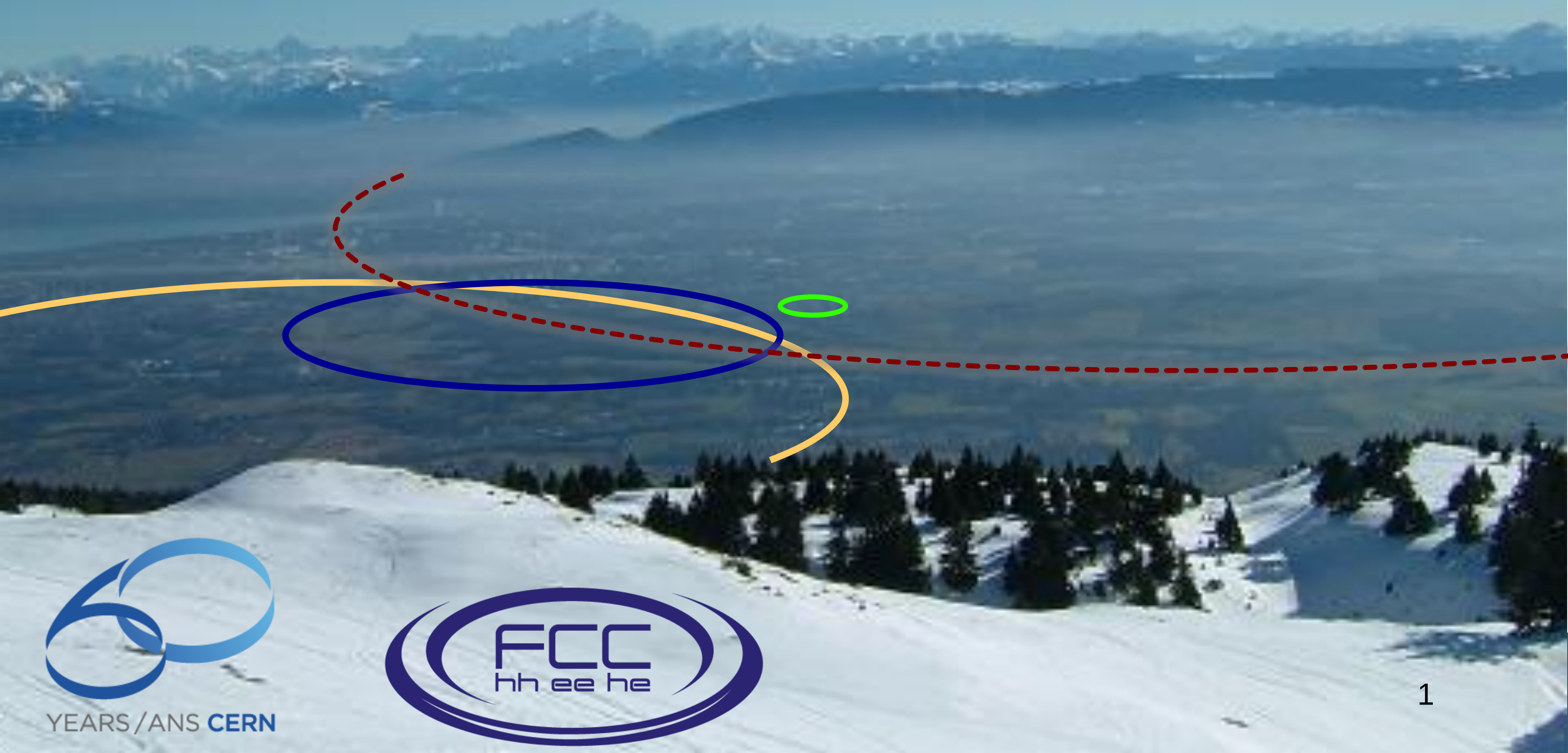
Review of FCC Detector Concepts

W. Riegler, H. Ten Kate, Mar. 30th 2016



Approach for Detector Design

Over the last year we worked out some detector concepts together with performance parametrizations that should be used for ‘fast’ simulation.

The software group had made significant progress and the software tools and examples for a ‘DELPHES’ type FCC detector simulation will be available by the FCC week in April.

Scanning performance parameters in the parametrized simulation will allow to narrow down the detector requirements.

In parallel we will stay quite open for different detector concepts and will perform specific full GEANT simulation of performance parameters.

The magnet system is the key driver for the overall dimensions, cavern, installation etc., so it is important to have an engineering design for a ‘worst case’ baseline together with some ‘scaling laws’.

Baseline Parameters for the FCC-hh Machine

The present working hypothesis is:

- peak luminosity baseline: $5 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- peak luminosity ultimate: $\leq 30 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$

- 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 O(20) ab^{-1} over 25 years of operation.

Parameters Assumed for the Detector Design

L_{peak} [$5\text{x}10^{34}$, $30\text{x}10^{34}$] $\text{cm}^{-2}\text{s}^{-1}$

→ Average N_{pileup} [170, 1020] at 25ns
→ Average N_{pileup} [34, 204] at 5ns

L_{int} [3, 30] ab^{-1}

These upper limits of L_{peak} and L_{int} should be read as Phase II goals that we use for detector studies and not as numbers promised by the machine!

The 5ns vs. 25ns bunch crossing time will stay an open parameter for some time.

FCC-hh Preliminary Layout

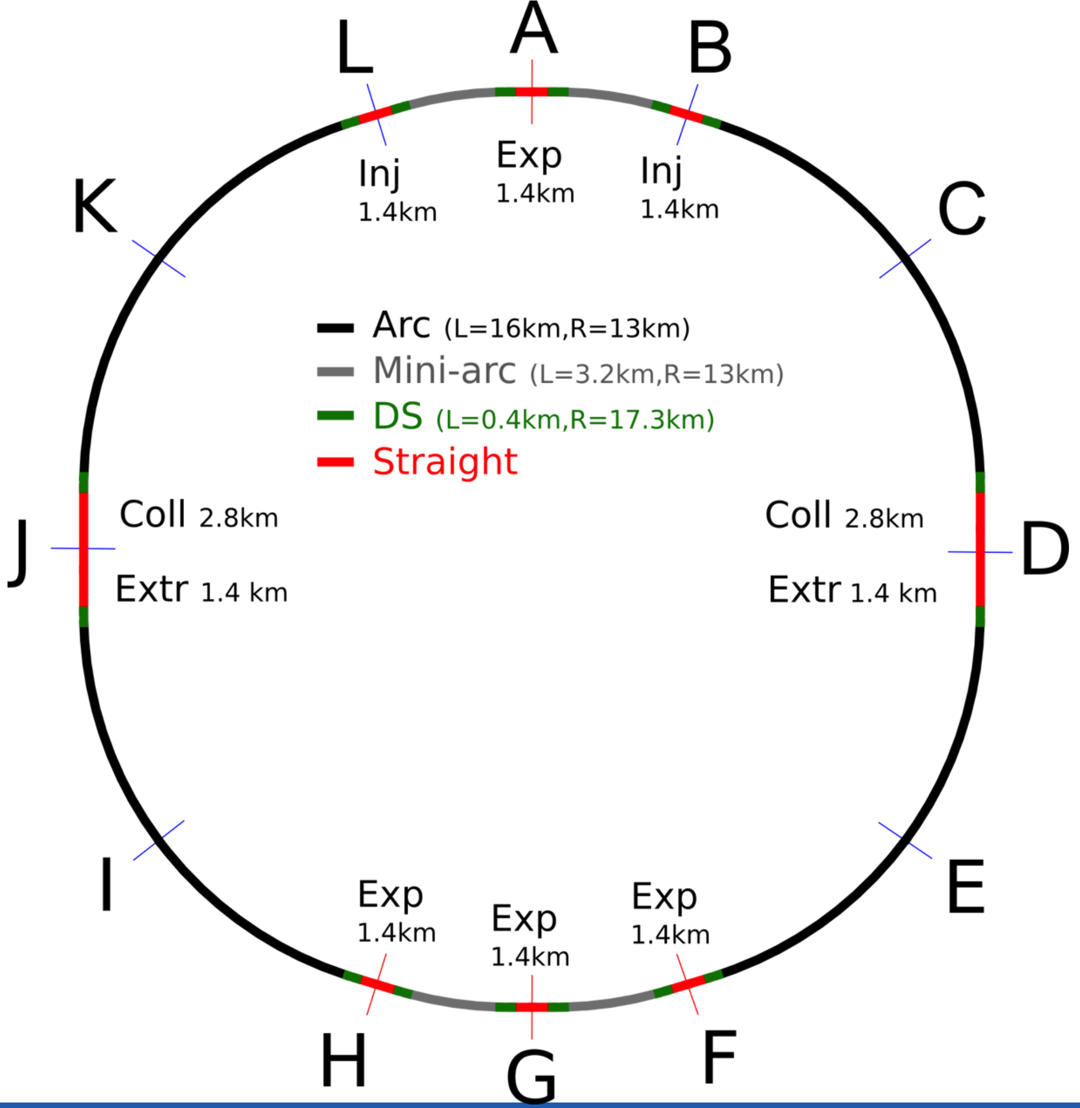
100 km layout for FCC-hh (different sizes under investigation)

⇒ **Two high-luminosity experiments (A and G)**

⇒ **Two other experiments (F and H) grouped with main experiment in G**

⇒ **Two collimation lines**

⇒ **Two injection and two extraction lines**

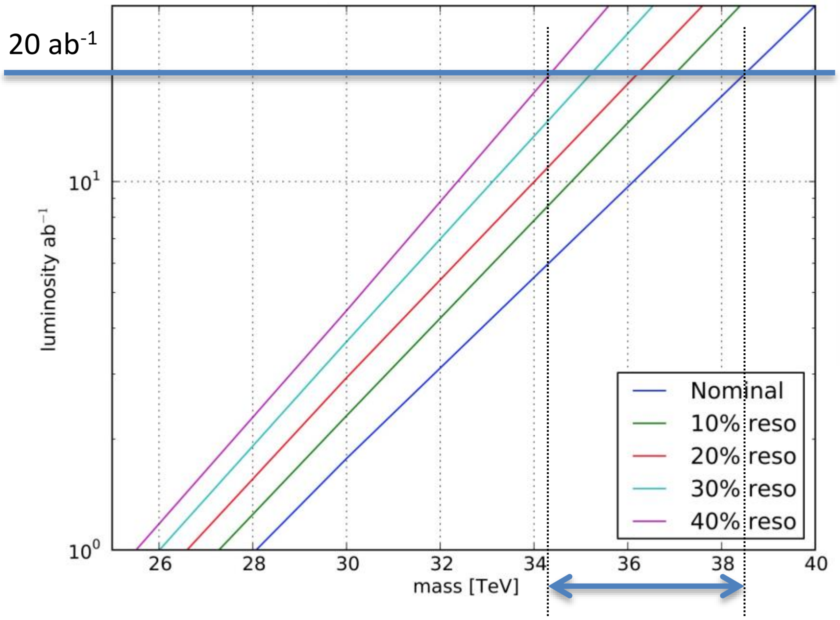


Physics at the Lσ Limit

Exploration potential through higher energy, increased statistics, increased precision

Example: Z’ $_{SSM}$ discovery

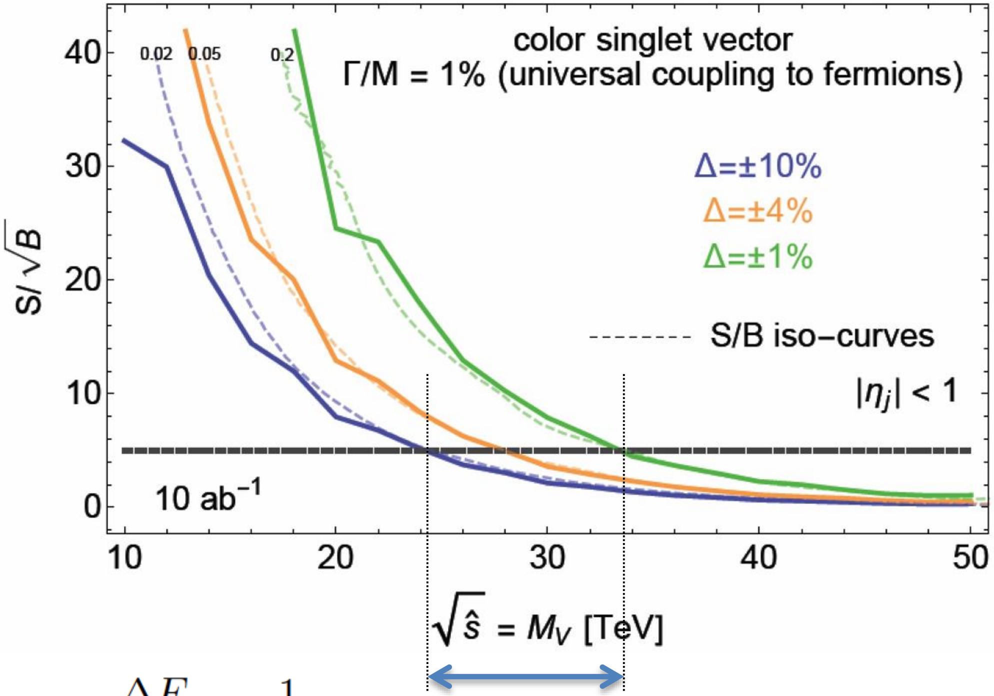
luminosity versus mass for a 5σ discovery



$$\frac{\Delta p}{p} \propto \frac{p}{BL^2}$$

Muon momentum resolution:

- **O(15%) at 10TeV.**
- **Compare to 10% at 1TeV spec. at LHC**



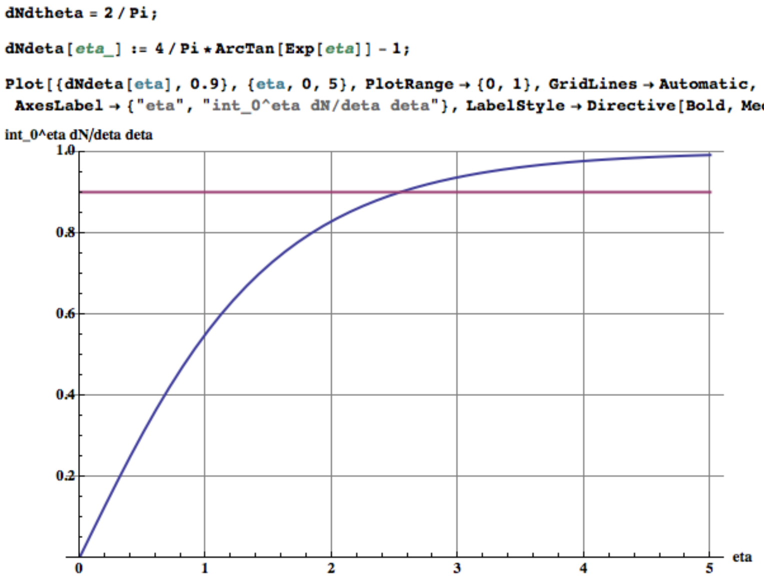
$$\frac{\Delta E}{E} \propto \frac{1}{\sqrt{E}} \oplus k$$

Di-jet resonances: Extend discovery potential by 10TeV between mass resolutions of Δ=±10% to Δ=±1%

2% jet resolution a reasonable choice (Δ=±4%)

- **Constant term dominates, ≈ 2% goal**
- **→ full shower containment is mandatory !**
- **→ HCAL depth of 12 λ_{int} !**

Rapidity distribution of an ‚Isotropic Track‘



```
dNdtheta = 2 / Pi;

dNdeta[eta_] := 4 / Pi * ArcTan[Exp[eta]] - 1;

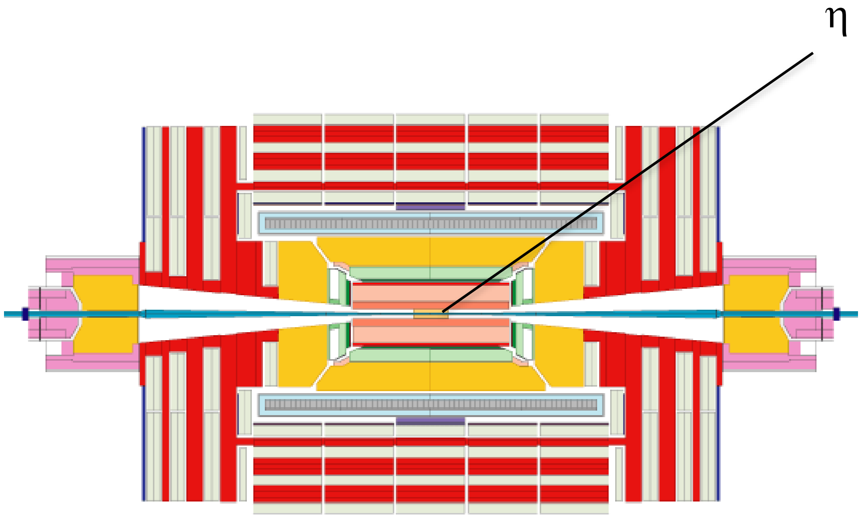
Plot[{dNdeta[eta], 0.9}, {eta, 0, 5}, PlotRange → {0, 1}, GridLines → Automatic, PlotStyle → Thick,
 AxesLabel → {"eta", "int_0^eta dN/deta deta"}, LabelStyle → Directive[Bold, Medium]]
```

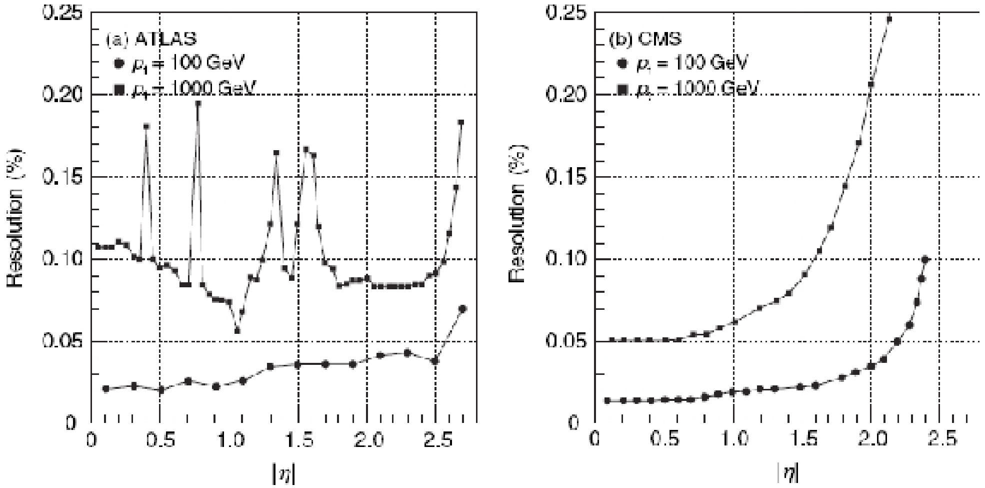
Probability that the track has η<2.5 is 90%

2 tracks η < 2.5 = 0.9^2=0.81
3 tracks η < 2.5 = 0.73
4 tracks η < 2.5 = 0.66

Probability that the track has η<1.5 is 72%

2 tracks η < 1.5 = 0.52
3 tracks η < 1.5 = 0.37
4 tracks η < 1.5 = 0.27

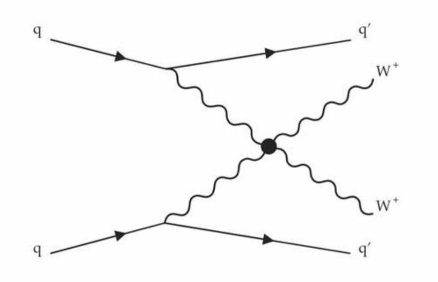


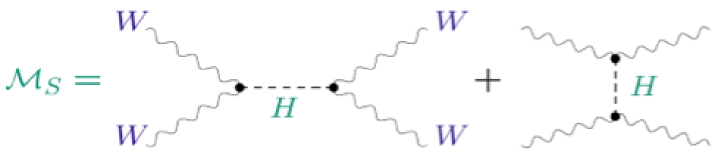


WW Scattering by VBF Mechanism

WW→WW scattering violates unitarity at high energies

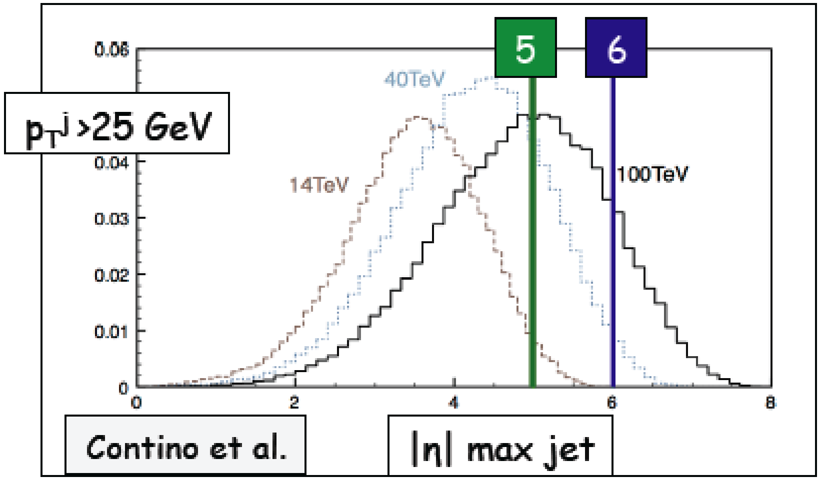
- A scalar, such as the Higgs boson, fixes this (partially)
- Probing characteristics of VV scattering is an important test of the nature of electroweak symmetry breaking
- New Physics would modify interferences between diagrams → modified V p_T and di-boson mass. Also: Are there high mass resonances WW, ZZ, HH, …





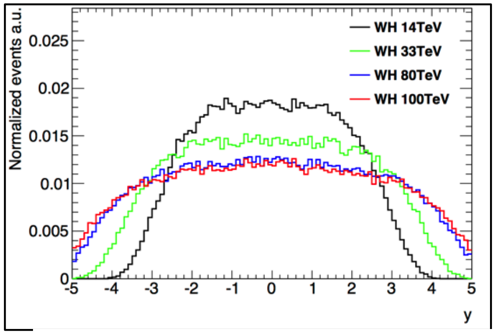
VBF jets also important for tagging of Higgs produced though VBF, like H->bb, H->tautau etc.

VBF jets between η~2 and η~6 need to be well measured and separated from pile-up



Higgs Measurements

H→ 4l acceptance vs η coverage (p_T cuts applied)



	14 TeV		100 TeV	
	2.5	4	2.5	4
ggF	0.74	0.99	**0.56**	0.88
WH	0.66	0.97	**0.45**	0.77
ZH	0.69	0.98	**0.48**	0.80
ttH	0.84	1	**0.56**	0.90
VBF	0.75	0.98	**0.55**	0.87

		|η| < 2.5	**|η| < 4**	**|η| < 5**
YY	100 TeV	0.74	0.95	0.99
	14 TeV	0.90	1	1

→ 30-50% acceptance loss for H→ 4l at 100 TeV wrt 14 TeV if tracking and precision EM calorimetry limited to |η|<2.5 (as ATLAS and CMS)

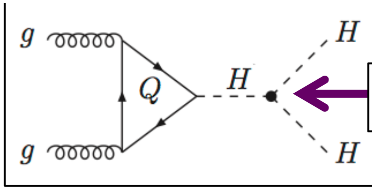
→ can be recovered by extending to |η|~ 4

Examples:
ttH : x 60 (from LHC 14)
HH : x 42

"Heavy" final states require high √s, e.g.:

HH production (including measurements of self-couplings λ)

ttH (note: ttH→ ttμμ, ttZZ "rare" and particularly clean)



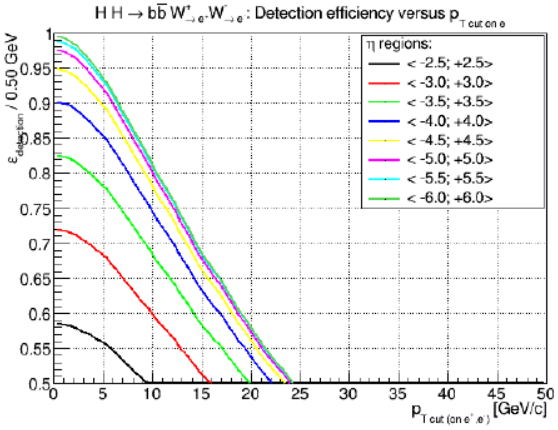
g_{HHH}~ λv

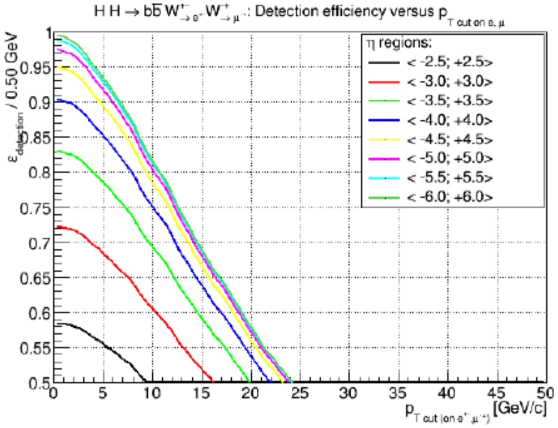
FCC

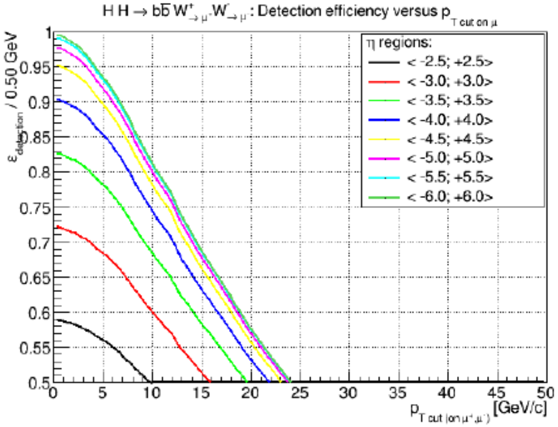
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	$1600^{\ddagger}$	500/1000	$1600/2500^{\ddagger}$	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

Results for decay modes: $H \rightarrow b\bar{b}$ + $H \rightarrow W^{+}W^{-}$

- **WW → ee,eμ,μμ ; Cuts in detail & numbers for 100 TeV machine**







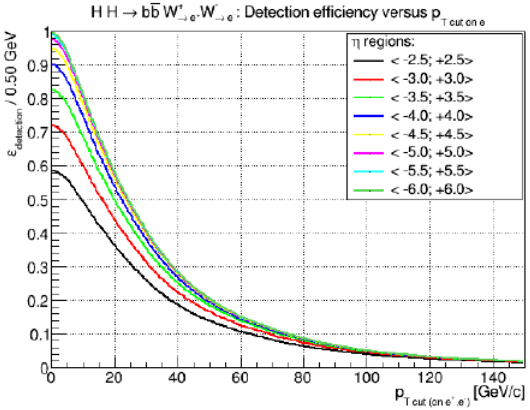
Efficiency (e,μ) [%] → very similar for all three leptonic decay channels

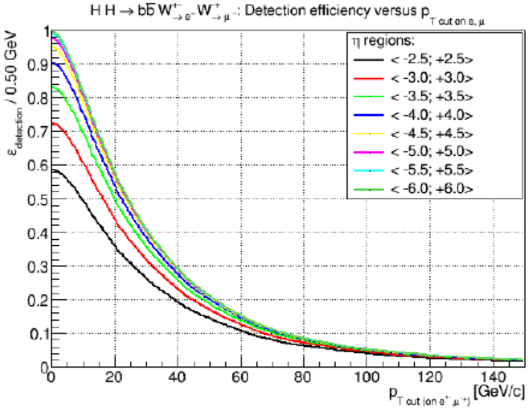
pT[GeV] ≥	0.0	5.0	10.0
<-4.5;+4.5>	94.9	89.2	77.6
<-5.0;+5.0>	97.6	91.6	79.6
<-6.0;+6.0>	99.6	93.2	80.8

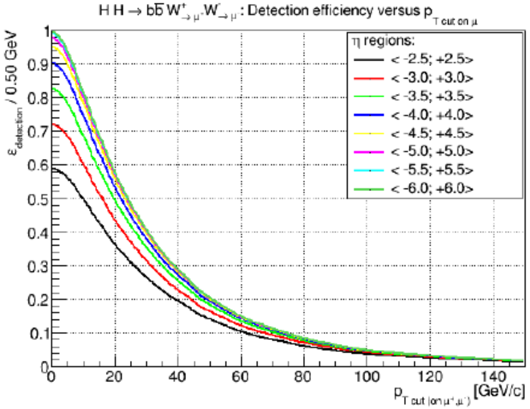
Circle diameter of 1GeV Pt particle in 6T field is 1.1m

Results for decay modes: $H\rightarrow b\bar{b}$ + $H\rightarrow W^{+}W^{-}$

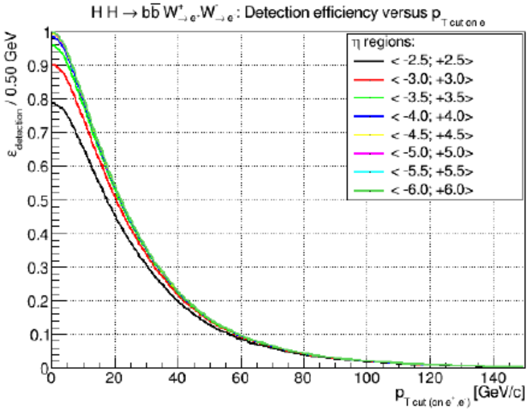
- WW → ee,eμ,μμ ; Apply P_T cuts versus eta acceptance for 100 TeV machine







- For 13 TeV machine



gg → HH studies: Summary & Outlook

- **Summary**:
  - The study is far from being complete:
    - b-tagging effects not yet implemented
    - tau reconstruction missing (in progress)
    - E_T reconstruction for W decay channel missing (in progress)
    - but the following can be stated:
  - gg → HH represents a "low" pT physics compared to FCC-hh TeV scale in terms of detector design! So, various channels "in other corners" of TeV scale spectra needs to be addressed to have a realistic picture of our detector
  - Rather than $\eta_{coverage} = <-6.0;+6.0>$, $\eta_{coverage} = <-5.0;+5.0>$ or even $\eta_{coverage} = <-4.5;+4.5>$ seems to be sufficient
  - More crucial are the applied p_T (E) cuts on final leptons (gammas), i.e. detector resolution rather than eta → the degradation in terms of efficiency is very steep!
- **Outlook:** Add study with DELPHES to understand other detector effects

Physics at a 100 TeV Hadron Collider

Exploration + Higgs as a tool for discovery

Numerous physics opportunities with a large number of possible measurements.

How to specify detectors for such a machine ?

ATLAS and CMS are general purpose detectors that were benchmarked with the 'hypothetical' Higgs in different mass regions with precision tracking and calorimetry up to η=2.5.

The Higgs is also key benchmark for the FCC detectors, with highly forward boosted features (E_{cm}= 100TeV, Higgs mass = 125GeV)

FCC detectors must be 'general general' purpose detectors with very large η acceptance and extreme granularity.

Approximate Overall Needs

Tracking: Momentum resolution H15% at p_T=10TeV

Precision tracking (momentum spectroscopy) and ECAL up to η=4

ECAL fine granularity for track-cluster matching (or particle flow) to mitigate pile-up and recover Bremstrahlungs losses

Tracking and calorimetry for jets up to η=6.
12 λ_{int} calorimetry ≈2% constant term.

HCAL granularity of 0.05x0.05 or 0.025x0.025 to mitigate pileup and measure jet substructure and boosted objects.

B-tagging, timing for pileup rejection etc. …

What Do Inelastic Collisions at 100TeV Look Like

Minimum Bias events scaling 14TeV → 100TeV:

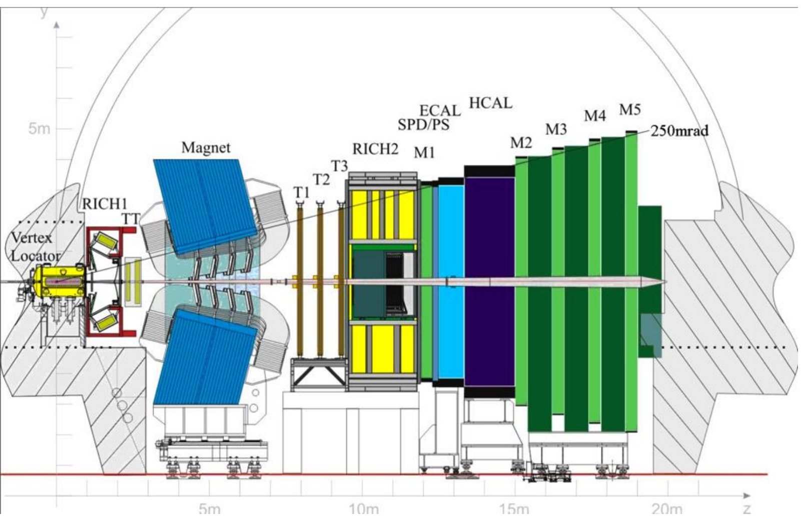
Inelastic cross-section changes from 80 → 108mb.

Multiplicity changes from 5.4 → 8 charged particles per rapidity unit.

Average p_T of charged particles changes from 0.6 → 0.8 GeV/c.
Hard scatter events (events of interest) with p_T up to 7 times higher (100/14).

→ Transverse energy sum increases by about a factor of 2.

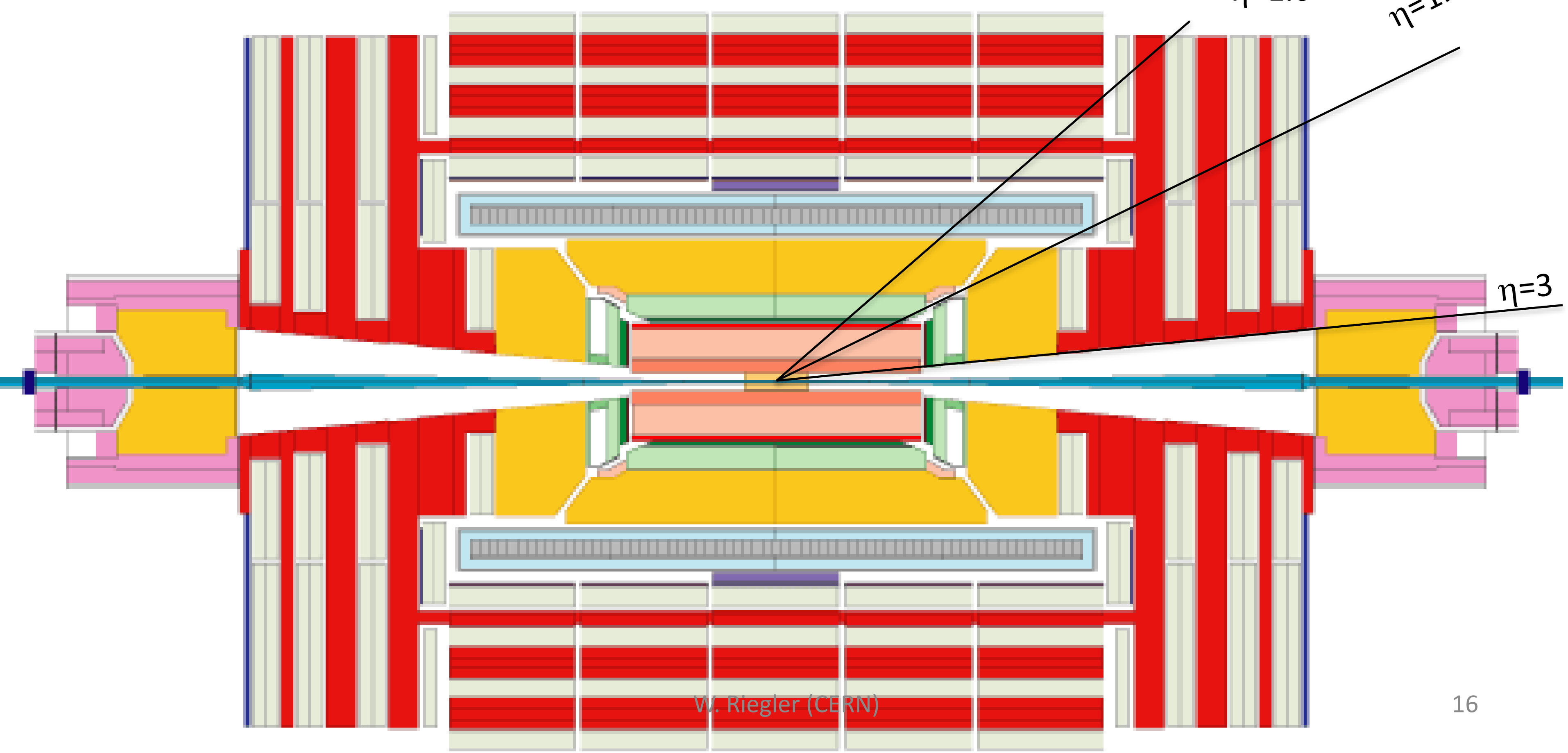
→ The Min. Bias events at FCC are quite similar to the Min. Bias events at LHC.



LHCb: Tracking, Calo η = 2 - 5

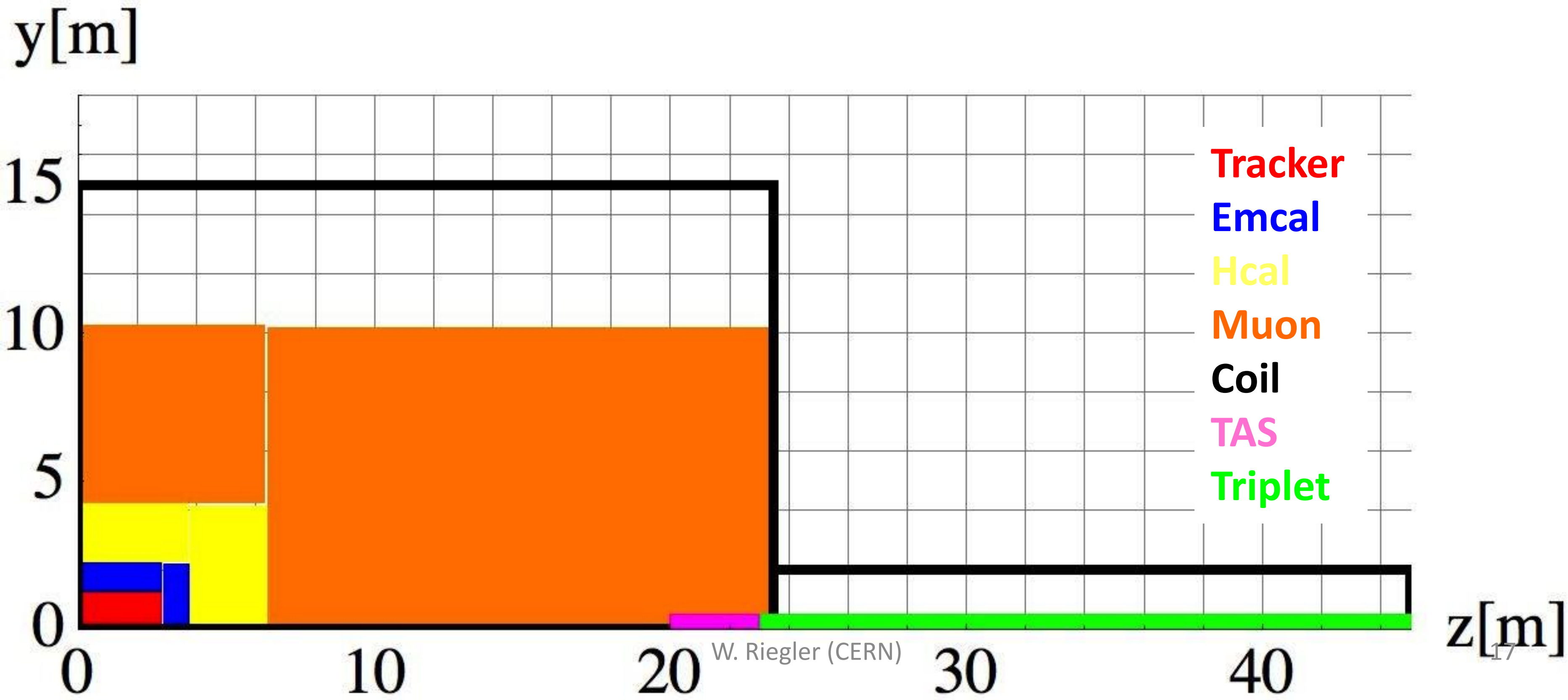
… all with impressive performance …

ATLAS, CMS: tracking, calo η -2.5,2.5



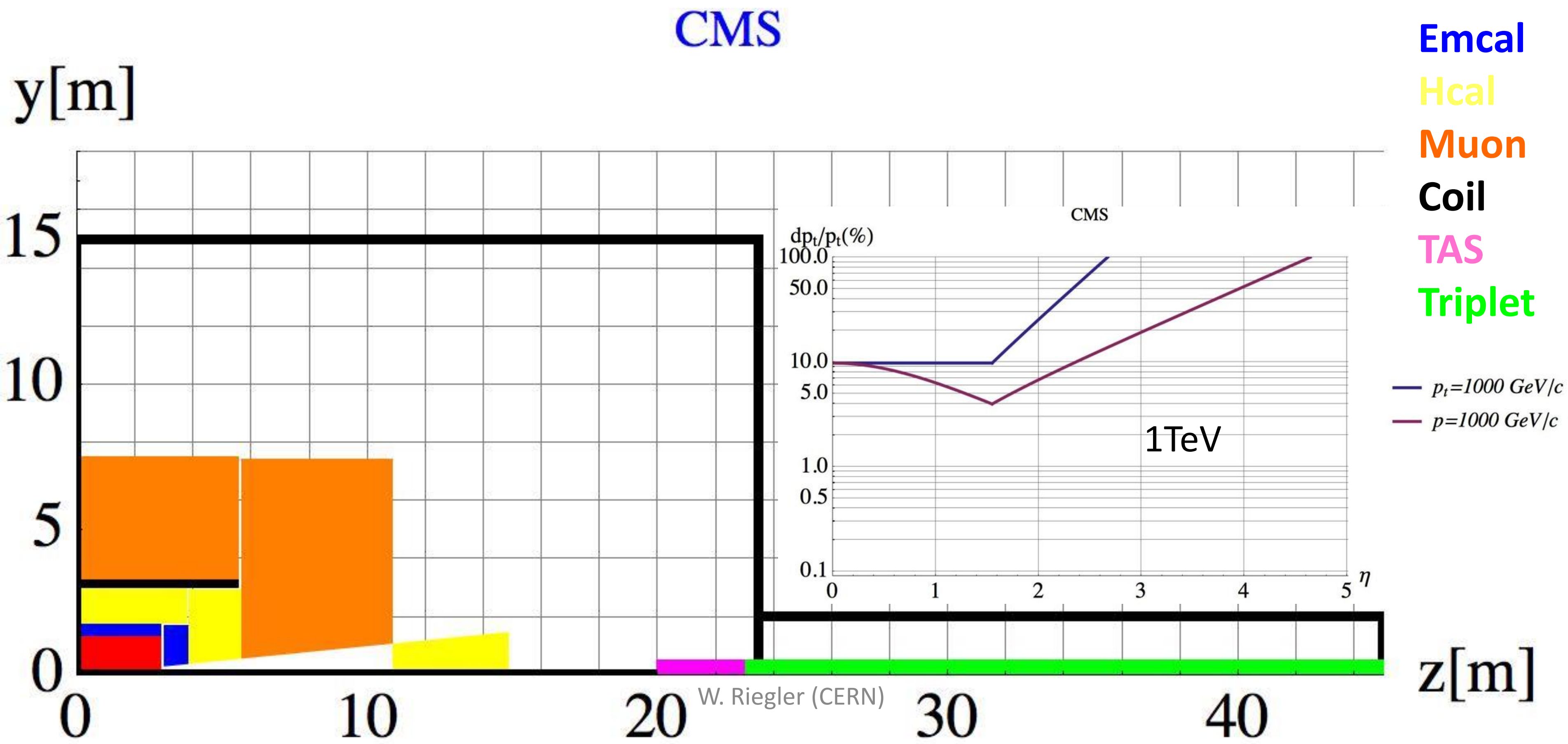
ATLAS

- Tracker r=1m, B=2T **thin solenoid coil** in front of the calorimeters
- LArg ECAL, HCAL and 7.4 λ_{int} that returns the flux
- **Large air core toroid**, B=0.5T ‘standalone muon system’



CMS

- Tracker r=1.2m
- **Compact** Crystal **ECAL, ‘short’ HCAL** of and 5.82 λ_{int}, cut at $\eta = 3$ to move FCAL away.
- **R=3m solenoid coil** with 3.8T field.
- **Iron Yoke to return Flux**, instrumented with muon chambers.
- CMS muons are relying on a properly working tracker.



Tracker
Emcal
Hcal
Muon
Coil
TAS
Triplet

How to Scale LHC Experiments to FCC ?

Let’s assume a tracking resolution of 10-15% for 10TeV particles and a calo constant term of ≈2% which requires full shower containment and therefore 12 λ_{int} of calo i.e. ≥3m

- **Coil with high B-field and low material budget in front of ECAL/HCAL seems very difficult, so scaling the ATLAS approach is questionable.**

- **Leaving the tracker radius similar to LHC values of r=1m, which is extremely challenging, with 12λ_{int} calo a coil radius of at least 4m is needed (→ CMS+).**
  → An iron yoke to return the flux for such a coil might still be affordable.

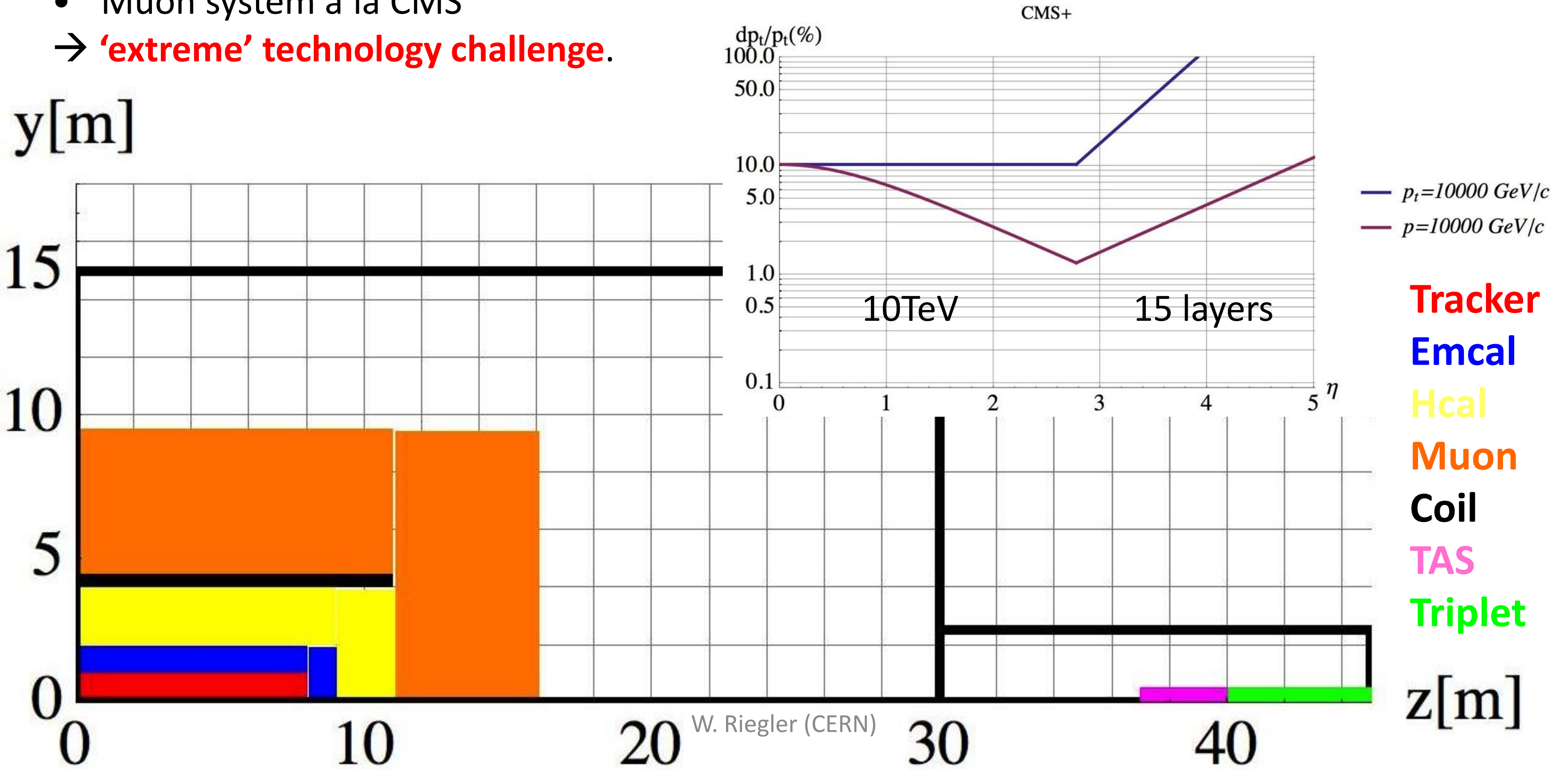
- **With a more realistic approach for calorimetry and tracking we end up with coil radii of 6m, which requires an iron yoke that is probably unaffordable.**

→ In this case one uses either active shielding (twin solenoid) or a yoke that only returns part of the flux (partial shielding) - stringent requirements on the equipment in the environment.

CMS Scaled Detector with Very Long Extreme Resol. Tracker

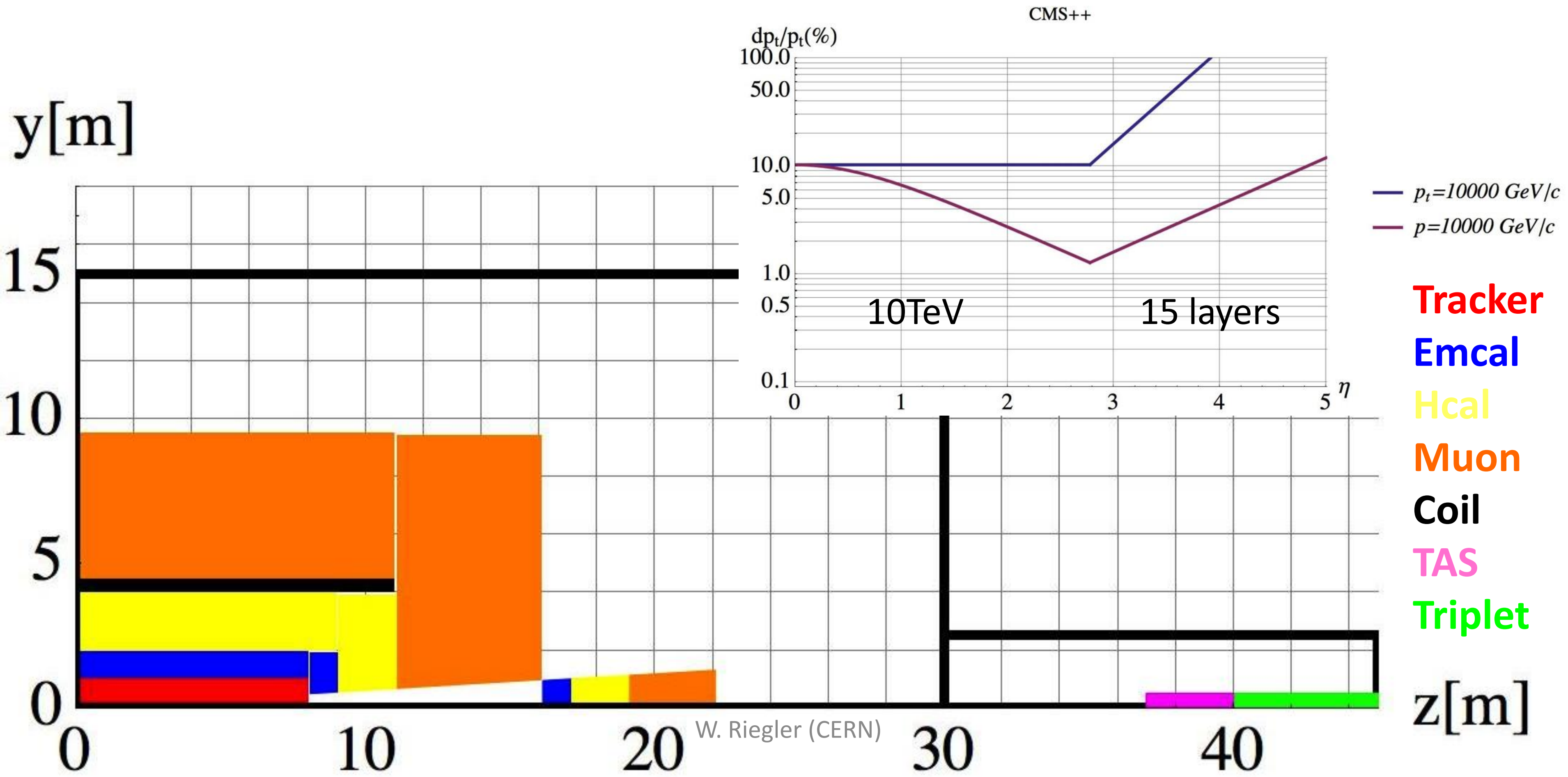
- **Maximum coil producing 6T with affordable iron yoke** (r=4m)
- Tracker radius 1m, 6T → resolution has to be improved by factor 6 with respect to CMS → 5µm layer resolution and less material (multiple scattering)
- 8m long tracker gives large η acceptance.
- 2.8m available for EMCAL+HCAL e.g. very compact W/Si particle flow calorimeters
- Very high granularity forward calorimeters needed
- Muon system a'la CMS

→ **'extreme' technology challenge**.



CMS Scaled Detector, Forward Calorimetry Moved Out

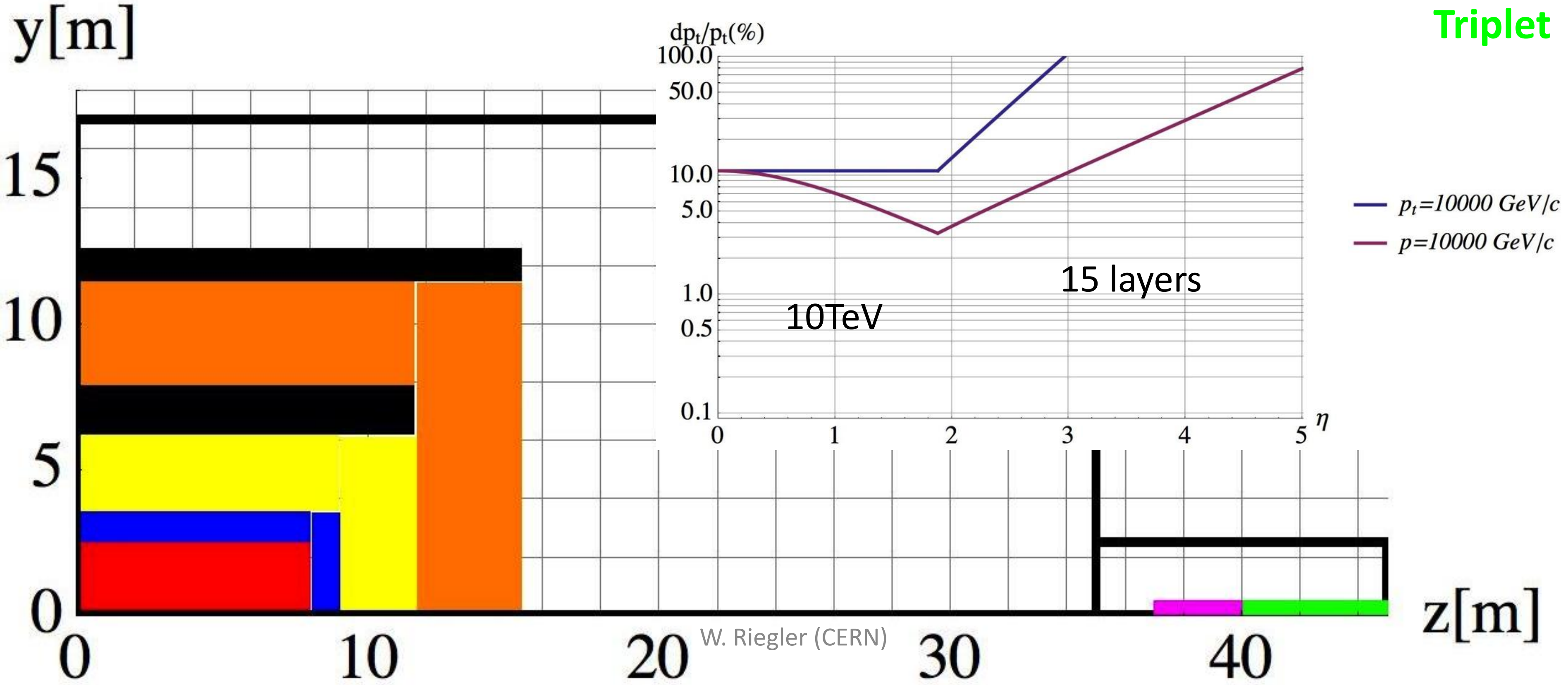
- Forward calorimetry moved to large distance from η = 3.5 for reduced occupancy and radiation load



Twin Solenoid BL^2 Scaling

- How to achieve 10% for a 10TeV charged particle **assuming tracker with nowadays layer resolution** (~20μm)?
- Solenoid and shielding solenoid with B=6T in Tracker and B=2.5T in Muon System
- Tracker r=2.5m, L=16m, tracking layer resolution similar to CMS detector
- ECAL+HCAL = 3.4m = 12 λ_{int}
- Momentum resolution gets marginal at η>3.

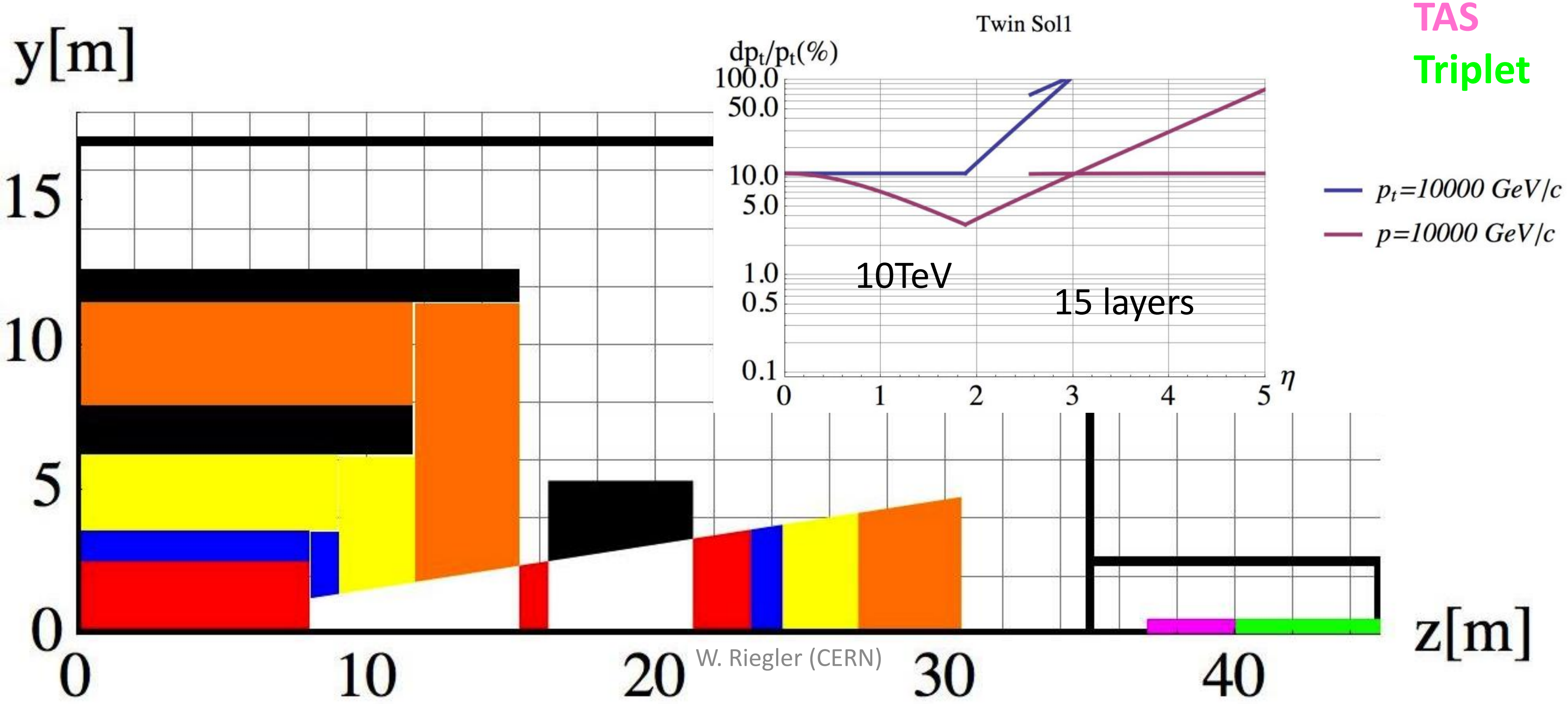
Tracker
Emcal
Hcal
Muon
Coil
TAS
Triplet

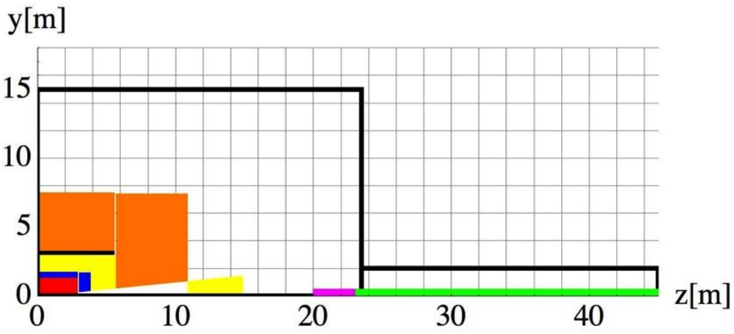


Twin Solenoid BL^2 Scaling + Forward Dipole

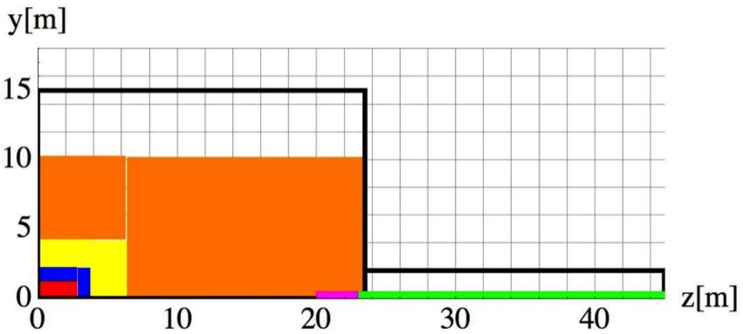
- Opening at η = 2.5
- Adding a **forward Dipole for momentum spectroscopy**.
- Moving forward calorimeters to larger distance decreasing the particle densities and overlaps.
- Allows separate instrumentation and upgrade of forward detectors
- Integration and maintenance is a challenge

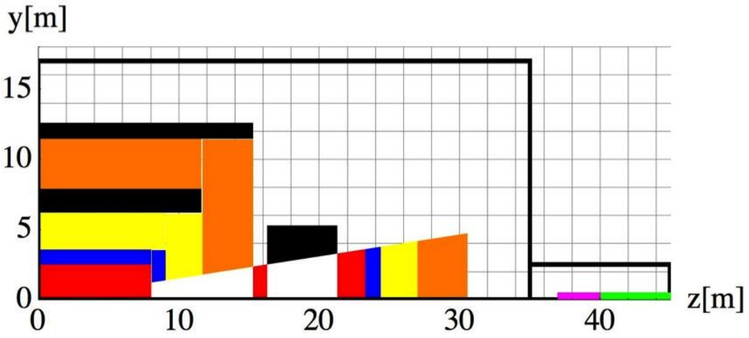
Tracker
Emcal
Hcal
Muon
Coil
TAS
Triplet





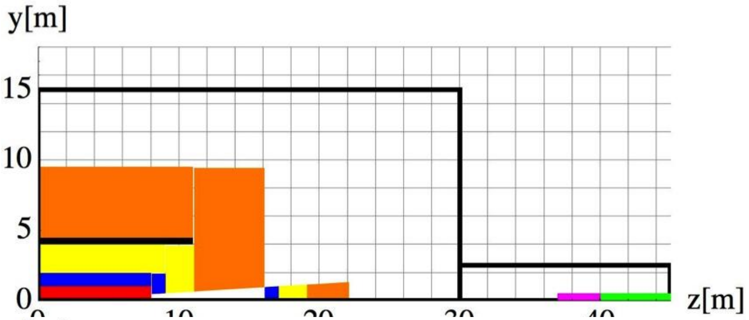
CMS & ATLAS



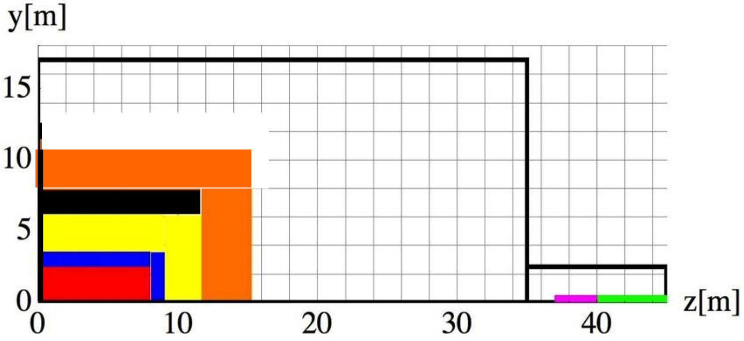


Twin Solenoid
+ Dipole

Popular at Present



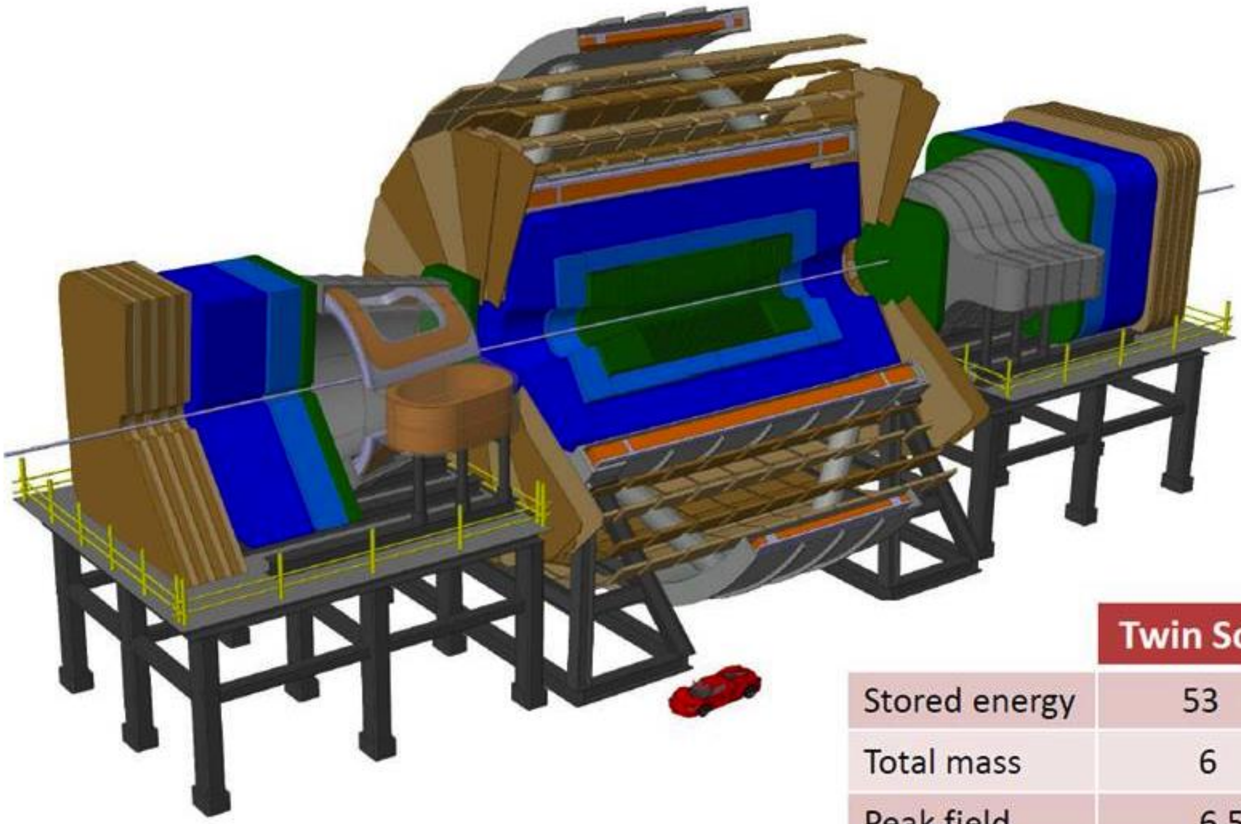
CMS+



Partially shielded large solenoid

Twin Solenoid + Dipole Magnet System

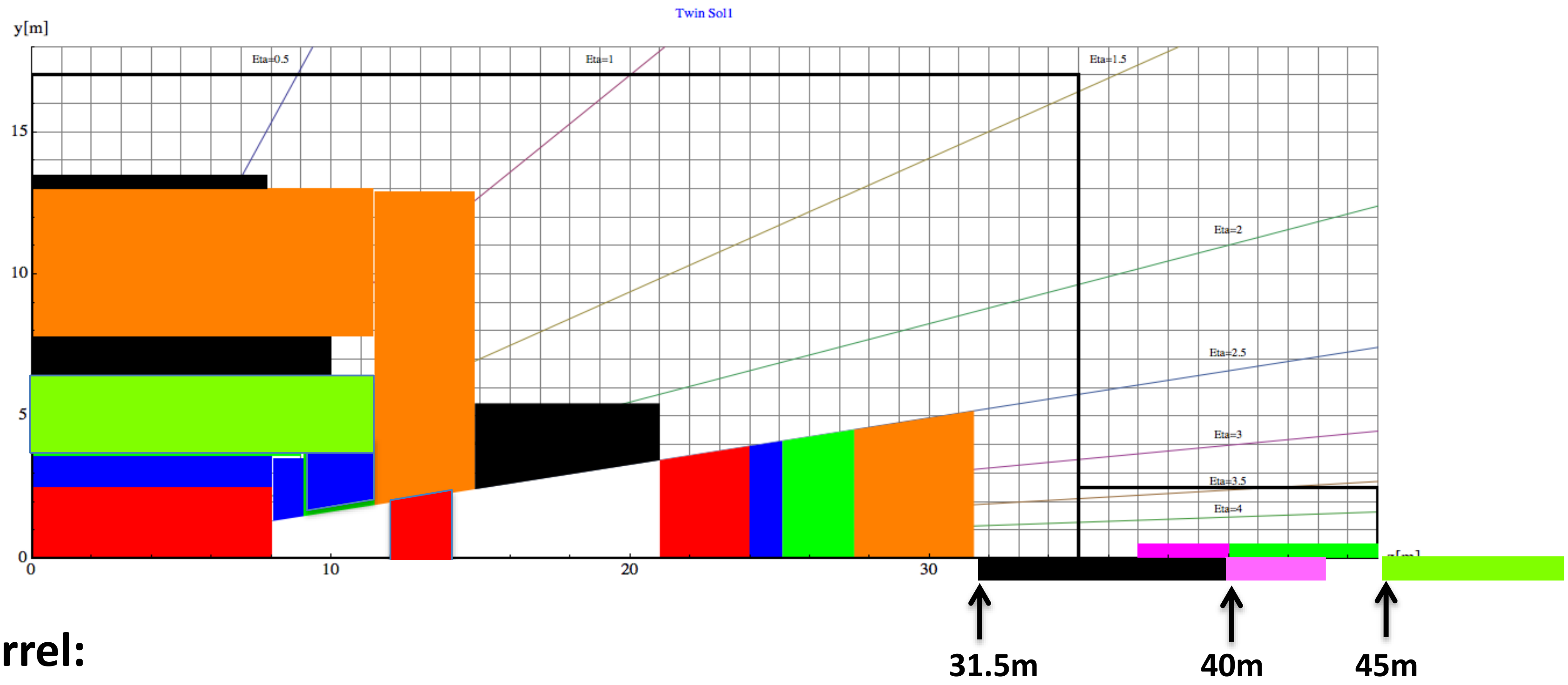
Matthias Mentink, Alexey Dudarev, Helder Filipe Pais Da Silva, Christophe Paul Berriaud, Gabriella Rolando,
Rosalinde Pots, Benoit Cure, Andrea Gaddi, Vyacheslav Klyukhin, Hubert Gerwig, Udo Wagner, and
Herman ten Kate



FCC Air core Twin solenoid and Dipoles

State of the art high stress / low mass design.

	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



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

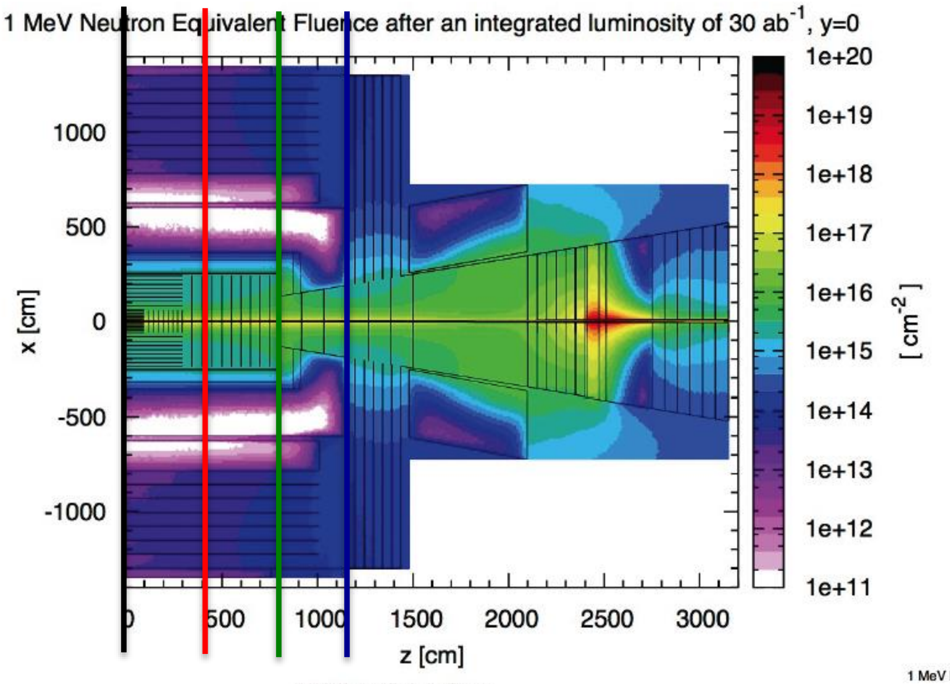
FEMCAL available space:
Z=24m to z= 25.1m → dz= 1.1m

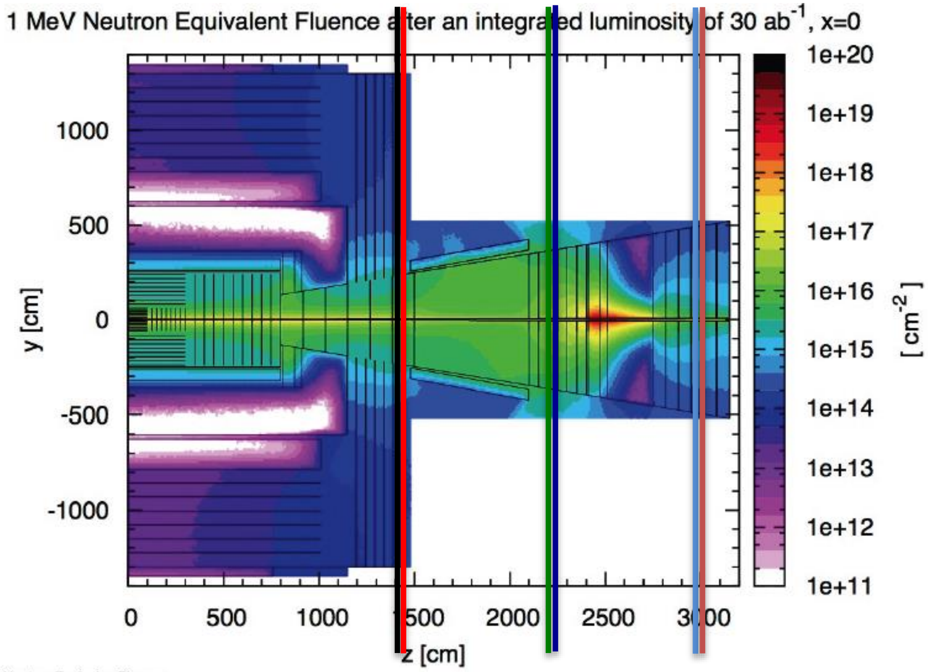
FHCAL available space:
z= 25.1m to z=27.5m → dz=2.4m

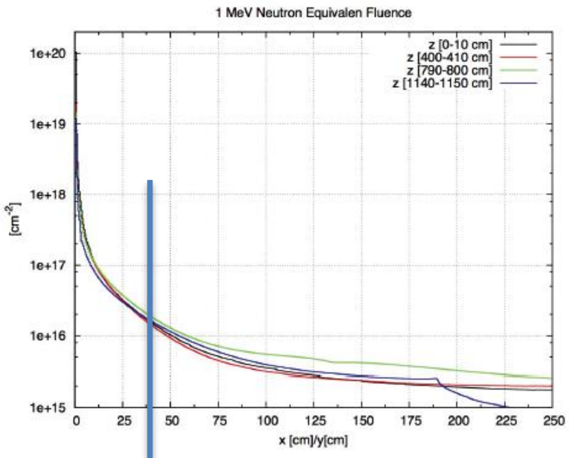
FMuon available space:
z= 27.5m to z=31.5m → dz=4m

Tracking

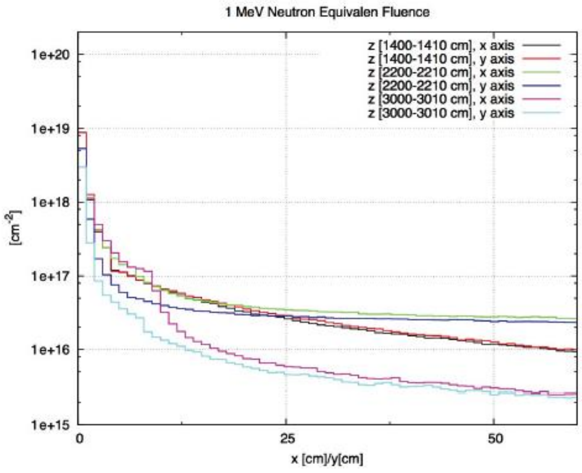
1 MeV Neutron Equivalent Fluence (FLUKA simulation, M.I.Besana)







ATLAS Phase II Tracker innermost pixel layer



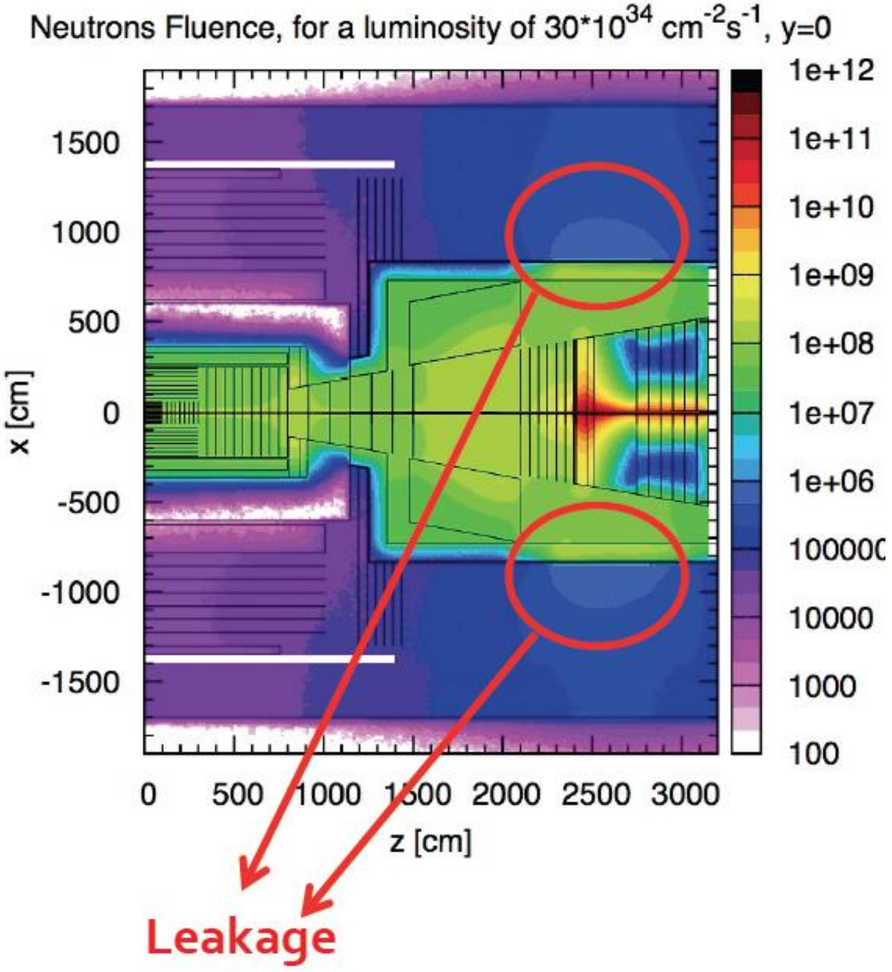
Detailed radiation simulations with FLUKA for the baseline detector exist.

Radiation load in the trackers shows primarily radial dependence from the beamline, weak dependence on z (as expected).

For radii <50cm we exceed the HL-LHC numbers (10^{16} cm^{-2}) by up to 2 orders of magnitude
→ Technology challenge !

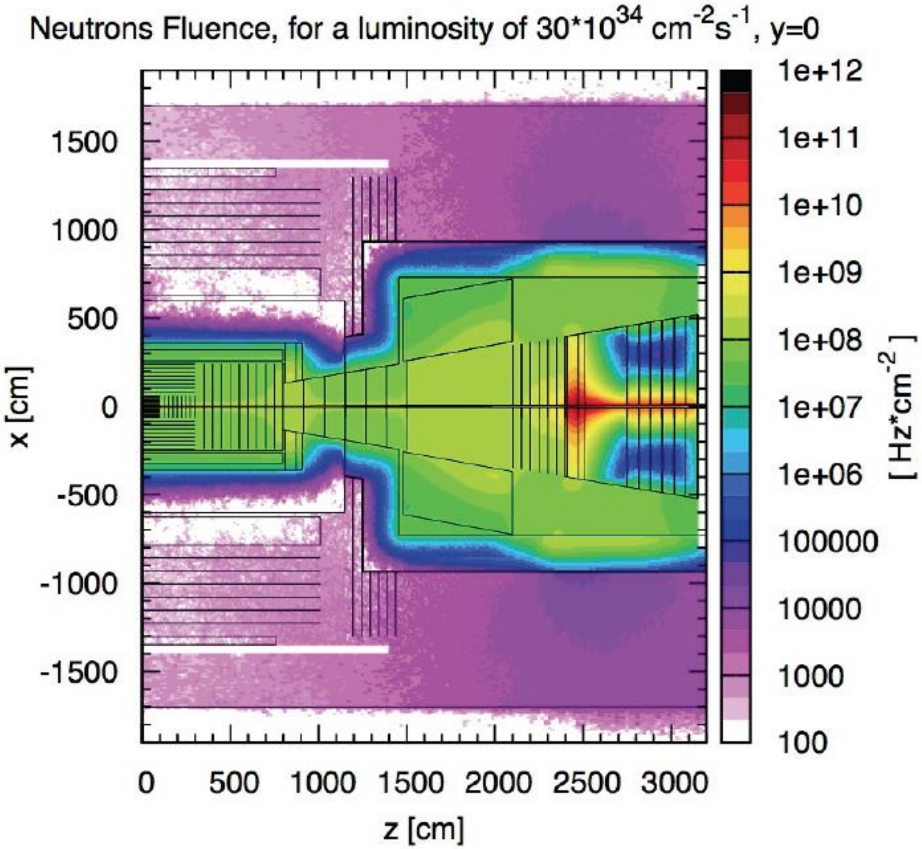
- 1 m iron shielding
  - equivalent to ~2.5 m of concrete

- 2 m iron shielding: leakage reduced by mo
  than an order of magnitude



Neutrons Fluence, for a luminosity of $30*10^{34}$ $cm^{-2}s^{-1}$, y=0

Leakage



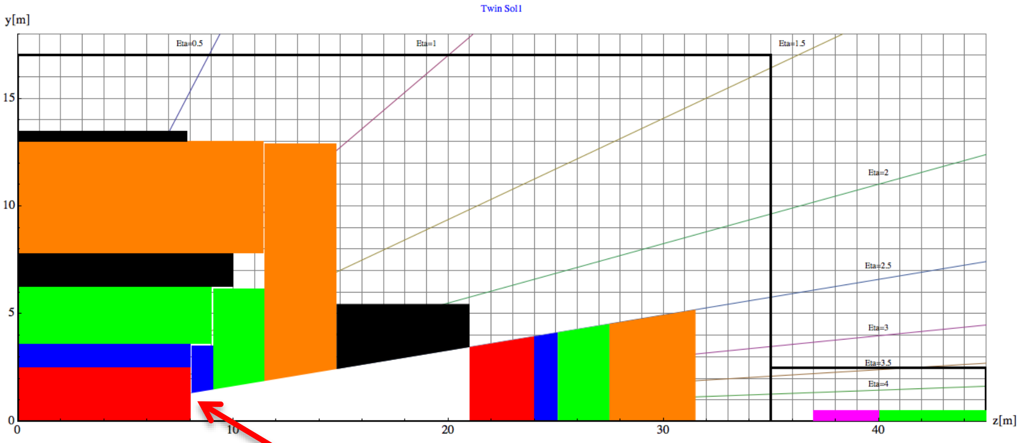
Neutrons Fluence, for a luminosity of $30*10^{34}$ $cm^{-2}s^{-1}$, y=0

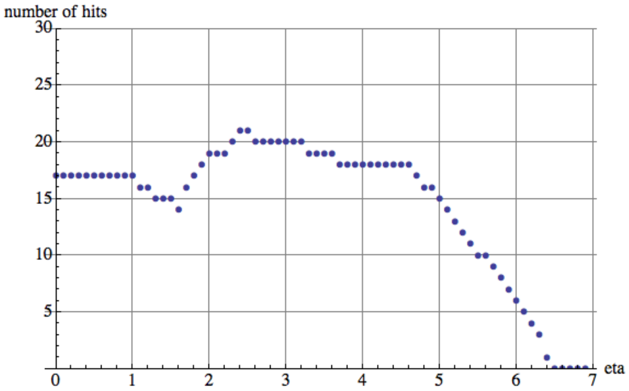
Simplified Tracker Assumptions

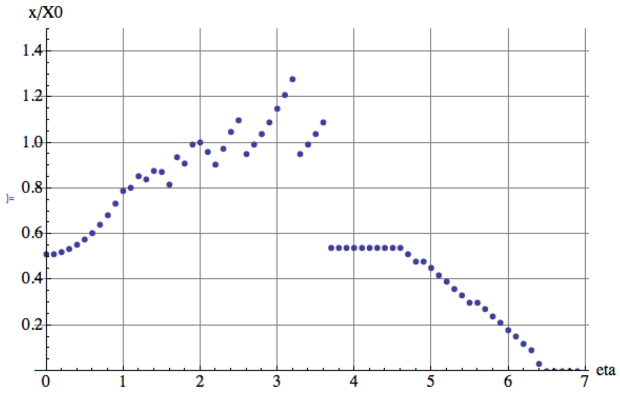
Neglecting radiation for a moment: is 10% resolution achievable (for 10TeV)?

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

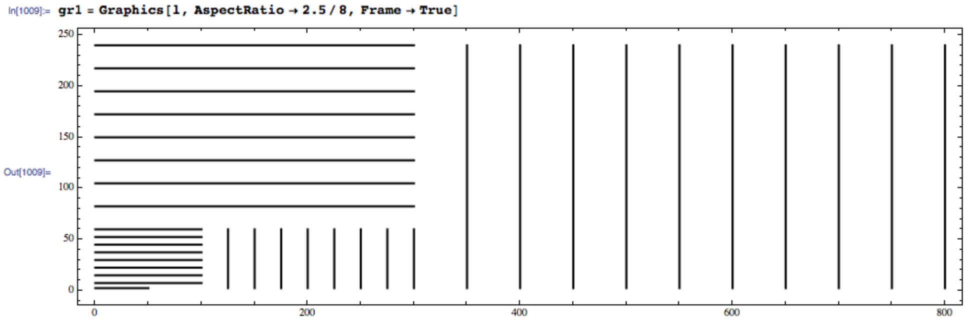
We assume 3% of radiation length per layer, i.e. each layer has a thickness of 0.43cm.





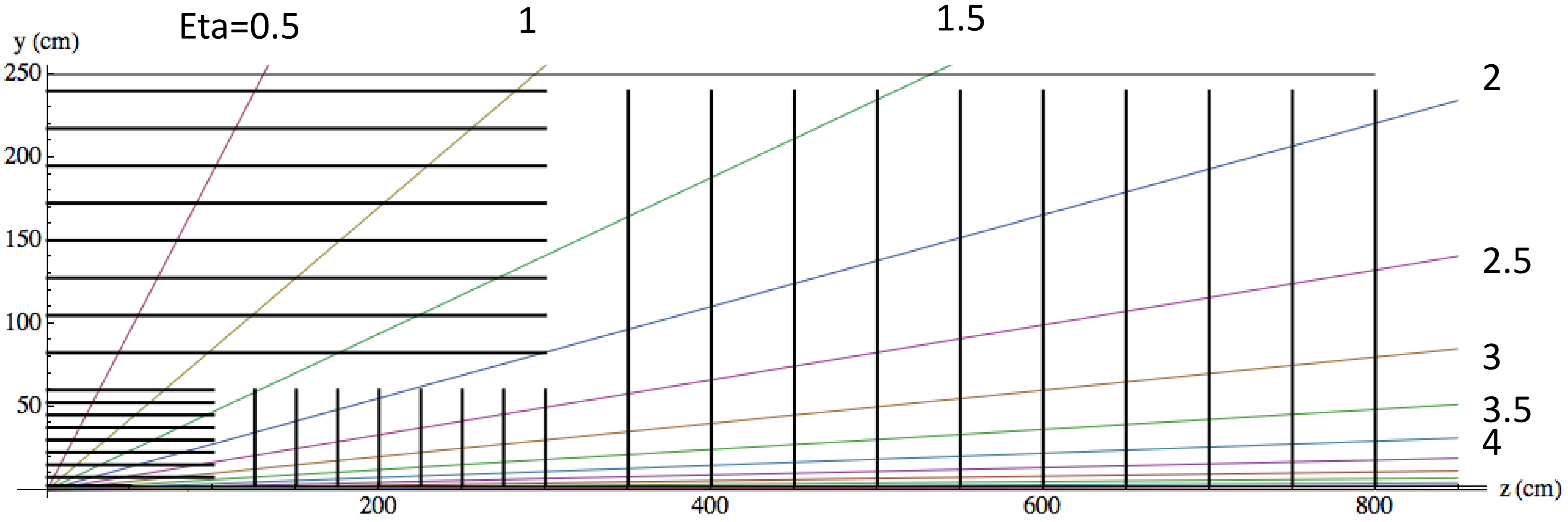


R_{out}=2.4m
Half the leaver arm at eta=2.6→ L=8m



```
In[1009]:= gr1 = Graphics[1, AspectRatio → 2.5 / 8, Frame → True]
```

Tracker



```
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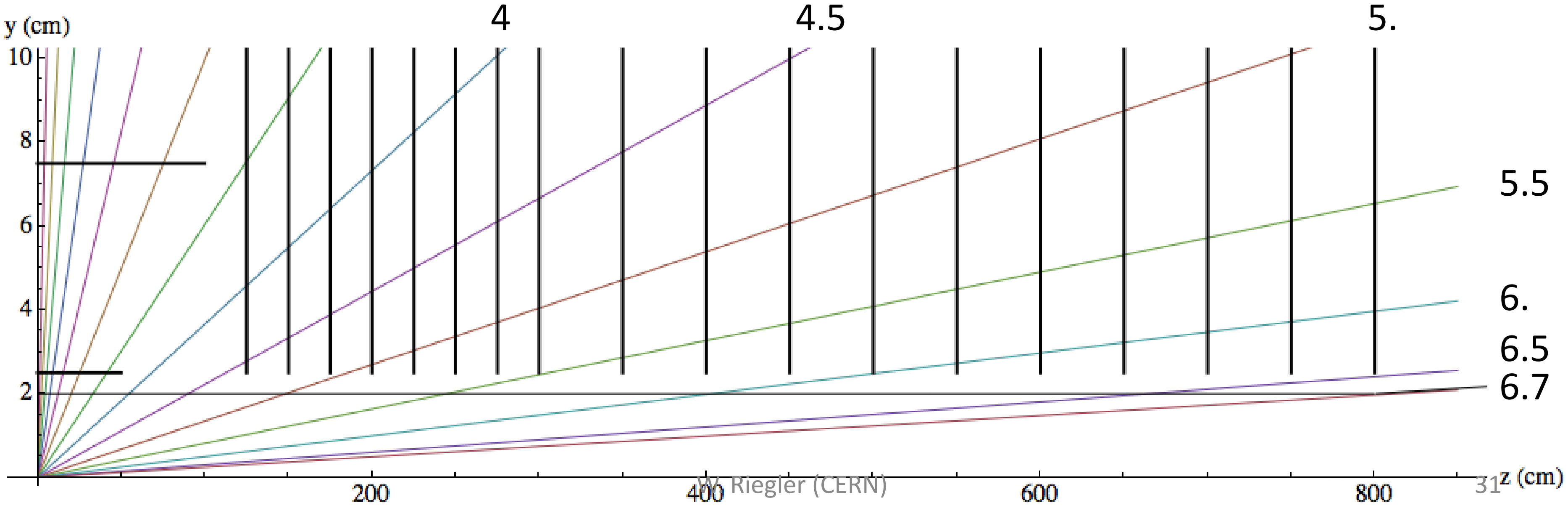
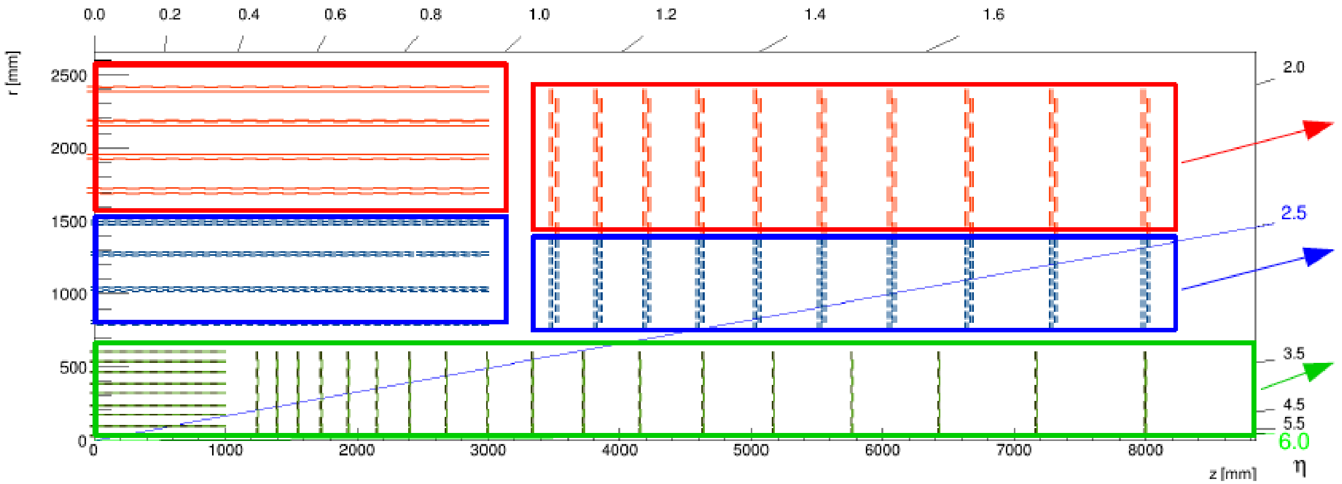


- Let me "extrapolate" the CMS phase 2 layout to FCC dimensions

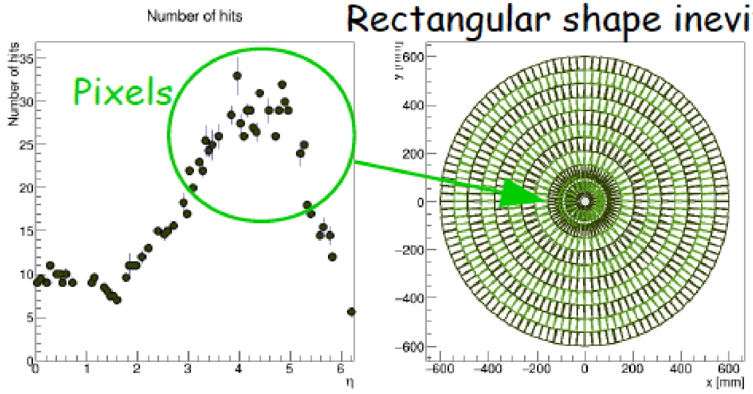


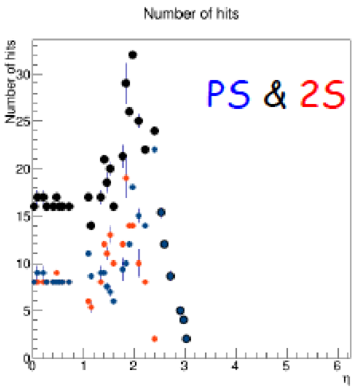
Strip-Strip (2S) modules

Pixel-Strip (PS) modules

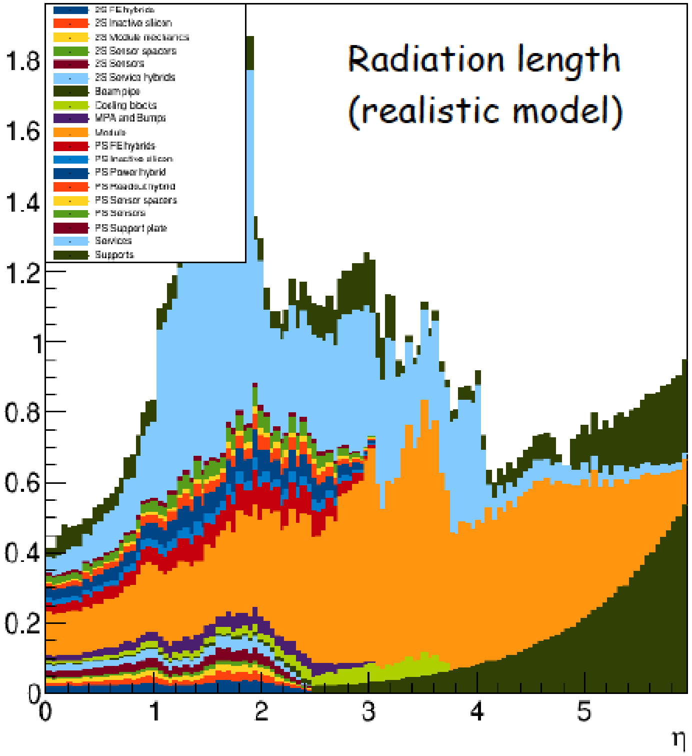
Pixel detectors

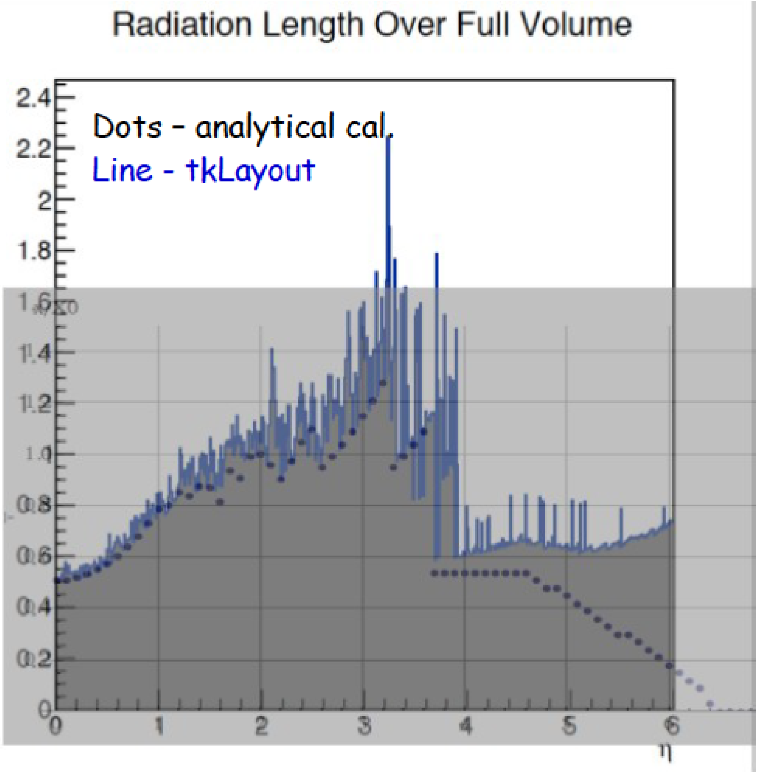
Rectangular shape inevitable





Tracker Comparison: Realistic versus Simplified

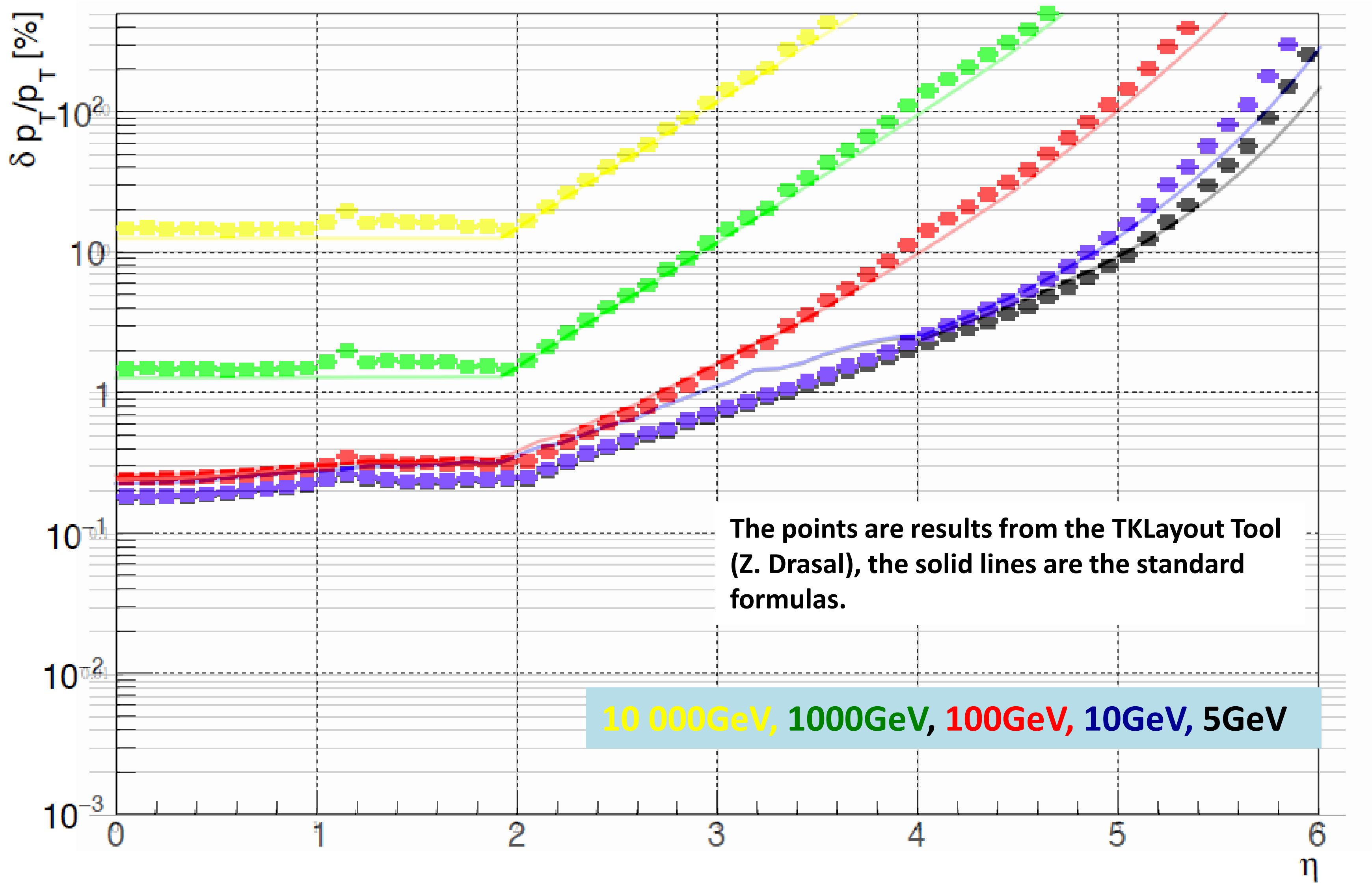




- **Summary:** The simplistic approach provides reasonable estimate on MB!
- **"Disclaimer":** One has to be careful when using an extrapolated geometry (without true engineering design - correct supports, mechanics, …), but still good hint!

Tracker

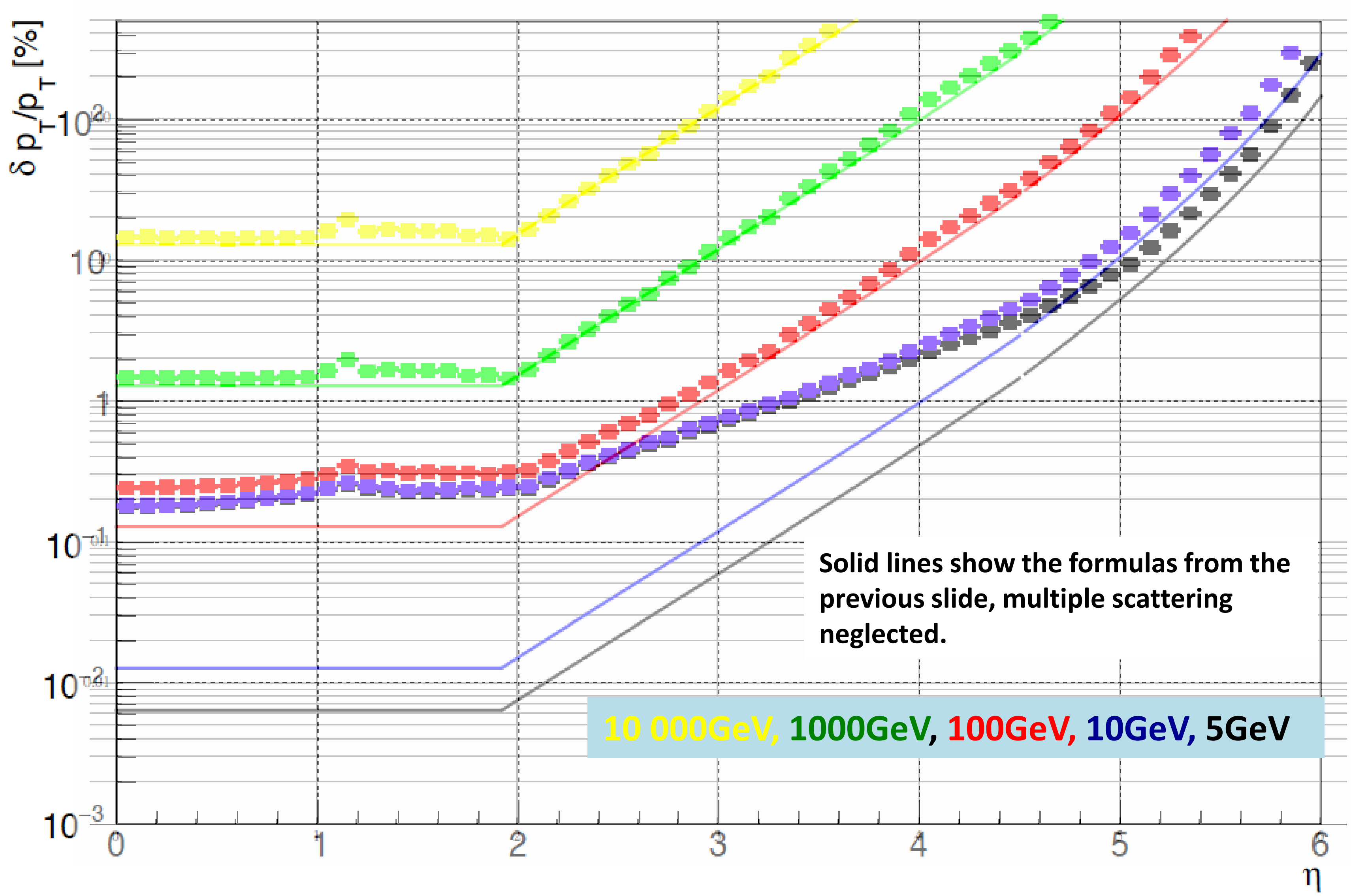
p_T resolution versus η - const P_T across η



The points are results from the TKLayout Tool (Z. Drasal), the solid lines are the standard formulas.

10 000GeV, 1000GeV, 100GeV, 10GeV, 5GeV

Tracker



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 → 10% for a 10TeV charged particle within reach for tracker radius of 2.5m (|eta|<2)!

Could we also reach that with a CMS like design (smaller tracker radius): How to scale the system and keep the performance constant ?

At constant B and 1/2 the tracker radius (2.5m → 1.2m) → free bore of solenoid from 12m to 10m we need:

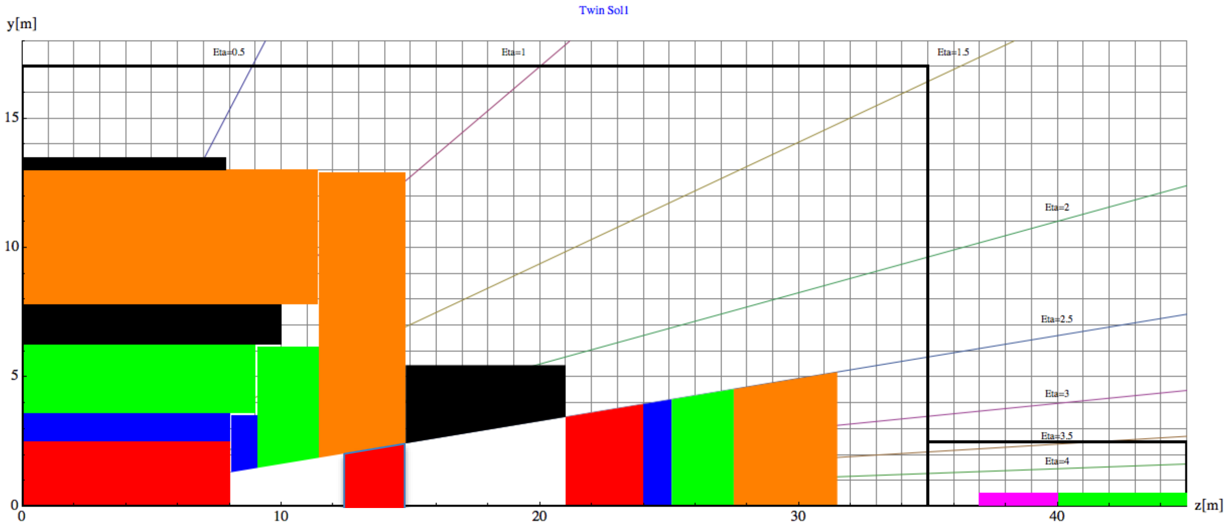
- **4 times the tracker resolution (20µm → 5µm) and**
- **4 times less material budget (x/X_0=50% at eta=0 to x/X_0=12.5% at eta=0 i.e. 3% per Layer to 0.75% per layer)**

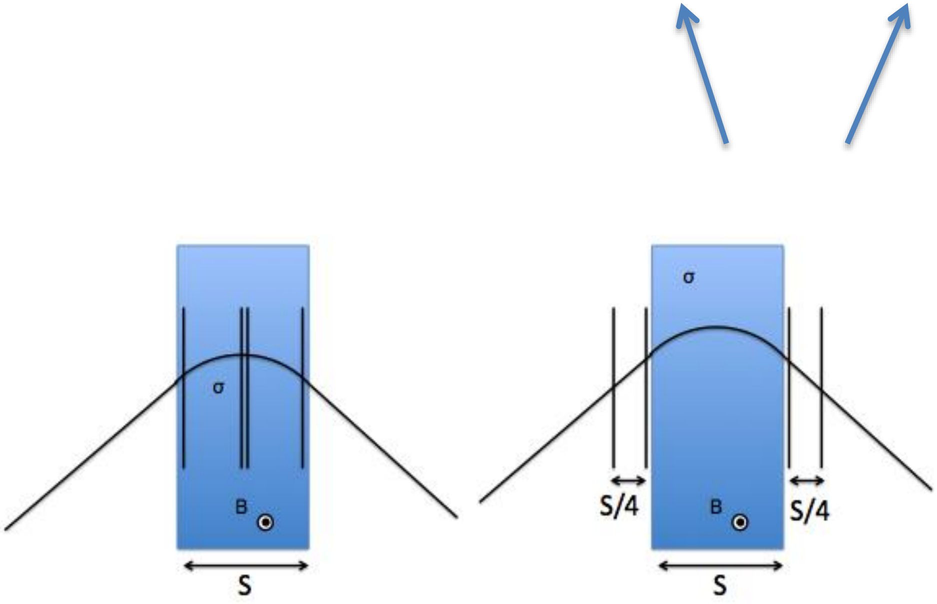
These values are challenging but not out of reach.

→ A final choice is part of an optimization that depends on future technologies

Forward Tracking

Forward Tracking Resolution, Position Resolution





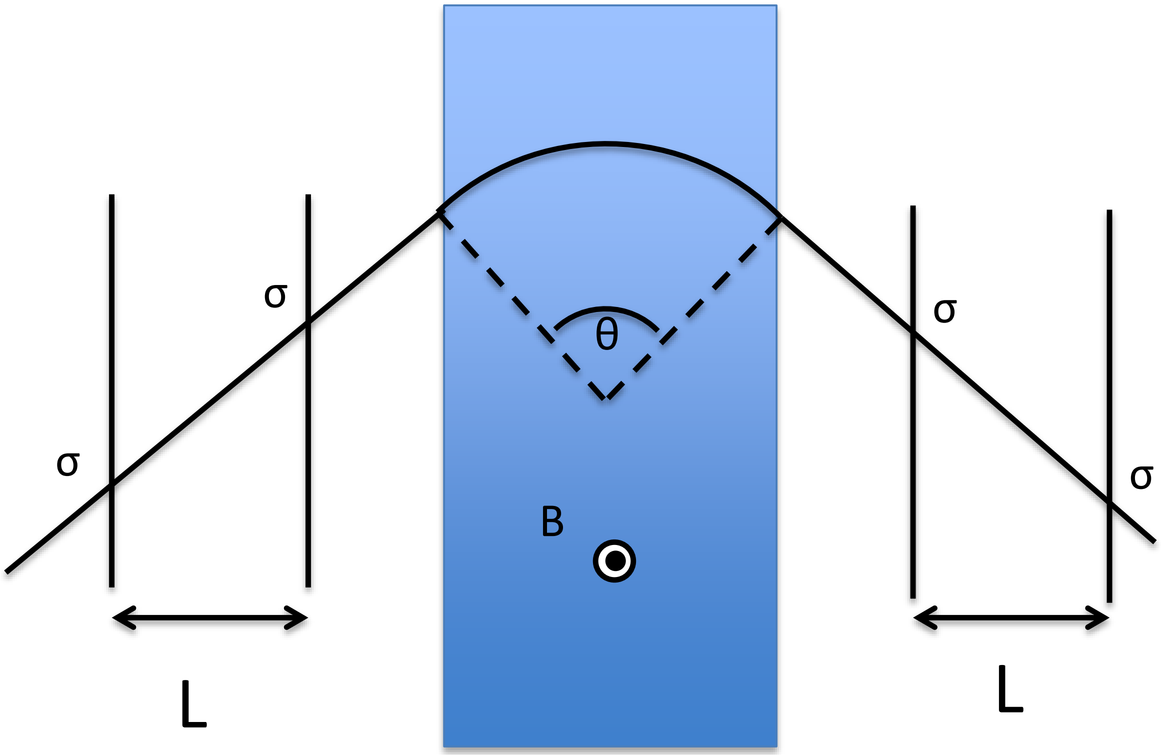
Using 4 tracking stations for a dipole with constant magnetic field and length S, the optimum spectrometer resolution is achieved by placing 2 stations in the center and one on each end to measure the sagitta.

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 (details 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 B dl that counts)

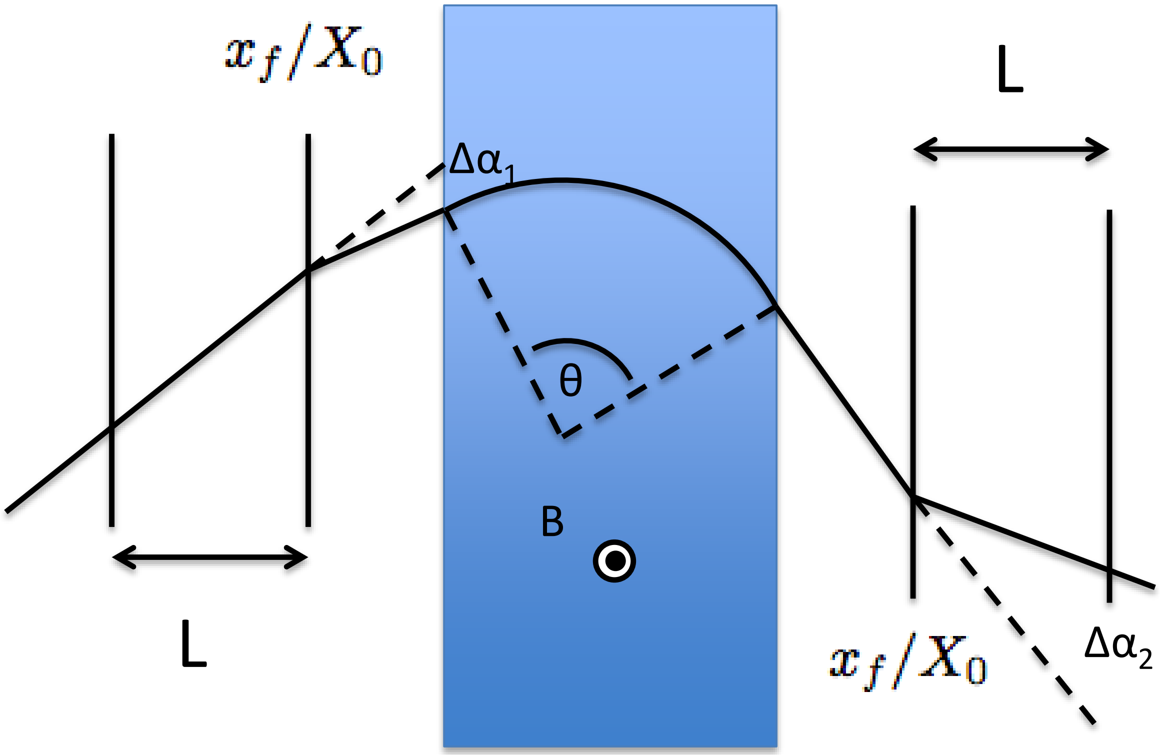
Forward Tracker Resolution, Position Resolution



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

$$\Delta\alpha_{res} = 2\sigma/L.$$

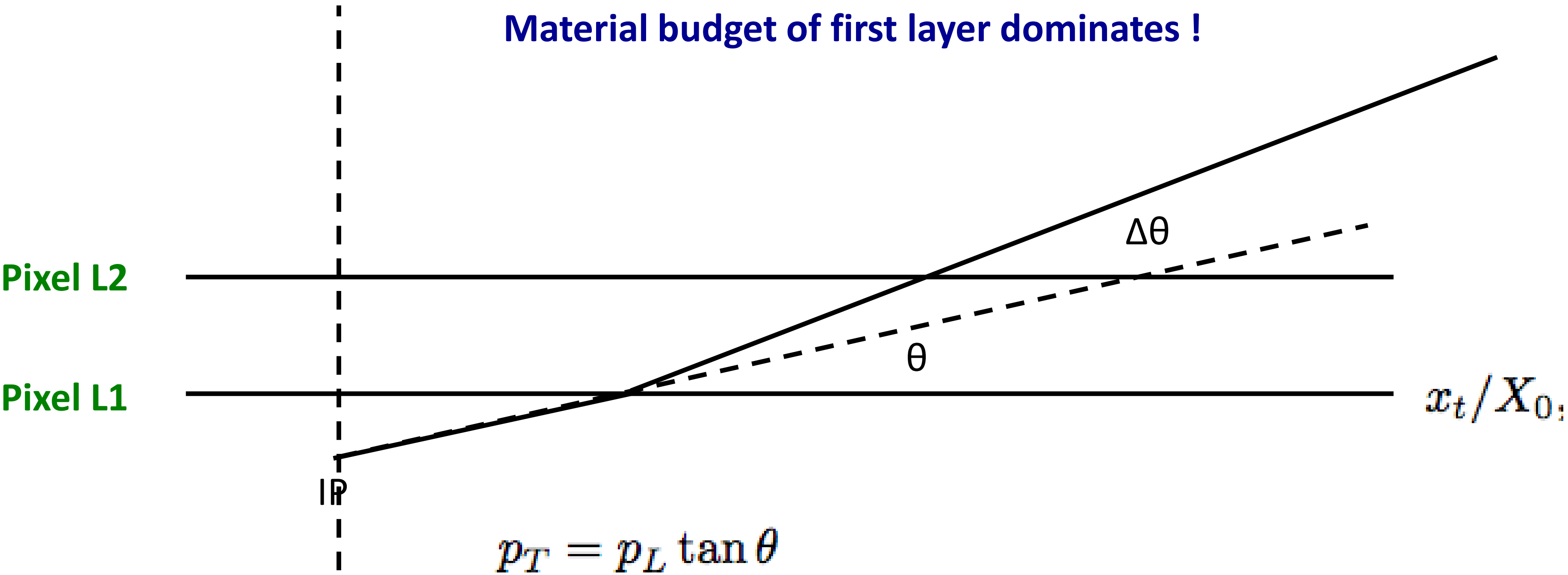
Forward Tracker Resolution, Multiple Scattering



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

Forward Tracker Resolution, Measurement of angle

Material budget of first layer dominates !



$$p_T = p_L \tan\theta$$

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

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

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

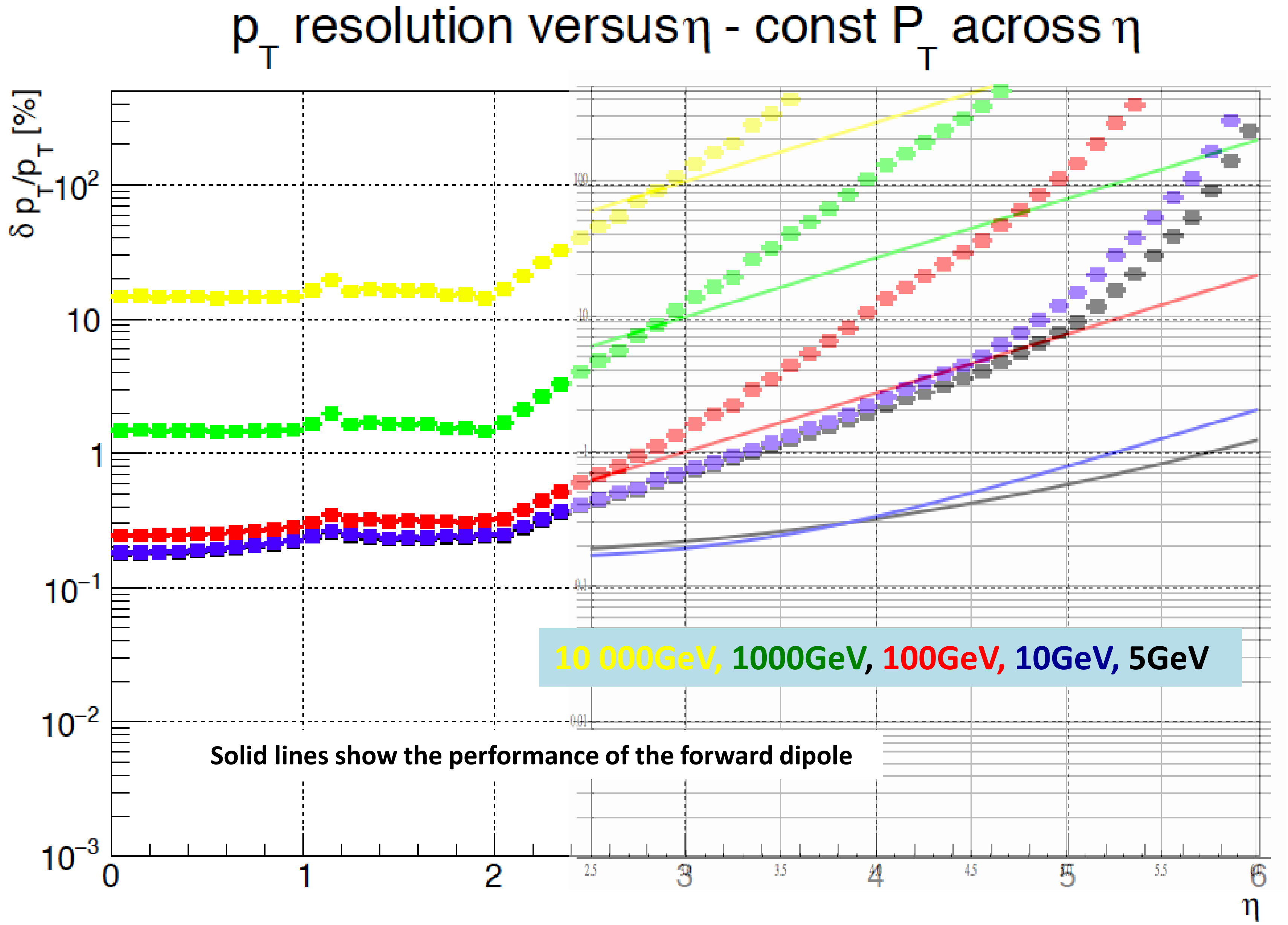
X_f/X_0=0.06
Int Bdl=10 Tm

X_t/X_0=0.03

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

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

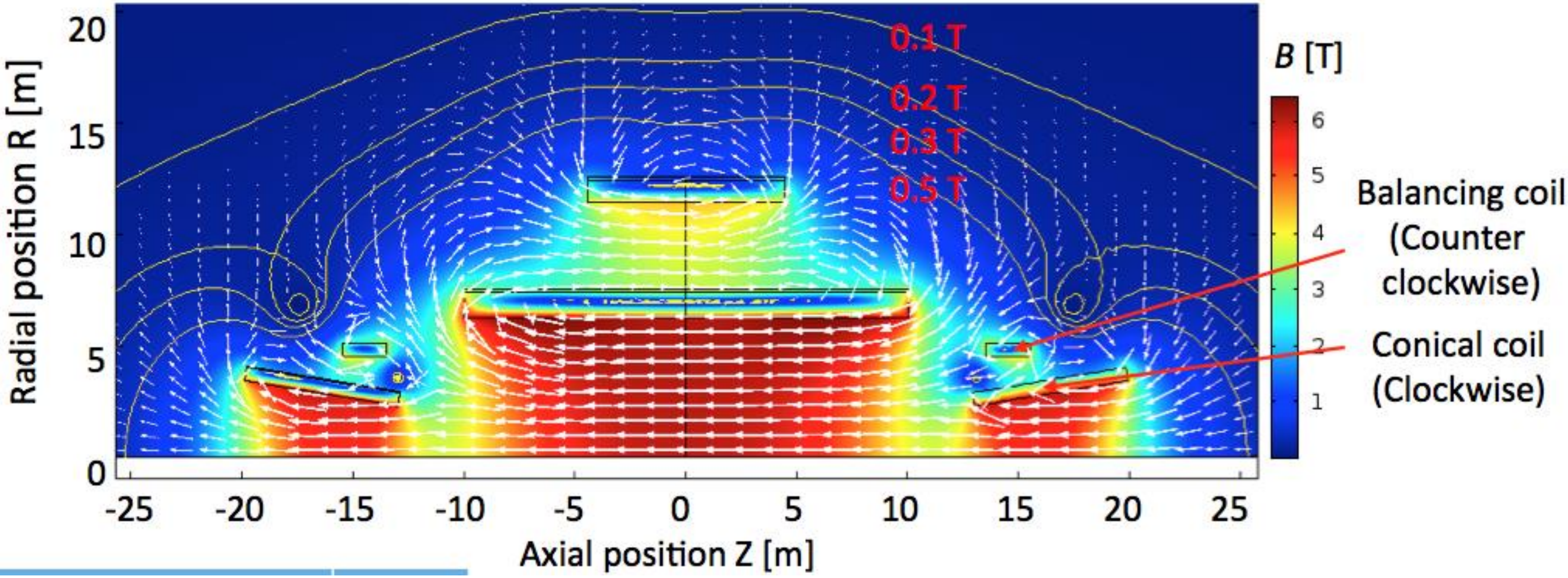
Forward Tracker Resolution



10 000GeV, 1000GeV, 100GeV, 10GeV, 5GeV

Solid lines show the performance of the forward dipole

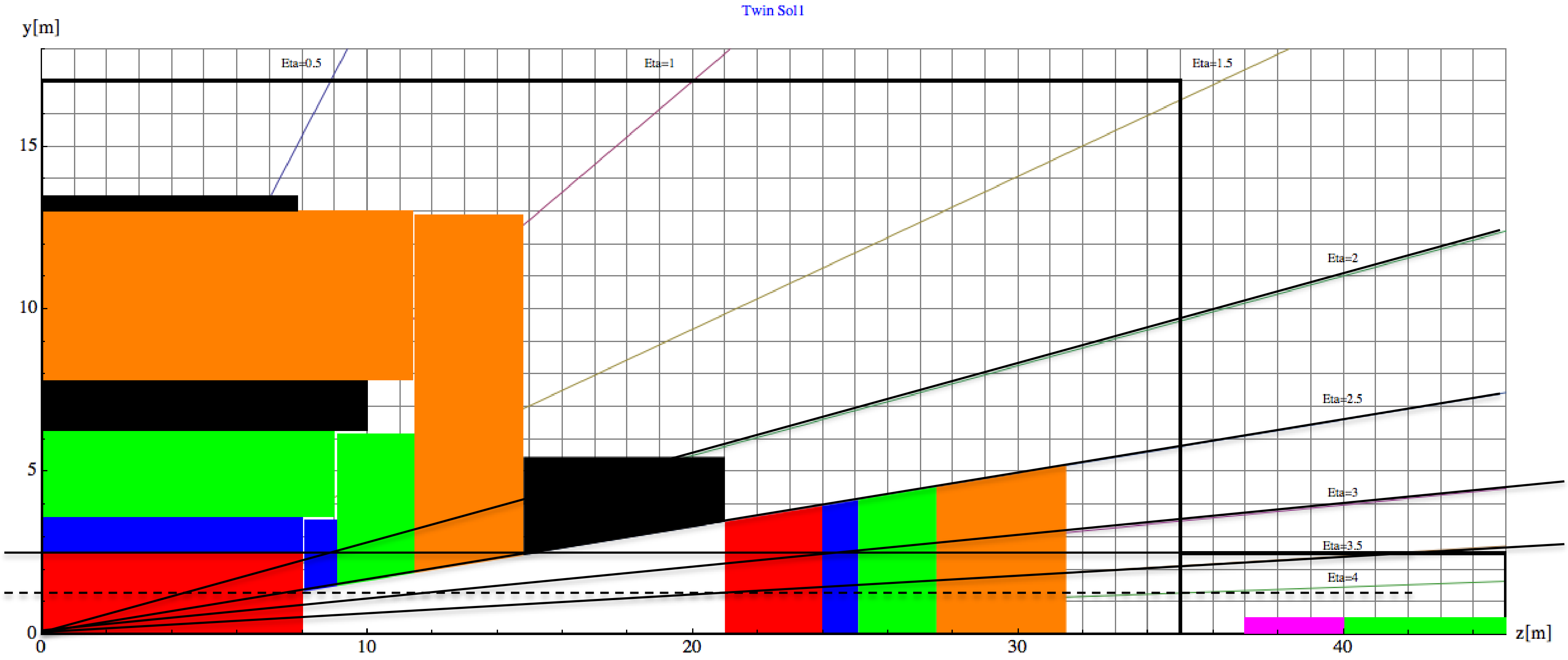
3. New option: a Balanced Conical Solenoid (BCS) magnet



Balancing coil (Counter clockwise)

Conical coil (Clockwise)

Solenoid Field extended to Z=22m

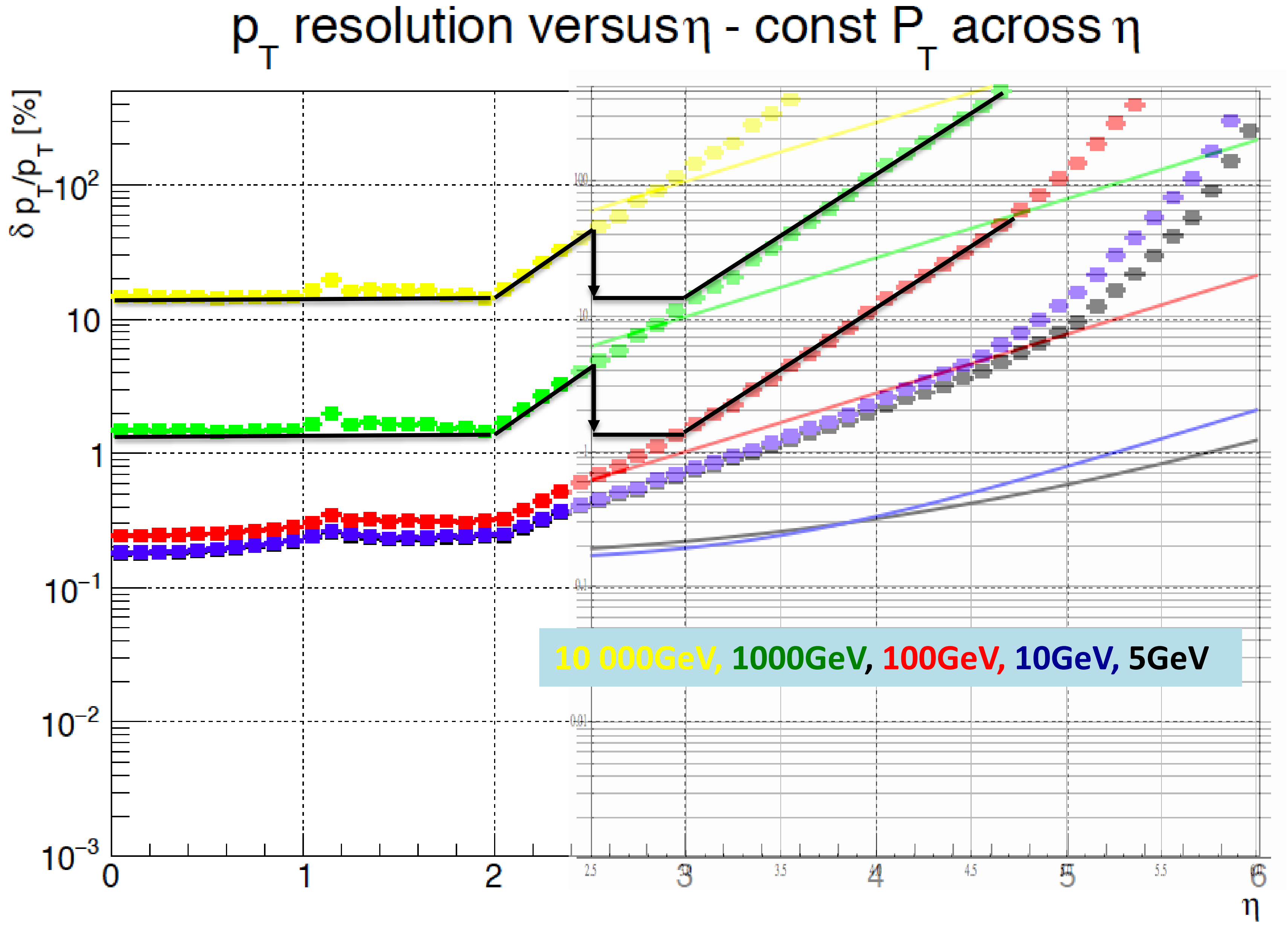


Replacing the dipole by a solenoid that extends the B=6T field up to Z=22m, we can extend shift the resolution curves by one unit of eta,

i.e. flat resolution (10% at p_T=10TeV/c) up to η =3 and ¼ of the resolution at η =3.5

This competed with our present performance parametrization of the Dipole up to η≈4.5

Forward Tracker Resolution



10 000GeV, 1000GeV, 100GeV, 10GeV, 5GeV

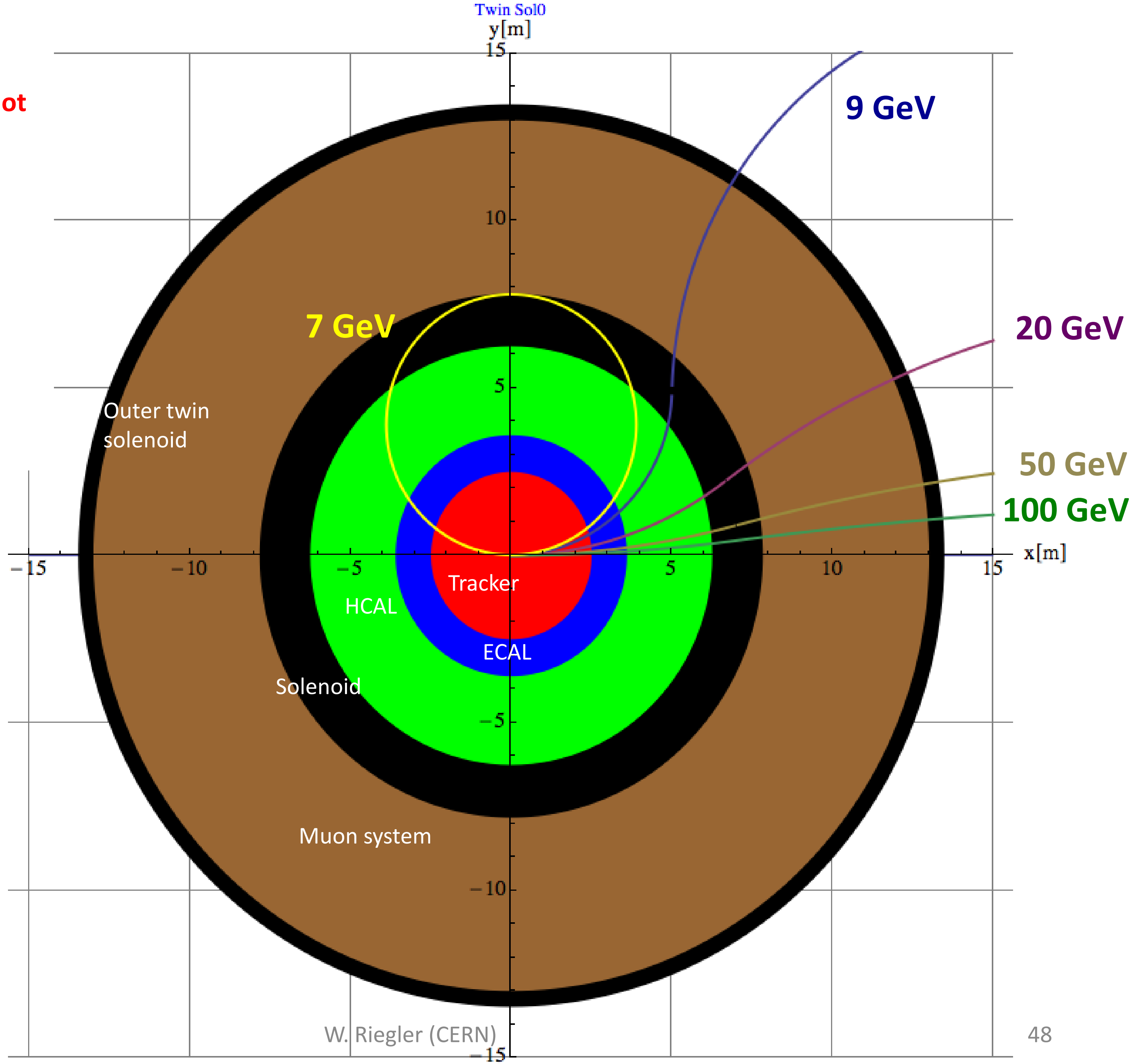
→Interesting ! Parametrized simulations will give indications

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 HCAL.



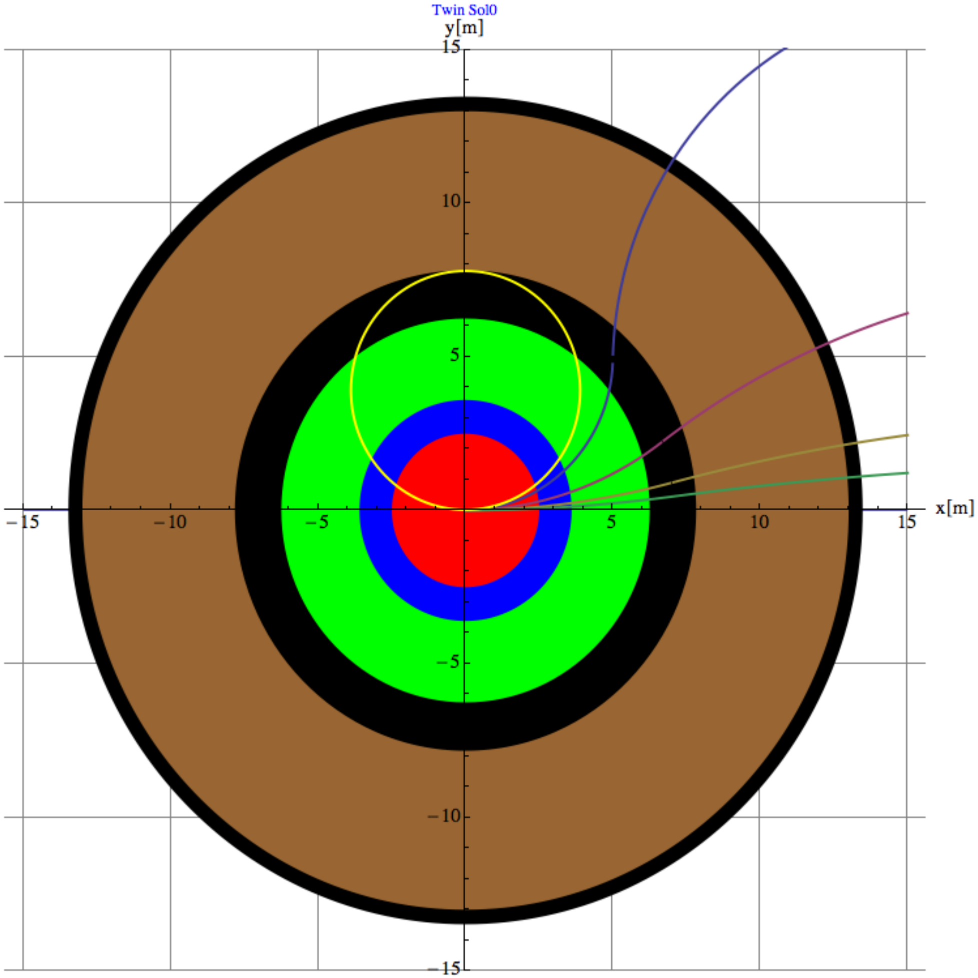
Muon Momentum Can Be Measured by…

1) The inner tracker
→ resolution plots from before

2) A 'standalone' sagitta measurement in the muon system (no iron → precise !)

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

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



CMS Muon Performance

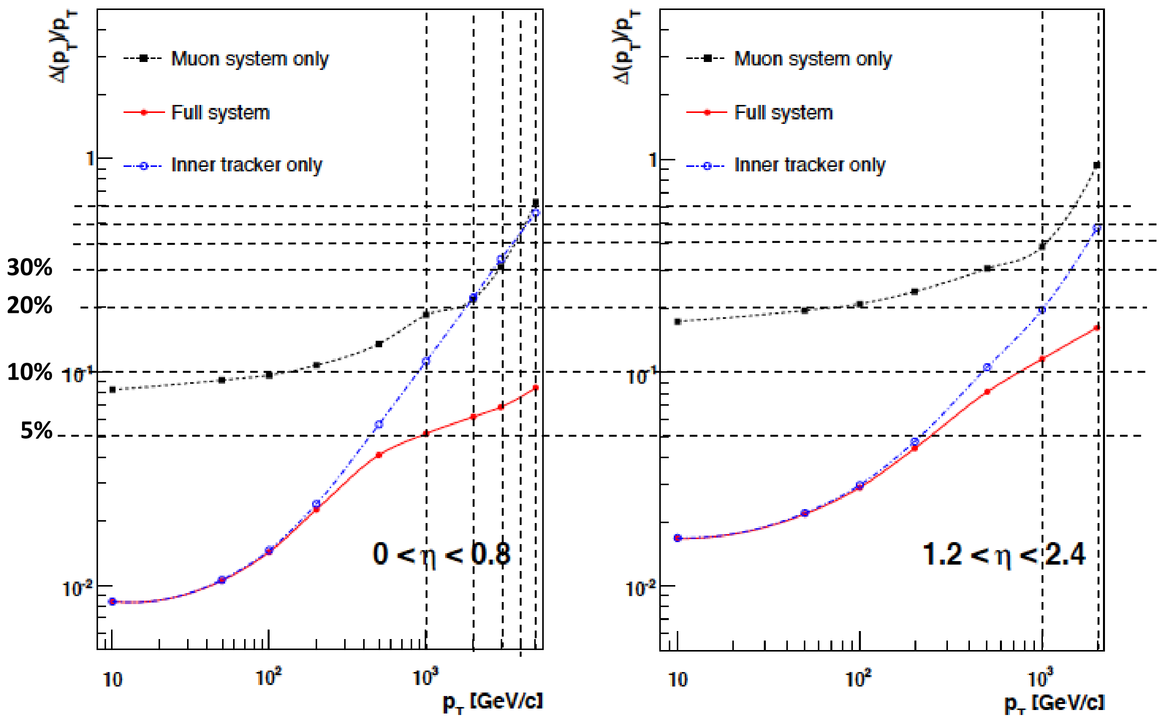


Figure 1.2: The muon transverse-momentum resolution as a function of the transverse-momentum (p_T) using the muon system only, the inner tracking only, and both. Left panel: $|\eta| < 0.8$, right panel: $1.2 < |\eta| < 2.4$.

P_T=1TeV/c, 0<eta < 0.8:

20% muon standalone (angle)
10% inner tracker only
5% combined

P_T=1TeV/c, eta 0<eta<2.4:

40% muon standalone (angle)
20% inner tracker only
10% combined

Sagitta Measurement in the Muon System

The return field is 2.45T

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

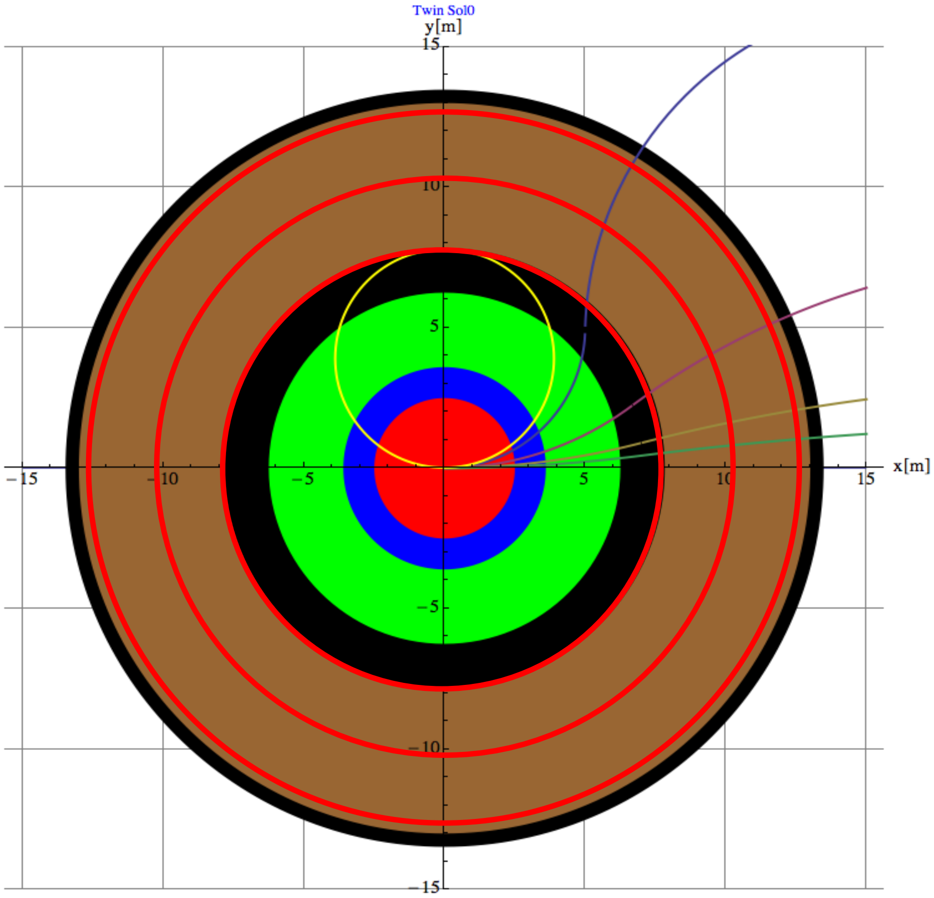
dp_T/p_T= sig*$p_T/(0.3 * B * L^2) * 8$
= 20% @ 10TeV

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

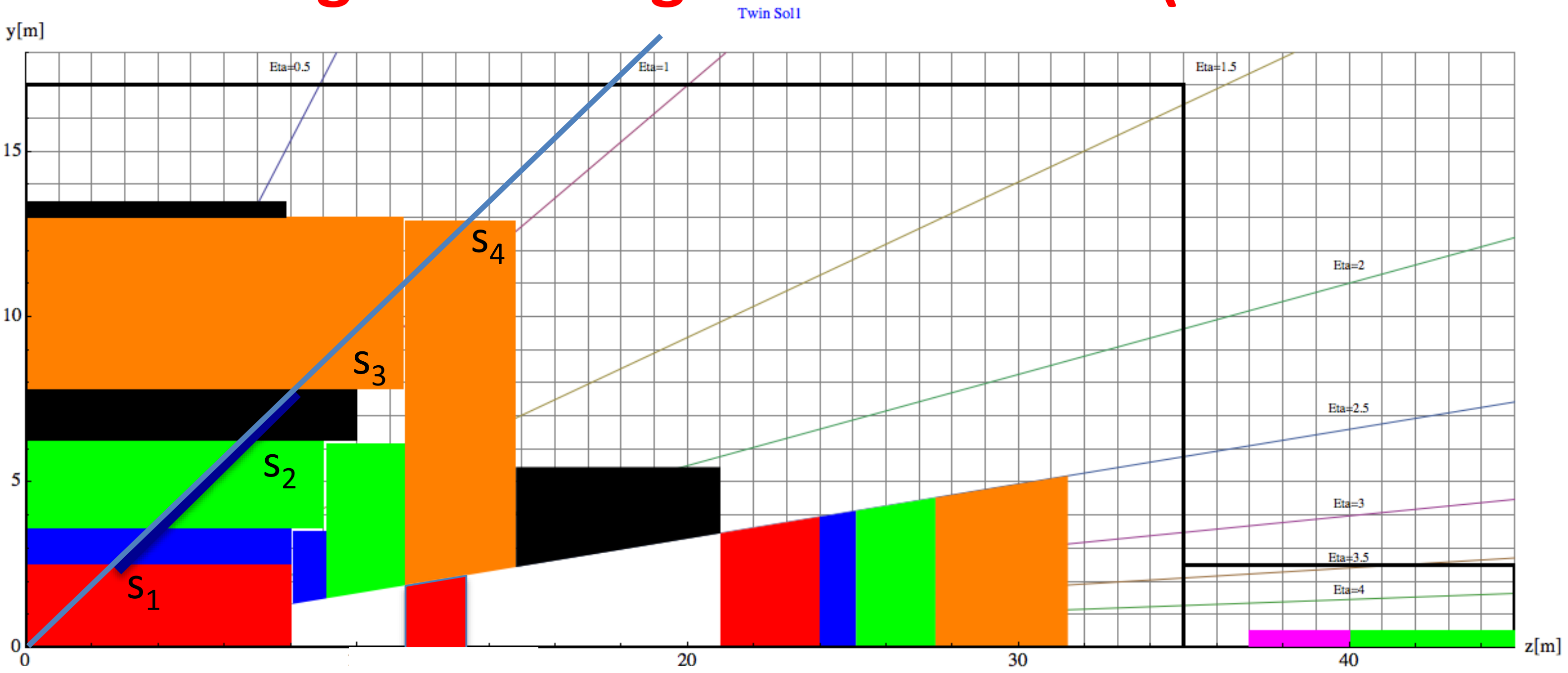
but very hard to beat the angular measurement and the inner tracker (10% at 10TeV)

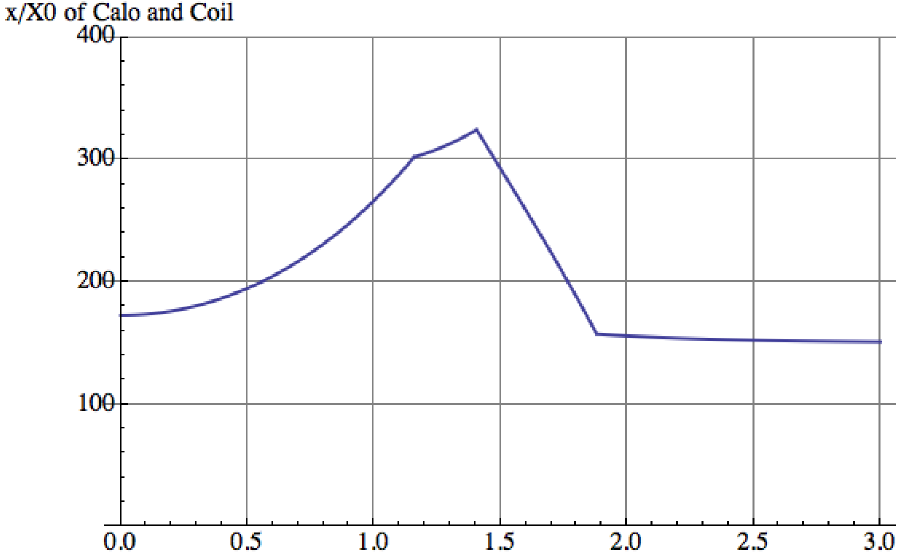
Surface > 5000 m^2

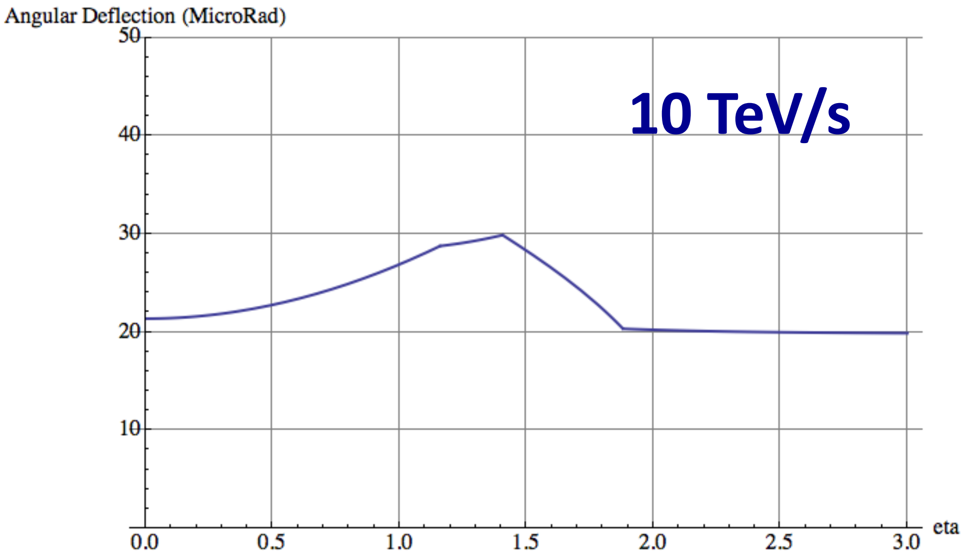
CMS sagitta measurement in the muon system is limited to dp_T/p_T = 20% due to multiple scattering alone.



Radiation Length and Angular Deflection (Mult. Scattering)

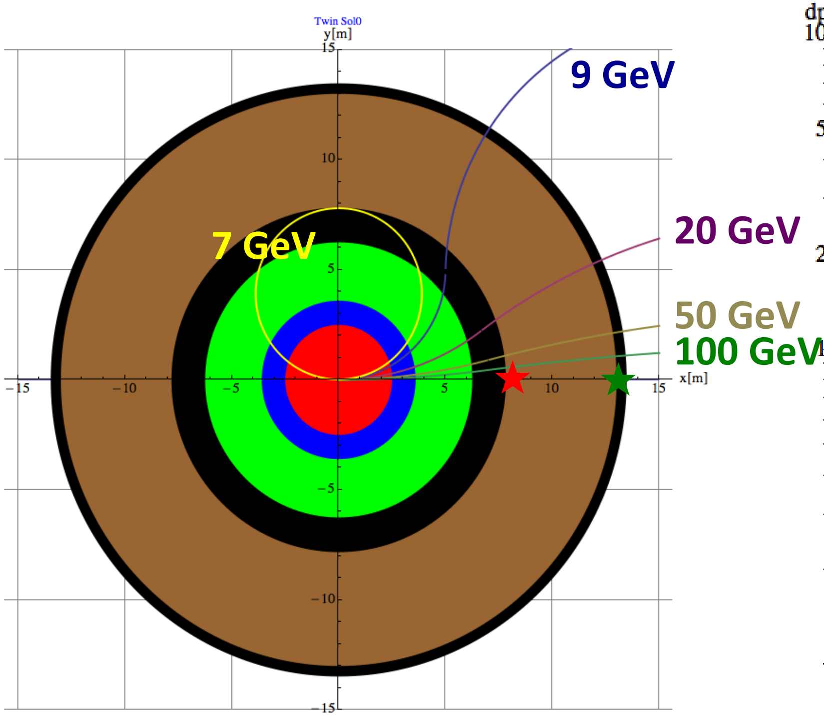


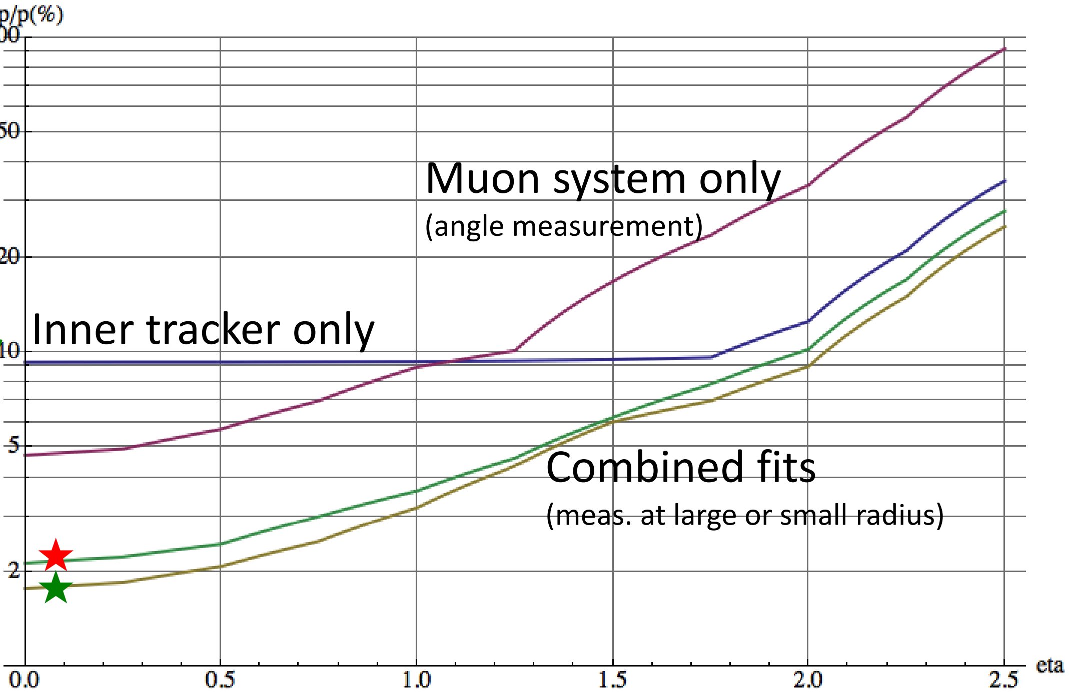




10 TeV/s

Momentum Resolution for a 10 TeV/s Muon





Twin Solenoid assuming inner tracker with baseline resolution curves and multiple scattering limit in the muons system.

P_T=10TeV/c eta = 0:	**5% muon standalone (angle)** **10% inner tracker only** **2% combined**	**P_T=10TeV/c eta=2.:**	**35% muon standalone (angle)** **12.5% inner tracker only** **8% combined**

Compare to the CMS numbers:

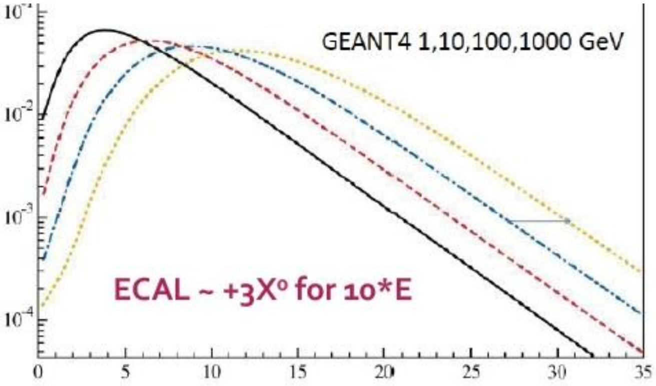
P_T=1TeV/c, 0<eta < 0.8:	**20% muon standalone (angle)** **10% inner tracker only** **5% combined**	**P_T=1TeV/c, eta 1.2<eta<2.4:**	**40% muon standalone (angle)** **20% inner tracker only** **10% combined**

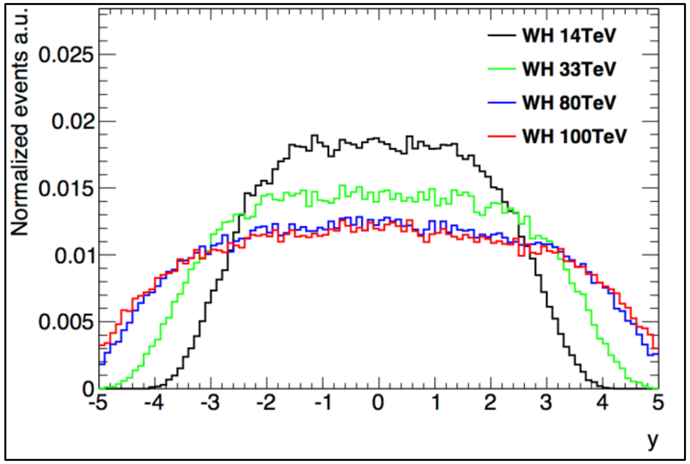
Calorimetry

Requirements ECAL

ECAL:

- Depth only moderately sensitive to √s: $30X_0$ enough for fully contained e/γ (ATLAS ~$22X_0$)
- Large acceptance up to $|\eta|=6$
- High granularity
  - highly collimated final states (high boost)
  - Pile-up mitigation (up to 1000 events per BC)
  - Track-cluster matching, position resolution
  - Pointing resolution
  - Tau reconstruction
- Excellent timing resolution could help for pile-up mitigation.
- High radiation tolerance and stability
- L1 triggering (low p_T thresholds for W and Z will be challenging!)





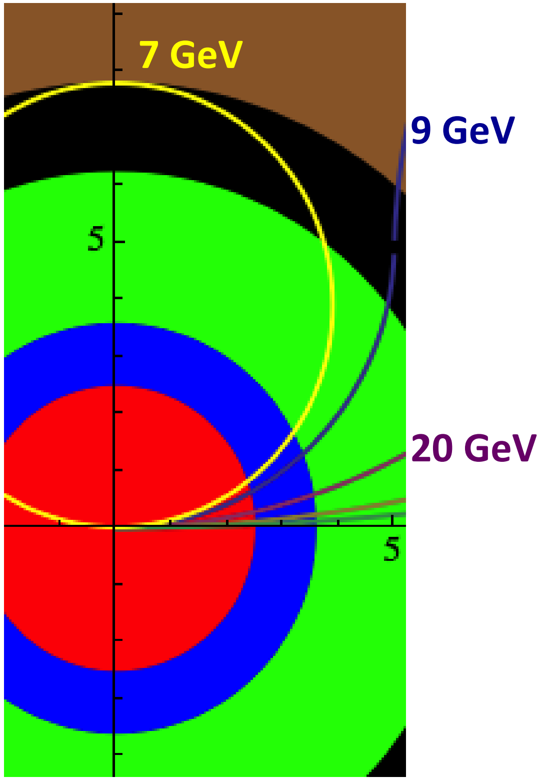
Requirements ECAL

Some general thoughts:

- High magnetic field and large radius: Bremsstrahlungs photons will end up far away from electron (i.e. will mostly not be contained in the same cluster)
  - e.g. distance of e^- and brem γ is up to ~30cm for 20GeV e^-, similar problem for photon conversions
- High pile-up: pile-up rejection (e.g. for isolation requirement for EM objects) will also need to rely on tracker information

→ EM energy measurement will not be able to rely on the ECAL only → EM energy measurement in FCC will consist in an intelligent combination between tracker measurement and ECAL measurement (of course the jet and E_T^{miss} measurement even more so)

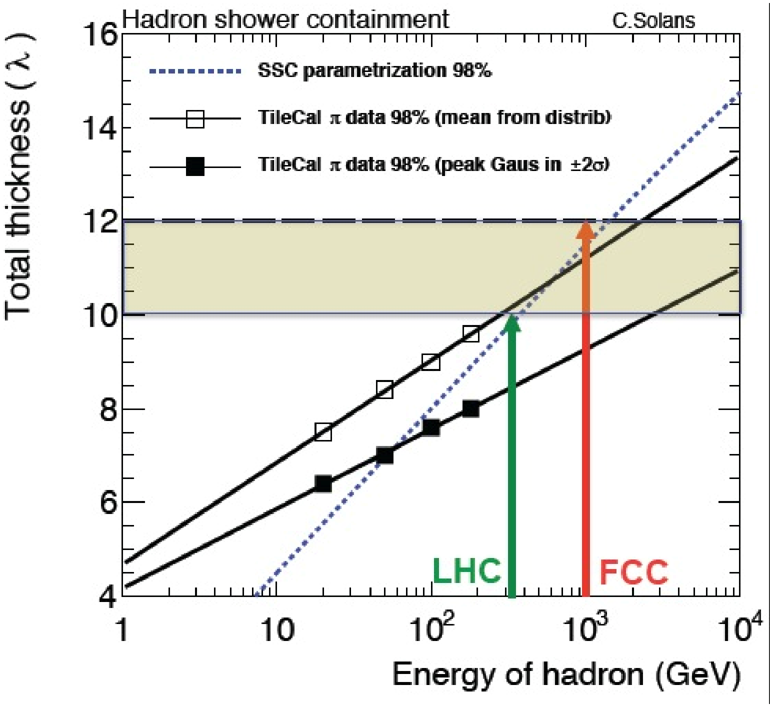
- Track-cluster matching is essential to achieve the above → fine (lateral) granularity and good position resolution should be achieved

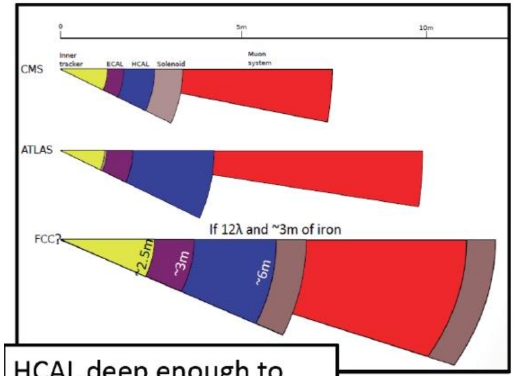


Requirements HCAL

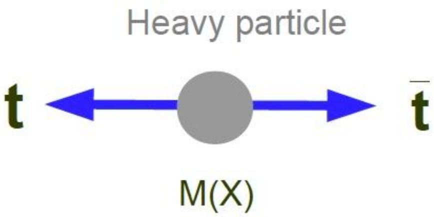
HCAL:

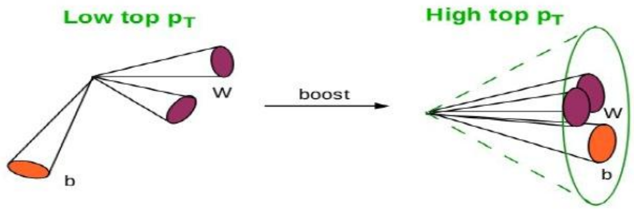
- Jet containment: 8% of single hadron constituents of 30TeV jets have E>1TeV. 98% containment requires 12λ
- Large acceptance up to |η|=6
- Highly collimated (boosted) final states
    - Minimal distance between two partons proportional to m/p_T (e.g. top)
- → high granularity also in the HCAL
    - Sub-structure identification will become difficult as the jet cone tends to be very narrow when particles enter the calorimeter → object overlap
    - Tau reconstruction





HCAL deep enough to prevent punch-through





HCAL Energy Resolution

Performance of calorimeters improves with energy

$$\boxed{\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c}$$

a – stochastic/sampling term,
b - electronic noise term
c - constant term

Single hadrons:

ATLAS: $\sigma_E/E \sim 50\%/\sqrt{E} + 3.0\%$

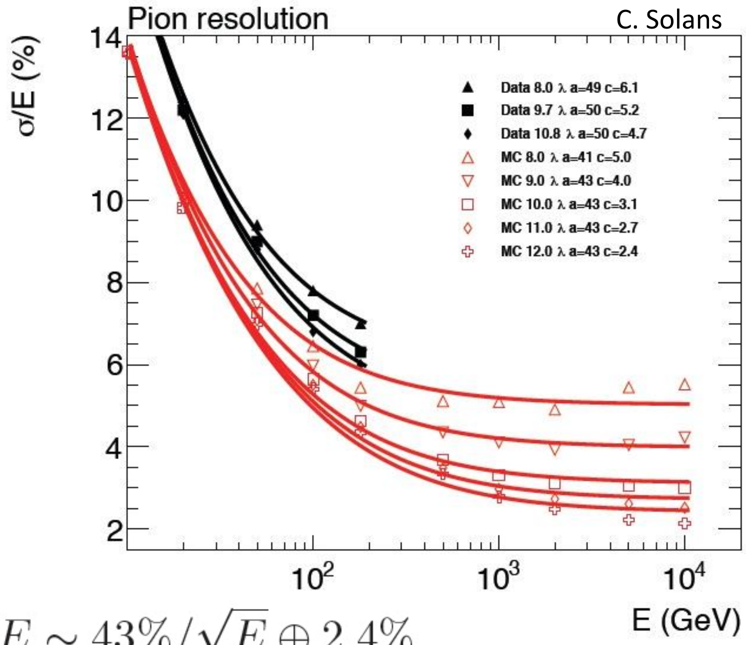
CMS: $\sigma_E/E \sim 100\%/\sqrt{E} + 4.5\%$

(small noise term for both)

Jet p_T > 5TeV: constant term dominates

Reduction of the constant term:

- **e/h ≠ 1**
- **dead material,**
- **longitudinal and lateral energy leakage,**
- **non-uniformity calibration,**
- **transition region, etc.**



C. Solans

Achievable resolution at 12λ (ATLAS like HCAL): $\sigma_E/E \sim 43\%/\sqrt{E} \oplus 2.4\%$