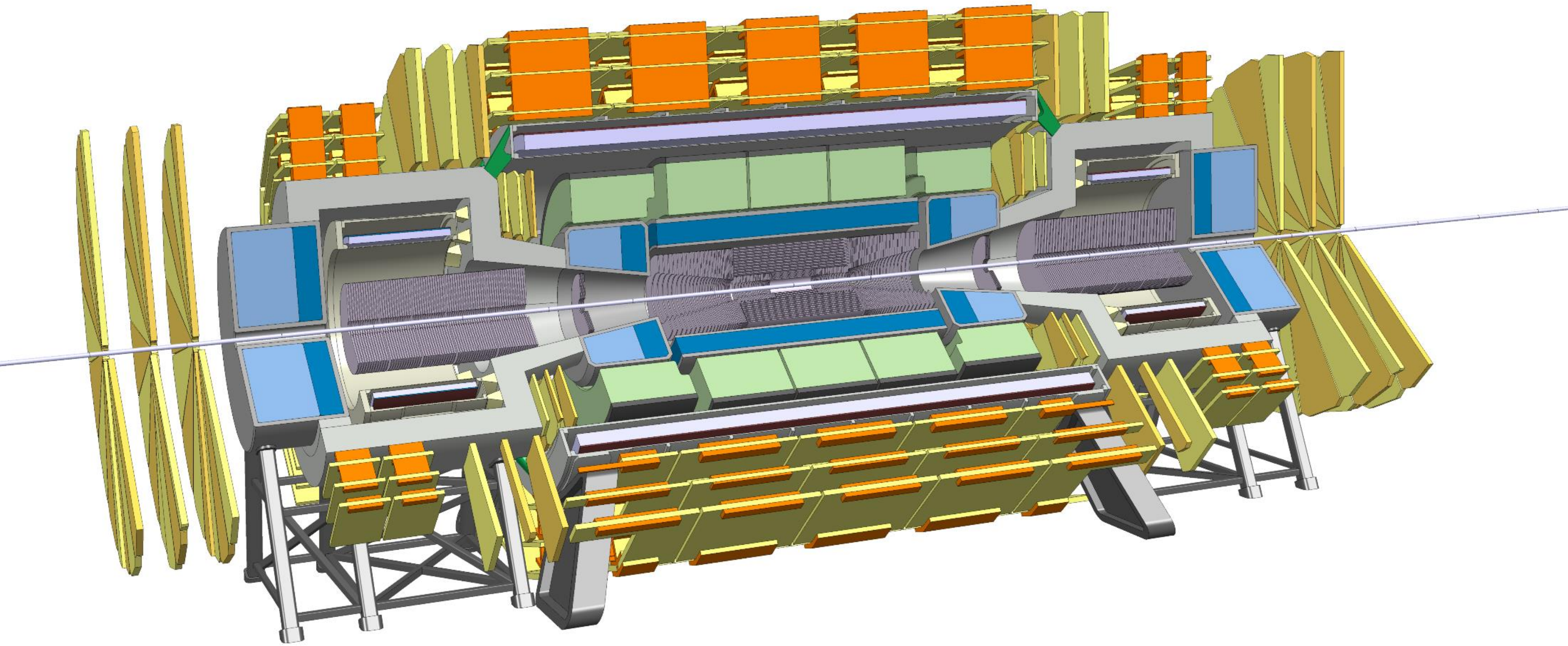
Muon System

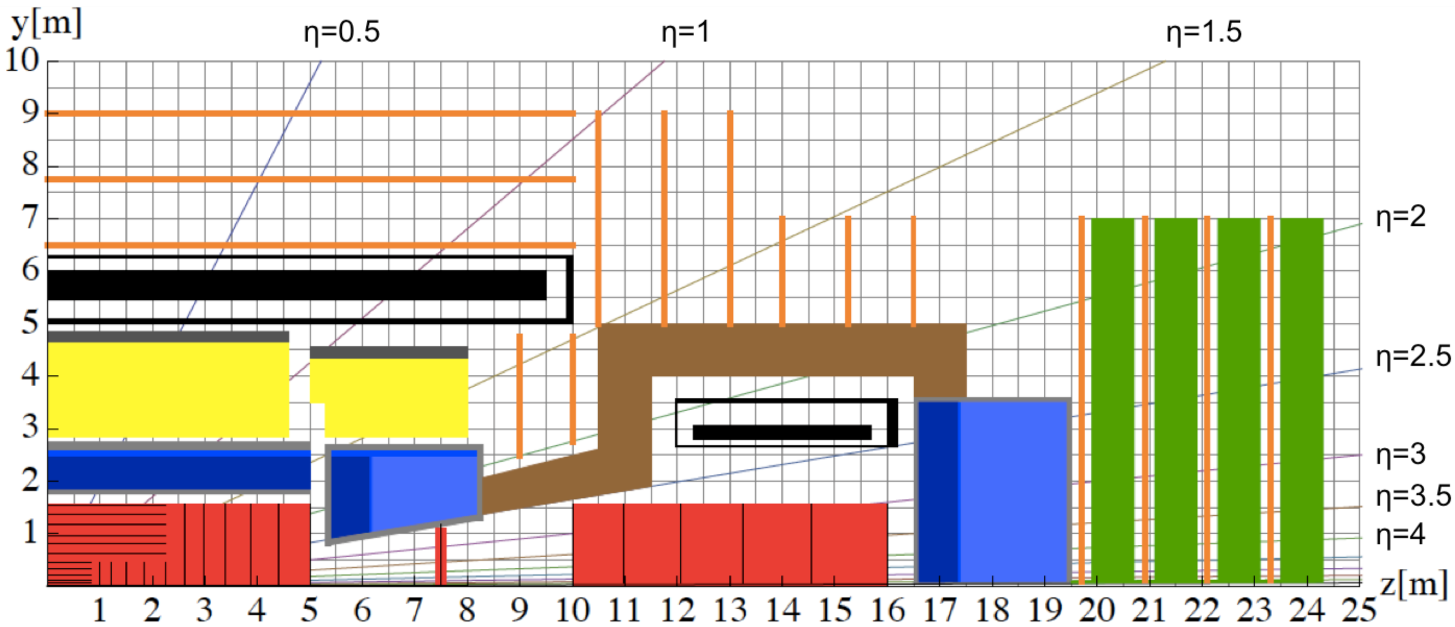
FCC week Berlin, May 29th – June 2nd 2017

W. Riegler, CERN

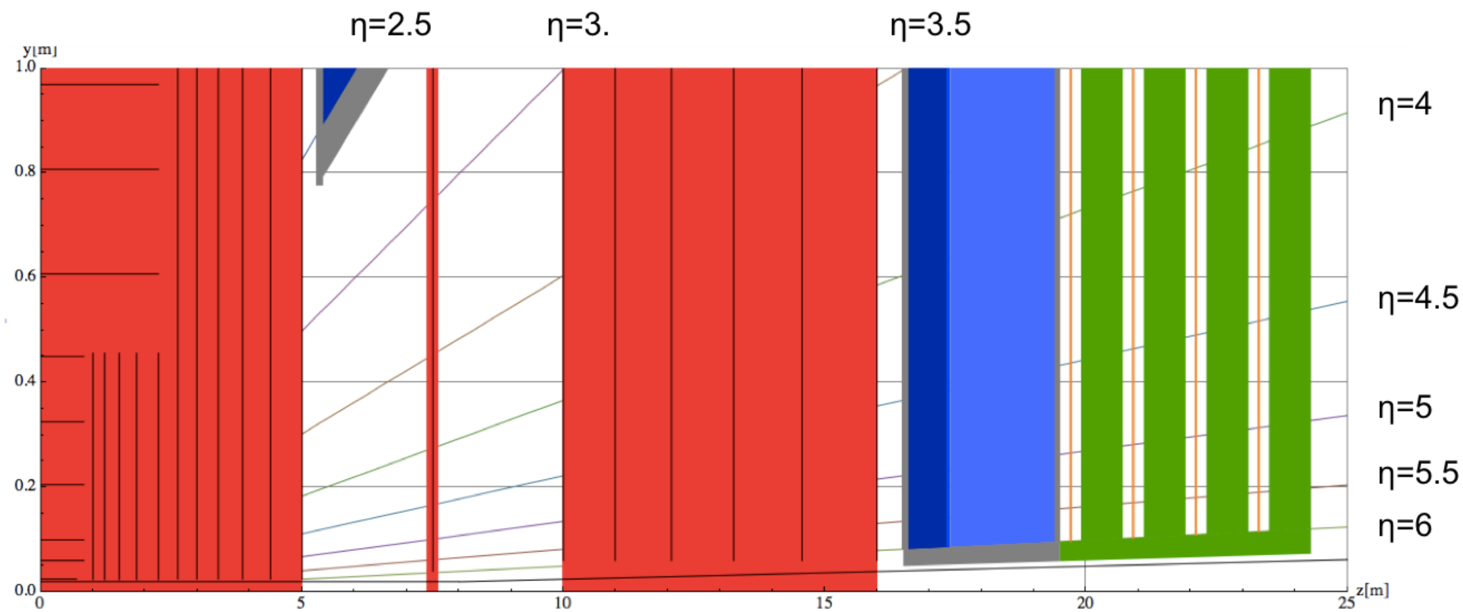
Only slide collection for now !

Detector overview

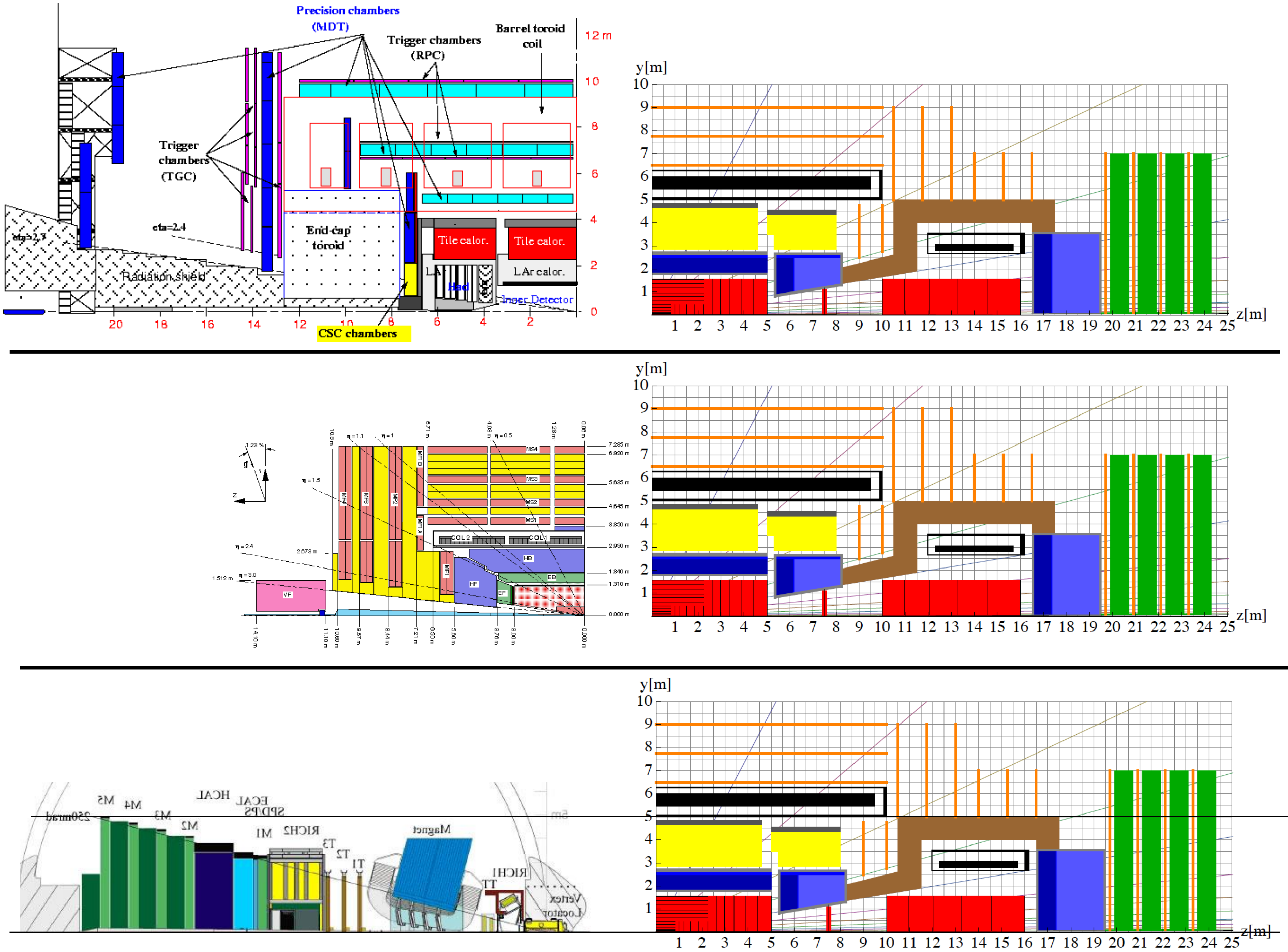




y[m]
η=0.5
η=1
η=1.5
η=2
η=2.5
η=3
η=3.5
η=4
z[m]
10
9
8
7
6
5
4
3
2
1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25



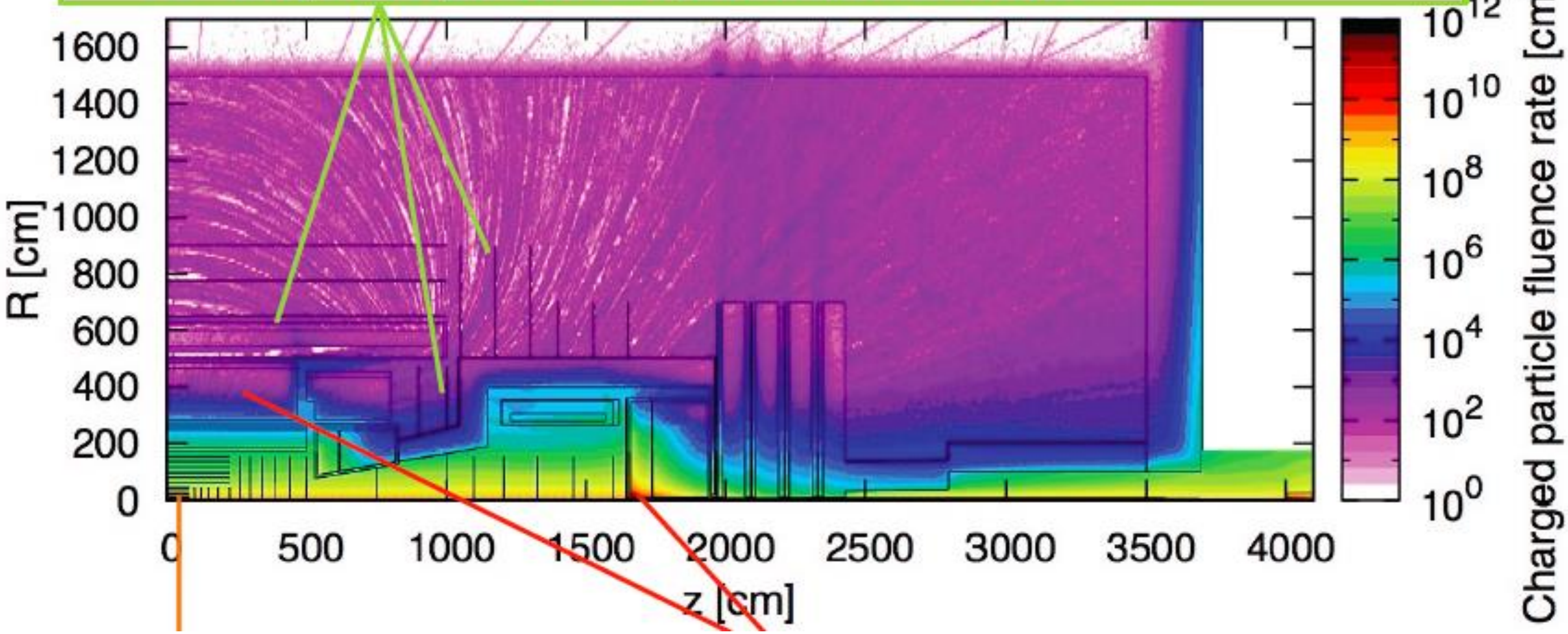
η=2.5
η=3.
η=3.5
y[m]
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
z[m]
η=4
η=4.5
η=5
η=5.5
η=6



Precision chambers
(MDT)
Trigger chambers
(RPC)
Barrel toroid
coil
12 m
Trigger
chambers
(TGC)
eta=2.4
eta=2.7
End-cap
toroid
Tile calor.
Tile calor.
LAr calor.
Radiation shield
Inner Detector
CSC chambers
y[m]
z[m]
MS4
MS3
MS2
MS1
COIL 2
COIL 1
HB
EB
HF
EF
VF
MF4
MF3
MF2
MF1

Fluence rates in the muon chambers:

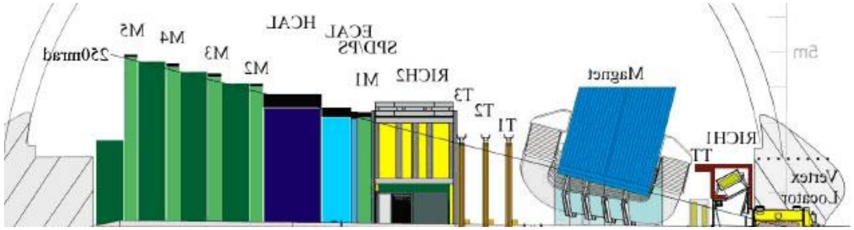
- barrel: ~300 $cm^{-2}s^{-1}$
- end-cap chambers for z > 10 m: ~500 $cm^{-2}s^{-1}$, but for the two chambers at z < 10 m: 10^4 $cm^{-2}s^{-1}$
- max previous layout: < 100 $cm^{-2}s^{-1}$, but with an hermetic detector



Compare to ATLAS Muon system with a maximum of
XXXHz/cm^2 for the drift tubes of the muon system @ HL-LHC $7x10^{34}$
XXXHz/cm^2 for the TGCs/MICROMEGAS of the muon system at HL-LHC $7x10^{34}$
XXXHz/cm^2 for the RPCs of the ATLAS muons system at HL-LHC $7x10^{34}$

XXXHz/cm^2 for the wire chambers of the LHCb muon system @ 2x10^33
XXXHz/cm^2 for the GEMs of the LHCb muon system @ 4x10^32

→ The HL-LHC muon system technology will be well adapted to a FCC muon system in terms of rate capability.



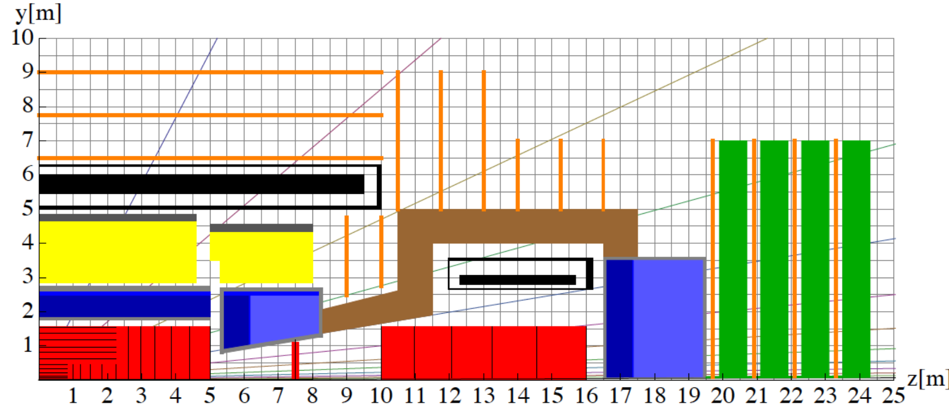
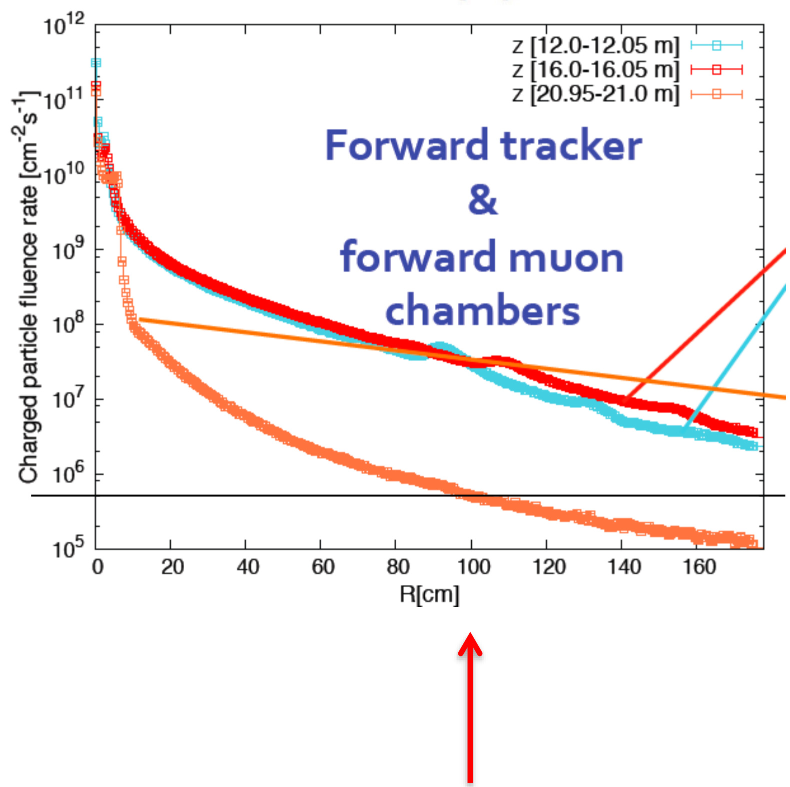


Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of 2×10^{33} cm^{-2}s^{-1} at a collision energy of 14 TeV. The values are averages, in kHz/cm^2, over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.

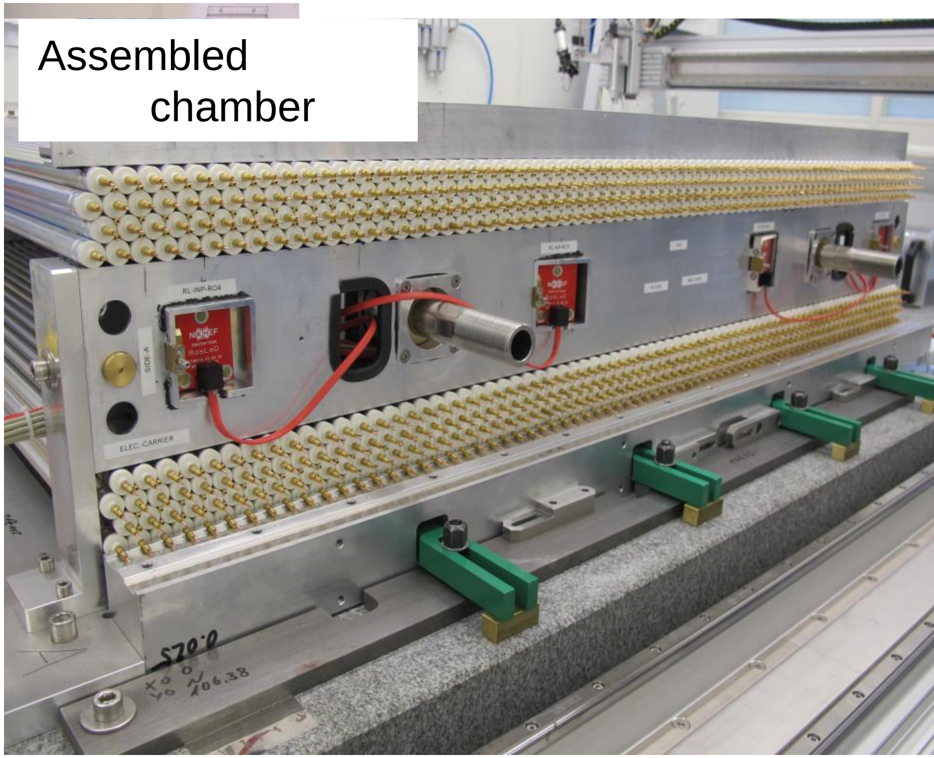
Region	Minimum	Average	Maximum
M2R1	162 ± 28	327 ± 60	590 ± 110
M2R2	15.0 ± 2.6	52 ± 8	97 ± 15
M2R3	0.90 ± 0.17	5.4 ± 0.9	13.4 ± 2.0
M2R4	0.12 ± 0.02	0.63 ± 0.10	2.6 ± 0.4
M3R1	39 ± 6	123 ± 18	216 ± 32
M3R2	3.3 ± 0.5	11.9 ± 1.7	29 ± 4
M3R3	0.17 ± 0.02	1.12 ± 0.16	2.9 ± 0.4
M3R4	0.017 ± 0.002	0.12 ± 0.02	0.63 ± 0.09
M4R1	17.5 ± 2.5	52 ± 8	86 ± 13
M4R2	1.58 ± 0.23	5.5 ± 0.8	12.6 ± 1.8
M4R3	0.096 ± 0.014	0.54 ± 0.08	1.37 ± 0.20
M4R4	0.007 ± 0.001	0.056 ± 0.008	0.31 ± 0.04
M5R1	19.7 ± 2.9	54 ± 8	91 ± 13
M5R2	1.58 ± 0.23	4.8 ± 0.7	10.8 ± 1.6
M5R3	0.29 ± 0.04	0.79 ± 0.11	1.69 ± 0.25
M5R4	0.23 ± 0.03	2.1 ± 0.3	9.0 ± 1.3



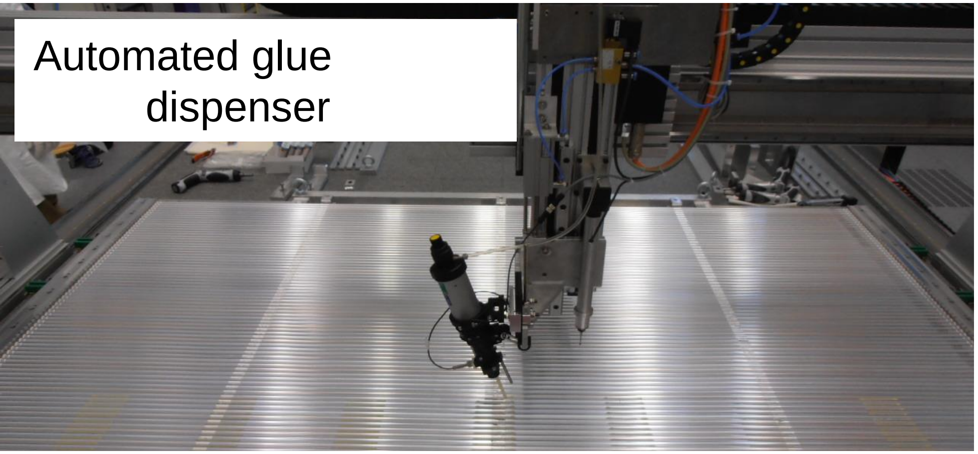
For r>1m the rates are similar to the ones of the upgraded LHCb muon system.

sMDT Chamber Construction for ATLAS Upgrades

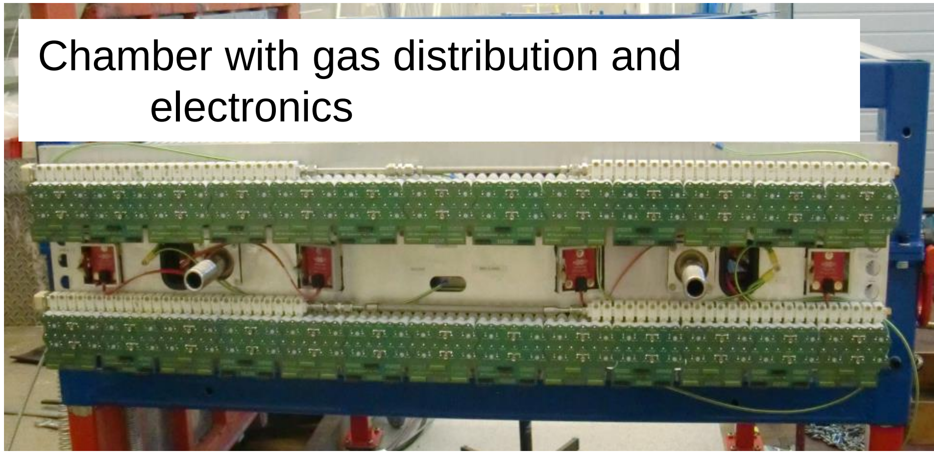
Drift tube stacking



Assembled chamber



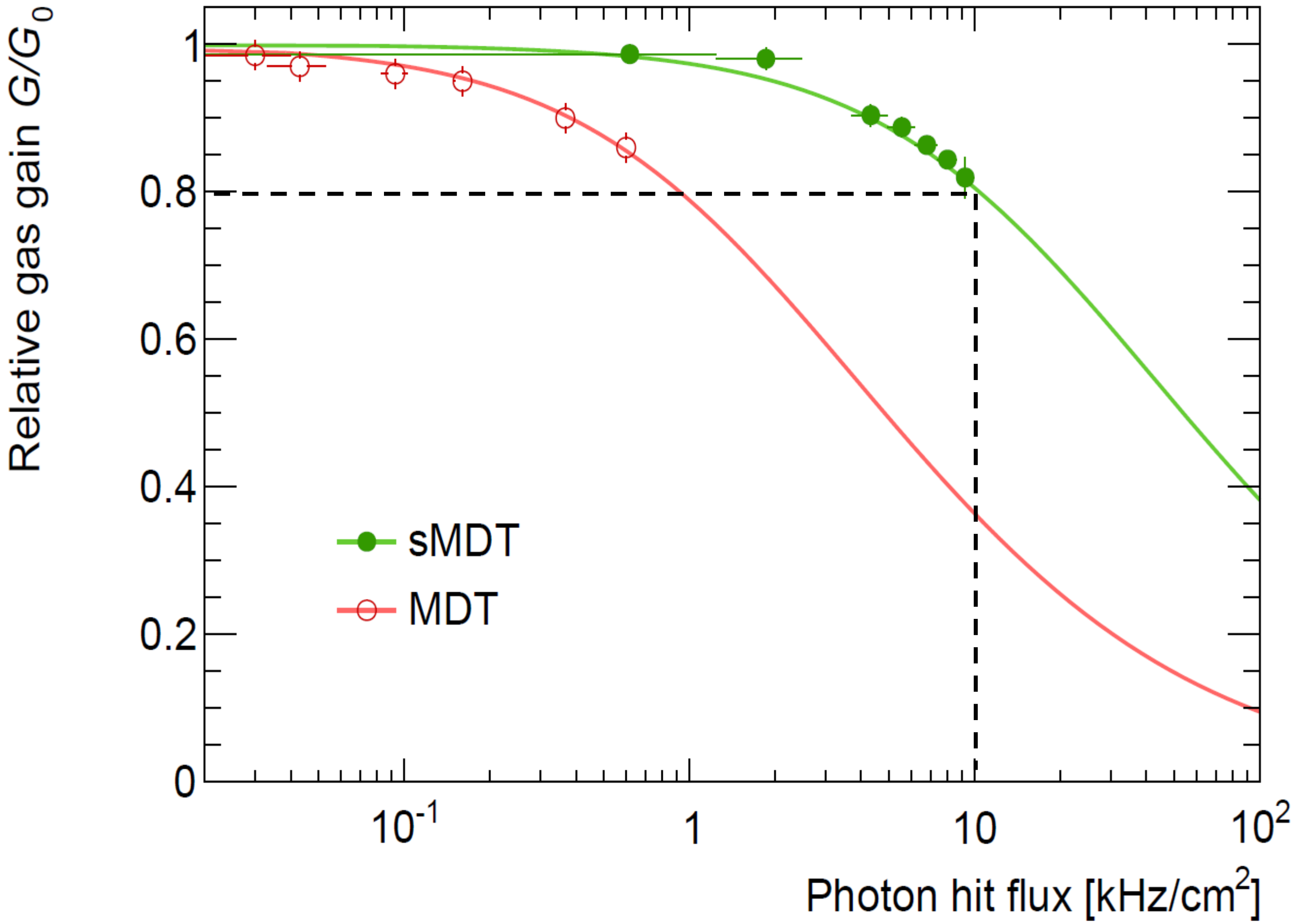
Automated glue dispenser



Chamber with gas distribution and electronics

Space Charge Effects

sMDT tubes show only 20% gain loss at 10 kHz/cm^2 γ hit rate



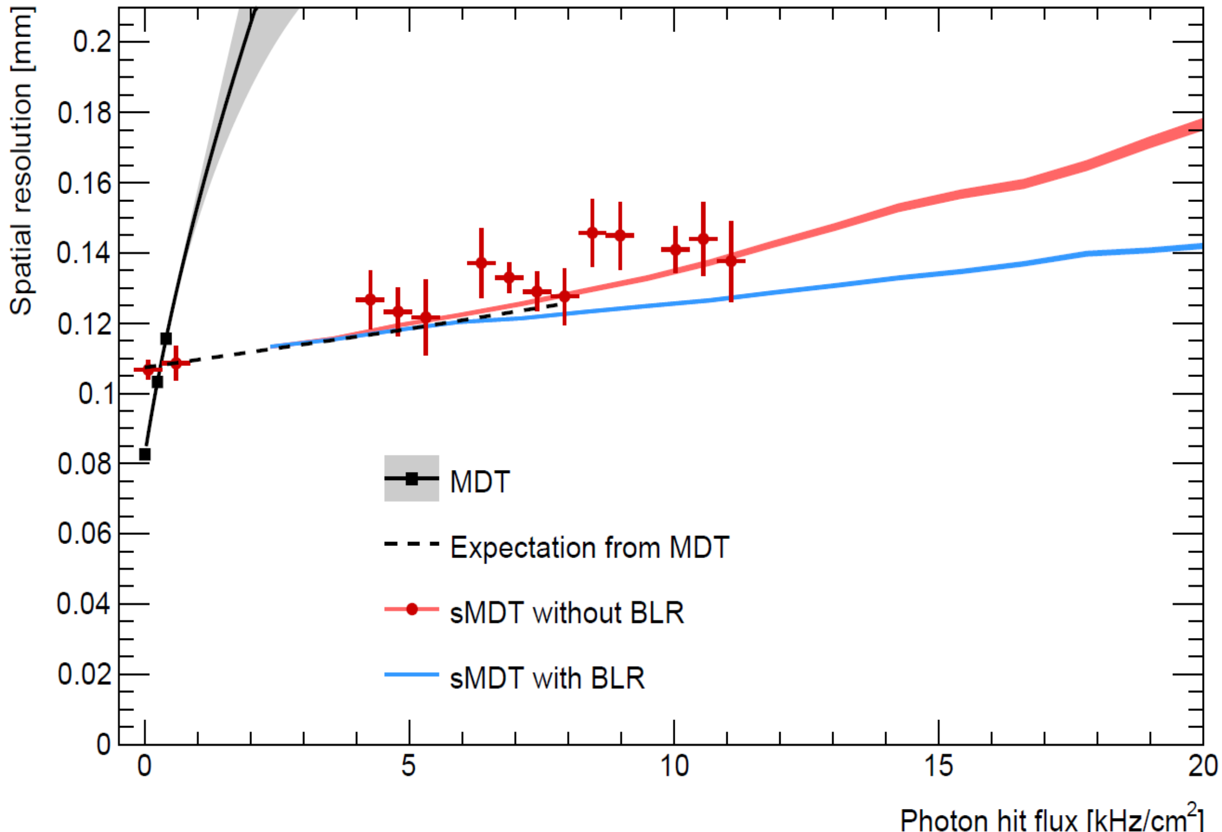
Measurements at the CERN Gamma Irradiation Facility GIF, compared to simulation of drift tube and electronics response. Current MDT RO electronics has 220 ns minimum deadtime and no BLR.

B. Bittner et al., Nucl.Instr.& Meth. A732 (2013) 250
Ph. Schwegler et al., Proc. IEEE NSS 2014

sMDT Single-Tube Resolution

sMDT resolution limited at high counting rates by signal pile-up effects of the electronics, in contrast to MDTs where space charge effects dominate

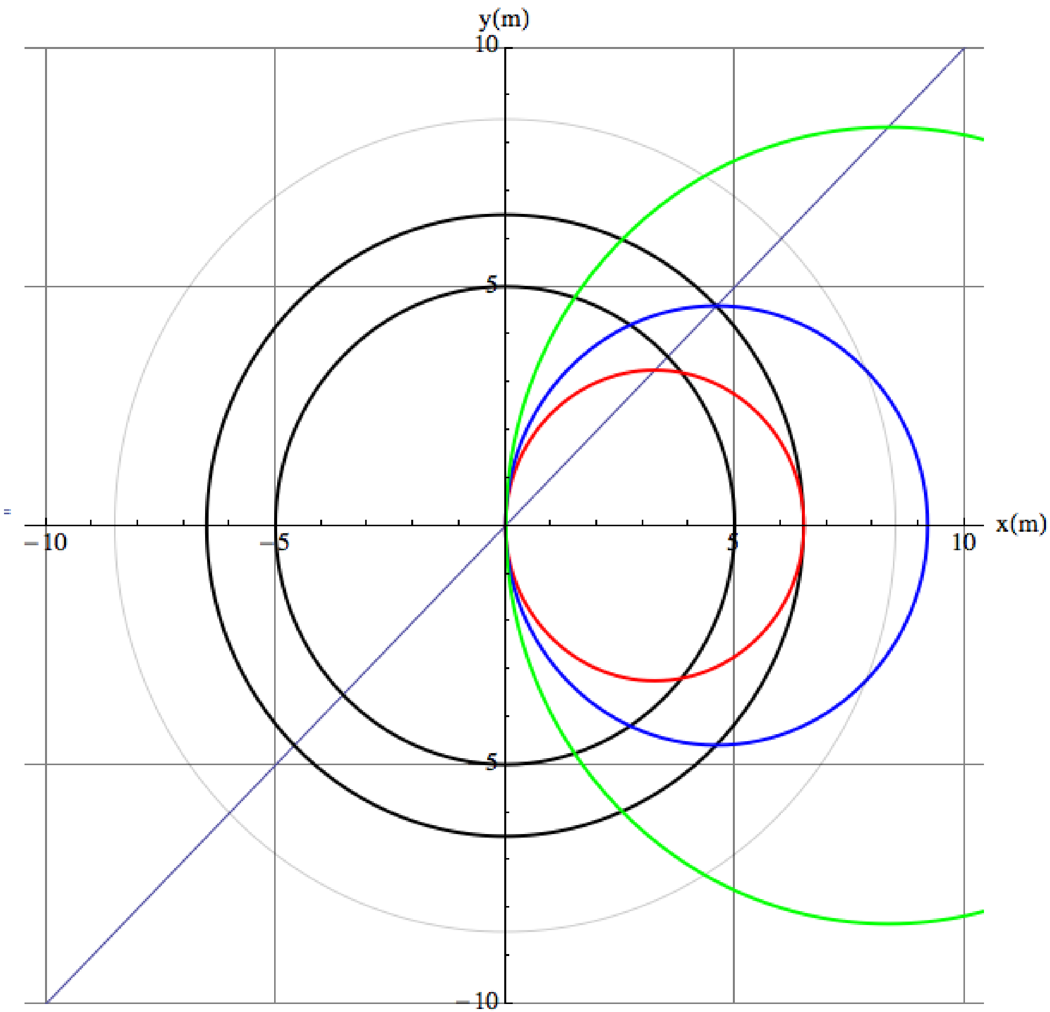
- suppression of signal pile-up effects with fast baseline restoration (BLR)



Measurements at the CERN Gamma Irradiation Facility, compared to simulation of drift tube and electronics response. Current MDT RO electronics has 220 ns minimum deadtime and no BLR.

B. Bittner et al., Nucl.Instr.& Meth. A732 (2013) 250
Ph. Schwegler et al., Proc. IEEE NSS 2014

Muon Pt cutoff and minimum trigger threshold in the main solenoid




```
In[3]:= (* ============== *)

In[4]:= Rmuon1 = 6.5;

In[5]:= Rcoil1 = 5.;

In[6]:= B0 = 4;

In[7]:= pmin1 = p[Rmuon1 / 2, B0]
Out[7]= 3.9

In[8]:= p45x1 = p[Rmuon1 / Sqrt[2], B0]
Out[8]= 5.51543

In[9]:= (* ============== *)
```

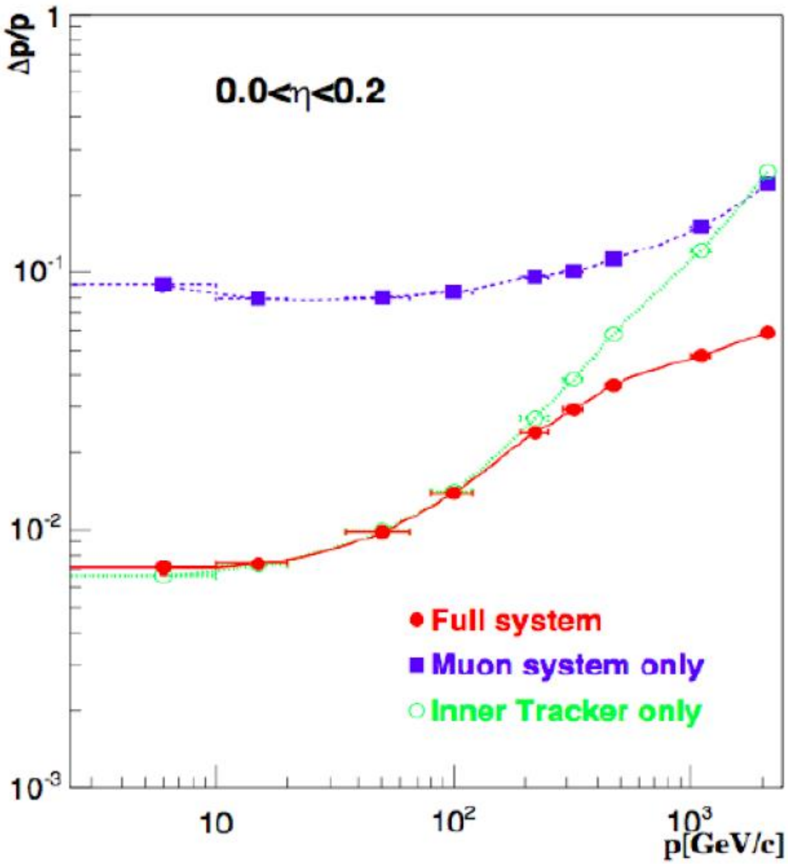
Pt=3.9GeV enters muon system

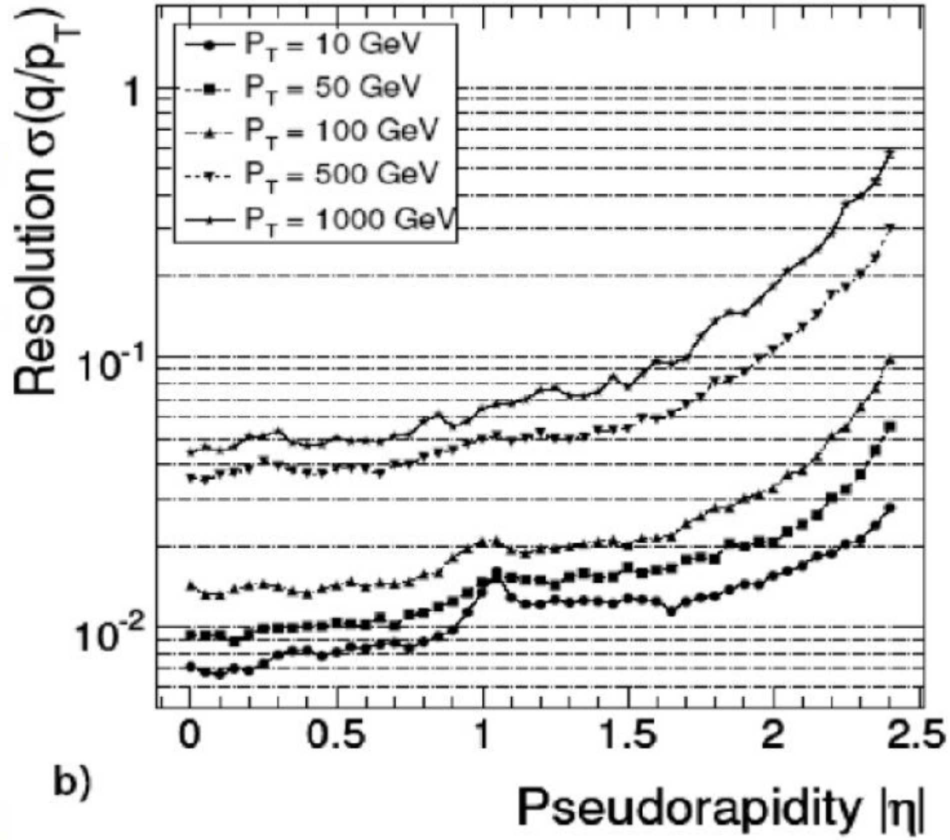
Pt=5.5GeV leaves coil at 45 degrees

Pt=10GeV

Muon Performance at η=0

CMS performance at eta zero



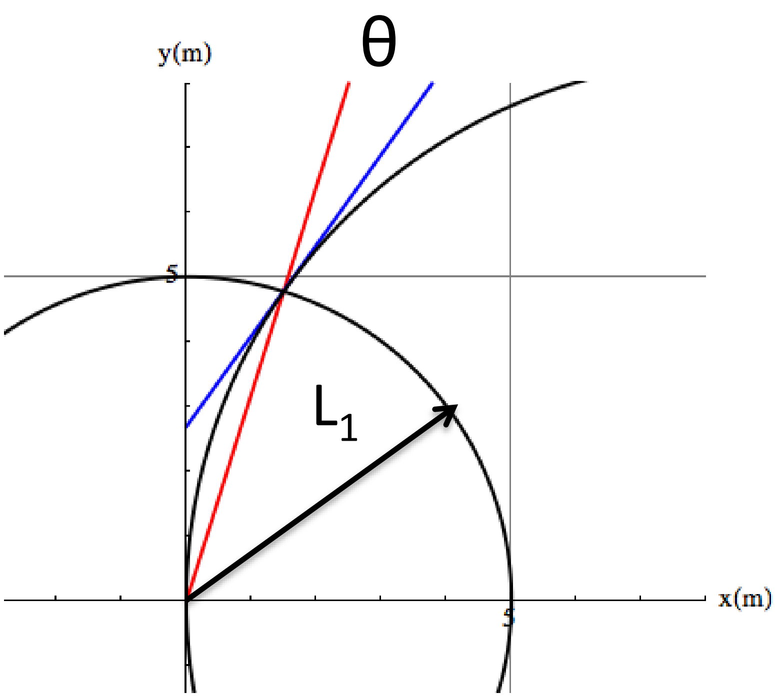


Muon System Only

The standalone muon momentum resolution is defined by the angular measurement of the muon as it enter the muon system, and is given by

$$\frac{\Delta p}{p} = \frac{2p}{0.3 L_1 B} \sqrt{\theta_0^2 + \sigma_{theta}^2} \tag{214}$$

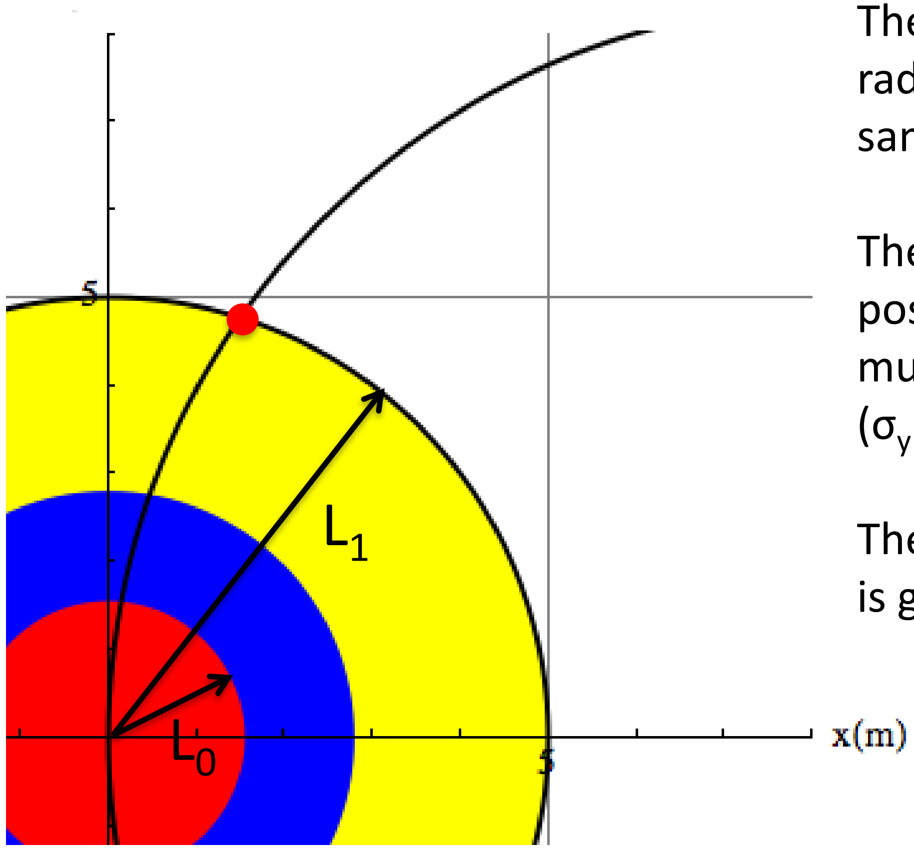
$$\theta_0 = \frac{0.0136}{\beta p[GeV/c]} \sqrt{\frac{L_{Calo}}{X0_{Calo}}} \left(1 + 0.038 \log \frac{L_{Calo}}{X0_{Calo}}\right) \tag{212}$$



σ_θ represents the angular measurement error of the muon chambers.

θ_0 represents the angular measurement error due to multiple scattering in the calorimeters.

Full System



We assume a constant magnetic field inside the coil radius L_1.

The measurement points in the tracker of radius L_0 are equidistant and have all the same resolution σ_0.

The measurement point at L_1 has a position error σ_1 that is given by the multiple scattering inside the calorimeters (σ_y in the following).

The formula for the momentum resolution is given in the next slide.

17. Combined muon fit formulas

The curvature error Δc^2 for a track in a constant magnetic field, measured at $N+1$ independent positions $x_0, x_1, ..., x_N$ with measurement errors $\sigma_0, \sigma_1, ..., \sigma_N$ is given by

$$S_m = \sum_{n=0}^{N} \frac{x_n^m}{\sigma_n^2} \qquad \Delta c^2 = \frac{4\,(S_1^2 - S_0 S_2)}{S_2^3 - 2S_1S_2S_3 + S_0S_3^2 + S_1^2S_4 - S_0S_2S_4} \tag{208}$$

and the resulting momentum resolution is

$$\frac{\Delta p}{p} = \frac{p}{0.3B}\,\Delta c \tag{209}$$

For $N+1$ equidistant layers $x_0 = 0, x_1 = L_0/N, x_2 = 2L/N, ..., x_N = L_0$ with resolutions $\sigma_0 = \sigma_1 = ... = \sigma_N = \sigma$ we get the result

$$\frac{\Delta p}{p} = \frac{p}{0.3B}\frac{\sigma}{L_0^2}\sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{p}{0.3B}\frac{\sigma}{L_0^2}\sqrt{\frac{720}{N+5}} \qquad N \gg 1 \tag{210}$$

The approximate expression stays within 5% of the correct one for all $N \geq 2$.

If we assume the above $N+1$ layers to have resolution σ_0 and one additional measurement point at position $x_{N+1} = L_1$ with resolution σ_1, the expression for Δp reads as

$$\frac{\Delta p}{p} = \frac{p}{0.3B}\frac{\sigma_0}{L_0^2}\sqrt{\frac{720N^3(c_1\sigma_0^2 + c_2\sigma_1^2)}{(N+1)(N+2)(c_3\sigma_0^2 + c_4\sigma_1^2)}} \tag{211}$$

$$\begin{aligned}
c_1 &= 2[2N(L_0^2 - 3L_0L_1 + 3L_1^2) + L_0^2] \\
c_2 &= L_0^2\,(N+1)(N+2) \\
c_3 &= 3\left[L_0^2(3N^3 - N - 2) - 12L_0L_1(2N^3 - N^2 - N) + 12L_1^2(7N^3 - N^2 - N)\right] + 60N^3\frac{L_1^4}{L_0^2} - 120N^3\frac{L_1^3}{L_0} \\
c_4 &= L_0^2(N-1)(N+1)(N+2)(N+3)
\end{aligned}$$

The position error of the track as it traverses the calorimeter of depth L_{Calo} is given by

$$\theta_0 = \frac{0.0136}{\beta p[GeV/c]}\sqrt{\frac{L_{Calo}}{X0_{Calo}}}\left(1 + 0.038\log\frac{L_{Calo}}{X0_{Calo}}\right) \tag{212}$$

$$\sigma_y = \frac{1}{\sqrt{3}}\,L_{Calo}\,\theta_0 \tag{213}$$

Muon Performance Formulas at η=0

Muon System standalone $\frac{\Delta p}{p} = \frac{2p}{0.3 L_1 B}\sqrt{\theta_0^2 + \sigma_{theta}^2}$ $\theta_0 = \frac{0.0136}{\beta p[GeV/c]}\sqrt{\frac{L_{Calo}}{X0_{Calo}}}\left(1 + 0.038\log\frac{L_{Calo}}{X0_{Calo}}\right)$

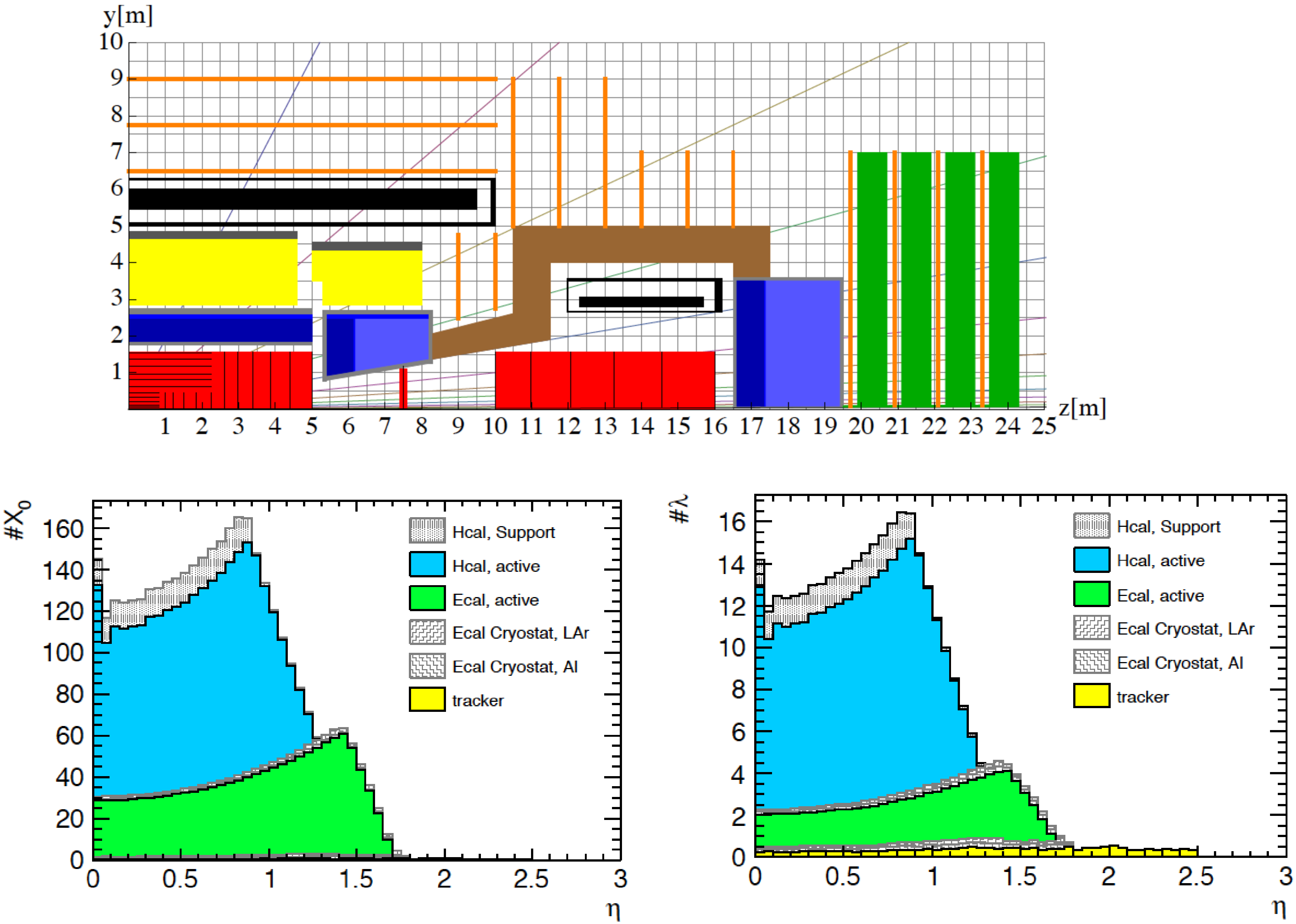
Inner Tracker $\frac{\Delta p}{p} = \frac{p}{0.3B}\frac{\sigma}{L_0^2}\sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{p}{0.3B}\frac{\sigma}{L_0^2}\sqrt{\frac{720}{N+5}}$ $N \gg 1$

Combined

$$\frac{\Delta p}{p} = \frac{p}{0.3B}\frac{\sigma_0}{L_0^2}\sqrt{\frac{720N^3(c_1\sigma_0^2 + c_2\sigma_1^2)}{(N+1)(N+2)(c_3\sigma_0^2 + c_4\sigma_1^2)}} \quad (211)$$

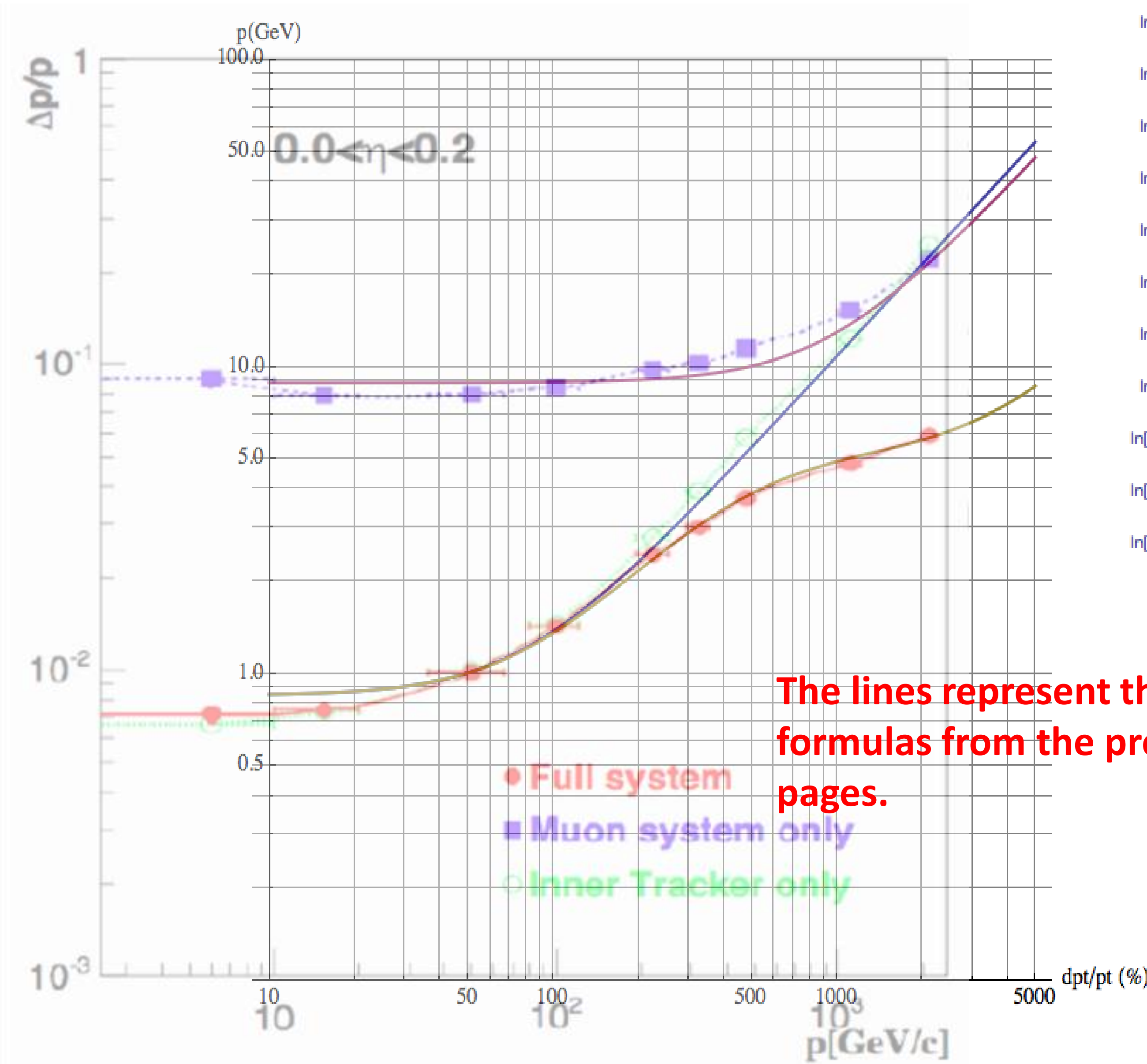
$$\begin{aligned}
c_1 &= 2[2N(L_0^2 - 3L_0L_1 + 3L_1^2) + L_0^2] \\
c_2 &= L_0^2\,(N+1)(N+2) \\
c_3 &= 3\left[L_0^2(3N^3 - N - 2) - 12L_0L_1(2N^3 - N^2 - N) + 12L_1^2(7N^3 - N^2 - N)\right] + 60N^3\frac{L_1^4}{L_0^2} - 120N^3\frac{L_1^3}{L_0} \\
c_4 &= L_0^2(N-1)(N+1)(N+2)(N+3)
\end{aligned}$$

$$\sigma_y = \frac{1}{\sqrt{3}}L_{Calo}\,\theta_0$$



y[m]
z[m]
#X0
Hcal, Support
Hcal, active
Ecal, active
Ecal Cryostat, LAr
Ecal Cryostat, Al
tracker
η
#λ
Hcal, Support
Hcal, active
Ecal, active
Ecal Cryostat, LAr
Ecal Cryostat, Al
tracker
η

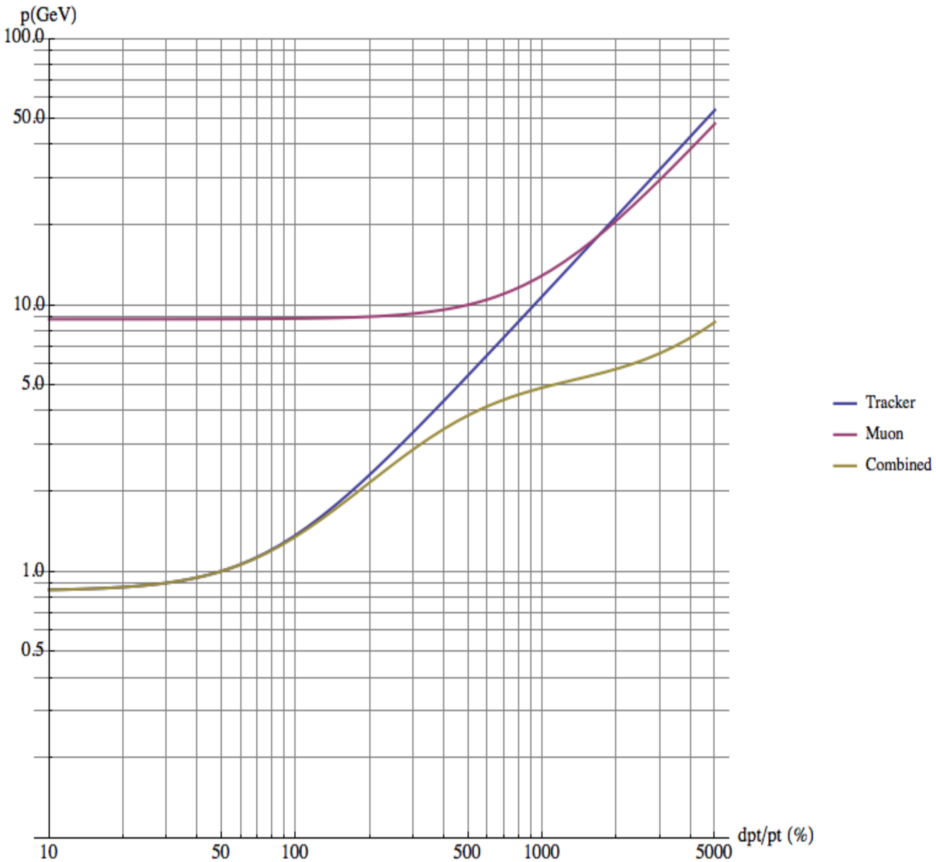
CMS muon resolution at η=0



The lines represent the formulas from the previous pages.

```
In[2]:= (* ================== *)
In[3]:= N0 = 10;
In[4]:= L = 1.1;
In[5]:= sig0 = 23 * 10 ^ (-6);
In[6]:= L1 = 3;
In[7]:= (* sig1=50*10^(-6); *)
In[8]:= B0 = 4;
In[9]:= X0Tracker = 0.7;
In[10]:= sigtheta = 170 * 10 ^ (-6);
In[11]:= X0Calo = 100;
In[12]:= LCalo = 2.1;
```

CMS muon resolution at η=0



The CMS muon system performance is well represented by assuming:

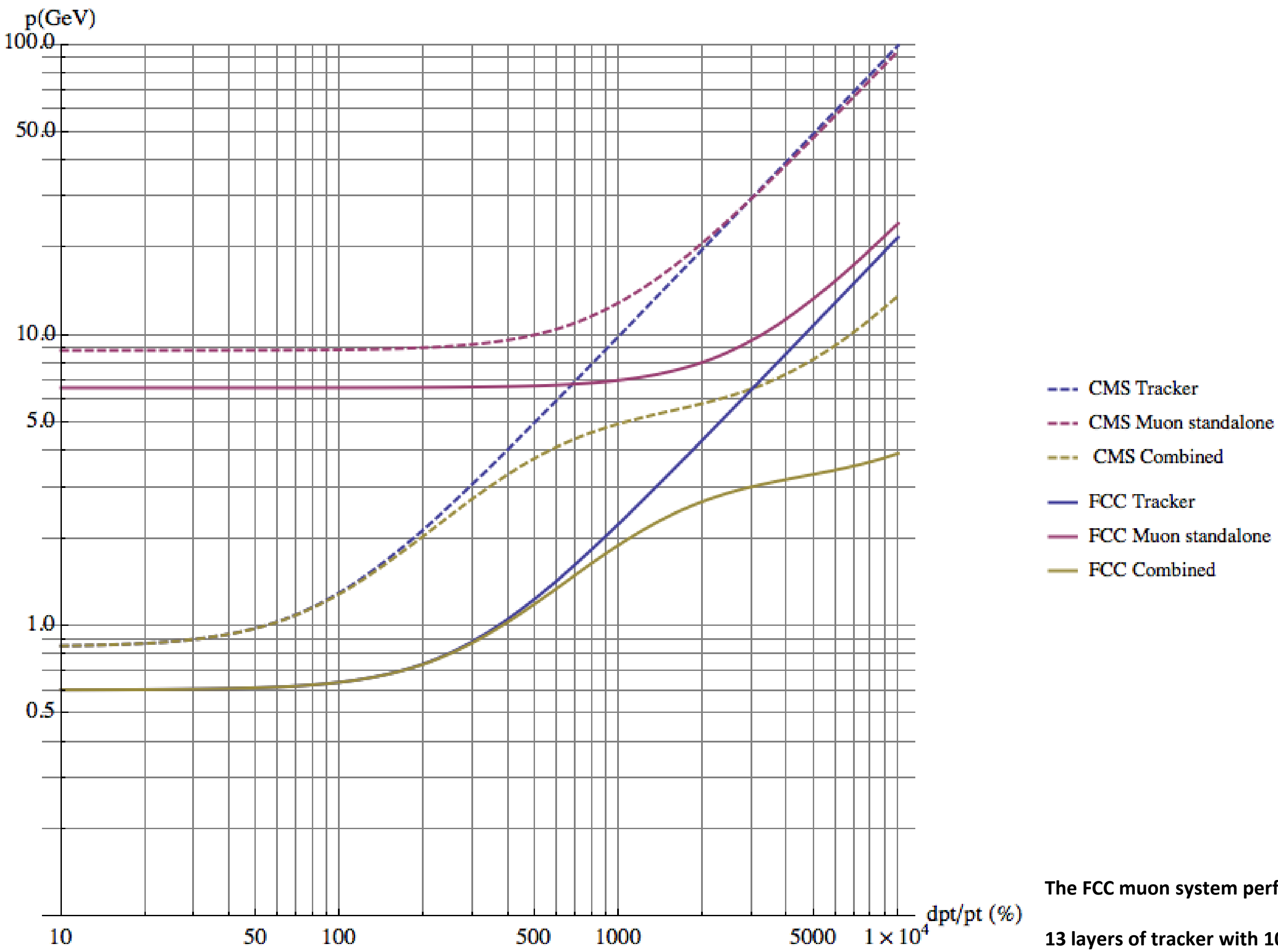
10 layers of tracker with 23um resolution.

170 microrad of angular resolution where the muon exits the coil.

Better than 100um position resolution where the muon exits the coil.

```
In[2]:= (* ================== *)
In[3]:= N0 = 10;
In[4]:= L = 1.1;
In[5]:= sig0 = 23 * 10 ^ (-6);
In[6]:= L1 = 3;
In[7]:= (* sig1=50*10^(-6); *)
In[8]:= B0 = 4;
In[9]:= X0Tracker = 0.7;
In[10]:= sigtheta = 170 * 10 ^ (-6);
In[11]:= X0Calo = 100;
In[12]:= LCalo = 2.1;
```

Comparing CMS to possible FCC resolution




```
In[14]:= BCMS = 4;
In[15]:= BFCC = 4;
In[16]:= NCMS = 13;
In[17]:= NFCC = 13;
In[18]:= L0CMS = 1.1;
In[19]:= L0FCC = 1.55;
In[20]:= s0CMS = 23 * 10 ^ (-6);
In[21]:= s0FCC = 10 * 10 ^ (-6);
In[22]:= X0traCMS = 0.7;
In[23]:= X0traFCC = 0.7;
In[24]:= L1CMS = 3;
In[25]:= L1FCC = 5.;
In[26]:= X0calCMS = 100;
In[27]:= X0calFCC = 150;
In[28]:= sigthCMS = 170 * 10 ^ (-6);
In[29]:= sigthFCC = 70 * 10 ^ (-6);
In[30]:= LCalCMS = 2.1;
In[31]:= LCalFCC = 3.;
```

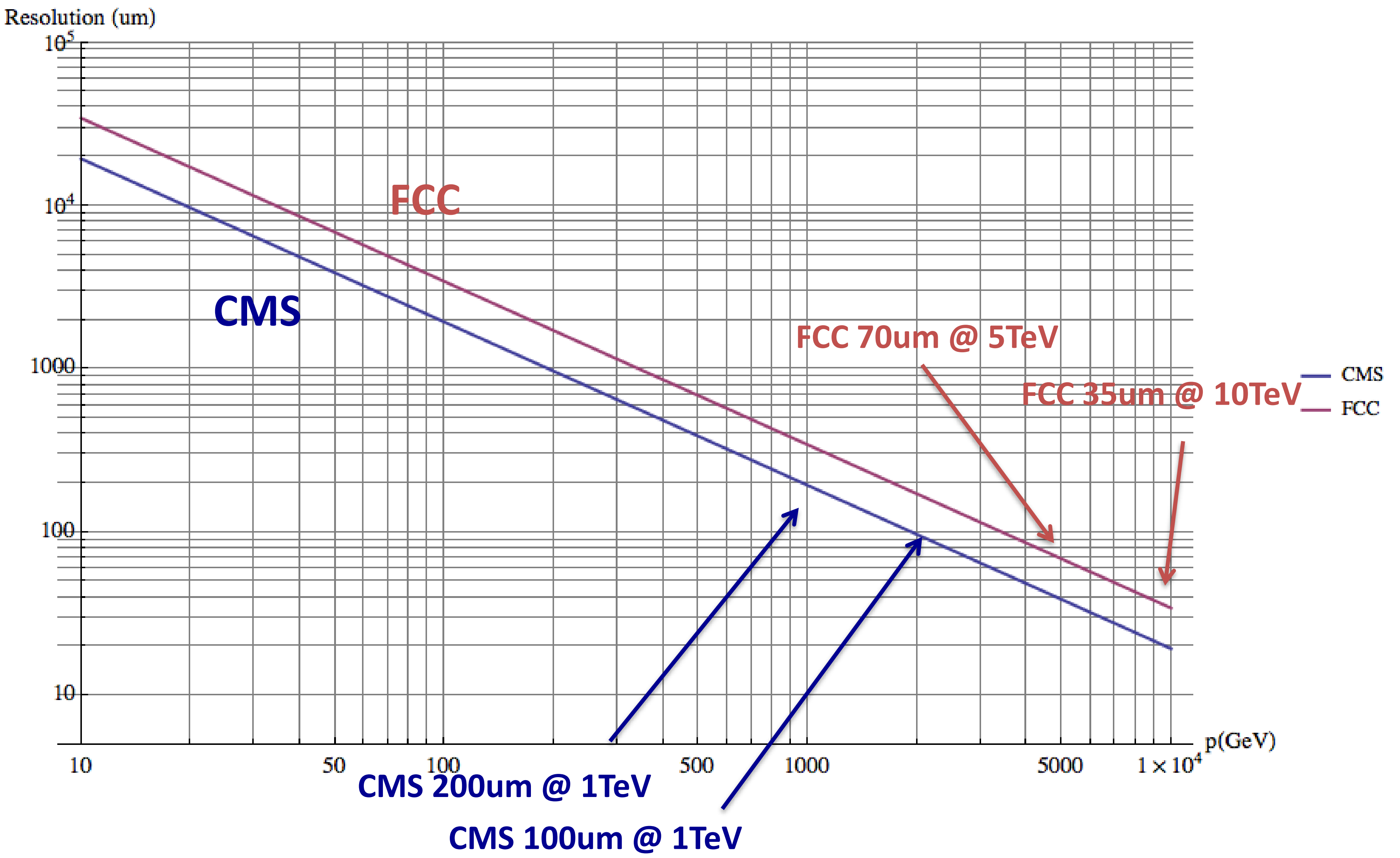
The FCC muon system performance assumes:

13 layers of tracker with 10um resolution and 1.55m radius.

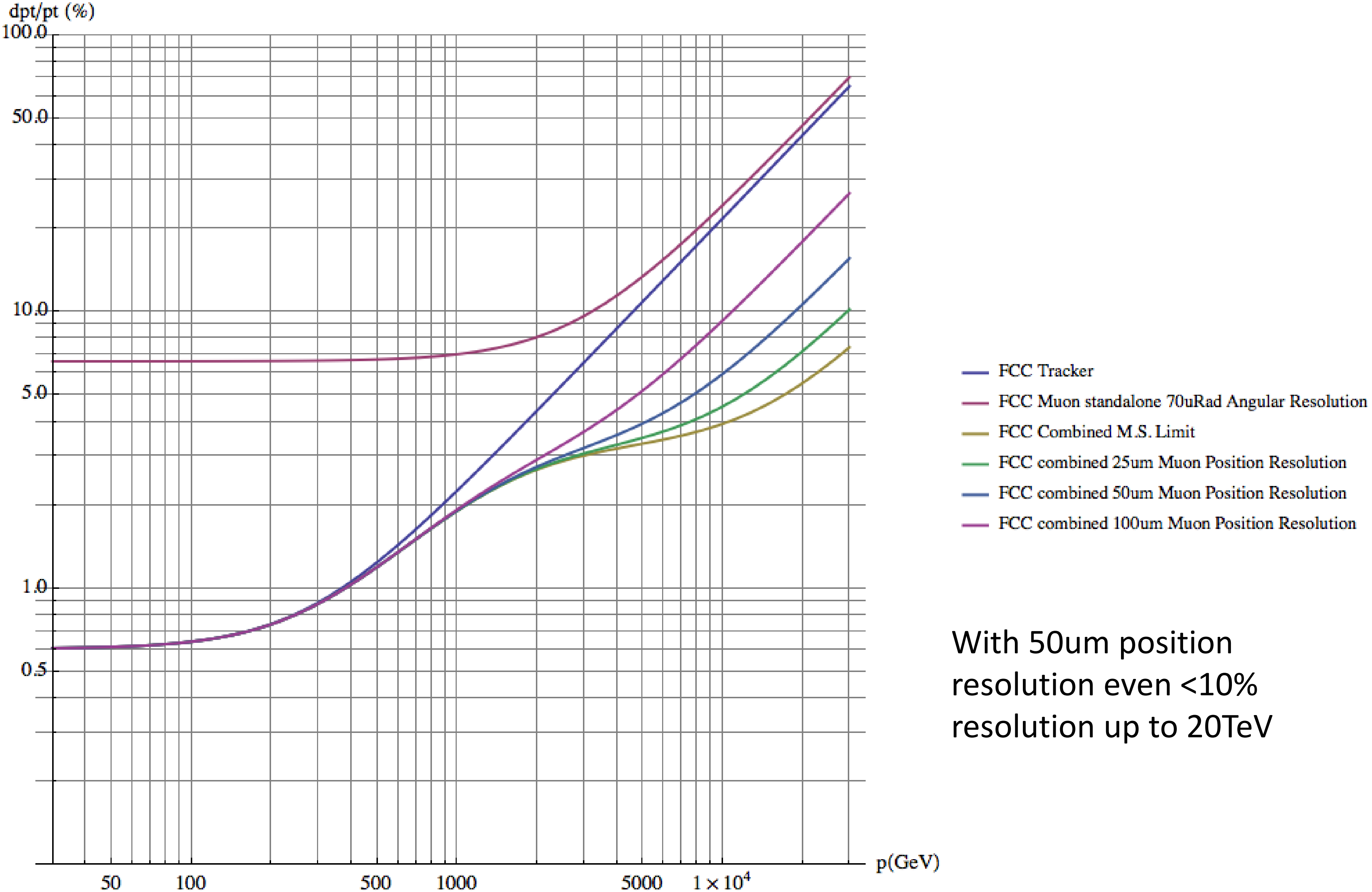
70 microrad of angular resolution where the muon exits the coil.

Better than 25um position resolution where the muon exits the coil.

Multiple scattering error dy at the entrance of the muon system

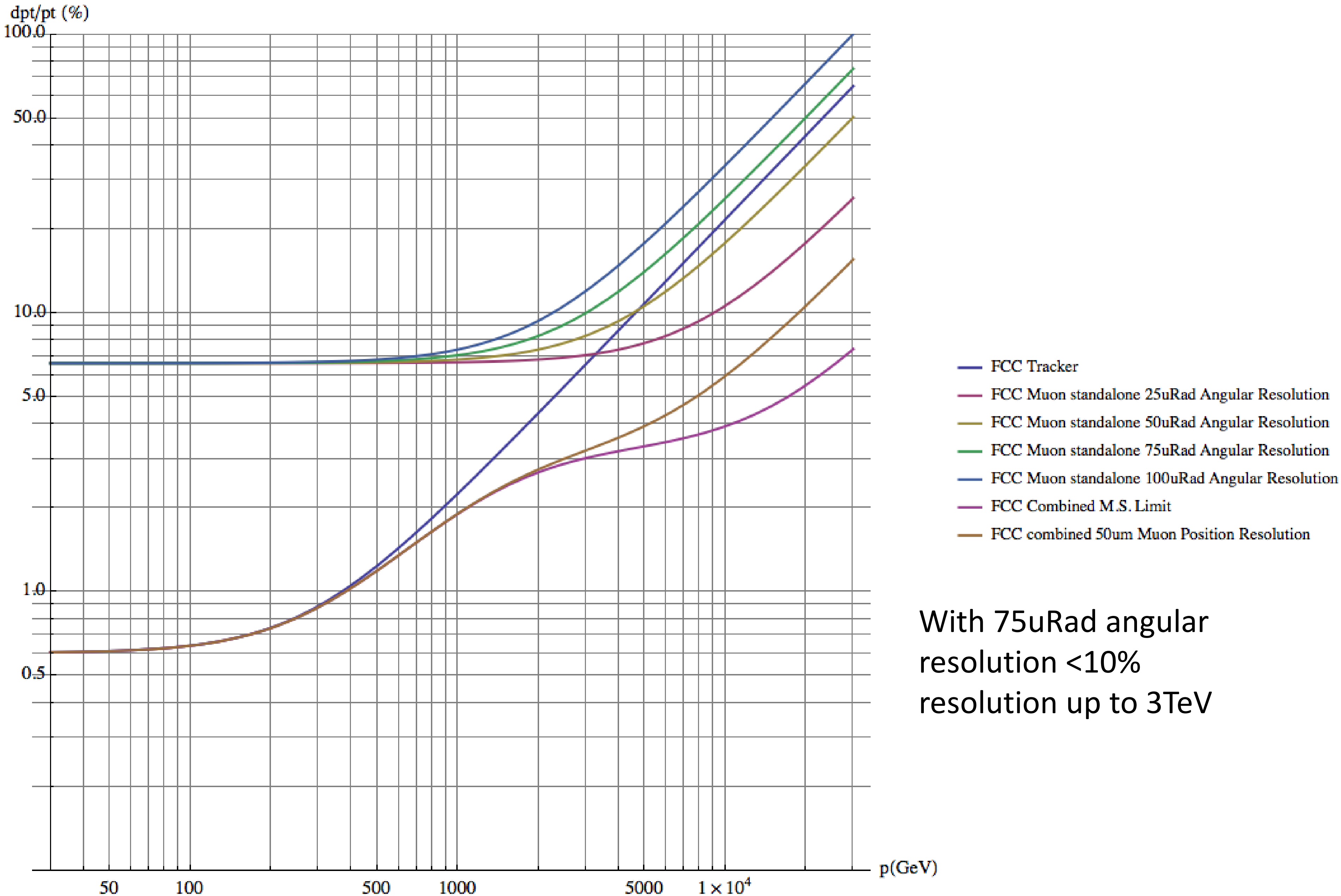


Combined performance for varying position resolution



With 50um position resolution even <10% resolution up to 20TeV

Standalone performance for varying angular resolution



With 75uRad angular resolution <10% resolution up to 3TeV

FCC detector muon system

A 50um position resolution and 70uRad angular resolution for muons exciting the solenoid will give excellent standalone and combined muon resolution at eta=0.

This can be easily realized by present technology.

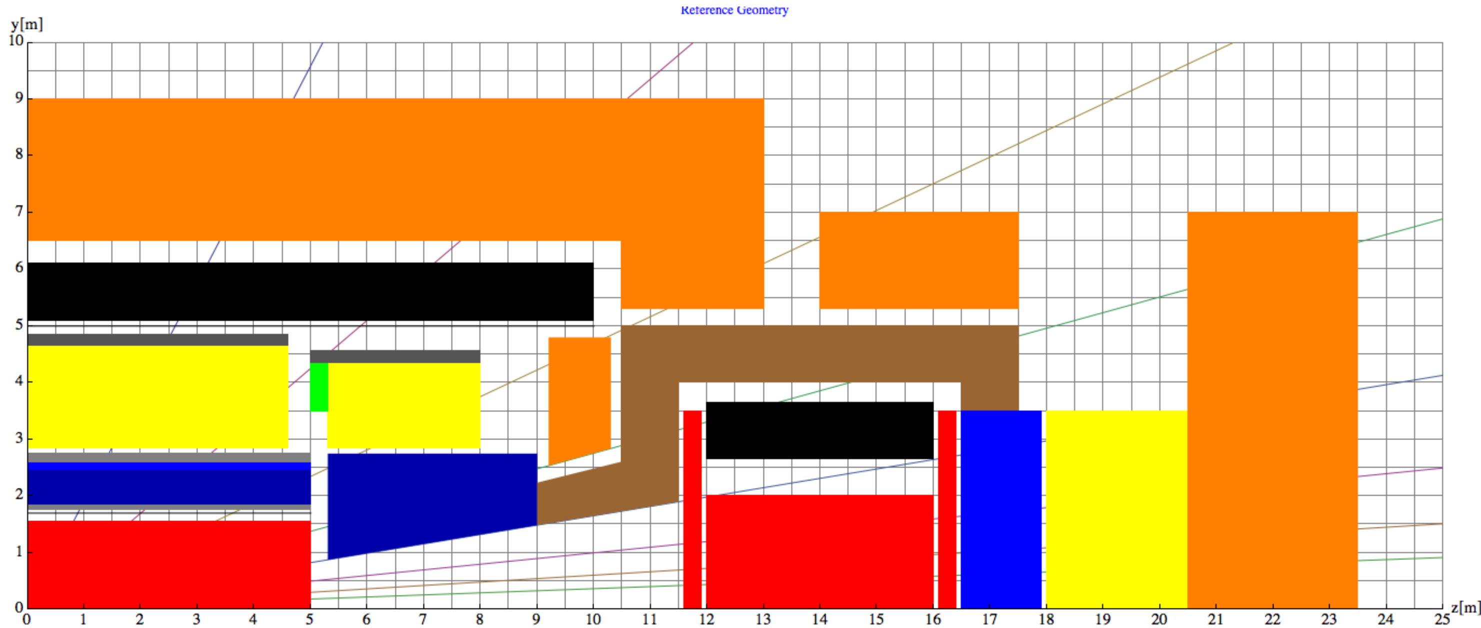
E.g. Two redundant stations of detectors with 50um position resolution at a separation of 1-2 meters will realize this requirement.

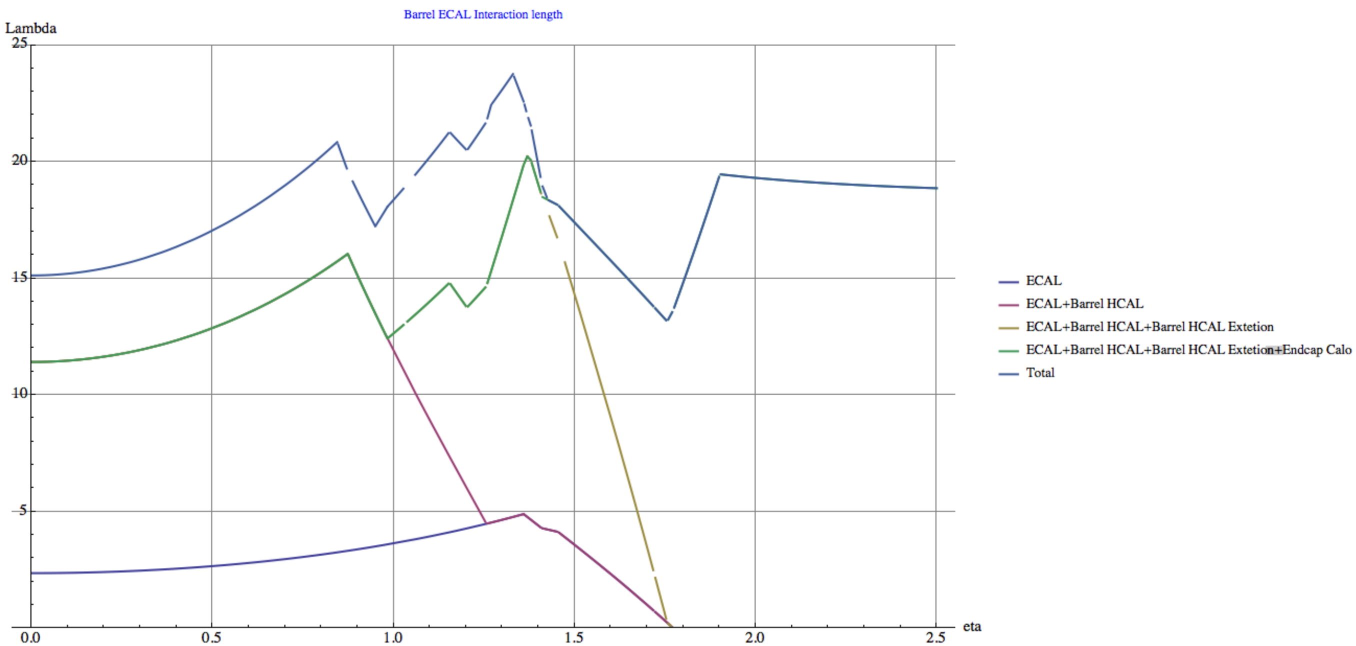
The distance between the stations must be large enough to make sure that correlated background is eliminated.

The existing magnetic fields around 1.5Tm should be sufficient for that. Simulations have to prove this fact.

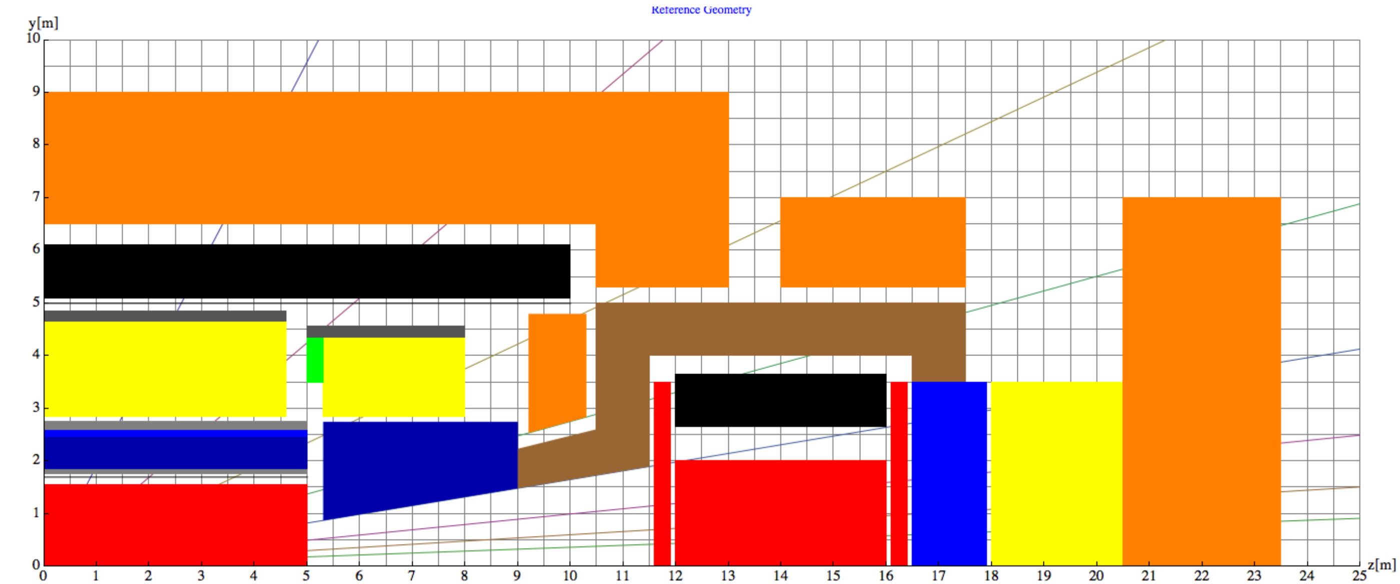
Resolution studies for larger η values still to be done.

Number of interaction lengths (λ) of the different Systems





Number of radiation lengths (X_0) in front of the Muon System



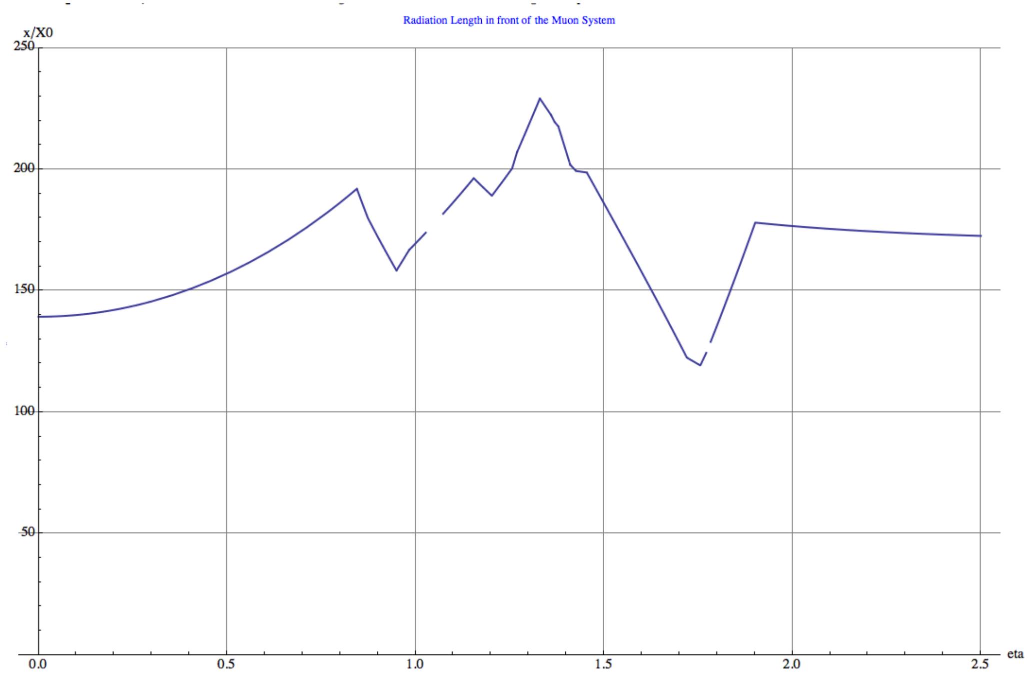


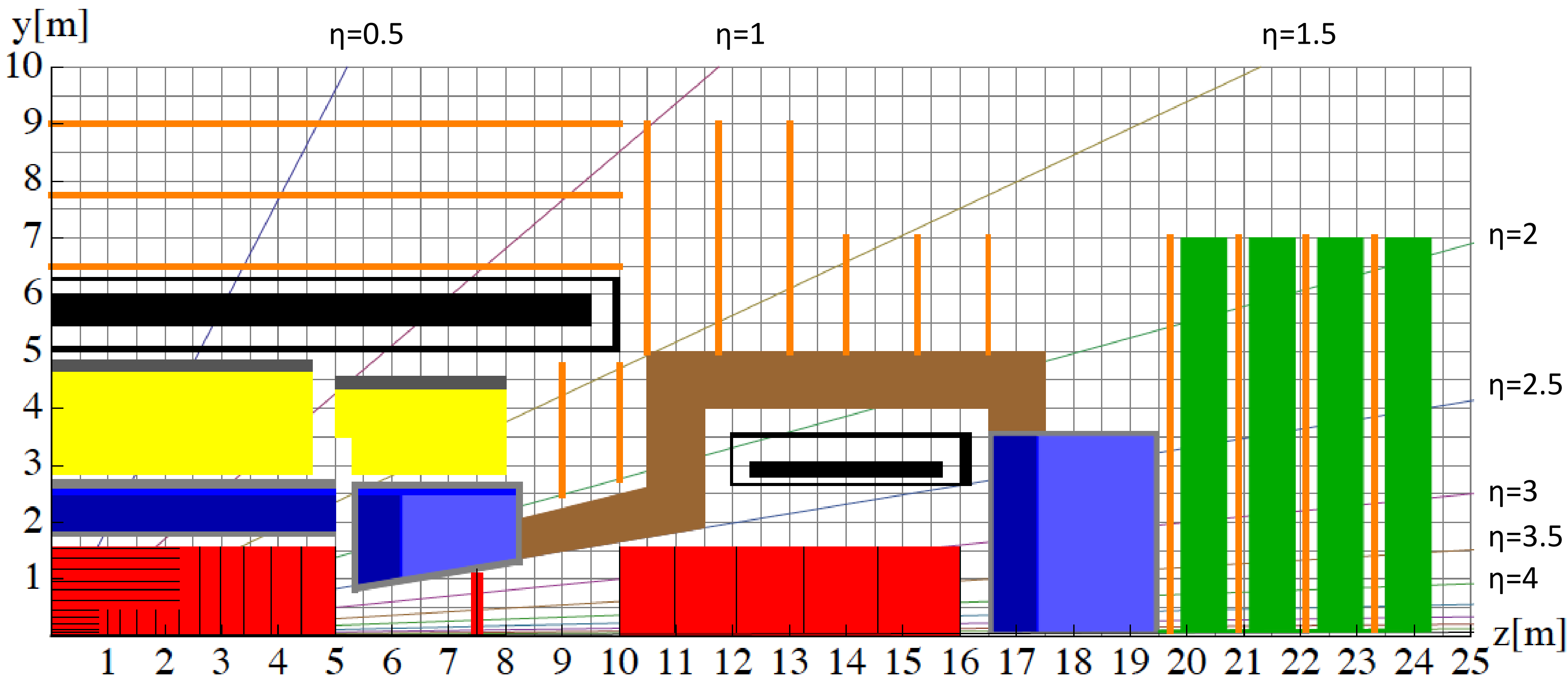
Table 4.5: Expected rates on the muon detector when operating at an instantaneous luminosity of 2×10^{33} cm^{-2}s^{-1} at a collision energy of 14 TeV. The values are averages, in kHz/cm^2, over the chamber with the minimum illumination, the whole region and the chamber with maximum illumination. The values are extrapolated from measured rates at 8 TeV.

Region	Minimum	Average	Maximum
M2R1	162 ± 28	327 ± 60	590 ± 110
M2R2	15.0 ± 2.6	52 ± 8	97 ± 15
M2R3	0.90 ± 0.17	5.4 ± 0.9	13.4 ± 2.0
M2R4	0.12 ± 0.02	0.63 ± 0.10	2.6 ± 0.4
M3R1	39 ± 6	123 ± 18	216 ± 32
M3R2	3.3 ± 0.5	11.9 ± 1.7	29 ± 4
M3R3	0.17 ± 0.02	1.12 ± 0.16	2.9 ± 0.4
M3R4	0.017 ± 0.002	0.12 ± 0.02	0.63 ± 0.09
M4R1	17.5 ± 2.5	52 ± 8	86 ± 13
M4R2	1.58 ± 0.23	5.5 ± 0.8	12.6 ± 1.8
M4R3	0.096 ± 0.014	0.54 ± 0.08	1.37 ± 0.20
M4R4	0.007 ± 0.001	0.056 ± 0.008	0.31 ± 0.04
M5R1	19.7 ± 2.9	54 ± 8	91 ± 13
M5R2	1.58 ± 0.23	4.8 ± 0.7	10.8 ± 1.6
M5R3	0.29 ± 0.04	0.79 ± 0.11	1.69 ± 0.25
M5R4	0.23 ± 0.03	2.1 ± 0.3	9.0 ± 1.3

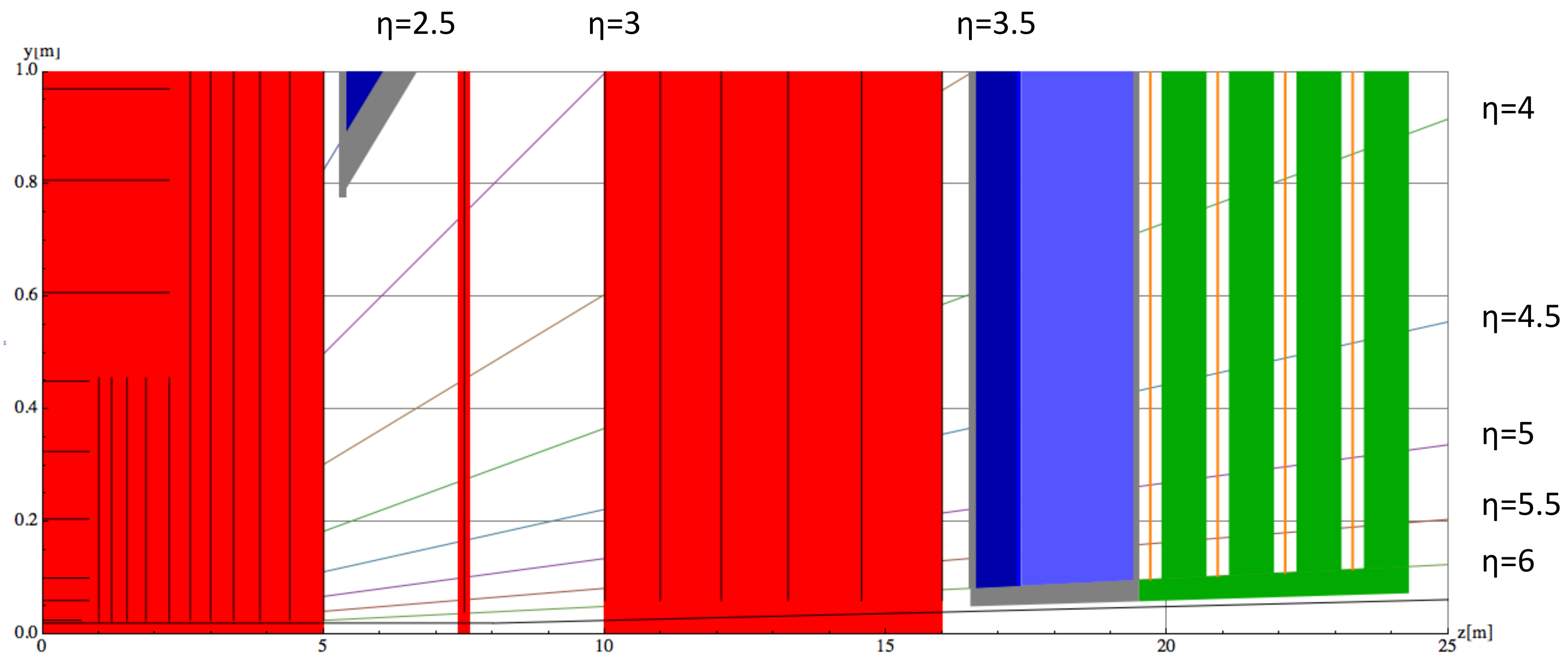
2 Particle rates in the muon system. The first row gives the maximal particle rate in each region tation per interaction as obtained from GCALOR; the second gives the calculated rate at a luminosity of 5×10^{32} cm^{-2} s^{-1} assuming a total p – p cross-section of σ=102.4 mb; and the last row the rate including fety factors.

	Station 1	Station 2	Station 3	Station 4	Station 5
gion 1	8.3×10^{-3}/cm^2 230 kHz/cm^2 460 kHz/cm^2	2.7×10^{-4}/cm^2 7.5 kHz/cm^2 37.5 kHz/cm^2	7.2×10^{-5}/cm^2 2 kHz/cm^2 10 kHz/cm^2	4.7×10^{-5}/cm^2 2.3 kHz/cm^2 6.5 kHz/cm^2	3.2×10^{-5}/cm^2 880 Hz/cm^2 4.4 kHz/cm^2
gion 2	3.3×10^{-3}/cm^2 93 kHz/cm^2 186 kHz/cm^2	1.9×10^{-4}/cm^2 5.3 kHz/cm^2 26.5 kHz/cm^2	2.3×10^{-5}/cm^2 650 Hz/cm^2 3.3 kHz/cm^2	1.6×10^{-5}/cm^2 430 Hz/cm^2 2.2 kHz/cm^2	1.3×10^{-5}/cm^2 350 Hz/cm^2 1.8 kHz/cm^2
gion 3	1.4×10^{-3}/cm^2 40 kHz/cm^2 80 kHz/cm^2	4.7×10^{-5}/cm^2 1.3 kHz/cm^2 6.5 kHz/cm^2	7.3×10^{-6}/cm^2 200 Hz/cm^2 1.0 kHz/cm^2	5.4×10^{-6}/cm^2 150 Hz/cm^2 750 Hz/cm^2	4.7×10^{-6}/cm^2 130 Hz/cm^2 650 Hz/cm^2
gion 4	4.5×10^{-4}/cm^2 12.5 kHz/cm^2 25 kHz/cm^2	8.3×10^{-6}/cm^2 230 Hz/cm^2 1.2 kHz/cm^2	3.0×10^{-6}/cm^2 83 Hz/cm^2 415 Hz/cm^2	1.8×10^{-6}/cm^2 50 Hz/cm^2 250 Hz/cm^2	1.7×10^{-6}/cm^2 45 Hz/cm^2 225 Hz/cm^2

Muon TDR for 5x10^32					Upgrade TDR for 2x10^33					ratio @ 2x10^33			
590	216	86	91		7.5	2	2.3	0.88		19.7	27.0	9.3	25.9
97	29	12.6	10.8		5.3	0.65	0.43	0.35		4.6	11.2	7.3	7.7
13.4	2.9	1.37	1.69		1.3	0.2	0.15	0.13		2.6	3.6	2.3	3.3
2.6	0.63	0.31	9		0.23	0.083	0.05	0.045		2.8	1.9	1.6	50.0



y[m]
η=0.5
η=1
η=1.5
η=2
η=2.5
η=3
η=3.5
η=4
z[m]
10
9
8
7
6
5
4
3
2
1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25


η=2.5
η=3
η=3.5
η=4
η=4.5
η=5
η=5.5
η=6
y[m]
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
z[m]