Neutrino Detectors for future facilities - III

Mark Messier
Indiana University

NUFACT Summer school
Benasque, Spain June 16-18, 2008

Neutrino detectors optimized for muons reconstruction

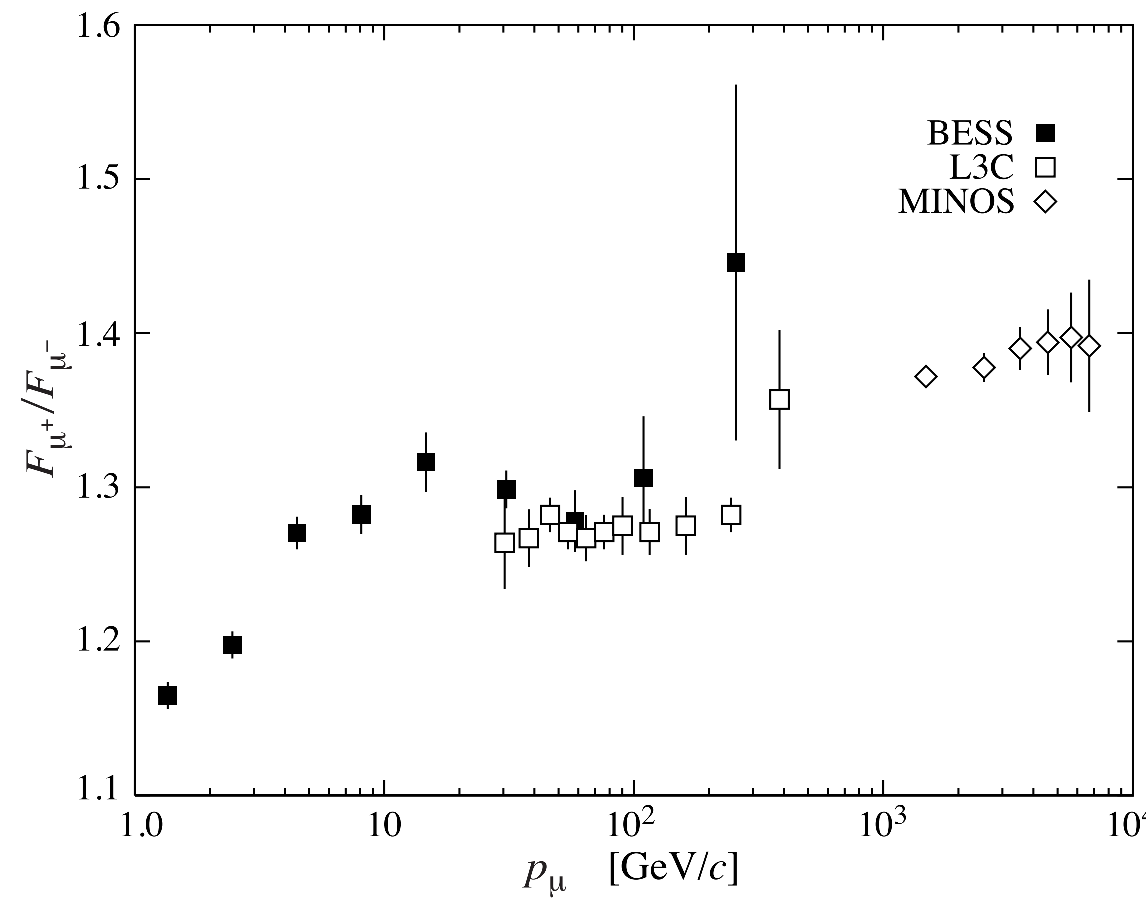
$\nu_\mu \rightarrow \nu_\mu$

and the

"Golden Channel" $\nu_e \rightarrow \nu_\mu$

Why magnetize?

- *Containment:* A magnetic field can keep muons from exiting the sides of your detector
- *Momentum measurement:* If the muon does exit your detector, the curvature of the track tells you the momentum even when you couldn't otherwise get it from the range of the particle
- *Charge sign:* There are physics measurements in knowing the charge sign of the muons in your detector. Crucial for the "golden channel" at a neutrino factory:



Cosmic-ray **μ**+/**μ**- ratio

$$\mu^+ \longrightarrow e^+ \bar{\nu}_\mu \nu_e \quad \begin{cases} \bar{\nu}_\mu \longrightarrow \bar{\nu}_\mu \\ \nu_e \longrightarrow \nu_\mu \end{cases}$$

$$\bar{\nu}_\mu + A \rightarrow \mu^+ + X$$

$$\nu_\mu + A \rightarrow \mu^- + X$$

production → *oscillation* → *detection*

"wrong" sign!

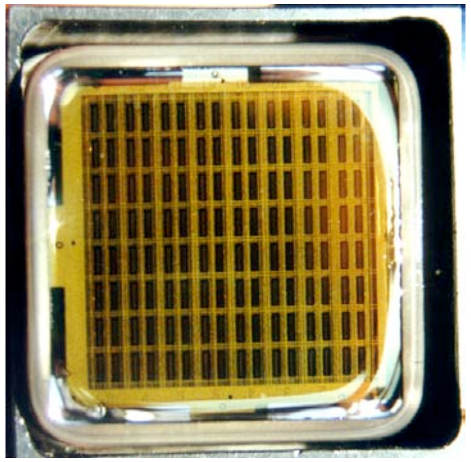
The MINOS Detectors

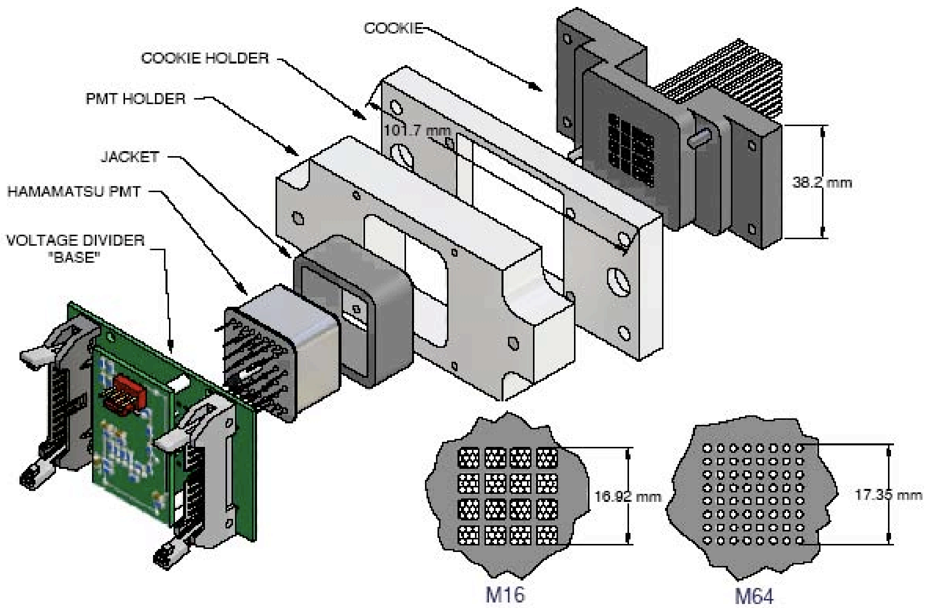
MINOS uses two functionally equivalent detectors:

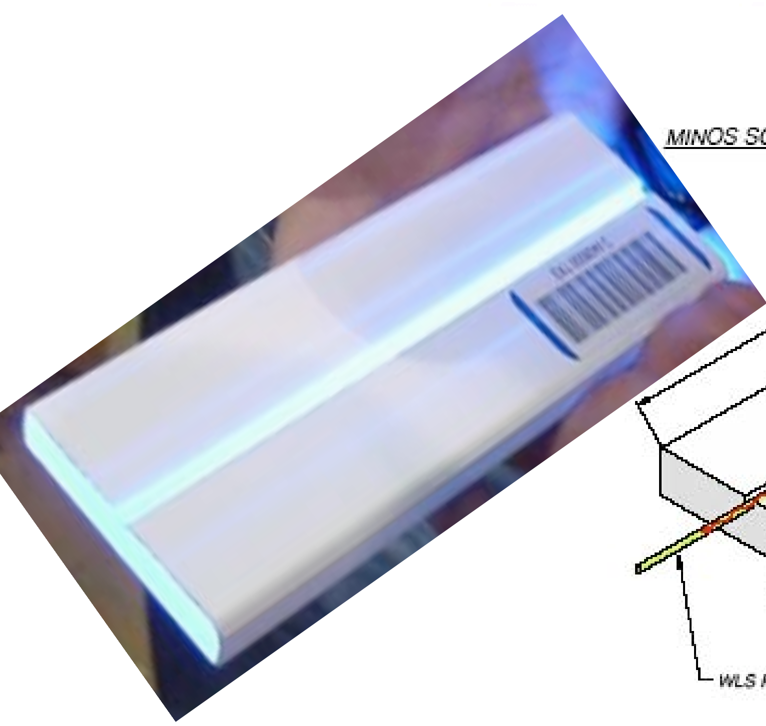
- 2.54 thick magnetized steel plates
- 4.1 x 1 cm co-extruded scintillator strips
- optical fiber readout to multi-anode PMT's

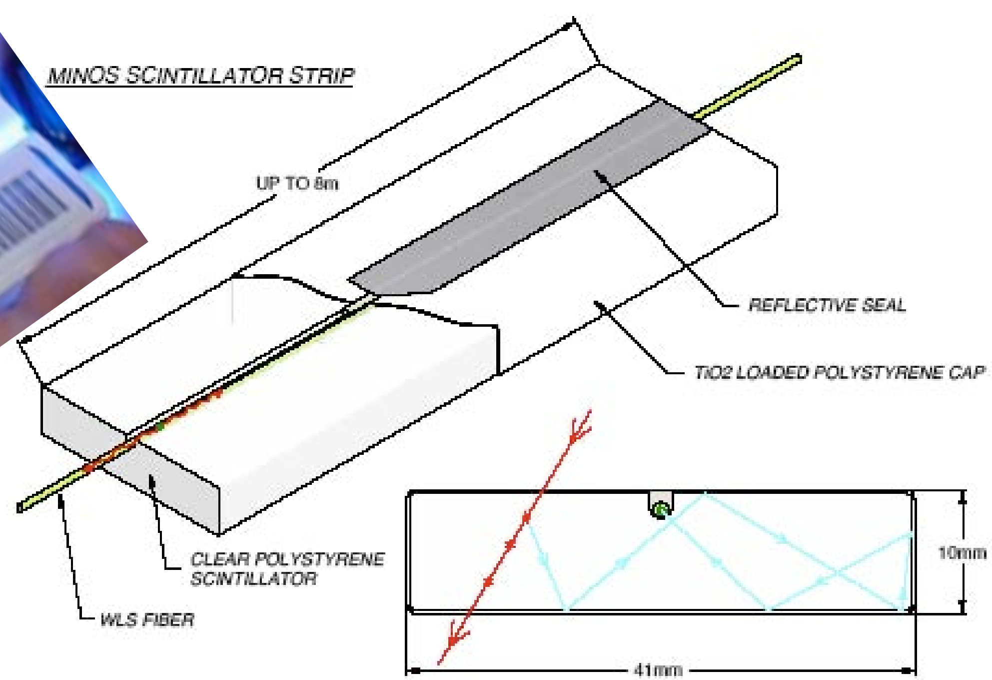
scintillator modules layered on steel plane

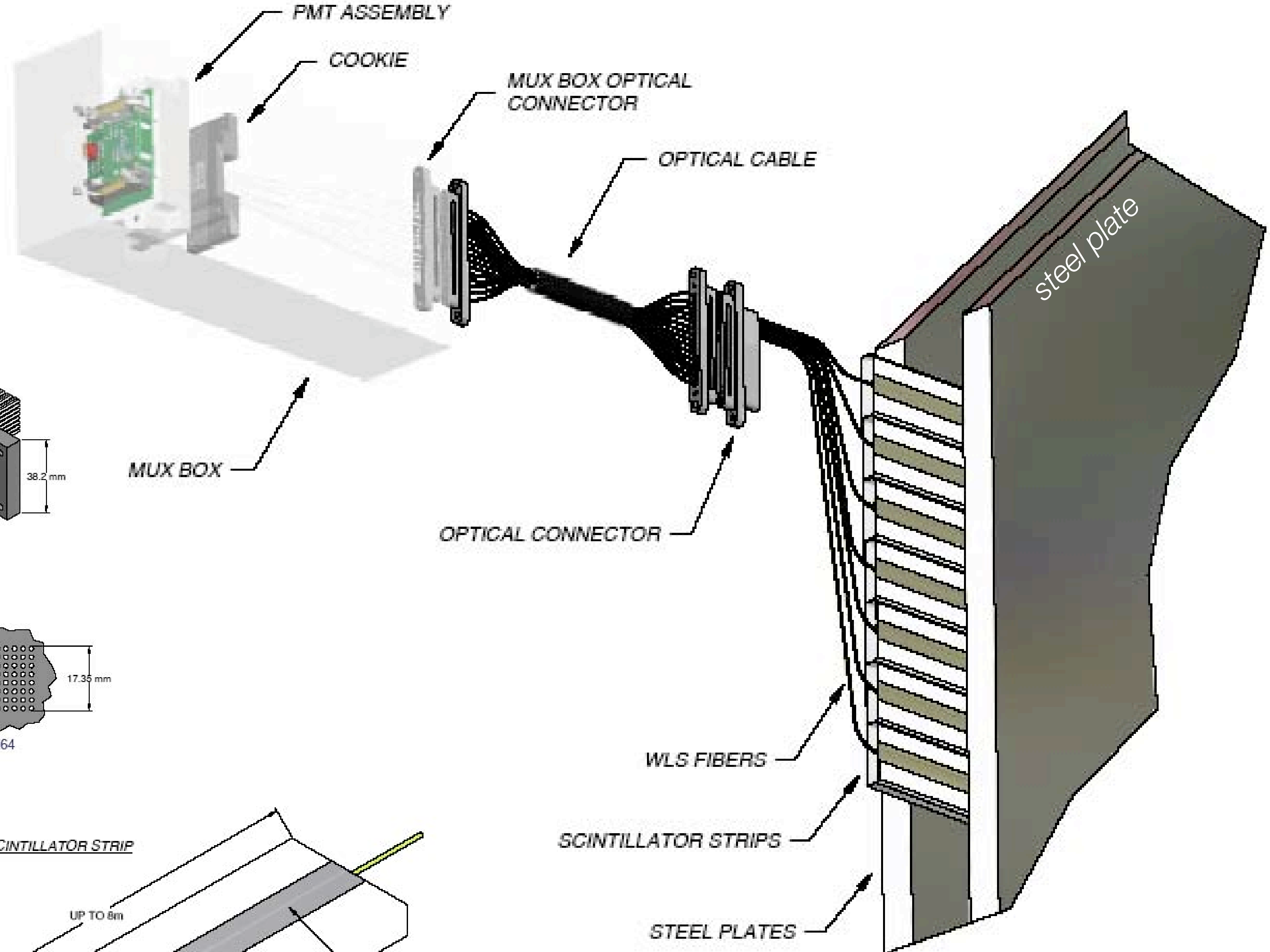
“strong back”. Removed after plane is hung in place





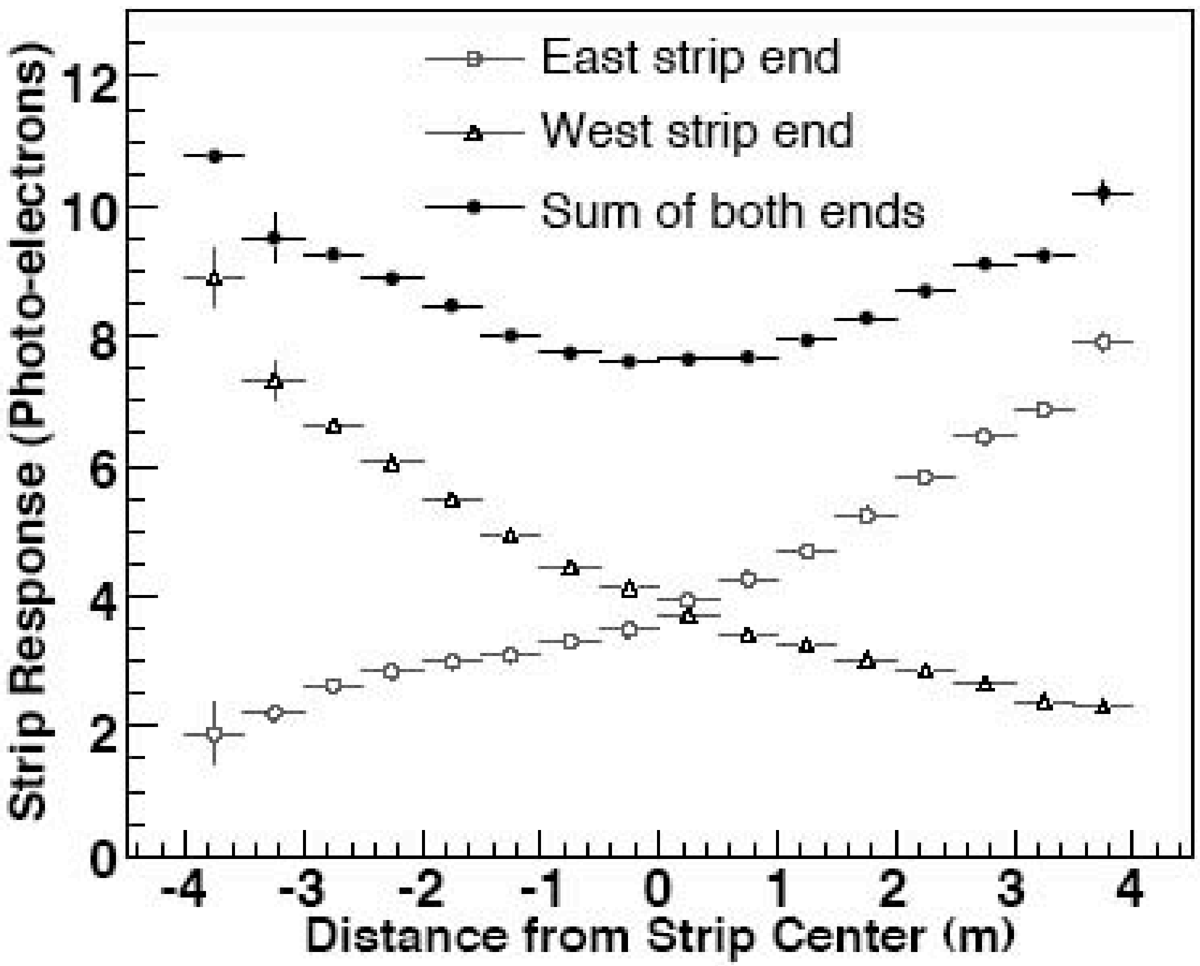






MINOS Detector

MINOS scintillator system



Single strip muon hit efficiency

Single sided:

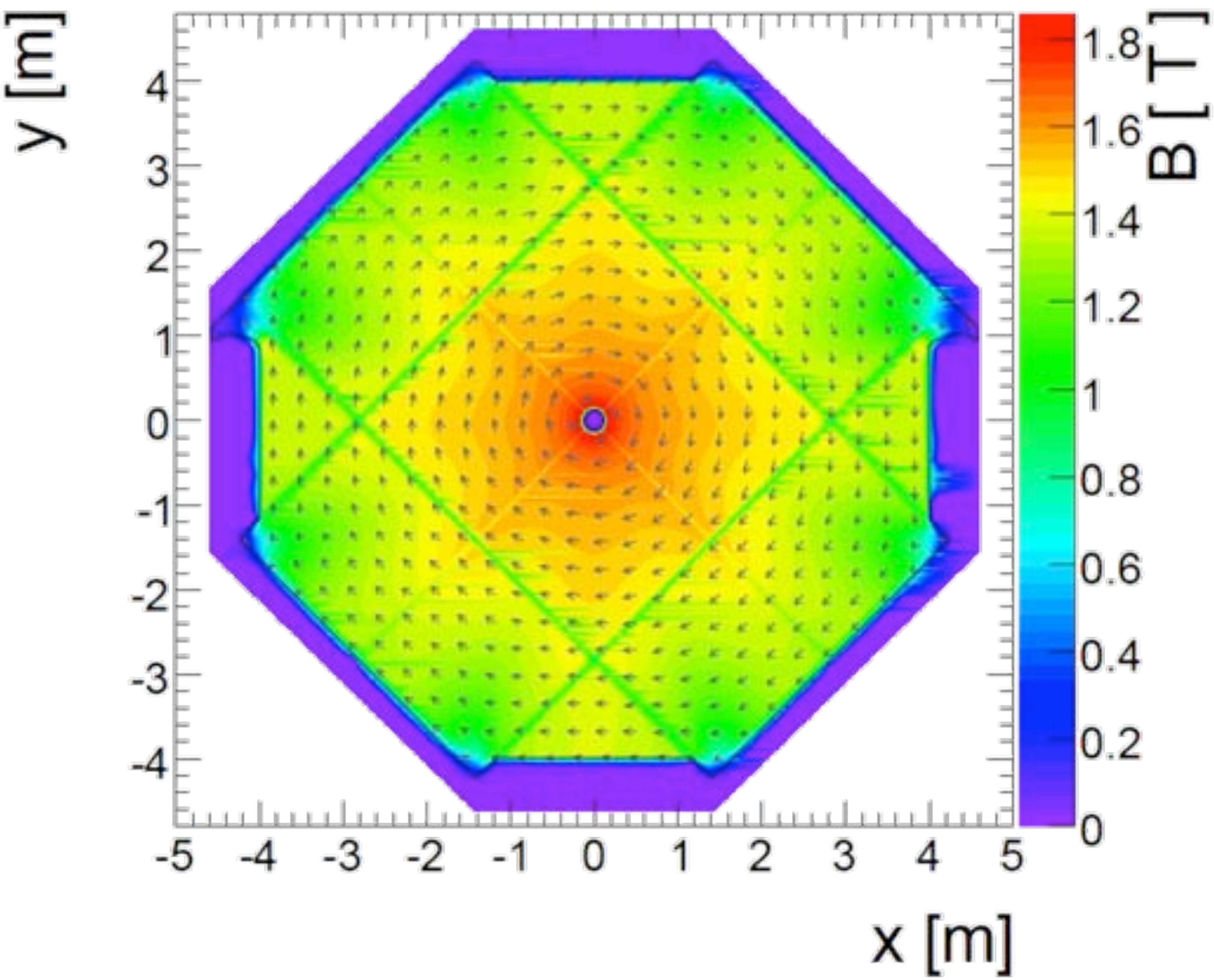
ε=1-exp(-4) = 98%

Double sided:

ε=1-exp(-8) = 99.97%

Fig. 26. Average light output from in-situ Far Detector strips as a function of distance from their center for normally incident MIPs. The data shown are from stopping cosmic-ray muons, for which containment criteria cause lower statistical precision at the ends of the strips.

Magnetic field in MINOS



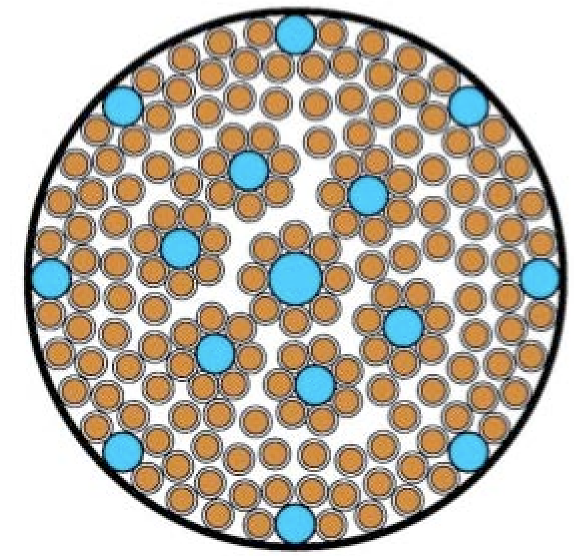
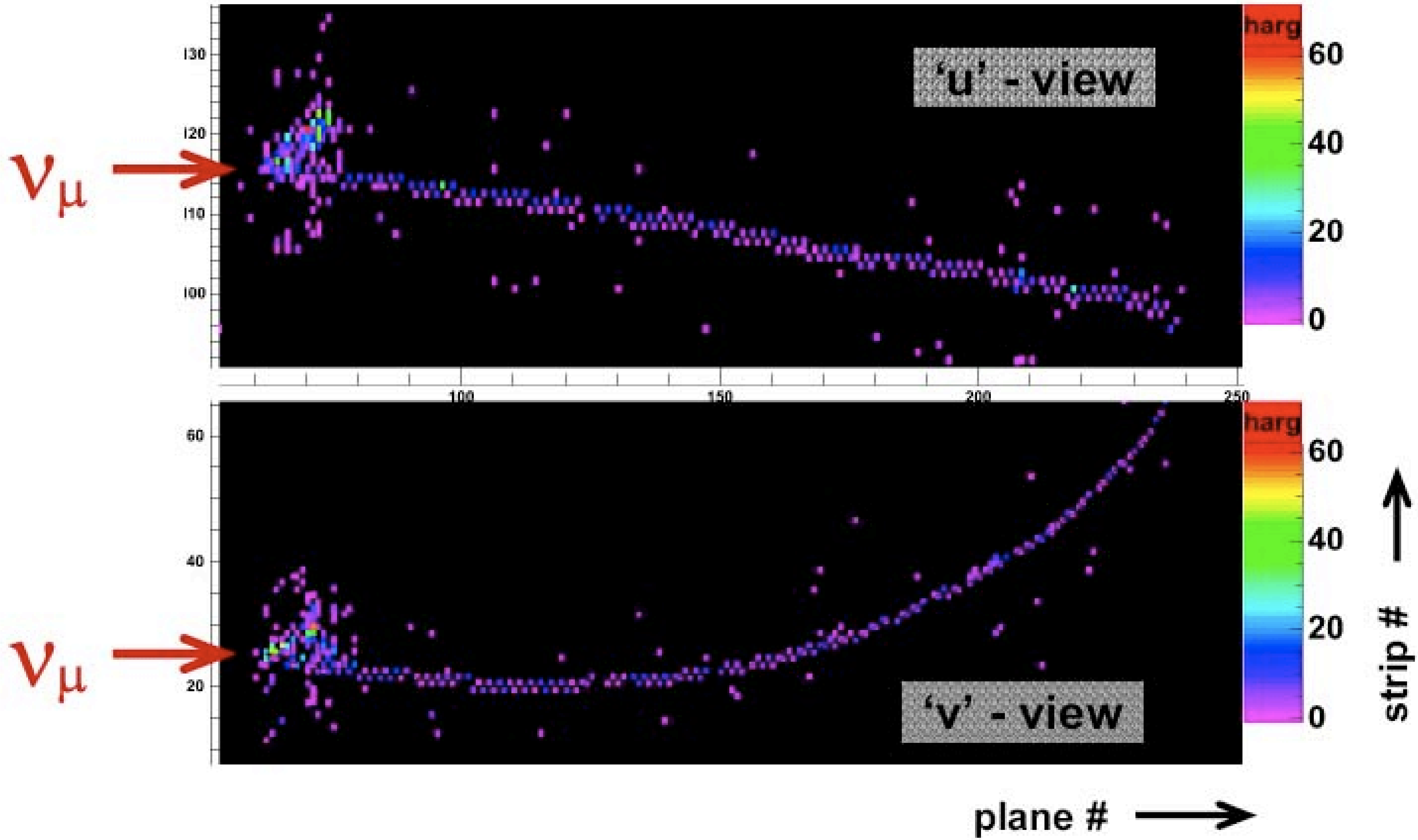


Fig. 6. Sketch of a cross section of one of the far detector supermodule coils. The larger diameter circles represent the copper cooling tubes and the smaller circles are the 190 turns of 1/0 gauge stranded copper wire. The outlines of these conductors are to-scale representations of the insulator thickness. The outer circumference of the assembly is a copper-sheet jacket that is directly cooled by eight cooling tubes.

- 15.2 kA-turn total current
- 80 A supply
- 10 gauge copper wire, water cooled

MINOS Event



130
120
110
100
100
150
200
250
60
40
20
harg
60
40
20
0
'u' - view
'v' - view
ν_μ
ν_μ
strip #
plane #

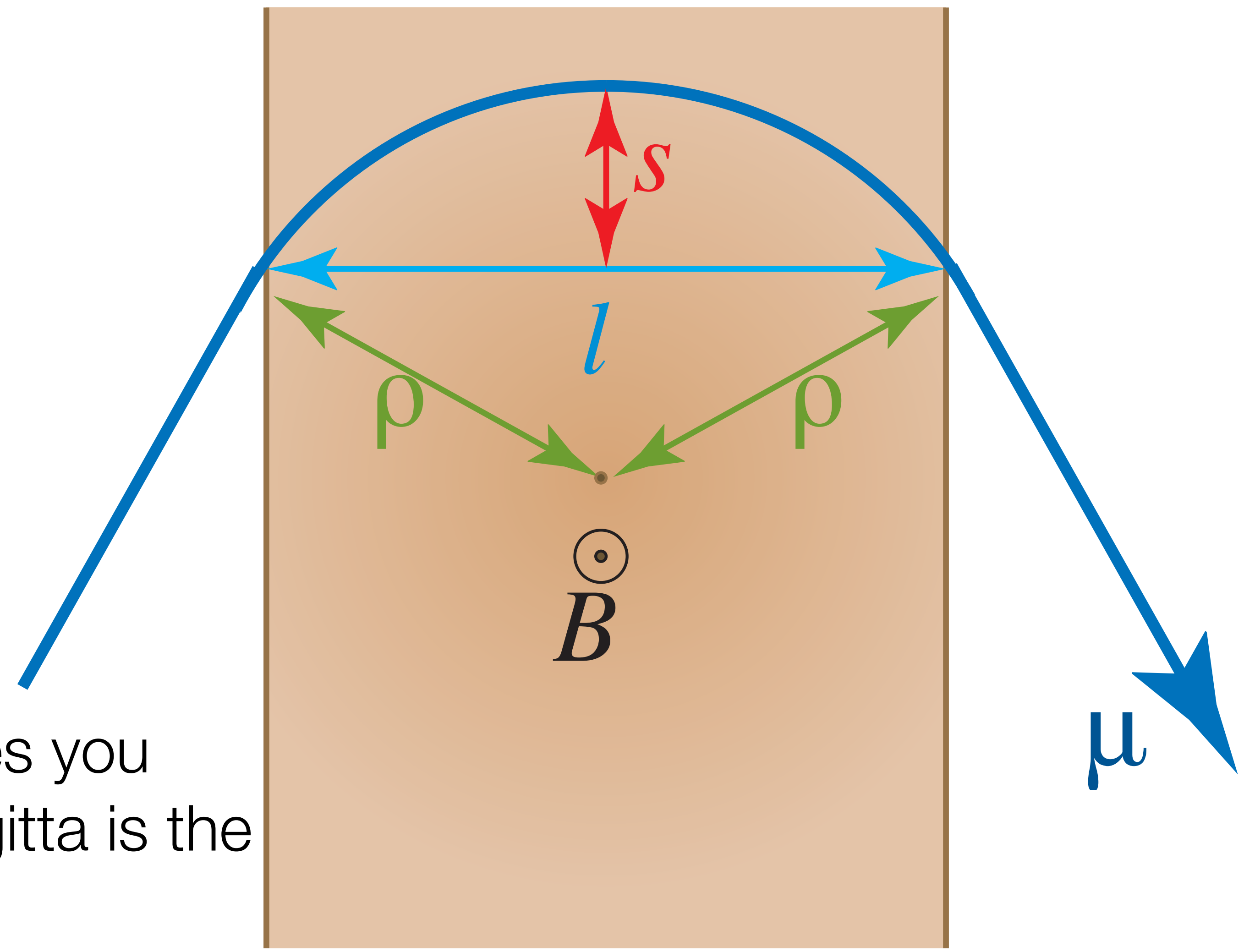
Track momentum using curvature

A particle with momentum p, traveling through a constant transverse magnetic field B will travel on a circle of radius ϱ

$$p[\mathrm{GeV}/c] = 0.2998 B[\mathrm{T}]\rho[\mathrm{m}]$$

$$\rho = \frac{l^2}{8s} + \frac{s}{2}$$

$$p \simeq 0.3\frac{Bl^2}{8s}$$



Measurement of sagitta and chord gives you momentum. Detector resolution on sagitta is the same as the momentum resolution:

$$\left|\frac{\delta p}{p}\right| = \left|\frac{\delta s}{s}\right|$$

More common to talk about the track curvature

$$k = \frac{1}{\rho}$$

which has roughly Gaussian errors.

Curvature errors for multiple position samples

- The uncertainty in curvature for a track which travels a distance *L* in a magnetic field *B* whose position is sampled *N* times at uniform intervals with a position uncertainty ε has been worked out by Gluckstern [NIM 24 (1963) 381-389]:

$$\sigma_{k,R}^2 = \frac{\epsilon^2}{L^4}\frac{720}{N+5}$$

Notice relative importance of L and ε

- Gluckstern has also worked out the contribution to the uncertainty in the curvature from multiple-scattering:

$$\sigma_{k,M.S.}^2 = \frac{KC_N}{L}$$

- *K* is the RMS projected multiple scattering angle per unit thickness *x*

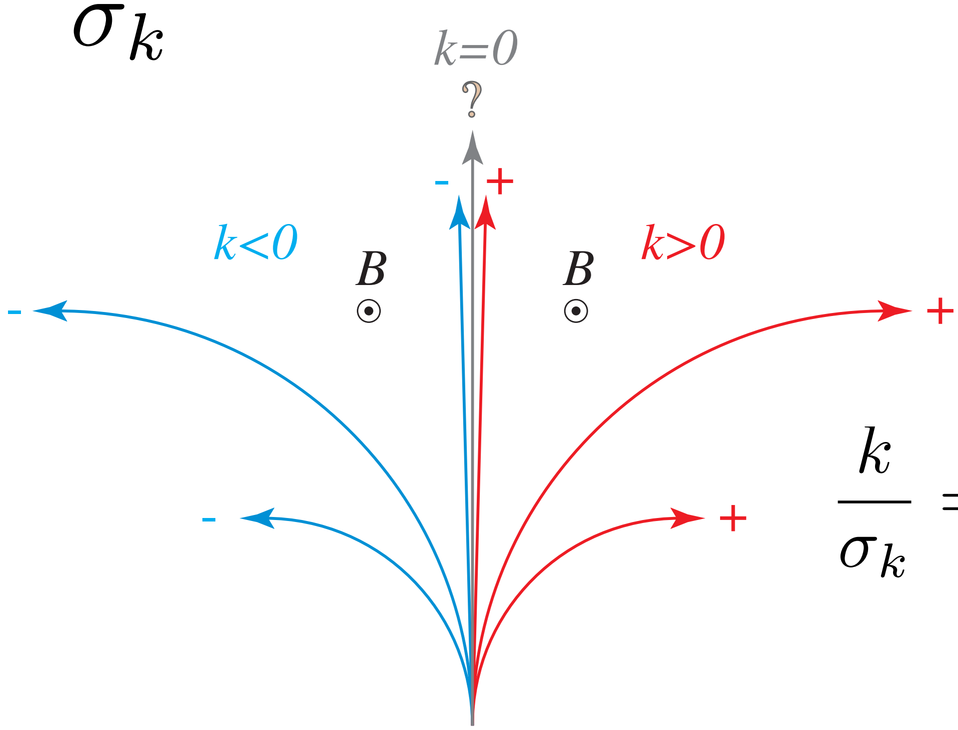
$$\begin{aligned} K &= \frac{\theta_0}{\sqrt{3}x} \\ &= \frac{13.6\ \mathrm{MeV}}{\beta c p} z\sqrt{\frac{1}{3xX_0}}\left[1 + 0.038\ln(x/X_0)\right] \end{aligned}$$

- C_N is a constant from lookup table. C_N=1.43 for large N.

- *x* is the distance traveled in the medium
- *z* is the charge of the particle

How well do we measure track curvature?

$\frac{k}{\sigma_k}$ determines how well the track curvature, and hence sign is known

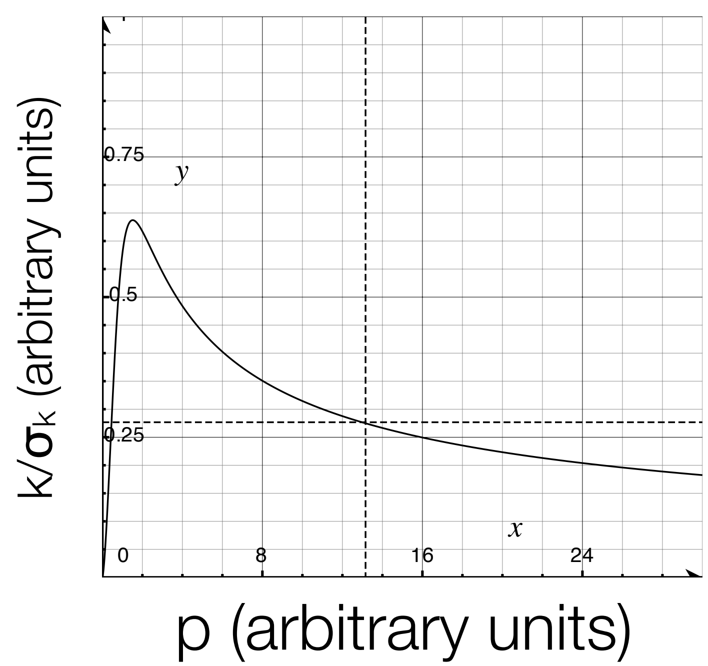


$$\frac{k}{\sigma_k} \quad k = \frac{0.3B}{p}$$

$$\sigma_k^2 = \sigma_{k,R}^2 + \sigma_{k,M.S.}^2$$

$$\frac{k}{\sigma_k} = \frac{0.3B}{\left(\frac{720\epsilon^2 p^2}{L^4(N+5)} + 0.0079 C_N \sqrt{\frac{p^2+m^2}{x X_0}}\left(1 + 0.038 \log \frac{x}{X_0}\right)\right)^{\frac{1}{2}}}$$

units: [T], [GeV], [m]

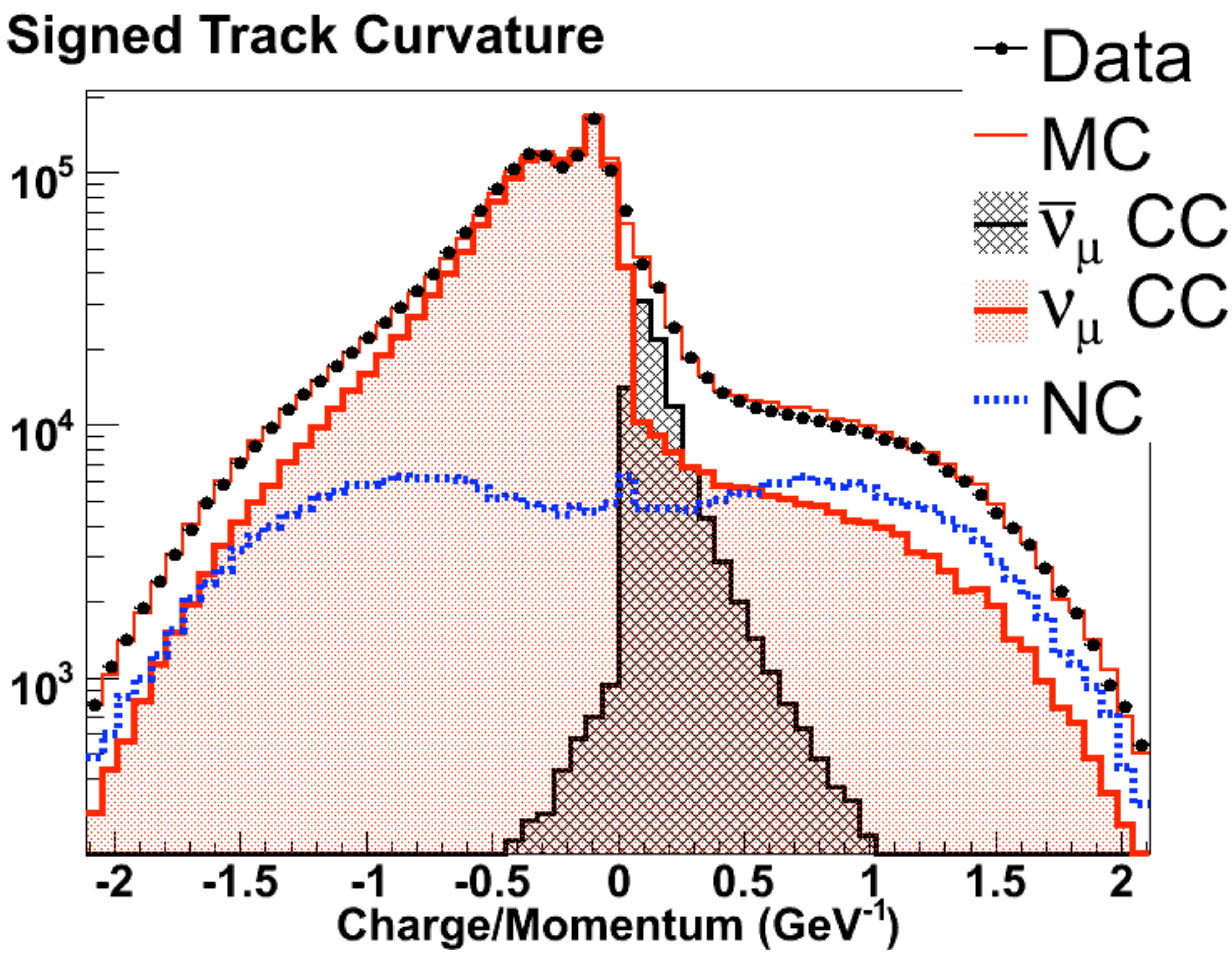


$$\text{Remember}: \; L \propto p, \; N \propto p, \; \text{and } x \propto p$$

- High field
- Small ε
- Large L (low Z to keep dE/dx low and range high)
- Large X_0 (low Z)
- “Just” right momentum (see plot at left)

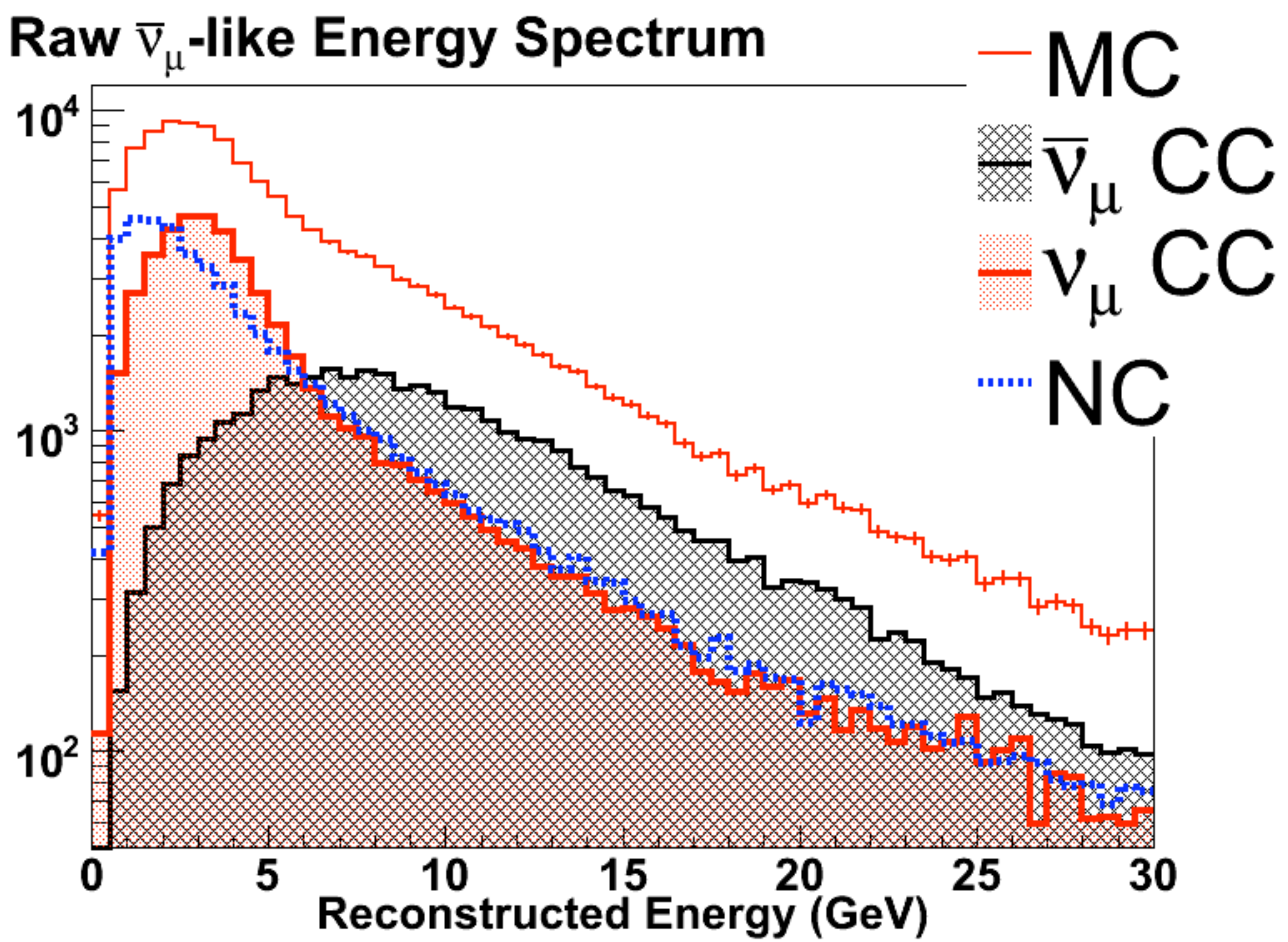
MINOS Track curvature

A. Weber, *"The MINOS Experience"*, Golden'07, Valencia, Spain June 2007.



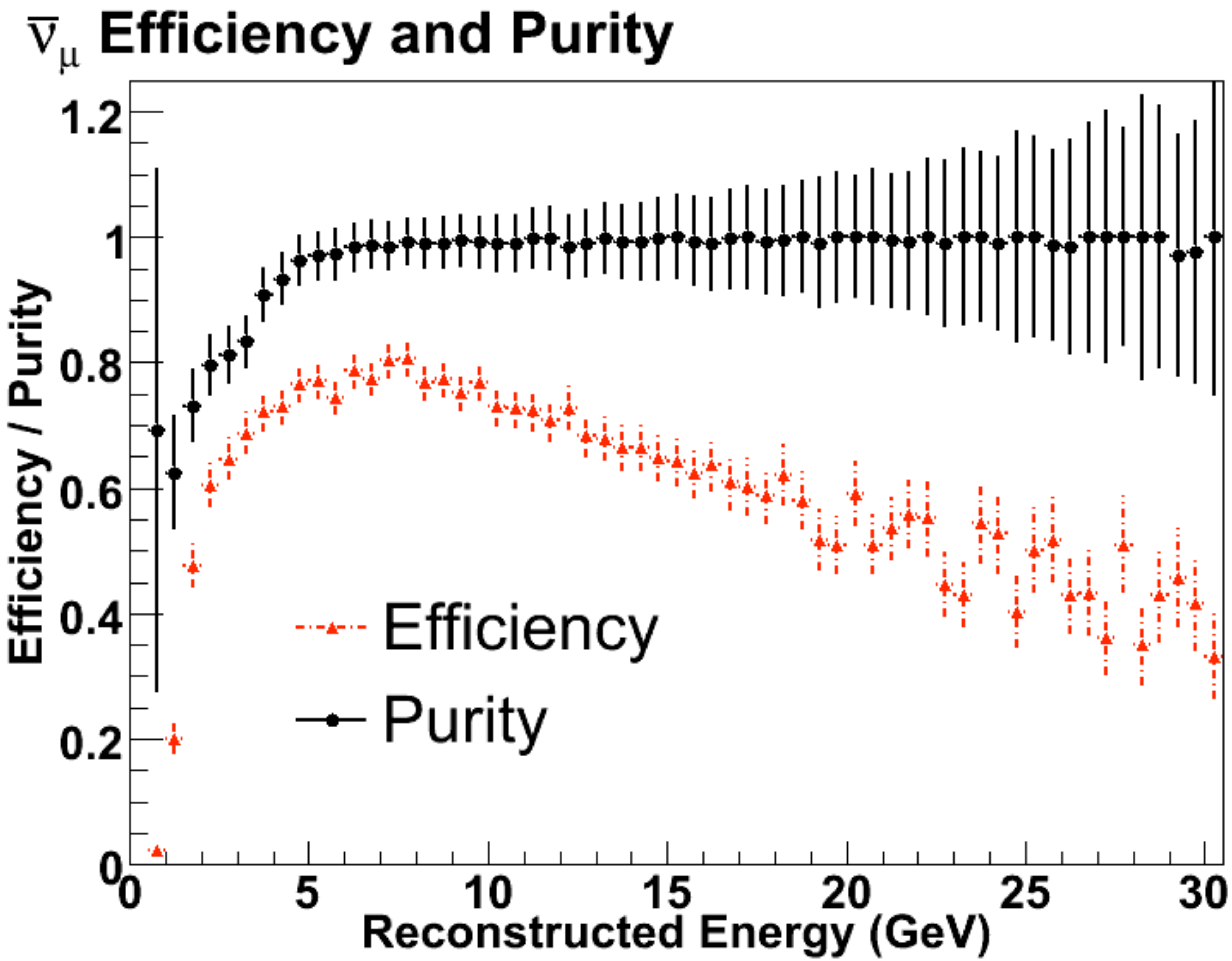
MINOS anti-neutrino spectrum

A. Weber, *"The MINOS Experience"*, Golden'07, Valencia, Spain June 2007.



MINOS charge sign selection efficiency

A. Weber, *"The MINOS Experience"*, Golden'07, Valencia, Spain June 2007.



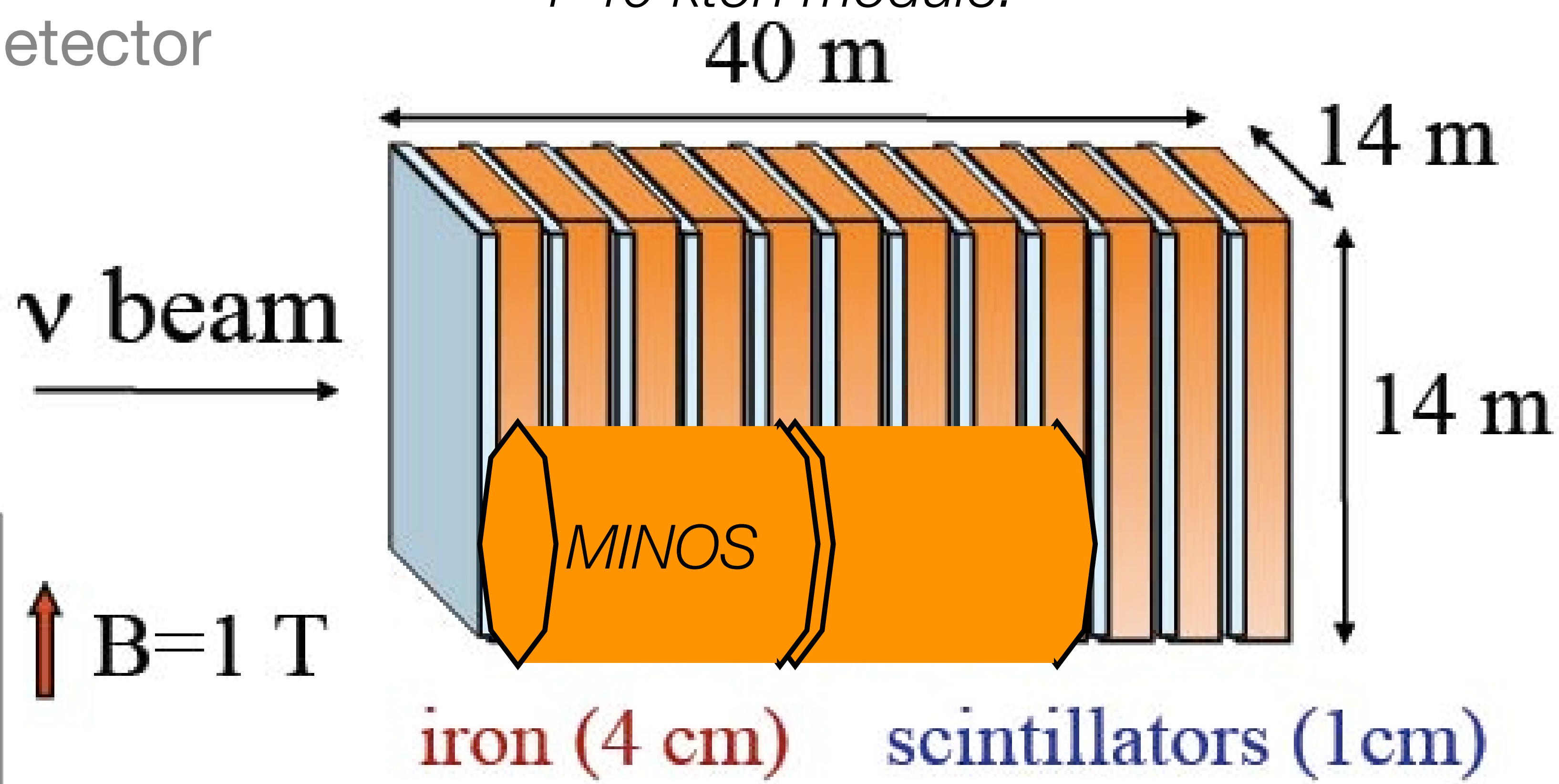
Not optimized for a neutrino factory analysis

“MIND” detector concept for a neutrino factory
(Magnetized Iron Neutrino Detector)

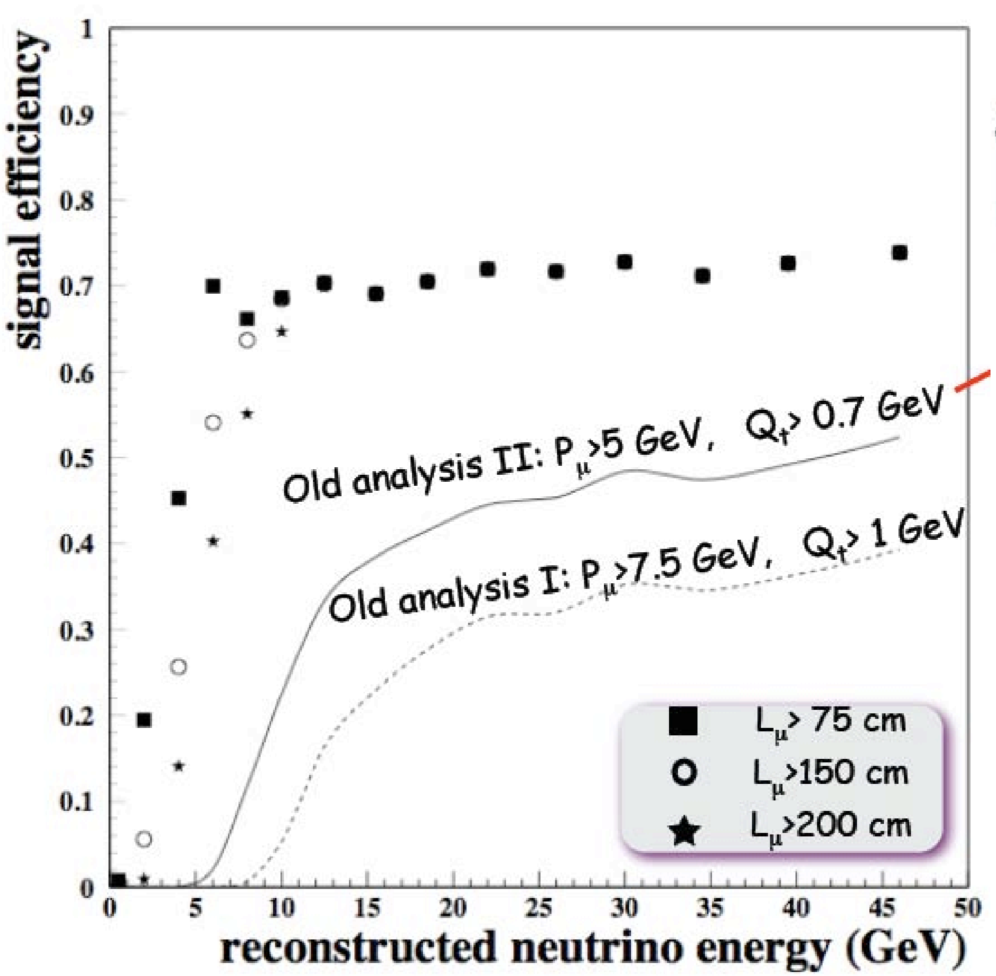
Anselmo Cervera Villanueva, Golden’07

- 50 - 100 kton MINOS-like detector

1 40 kton module:

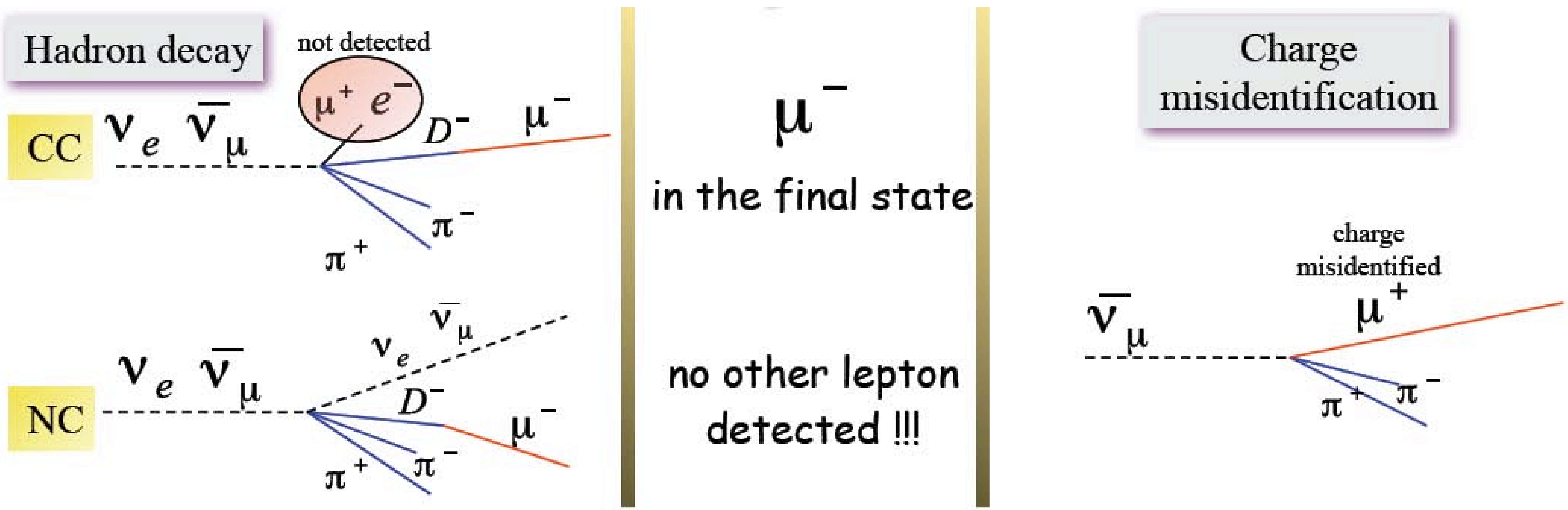


1cm transverse resolution



Backgrounds to the golden channel

Anselmo Cervera Villanueva, Golden'07

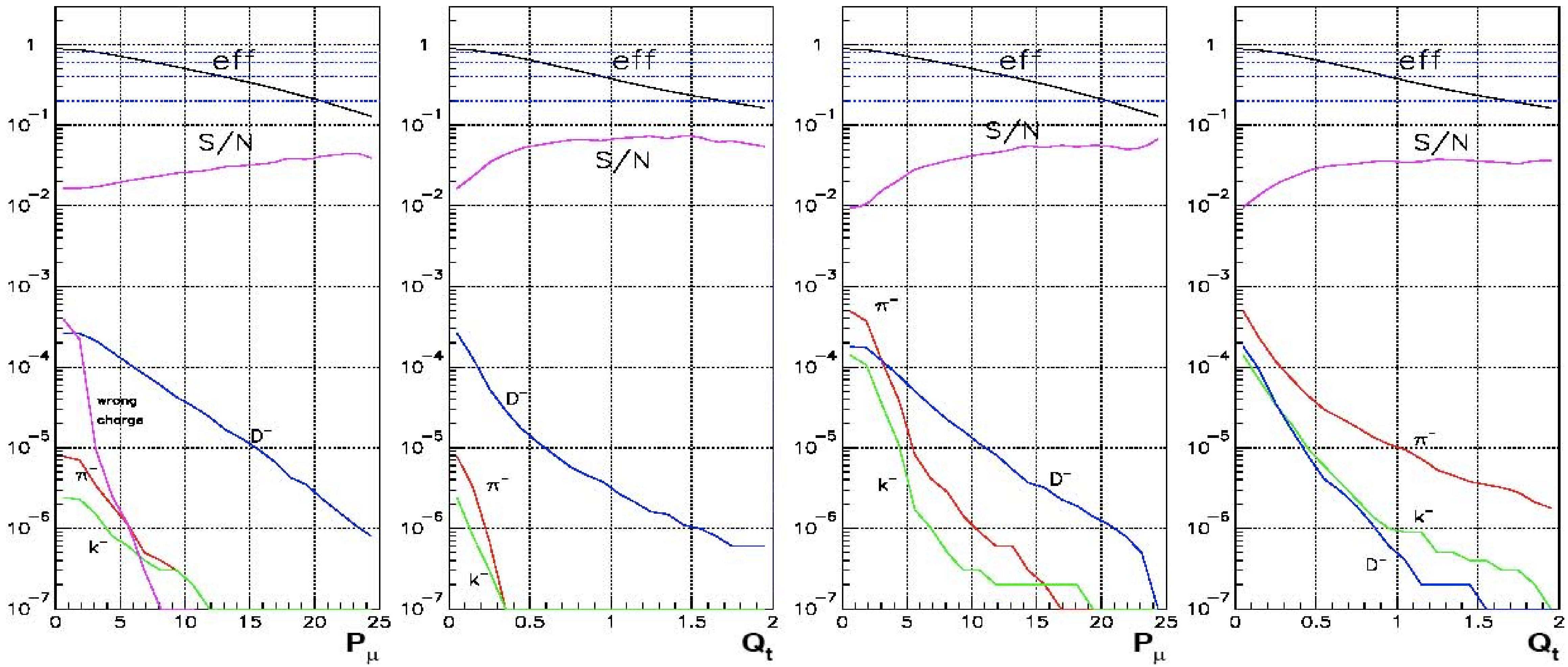


Backgrounds in MIND detector

$\overline{\nu}_\mu$ CC events

$(\overline{\nu}_\mu + \nu_e)$ NC events

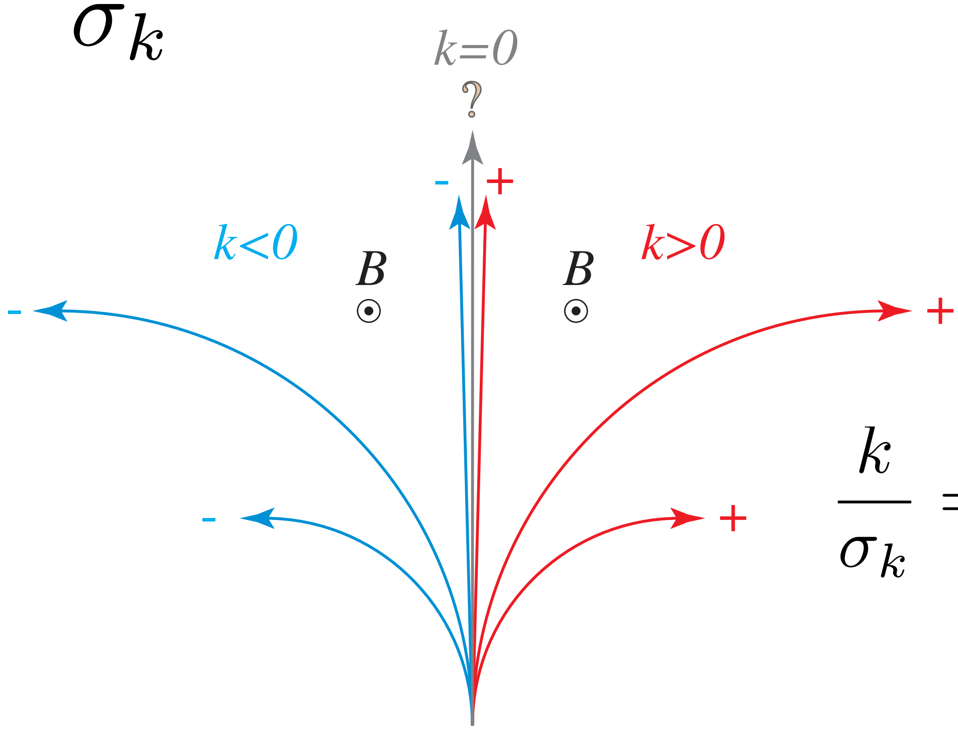
arXiv:0712.4129v1



$Q_t = p_\mu sin\theta_{\mu h}$ measures separation between muon and hadron shower

How well do we measure track curvature?

$\frac{k}{\sigma_k}$ determines how well the track curvature, and hence sign is known

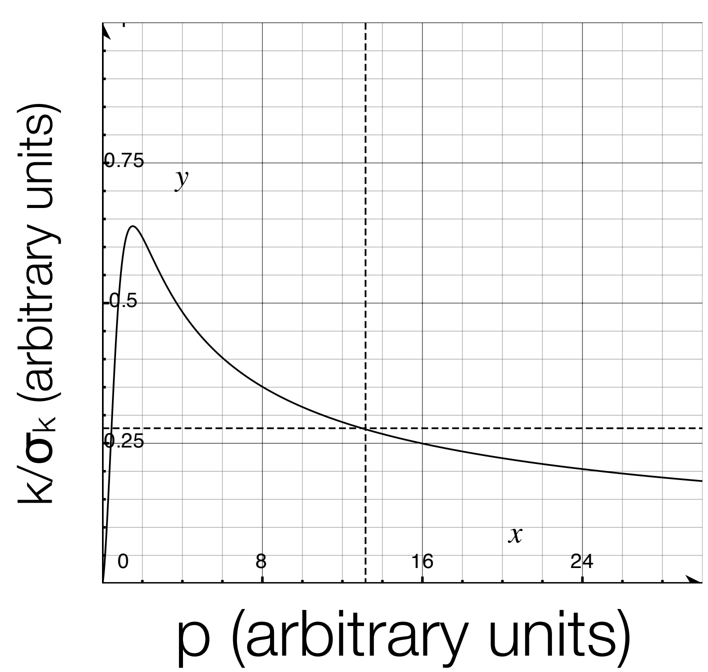


$$\frac{k}{\sigma_k} \quad k = \frac{0.3B}{p}$$

$$\sigma_k^2 = \sigma_{k,R}^2 + \sigma_{k,M.S.}^2$$

$$\frac{k}{\sigma_k} = \frac{0.3B}{\left(\frac{720\epsilon^2 p^2}{L^4(N+5)} + 0.0079 C_N \sqrt{\frac{p^2+m^2}{x X_0}}\left(1 + 0.038 \log \frac{x}{X_0}\right)\right)^{\frac{1}{2}}}$$

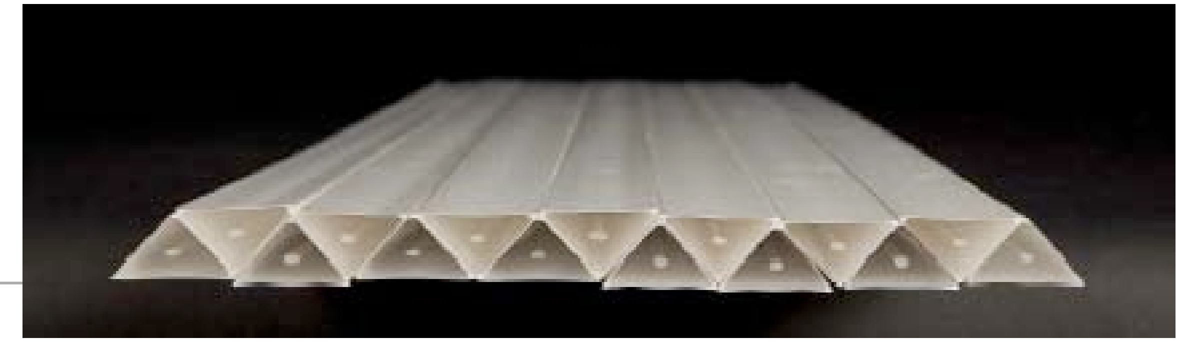
units: [T], [GeV], [m]



$$\text{Remember}: \quad L \propto p, \;\; N \propto p, \;\; \text{and } x \propto p$$

- High field
- Small ε
- Large L (low Z to keep dE/dx low and range high)
- Large X_0 (low Z)
- “Just” right momentum (see plot at left)

Magnetized “TASD”?



- 25 kton “NOVA-like” detector
- 15m x 15m x 100m constructed entirely from “MINERvA”-like solid scintillator
- 0.5 T magnetic field

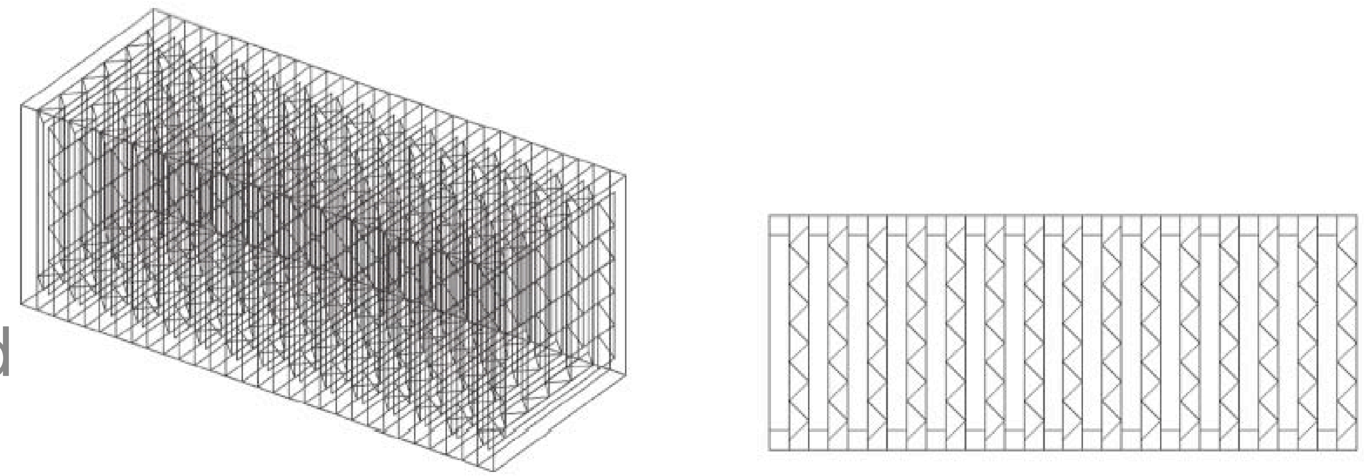
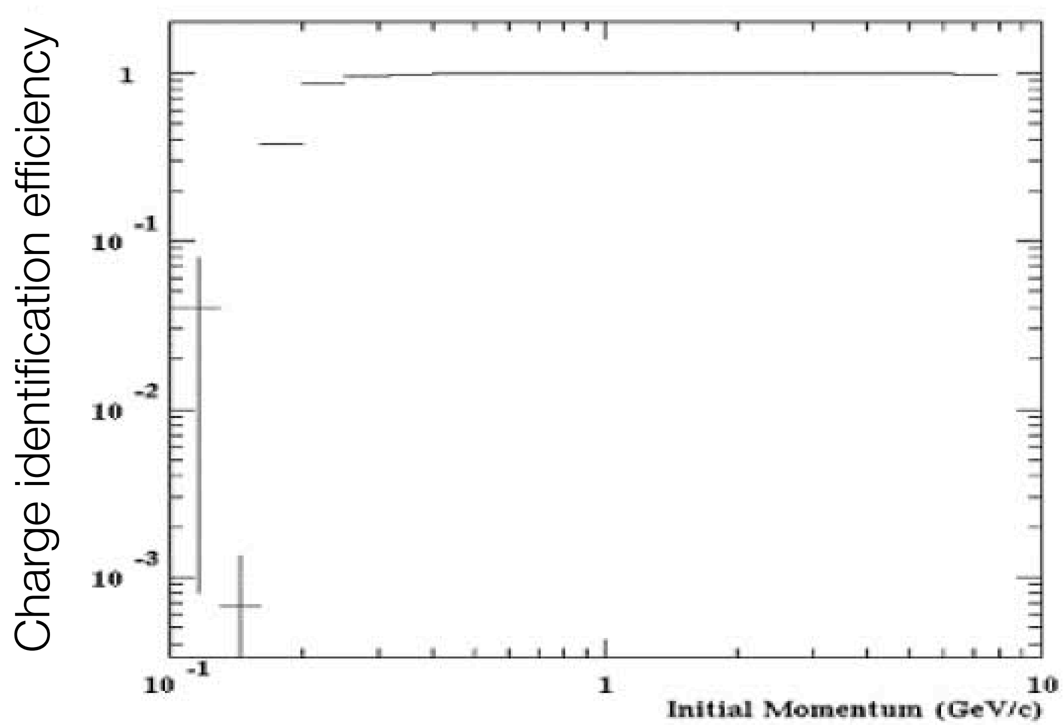
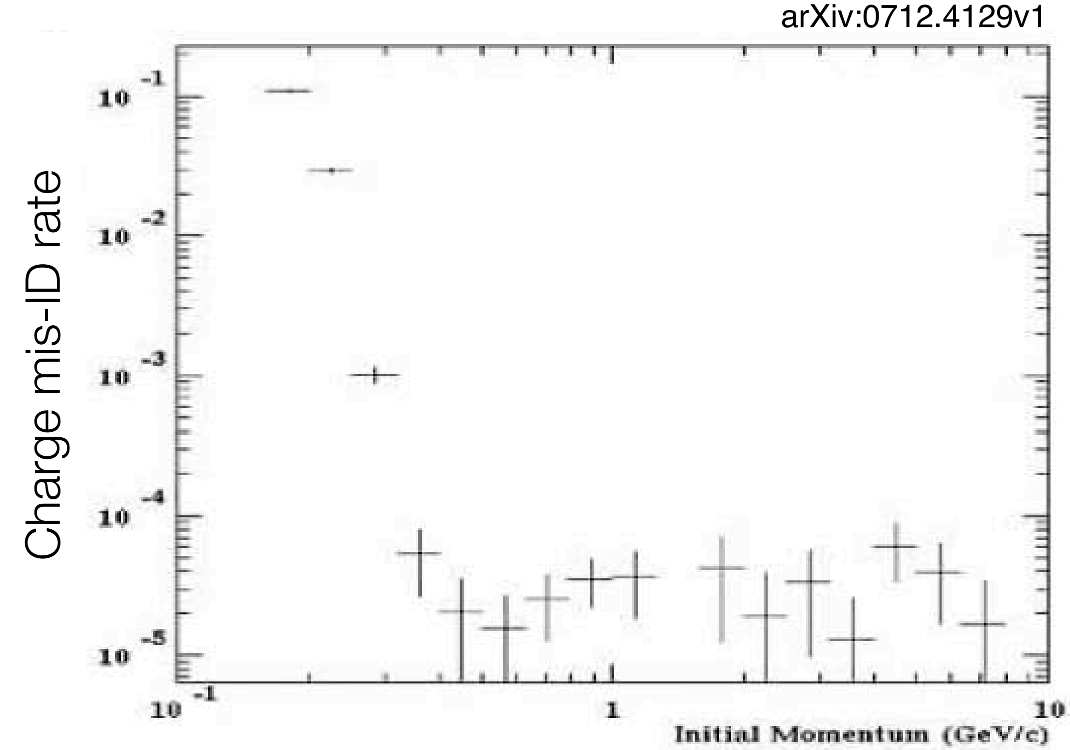


Figure 24: GEANT4 view of the simulated TASD detector.

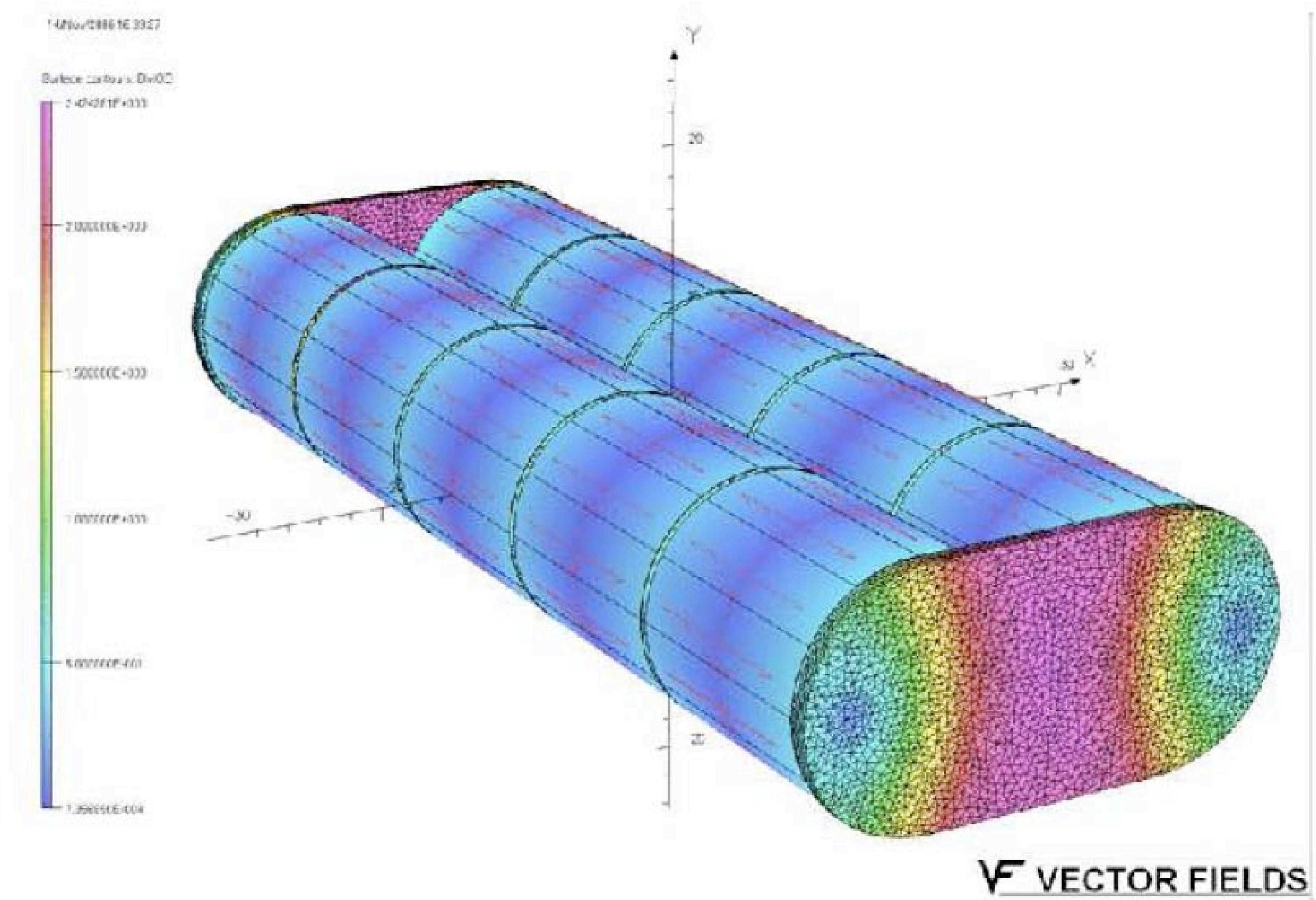


arXiv:0712.4129v1



How to magnetize a large volume?

- Creation of large magnetic fields in a large volume are conceivable if one can sustain a large DC current in transmission lines lining the cavern walls
- Assuming solenoid:



$$
\begin{aligned}
n &= \frac{B}{\mu_0 I} = \frac{1\ \mathrm{T}}{(4\pi \times 10^{-7} \frac{\mathrm{T}}{\mathrm{m \cdot A}})(100\ \mathrm{kA})} \\
&= 8 \frac{\mathrm{turns}}{\mathrm{m}} \\
U &= \frac{1}{2} \frac{B^2}{\mu_0} V \\
&= \frac{1}{2} \frac{(\frac{1}{2}[\mathrm{T}])^2}{4\pi \times 10^{-7} \frac{\mathrm{T}}{\mathrm{m \cdot A}}} (20\ \mathrm{m} \cdot 20\ \mathrm{m} \cdot 20\ \mathrm{m}) \\
&= 1\ \mathrm{GJ} = 300\ \mathrm{kW \cdot hr}
\end{aligned}
$$

Compare to CMS: 2.7 GJ

Cost: Scaling from previous magnets ranges from $20M to $60M

How to magnetize a large volume?

- Creation of large magnetic fields in a large volume are conceivable if one can sustain a large DC current in transmission lines lining the cavern walls
- Assuming solenoid:

$$
\begin{aligned}
n &= \frac{B}{\mu_0 I} = \frac{1\ \mathrm{T}}{(4\pi \times 10^{-7} \frac{\mathrm{T}}{\mathrm{m \cdot A}})(100\ \mathrm{kA})} \\
&= 8 \frac{\mathrm{turns}}{\mathrm{m}} \\
U &= \frac{1}{2} \frac{B^2}{\mu_0} V \\
&= \frac{1}{2} \frac{(\frac{1}{2}[\mathrm{T}])^2}{4\pi \times 10^{-7} \frac{\mathrm{T}}{\mathrm{m \cdot A}}} (20\ \mathrm{m} \cdot 20\ \mathrm{m} \cdot 20\ \mathrm{m}) \\
&= 1\ \mathrm{GJ} = 300\ \mathrm{kW \cdot hr}
\end{aligned}
$$

Compare to CMS: 2.7 GJ

Cost: Scaling from previous magnets ranges from $20M to $60M

FERMILAB-CONF-05-393-TD

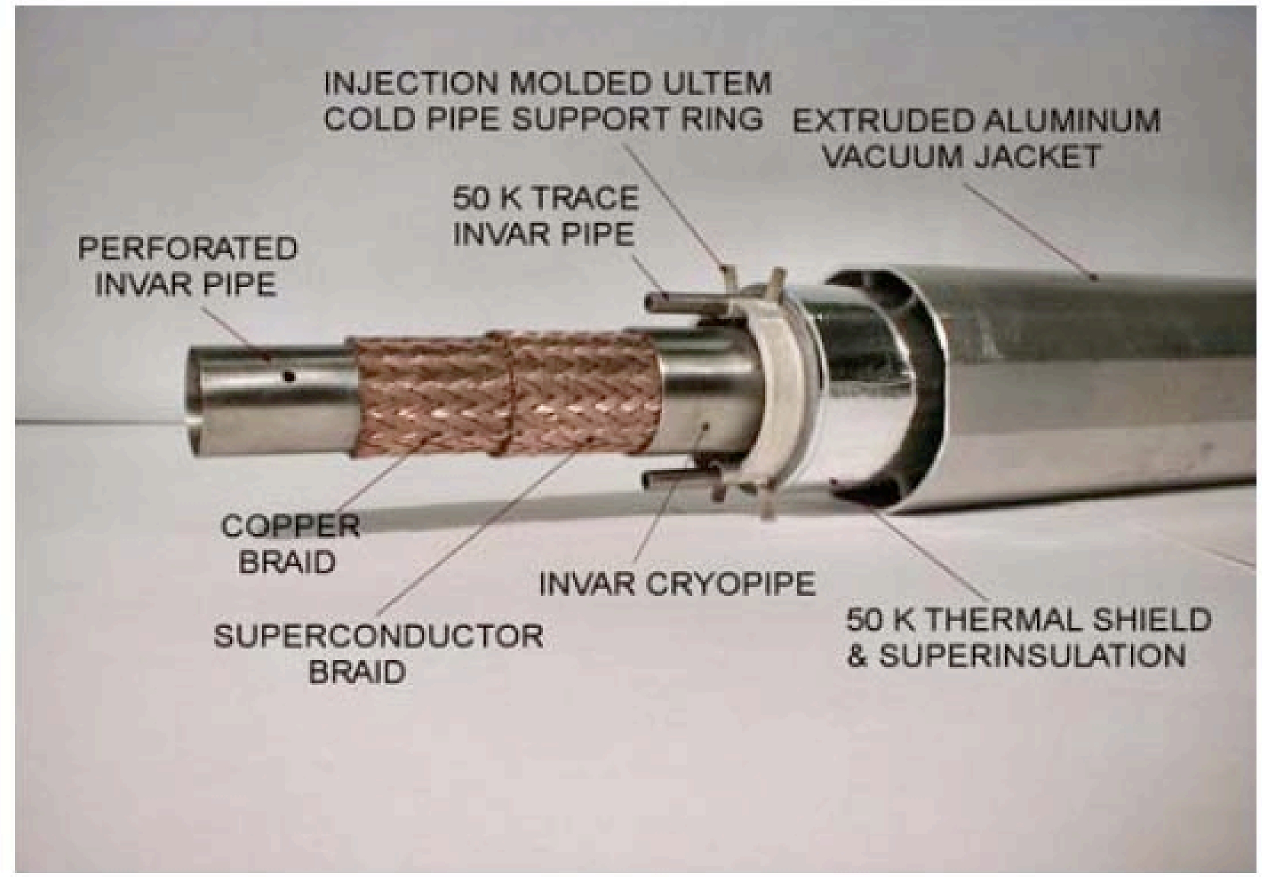
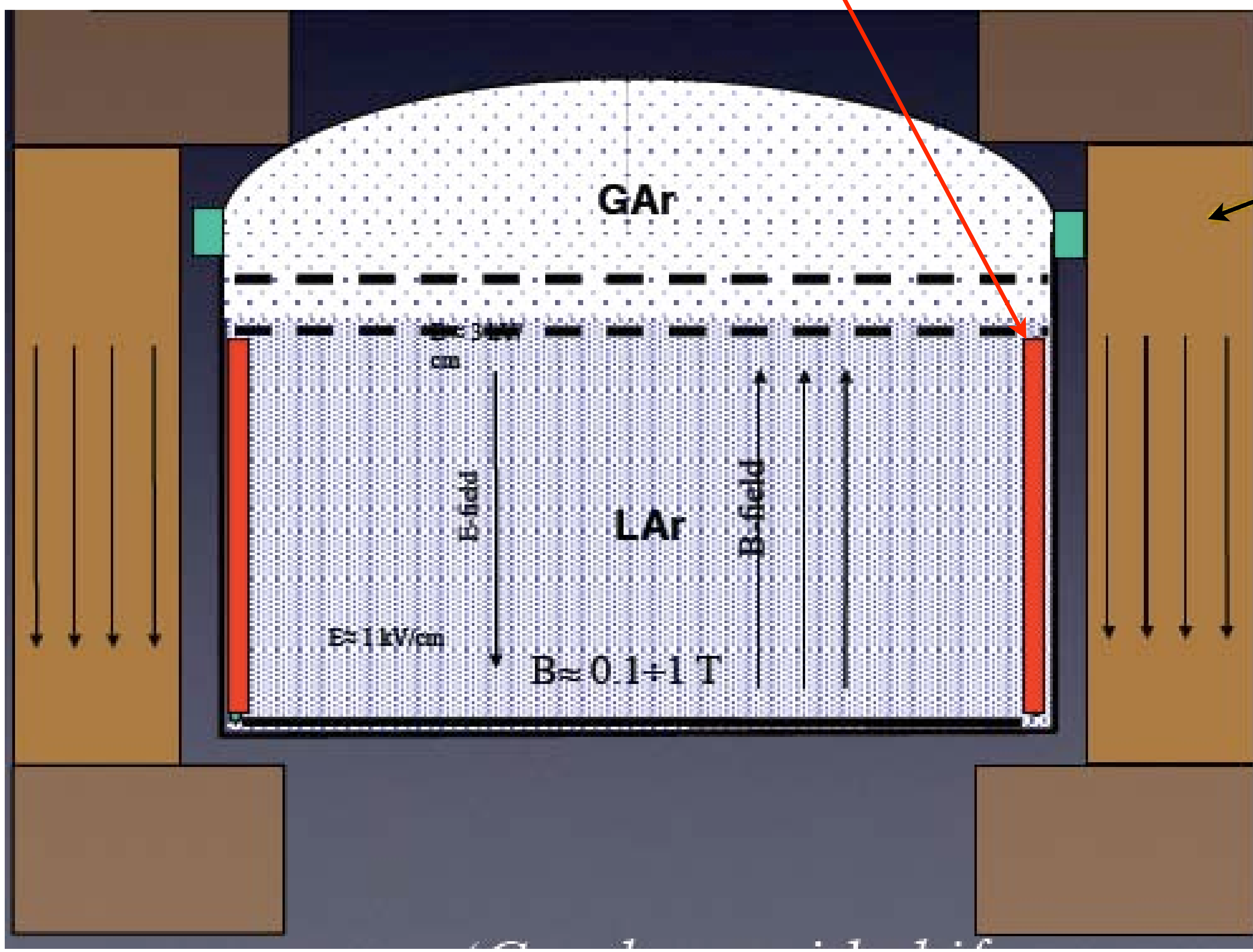


Fig.2. Transmission line superconductor assembly as used in the magnet test.

Superconducting transmission line developed for VHLC magnets at FNAL. Held 100 kA DC operating at Lq HE temperatures.

Concepts for large, magnetized, LqAr detectors

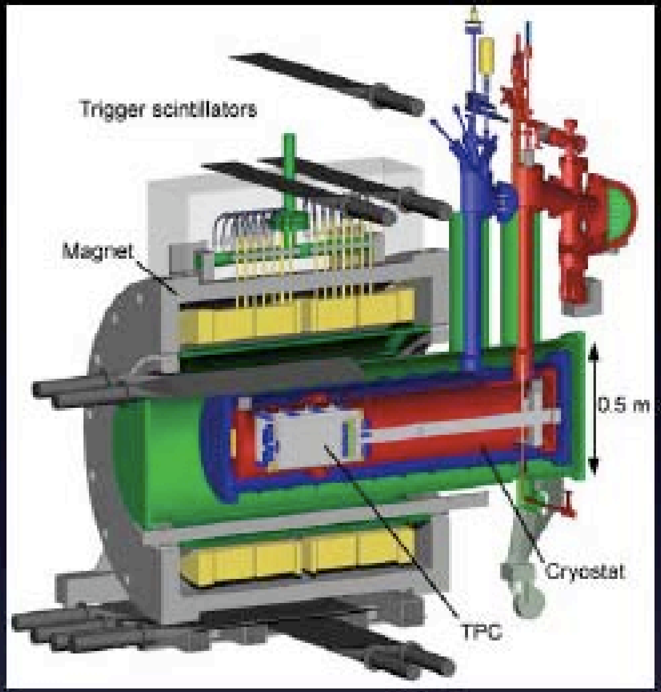
Andre Rubbia, Golden'07

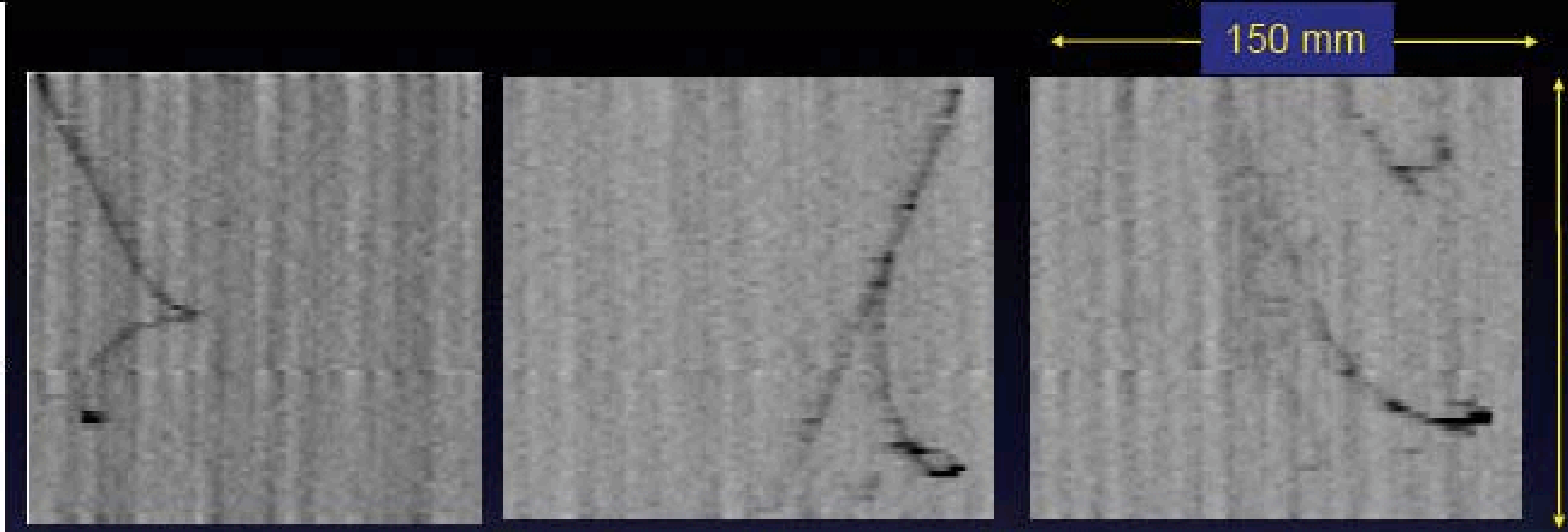


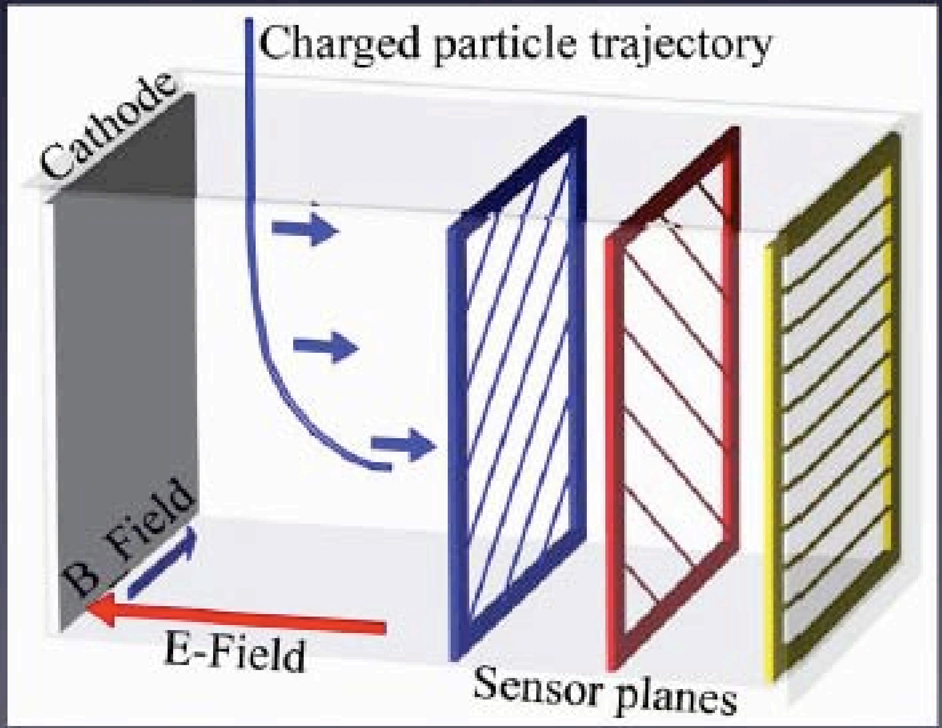
First operation of a LAr TPC embedded in a B-field

First real events in B-field (B=0.55T):

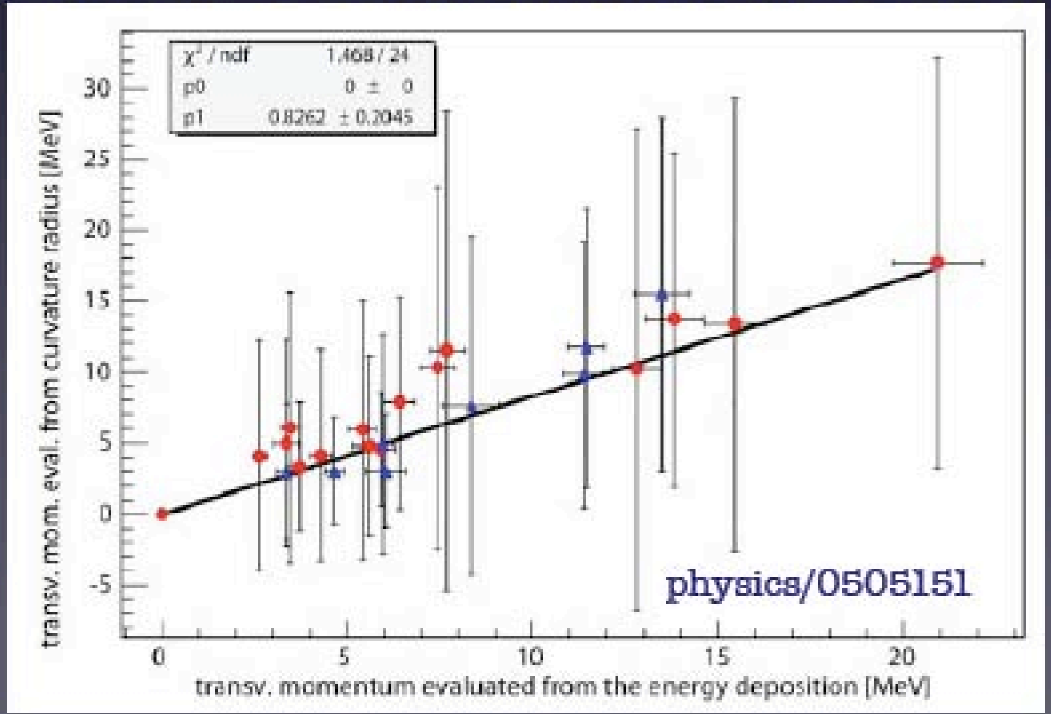
New J. Phys. 7 (2005) 63
NIM A 555 (2005) 294







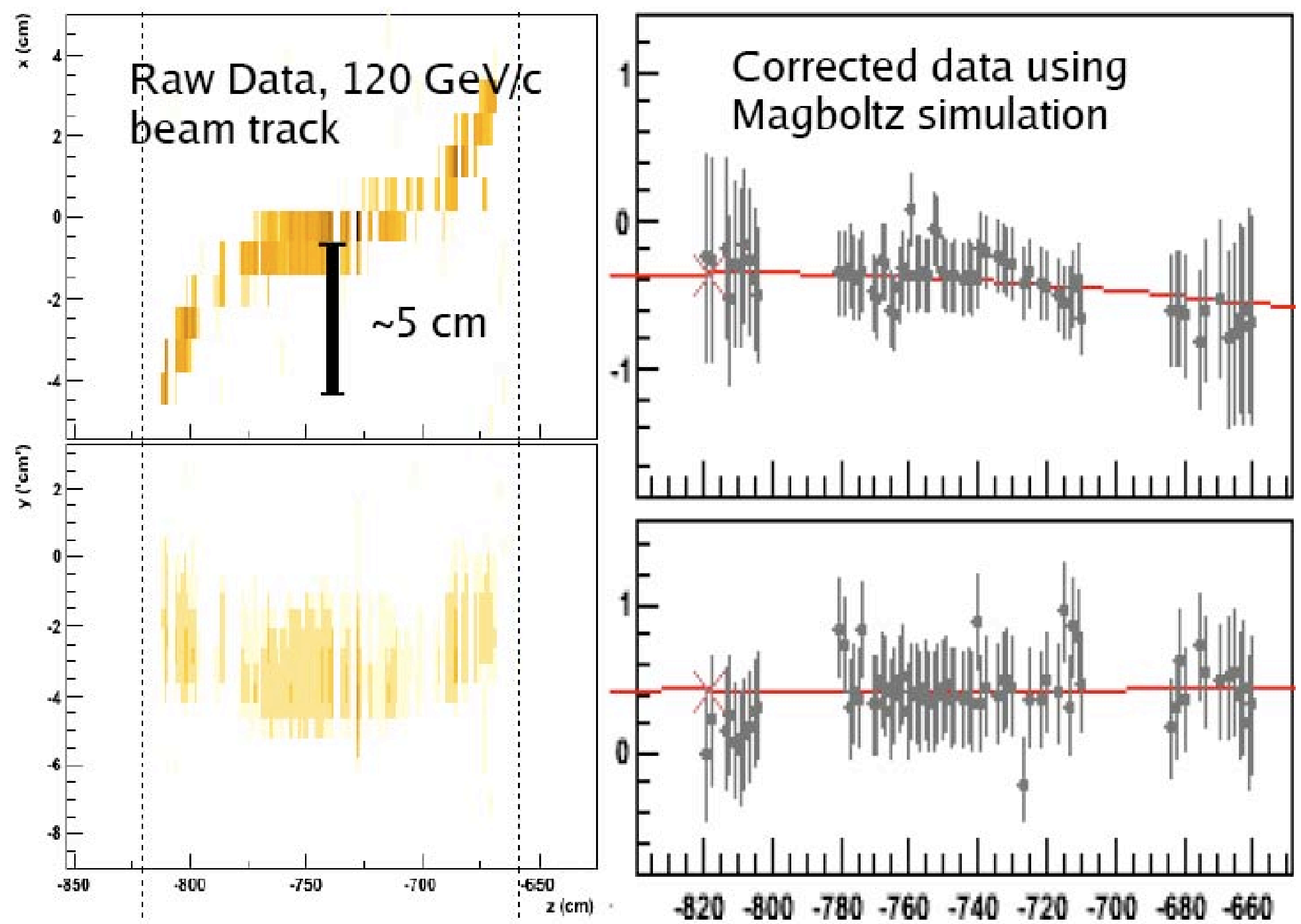
Correlation between calorimetry and magnetic measurement for contained tracks:



A. Rubbia

Challenges to magnetized LqAr *(my opinion)*

- Need to minimize $\vec{E} \times \vec{B}$ or electron drifts become extremely complicated
- Many LqAr detector concepts use photomultiplier tubes to detect scintillation light to form trigger and T_0. To function, the PMT's must be well shielded from magnetic field.
- Long wires, high voltage, strong magnetic fields: need to control oscillations very well



5 cm distortion over ~1 m drift in a gas Ar TPC (MIPP) due to ExB effects

Summary

✦ *Basics of neutrino event topology*

- Muons: Long, penetrating tracks
- EM showers: Short, compact
- Hadron showers: Short, diffuse

✦ *Detectors optimized for electron neutrinos*

- Water Cherenkov: Excellent performance for 1-ring events
- NOvA ("TASD"): Segmented solution for higher neutrino energies
- LqAr: Active R&D program. Great promise for the future

✦ *Detectors optimized for muon neutrinos*

- MINOS: Optimized for muon neutrino detection in few GeV range
- MIND: Pushing MINOS technology to high mass
- TASD w/ B field: The possibilities with magnetized caverns
- LqAr w/ B field: Pushing the envelope!