A Magnetised Muon Range Detector for TITUS

A tool to increase δ_{CP} sensitivity

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Acknowledgements: Ryan, Matthew, Francesca, Alain and Etam

Advantages of TITUS:

a) the right target nuclei
b) similar acceptance
c) similar flux profile
d) plus, with Gd doping…

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

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

detect with Gd

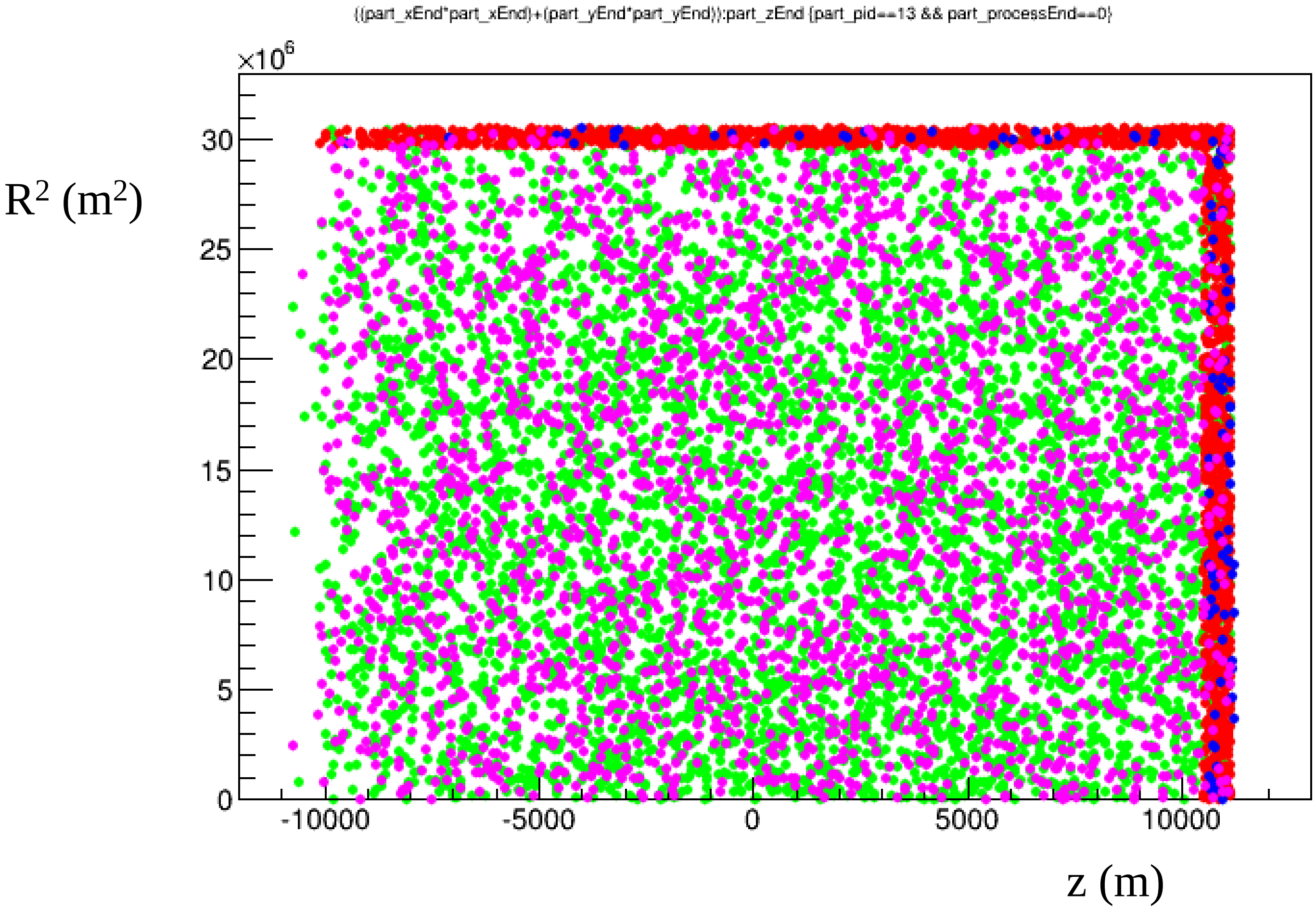
ε_Q **= 88%** (± 10%)

(Matthew's talk)

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



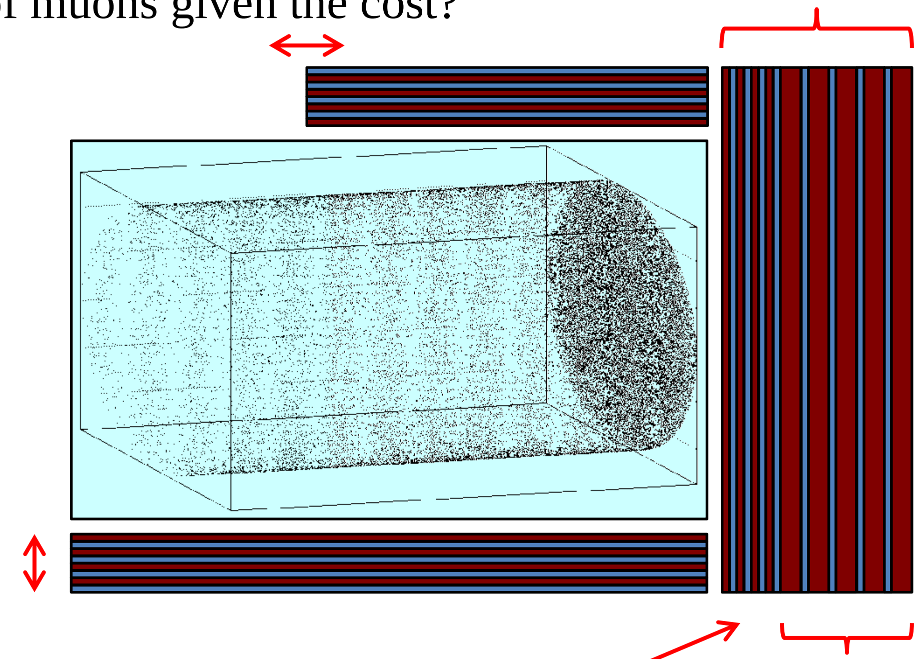
courtesy of Matthew Malek

Design considerations

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

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

neutrino beam



~30 Fe+scintillator modules
~50cm

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

Constant scintillator thickness
Total (x layer + y layer) = 1.5 cm
20 CHF / SiPM + 20 CHF / electronics channel

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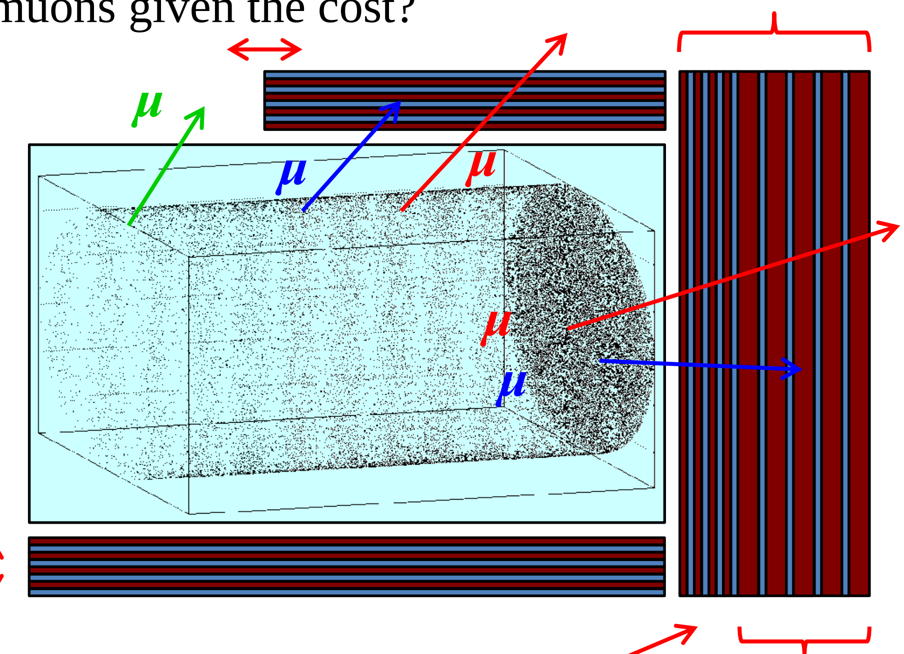

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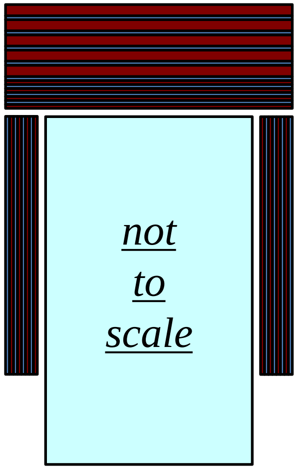
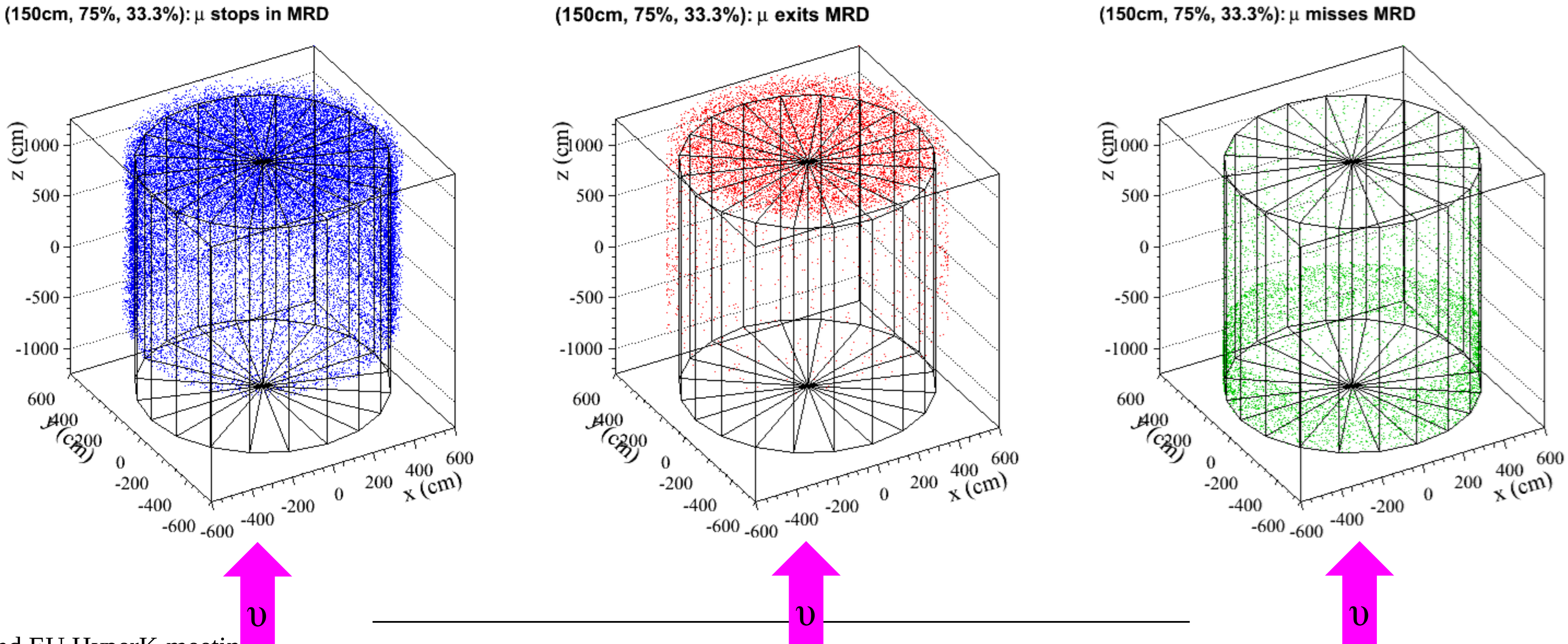
MRD tracks of muons which escape TITUS tank

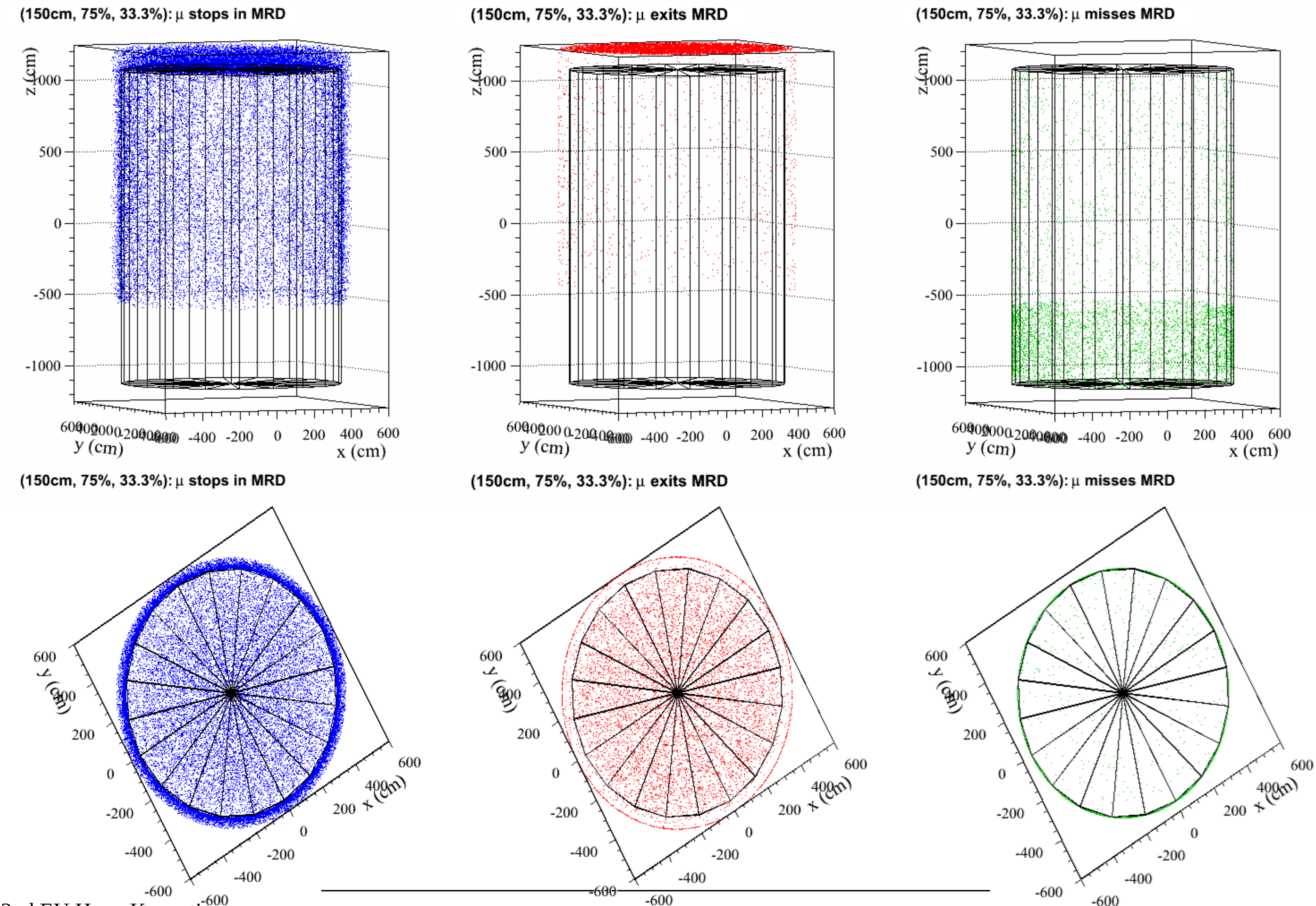
A simulation with 150cm end Fe and 75% side coverage of 50cm of Fe

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

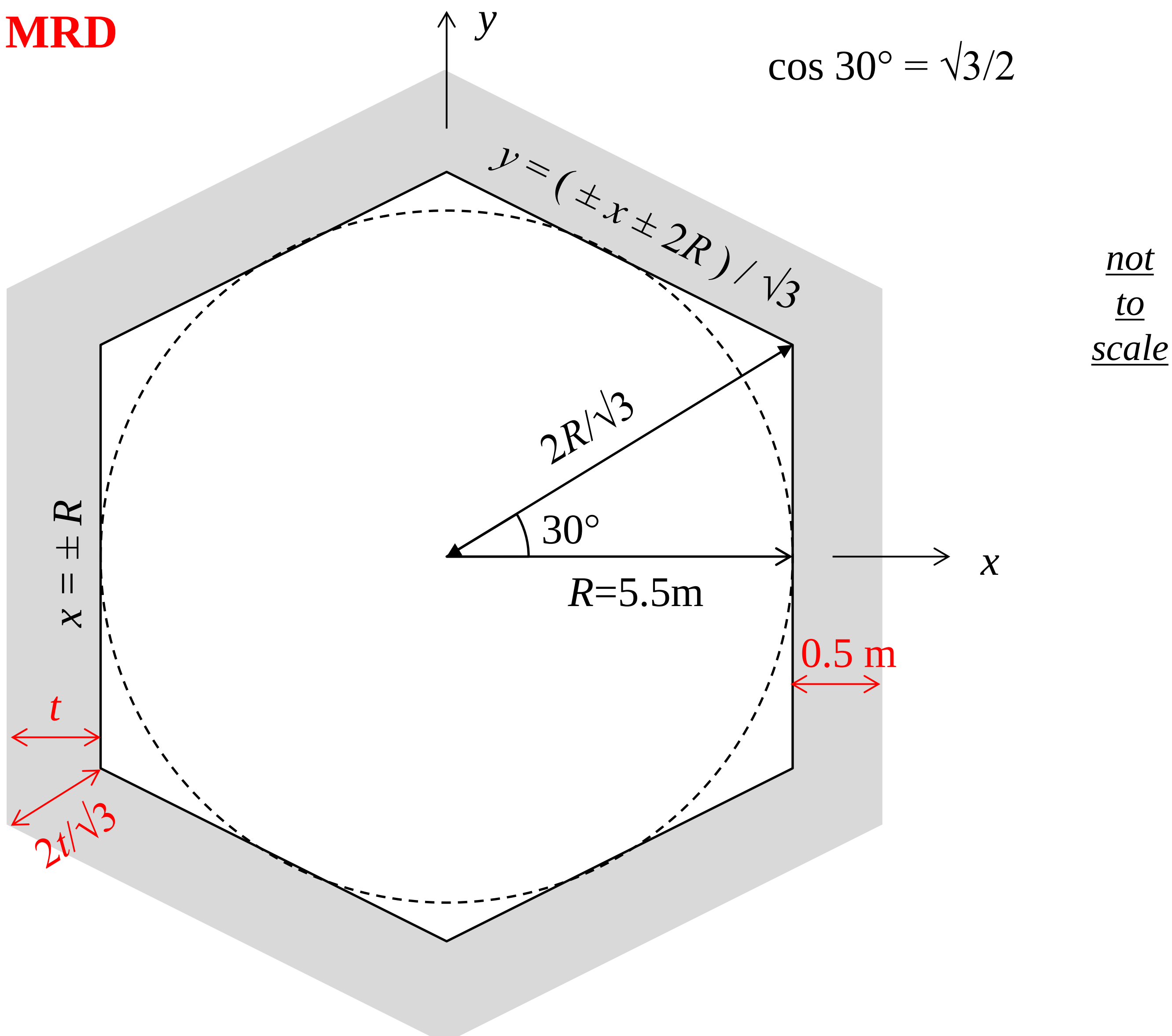


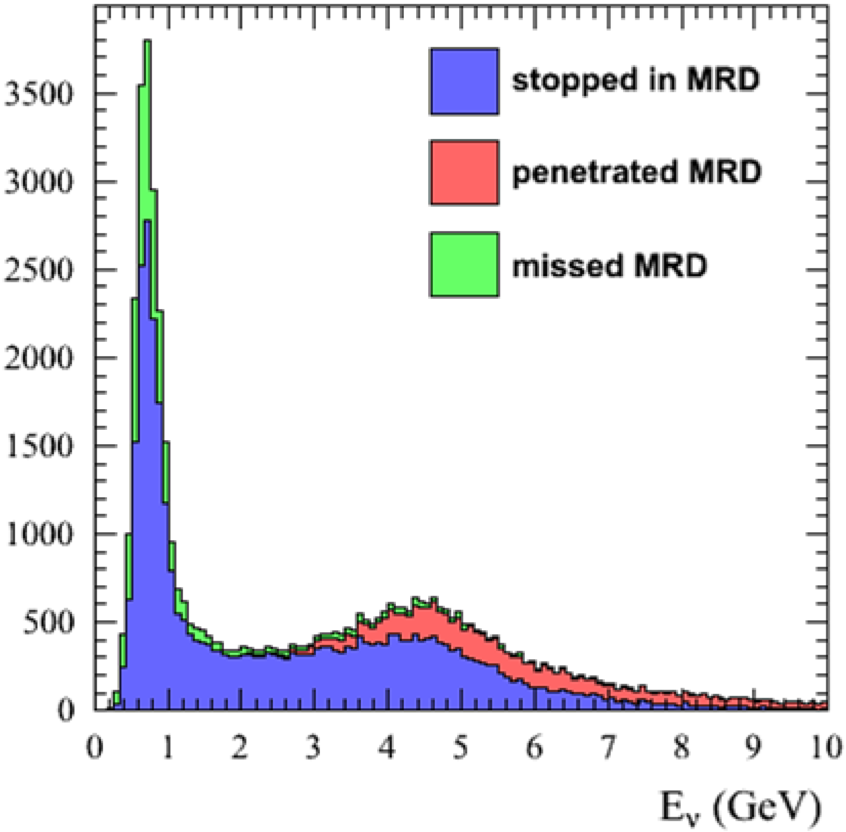


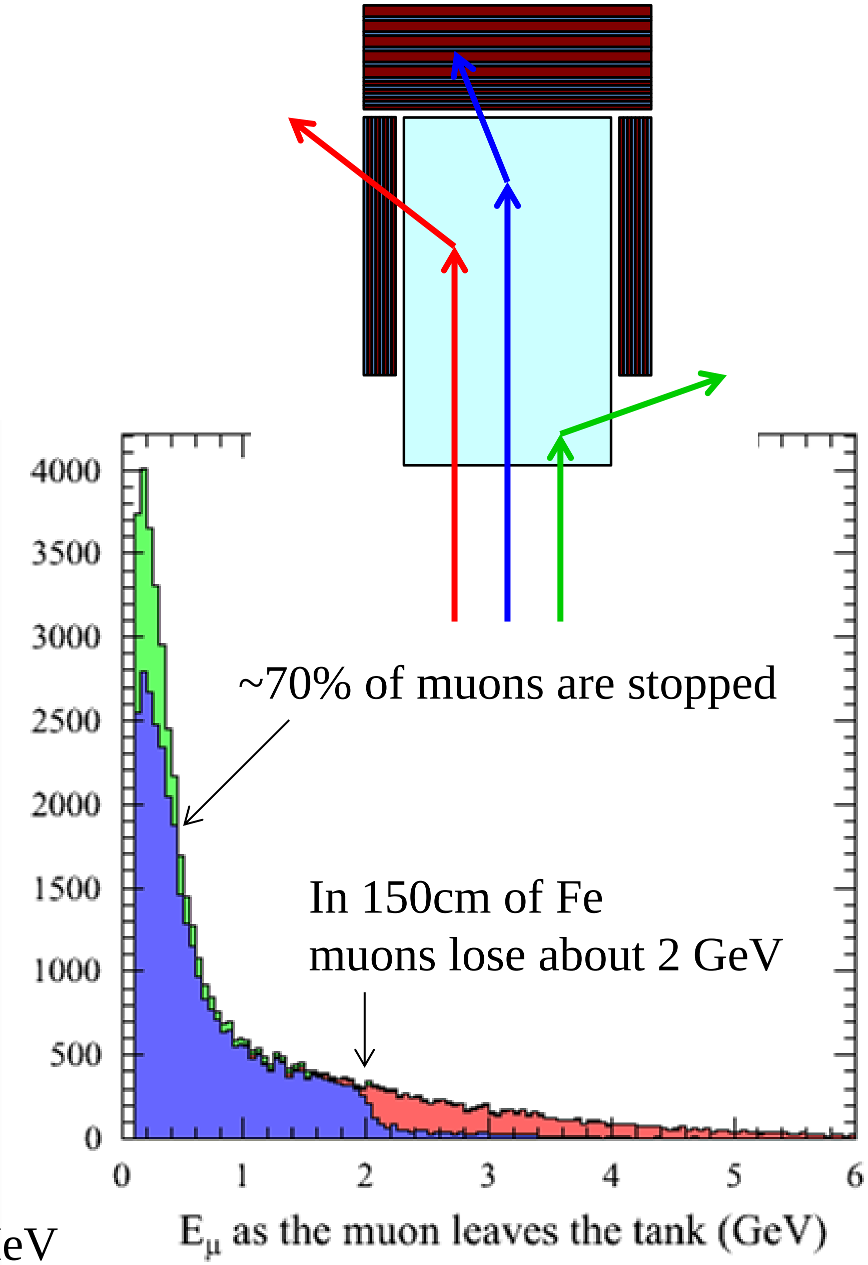
And from two more projections…



Model of the MRD





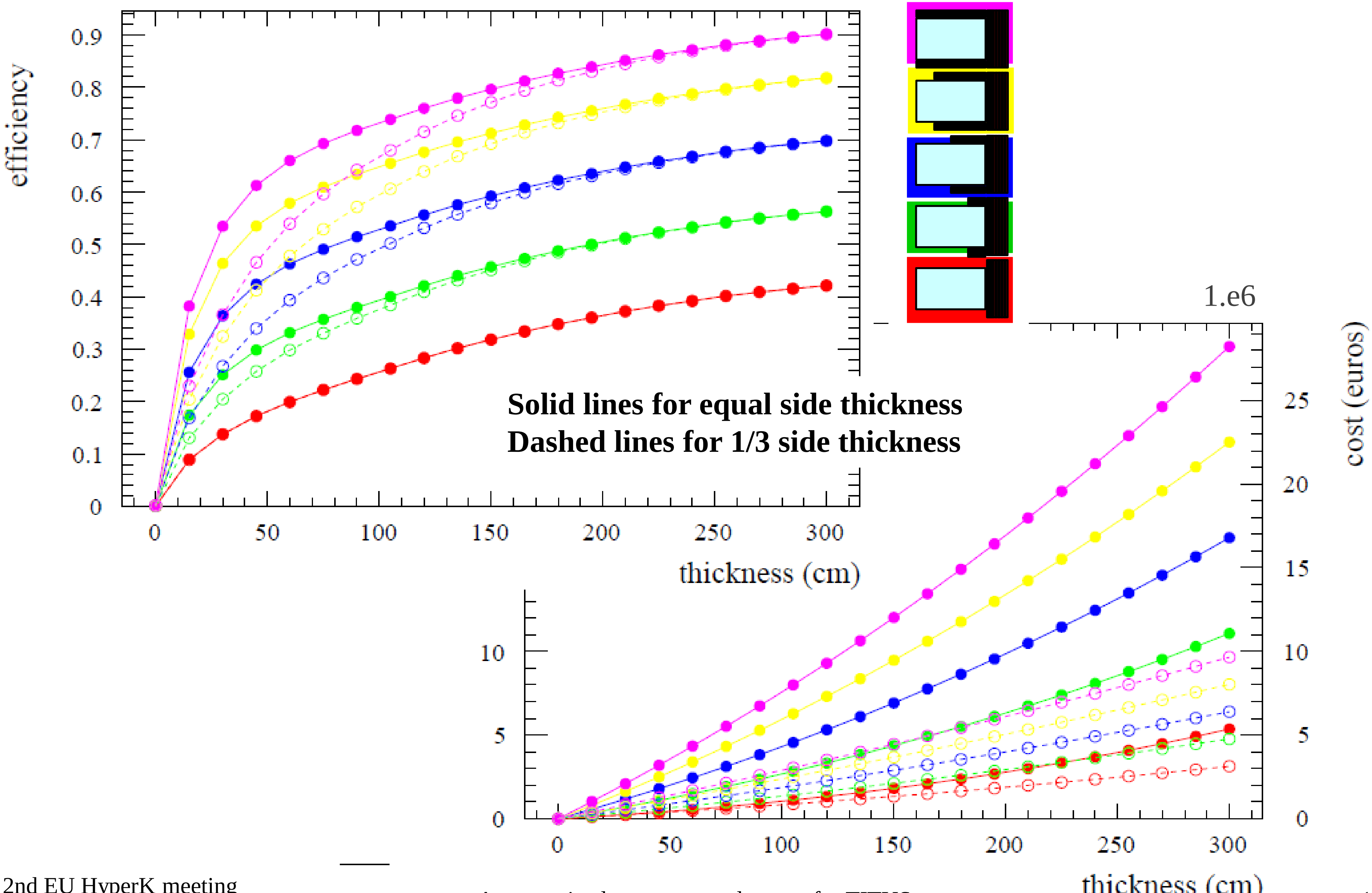


Aside

Momentum for the stopping sample:

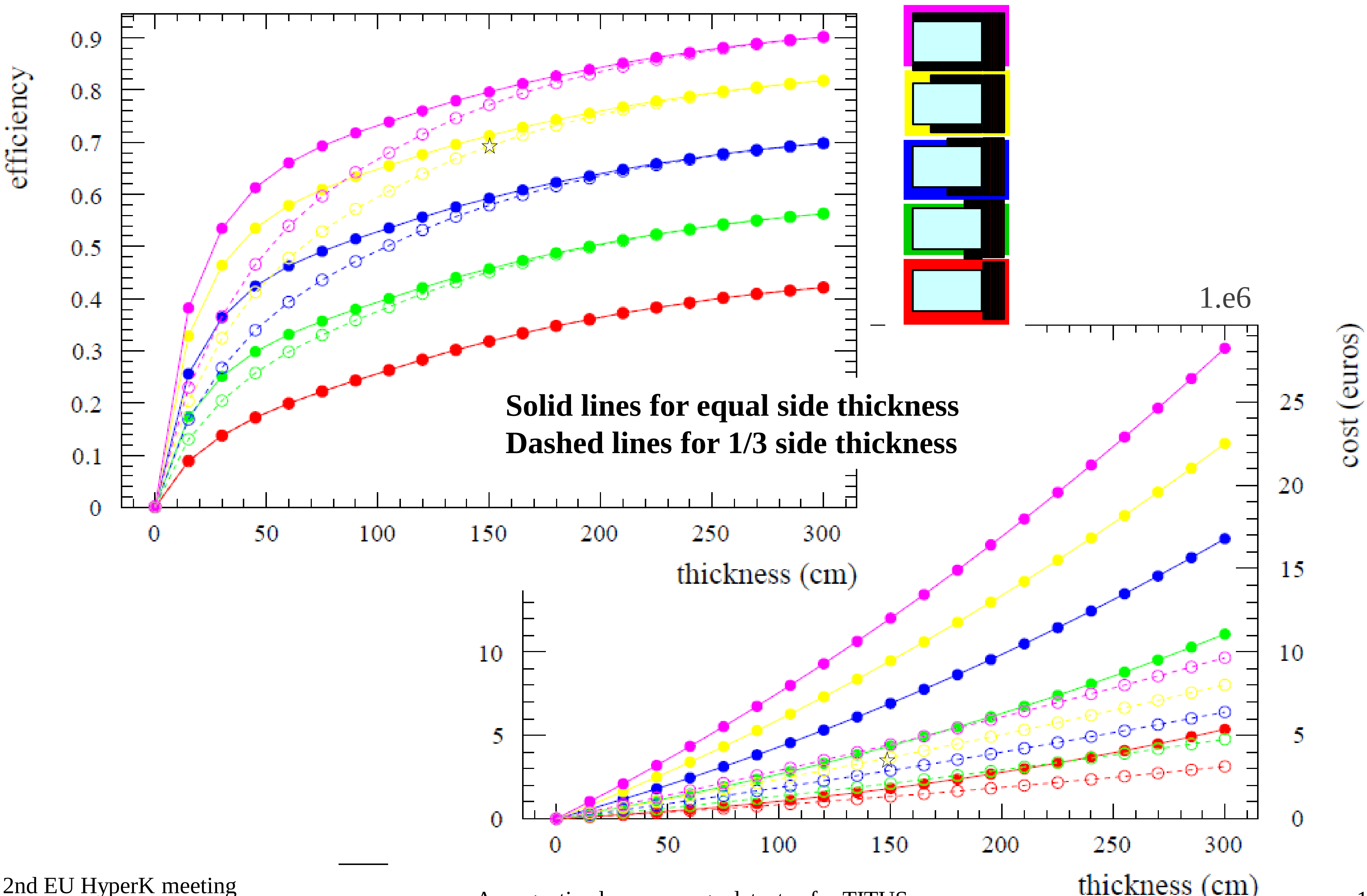
For *e.g.* 5 cm iron planes, sample energy at 70 MeV

Optimizing efficiency for stopping muons, and cost

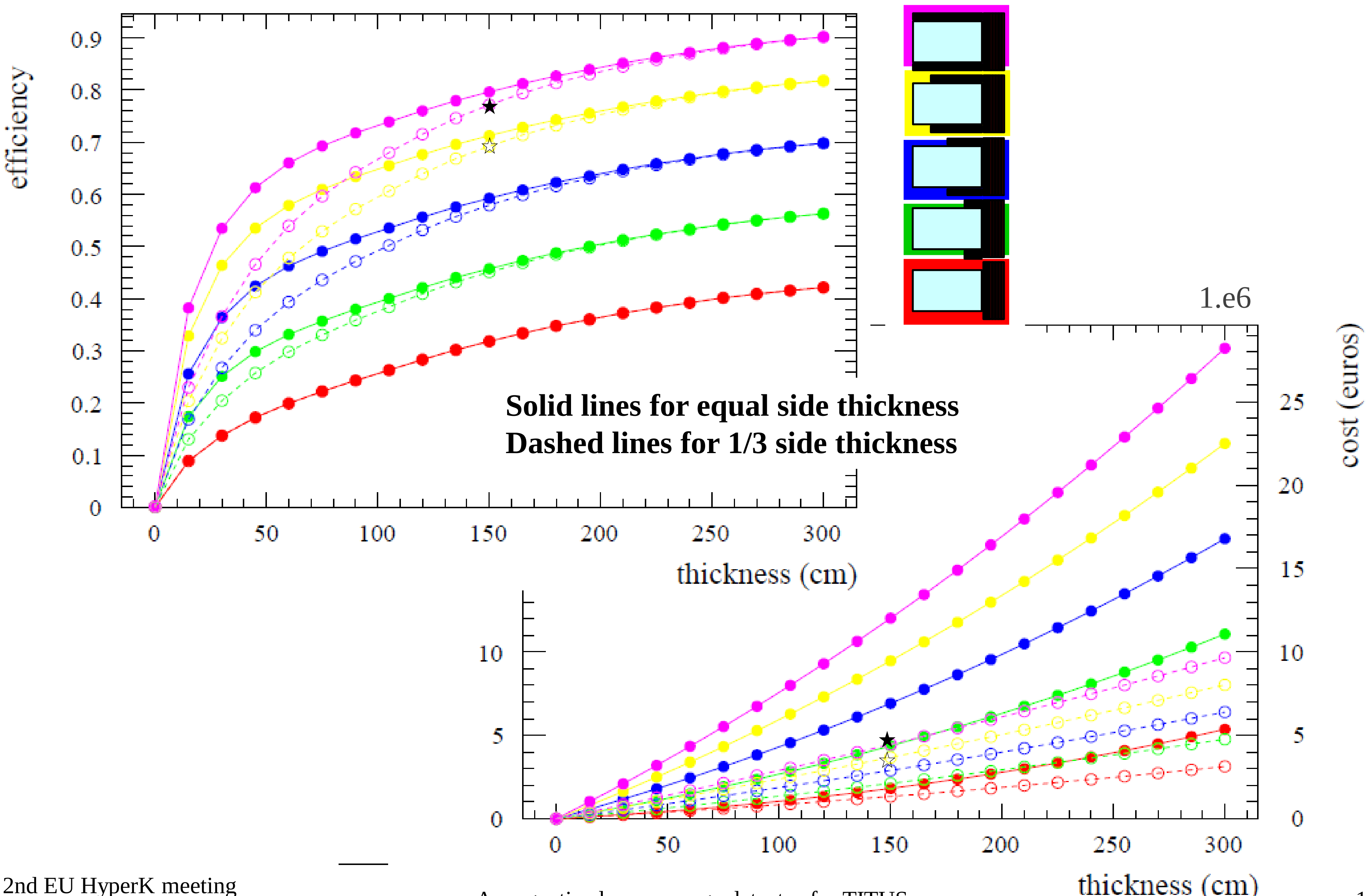


Solid lines for equal side thickness
Dashed lines for 1/3 side thickness

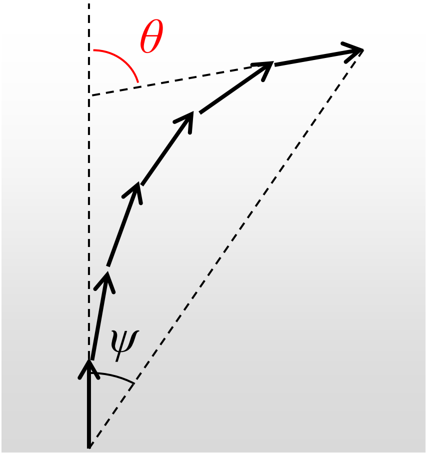
Optimizing efficiency for stopping muons, and cost



Optimizing efficiency for stopping muons, and cost



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

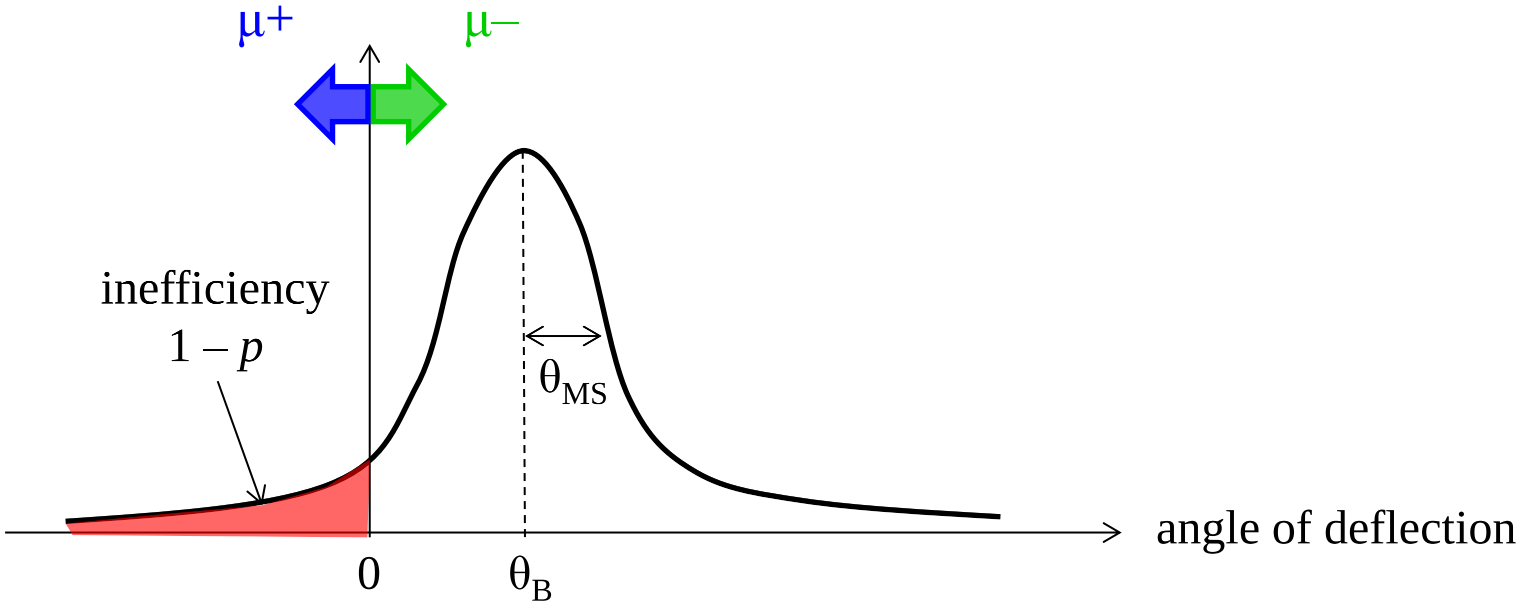
$\Delta p_{\perp}$ = 4.5 MeV/c (for every cm)

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

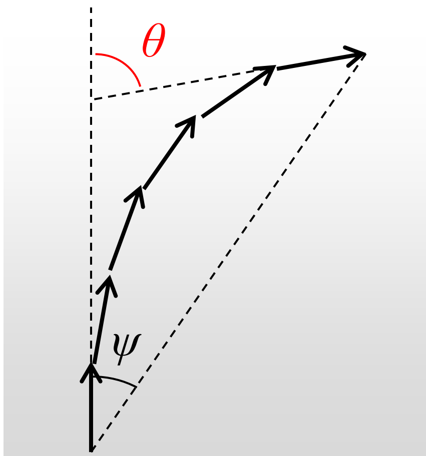
θ > Multiple Scattering


μ+
μ−
inefficiency
1 − p
θMS
angle of deflection
0
θB

Multiple Scattering

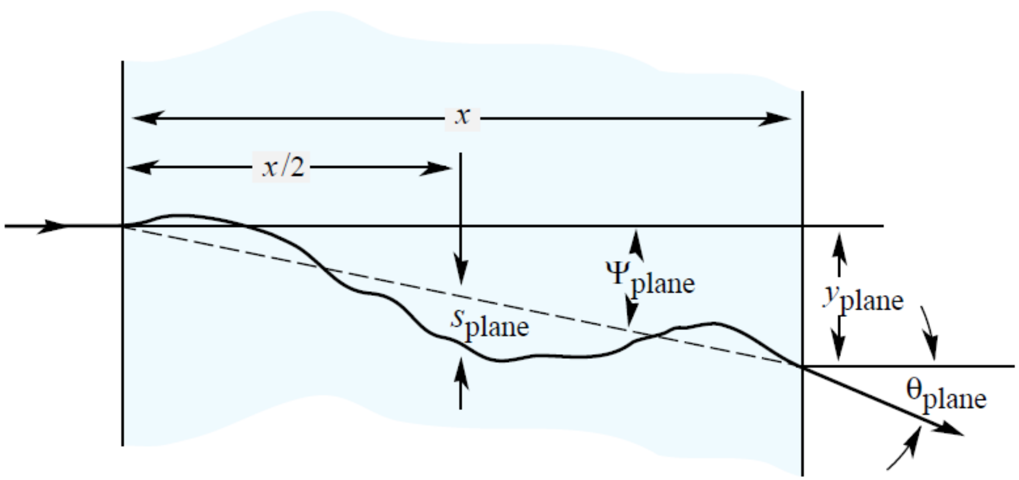
X_0 = 1.757 cm in Fe
X_0 = 50.31 cm in polyethylene

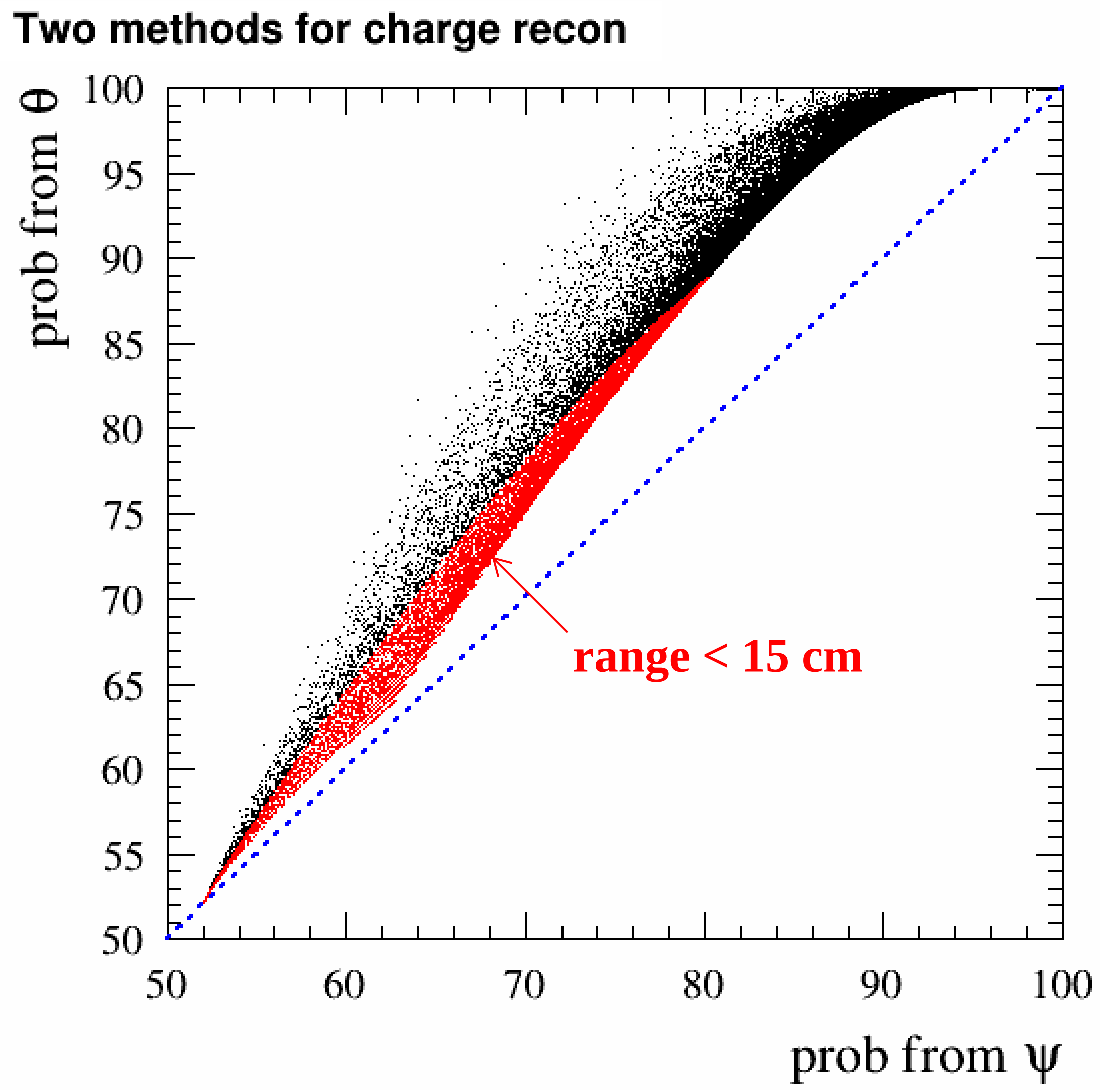
$(X_0 / X_0)^{1/2}$ = 1.9%



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

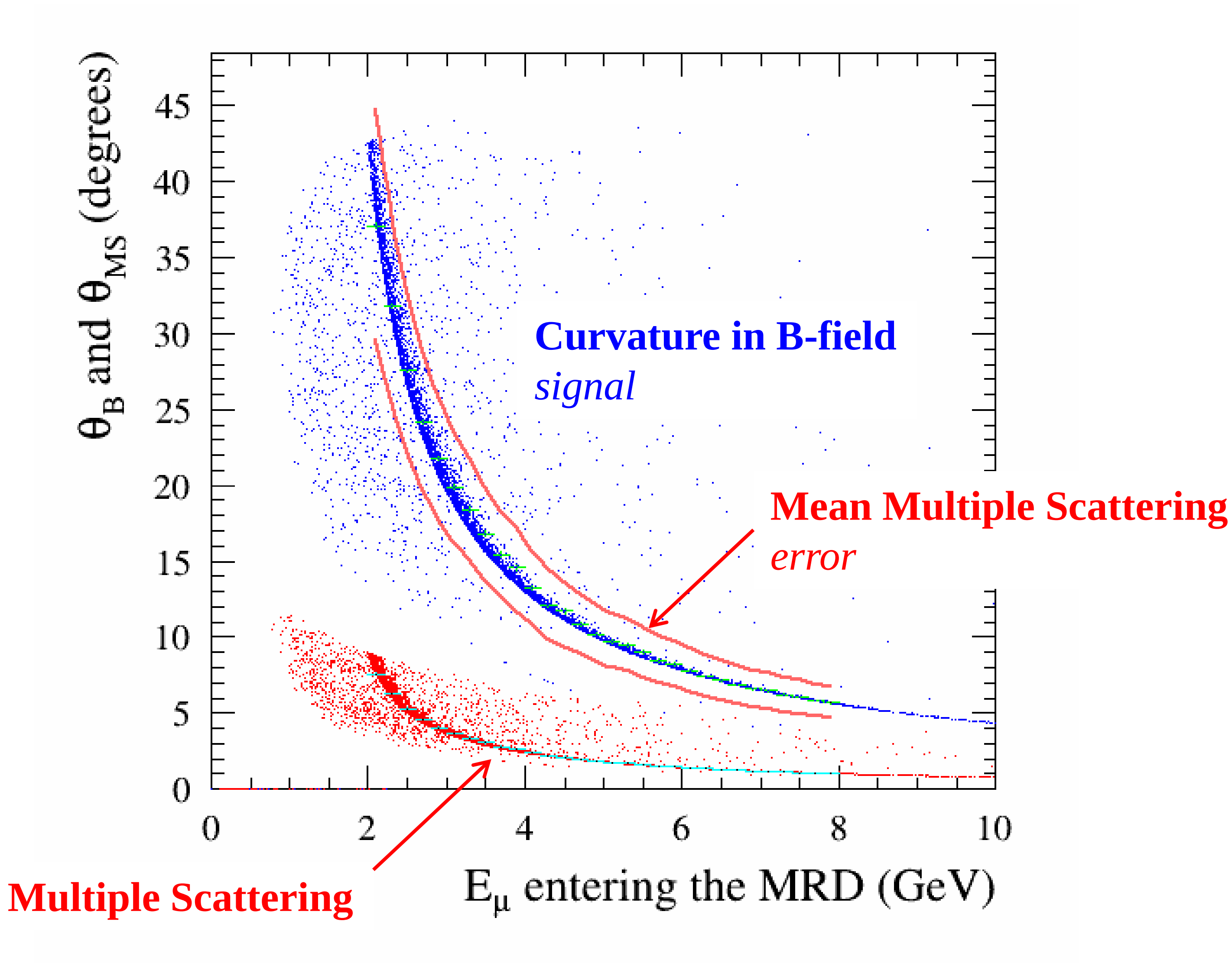
$$\psi^{\mathrm{rms}}_{\mathrm{plane}} = \frac{1}{\sqrt{3}}\,\theta^{\mathrm{rms}}_{\mathrm{plane}} = \frac{1}{\sqrt{3}}\,\theta_0$$

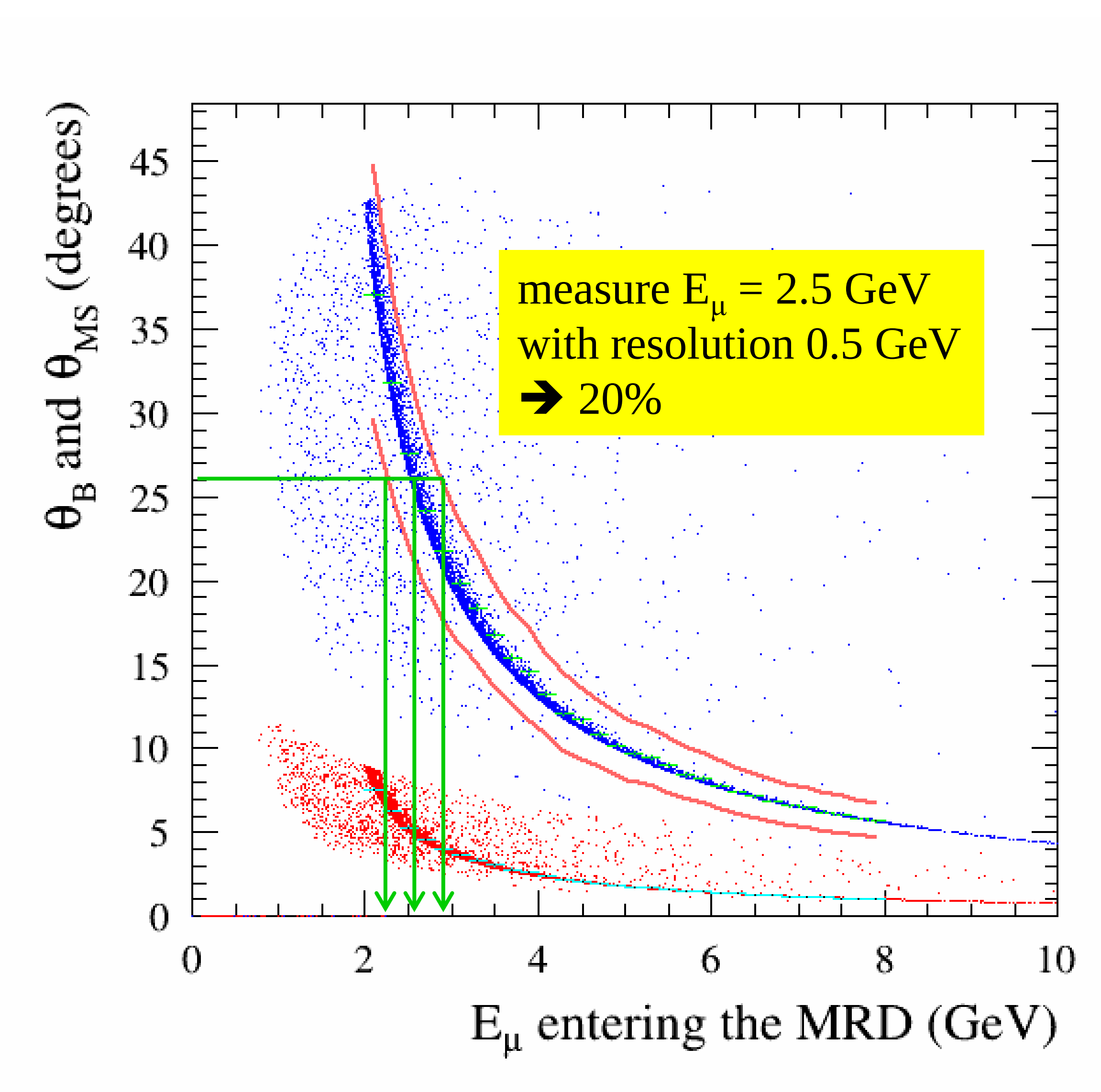




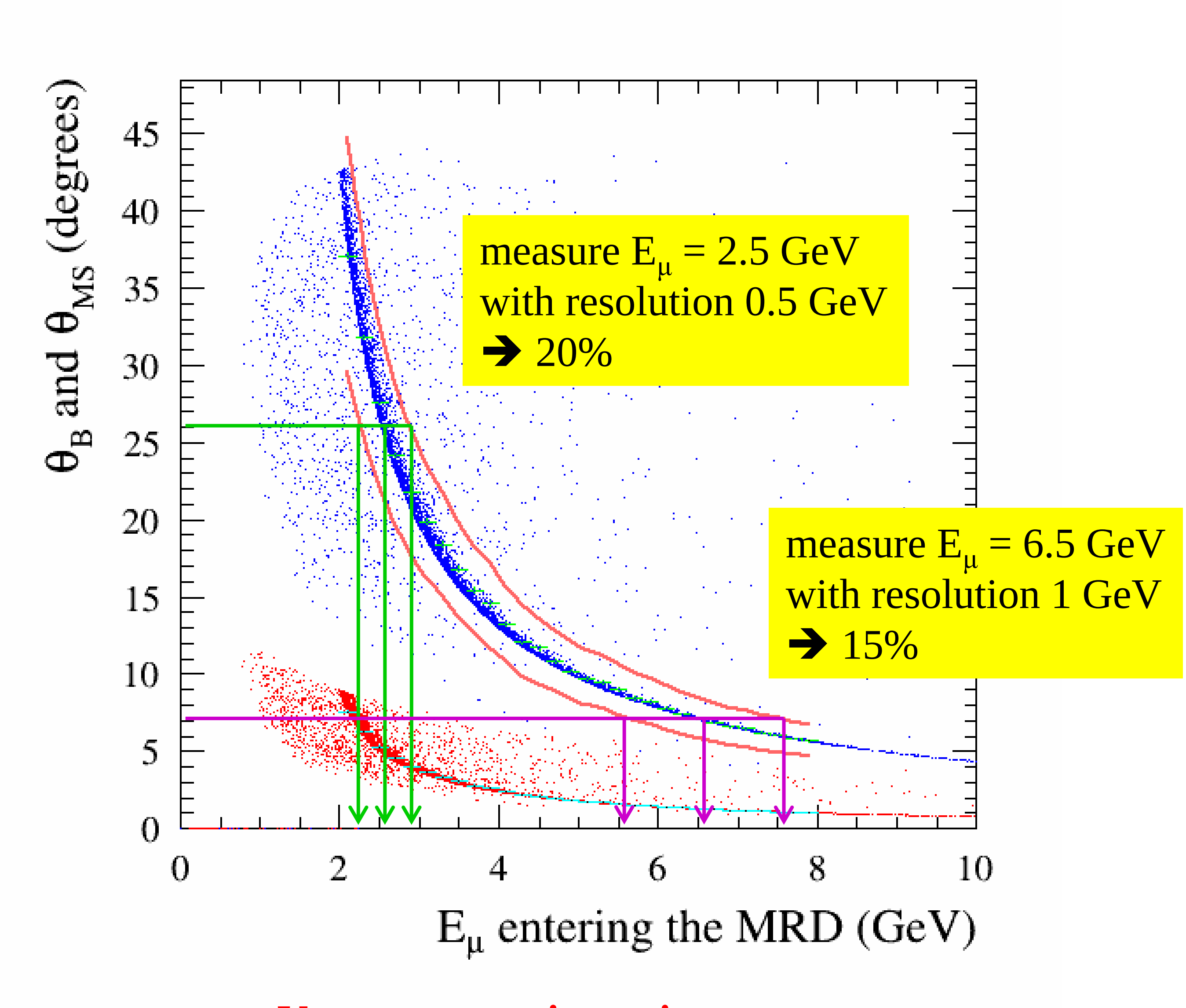
Two methods for charge recon
prob from θ
100
95
90
85
80
75
70
65
60
55
50
50
60
70
80
90
100
prob from ψ
range < 15 cm

Aside: Momentum for the penetrating sample





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



Very conservative estimates

Sketch analysis of a magnetised MRD

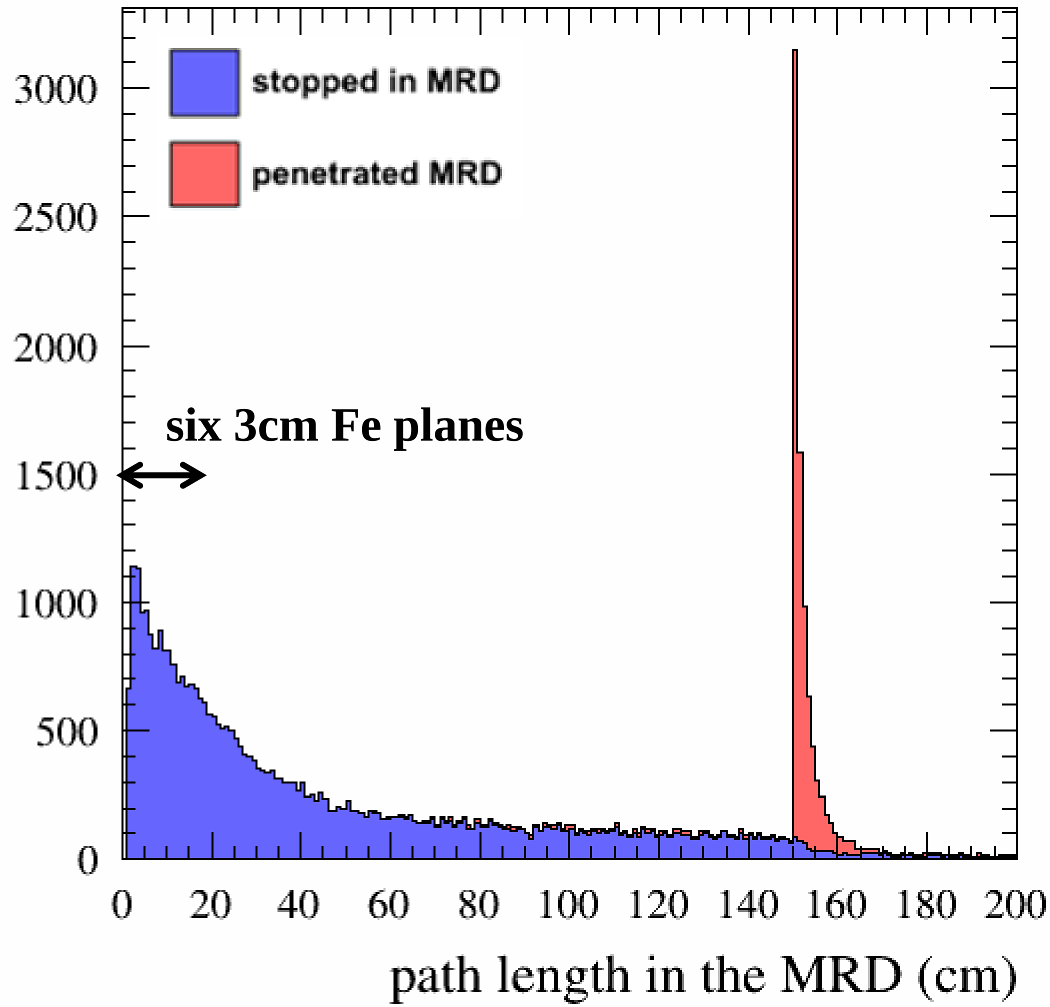
only **one** scintillator plane → upper bound on muon energy

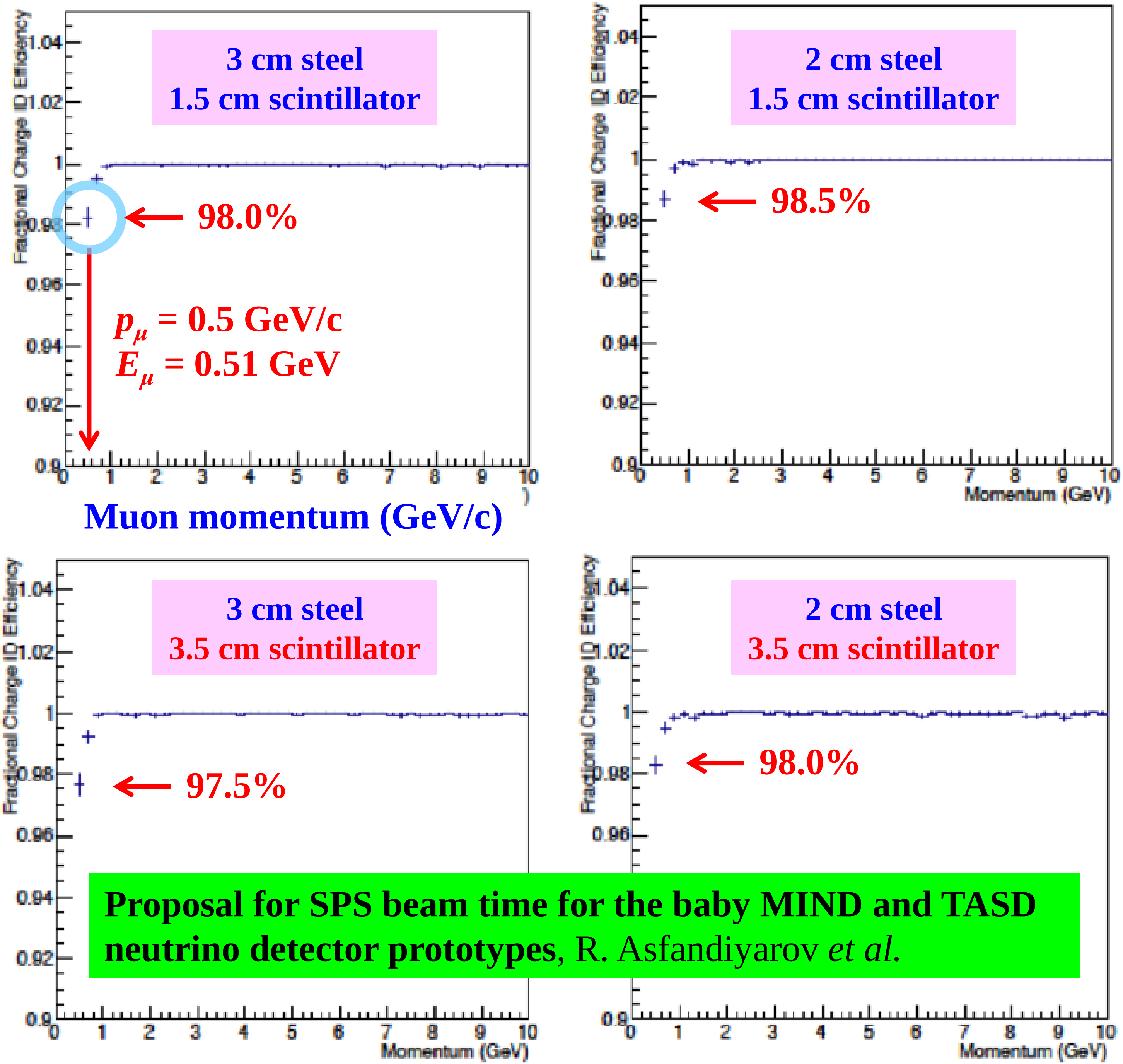
two scintillator planes hit → energy measurement from range
ψ measurement of charge if $\psi_B > \psi_{pix}$

3 – 6 scintillator planes hit → energy measurement from range
ψ measurement of charge

> 6 scintillator planes hit → energy measurement from range
energy measurement from curvature
θ and ψ measurement of charge

Muon path length in the iron of the MRD

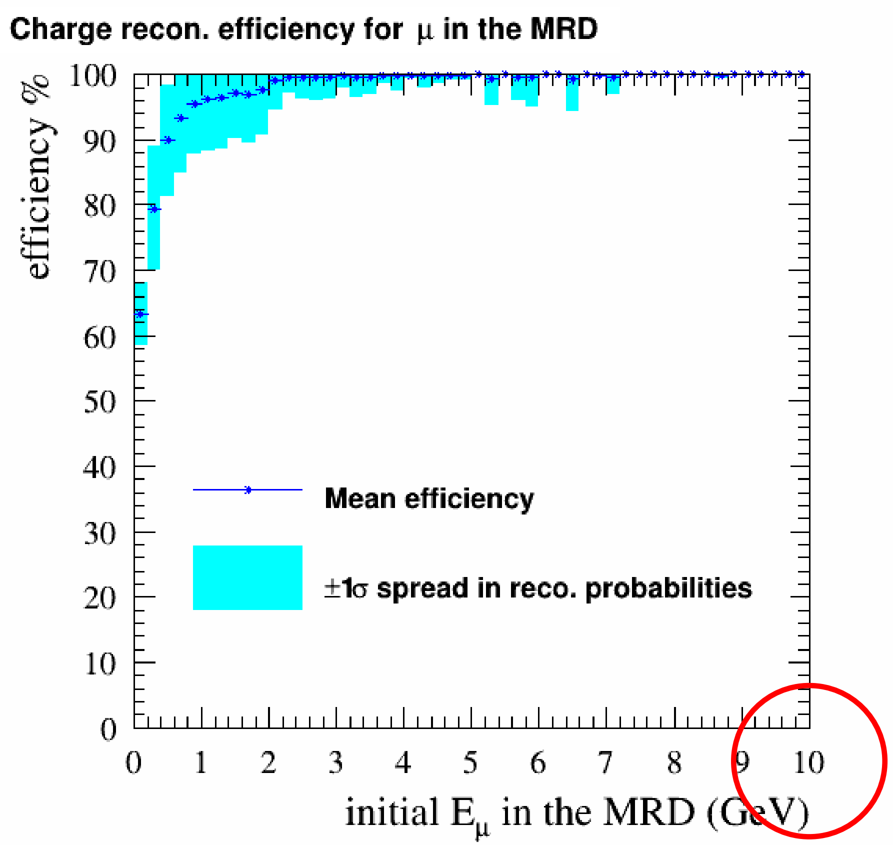


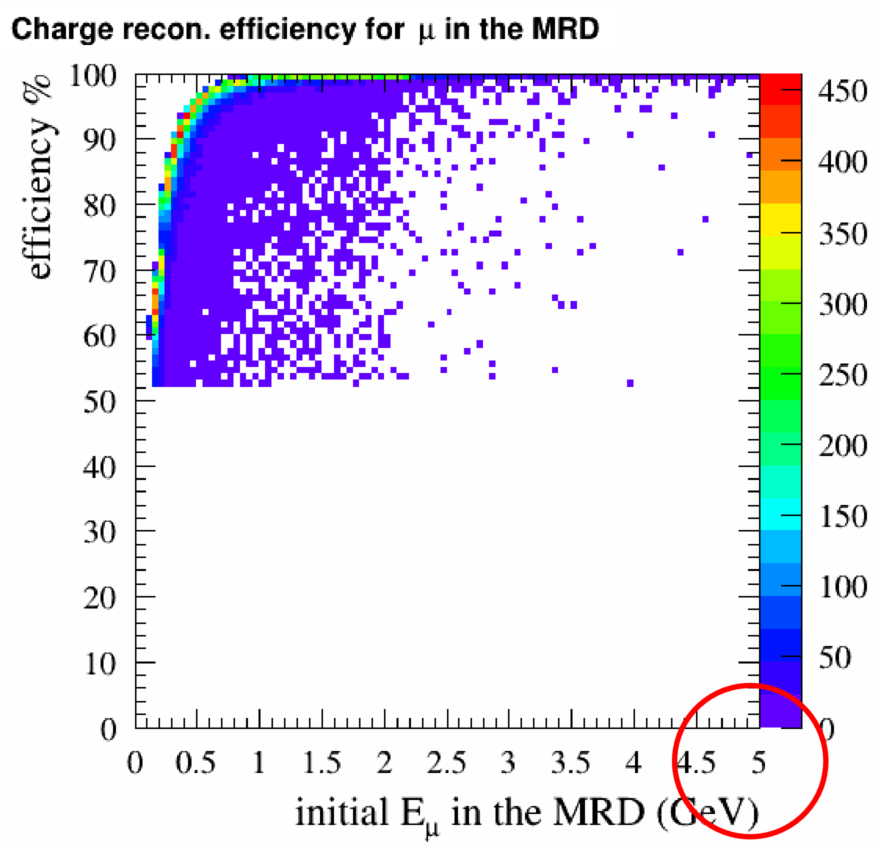


Proposal for SPS beam time for the baby MIND and TASD neutrino detector prototypes, R. Asfandiyarov *et al.*

TITUS MRD charge recon. efficiency vs. muon energy

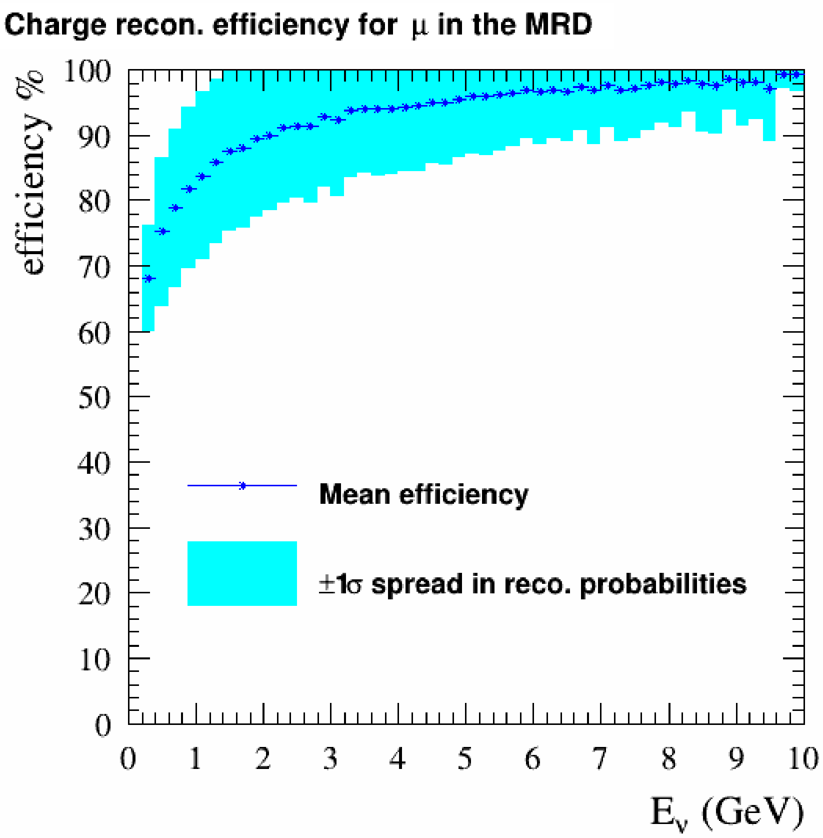
PRELIMINARY

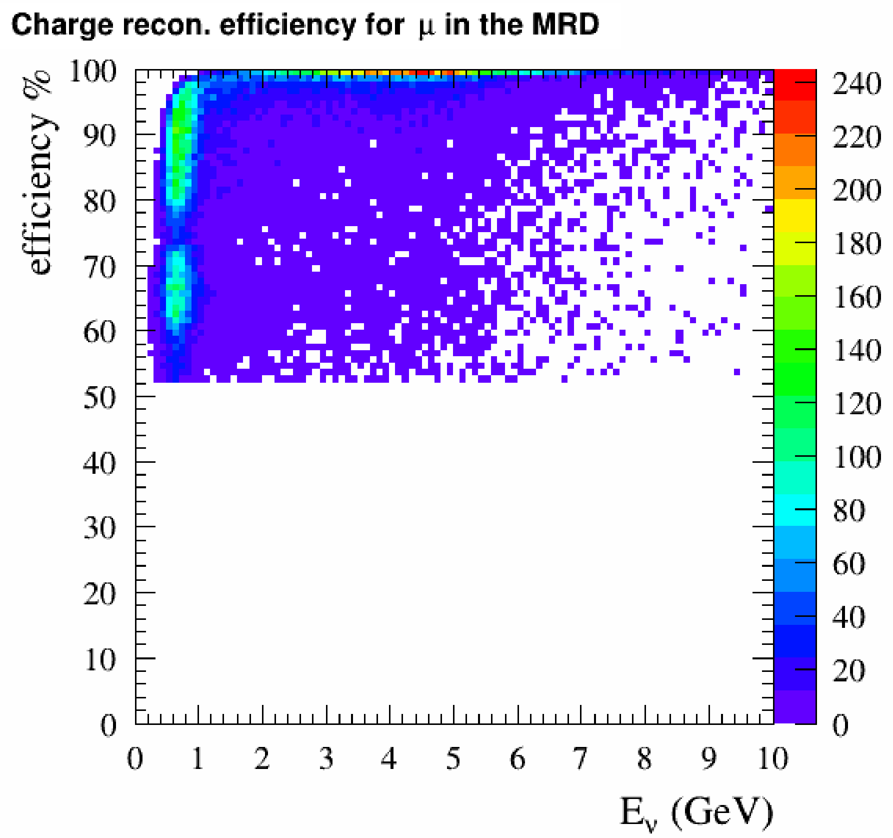




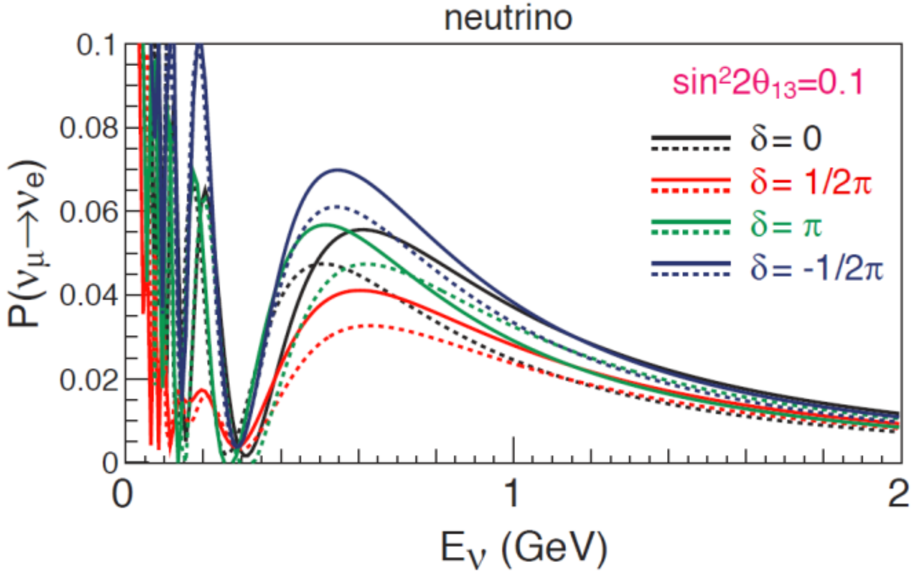
TITUS MRD charge recon. efficiency vs. neutrino energy

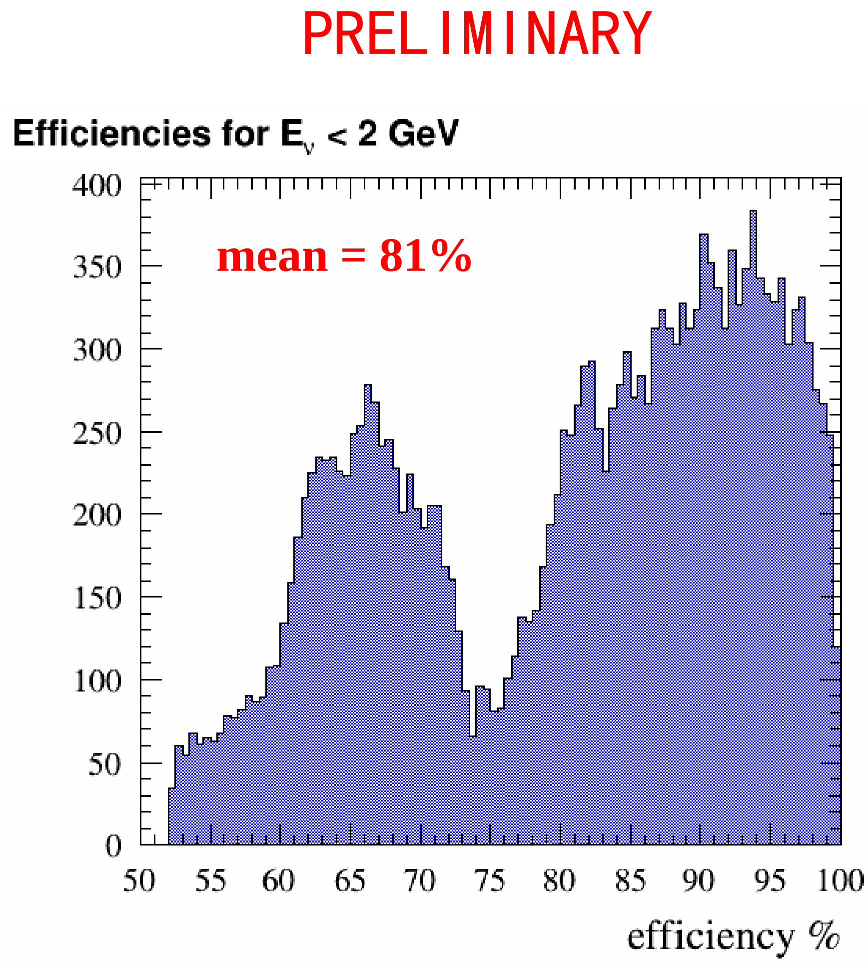
PRELIMINARY





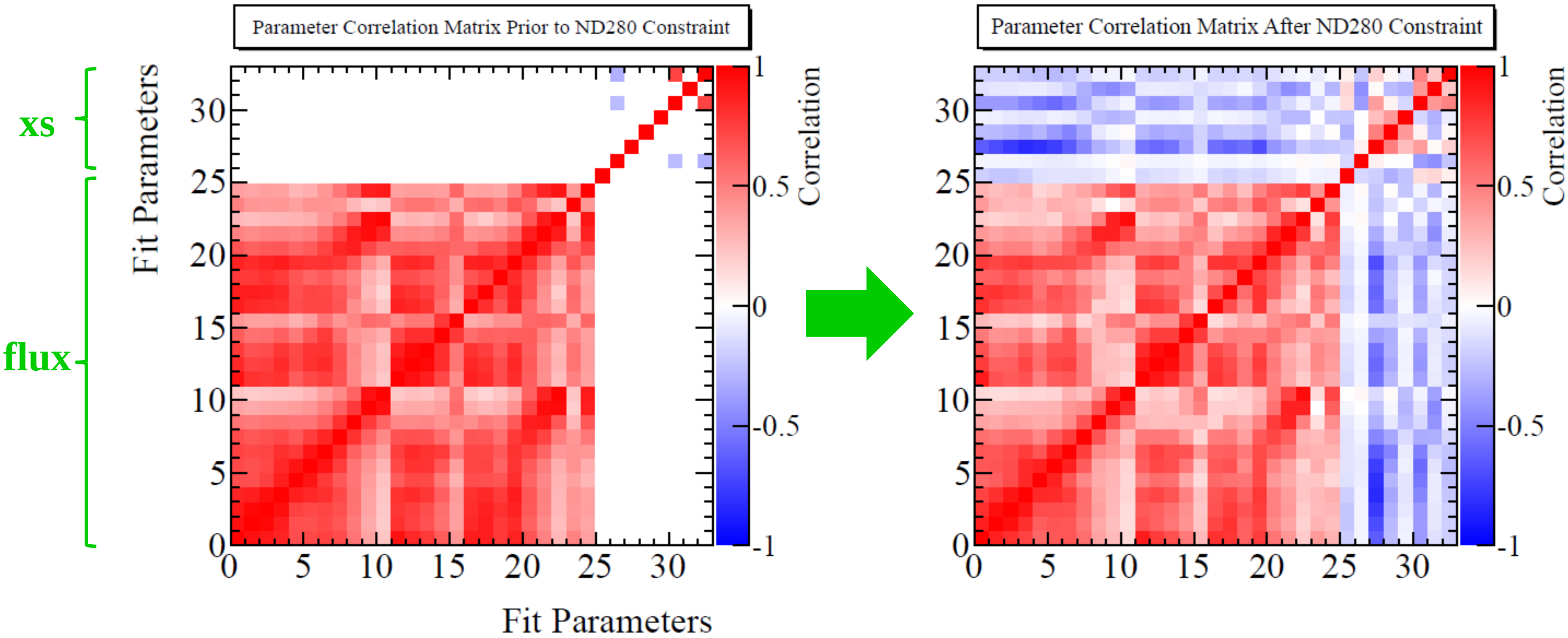
but of course $E_\nu < 2$ GeV is of particular interest





Here we expect 81% efficiency
(conservatively)

Such information, especially when combined with the Gd charge measurement, could constrain previously assumed parameters in a BANFF –style fit



ND280 does not constrain every cross-section parameter (NC, coherent, $\sigma(\upsilon_e)/\sigma(\upsilon_\mu)$…)
In particular, we rely on external data for $\sigma(\bar{\upsilon})$ / $\sigma(\upsilon)$

We plan to estimate the effect of a magnetised MRD on the ability of TITUS to constrain parameters such as these, and re-calculate the sensitivity to δ_{CP}
(e.g. via the Simple Fitter, with covariance in Erec bins)

Summary

18% of muons escape the 22 m long, 11 m diameter TITUS tank

With a 1.5 Tesla magnetized iron muon range detector (150 cm end, 50 cm sides):

75% of muons which escape the tank are stopped

Excellent momentum resolution from range

In the oscillation region, ~81% charge reconstruction efficiency

(with independent Gd measurement, ~96%)

90 – 100% for E > 2GeV

25% of muons which escape the tank penetrate through the MRD

~15% momentum resolution from curvature (conservative estimate)

~100% charge reconstruction efficiency

Can be used to test Gd charge reconstruction

Work in progress

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

Backup slides

Landau-Vavilov most probable energy loss in iron

density = 7.87 g cm^{-2}

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

$$\xi = (K/2)\,\langle Z/A\rangle\,(x/\beta^2)\ \text{MeV}$$ ~ **1.13 MeV / cm (ultra-relativistic)**

Z/A = 26 / 55.845 = 0.466

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

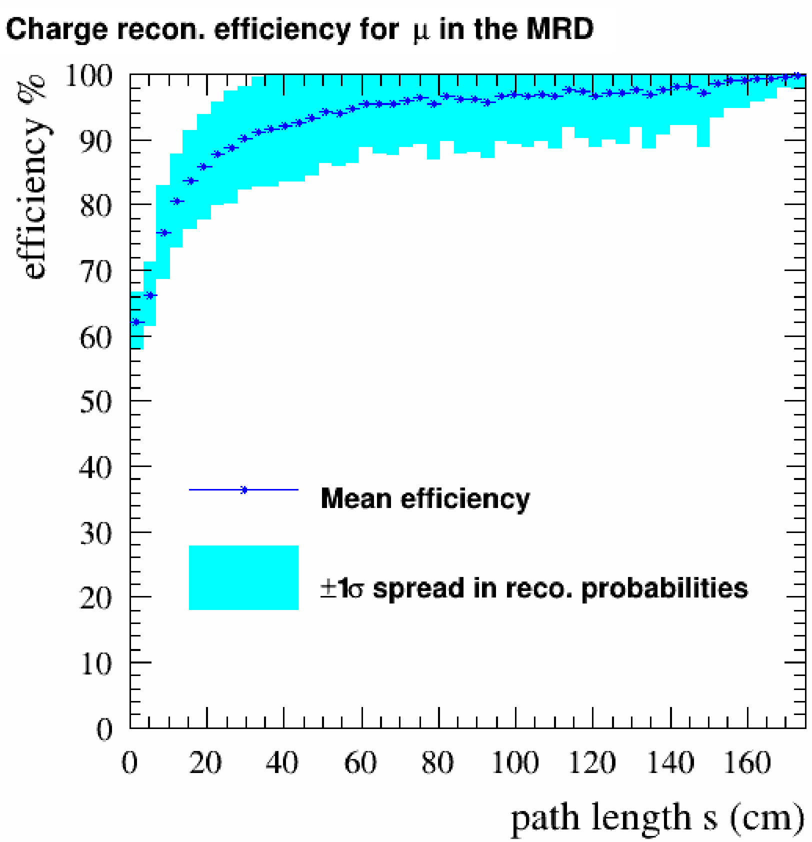
0.511 MeV

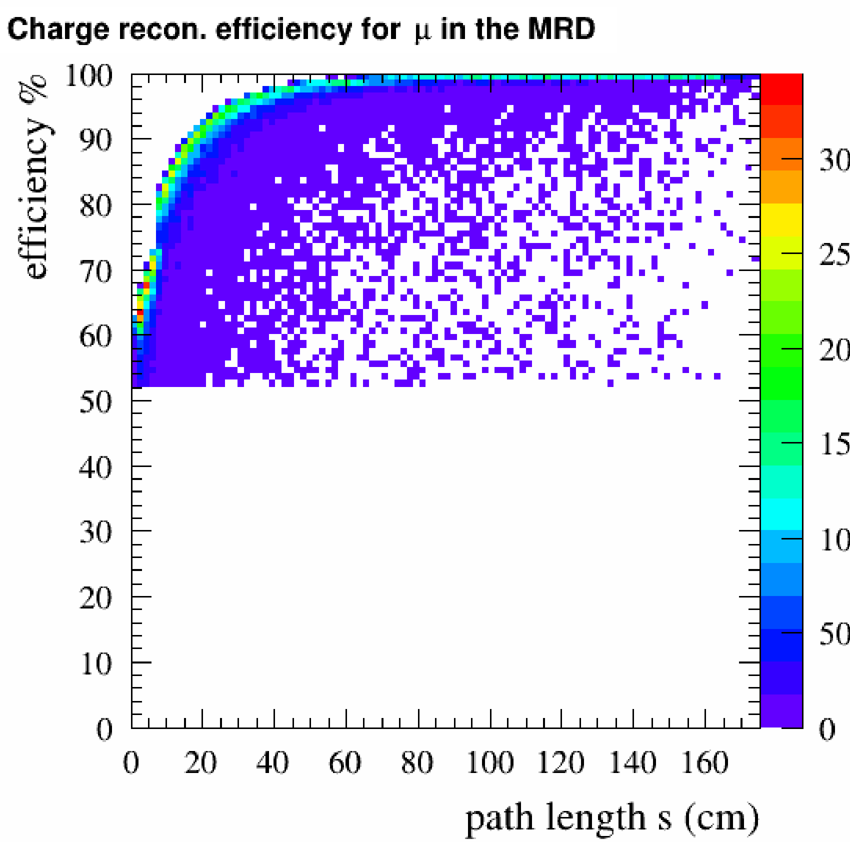
neglect density effect

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

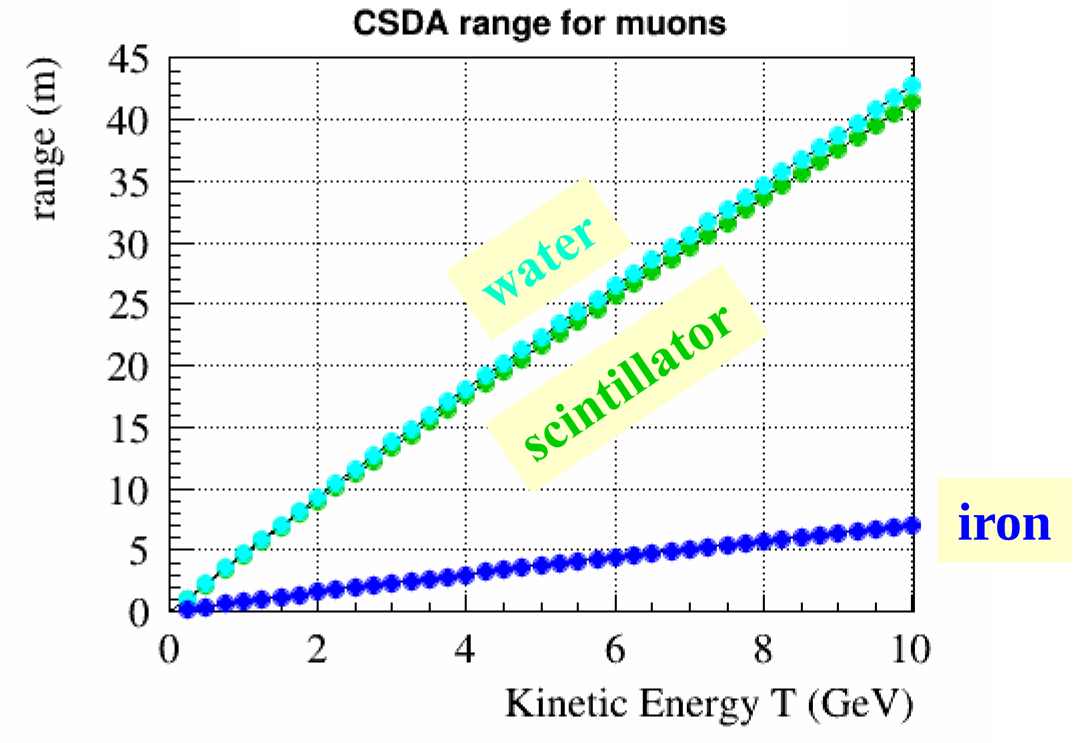
0.200 all materials

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
20
40
60
80
100
120
140
160
10
30
50
70
90

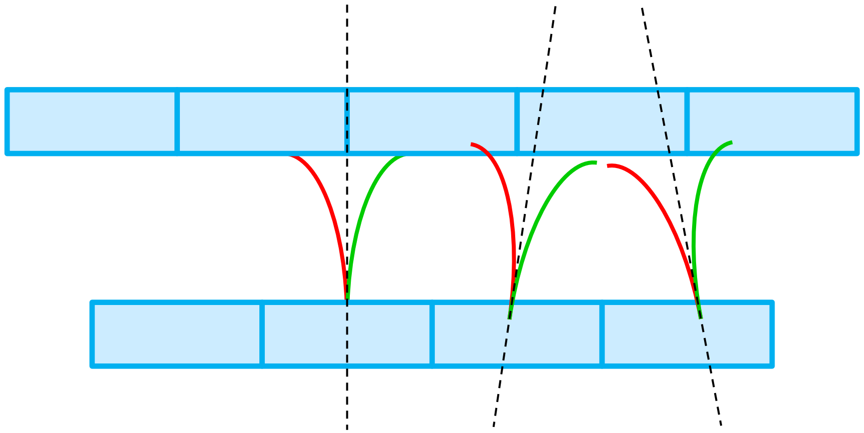

Charge recon. efficiency for μ in the MRD
efficiency %
path length s (cm)
0
20
40
60
80
100
120
140
160
10
30
50
70
90
150
200
250
300

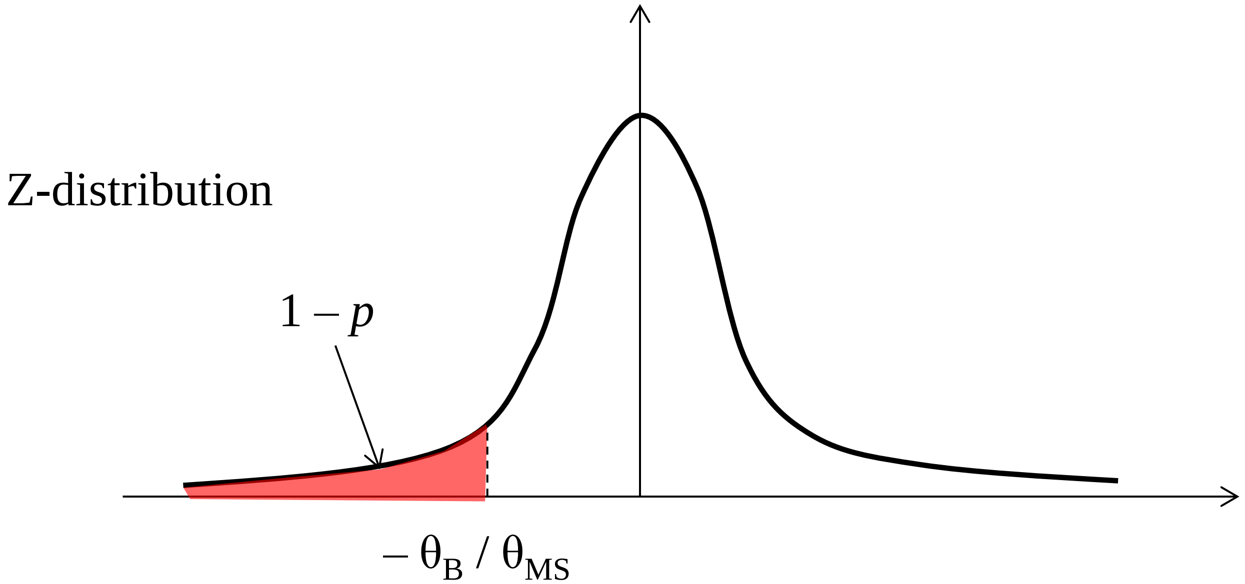
Range of muons in iron



Fiducial volume cut = 1 m
with LAPPDs = 0.5 m

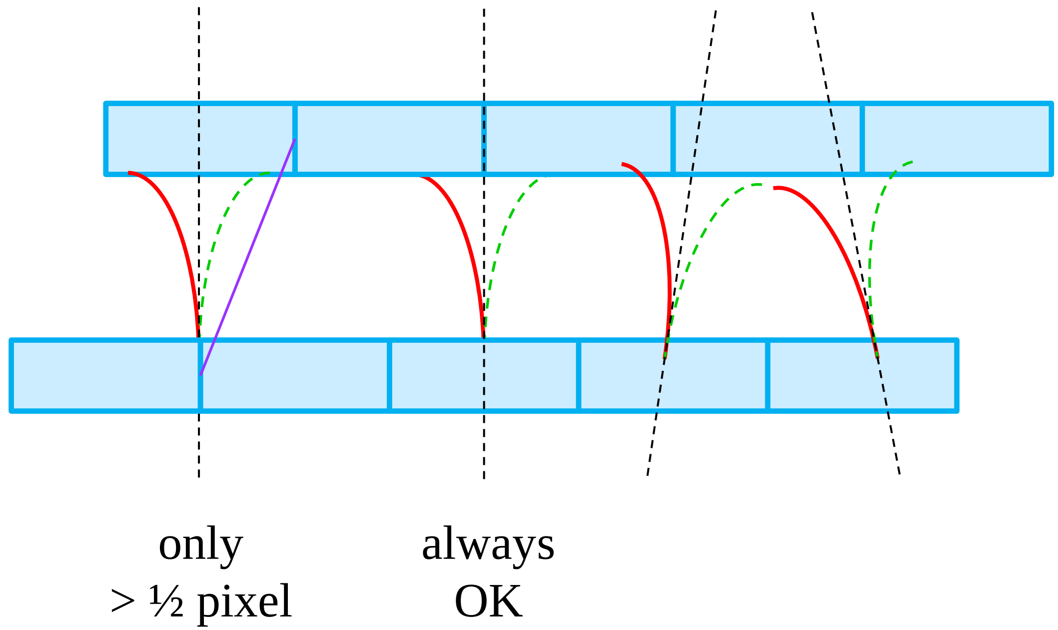
How should we arrange the 'pixels'?

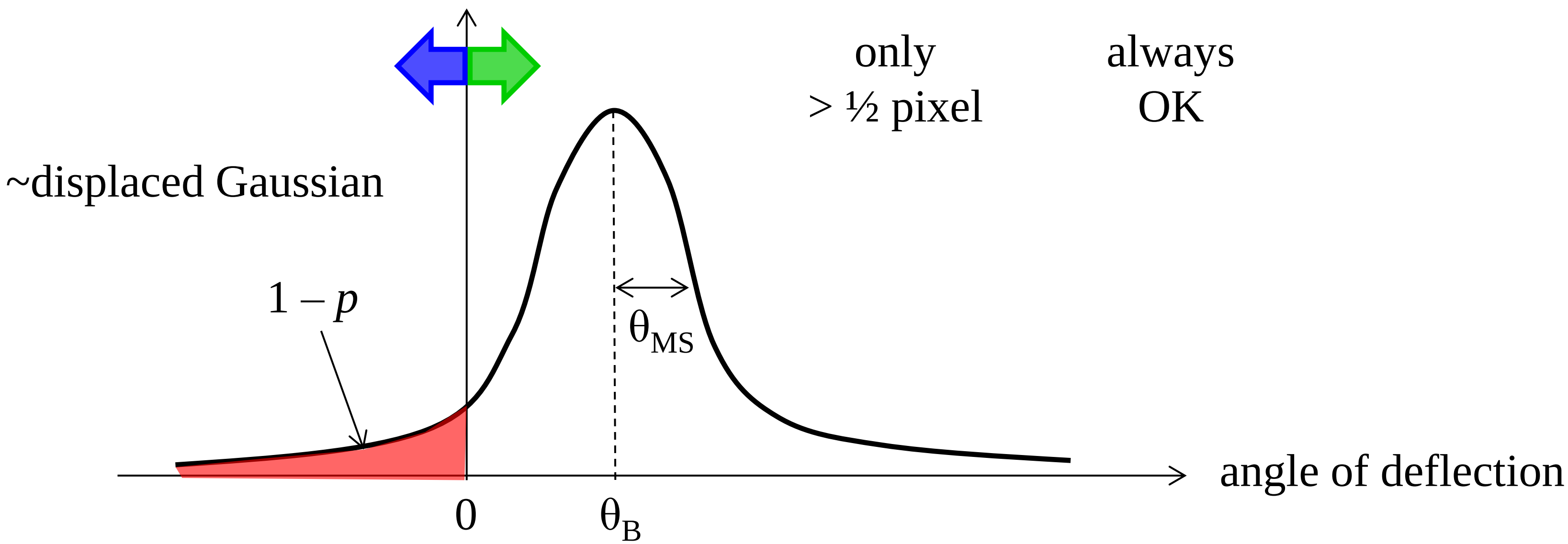




This will reduce the charge reconstruction efficiency slightly

How should we arrange the ‘pixels’?





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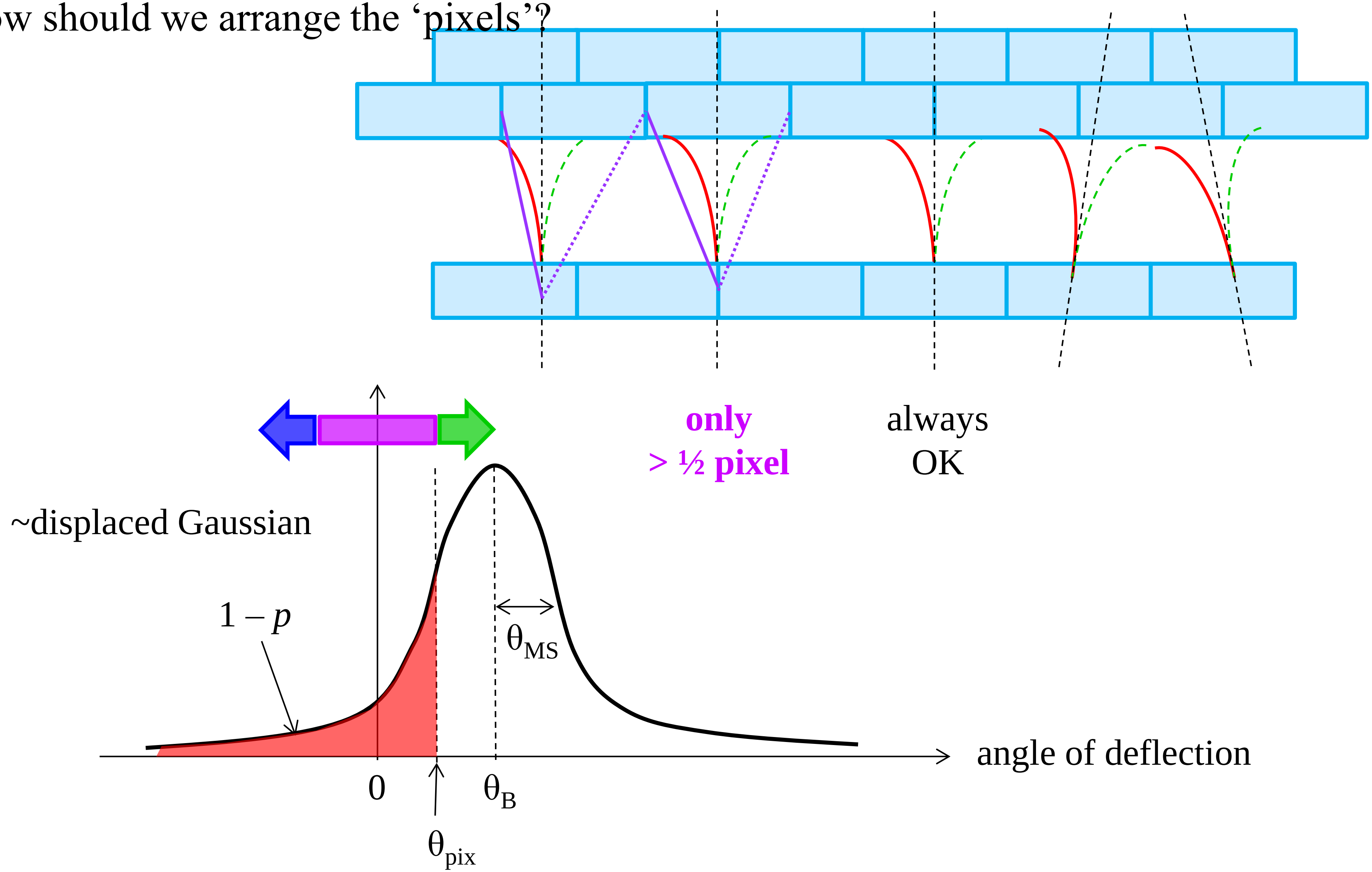
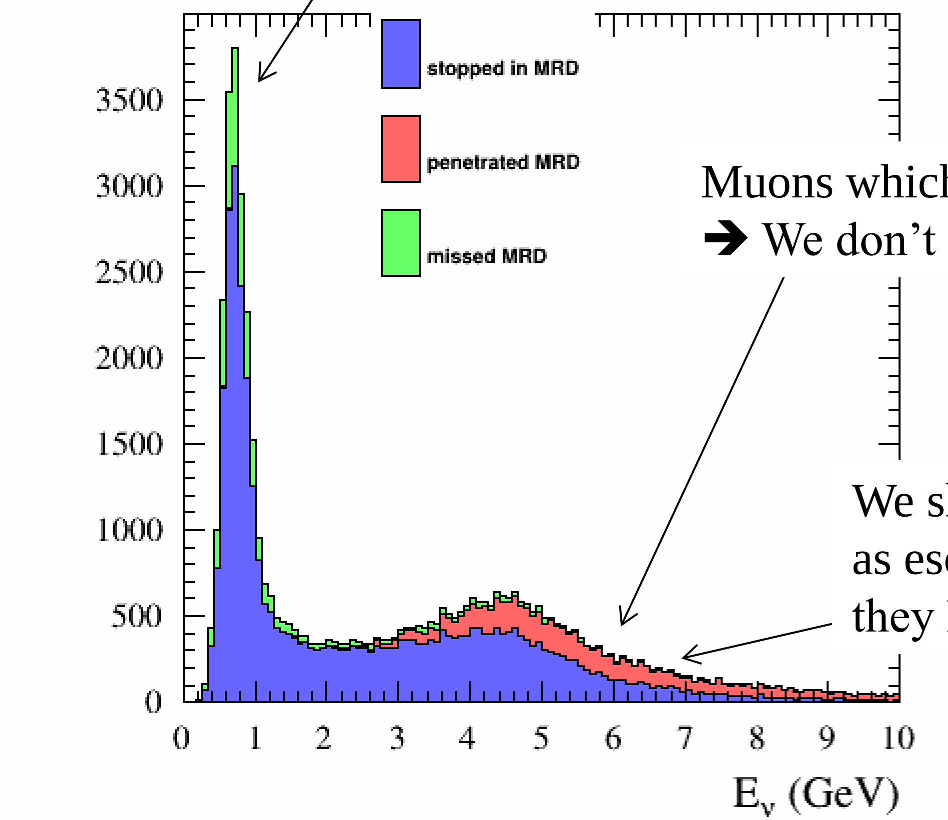
How should we arrange the 'pixels'?



This will reduce the charge reconstruction efficiency slightly

Charge reconstruction efficiency

We should probably consider full side coverage

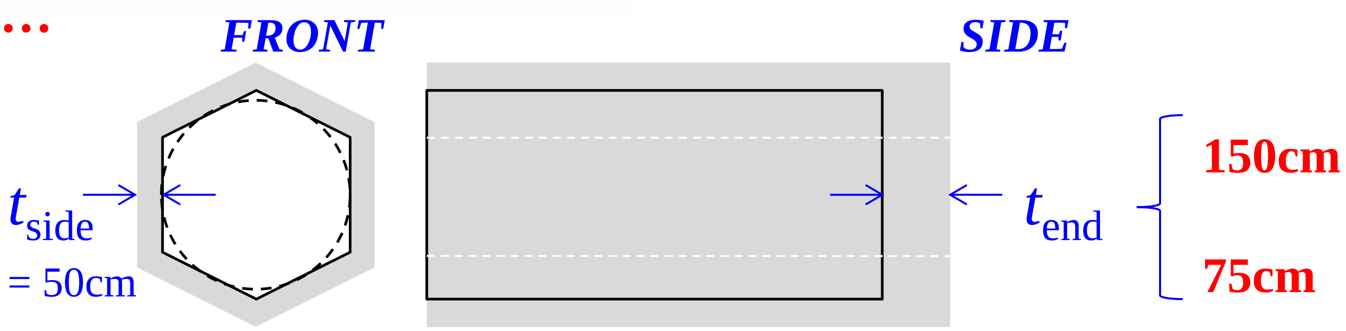


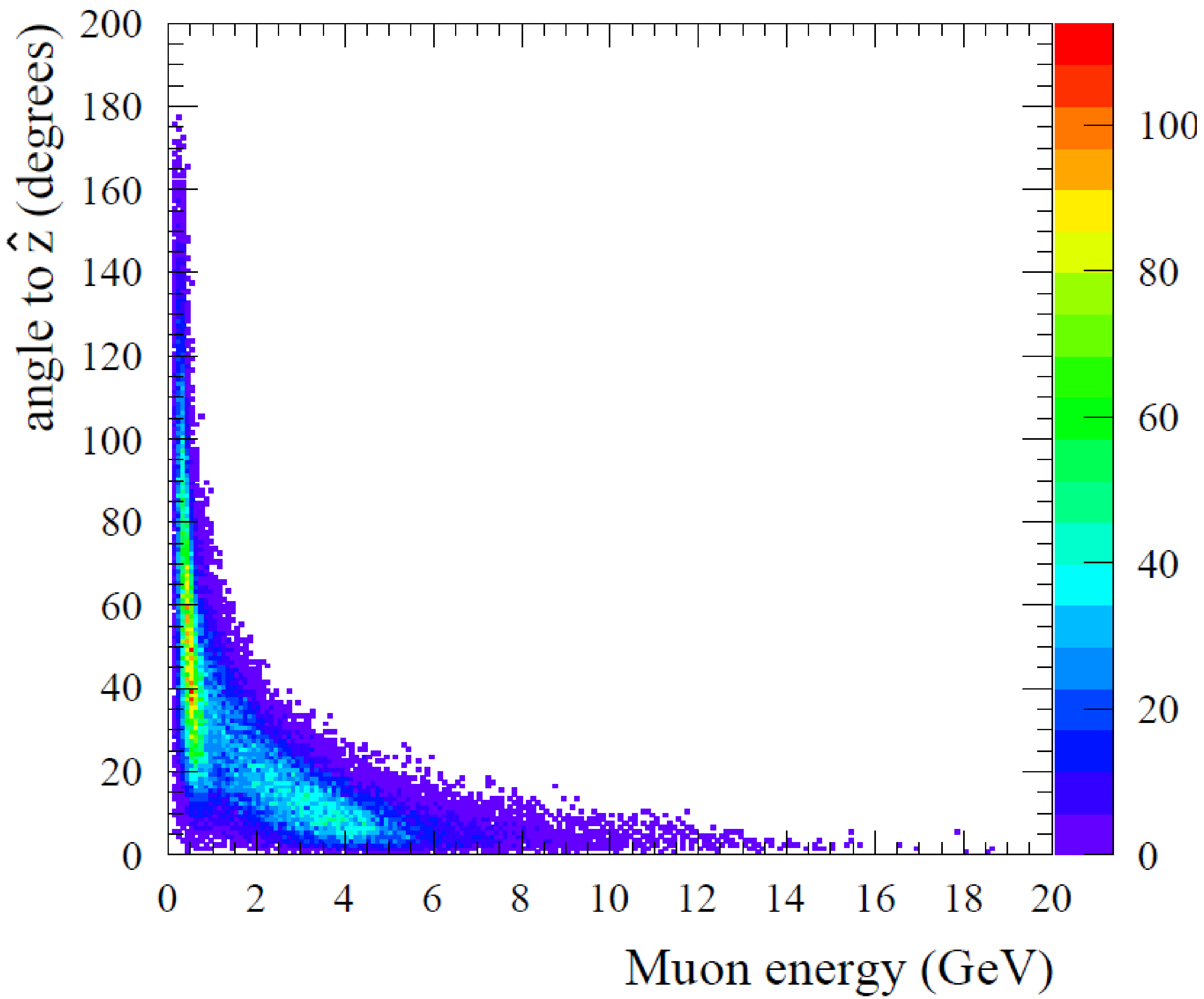
Muons which penetrate are out of the oscillation region
➔ We don't gain by thickening the sides of the MRD

And economy

We should economise with a thinner end MRD as escaping muons are still measurable given they have 'sufficient' curvature before they exit

Let's compare…





angle to ẑ (degrees)
200
180
160
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
16
18
20
Muon energy (GeV)
100
80
60
40
20
0

With a uniform 1.5 Tesla magnetic field, we can reconstruct the charge of a high percentage of muons

Muons from neutrinos in the <u>oscillation energy domain</u> ($E_\nu < 2$ GeV) have low energy and present the biggest challenge

- The ratio curvature / multiple scattering decreases at low energy
- Nevertheless (conservatively?) >50% can be reconstructed

With this approach muons which <u>penetrate</u> through the MRD can be efficiently reconstructed with high efficiency

- (Zero otherwise!)

➔ In fact we can ~halve the thickness of the end MRD, at a saving of ~30%

Now optimize the scintillator placement

- Vary number of planes, thickness etc
- Maximize low-energy charge reconstruction
- $(X_0^{Fe} / X_0^{scint})^{½} = 1.9\%$
- $<Z/A>\rho$ ratio (~energy loss / cm) = 1.4%

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 δk = 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

ϵ = 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

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

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)
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 $\delta k_{\rm ms} \approx 8 s^{\rm rms}_{\rm plane}/L^2$, where $s^{\rm rms}_{\rm plane}$ is defined there.