MA-1pi	0.03
nQE/QE	0.03
Statistics	0.012
TOTAL	0.12

K2K: SciBar

- Event selection similar to SciBooNE's
  - (actually, SciBooNE's was based on K2K's)

Sample	Q^2>0.0	Purity	Q^2>0.2	Purity
1-trk	7405	54%	4032	59%
2-trk QE	1264	77%	1142	80%
2-trk non-QE	1537	19%	923	28%
TOTAL	10206	52%	6097	59%

F. Sanchez

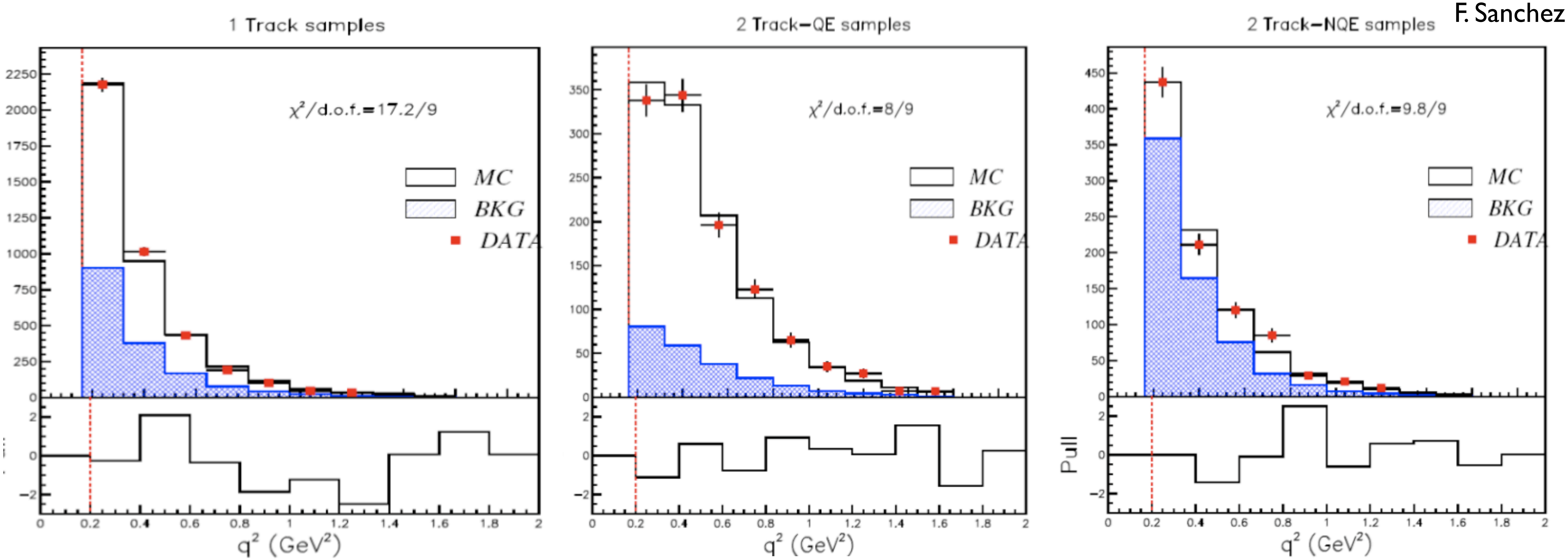


K2K: SciBar

- Fit 3 data samples, allowing these parameters to float:
  - Overall normalization
  - M_A
  - Ratio of nonQE/QE
  - Ratio of 2-trk/1-trk
  - Ratio of 2-trk nonQE/2-trk QE
  - 4 energy bins constrained by PIMON data

K2K: SciBar

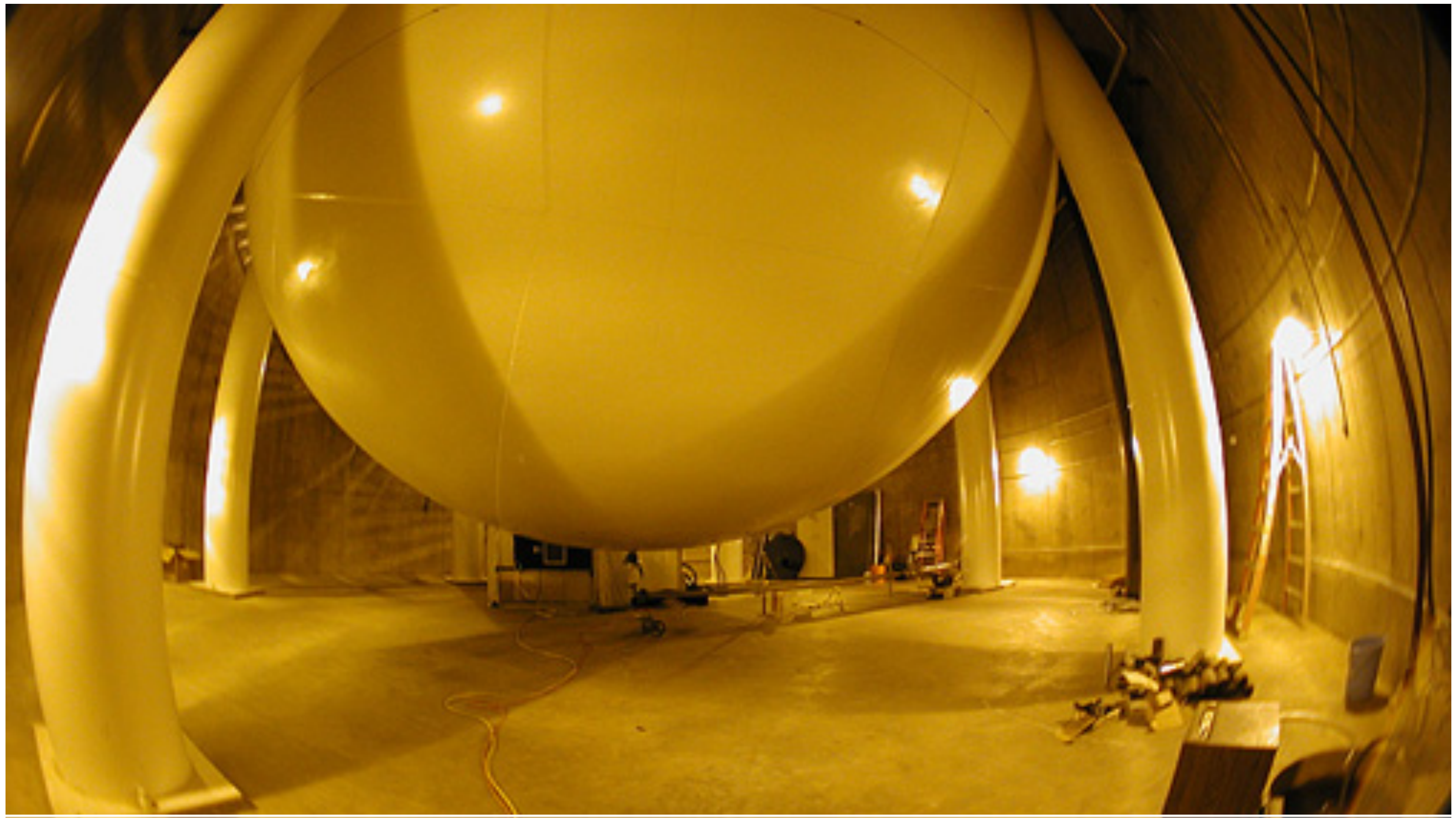
F. Sanchez



$$M_A = 1.144 \pm 0.077 \text{ (fit)} +0.078 -0.072 \text{ (syst)}$$

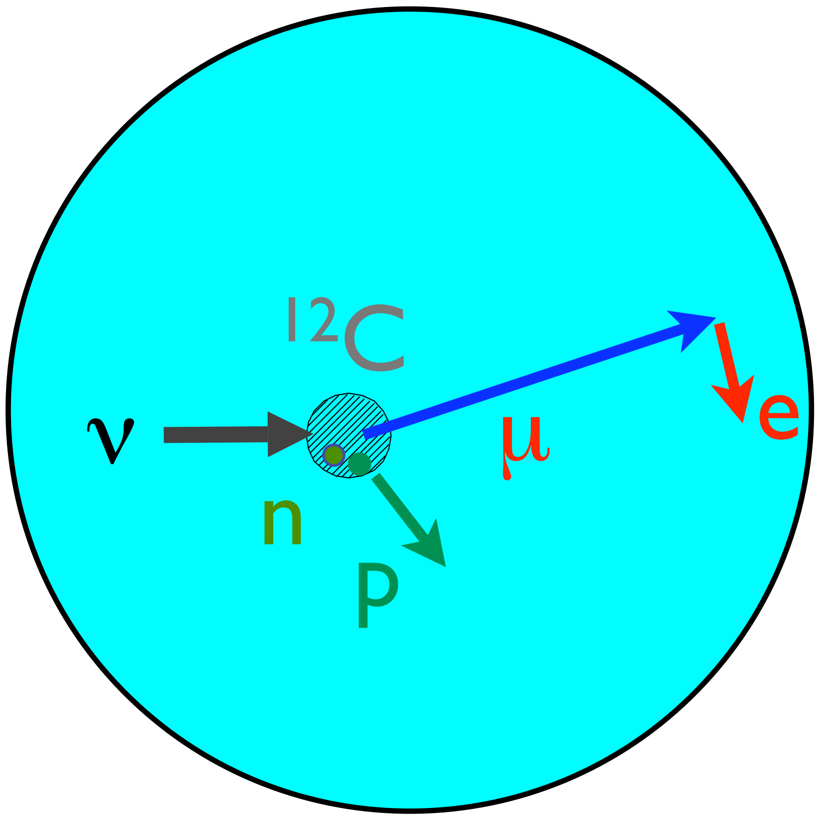
K2K: SciBar Systematics

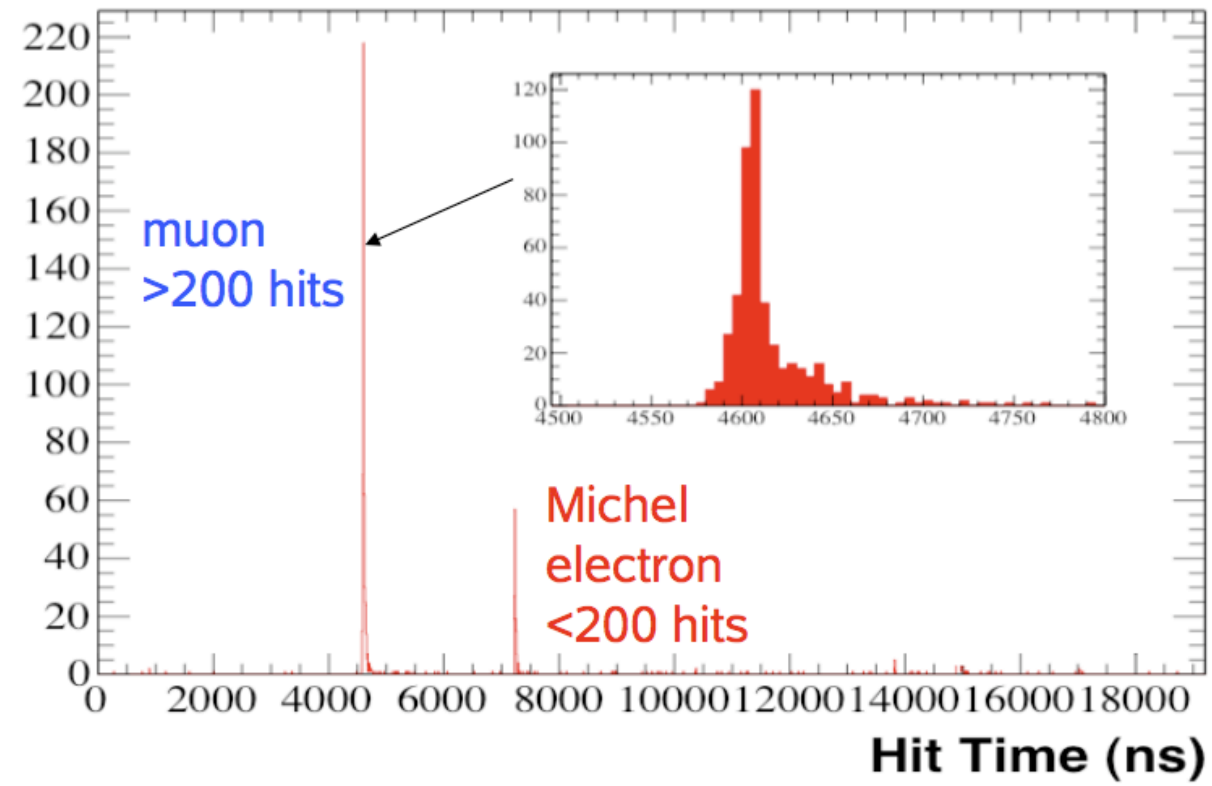
Sources of uncertainty	Error in M_A	Error in $R^{nQE/QE}$
Momentum Scale	$+0.030$ -0.030	$+0.014$ -0.014
Cross section and nuclear effects	$+0.035$ -0.058	$+0.09$ -0.15
Detector	$+0.051$ -0.027	$+0.024$ -0.030
Analysis	$+0.012$ -0.037	$+0.0$ -0.34
Total	$+0.078$ -0.072	$+0.094$ -0.37



MiniBooNE CCQE

MiniBooNE Cuts



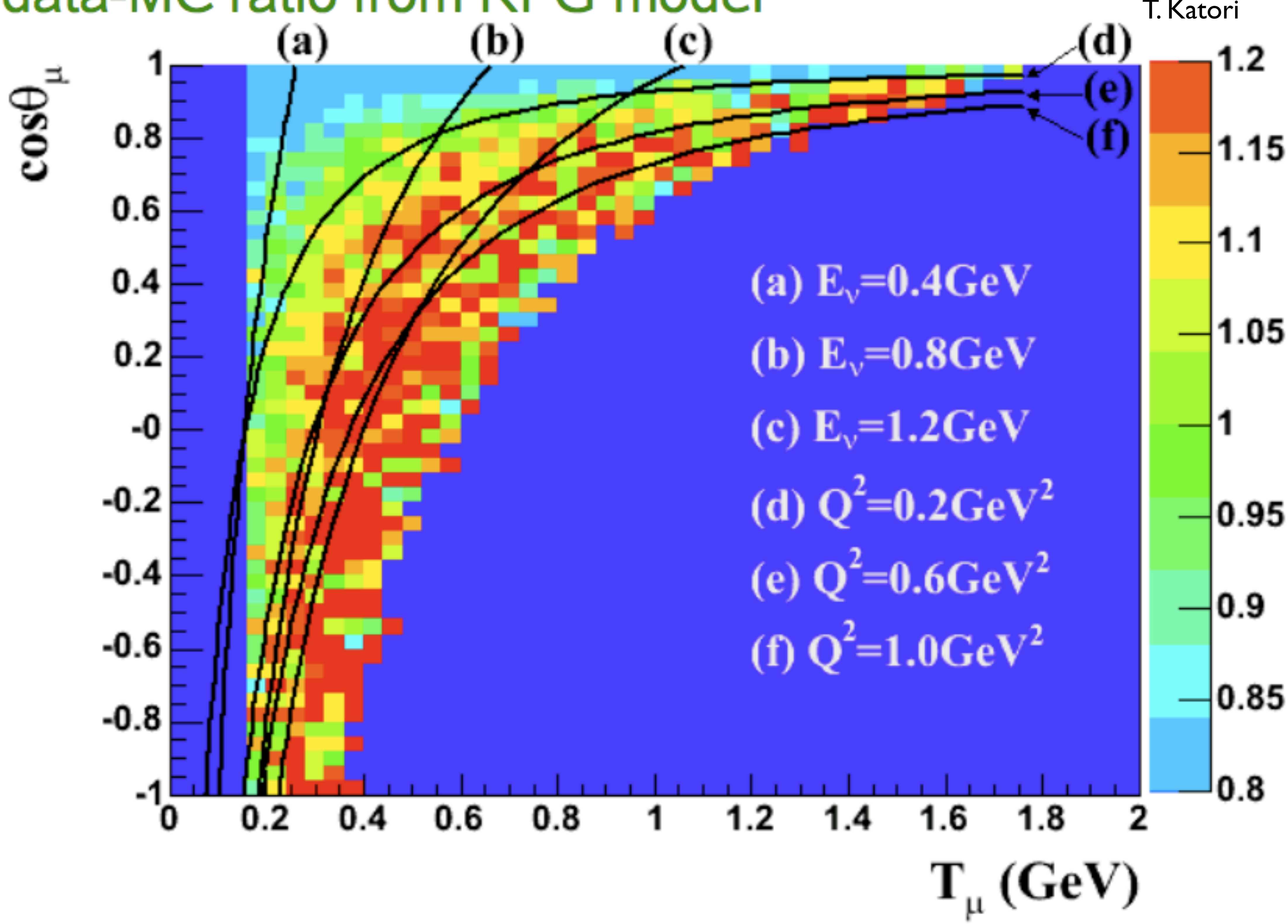


total 2 subevents	54.2%
muon in beam window (4400ns < Time < 6400ns)	52.9%
muon veto hits < 6 and Michel electron veto hits < 6	46.4%
muon tank hits > 200 and Michel electron tank hits < 200	41.6%
fiducial reconstruction for muon	41.3%
muon and electron distance < 100cm	35.0%

74% pure CCQE (NUANCE)

MiniBooNE Data/MC

data-MC ratio from RFG model



2. Prediction for CCQE events

Smith and Moniz, Nucl.,Phys.,B43(1972)605

Relativistic Fermi Gas (RFG) Model

Carbon is described by the collection of incoherent Fermi gas particles.
All details come from hadronic tensor.

$$(W_{\mu\nu})_{ab} = \int_{Elo}^{Ehi} f(\vec{k}, \vec{q}, w) T_{\mu\nu} dE : \text{hadronic tensor}$$

$$f(\vec{k}, \vec{q}, w) : \text{nucleon phase space density function}$$

$$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P) : \text{nucleon tensor}$$

$$F_A(Q^2) = g_A/(1 + Q^2/M_A^2)^2 : \text{Axial form factor}$$

$$Ehi : \text{the highest energy state of nucleon} = \sqrt{(p_F^2 + M^2)}$$

$$Elo : \text{the lowest energy state of nucleon} = \sqrt{(p_F^2 + M^2)} - w + E_B$$

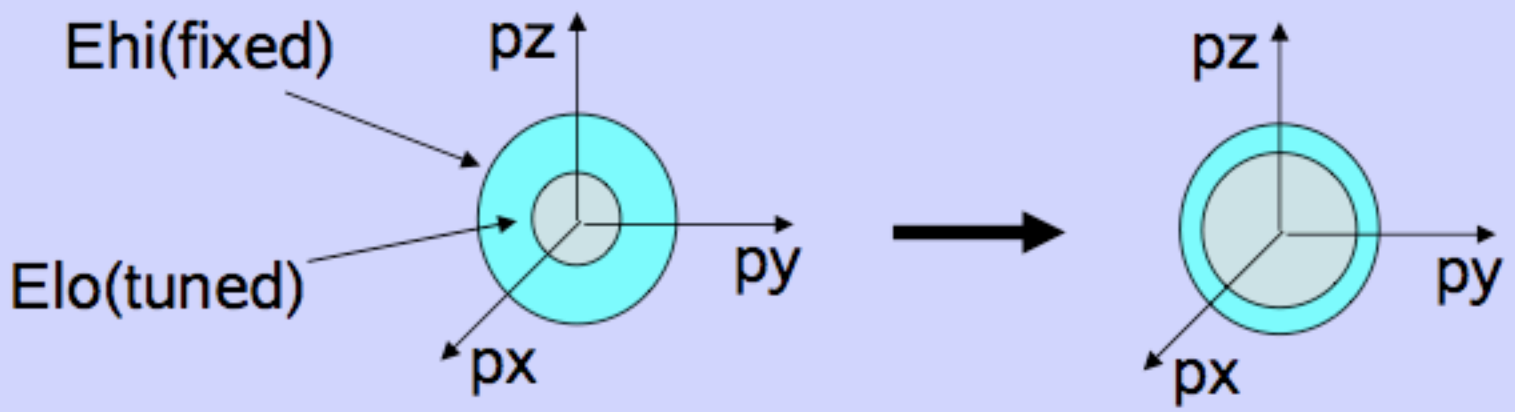
3 parameters are especially important to control nuclear effect of Carbon;
M_A = 1.03GeV : axial mass
P_F = 220MeV : Fermi momentum
E_B = 34MeV : binding energy

3. CCQE data-MC comparison

Pauli blocking parameter "kappa" : κ

To enhance the Pauli blocking at low Q^2, we introduced a new parameter κ, which is the scale factor of lower bound of nucleon sea and controls the size of nucleon phase space

$$Elo = \boxed{\kappa}\left(\sqrt{(p_F^2 + M^2)} - w + E_B\right)$$



This modification gives significant effect only at low Q^2 region

We tune the nuclear parameters in RFG model using Q^2 distribution;

M_A = tuned

P_F = fixed

E_B = fixed

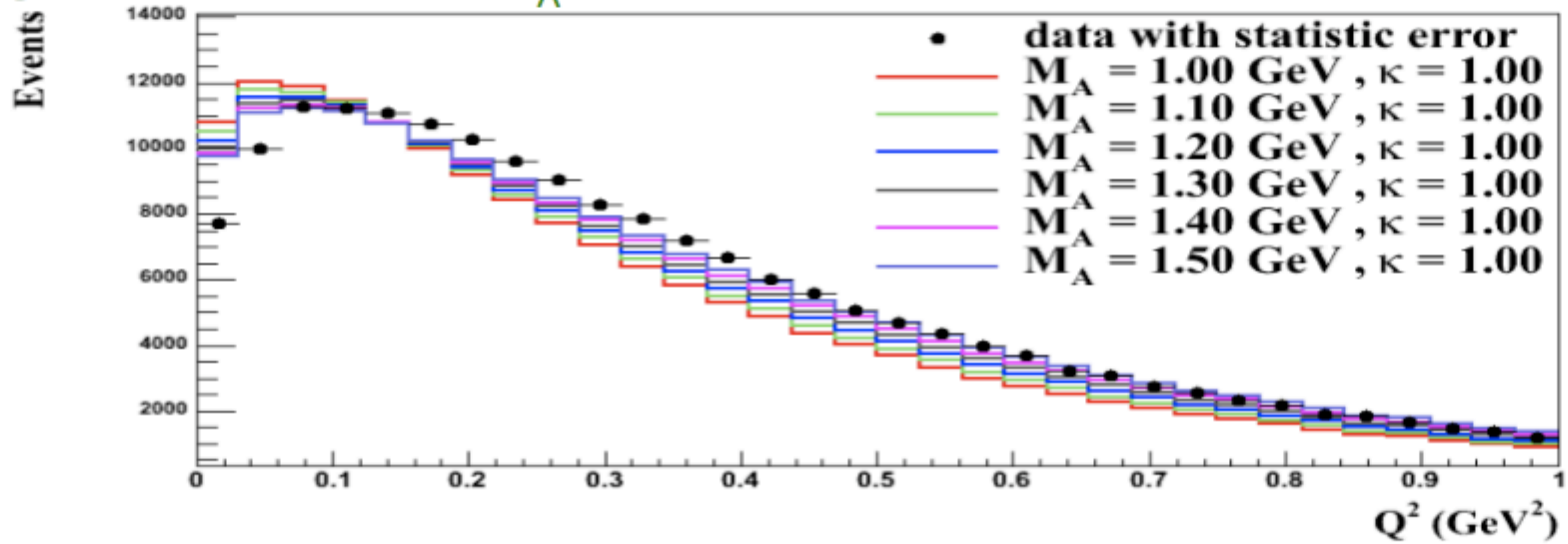
κ = tuned

Imperial College London

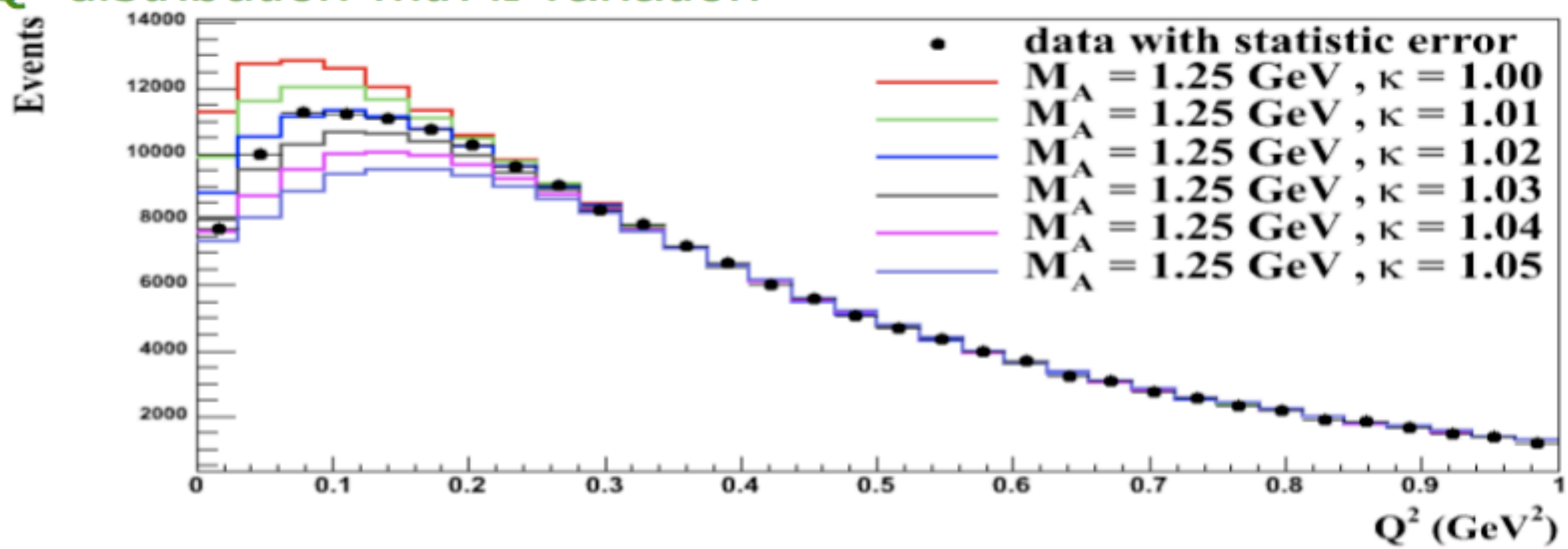
Effect of M_A and κ

Q^2 distribution with M_A variation

T. Katori

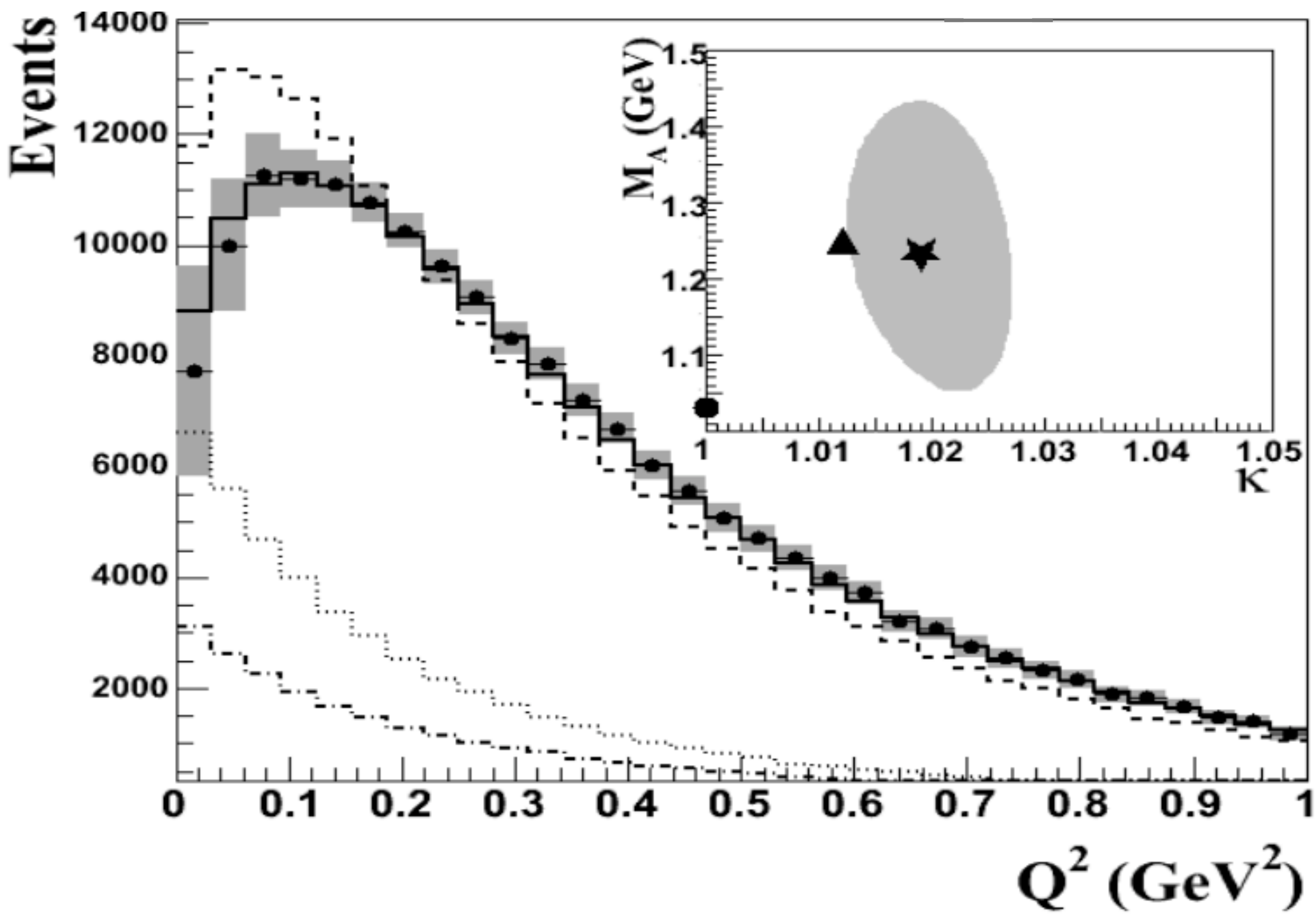


Q^2 distribution with κ variation



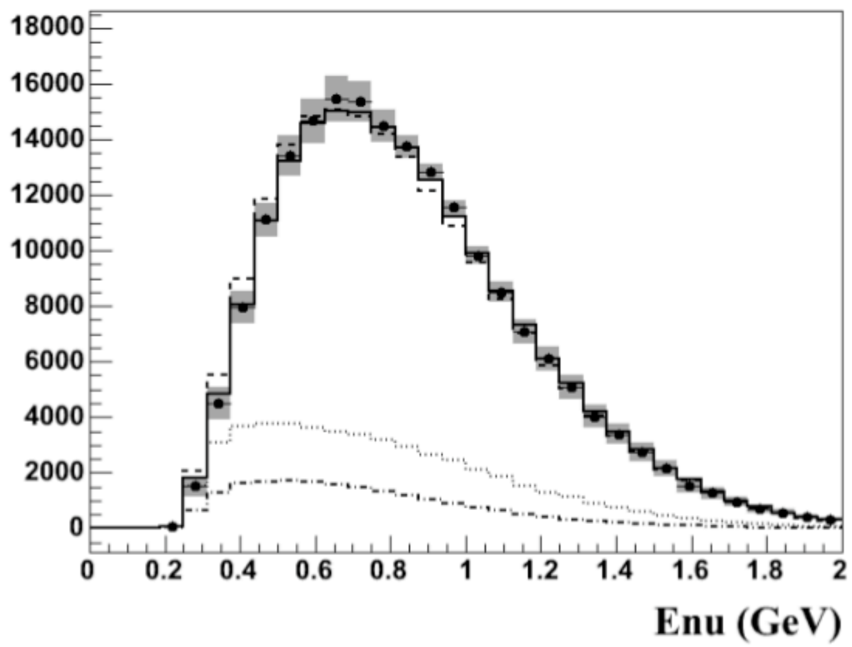
After Fitting

T. Katori

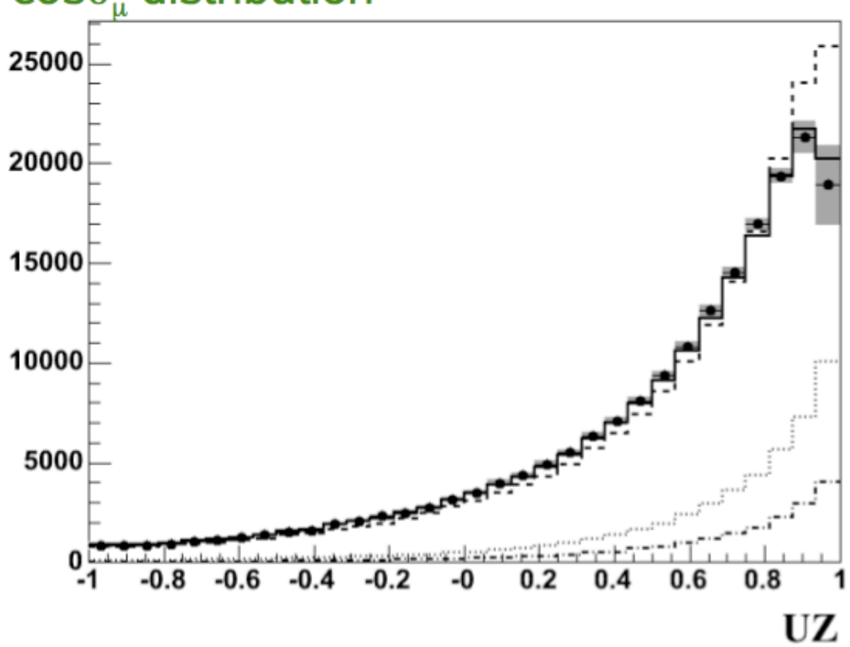


After fitting

Eν distribution

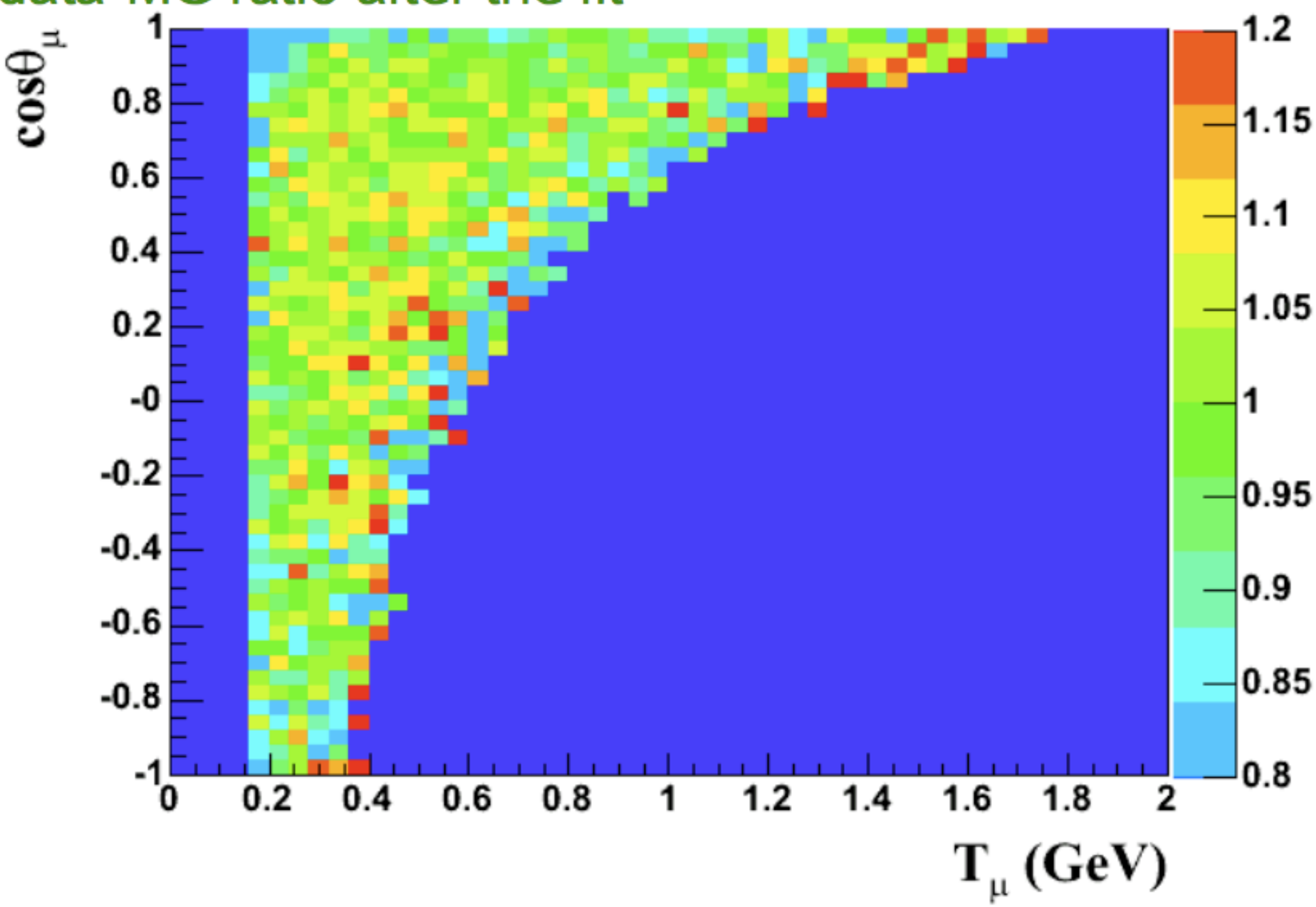


$\cos\theta_\mu$ distribution



data-MC ratio after the fit

T. Katori

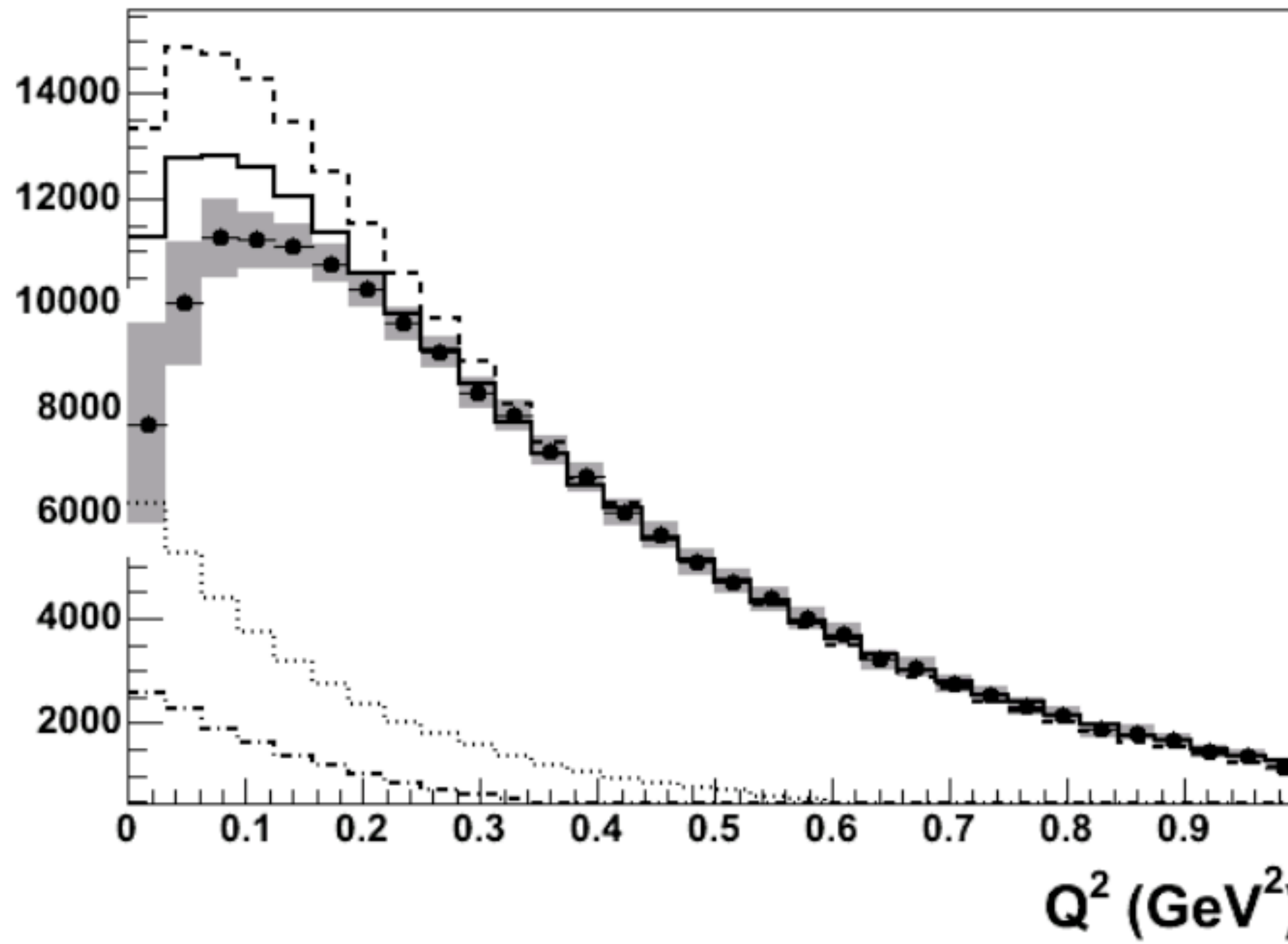


Is κ necessary?

- Only MA is allowed to vary in this fit
- Such a fit cannot improve over all phase space

- (Additional experimental information would allow different tests)

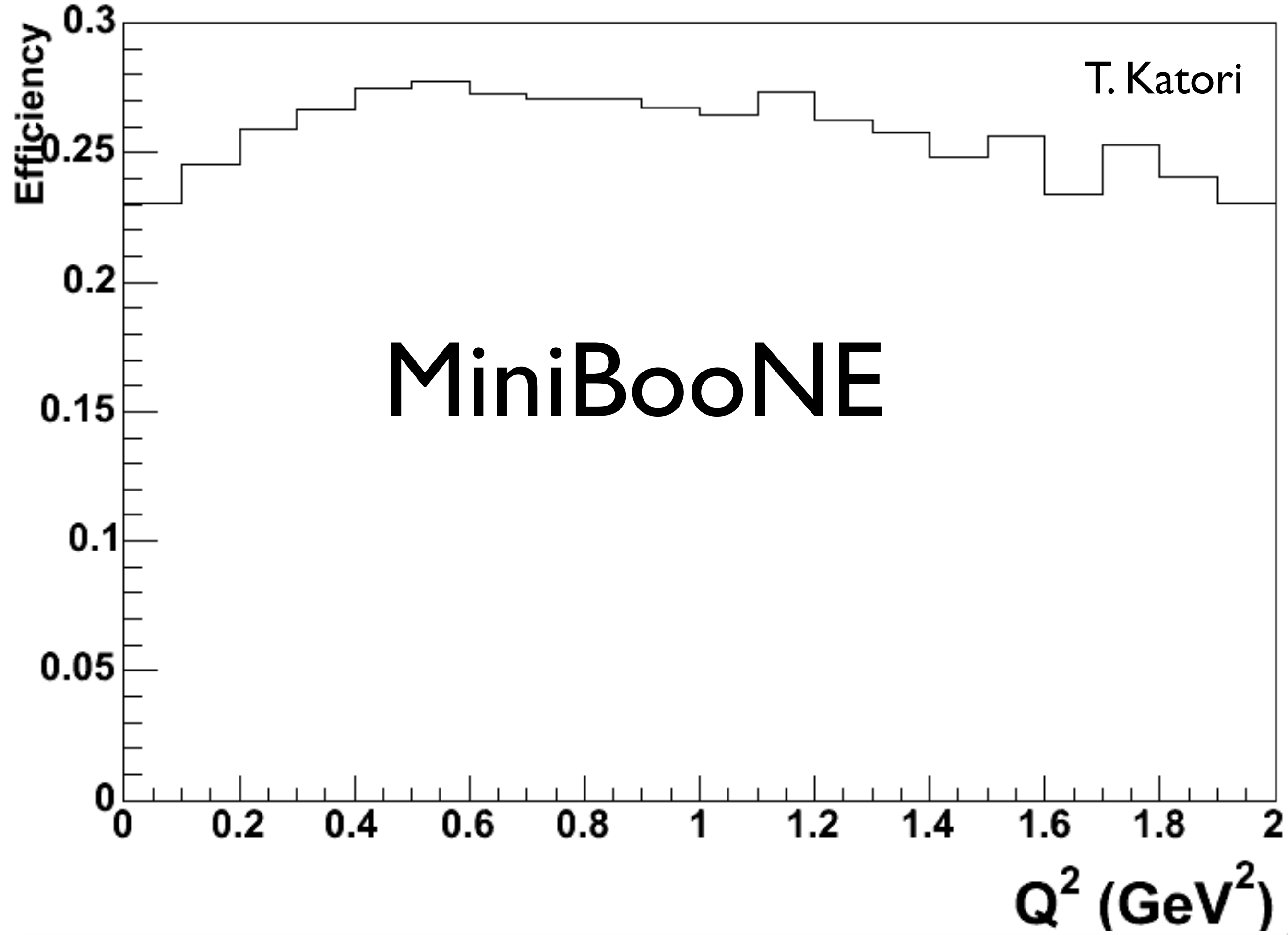
T. Katori

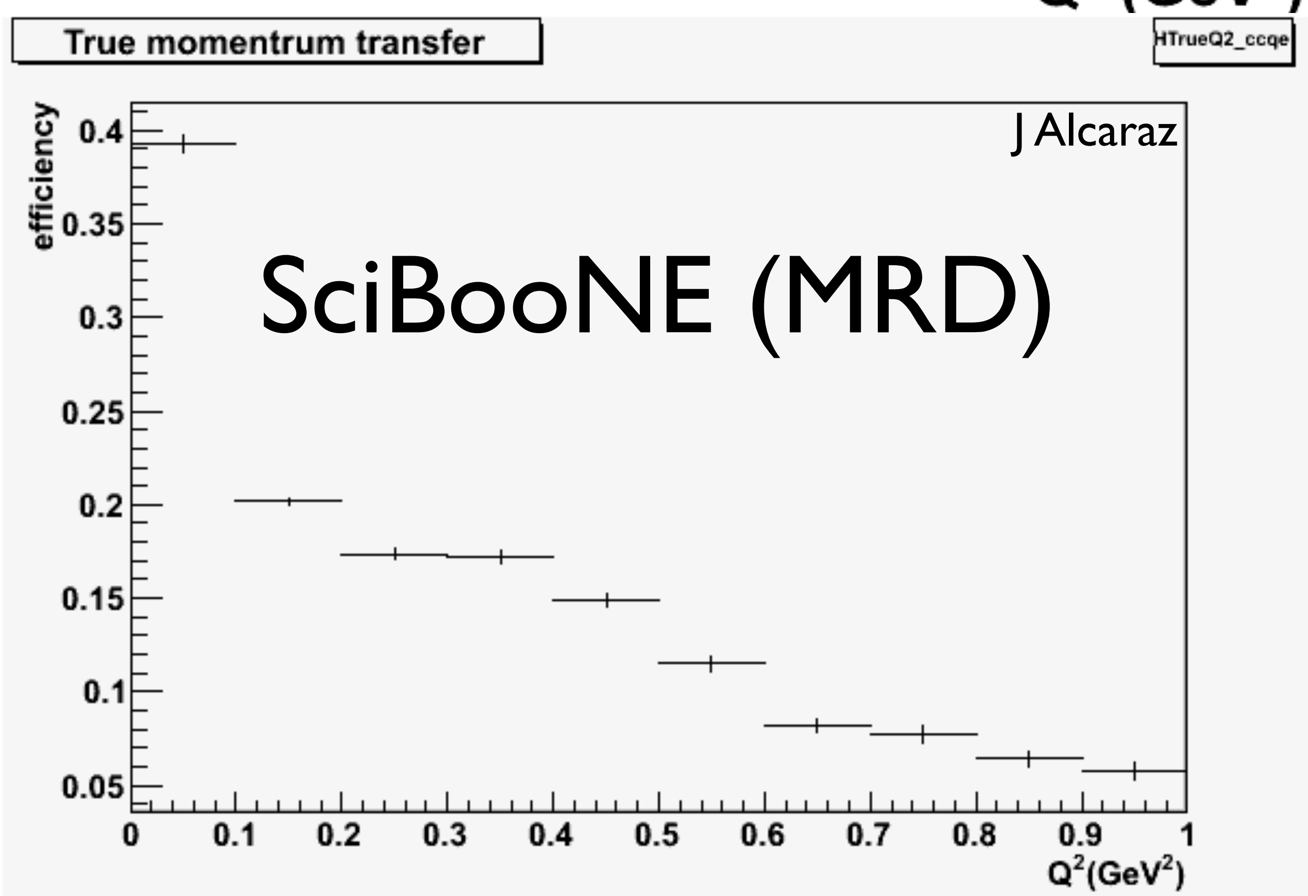


MB CCQE Systematics

Source	δM_A(GeV)	$\delta\kappa$
Data statistics	0.03	0.003
neutrino flux	0.04	0.003
neutrino cross section	0.06	0.004
detector model	0.10	0.003
CCpi+ background shape	0.02	0.007
TOTAL	0.20	0.011

Comparisons

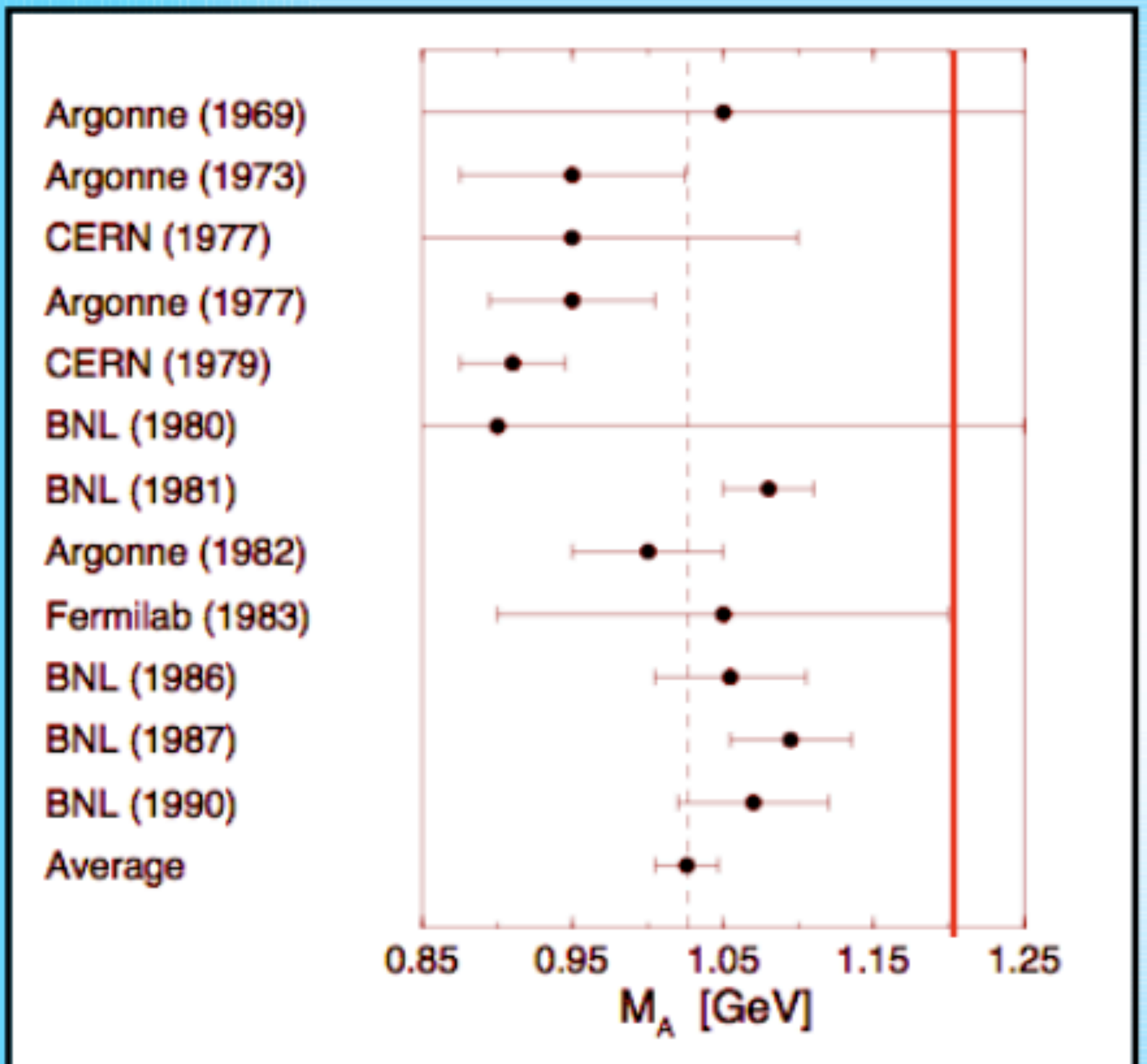




- MiniBooNE has nearly flat acceptance in Q2
  - But no resolution of protons
- SciBooNE (with MRD) falls off quickly because we require a forward going muon
  - SciBar contained analysis is needed!

Summary

Why is this Interesting?



(world avg: $M_A = 1.03 \pm 0.02$ GeV
J.Phys.**G28**, R1 (2002))

- **K2K SciFi** (H_2O, $Q^2>0.2$)
  Phys. Rev. **D74**, 052002 (2006)
  $M_A=1.20 \pm 0.12$ GeV
- **K2K SciBar** (^{12}C, $Q^2>0.2$)
  $M_A=1.14 \pm 0.11$ GeV
- **MiniBooNE** (^{12}C, $Q^2>0.25$)
  $M_A=1.25 \pm 0.12$ GeV

- new results consistent
- 10% measurements of M_A
- modern data measuring systematically higher M_A **(measuring an "effective M_A")**

?

Sam Zeller, 06/01/07

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References

- SciFi: Phys.Rev. D74 (2006) 052002, hep-ex/0603034v1
- SciBar: NuInt07 proceedings
- MinBooNE: Phys.Rev.Lett **100**:032301 (2008) arXiv:0706.0926v2 [hep-ex]

I didn't mention:

- NOMAD: arXiv:0812.4543v3 [hep-ex]
    - $M_A = 1.05 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$ GeV.