Charge Reconstruction with a Magnetised Muon Range Detector in TITUS

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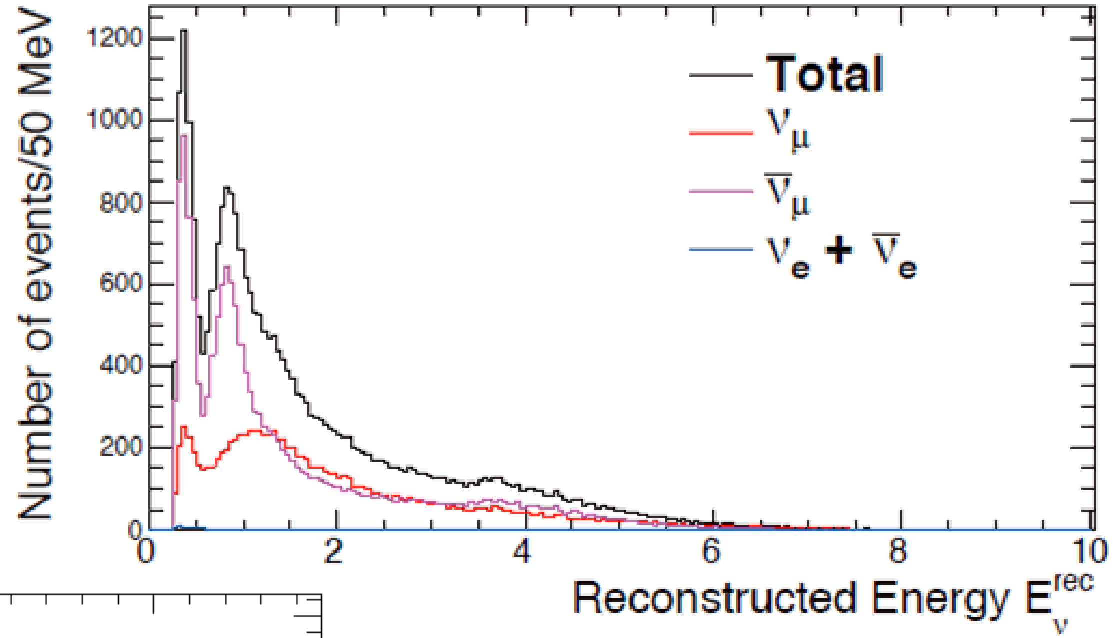
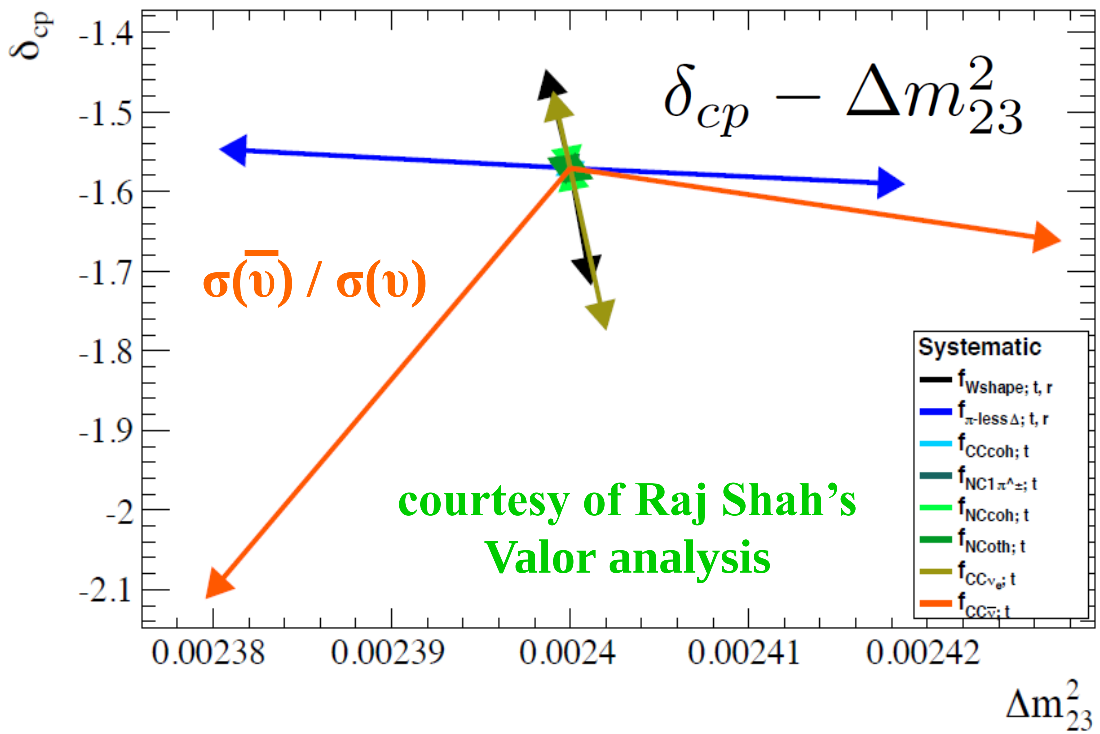
5th open Hyper-Kamiokande meeting, Vancouver

19th July 2014, Near Detector pre-meeting

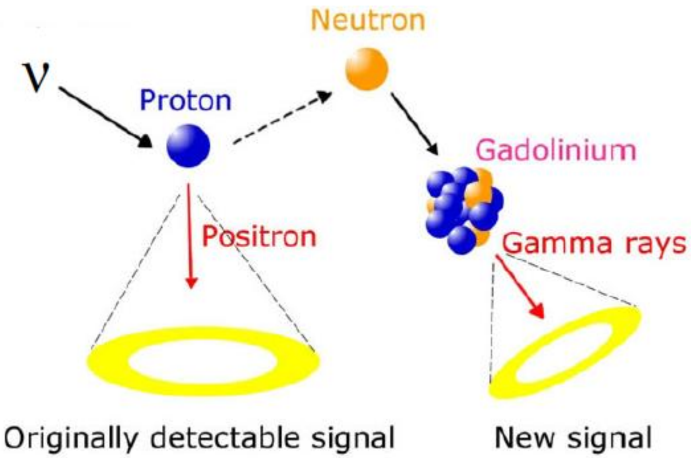
Motivation

Significant wrong-sign component in anti-neutrino mode





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



$$\upsilon\, n \rightarrow \ell\, p$$

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

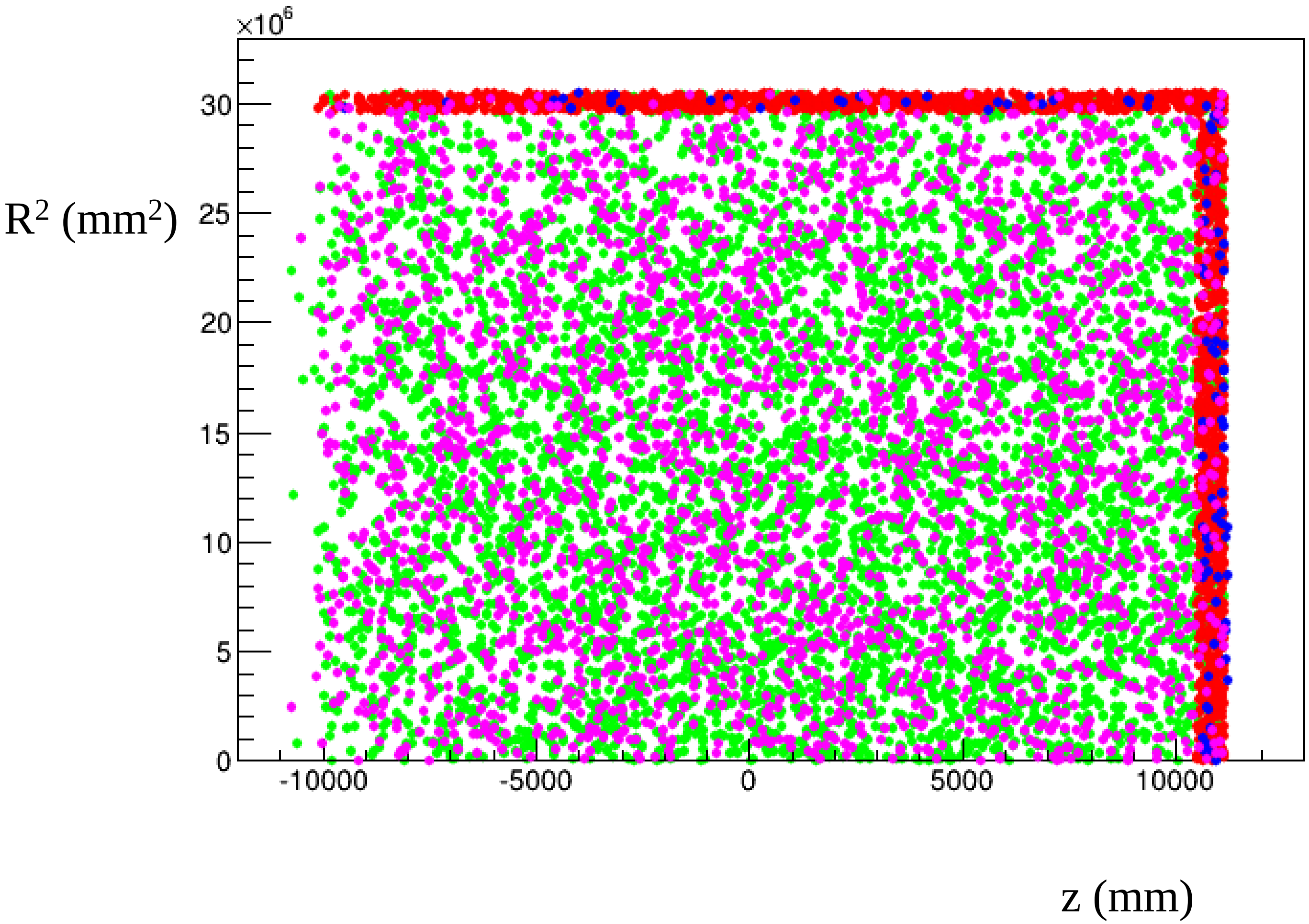
detect with Gd

$\varepsilon_Q \approx$ **88%**

Exciting, but somewhat untested

18% of muons escape the tank

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



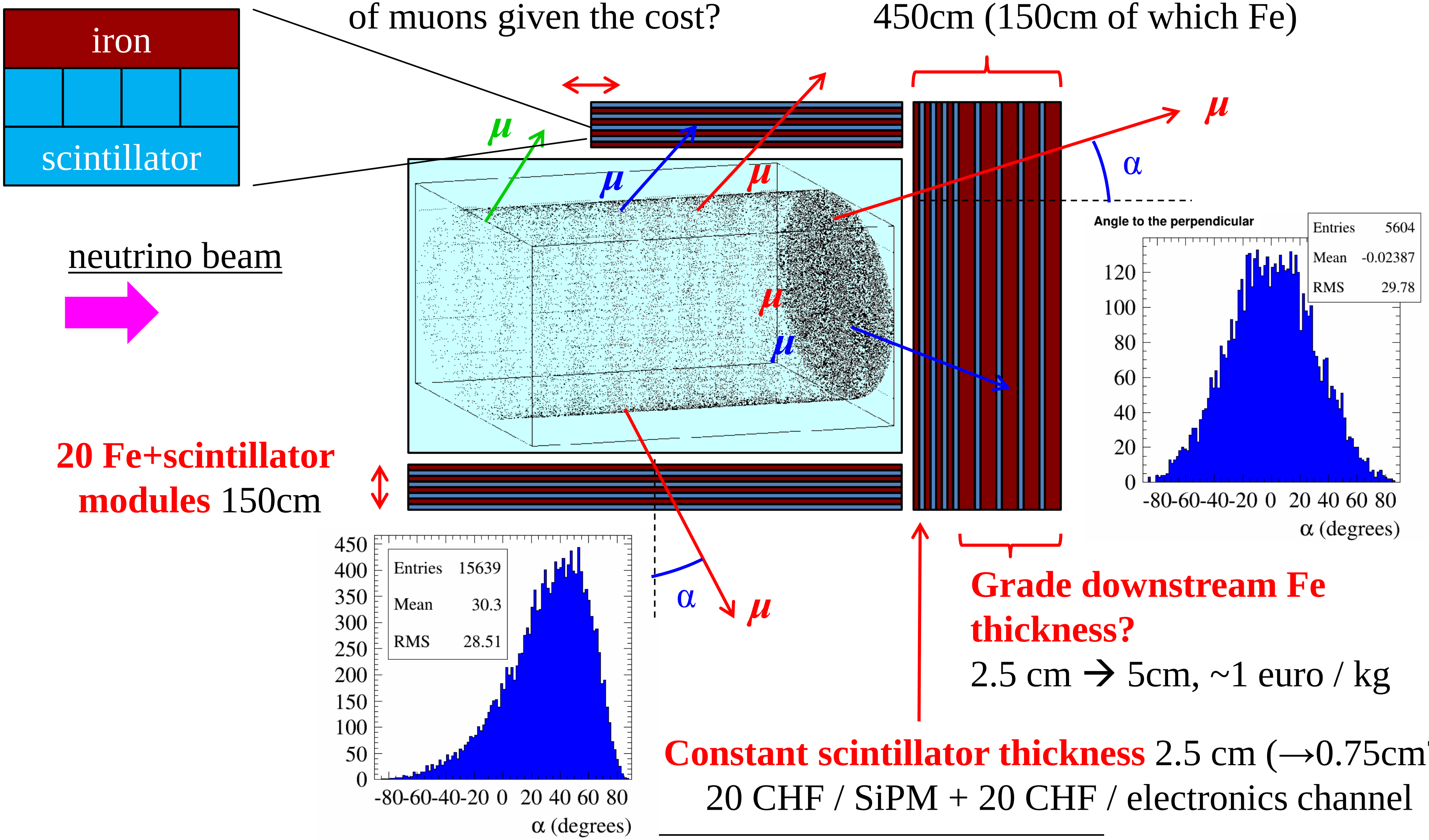
N.B. The tank size could be re-optimized with the MRD in mind

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)



20 Fe+scintillator modules 150cm

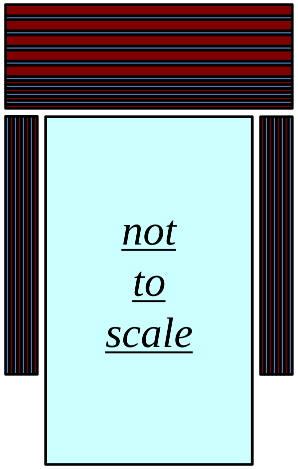
Grade downstream Fe thickness?
2.5 cm ➔ 5cm, ~1 euro / kg

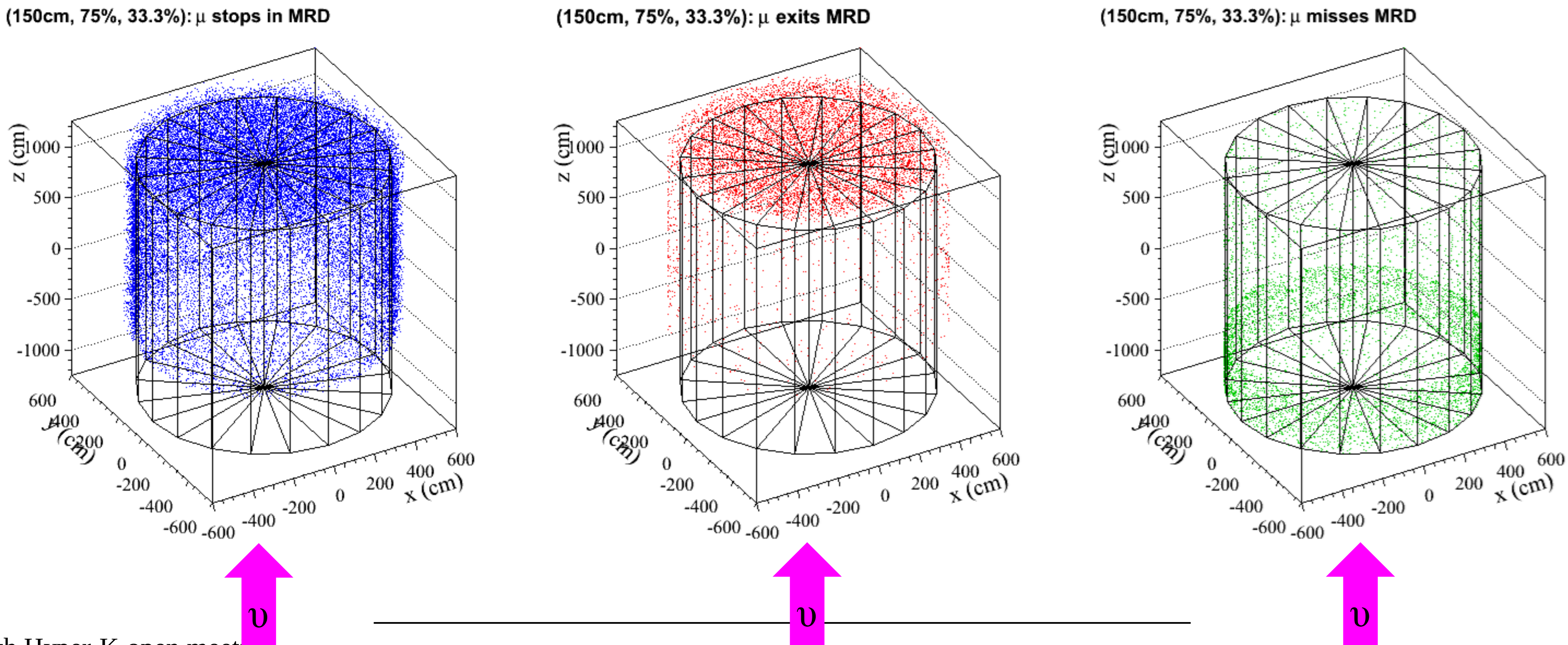
Constant scintillator thickness 2.5 cm (→0.75cm?)
20 CHF / SiPM + 20 CHF / electronics channel

Muons tracks in the TITUS MRD

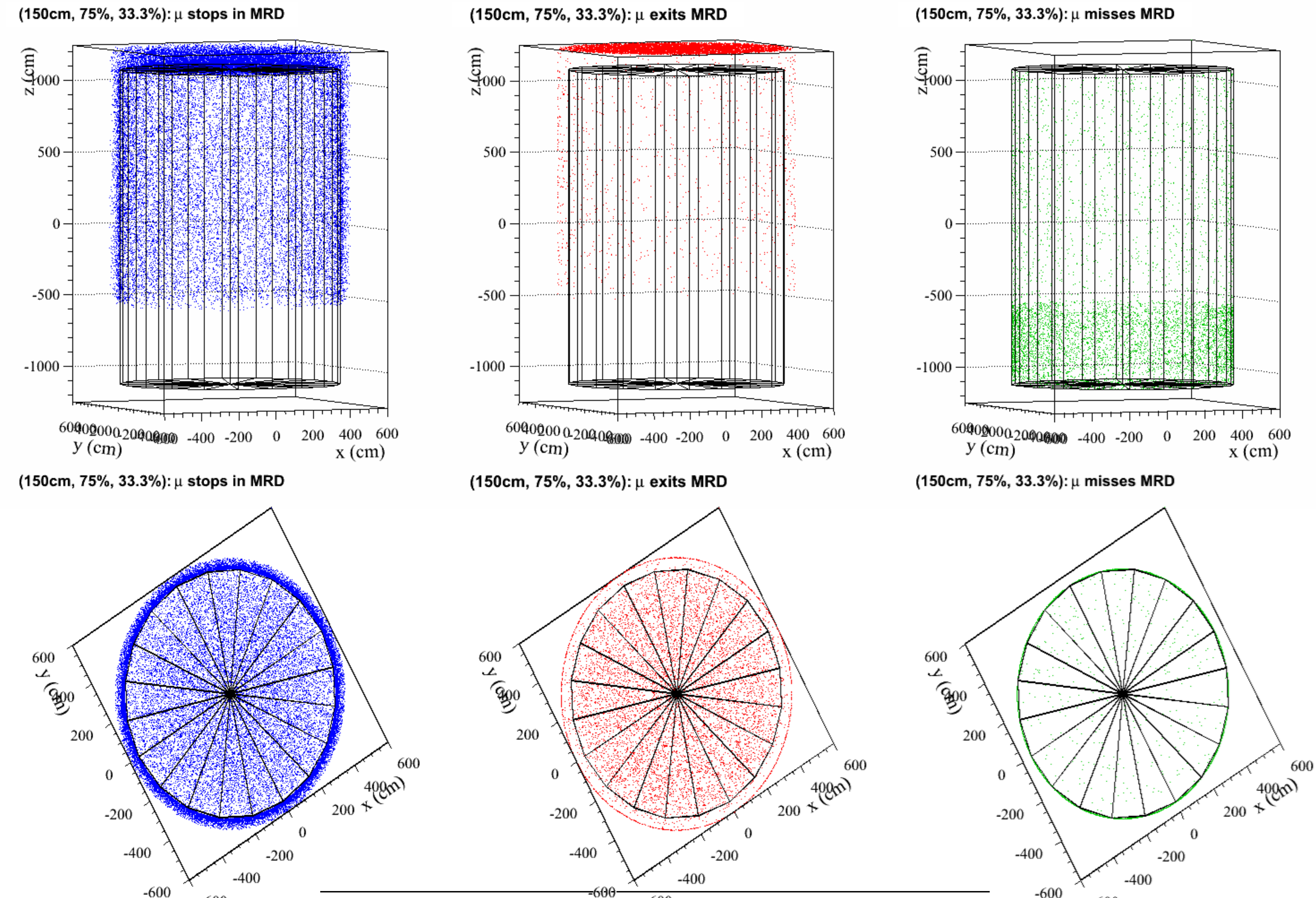
A simulation with 150cm end Fe and 75% side coverage of 50cm of Fe

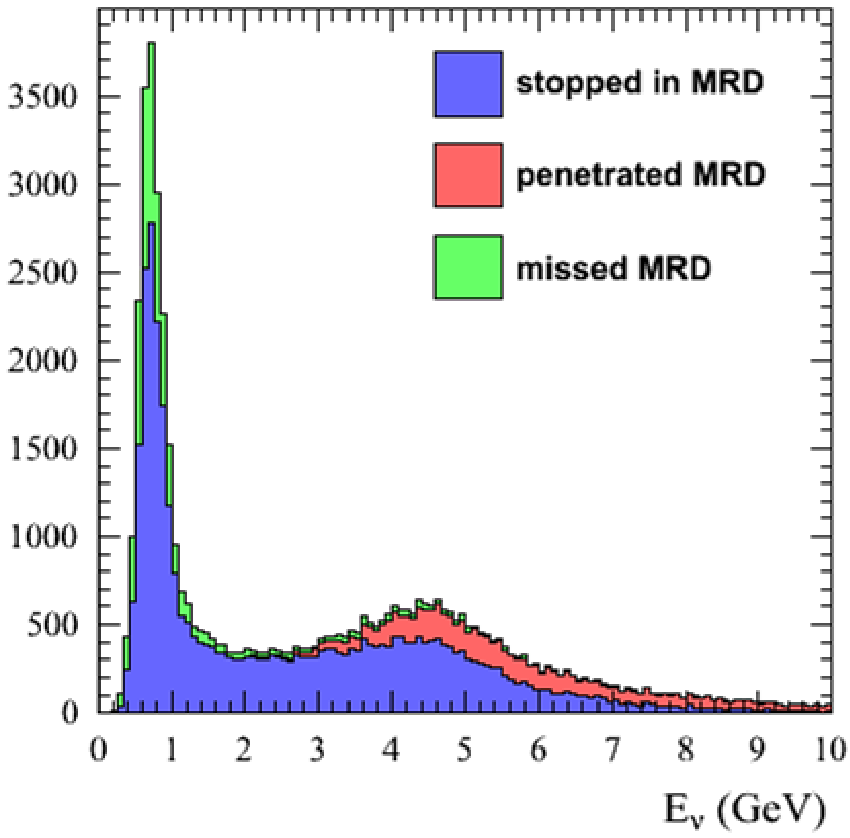
- **range-out and stop in the MRD**
- **penetrate through the MRD**
- **miss the MRD**

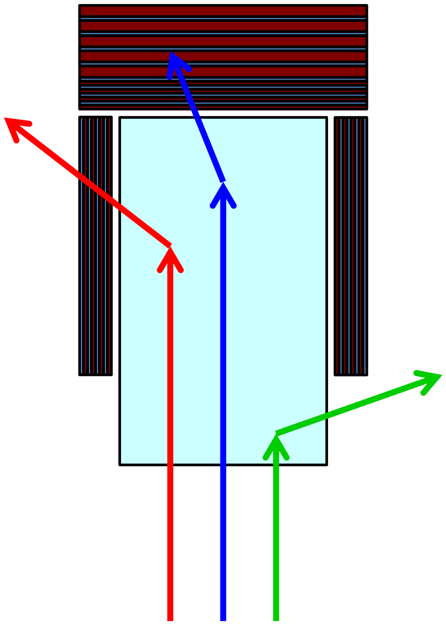


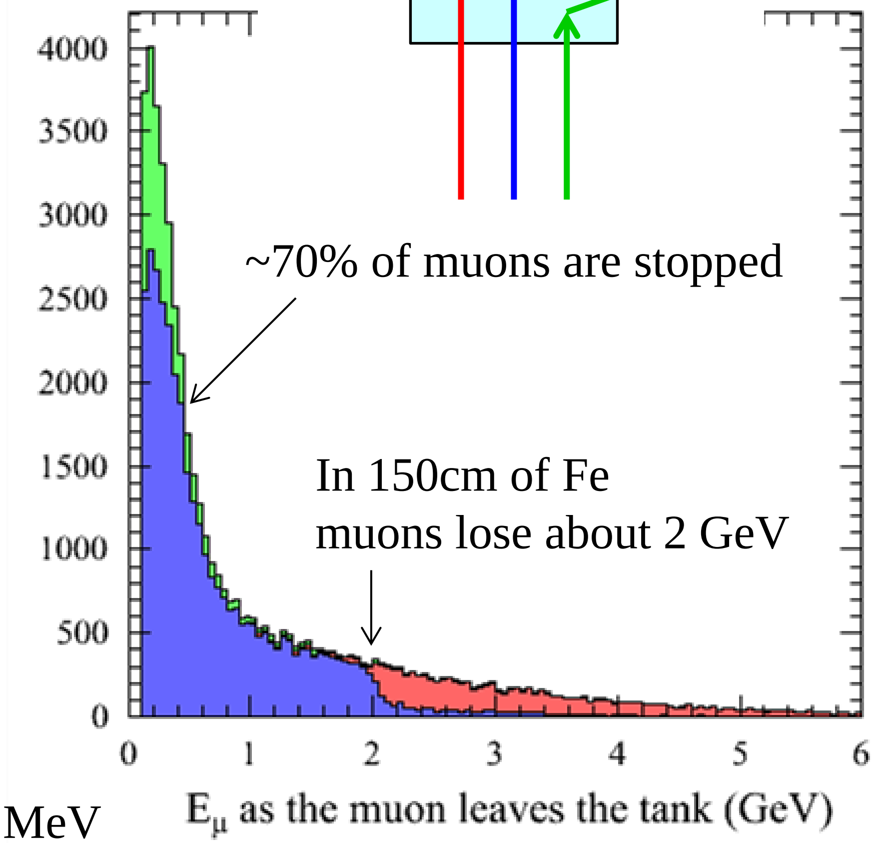


And from two more projections…







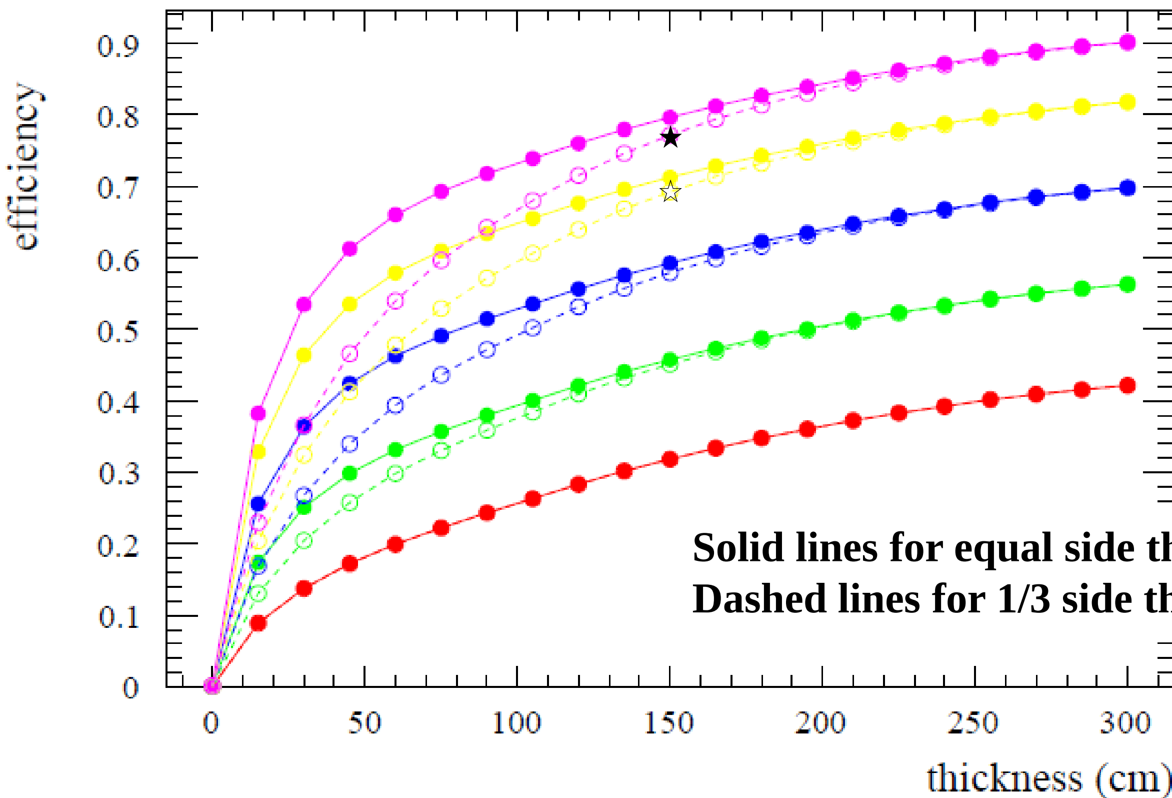


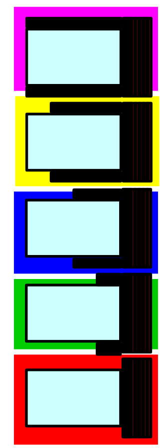
Aside

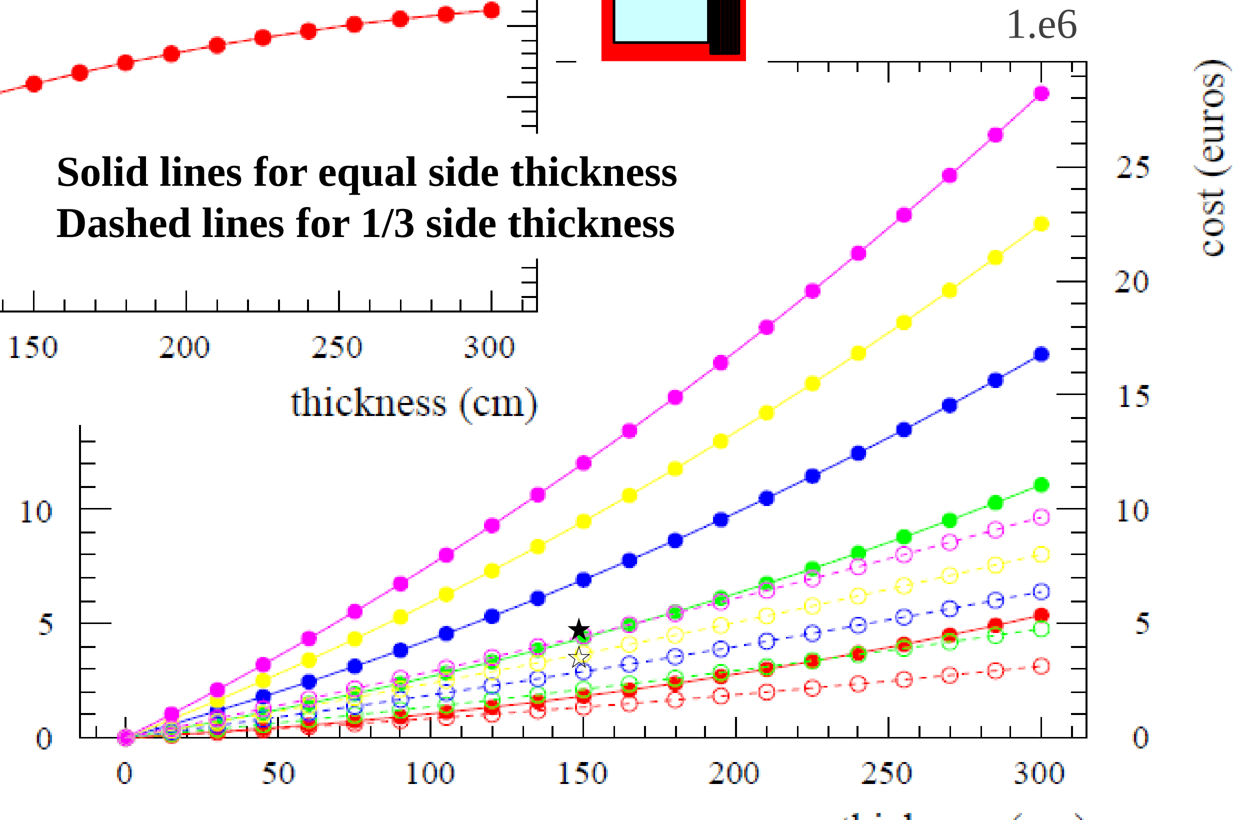
Momentum for the stopping sample:

For *e.g.* 2.5 cm iron planes, sample energy at 35 MeV

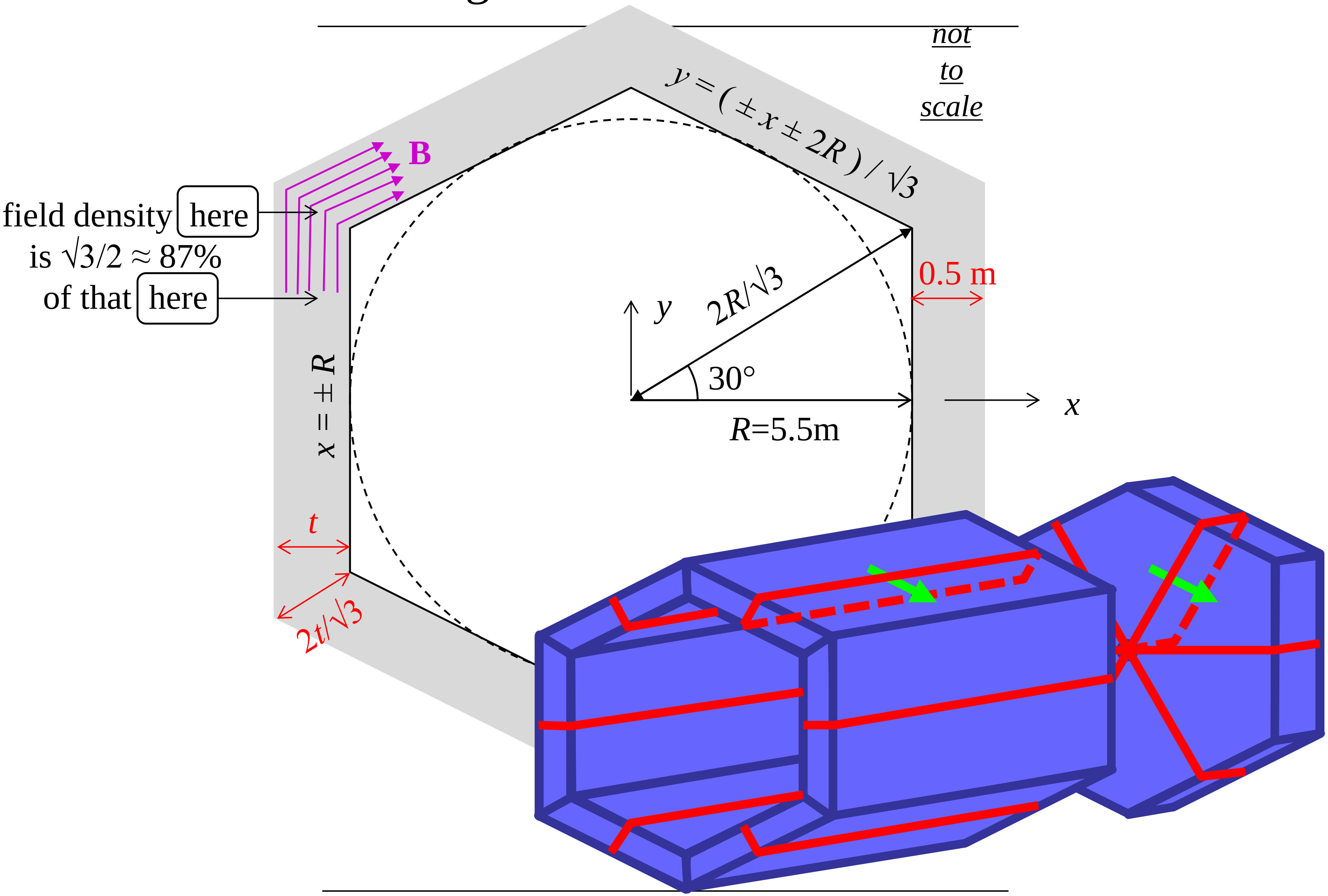
Optimizing efficiency for stopping muons, and cost





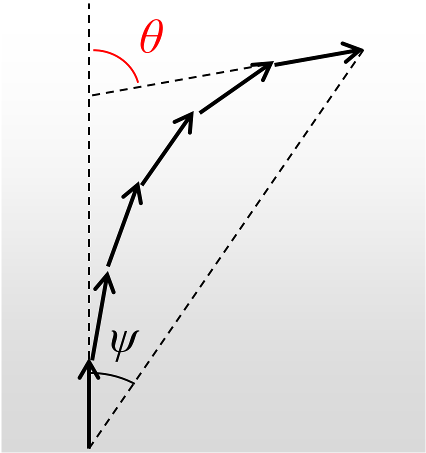


Magnetization of the MRD



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

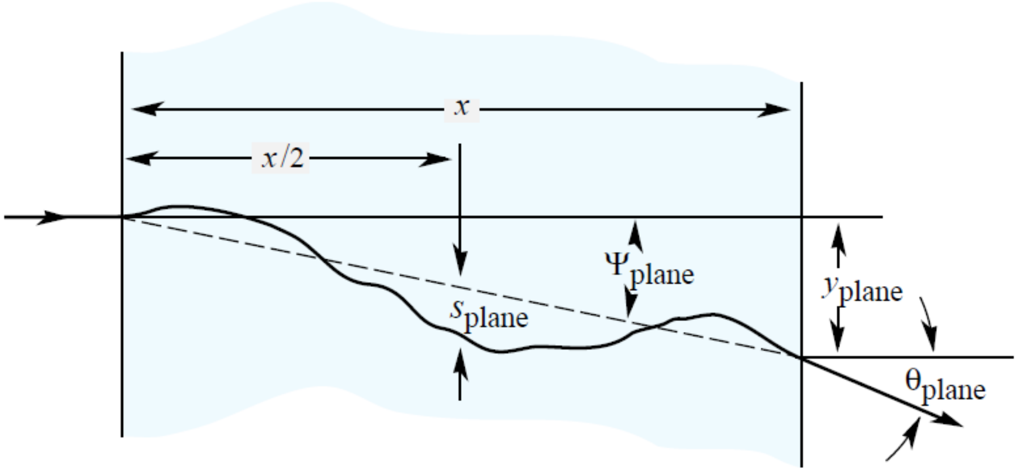
X_0 = 1.757 cm in Fe
X_0 = 50.31 cm in polyethylene



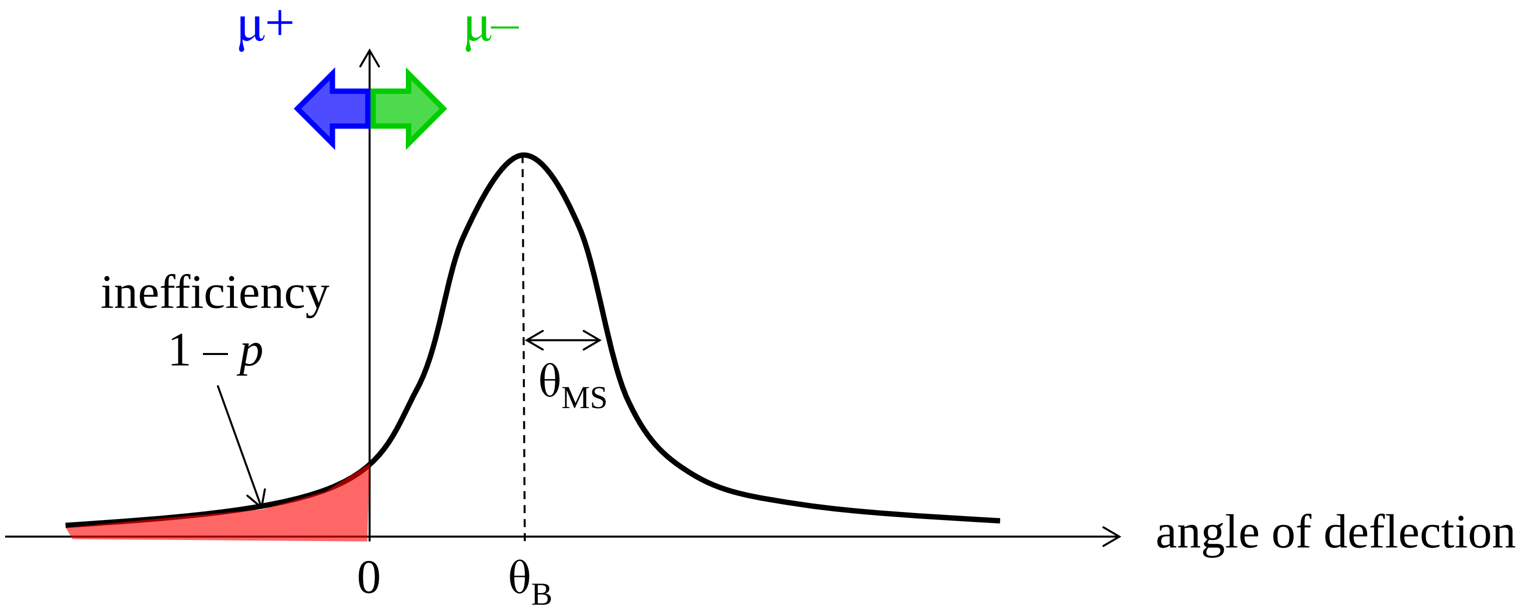
$(X_0 / X_0)^{½}$ = 1.9%

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

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

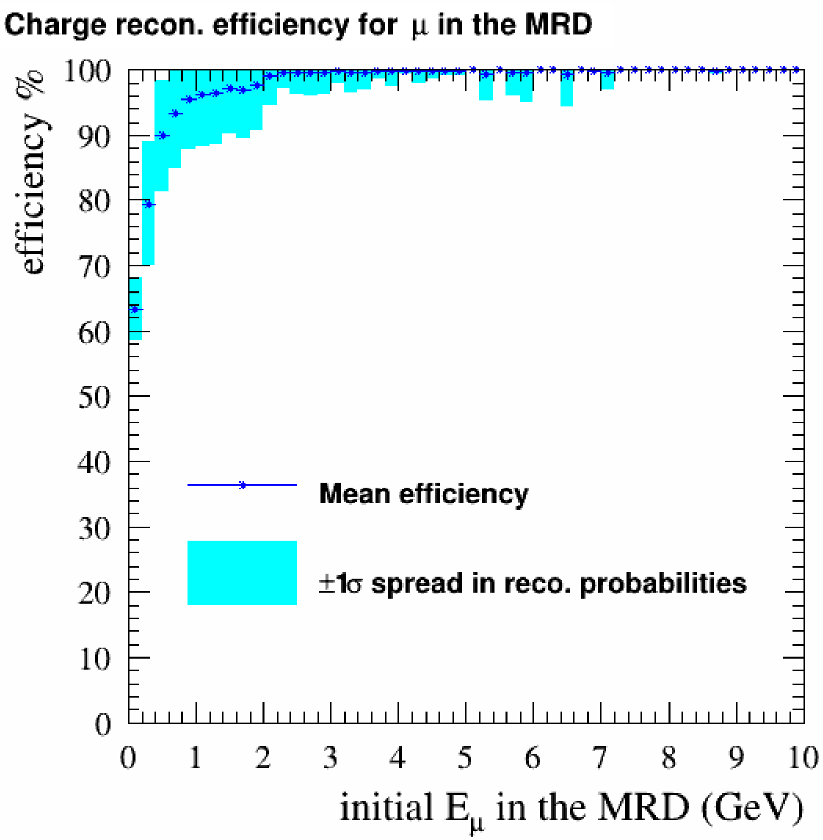


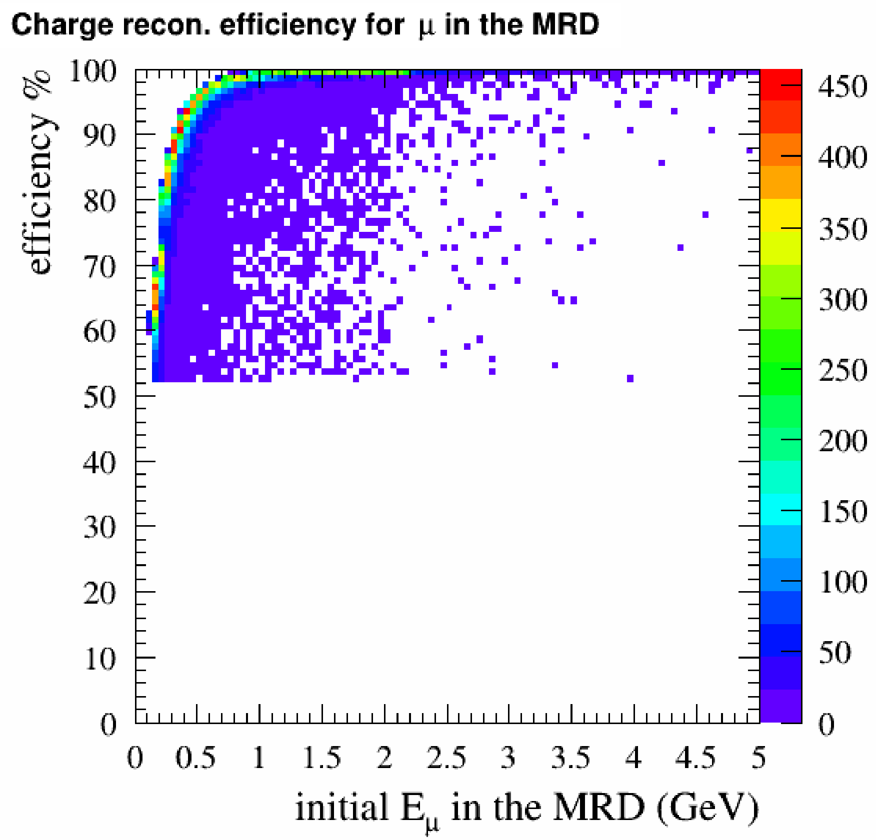
To start with, a probabilistic, back of a (fairly big) envelope calculation



TITUS MRD charge recon. efficiency vs. muon energy

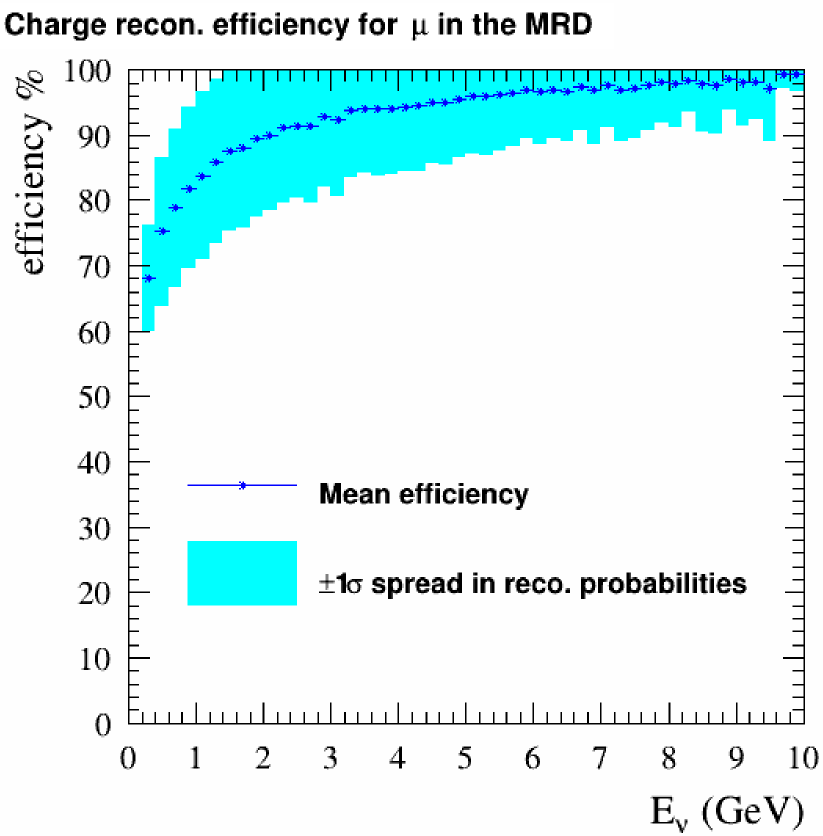
PRELIMINARY

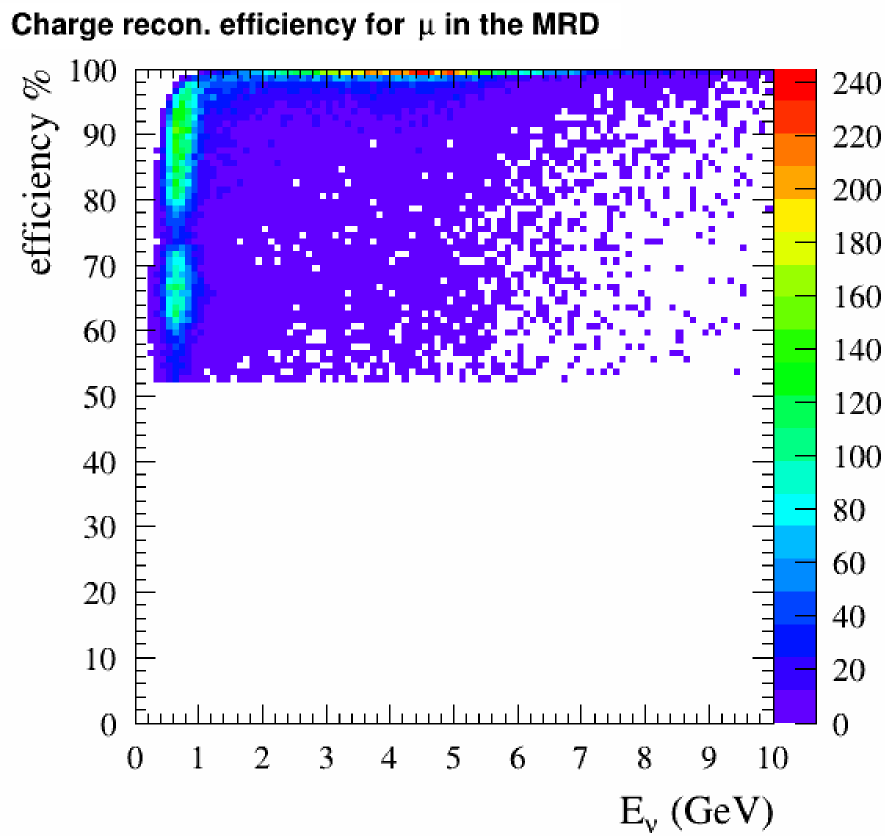




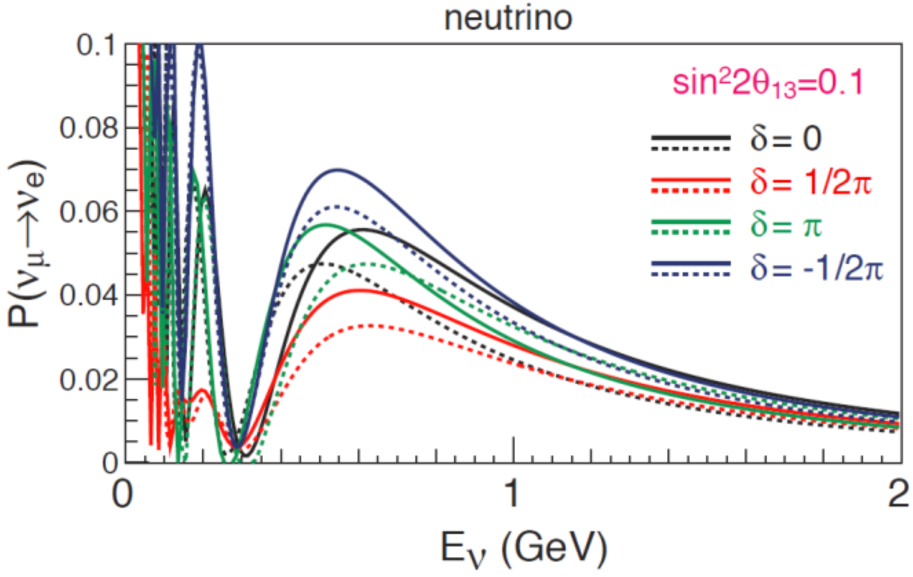
TITUS MRD charge recon. efficiency vs. neutrino energy

PRELIMINARY

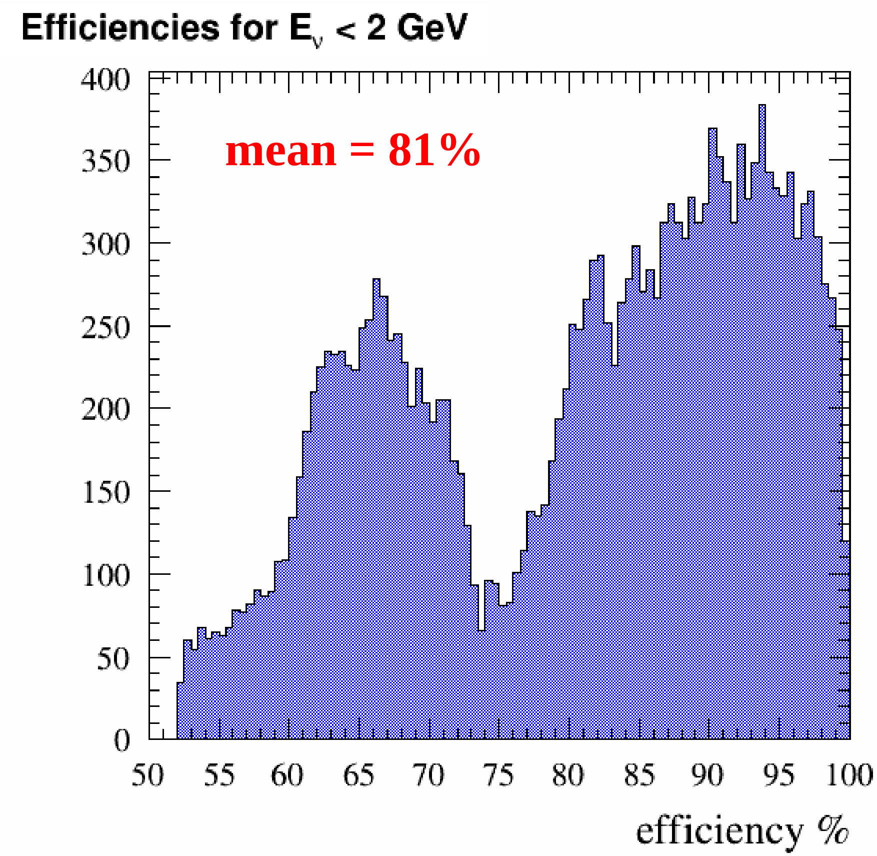




but of course E_ν < 2 GeV is of particular interest



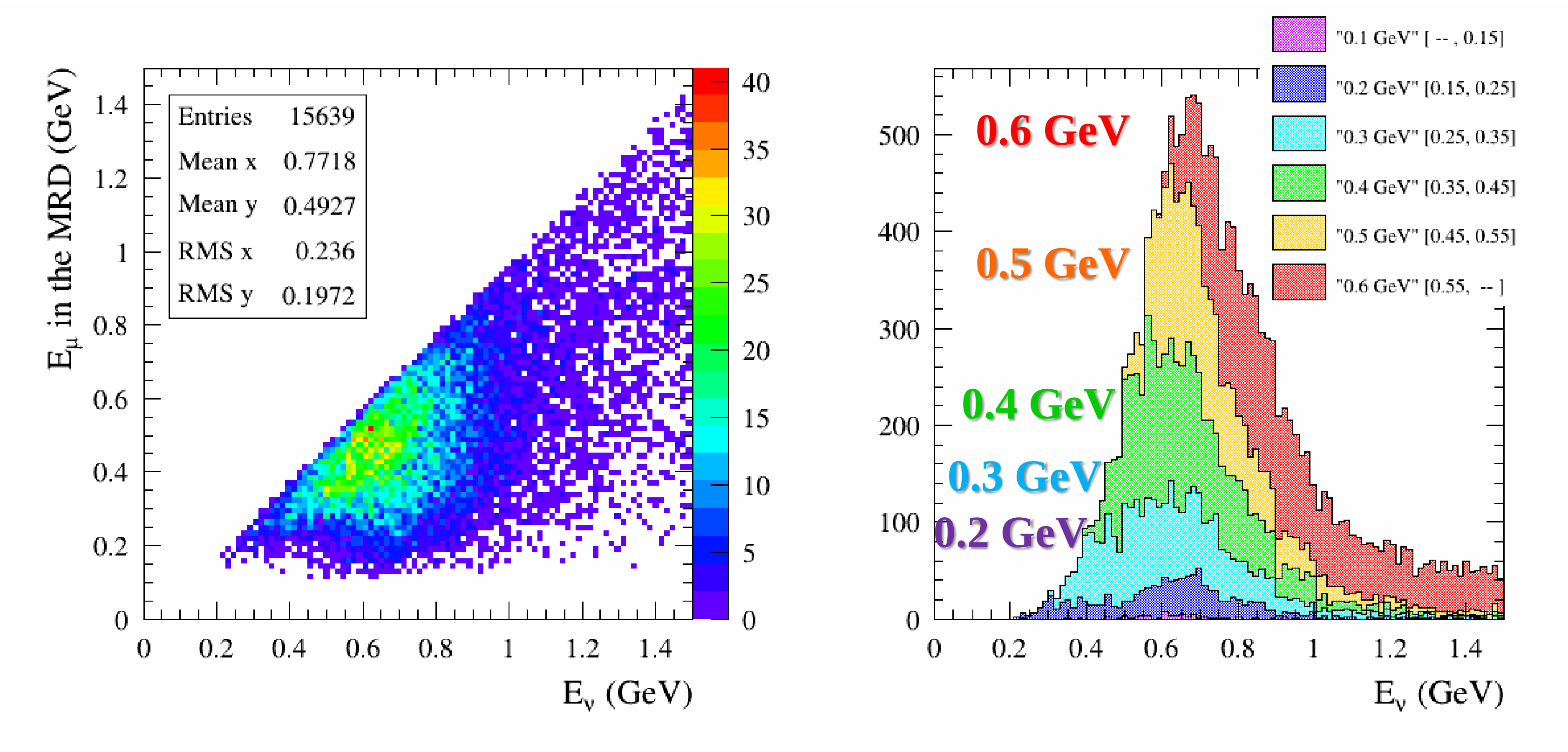
PRELIMINARY



Here we expect ~80% efficiency

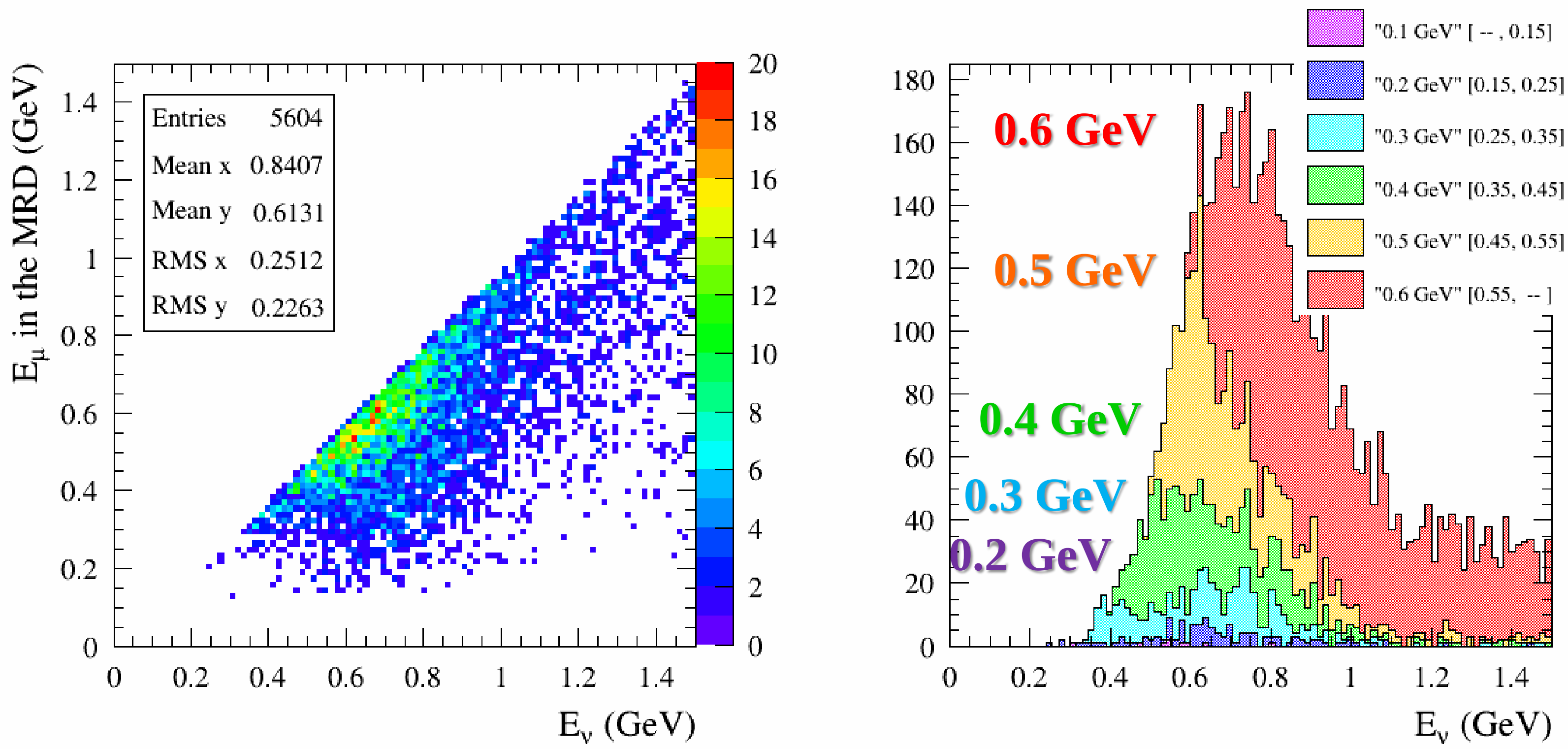
Let's think more carefully about this region…

What is the E_μ composition of the side MRD?



¾ of events with muons which leave the tank

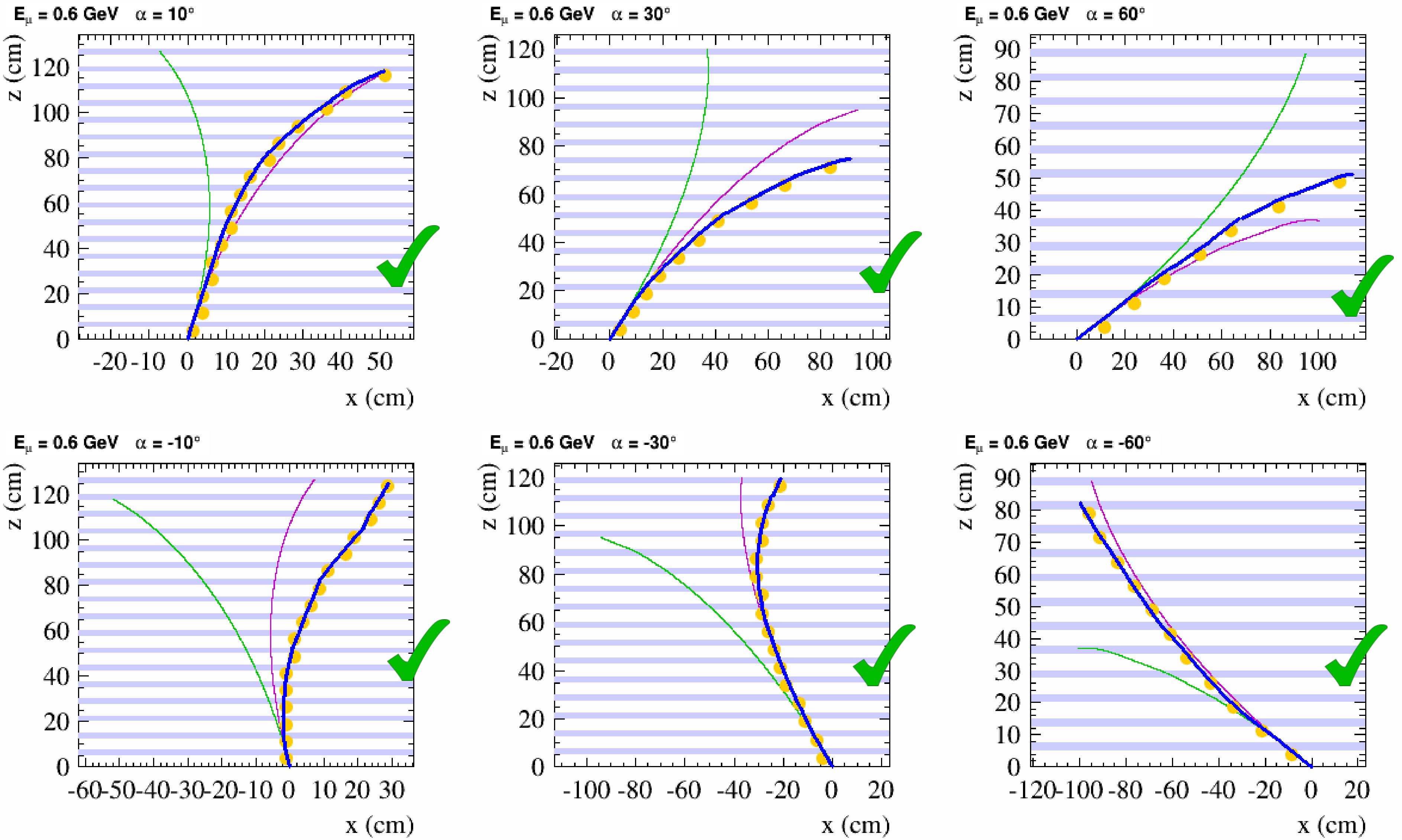
What is the E_μ composition of the end MRD?



More forward muons have slightly higher energies

E_μ = 0.6 GeV

56% of END muons
32% of SIDE muons



E_μ = 0.6 GeV

56% of END muons
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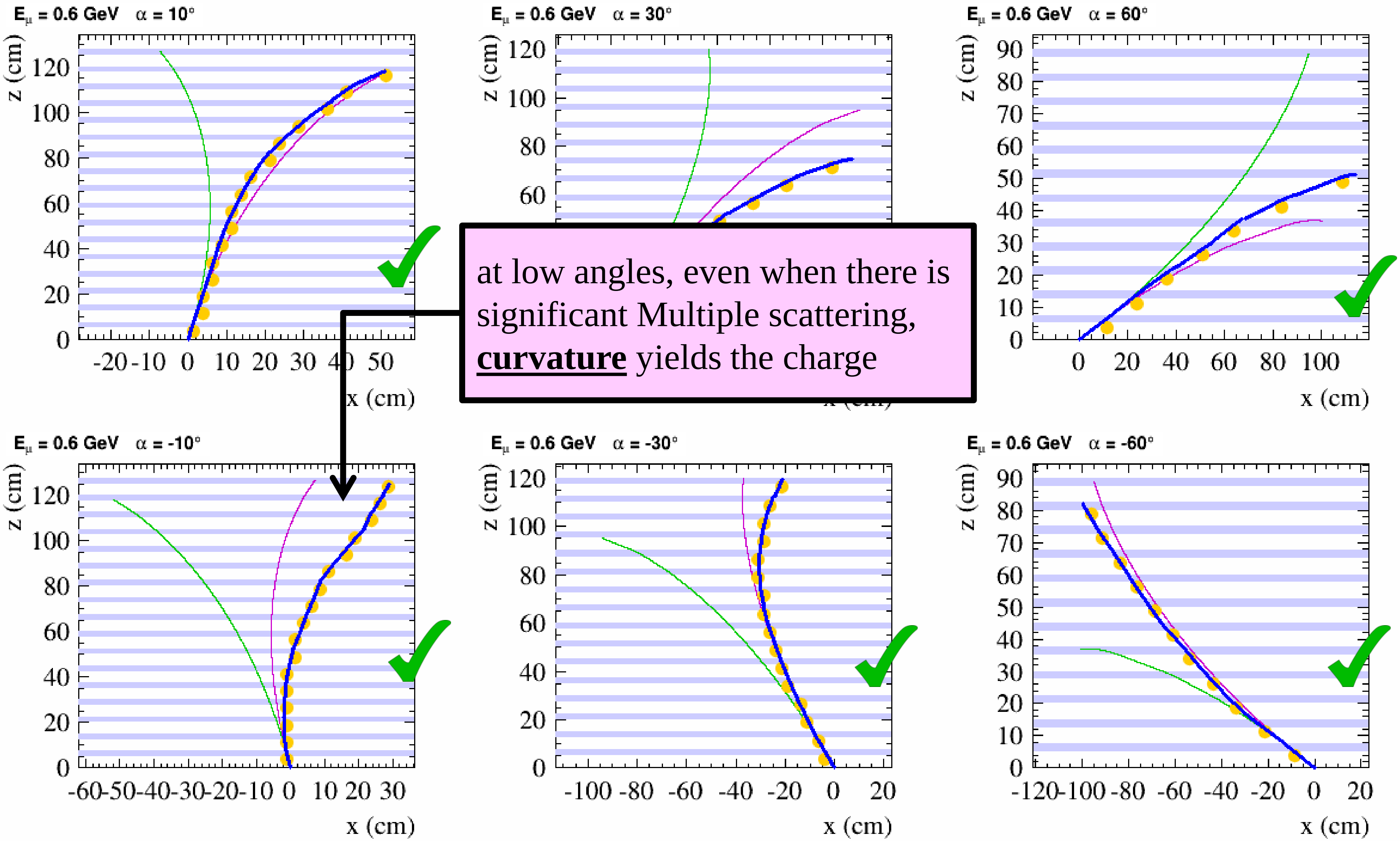

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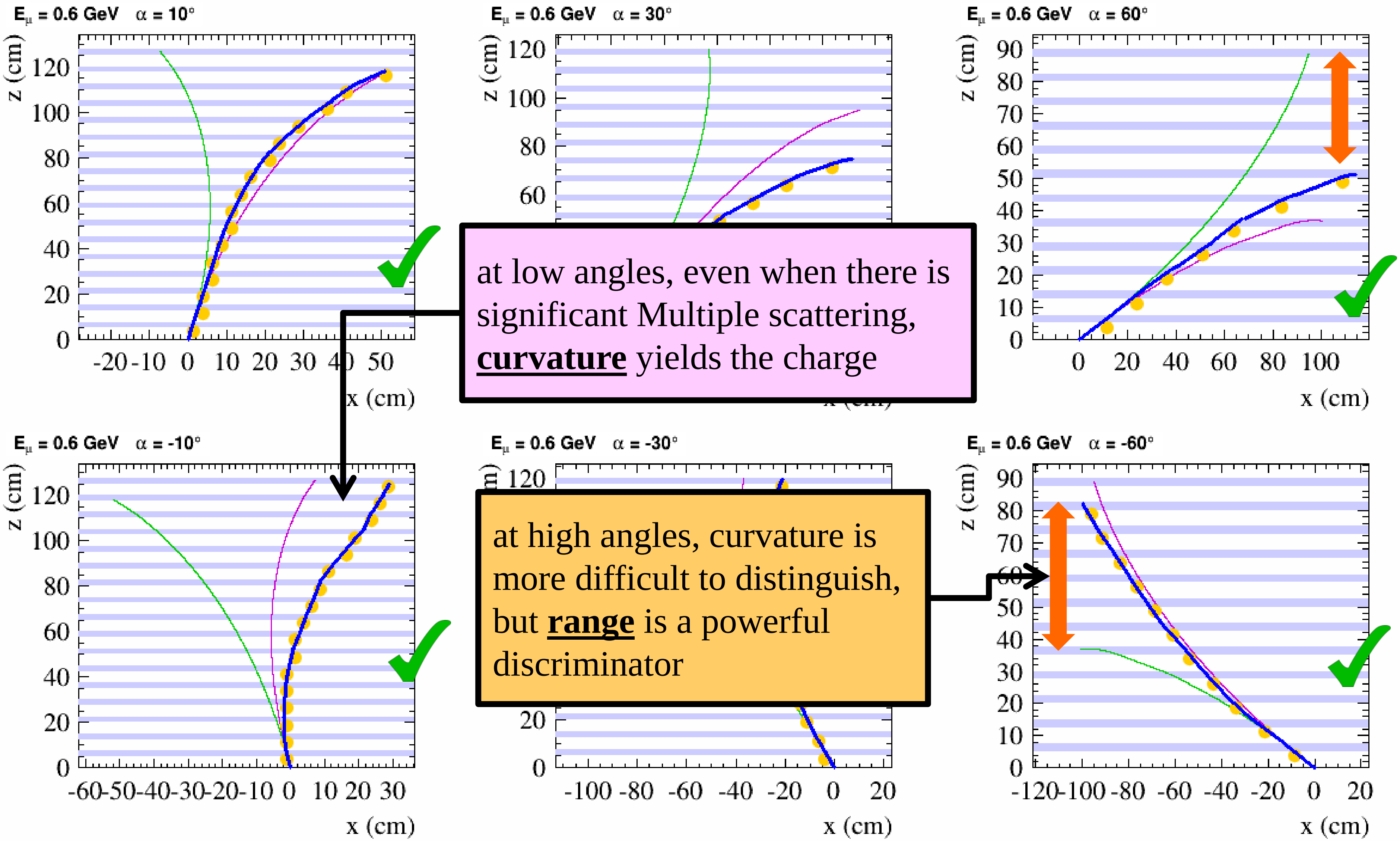
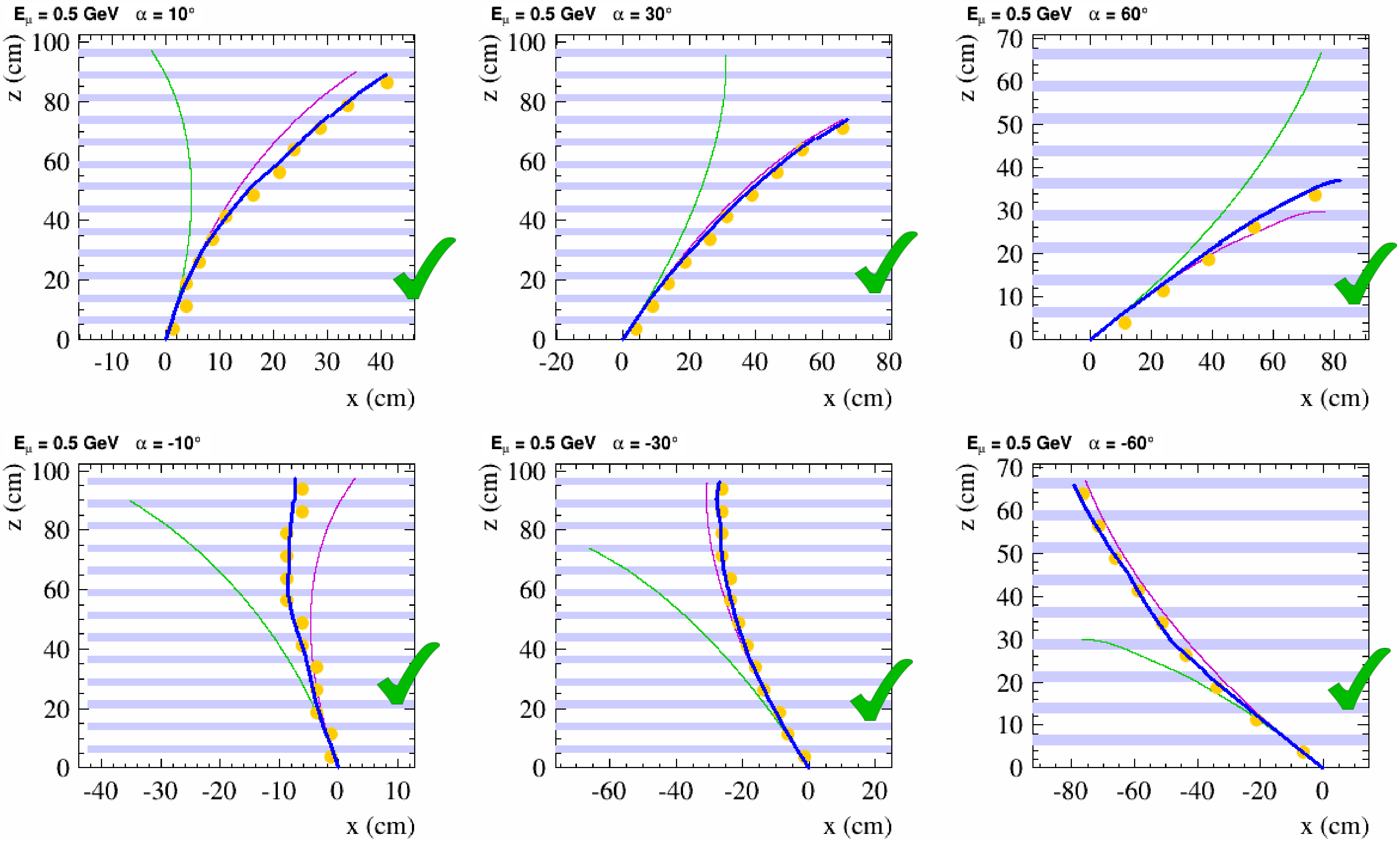


at low angles, even when there is significant Multiple scattering, **curvature** yields the charge

at high angles, curvature is more difficult to distinguish, but **range** is a powerful discriminator

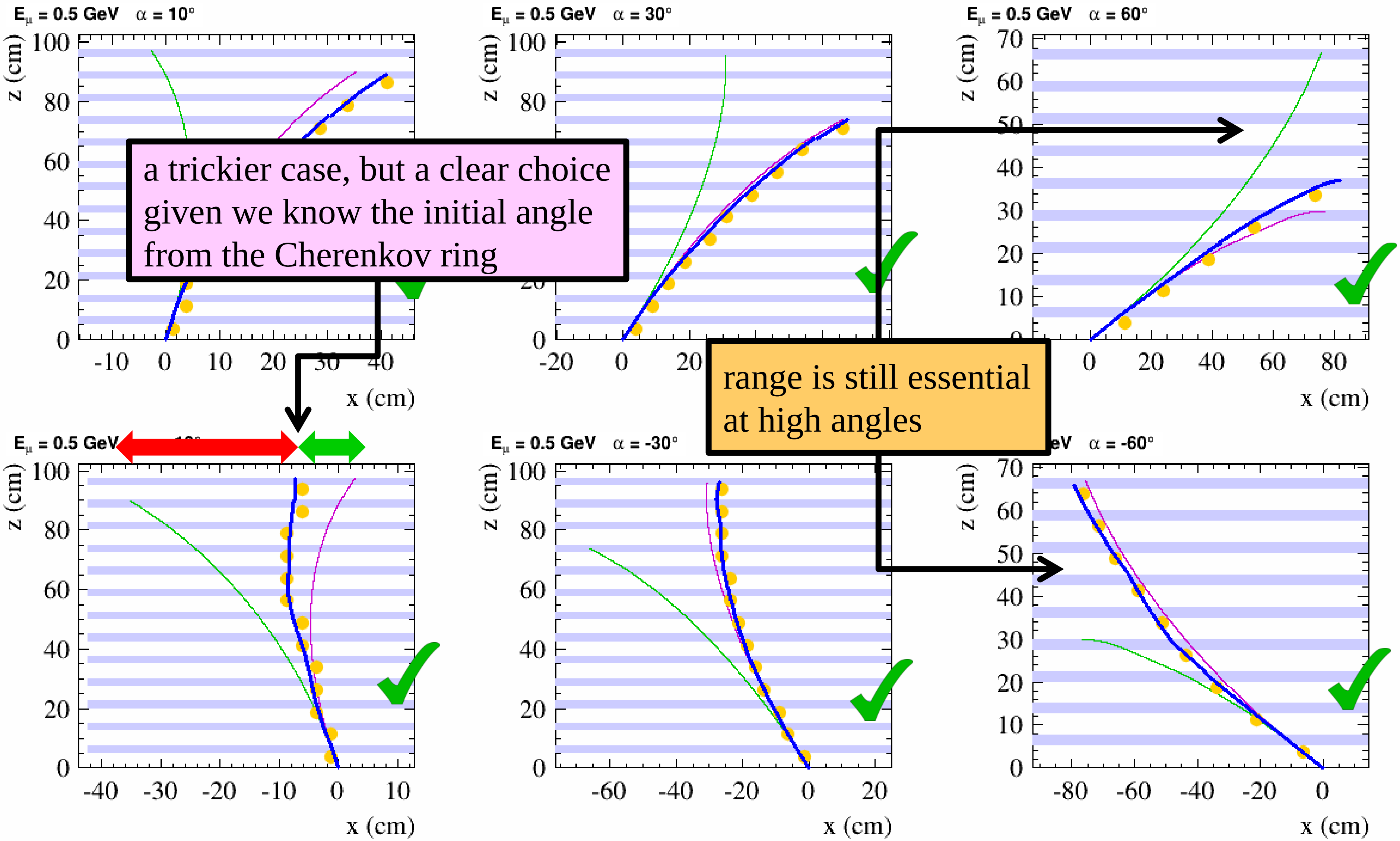
E_μ = 0.5 GeV

20% of END muons
21% of SIDE muons



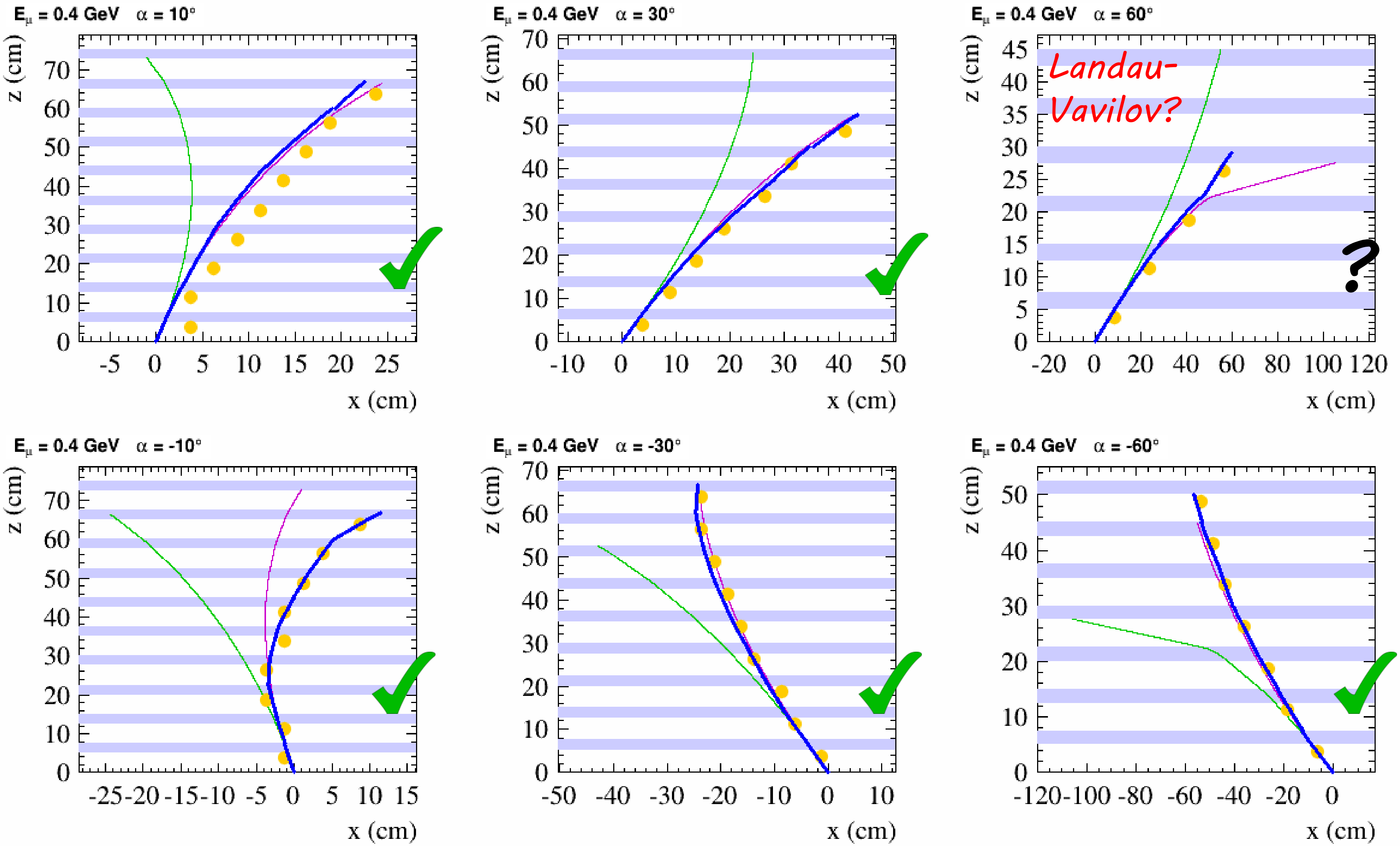
$E_{\mu} = 0.5$ GeV

20% of END muons
21% of SIDE muons



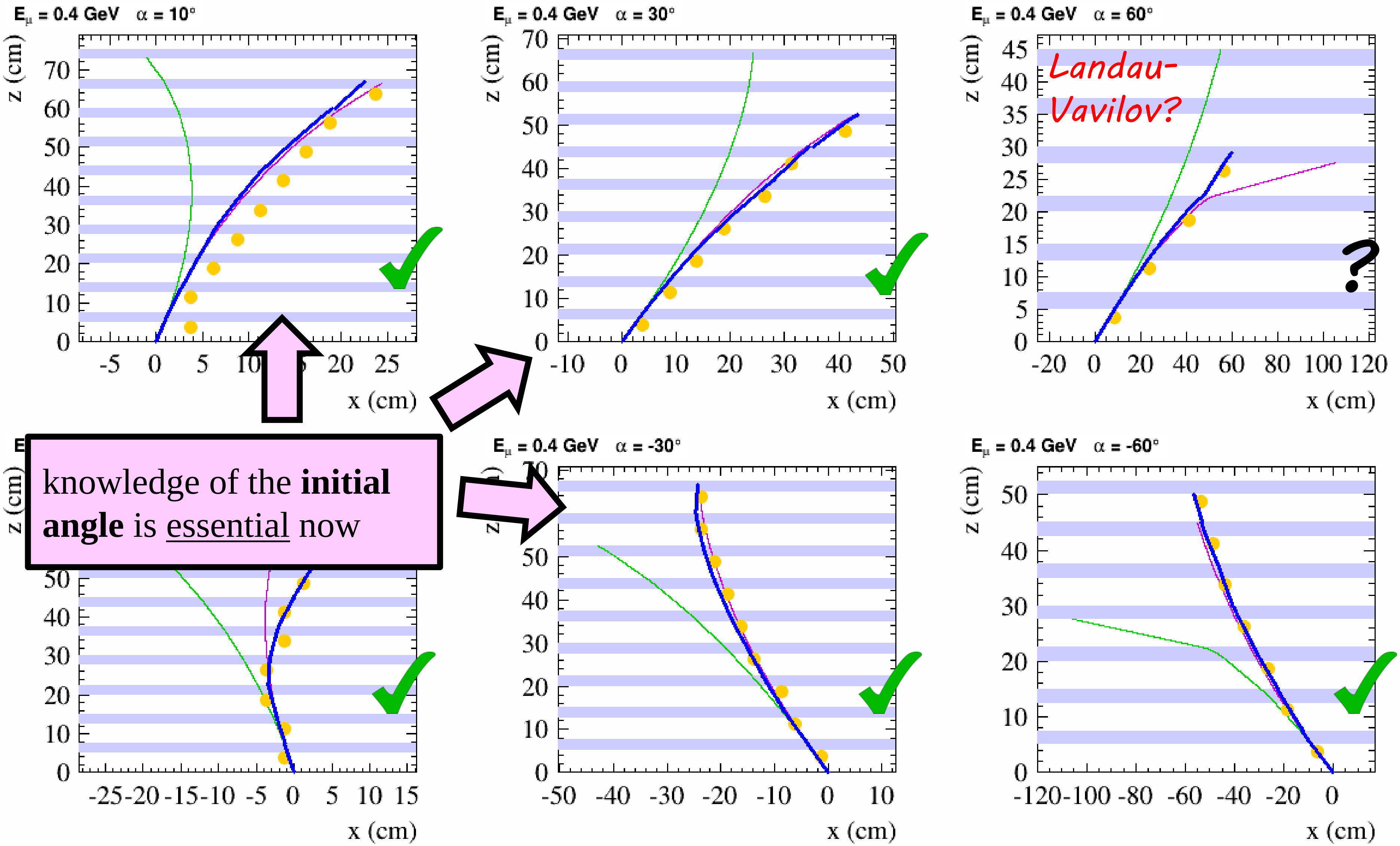
E_μ = 0.4 GeV

14% of END muons
24% of SIDE muons



E_μ = 0.4 GeV

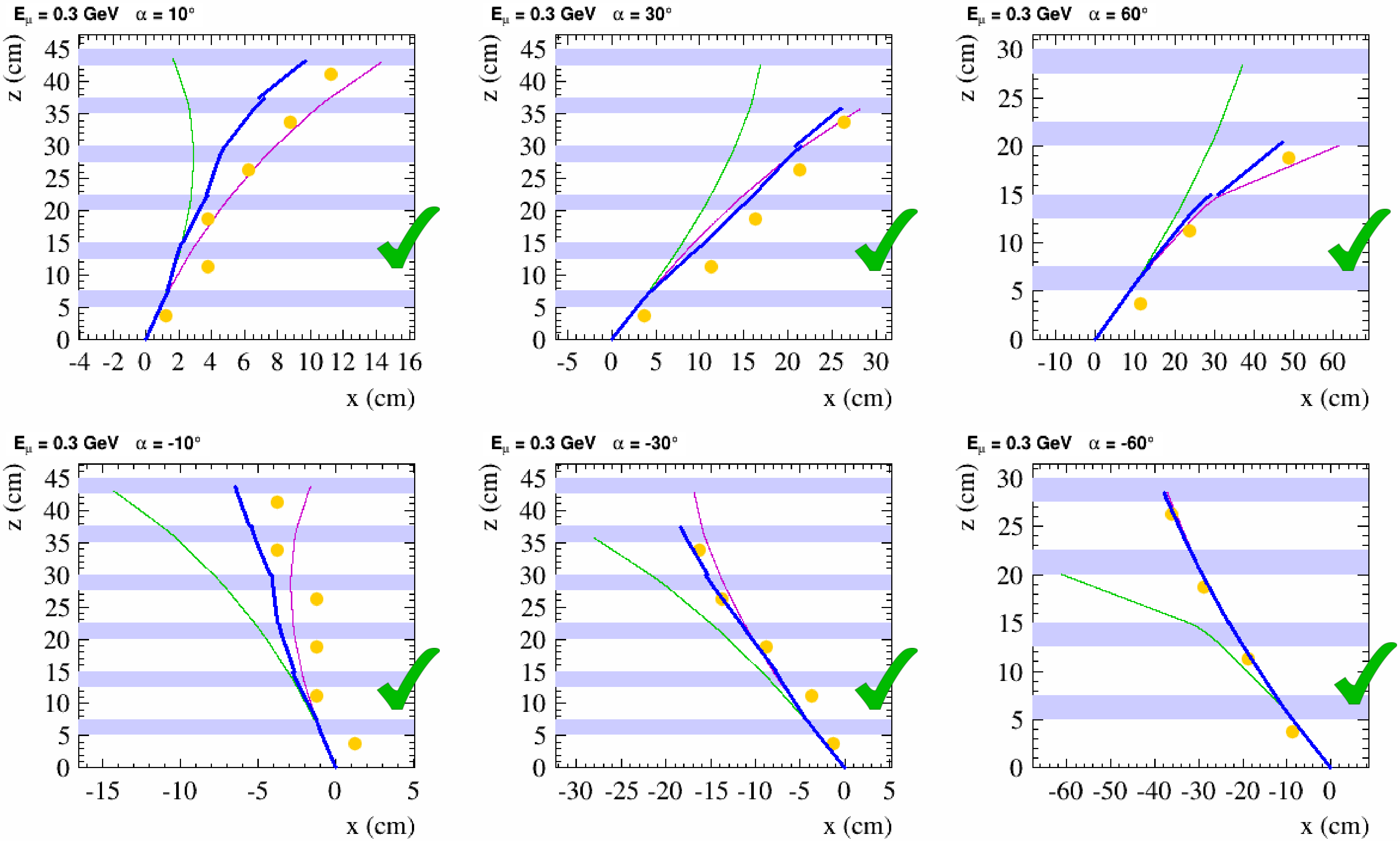
14% of END muons
24% of SIDE muons



knowledge of the **initial angle** is essential now

$E_\mu = 0.3$ GeV

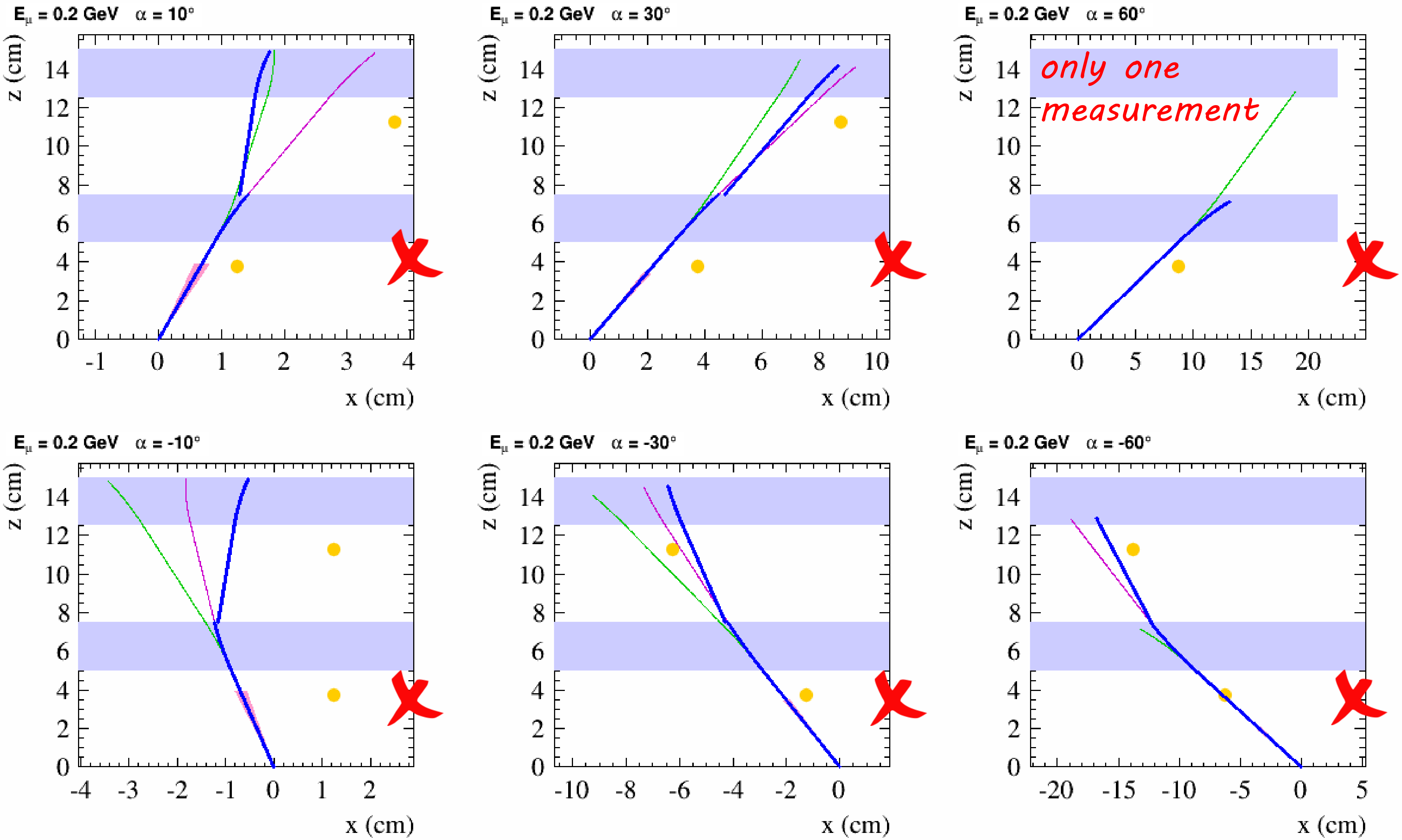
7% of END muons
17% of SIDE muons



Here I suspect we got a bit lucky! It's a probabilistic game, but still promising at 0.3 GeV

$E_\mu = 0.2$ GeV

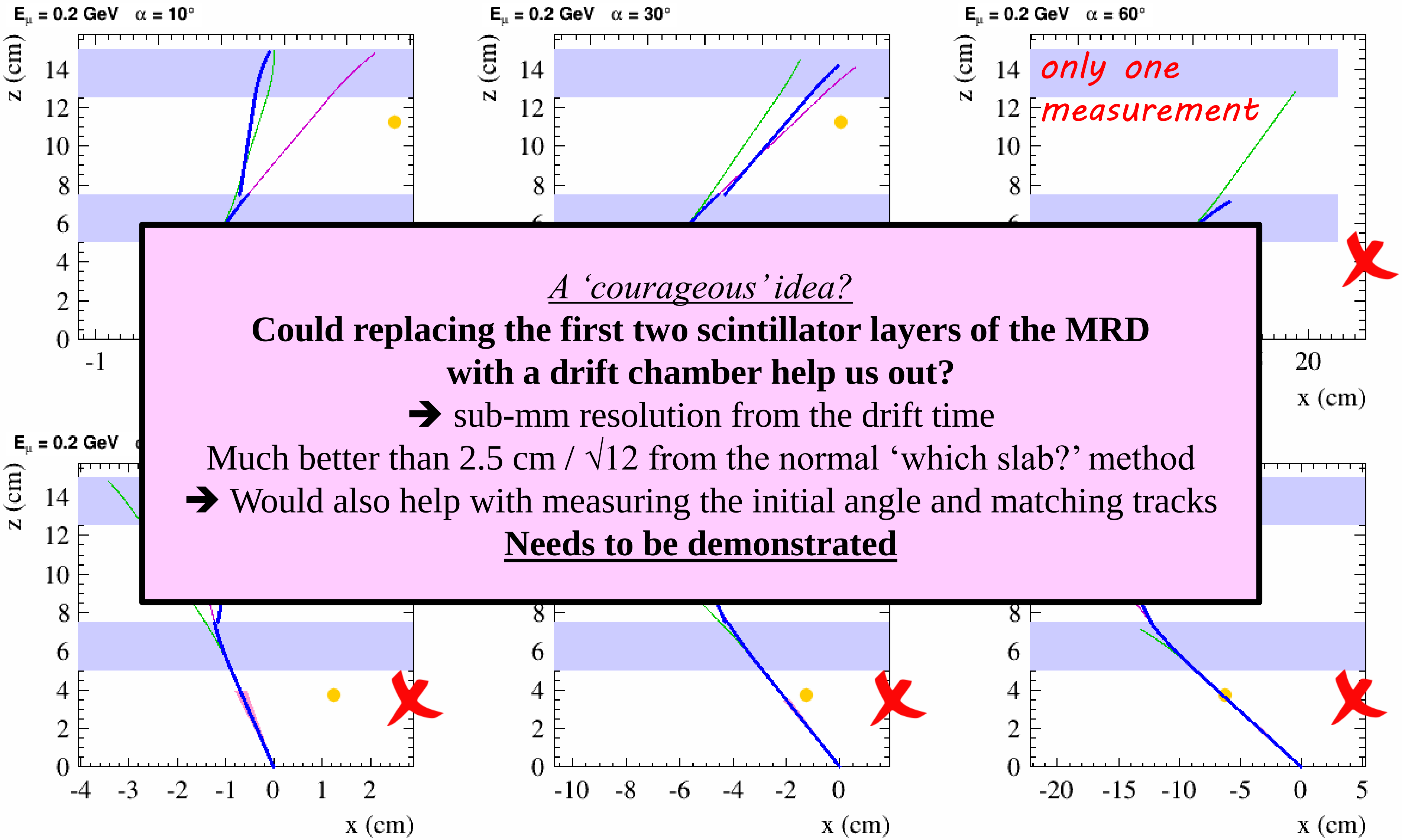
2% of END muons
7% of SIDE muons



Totally dominated by position resolution and number of sampling points

E_μ = 0.2 GeV

2% of END muons
7% of SIDE muons



A 'courageous' idea?

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

Needs to be demonstrated

Totally dominated by position resolution and number of sampling points

Baby-MIND and TASD: H8 beamline in North Area

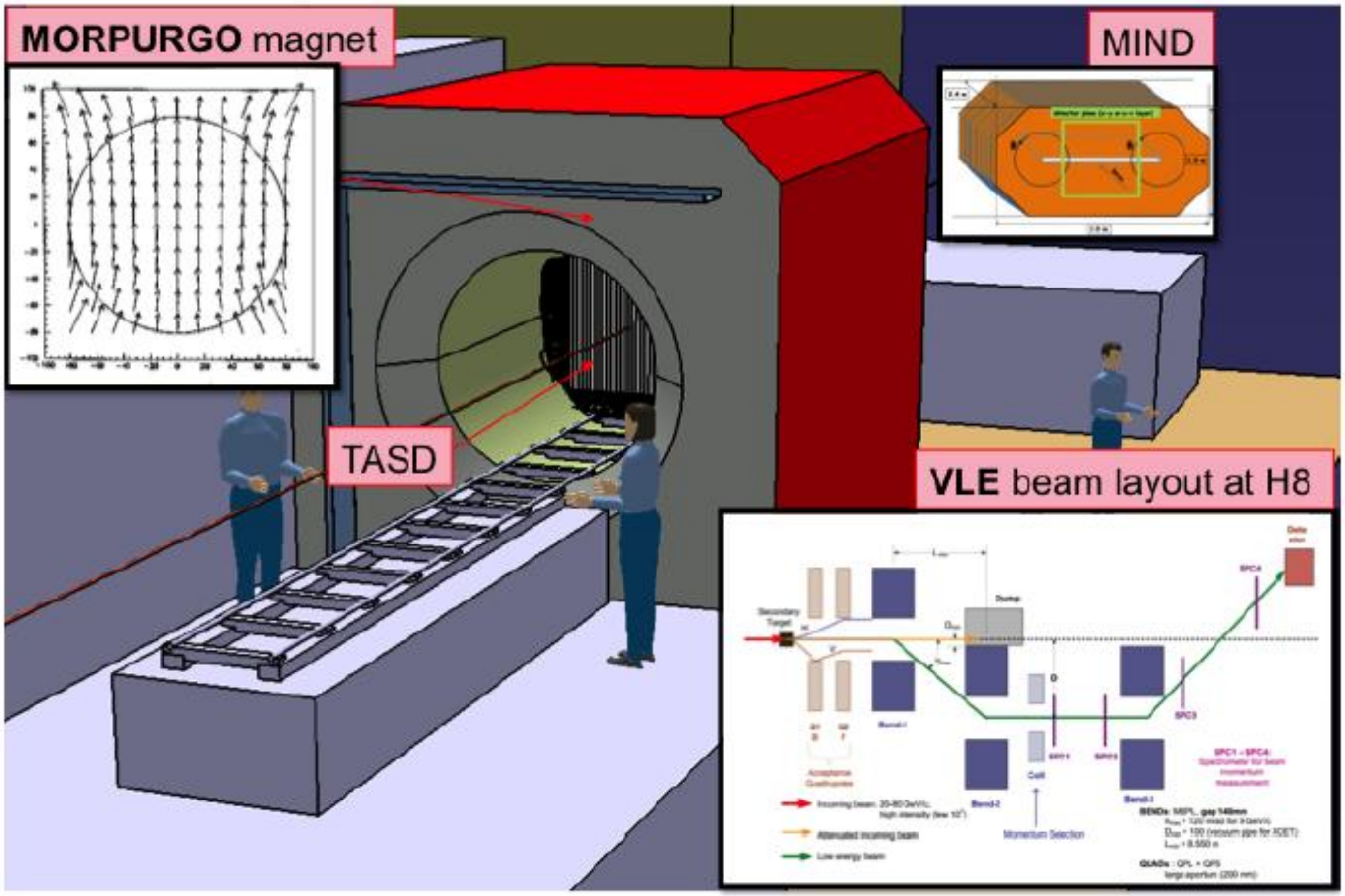
(or possibly behind the LBNO-Demo)

1.5 Tesla

3 m

2.5 m

1.5 m



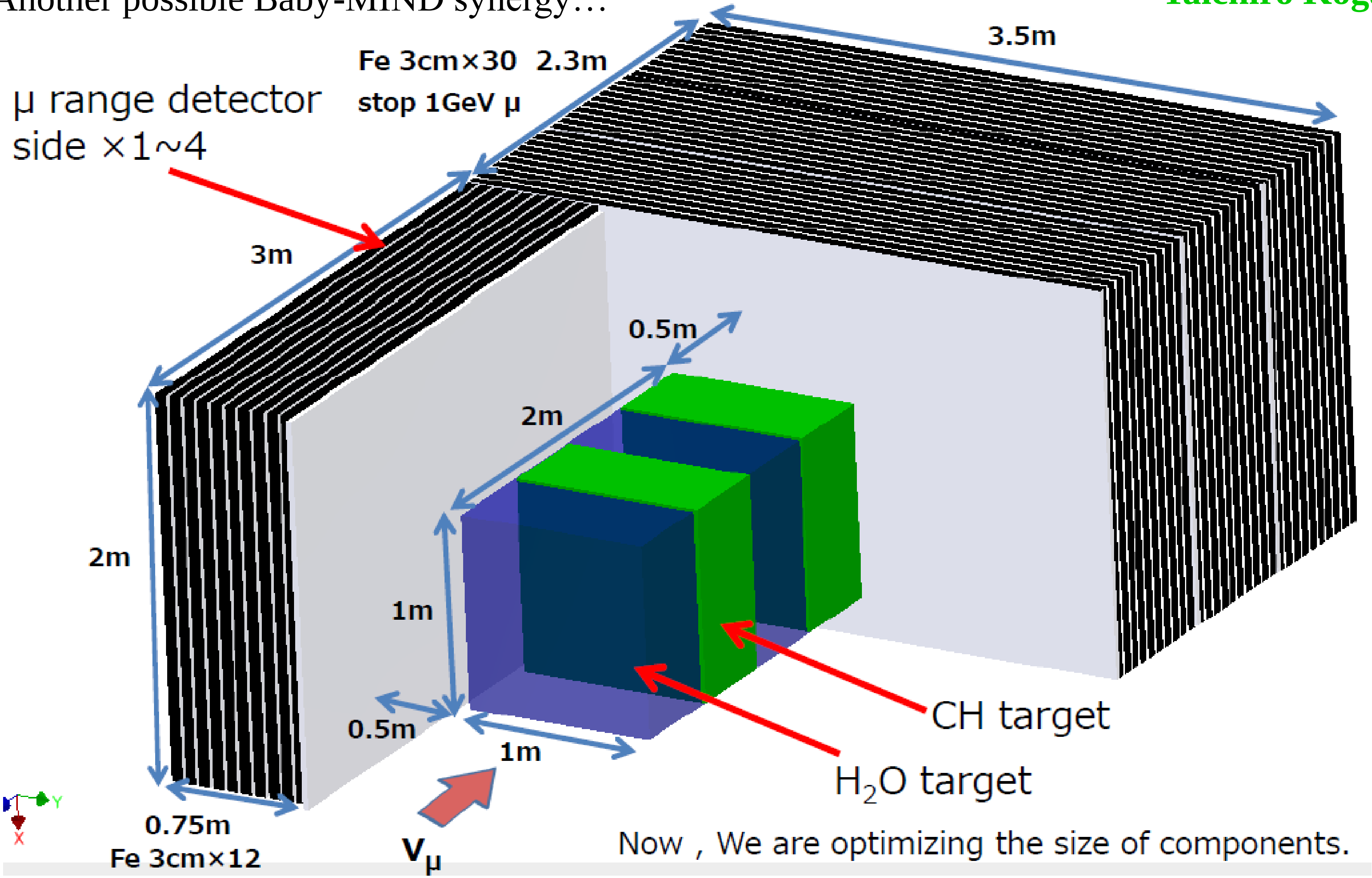
Could also be a test of the TITUS MRD charge reconstruction

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

- 18% of muons escape the 22 m long, 11 m diameter TITUS tank
  75% through the sides, 25% through the end

- With 150 cm of iron at the end, 50 cm of iron at the sides:
  → 75% of muons which escape the tank are stopped
  → 25% of muons which escape the tank penetrate through the MRD

- **Preliminary studies show promising charge reconstruction in the oscillation region and impeccable resolution in the high energy tail (1.5 Tesla)**

Work in progress

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

Backup slides

TITUS tank angle reconstruction?

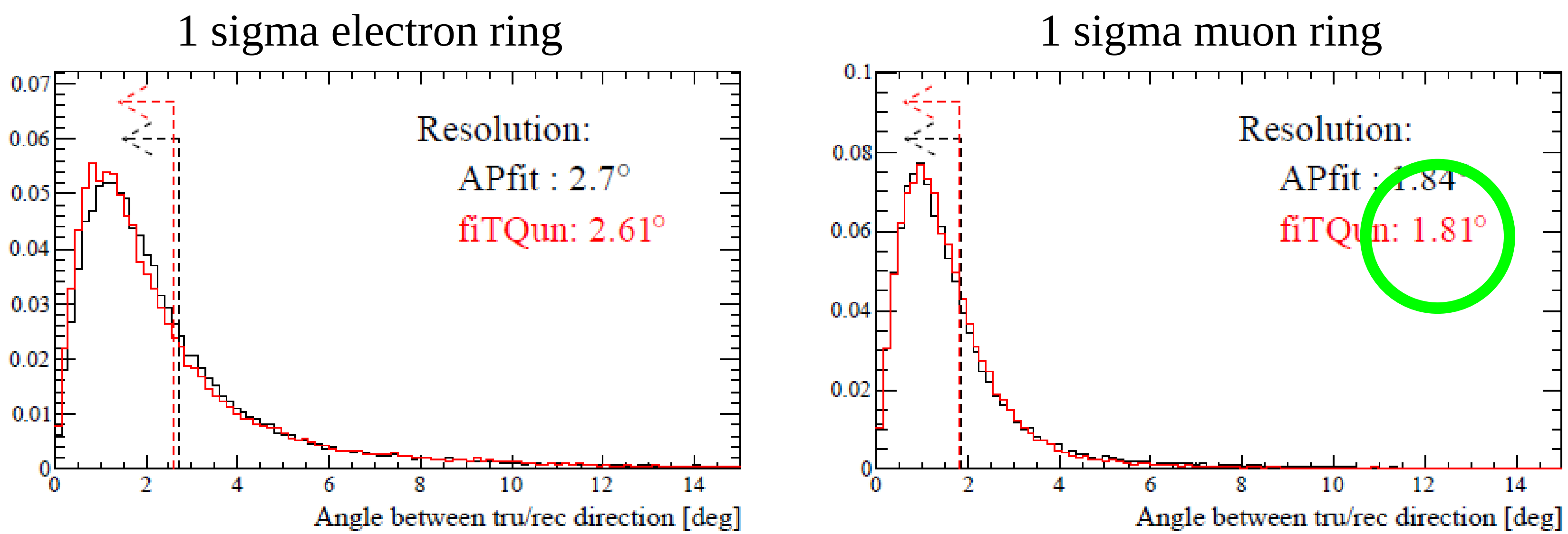
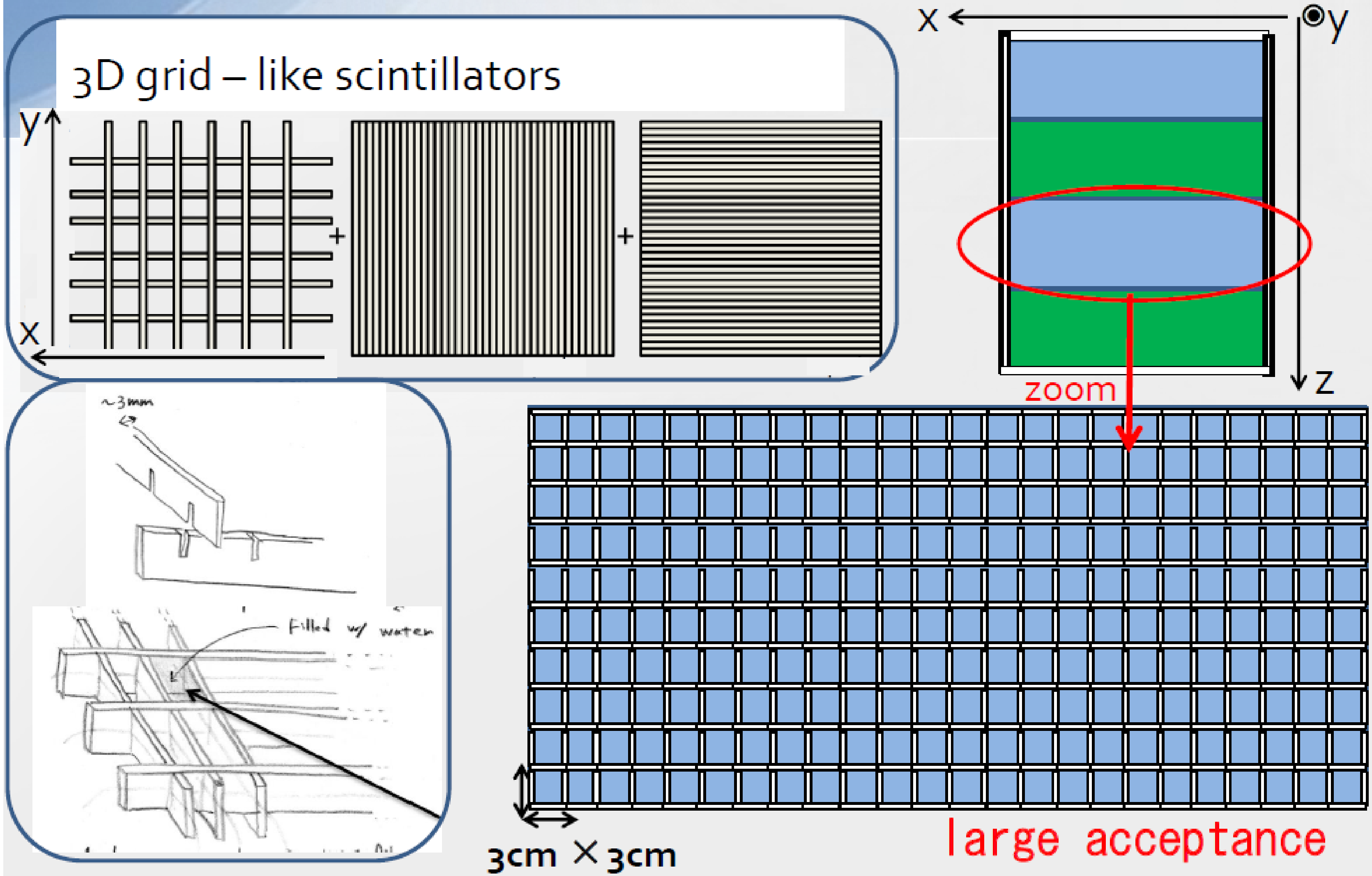


Figure 22: Distributions of the angle between the true and the reconstructed particle directions, for single-ring electron(left) and muon(right) particle gun events. The red histograms are the distributions for fiTQun, and the black histograms are for APfit. The resolutions are defined as the 68.3 percentiles,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

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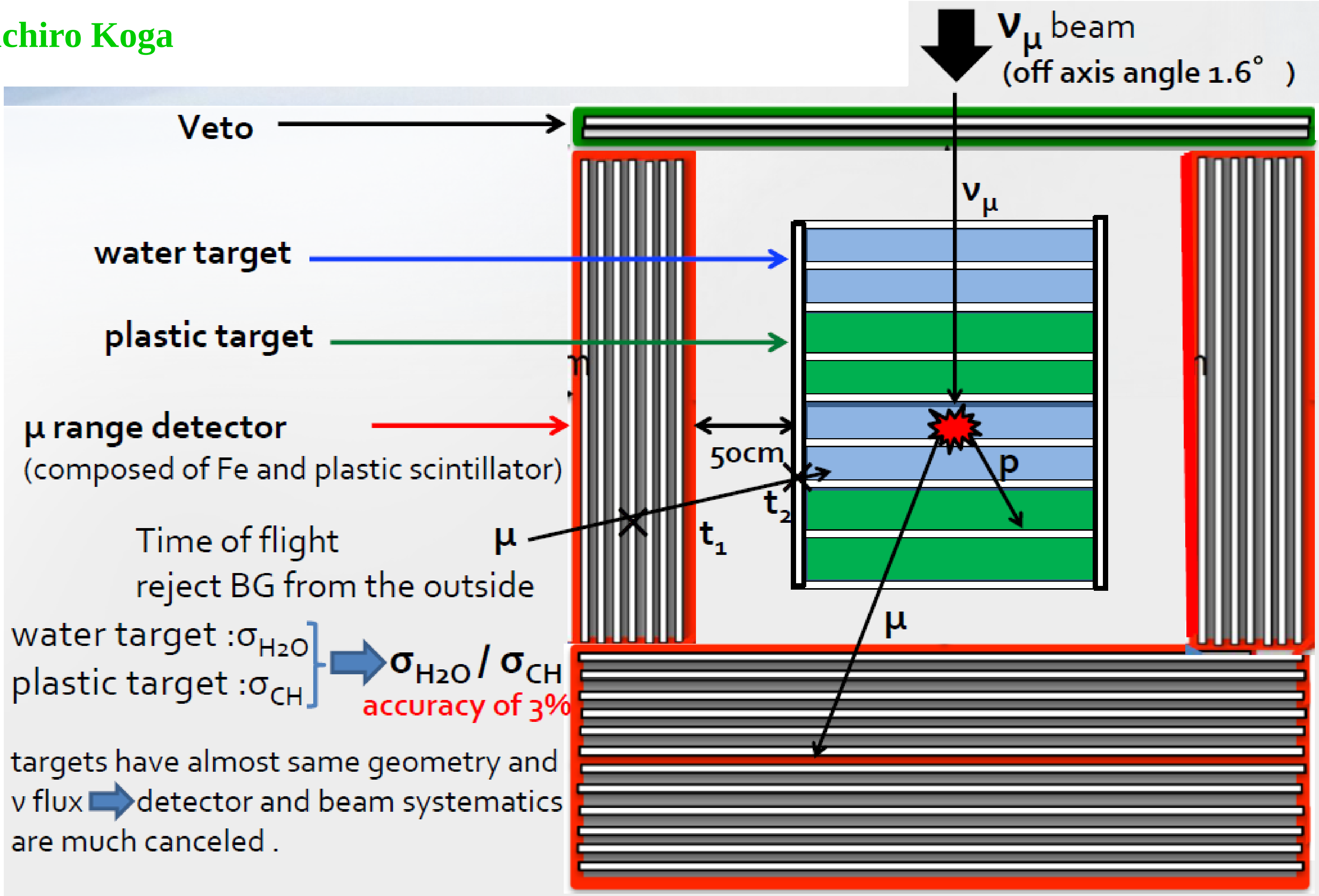
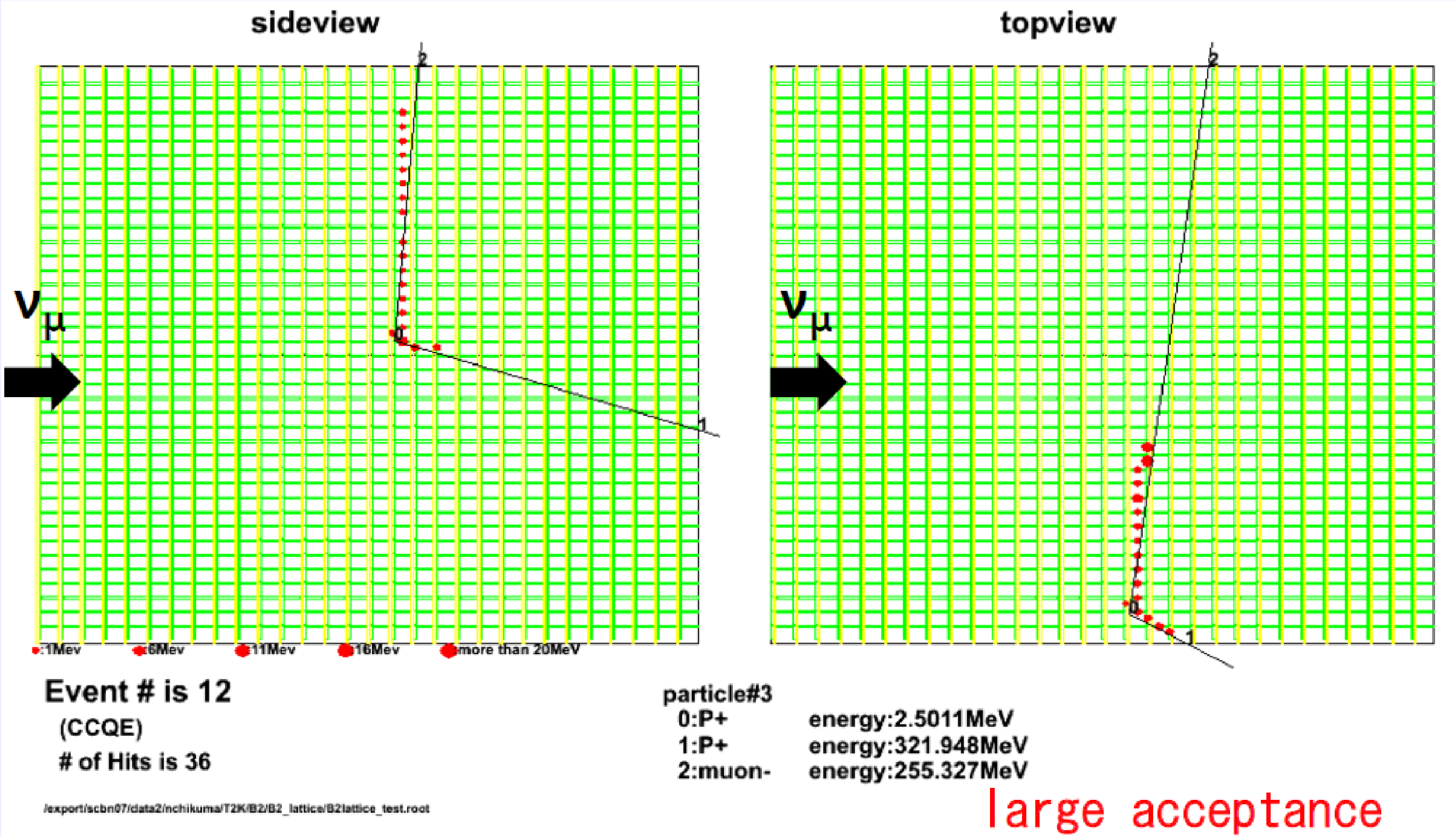
The B2 experiment

Taichiro Koga



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



Taichiro Koga

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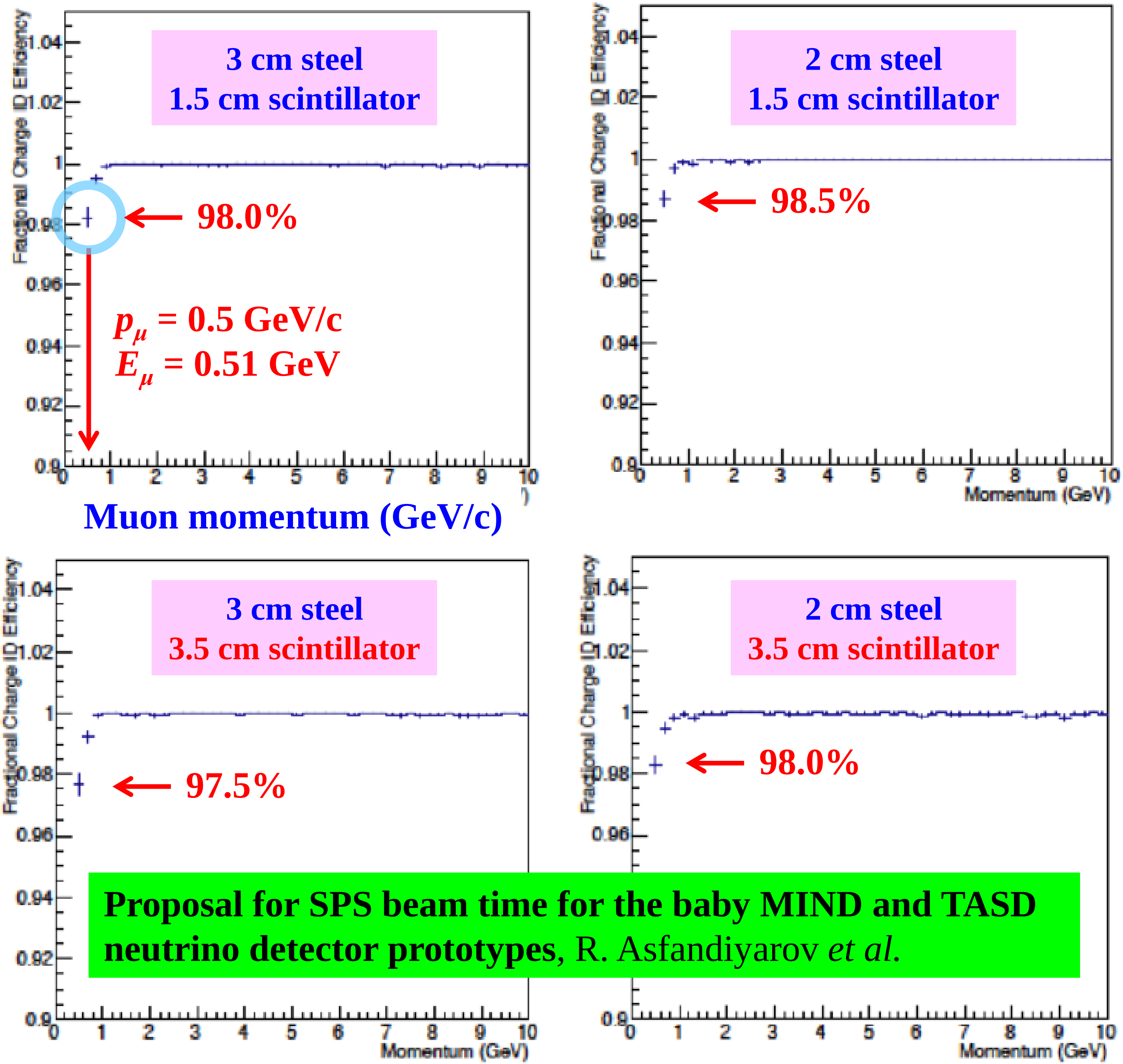
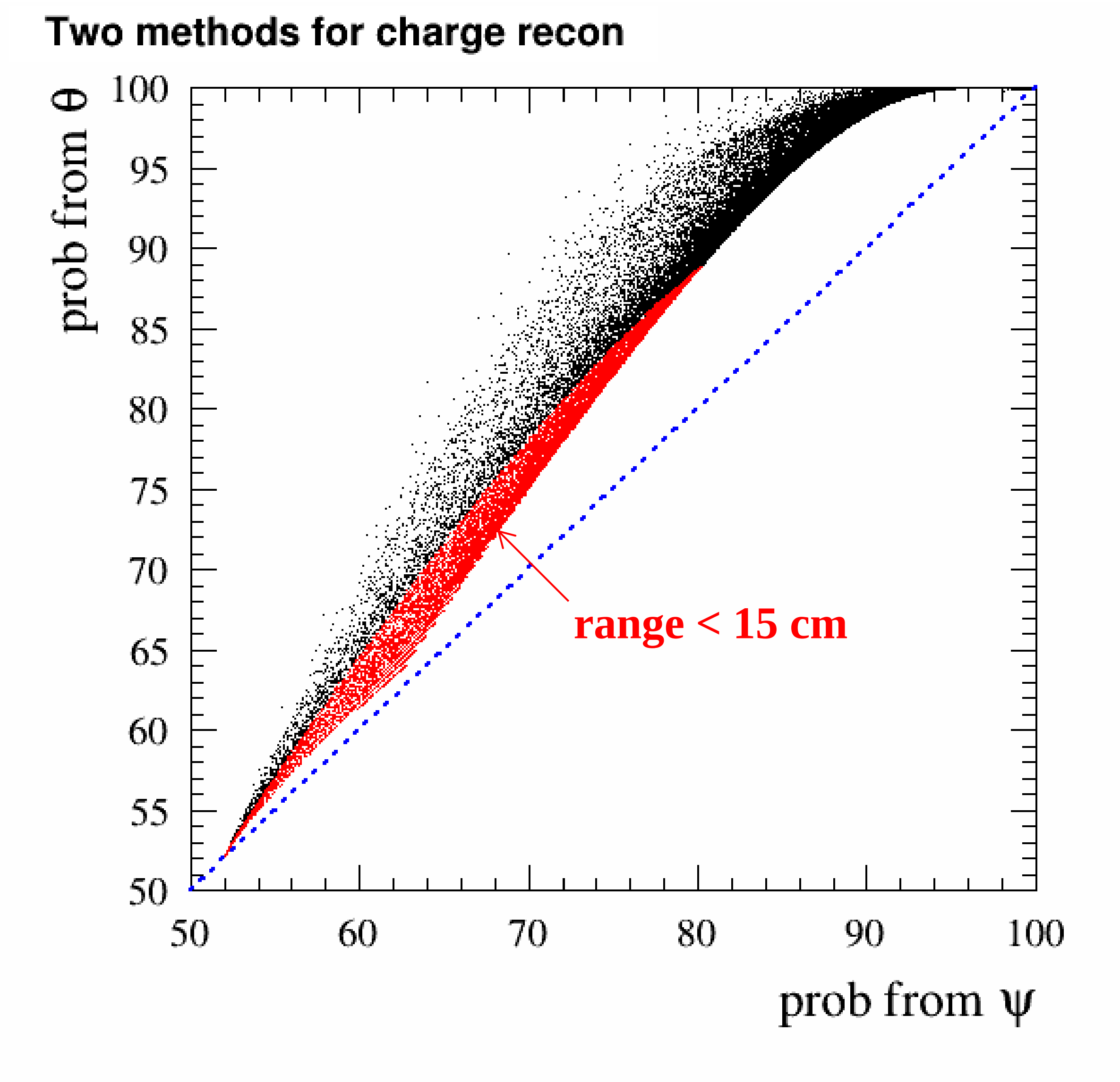
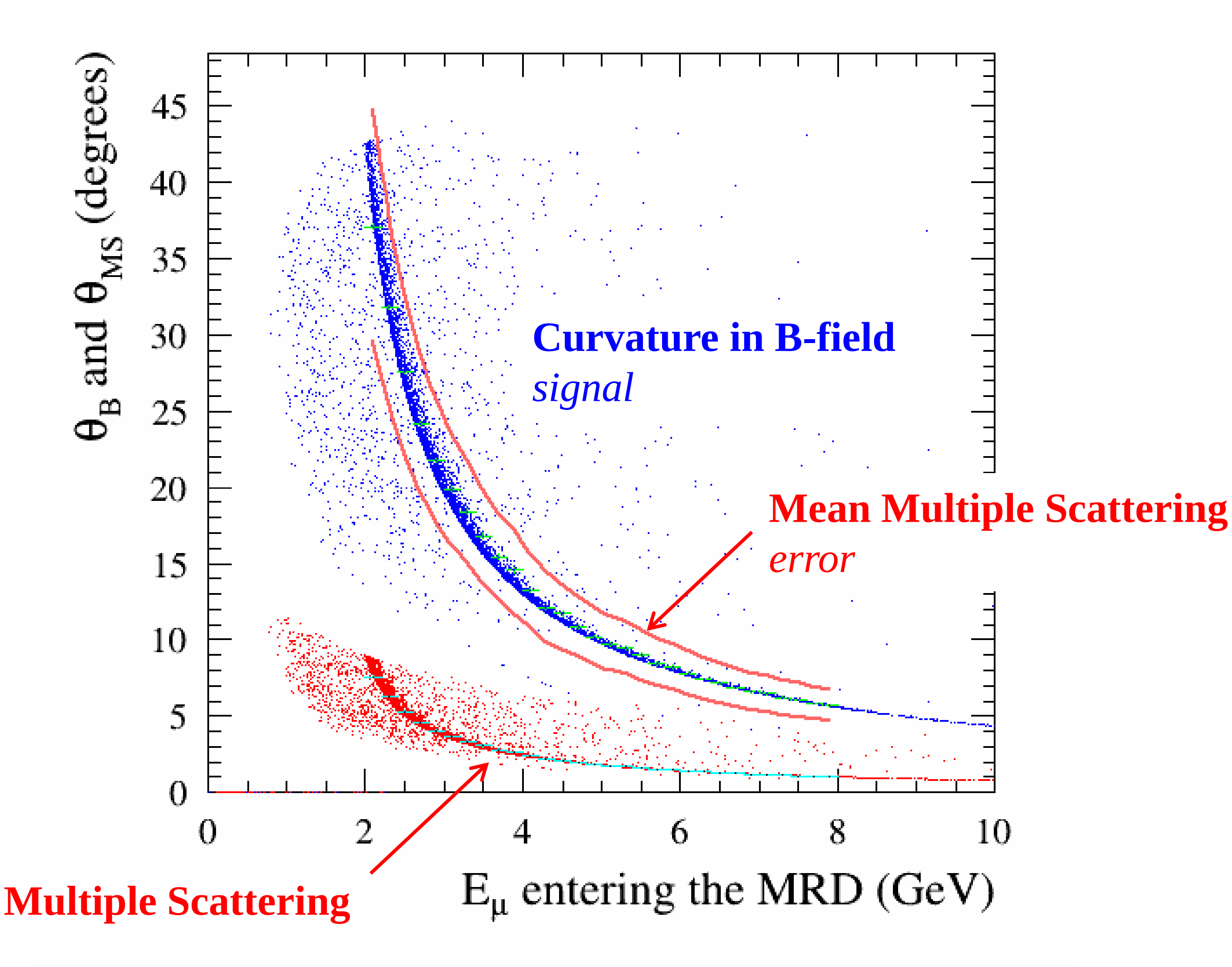
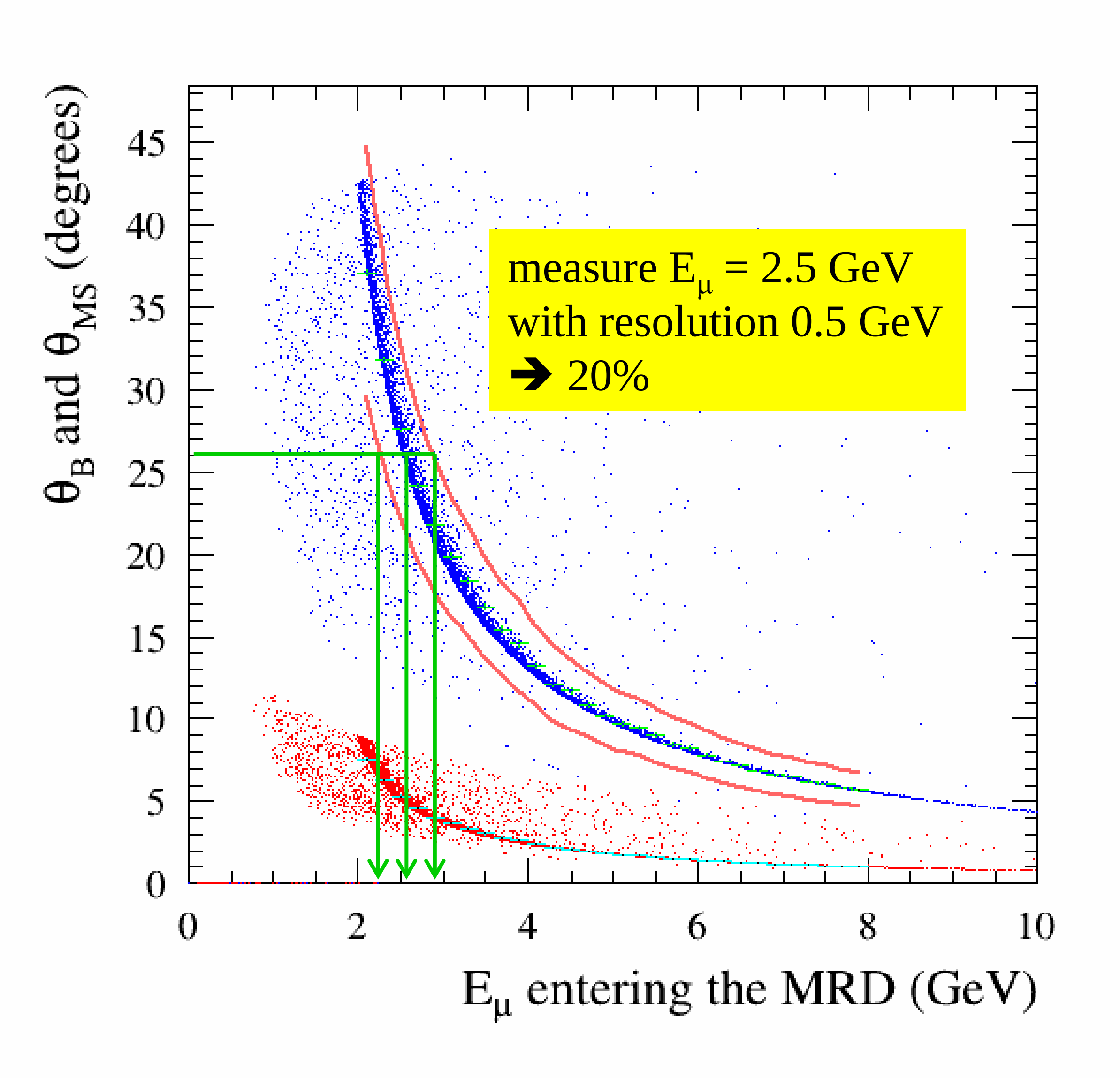


Proposal for SPS beam time for the baby MIND and TASD neutrino detector prototypes, R. Asfandiyarov *et al.*

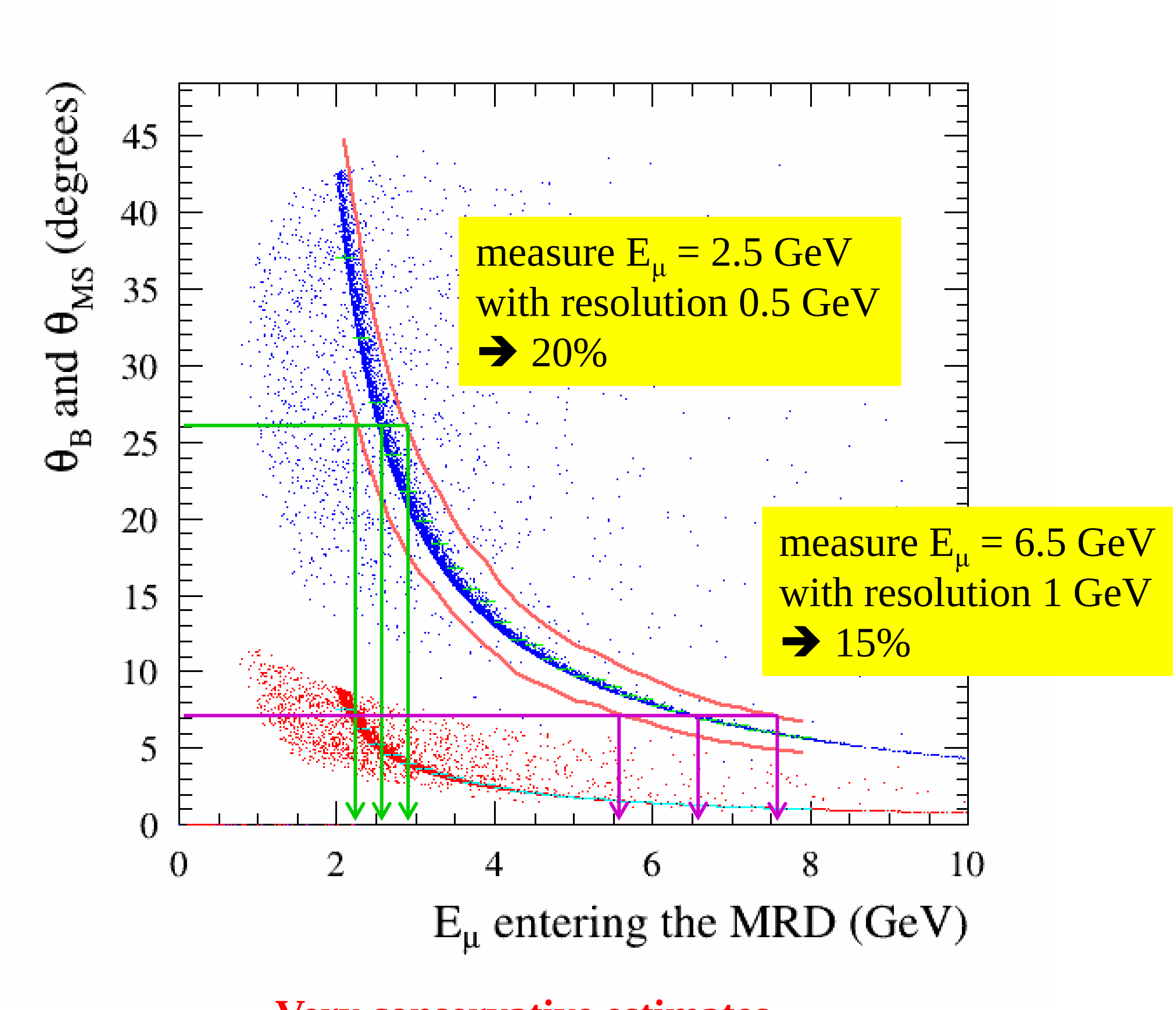

Two methods for charge recon
prob from θ
prob from ψ
100
95
90
85
80
75
70
65
60
55
50
50
60
70
80
90
100
range < 15 cm

Aside: Momentum for the penetrating sample





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



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%

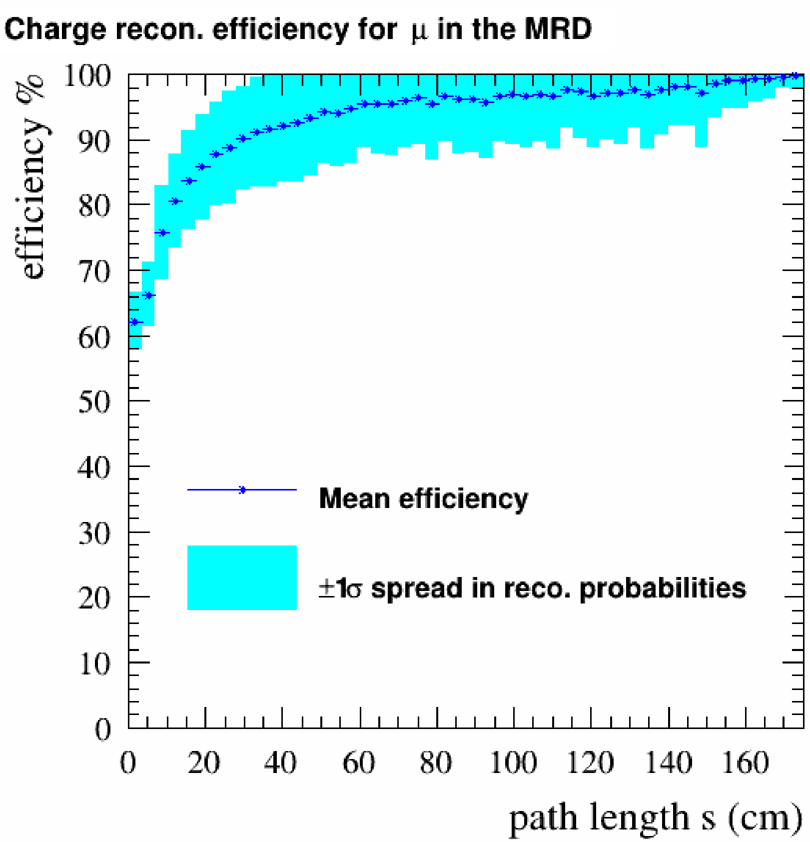
0.511 MeV

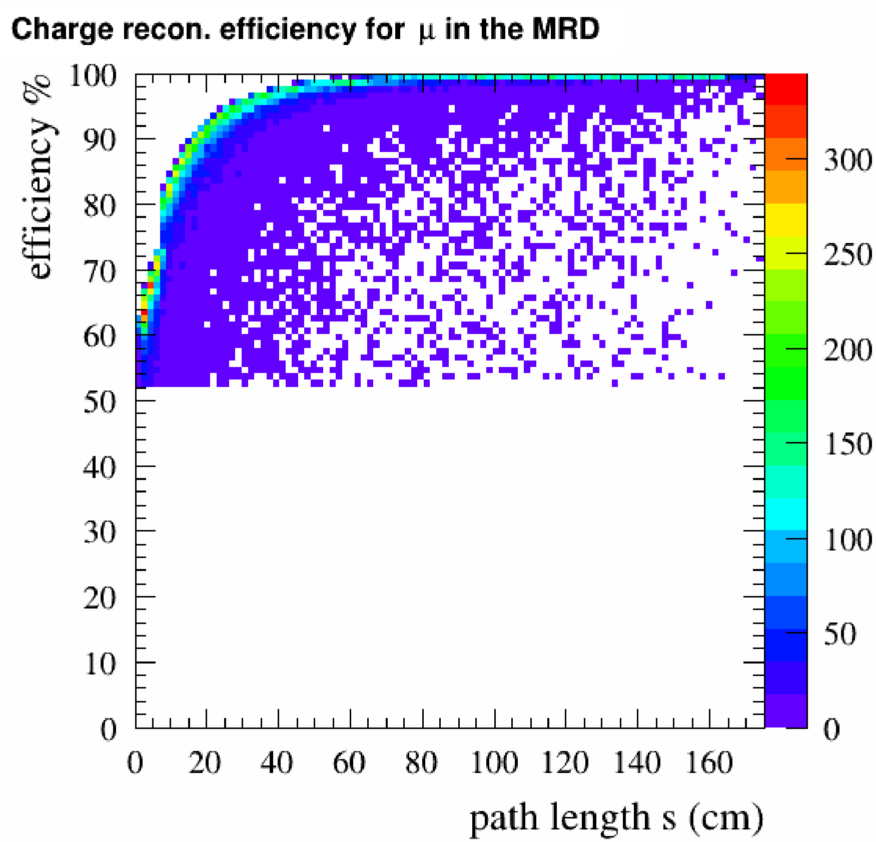
neglect density effect

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

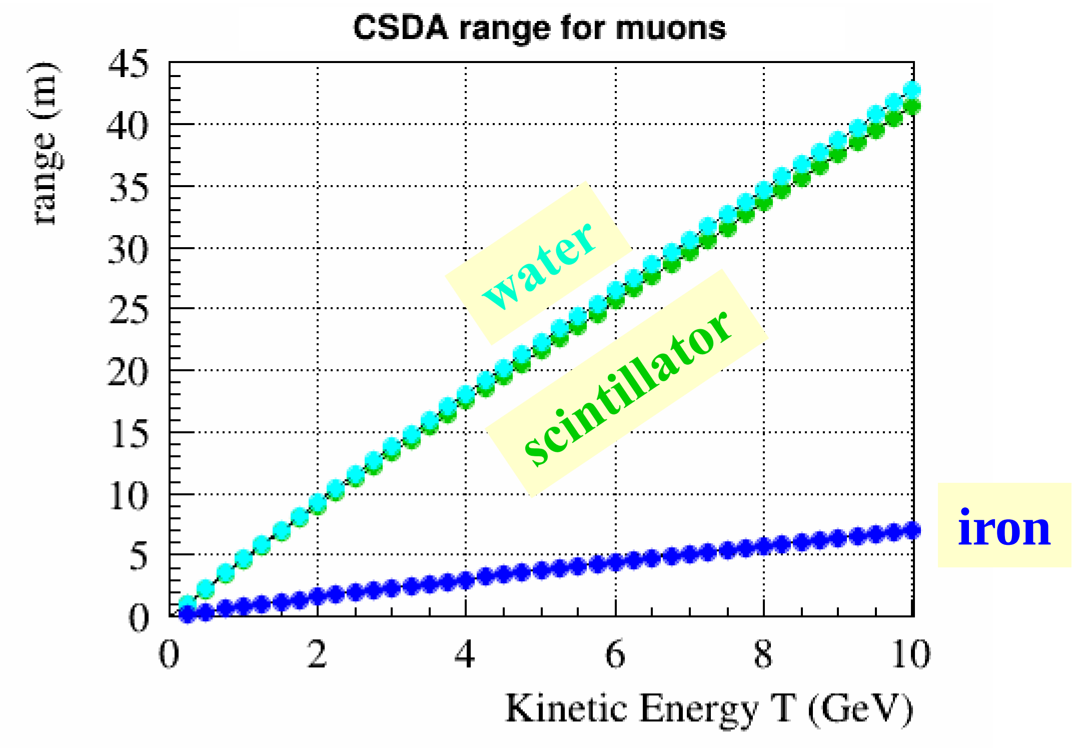
0.200 all materials

Mean excitation energy
I = 286.0 eV in iron


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


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

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

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

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

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

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

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 $\delta k_{\rm res}$ is calculated from:

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

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 $w = \sum {\epsilon_i}^{-2}$.

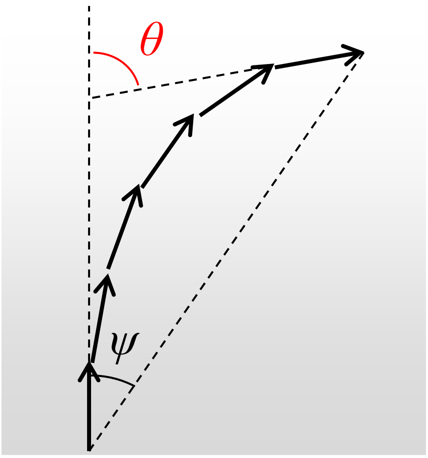
The contribution due to multiple Coulomb scattering is approximately

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

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)
β = 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 $\delta k_{\rm ms} \approx 8s^{\rm rms}_{\rm plane}/L^2$, where $s^{\rm rms}_{\rm plane}$ 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