FCC-hh Detectors and Experiments

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FCC Academic Training Lectures

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Material from Discussions on FCC-hh Detector Meetings:

FCC-hh Detector Magnets
https://indico.cern.ch/category/6244/

FCC-hh Detectors
https://indico.cern.ch/category/6069/
e-mail-list: fcc-experiments-hadron@cern.ch

FCC-hh machine detector interface
https://indico.cern.ch/category/5901/

With input from:
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FCC-hh Detectors and Experiments

Abstract

This lecture will outline detector concepts for a 100 TeV proton collider that is being investigated in the context of the Future Circular Collider (FCC) study. An ultimate instantaneous luminosity of about 3×10^{35} $cm^{-2}s^{-1}$ and a total integrated luminosity in the range of 20 ab^{-1} pose significant challenges on detector technology beyond the LHC Phase II upgrades. The baseline specifications for detectors at such a machine are presented and first implementation ideas are being shown. Key areas of necessary detector R&D are discussed as well.

Baseline Parameters for the FCC-hh Machine

The present working hypothesis is:

- peak luminosity baseline: $5x10^{34}$ $cm^{-2}s^{-1}$
- peak luminosity ultimate: ≤ $30x10^{34}$ $cm^{-2}s^{-1}$

- 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} [5×10^{34}, 30×10^{34}] $cm^{-2}s^{-1}$

→ 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 Motivation: Pushing the Energy Frontier

The name of the game of a hadron collider is energy reach

$$E \;\alpha\; B_{dipole} \times R_{bending}$$

Cf. LHC: factor ~4 in radius, factor ~2 in field → O(10) in E_{cms}

FCC-hh Preliminary Layout

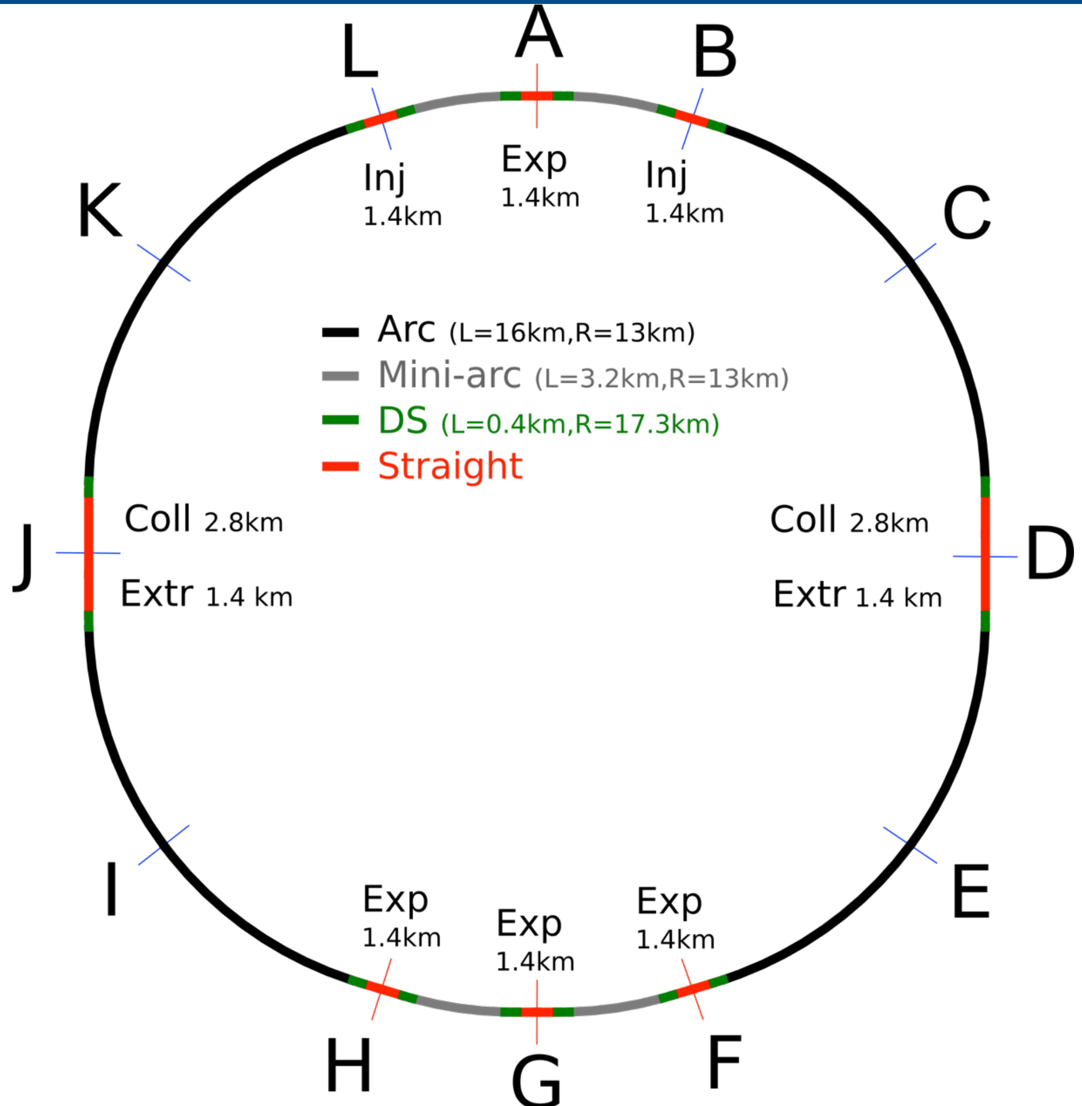
100 km layout for FCC-hh (different sizes under investigation)

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

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

⇒ **Two collimation lines**

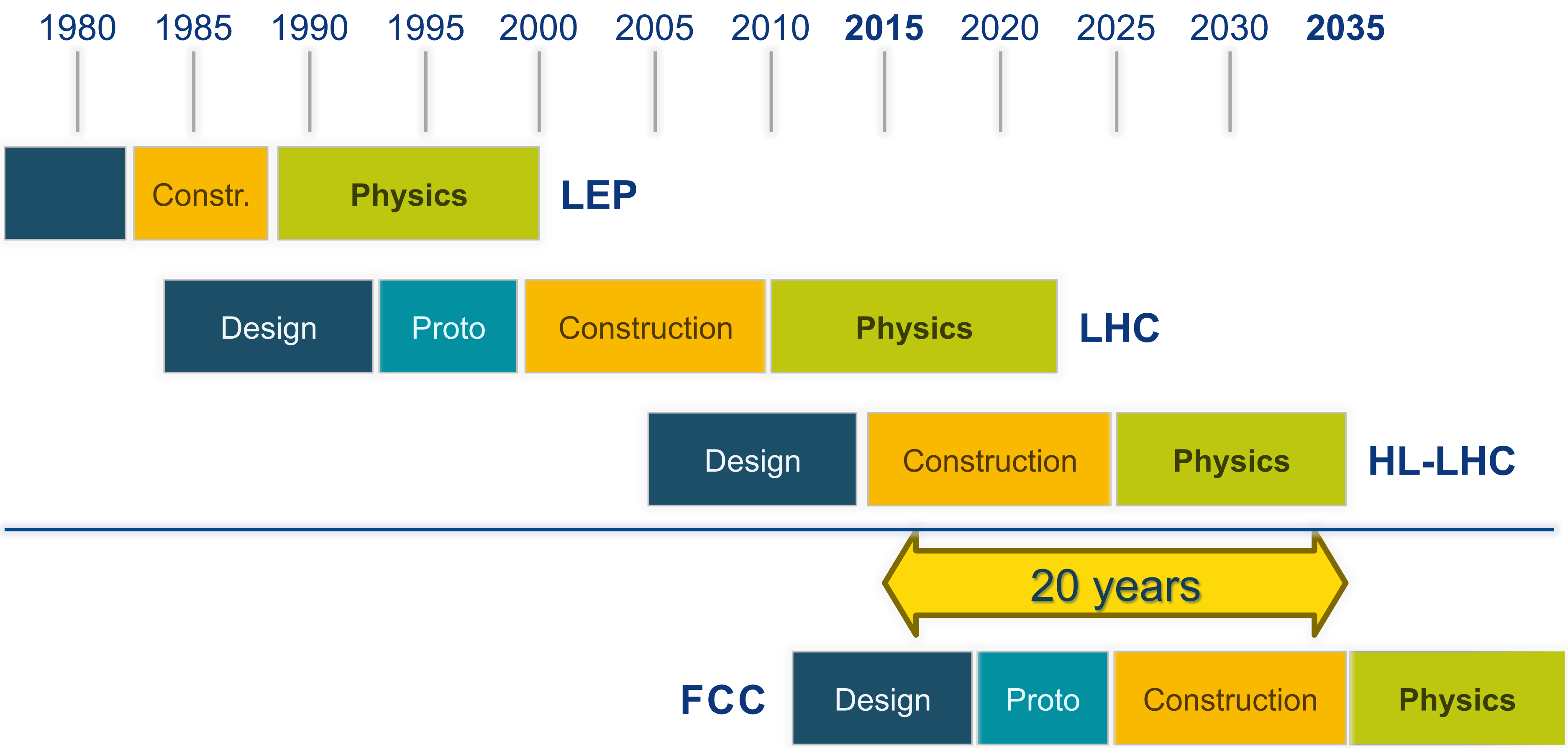
⇒ **Two injection and two extraction lines**



FCC-hh Machine Parameters

Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	~25	12	1	5
events/bunch crossing	170	~850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchrotron radiation [W/m/aperture]	30		58	0.2	0.35

CERN Circular Colliders and FCC



FCC Conceptual Design Report by end 2018 for the European strategy update

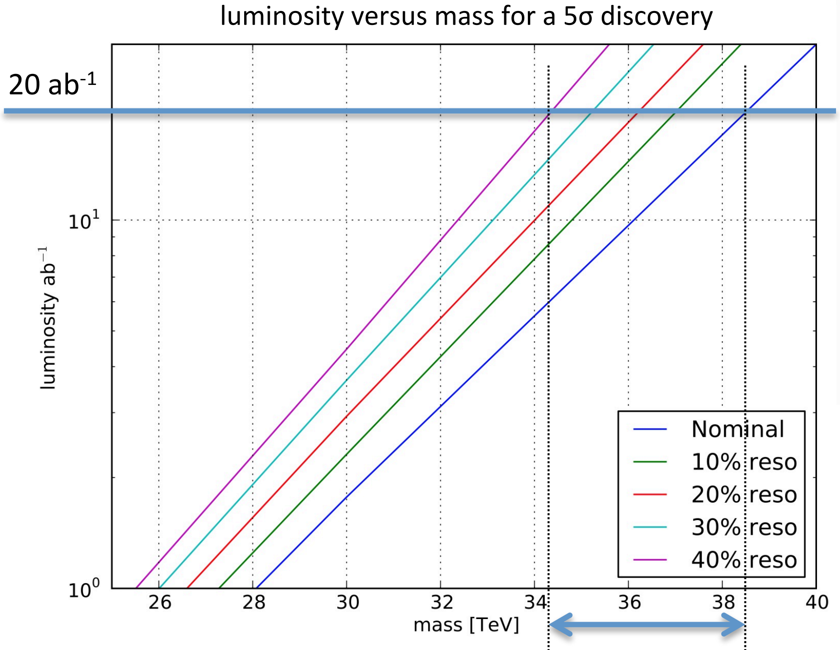
Summary of Requirements from Physics for the FCC Detectors (very preliminary)

...please see yesterday's lectures for many more details on possible measurements

Physics at the Lσ Limit

Exploration potential through higher energy, increased statistics, increased precision

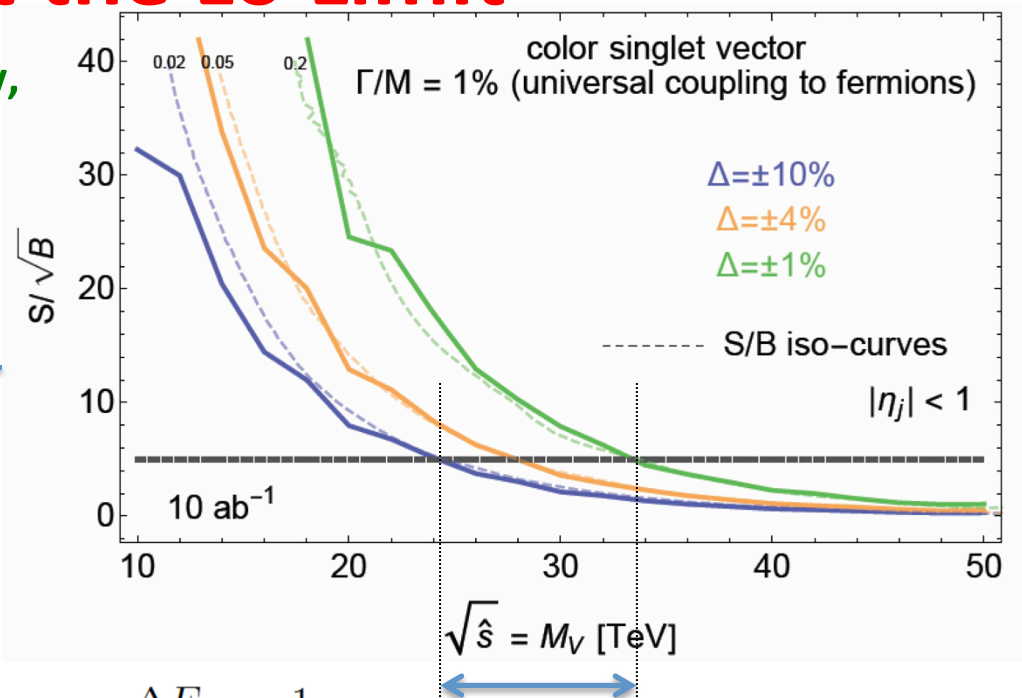
Example: Z' $_{SSM}$ discovery



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

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%

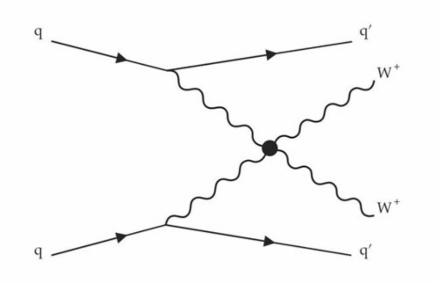
2% jet resolution a reasonable choice (Δ=±4%)

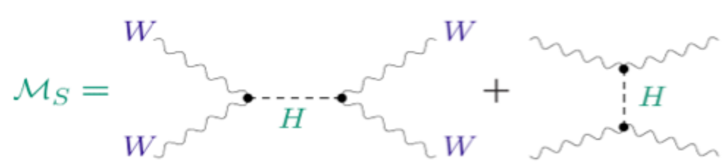
- **Constant term dominates, ≈ 2% goal**
- **→ full shower containment is mandatory !**
- **→ HCAL depth of 12 λ_{int} !**

WW Scattering by VBF Mechanism

WW→WW scattering violates unitarity at high energies

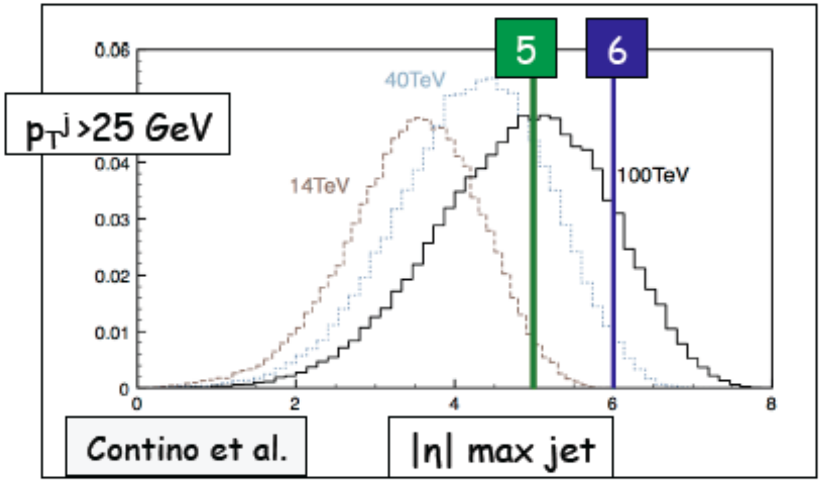
- A scalar, such as the Higgs boson, fixes this (partially)
- Probing characteristics of VV scattering is an important test of the nature of electroweak symmetry breaking
- New Physics would modify interferences between diagrams → modified V p_T and di-boson mass. Also: Are there high mass resonances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





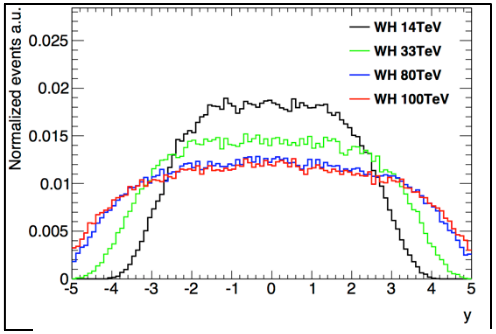
VBF jets also important for tagging of Higgs produced though VBF, like H->bb, H->tautau etc.

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

		$\|\eta\| < 2.5$	$\|\eta\| < 4$	$\|\eta\| < 5$
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)

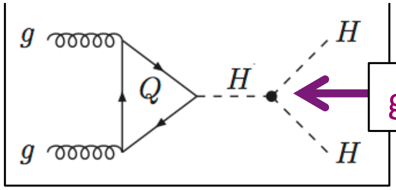
→ can be recovered by extending to |η|~ 4

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)



$g_{HHH} \sim \lambda v$

FCC

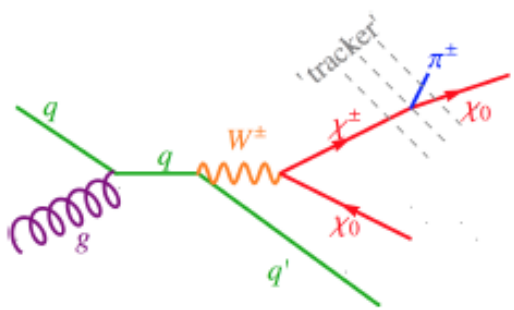
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

More Exotic

Disappearing Tracks - Introduction

$$M_{\chi^\pm} - M_{\chi_0} = 165\ \text{MeV} > m_\pi \quad \Rightarrow \quad \text{lifetime } \tau \simeq 6\,\text{cm} \simeq 0.2\,\text{ns}$$

Almost all $\chi^\pm$s decay to χ_0 + soft pions before reaching detectors



Feng Strassler 1994

Feng Moroi Randall Strassler Su 1999

...

Low Wang 1404.0682

Filippo Sala

→ **Missing E_T Measurement important! E_T^{miss} distributions with smallest tails possible to keep sensitive to very rare processes → high eta coverage!**

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 ≈15% 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.

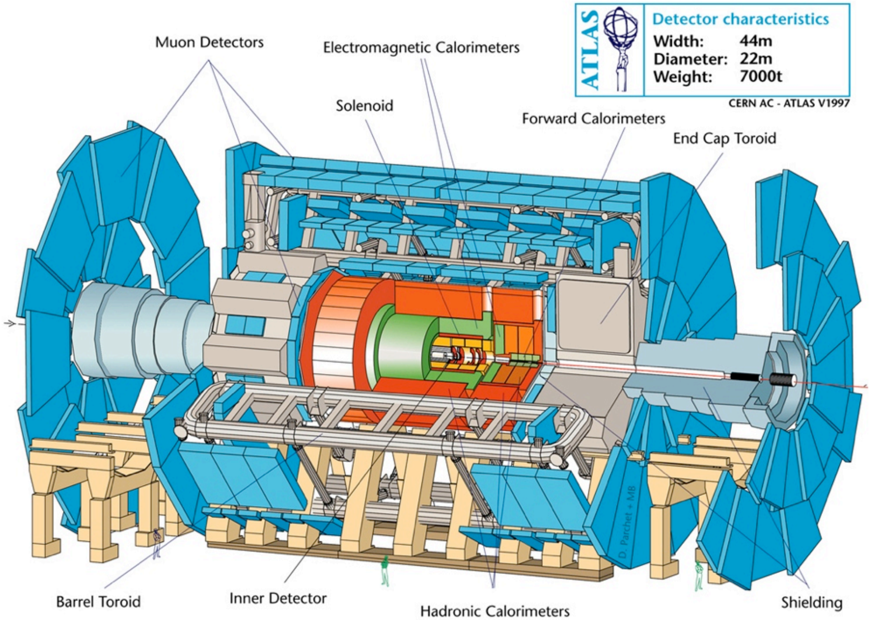
Key Point and Strategy

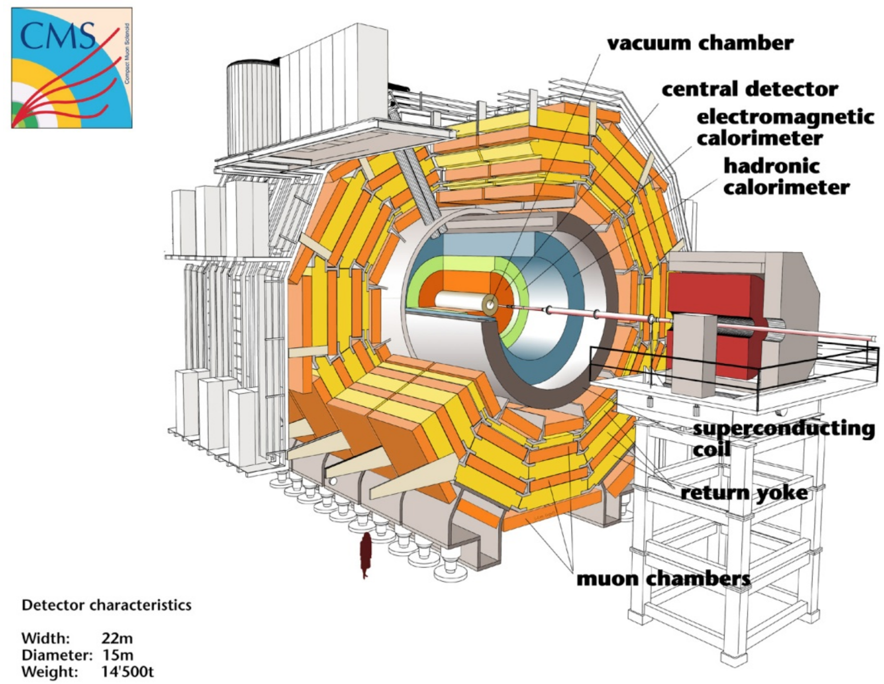
If the FCC hadron machine with 16T magnets, 5MW synchrotron radiation and a 100km tunnel can be realized, there is no doubt that a detector, that makes full use of the physics potential, can be built.

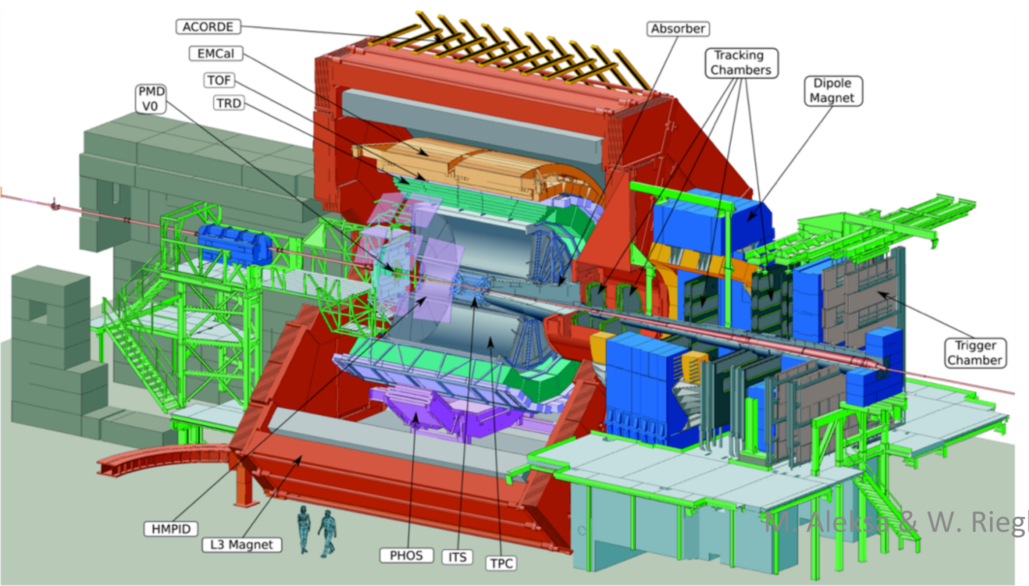
Much of detector technology is driven by silicon technology and computing power i.e. we can count on significant improvements.

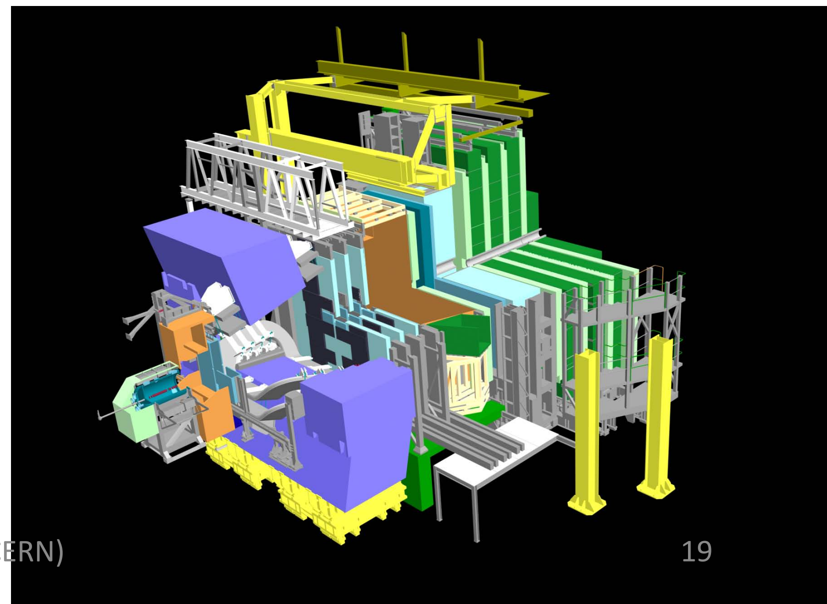
Since the maximum energy and delivered luminosity are the key goals for the FCC-hh machine, the detector efforts should put minimal constraints at the machine efforts.

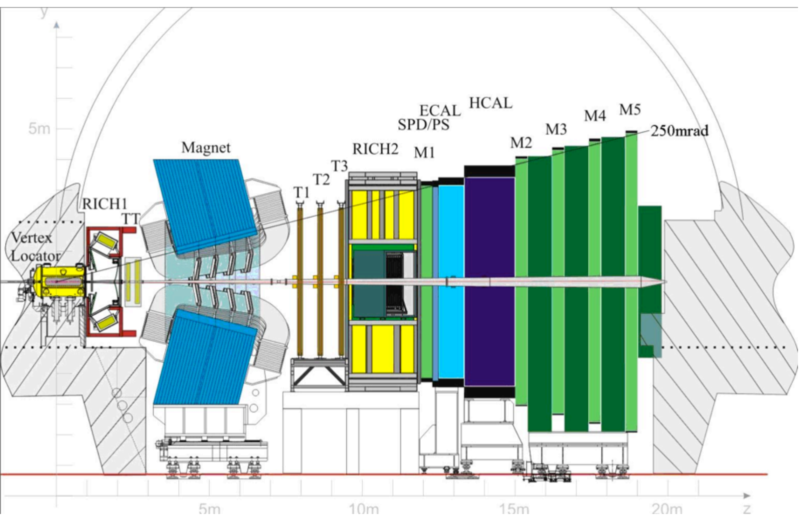
Guidance and Scaling from ATLAS, CMS, ALICE, LHCb







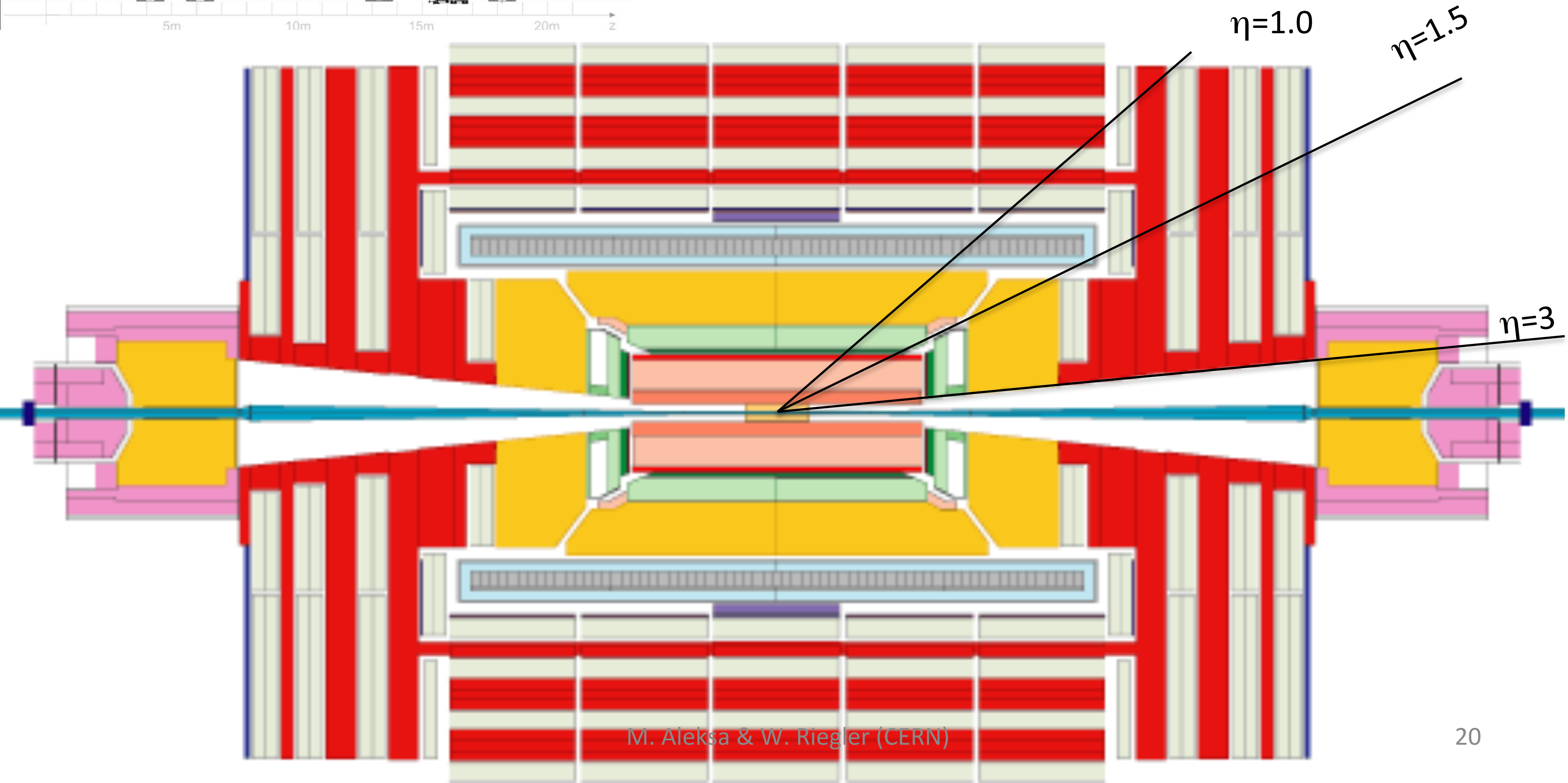




LHCb: Tracking, Calo η = 2 - 5

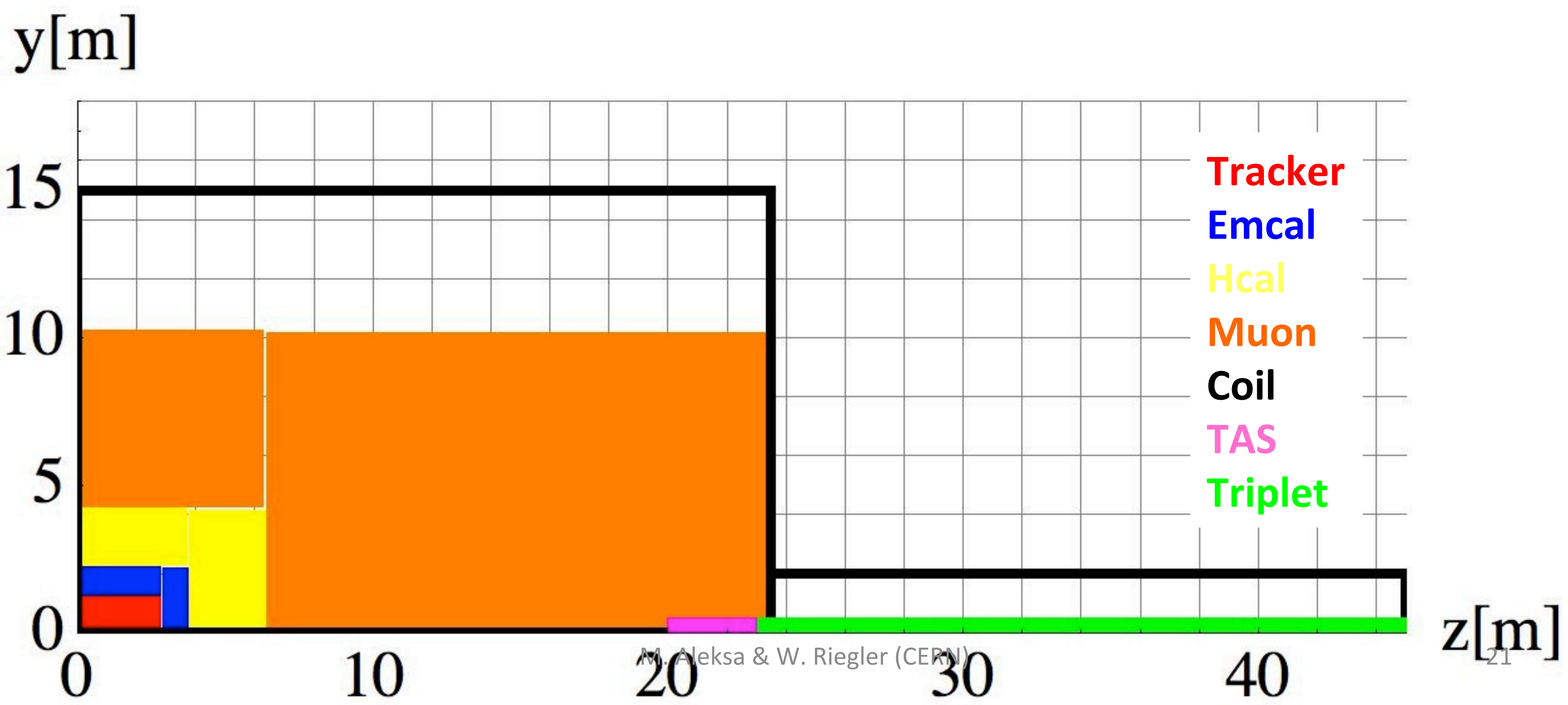
… all with impressive performance …

ATLAS, CMS: tracking, calo η -2.5,2.5



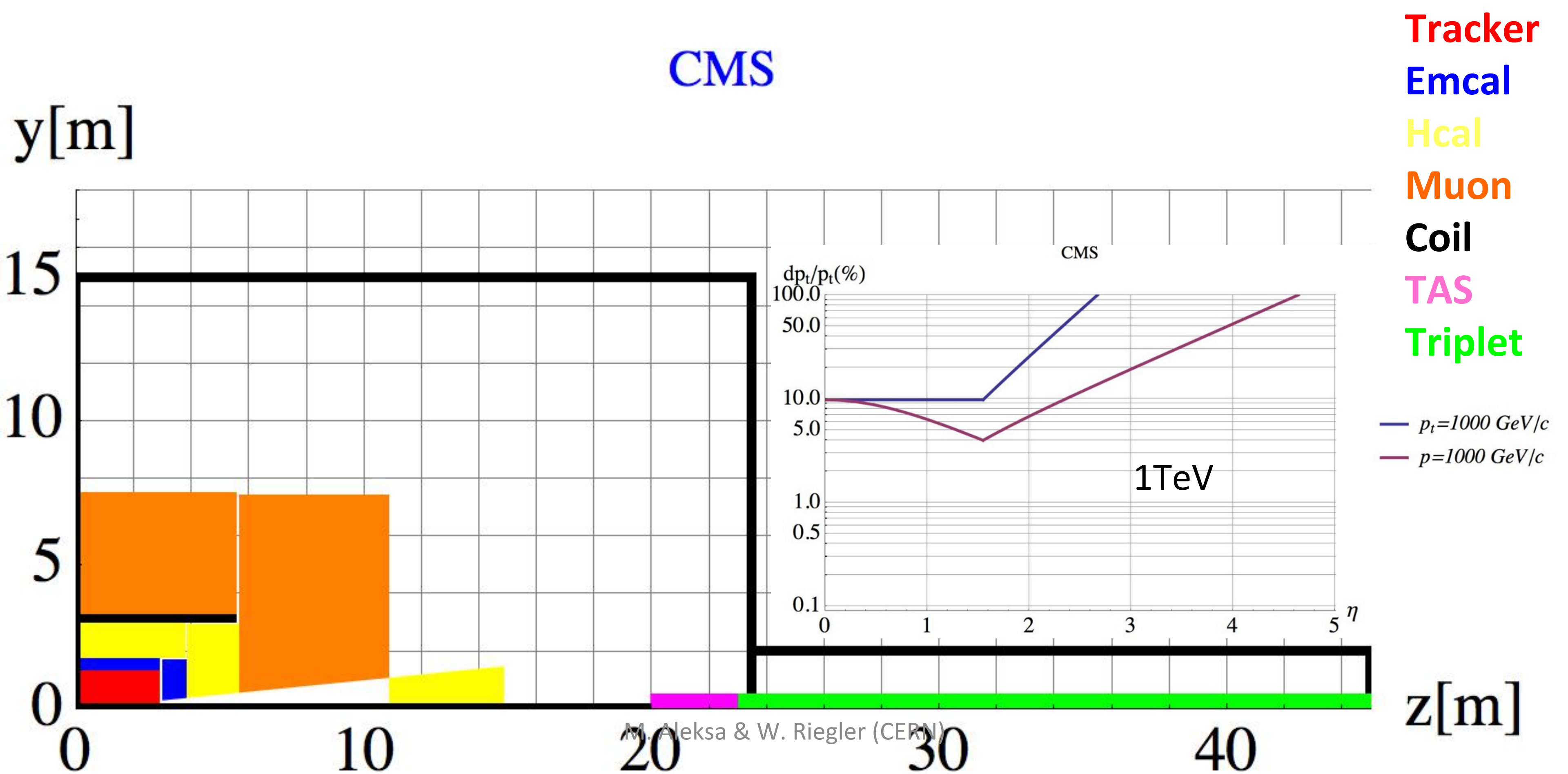
ATLAS

- 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 η = 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.



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.

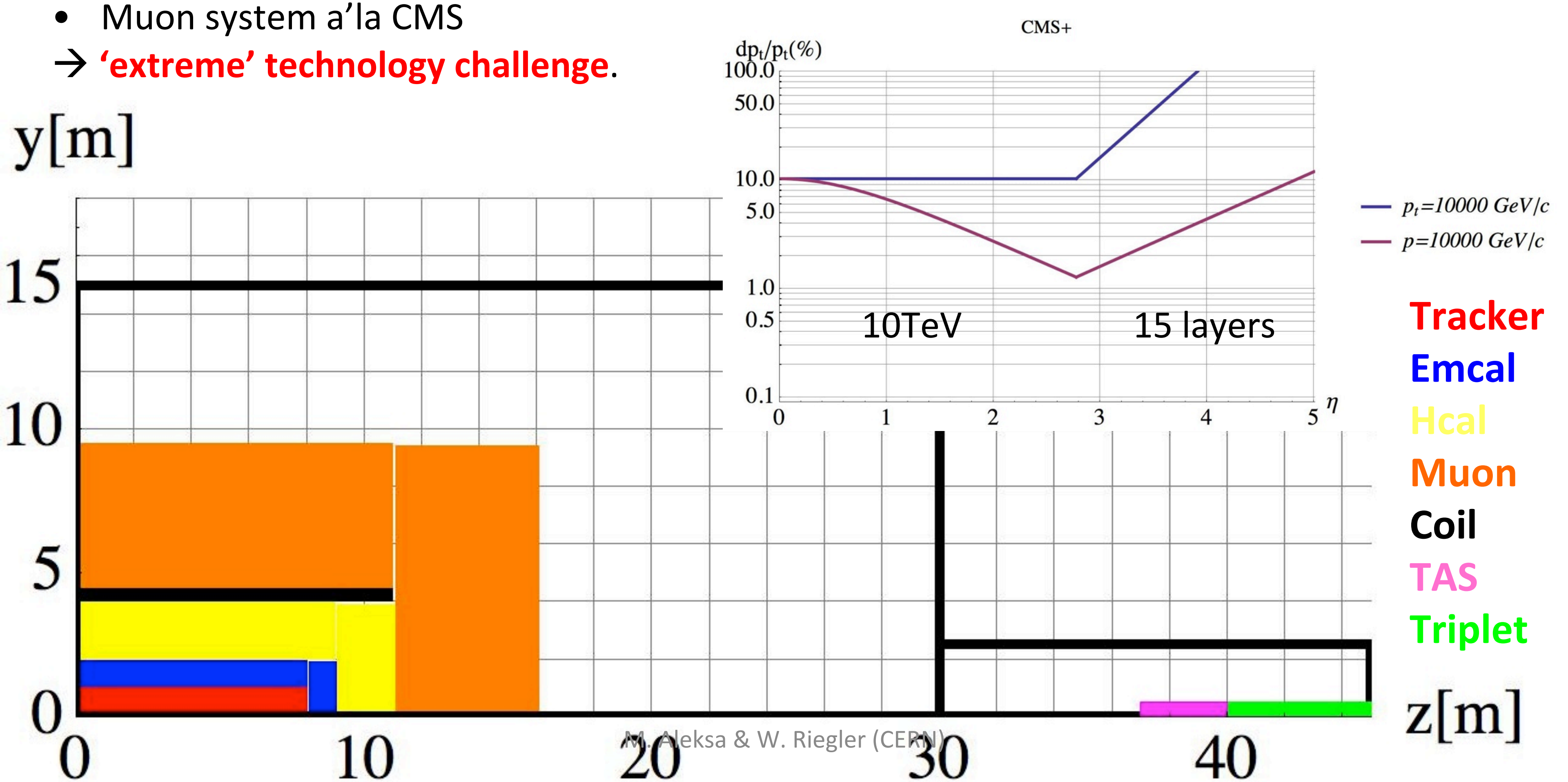
- **With a more realistic approach for calorimetry and tracking we end up with coil radii of 6m, which requires an iron yoke that is probably unaffordable.**

→ 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

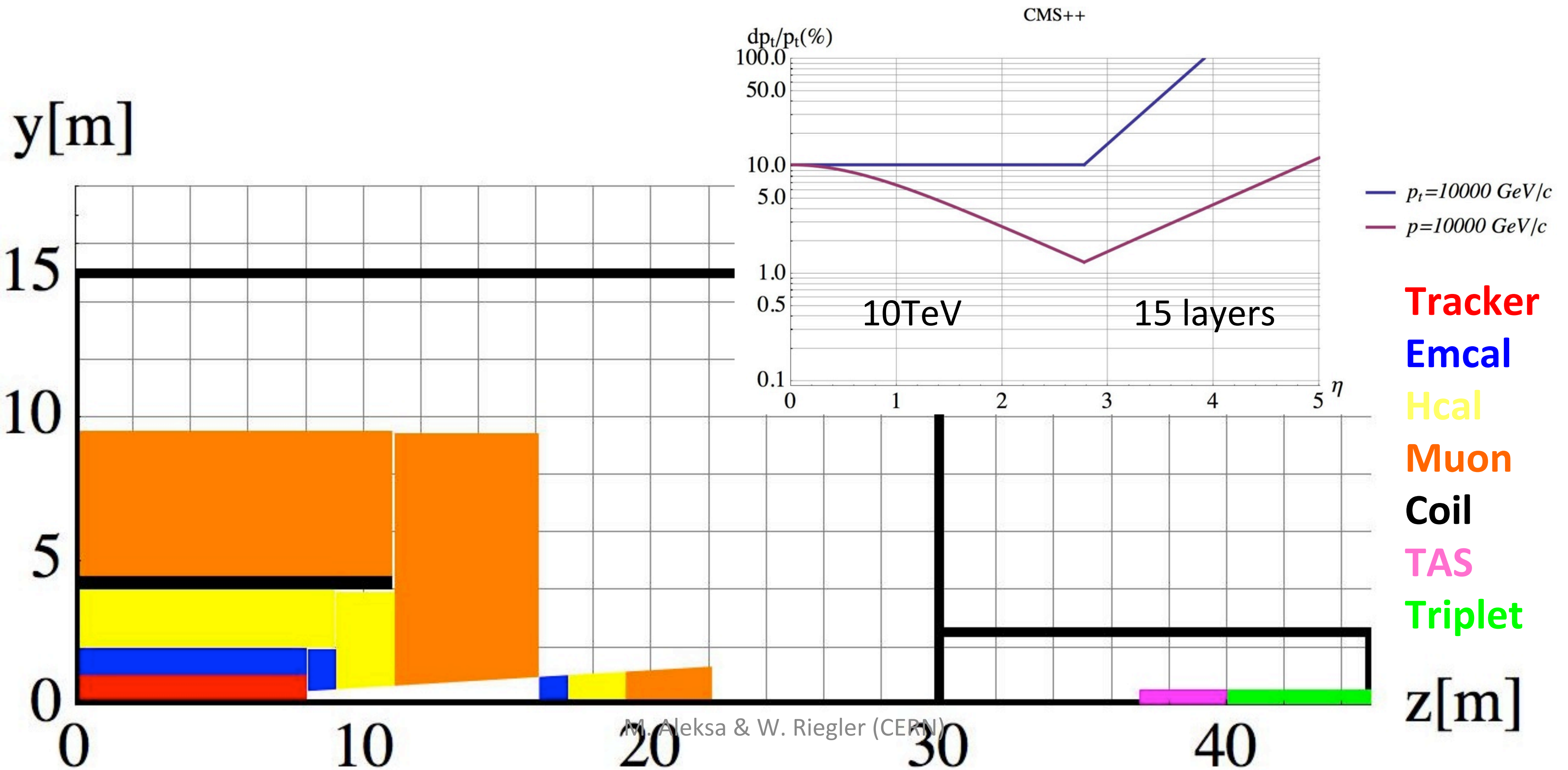
- **Maximum coil producing 6T with affordable iron yoke** (r=4m)
- Tracker radius 1m, 6T → resolution has to be improved by factor 6 with respect to CMS → 5µm layer resolution and less material (multiple scattering)
- 8m long tracker gives large η acceptance.
- 2.8m available for EMCAL+HCAL e.g. very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

→ **'extreme' technology challenge**.



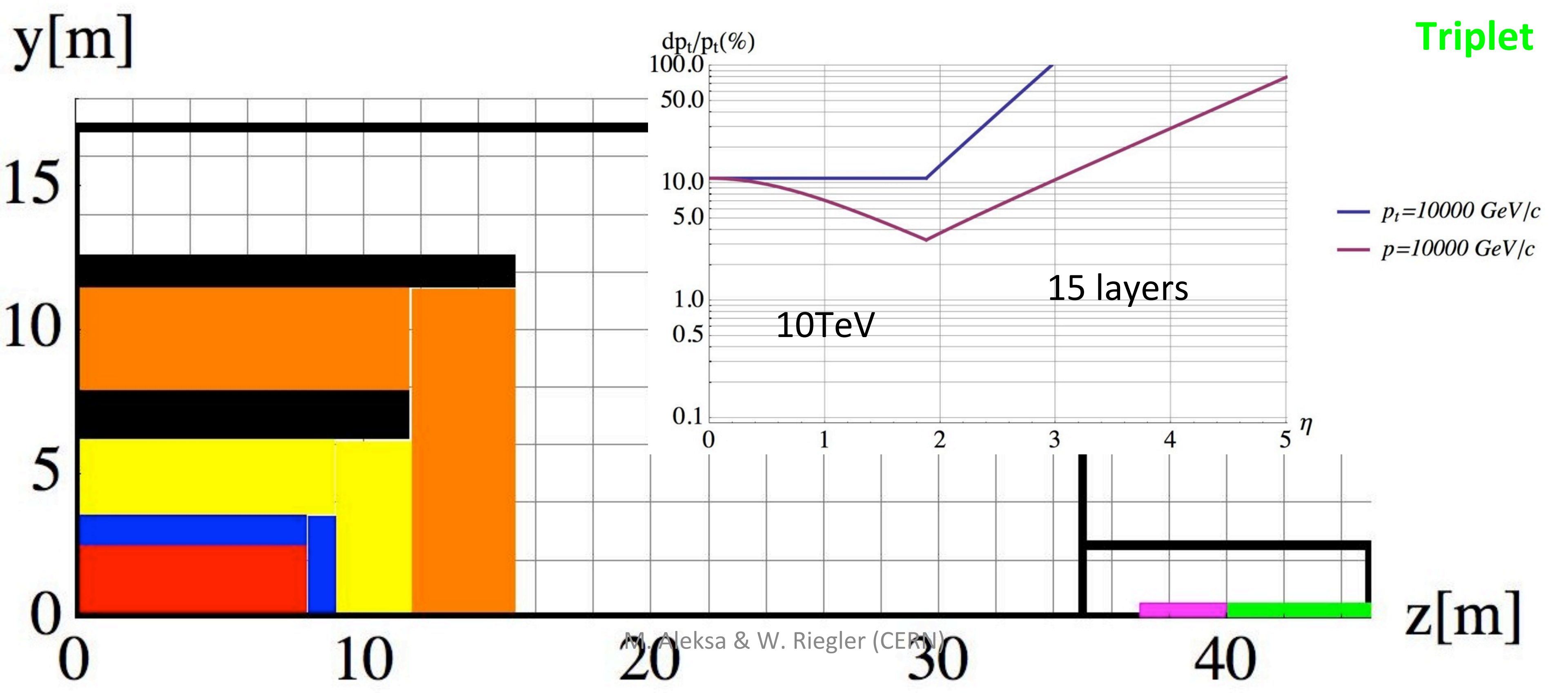
CMS Scaled Detector, Forward Calorimetry Moved Out

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



Twin Solenoid BL^2 Scaling

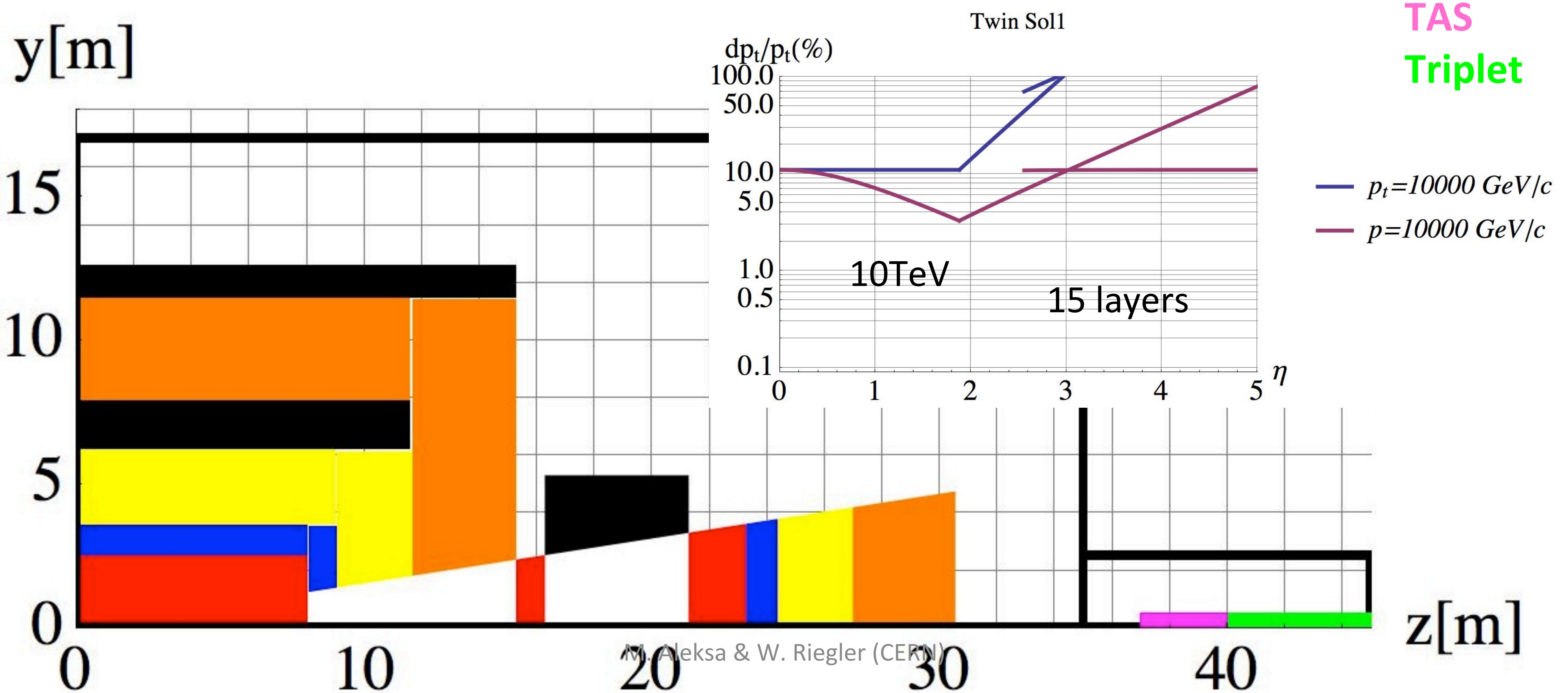
- How to achieve 10% for a 10TeV charged particle **assuming tracker with nowadays layer resolution** (~20µm)?
- Solenoid and shielding solenoid with B=6T in Tracker and B=2.5T in Muon System
- Tracker r=2.5m, L=16m, tracking layer resolution similar to CMS detector
- ECAL+HCAL = 3.4m = 12 λ_{int}
-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

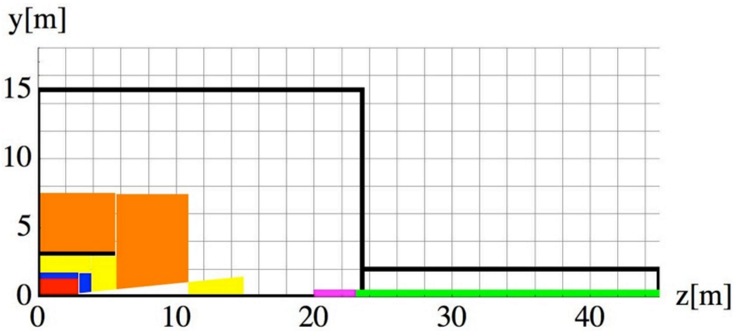


Twin Solenoid BL^2 Scaling + Forward Dipole

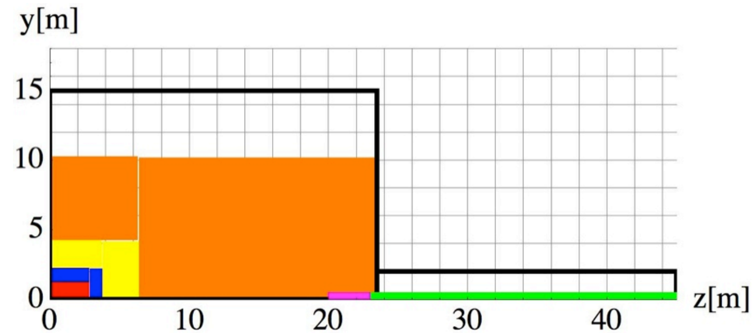
- Opening at η = 2.5
- Adding a **forward Dipole for momentum spectroscopy**.
- Moving forward calorimeters to larger distance decreasing the particle densities and overlaps.
- Allows separate instrumentation and upgrade of forward detectors
- Integration and maintenance is a challenge

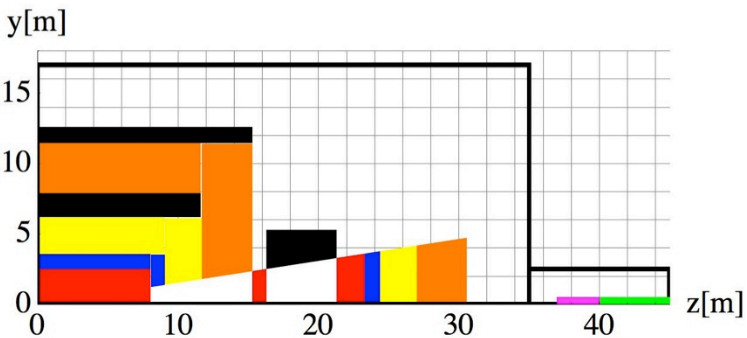
Tracker
Emcal
Hcal
Muon
Coil
TAS
Triplet





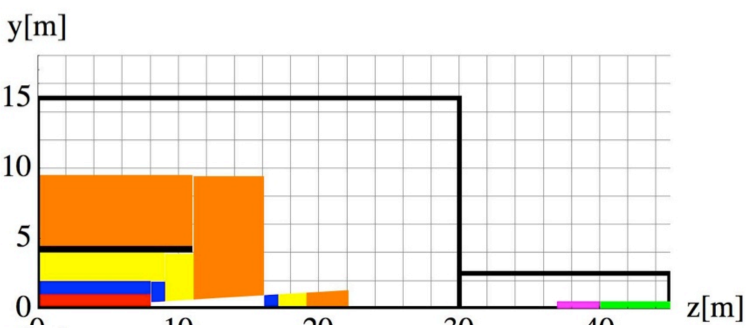
CMS & ATLAS



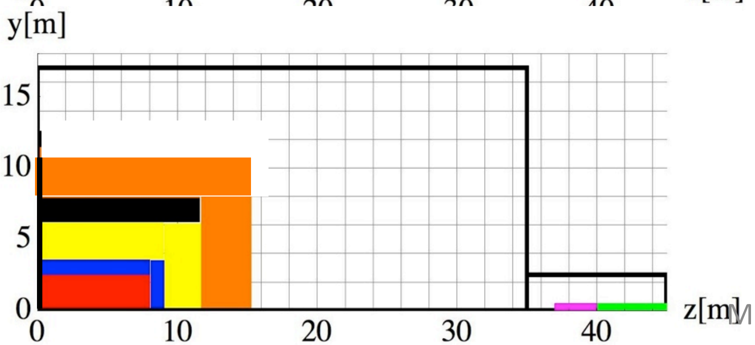


Twin Solenoid
+ Dipole

Popular at Present



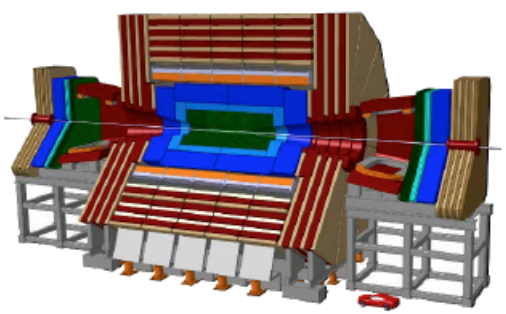
CMS+



Partially shielded large solenoid

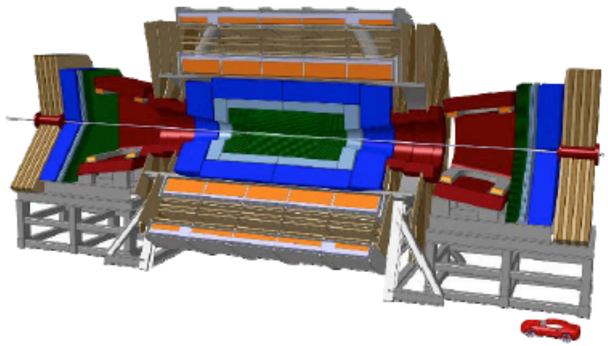
FCC Magnet System Concepts

Inclusion of Dipoles in the Forward region for momentum measurement over a large eta range.



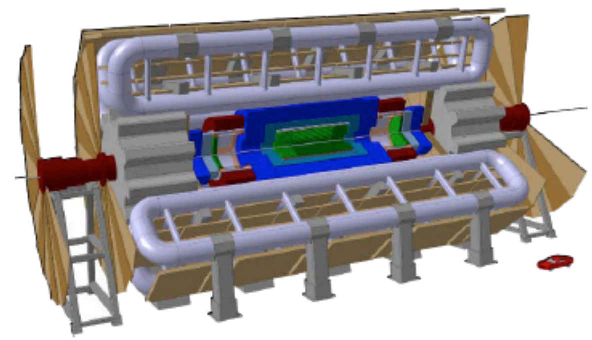
Large coil (r=6m, 6T) with Yoke that returns all the flux:

Huge mass,
Iron very expensive



Large coil (r=6m, 6T) with active shielding

This concept is at present studied in quite some detail to have a baseline reference design.
But we have to stay very open for alternative designs



Scaling the ATLAS approach.

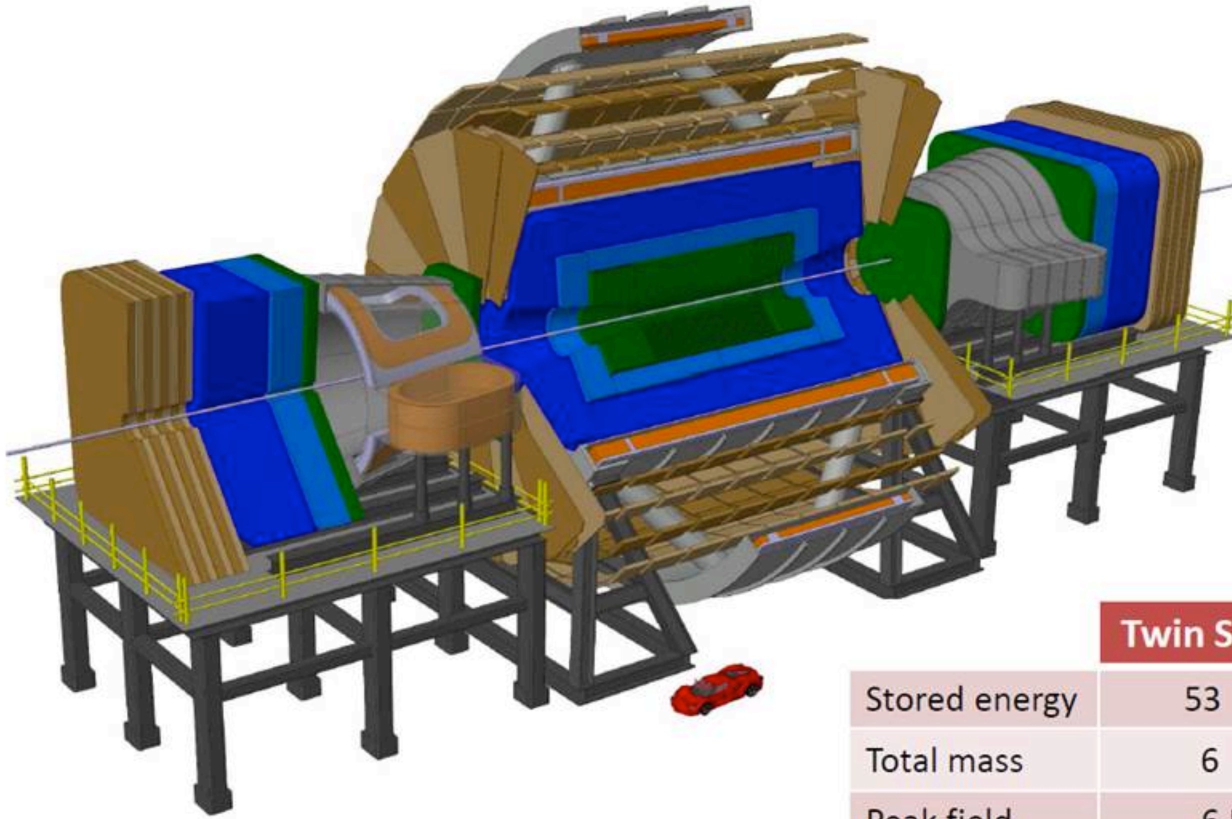
The ATLAS 'standalone' Muon Toroid was motivated by things like:

- **worries that trackers might not work at LHC rate**
- **Space for excellent HCAL, good jet calorimetry**
- **Independent magnet system**

These points are not very strong as of today.

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
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.

Twin Solenoid + Dipole Magnet System

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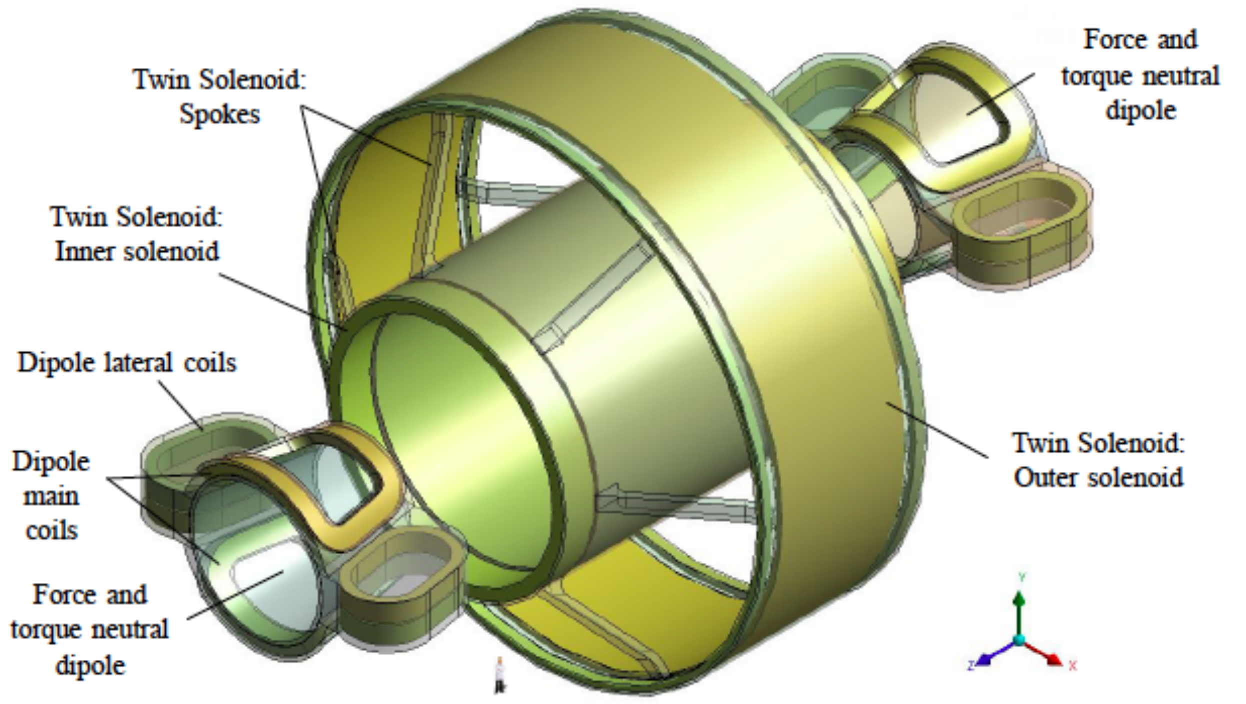


Dipoles are also actively shielded with SC coils → No Iron Yoke → Decoupling of mechanical forces between solenoid and dipole.

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
Revision of outer radius is ongoing.

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

Radiation Estimate for Inner Tracker Layers

Scaling radiation load of first Pixel layer at r=3.7cm from ATLAS PHASE II tracker numbers to find the orders of magnitude:

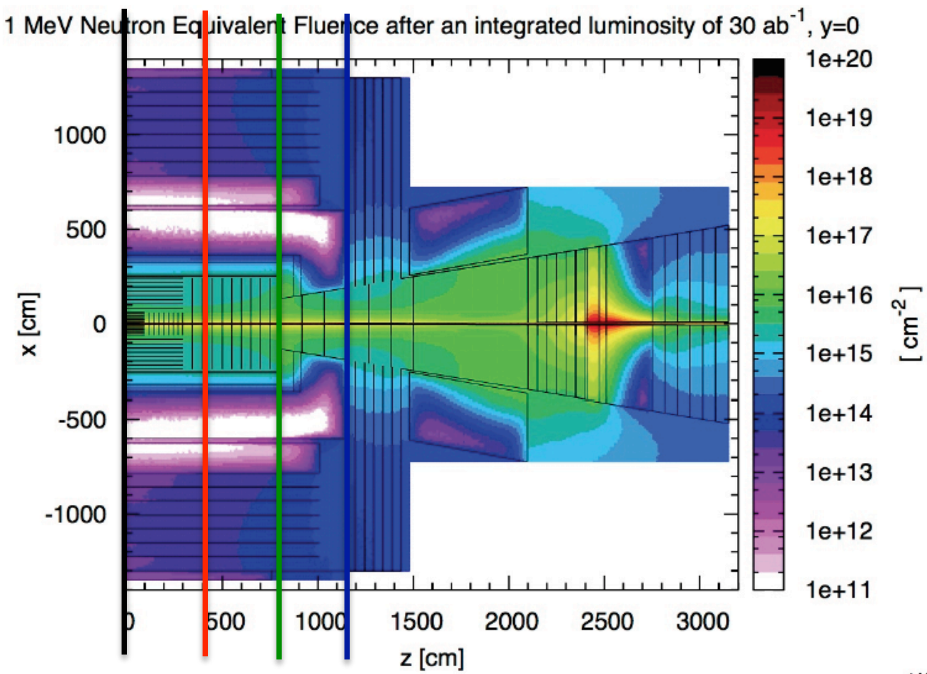
HL-LHC 3ab^{-1}
1MeVneq Fluence (NIEL) = 1.5×10^{16} cm^{-2}
Dose = 5MGy

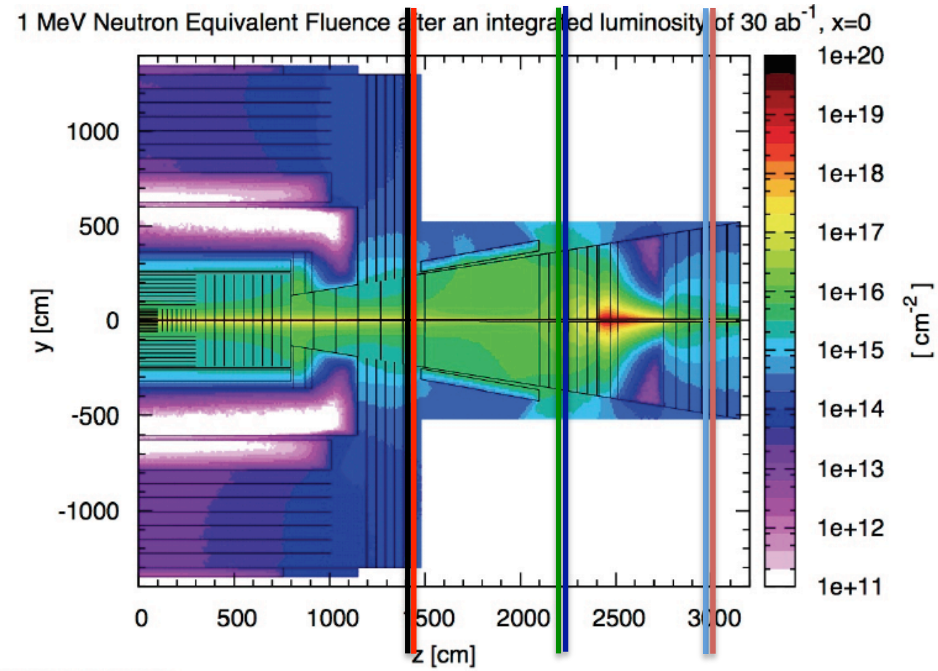
FCC 3ab^{-1}
1MeVneq Fluence = 3×10^{16} cm^{-2}
Dose = 10MGy

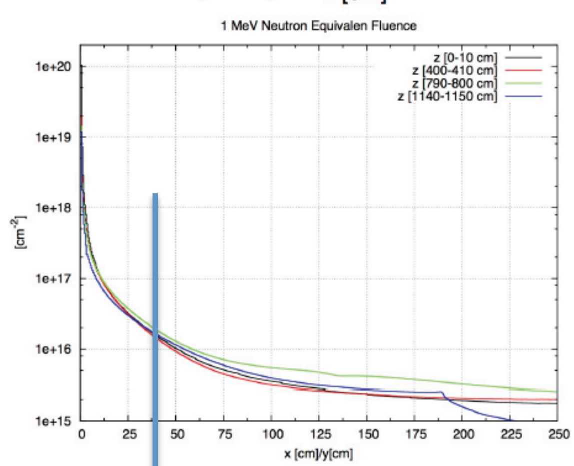
FCC 30ab^{-1}
1MeVneq Fluence = 3×10^{17} cm^{-2}
Dose = 100MGy

FCC 30ab^{-1} r_{pixel}=2.1cm:
1MeVneq Fluence = 10^{18} cm^{-2}
Dose = 350MGy

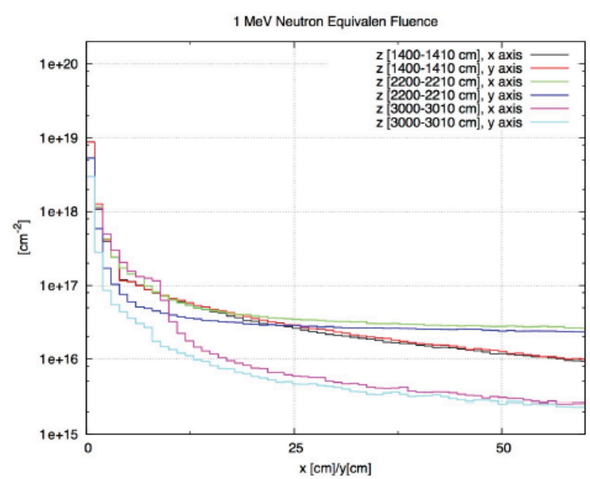
1 MeV Neutron Equivalent Fluence (FLUKA simulation, M.I.Besana)







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).

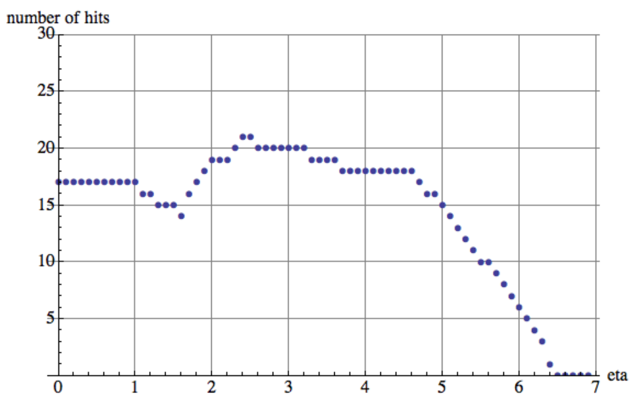
For radii <50cm we exceed the HL-LHC numbers (10^{16} cm^{-2}) by up to 2 orders of magnitude
→ Technology challenge !

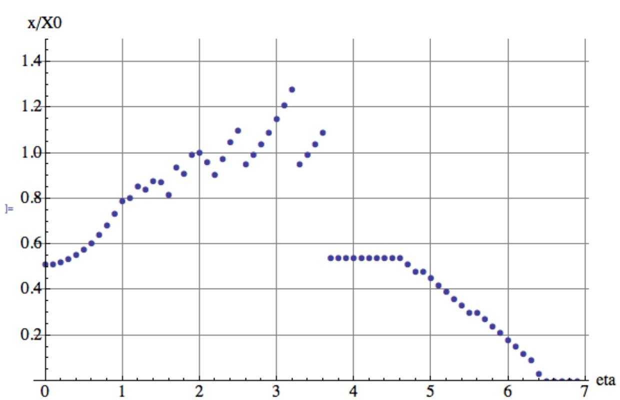
Simplified Tracker Assumptions

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

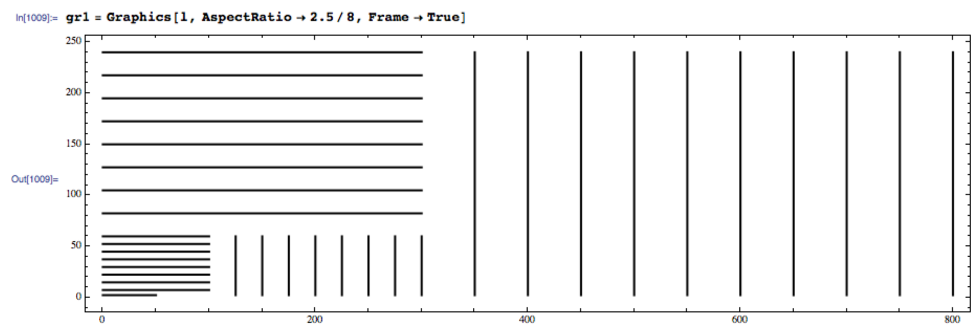
Material composition in Volume (%):
Si 20%, C 42%, Cu 2%, Al 6%, Plastic 30%
X_0 of this mix: 14.37cm

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

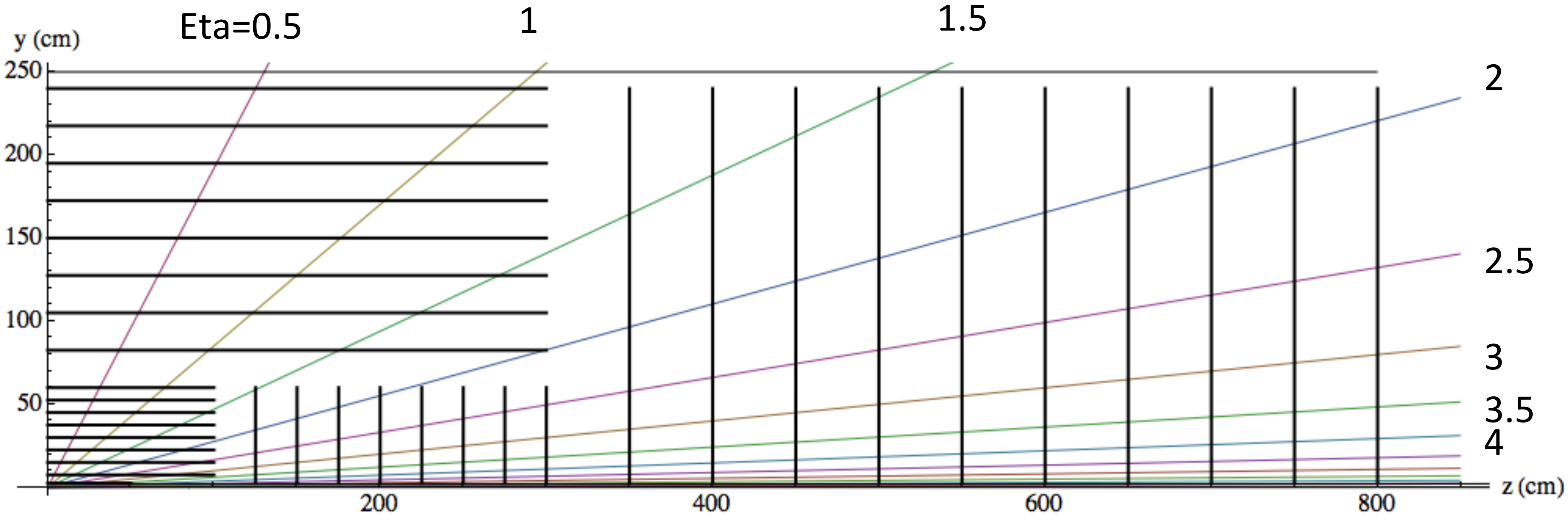




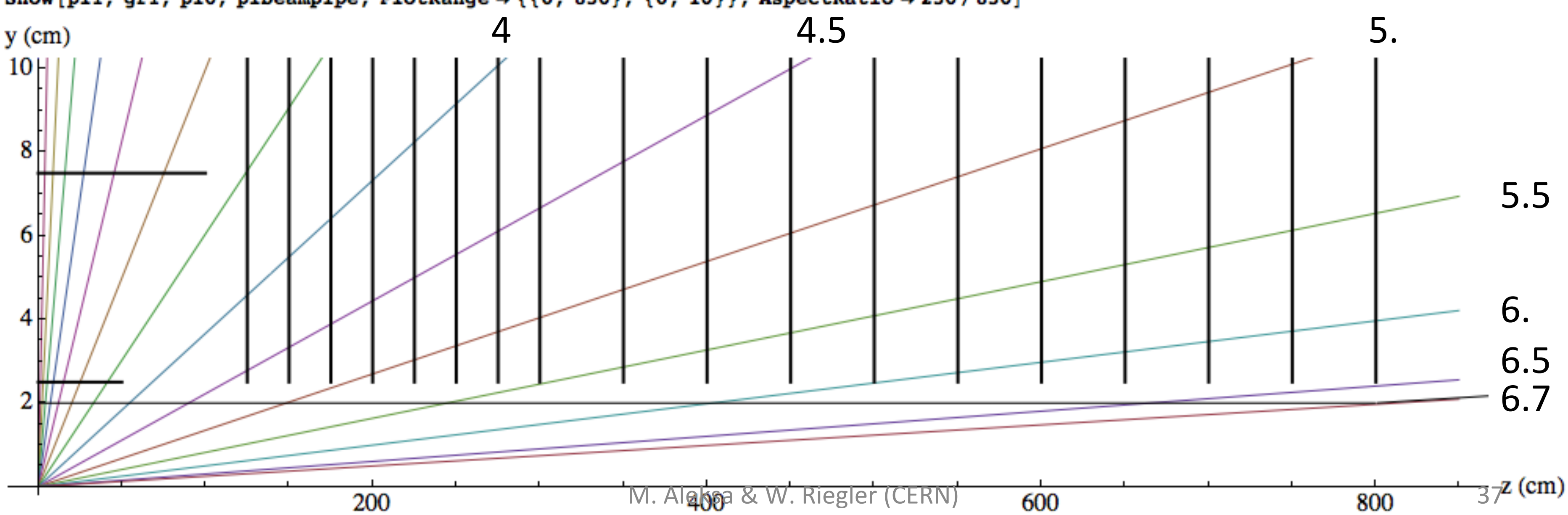
R_{out}=2.4m
Half the leaver arm at eta=2.6→ L=8m



Tracker



Show[pl1, gr1, pl0, plbeampipe, PlotRange → {{0, 850}, {0, 10}}, AspectRatio → 250 / 850]



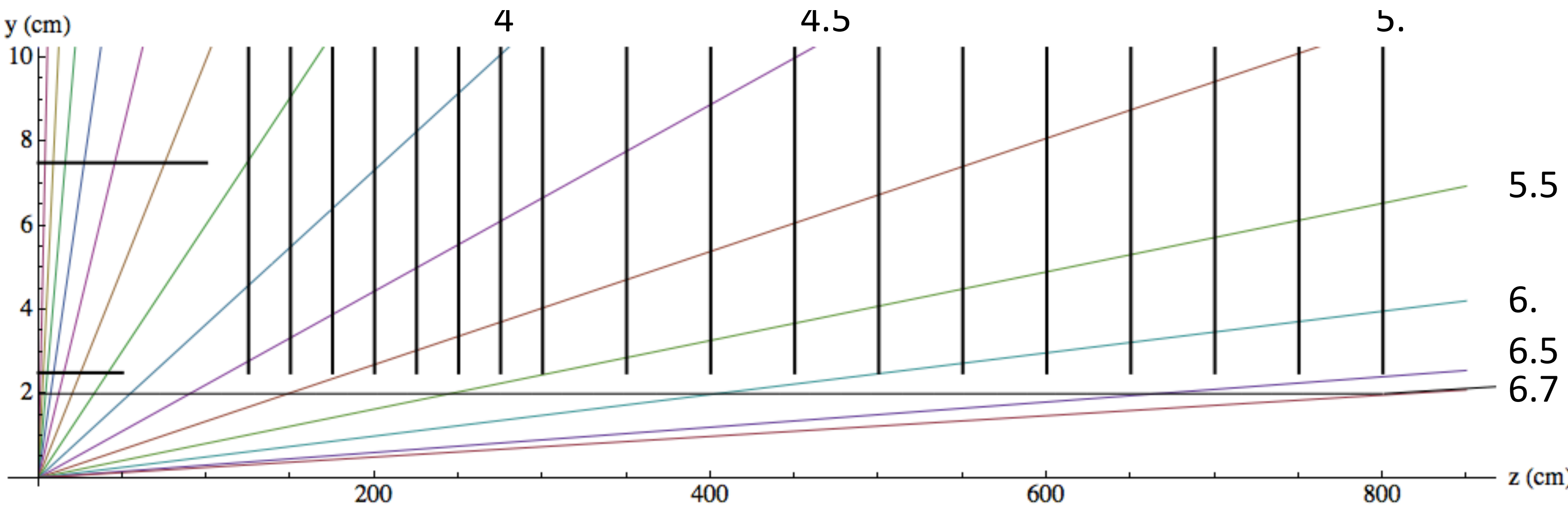
Tracker

Side remark: 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.

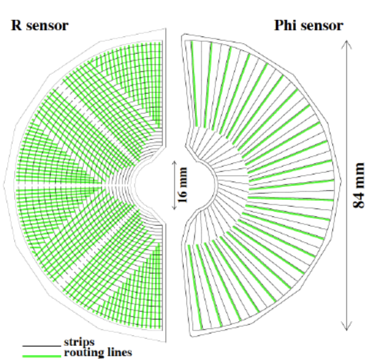
LHCb has the VELO with discs only a few mm from the beam in a secondary vacuum.

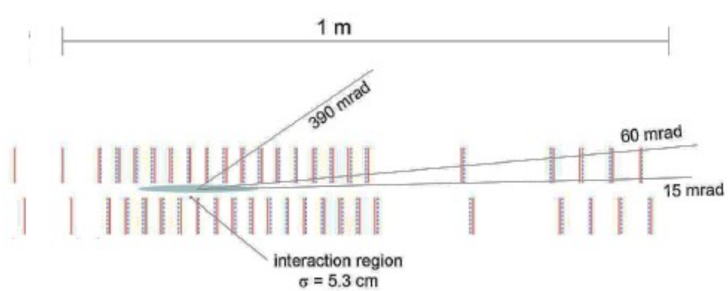
This arrangement has significant infrastructure around the IP which is not compatible with a co-existent central detector.

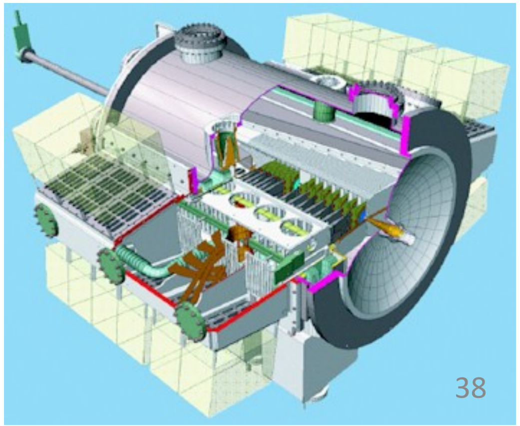
→ Clever ideas needed !!



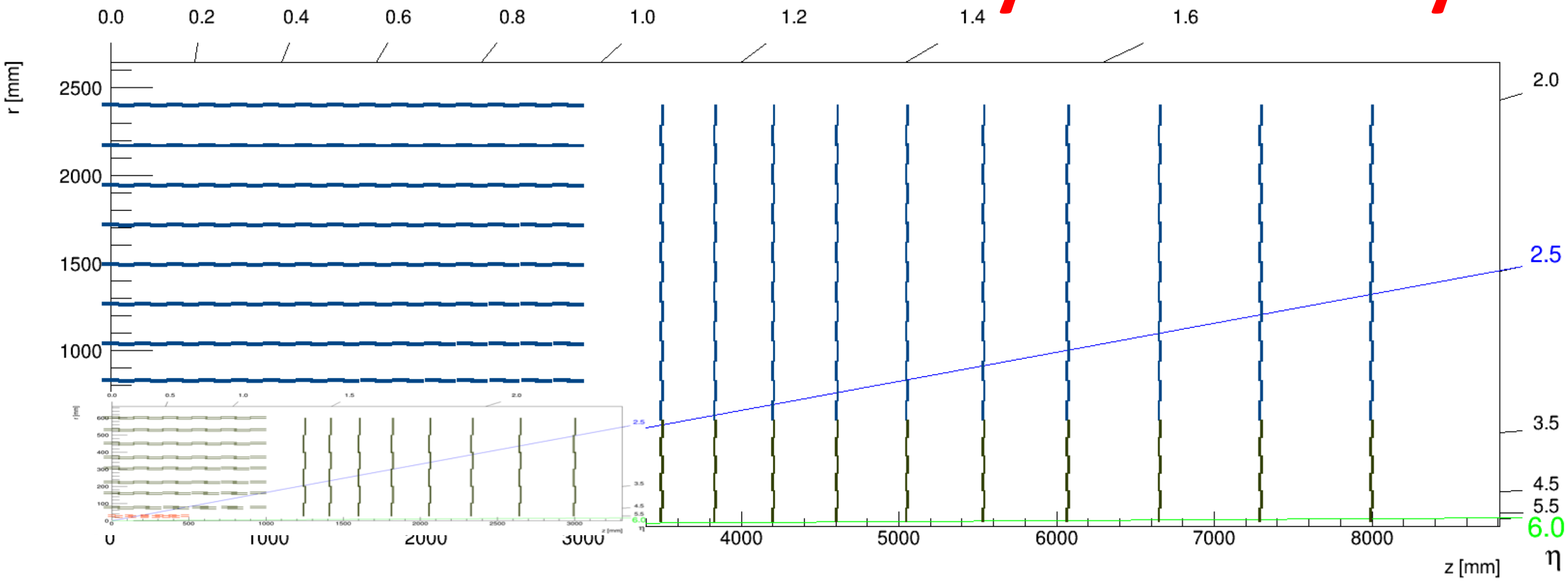
LHCb:

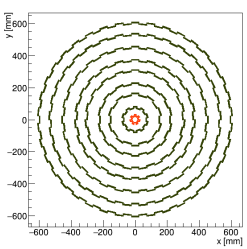


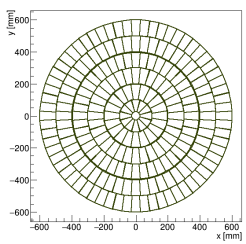


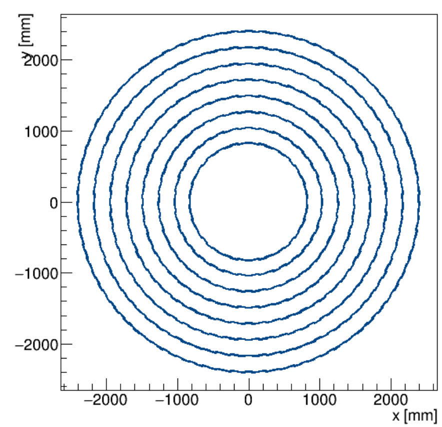


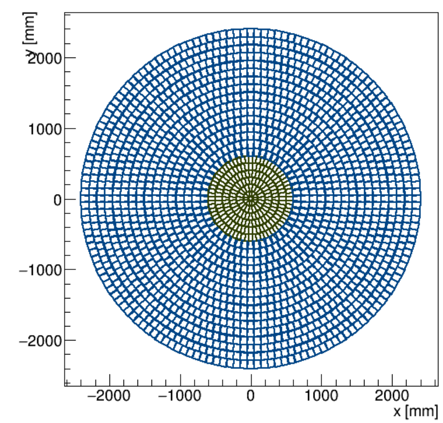
Tracker – Realistic FCC Layout in TKLayout

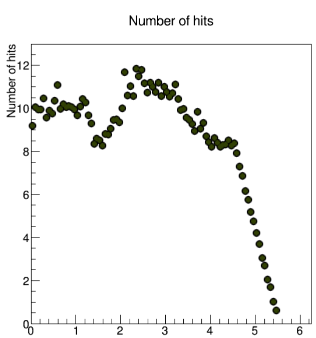


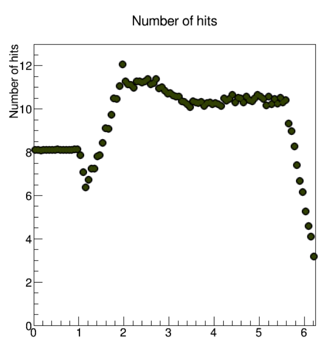








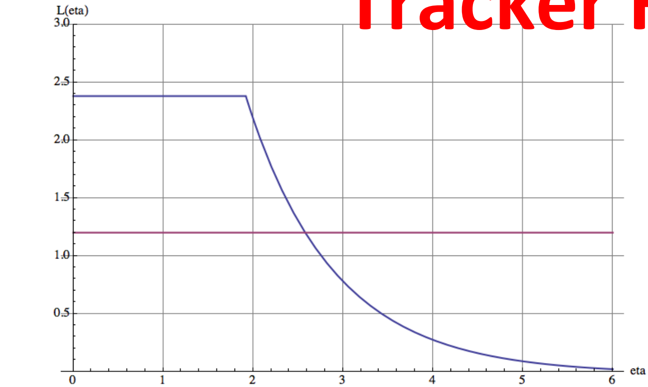


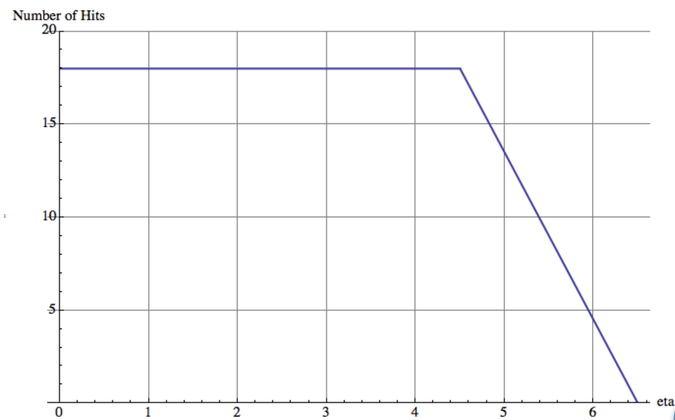


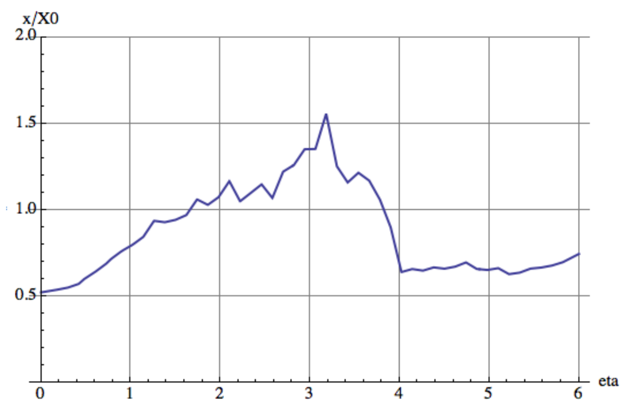
Realistic Layout with correct modules using TKLayout (CMS PhaseII upgrade tool)

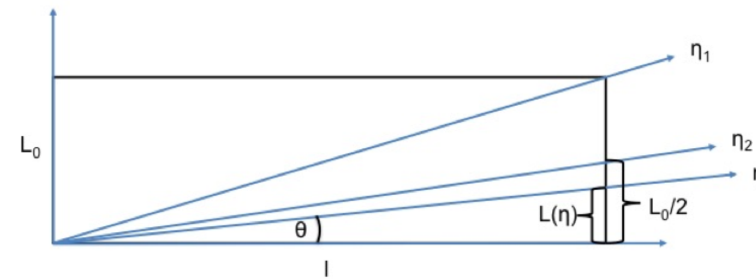
http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option2/errorsTRK.html

Tracker Resolution First Principles









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

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

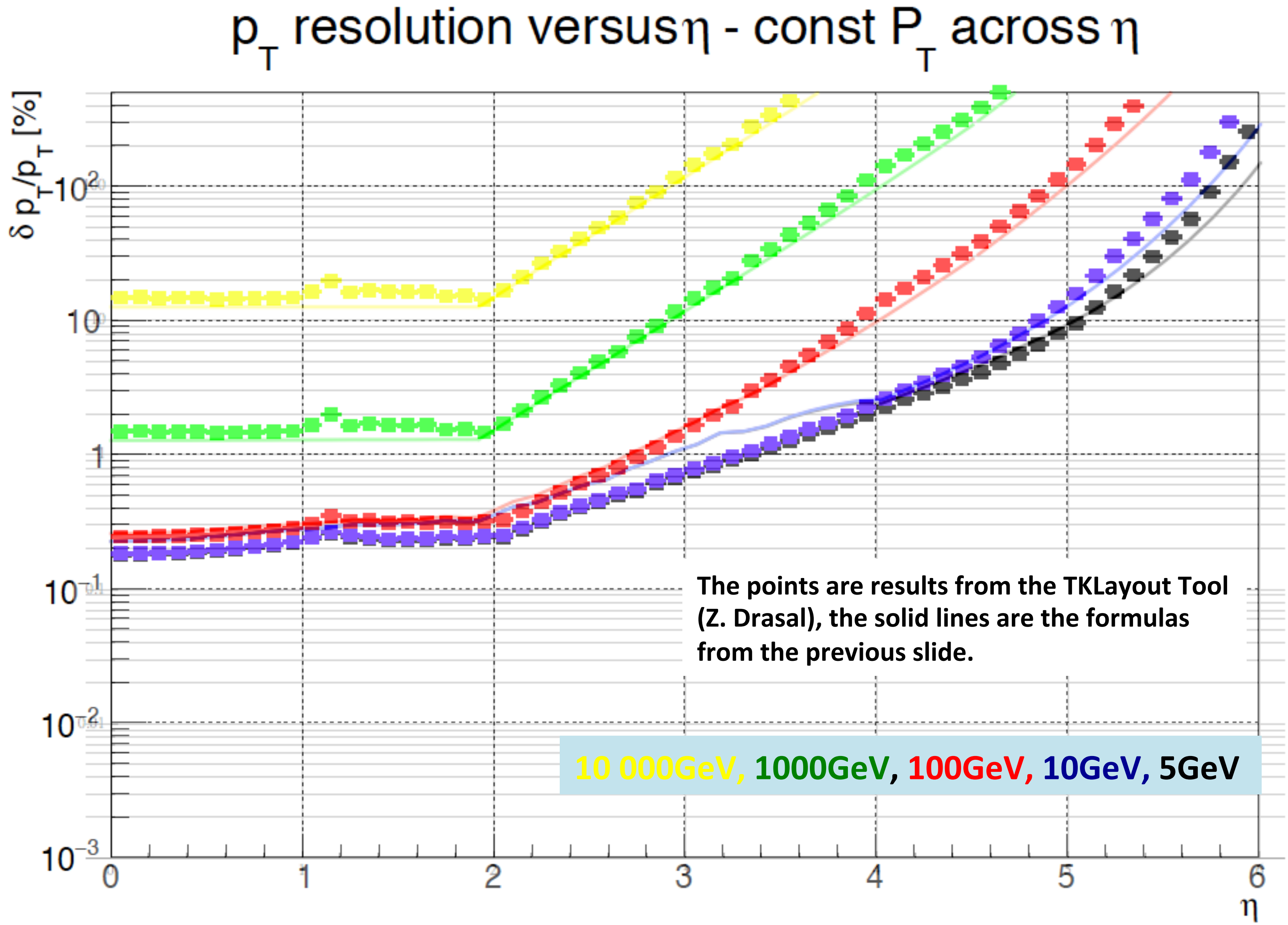
$$L(\eta) = L_0 \quad \eta < \eta_1 \qquad L(\eta) = L_0\frac{\sinh\eta_1}{\sinh\eta} \quad \eta > \eta_1$$

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

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

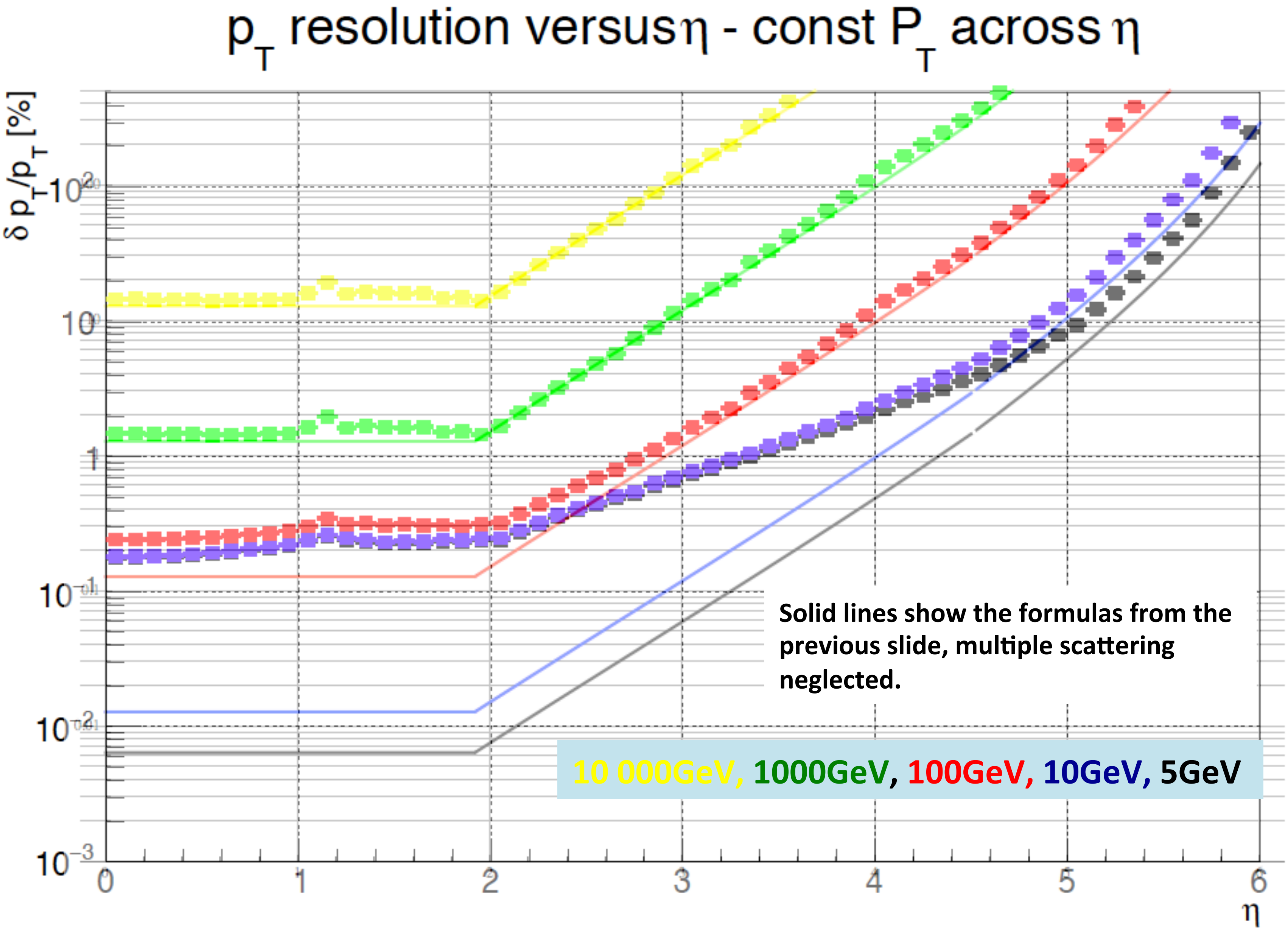
```
In[60]:= L0 = 2.4;
In[61]:= l = 8;
In[62]:= B = 6;
In[63]:= sig = 23 * 10 ^ (-6);
```

Tracker



p_T resolution versus η - const P_T across η
$\delta p_T/p_T$ [%]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
0
1
2
3
4
5
6
η
The points are results from the TKLayout Tool (Z. Drasal), 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
δ 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 → 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:

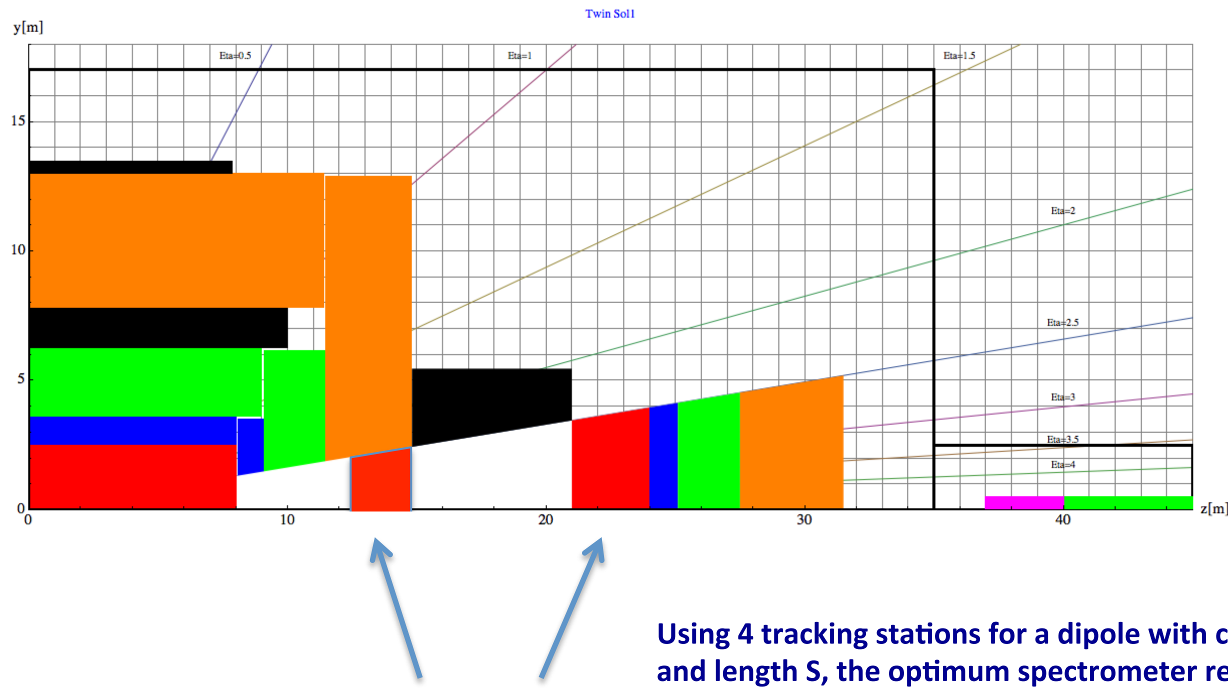
- **4 times the tracker resolution (20µm → 5µm) and**
- **4 times less material budget (x/X_0=50% at eta=0 to x/X_0=12.5% at eta=0 i.e. 3% per Layer to 0.75% per layer)**

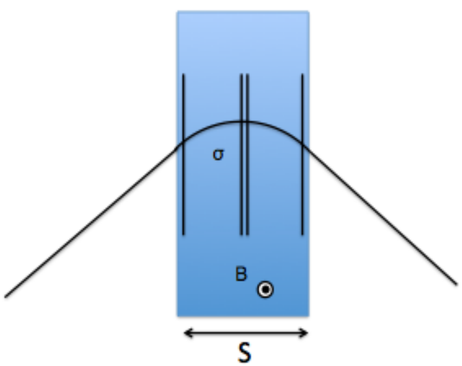
These values are challenging but not out of reach.

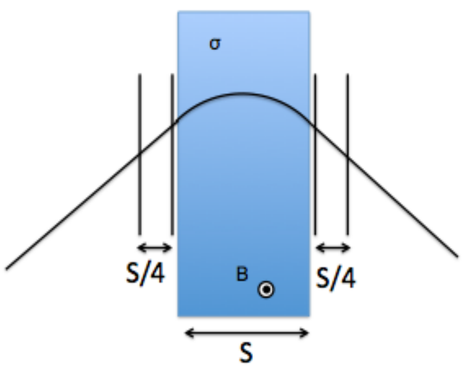
→ A final choice is part of an optimization that depends on future technologies

Forward Tracking

Forward Tracking Resolution, Position Resolution







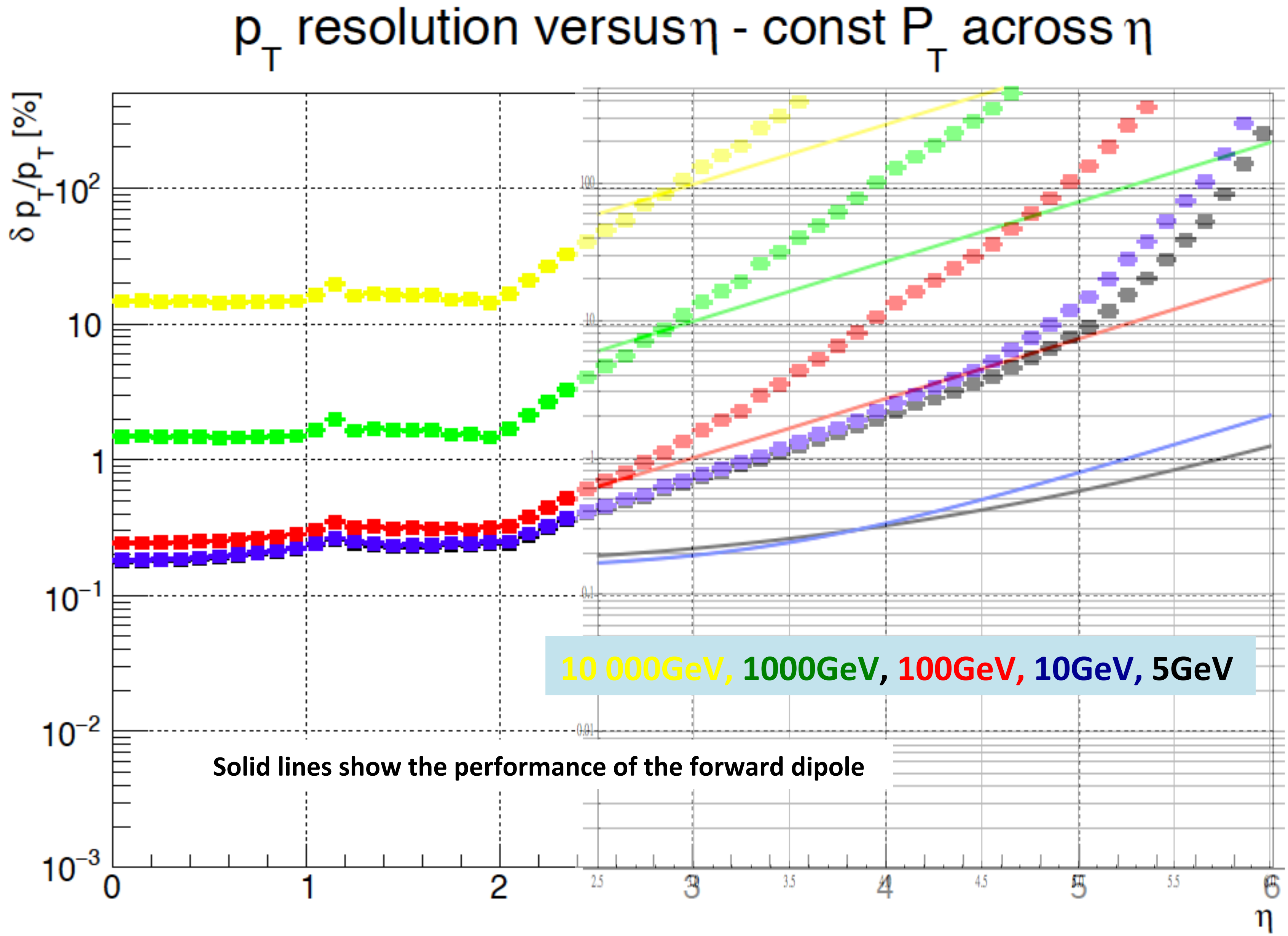
Using 4 tracking stations for a dipole with constant magnetic field and length S, the optimum spectrometer resolution is achieved by placing 2 stations in the center and one on each end to measure the sagitta.

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

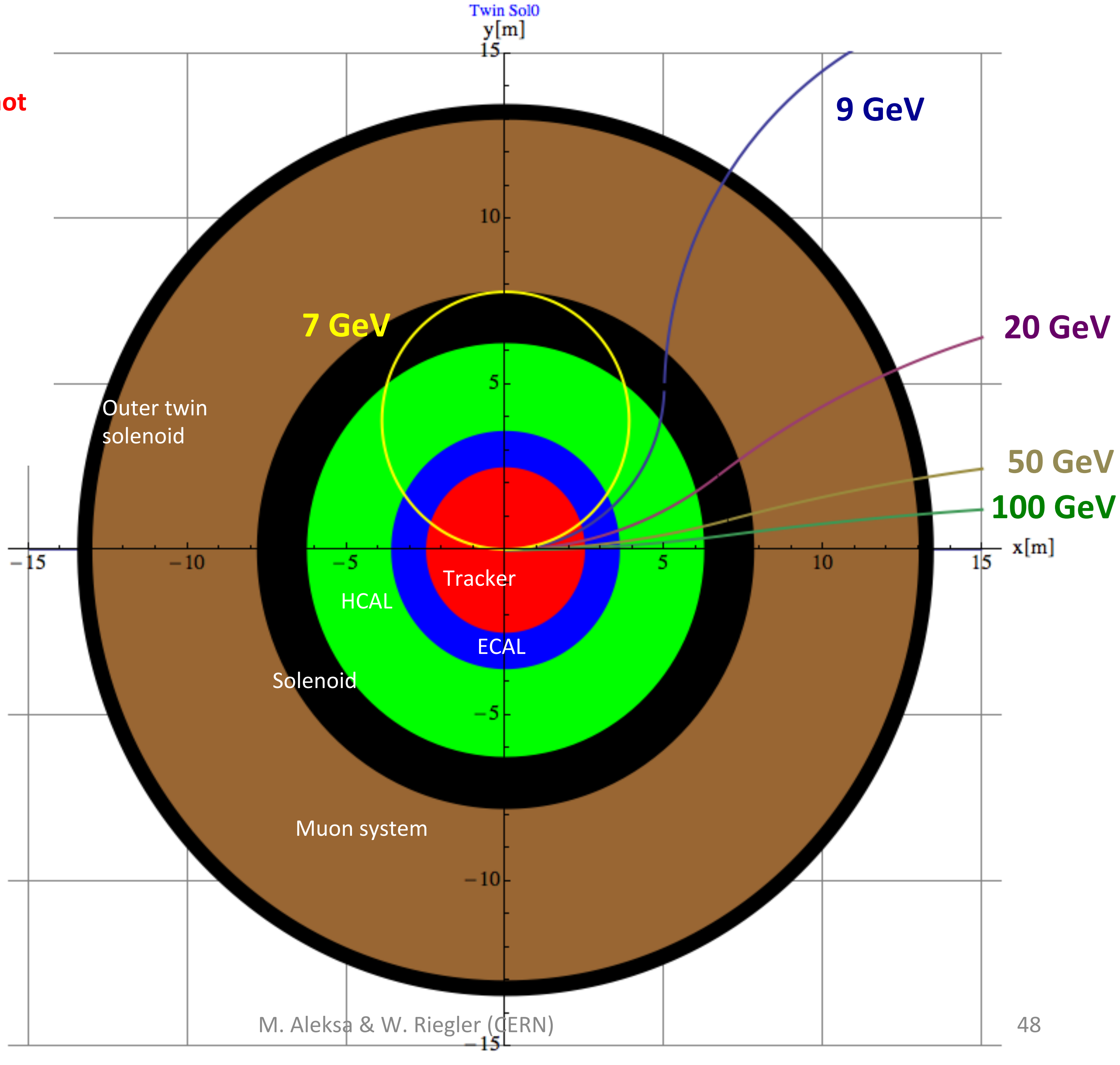


Muon System

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.



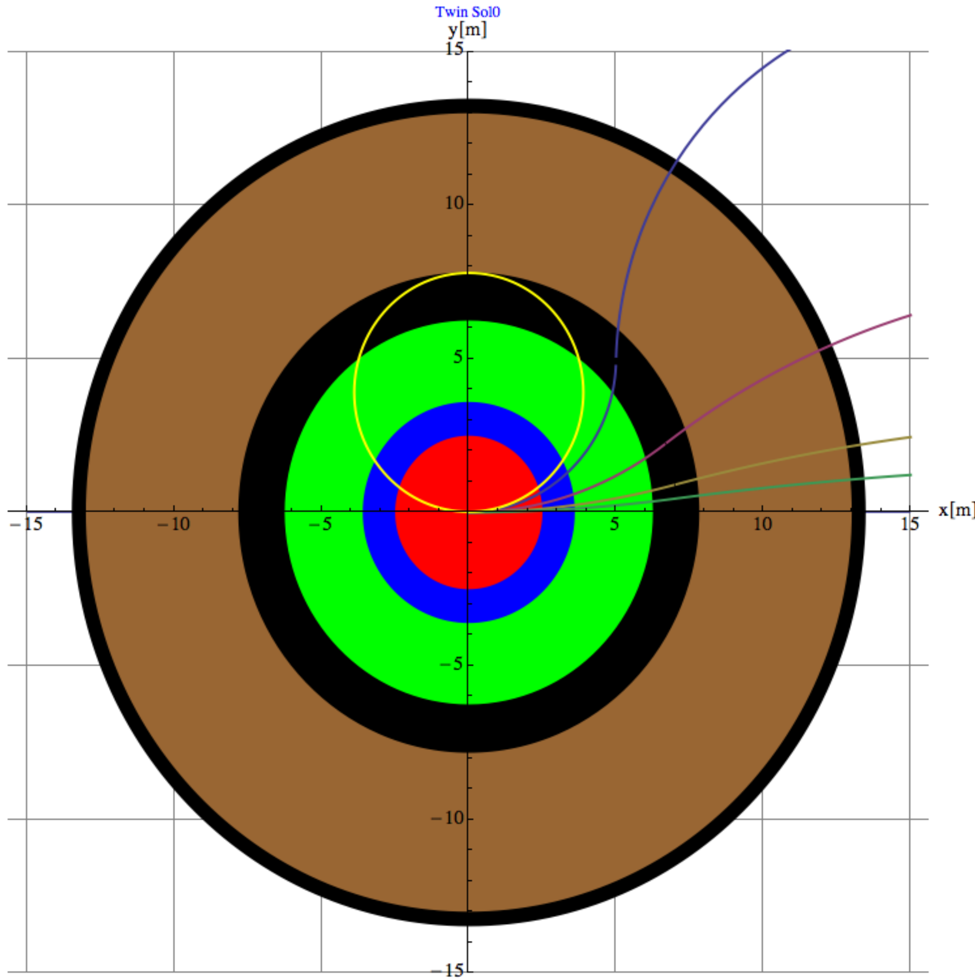
Muon Momentum Can Be Measured by…

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

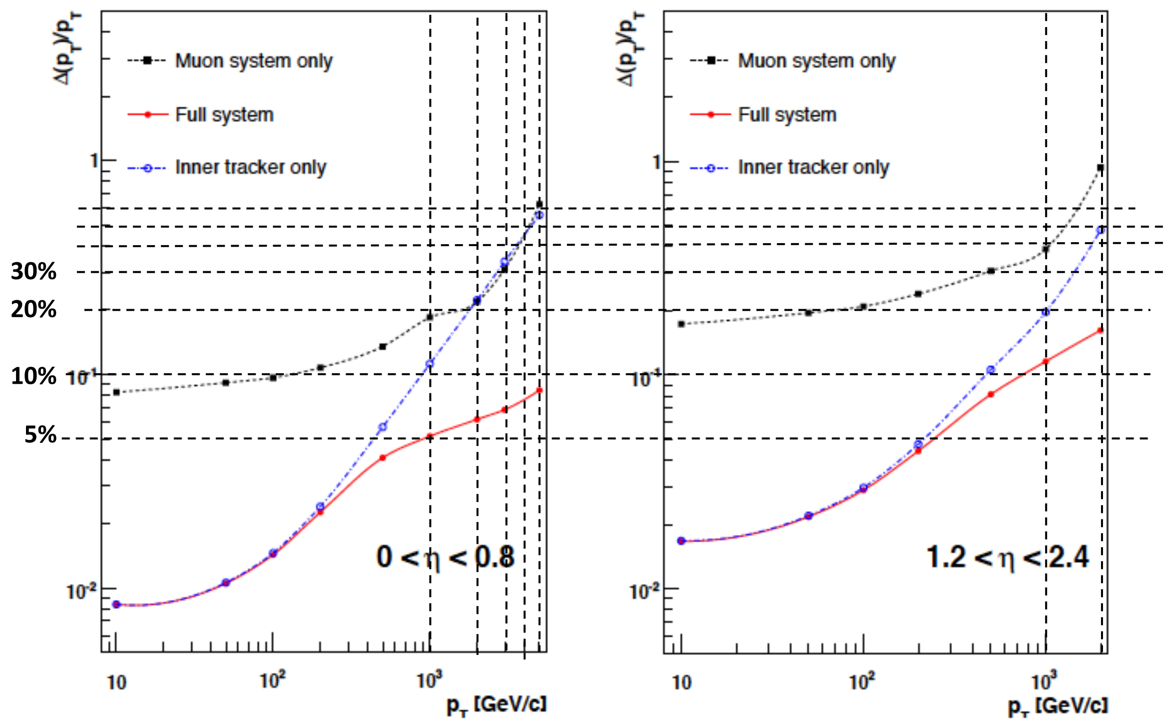


Figure 1.2: The muon transverse-momentum resolution as a function of the transverse-momentum (p_T) using the muon system only, the inner tracking only, and both. Left panel: $|\eta| < 0.8$, right panel: $1.2 < |\eta| < 2.4$.

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

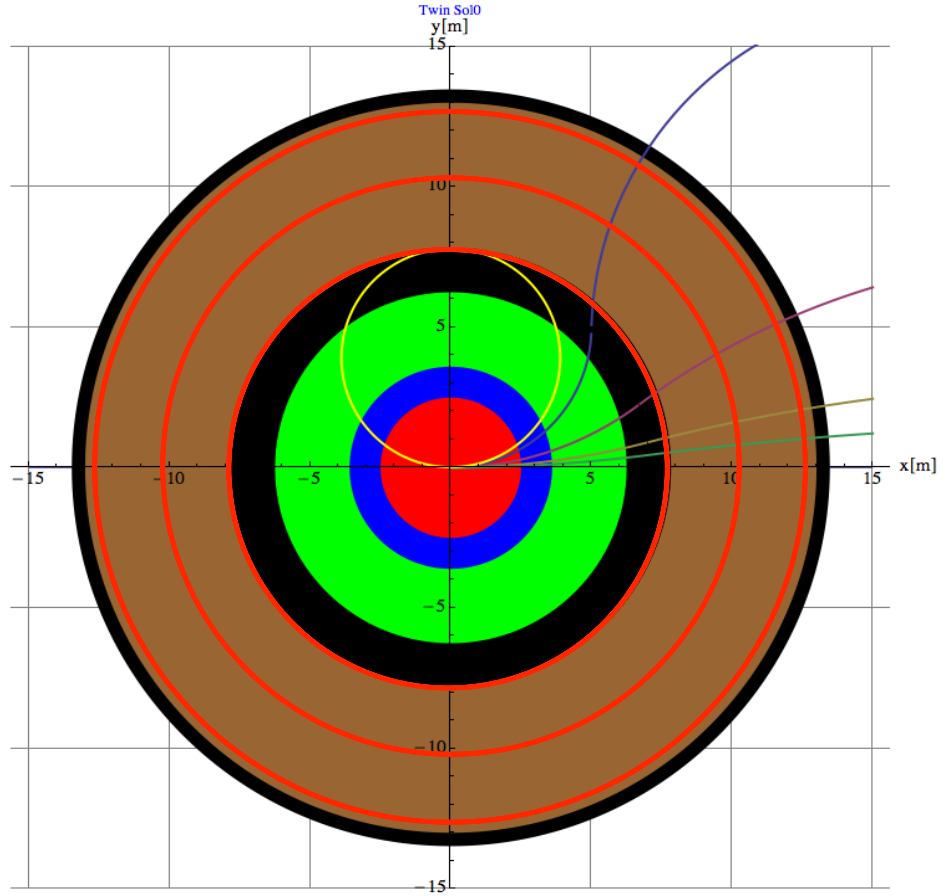
$dp_T/p_T = sig*p_T/(0.3*B*L^2)*8$
$= 20\%$ @ 10TeV

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

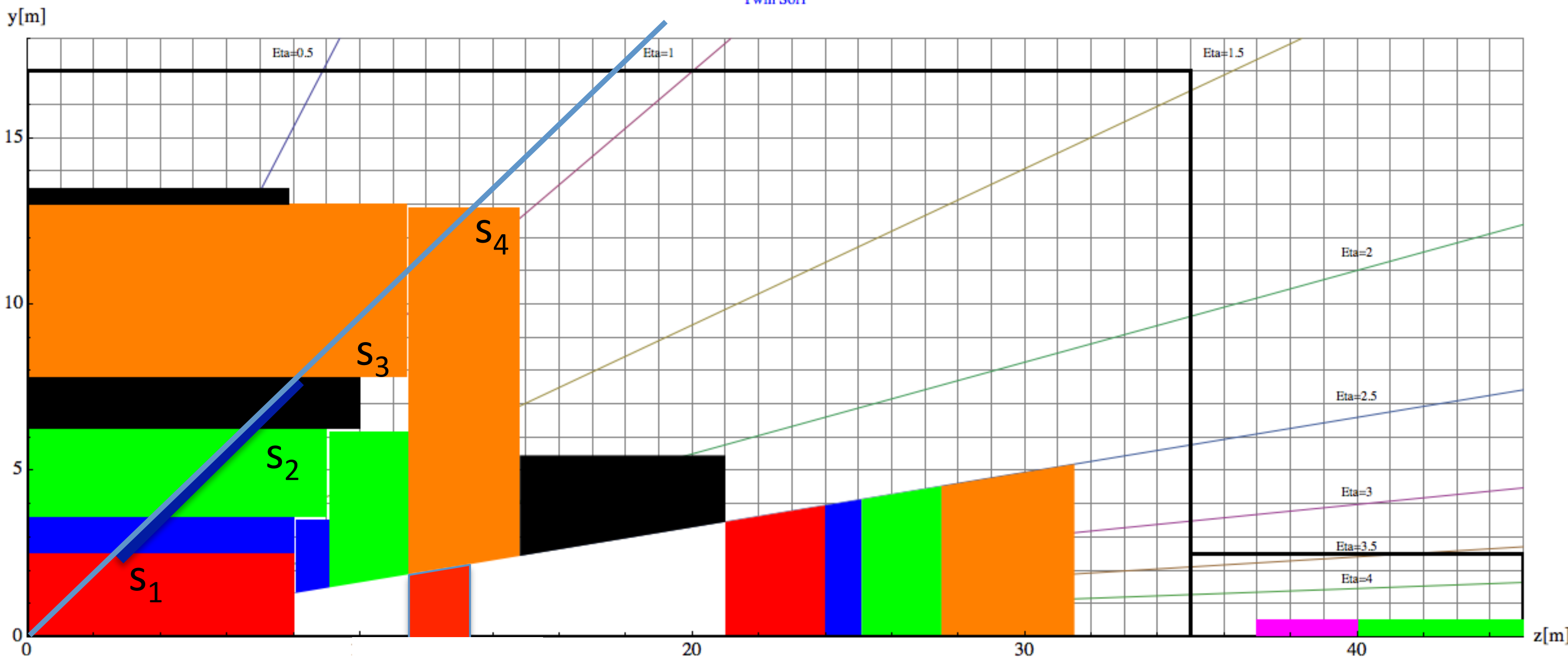
but very hard to beat the angular measurement and the inner tracker (10% at 10TeV)

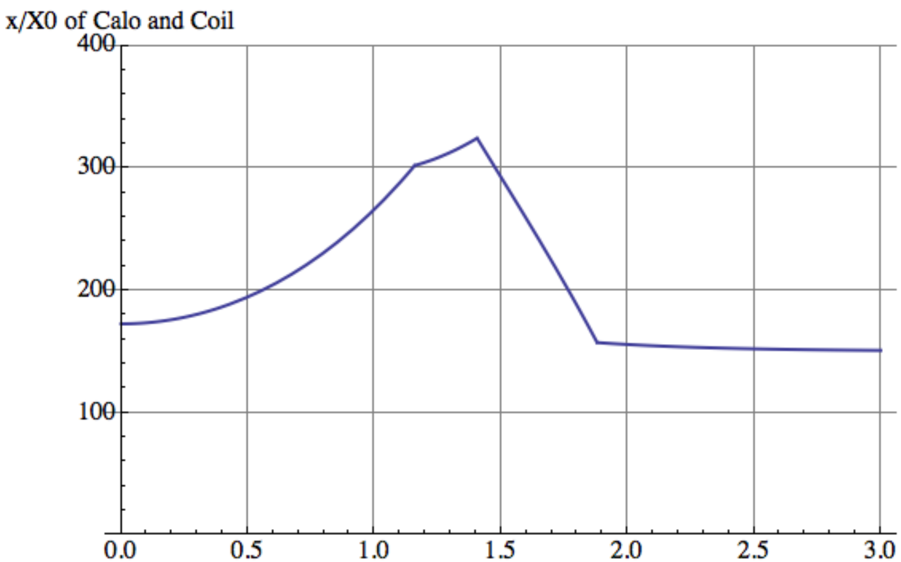
Surface > 5000 m^2

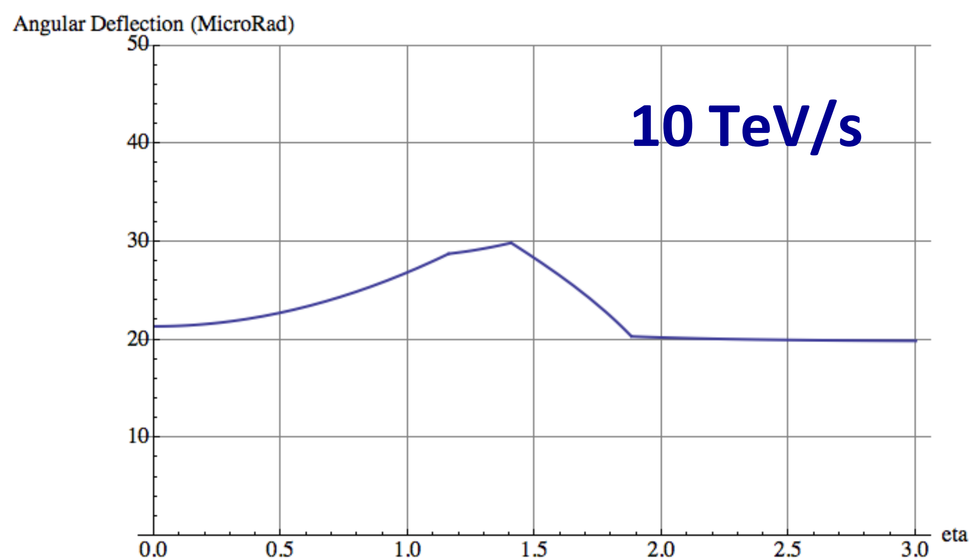
CMS sagitta measurement in the muon system is limited to $dp_T/p_T = 20\%$ due to multiple scattering alone.



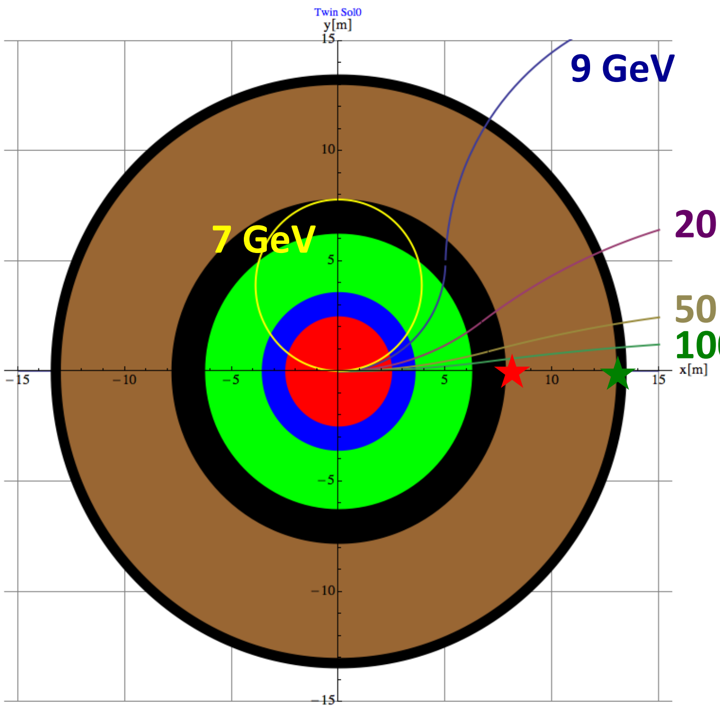
Radiation Length and Angular Deflection (Mult. Scattering)

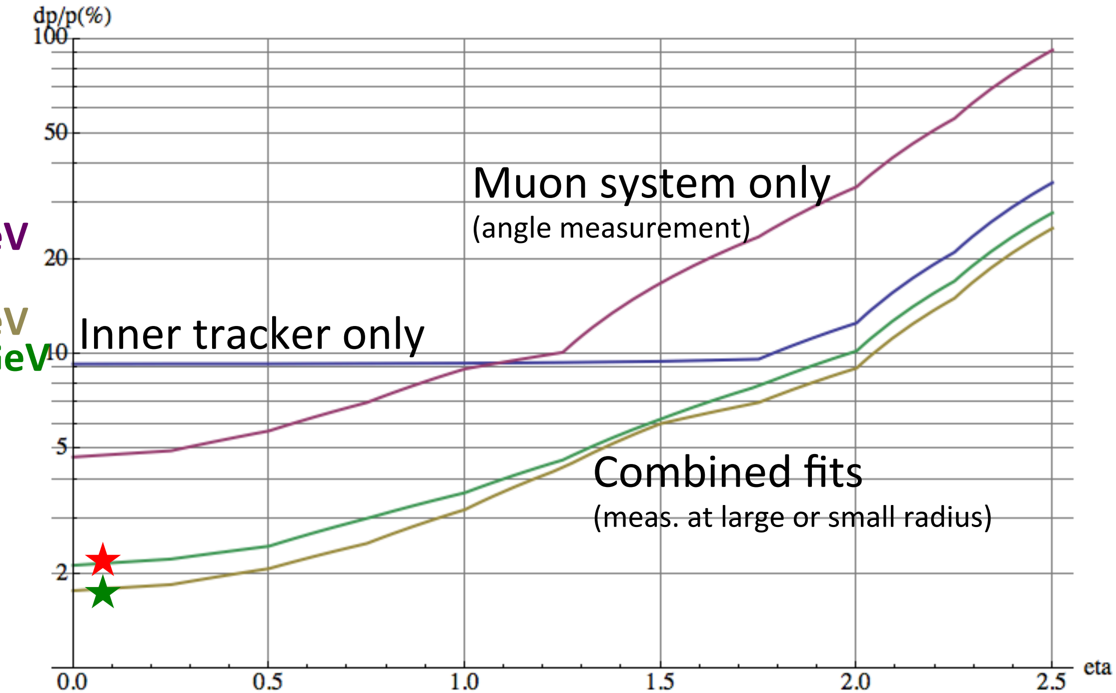






Momentum Resolution for a 10 TeV/s Muon





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**

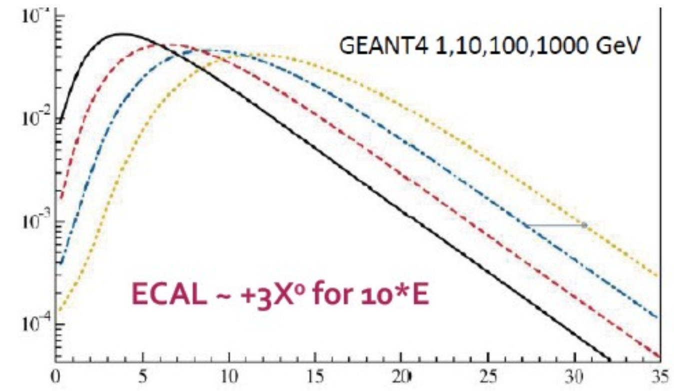
P_T=1TeV/c, eta 1.2<eta<2.4:
- **40% muon standalone (angle)**
- **20% inner tracker only**
- **10% combined**

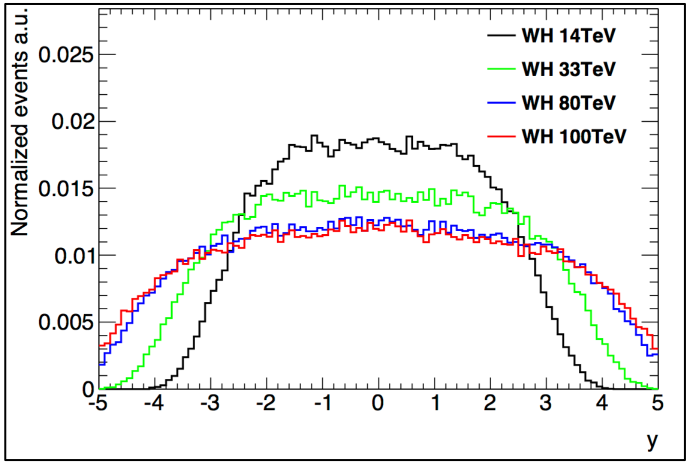
Calorimetry

Requirements ECAL

ECAL:

- Depth only moderately sensitive to √s: $30X_0$ enough for fully contained e/γ (ATLAS ~$22X_0$)
- Large acceptance up to |η|=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!)





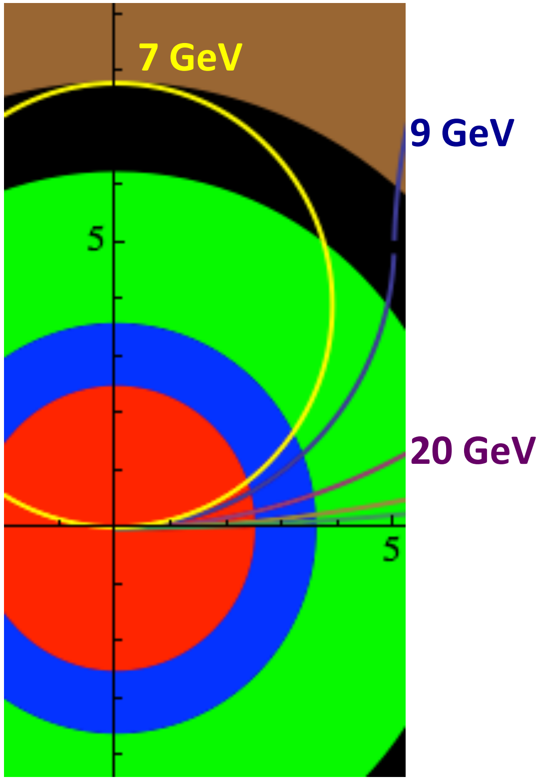
Requirements ECAL

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)

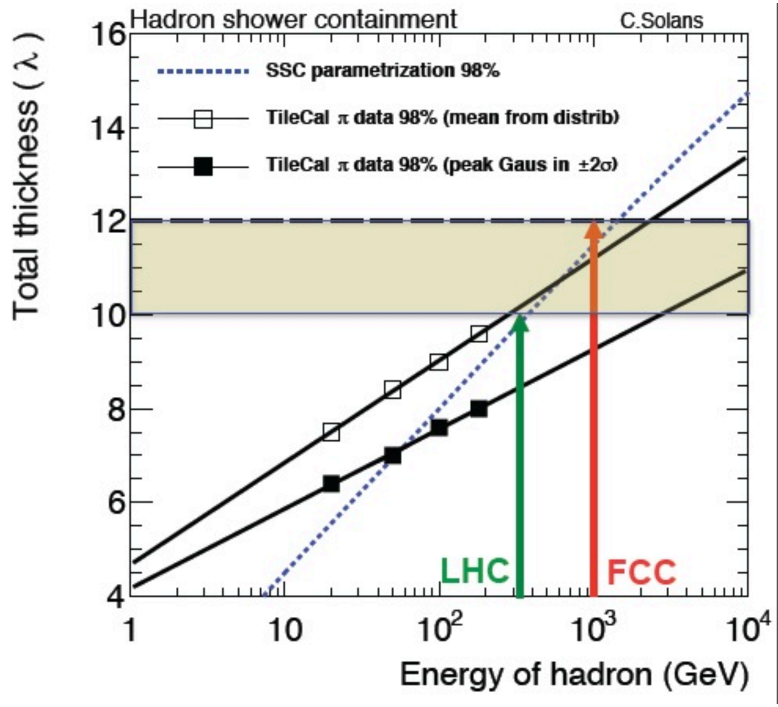
- Track-cluster matching is essential to achieve the above → fine (lateral) granularity and good position resolution should be achieved

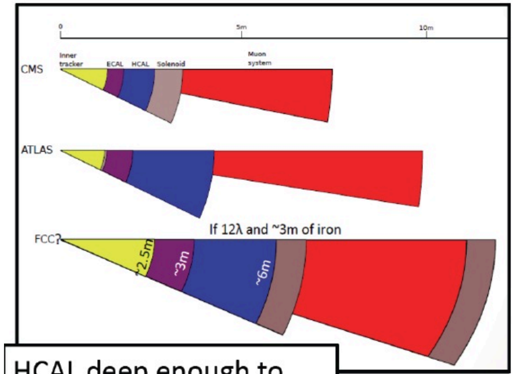


Requirements HCAL

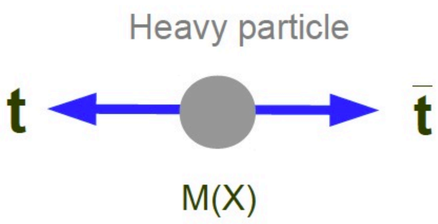
HCAL:

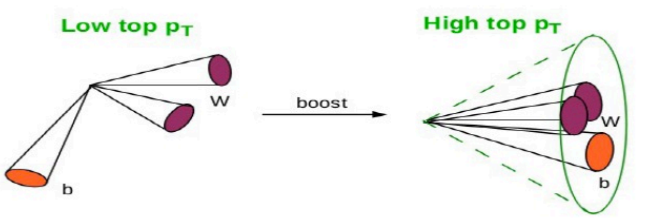
- Jet containment: 8% of single hadron constituents of 30TeV jets have E>1TeV. 98% containment requires 12λ
- Large acceptance up to |η|=6
- Highly collimated (boosted) final states
  - Minimal distance between two partons proportional to m/p_T (e.g. top)
- → high granularity also in the HCAL
  - Sub-structure 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

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

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

Single hadrons:

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

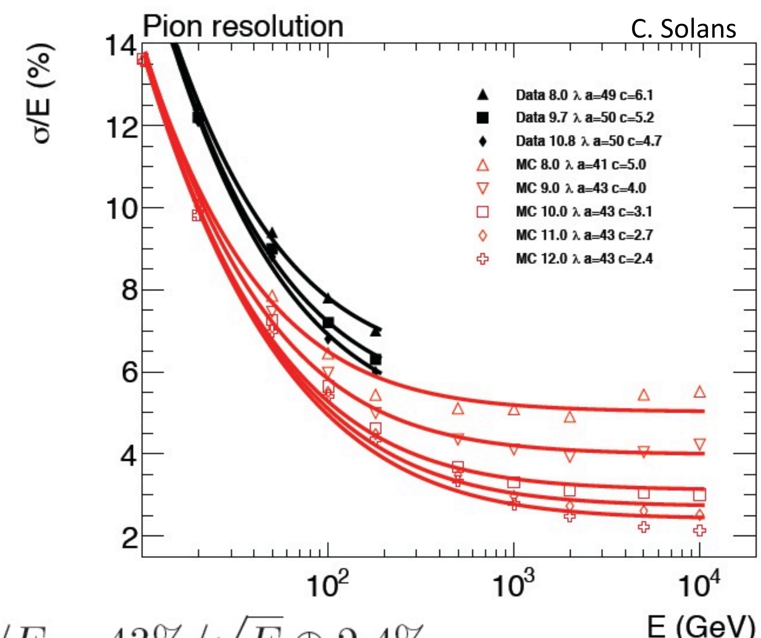
CMS: $\sigma_E/E \sim 100\%/\sqrt{E} + 4.5\%$

(small noise term for both)

Jet p_T > 5TeV: constant term dominates

Reduction of the constant term- need to work on:

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



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

Conclusions

Studies of accelerators and detectors for the post-LHC energy frontier are on-going.

A conceptual design report is planned for 2018.

Basic concepts for detectors at these future colliders are being worked on and have been shown.

Detector technology choices will depend on the requirements from physics – further refinement under way.

Concentrating on few example designs while staying open for innovative concepts.

New ideas and person-power are highly welcome!

Join in!

Backup

Luminosity goals for a 100-TeV pp collider

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Abstract

We consider diverse examples of science goals that provide a framework to assess luminosity goals for a future 100-TeV proton-proton collider.

An integrated luminosity goal of 20ab^{-1}

matches very well the 100TeV c.m. Energy

Synchrotron radiation/beam screen

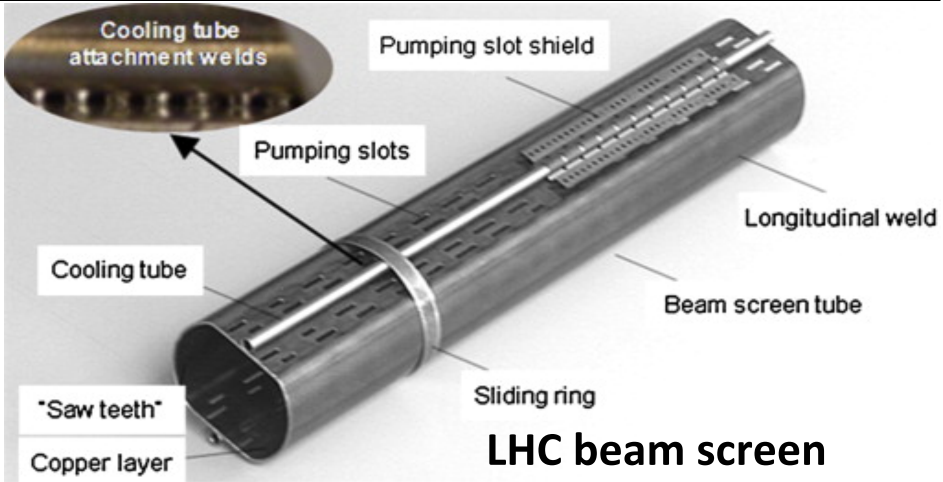
High synchrotron radiation load (SR) of protons @ 50 TeV:

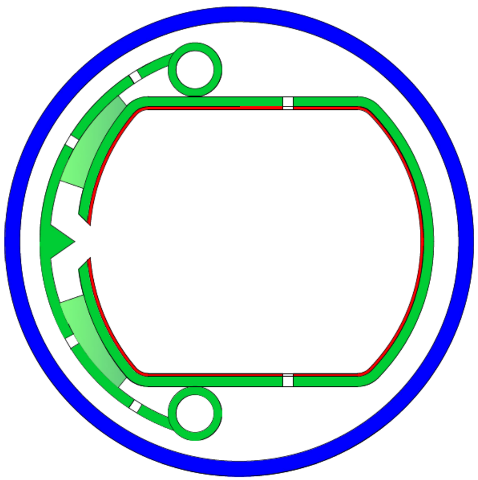
~30 W/m/beam @16 T (LHC <0.2W/m)

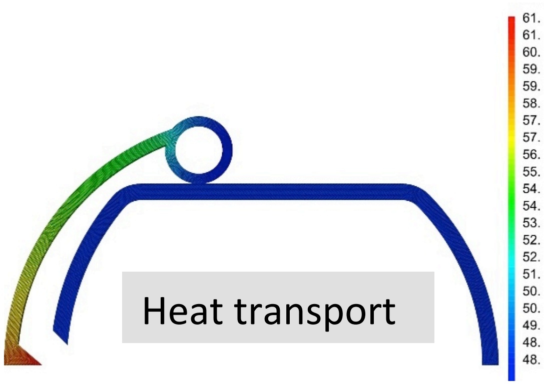
→ 5 MW total in arcs

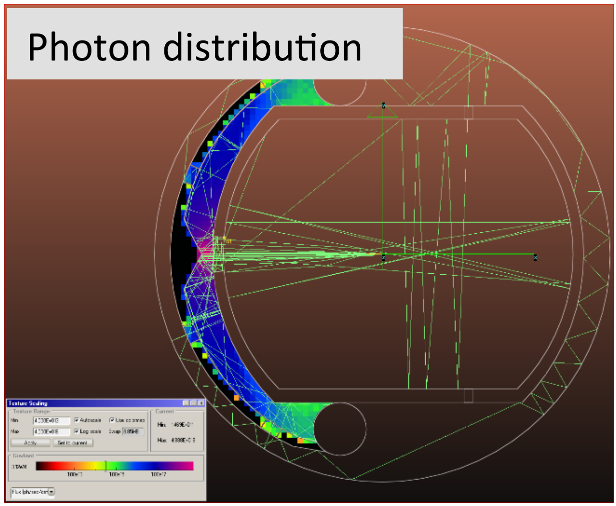
New type of chamber

- absorption of synchrotron radiation
- avoids photo-electrons, helps vacuum

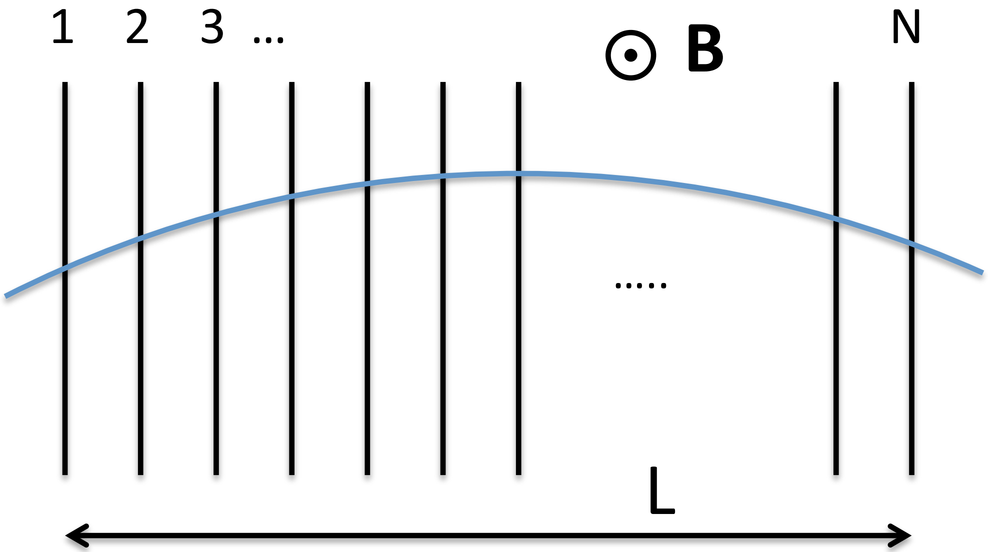








Point Resolution and Multiple Scattering



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

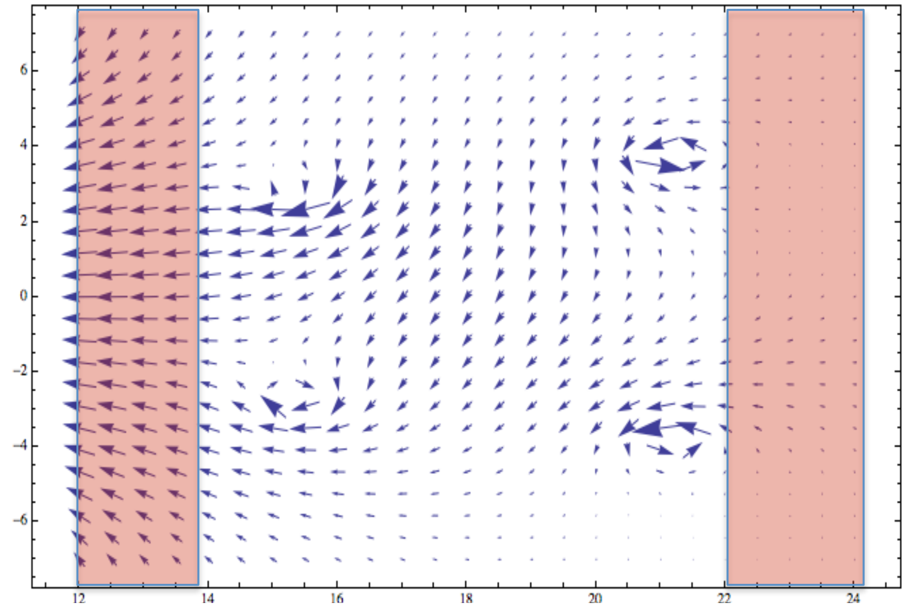
$$\frac{\Delta p_t}{p_t} = \frac{0.0136}{0.3\beta\,B[T]\,L[m]}\sqrt{\frac{X_{tot}}{X_0}}\sqrt{\frac{10}{7}\,\frac{12+(N-1)N^2(N+1)}{(N-2)N(N+1)(N+2)}}$$

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

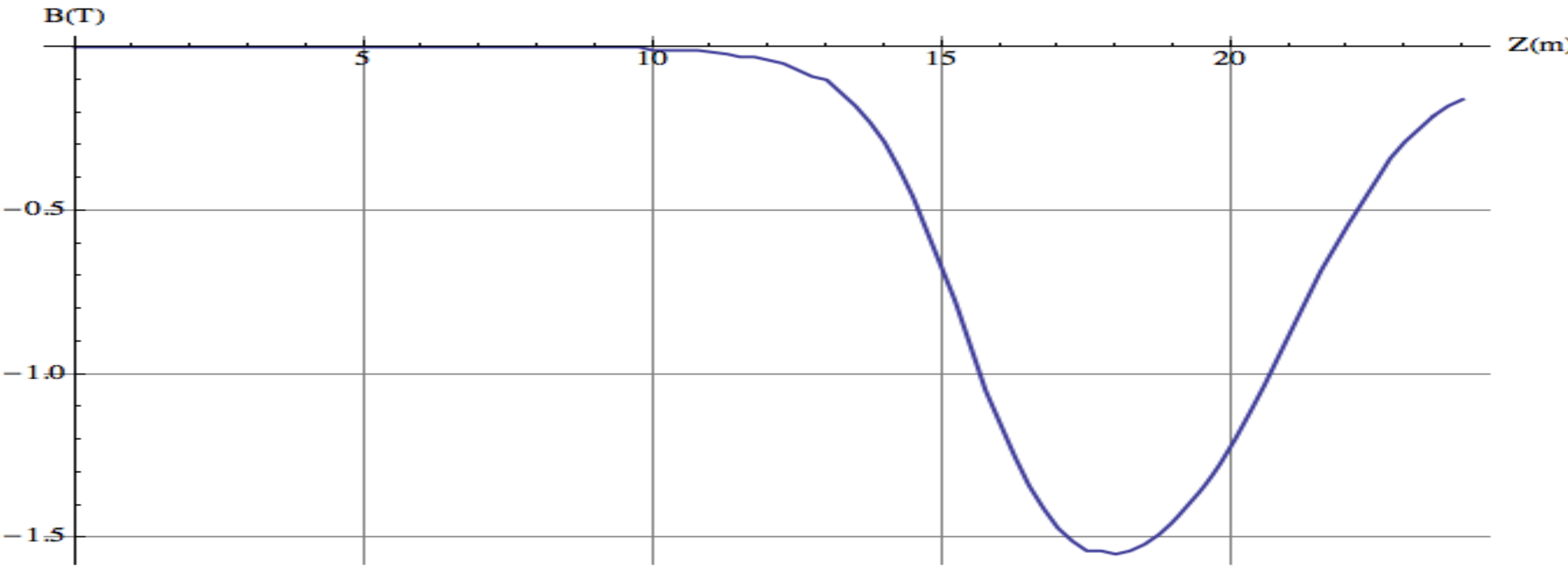
$$\approx \frac{0.0542}{\beta\,B[T]\,L[m]}\sqrt{\frac{X_{tot}}{X_0}}$$

≈1.2

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

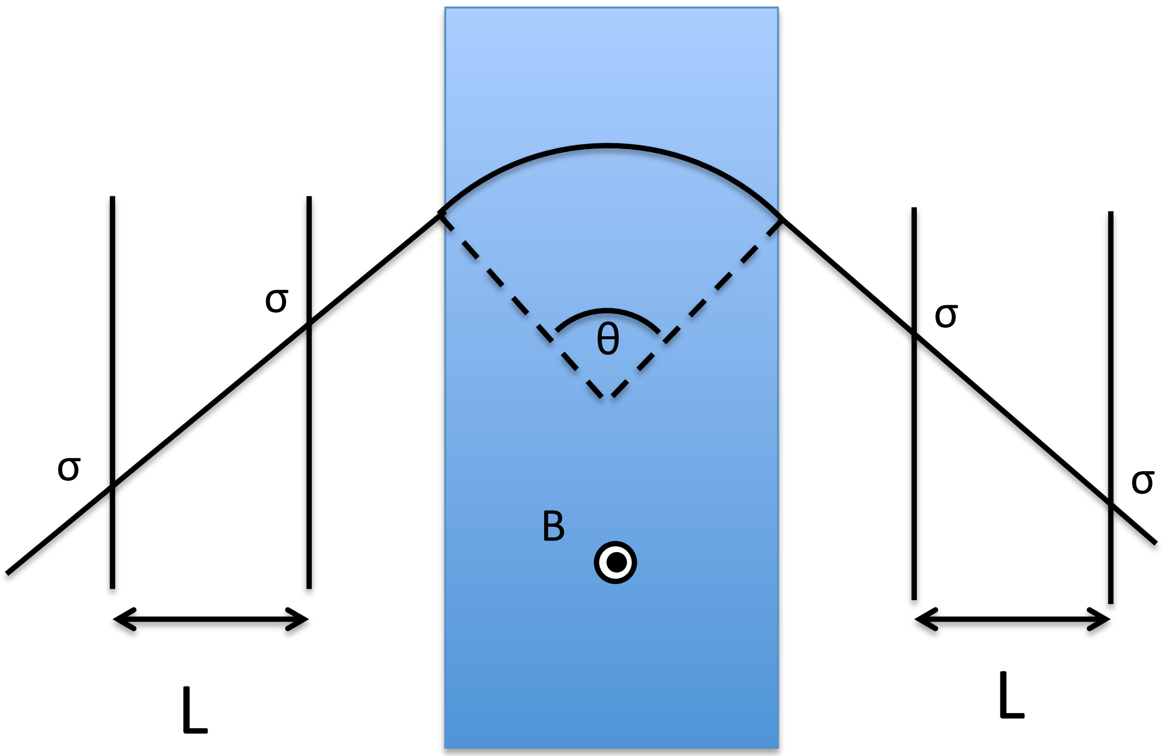


6
4
2
0
-2
-4
-6
12
14
16
18
20
22
24



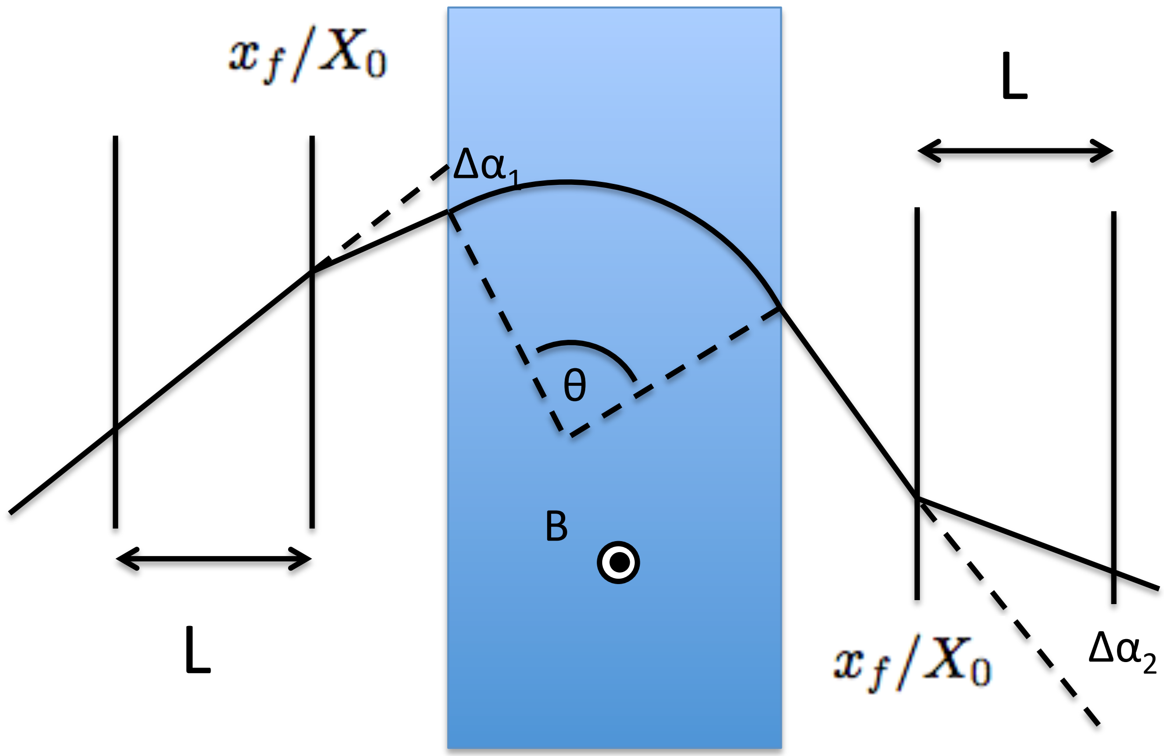
B(T)
Z(m)
5
10
15
20
−0.5
−1.0
−1.5

Forward Tracker Resolution, Position Resolution



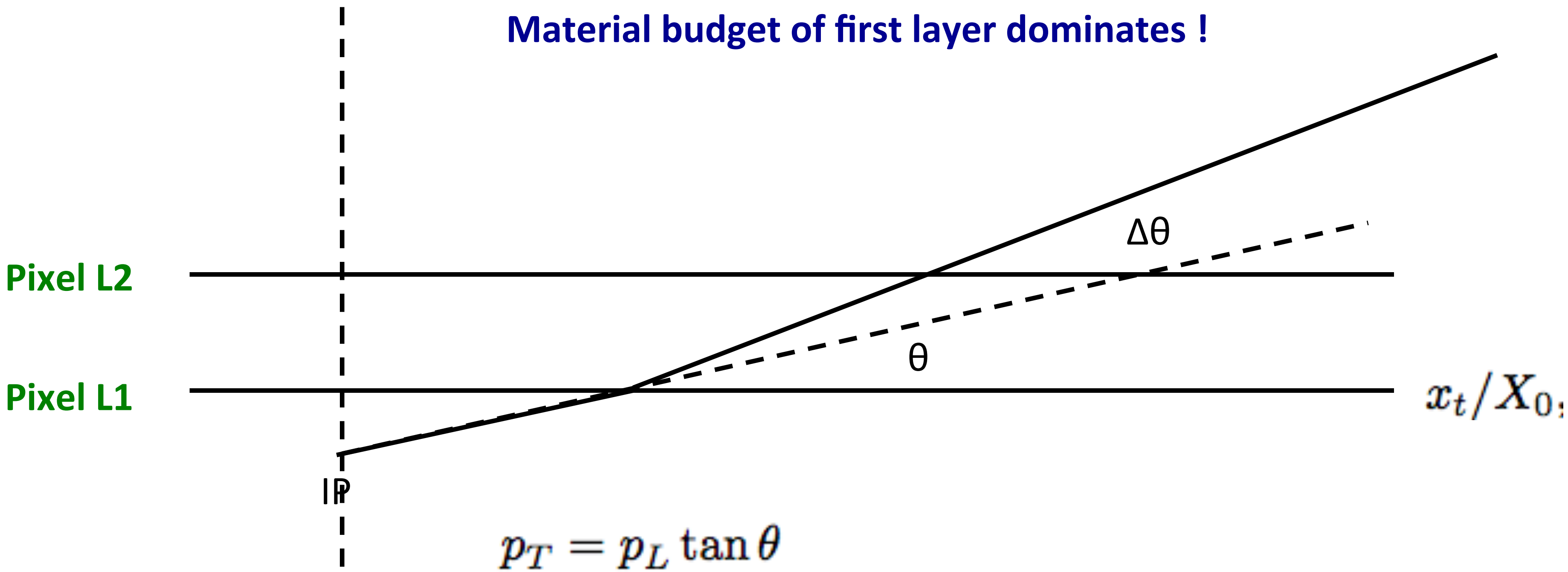
$$\left(\frac{\Delta p_L}{p_L}\right)^2 = \left(\frac{p_L}{0.3\int B_T dl}\right)^2 (\Delta\alpha_{res}^2 + \Delta\alpha_{ms}^2) \qquad \Delta\alpha_{res} = 2\sigma/L.$$

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

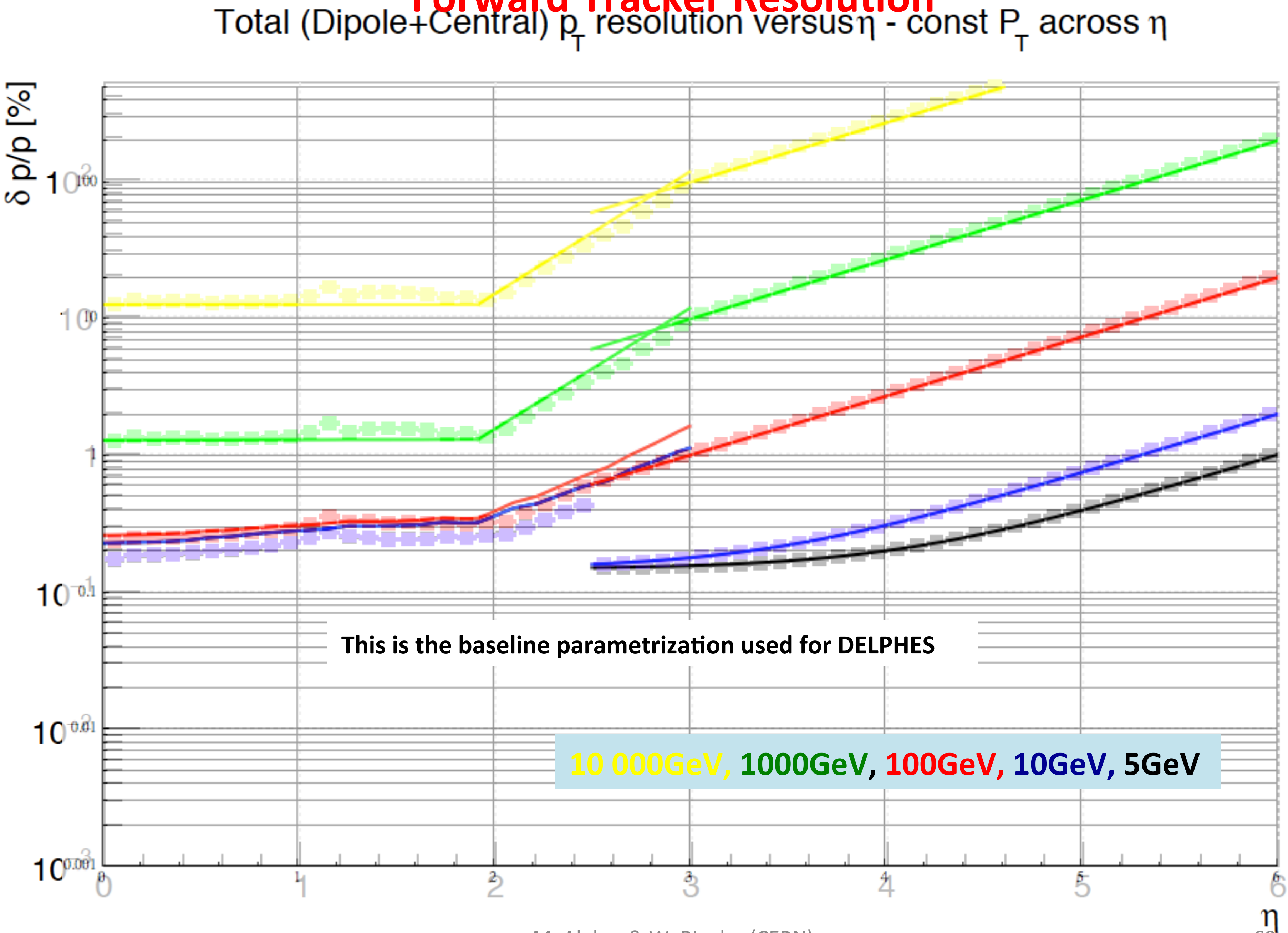
X_f/X_0=0.06
Int Bdl=10 Tm

X_t/X_0=0.03

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

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

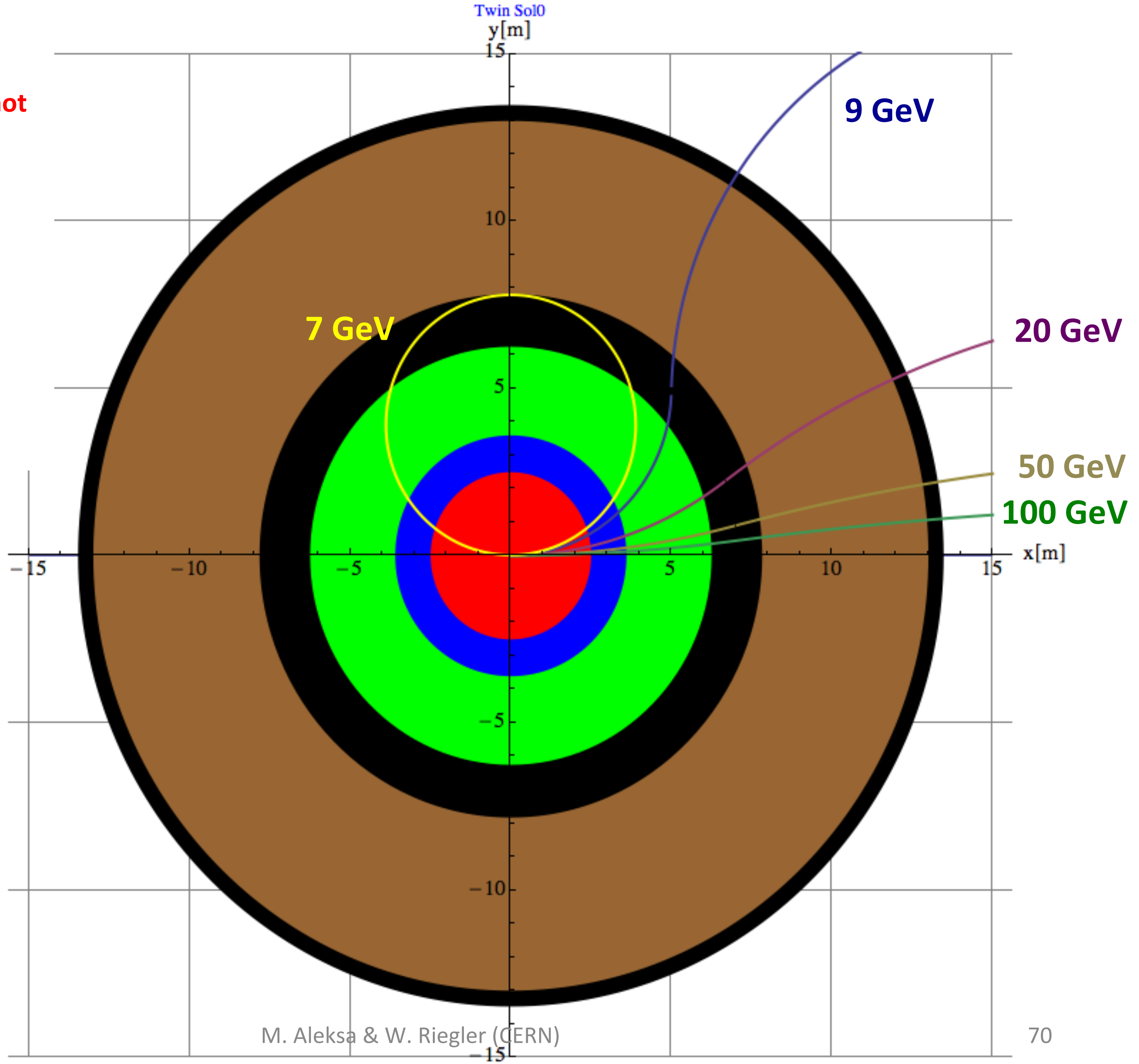
Forward Tracker Resolution



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.



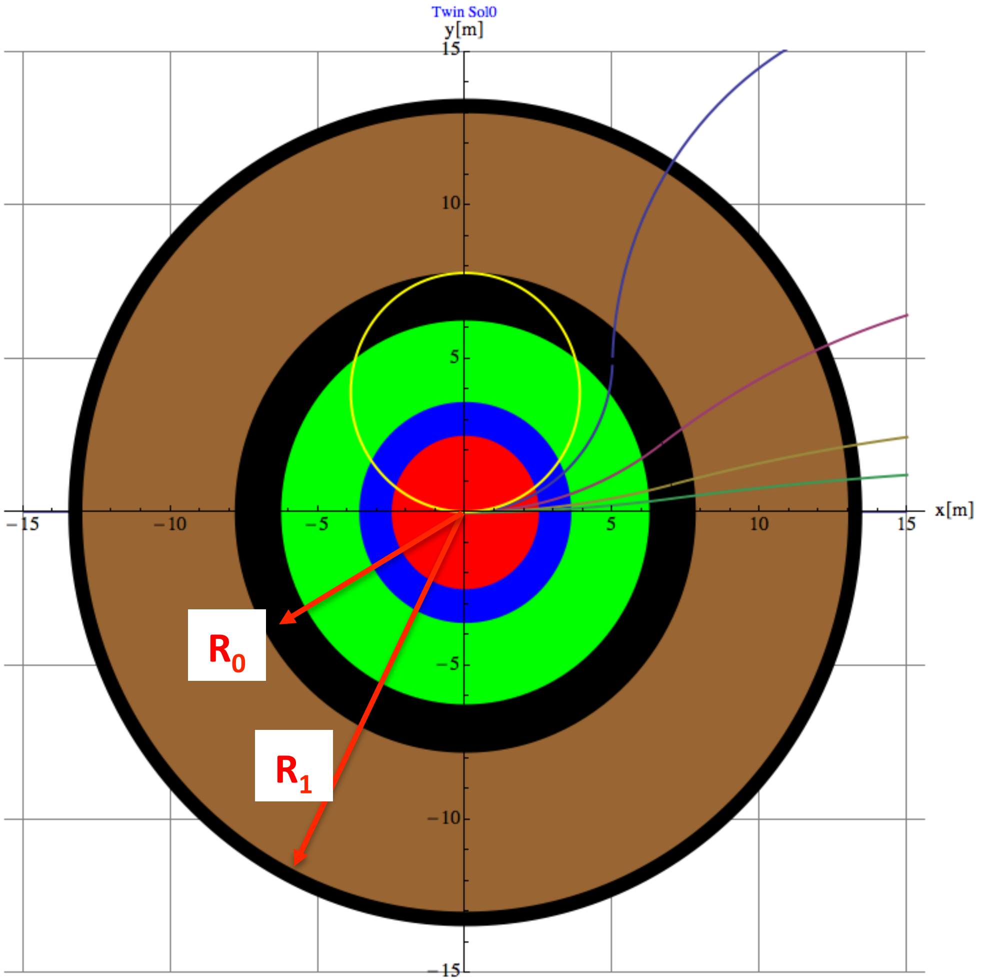
Muon Momentum can be measured by

1) The inner tracker
→ resolution plots from before

2) 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

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

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

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

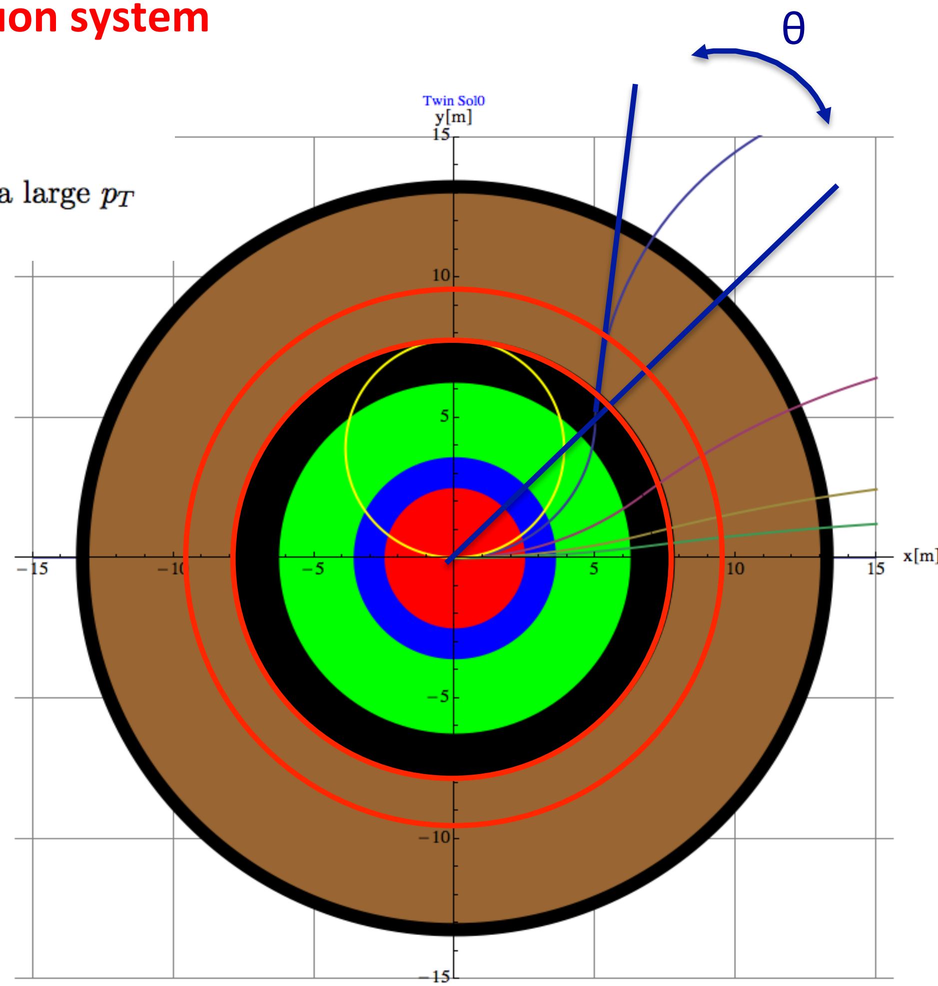
For low momentum, limit due to multiple scattering in the calorimeters and coil:

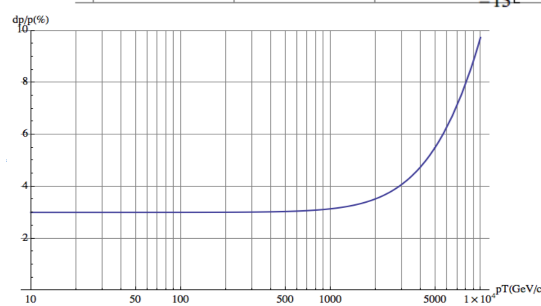
Calorimeter+Cryostat: 35X_0
HCAL: 110X_0
Coil: 5X_0
→ **x_{tot}/X_0 ≈150**

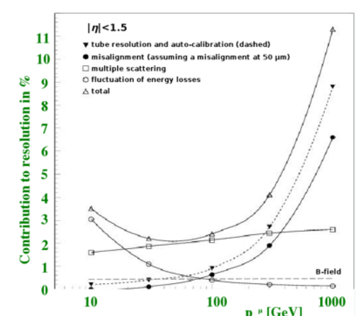
$$\frac{\Delta p_T}{p_T} = \frac{2 \times 0.0136}{0.3B_0R_0}\sqrt{\frac{x_{tot}}{X_0}}$$

B_0=6T, R_0=6m
→ **dp/p=3% !!!**

(CMS 9% because B_0R_0=1/3)

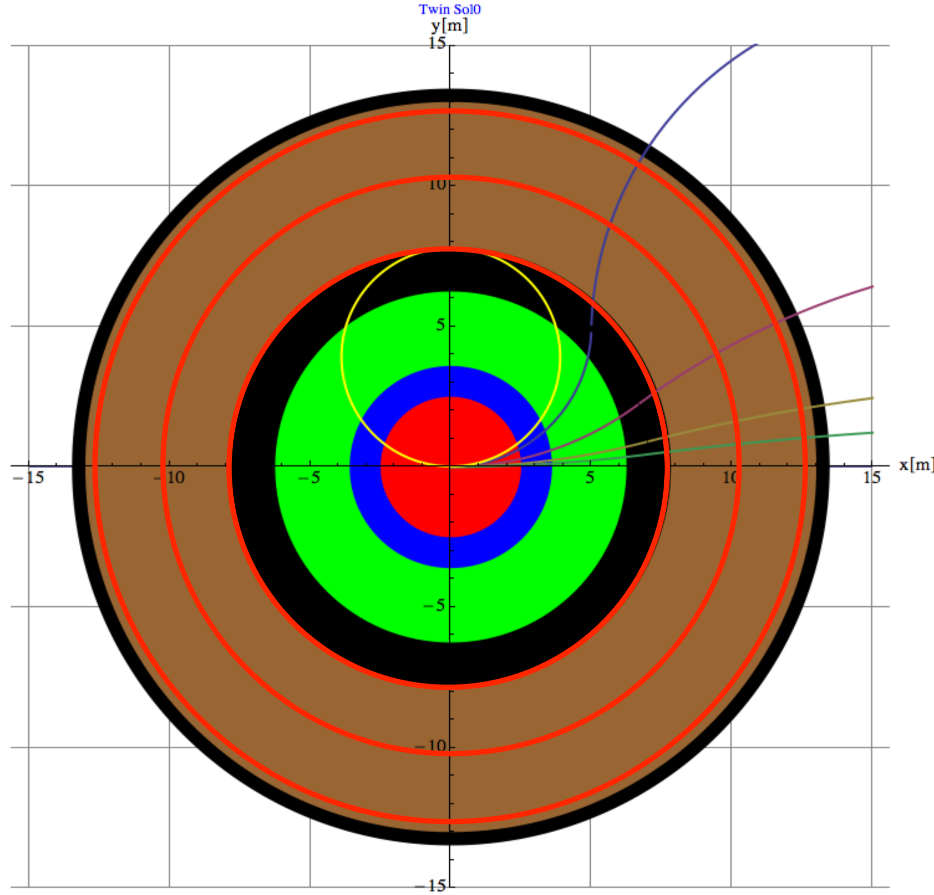






At eta=0 ATLAS type standalone Muon Performance up to 10TeV !!!

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.

Combined Measurement

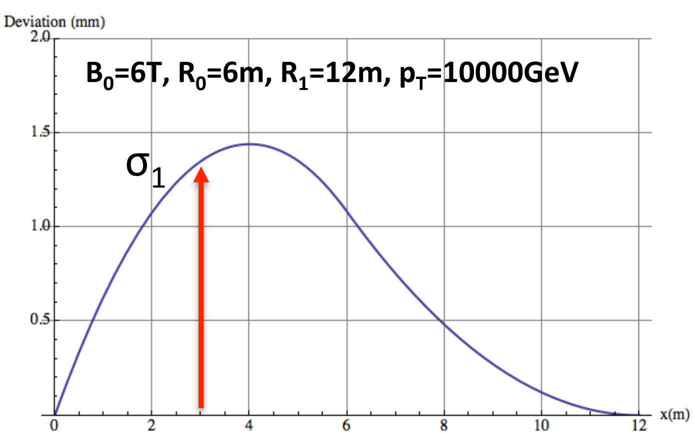
If the full flux is returned trough the muon system, the muon trajectory at the exit of the system points exactly to the IP !

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

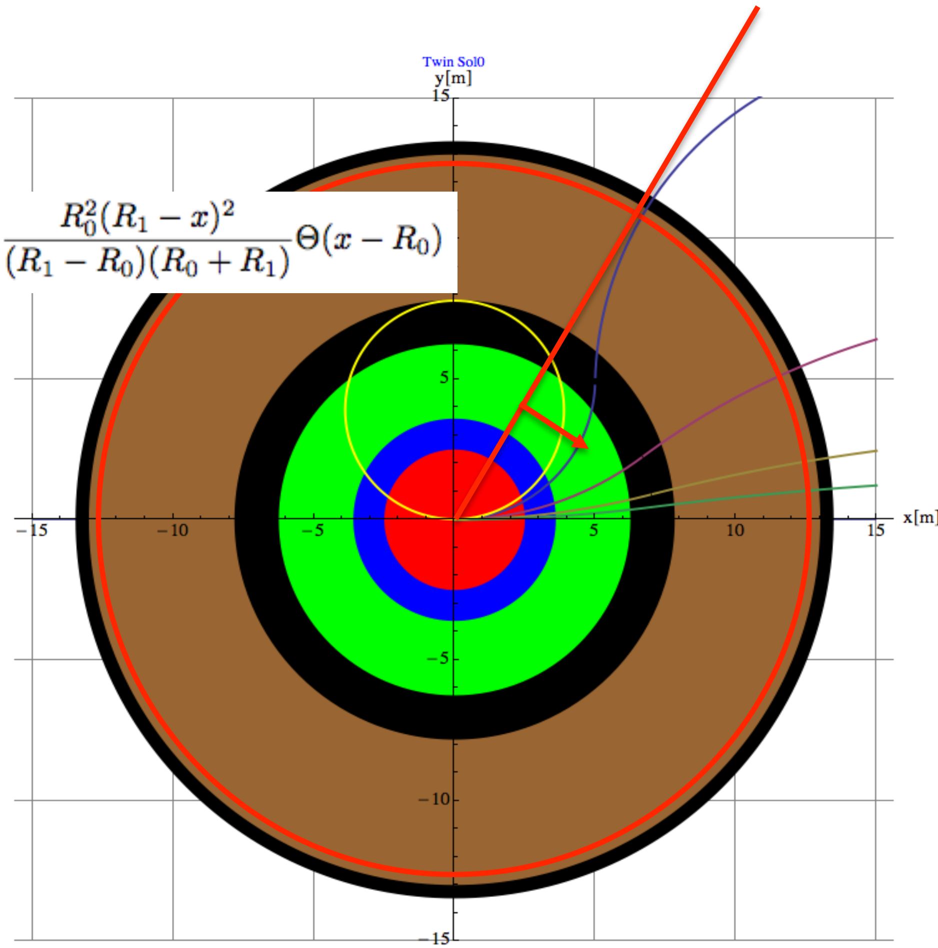
The maximum excursion $y_t(x_0)$ is always at the same radial distance of x_0

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

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 !



σ_2

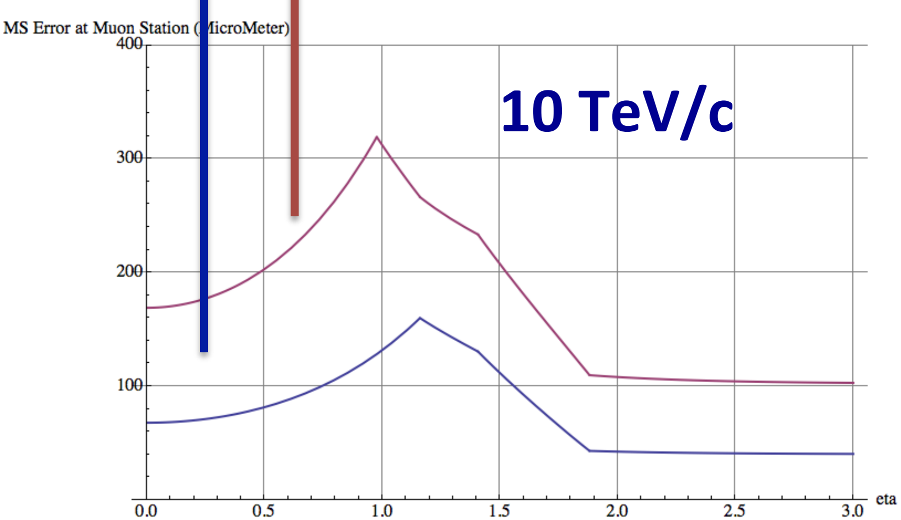


$\sigma^2=\sigma_1^2+(x/R_1\sigma_2)^2$

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).

Measurement error in the muon system due to multiple scattering



The r.m.s. (in plane) angular deflection θ_0 and spatial displacement σ_y of a particle passing through material of thickness x are given by

$$\theta_0 = \frac{0.0136}{\beta p[GeV/c]} \sqrt{\frac{x}{X_0}} \left(1 + 0.038 \log \frac{x}{X_0}\right) \tag{184}$$

$$\sigma_y = \frac{1}{\sqrt{3}} x \theta_0 \tag{185}$$

For the proper correlated M.C. generation of these two quantities, one uses two independent Gaussian random variables z_1, z_2 with mean of zero and sigma of one, and calculates

$$y = z_1 x \frac{\theta_0}{\sqrt{12}} + z_2 x \frac{\theta_0}{2} \tag{186}$$

$$\theta = z_2 \theta_0 \tag{187}$$

In case a muon passes the calorimeter of thickness L_1 and then propagates through the (material less) muons system of length L_2 the spatial deflection is given by

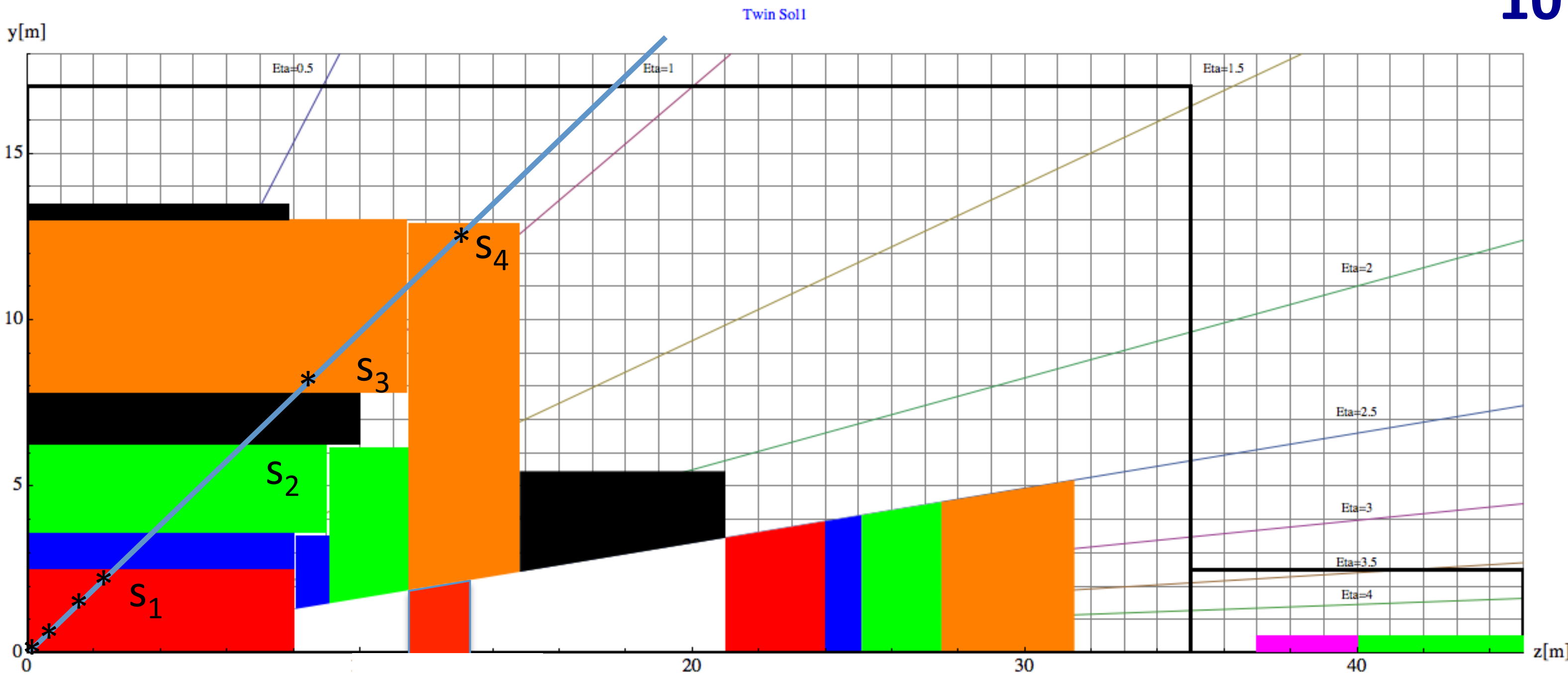
$$s = z_1 L_1 \frac{\theta_0}{\sqrt{12}} + z_2 L_1 \frac{\theta_0}{2} + z_2 \theta_0 L_2 \tag{188}$$

and therefore a position error of

$$\sigma_s^2 = \theta_0^2 \left[\frac{L_1^2}{12} + \left(\frac{L_1}{2} + L_2\right)^2\right] \tag{189}$$

Radiation length and angular deflection of muons in calo+coil

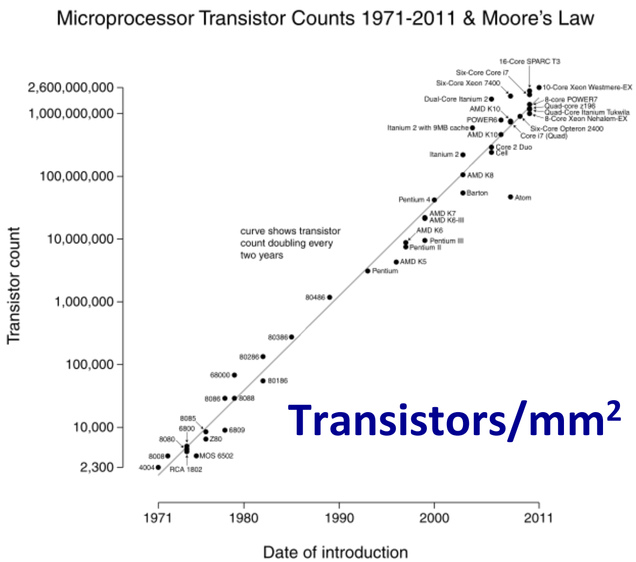
10 TeV/s

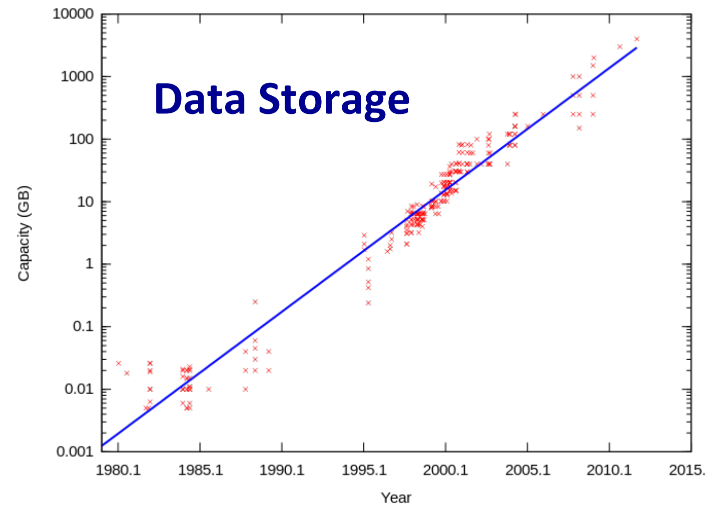


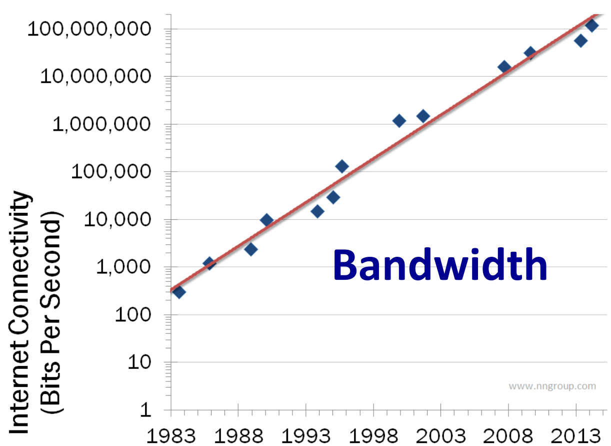
Fit of the template function to 14 measurement points of 23um in the inner tracker and 1 layer in the muon system with a resolution that is much better than the multiple scattering limit.

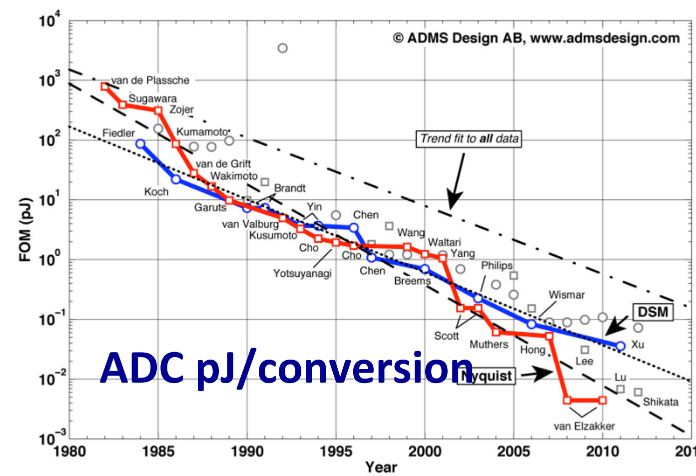
i.e. assuming the resolution ats3 to be better than 50um and at s4 to be better than 100um and the resolution of the angular measurement better than 20uRad.

Prospects for ‚Microelectronics‘







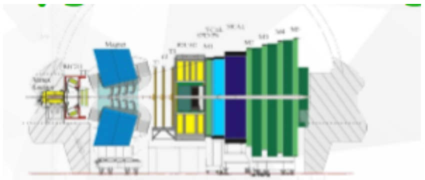


All these figures showed doubling times of < 2 years up to now ! Some scalings will stop, but different tricks might come in.

May dream about a factor 2^{10} = 1024 from 2014 – 2034 (of course optimistic)

This will allow major detector improvements !

LHCb & ALICE in 2018



40 MHz

DAQ

40 MHz

LLT: μ,e/γ, hadrons

5-40 MHz

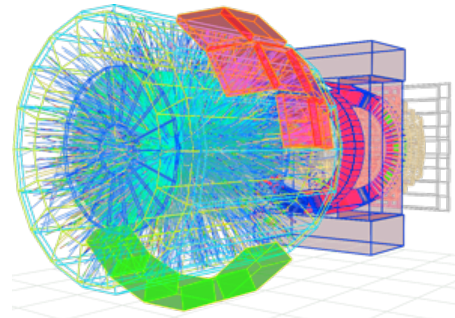
HLT: event recon.

20 kHz (0.1 MB/event)

Storage

2 GB/s

4 TByte/s into PC farm for HLT selection.



1 TByte/s into PC farm for data compression. All events to disc.

50 kHz

Reconstruction + Compression

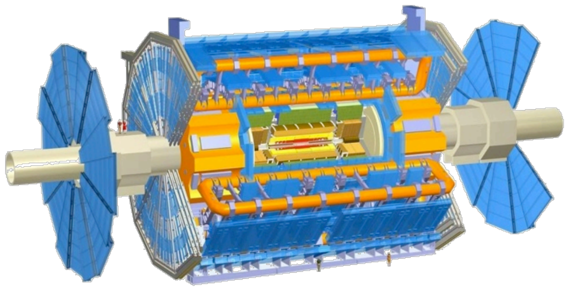
50 kHz (1.5 MB/event)

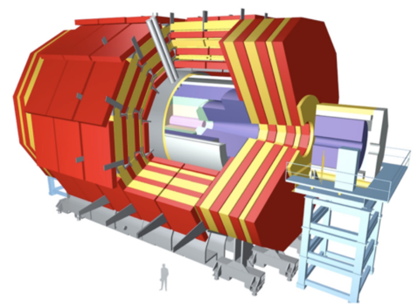
Storage

75 GB/s

← PEAK OUTPUT →

ATLAS & CMS in 2018





40 MHz

Level 1 | Level 1

0.5-1 MHz

5 TByte/s into PC farm for HLT selection.

Would be 200TByte/s without Level1

HLT | HLT

5-10 kHz (2MB/event) | 10 kHz (4MB/event)

Storage | Storage

10-20 GB/s ← PEAK OUTPUT → 40 GB/s

Hardware Trigger ?

CMS HL-LHC results in 200TByte/s into the online system for a triggerless readout.

For 2022 this is considered too difficult.

Assuming that the total track rate for 100TeV pp collisions (Phase I) is only a factor 2 larger, there is very little doubt that by 2035 and FCC-hh detector can be read out in a triggerless fashion.

In 2035 maybe no hardware trigger necessary ! All data to the online system, synchronous or asynchronous, where a sophisticated selection and compression can be done.

N.b. the techniques to get the data out of the detector with a small amount of material is a key question to be solved.

Even if one would afford to read all data to HLT for PhaseII, the amount of copper lines to get all the signals out of the silicon detector would destroy the tracker performance.

Moore‘s Law

http://www.livescience.com/23074-future-computers.html

“If the doubling of computing power every two years continues to hold, then by 2030 whatever technology we're using will be sufficiently small that we can fit all the computing power that's in a human brain into a physical volume the size of a brain”,

explained Peter Denning, distinguished professor of computer science at the Naval Postgraduate School and an expert on innovation in computing.

"Futurists believe that's what you need for artificial intelligence. At that point, the computer starts thinking for itself.“

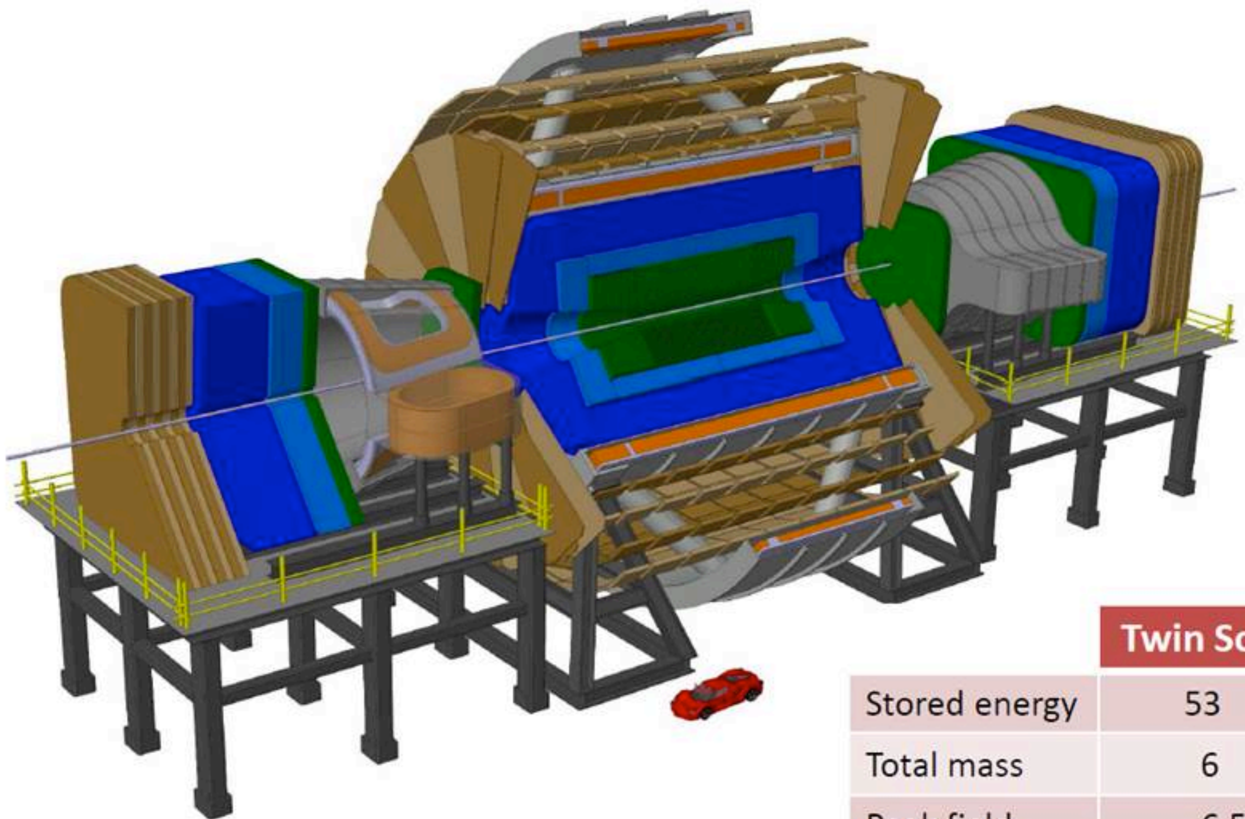
→ **Computers will anyway by themselves figure out what to do with the data by 2035.**

Magnet systems and shielding will be rather conventional and can be worked out to some detail now.

For detector technology and computing power we are allowed to dream a bit.

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
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.

Twin Solenoid + Dipole Magnet System

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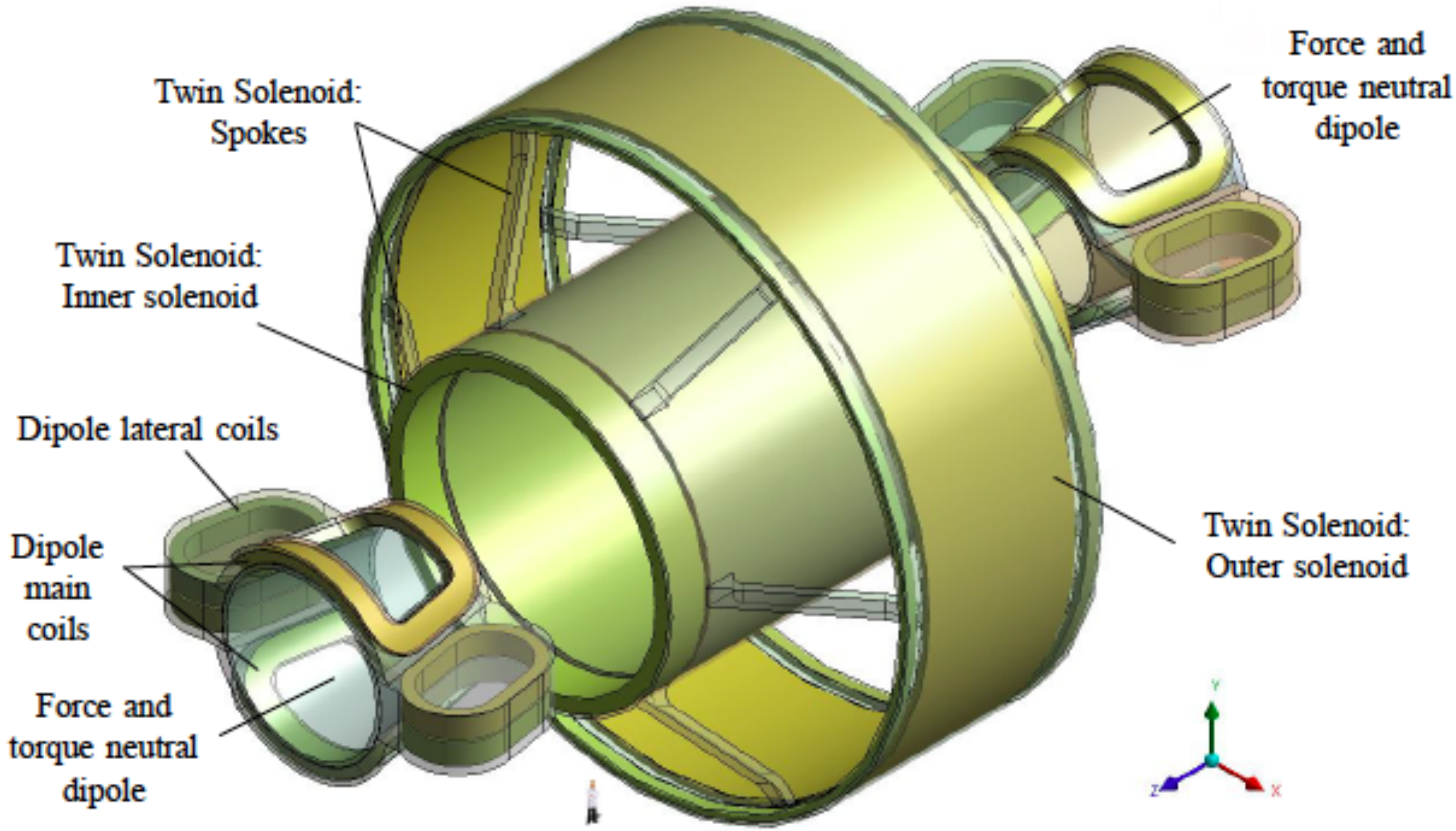
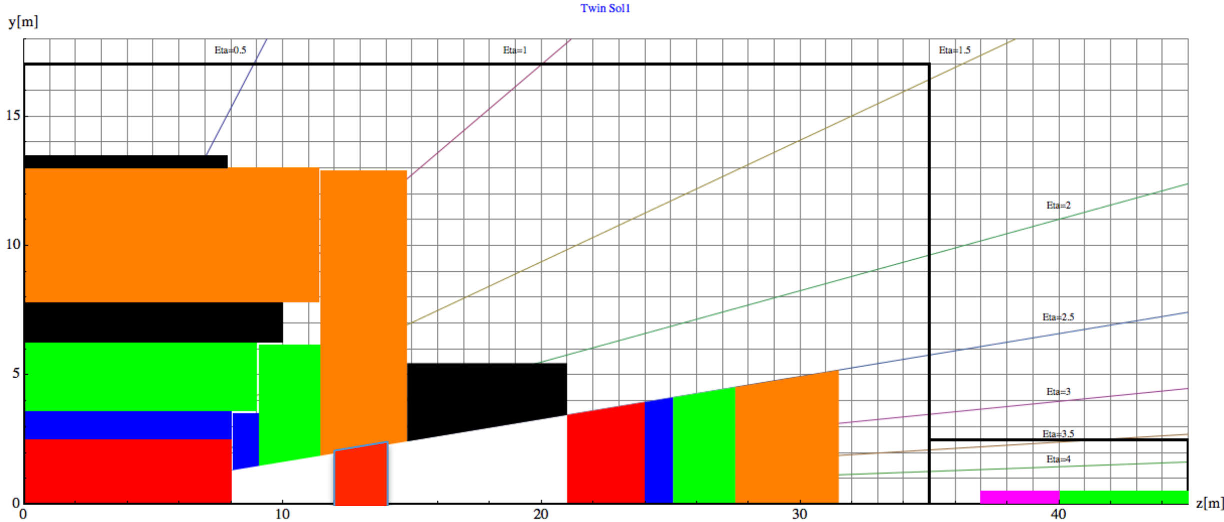


Baseline Geometry, Twin Solenoid



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

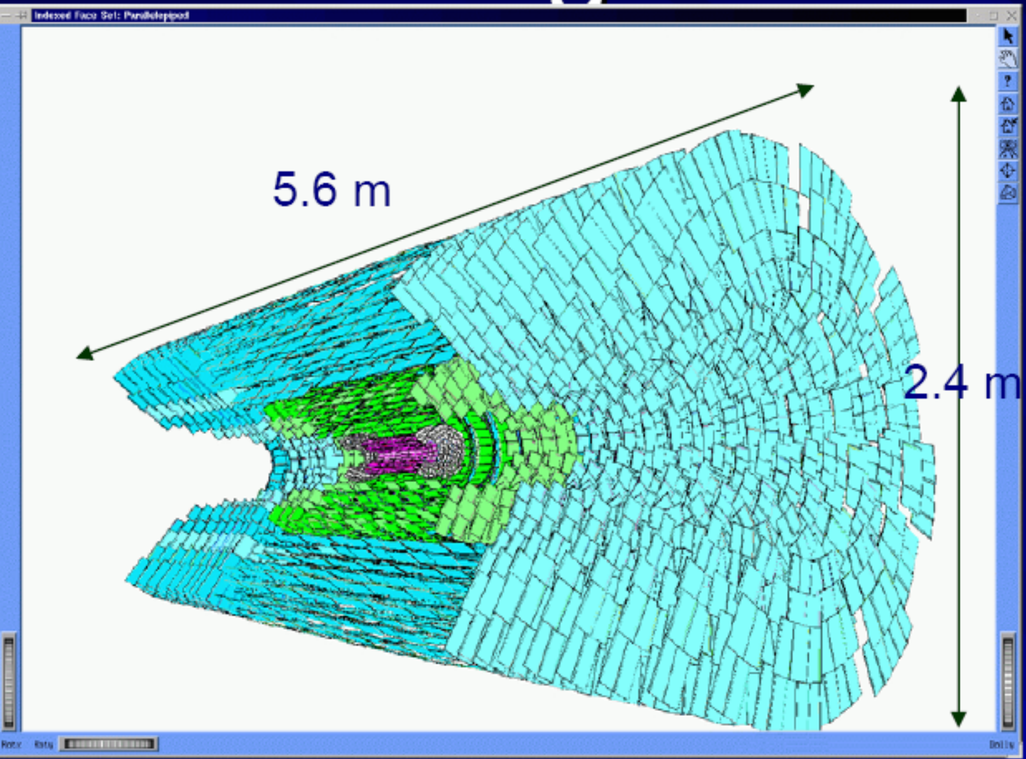
FTracker available space:
z=21m to R=24m, L=3m

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

Large Silicon Systems



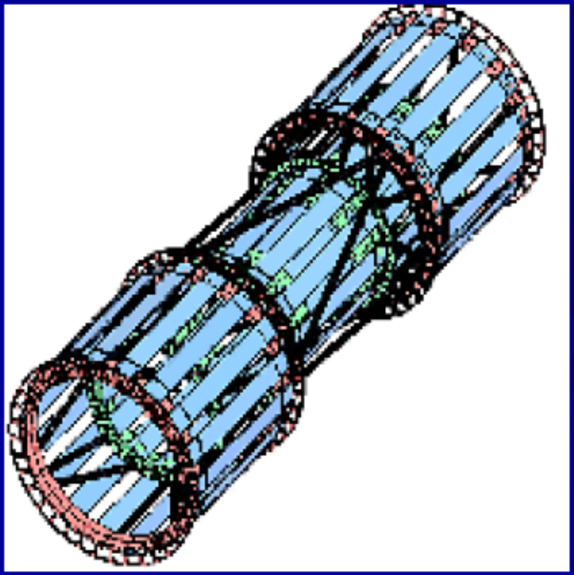
CMS tracker (~2007)

12000 modules

~ 445 m² silicon area

~ 24,328 silicon wafers

~ 60 M readout channels



CDF SVX IIa (2001-)

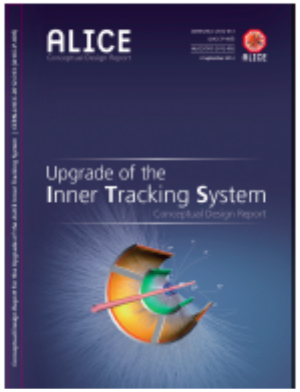
~ 11m² silicon area

~ 750 000 readout channels

ALICE 2018 upgrade, 20x20um monolithic pixels

New ITS Layout

25 G-pixel camera
(10.3 m^2)



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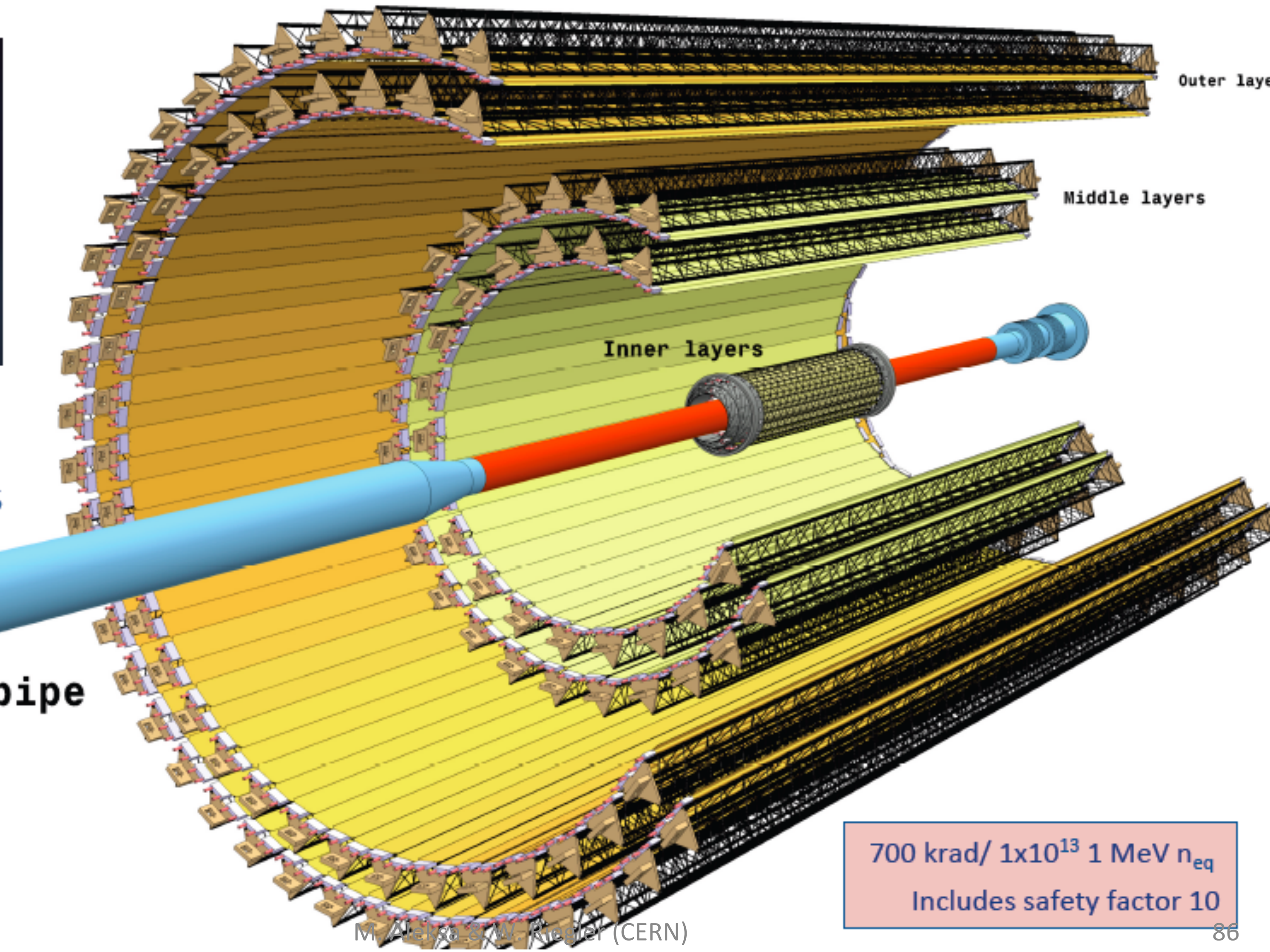
7 layers of MAPS

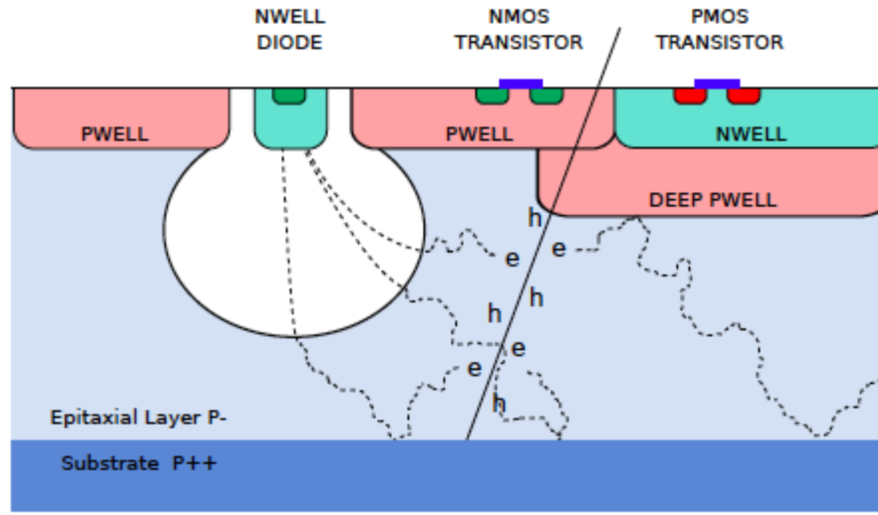


Radial coverage
22 – 406 mm

700 krad/ 1x10^{13} 1 MeV n_{eq}
Includes safety factor 10

PIXEL Chip - technology

→ **Technical design report for the upgrade of the ALICE inner tracking system** CERN-LHCC-2013-024



Schematic cross-section of CMOS pixel sensor (*ALICE ITS Upgrade TDR*)

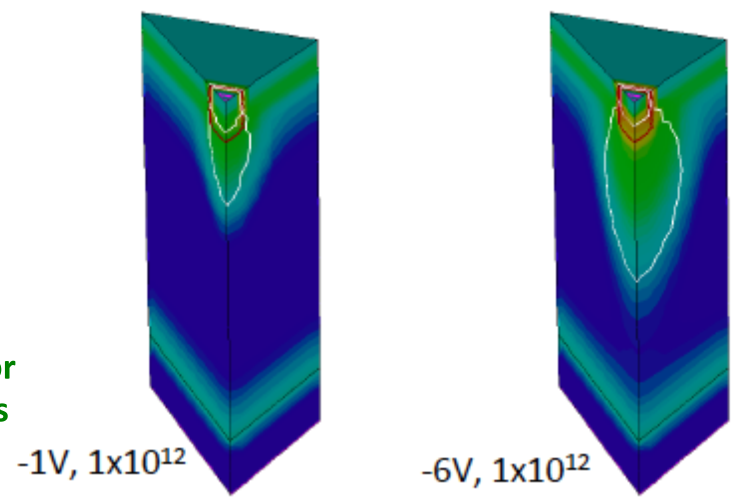
Monolithic PIXEL chip using Tower/Jazz 0.18 μm technology

- feature size 180 nm
- gate oxide < 4nm
- metal layers 6
- high resistivity epi-layer
  - thickness 18-40 μm
  - resistivity 1-6 k Ω×cm
- "special" deep p-well layer to shield PMOS transistors (allows in-pixel truly CMOS circuitry)
- Possibility to build single-die circuit larger than reticle size

Standard processing, no bump bonding (>>50% of Pixel detector cost). Allows implementation of complex processing electronics inside the entire pixel area.

→ **Revolution !**

TCAD simulation of total diode reverse bias (*ALICE ITS Upgrade TDR*)



diode 3μm x 3μm square n-well with 0.5μm spacing to p-well white line: boundaries of depletion region

Pixel Revolution Hybrid → Monolythic

Table 2.2: Chip design options.

Architecture (discriminator, read-out)	Pitch ($r\phi \times z$) (μm^2)	Integration time (μs)	Power consumption ($mW\,cm^{-2}$)
MISTRAL (end-of-column, rolling-shutter)	22 × 33.3	30	200
ASTRAL (in-pixel, rolling-shutter)	24 × 31 36 × 31	20	85 60
CHERWELL (in-strixel[a], rolling-shutter)	20 × 20	30	90
ALPIDE (in-pixel, in-matrix sparsification)	28 × 28	4	< 50

[a] A strixel is a 128-pixel column over which the electronics are distributed.

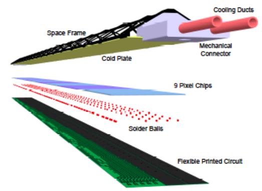
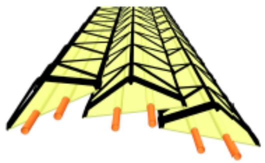
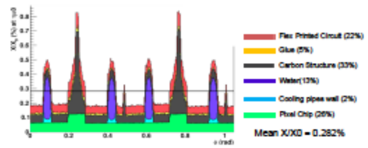
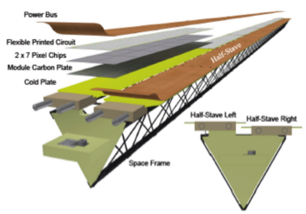
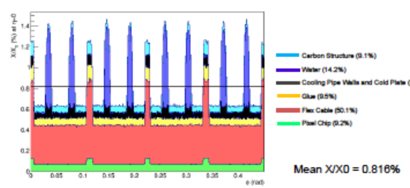


Figure 4.1: Schematic view of the Inner Barrel Stave.









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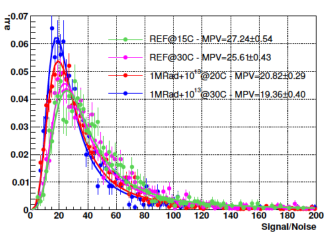

Figure 2.22: SNR of seed pixel measured with MIMOSA-32ter at the CERN-SPS, at two operating temperatures, before and after irradiation with the combined load of 1 Mrad and 10^{13} 1 MeV n_{eq}/cm^2.

Dramatic decrease in cost.

Very low power consumption, possibly <100mW/cm² i.e. simple water cooling

Ultra low material budget <0.5% for inner layers, <1% for outer layers.

Question of speed and radiation hardness:

At present,
integration time of 4µs (noise, electron diffusion)
radiation resistance up to few 10^{13} neq.

Development (next 20 years) towards larger (full) depletion will improve speed and radiation hardness significantly.

Also – in case one has a full pixel tracker one can use 1 or 2 layers with ‚fast' pixels to do the BCID (25ns or even 5ns) and then match the other hits.

With a full pixel tracker of 20x20um pixels one can pile up a fair amount of events before occupancy gets to large !!!