Charge Reconstruction with a Magnetized Muon Range Detector in TITUS

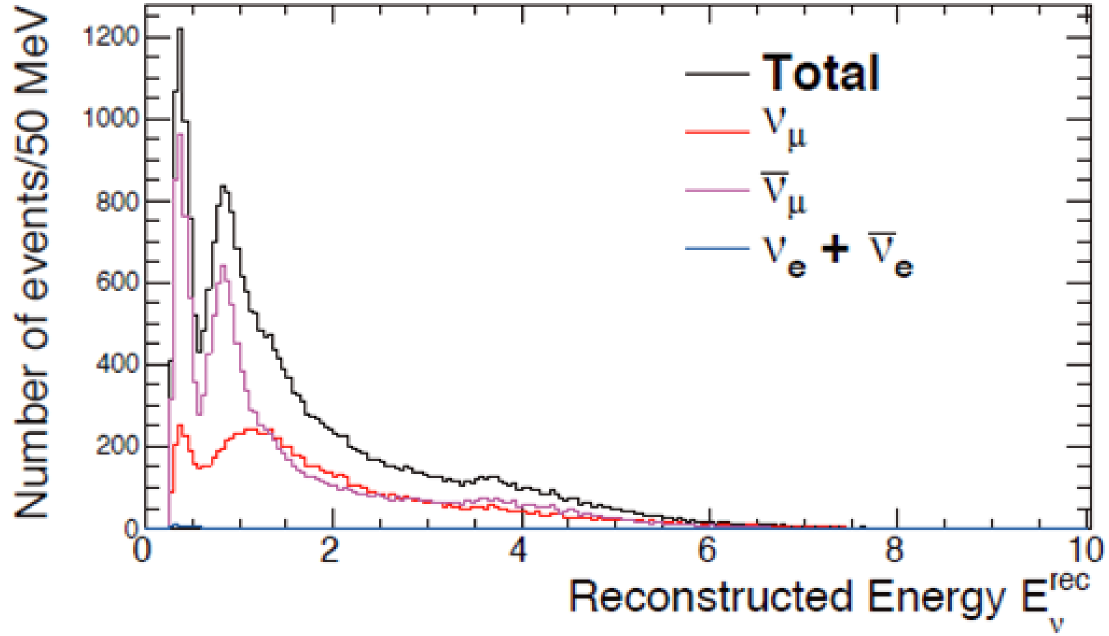
Mark A. Rayner (Université de Genève) on behalf of the TITUS working group

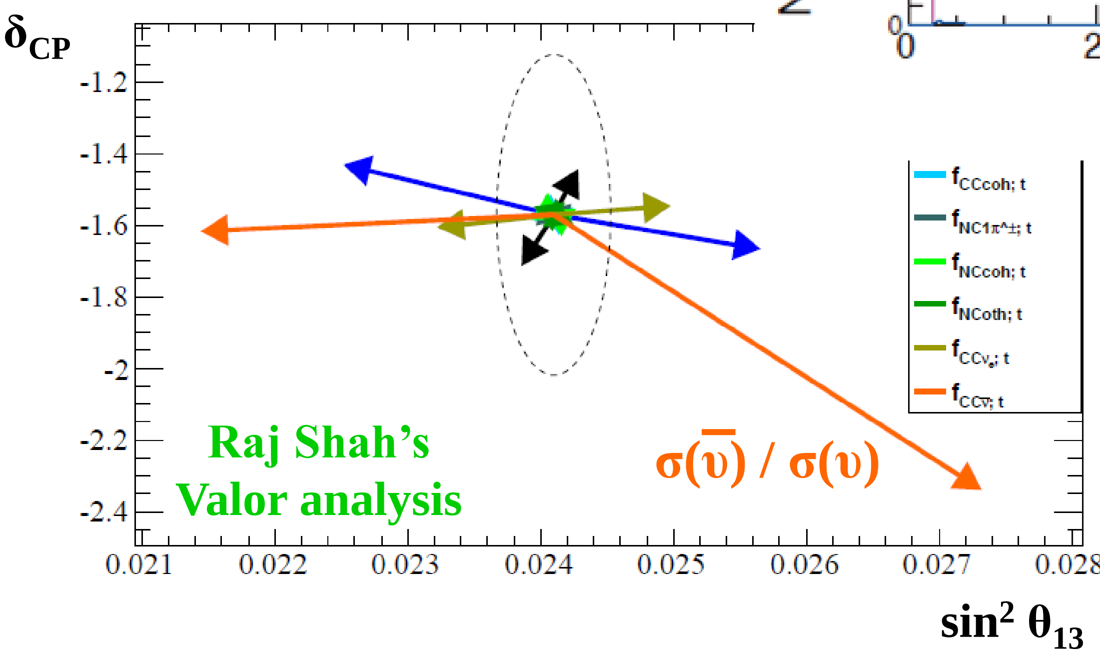
5th open Hyper-Kamiokande meeting

UBC Vancouver, 22nd July 2014

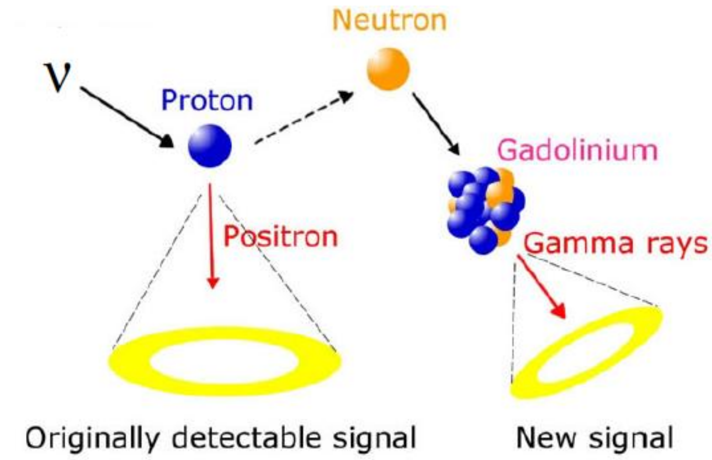
Why reconstruct the charge?

Significant wrong-sign component in anti-neutrino mode





The anti-neutrino cross-section is the biggest unconstrained model systematic



$$\nu\, n \rightarrow \ell\, p$$

$$\bar{\nu}\, p \rightarrow \ell\, n$$

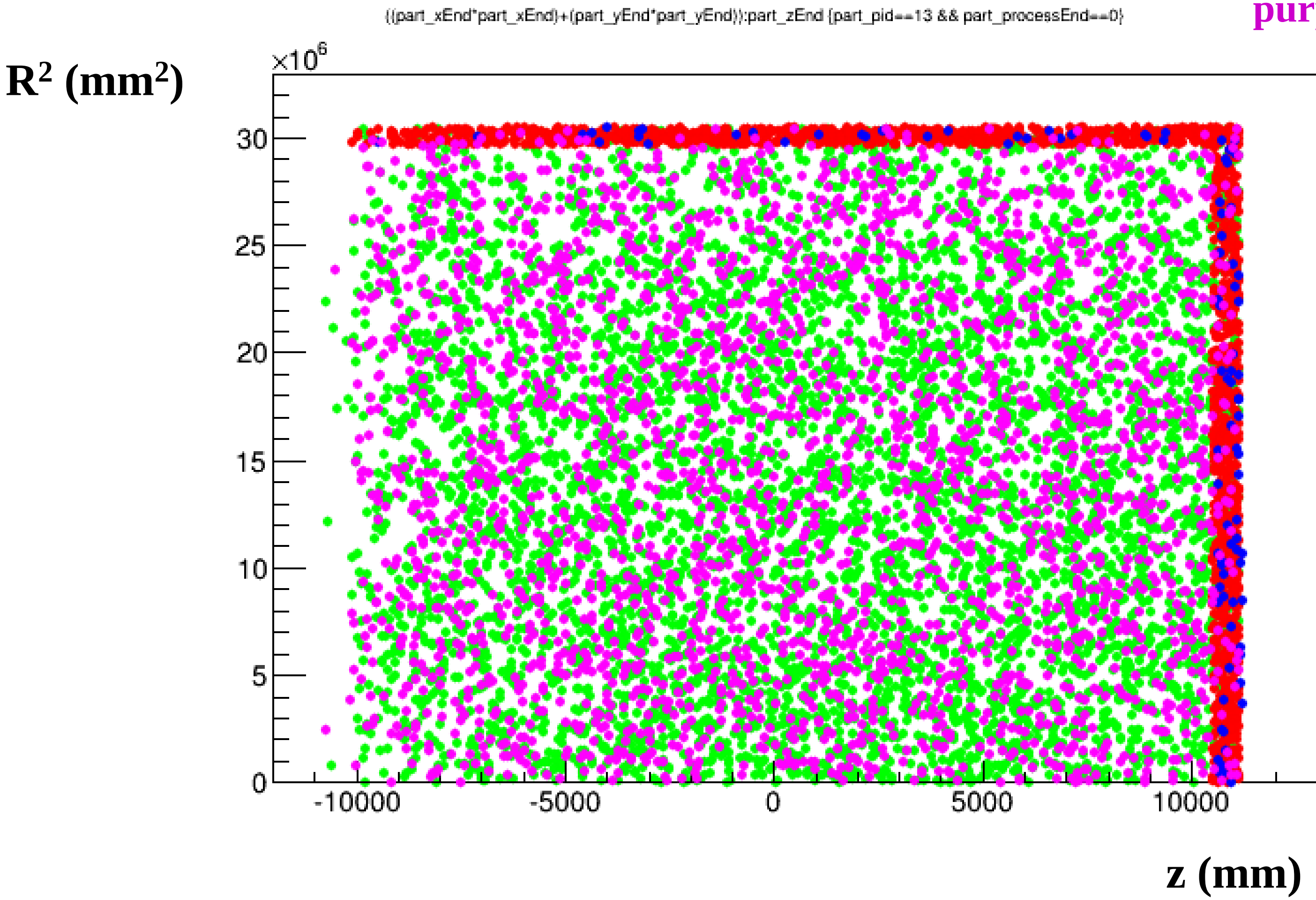
detect with Gd

$\varepsilon_Q \approx 88\%$

Gadolinium is exciting, but somewhat untested

red: mu- leave tank
blue: mu+ leave tank
green: mu- stop in tank
purple: mu+ stop in tank

18% of muons escape the tank



The tank size could be re-optimized with the MRD in mind

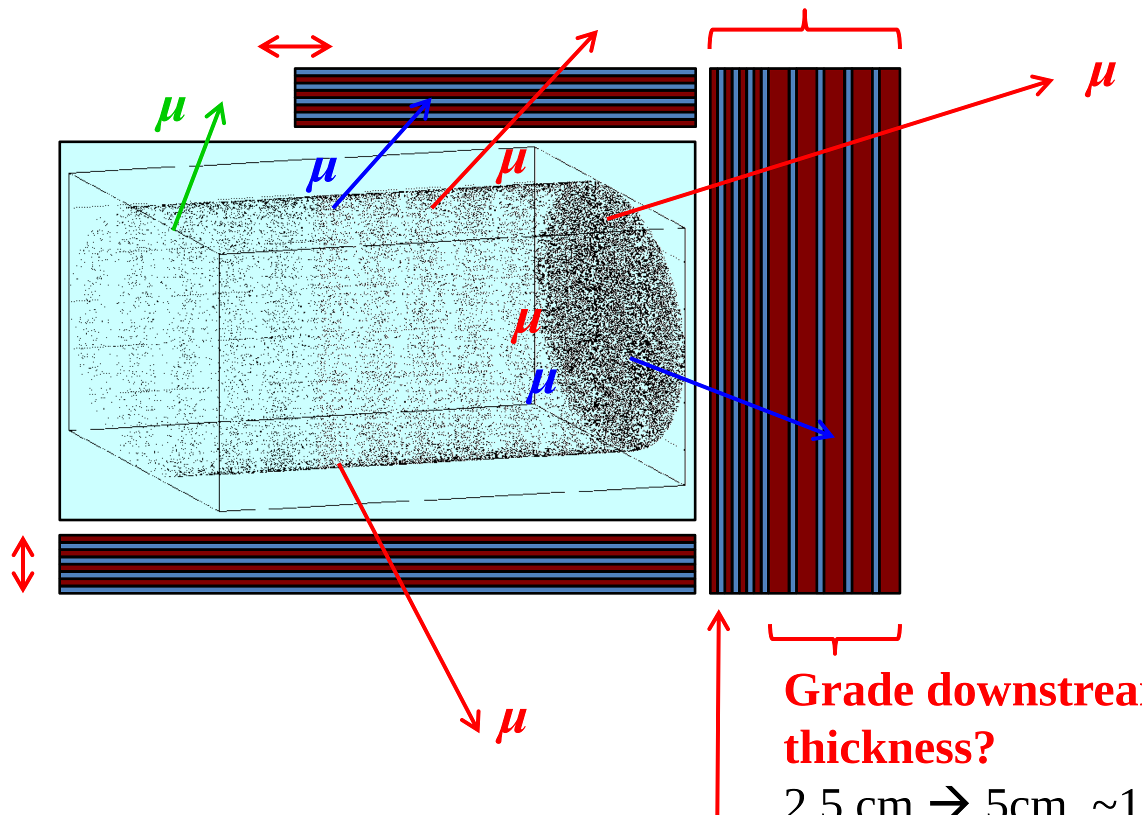
courtesy of Matthew Malek

MRD design considerations

Vary side coverage
Do we stop a useful fraction of muons given the cost?

Magnetize ➔ charge and momentum
1.5 Tesla (near saturation in cheap steel)
450cm (150cm of which Fe)

neutrino beam



20 Fe+scintillator modules 150cm

Grade downstream Fe thickness?
2.5 cm → 5cm, ~1 euro / kg

Constant scintillator thickness 2.5 cm (→0.75cm?)
20 CHF / SiPM + 20 CHF / electronics channel

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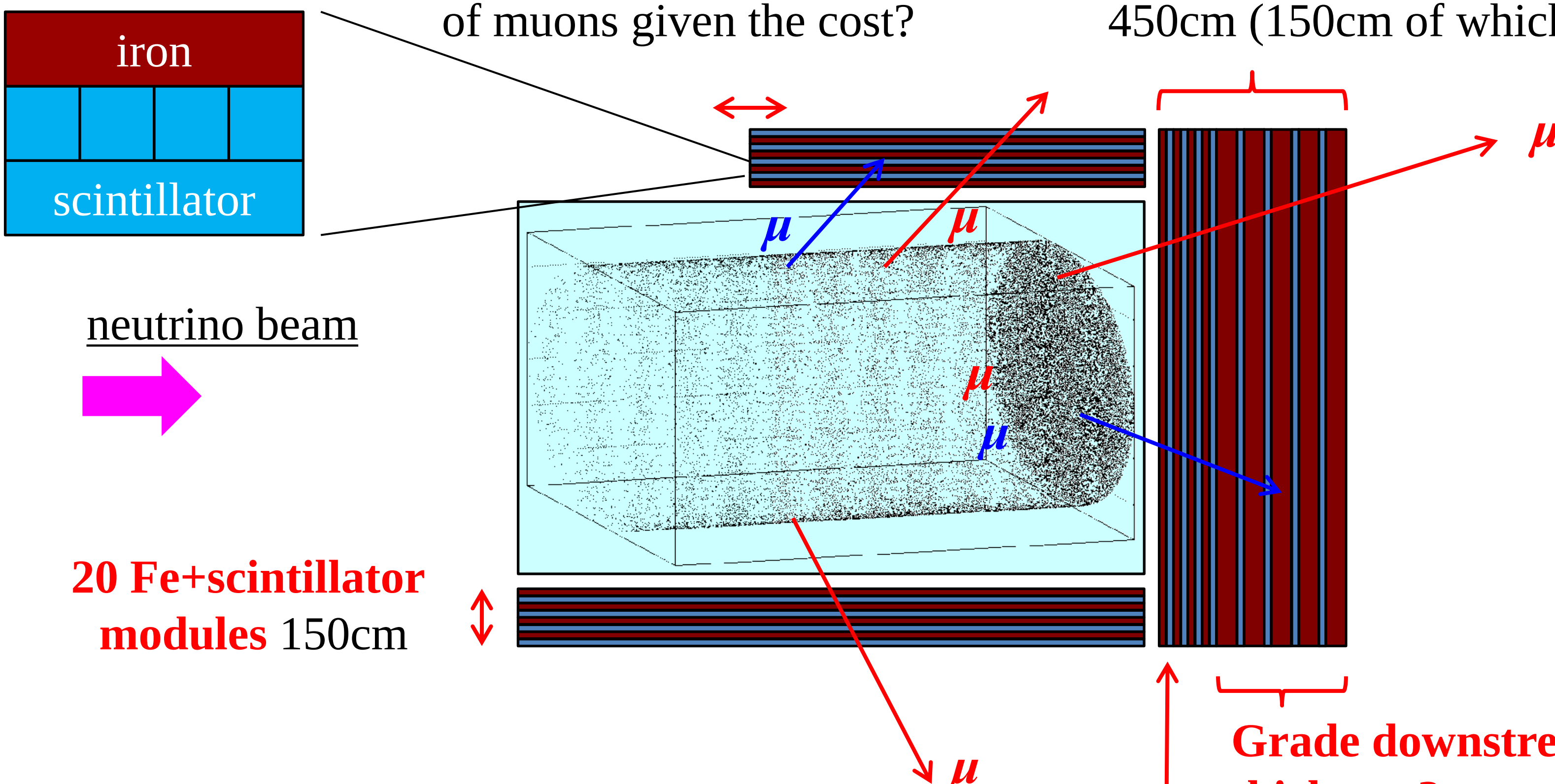

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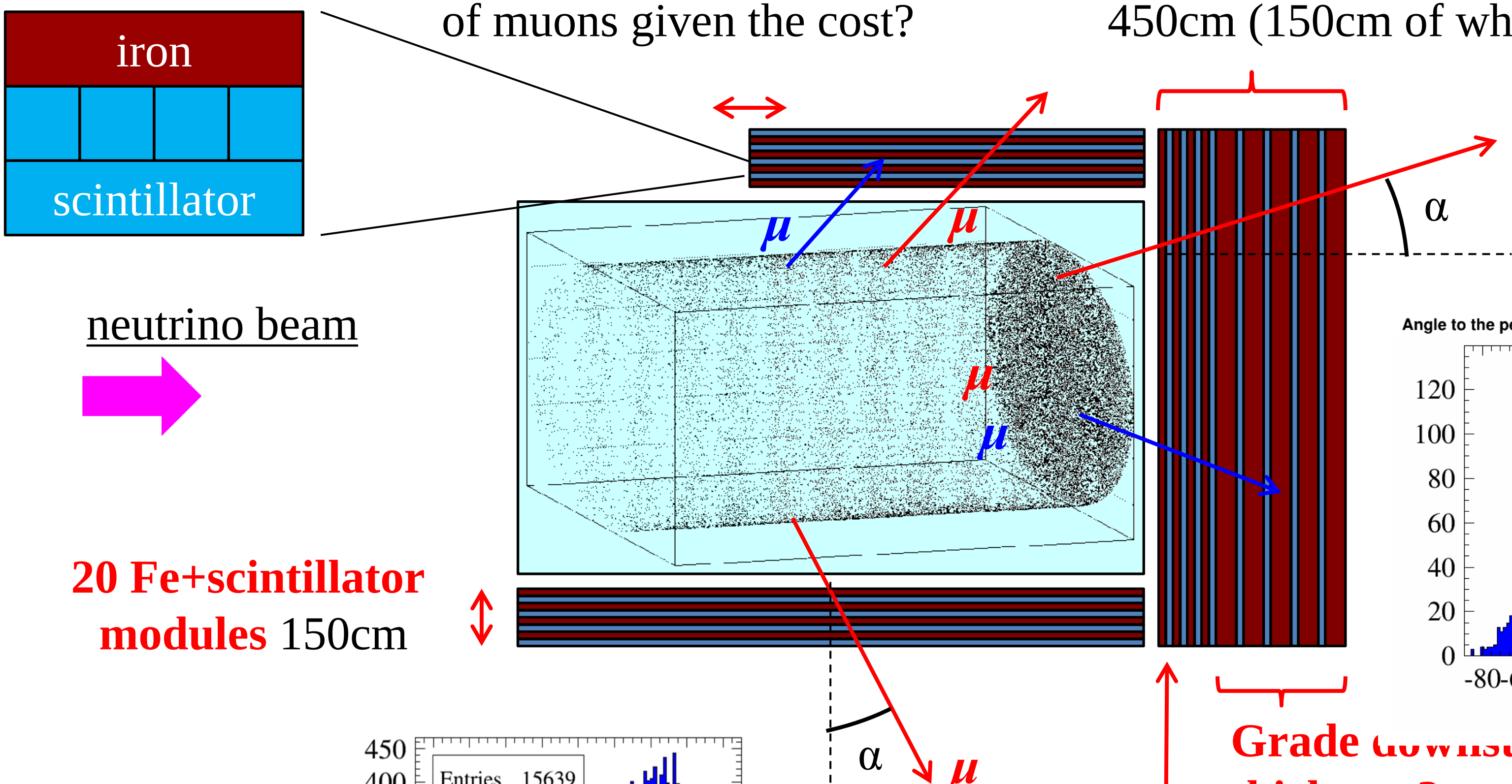

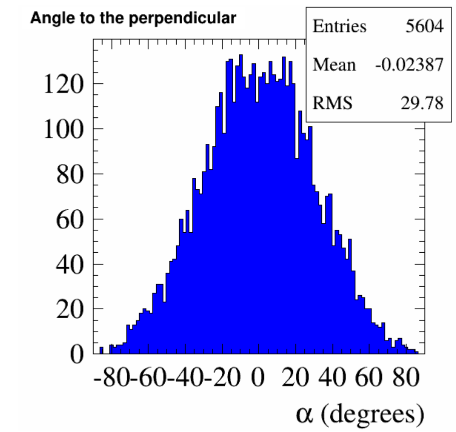

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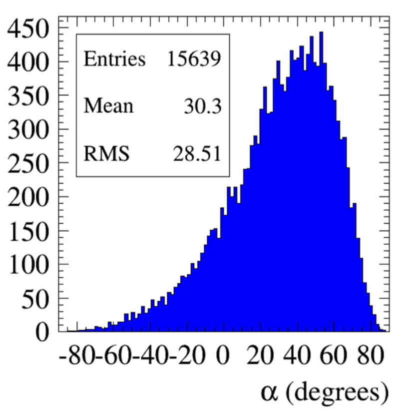
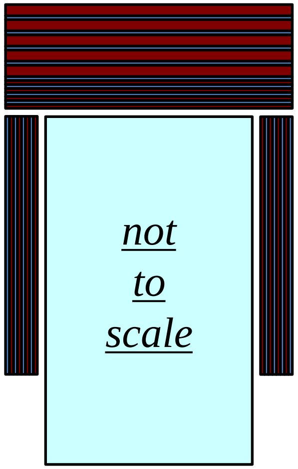


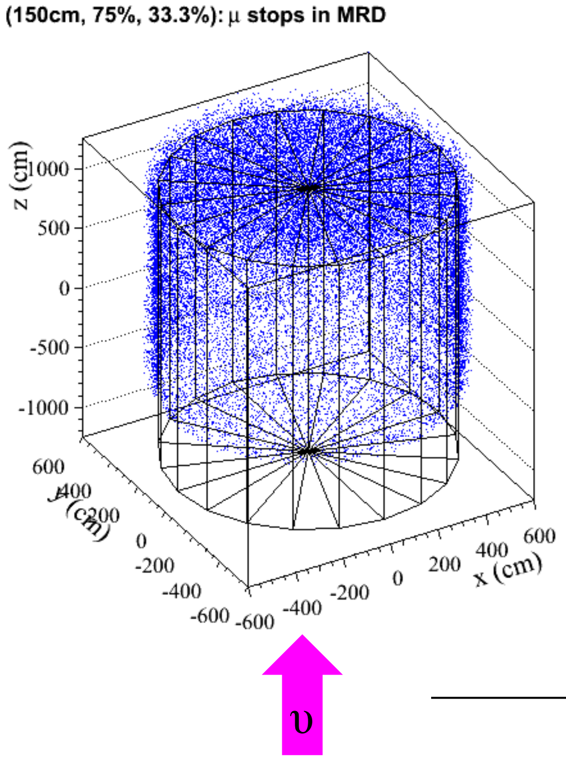
Constant scintillator thickness 2.5 cm (→0.75cm?)
20 CHF / SiPM + 20 CHF / electronics channel

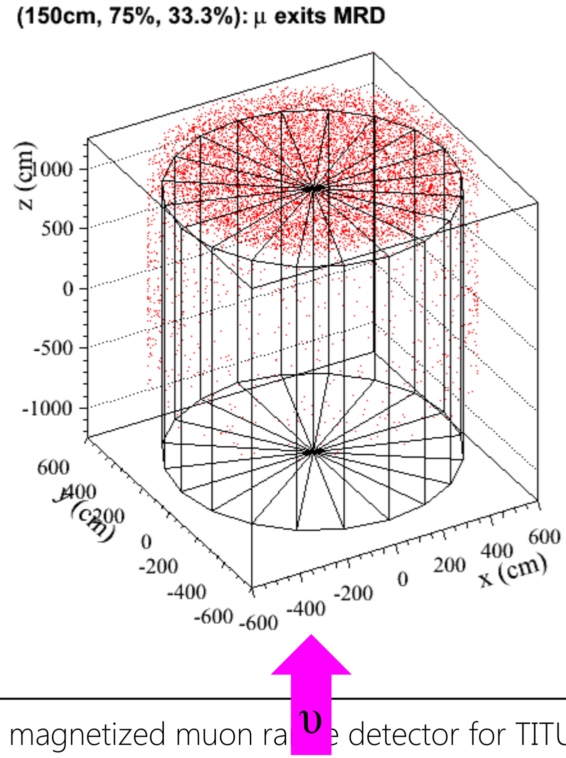
Muons tracks in the TITUS MRD

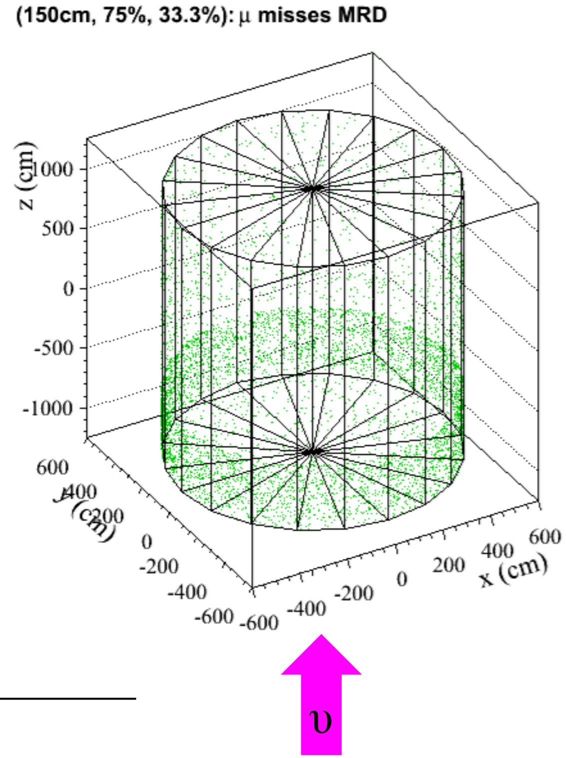
- A simulation with 150cm end Fe and 75% side coverage of 50cm of Fe
  - **range-out and stop in the MRD**
  - **penetrate through the MRD**
  - **miss the MRD**



A muon with 2 GeV can penetrate 1.5 m of steel

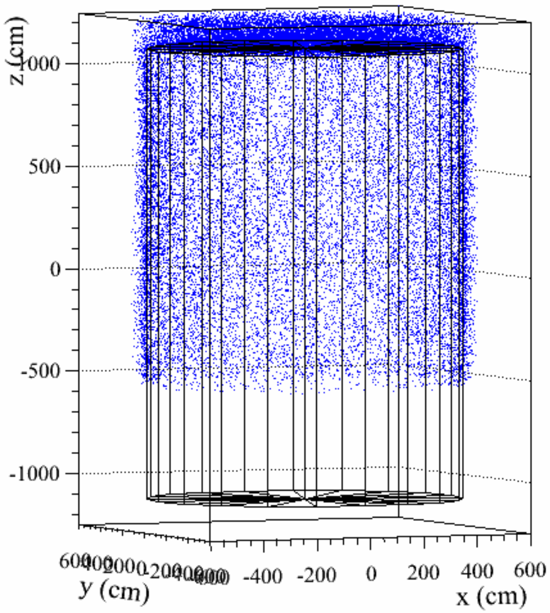




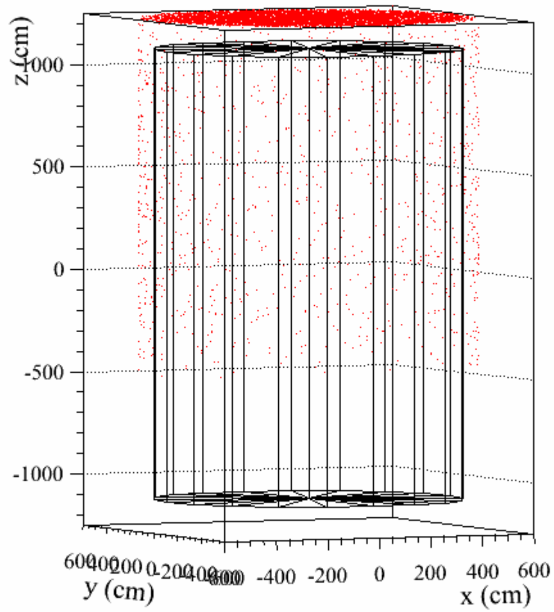


And from two more projections…

(150cm, 75%, 33.3%): μ stops in MRD



(150cm, 75%, 33.3%): μ exits MRD



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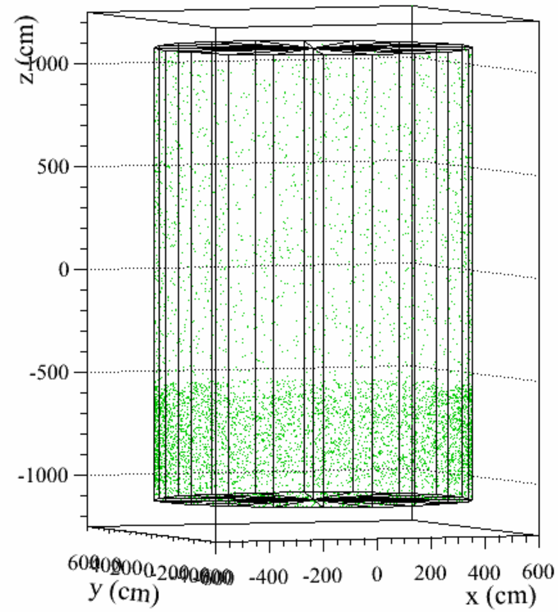

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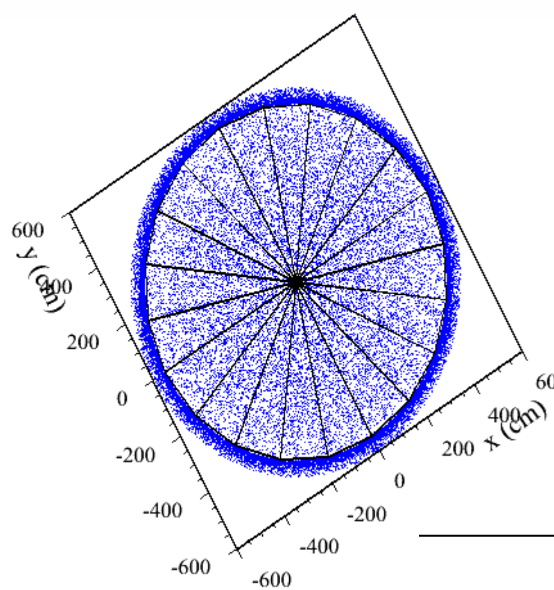

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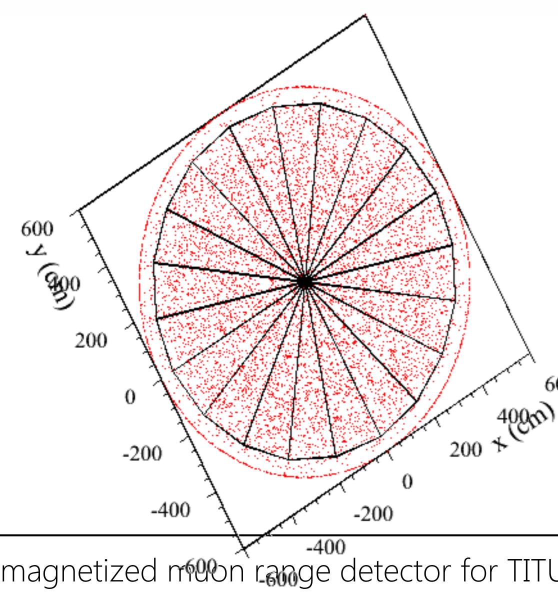

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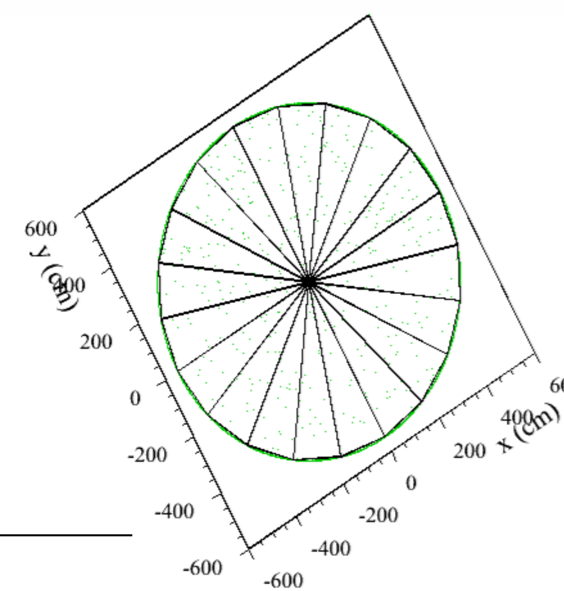
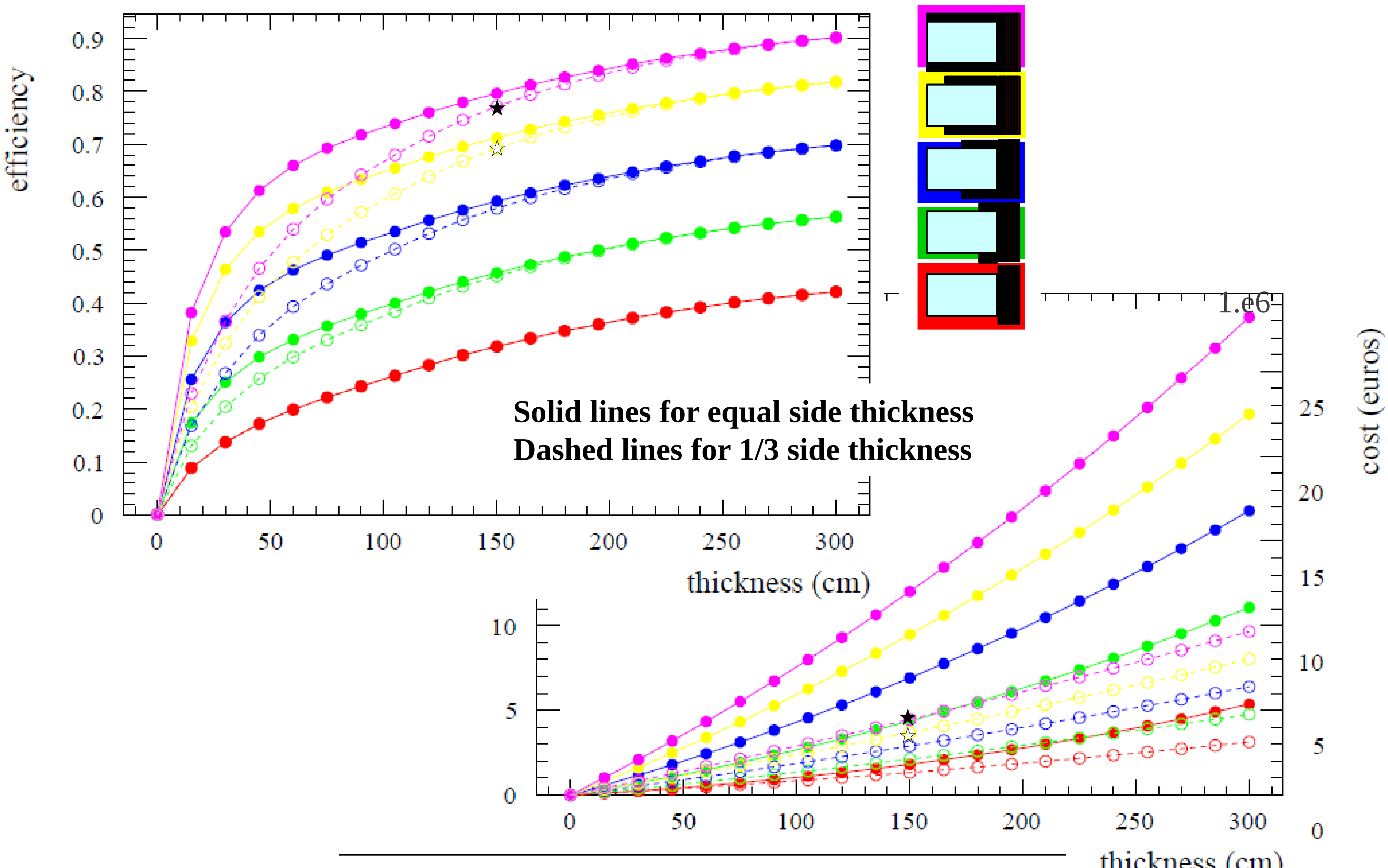
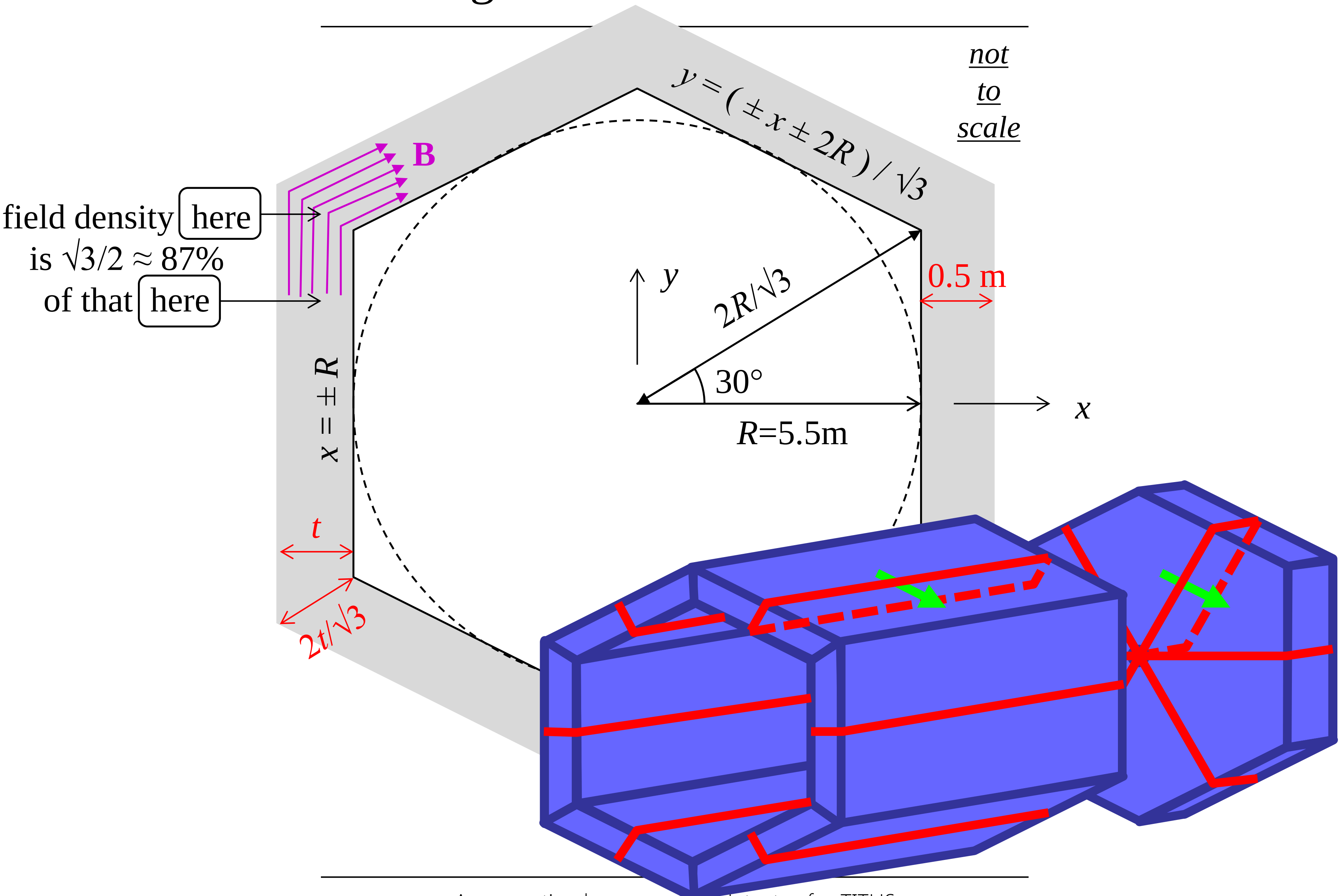


Optimizing efficiency for stopping muons, and cost



Magnetization of the MRD

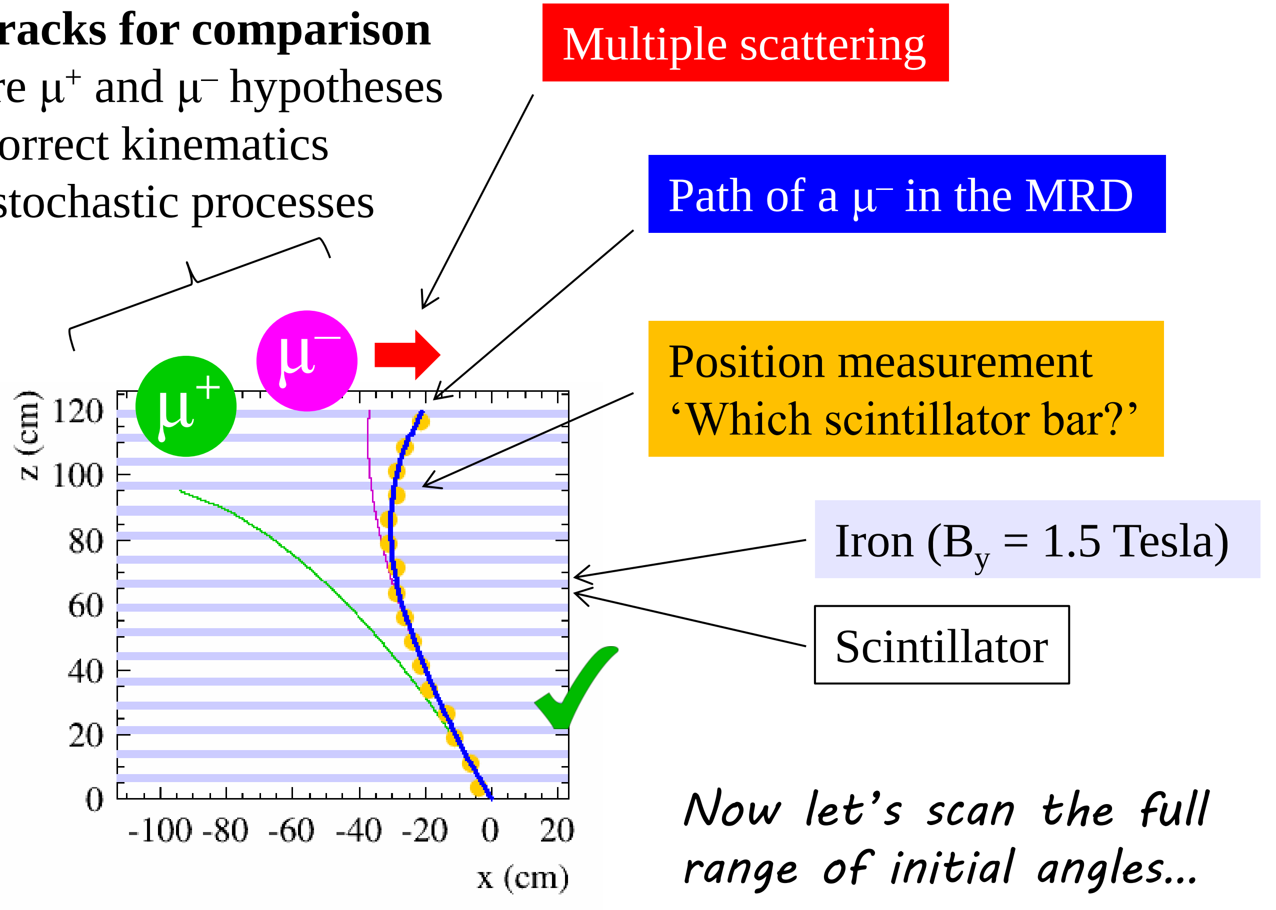


Charge reconstruction *via* event display scanning

Let's start with a muon entering the MRD with E_μ = 0.6 GeV

Can we reconstruct the charge?

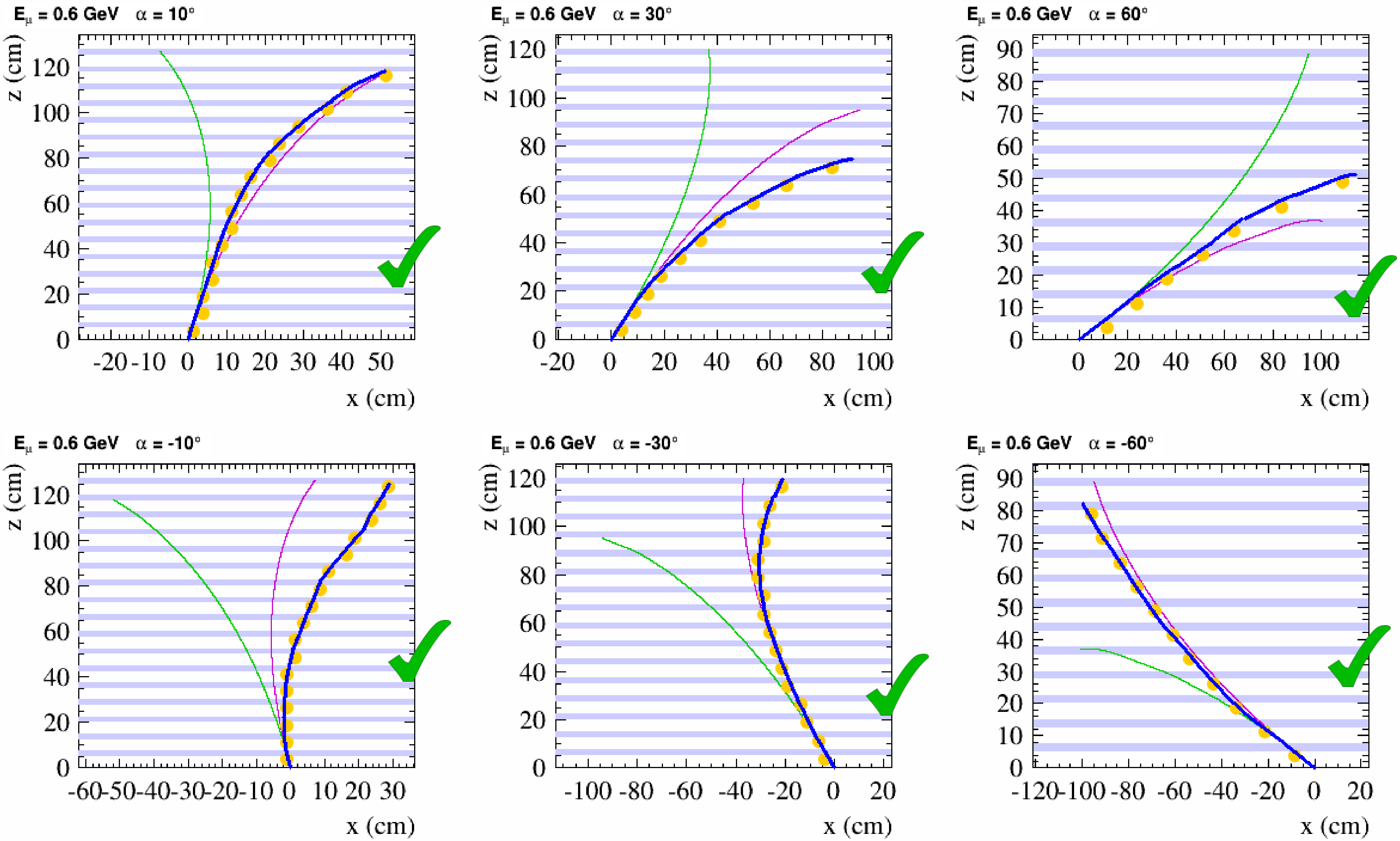
Ideal tracks for comparison
Compare μ^+ and μ^- hypotheses
Correct kinematics
No stochastic processes



Now let's scan the full range of initial angles…

$E_\mu = 0.6$ GeV

56% of END muons
32% of SIDE muons



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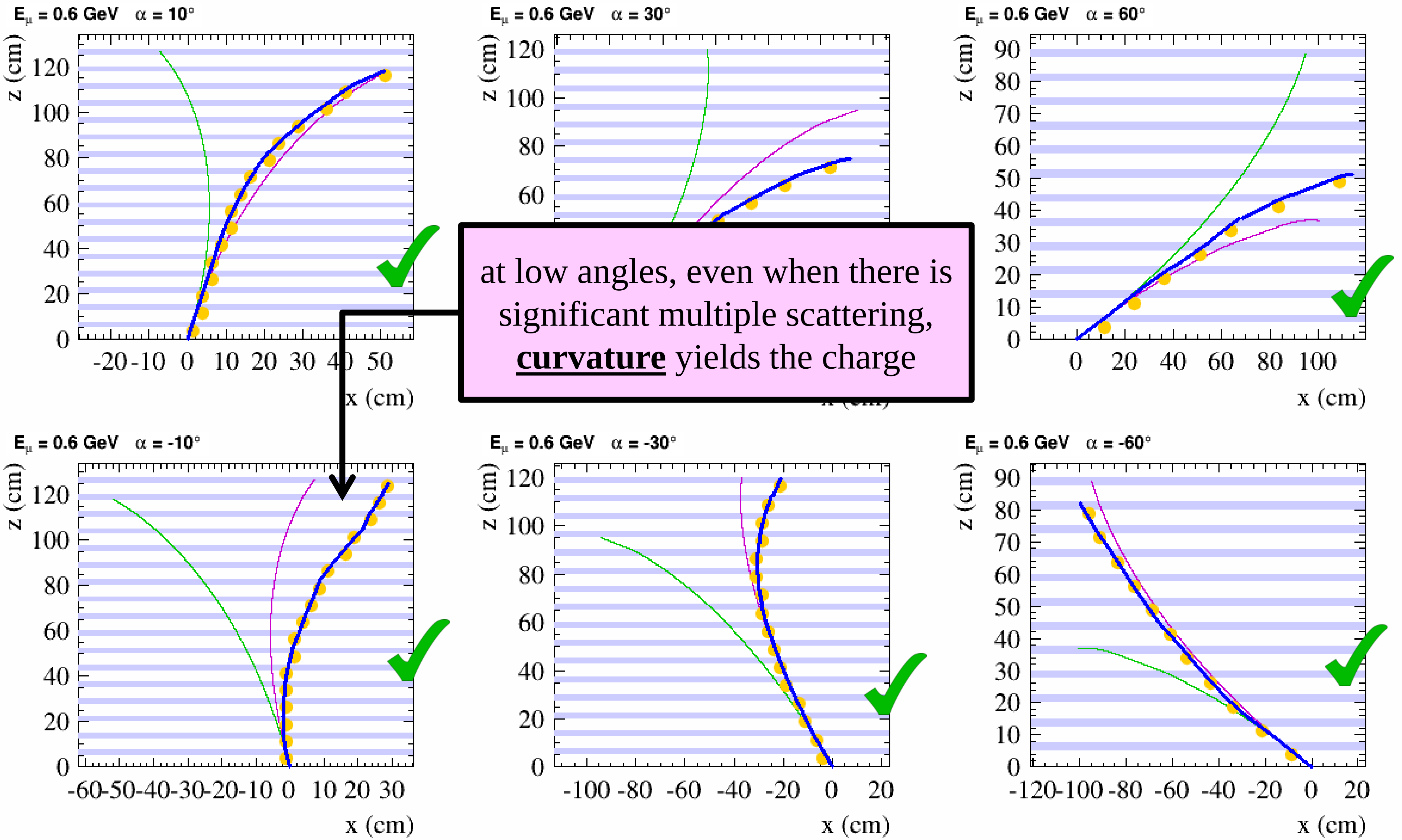
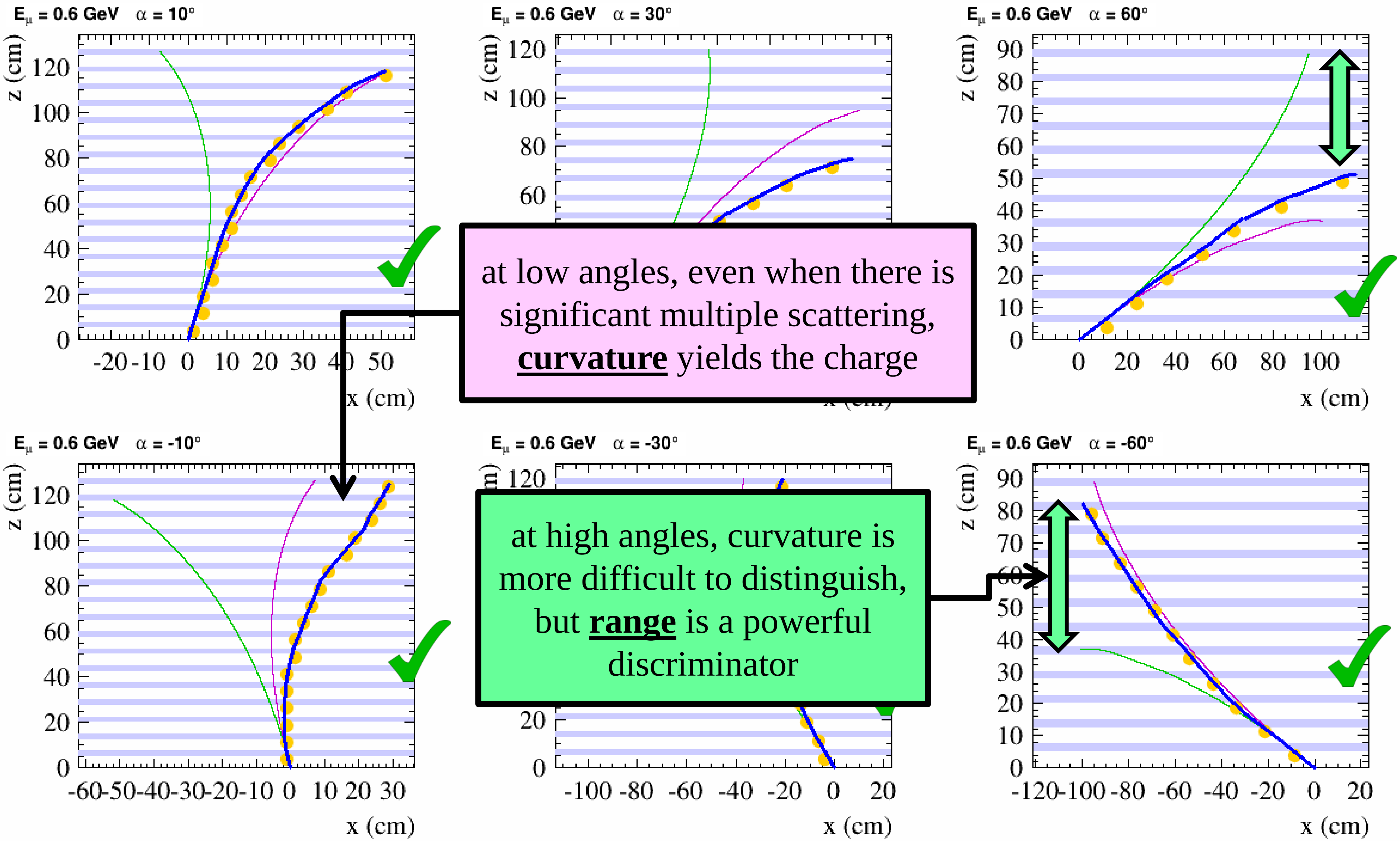


at low angles, even when there is significant multiple scattering, **curvature** yields the charge

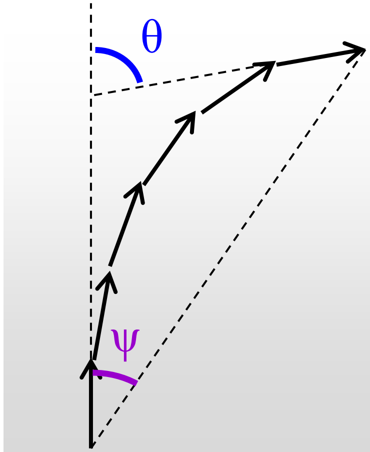
$E_\mu = 0.6$ GeV

56% of END muons
32% of SIDE muons



We can do a back of the envelope calculation at this point…

Multiple Scattering in the iron is the biggest obstacle to charge reconstruction



Long tracks

Is $\theta_{B\text{-field}} > \theta_{MS}$?

A little like a Kalman Filter

Short tracks

Is $\psi_{B\text{-field}} > \psi_{MS}$?

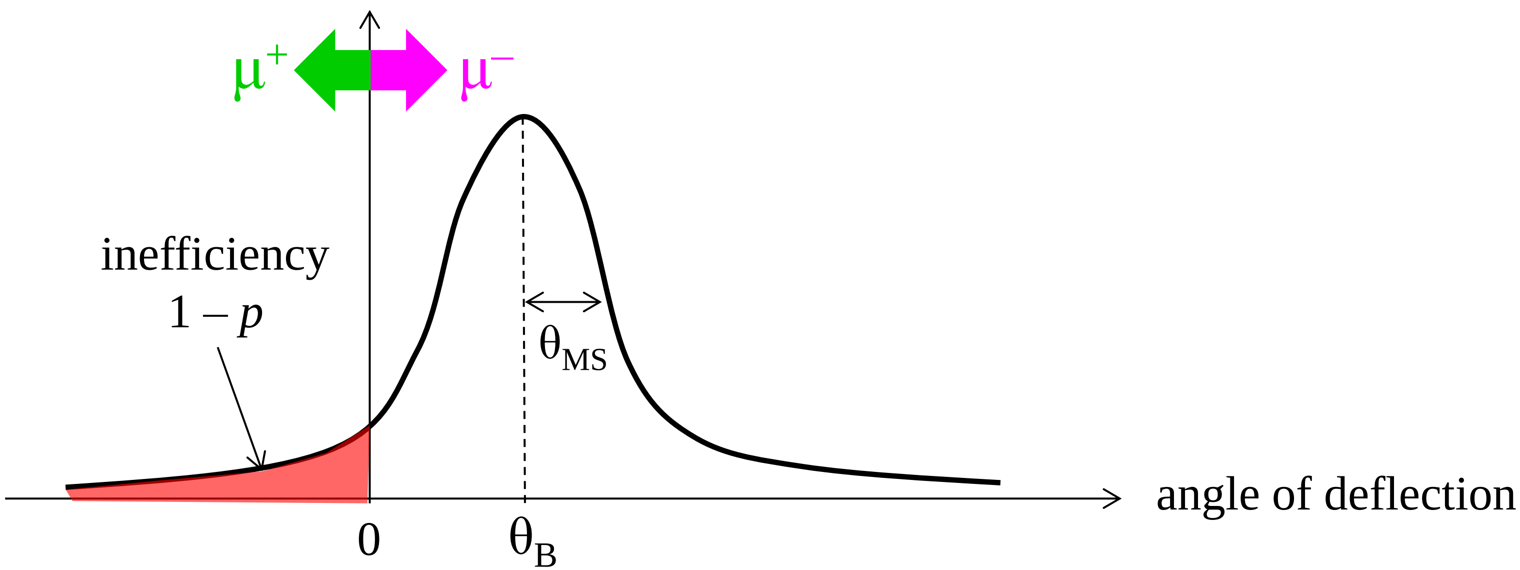
Does the muon move left or right?

X_0 = 1·757 cm in Fe

X_0 = 50·31 cm in polyethylene

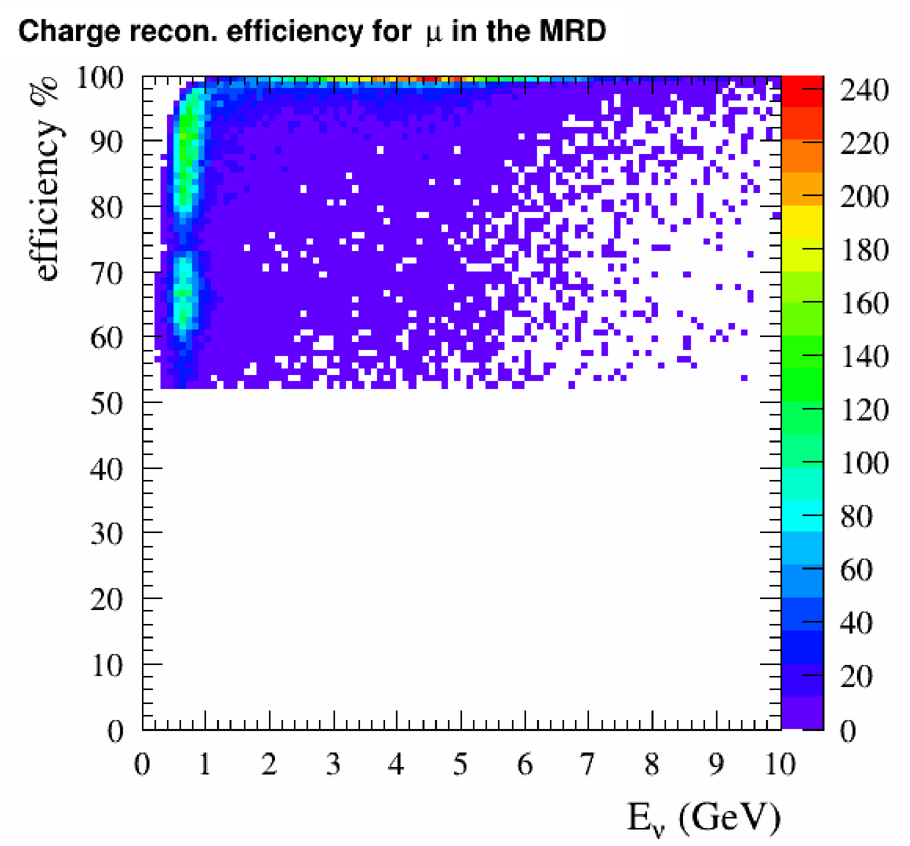
$(X_0 / X_0)^{½}$ = 1·9%

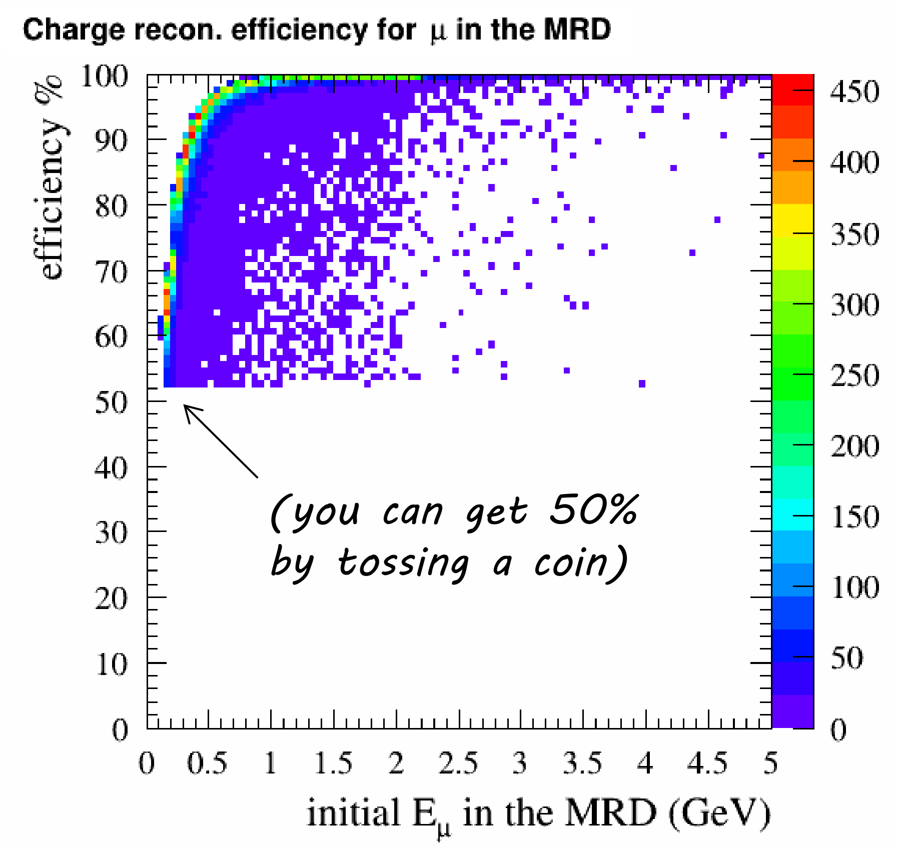
$$\psi^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta^{\rm rms}_{\rm plane} = \frac{1}{\sqrt{3}}\,\theta_0$$



Estimated charge reconstruction efficiency *versus* E_μ and E_υ

PRELIMINARY

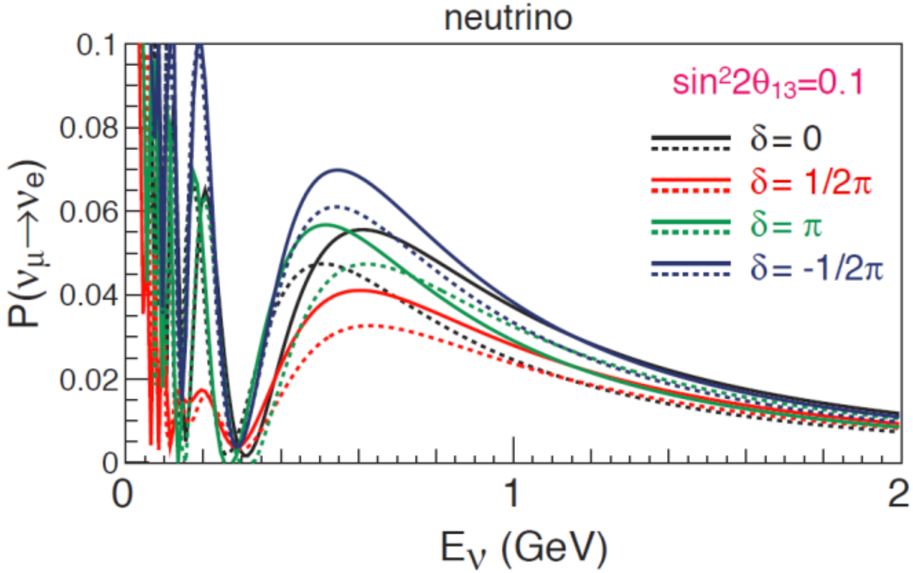




We should expect near 100% efficiency for the high energy tail

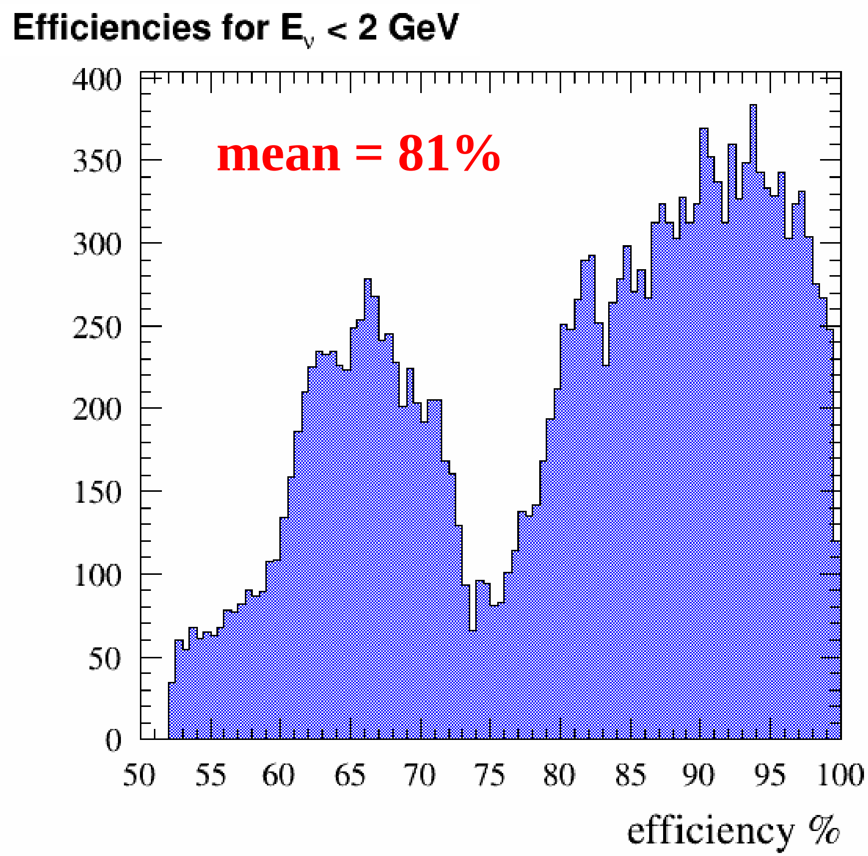
This could be used to test the reliability of the gadolinium technique

but of course E_ν < 2 GeV is of particular interest



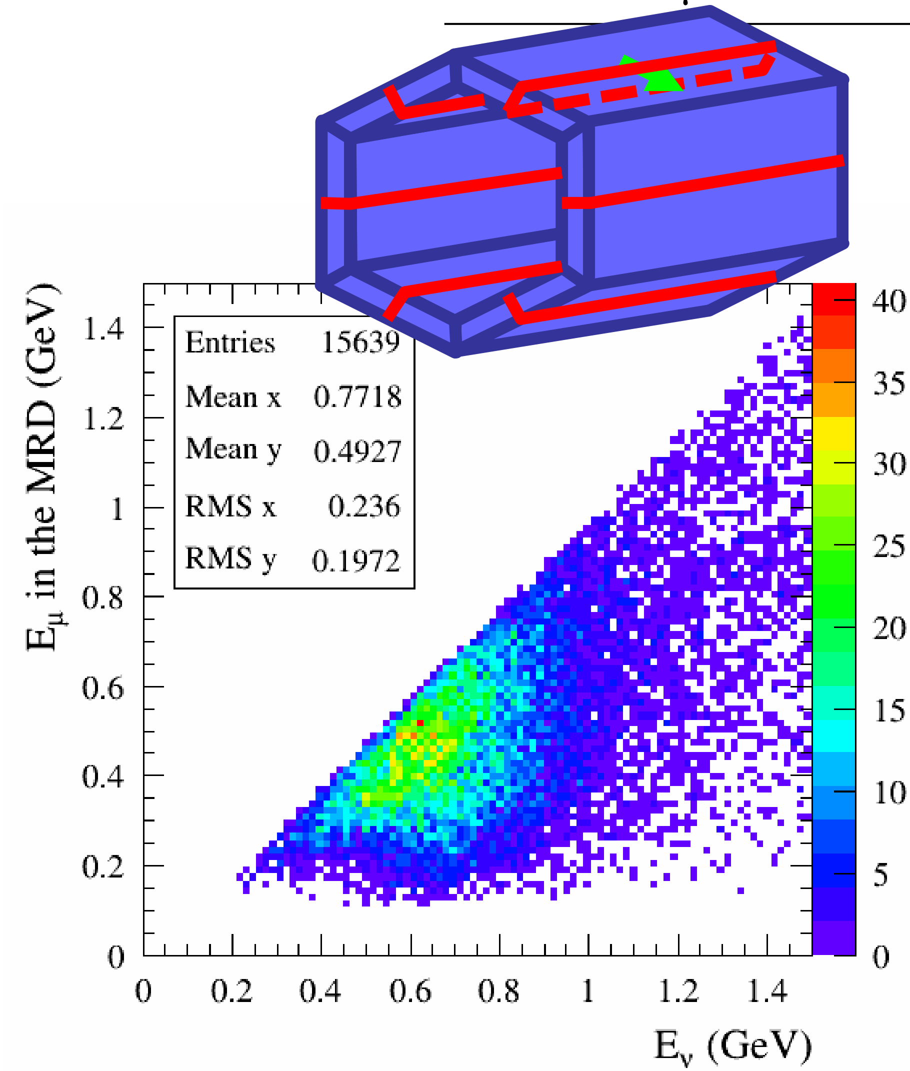
Here we expect ~80% efficiency (rough calculation)

PRELIMINARY

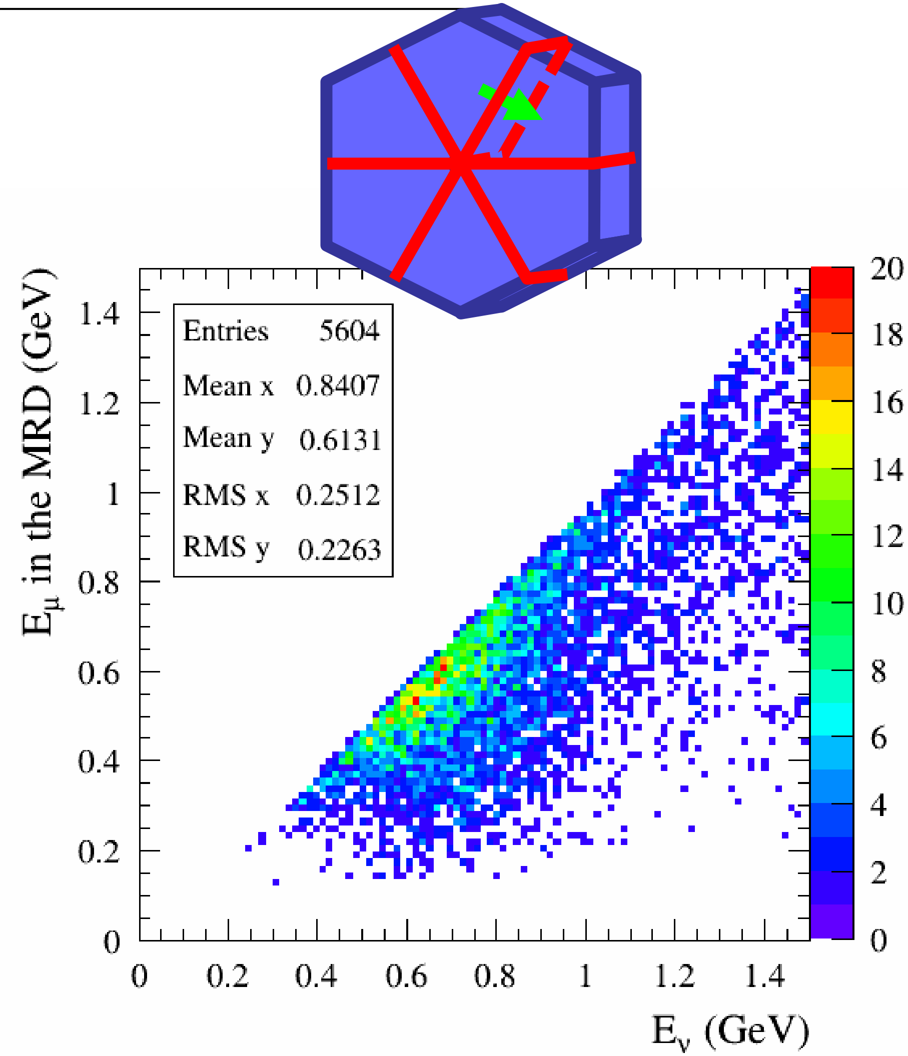


Let's think more carefully about this region…

Connecting E_υ and E_μ for muons in the barrel and end MRD

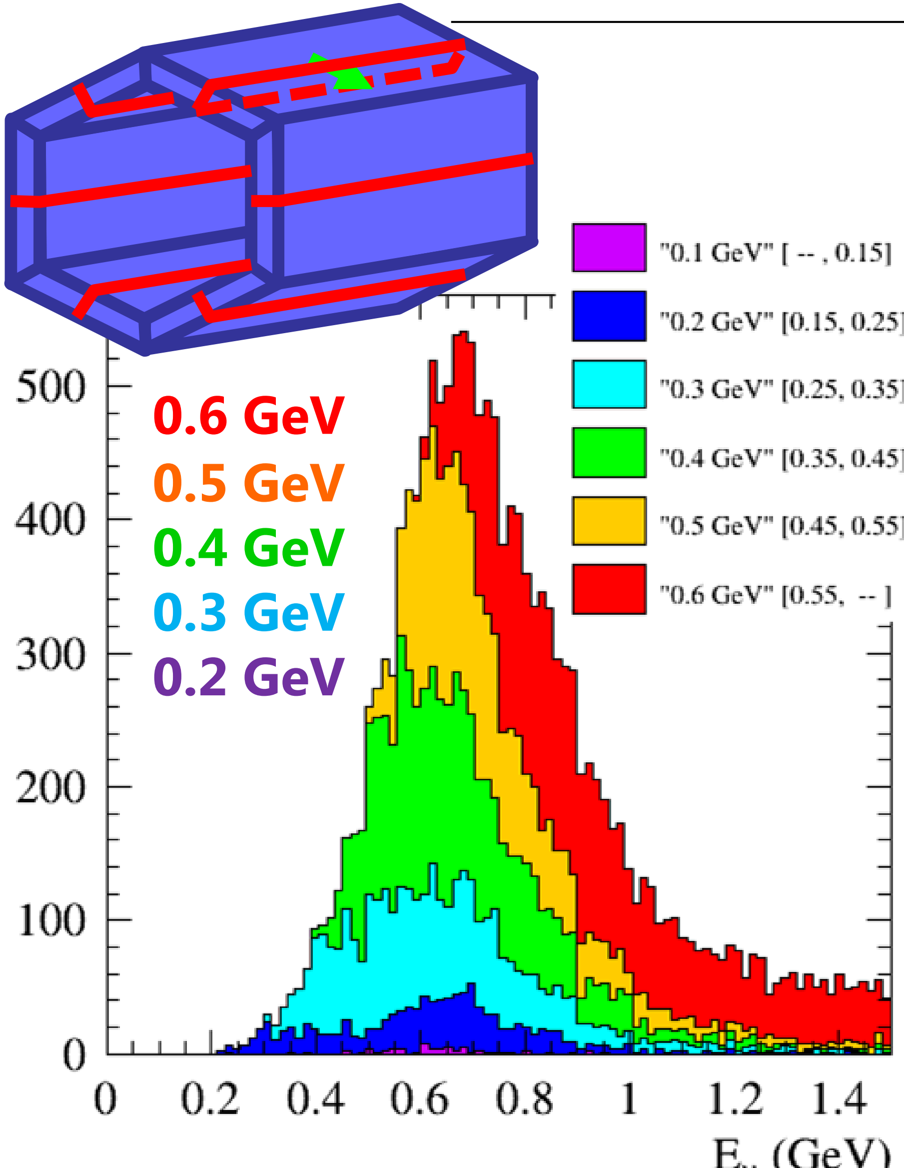


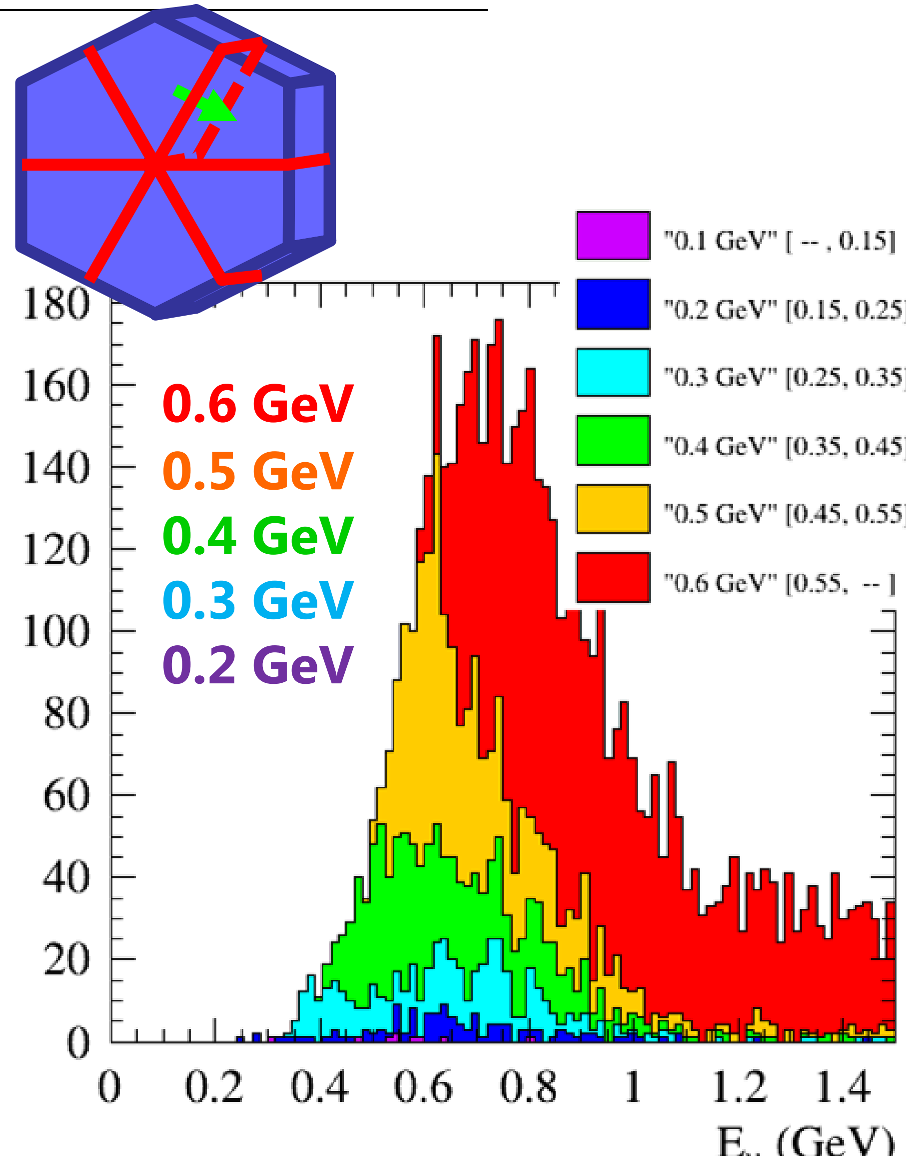
Three quarters of events leave the tank through the sides



More forward muons have slightly higher energies

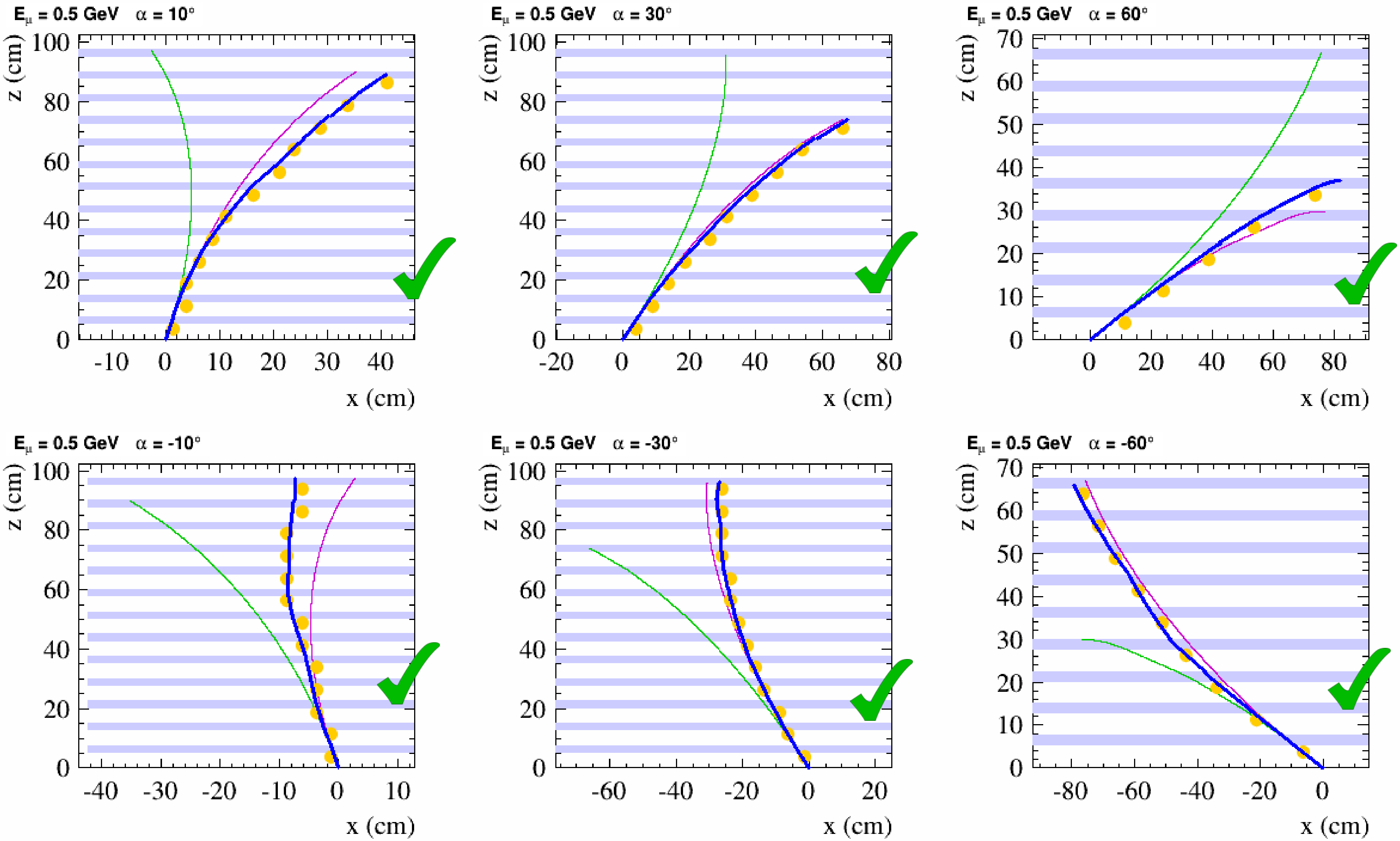
Let's divide the E_υ distributions into E_μ slices and scan down





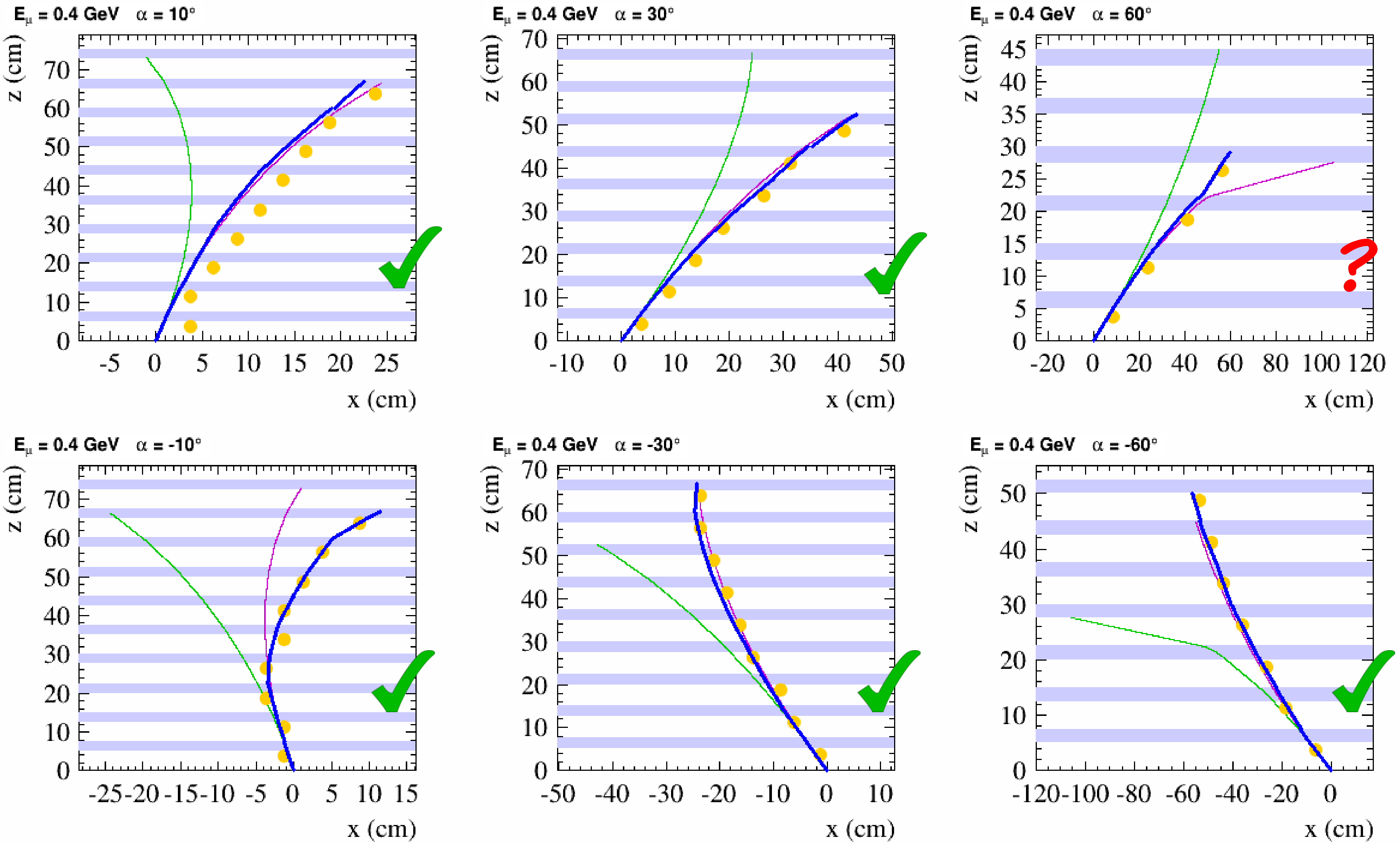
$E_\mu = 0.5$ GeV

20% of END muons
21% of BARREL muons



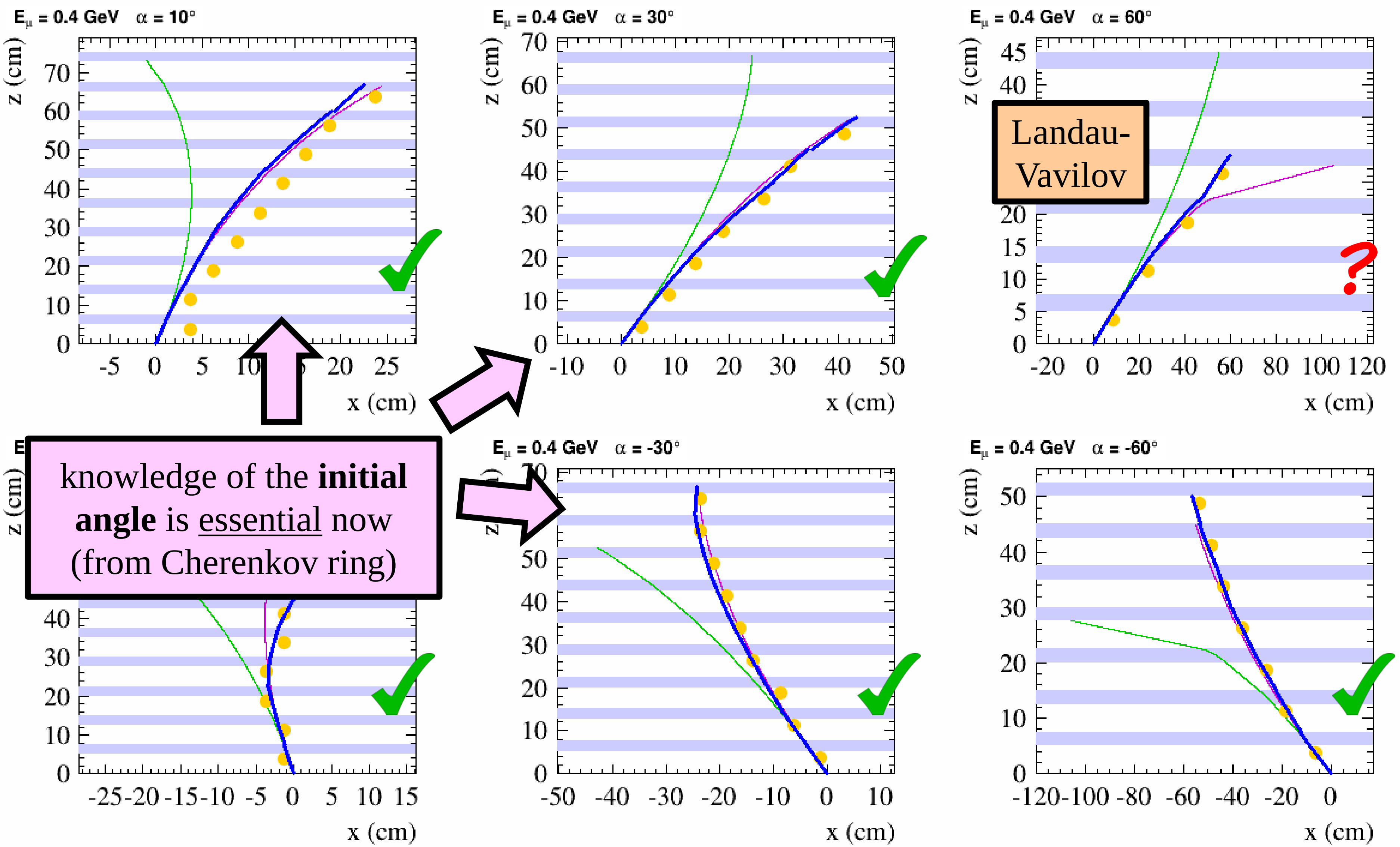
$E_\mu = 0.4$ GeV

14% of END muons
24% of BARREL muons



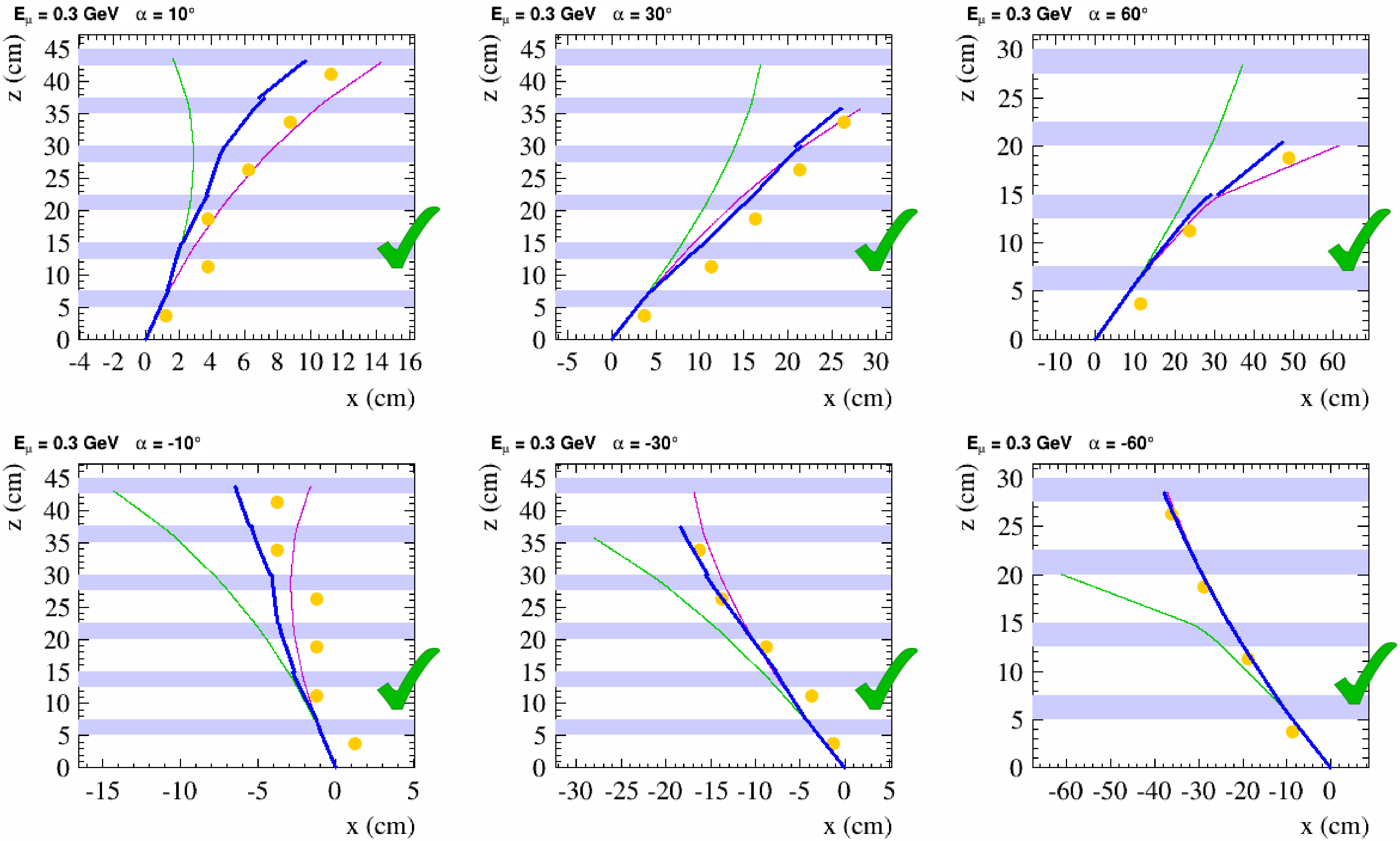
$E_\mu = 0.4$ GeV

14% of END muons
24% of BARREL muons



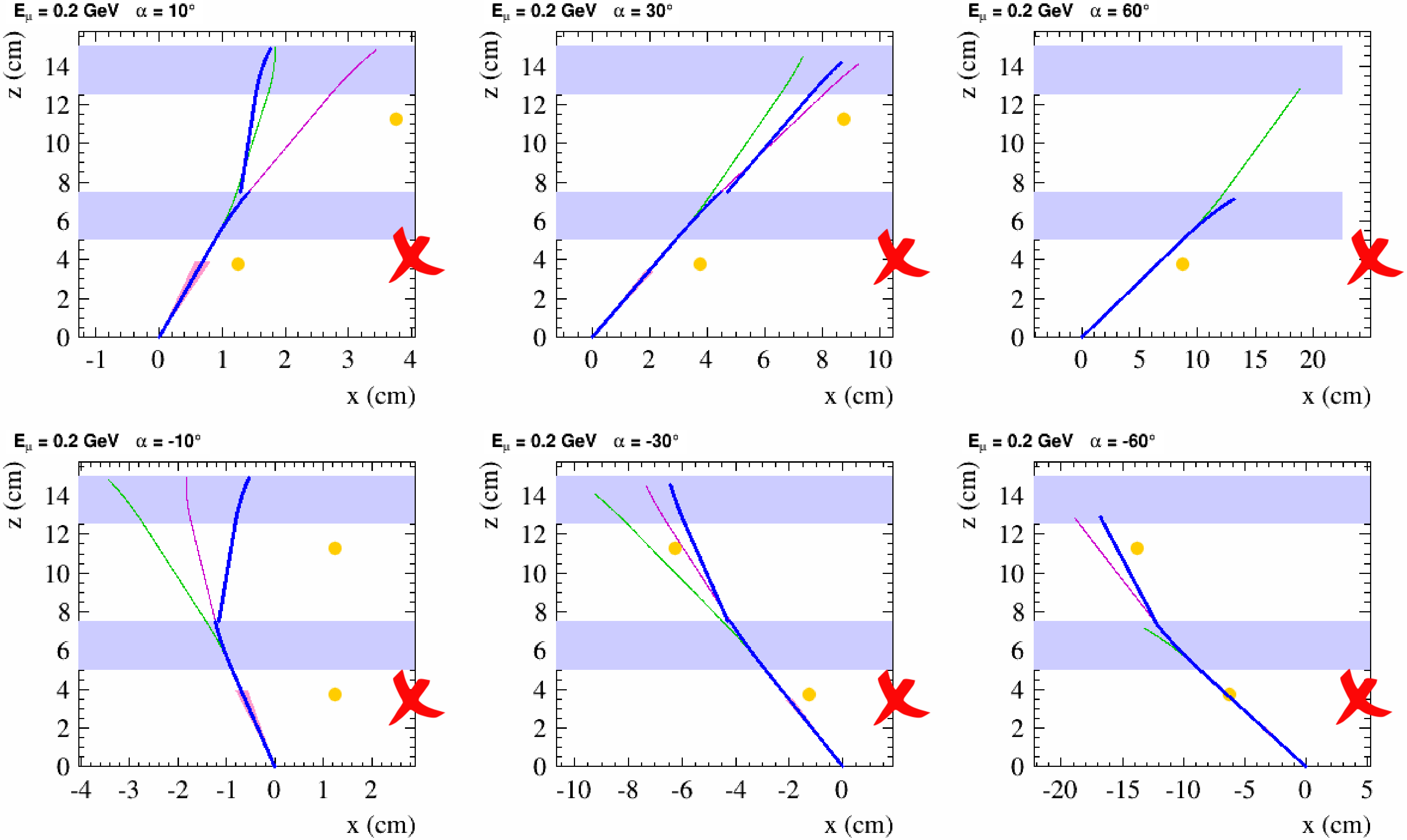
$E_\mu = 0.3$ GeV

7% of END muons
17% of BARREL muons



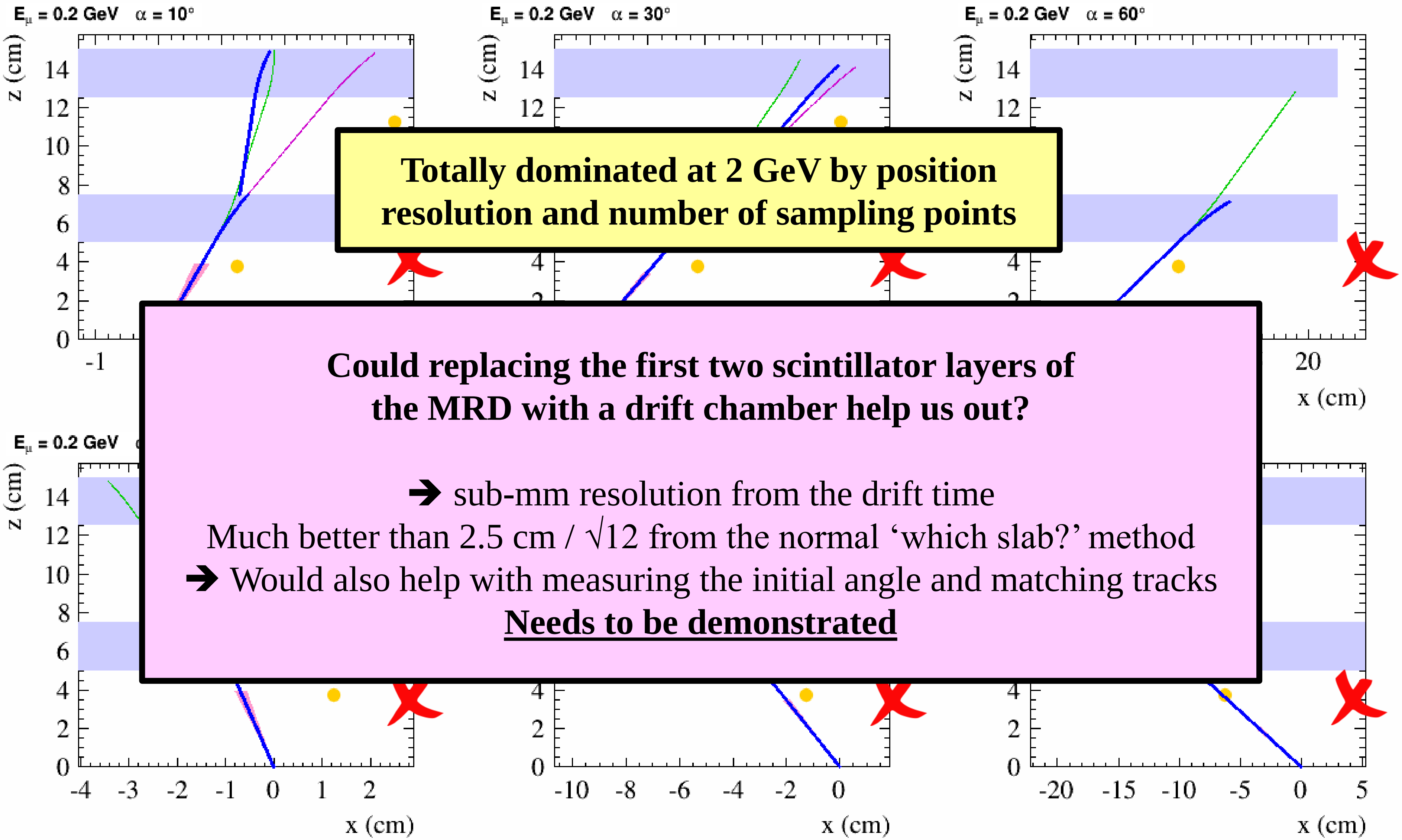
$E_\mu = 0.2$ GeV

2% of END muons
7% of BARREL muons



$E_\mu = 0.2$ GeV

2% of END muons
7% of BARREL muons



Totally dominated at 2 GeV by position resolution and number of sampling points

Could replacing the first two scintillator layers of the MRD with a drift chamber help us out?

➔ sub-mm resolution from the drift time
Much better than 2.5 cm / √12 from the normal 'which slab?' method
➔ Would also help with measuring the initial angle and matching tracks
<u>Needs to be demonstrated</u>

Baby-MIND and TASD: H8 beamline in North Area

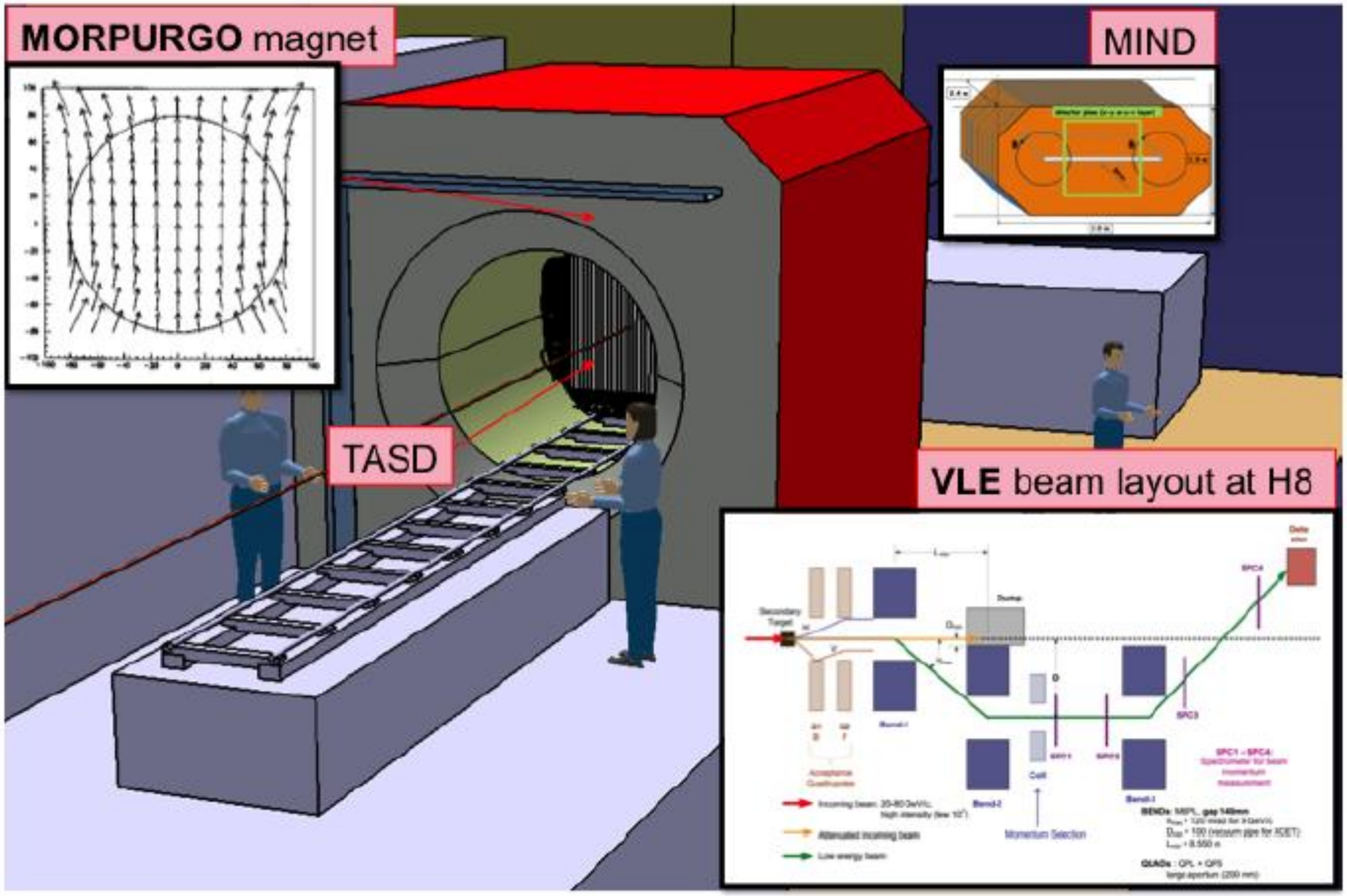
(or possibly behind the LBNO-Demo)

1.5 Tesla

3 m

2.5 m

1.5 m



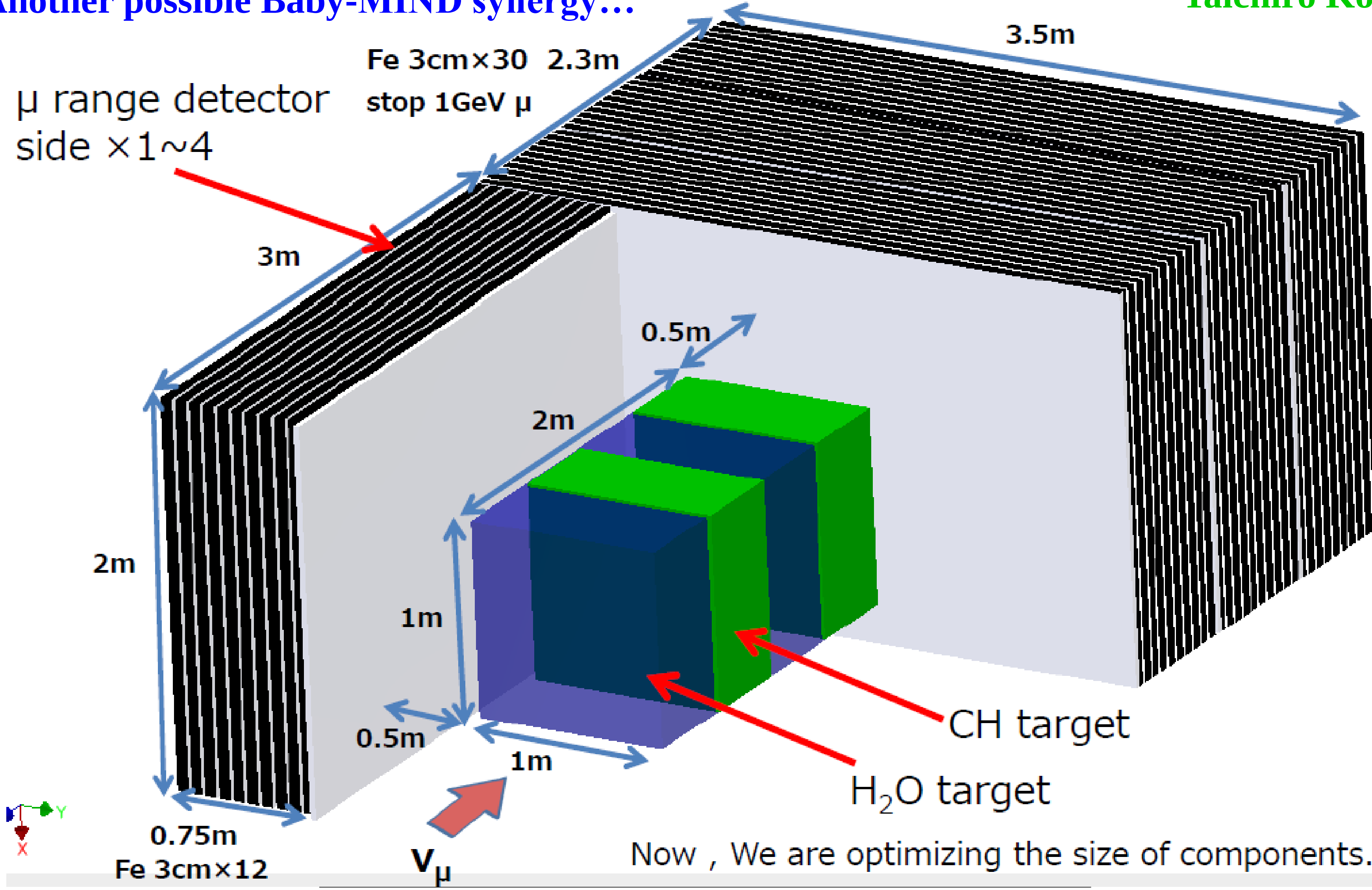
Could also be a practical demonstration of the TITUS MRD charge reconstruction

Contact: *Etam Noah, University of Geneva*

The B2 experiment / 'WAGASCI'

Another possible Baby-MIND synergy…

Taichiro Koga



Now , We are optimizing the size of components.

Summary

With the current tank design 18% of muons escape the tank ←*re-optimize?*

- Of these 75% leave through through the sides

Initial studies show promising charge reconstruction for a TITUS MRD

- Impeccable in the high energy tail (could test the ~80% efficient Gd method)
- Very promising resolution down to $E_\mu = 0.3$ GeV
- Problematic at $E_\mu = 0.2$ GeV (this concerns only 6% of oscillating neutrinos)

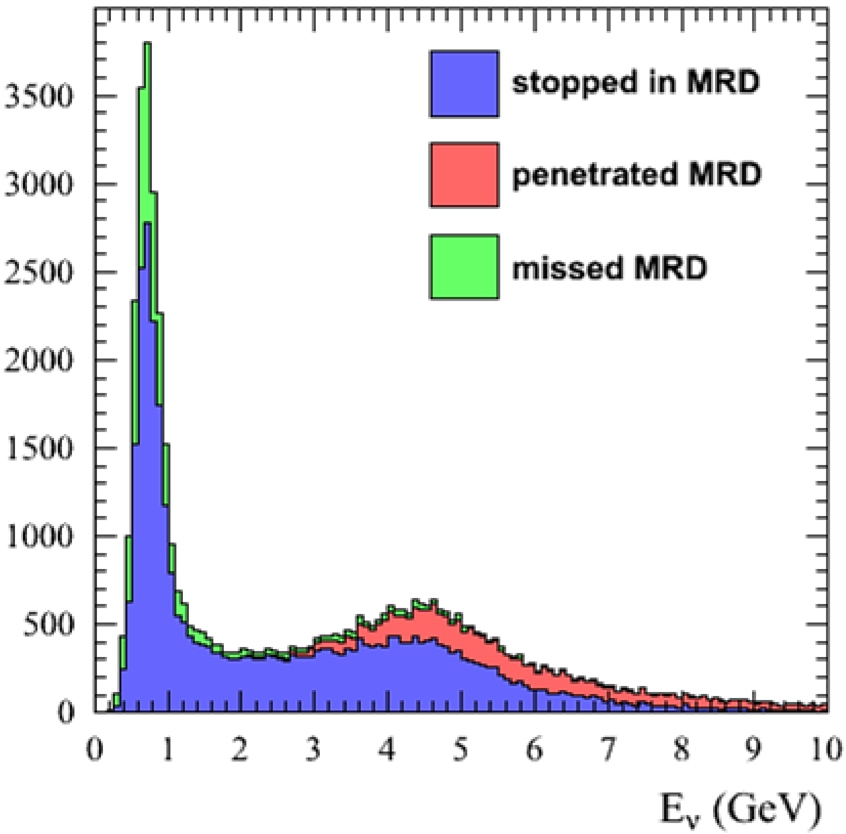
75% of muons which escape the tank are stopped by the MRD

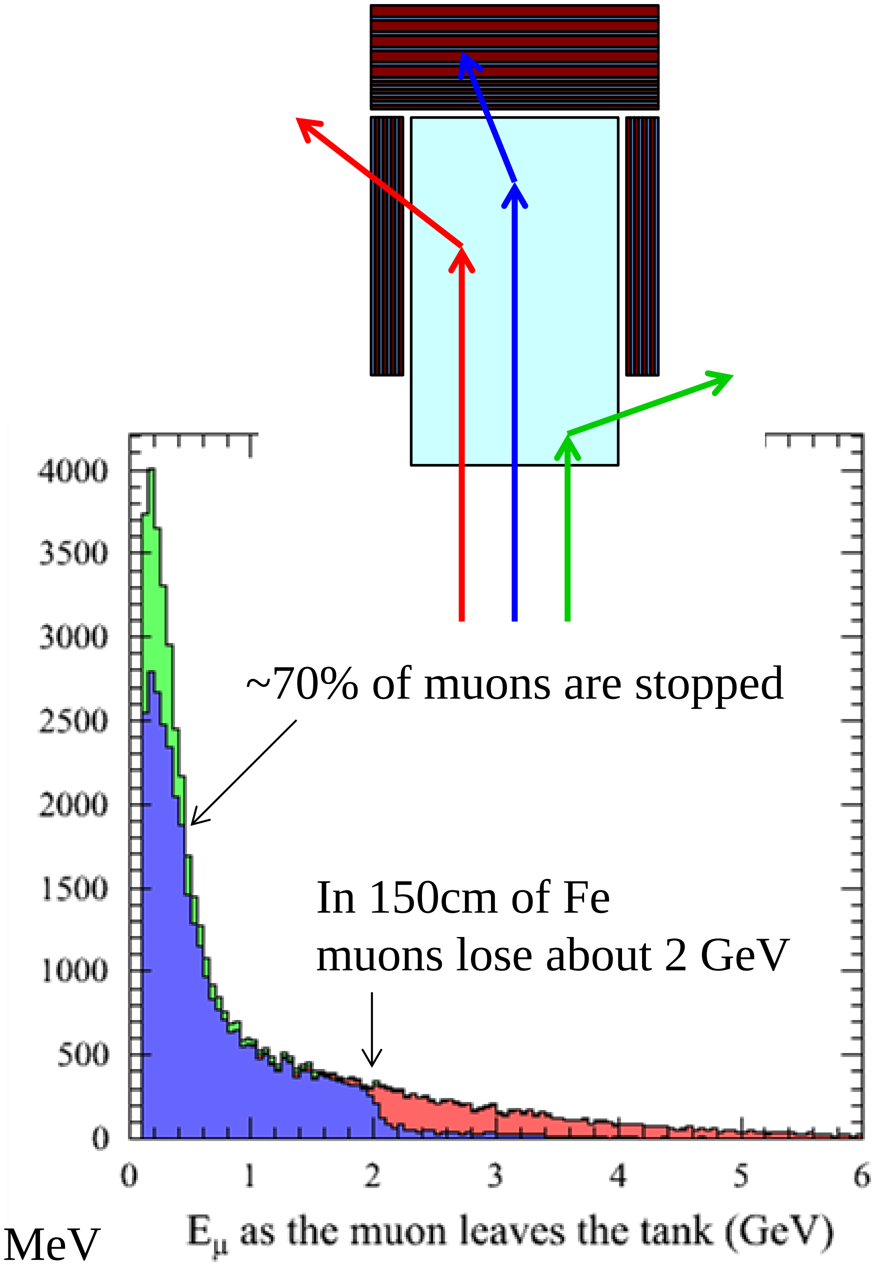
- This essentially includes all those in the oscillation region

Work in progress

- Find the effect on δ_{CP} sensitivity
- Optimization of scintillator and iron thicknesses
- Answers to practical questions, such as PMT shielding
- The last lever: consider re-optimising the tank size and MRD size simultaneously

Backup slides

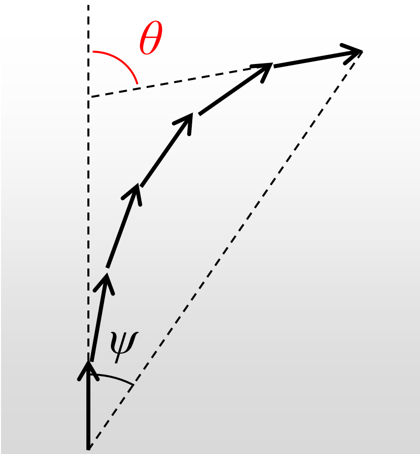




Aside
Momentum for the stopping sample:
For *e.g.* 2.5 cm iron planes, sample energy at 35 MeV

Multiple Scattering in the iron is the biggest obstacle to charge reconstruction

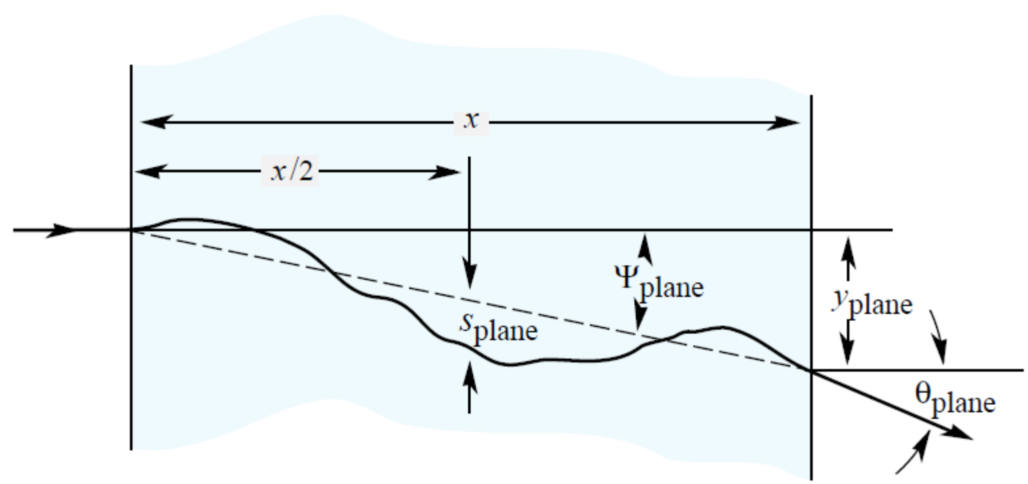
X_0 = 1.757 cm in Fe
X_0 = 50.31 cm in polyethylene



$(X_0 / X_0)^{½}$ = 1.9%

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$

$$\psi^{\mathrm{rms}}_{\mathrm{plane}} = \frac{1}{\sqrt{3}}\, \theta^{\mathrm{rms}}_{\mathrm{plane}} = \frac{1}{\sqrt{3}}\, \theta_0$$



TITUS tank angle reconstruction?

1 sigma electron ring

1 sigma muon ring

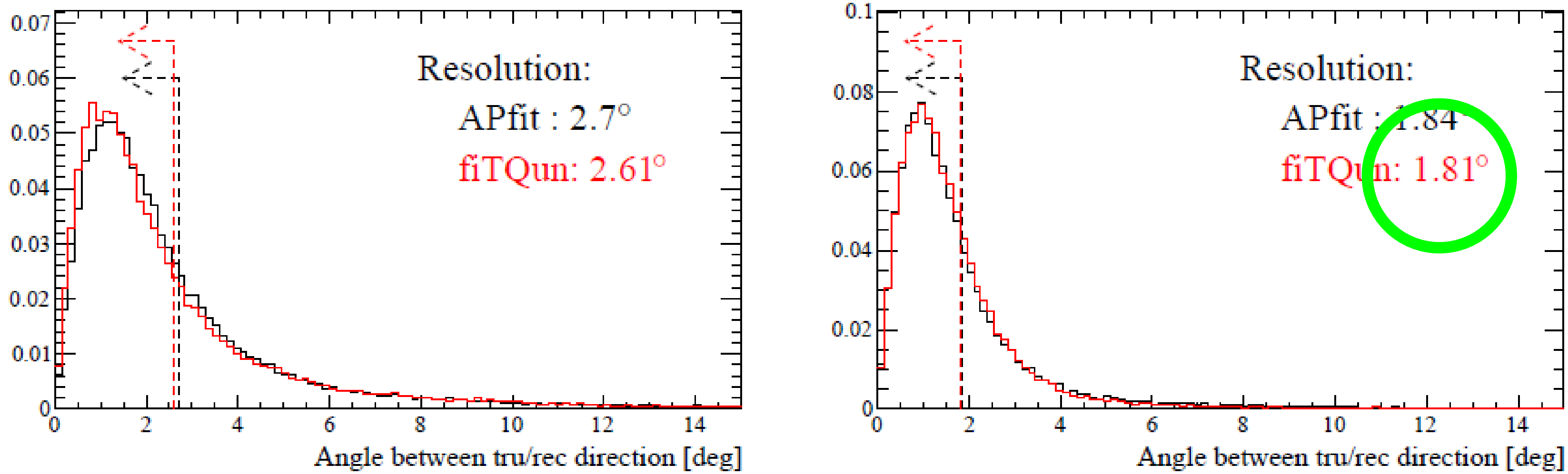
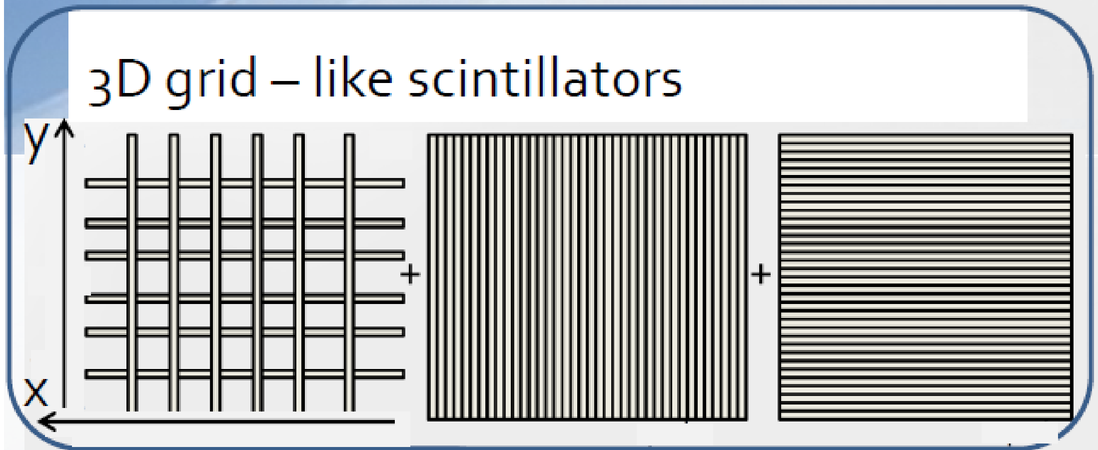


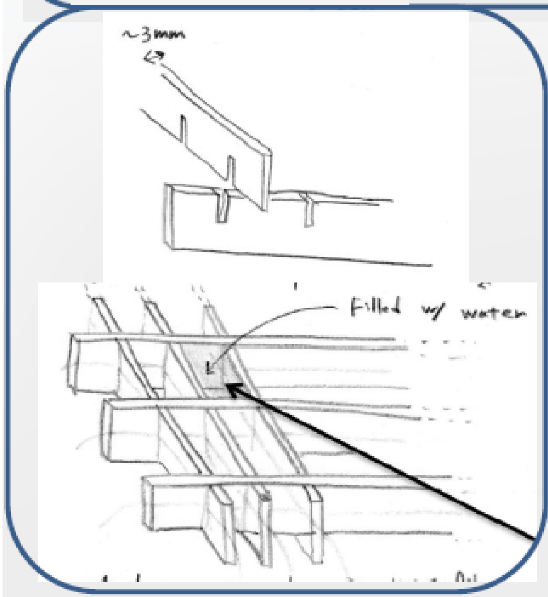
Figure 22: Distributions of the angle between the true and the reconstructed particle directions, for single-ring electron(left) and muon(right) particle gun events. The red histograms are the distributions for fiTQun, and the black histograms are for APfit. The resolutions are defined as the 68.3 percentiles, which are indicated by the dashed arrows.

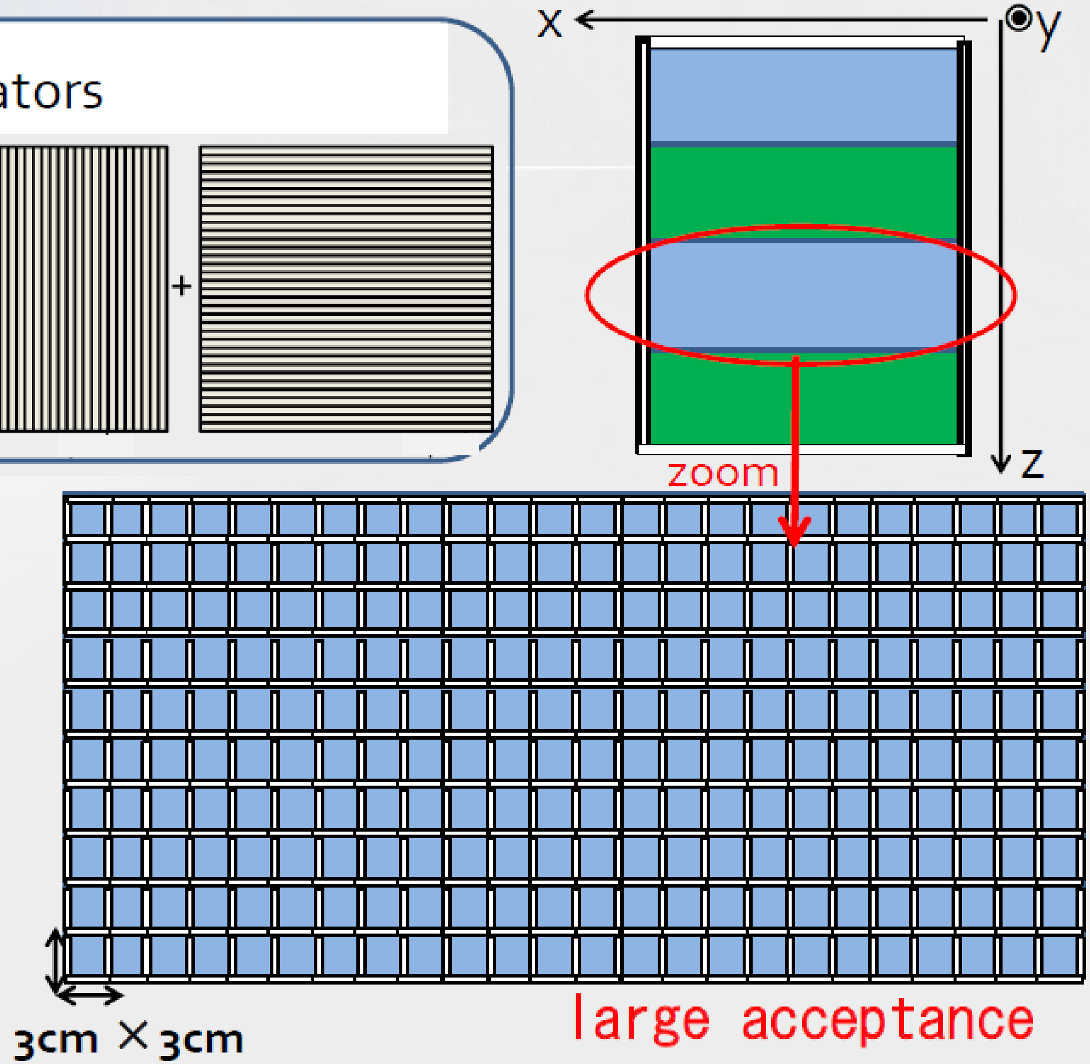
from the fitQun technical note

plastic scintillators in target

Taichiro Koga







- We use thin plastic scintillators(~3mm) to increase water ratio in target.
  Now **H_2O:CH=70:30.** If the size of grid is changed to 5cm × 5cm, **H_2O:CH=80:20.**

8

The B2 experiment

Taichiro Koga

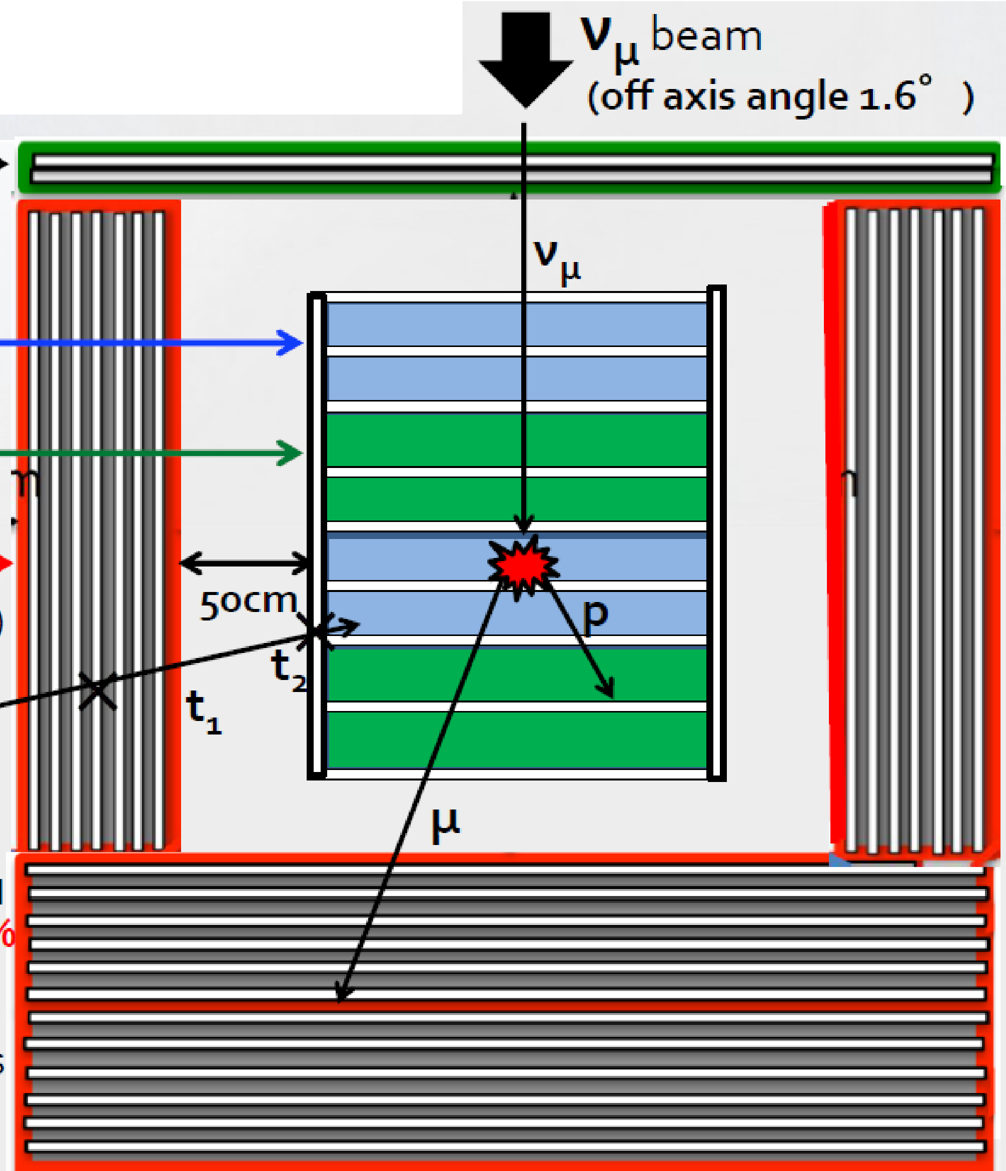
Veto

water target

plastic target

μ range detector
(composed of Fe and plastic scintillator)

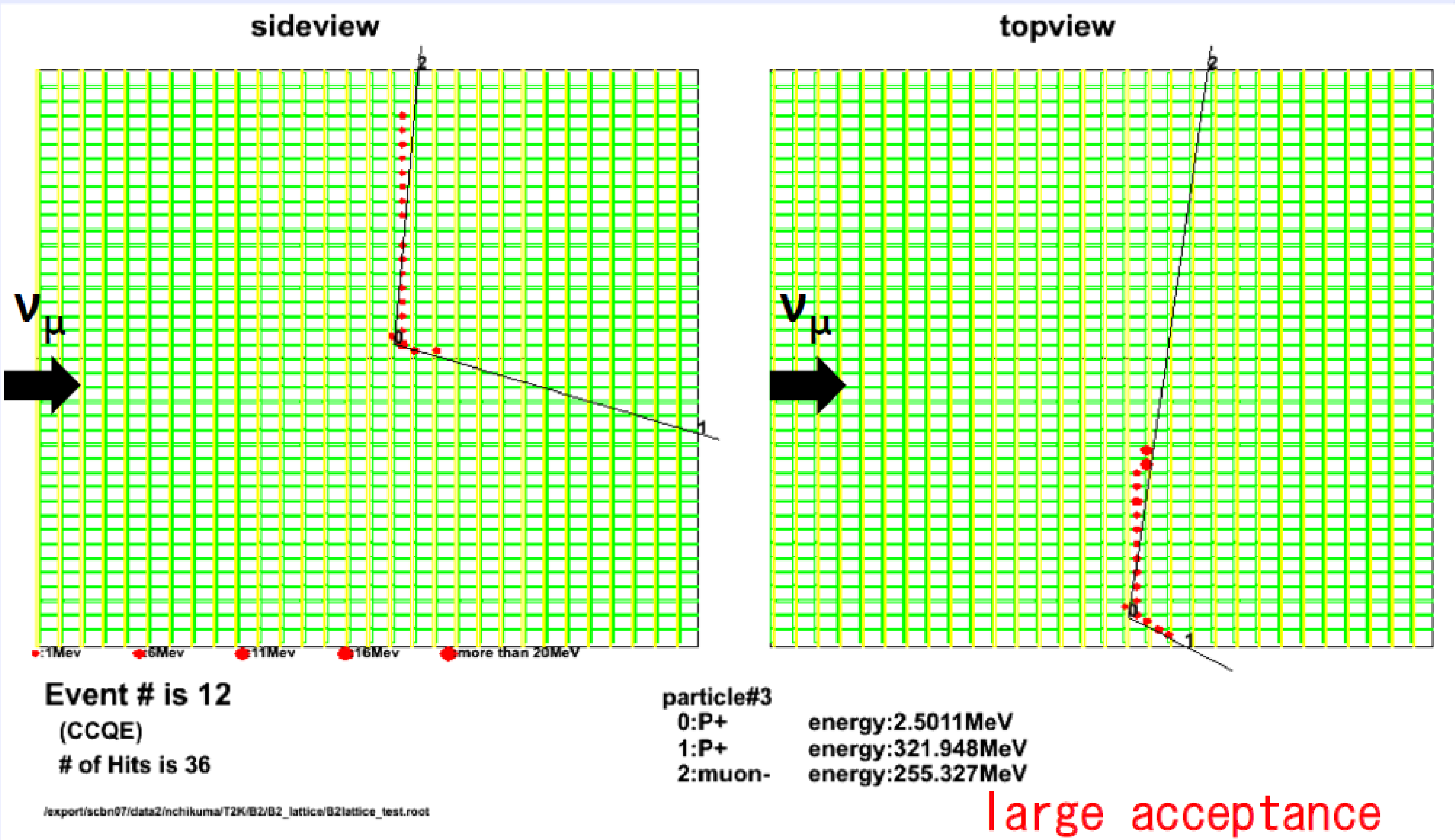
Time of flight
reject BG from the outside



water target : σ_{H_2O}
plastic target : σ_{CH}
⇒ $\sigma_{H_2O} / \sigma_{CH}$ accuracy of 3%

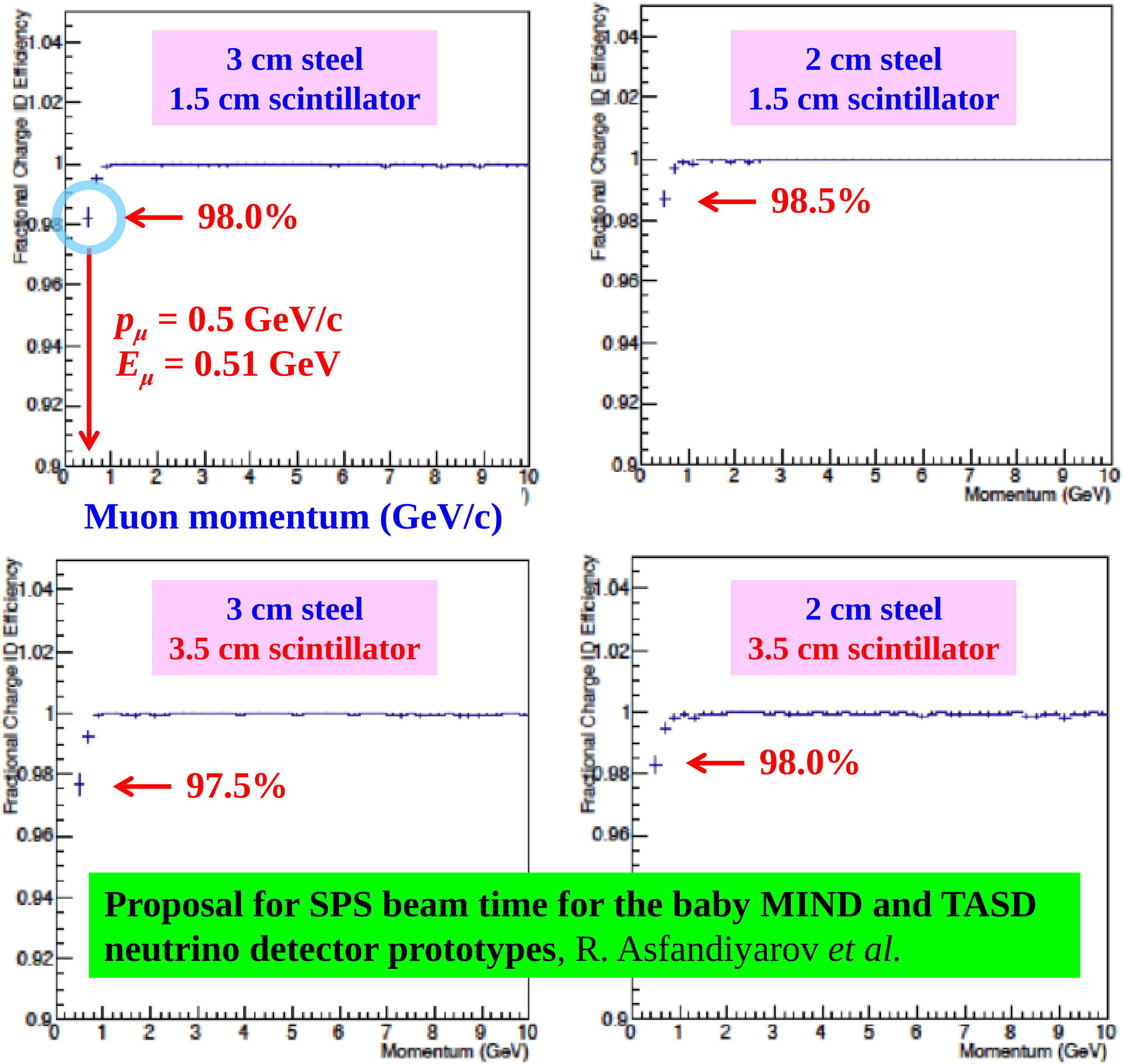
targets have almost same geometry and
ν flux ⇒ detector and beam systematics
are much canceled .

plastic scintillators in target
event display(※chikuma san's figure)

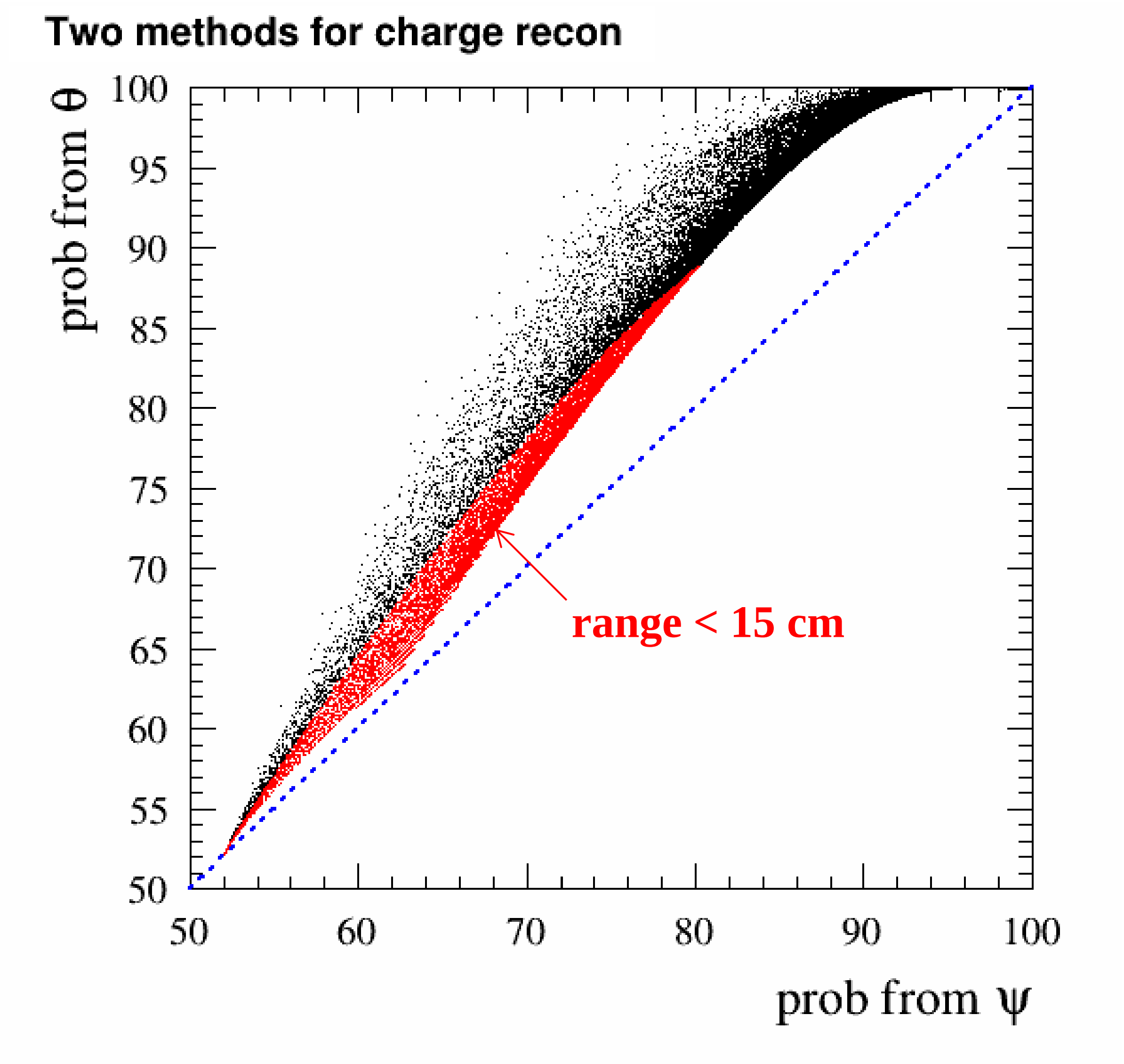


Taichiro Koga

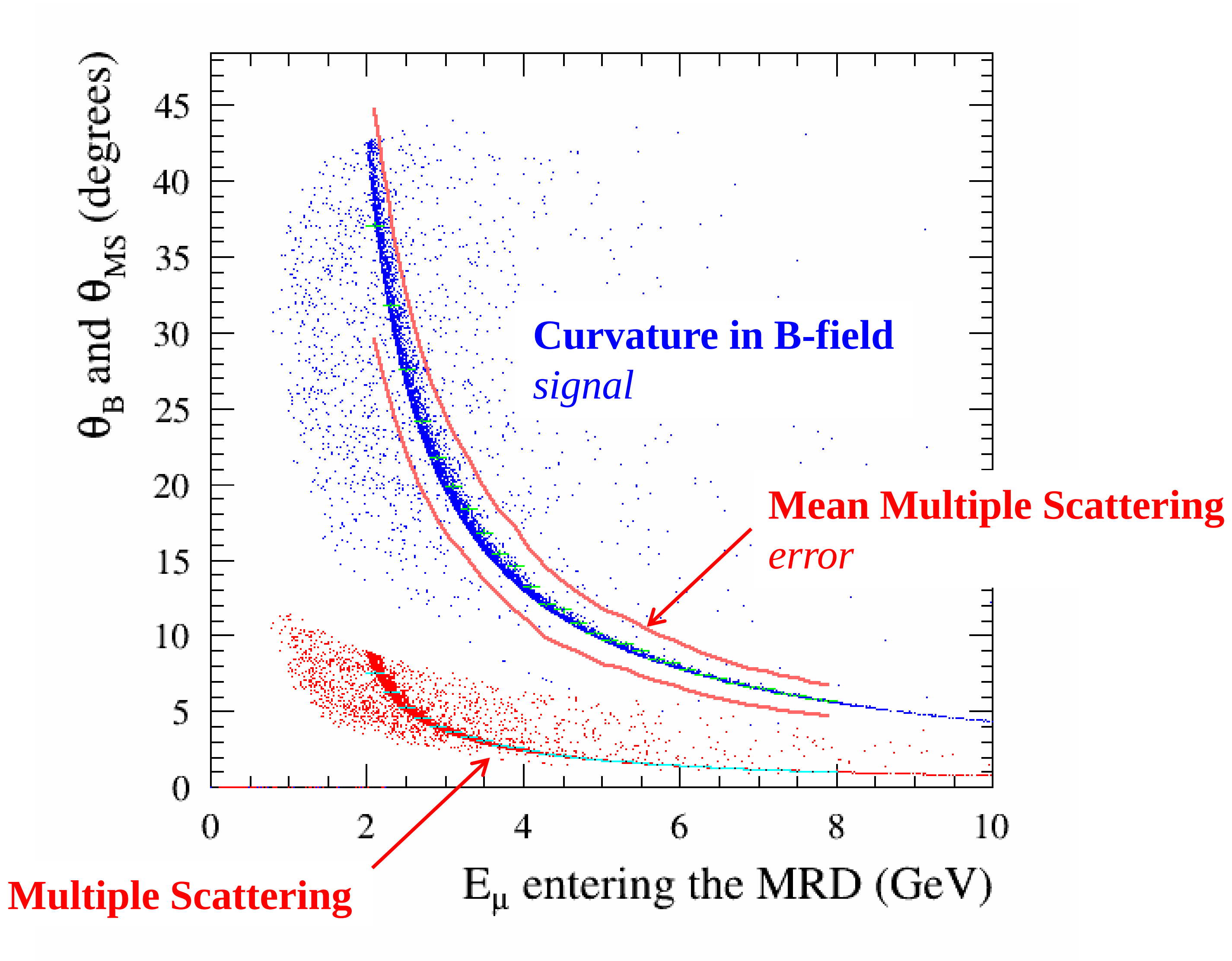
9

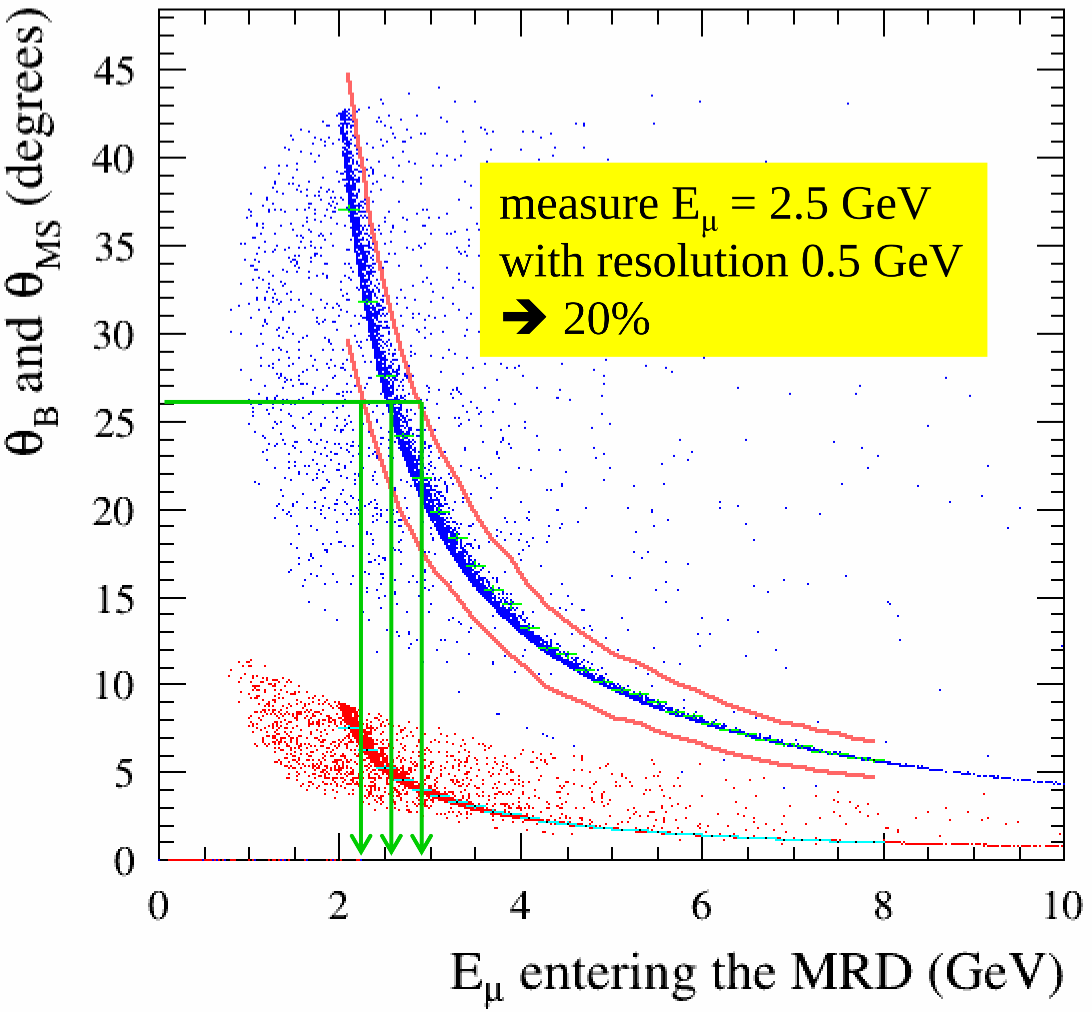


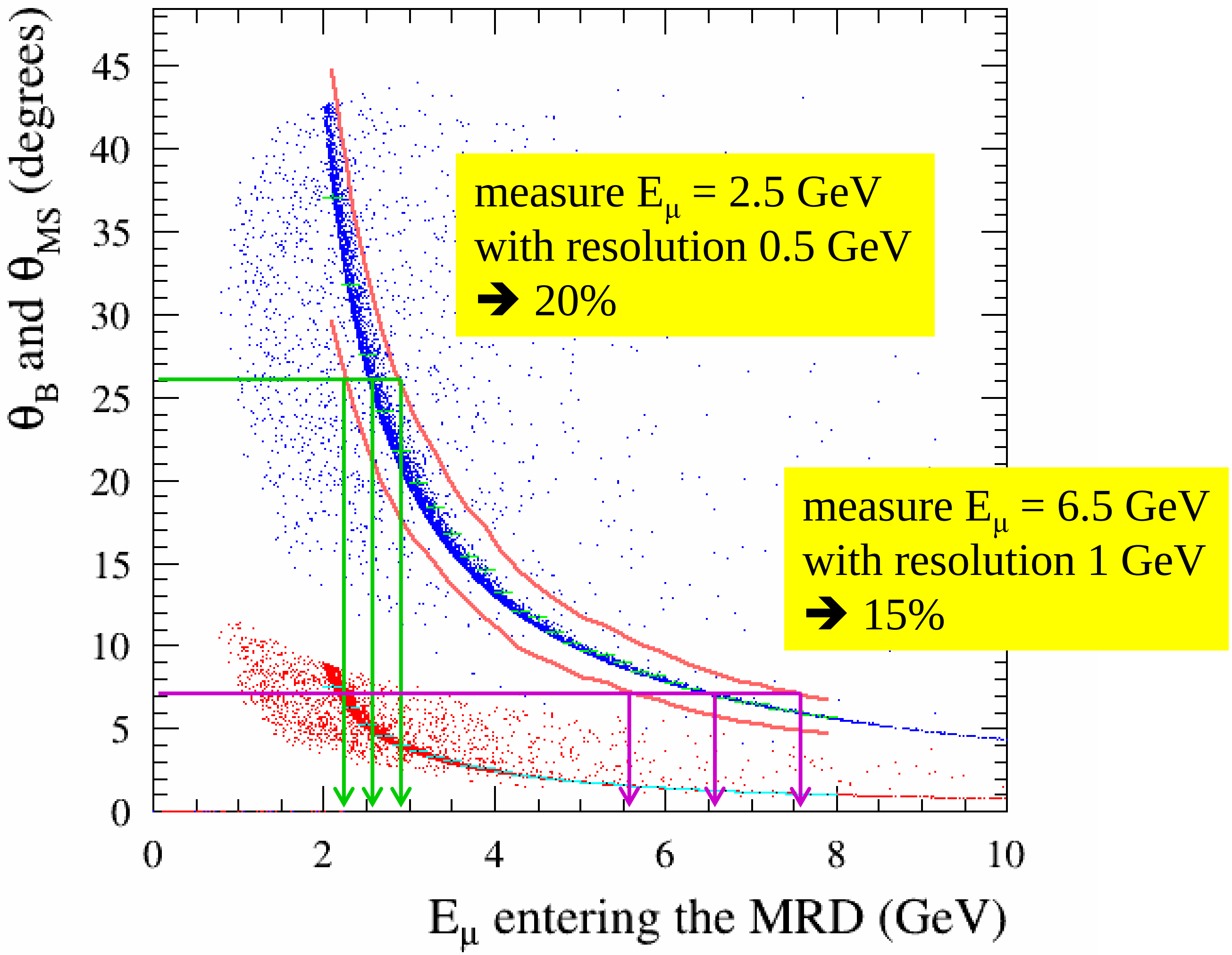
Proposal for SPS beam time for the baby MIND and TASD neutrino detector prototypes, R. Asfandiyarov *et al.*


Two methods for charge recon
prob from θ
prob from ψ
range < 15 cm
100
95
90
85
80
75
70
65
60
55
50
50
60
70
80
90
100

Aside: Momentum for the penetrating sample




measure E_μ = 2.5 GeV
with resolution 0.5 GeV
➔ 20%
θ_B and θ_MS (degrees)
E_μ entering the MRD (GeV)
45
40
35
30
25
20
15
10
5
0
0
2
4
6
8
10



Very conservative estimates

Landau-Vavilov most probable energy loss in iron

density = 7.87 g cm^{-2}

K = 0.307075 MeV g^{-1} cm^2

$$\xi = (K/2)\,\langle Z/A \rangle\,(x/\beta^2)\ \text{MeV}$$

~ 1.13 MeV / cm (ultra-relativistic)

Z/*A* = 26 / 55.845 = 0.466

<*Z*/*A*>*ρ* ratio (~energy loss / cm) = 1.4%

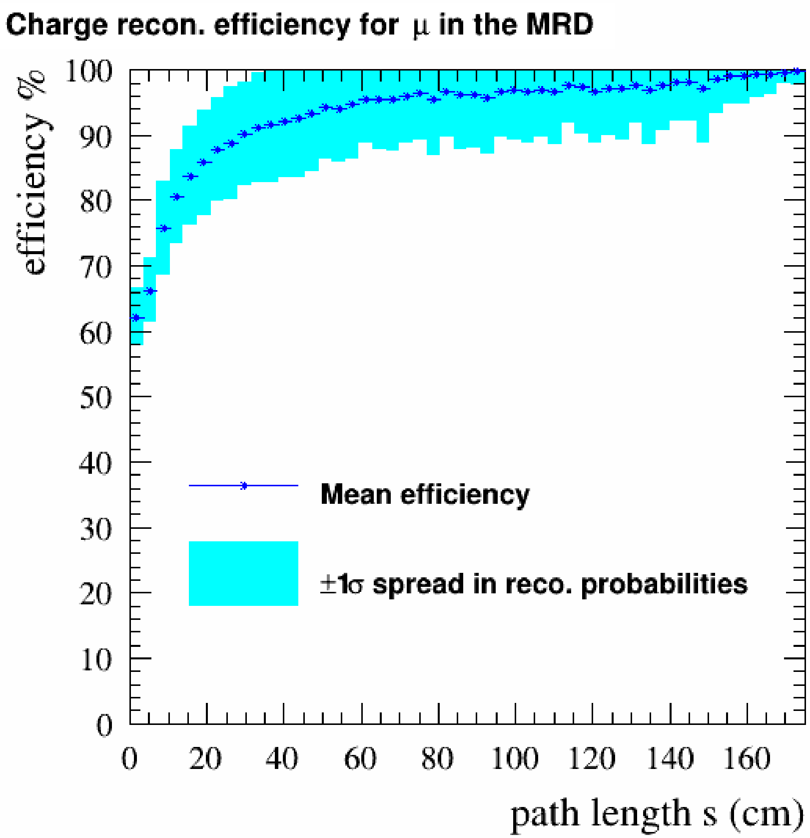
0.511 MeV

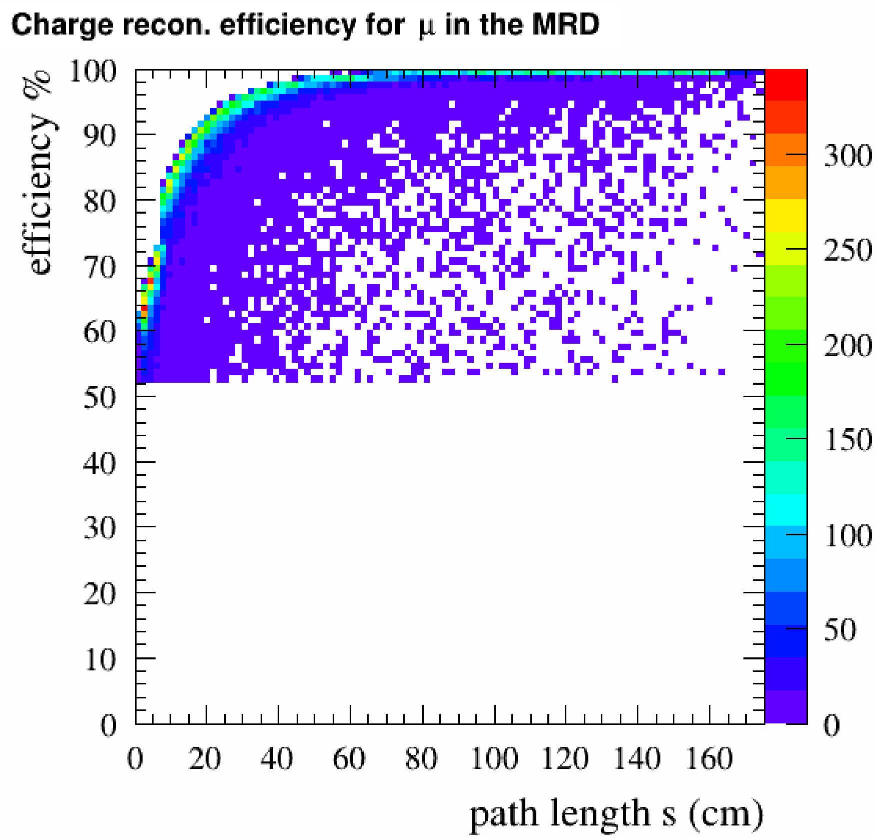
neglect density effect

$$\Delta_p = \xi\left[\ln\frac{2mc^2\beta^2\gamma^2}{I} + \ln\frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma)\right]$$

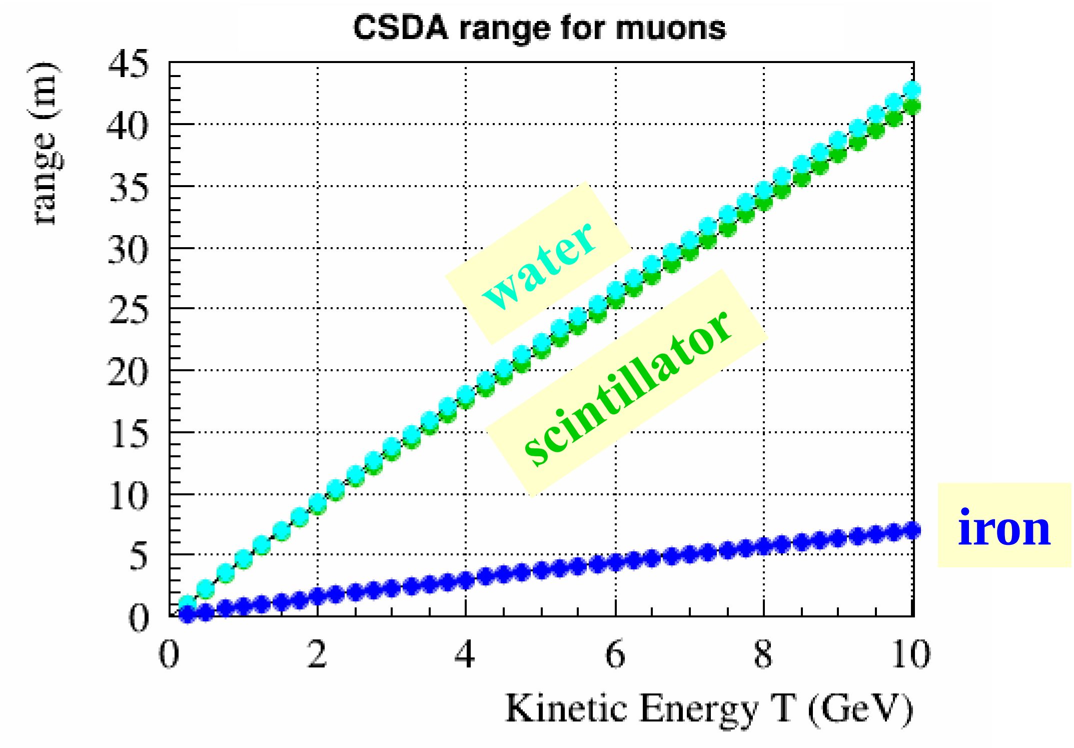
0.200 all materials

Mean excitation energy
I = 286.0 eV in iron


Charge recon. efficiency for μ in the MRD
efficiency %
path length s (cm)
Mean efficiency
±1σ spread in reco. probabilities
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160


Charge recon. efficiency for μ in the MRD
efficiency %
path length s (cm)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
0
50
100
150
200
250
300

Range of muons in iron



Fiducial volume cut = 1 m
with LAPPDs = 0.5 m

PDG 32.11. Measurement of particle momenta in a uniform magnetic field

The trajectory of a particle with momentum p (in GeV/c) and charge ze in a constant magnetic field $\vec{B}$ is a helix, with radius of curvature R and pitch angle λ. The radius of curvature and momentum component perpendicular to $\vec{B}$ are related by

assumes no energy loss

$$p \cos\lambda = 0.3\, z\, B\, R\,, \tag{32.49}$$

where B is in tesla and R is in meters.

The distribution of measurements of the curvature $k \equiv 1/R$ is approximately Gaussian. The curvature error for a large number of uniformly spaced measurements on the trajectory of a charged particle in a uniform magnetic field can be approximated by

$$(\delta k)^2 = (\delta k_{\rm res})^2 + (\delta k_{\rm ms})^2\ , \tag{32.50}$$

where $\delta k =$ curvature error
$\delta k_{\rm res} =$ curvature error due to finite measurement resolution
$\delta k_{\rm ms} =$ curvature error due to multiple scattering.

If many (≥ 10) uniformly spaced position measurements are made along a trajectory in a uniform medium,

$$\delta k_{\rm res} = \frac{\epsilon}{L'^2}\sqrt{\frac{720}{N+4}}\ , \tag{32.51}$$

where $N =$ number of points measured along track
$L' =$ the projected length of the track onto the bending plane
$\epsilon =$ measurement error for each point, perpendicular to the trajectory.

If a vertex constraint is applied at the origin of the track, the coefficient under the radical becomes 320.

For arbitrary spacing of coordinates s_i measured along the projected trajectory and with variable measurement errors ϵ_i the curvature error δk_{res} is calculated from:

$$(\delta k_{\mathrm{res}})^2 = \frac{4}{w} \; \frac{V_{ss}}{V_{ss}V_{s^2s^2} - (V_{ss^2})^2} \; , \tag{32.52}$$

where V are covariances defined as $V_{s^m s^n} = \langle s^m s^n \rangle - \langle s^m \rangle \langle s^n \rangle$ with $\langle s^m \rangle = w^{-1} \sum ({s_i}^m / {\epsilon_i}^2)$ and $w = \sum {\epsilon_i}^{-2}$.

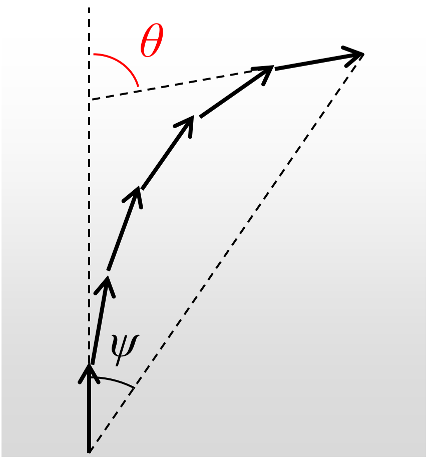
The contribution due to multiple Coulomb scattering is approximately

$$\delta k_{\mathrm{ms}} \approx \frac{(0.016)(\mathrm{GeV}/c) z}{L p \beta \cos^2 \lambda} \sqrt{\frac{L}{X_0}} \; , \tag{32.53}$$

where $p =$ momentum (GeV/c)
$z =$ charge of incident particle in units of e
$L =$ the total track length
$X_0 =$ radiation length of the scattering medium (in units of length; the X_0 defined elsewhere must be multiplied by density)
$\beta =$ the kinematic variable v/c.

More accurate approximations for multiple scattering may be found in the section on Passage of Particles Through Matter (Sec. 31 of this *Review*). The contribution to the curvature error is given approximately by $\delta k_{\mathrm{ms}} \approx 8 s_{\mathrm{plane}}^{\mathrm{rms}} / L^2$, where $s_{\mathrm{plane}}^{\mathrm{rms}}$ is defined there.

Curvature in the magnetic field



The uniform magnetic field B = 1.5T is in the z direction

The particle moves along a curve of length s in the (x,y) plane

$$dp_{\perp}/dt = B\,q\,ds/dt$$

$$\Delta p_{\perp} = B\,q\,\Delta s$$

Take uniform steps of Δs = 1 cm

$\Delta p_{\perp}$ = 4.5 MeV/c (for every cm)

And hence the angle curved, depending on E at the time

ΔE using most probable Landau-Vavilov value (Bethe overestimates due to long tails)

Charge identification for the muon if

θ > Multiple Scattering

Muon path length in the iron of the MRD