Baseline Geometry and Performance Characterization

FCC Hadron Detector Meeting
Sept, 16th 2015

W. Riegler

Dates for Next Meetings

We have defined the dates for all FCC hadron detector meetings, leading up to the next FCC week in Rome (April 11-15, 2016).

Nov. 03, 2015
Dec. 09, 2015
Jan. 21, 2016
Mar. 03, 2016
Apr. 06, 2016

https://indico.cern.ch/category/6069/

Baseline FCC-hh Parameters

Version 1.0 (2014-02-11)	LHC	HL-LHC	FHC-hh
c.m. Energy [TeV]	14		100
Circumference *C* [km]	26.7		100 (83)
Dipole field [T]	8.33		16 (20)
Arc filling factor	0.79		0.79
Straight sections	8		12
Average straight section length [m]	528		1400
Number of IPs	4		2 + 2
Injection energy [TeV]	0.45		3.3
Peak luminosity [10^{34} $cm^{-2}s^{-1}$]	1.0	5.0	5.0
Peak no. of inelastic events / crossing at - 25 ns spacing - 5 ns spacing	27	135 (lev.)	171 34
Total / inelastic cross section [mbarn]	111 / 85		153 / 108
Number of bunches at - 25 ns - 5 ns	2808		10600 (8900) 53000 (44500)
Bunch population N_b [10^{11}] - 25 ns - 5 ns	1.15	2.2	1.0 0.2
Nominal transverse normalized emittance [mm] - 25 ns - 5 ns	3.75	2.5	2.2 0.44
IP beta function [m]	0.55	0.15 (min)	1.1
RMS IP spot size [mm] - 25 ns - 5 ns	16.7	7.1 (min)	6.8 3
Stored beam energy [GJ]	0.392	0.694	8.4 (7.0)
SR power per ring [MW]	0.0036	0.0073	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	0.33	28.4 (44.3)
Critical photon energy [keV]	0.044		4.3 (5.5)
Longitudinal emittance damping time [h]	12.9		0.54 (0.32)

The baseline FCC hadron accelerator parameters are defined in a table linked from the FCC homepage.

https://fcc.web.cern.ch/Pages/Hadron-Collider.aspx

Peak Luminosity and Integrated Luminosity for the different phases are not yet listed there, so we should use the following assumptions →

Baseline Parameters

From M. Benedikt: The present working hypothesis is:

- peak luminosity baseline: 5E34
- peak luminosity ultimate: <= 30E34

- integrated luminosity baseline ~250 fb-1 (average per year)
- integrated luminosity ultimate ~1000 fb-1 (average per year)

An operation scenario with:
- 10 years baseline, leading to 2.5 ab-1
- 15 years ultimate, leading to 15 ab-1

would result in a total of 17.5 ab-1 over 25 years of operation.

Since the operation scenario is somewhat arbitrary we quote O(20ab-1) as total integral luminosity over the lifetime.

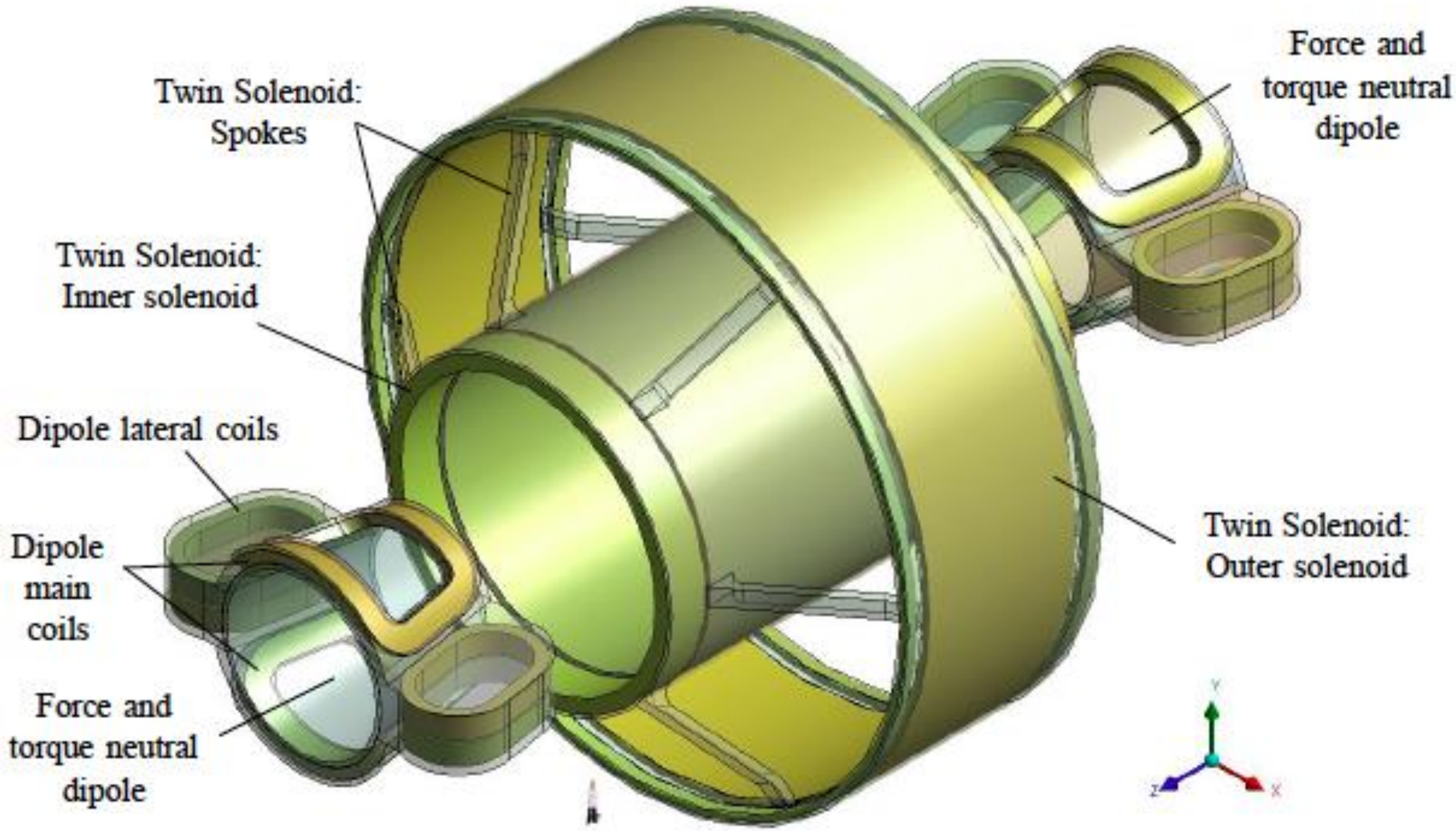
Please use these numbers in presentations/talks.

More importantly (at least for the design and maintenance concepts) than the operation scenario might be the fact that we foresee a periodicity of 5 years: beam operation over around 3 to 3.5 years followed by a shutdown of 2 to 1.5 years.

For your information, the above numbers will be published as deliverable report for EuroCirCol and the FCC-hh parameter list will be updated accordingly.

Twin Solenoid + Dipole Magnet System

Matthias Mentink, Alexey Dudarev, Helder Filipe Pais Da Silva, Christophe Paul Berriaud, Gabriella Rolando, Rosalinde Pots, Benoit Cure, Andrea Gaddi, Vyacheslav Klyukhin, Hubert Gerwig, Udo Wagner, and Herman ten Kate



Twin Solenoid + Dipole Magnet System

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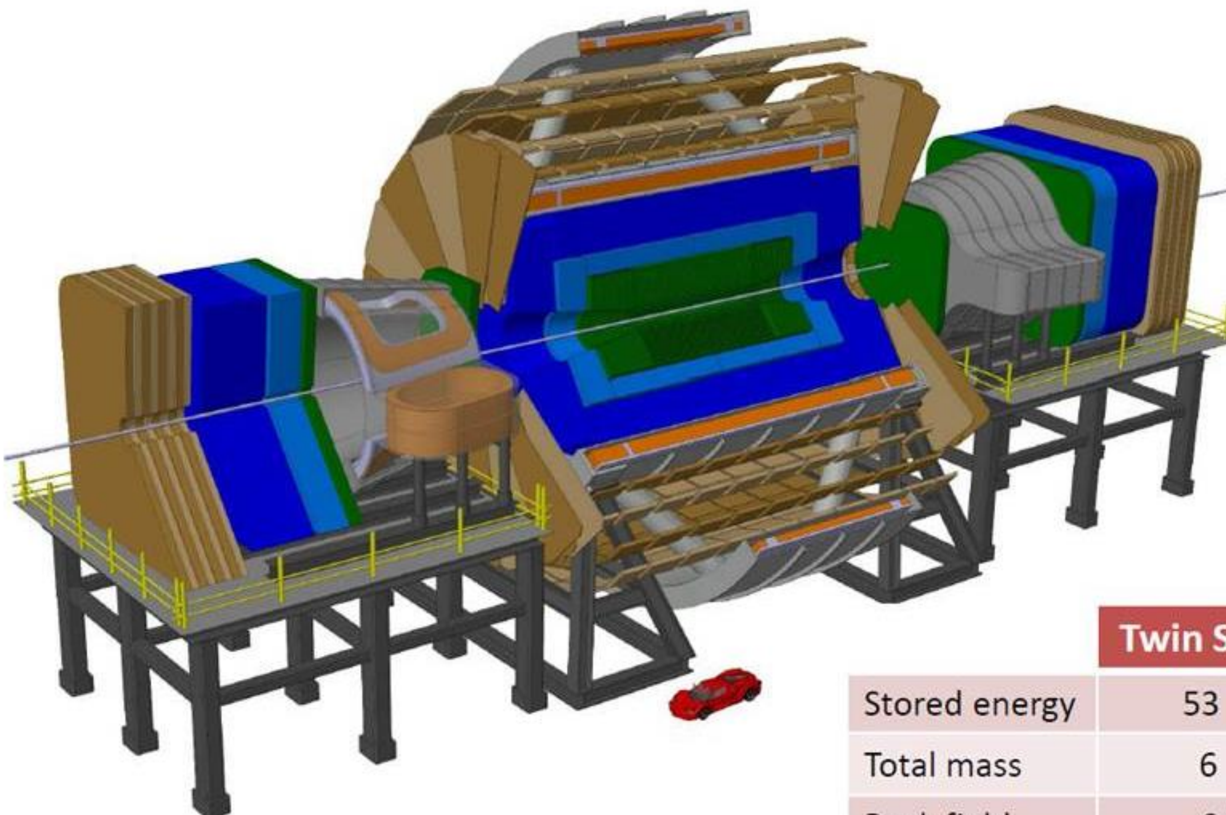


	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

FCC Air core Twin solenoid and Dipoles

State of the art high stress / low mass design.

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

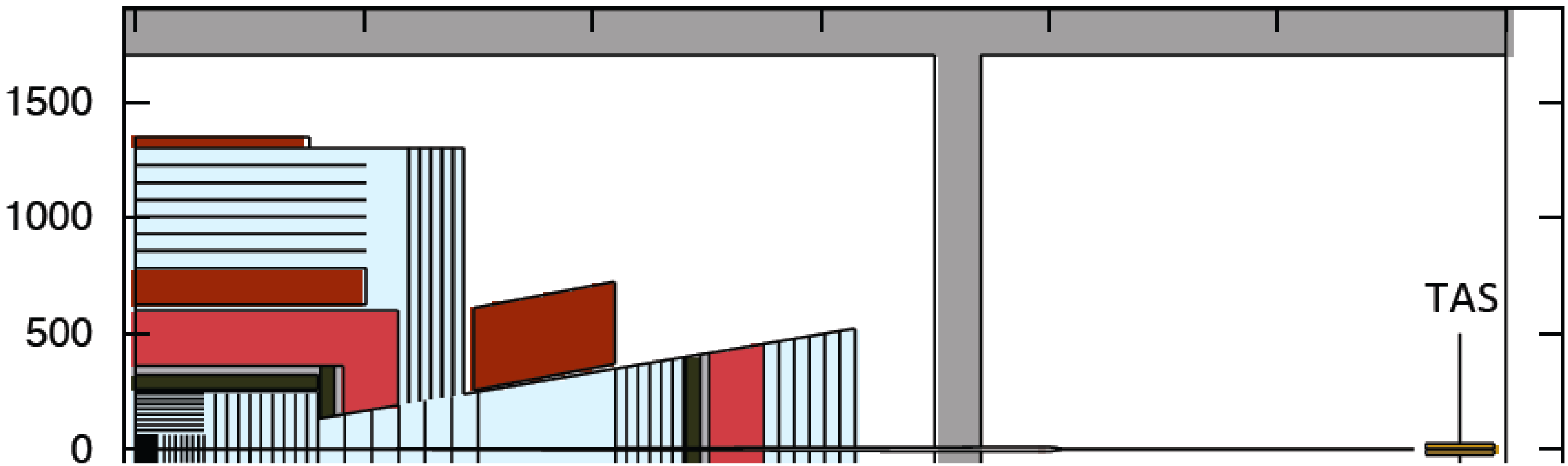
FTracker available space:
z=21m to R=24m, L=3m

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

Geometry for Radiation Calculations

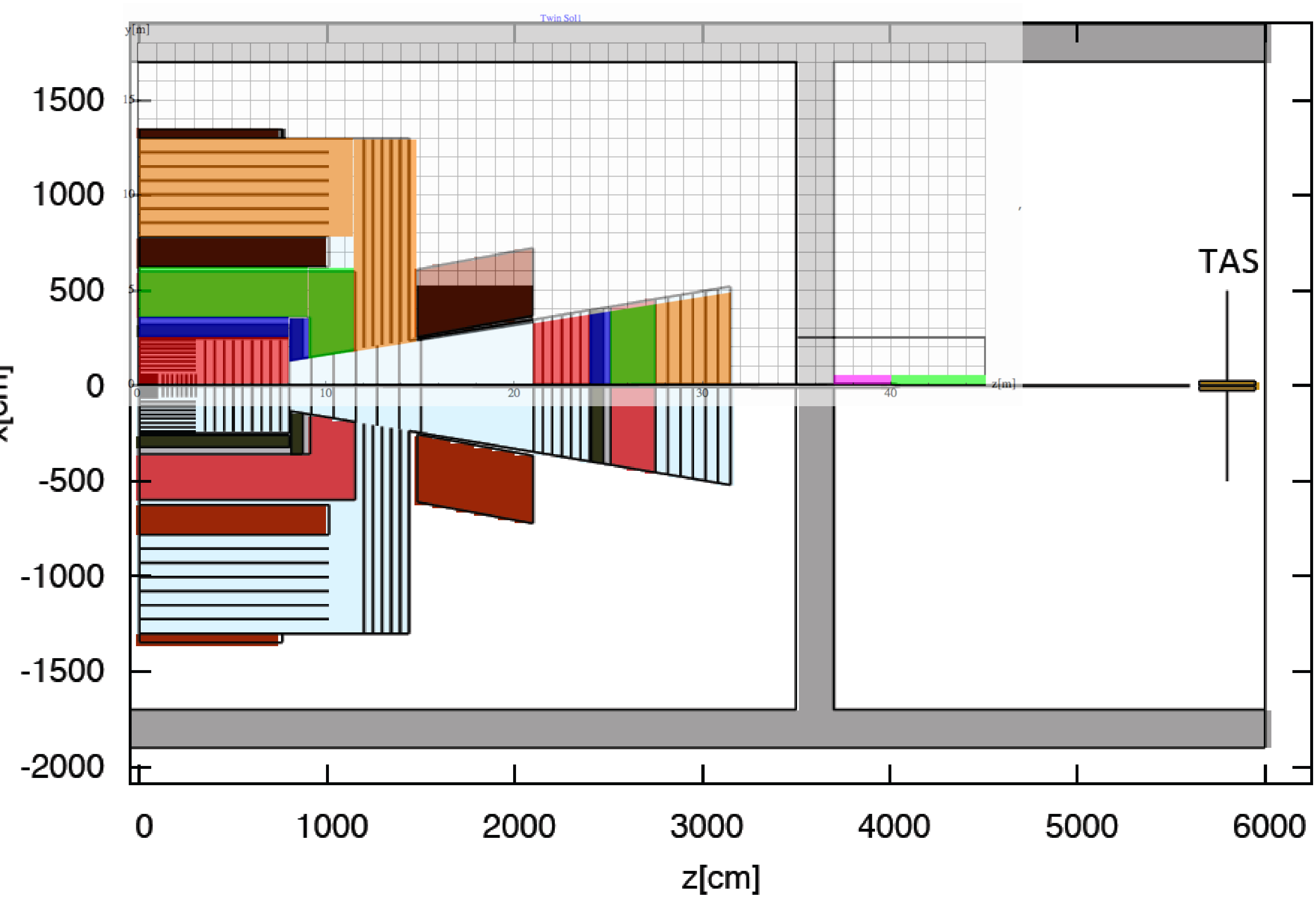


The CERN FLUKA Team (M. I. Besana, F. Cerutti) has implemented this geometry with

- The proper coil geometry
- The correct field map
- A basic tracker geometry with 3% of radiation length/layer and proper material
- A LArg Calorimeter with ATLAS material composition
- A Iron/Scintillator TILECAL style calorimeter.

→ Simulations started.

Geometry for Radiation Calculations, superposition for Check



Beampipe

Central beampipe: Cylinder
Beryllium R_{in} =2cm, R_{out}=2.1cm
From z=0 to z=800cm

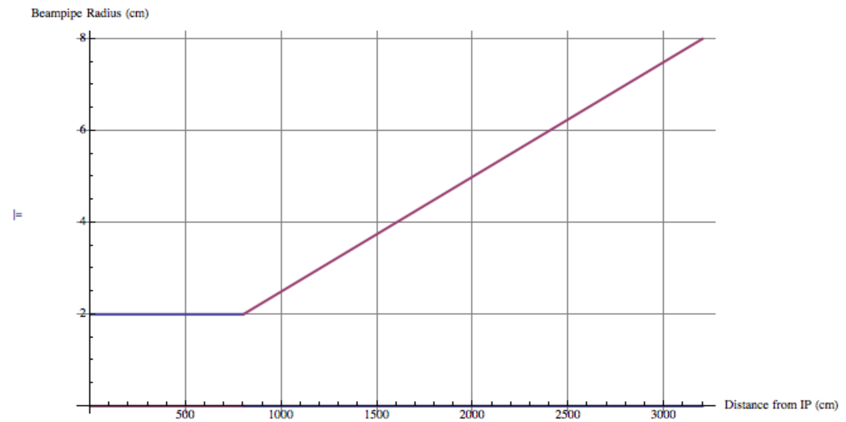
Forward beampipe: Cone
Beryllium 1mm wall thickness
Projective cone (inner envelope) along 2.5mRad
From z=800cm to z=32000cm
Radius at 32m: 8cm

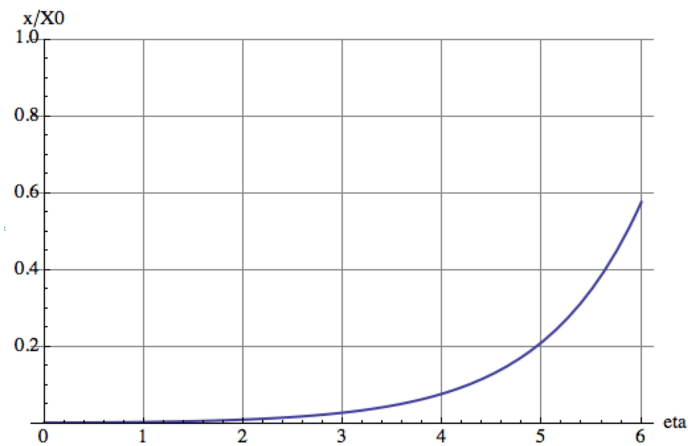
From z=3200 to 3230cm – cone to go from R=8cm to R=1cm-2cm (matching TAS), Aluminum

Between 3230cm and TAS – keep cylindrical beampipe, Aluminum

Cylindrical shield around this beampipe will be necessary.

Still to be checked with FCC aperture requirements !!



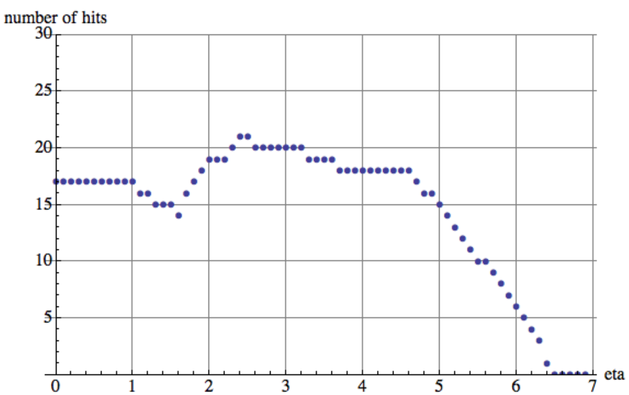


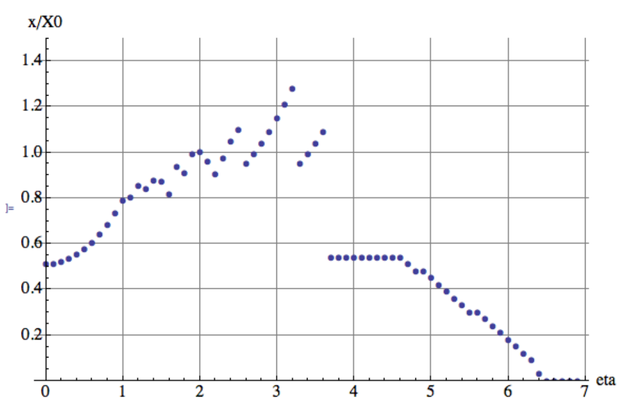
X0beampipe[eta_] := 0.00286*Cosh[eta]

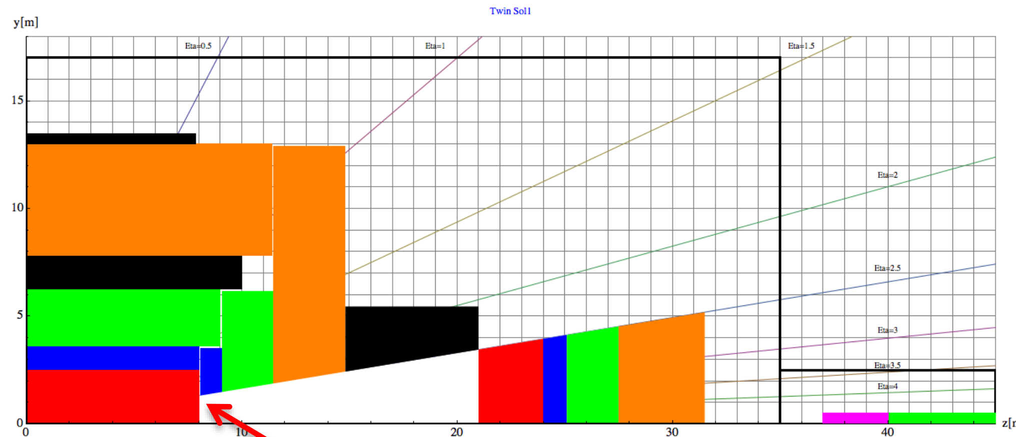
Tracker

Material composition in Volume (%):
Si 20%, C 42%, Cu 2%, Al 6%, Plastic 30%
X_0 of this mix: 14.37cm

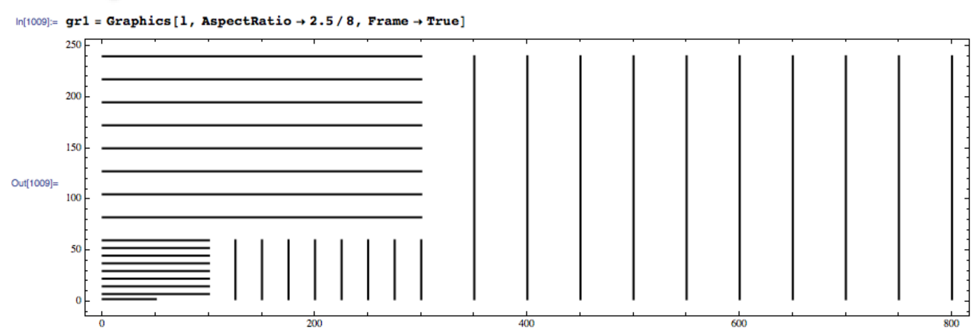
We assume 3% of radiation length per layer, i.e. each layer has a thickness of 0.43cm.



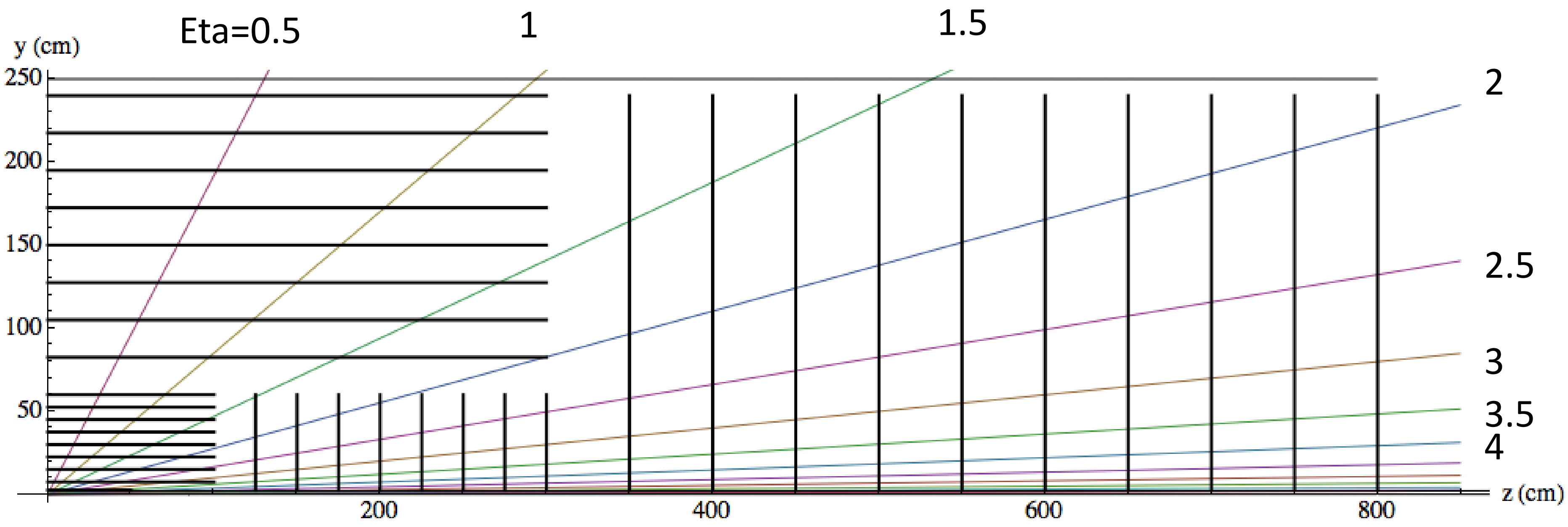




R_{out}=2.4m
Half the leaver arm at eta=2.6→ L=8m



Tracker

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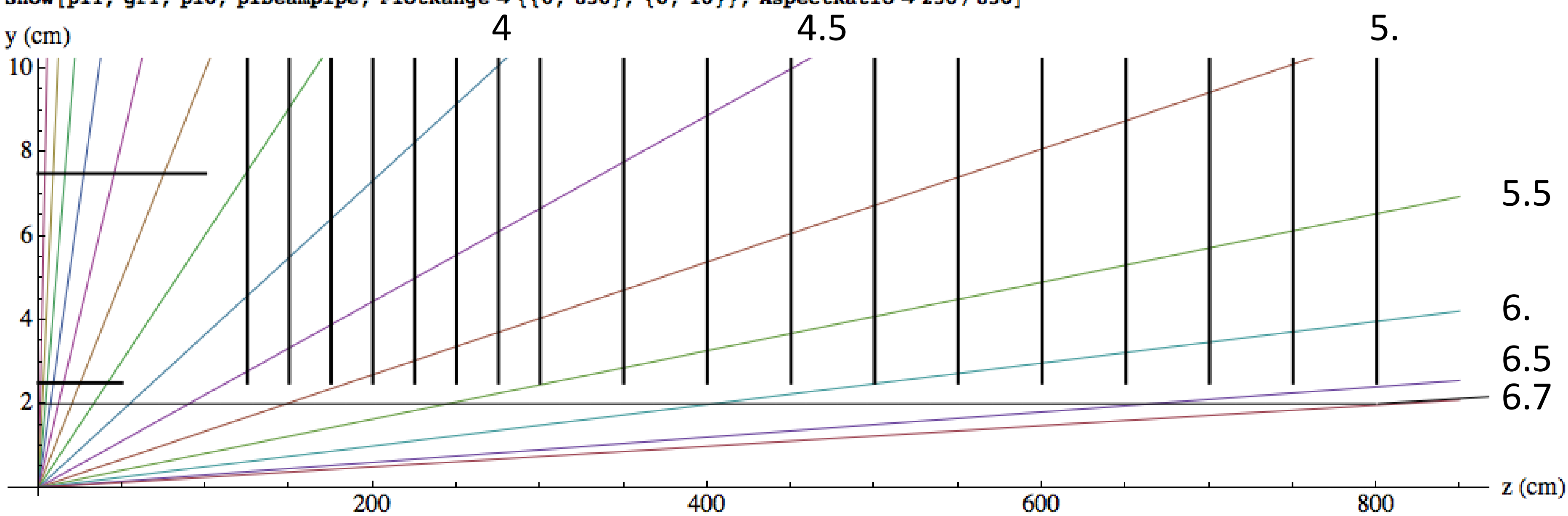


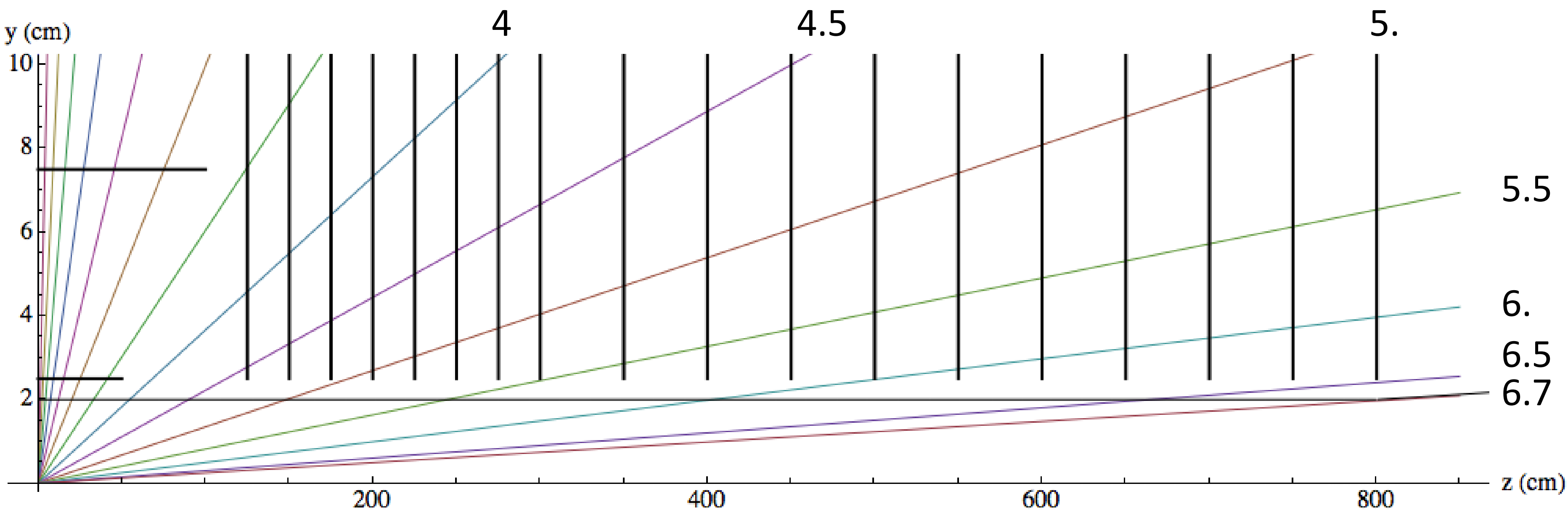
Tracker

Note: A track at eta=5 hits the first detector layer only at 200cm distance from the IP. We cannot dream of B-tagging a'la LHCb.

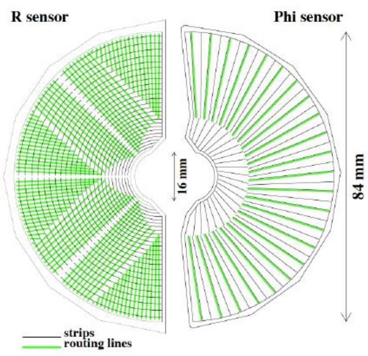
LHCb has the VELO with discs only a few mm from the beam in a secondary vacuum.

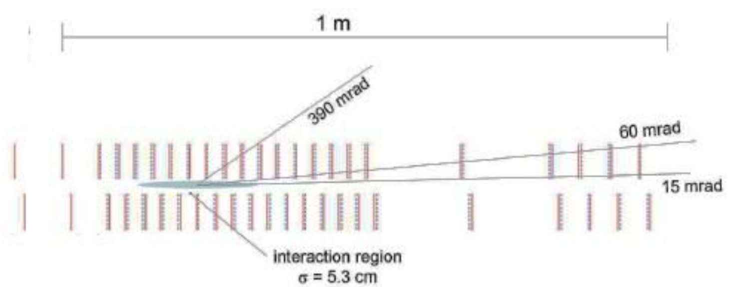
This arrangement has significant infrastructure around the IP which is not compatible with a co-existent central detector.

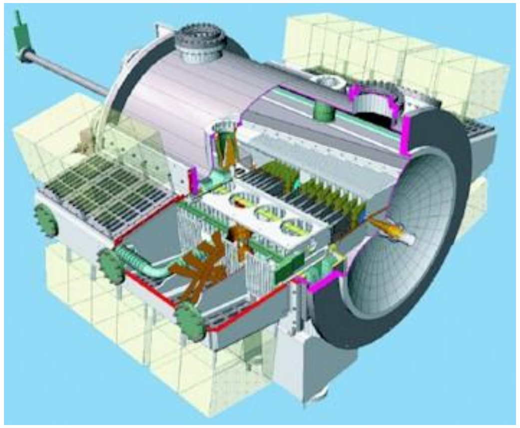
→ Clever ideas needed !!



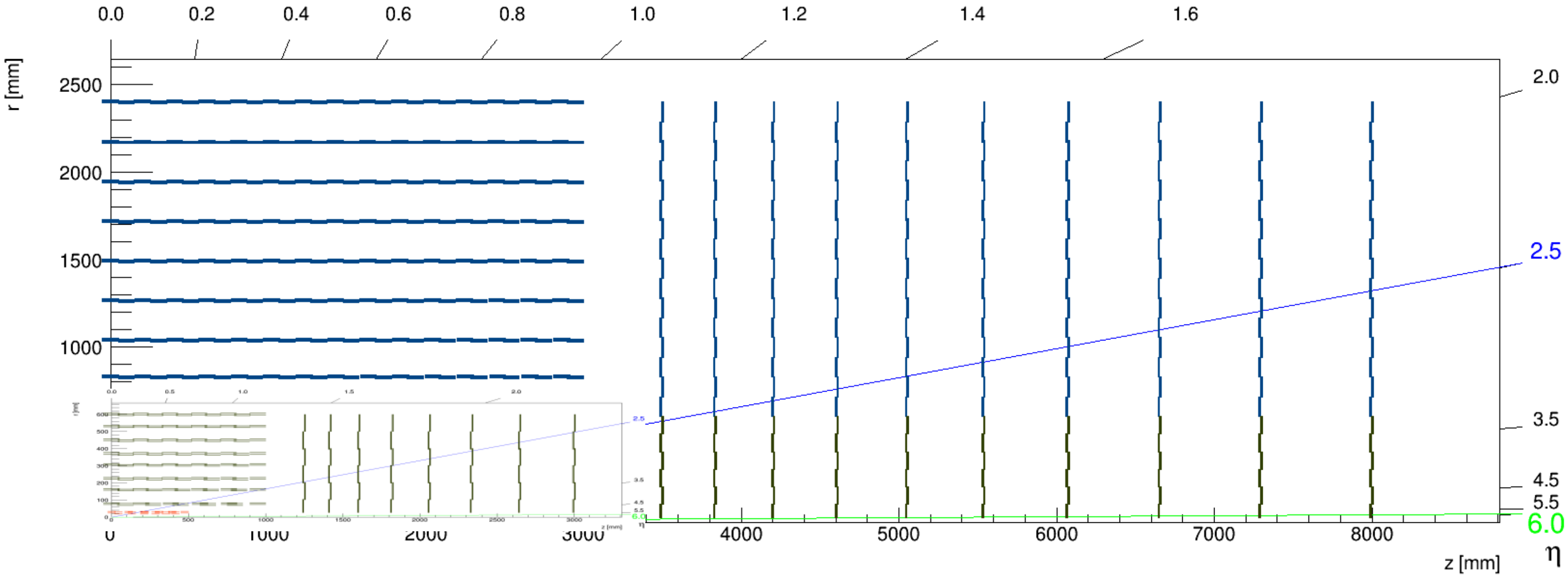
LHCb:

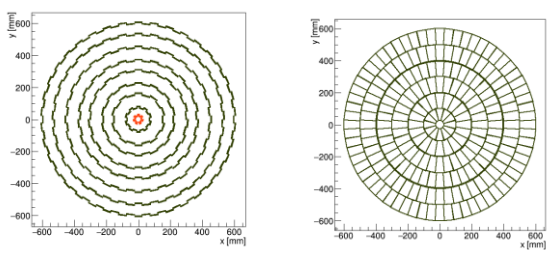


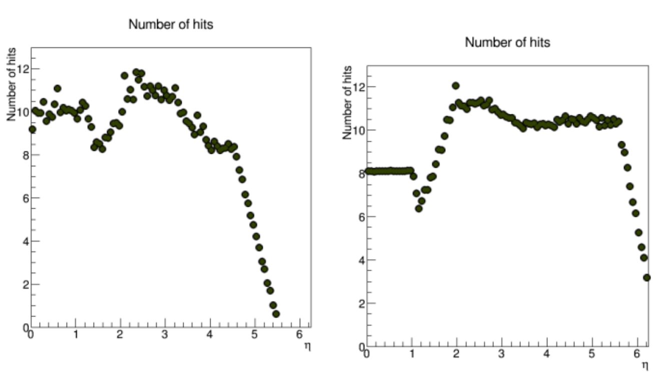


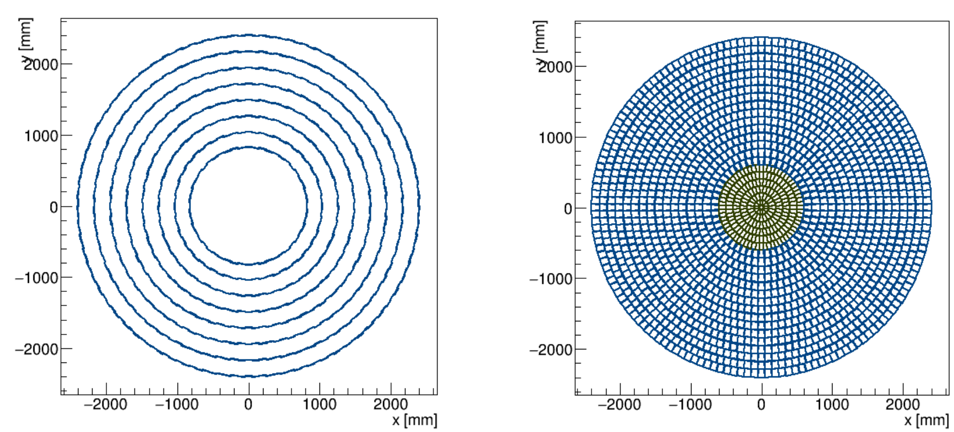


Tracker





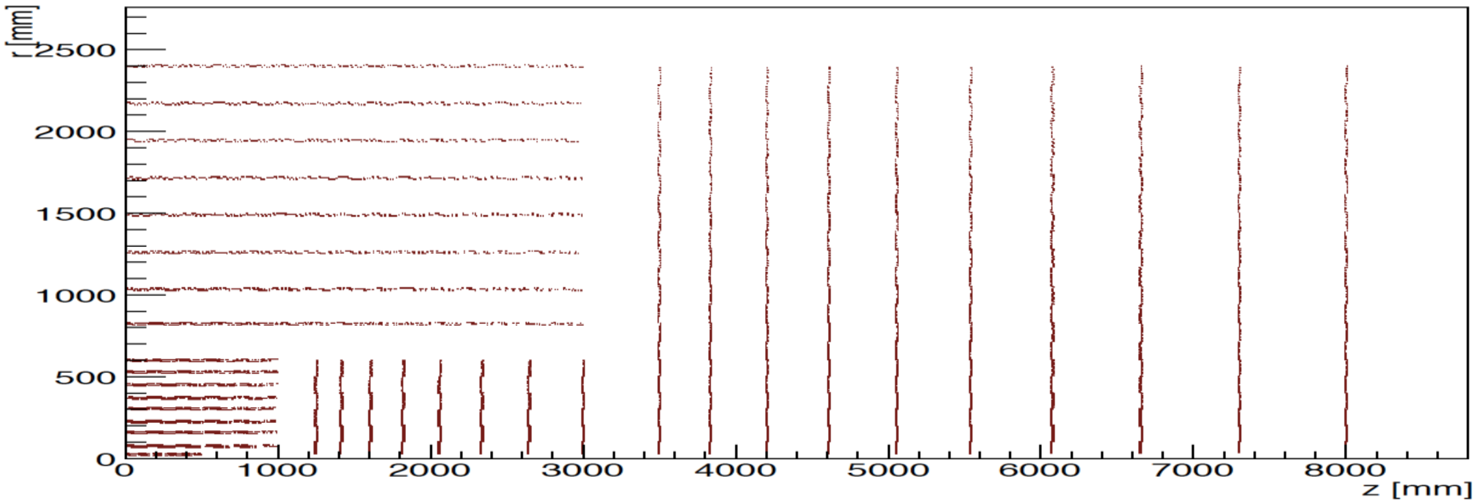


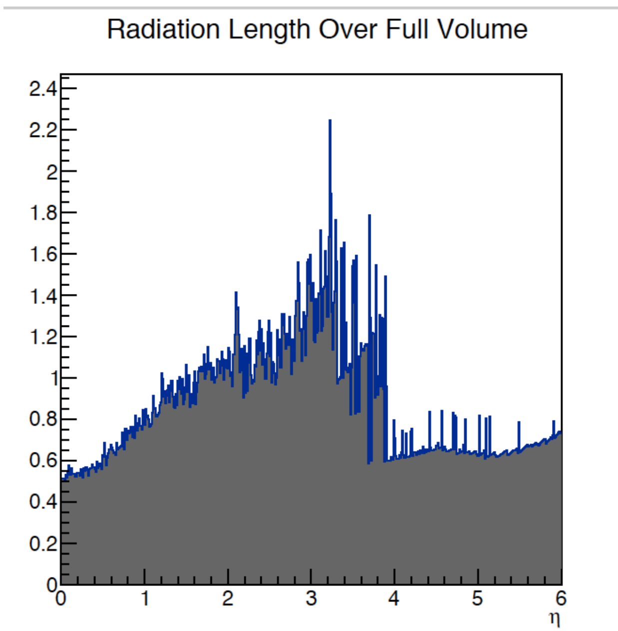


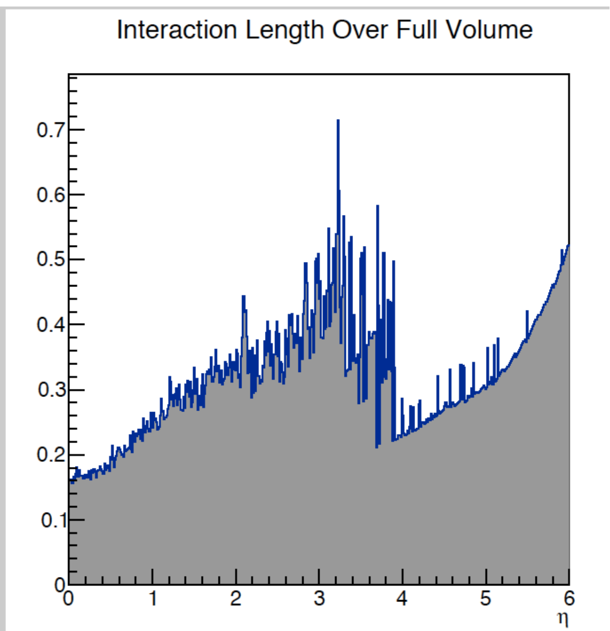
Z. Drasal, M. Manelli: Realistic Layout with correct modules using TKLayout (CMS PhaseII upgrade tool)

http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option2/errorsTRK.html

Tracker

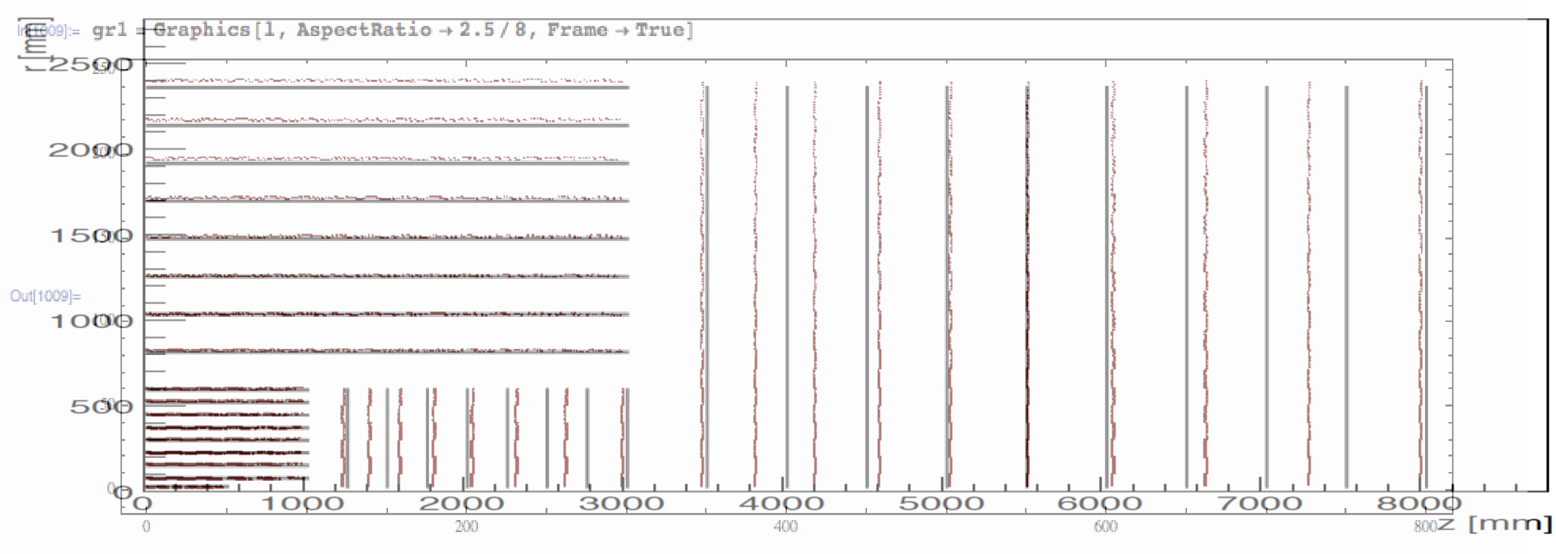


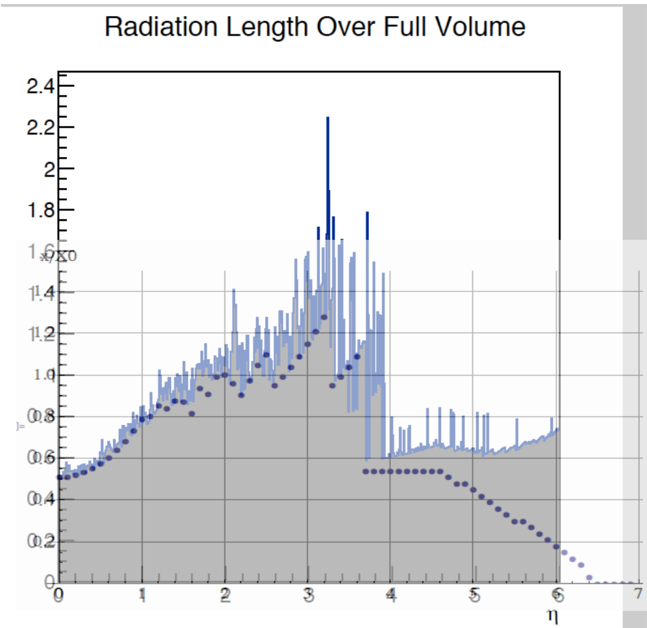


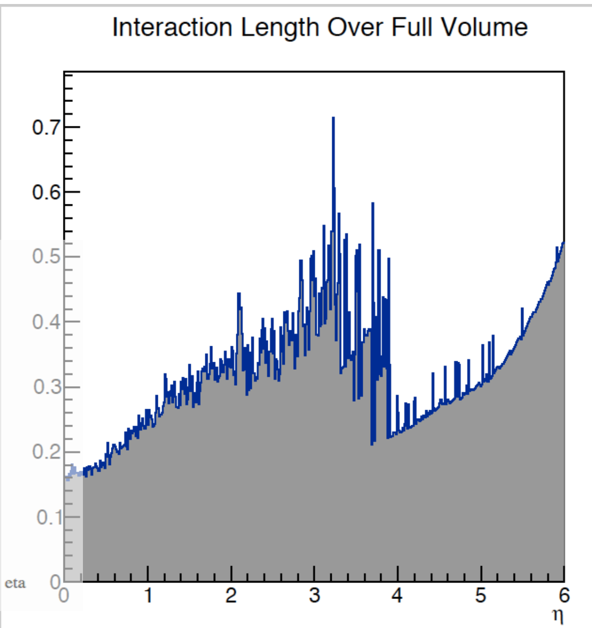


Z. Drasal,
M. Manelli

Tracker



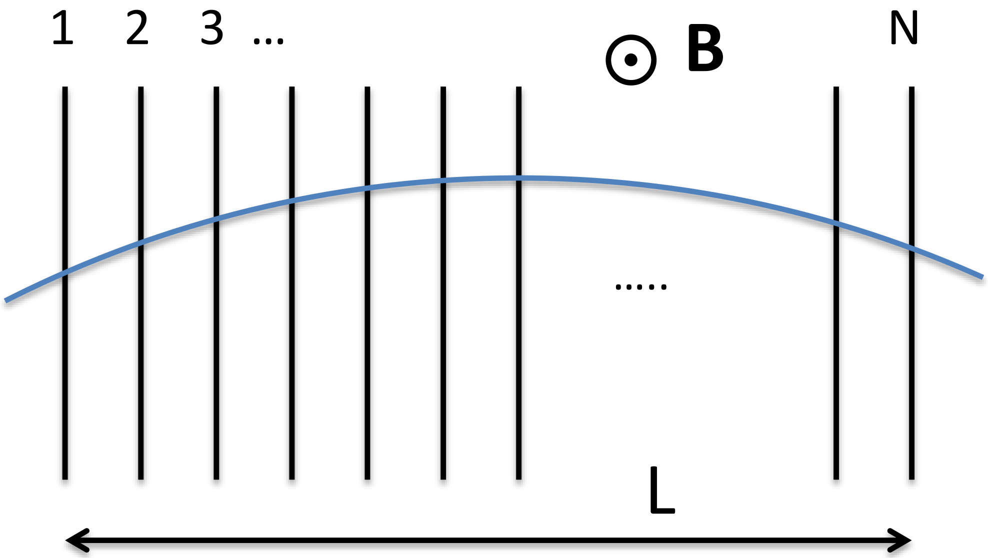




Realistic Layout with correct modules using TKLayout (CMS PhaseII upgrade tool)

Trivial model with x/X_0=3% per layer superimposed.

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

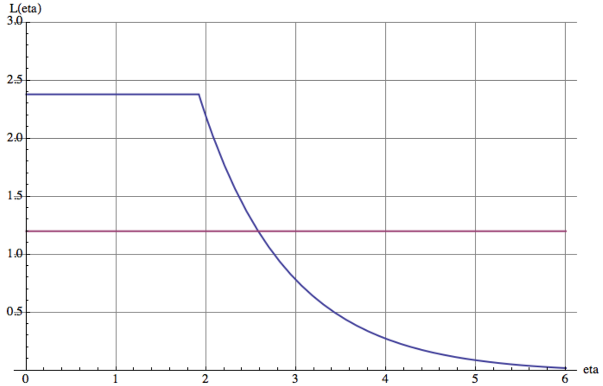
$$\frac{\Delta p_t}{p_t} = \frac{0.0136}{0.3\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}} \sqrt{\frac{10}{7}\,\frac{12+(N-1)N^2(N+1)}{(N-2)N(N+1)(N+2)}}$$

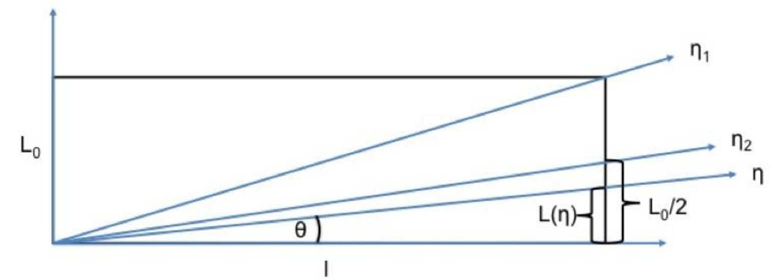
$$\approx \frac{0.0136}{0.3\beta\, B[T]\, L[m]} \sqrt{\frac{X_{tot}}{X_0}} \sqrt{\frac{10}{7}}$$

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

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

Tracker

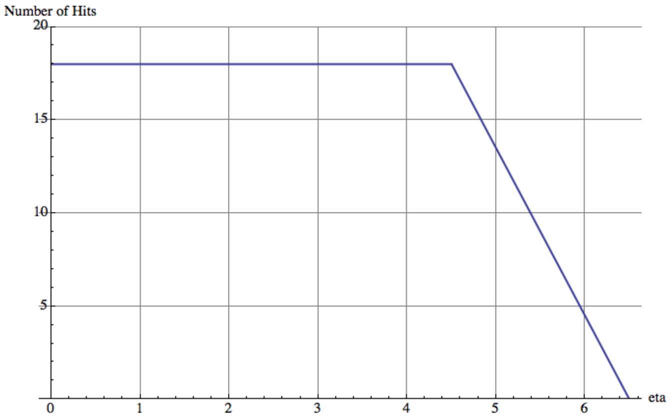




$$\eta_1 = -\ln\tan\left(\frac{1}{2}\arctan\frac{L_0}{l}\right) \qquad \eta_2 = -\ln\tan\left(\frac{1}{2}\arctan\frac{L_0}{2l}\right)$$

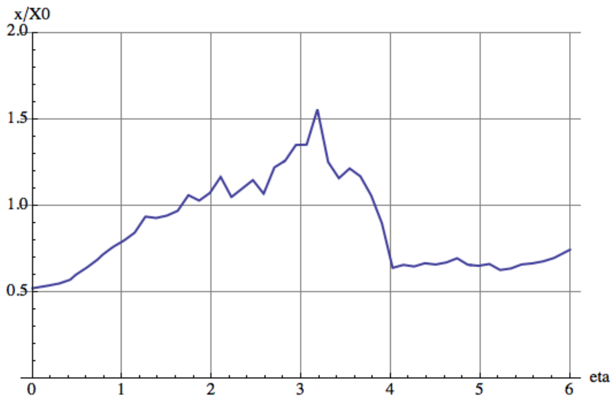
For a geometry with $L_0 = 2.4m$ and $l = 8m$ we have $\eta_1 = 1.9$ and $\eta_2 = 2.6$

$$L(\eta) = L_0 \quad \eta < \eta_1 \qquad L(\eta) = L_0\frac{\sinh\eta_1}{\sinh\eta} \quad \eta > \eta_1$$



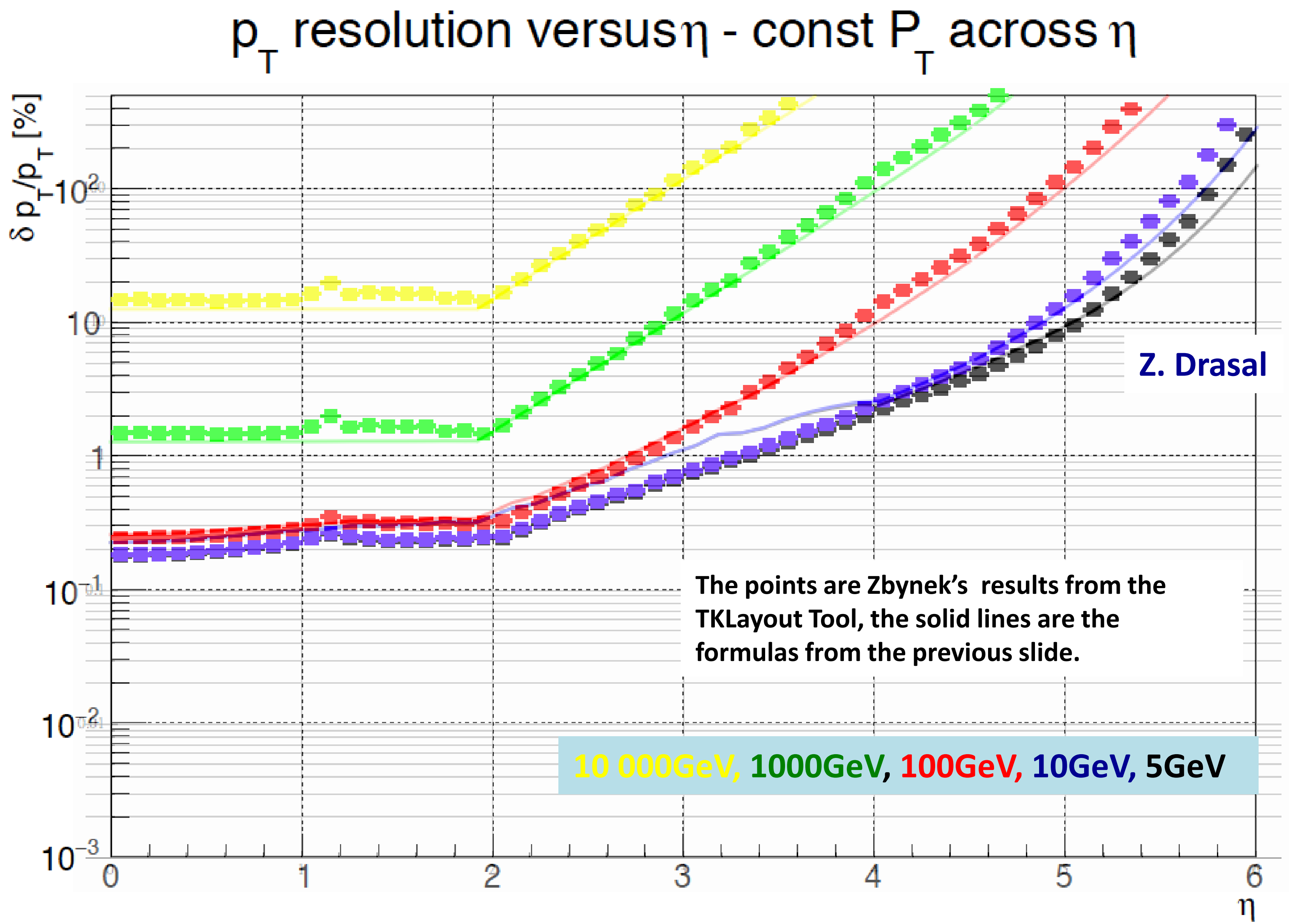
$$\frac{\Delta p_T}{p_T}\Big|_{reso.} = \frac{\sigma\, p_T}{0.3BL(\eta)^2}\sqrt{\frac{720}{N(\eta)+4}} \qquad \frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{0.0136}{0.3\,BL(\eta)}\sqrt{\frac{x}{X_0}(\eta)}$$

$$\frac{\Delta p_T}{p_T} = \sqrt{\left(\frac{\Delta p_T}{p_T}\Big|_{reso.}\right)^2 + \left(\frac{\Delta p_T}{p_T}\Big|_{m.s.}\right)^2}$$



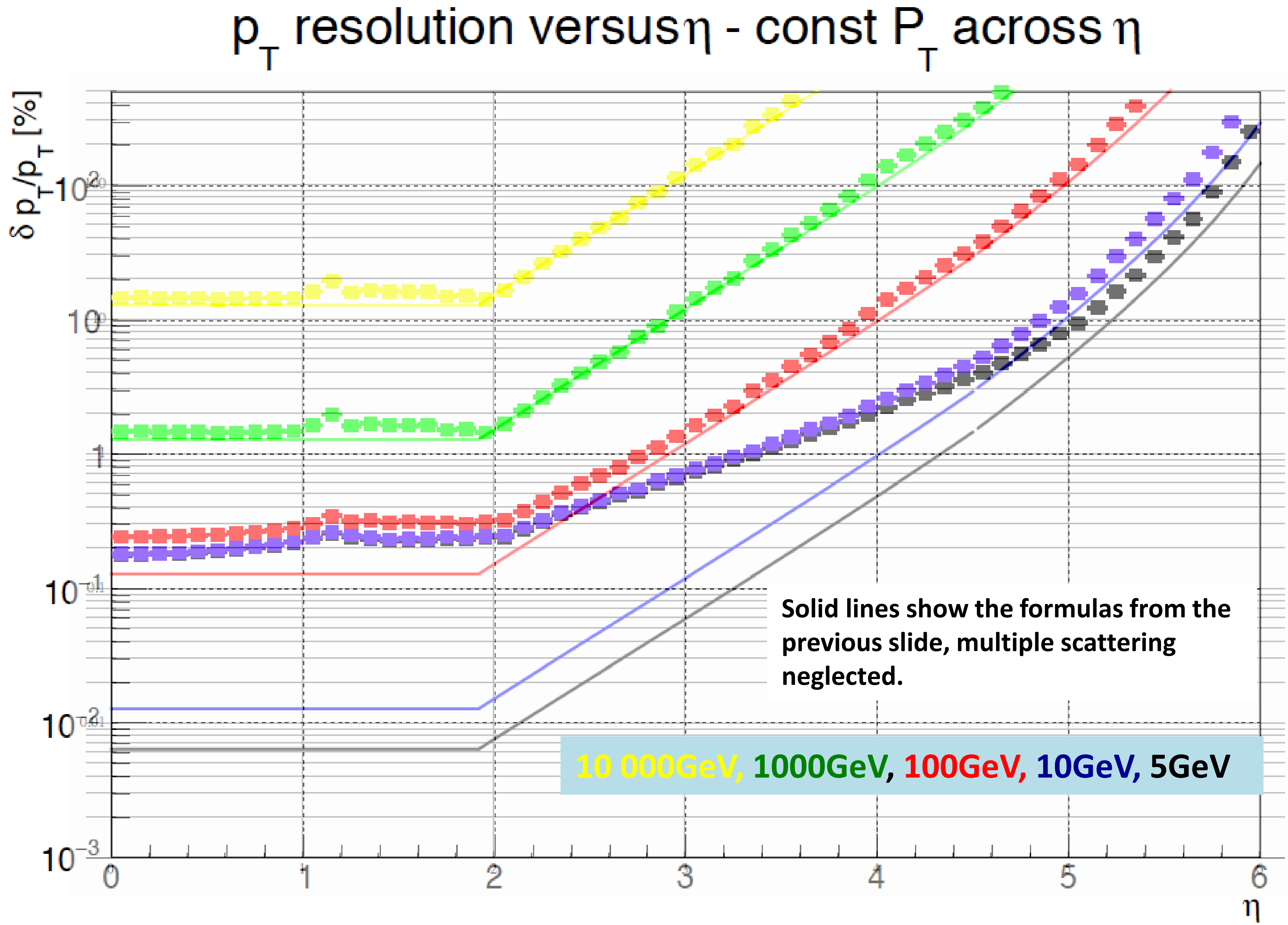

```
In[60]:= L0 = 2.4;
In[61]:= l = 8;
In[62]:= B = 6;
In[63]:= sig = 23 * 10 ^ (-6);
```

Tracker



p_T resolution versus η - const P_T across η
δ p_T/p_T [%]
10^2
10
1
10^-1
10^-2
10^-3
0
1
2
3
4
5
6
η
Z. Drasal
The points are Zbynek's results from the TKLayout Tool, the solid lines are the formulas from the previous slide.
10 000GeV, 1000GeV, 100GeV, 10GeV, 5GeV

Tracker



p_T resolution versus η - const P_T across η
$\delta p_T/p_T$ [%]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
0
1
2
3
4
5
6
η
Solid lines show the formulas from the previous slide, multiple scattering neglected.
10 000GeV, 1000GeV, 100GeV, 10GeV, 5GeV

Tracker

$$\frac{\Delta p_T}{p_T}\Big|_{reso.} = \frac{\sigma\, p_T}{0.3BL(\eta)^2}\sqrt{\frac{720}{N(\eta)+4}} \qquad \frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{0.0136}{0.3\,BL(\eta)}\sqrt{\frac{x}{X_0}(\eta)}$$

Large BL^2 needed for high momenta, but large BL also key to minimize multiple scattering contribution.

With BL 2.5 times larger than CMS, the multiple scattering contribution for the same amount of tracker material is a factor 2.5 smaller (reso: 0.8% → 0.32%).

How to scale the system and keep the performance constant ?

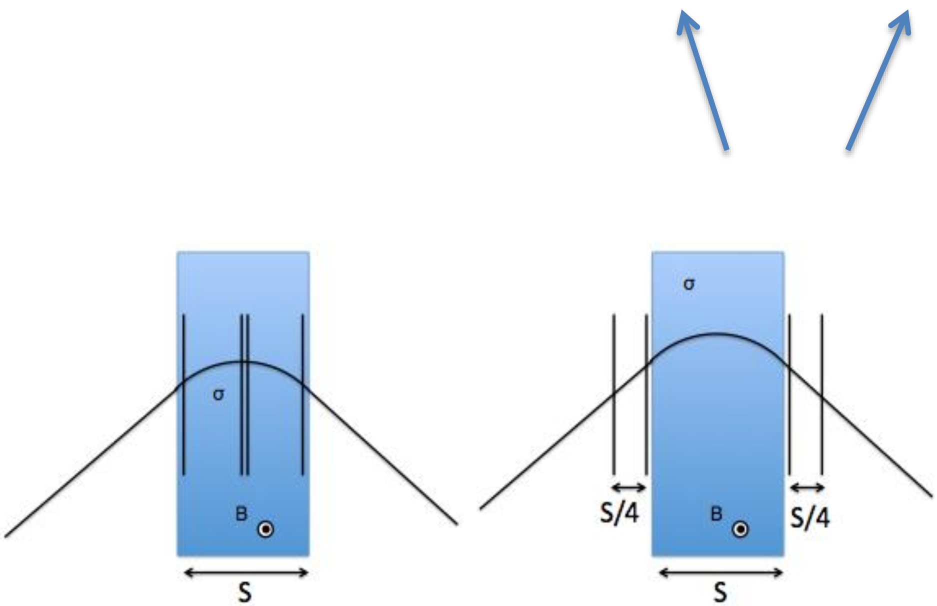
At constant B and 1/2 the tracker radius (free bore of solenoid from 12m to 10m) we need:
4 times the tracker resolution (20um → 5um) and
4 times less material budget (x/X_0=50% at eta=0 to x/X_0=12.5% at eta=0 i.e. 3% per Layer to 0.75% per layer)

These values are challenging but not out of reach.
Tracker instead of diam=4.8m, length=16m to half of that !

→ A final choice is part of an optimization that depends on future technologies
→ We will have to show 'cost scaling' models in the 2018 report.

Forward Tracking

Forward Tracking Resolution, Position Resolution

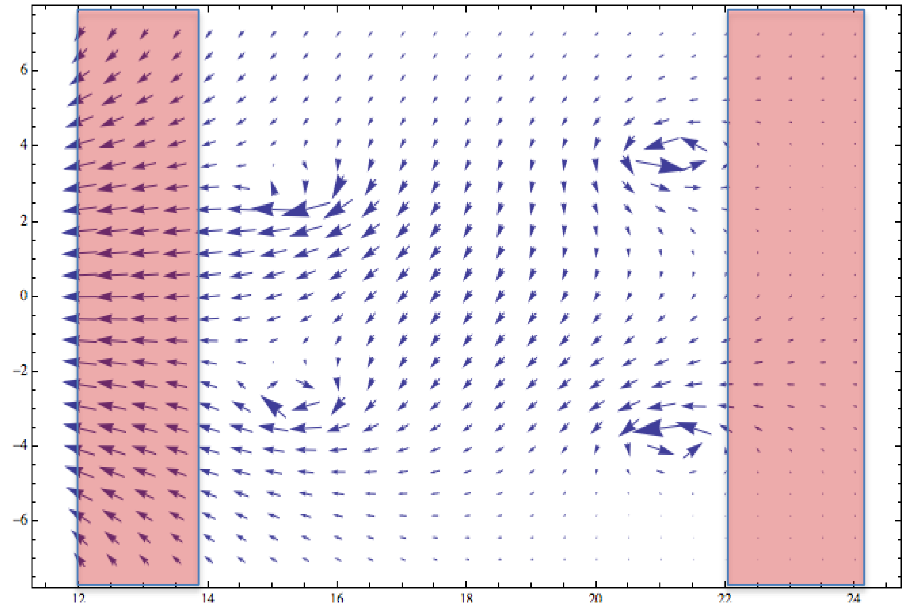


Using 4 tracking stations for a dipole with constant magnetic field and length S, the optimum spectrometer resolution is achieved by placing 2 stations in the center and one on each end to measure the sagitta.

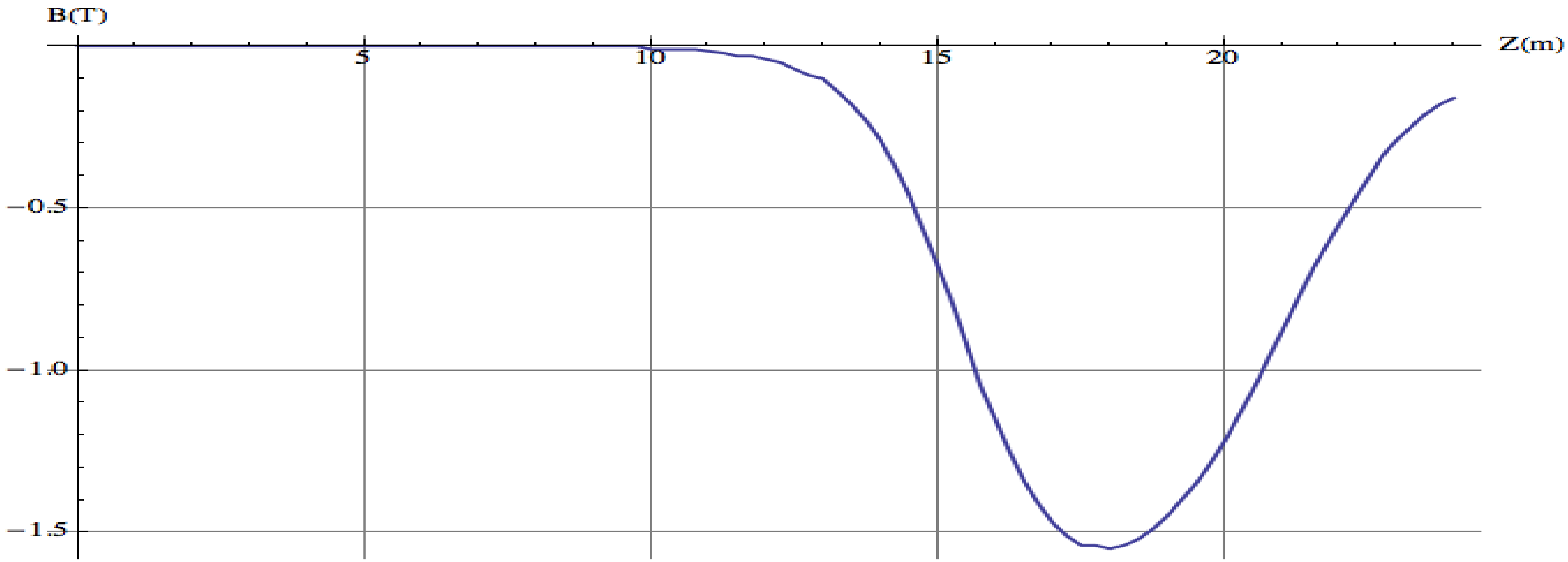
The same performance is achieved by placing the chambers outside the dipole at separation of S/4.

This is what LHCb uses, because if space is available it is more easy to implement the detectors outside, and also avoid occupancy from loopers in the field (detals on catching Ks etc. are of curse to be considered …)

We use this idea for now (is also easier to calculate ! It is just the Int Bdl that counts)

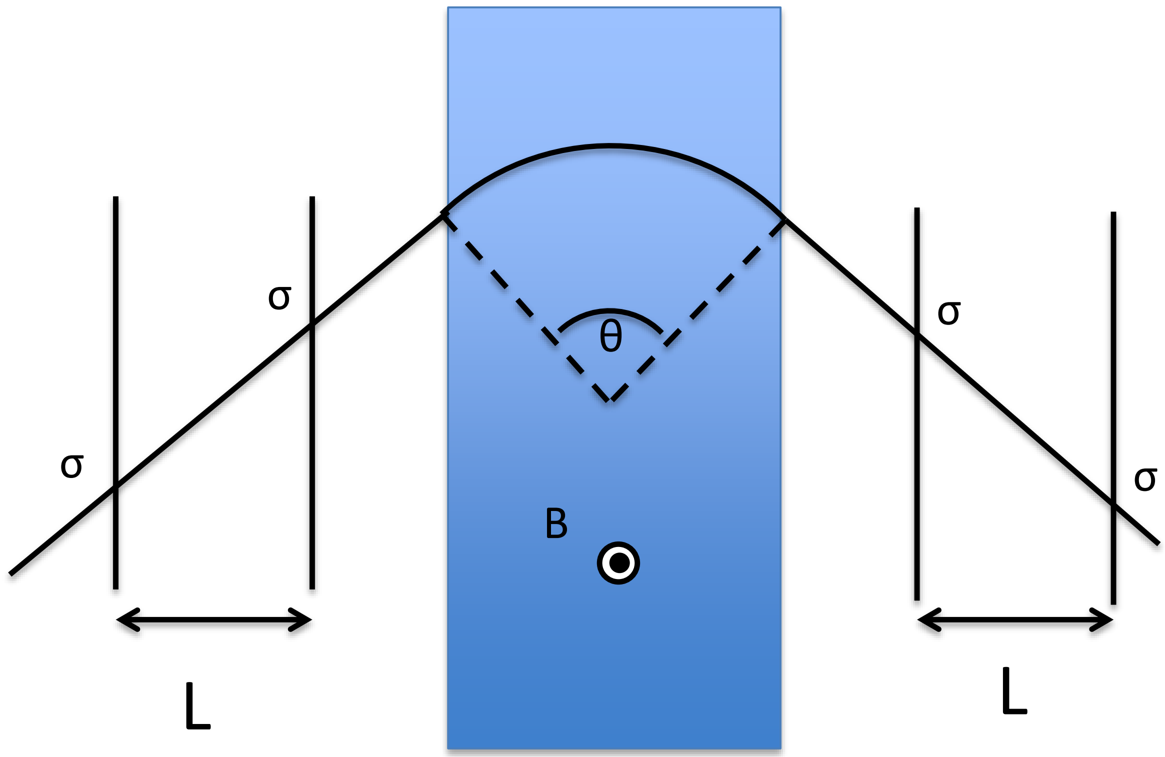


6
4
2
0
-2
-4
-6
12
14
16
18
20
22
24



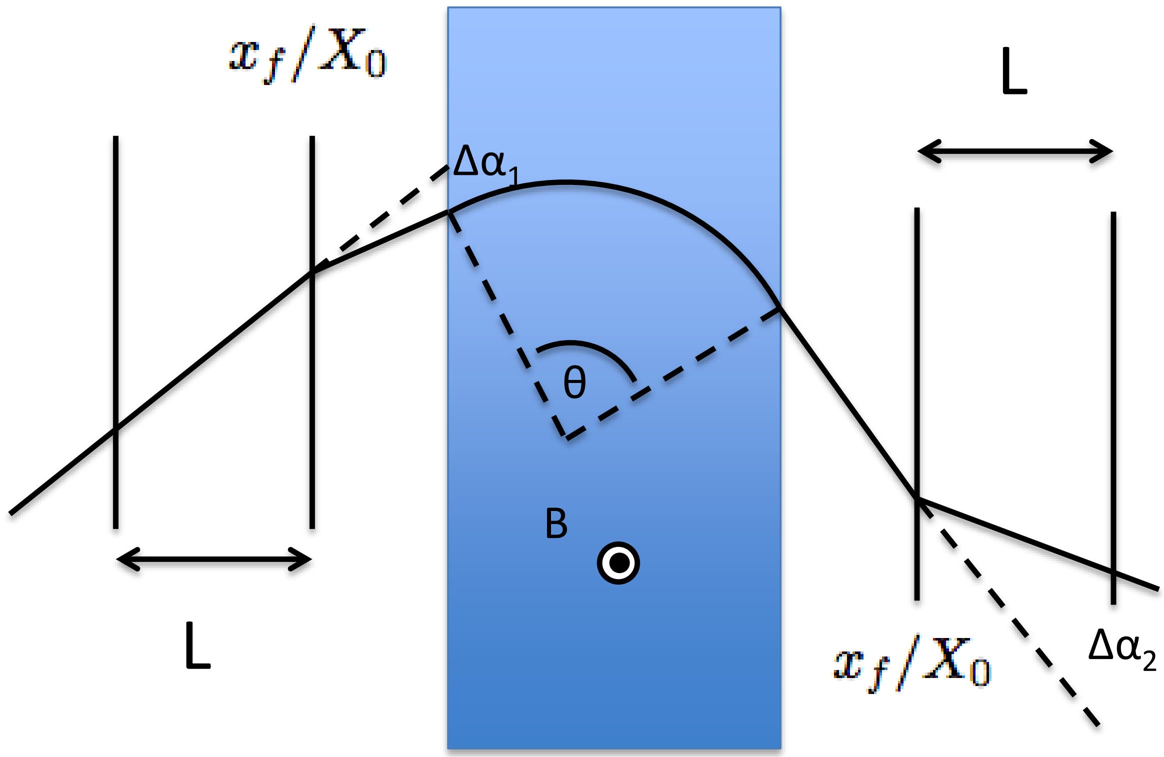
B(T)
Z(m)
5
10
15
20
−0.5
−1.0
−1.5

Forward Tracker Resolution, Position Resolution



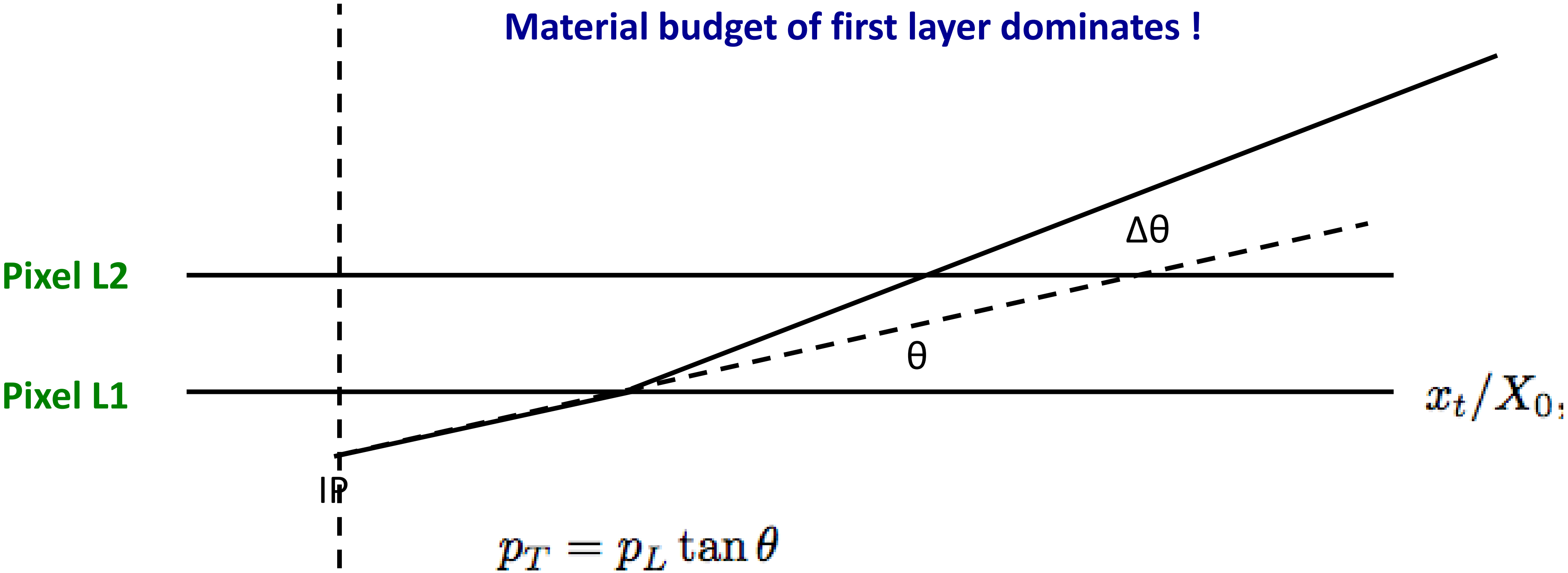
$$\left(\frac{\Delta p_L}{p_L}\right)^2 = \left(\frac{p_L}{0.3\int B_T dl}\right)^2 (\Delta\alpha_{res}^2 + \Delta\alpha_{ms}^2) \qquad \Delta\alpha_{res} = 2\sigma/L.$$

Forward Tracker Resolution, Multiple Scattering



$$\left(\frac{\Delta p_L}{p_L}\right)^2 = \left(\frac{p_L}{0.3\int B_T dl}\right)^2 (\Delta\alpha_{res}^2 + \Delta\alpha_{ms}^2) \qquad \Delta\alpha_{ms} = 0.0136/p_L\sqrt{2x_f/X_0}.$$

Forward Tracker Resolution, Measurement of angle



$$p_T = p_L \tan\theta$$

$$\left(\frac{\Delta p_T}{p_T}\right)^2 = \left(\frac{\Delta p_L}{p_L}\right)^2 + \left(\frac{1}{\sin\theta\cos\theta}\right)^2 \Delta\theta^2$$

$$\Delta\theta = \frac{0.0136}{p}\sqrt{\frac{x_t}{X_0}\frac{1}{\sin\theta}} = \frac{0.0136\,\sin\theta}{p_T}\sqrt{\frac{x_t}{X_0}\frac{1}{\sin\theta}}$$

Forward Tracker Resolution

$$\left(\frac{\Delta p_T}{p_T}\right)^2 = \left(\frac{2\sigma\, p_T}{\tan\theta 0.3L\ \int B_T dl}\right)^2 + \left(\frac{0.0136}{0.3\int B_T dl}\sqrt{2\frac{x_f}{X_0}}\right)^2 + \left(\frac{0.0136}{p_T\cos\theta}\sqrt{\frac{x_t}{X_0}\frac{1}{\sin\theta}}\right)^2$$

$$\left(\frac{\Delta p_T}{p_T}\right)^2 = \left(\frac{2\sigma\, p_T\ \sinh\eta}{0.3L\ \int B_T dl}\right)^2 + \left(\frac{0.0136}{0.3\int B_T dl}\sqrt{2\frac{x_f}{X_0}}\right)^2 + \left(\frac{0.0136\ \coth\eta}{p_T}\sqrt{\frac{x_t}{X_0}\cosh\eta}\right)^2$$

σ=30μm
Int Bdl=10 Tm
L=2m

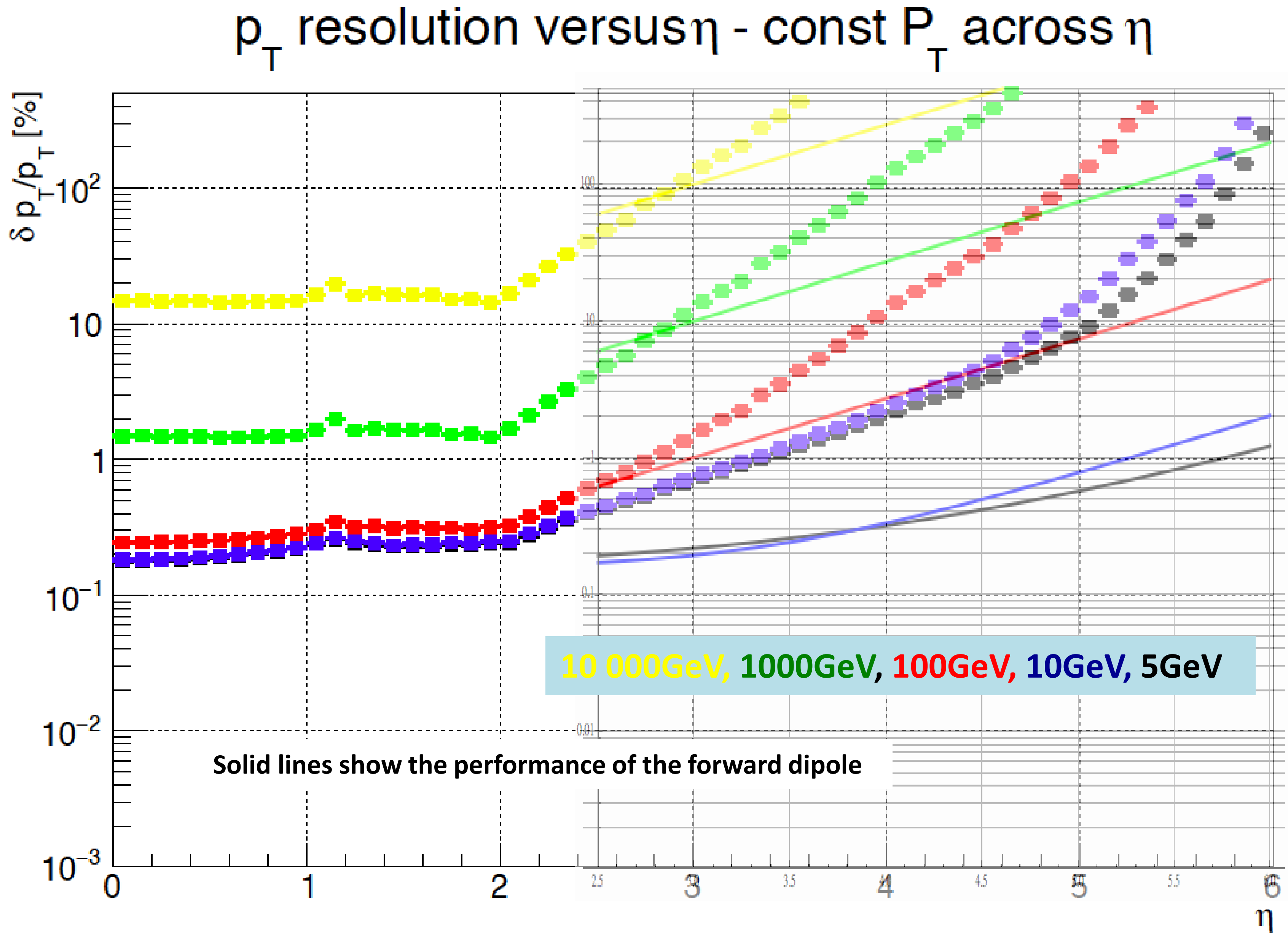
X_f/X_0=0.06
Int Bdl=10 Tm

X_t/X_0=0.03

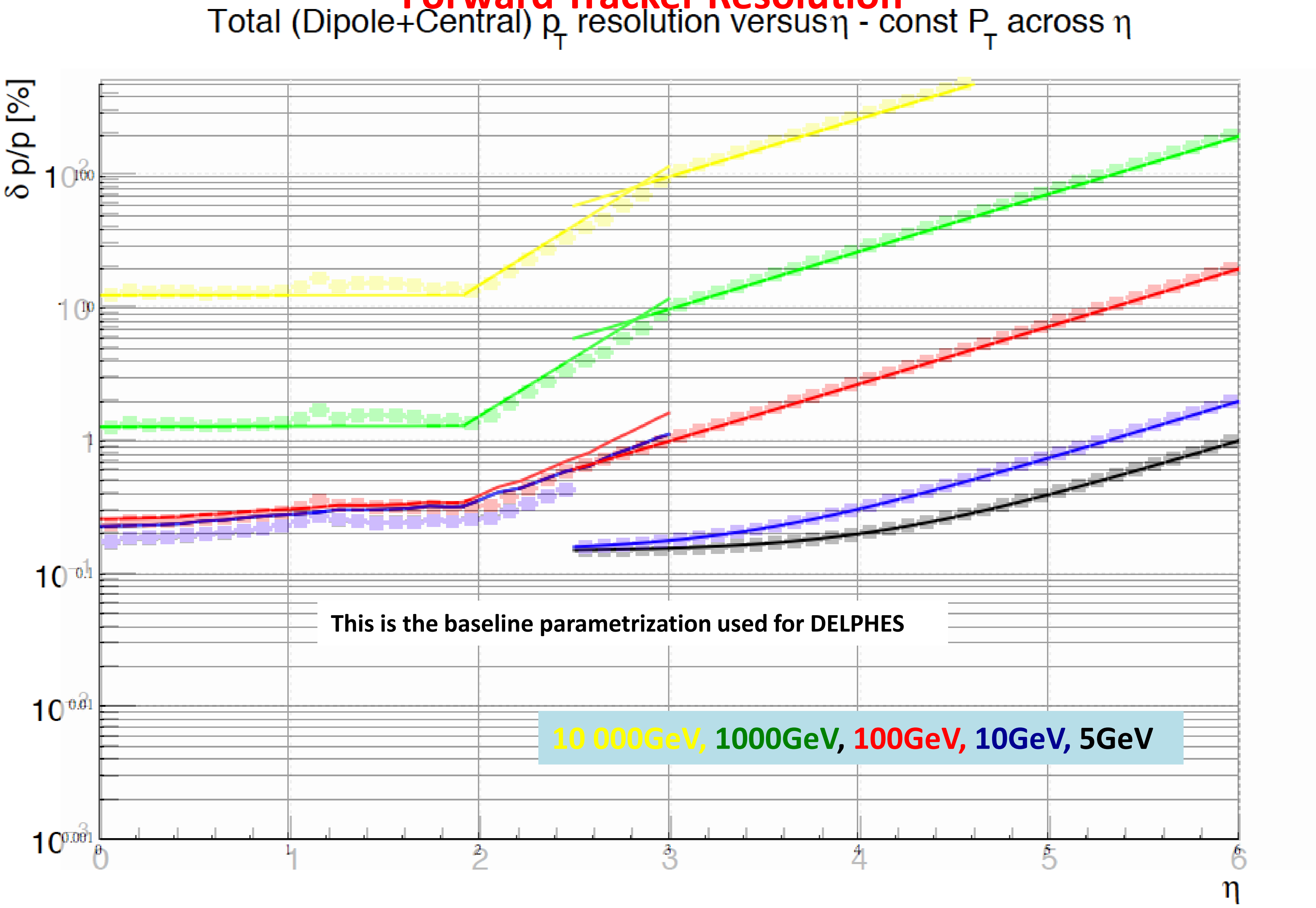
Using $L = 2\,\mathrm{m}$, $\sigma = 30\,\mu\mathrm{m}$, $x_f/X_0 = 0.06$, $x_t/X_0 = 0.03$

$$\frac{\Delta p_T}{p_T} = 10^{-3}\sqrt{1.5^2 + (10^{-2}p_T\sinh\eta)^2 + \left(2.4\frac{\coth\eta}{p_T}\sqrt{\cosh\eta}\right)^2}$$

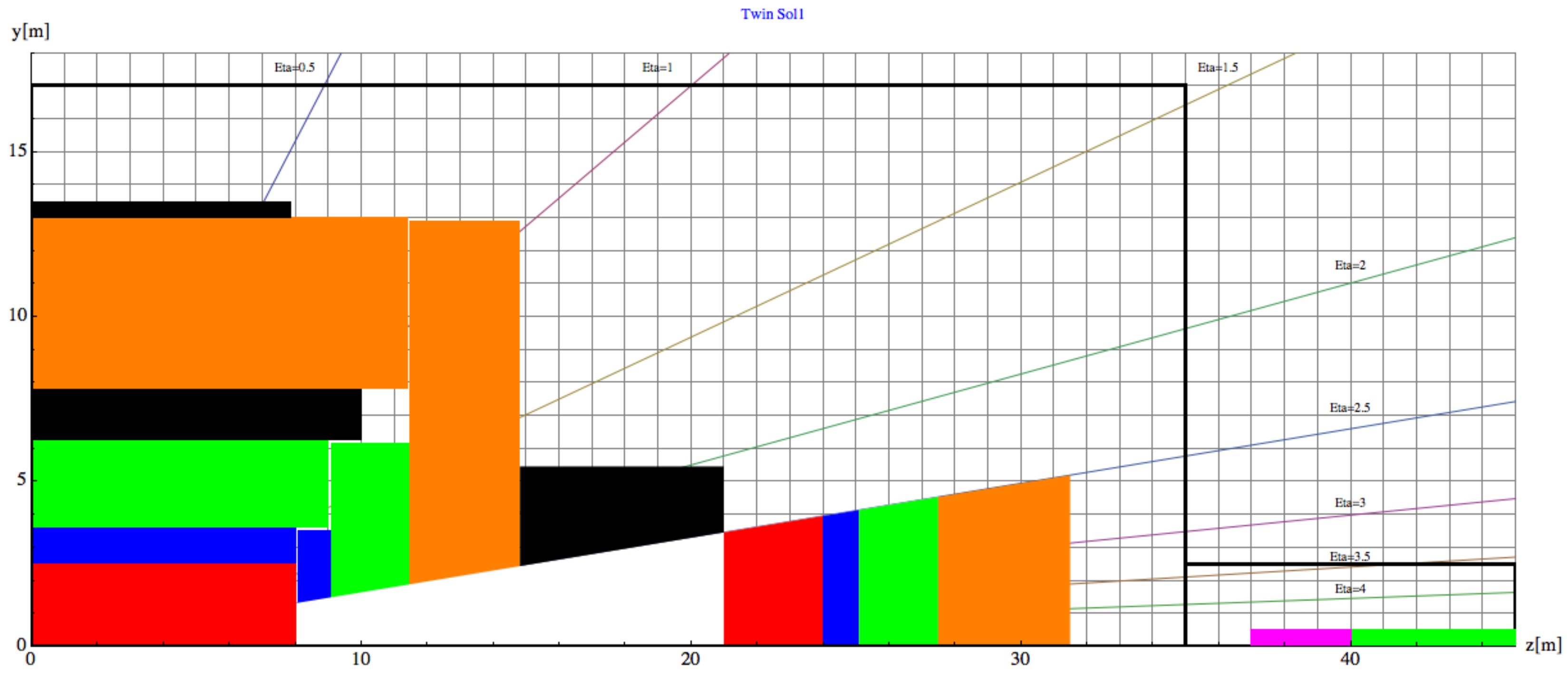
Forward Tracker Resolution



Forward Tracker Resolution



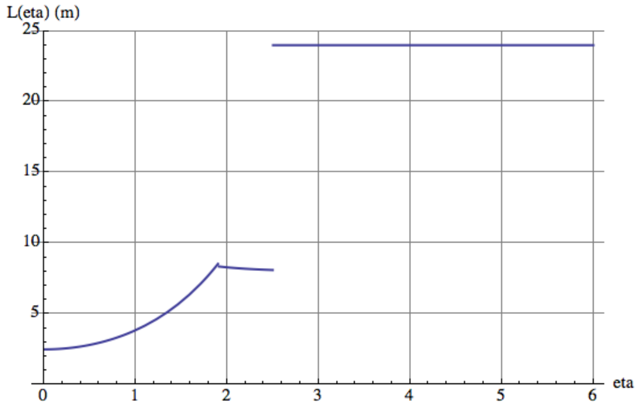
Calorimeter Granularity

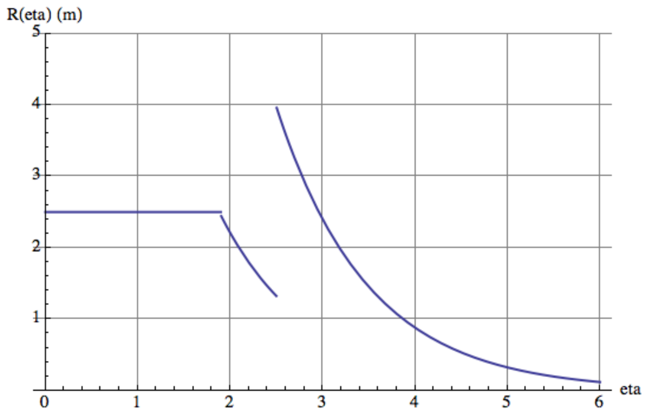


ECAL: granularity : 0.0125 x 0.0125 for eta<2.5,
0.025 x 0.025 for eta<4.0,
0.05 x 0.05 for eta<6.0

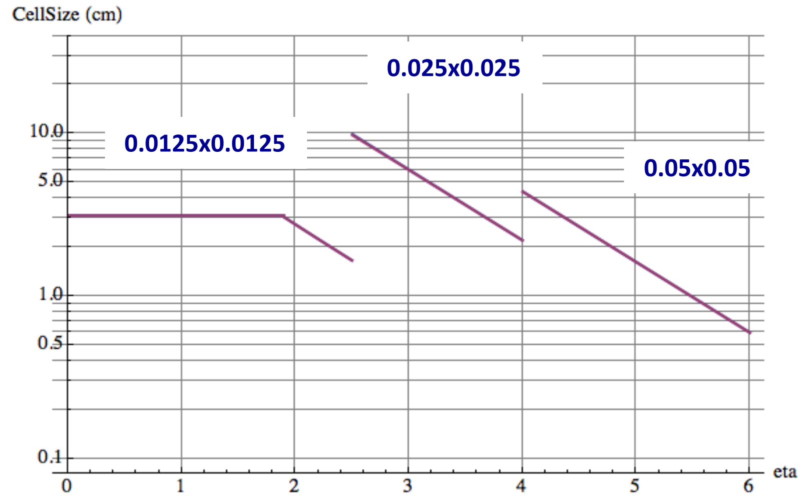
HCAL: granularity : 0.05 x 0.05 for eta<2.5,
0.1 x 0.1 for eta<4.0,
0.2 x 0.2 for eta<6.0

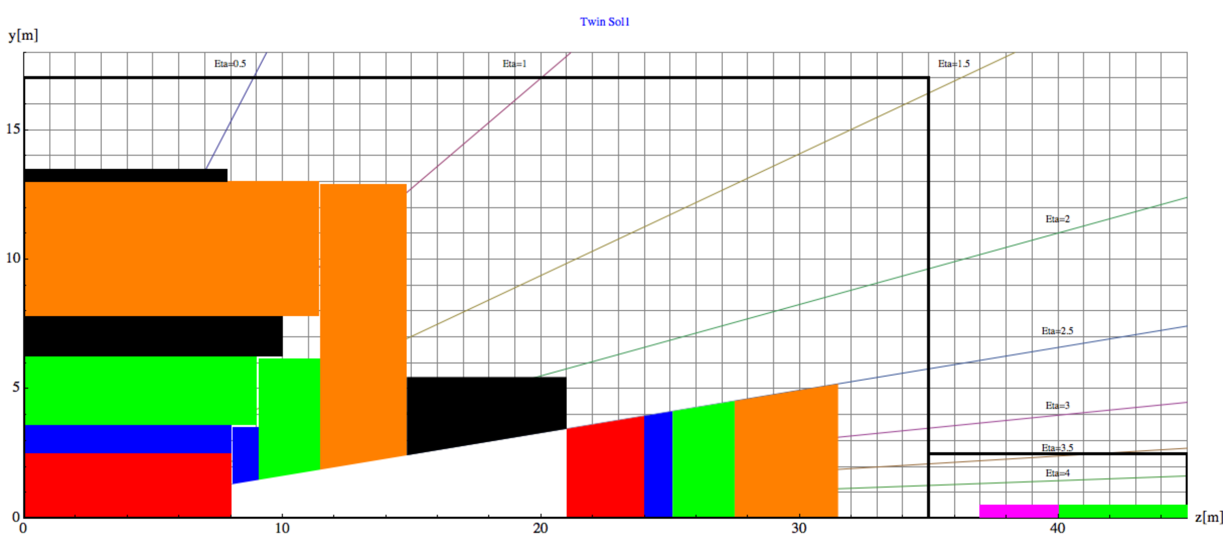
Calorimetry





Cell Size in cm





Calorimeters

Simple calorimeter (no longitudinal segmentation at the moment):

ECAL: granularity : 0.0125 x 0.0125 for eta<2.5,
0.025 x 0.025 for eta<4.0,
0.05 x 0.05 for eta<6.0

```
# set ECalResolutionFormula {resolution formula as a function of eta and energy}
  set ResolutionFormula {      (abs(eta) <= 4.0) * sqrt(energy^2*0.01^2 + energy*0.10^2) + \
                     (abs(eta) > 4.0 && abs(eta) <= 6.0) * sqrt(energy^2*0.01^2  + energy*0.10^2)}
```

i.e. stochastic term: 10%, constant term: 1%

HCAL: granularity : 0.05 x 0.05 for eta<2.5,
0.1 x 0.1 for eta<4.0,
0.2 x 0.2 for eta<6.0

```
# set HCalResolutionFormula {resolution formula as a function of eta and energy}
  set ResolutionFormula {       (abs(eta) <= 4.0) * sqrt(energy^2*0.03^2 + energy*0.50^2) + \
                     (abs(eta) > 4.0 && abs(eta) <= 6.0) * sqrt(energy^2*0.05^2 + energy*1.00^2)}
```

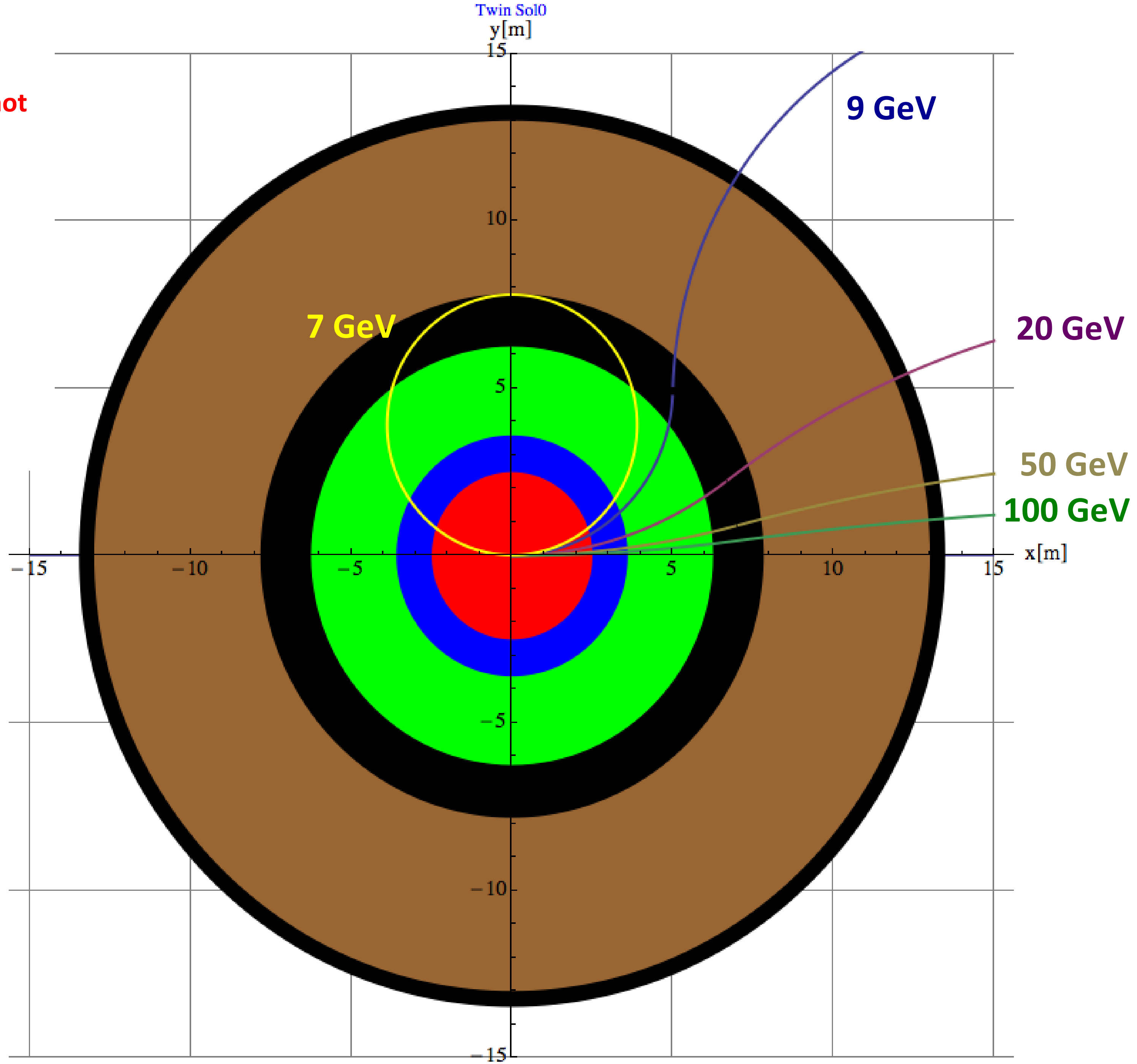
i.e. stochastic term: 50% (100%), constant term: 3% (5%)

Muon System

At B_0=6T and R_0=6m, Muons below 7GeV do not enter the muon system.

No Muon Trigger below 7GeV.

Possibly muon ID with HGCAL.



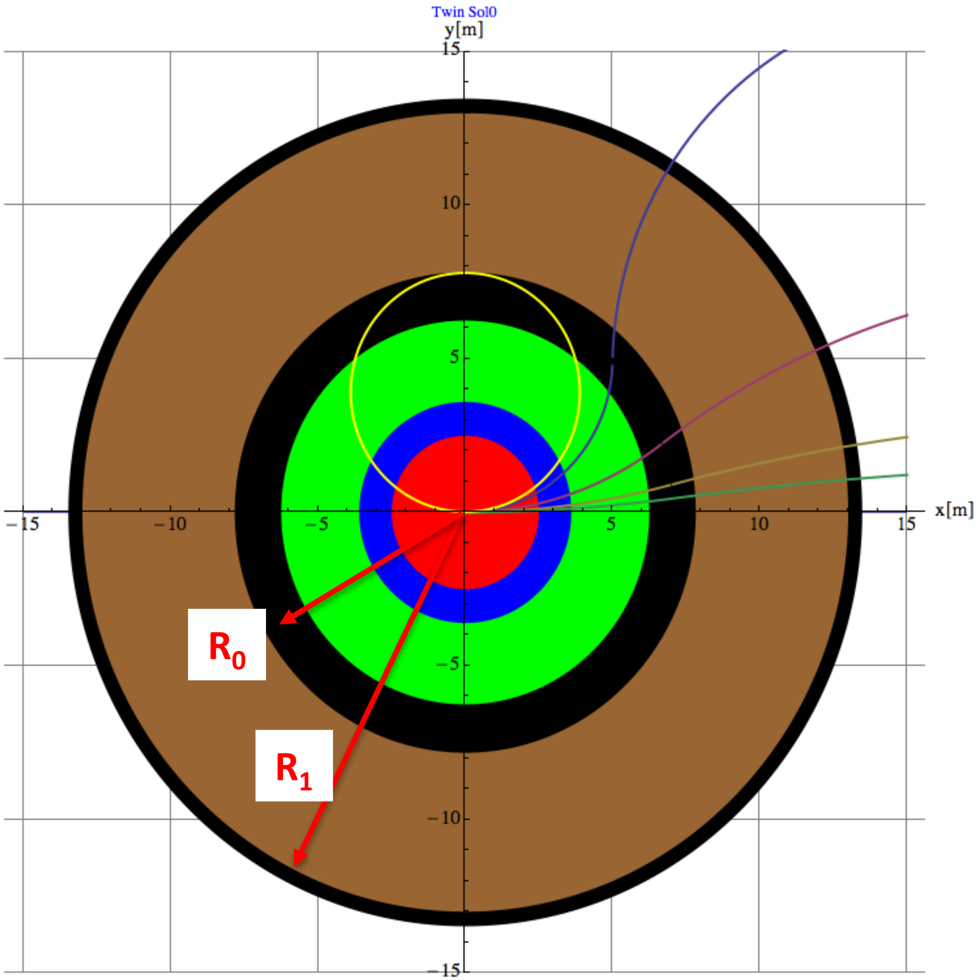
Muon Momentum can be measured by

1) The inner tracker
→ resolution plots from before

2) The track angle at the entrance of the muon system → Trigger

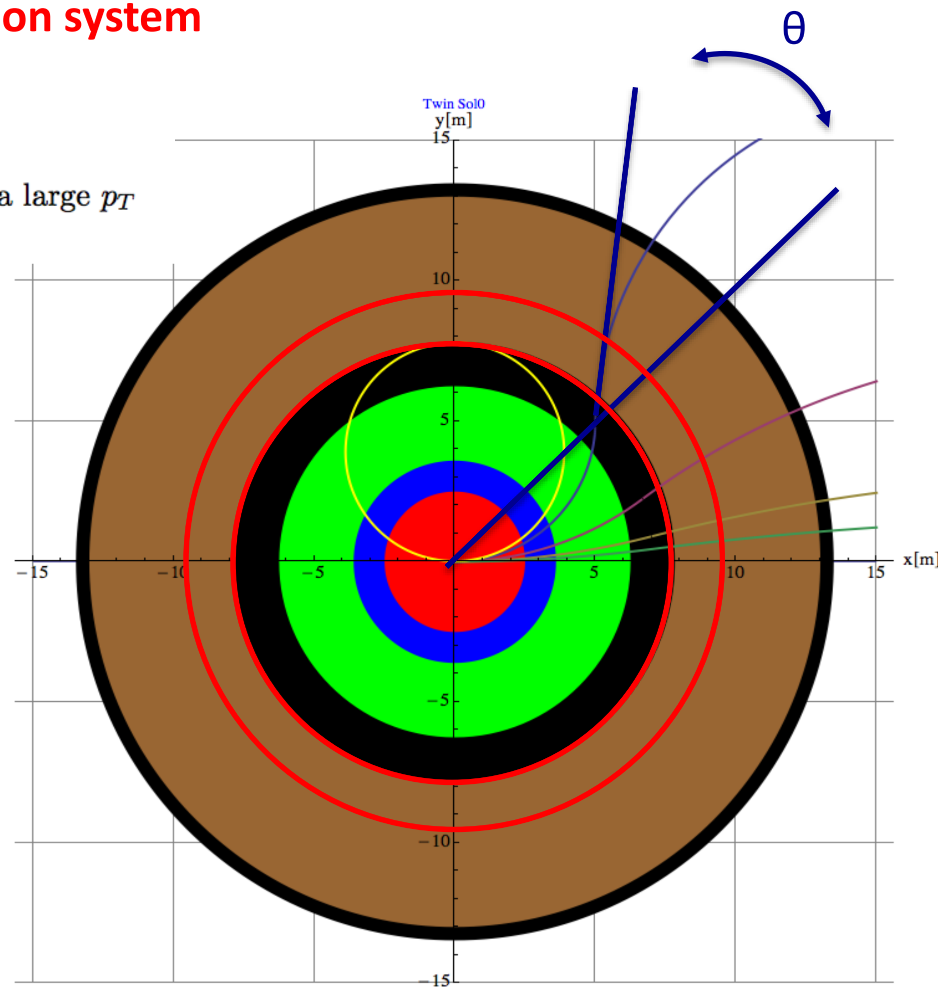
3) A sagitta measurement in the muon system (no iron → precise !)

4) The combined fit of inner tracker and outer layers of the muon system.



2) Track angle at the entrance of the muon system

$$\frac{\Delta p_T}{p_T} = \Delta\theta \sqrt{\left(\frac{2p_T}{0.3B_0R_0}\right)^2 - 1} \quad \approx \quad \frac{2p_T}{0.3B_0R_0}\Delta\theta \quad \text{for a large } p_T$$



10% at 10TeV, B_0=6T, R_0=6m
Δθ=50μRad

→ **2 stations at 1.5m distance with 50um position resolution**

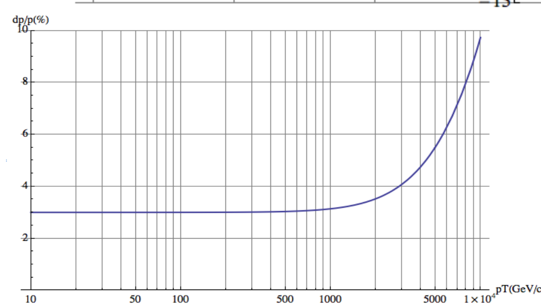
For low momentum, limit due to multiple scattering in the calorimeters and coil:

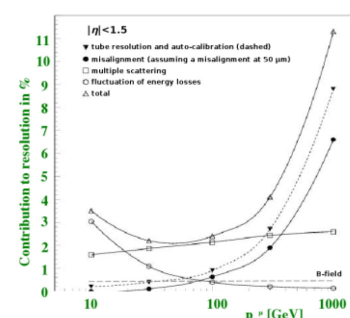
Calorimeter+Cryostat: 35X_0
HCAL: 110X_0
Coil: 5X_0
→ **x_{tot}/X_0 ≈150**

$$\frac{\Delta p_T}{p_T} = \frac{2 \times 0.0136}{0.3B_0R_0}\sqrt{\frac{x_{tot}}{X_0}}$$

B_0=6T, R_0=6m
→ **dp/p=3% !!!**

(CMS 9% because B_0R_0=1/3)





At eta=0 ATLAS type standalone Muon Performance up to 10TeV !!!

3) Sagitta measurement in the muon system

The return field is 2.45T

Measuring over the 5m lever arm with stations of sig=50um resolution we have

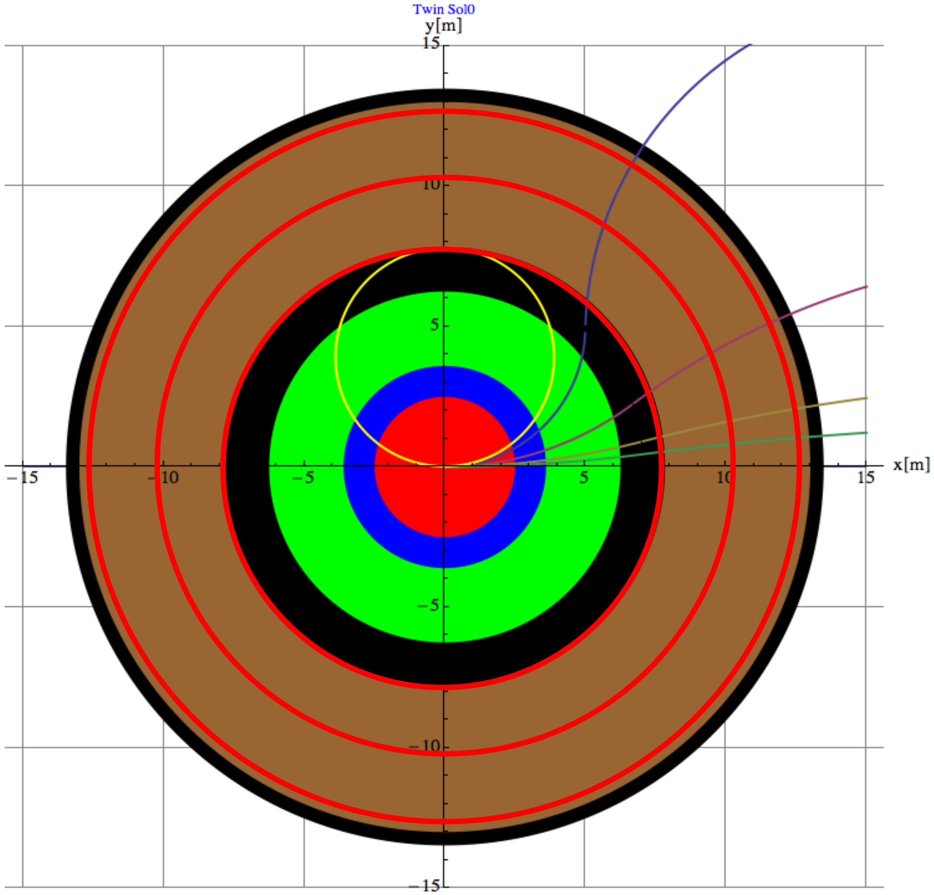
dp_T/p_T= sig*p_T/(0.3*B*L^2)*8
= 20% @ 10TeV

with possibly excellent performance at low p_T due to the absence of iron (vs. CMS) .

but very hard to beat the angular measurement at high p_T and the inner tracker at low p_T.

Surface > 5000 m^2

CMS sagitta measurement in the muon system is limited to dp_T/p_T = 20% due to multiple scattering alone.



CMS Muon Performance

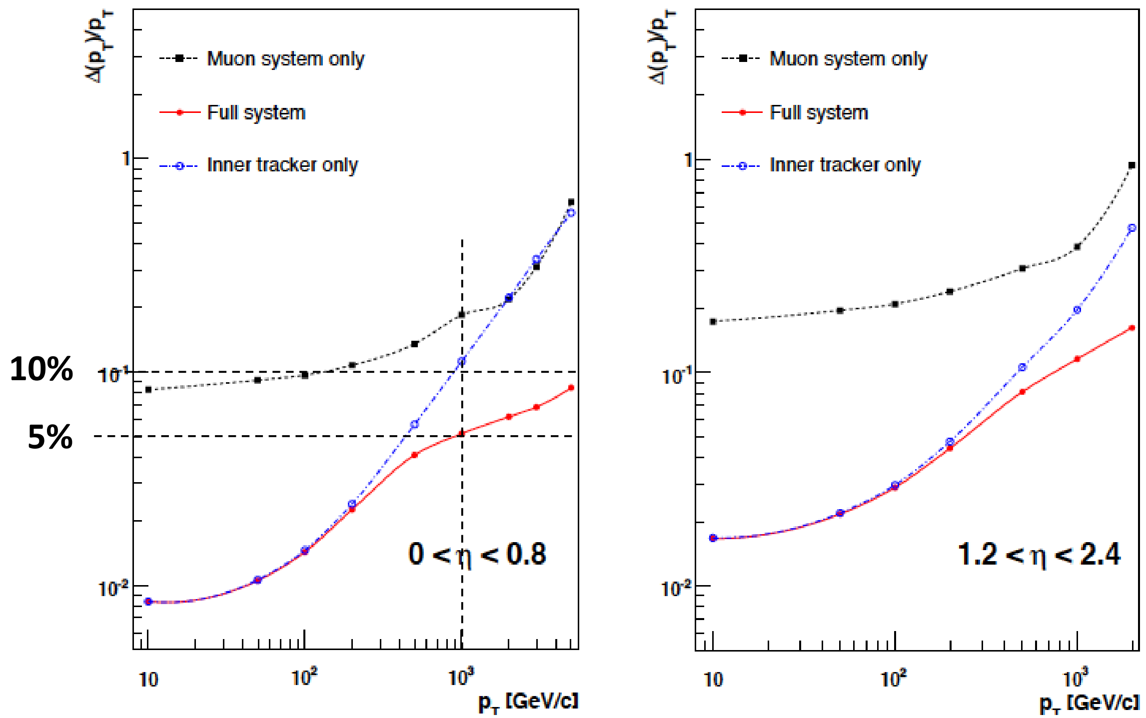


Figure 1.2: The muon transverse-momentum resolution as a function of the transverse-momentum (p_T) using the muon system only, the inner tracking only, and both. Left panel: $|\eta| < 0.8$, right panel: $1.2 < |\eta| < 2.4$.

Due to multiple-scattering in the detector material before the first muon station, the offline muon momentum resolution of the standalone muon system is about 9% for small values of η and p for transverse momenta up to 200 GeV [17]. At 1 TeV the standalone momentum resolution varies between 15% and 40%, depending on $|\eta|$. A global momentum fit using also the inner tracker

Combined Measurement

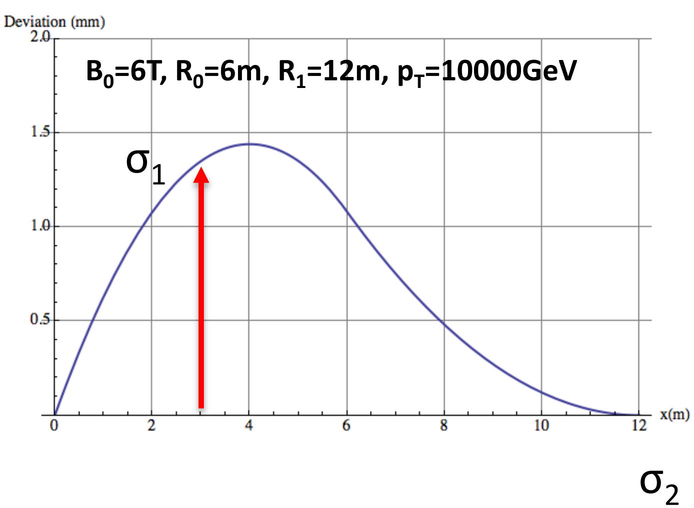
If the full flux is returned trough the muon system, the muon trajectory at the exit of the system points exactly to the IP !

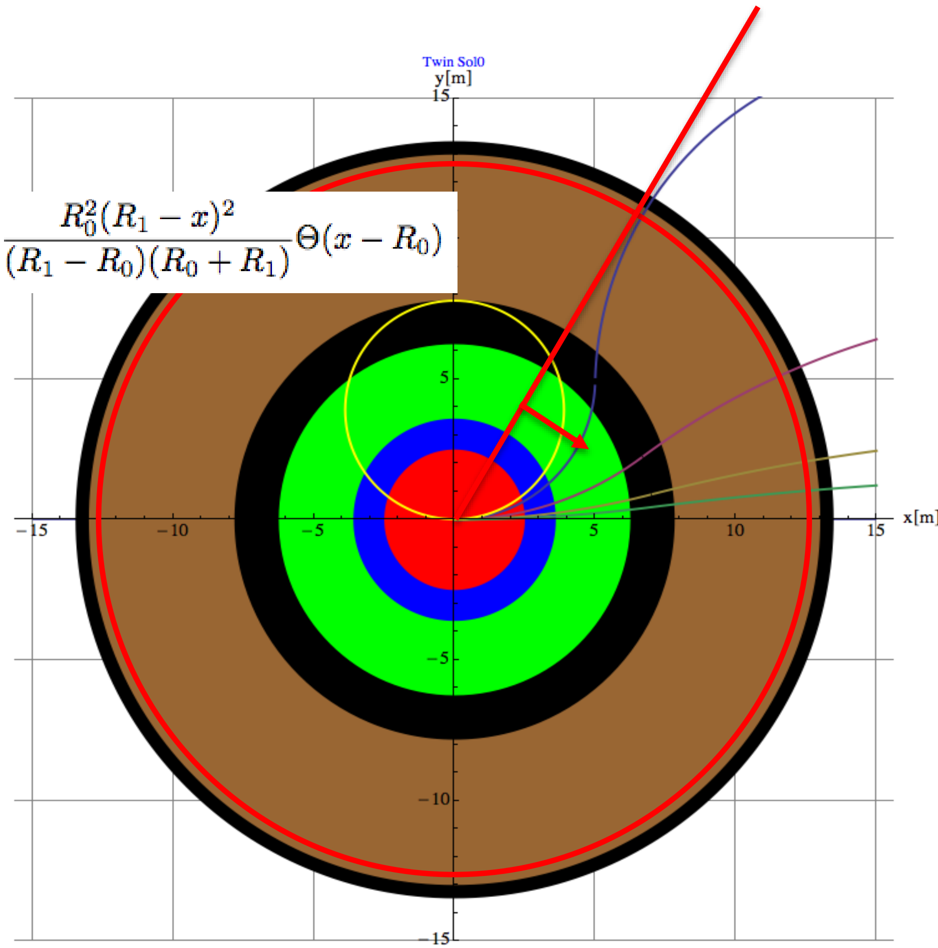
$$y_t(x) = \frac{0.3B_0}{2p_T}\left(x^2 - \frac{2R_0R_1}{R_0+R_1}x\right)\Theta(R_0 - x) - \frac{0.3B_0}{2p_T}\frac{R_0^2(R_1-x)^2}{(R_1-R_0)(R_0+R_1)}\Theta(x-R_0)$$

The maximum excursion $y_t(x_0)$ is always at the same radial distance of x_0

$$x_0 = \frac{R_0R_1}{R_0+R_1} \qquad y_t(x_0) = -\frac{0.3B_0}{2p_T}x_0^2 = -\frac{0.3B_0}{2p_T}\left(\frac{R_0R_1}{R_0+R_1}\right)^2$$

For values below: x_0=4m, y_t(x0)=1.44mm
Ideal measurement point is at the peak, but y_t(2.4m)= 1.24mm still good !





$\sigma^2=\sigma_1^2+(x/R_1\sigma_2)^2$

x=2.4m, R_1=12m, σ_1=50µm, σ_1=250µm,
σ=64µm, dp_T/p_T=5% at 10TeV !

Measuring just in the last tracker layer and in the outermost muon station already beats the full inner tracker performance (14 layers, 23um).

Preliminary Conclusion on Muon Measurement:

No Muons below 7 GeV in the Muon System.

Angle measurement at entrance of the muon system provides excellent performance.

Sagitta measurement in the muon system is not competitive with angle measurement and the inner tracker.

Using the last layer of the muon system together with the last layer of the central tracker alone gives excellent performance at high p_T.

→ Minimizing the gap size is a very interesting option, because it does not affect the angle measurement and has only small impact on the full sagitta measurement.

→ An Iron return yoke with partial shielding is also interesting.

- The achievable precision on the angular measurement has to be evaluated, should be OK
- The full sagitta measurement will suffer – to be evaluated.
- Stray fields are of course a pain

→ To be done: eta dependence of all these arguments !!