FCC Muon Measurement ideas

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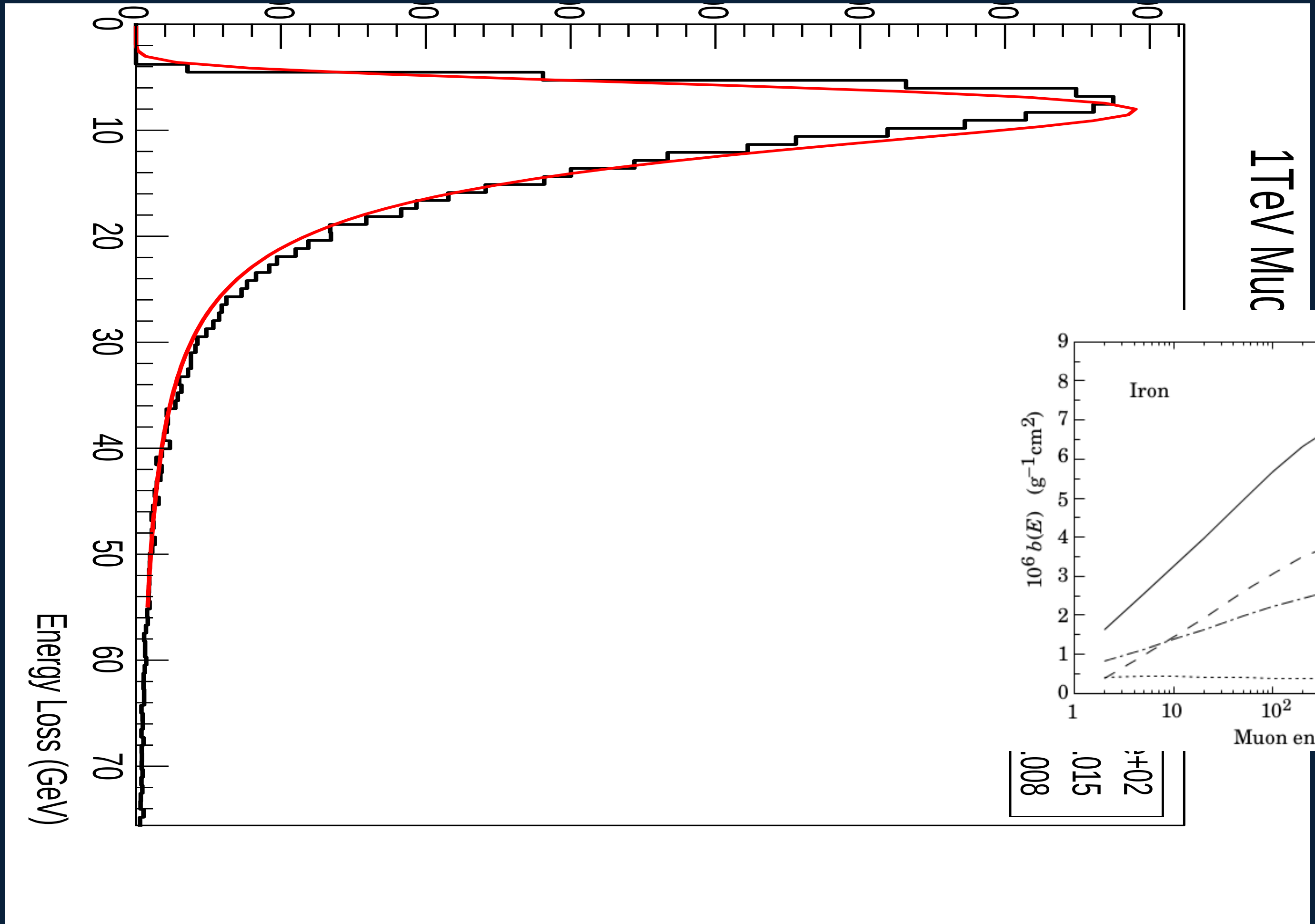
Calorimeter or Tracking based μ detection and measurement

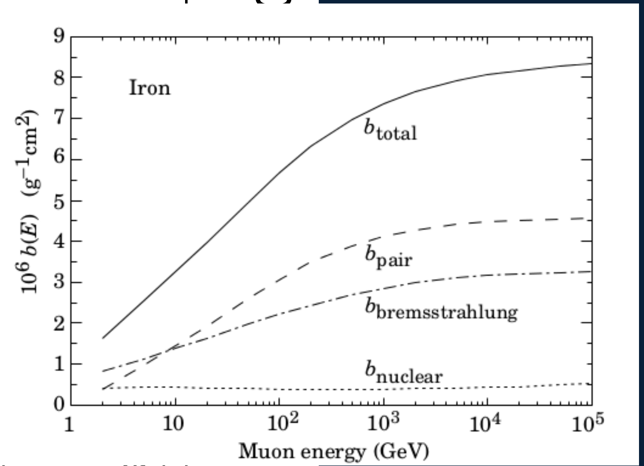
μ momentum measurement based on

- dE/dx in Calorimeter(s)
- Tracking in B-field

1 TeV Muon energy loss in 3m Fe

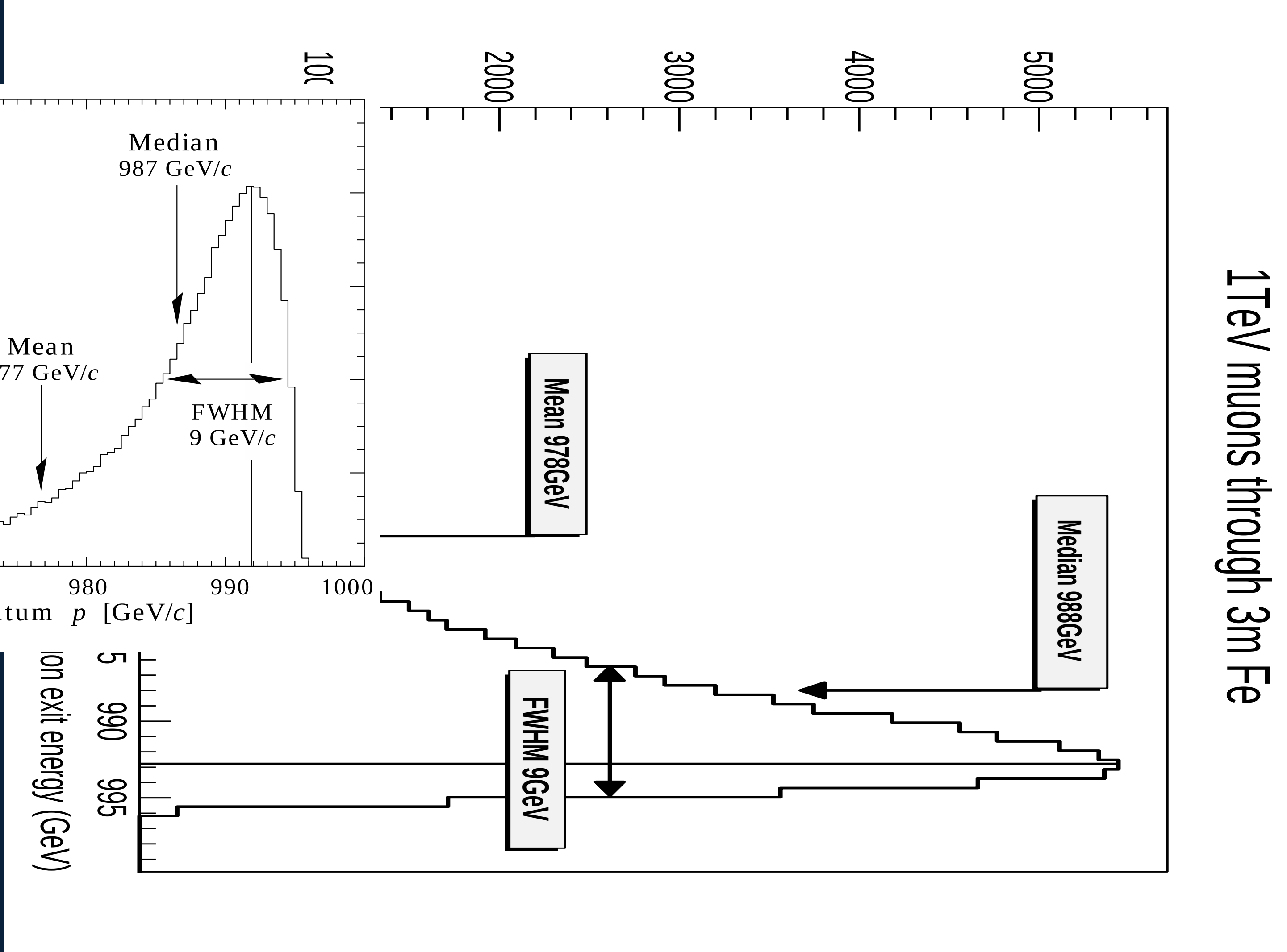


PDG

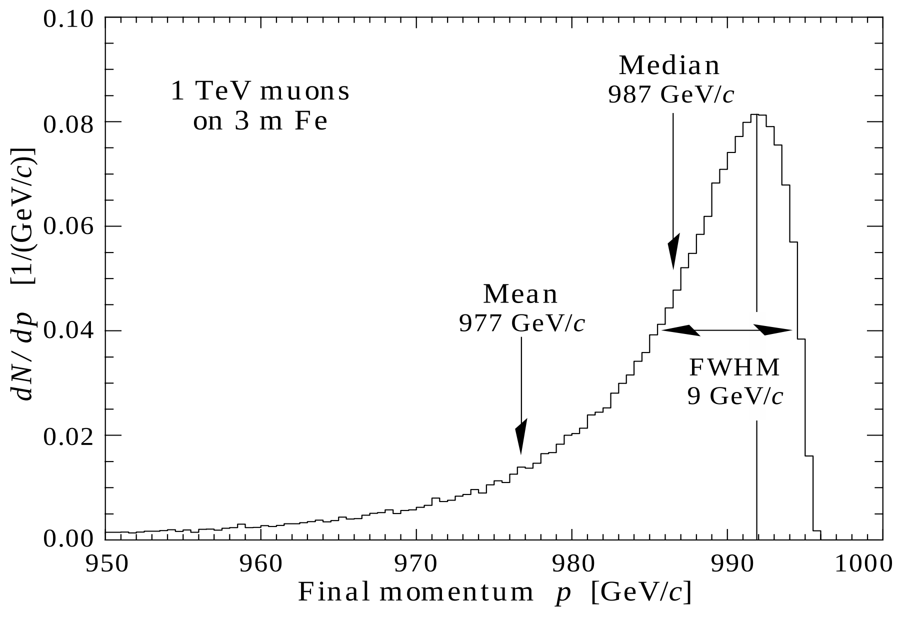


1 TeV muons in 3m Fe

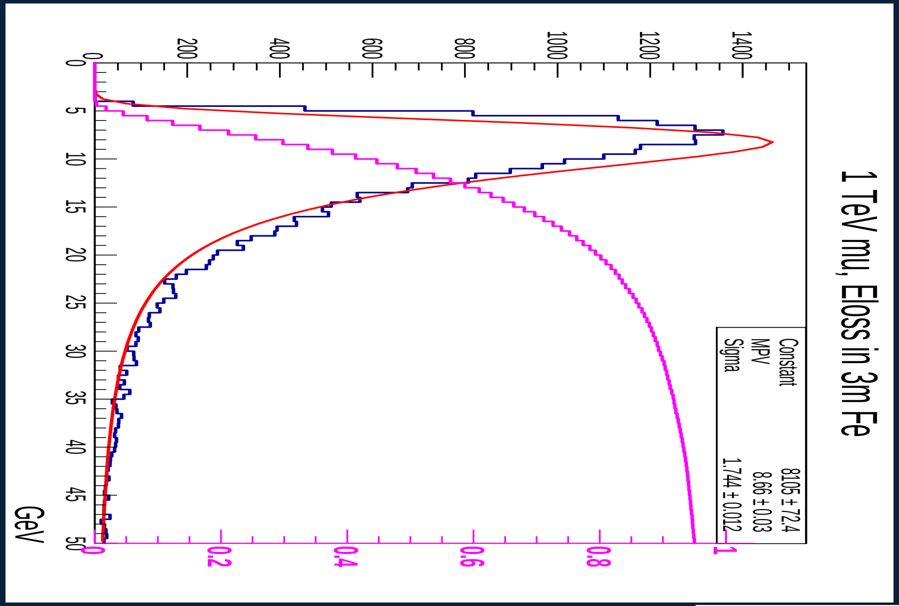
Stand-alone GEANT4

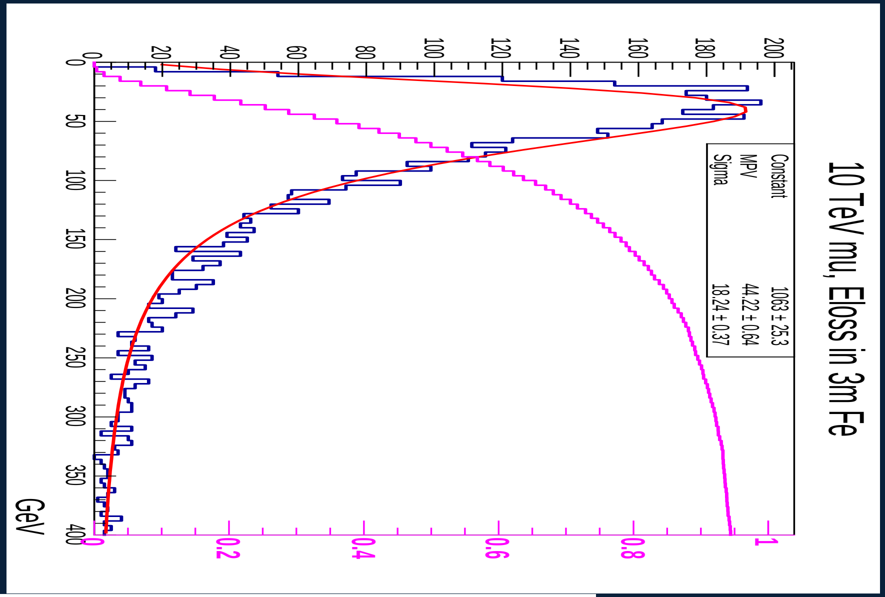


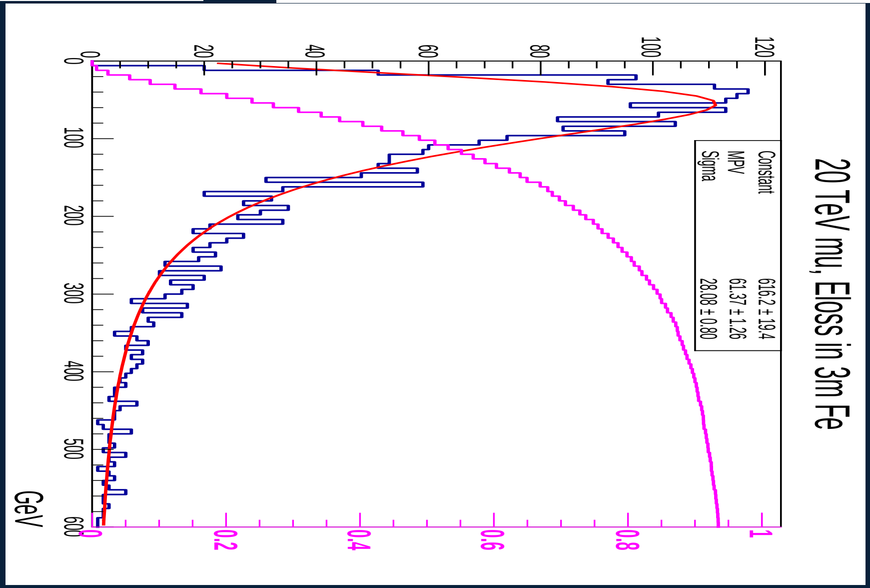
PDG



Muons in 3m Fe, Cumulative distr.



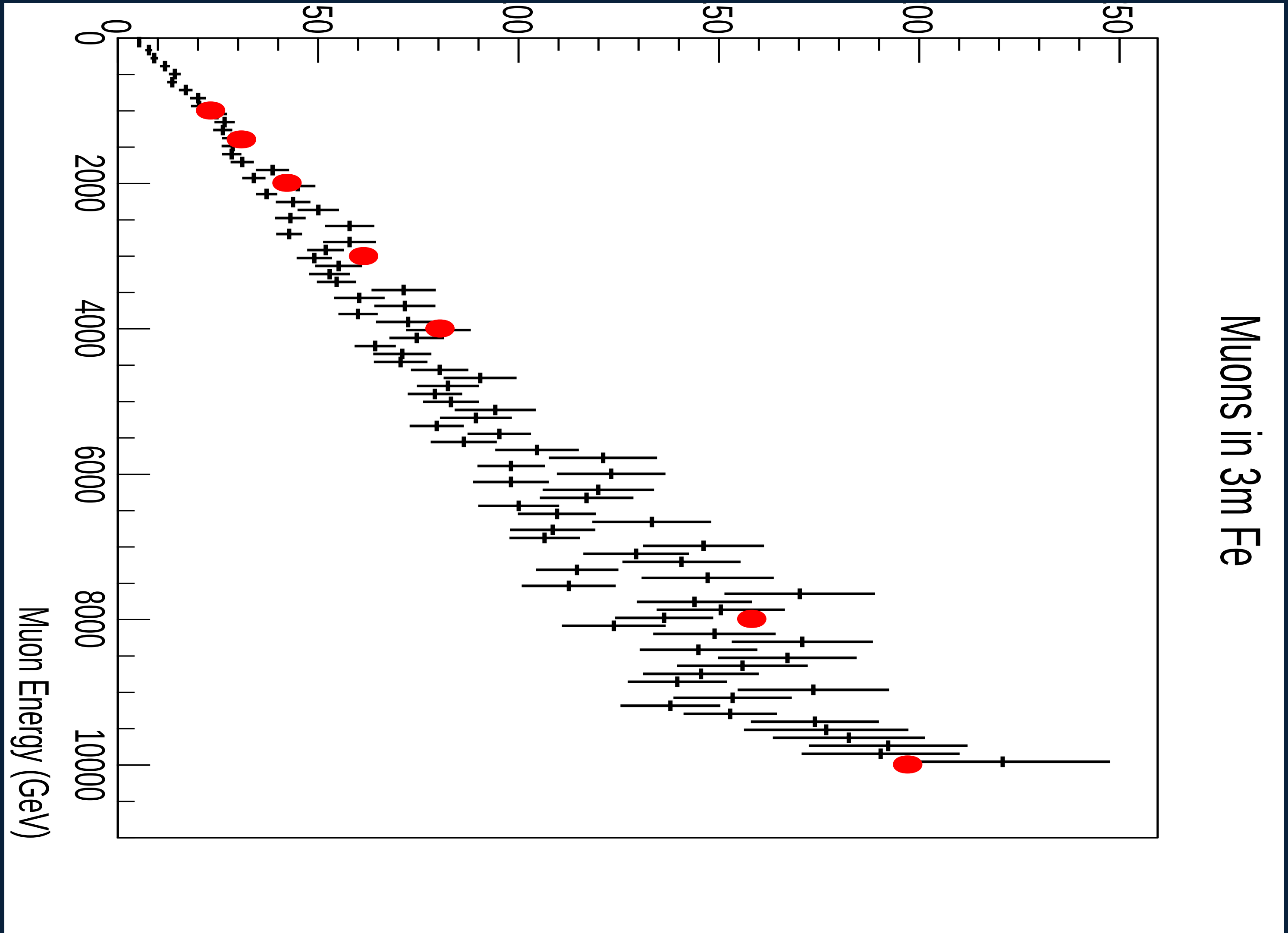




1 – 10 TeV muons in Fe, PDG vs GEANT4 mean dE/dx

Red Points: PDG analytic approximation

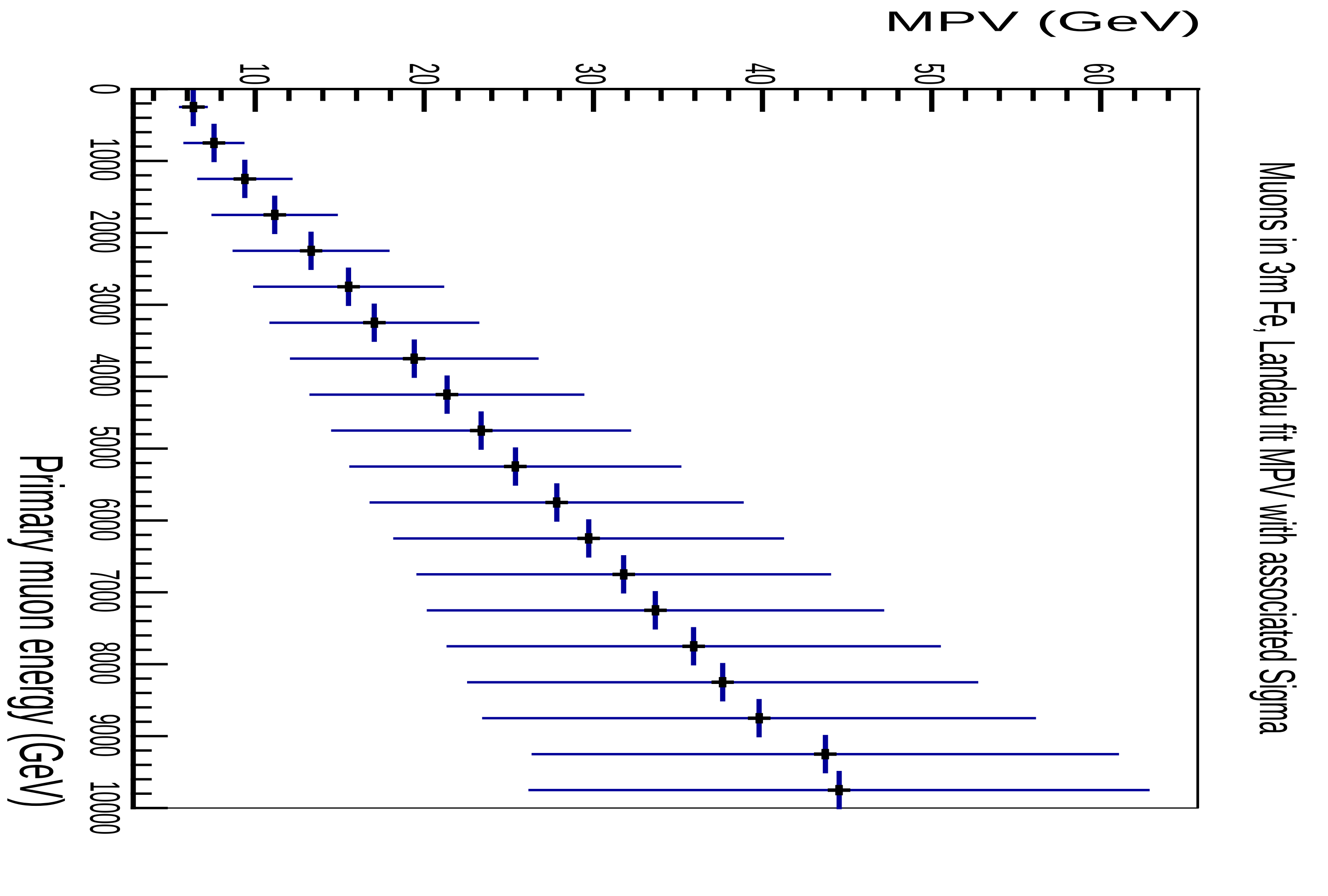
Crosses: Geant4



Various materials, same thickness (18 λ_I) GEANT4 Mean, MPV Eloss, FWHM for 1Tev muons

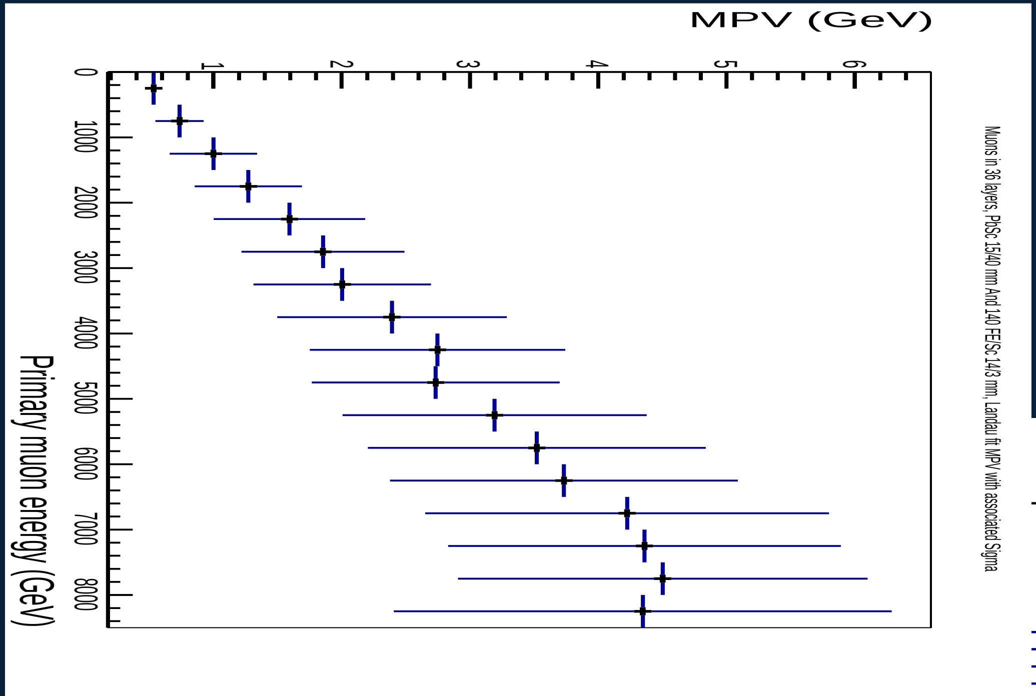
	18 λ_I (m)	PDG Mean (GeV)	Mean (GeV)	MPV_{Landau} (GeV)	σ_{Landau} (GeV)	FWHM (GeV)
Fe	3.0	23	22	8.6	1.9	9.0
W	1.8	61	59	26	6.3	28
Cu	2.8	26	24	9.6	2.3	10
Pb	3.2	68	66	29	7.1	33
U	2.0	75				
Al	7.1	13				

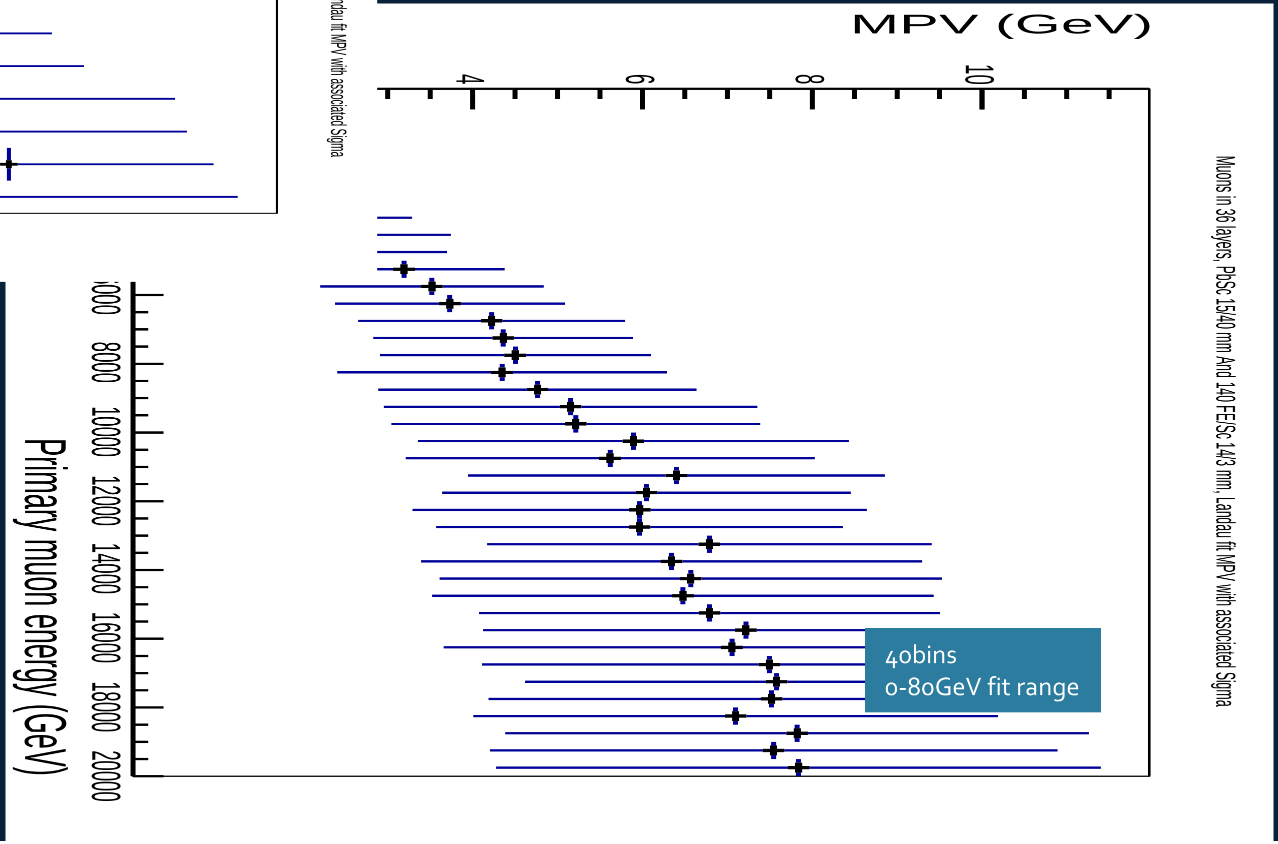
Slice Fit with Landau distributions



20 bins,
0-400GeV fit range

Eloss in μCalo + HCAL scintillator





40bins
0-80GeV fit range

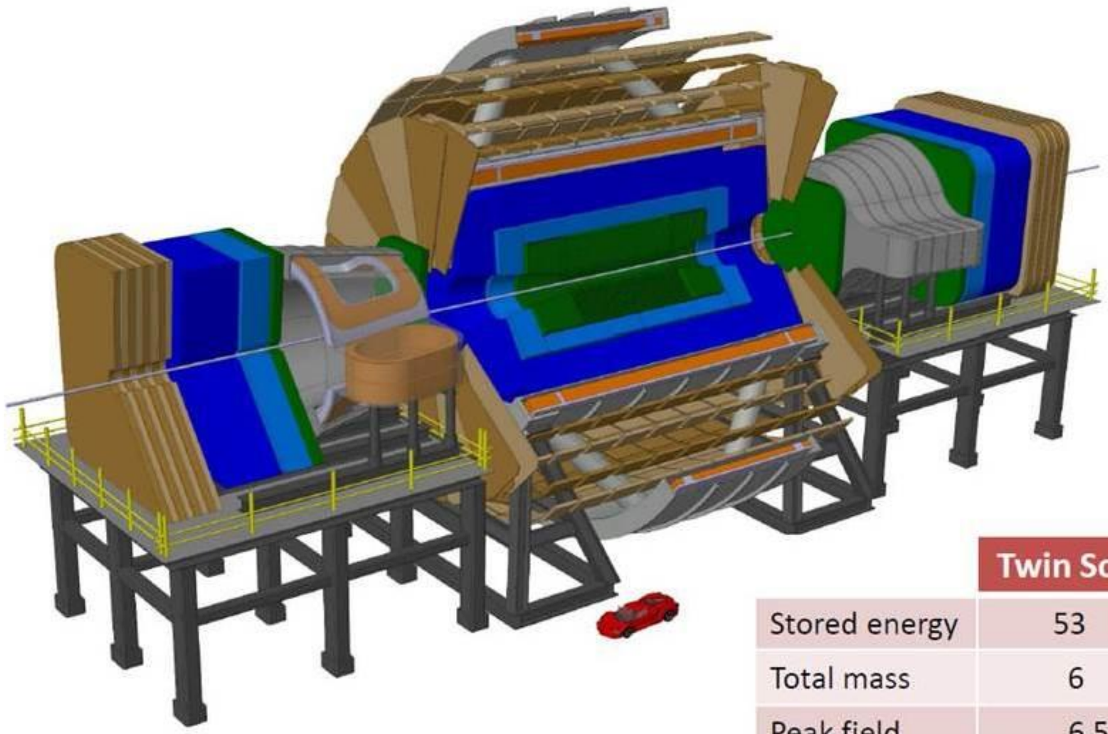
Some remarks

- Geant4, default settings reproduce well PDG numbers (tested up to 10TeV)
- Eloss indeed proportional to incident energy (!)
- ELoss in 3m Fe not exactly Landau for TeV incident particles
- At first approximation GEANT4 or analytic 'PDG' estimations are equivalent
- … measurement resolution ~ O(50%-100%) (for few TeV μ) (Landau tails…..)

(a more detailed study of a calorimenter simulation leads to the same conclusion)

FCC detector magnet baseline geometry

Most Advanced Twin Solenoid & Dipole system

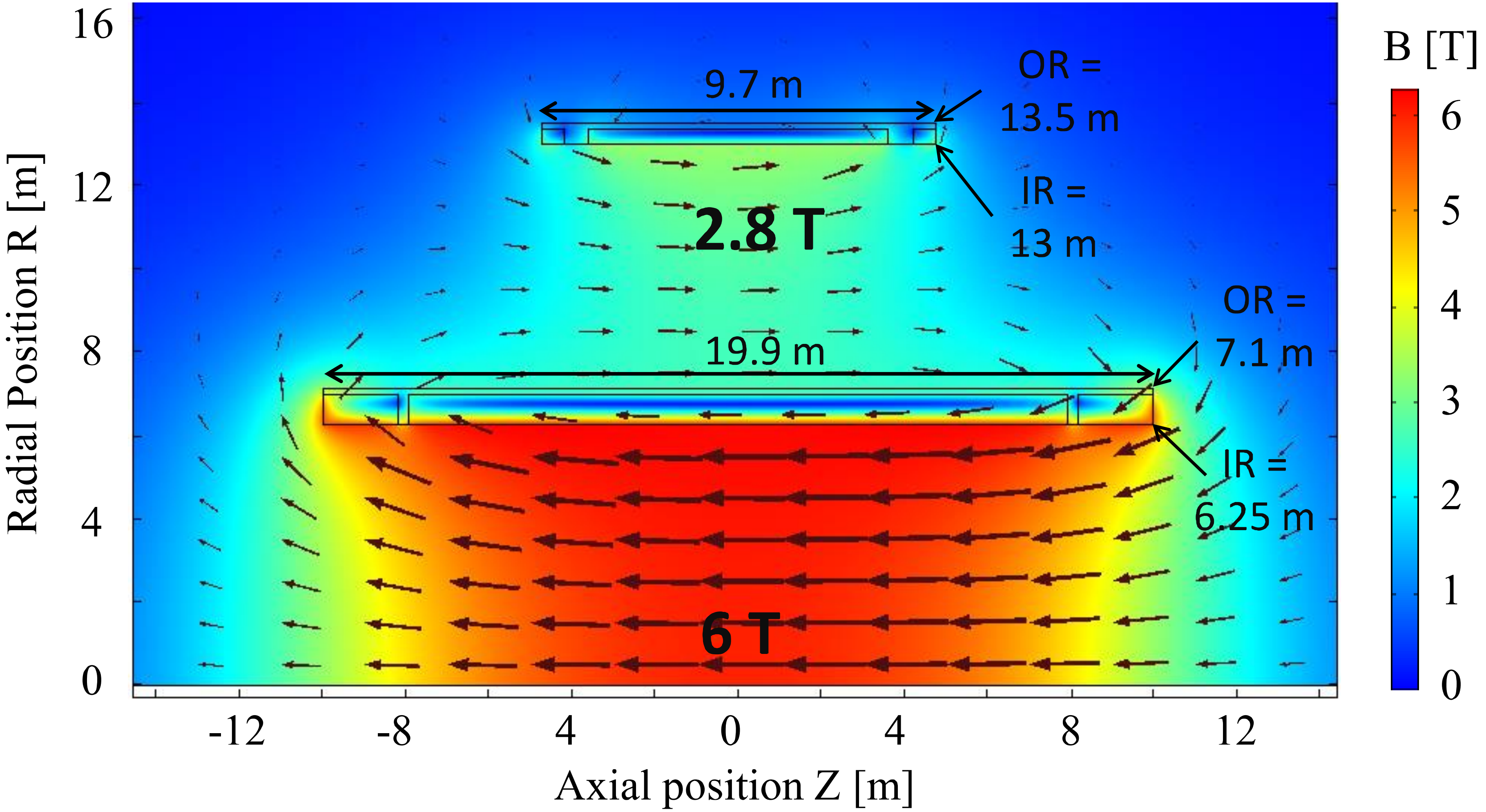


	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

FCC Air core Twin solenoid and Dipoles

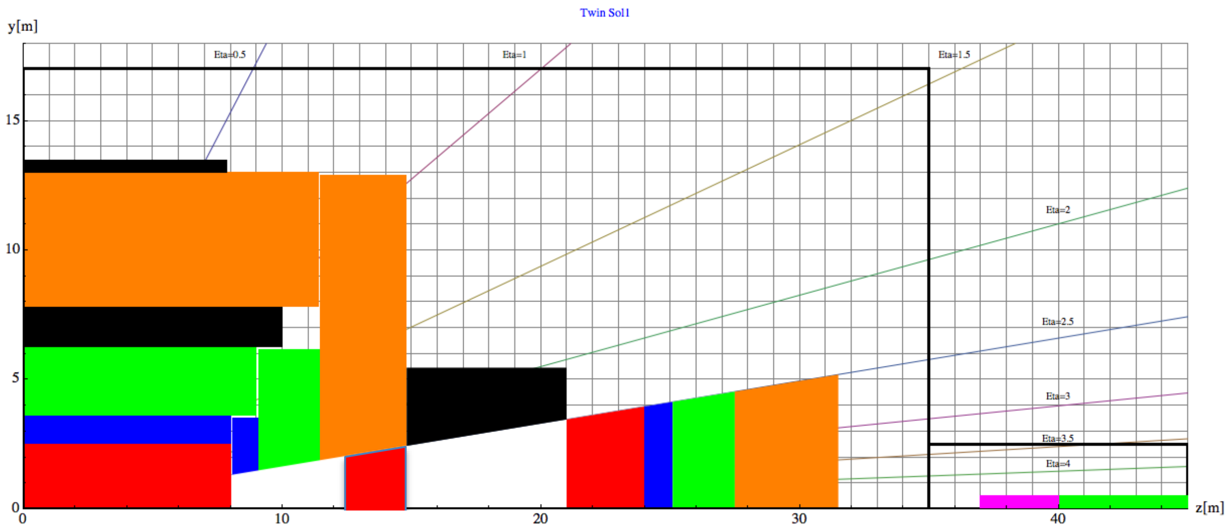
State of the art high stress / low mass design.

B (Dipole) = 6 T
Calo. Rad. length equivalent = 3 m Fe
Return field = 3 T
L in rerturn field = 3 m



B [T]
6
5
4
3
2
1
0
16
12
8
4
0
Radial Position R [m]
-12
-8
4
0
4
8
12
Axial position Z [m]
9.7 m
OR =
13.5 m
IR =
13 m
2.8 T
19.9 m
OR =
7.1 m
IR =
6.25 m
6 T

Baseline Geometry, Twin Solenoid



Barrel:

Tracker available space:
R=2.1cm to R=2.5m, L=8m

EMCAL available space:
R=2.5m to R= 3.6m → dR= 1.1m

HCAL available space:
R= 3.6m to R=6.0m → dR=2.4m

Coil+Cryostat:
R= 6m to R= 7.825 → dR = 1.575m, L=10.1m

Muon available space:
R= 7.825m to R= 13m → dR = 5.175m

Coil2:
R=13m to R=13.47m → dR=0.475m, L=7.6m

Endcap:

EMCAL available space:
z=8m to z= 9.1m → dz= 1.1m

HCAL available space:
z= 9.1m to z=11.5m → dz=2.4m

Muon available space:
z= 11.5m to z= 14.8m → dz = 3.3m

Forward:

Dipole:
z= 14.8m to z= 21m → dz=6.2m

FTracker available space:
z=21m to R=24m, L=3m

FEMCAL available space:
Z=24m to z= 25.1m → dz= 1.1m

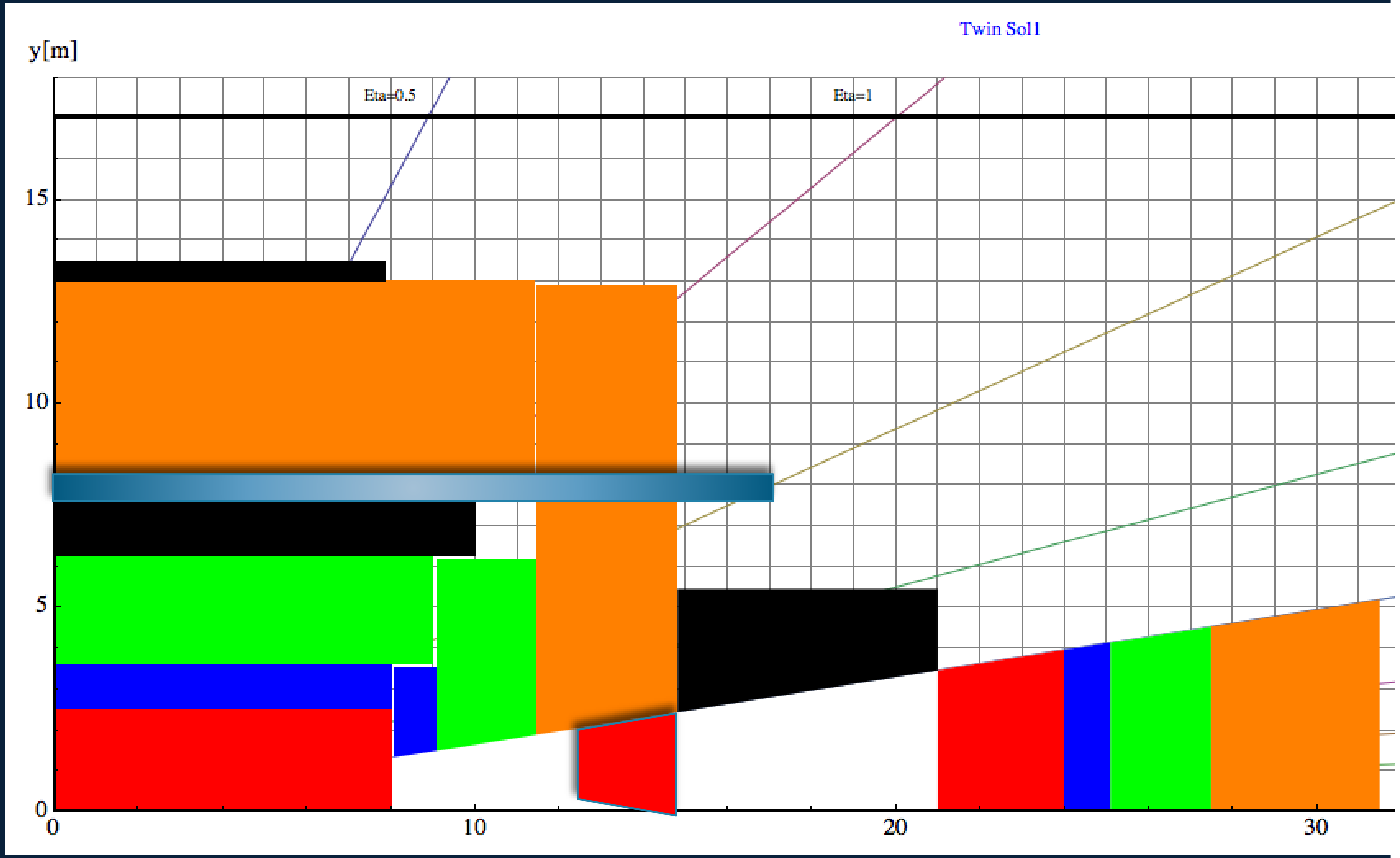
FHCAL available space:
z= 25.1m to z=27.5m → dz=2.4m

FMuon available space:
z= 27.5m to z=31.5m → dz=4m

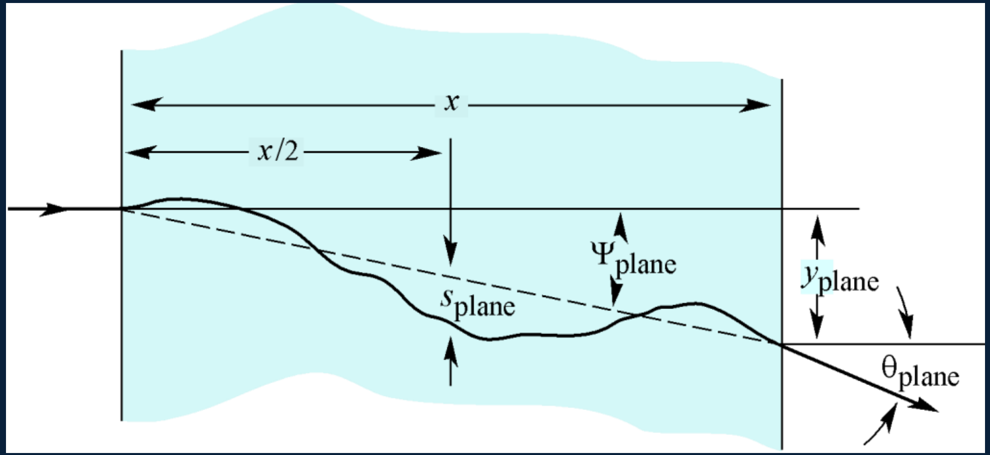
Various tracking based μ momentum measurement strategies

- φ-momentum
- μ-Tracker

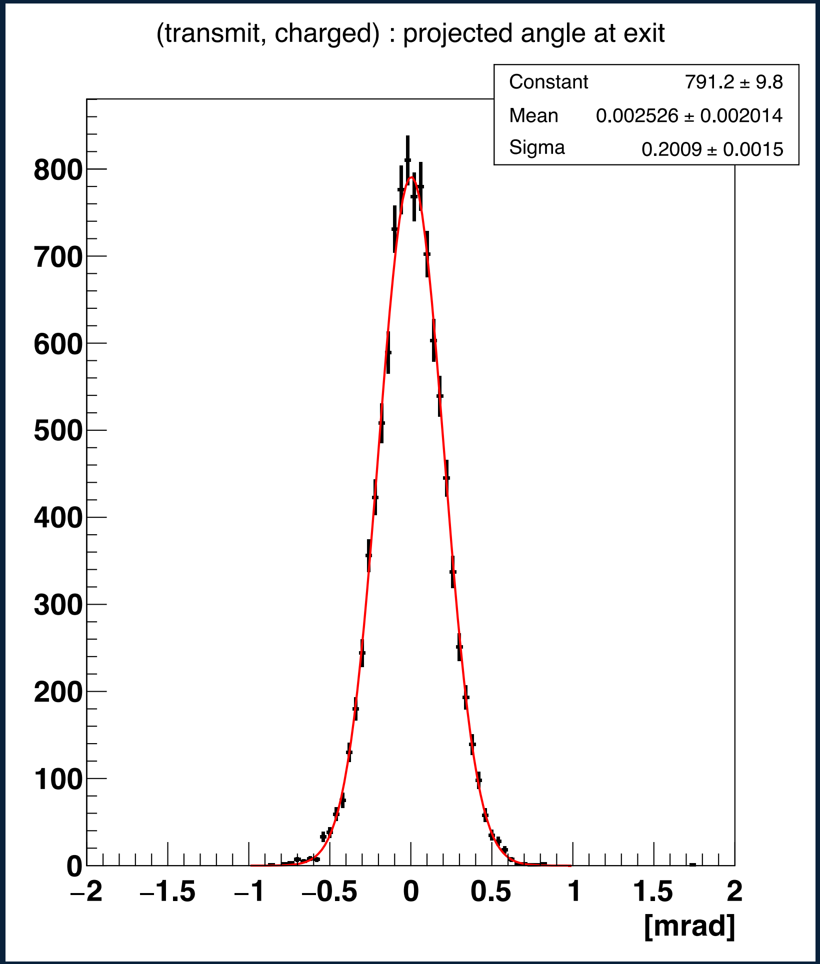
ϕ-momentum



μ multiple scattering



θ_{plane} distribution,
1 TeV μ
3 m thick Fe block



MS Analytic model vs GEANT4

$$\mathrm{RMS}(\theta_{plane}) = \frac{0.0136\ GeV}{\beta c p} z\sqrt{x/X_0}[1+0.038\ln(x/X_0)]$$

$x = 4$ m, X_0(Fe) = 1.76cm, $z = 1$, $\beta c = 1$

Muon momentum (TeV)	GEANT4 MSc θ RMS (mrad)	Analytic RMS (mrad)	Δ (%)
1	0.234	0.246	5
2	0.114	0.123	7
5	0.046	0.049	6
10	0.023	0.025	8
20	0.011	0.012	8

μ exit angle after FCC calorimeters/solenoid

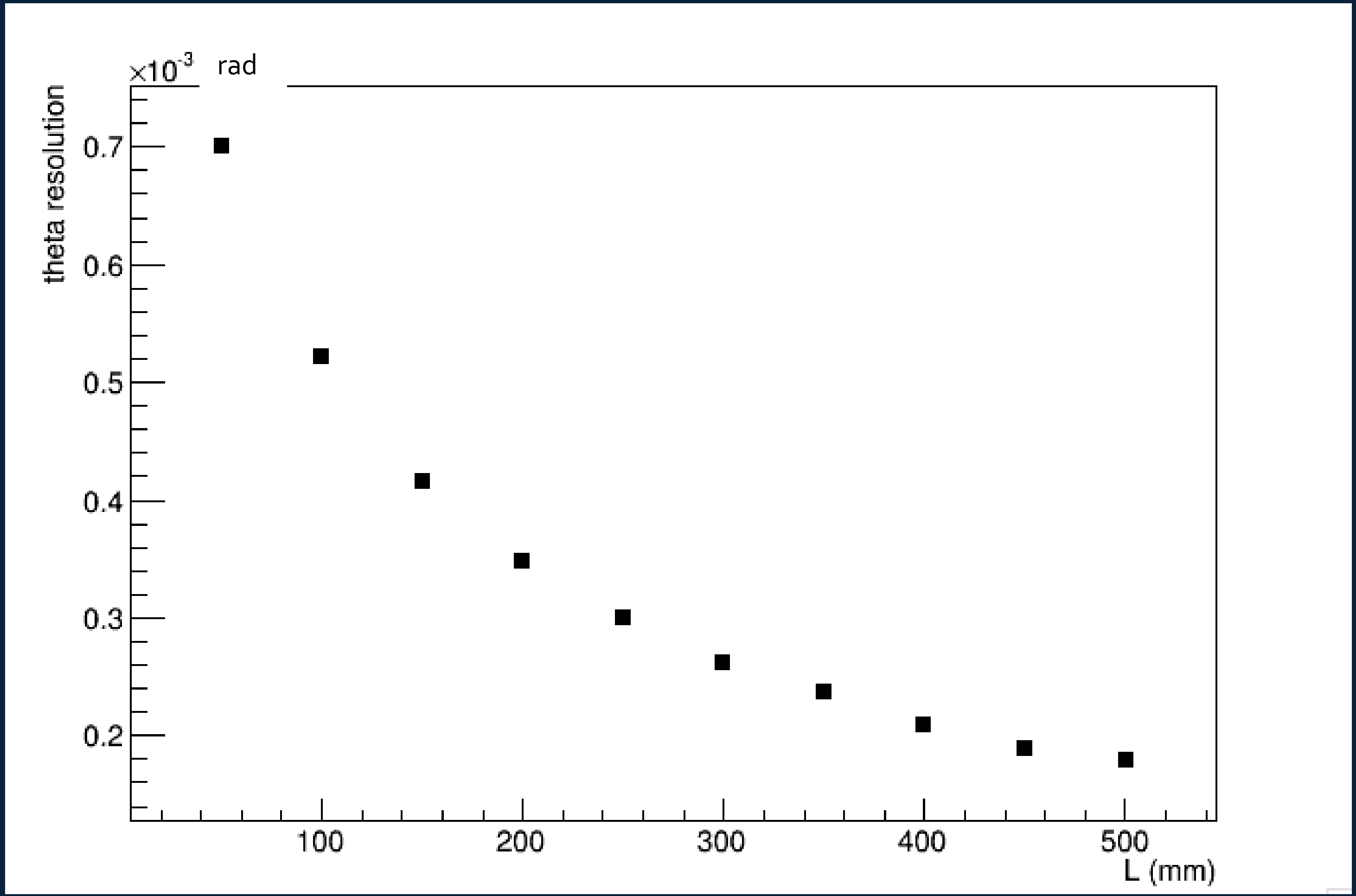
$$\phi = \frac{0.3\ \mathrm{B\ (T)}\ L\ (m)}{p_T\ (GeV)}$$, B = 6 T, L = 6 m

Muon momentum (TeV)	ϕ (mrad)	GEANT4 MS θ RMS (mrad)	RMS(θ)/ϕ (%)
1	10	0.234	2.3
2	5	0.114	2.3
5	2	0.046	2.3
10	1	0.023	2.3
20	0.5	0.011	2.3

Resolution due to MS: 2.3% (independent of p)

For simplification $p_T = p$

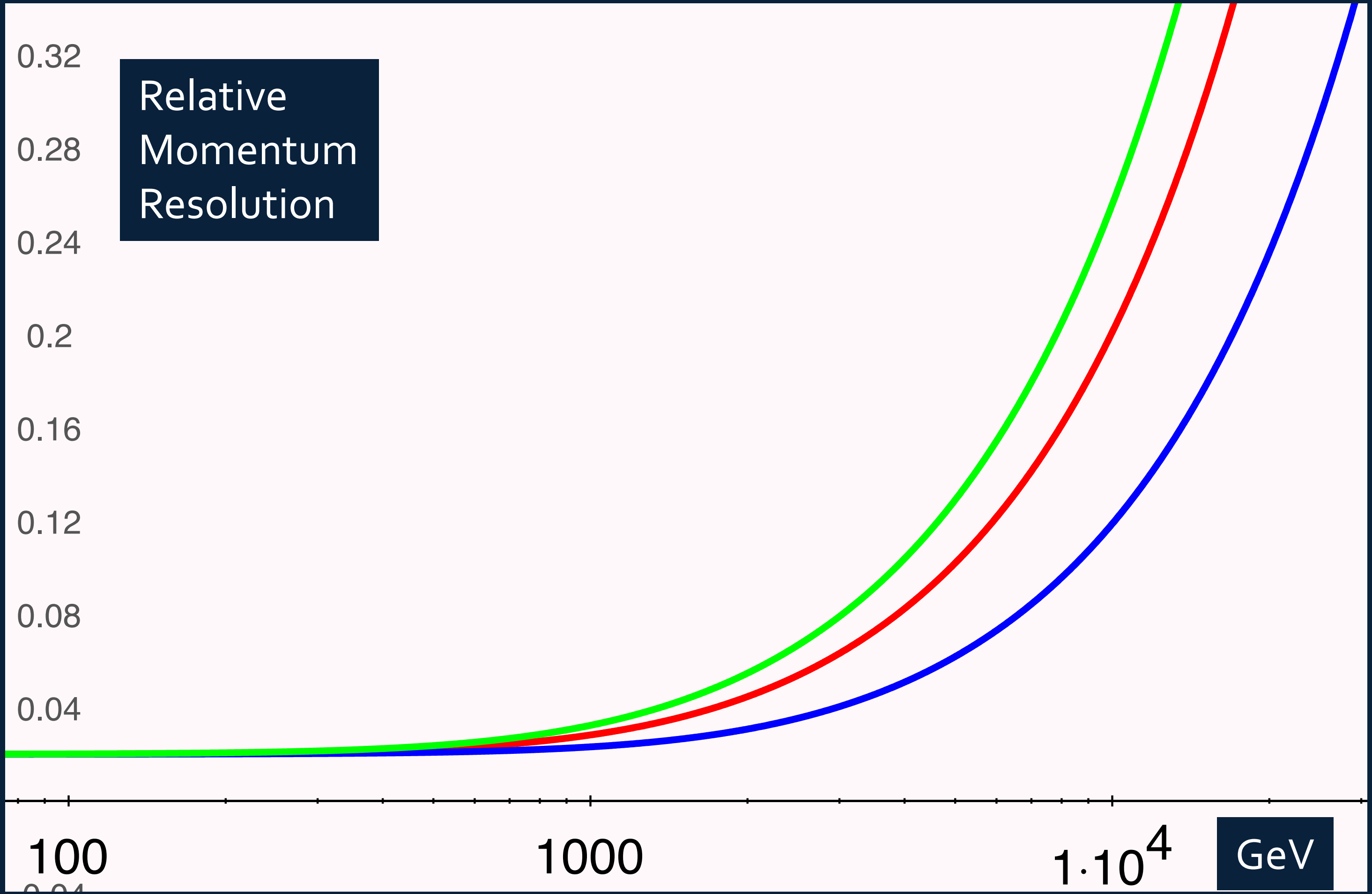
Angle resolution and lever-arm



Example:
2 multilayers,4 planes each
Micromegas detector
100μm point resolution
L = distance between multilayers

0.2 mrad angular resolution seems achievable

μ momentum resolution, measuring track deviation after FCC CALO



Green :
3T field
5m L
10 points
80μm point res.

M momentum Stand-alone Measurement outside FCC Calo

Red:
6T field
6m Radius
ϕ resolution = 0.2 mrad

Angle measurement at FCC Calo exit

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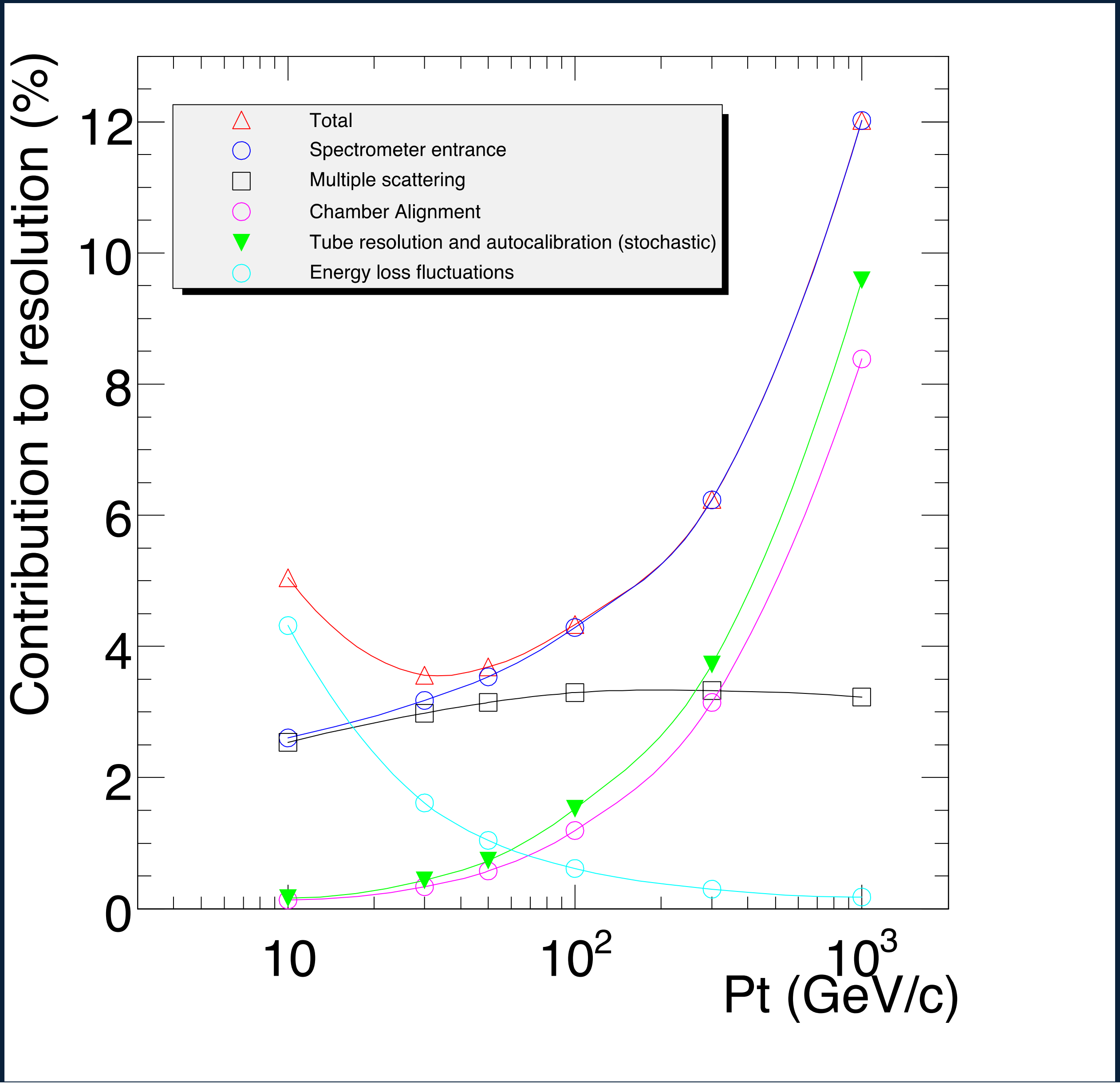
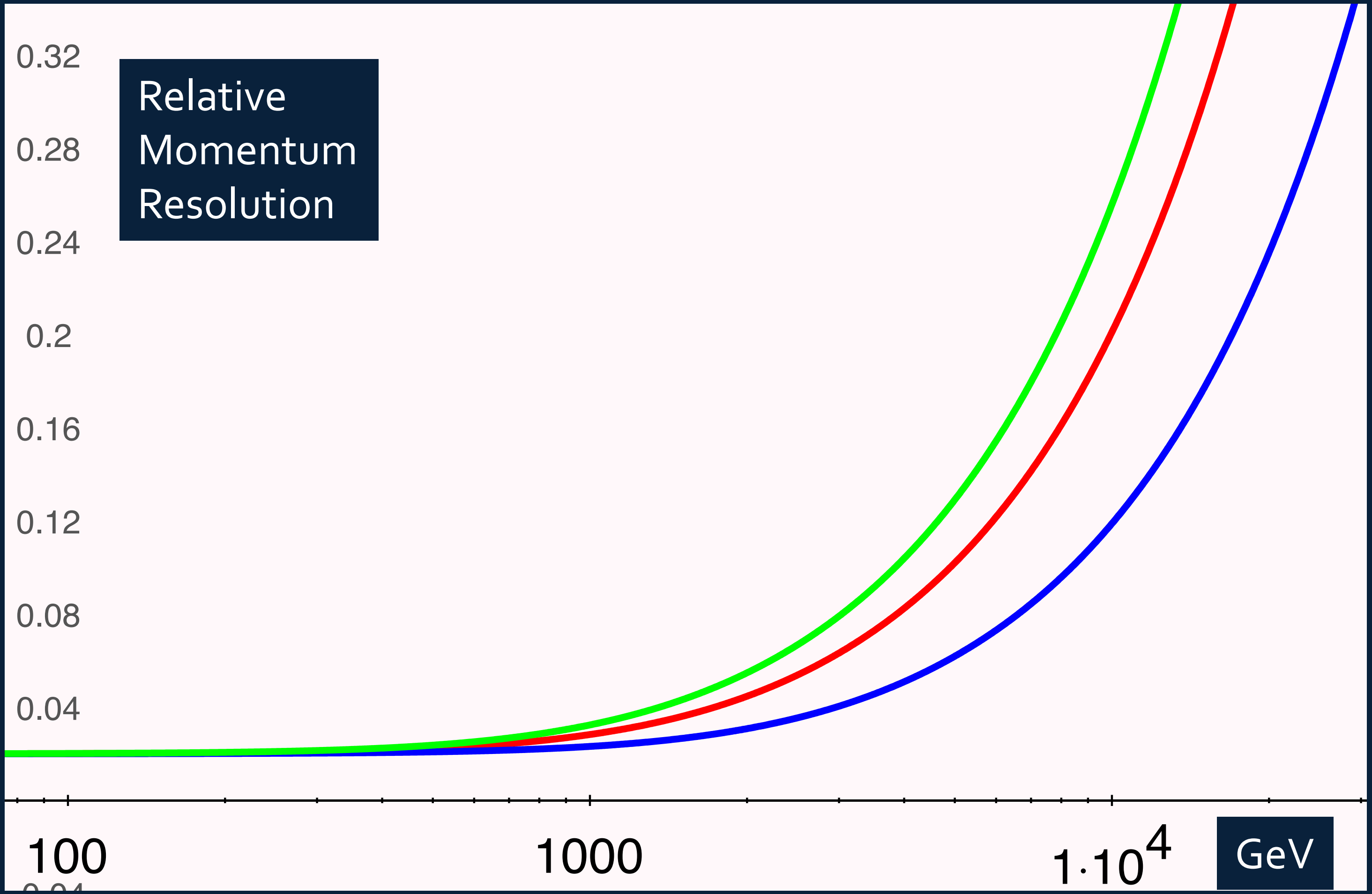
Atlas μ momentum resolution for comparison



μ-Tracker

Muon momentum (TeV)	ϕ (mrad)	GEANT4 MS θ RMS (mrad)	RMS(θ)/ϕ (%)	Sagitta inside Dipole (cm)
1	10	0.234	2.3	8.10
2	5	0.114	2.3	4.05
5	2	0.046	2.3	1.62
10	1	0.023	2.3	0.81
20	0.5	0.011	2.3	0.41

Muon tracking resolution



Green :
3T field
3m L
10 points
80μm point res.

Red:
6T field
6m Radius
Angle measurement at exit

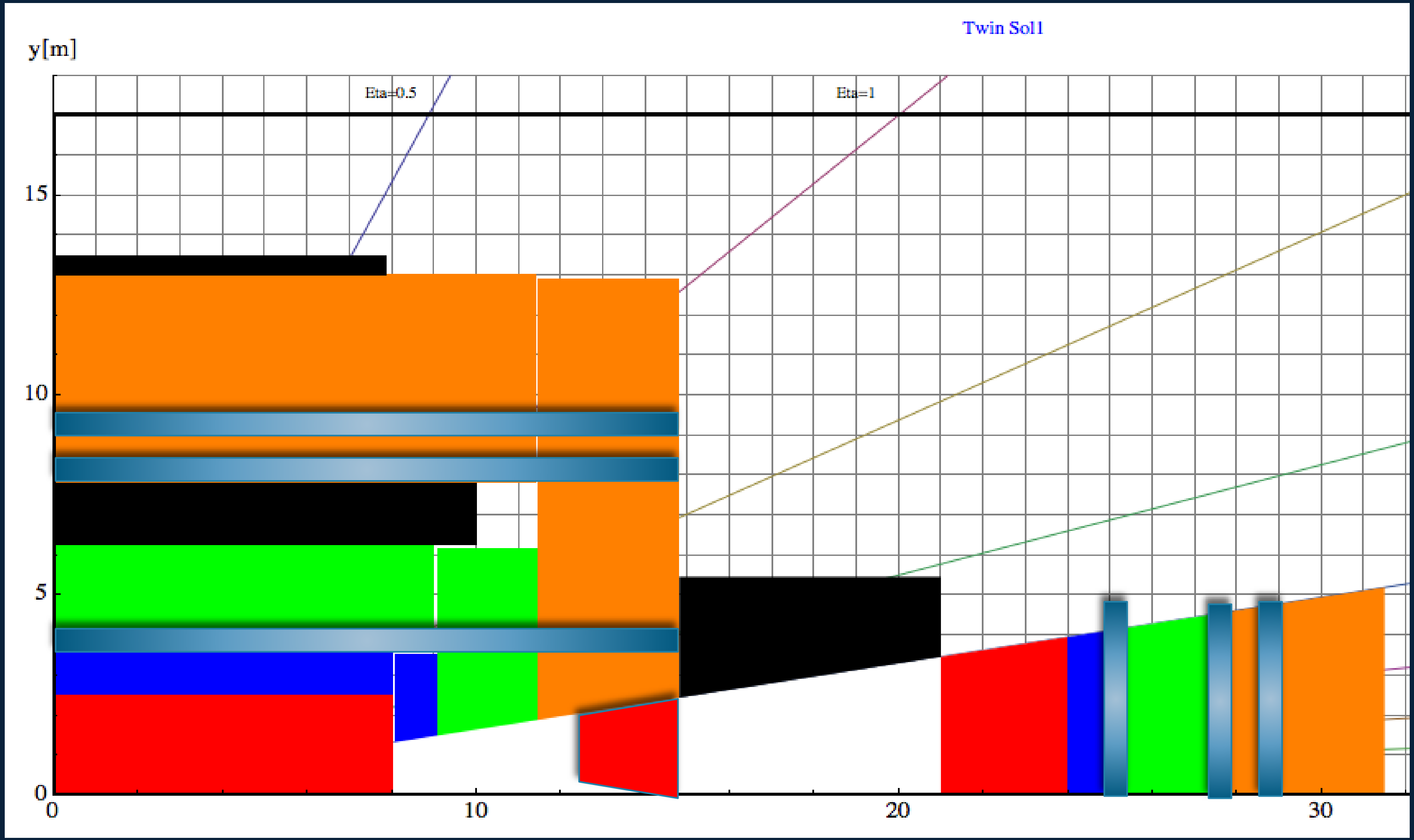
Blue:
6T filed
6m Radius
4 poins
80μm point res.

A modification to the FCC baseline detector

A singe (multi-)layer of spatial precision detector (~10 cm thickness)

Two multilayers in 'muon' area needed for angle measurement only (distance between them ~ 50cm)

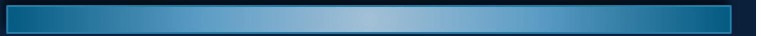
For muon reconstruction using the solenoid bending power 2 multi-layers may be enough

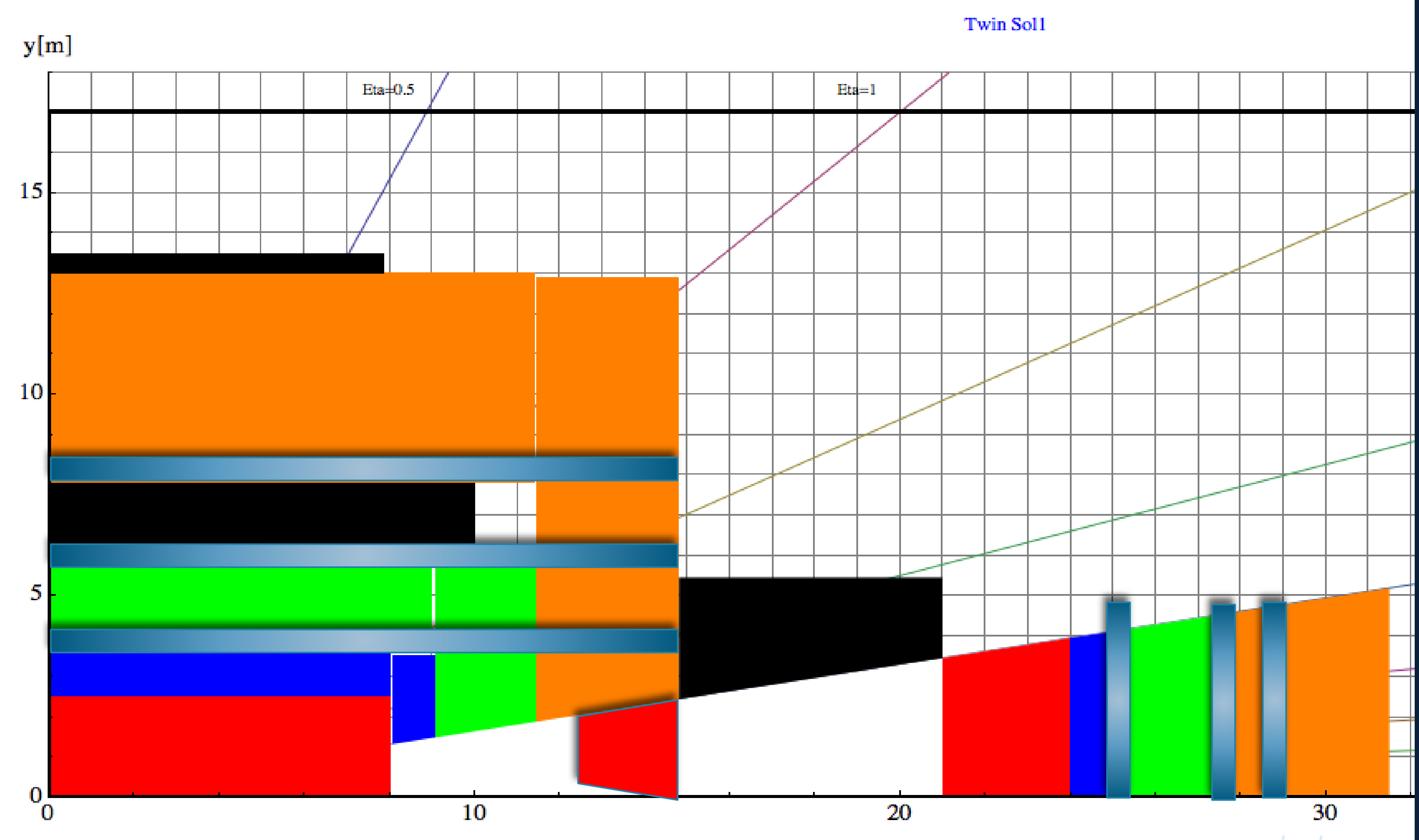


'Exotic' FCC baseline detector

For TeV muons, MS is 'negligible', can also measure through coil

A singe (multi-)layer of
spatial precision detector
(~10 cm thickness)





Two multilayers in 'muon' area
needed for angle measurement only
(distance between them ~ 50cm)

For muon reconstruction
using the solenoid bending power
2 multi-layers may be enough

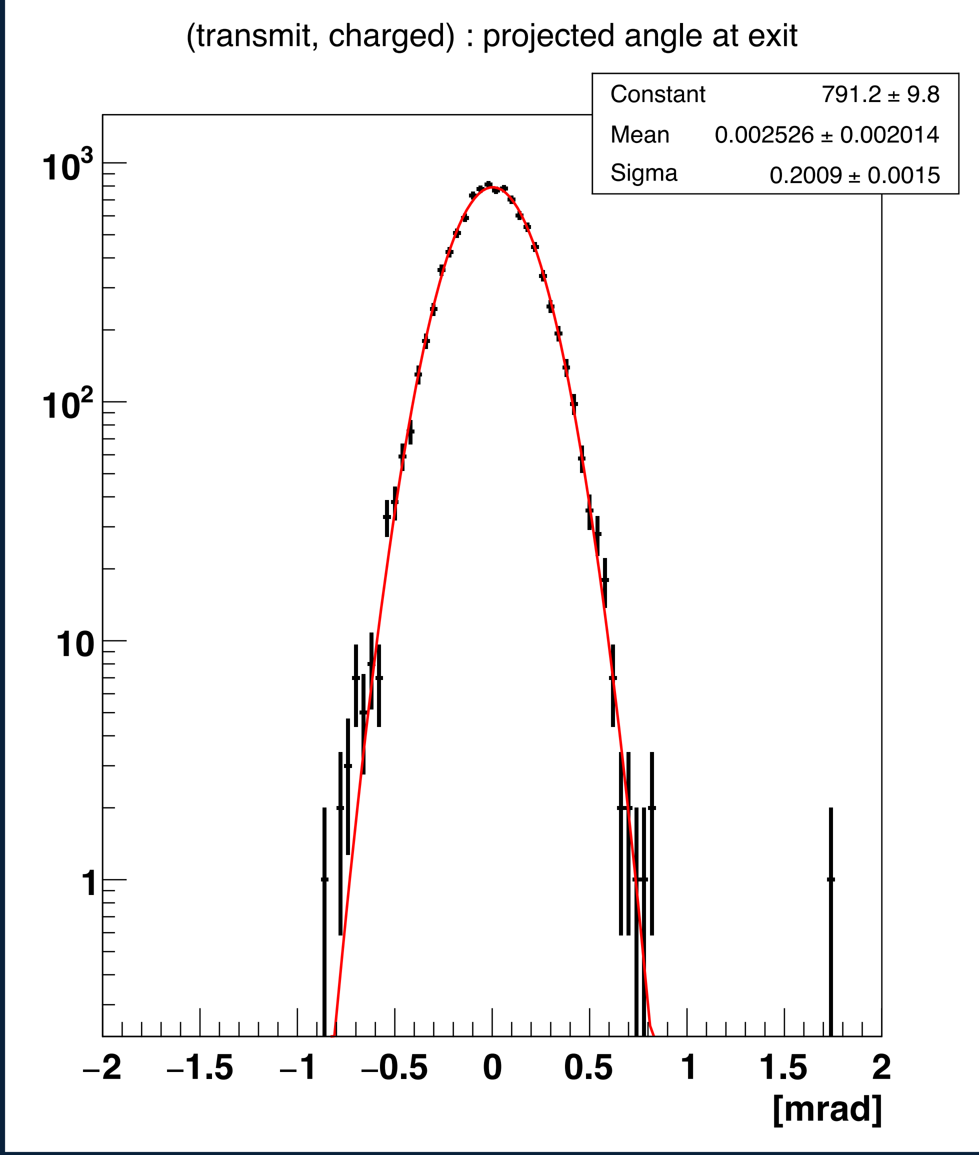
Muon Tracking Summary

- GEANT4 seems fine (again) for TeV muons (no surpise !)
- Angle based μ momentum measurement is better than stand-alone muon reconstruction – Will there be any issue with punch-through particles from CALOs?
- Even better : Reconstruct muons with precision planes (1-2) within CALOs. Is it feasible, can a sensible measurement be done in a CALO environment? What detectors can work in 6T field?…

This may also liberate the magnet design from B-field and space requirements in the 'muon' zone.Size ans (R-)position of return yoke become free parameters…

Additional slides

μ multiple scattering and gaussin fit in LogY



Slight data excess at tails as expected

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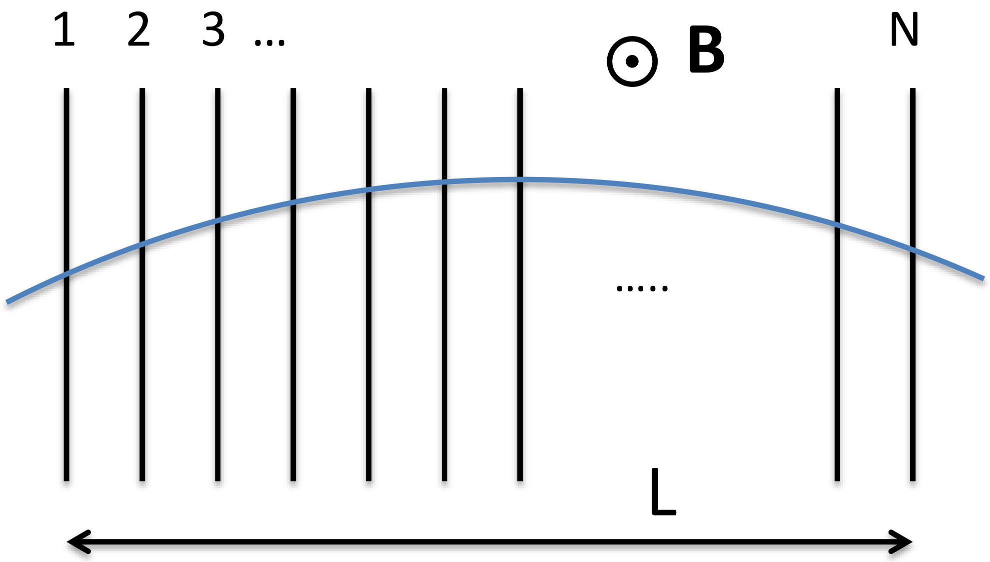
Momentum resolution with N points in B field

- $\sigma_p/p = \frac{\sqrt{720/(N_{points}+4)}}{0.3\ B\ (T) L^2 (m)} p\sigma_x$

- Sagitta = $\frac{0.3\ B\ L^2}{8p_T}$

Point Resolution and Multiple Scattering



σ … point resolution/plane

X_{tot}/X_0 … total material budget

N equidistant layers

Position Resolution

$$\frac{\Delta p_t}{p_t} = \frac{\sigma[m]\, p[\mathrm{GeV/c}]}{0.3\, B[T]\, L^2[m^2]} \sqrt{\frac{720\,(N-1)^3}{(N-2)\,N\,(N+1)\,(N+2)}}$$

$$\approx \frac{\sigma[m]\, p[\mathrm{GeV/c}]}{0.3\, B[T]\, L^2[m^2]} \sqrt{\frac{720}{N+4}}$$

Multiple Scattering, Equal weighting

$$\frac{\Delta p_t}{p_t} = \frac{0.0136}{0.3\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}} \sqrt{\frac{10}{7}\,\frac{12+(N-1)N^2(N+1)}{(N-2)N(N+1)(N+2)}}$$

$$\approx \frac{0.0136}{0.3\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}} \sqrt{\frac{10}{7}}$$

$$\approx \frac{0.0542}{\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}}$$

≈1.2. Taking into account the correlation (Kalman filter etc.) this number can be reduced to 1.0

Energy Deposit = f(Incident Energy)

- Muon critical energy for Fe = 350GeV
- $-dE/dx = a(E) + b(E)E$