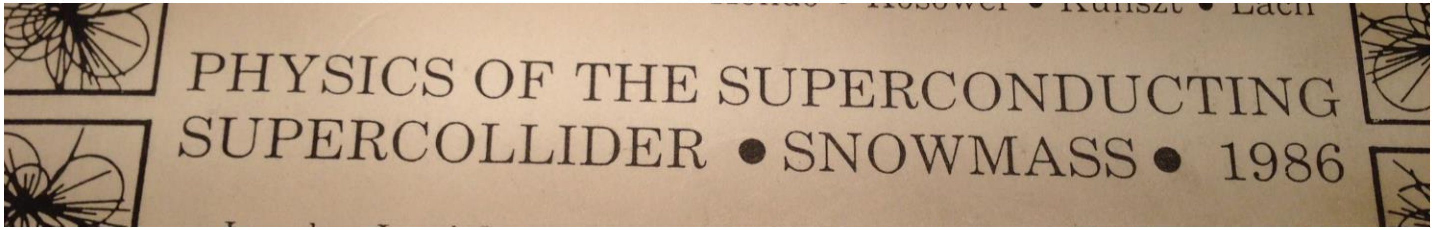
FCC-hh Machine Detector Interface and General Consideratios

Workshop on requirements for future detector technologies in view of FCC-hh

W. Riegler, CERN

for the FCC-MDI working group

SSC detector concepts



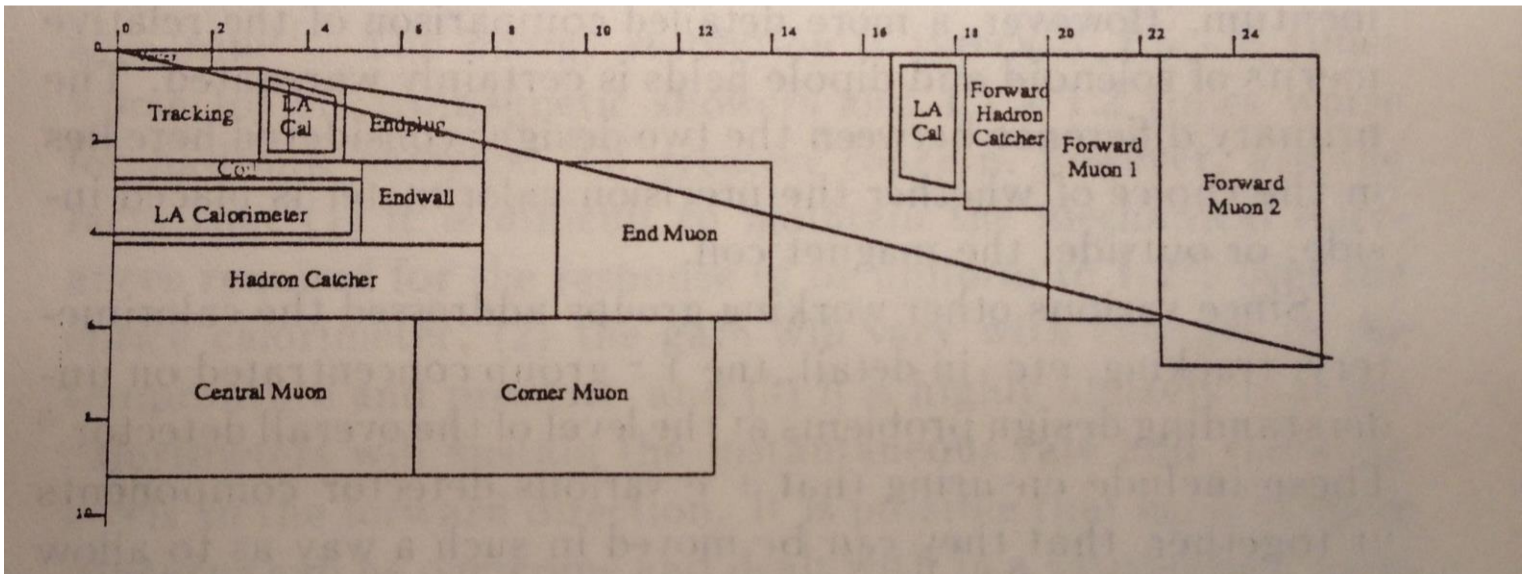


Figure 1a
A plan view of Detector B arranged along the beamline with all elements positioned for data taking.

SSC detector concepts

Detectors for the SSC: Summary Report

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SUMMARY

A review is presented of the major considerations for detectors at the SSC. Particular emphasis is placed on the design of a large 4π magnetic detector and on the feasibility of building such a detector. The results of each of the Working Groups are summarized. It appears to be possible to build a detector that incorporates nearly all of the desired features, but significant R & D on detectors particularly in the area of electronics, will be required.

* hermetic calorimeter co
at least $|y| < 5.5$ in orde
of missing transverse e

* measurement capabili
TeV range with good

* optimized efficiency f
construction of part
leptons.

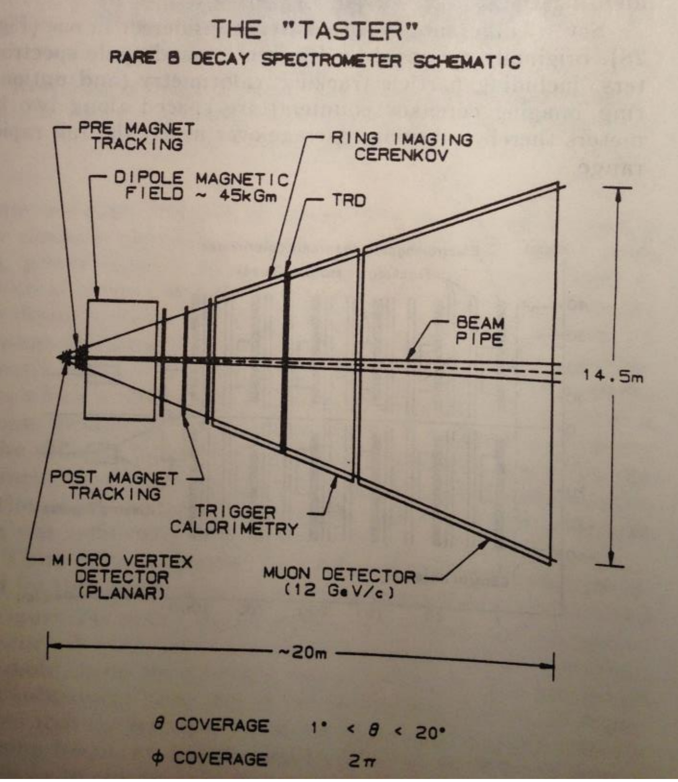
INTRODUCTION

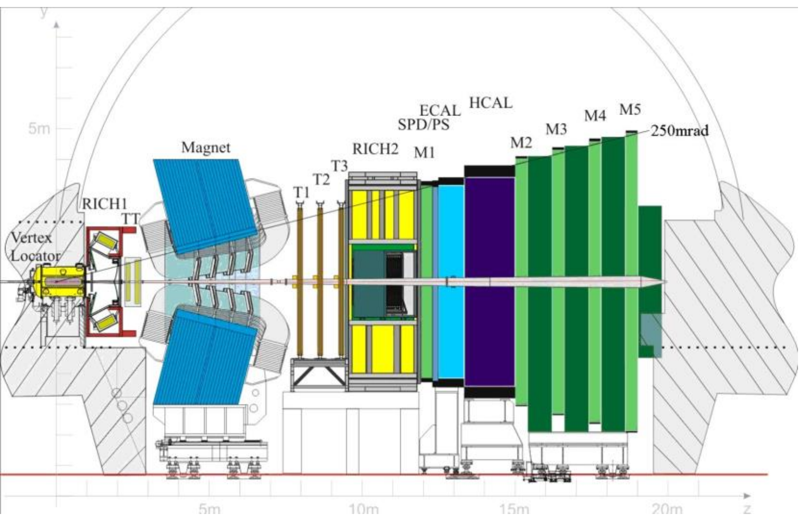
Forward and Other Specialized Detectors

While many of the participants pursued the Nirvana of a large 4π detector that is capable of doing all physics, a small group of enthusiasts[40] pursued detectors in the forward direction, spurred on by the observation that the rapidity interval

While many of the participants pursued the Nirvana of a large 4π detector that is doing all physics, a small group of enthusiasts pursued detectors in the forward direction …

Still another design is that of the "Taster" which is illustrated in Figure 30 and discussed in detail in the report of the Heavy Quark group.[42] One of the primary goals in the design of this detector is that one be able to study rare B decays and CP violation. Even at the SSC B mesons will be produced primarily at low p_t. It is argued that the detection of leptons of several GeV transverse momentum is much easier in the forward direction where the momentum of such particles is of order 10-30 GeV rather than 2-5 GeV. In addition, charged particle identification, which is apt to be important in the ultimate B decay experiment, may be easier to implement in the forward direction.

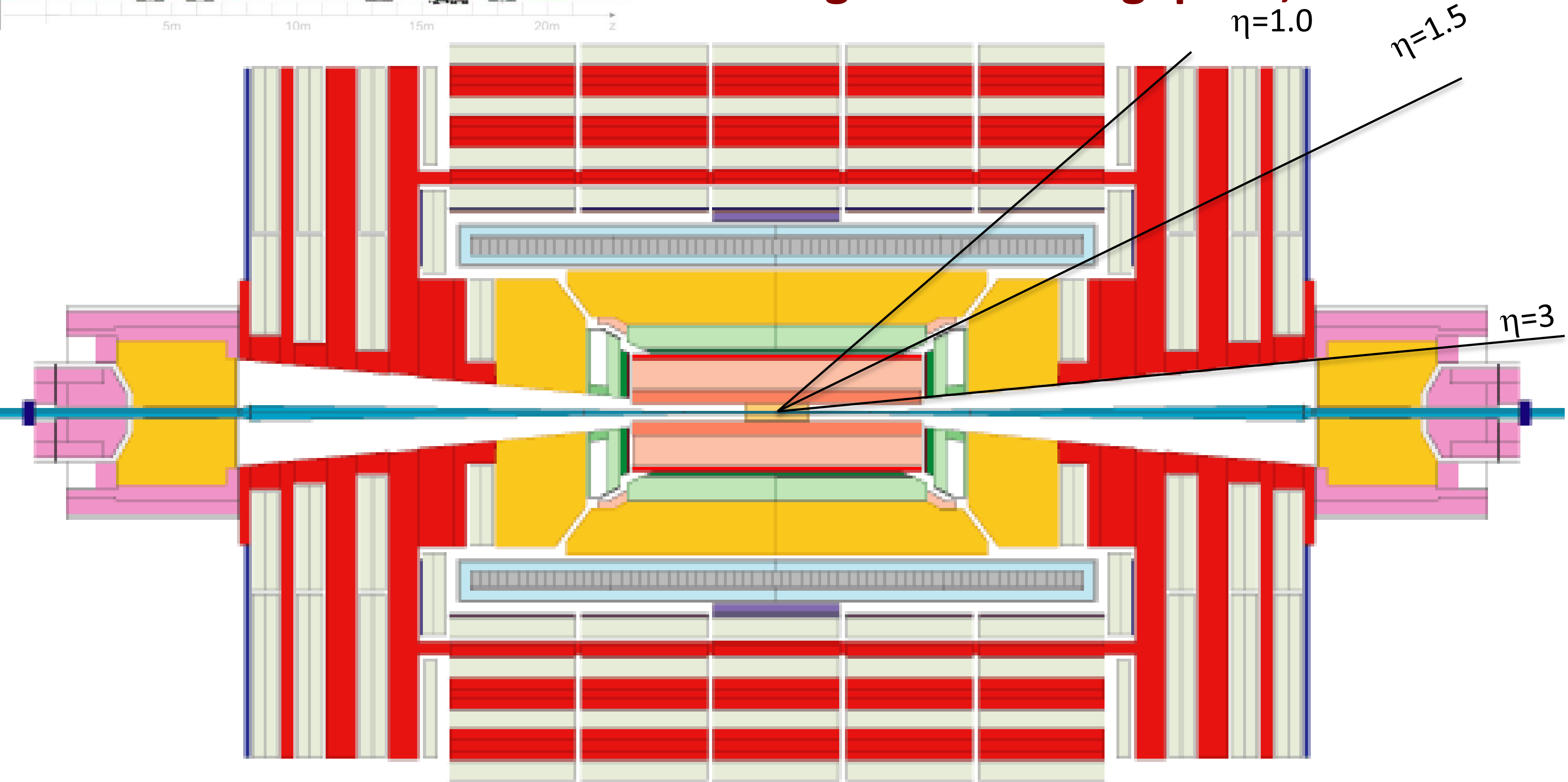




Tracking LHCb η = 2 - 5

… all with impressive performance …

Tracking CMS tracking η -2.5,2.5

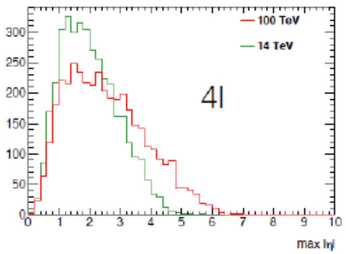


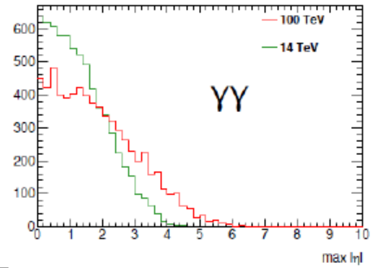
3 Approaches to design Hadron Detectors for a 100TeV Collider

Knowing that the important physics is very much boosted (forward)

Lepton/photon acceptance from Higgs decay (H.M.Gray)

ggF



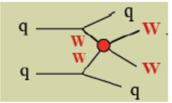


		|η| < 2.5	|η| < 4	|η| < 5
ll	100 TeV	0.56	0.88	0.97
	14 TeV	0.74	0.99	0.99
YY	100 TeV	0.74	0.95	0.99
	14 TeV	0.90	1	1

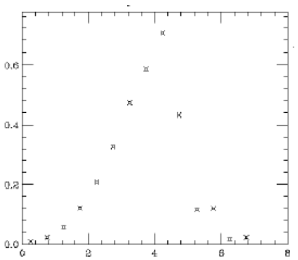
η=2.5 ↓ η>4

Physics moving forward …

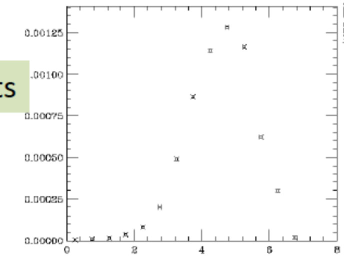
VBF jets acceptance



H & Co. -- the ‘bread and butter physics’ that has to be performed to maximum precision at the FCC



Max η of forward jets



WW by VBF M_{WW}>1 TeV

HH by VBF M_{HH} > 1 TeV

VBF measurement up to eta=6 desirable (means coverage beyond 6…)
ETmiss ?? No investigation so far
To gain 1 η unit, an EC calo of fixed Inner Radius needs to be moved 2.7 times further away from the collision point (from ~5m in present expts to ~15m)
High density(W) desirable –inner part at least- to limit transverse size of particle showers
Fast response mandatory. 5ns bc would be an asset if detector speed can follow…

1^{st} Approach:

Require 10% momentum resolution for the highest p_t particles, assuming detector resolutions similar to the present one.

→ Scale BL^2 by 100TeV(FCC)/14TeV(LHC)=7

Central and Forward in one Detector (Nirvana)

1. Requirements, design drivers

Bending power: higher collision energy 14>100TeV, same tracking resolution

BL^2 has to be increased by factor 7!

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

---> higher field, in single solenoid, up to 6.0 T

---> higher field, longer track in inner solenoid around ID, 3.5T/3m or 2T/4m, and a toroid of 1.8T useful field and increase of tracking length.

Low angle coverage in forward direction, solenoid useless, toroid difficult since all current has to pass the inner bore

---> add a dipole for on-beam bending, some 10Tm!

HCAL depth from 10 λ to 12λ (iron) radial thickness some 3.0 m!

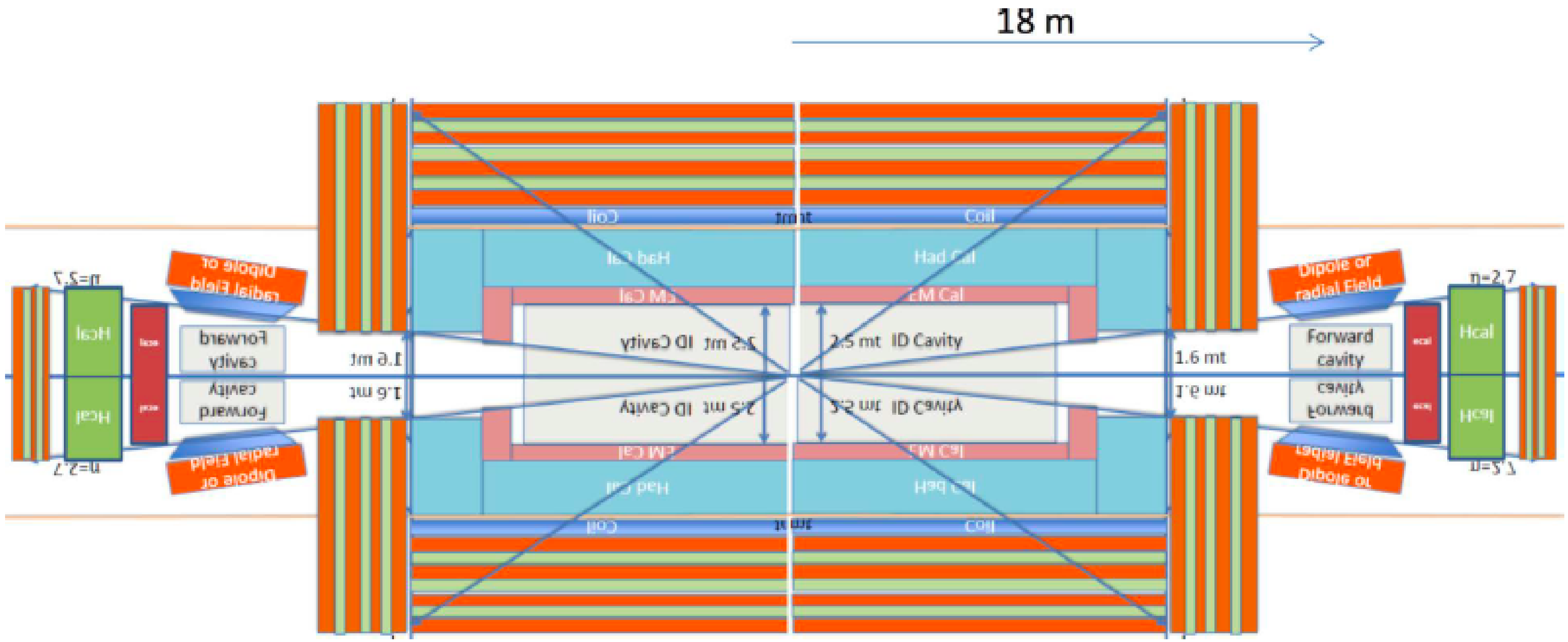
---> bore of big solenoid or inner radius toroid increases to 6m and length increases accordingly.

ECAL to cover low angles, move unit out, from 5 to 15 m, system gets longer.

Thus: higher field, larger bore and longer system. 3 options analyzed.

Herman ten Kate and Jeroen van Nugteren

Option 1: Solenoid-Yoke + Dipoles (CMS inspired)



Solenoid: 5-6 m diameter, 5-6 T, 23 m long

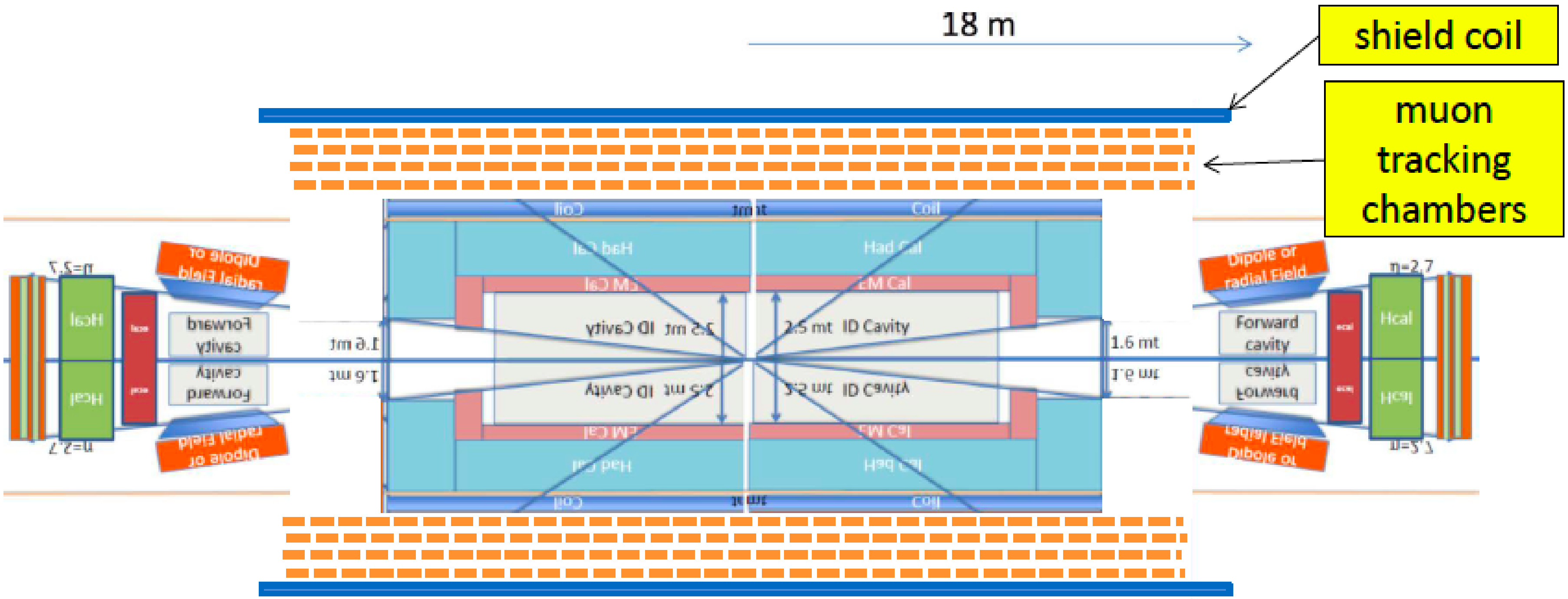
+ massive Iron yoke for flux return (shielding) and muon tagging.

Dipoles: 10 Tm with return yoke placed at 18 m.

Practically no coupling between dipoles and solenoid.

They can be designed independently at first.

Option 2: Twin Solenoid + Dipoles



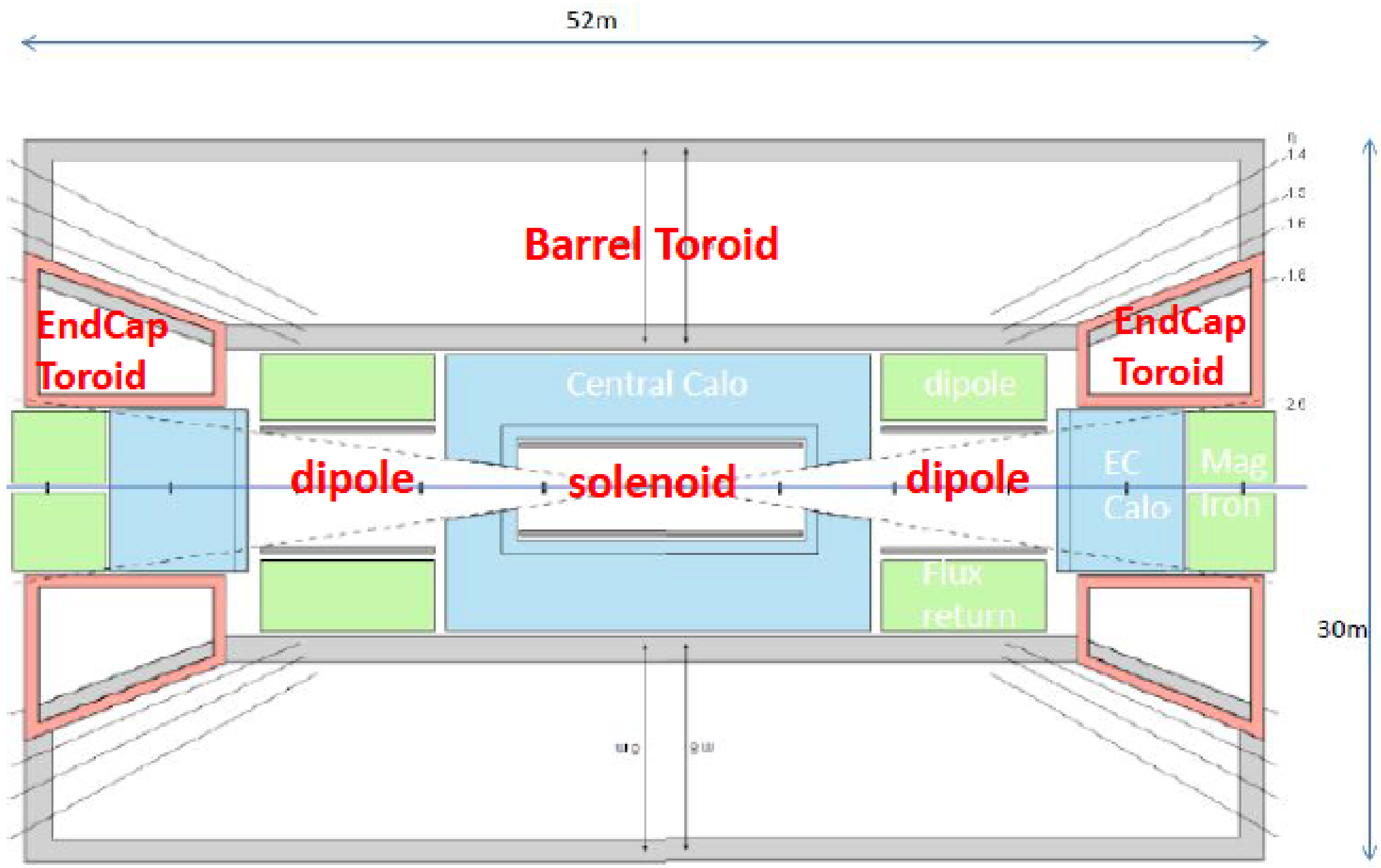
Twin Solenoid: the original 6 T, 12 m x 23 m solenoid + now with a shielding coil {concept proposed for the 4th detector @ILC, also an option for the LHeC in the case of large solenoid; and this technique is in all modern MRI magnets!}.

Gain?

- **+ Muon tracking space:** nice new space with 3 T for muon tracking in 4 layers.
- **+ Very light:** 2 coils + structures, ≈ 5 kt, only ≈4% of the option with iron yoke!
- **+ Smaller:** outer diameter is less than with iron .

Herman ten Kate and Jeroen van Nugteren

Option 3: Toroids + Solenoid + Dipoles (ATLAS +)



- Air core Barrel Toroid with 7 x muon bending power BL^2.
- 2 End Cap Toroids to cover medium angle forward direction.
- 2 Dipoles to cover low-angle forward direction.
- Overall dimensions: 30 m diameter x 51 m length (36,000 m^3).

Sizes - Stored Energy and Protection

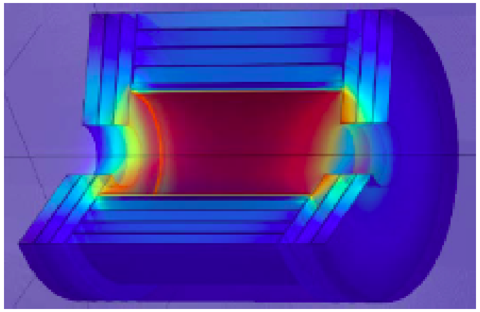
Sizes: 12m bore, 30m diameter, 30-50m length……

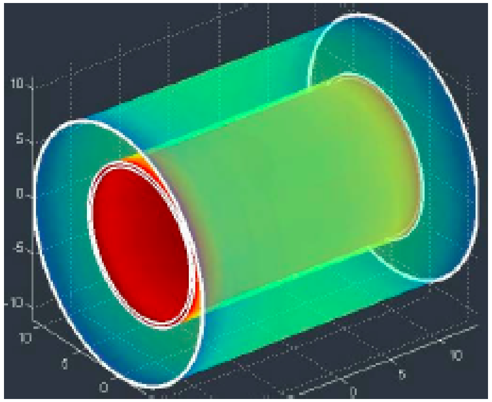
- It looks gigantic but similar sized magnets are being made these days (ITER PF coils, 26m).
- Production is required on site, in smaller modules, but very well possible.

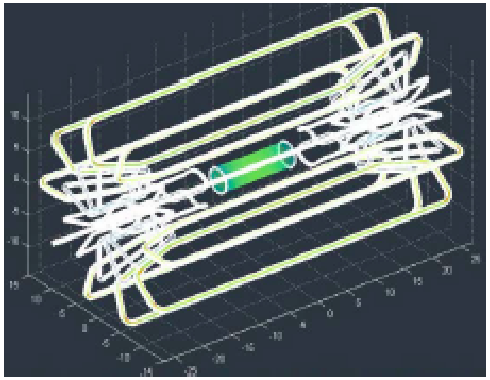
Stored Energy: 50 - 100 GJ……

- Looks scaring but it isn’t.
- In practice always solvable!
- A clever combination of energy extraction and dumping in cold mass, controlled by a redundant, fail-safe quench protection system.

I don’t see a principle technical problem that would stop us from constructing such systems………







2^{nd} Approach:

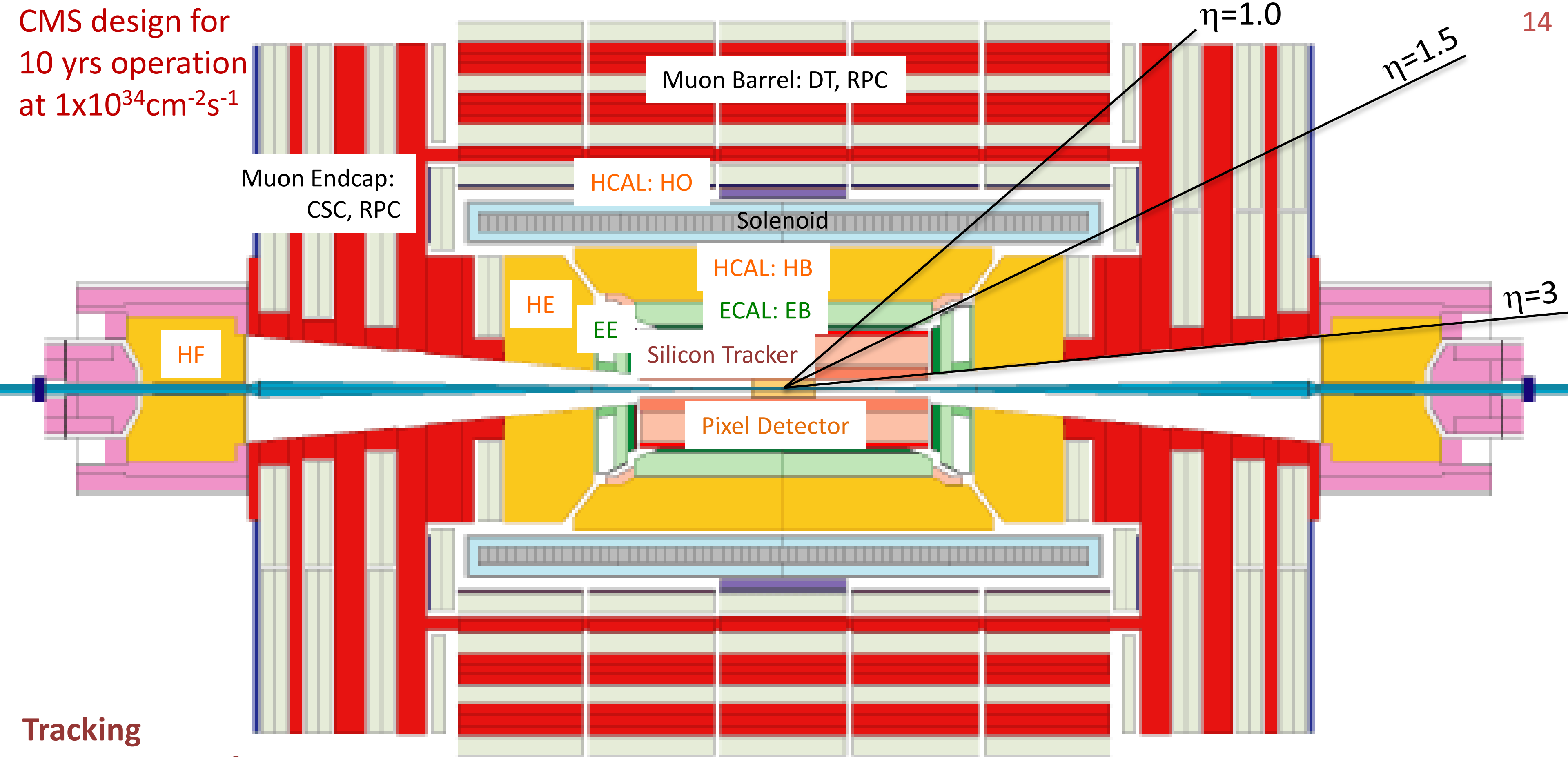
Use a present magnet system (ATLAS/CMS, LHCb) and understand possible improvement of detector resolution.

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

Explore techniques like particle flow etc., understand whether 10% resolution for the highest p_t particle is really needed.

Think about dedicated 'smaller' experiments like ATLAS/CMS or dedicated forward experiments like LHCb.

CMS design for
10 yrs operation
at $1x10^{34}cm^{-2}s^{-1}$



Tracking

More than 220m² surface and
76M channels (pixels & strips)
6m long, ~2.2m diameter
Tracking to |η|<2.4

ECAL

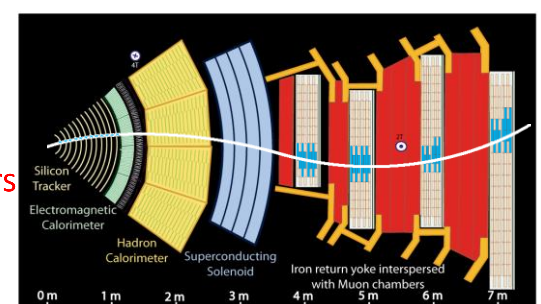
Lead Tungstate ($PbWO_4$)
EB: 61K crystals, EE: 15K crystals

HCAL

HB and HE: Brass/Plastic scintillator
Sampling calorimeter. Tiles and WLS fiber
HF: Steel/Quartz fiber Cerenkov calo.
HO: Plastic scintillator "tail catcher"

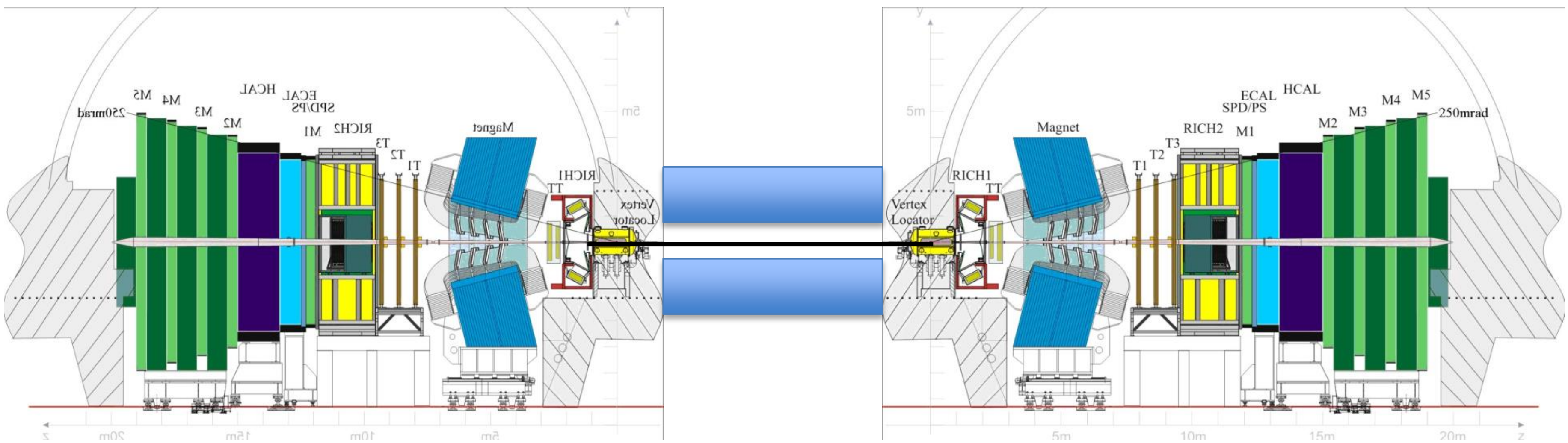
Muon System

Muon tracking in the return field
Barrel: Drift Tube & Resistive Plate Chambers
Endcap: Cathode Strip Chambers & RPCs



Trigger

Level 1 in hardware, 3.2μs latency ,100 kHz
ECAL+HCAL+Muon
HLT Processor Farm,1 kHz: Tracking , Full reco



Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
ECAL
SPD/PS
HCAL
M2
M3
M4
M5
250mrad
5m
10m
15m
20m
z
y

3nd Approach:

Think about something very different …

How to define boundaries between machine and detectors for the next steps ?

Boundary Conditions for Experiments at the FCC-hh Collider

Try to work out a set of Machine Detector Interface (MDI) Parameters that allow detector efforts and machine efforts to explore options with maximum ‚freedom'.

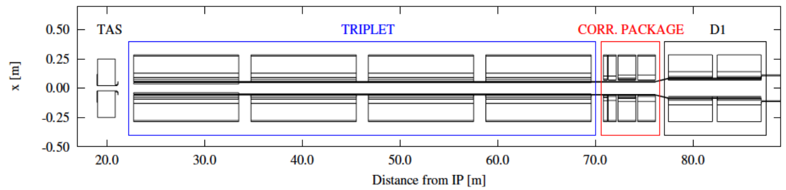
L* ... the disance between IP and triplet magnet, which determines the maximum size of the detector.

L_{peak} ... The peak luminosity, that determines the detector rates and pileup numbers.

L_{int} ... The total integrated luminosity, that determines the ageing and radiation damage of the detector, the radiation damage of the triplet magnets.

L* [25m, 40m]

The L* of LHC is 23m, many FCC-hh studies were performed with an L* of 36m.



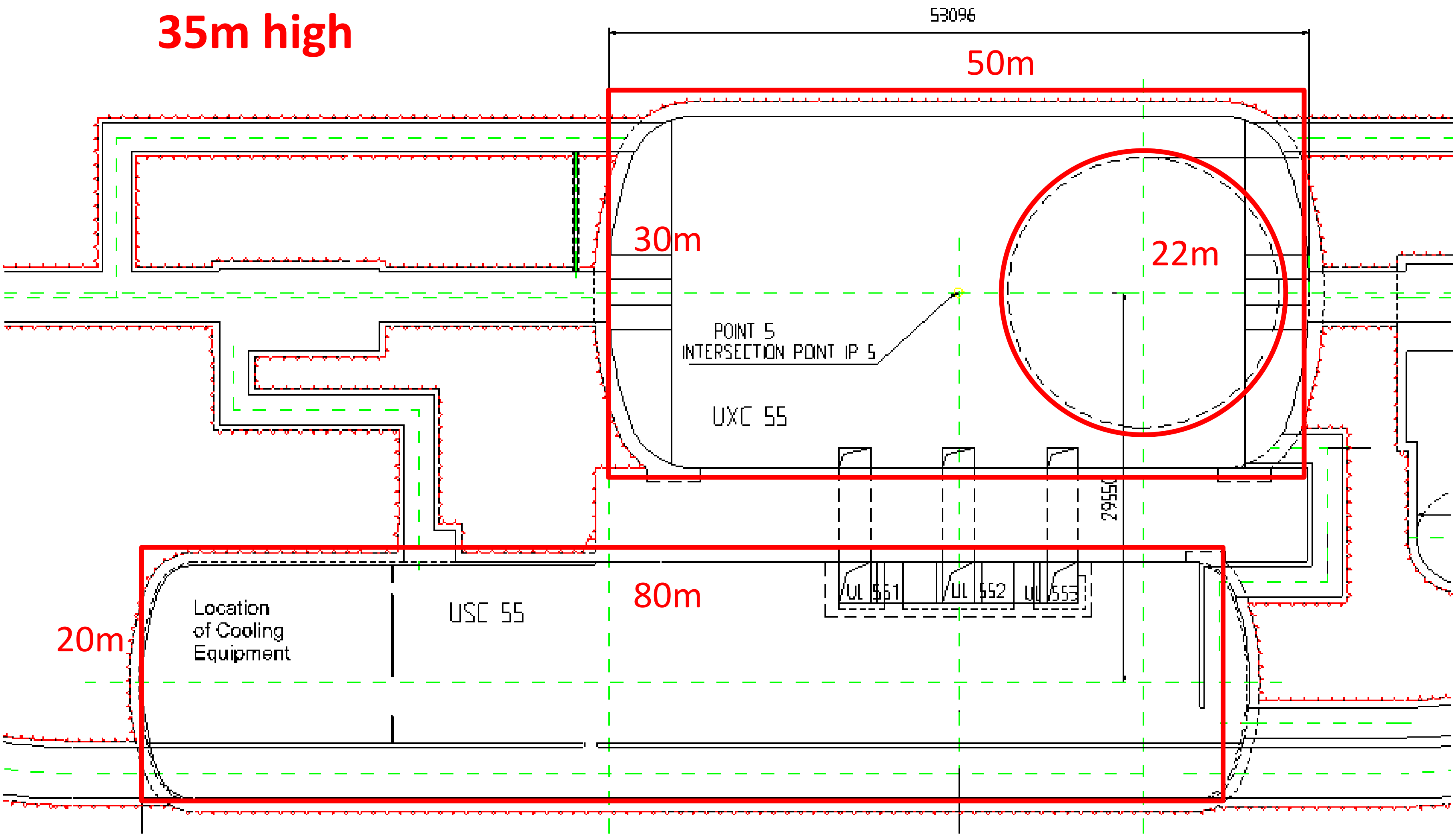
A large number of L* does of course allow some fantastic all in one ‚Nirvana' detector concepts.

Since one of the key criteria of the FCC-hh machine is the maximum delivered luminosity one should be very open on this number and see whether a significant gain can be found by small L* numbers.

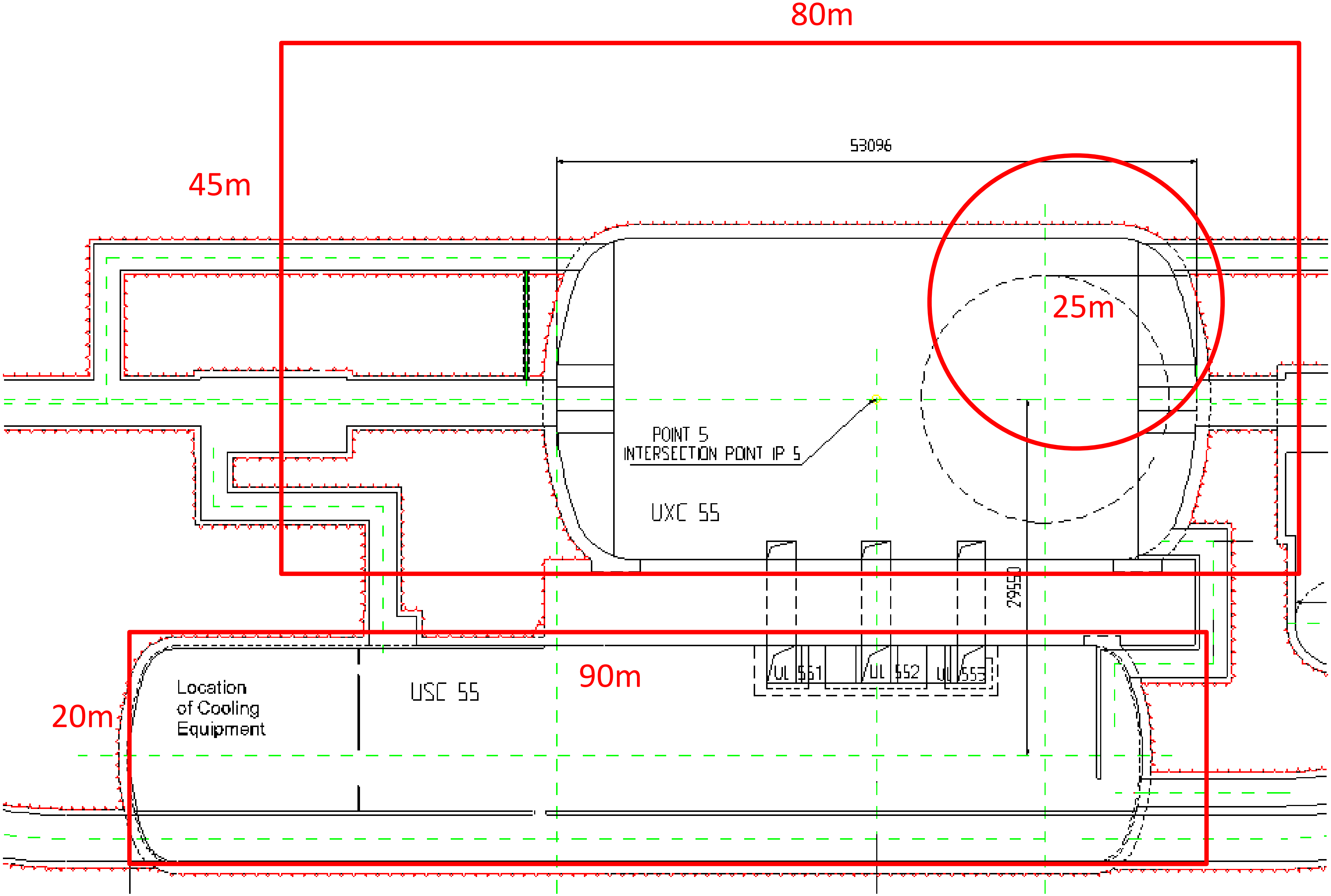
It also has to be seen whether such very large caverns are feasible at the very large cavern depthth and probably difficult terrain that are discussed at this moment (300-500m).

… e.g. water column of 400m is 50 bars …

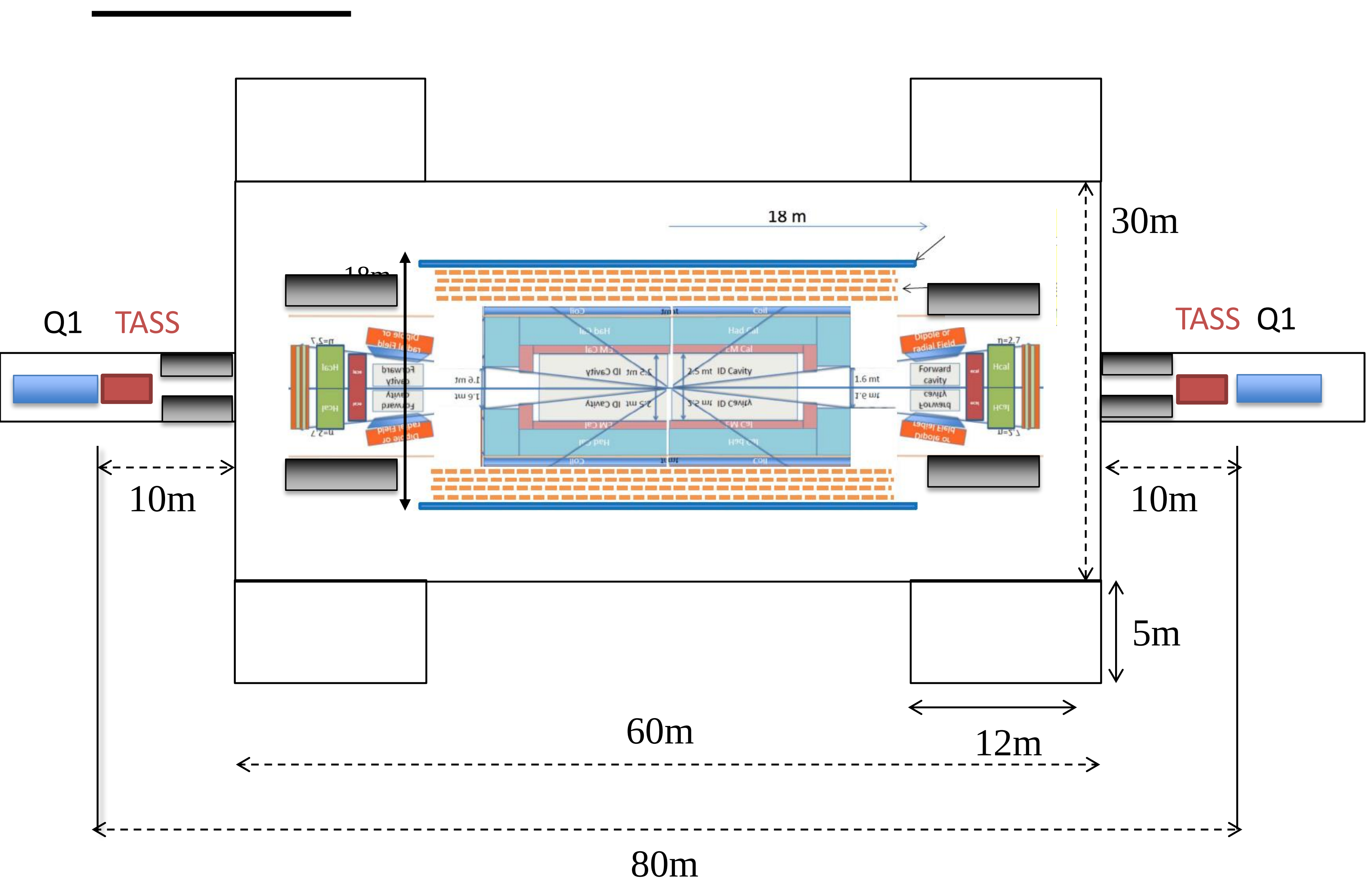
Cavern Layout1 for L* = 25m, Same as CMS (ATLAS is similar)



Cavern Layout2 for L* = 40m, 45m high



Luxury Version: L*=40m and TAS outside the Experimental Cavern



Peak Luminosity and Pileup

The baseline peak luminosity for FCC-hh is $5x10^{34}$ (first Phase)
The maximum peak luminosity at approx. $30x10^{34}$ (second Phase)

The pp crossection at 100TeV is around 100mbarn.
The corresponding collision rates are therefore $5x10^{9}$Hz and $30x10^{9}$Hz

The revolution frequency for a 100km FCC is 3kHz.
There are around 11000 bunches at 25ns and 55000 bunches at 5ns.

L_{peak} [$5x10^{34}$, $30x10^{34}$]

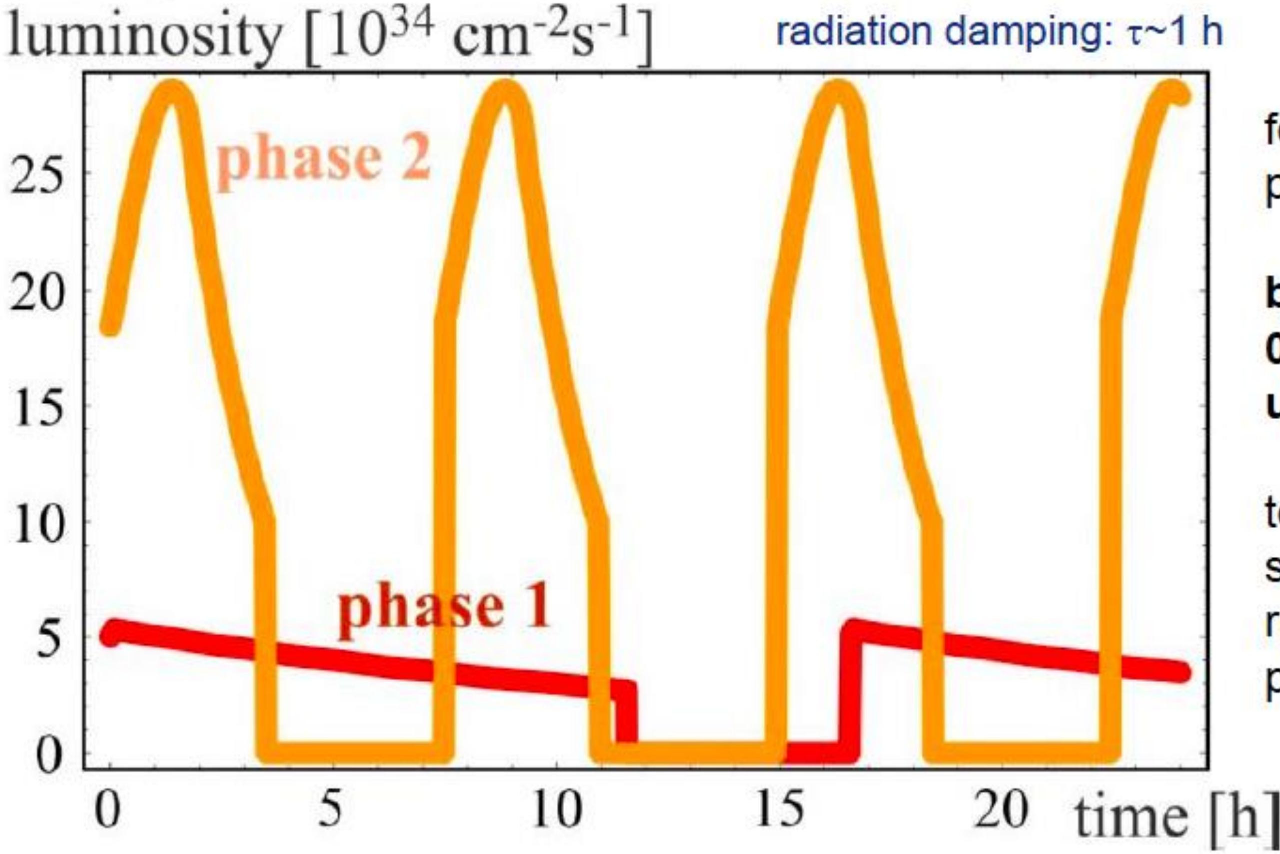
corresponds to an average pileup of

N_{pileup} [150, 900] at 25ns bunch spacing and
N_{pileup} [30, 180] at 5ns bunch spacing

Clearly 5ns is preferred, however the 25ns are not totally insane
(HL-LHC: Average pileup 150)

luminosity evolution over 24 h

radiation damping: τ~1 h



for both phases:

beam current 0.5 A unchanged!

total synchrotron radiation power ~5 MW.

phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h → phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h

Integrated Luminosity

The integrated luminosity target is [3ab^{-1}, 30ab^{-1}] for the first and second phase.

The 30ab^{-1} is probably quite optimistic and 20ab^{-1} would be a more reasonable target. For all questions of radiation damage the effects do anyway scale with this number, and safety factors for simulation uncertainties and background uncertainties have to be taken into account.

Which number to chose is more a ‚strategic and pragmatic' questions, so 20ab^{-1} might be more suitable – to be decided by the FCC machine and physics effort.

Conclusions on MDI Parameters

L^* [25, 40]m

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

→ N_{pileup} [150, 900] at 25ns

→ N_{pileup} [30, 180] at 5ns

L_{int} [3, 20] ab^{-1}

How do Min. Bias events at FCC compare to LHC ?

Informal meeting of the Future Hadron Collider group Jan. 27th 2014
https://indico.cern.ch/conferenceDisplay.py?confId=292284

14TeV → 100TeV:

Inelastic crossection 14 →100TeV changes from 80 → 100mb.

Multiplicity 14 →100TeV changes from 5.4 → 8 charged particles per rapidity unit.

Average p_T of charged particles 14 → 100 TeV 0.6 →0.8 GeV/c, i.e. bending radius in 4T magnetic field is 50 → 67cm.

Transverse energy increase by about a factor of 2.

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

Peter Skands:

See more control plots at http://mcplots.cern.ch

If you don't require precision better than 10%

And if you don't look at very exclusive event details (such as isolating specific regions of phase space or looking at specific identified particles)

Then I believe these guesses are reasonable

σ_{INEL}	σ_{EL}	
~ 80 mb	~ 22 mb	@ 13 TeV
~ 90 mb	~ 25 mb	@ 30 TeV
~ 105 mb	~ 32 mb	@ 100 TeV

Central <N_{ch}> density (INEL>0)
- ~ 1.1 ± 0.1 / $\Delta\eta\Delta\varphi$ @ 13 TeV
- ~ 1.33 ± 0.14 / $\Delta\eta\Delta\varphi$ @ 30 TeV
- ~ 1.8 ± 0.4 / $\Delta\eta\Delta\varphi$ @ 100 TeV

Central <E_T> density (INEL)
- ~ 1.0 ± 0.15 GeV / $\Delta\eta\Delta\varphi$ @ 13 TeV
- ~ 1.3 ± 0.2 GeV / $\Delta\eta\Delta\varphi$ @ 30 TeV
- ~ 2.0 ± 0.4 GeV / $\Delta\eta\Delta\varphi$ @ 100 TeV

UE TRNS <Σp_T> density (j100)
- ~ 3.3 ± 0.2 / $\Delta\eta\Delta\varphi$ @ 13 TeV
- ~ 3.65 ± 0.25 / $\Delta\eta\Delta\varphi$ @ 30 TeV
- ~ 4.4 ± 0.45 / $\Delta\eta\Delta\varphi$ @ 100 TeV

For tuning, Perugia 2012 (PY6) → Monash 2013 (PY8)

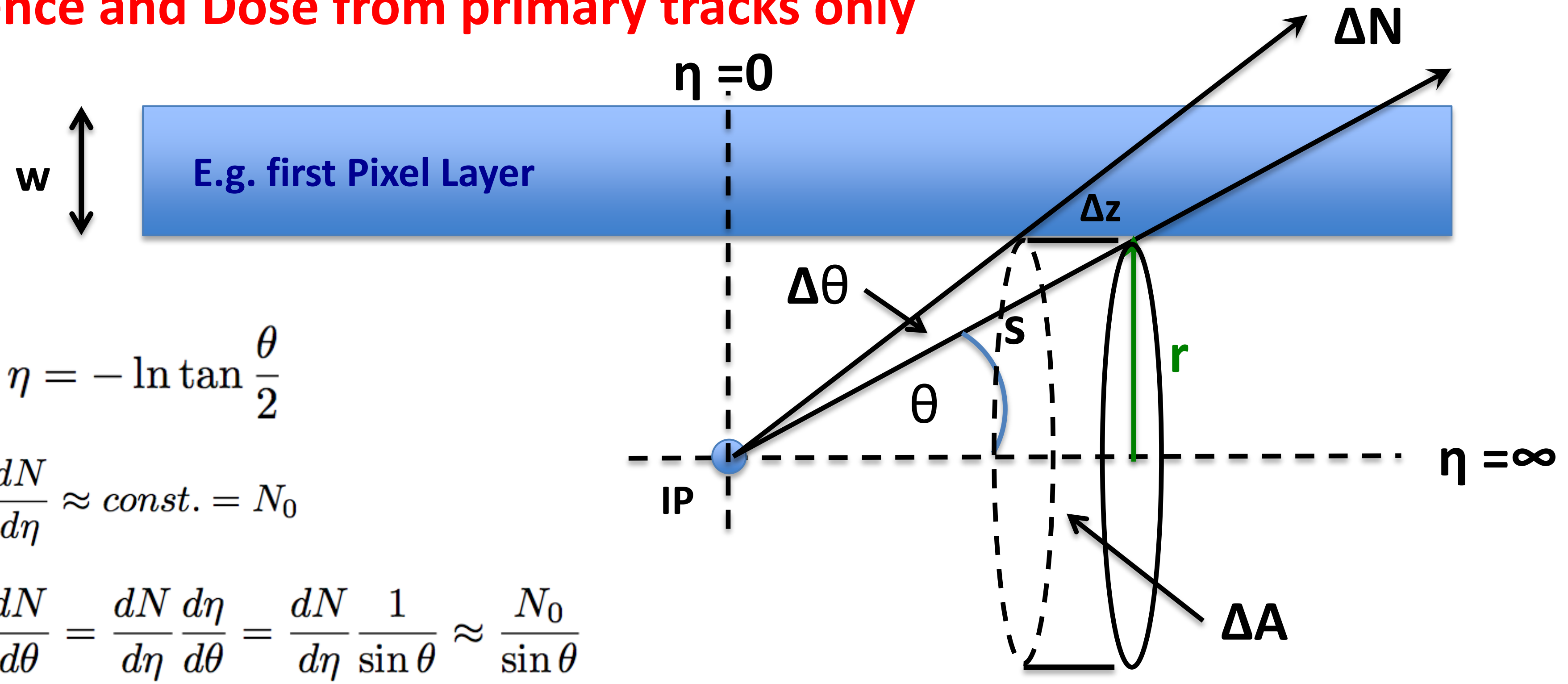
Diffraction could still use more dedicated pheno / tuning studies

Baryon and strangeness spectra in pp still not well understood → color reconnections?

Forward region highly sensitive to PDF choice → what do low-x PDFs mean?

Estimated of the Radiation Load in the Tracker

Fluence and Dose from primary tracks only



$$\eta = -\ln \tan \frac{\theta}{2}$$

$$\frac{dN}{d\eta} \approx const. = N_0$$

$$\frac{dN}{d\theta} = \frac{dN}{d\eta}\frac{d\eta}{d\theta} = \frac{dN}{d\eta}\frac{1}{\sin\theta} \approx \frac{N_0}{\sin\theta}$$

$$\Delta N = \frac{dN}{d\theta}\Delta\theta$$

$$\Delta A = 2r\pi\Delta z = 2r\pi\frac{s\Delta\theta}{\sin\theta} = \frac{2r^2\pi}{\sin^2\theta}\Delta\theta$$

$$\frac{\Delta N}{\Delta A} = \frac{dN}{d\theta}\frac{\sin^2\theta}{2r^2\pi}$$

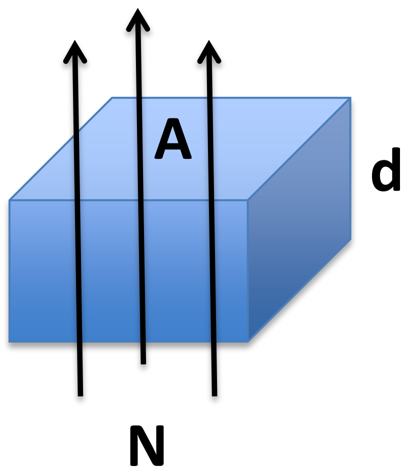
$$\text{Fluence} = \frac{\Delta N}{\Delta A}\frac{w}{w\sin\theta} = \frac{dN}{d\theta}\frac{\sin\theta}{2r^2\pi} \approx \frac{N_0}{2r^2\pi}$$

Fluence = number of particles traversing a detector elements weighted by the track length in the material.

→ **The hadron fluence due to primary particles is just a function of the distance from the beamline.**

→ **Eqi-fluence and equi-dose lines are parallels to the beamline.**

From charged particle fluence to 1MeV neutron equivalent fluence



Assuming N ionizing particles per cm^2
there are N*A particles passing the volume.

$\Delta E = N*A*\rho[g/cm^3]*2\text{ MeV}[cm^2/g]*d[cm]$

$\Delta mass = \rho[g/cm^3]*d[cm]*A[cm^2]$

Dose = $\Delta E/\Delta mass$
= $3.2e\text{-}10*N[cm^{-2}]$ Gray

Assuming no magnetic field and only primary charged hadrons from pp collisions, we expect that the ionizing dose and the 1 MeV neutron equivalent fluence are only a function of the distance from the beampipe and independent of the detector orientations, and given by

$$1\text{MeV neq Fluence}[cm^{-2}] \approx \frac{N_0}{2r[cm]^2\pi} \times N_{pp}$$

$$\text{Dose}[Gray] \approx 3.2 \times 10^{-10} \frac{N_0}{2r[cm]^2\pi} \times N_{pp}$$

N_0 = dN/dη at mid rapidity
N_{pp} = number of pp collisions

Crosscheck with ATLAS Phase II LOI

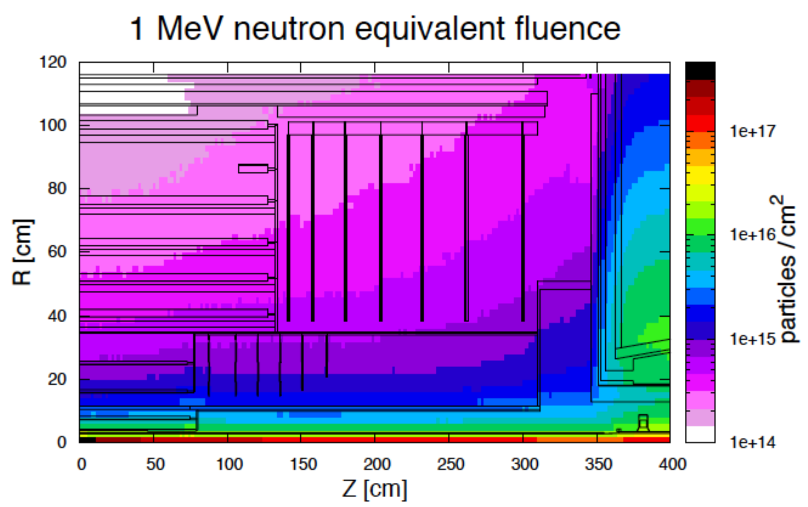


Figure 6.2: *RZ*-map of the 1 MeV neutron equivalent fluence in the Inner Tracker region, normalised to 3000 fb^{-1} of 14 TeV minimum bias events generated using PYTHIA8.

Layer	Occupancy with 200 pile-up events (%)				
	Radius mm	Barrel (z = 0 mm)		Z mm	Endcap
Pixel: layer 0	37	0.57	Disk 0	710	0.022– 0.076

3000 fb^{-1}
80mb inelastic pp crossection
2.4 * 10^{17} events
dN/dη = N0=5.4 at 14 TeV
Pixel layer1 at r=3.7cm

1MeVneq Fluence =
$2.4*10^{17}*5.4/(2*\pi*3.7^2)$ =
$1.5*10^{16}$ cm^{-2}

Dose = $3.2x10^{-8}*1.5*10^{16}$ =
4.8MGy

The predictions for the maximum 1MeV-neq fluence and ionising dose for 3000fb^{-1} in the pixel system is $1.4 \times 10^{16}cm^{-2}$ and 7.7 MGy at the centre of the innermost barrel layer. For the

Crosscheck with ATLAS Phase II LOI

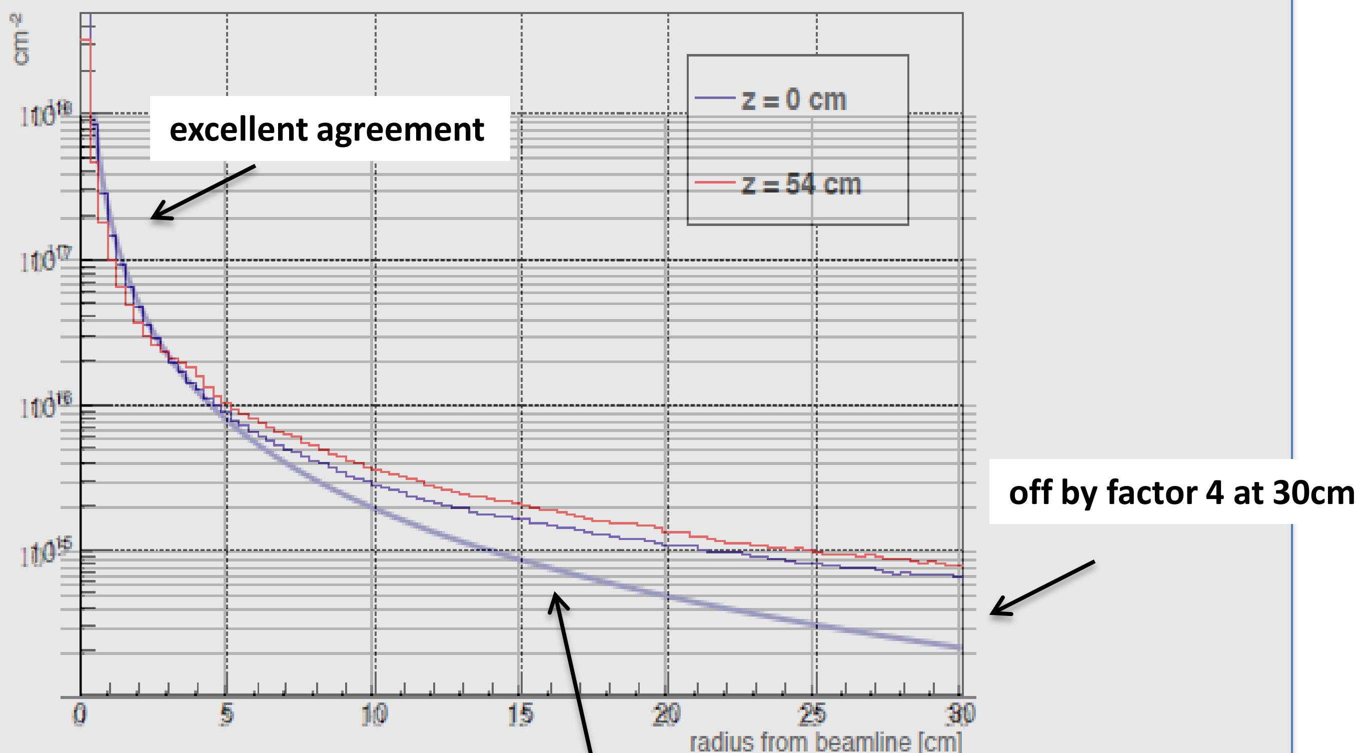


Figure 3. *Radial evolution of 1 MeV neutron equivalent fluence at z=0, 54 cm for an integrated fluence of 3000 fb⁻¹ [4].*

ATL-UPGRADE-PUB-2012-003

$$1\mathrm{MeV\ neq\ Fluence}[cm^{-2}] \approx \frac{N_0}{2r[cm]^2\pi} \times N_{pp}$$

Crosscheck with ATLAS Phase II LOI

ATL-UPGRADE-PUB-2012-003

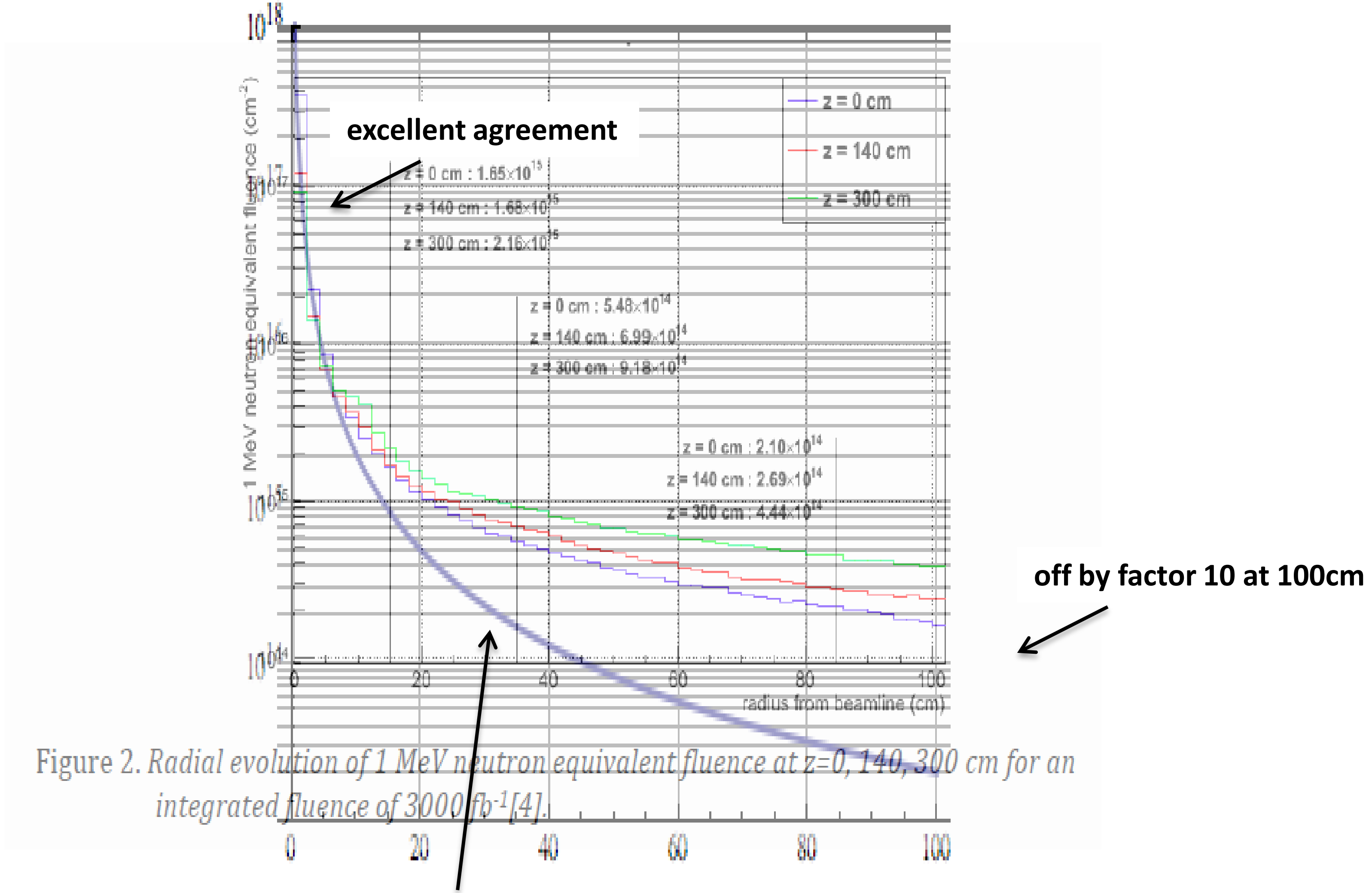


Figure 2. *Radial evolution of 1 MeV neutron equivalent fluence at z=0, 140, 300 cm for an integrated fluence of 3000 fb⁻¹[4].*

$$1\text{MeV neq Fluence}[cm^{-2}] \approx \frac{N_0}{2r[cm]^2\pi} \times N_{pp}$$

Estimated of the radiation load

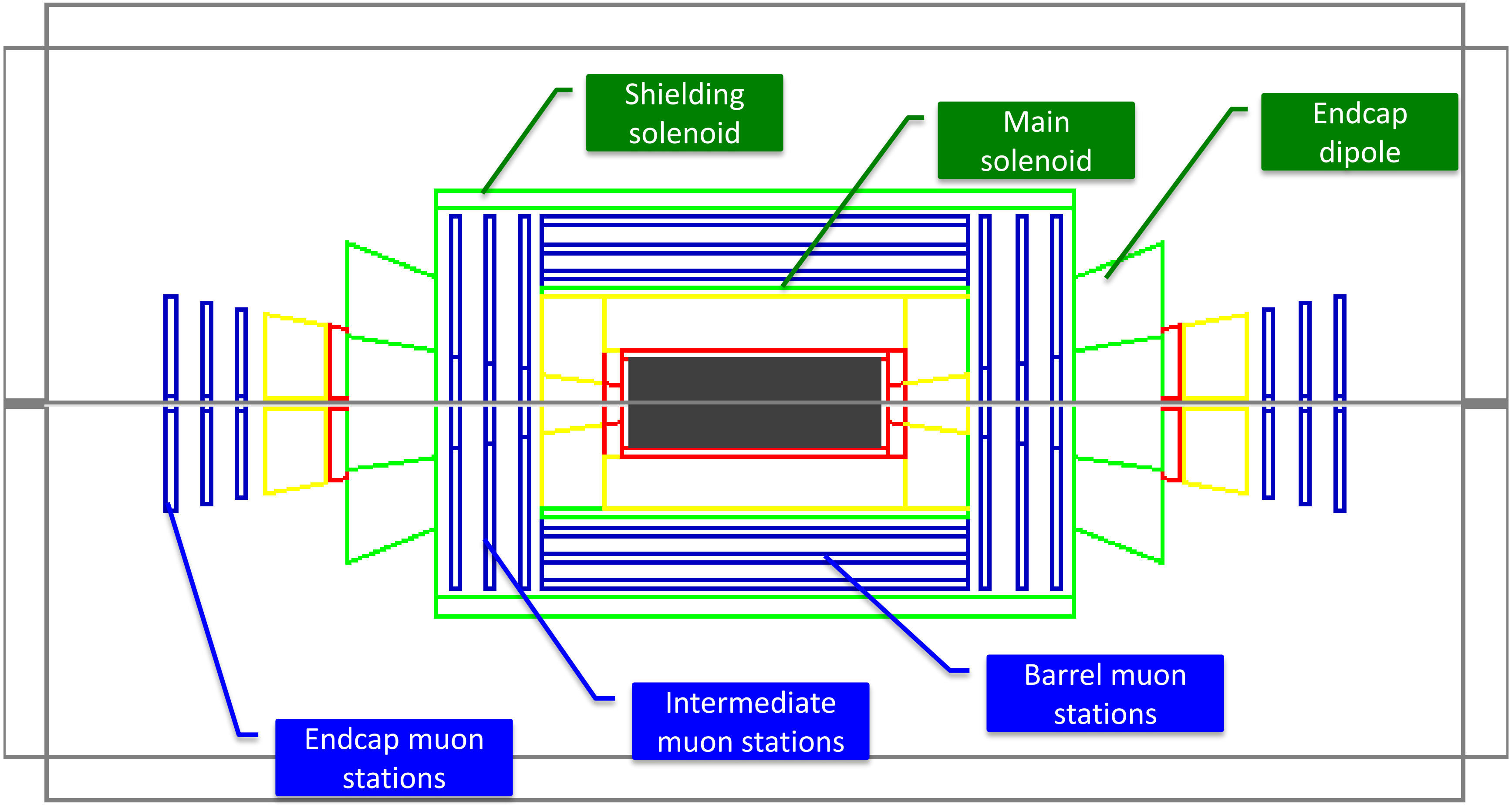
Radiation load of first Pixel Layer at r=3.7cm:

HL-LHC 3ab^{-1}
1MeVneq Fluence = 1.5×10^{16} cm^{-2}
Dose = 4.8MGy

FCC 3ab^{-1} (phase I)
1MeVneq Fluence = 2.8×10^{16} cm^{-2}
Dose = 9MGy

FCC 30ab^{-1} (phase II)
1MeVneq Fluence = 2.8×10^{17} cm^{-2}
Dose = 90MGy

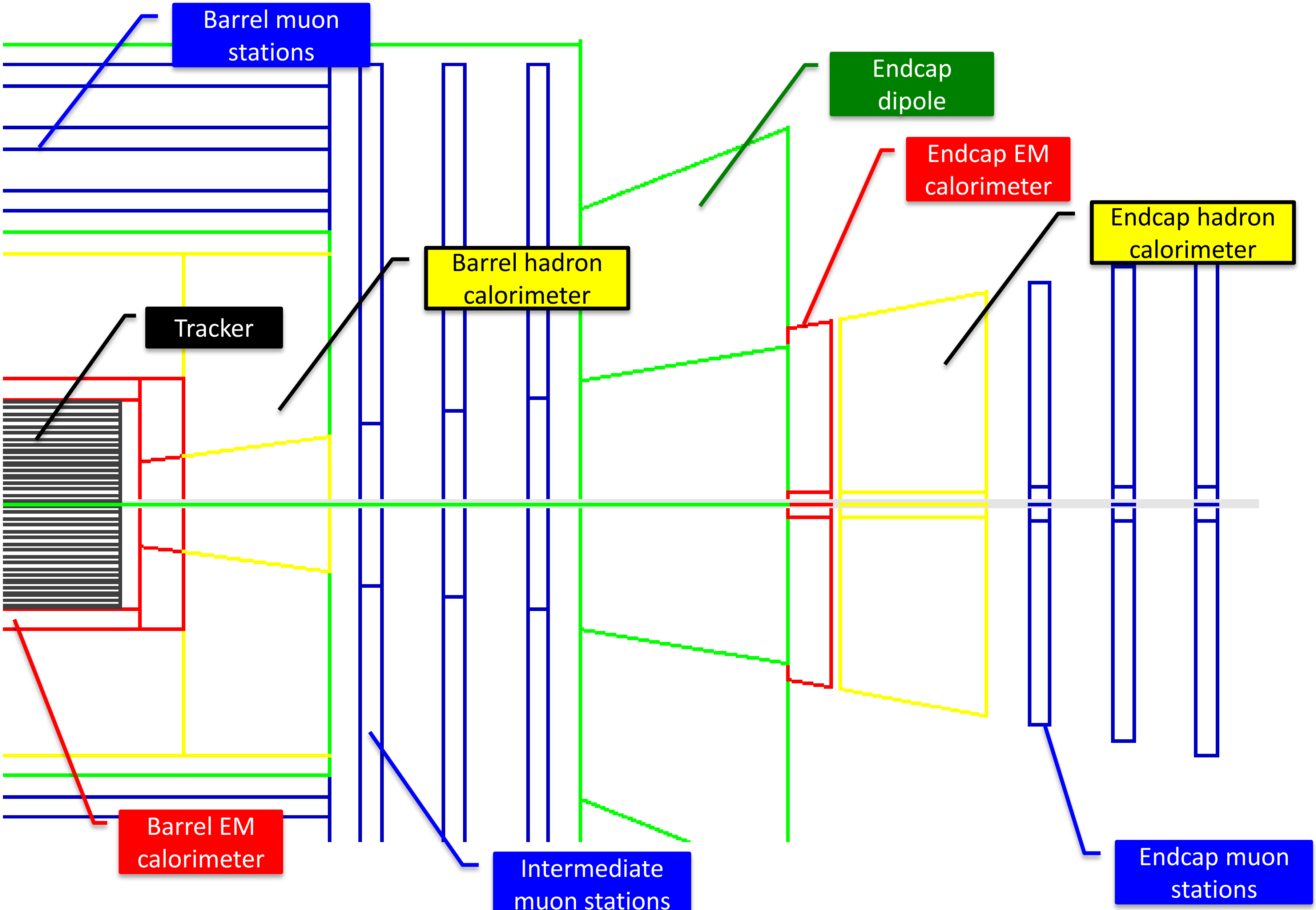
Magnets and Muon Detectors



From Charles C. Young

From Charles C. Young

Tracker and Calorimeters



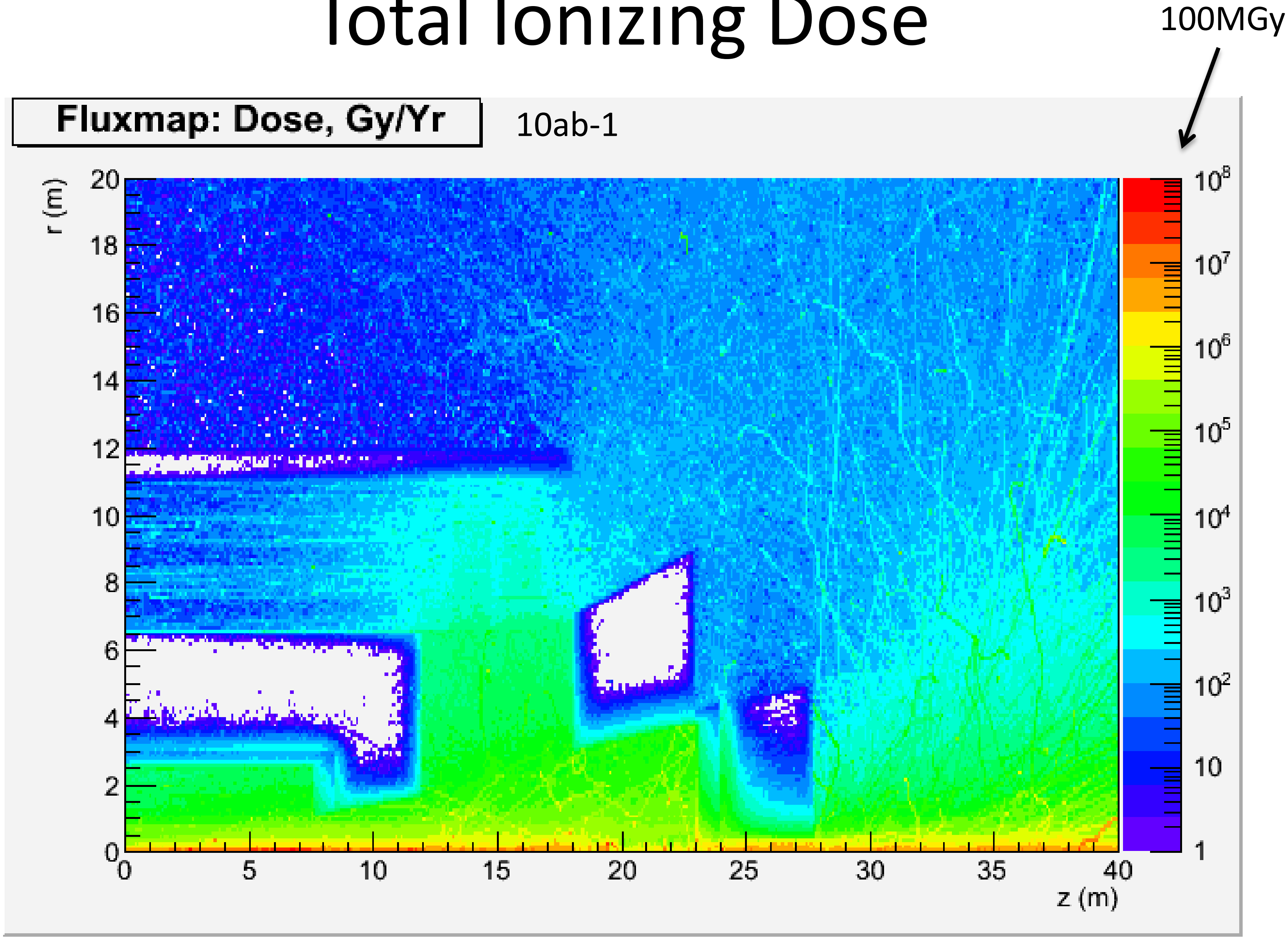
Simulated *pp* Events

- Phojet
- $\sqrt{s}$ = 100 TeV
- Normalization factors
  - σ_{pp} = 100 mb
  - Instantaneous luminosity = 10^{36} cm^{-2} s^{-1}
  - "Year" = 10^{7} sec

→ 10^{36} cm^{-2} s^{-1} x 10^{7} sec =10ab^{-1}

From Charles C. Young

Total Ionizing Dose

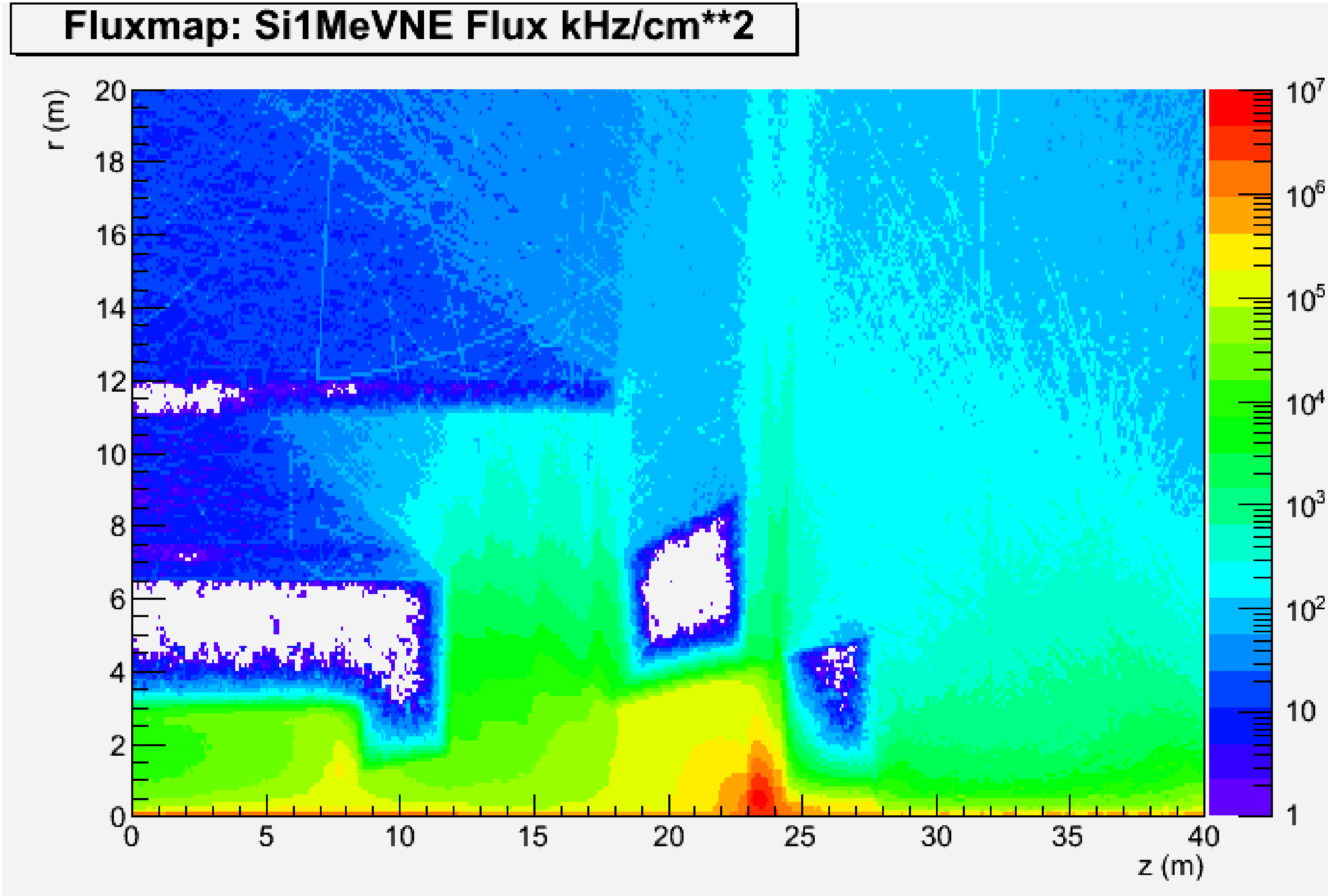


From Charles C. Young

1-MeV n_{eq} Fluence

10ab-1

10^7sx10^7kHz=10^{17}/cm^2



From Charles C. Young

Detector Simulation

Simulation Tools

Julia Hrdinka, Andreas Salzburger, Benedikt Hegner et al.

The aim of the present project is to establish a fast tracking simulation engine for the FCC detector design, directly derived from the full simulation engine. At this moment, the focus of this work is on tracking detectors, but the overall design is chosen to be compatible with all detector technologies.

The simulation steering of full, fast and parametric simulation will be enabled from one Gaudi based framework. The framework is fully embedded in the context of the FCC software group.

The event loop is done in the Gaudi Framework, while DD4Hep is used to describe and construct the detector. Afterwards this geometry has to be translated into geometries, used by the different simulations.

A dedicated DD4HepDetDesSvc was designed that invokes the conversion via converter tools. The converter tools have one common interface, allowing to add conversion tools to different geometries. At the moment there are two converters established:

The first tool induces to build the detector for the Geant4 detector simulation. This enables the integration of Geant4 based simulations (full and parametric simulation), within the framework. A full integration of Geant4 in this framework is foreseen.

The second tool builds the reconstruction geometry, which will be used for the fast simulation and reconstruction purposes. At the moment the tool for direct translation from the full DD4hep geometry into the simplified reconstruction geometry is being developed.

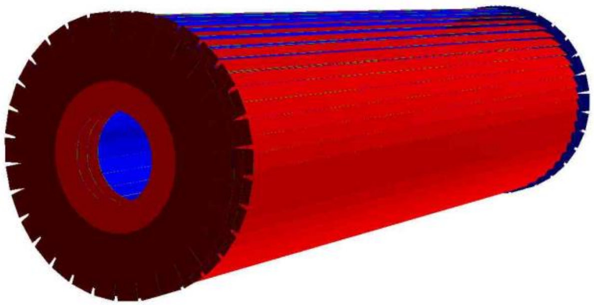
Simulation Tools

Julia Hrdinka, Andreas Salzburger

At present day it is possible to build a first test detector in the reconstruction geometry, from a DD4Hep Detector and make Histograms of the material distribution of specific modules. This test detector consists of box modules, made of different components, placed in cylindrical layers, for the barrel and disc layers, for the endcaps.

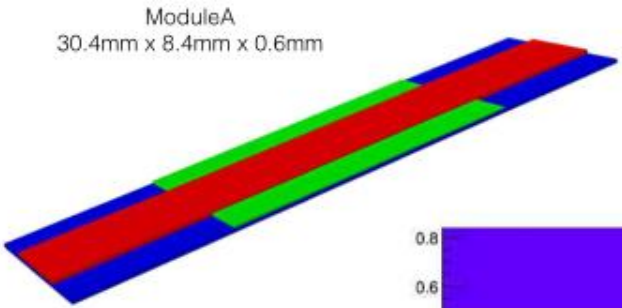
The next steps will be the implementation of the transport tool from the ATLAS code and the adaption of the Atlas Fast Track Simulation on the reconstruction geometry.

Then, the major fast simulation modules will be ported from existing ATLAS code and in a case study it will be shown, that both, full and fast detector simulation can be evoked from a common source and their output will be compared.

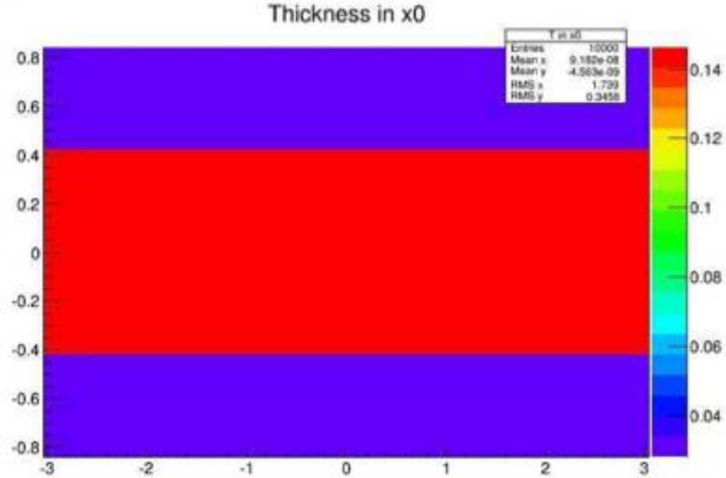


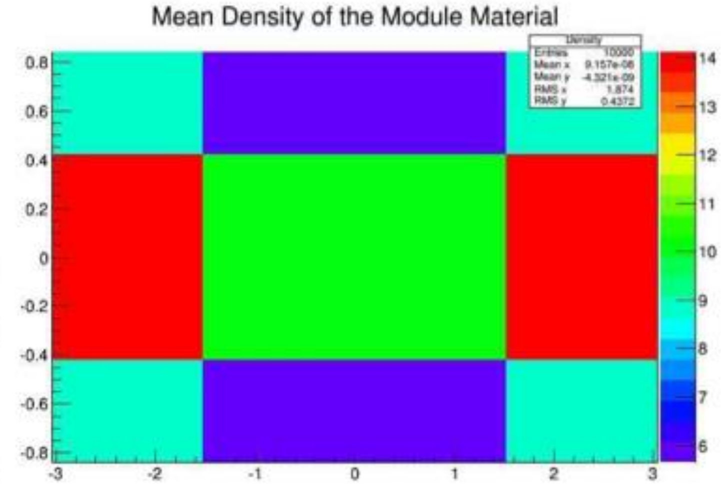
Approximation of a Module

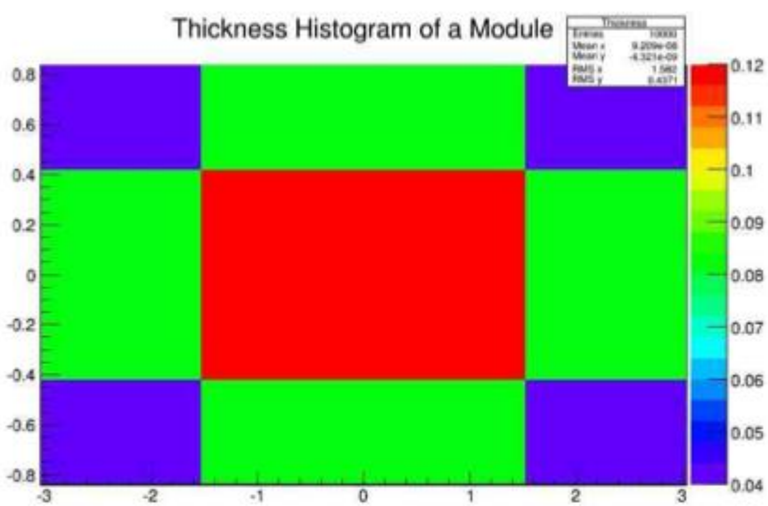
Example

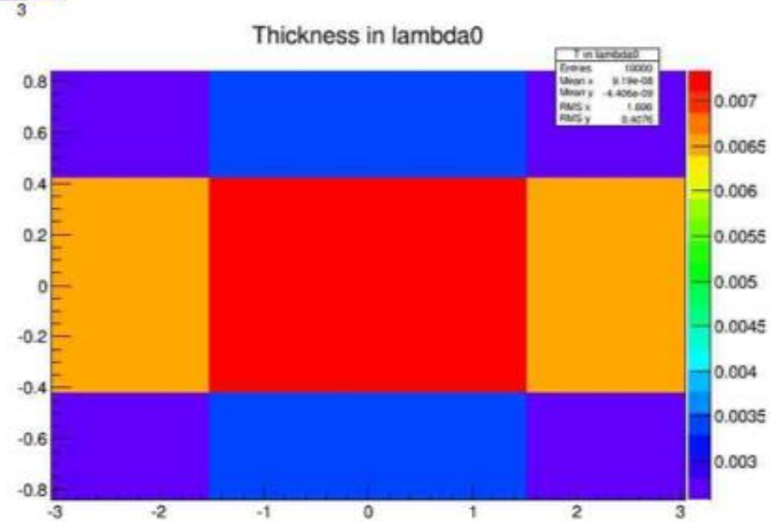


- Copper (30.4mm x 8.4mm x 0.2mm)
- Silicon (15.2mm x 8.4mm x 0.2mm)
- Tungsten (30.4mm x 4.2mm x 0.2mm)





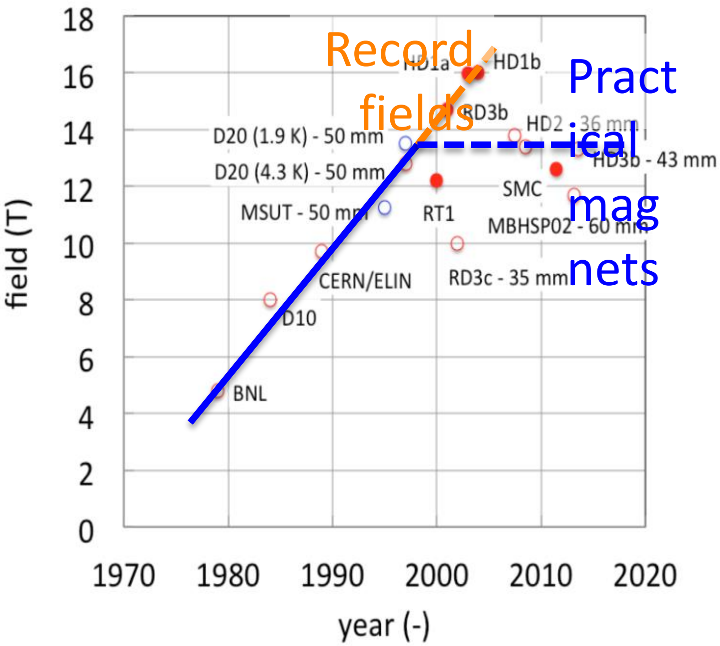


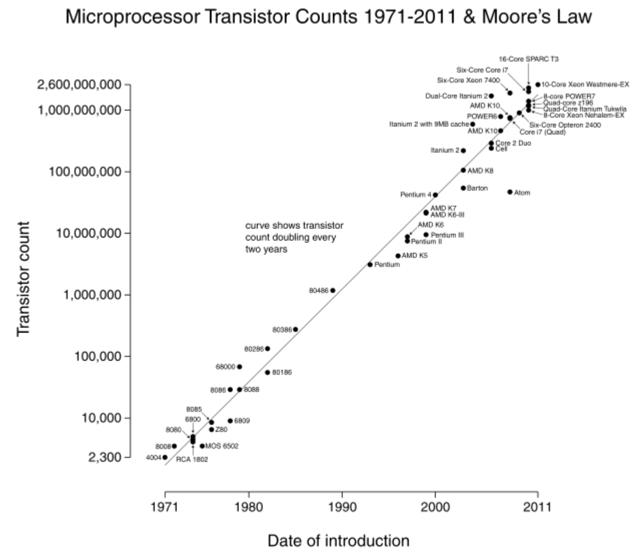


General Points

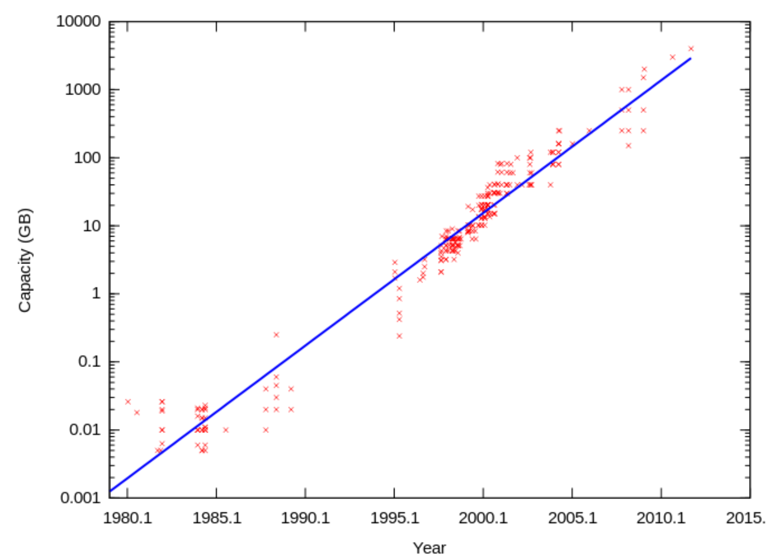
Informal meeting of the Future Hadron Collider group Jan. 27th 2014
https://indico.cern.ch/conferenceDisplay.py?confId=292284

Detector Technologies





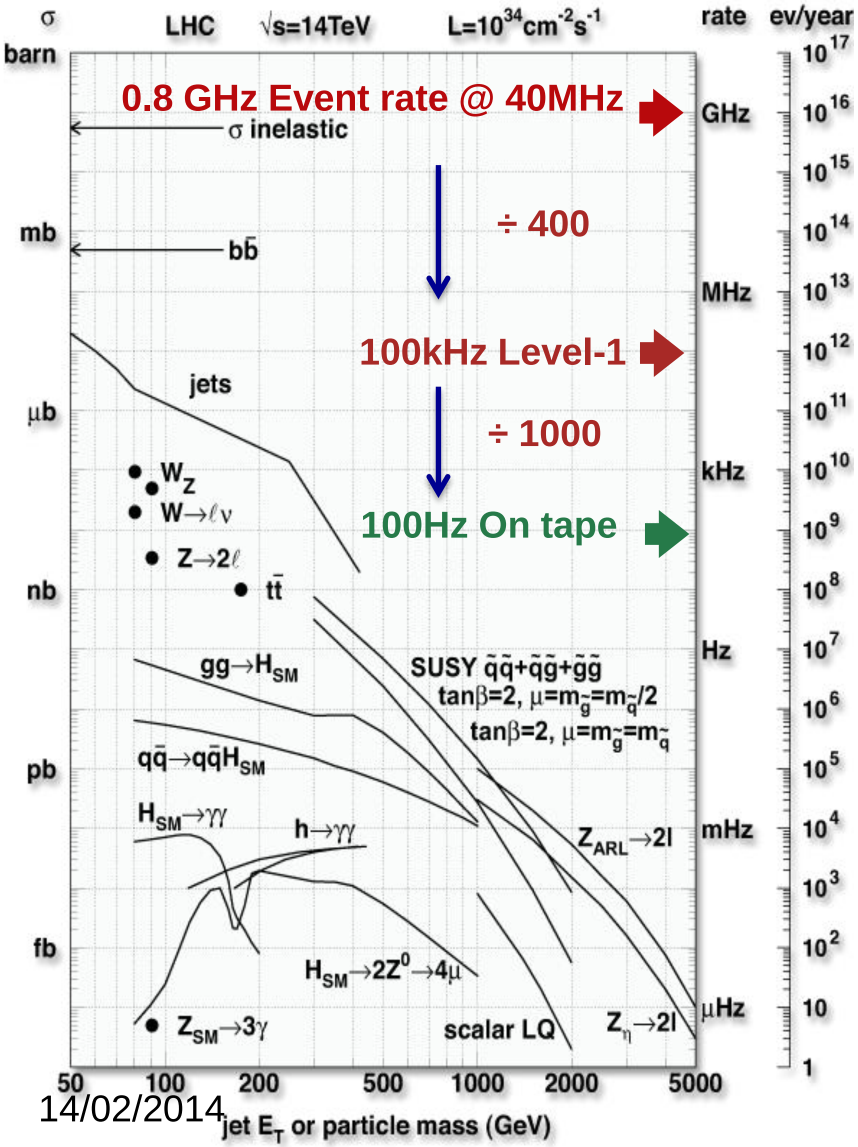
Magnets between 1980 to 2000: factor 3 with difficult prospects ...



Transistor count & storage capacity -- factor 2 every two years since 1960ies with good hope for continuation !

Assume factor 2^{10} = 1024 from 2014 – 2034 (of course optimistic)

LHC to HL-HLC



ATLAS/CMS plans for L=5x10^{34}

4 GHz Event Rate @ 40MHz

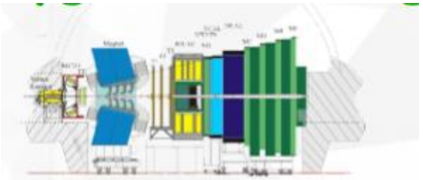
÷ 40

0.5-1 MHz Level-1 Rate

÷ 100

5-10kHz Rate to Tape

LHCb & ALICE in 2018



40 MHz

DAQ

40 MHz

LLT: μ,e/γ, hadrons

5-40 MHz

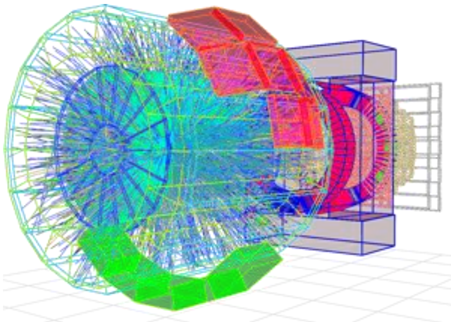
HLT: event recon.

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 Triggered vs. Triggerless Architectures (2022)

1 MHz (Triggered):

- **Network:**
  - 1 MHz with ~5 MB: aggregate ~40 Tbps **(→ 5 TByte/s)**
  - Links: Event Builder-cDAQ: ~ 500 links of 100 Gbps
  - Switch: almost possible today, for 2022 no problem
- **HLT computing:**
  - General purpose computing: 10(rate)x3(PU)x1.5(energy)x200kHS6 (CMS)
    - **Factor ~50 wrt today maybe for ~same costs**
  - Specialized computing (GPU or else): Possible

40 MHz (Triggerless):

- **Network:**
  - 40 MHz with ~5 MB: aggregate ~2000 Tbps **(→ 200 TByte/s)**
  - Event Builder Links: ~2,500 links of 400 Gbps
  - Switch: has to grow by factor ~25 in 10 years, difficult
- **Front End Electronics**
  - Readout Cables: Copper Tracker! – Show Stopper
- **HLT computing:**
  - General purpose computing: 400(rate) x3(PU)x1.5(energy)x200kHS6 (CMS)
    - **Factor ~2000 wrt today, but too pessimistic since events easier to reject w/o L1**
    - **This factor looks impossible with realistic budget**
  - Specialized computing (GPU or …)
    - **Could possibly provide this …**

Trigger

CMS assumes 5MByte/event for the Phase II upgrade detector i.e. for a levelled luminosity of $5x10^{34}$.

At 40MHz bunch crossing rate this results in 200TByte/s into the online system for a triggerless readout.

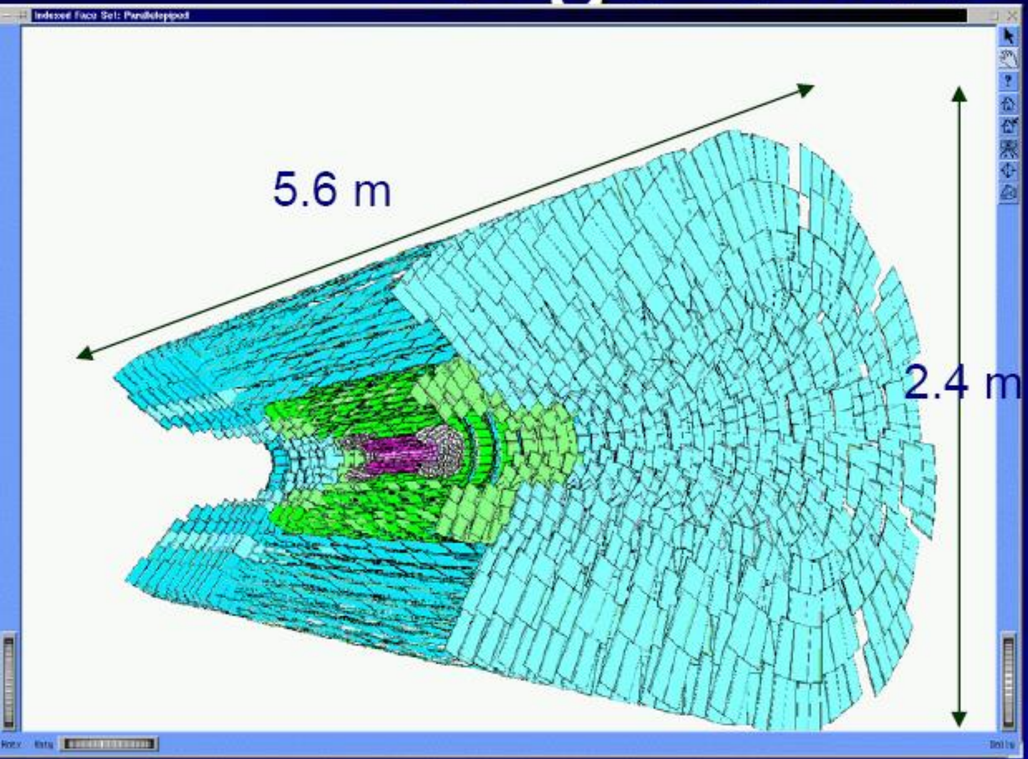
For 2022 this is considered too difficult.

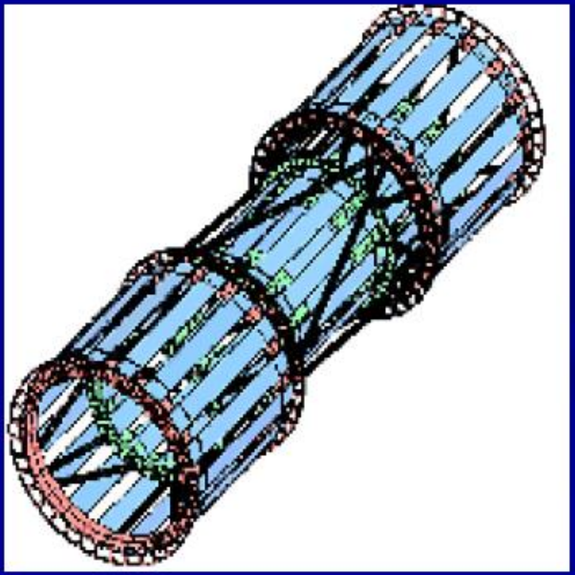
Assuming that the total track rate for 100TeV pp collisions (Phase I) is only a factor 2 larger, there is very little doubt that by 2035 and FCC-hh detector can be read out in a triggerless fashion.

In 2035 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.

Large Silicon Systems





CMS tracker (~2007)

12000 modules

~ 445 m^2 silicon area

~ 24,328 silicon wafers

~ 60 M readout channels

CDF SVX IIa (2001-)

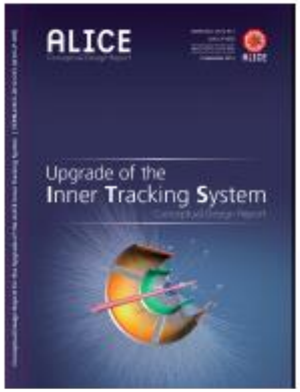
~ 11m^2 silicon area

~ 750 000 readout channels

ALICE 2018 upgrade, 20x20um monolithic pixels

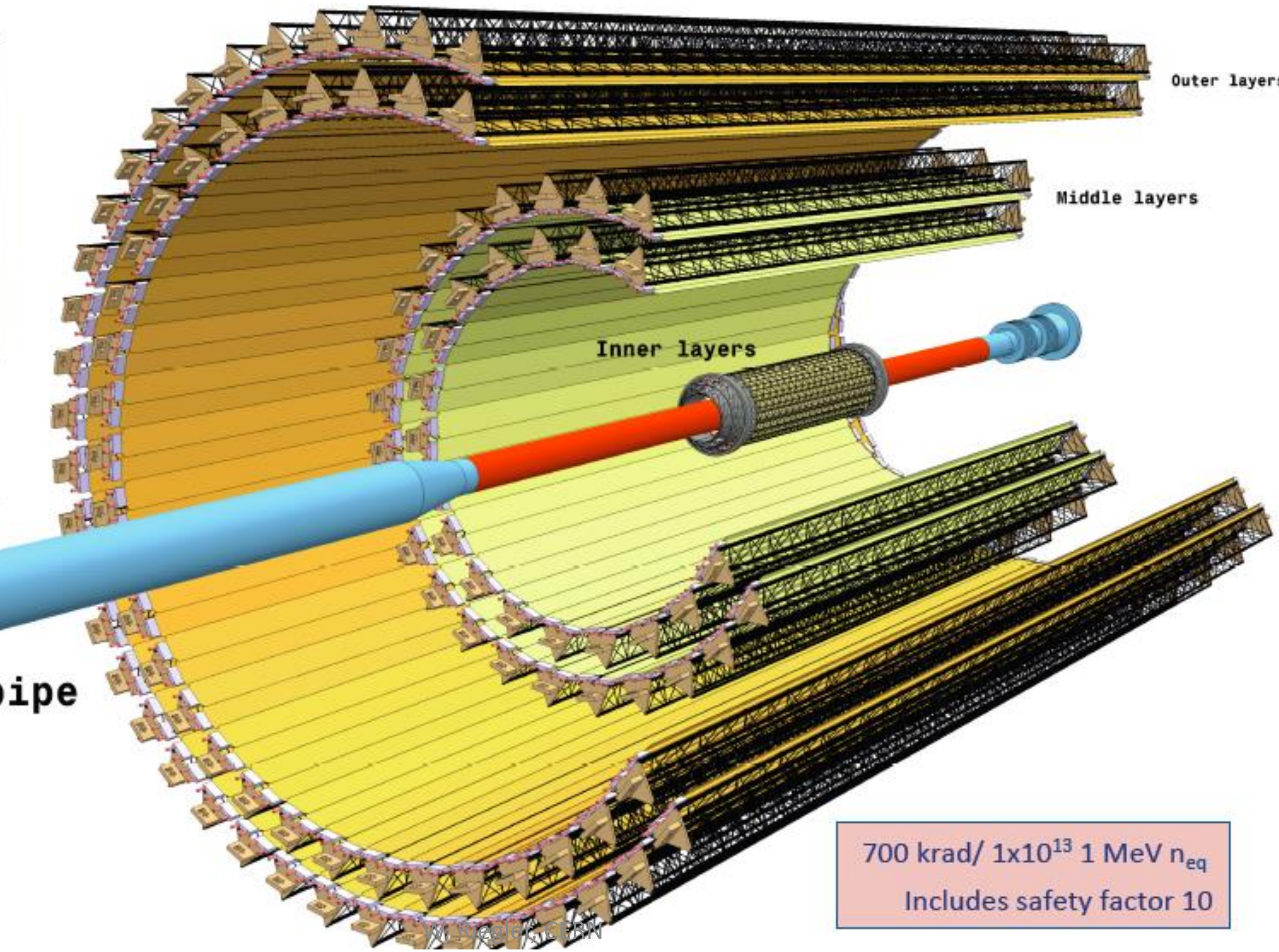
New ITS Layout

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



CERN-LHCC-2013-024

7 layers of MAPS

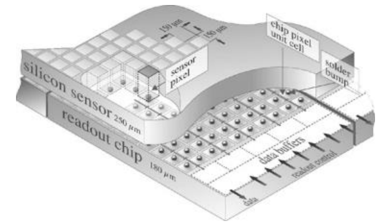


Radial coverage
22 – 406 mm

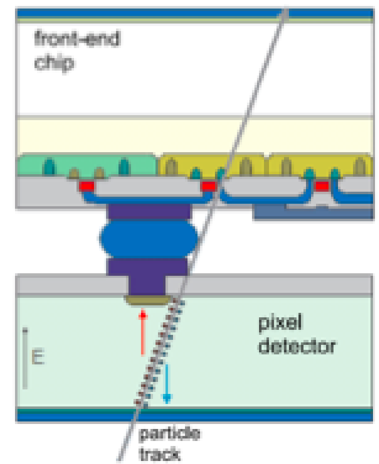
700 krad/ $1x10^{13}$ 1 MeV n_{eq}
Includes safety factor 10

CMOS Sensors

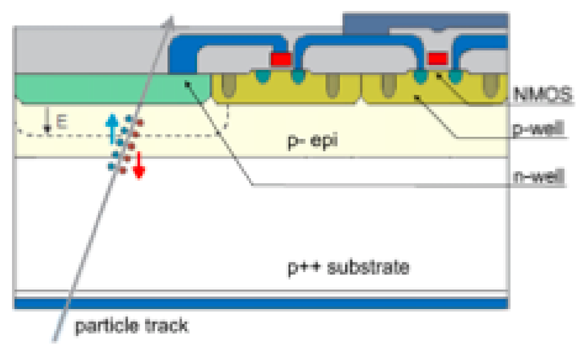
- CMOS sensors **contain sensor and electronics combined in one chip**
  - No interconnection between sensor and chip needed
- Standard CMOS processing
  - Wafer diameter (8")
  - Many foundries available
  - Lower cost per area
  - Small cell size – high granularity
  - Possibility of stitching (combining reticles to larger areas)
- Very low material budget
- CMOS sensors installed in STAR experiment
- Baseline for ALICE ITS upgrade (and MFT, LOI submitted to LHCC)



Hybrid Pixel Detector



CMOS (Pixel) Detector



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.

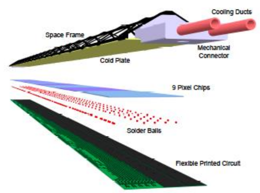
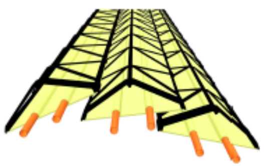
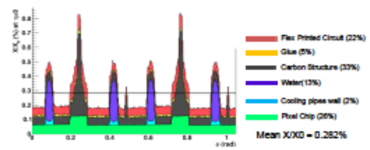
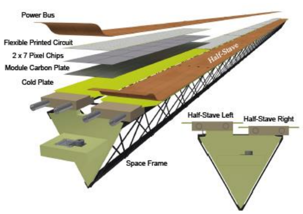
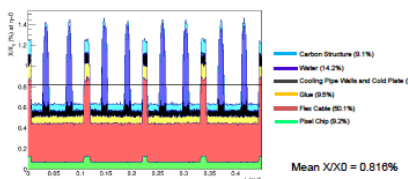


Figure 4.1: Schematic view of the Inner Barrel Stave.









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

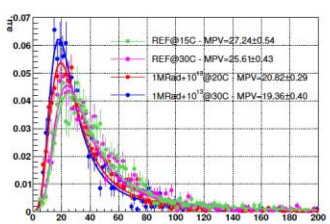


Figure 2.22: SNR of seed pixel measured with MIMOSA-32ter at the CERN-SPS, at two operating temperatures, before and after irradiation with the combined load of 1 Mrad and 10^{13} 1 MeV n_{eq}/cm^2.

Dramatic decrease in cost.

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

Ultra low material budget <0.3% 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 !!!

Top 10 IC Wafer Capacity Leaders* as of Dec-2013
(200mm-Equiv. Wafers per Month x1000)

2013 Rank	Company	Headquarters Region	Installed Capacity (K w/m)	% of Worldwide Total
1	Samsung	South Korea	1,867	12.6%
2	TSMC	Taiwan	1,475	10.0%
3	Micron**	Americas	1,380	9.3%
4	Toshiba/SanDisk	Japan	1,177	8.0%
5	SK Hynix	South Korea	1,035	7.0%
6	Intel	Americas	961	6.5%
7	ST	Europe	551	3.7%
8	UMC	Taiwan	520	3.5%
9	GlobalFoundries	Americas	482	3.3%
10	TI	Americas	441	3.0%
—	Total	—	9,889	66.8%

*Includes shares of capacity from joint ventures.

**Includes the former Elpida and Rexchip fabs.

Source: Companies, IC Insights

200mm wafer = 0.03m^2

10^6 wafers= 30 000 m^2

An FCC detector with 3000m^2 = 3 days

Data Rates For Heavy Ions

TABLE 1. Peak luminosity and Integrated luminosity per month of running.

	LHC Run 2 [1]	LHC after LS2 [1]	FHC [2]
Pb–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{27}	5×10^{27}	13×10^{27}
Pb–Pb L_{int} / month (nb^{-1})	0.8	1	5
p–Pb peak $\mathcal{L}$ ($cm^{-2}s^{-1}$)	10^{29}	t.b.d.	3.5×10^{30}
p–Pb L_{int} (nb^{-1})	80	t.b.d.	1000

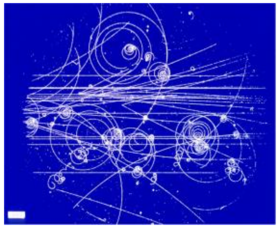
TABLE 2. Pb–Pb collisions at 2.76, 5.5 (extr) and 39 (extr) TeV.

Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

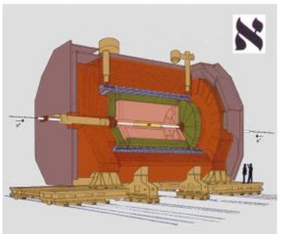
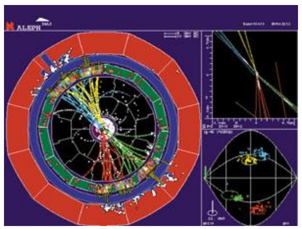
pp: $L=5\times10^{34}$, σ=100mb, dN/deta = 8
→ 40GHz of tracks per unit of rapidity

PbPb: $L=13\times10^{27}$, σ=8barn, dN/deta = 1000 (Min. Bias)
→ 0.1GHz of tracks per unit of rapidity

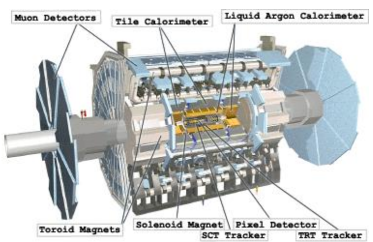
→ If bandwidth is fine for pp it is fine for PbPb

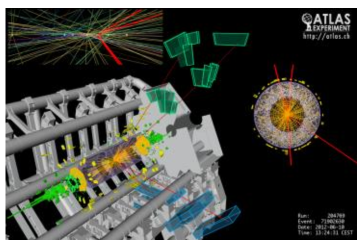



BEBC photopgraphs, untriggered

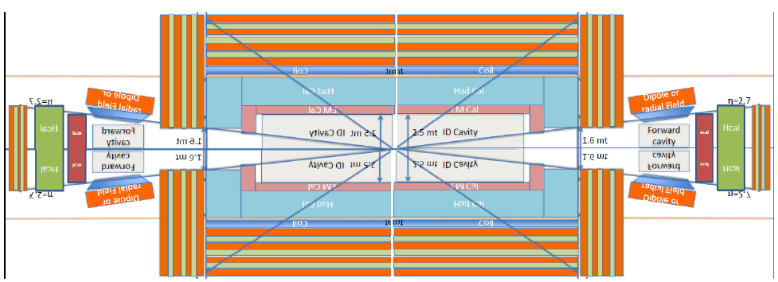



ALEPH triggered, only wire chamber readout.





ATLAS/CMSLHCb/ALICE complex trigger, Si, Larg, Wires, RPC, Crystals, Scintillator ...



Only one pixel chip, for tracking and calorimetry with triggereless readout to PCs ?

Conclusion

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.

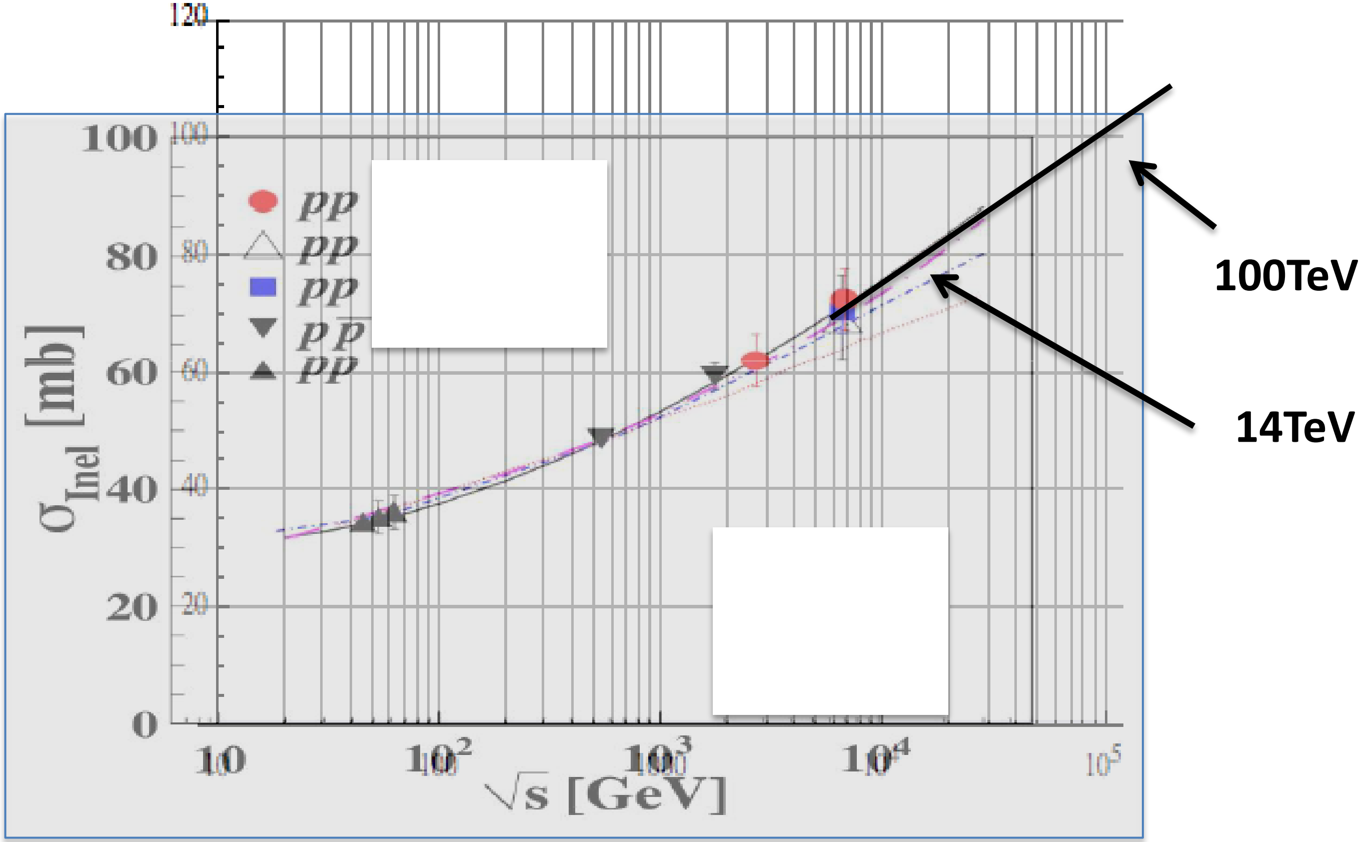
Since the maximum energy an delivered luminosity are the key goals for the FCC-hh machine, the detector efforts should not put any constraints at the machine efforts, and a basic set of parameters was defined.

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

Radiation hard monolithic silicon detectors pixel sensors produced with standard CMOS processes are a very intriguing possibility. Detector mechanics and tricks to transport data from the sensors are the interesting challenges.

The R&D on these technologies will and should naturally happen within the R&D for the HL-LHC detectors.

Inelastic pp crossection



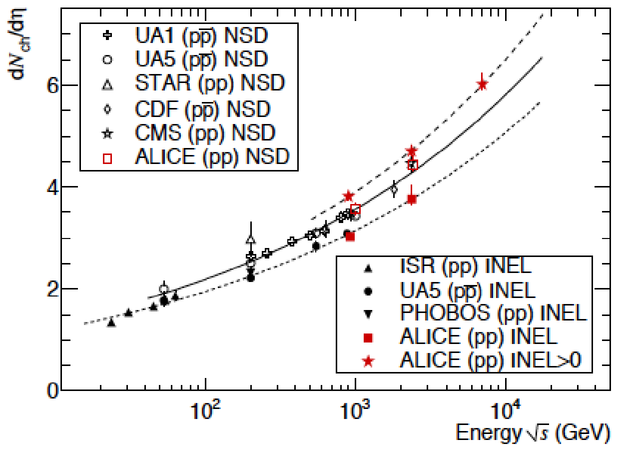
Inelastic pp crossection, hand extrapolation from data up to 7 TeV:

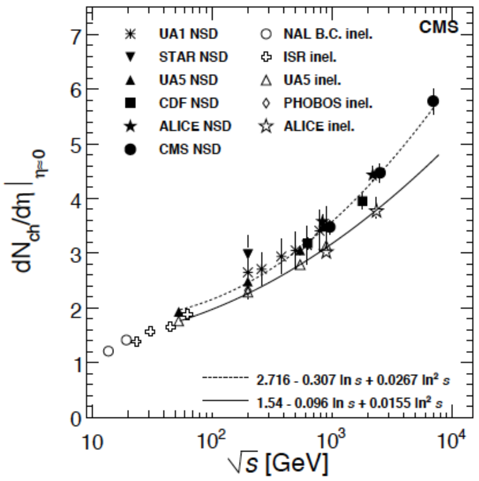
≈ 80mb at 14TeV

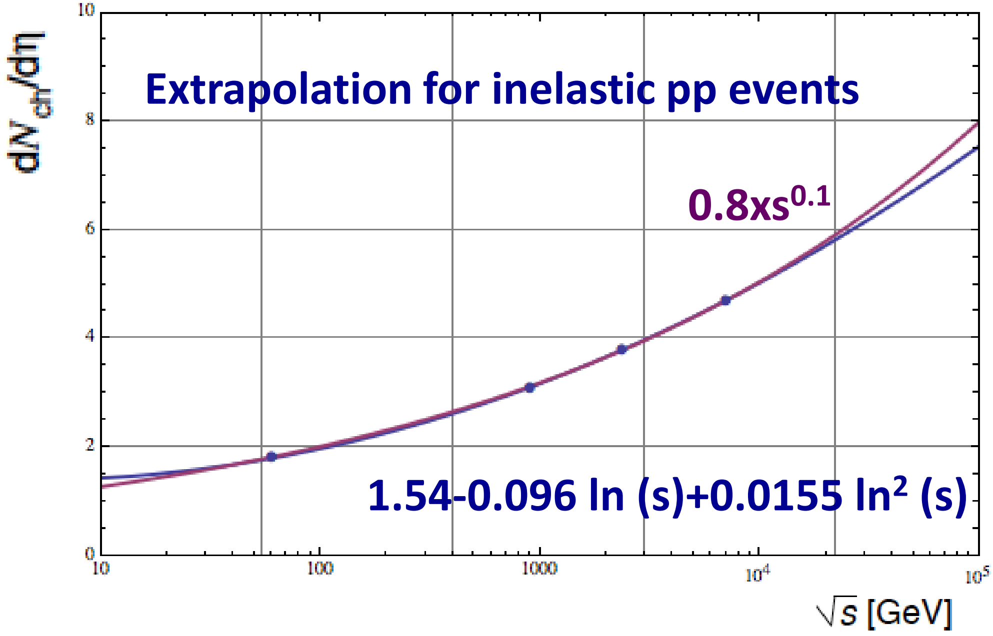
≈ 100mb at 100TeV

→ 25% increase

Multiplicities



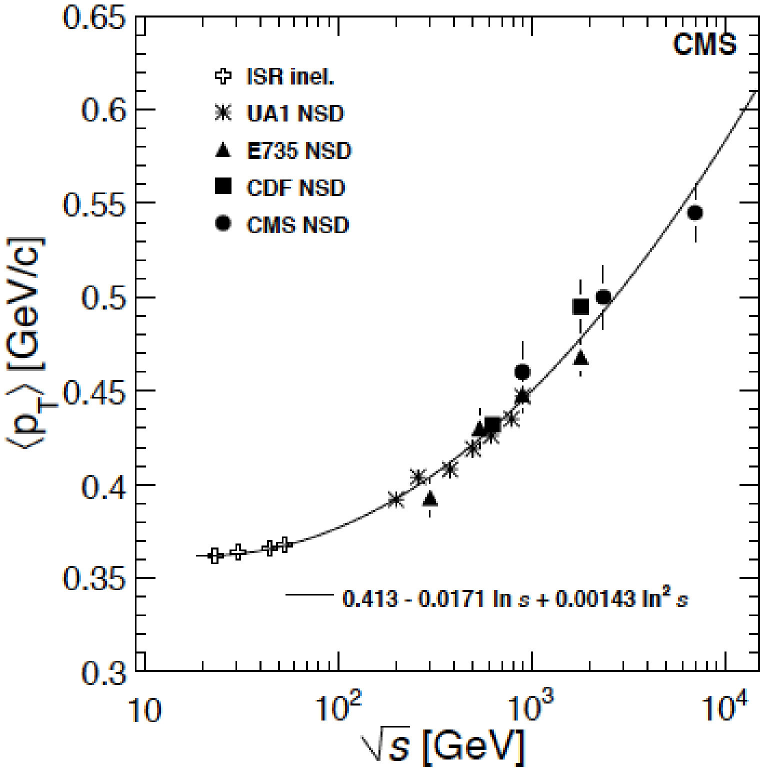


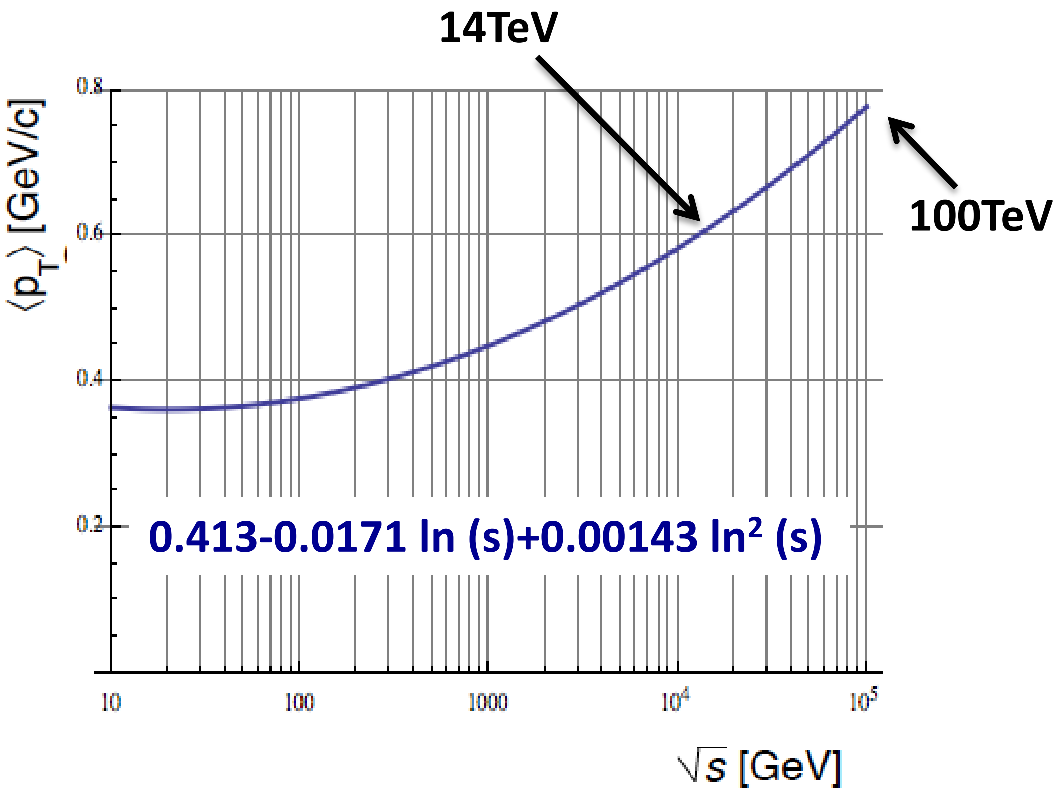


100TeV

Charged particle multiplicity at
14TeV ≈ 5.4
100TeV ≈ 8
→ only about 1.5 times larger

Average Particle Momentum

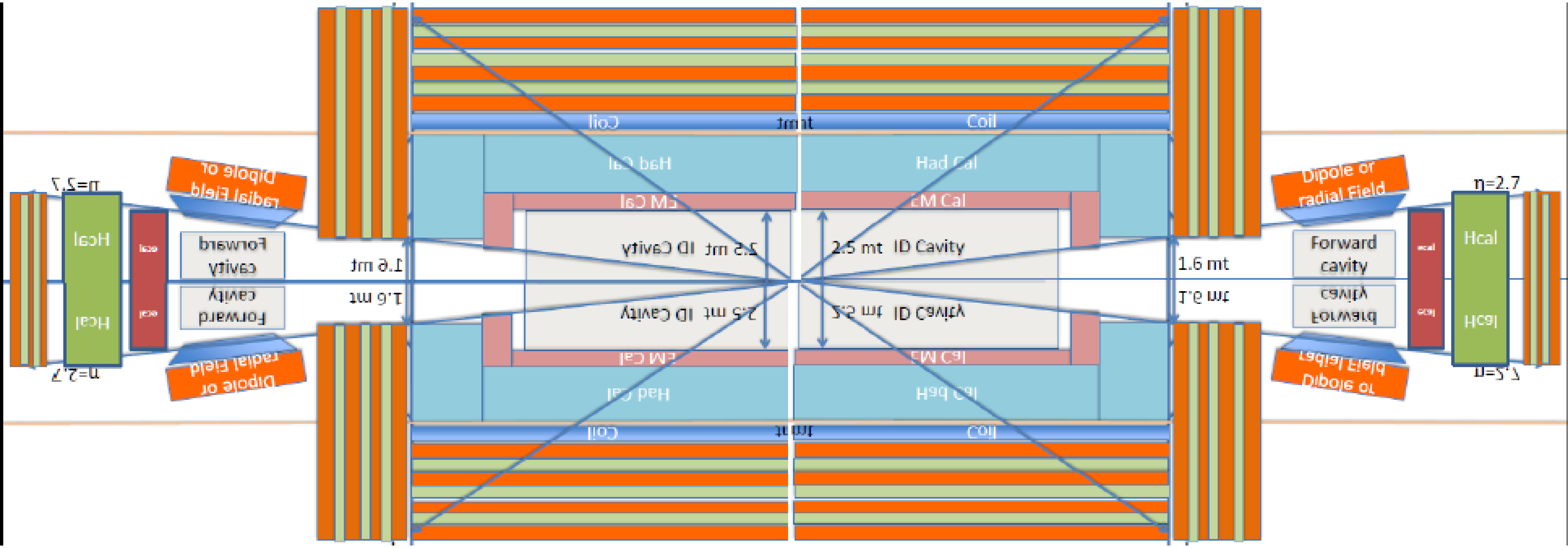




Average p_T approx. 0.6GeV/c for 14 TeV and 0.8GeV/c at 100TeV
i.e. increase of 33%.

Bending in radius in 4T field:
R[m] = 3.33 * p_T[GeV/c] / B[T] = 3.33 * 0.8/4 = 0.67m

→ Average particle will curl with 1.33m diameter inside the ID.



Curling circle of average p_T particle at B=4T