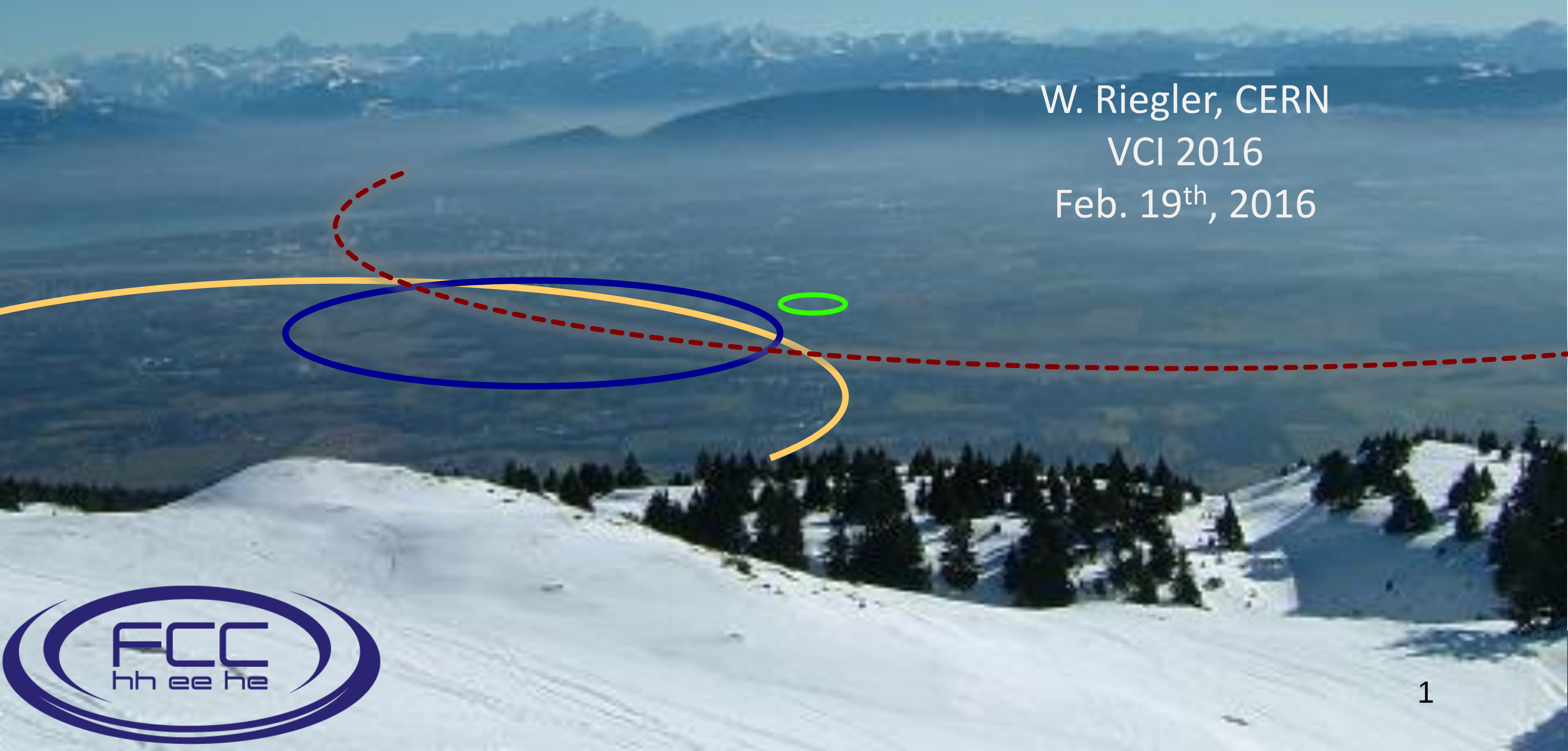
Detectors Requirements for a 100TeV Hadron Collider

W. Riegler, CERN

VCI 2016

Feb. 19th, 2016



LHC evolution

1983 first LHC proposal, launch of design study

1994 CERN Council: LHC approval

2010 first collisions at 3.5 TeV beam energy

2015 collisions at design energy

now is the time to plan for ~2040!

Strategic Motivation

- **European Strategy for Particle Physics 2013:**

  "…to **propose an ambitious post-LHC accelerator project**….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines….coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures,…."

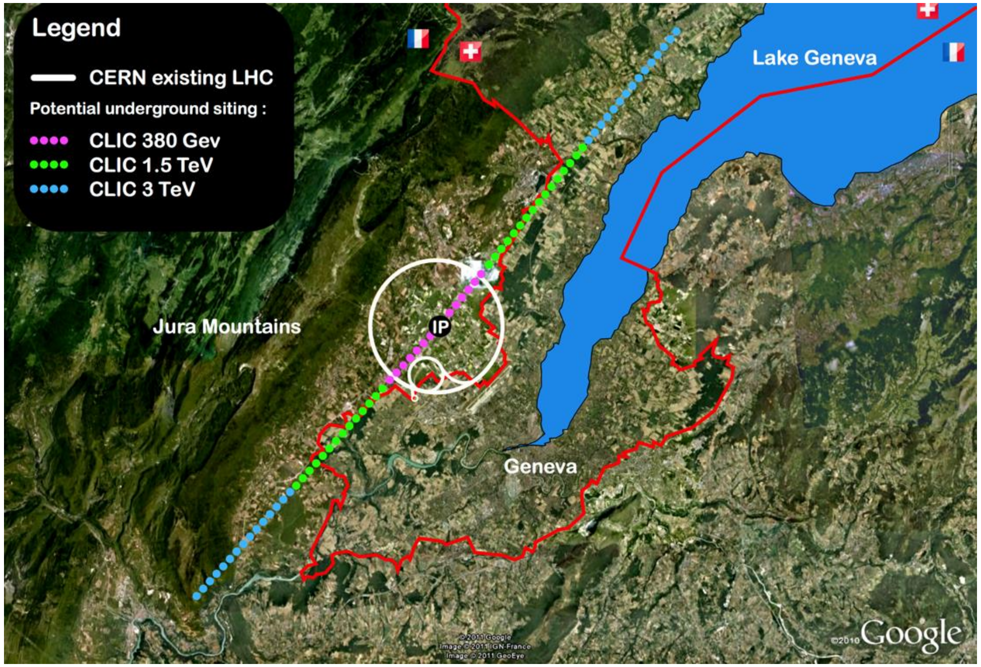
- **ICFA statement 2014:**

  "…. ICFA supports studies of energy frontier circular colliders and encourages global coordination….."

- **US P5 recommendation 2014:**

  "….A very high-energy proton-proton collider is the most powerful tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window…."

CLIC, e^+e^- collider at energy frontier



Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100

Main CLIC detector challenges:

- **Vertex detector**
  - 3 µm single-point accuracy
  - Low mass, <0.2% X_0/layer
  - 10 ns hit time accuracy
- **Tracker**
  - Large volume, 1.5 m radius
  - 7 µm single-point accuracy
  - Pixels or short strips
  - Low mass, <2% X_0/layer
  - 10 ns hit time accuracy
- **Calorimeter**
  - Highly granular (PFA)
  - 3.5% E_{jet} resol. (for E_{jet}>100 GeV)
  - 1 ns hit time accuracy

Active R&D ongoing in above fields

http://clicdp.web.cern.ch/

See talks N. Alipour Tehrani and E. Sicking at VCI

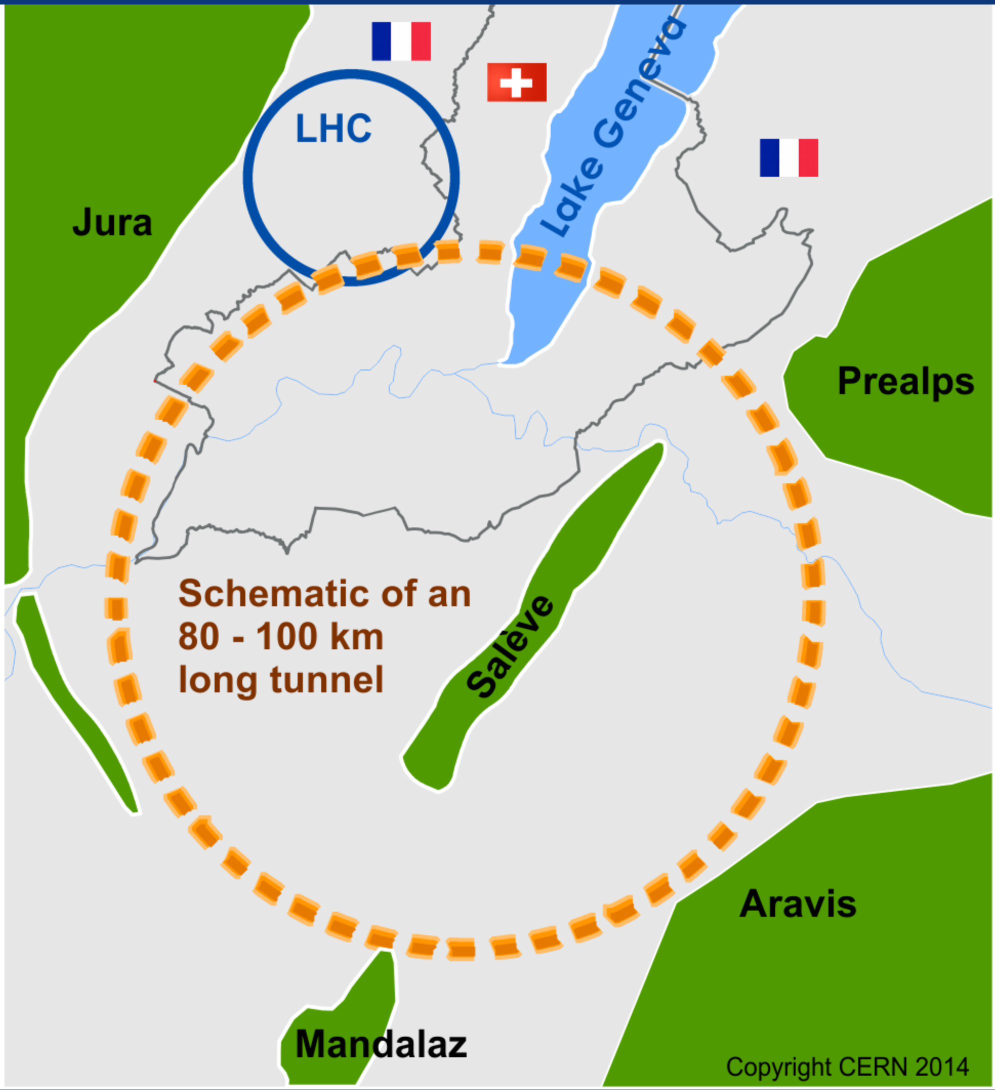
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area
- ***e⁺e⁻* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **HE-LHC** with *FCC-hh* technology



FCC motivation: pushing the energy frontier

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

$$E \propto B_{dipole} \times R_{bending}$$

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

Hadron collider 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

10 years baseline, leading to 2.5 ab^{-1}
15 years ultimate, leading to 15 ab^{-1}

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

FCC-hh preliminary layout

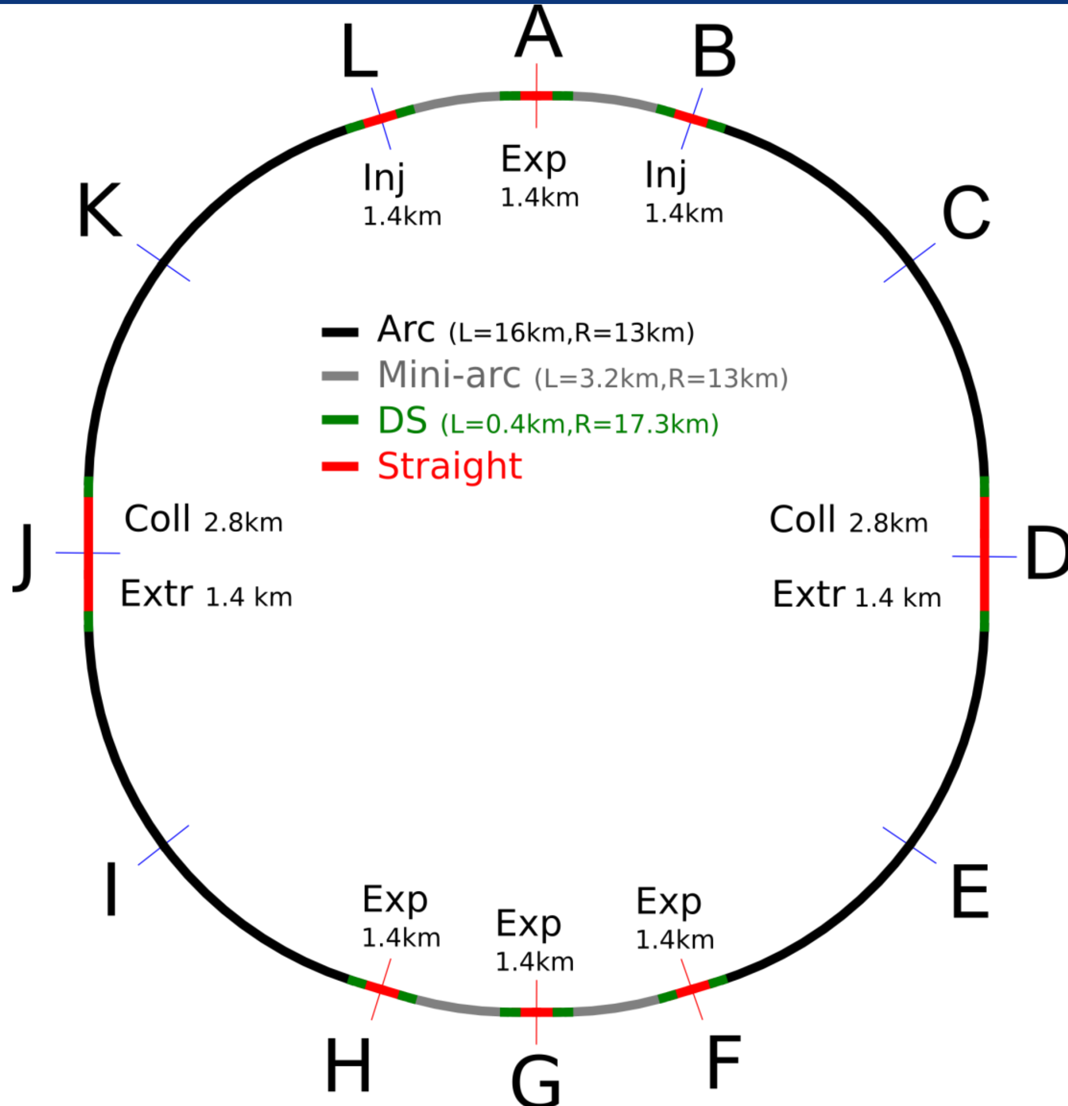
100 km layout for FCC-hh (different sizes under investigation)

⇒ **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**



Site investigations

Alignment | Shaft Tools

Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 299mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .5

Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2499812 Y: 1106889

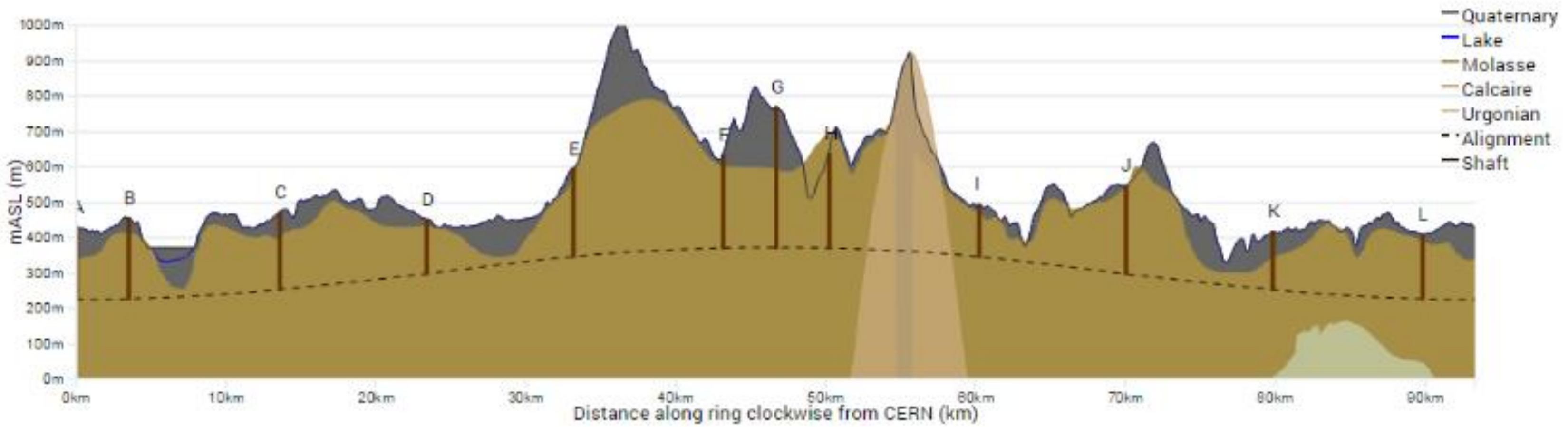
LHC Intersection	CP 1	CP 2
Angle		
Depth	589m	589m

Alignment Location

Geology Intersected by Shafts | Shaft Depths

	Shaft Depth (m)				Geology (m)			
Point	Actual	Min	Mean	Max	Quaternary	Molasse	Urgonian	Calcaire
A	203	200	204	212	93	111	0	0
B	227	219	226	231	41	185	0	0
C	218	208	217	225	75	143	0	0
D	153	150	154	158	19	134	0	0
E	247	233	249	261	24	223	0	0
F	262	251	269	304	32	230	0	0
G	396	392	393	396	177	220	0	0
H	266	231	274	322	0	325	0	0
I	146	141	144	149	26	120	0	0
J	248	247	251	258	6	242	0	0
K	163	153	159	164	76	87	0	0
L	182	182	184	187	17	165	0	0
Total	2711	2607	2724	2867	585	2185	0	0

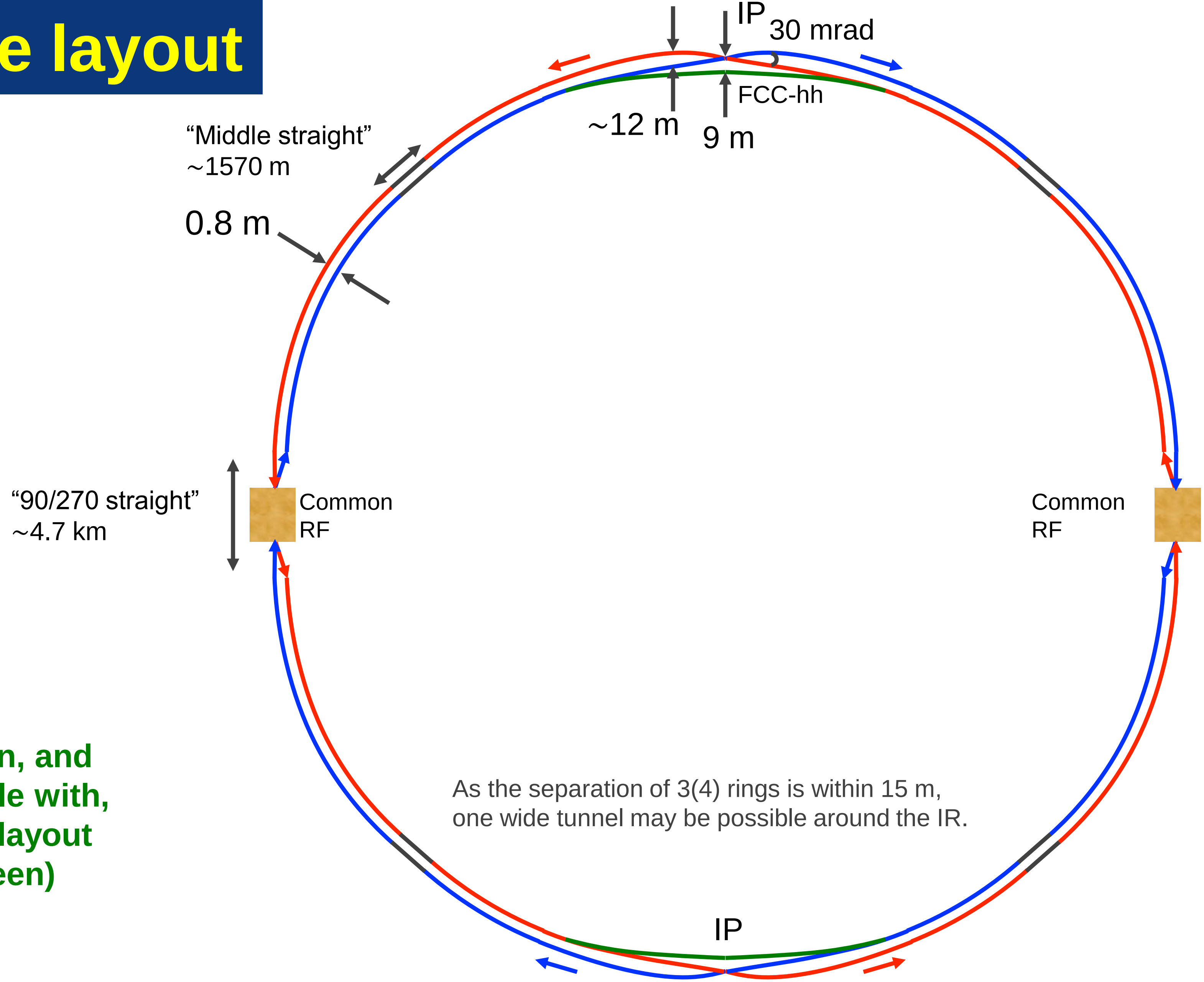
Alignment Profile



Lepton collider parameters

parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45 (Z)**	**120 (H)**	**175(t)**	**120**	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**5**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	**100**			**103**	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5

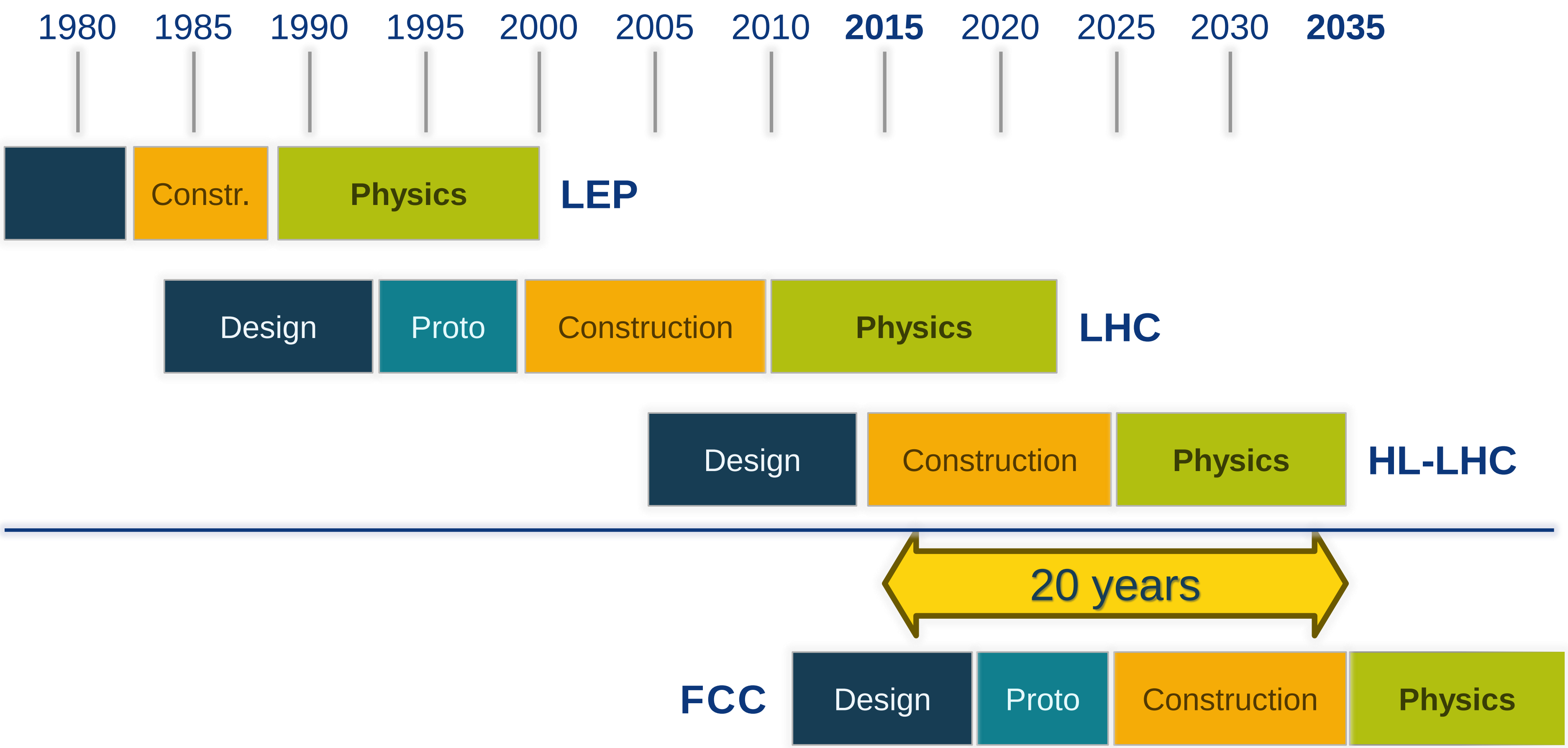
FCC-ee layout



As the separation of 3(4) rings is within 15 m, one wide tunnel may be possible around the IR.

Based on, and compatible with, FCC-hh layout (in green)

CERN Circular Colliders and FCC



CDR by end 2018 for next strategy update

Parameters assumed for the FCC-hh Detector Design

L_{peak} [$5x10^{34}$, $30x10^{34}$] $cm^{-2}s^{-1}$

→ 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.

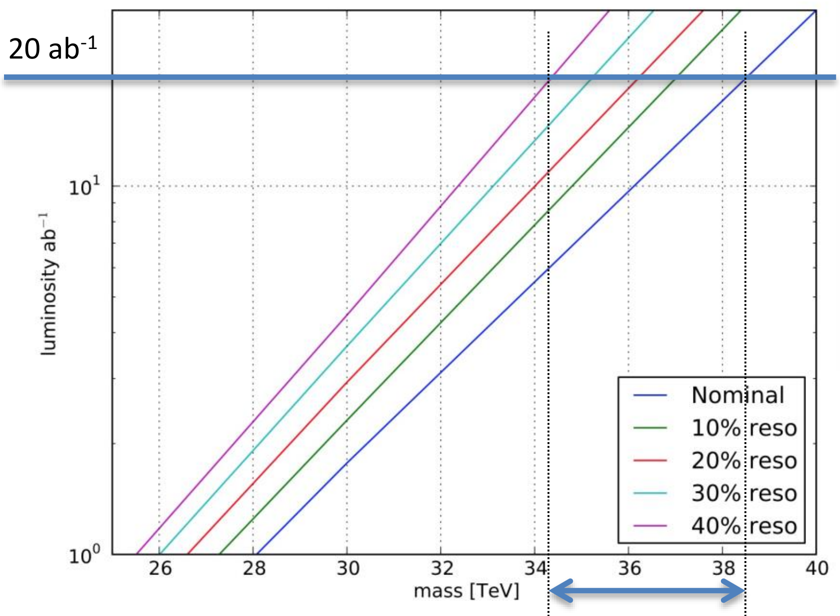
Summary of Requirements from Physics for the FCC Detectors (very preliminary)

Physics at the Lσ Limit

Exploration potential through higher energy, increased statistics, increased precision

Example: Z' $_{SSM}$ discovery

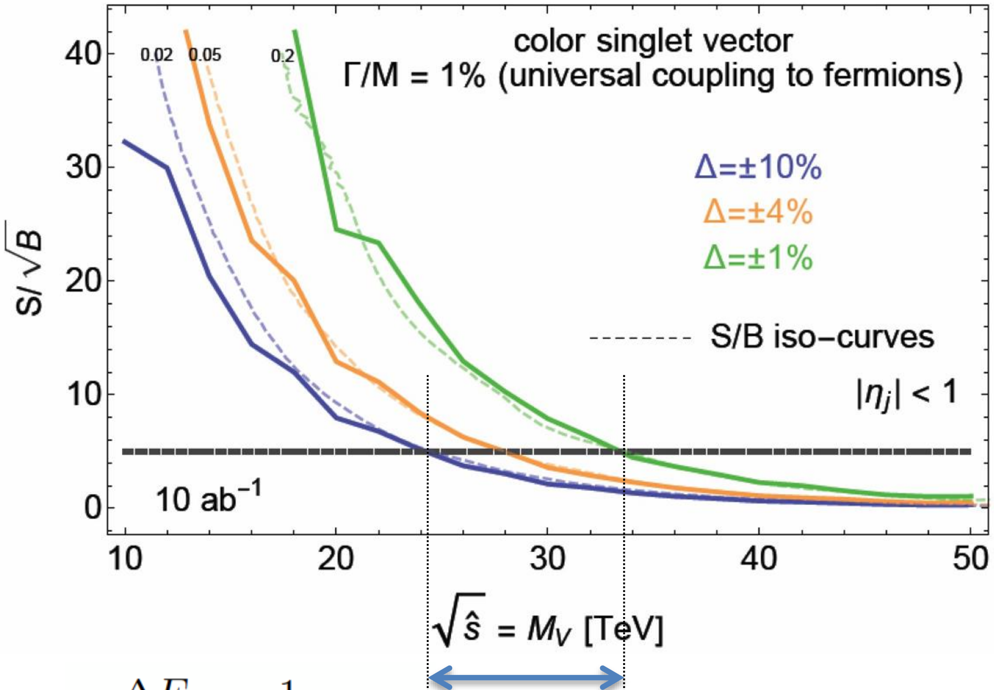
luminosity versus mass for a 5σ discovery



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

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%

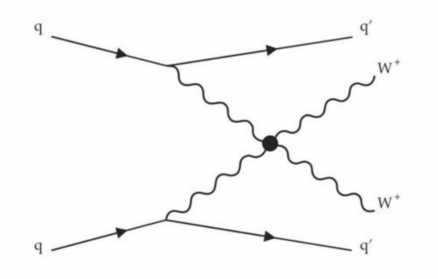
2% jet resolution a reasonable choice (Δ=±4%)

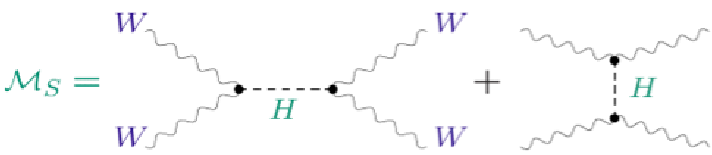
- **Constant term dominates, ≈ 2% goal**
- **→ full shower containment is mandatory !**
- **→ HCAL depth of 12 λ_{int} !**

WW Scattering by VBF Mechanism

WW→WW scattering violates unitarity at high energies

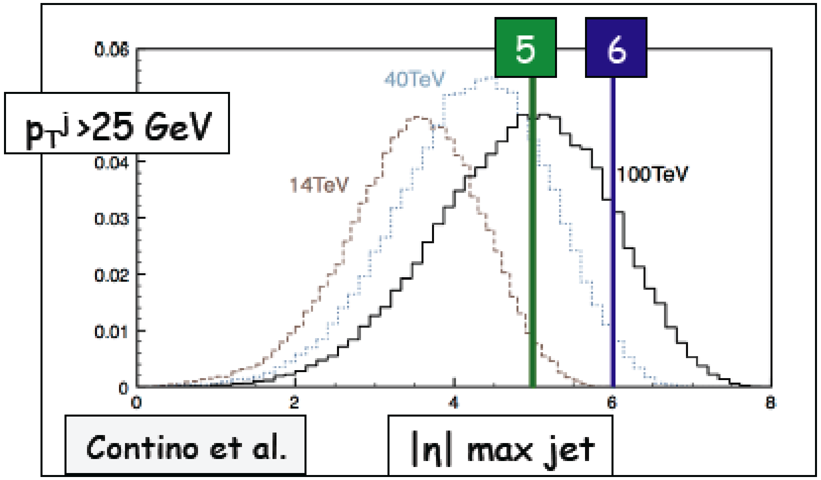
- A scalar, such as the Higgs boson, fixes this (partially)
- Probing characteristics of VV scattering is an important test of the nature of electroweak symmetry breaking
- New Physics would modify interferences between diagrams → modified V p_T and di-boson mass. Also: Are there high mass resonances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





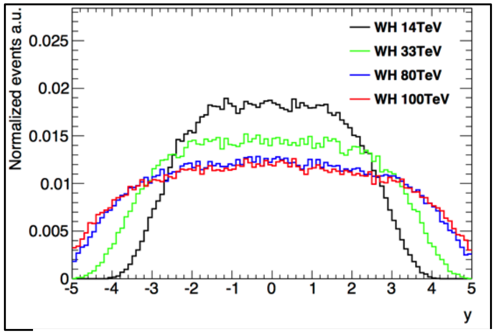
VBF jets also important for tagging of Higgs produced though VBF, like H->bb, H->tautau etc.

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)**

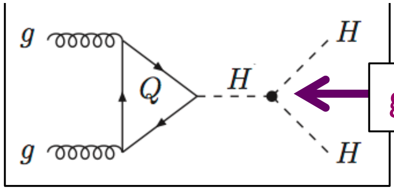
→ **can be recovered by extending to |η|~ 4**

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)



$g_{HHH} \sim \lambda v$

FCC

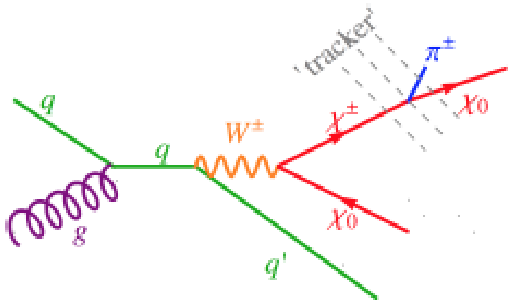
	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000	500	1600‡	500/1000	1600/2500‡	1500	+2000	3000	3000
λ	[redacted]	83%	46%	21%	13%	21%	10%	20%	8%

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

→ **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 $\eta=2.5$.

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.

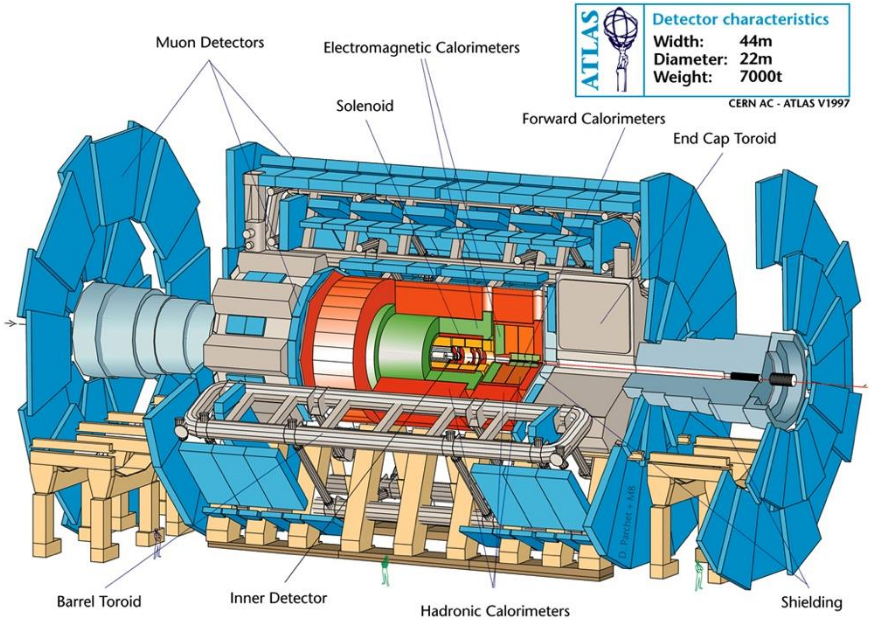
Key Point and Strategy

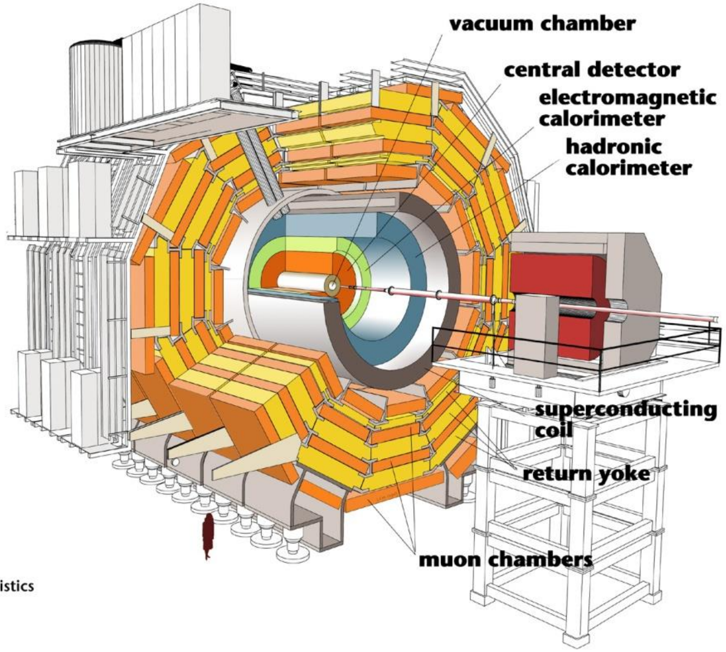
If the FCC hadron machine with 16T magnets, 5MW synchrotron radiation and a 100km tunnel can be realized, there is no doubt that a detector, that makes full use of the physics potential, can be built.

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.

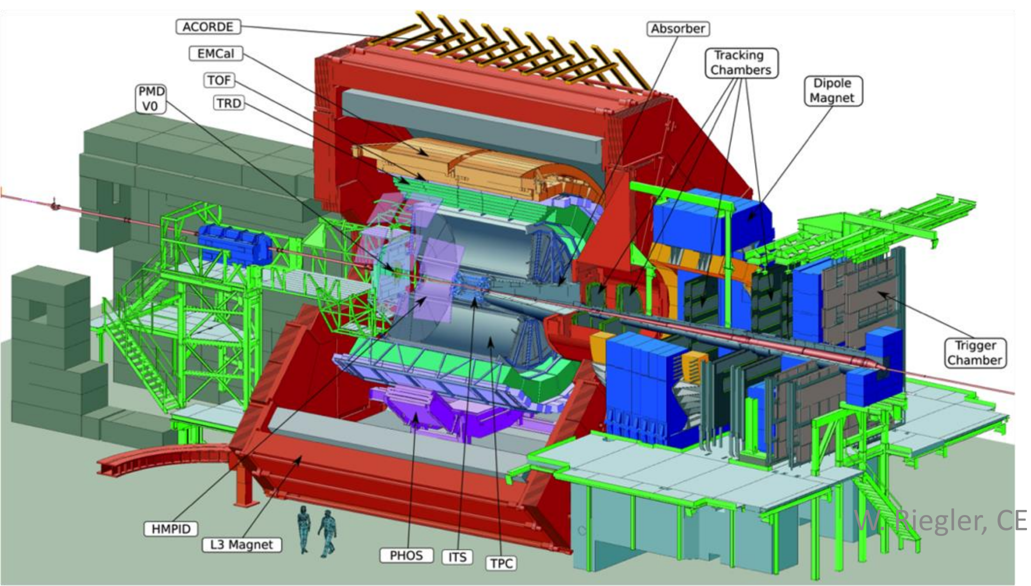
Guidance and Scaling from ATLAS, CMS, ALICE, LHCb

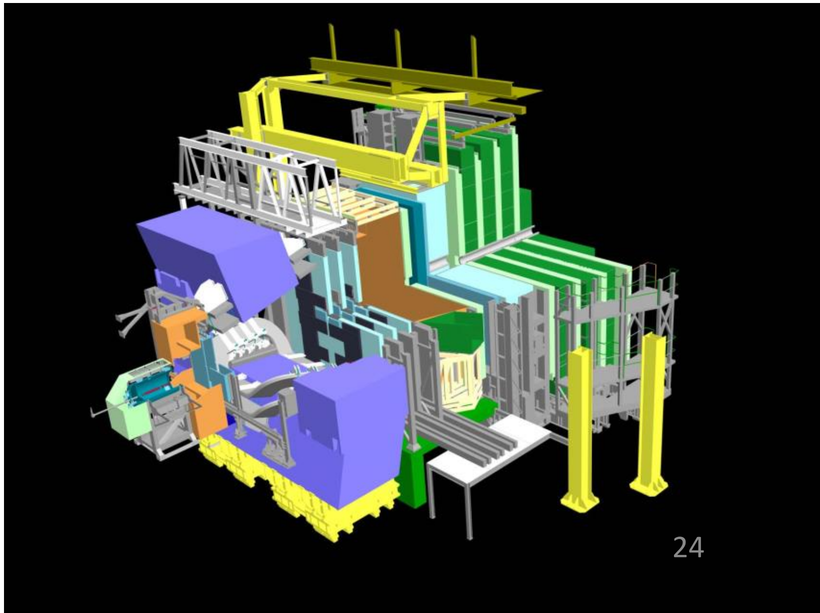


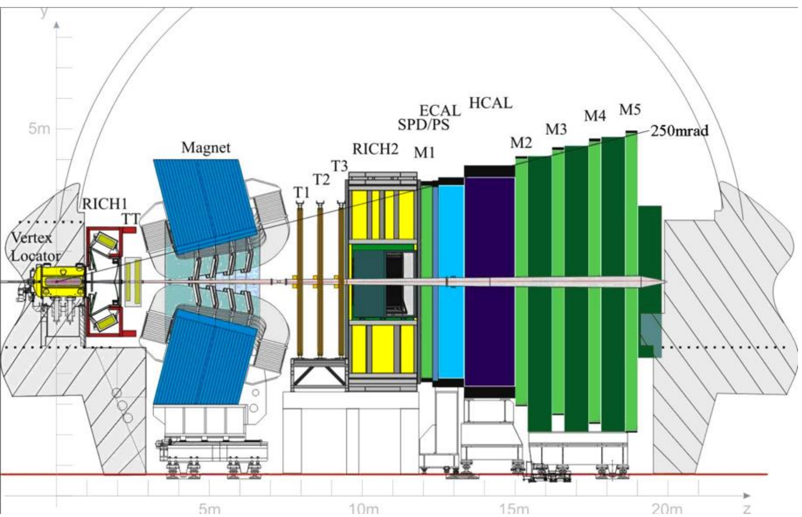


Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t



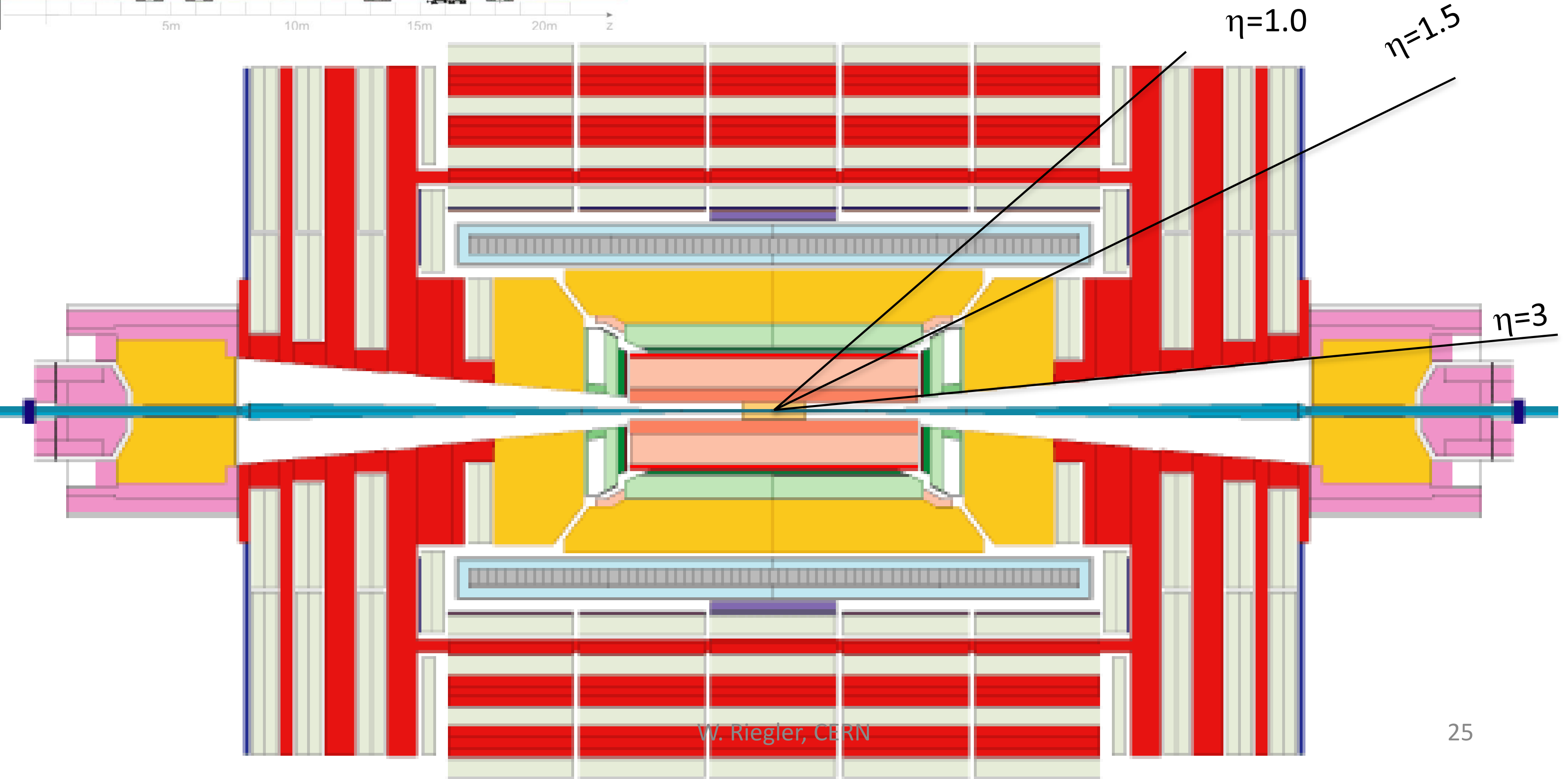




LHCb: Tracking, Calo η = 2 - 5

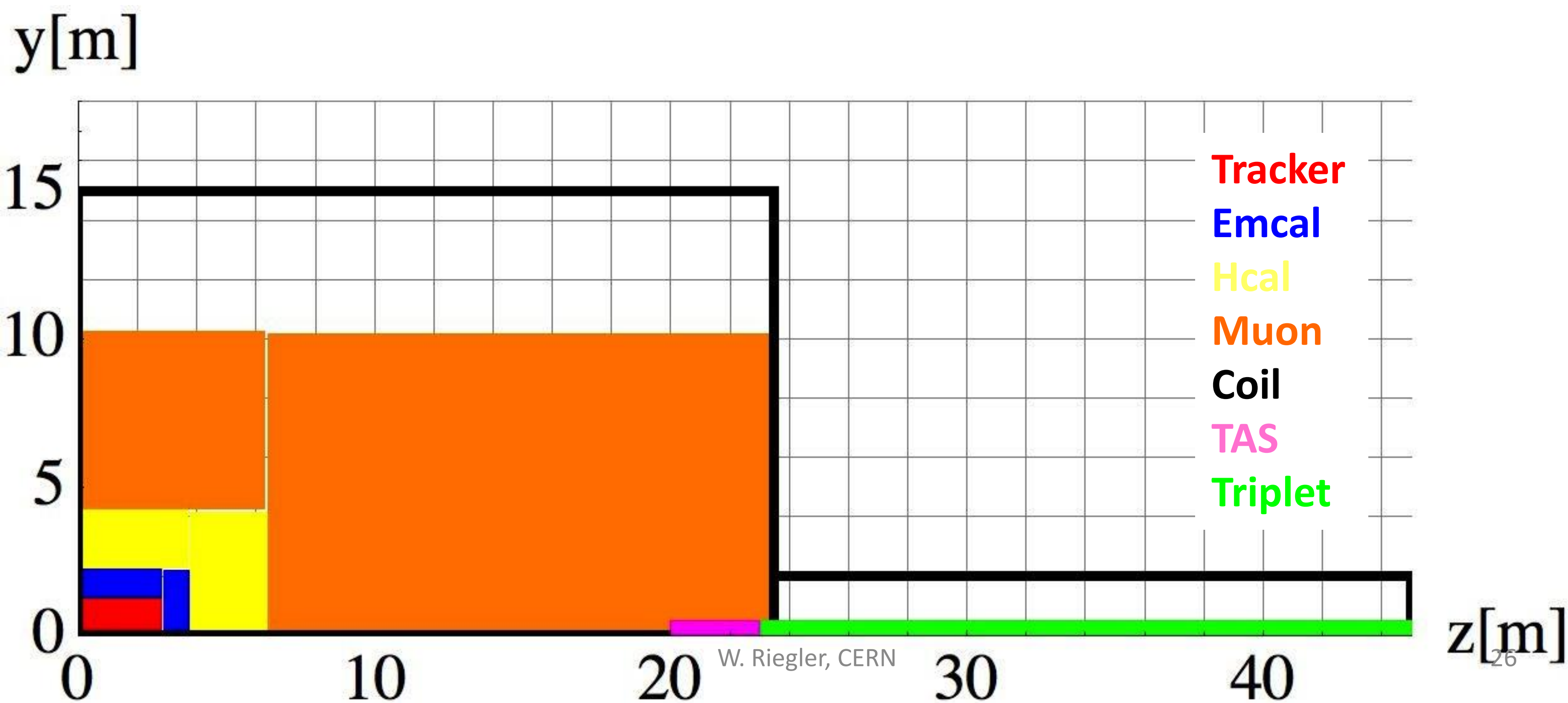
… all with impressive performance …

ATLAS, CMS: tracking, calo η -2.5,2.5



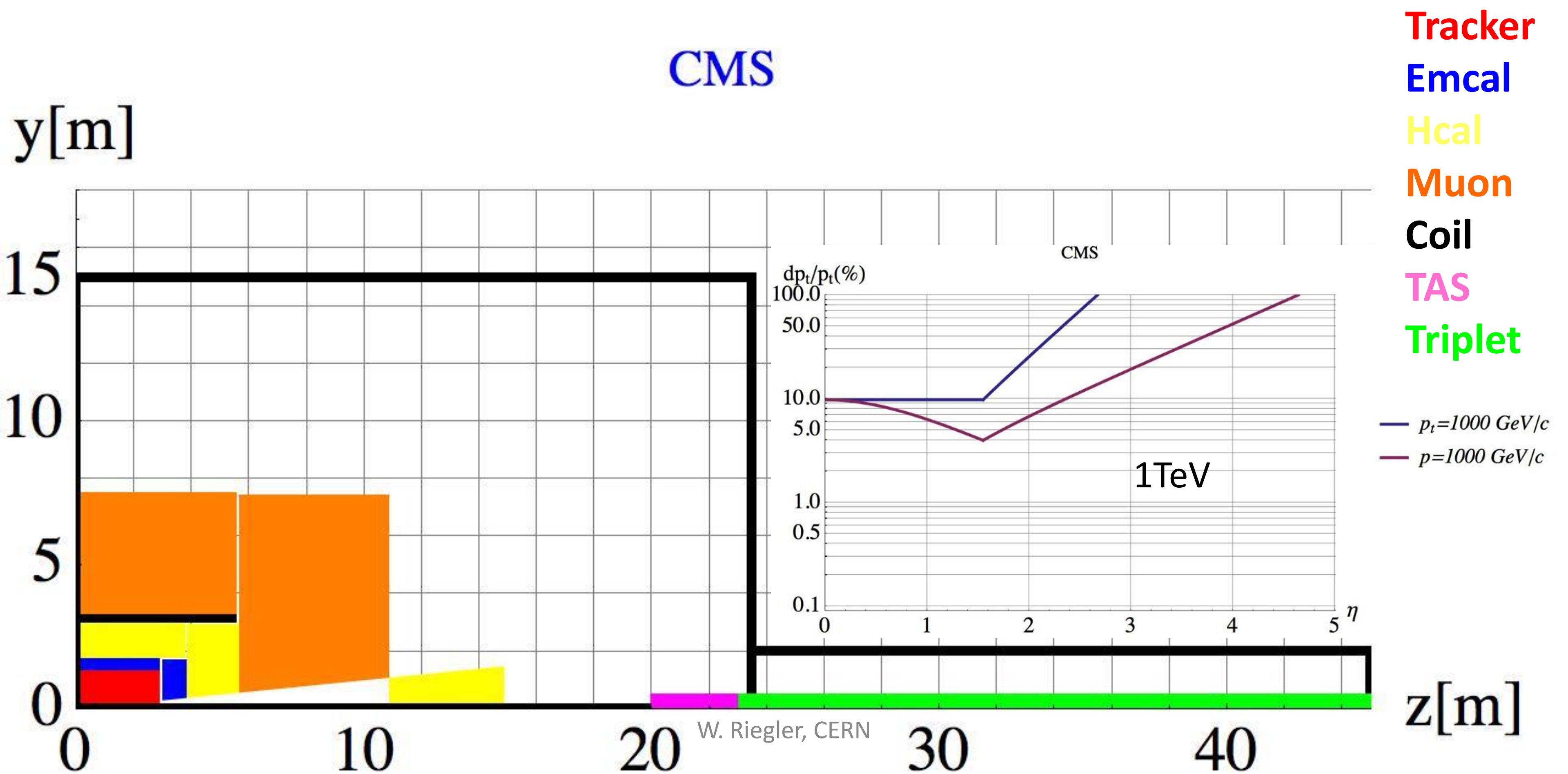
ATLAS

- 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.

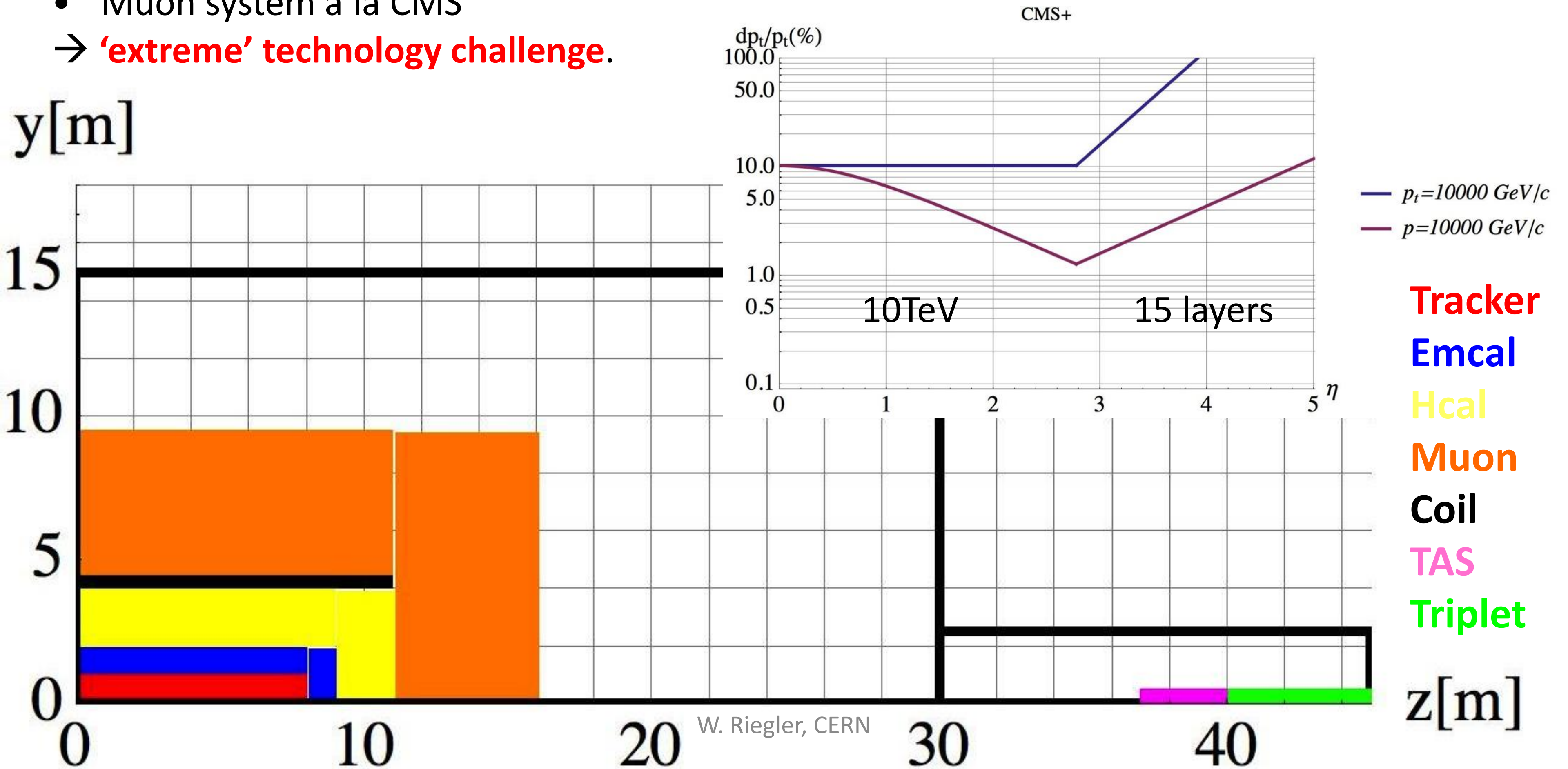
- **With a more realistic approach for calorimetry and tracking we end up with coil radii of 6m, which requires an iron yoke that is probably unaffordable.**

→ In this case one can use 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**.



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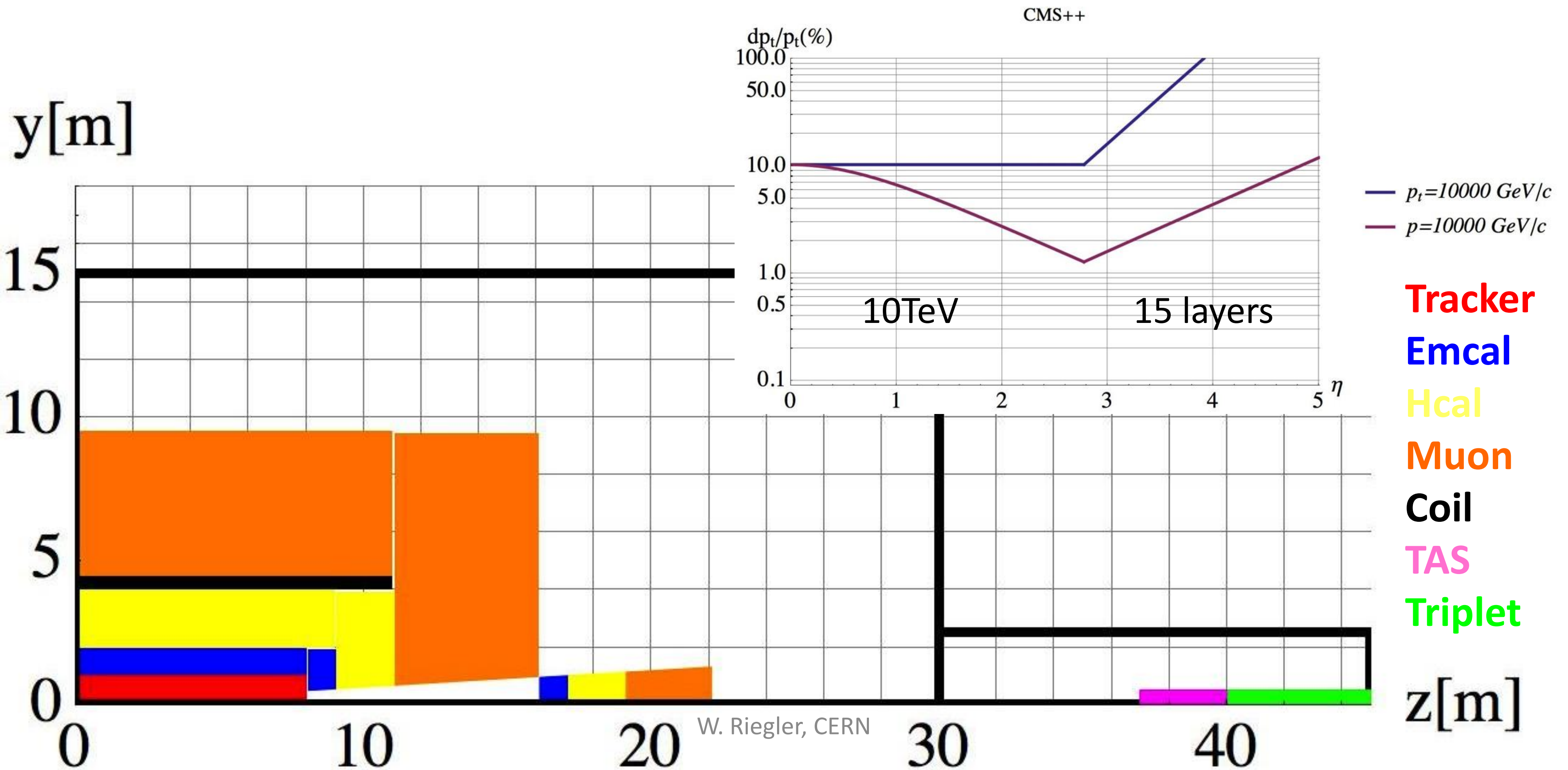
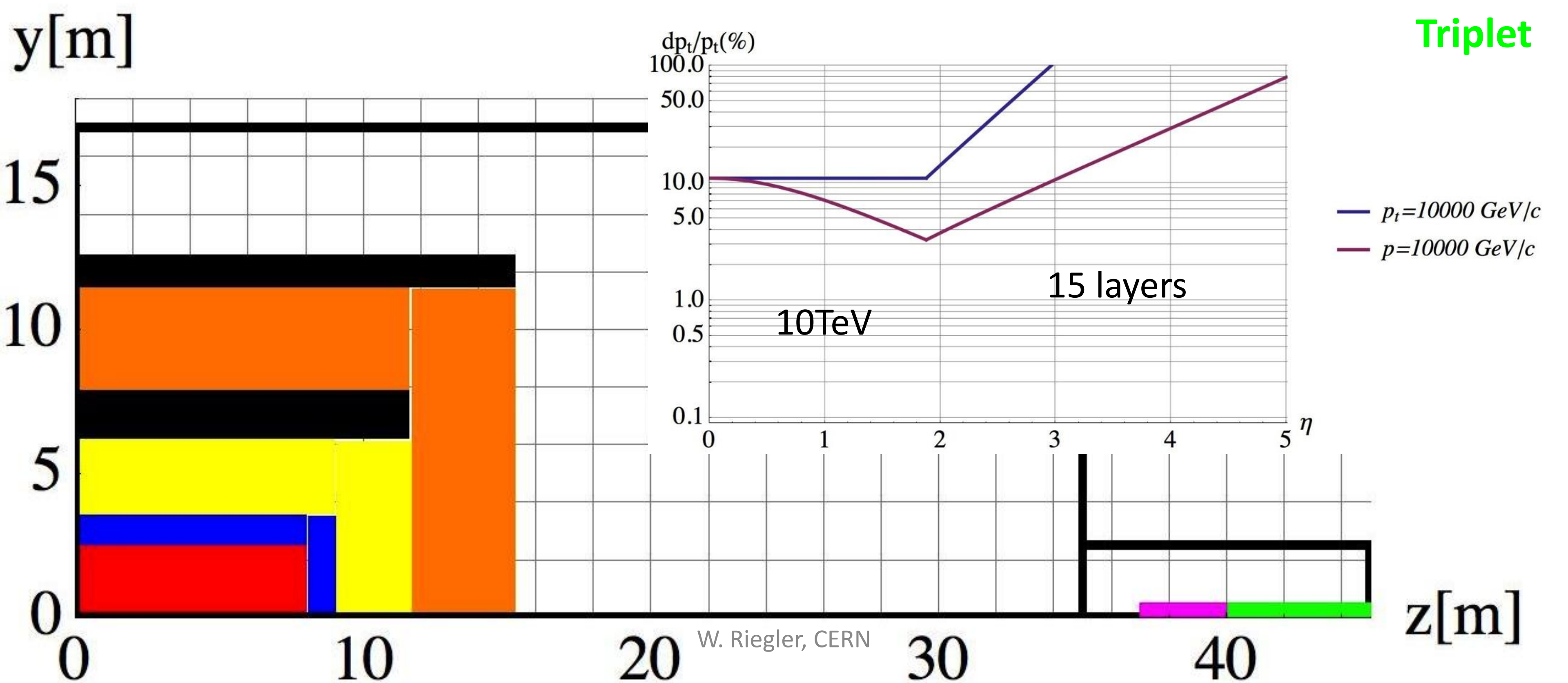
CMS Scaled Detector, Forward Calorimetry Moved Out

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



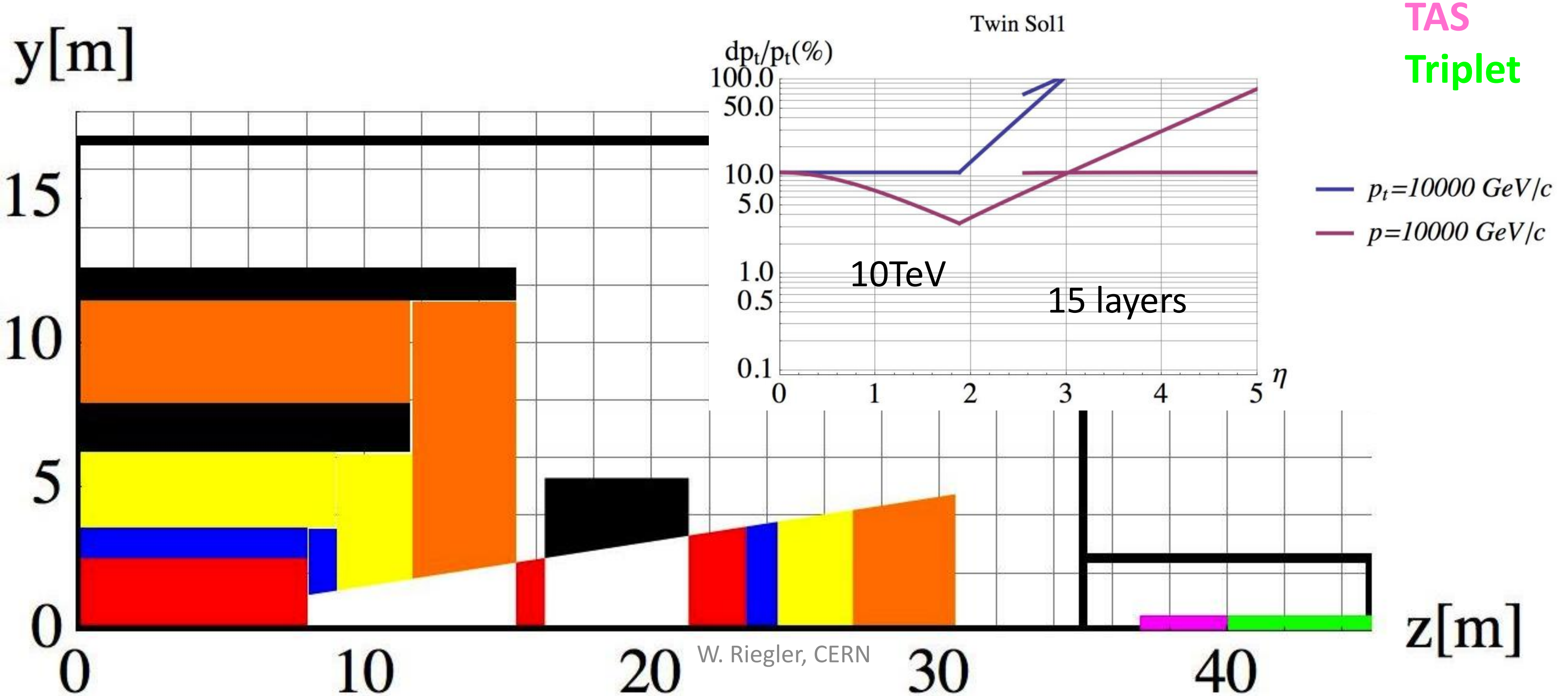
Twin Solenoid BL^2 Scaling

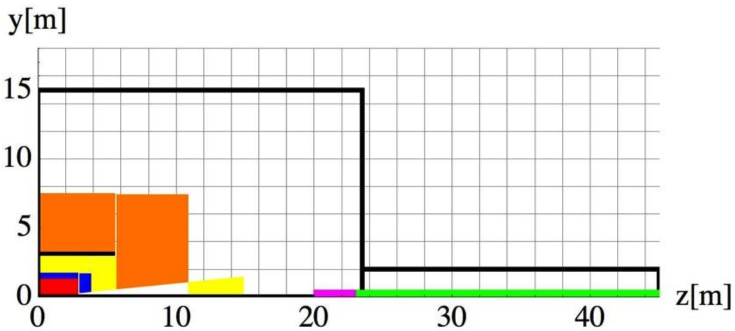
- How to achieve 10% for a 10TeV charged particle **assuming tracker with nowadays layer resolution** (~20μm)?
- Solenoid and shielding solenoid with B=6T in Tracker and B=2.5T in Muon System
- Tracker r=2.5m, L=16m, tracking layer resolution similar to CMS detector
- ECAL+HCAL = 3.4m = 12 λ_{int}
-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



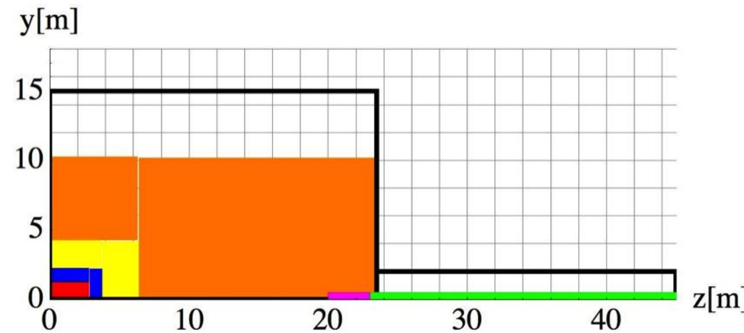
Twin Solenoid BL^2 Scaling + Forward Dipole

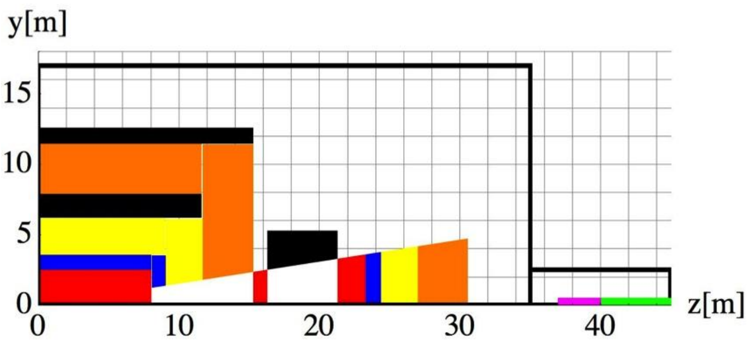
- Opening at η = 2.5
- Adding a **forward Dipole for momentum spectroscopy**.
- Moving forward calorimeters to larger distance decreasing the particle densities and overlaps.
- Allows separate instrumentation and upgrade of forward detectors
- Integration and maintenance is a challenge





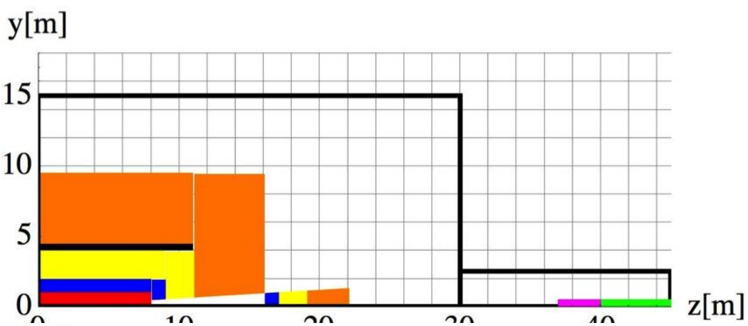
CMS & ATLAS



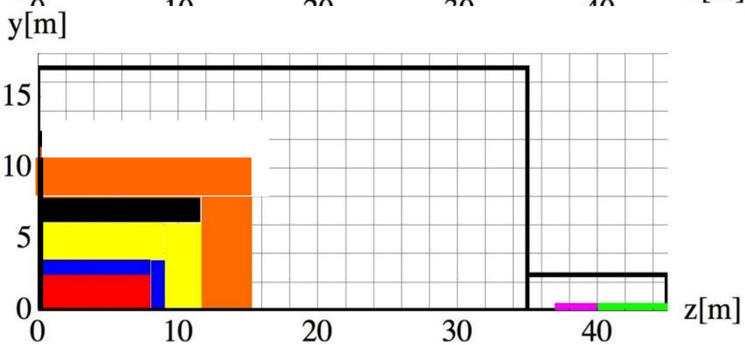


Twin Solenoid
+ Dipole

Popular at present



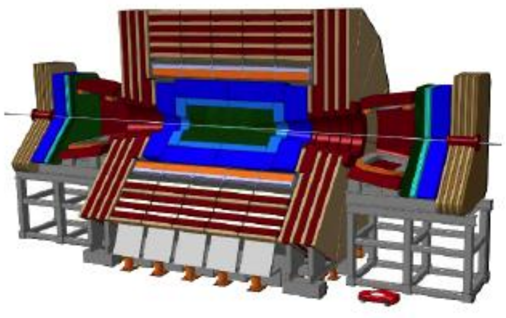
CMS+

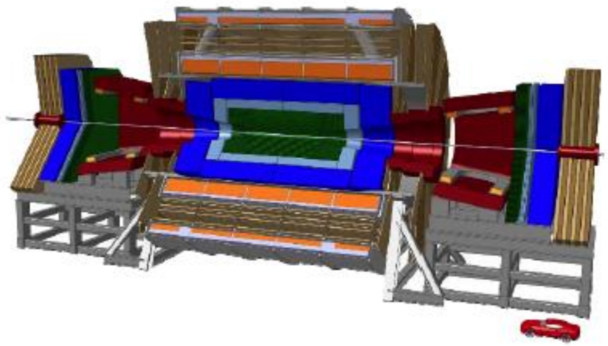


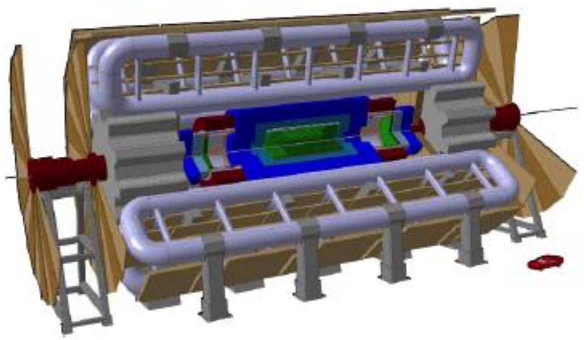
Partially shielded large solenoid

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.

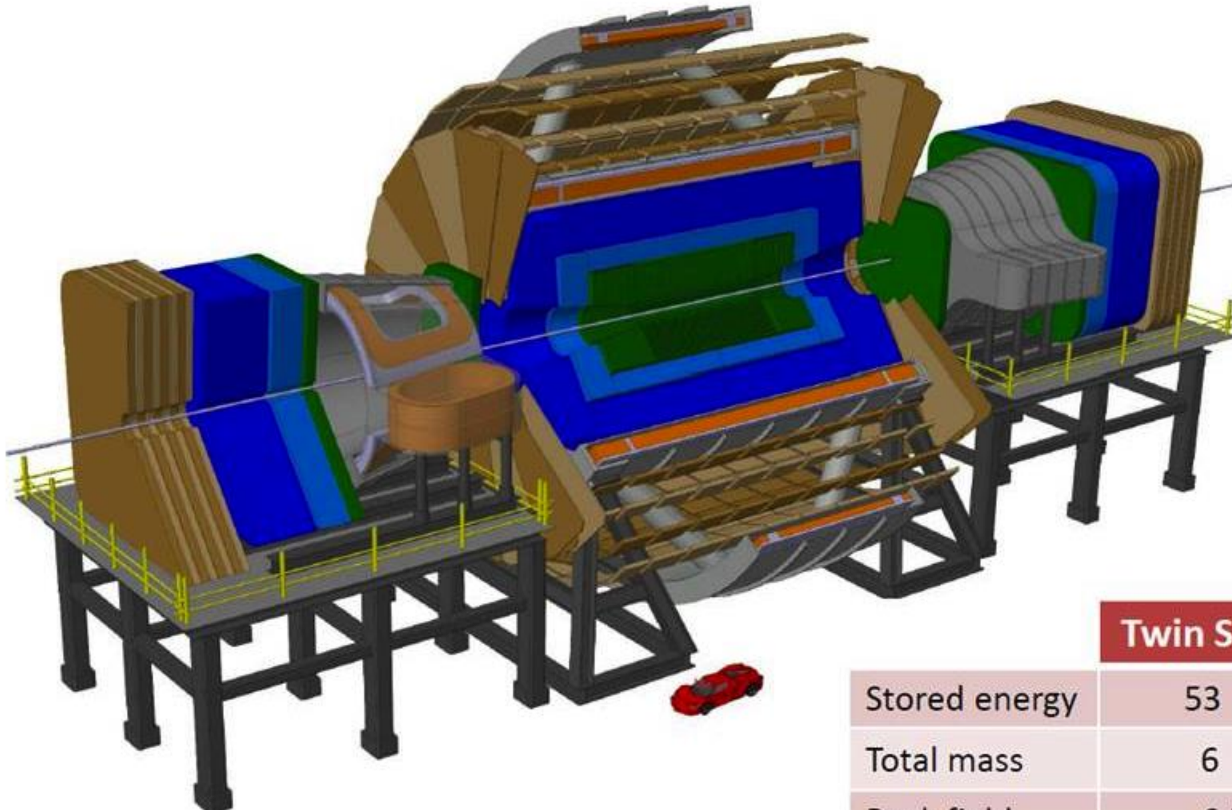
The ATLAS 'standalone' Muon Toroid was motivated by things like:

- **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



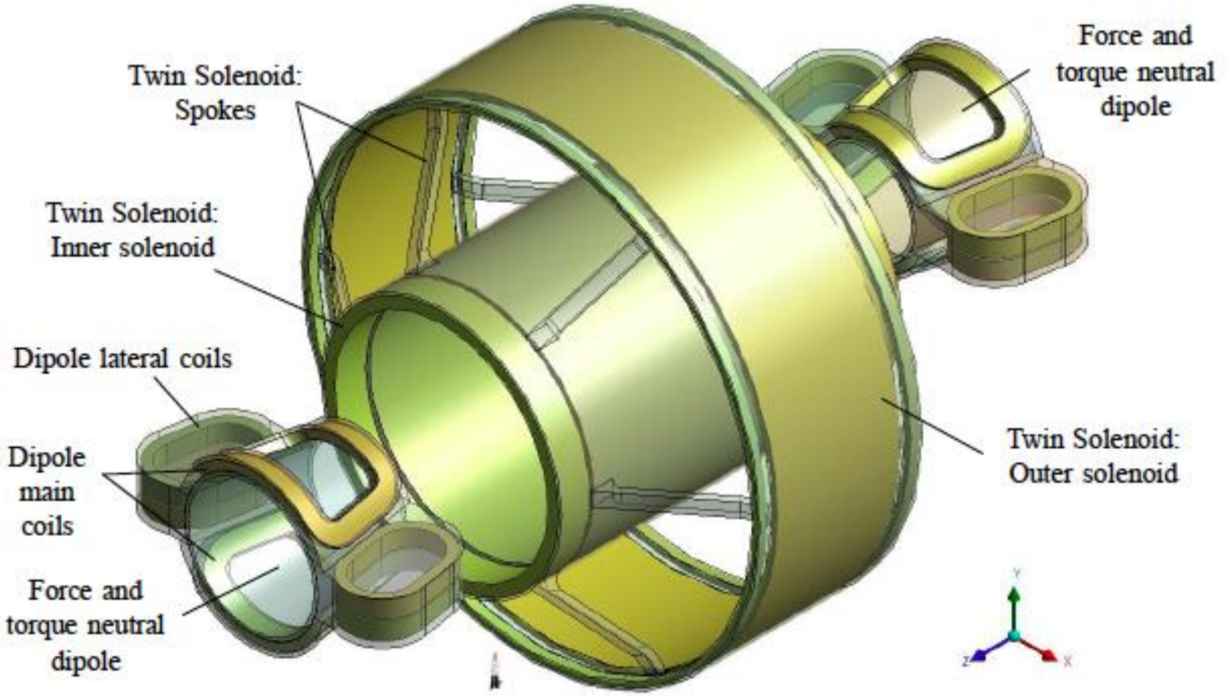
FCC Air core Twin solenoid and Dipoles

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

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



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:

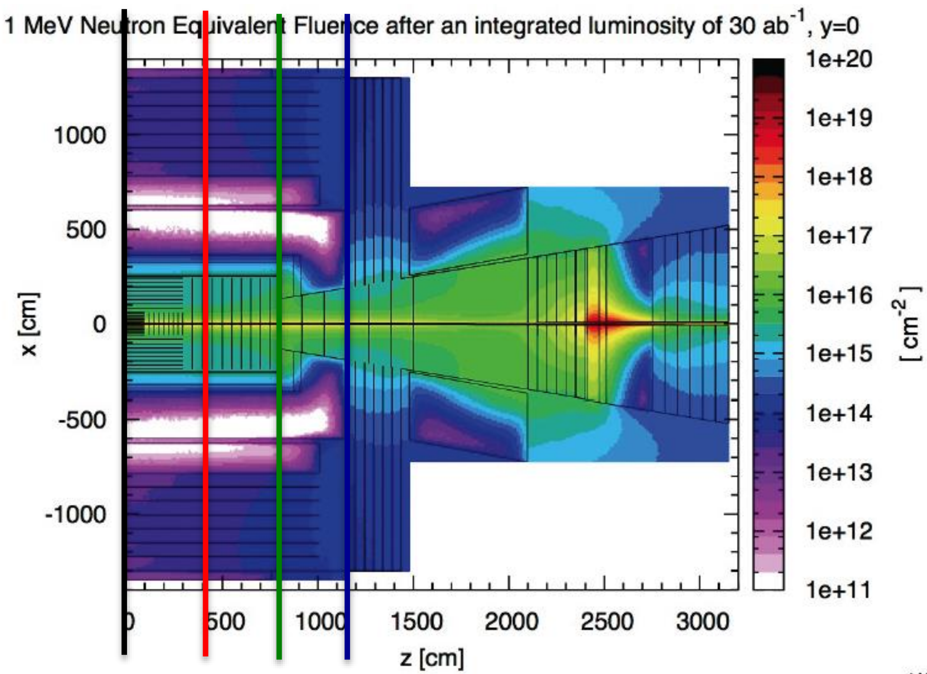
HL-LHC 3ab^{-1}
1MeVneq Fluence (NIEL) = 1.5×10^{16} cm^{-2}
Dose = 5MGy

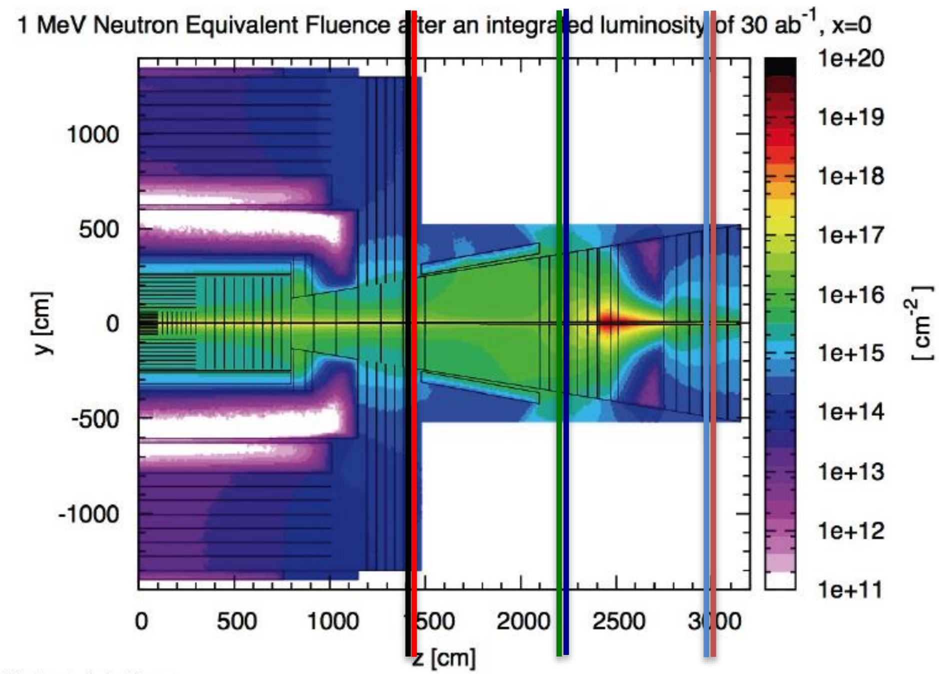
FCC 3ab^{-1}
1MeVneq Fluence = 3×10^{16} cm^{-2}
Dose = 10MGy

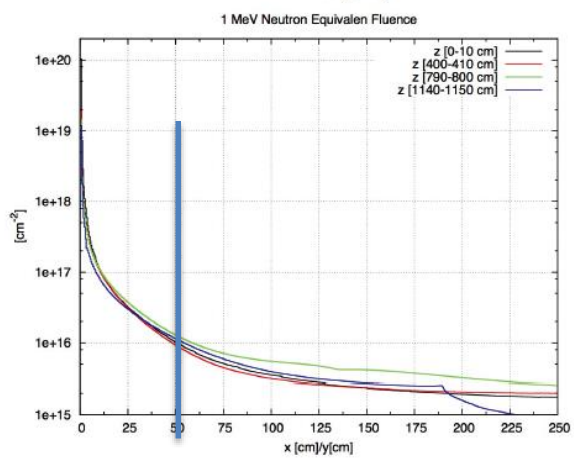
FCC 30ab^{-1}
1MeVneq Fluence = 3×10^{17} cm^{-2}
Dose = 100MGy

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

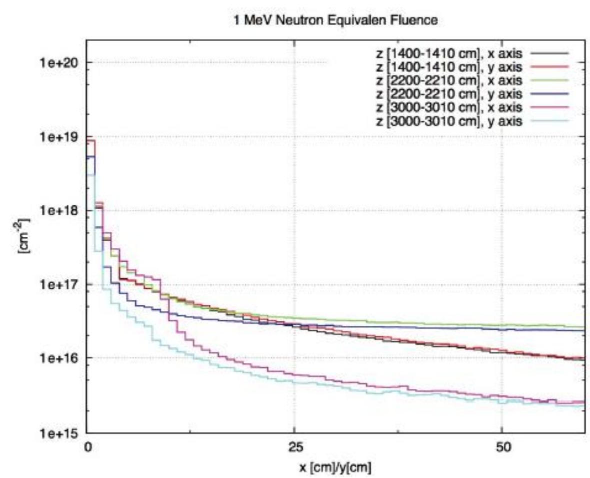
1 MeV Neutron Equivalent Fluence (FLUKA simulation, M.I.Besana)







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).

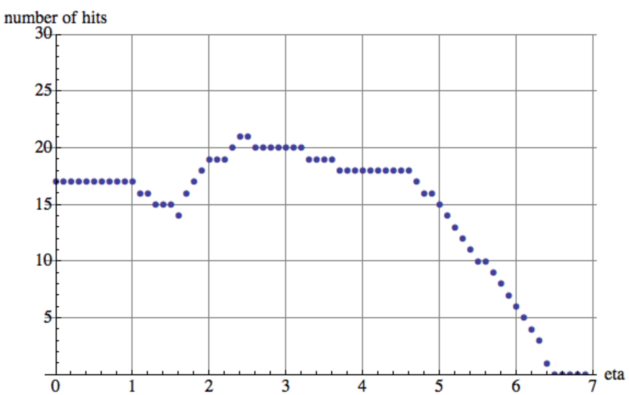
For radii <50cm we exceed the HL-LHC numbers (10^{16} cm^{-2}) by up to 2 orders of magnitude
→ Technology challenge !

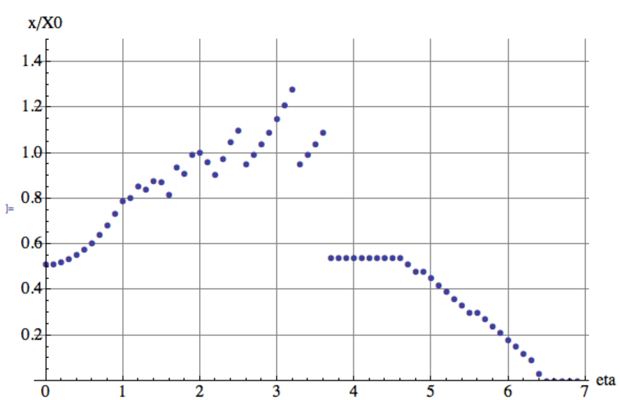
Simplified Tracker Assumptions

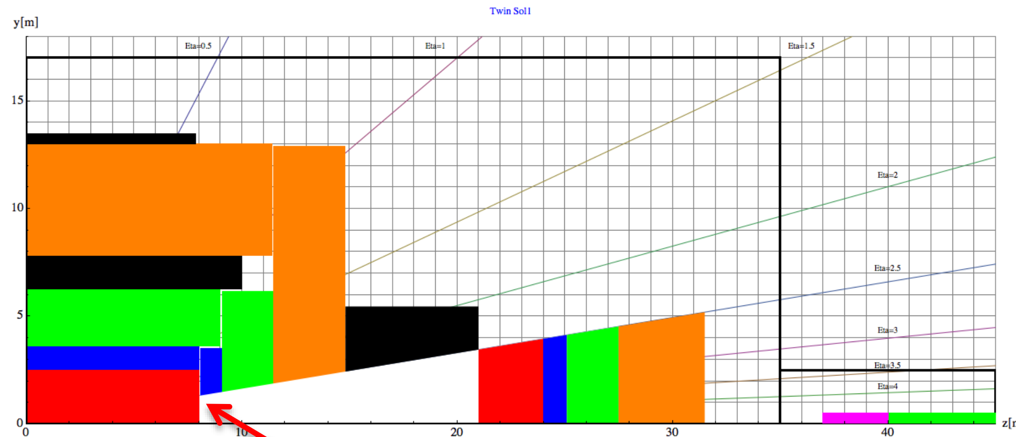
Neglecting radiation for a moment: is 10% resolution achievable (for 10TeV)?

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

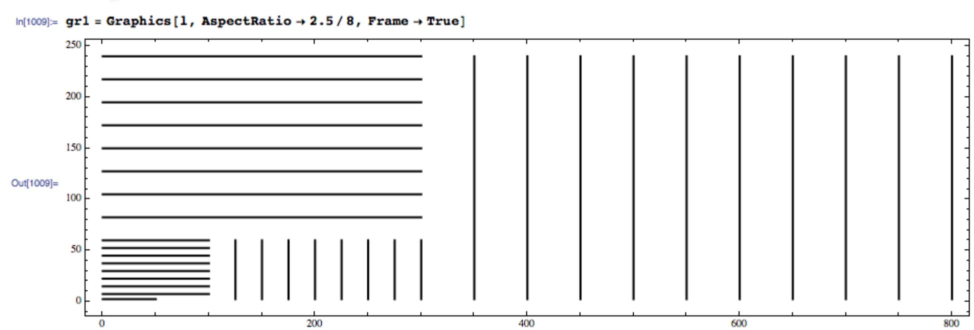
We assume 3% of radiation length per layer, i.e. each layer has a thickness of 0.43cm.







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



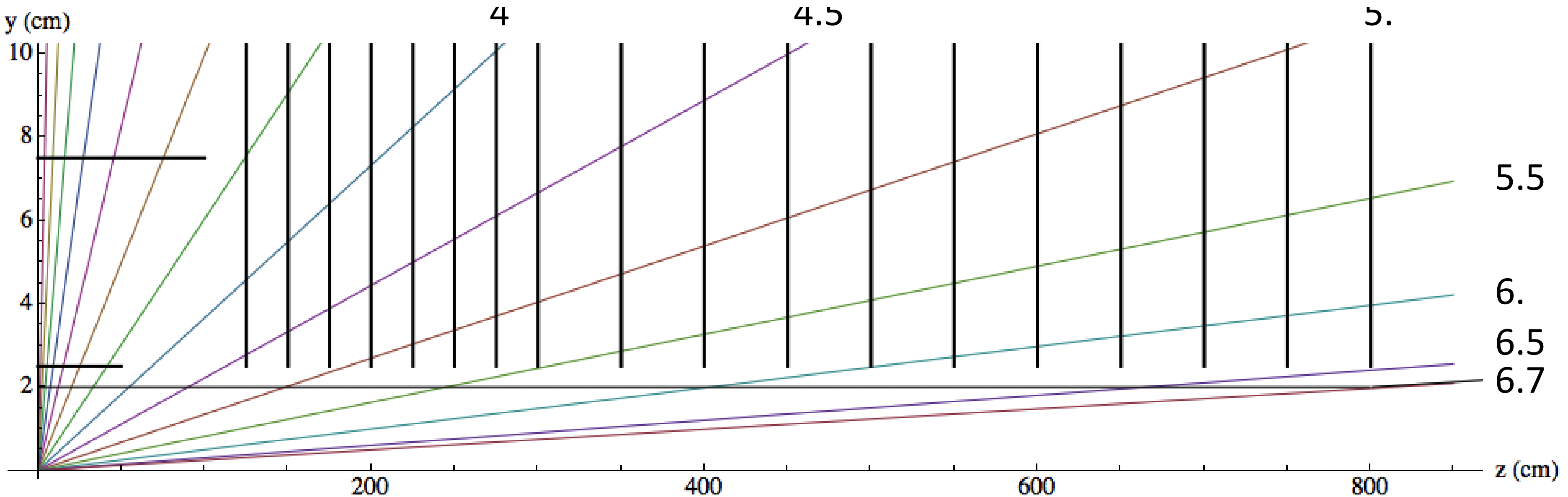
Tracker

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.

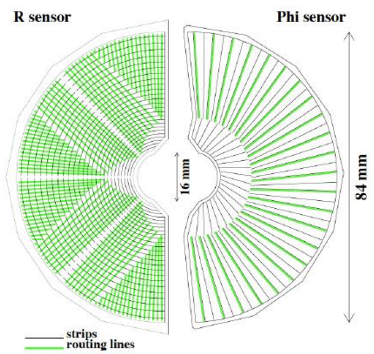
LHCb has the VELO with discs only a few mm from the beam in a secondary vacuum.

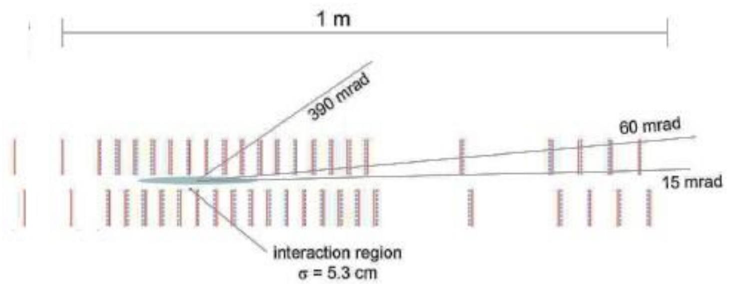
This arrangement has significant infrastructure around the IP which is not compatible with a co-existent central detector.

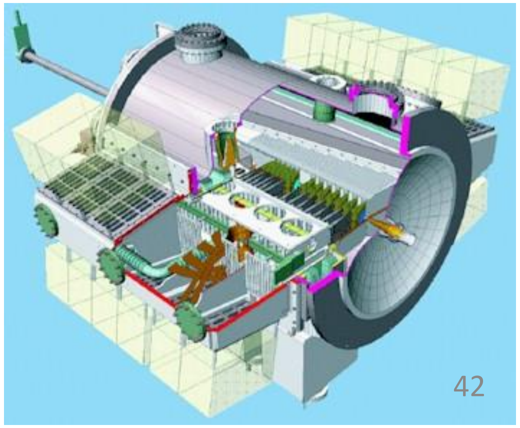
→ Clever ideas needed !!



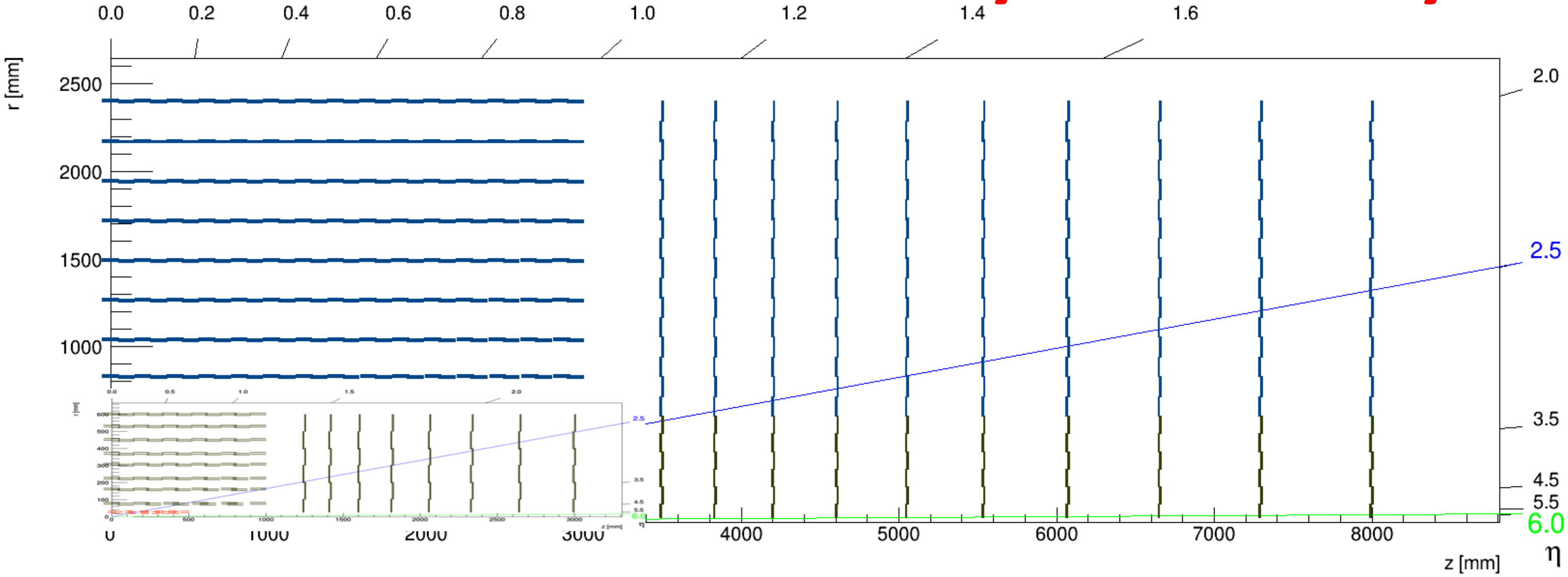
LHCb:

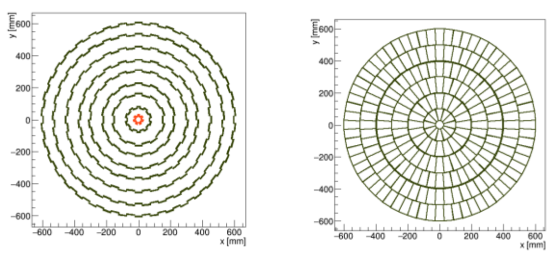


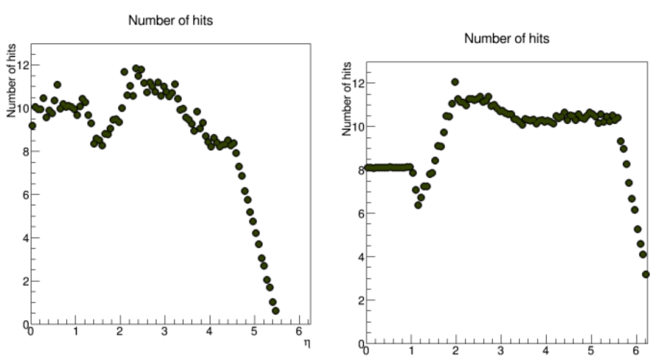


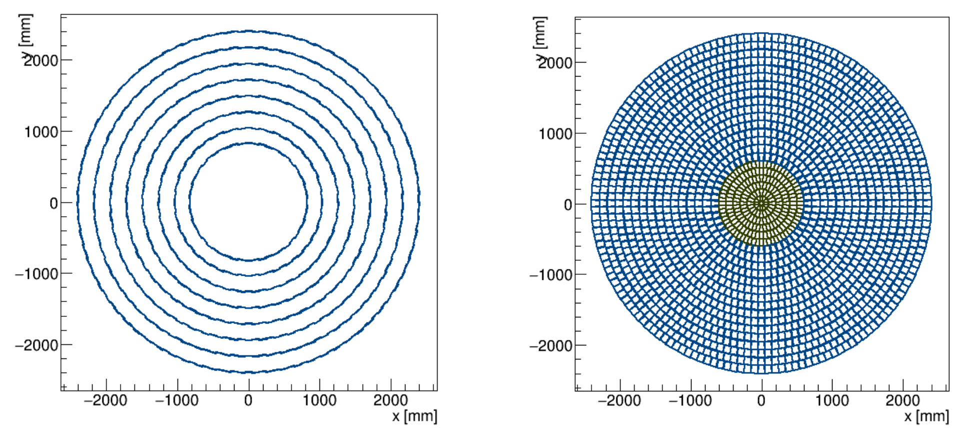


Tracker – Realistic FCC Layout in TKLayout





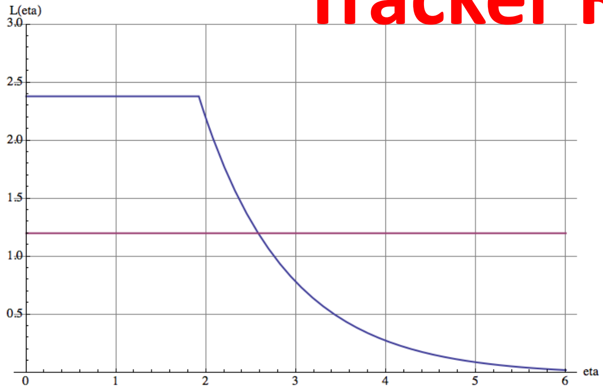


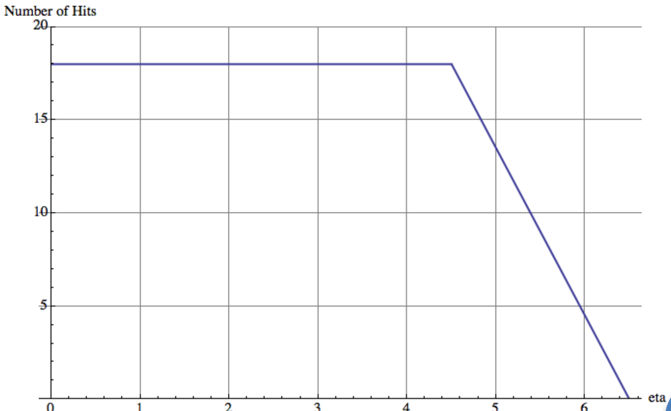


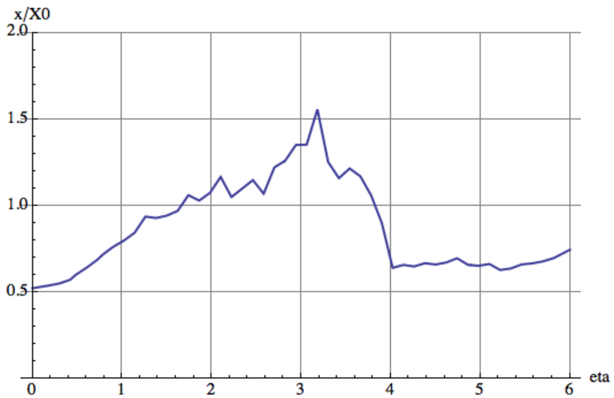
Realistic Layout with correct modules using TKLayout (CMS PhaseII upgrade tool)

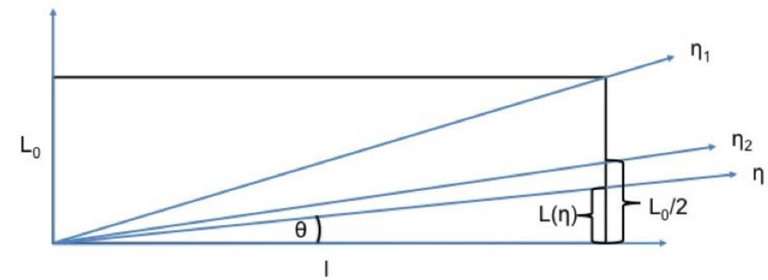
http://fcc-tklayout.web.cern.ch/fcc-tklayout/FCChh_Option2/errorsTRK.html

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 $\eta_2 = 2.6$

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

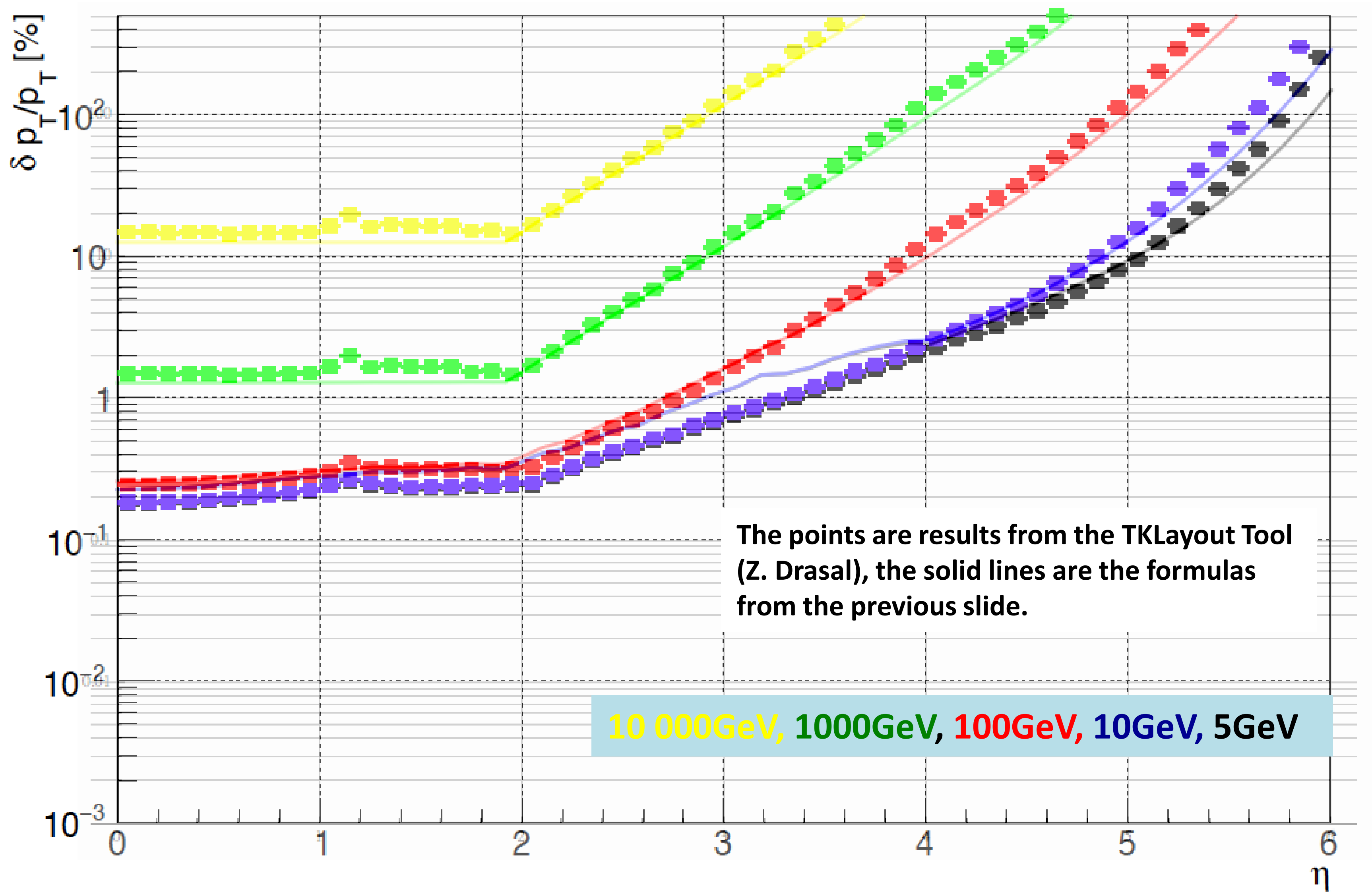
$$\frac{\Delta p_T}{p_T}\Big|_{reso.} = \frac{\sigma\, p_T}{0.3BL(\eta)^2}\sqrt{\frac{720}{N(\eta)+4}} \qquad \frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{0.0136}{0.3\,BL(\eta)}\sqrt{\frac{x}{X_0}(\eta)}$$

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

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

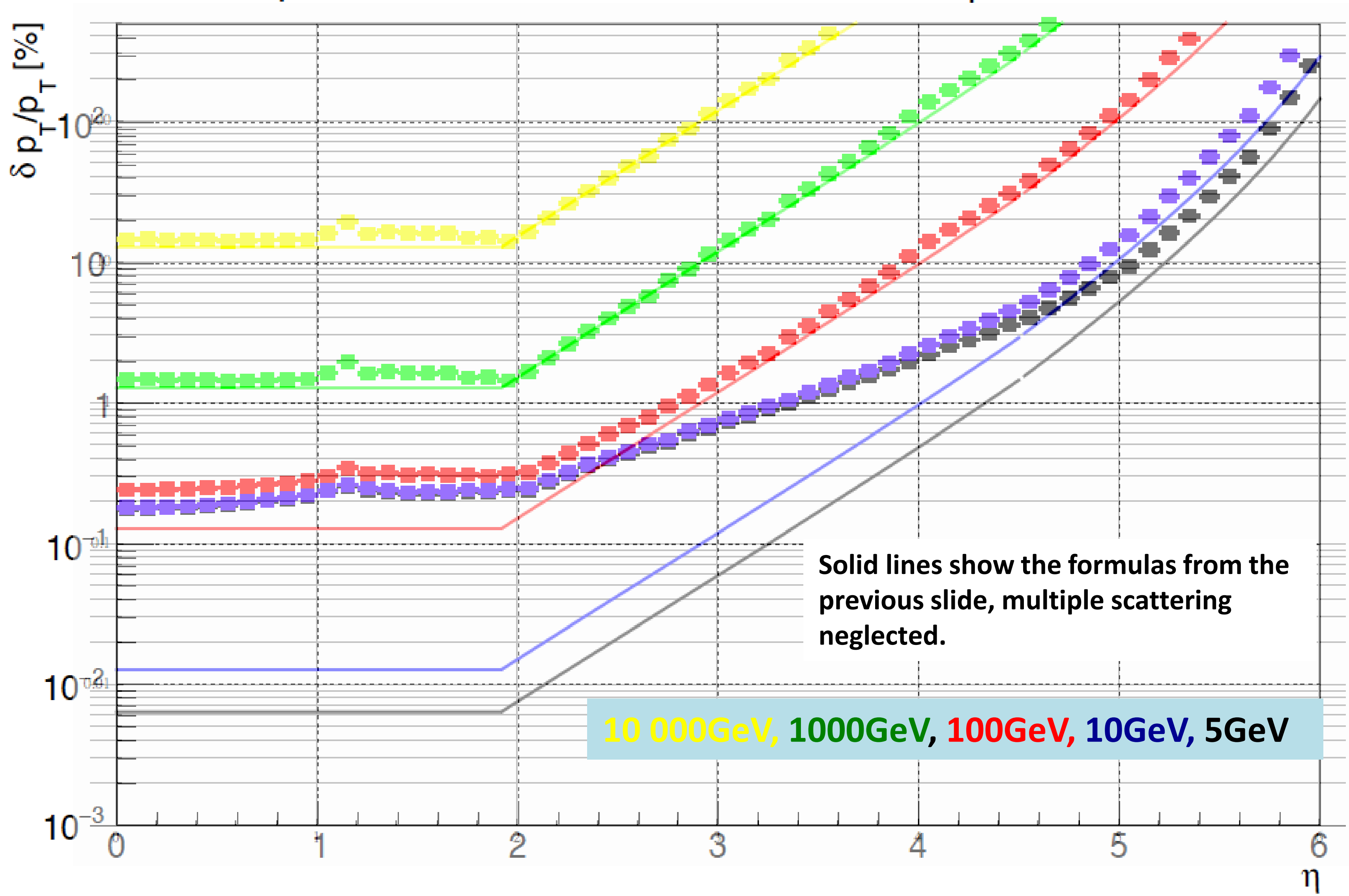
Tracker

p_T resolution versus η - const P_T across η



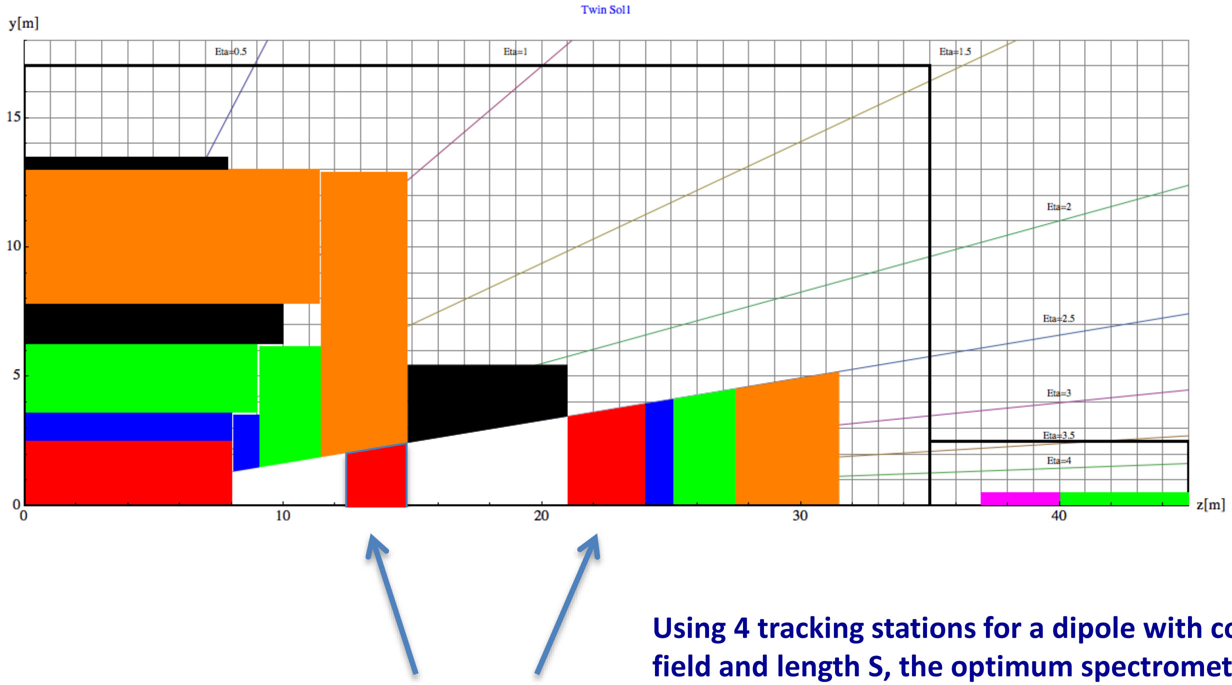
Tracker

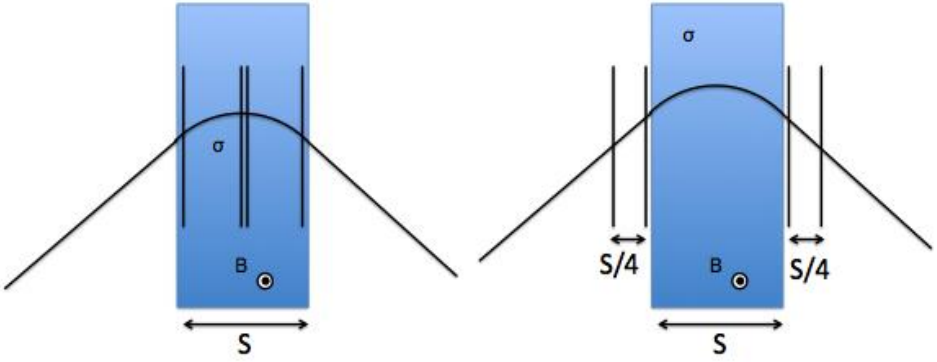
p_T resolution versus η - const P_T across η



Forward Tracking

Forward Tracking Resolution, Position Resolution





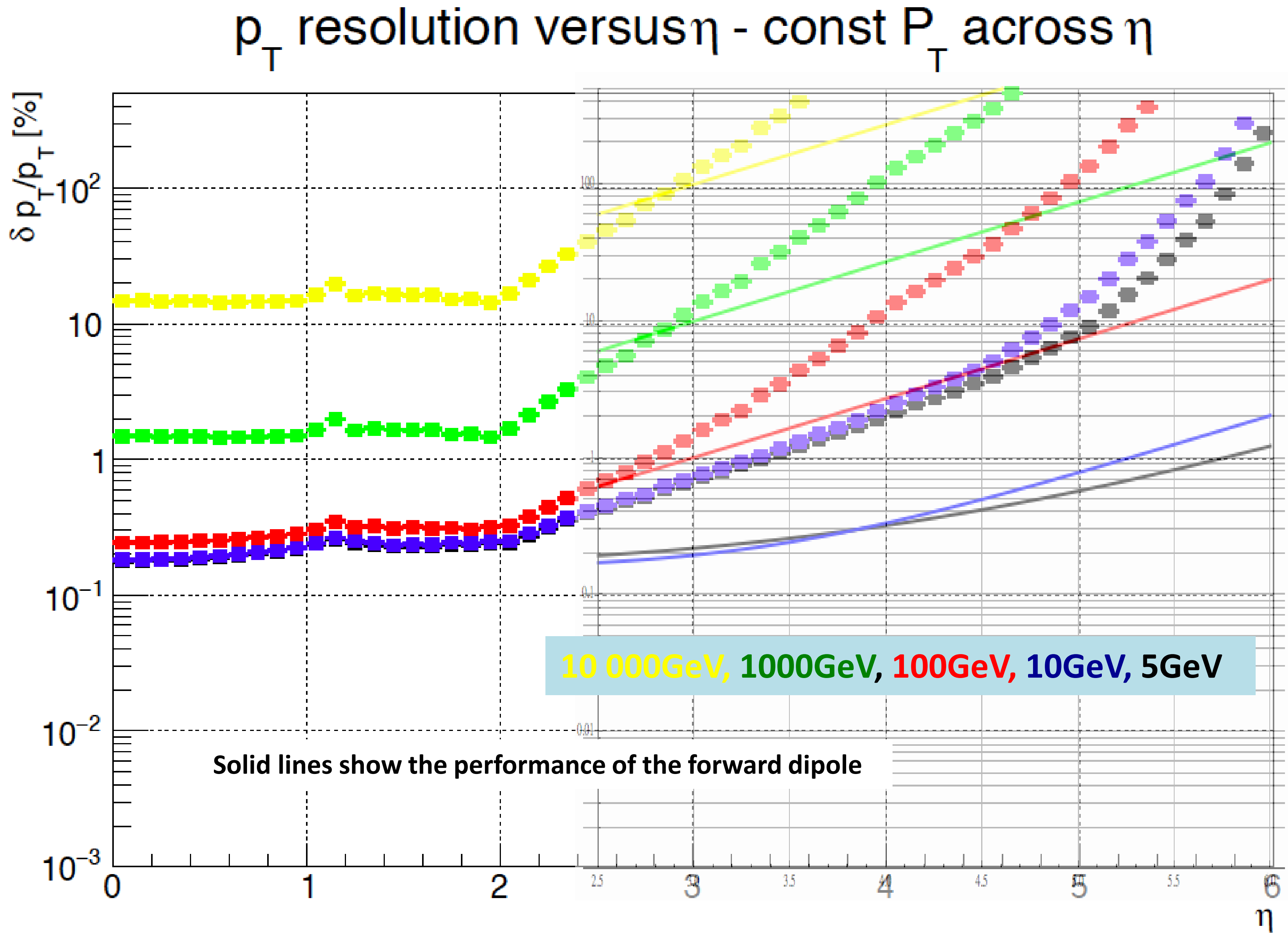
Using 4 tracking stations for a dipole with constant magnetic field and length S, the optimum spectrometer resolution is achieved by placing 2 stations in the center and one on each end to measure the sagitta.

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

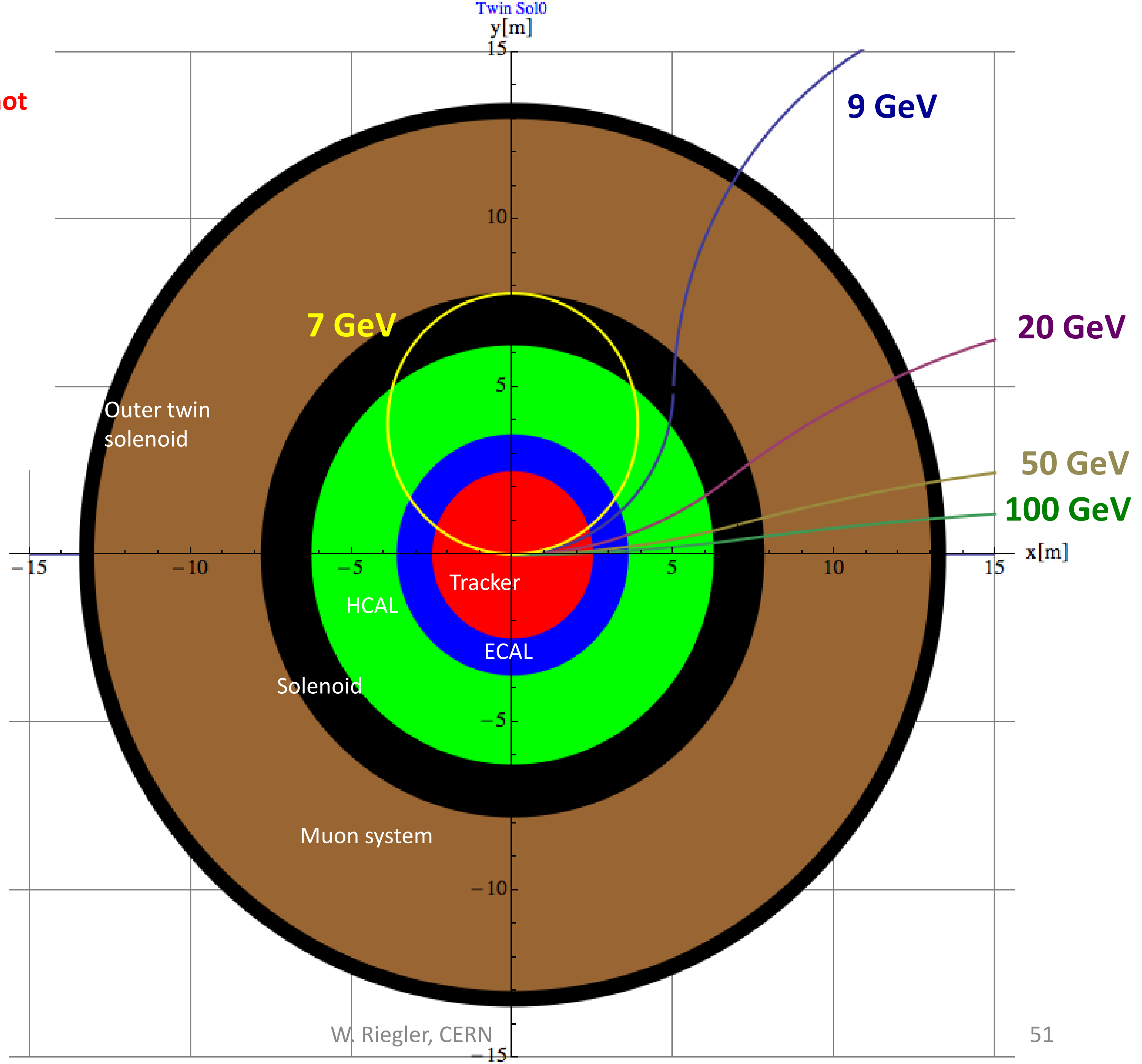


Muon System

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.



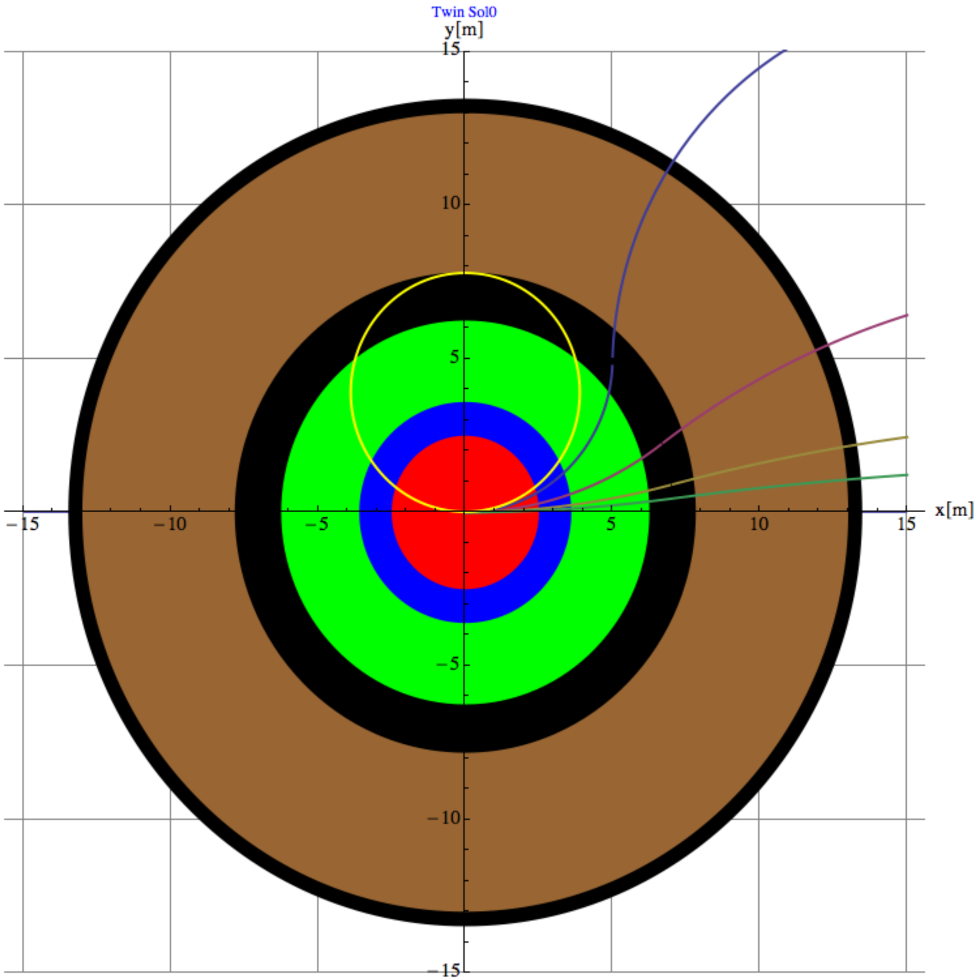
Muon Momentum Can Be Measured by…

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.



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

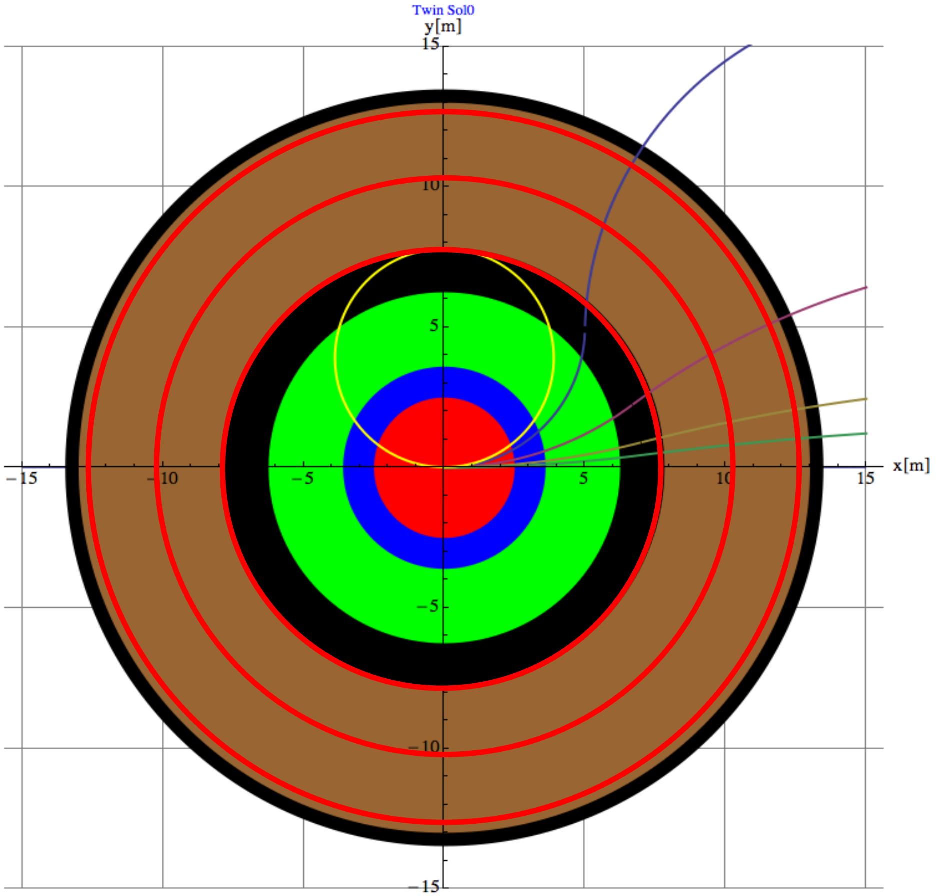
$dp_T/p_T = sig*p_T/(0.3*B*L^2)*8$
$= 20\%$ @ 10TeV

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

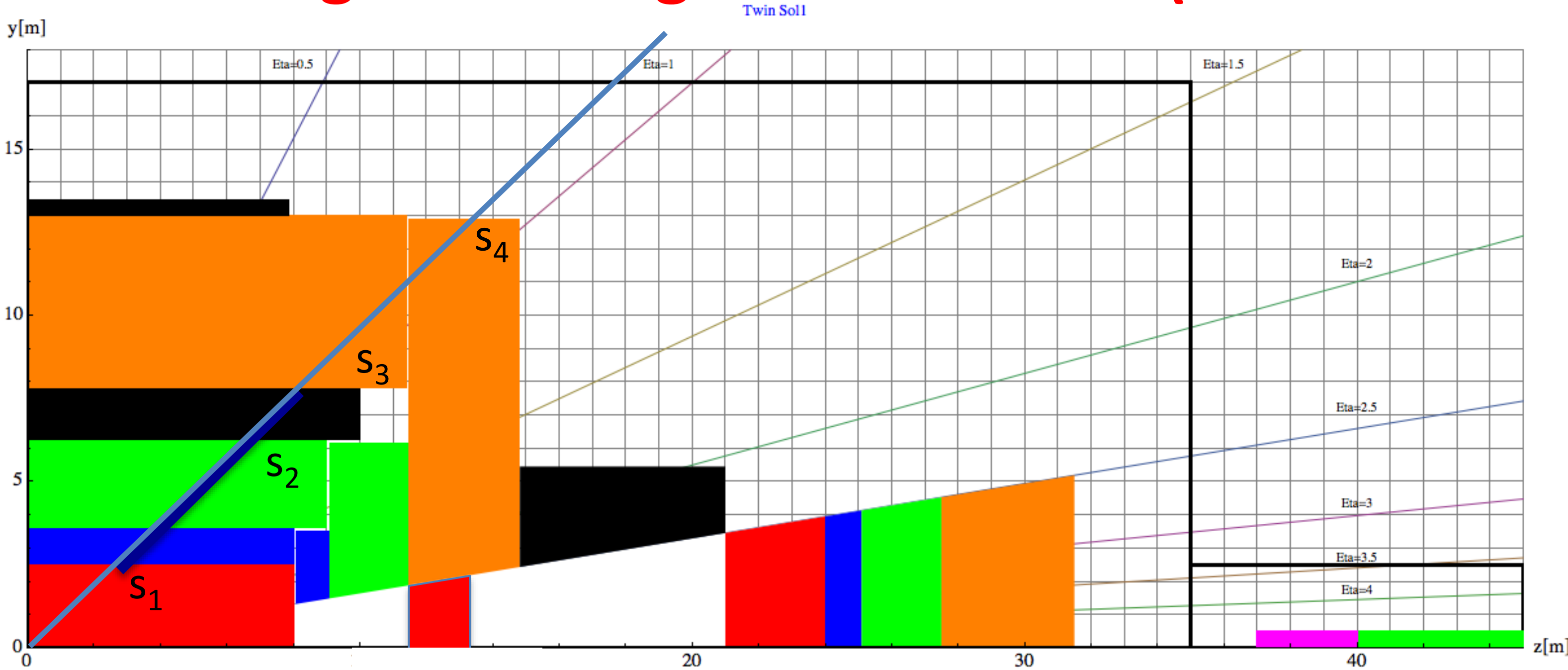
but very hard to beat the angular measurement and the inner tracker (10% at 10TeV)

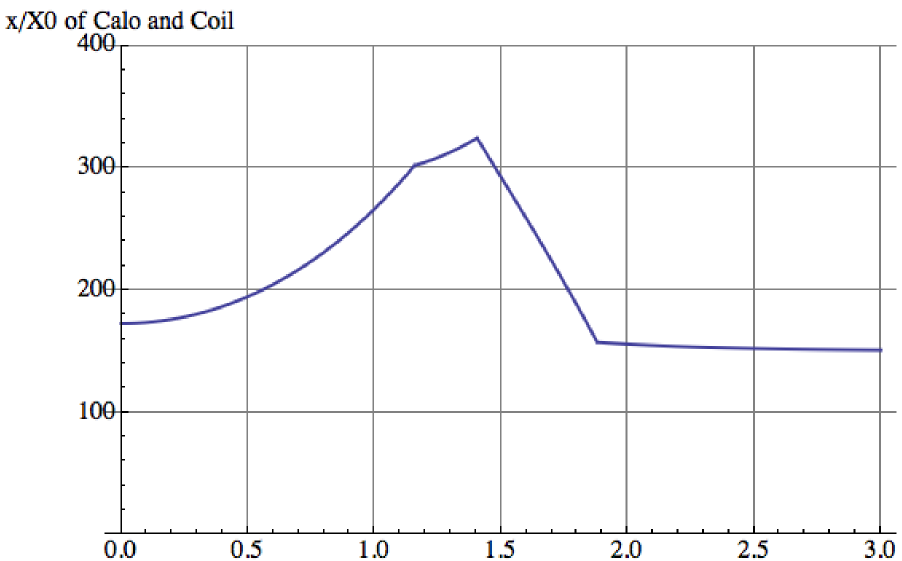
Surface > 5000 m^2

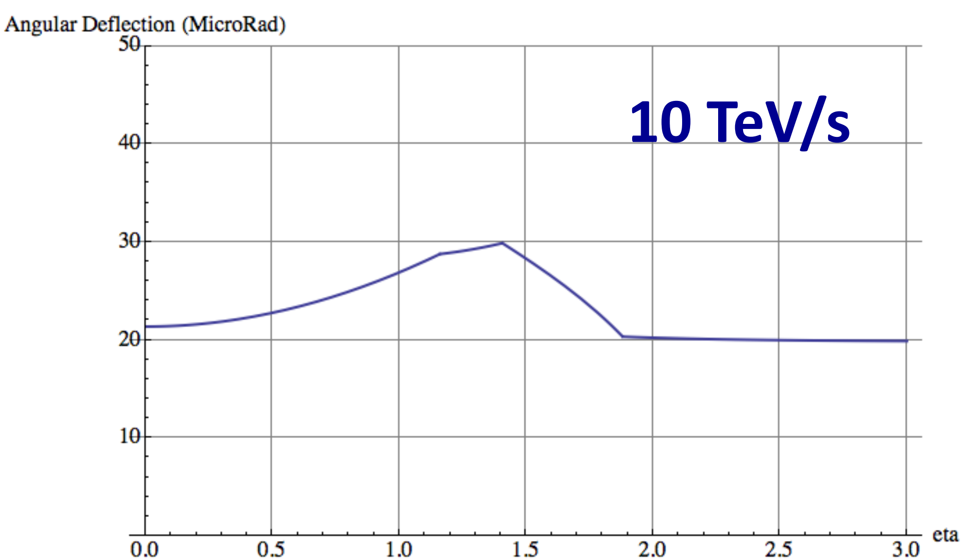
CMS sagitta measurement in the muon system is limited to $dp_T/p_T = 20\%$ due to multiple scattering alone.



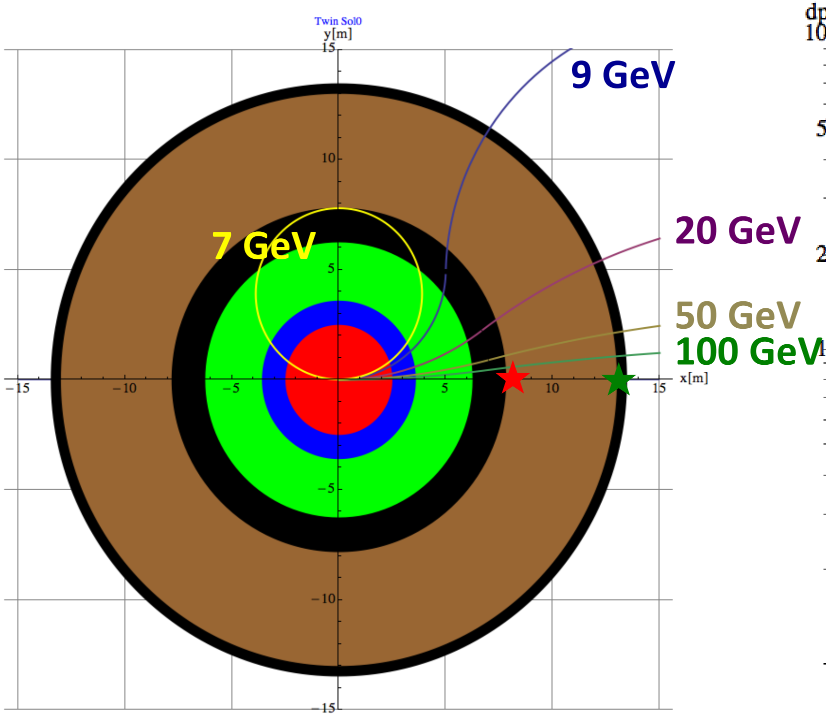
Radiation Length and Angular Deflection (Mult. Scattering)

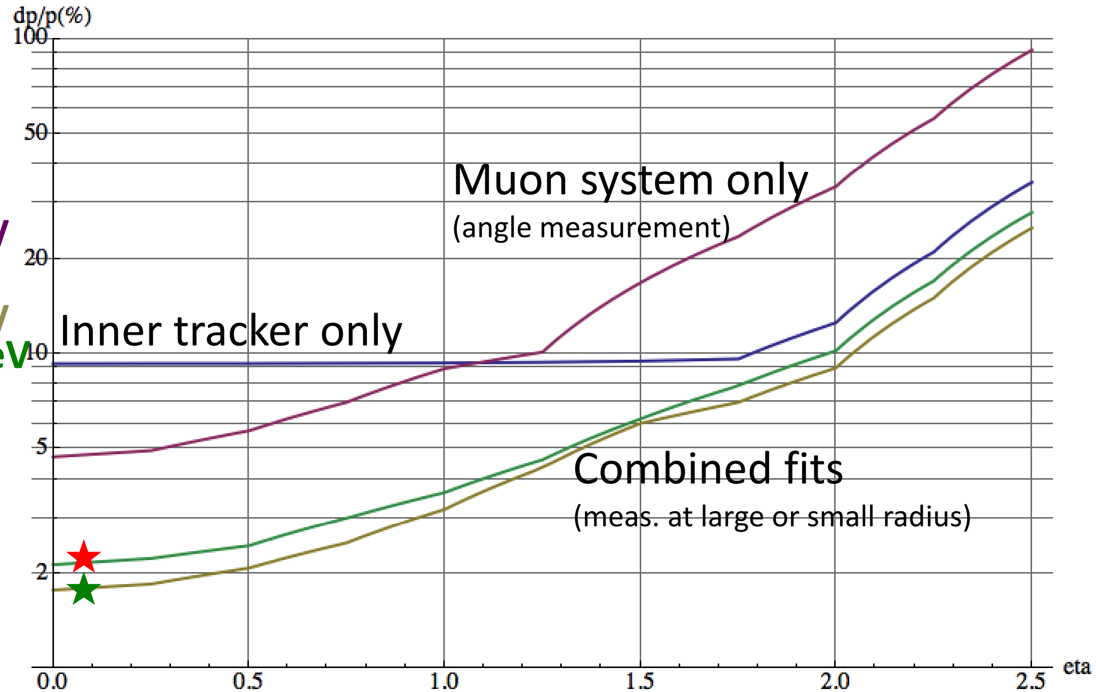






Momentum Resolution for a 10 TeV/s Muon





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

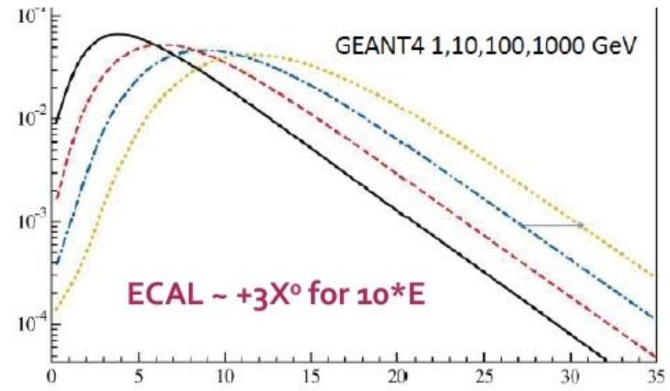
P_T=1TeV/c, eta 1.2<eta<2.4:
- 40% muon standalone (angle)
- 20% inner tracker only
- 10% combined

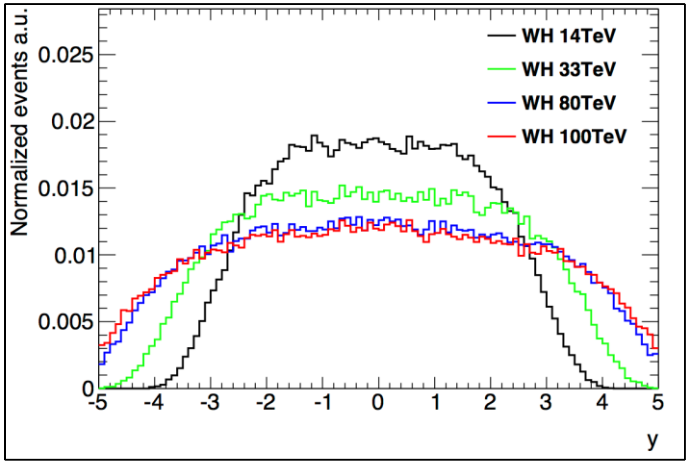
Calorimetry

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!)





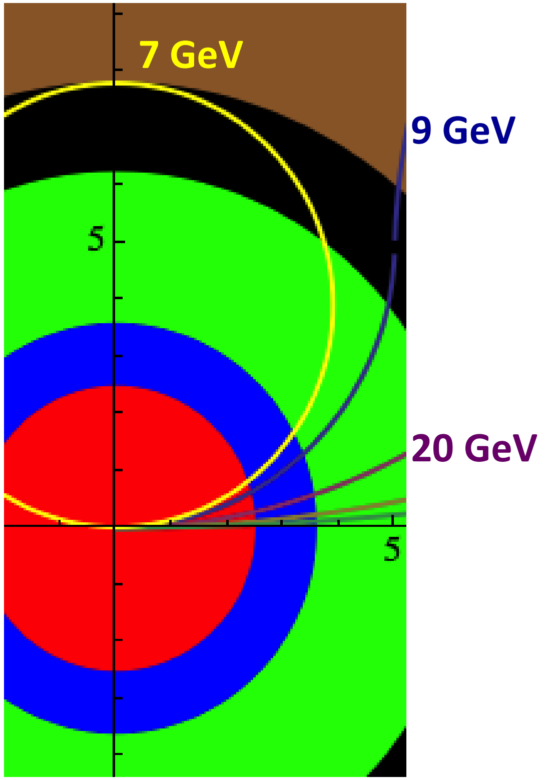
Requirements ECAL

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)

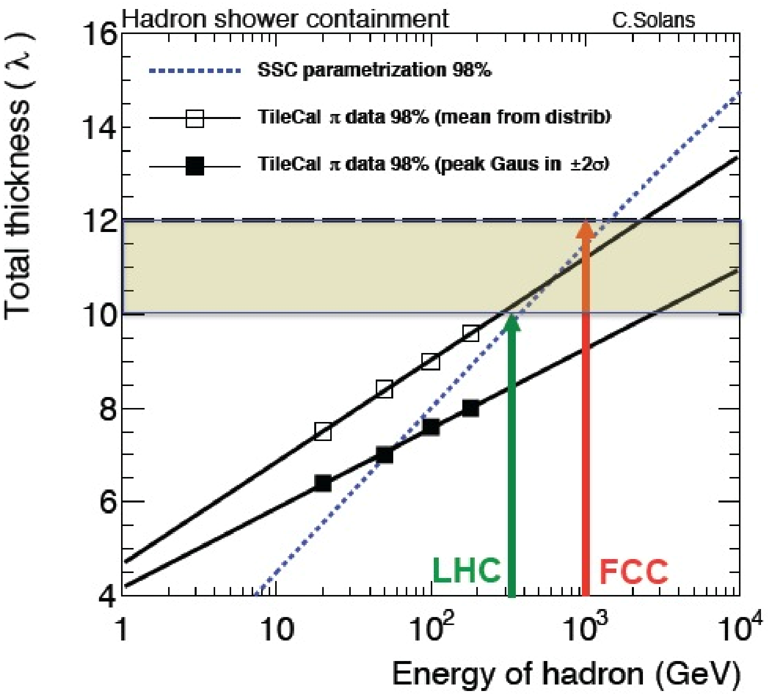
- Track-cluster matching is essential to achieve the above → fine (lateral) granularity and good position resolution should be achieved

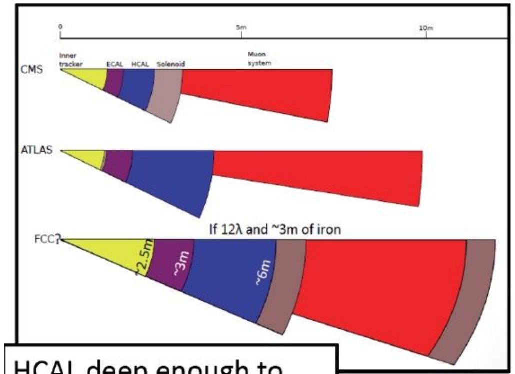


Requirements HCAL

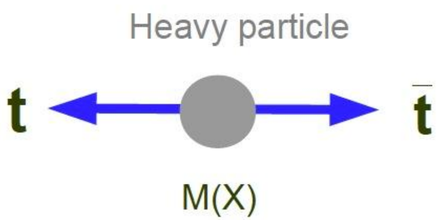
HCAL:

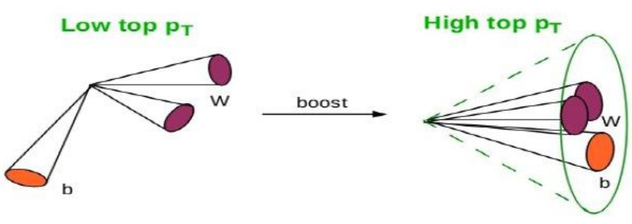
- Jet containment: 8% of single hadron constituents of 30TeV jets have E>1TeV. 98% containment requires 12λ
- Large acceptance up to |η|=6
- Highly collimated (boosted) final states
  - Minimal distance between two partons proportional to m/p_T (e.g. top)
- → high granularity also in the HCAL
  - Sub-structure 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: $\sigma_E/E \sim 50\%/\sqrt{E} + 3.0\%$

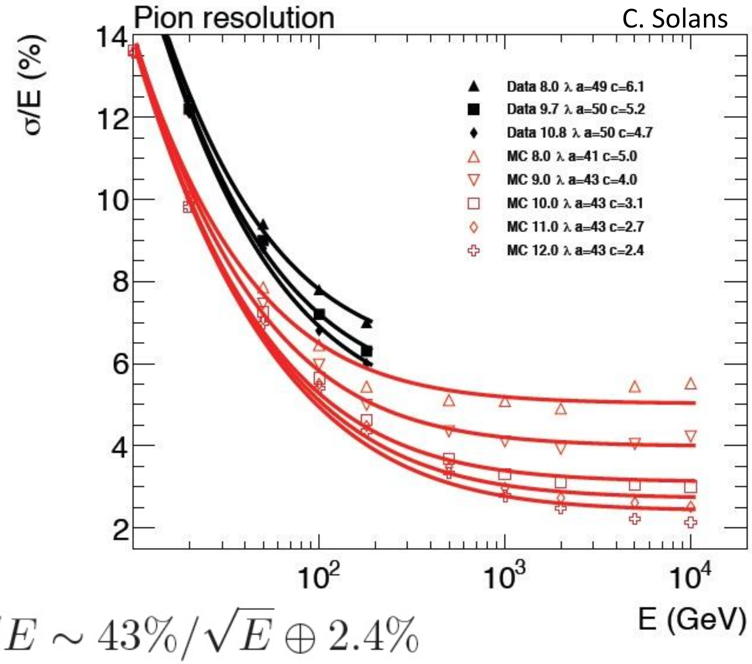
CMS: $\sigma_E/E \sim 100\%/\sqrt{E} + 4.5\%$

(small noise term for both)

Jet p_T > 5TeV: constant term dominates

Reduction of the constant term:

- **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!

FCC Week 2016

Rome, 11-15 April 2016

http://cern.ch/fccw2016

IEEE CSC Council on Superconductivity

SAPIENZA Università di Roma

Istituto Nazionale di Fisica Nucleare
Sezione di Roma

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Universita' degli Studi di Roma Tor Vergata

Roma Tre Università degli Studi

CERN

Material from Discussions on FCC-hh Detector Meetings:

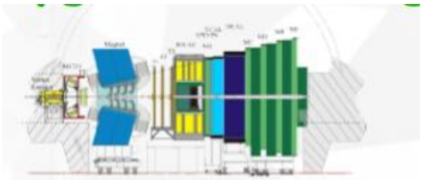
FCC-hh Detector Magnets
https://indico.cern.ch/category/6244/

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:
H. Ten Kate, M. Mentink, M. Aleksa, S. Klyukhin, Z. Drasal, I. Besana, F. Cerutti, A. Ferrari, A. Henriques, M. Mannelli, A. Ball, S. Chekanov, B. Hegner, A. Salzburger, J. Hrdinka, A. Zaborowsa, J. Lingemann, V. Volkl, P. Roloff, C. Helsens, H. Grey, F. Moortgat, J. Incandela, D. Fournier, L. Pontecorvo, S. Vlachos, V. Invantchenko, F. Lanni, H. Ma, M. Mangano, A. Dell'Acqua, C. Solans and others …

LHCb & ALICE in 2018



40 MHz

DAQ

40 MHz

LLT: μ,e/γ, hadrons

5-40 MHz

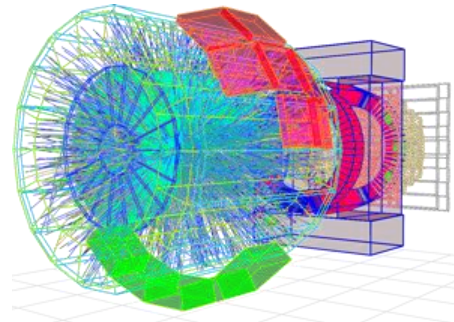
HLT: event recon.

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

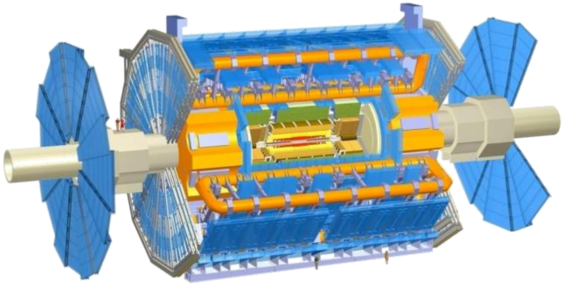
50 kHz (1.5 MB/event)

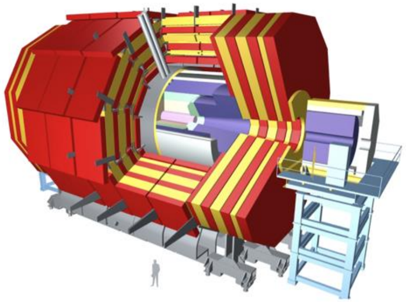
Storage

75 GB/s

← PEAK OUTPUT →

ATLAS & CMS in 2018





ATLAS		CMS
↓	40 MHz	↓
Level 1		Level 1
↓	0.5-1 MHz	↓
HLT		HLT
↓	5-10 kHz (2MB/event)	↓ 10 kHz (4MB/event)
Storage		Storage
10-20 GB/s	← PEAK OUTPUT →	40 GB/s

5 TByte/s into PC farm for HLT selection.

Would be 200TByte/s without Level1

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.

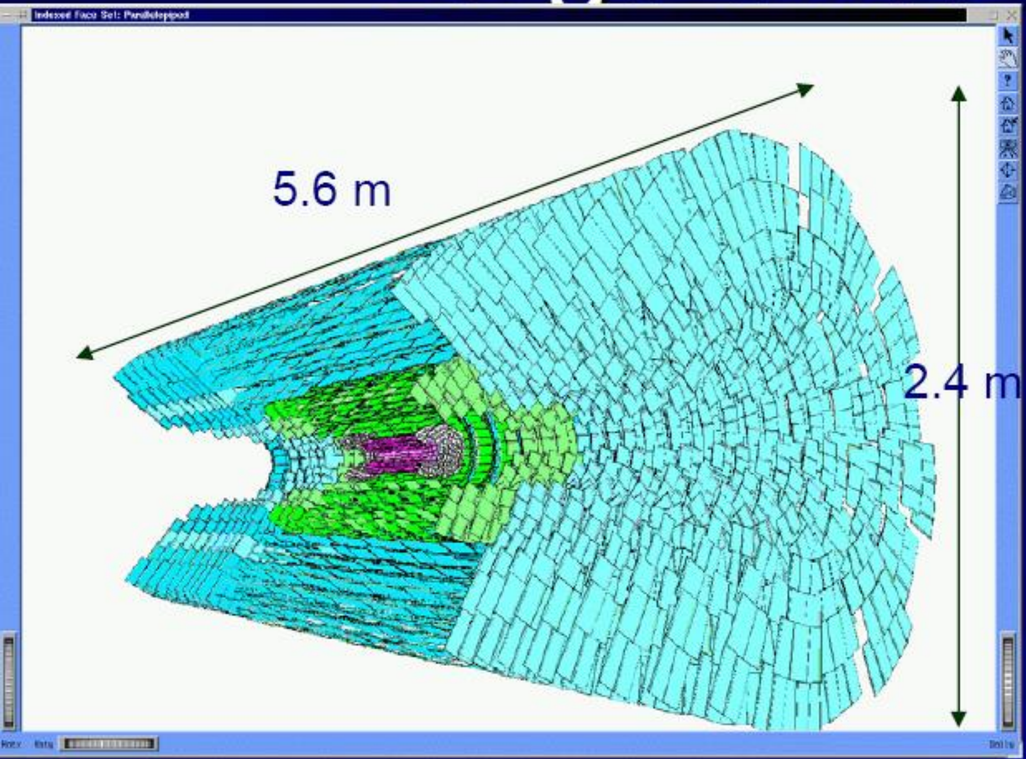
"Futurists believe that's what you need for artificial intelligence. At that point, the computer starts thinking for itself.“

→ **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.

Large Silicon Systems



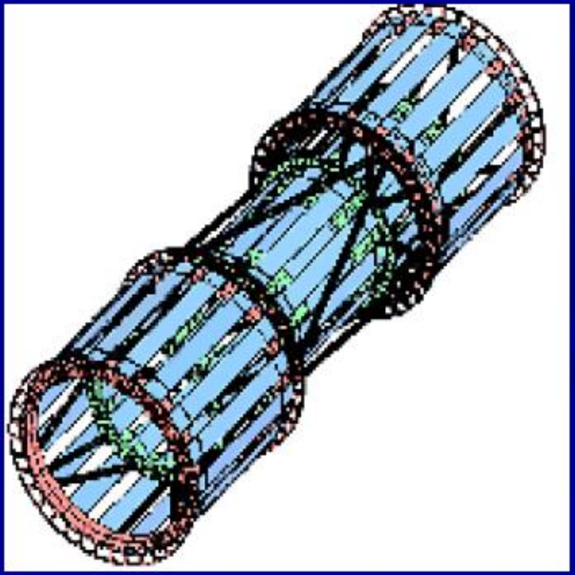
CMS tracker (~2007)

12000 modules

~ 445 m² silicon area

~ 24,328 silicon wafers

~ 60 M readout channels



CDF SVX IIa (2001-)

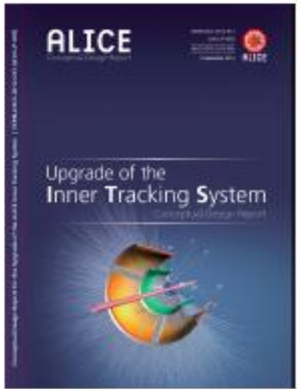
~ 11m² silicon area

~ 750 000 readout channels

ALICE 2018 upgrade, 20x20um monolithic pixels

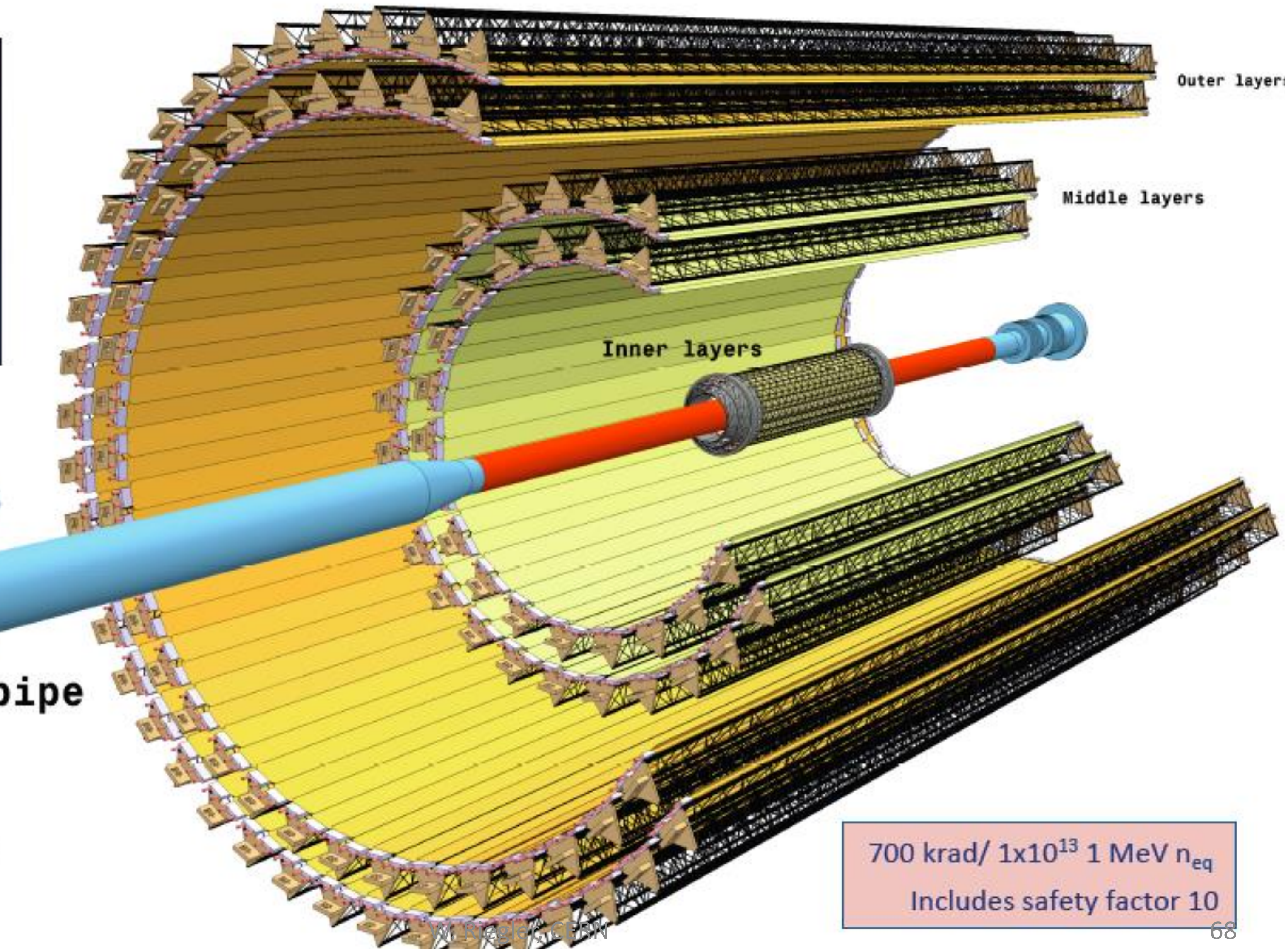
New ITS Layout

25 G-pixel camera
($10.3\ m^2$)



CERN-LHCC-2013-024

7 layers of MAPS



Radial coverage
22 – 406 mm

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