Possible Detector Developments for a Future O(100TeV) Hadron Collider

Exploring the Physics Frontier with Circular Colliders
Aspen Winter Conference
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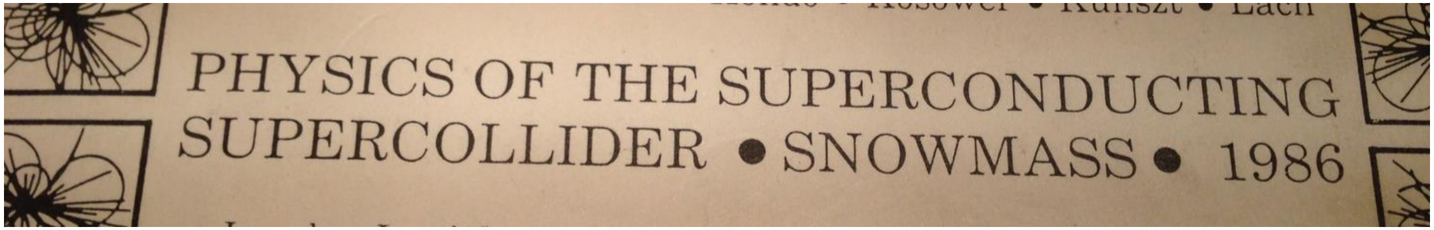
W. Riegler, CERN

SSC detector concepts



PHYSICS OF THE SUPERCONDUCTING SUPERCOLLIDER • SNOWMASS • 1986

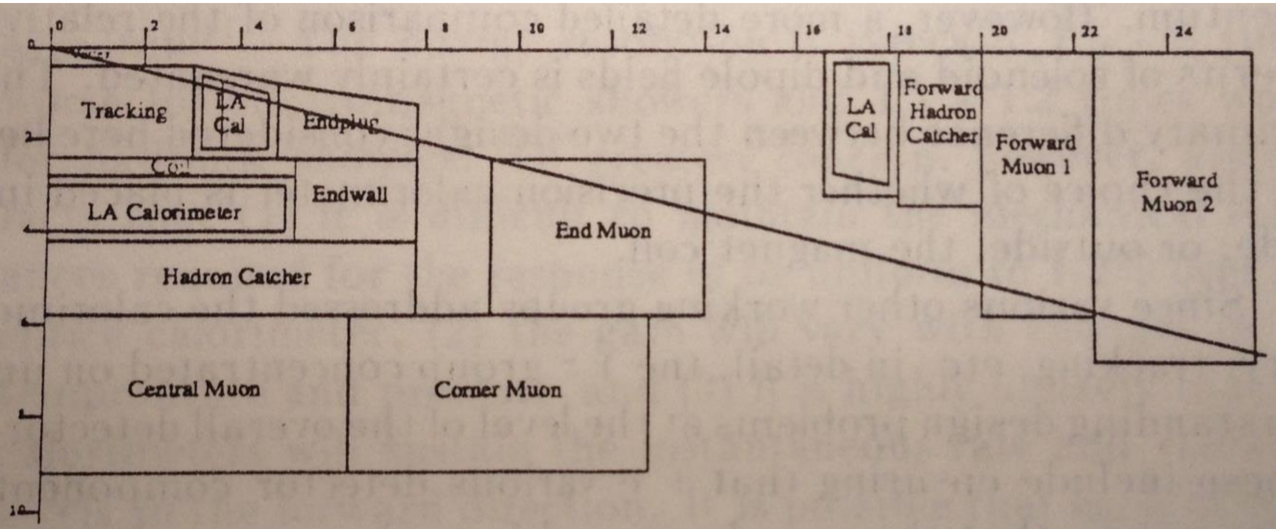
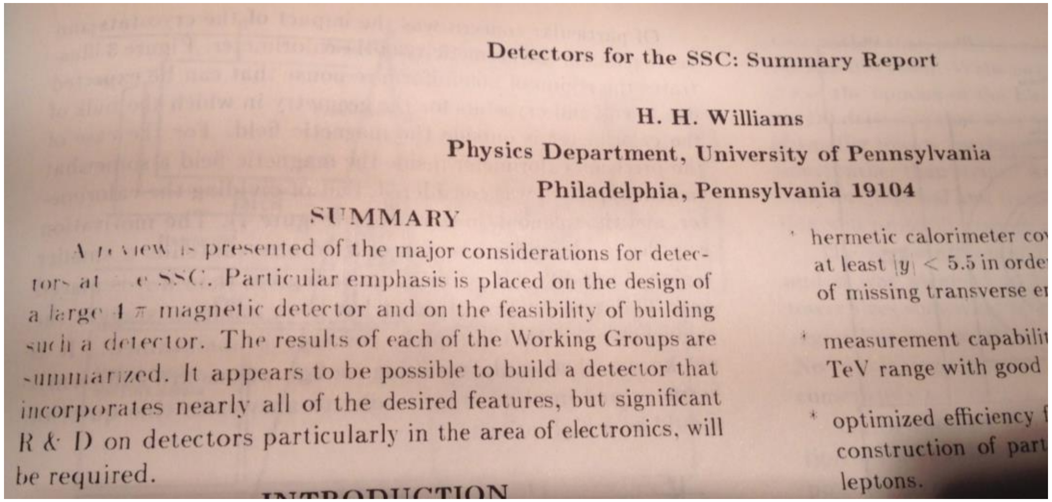


Figure 1a

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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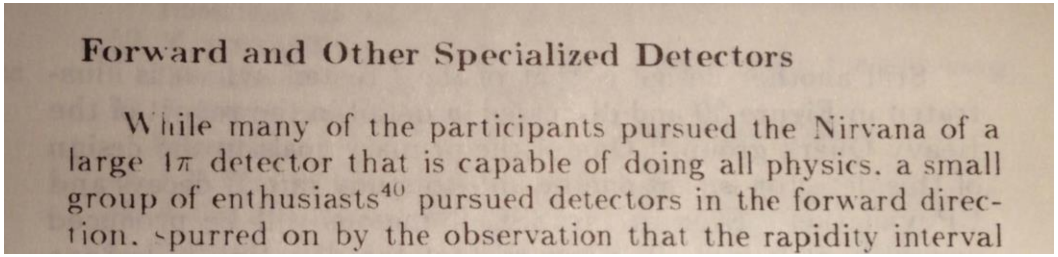
SUMMARY

A review is presented of the major considerations for detectors at the SSC. Particular emphasis is placed on the design of a large 4 π 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.

INTRODUCTION

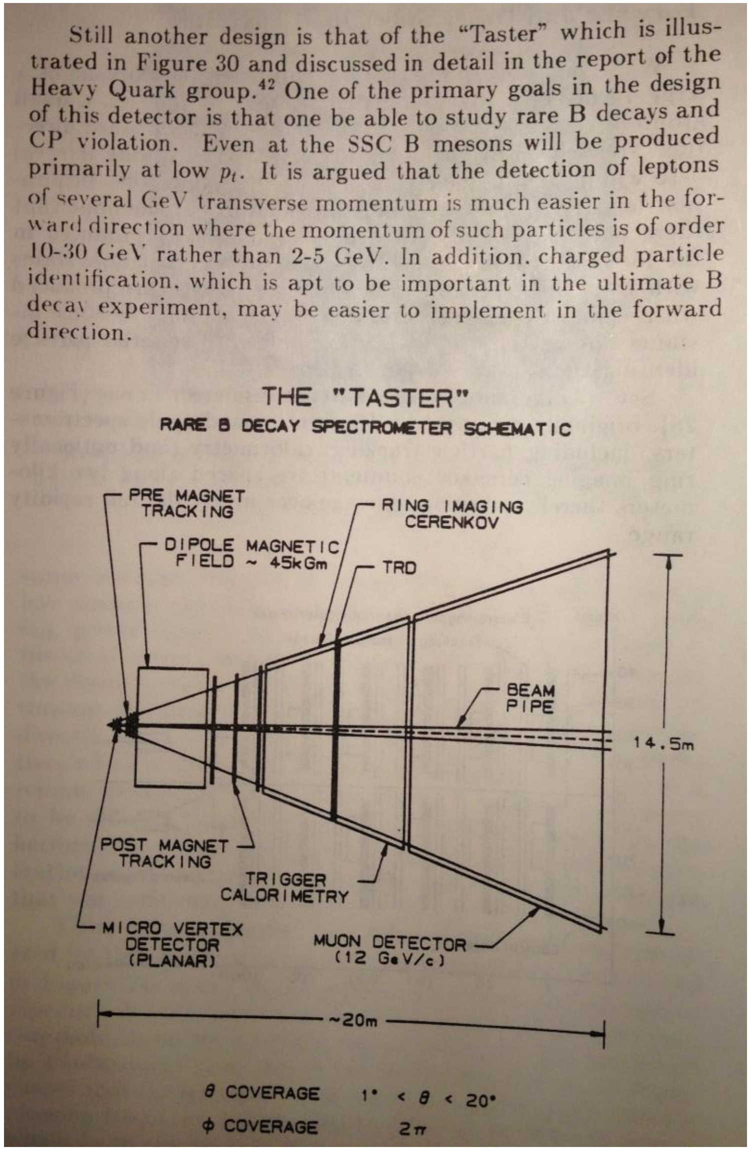
- hermetic calorimeter co at least $|y| < 5.5$ in orde of missing transverse e
- measurement capabili TeV range with good
- optimized efficiency construction of part leptons.



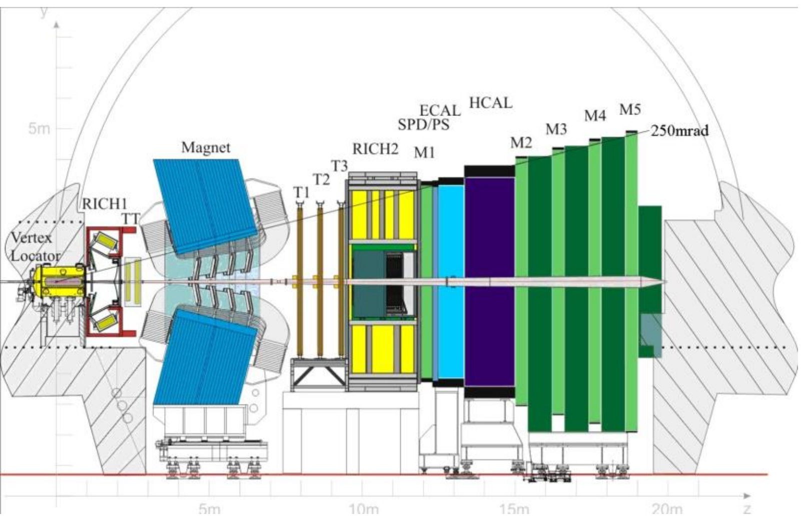
Forward and Other Specialized Detectors

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 …



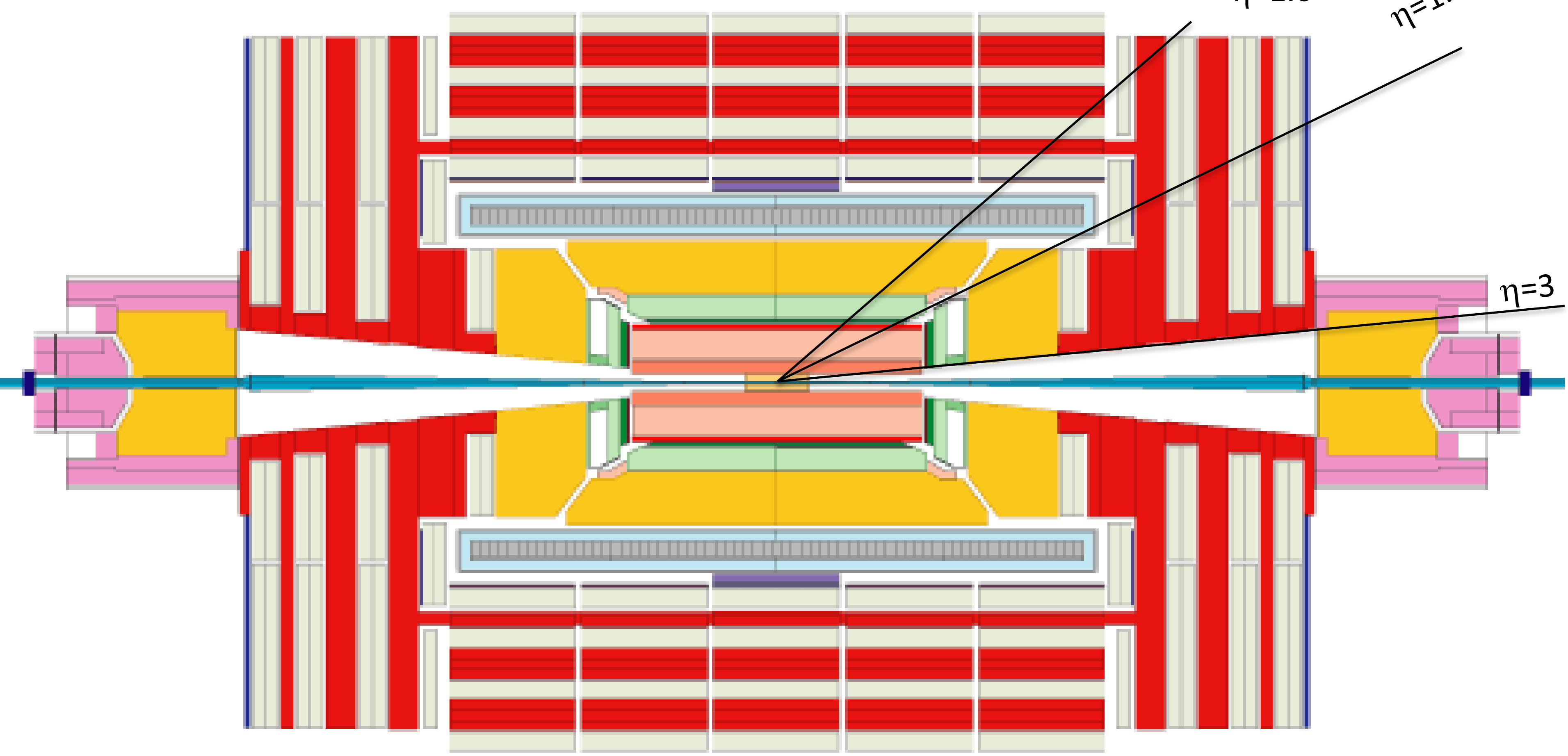
Still another design is that of the "Taster" which is illustrated in Figure 30 and discussed in detail in the report of the Heavy Quark group.[42] One of the primary goals in the design of this detector is that one be able to study rare B decays and CP violation. Even at the SSC B mesons will be produced 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

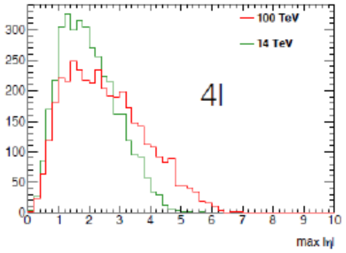


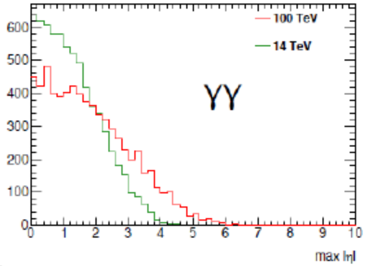
3 Approaches to design Hadron Detectors for a 100TeV Collider

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

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

ggF



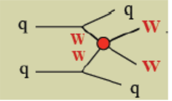


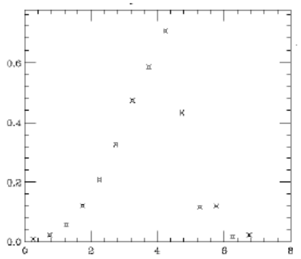
		|η| < 2.5	|η| < 4	|η| < 5
ll	100 TeV	0.56	0.88	0.97
	14 TeV	0.74	0.99	0.99
YY	100 TeV	0.74	0.95	0.99
	14 TeV	0.90	1	1

η=2.5
↓
η>4

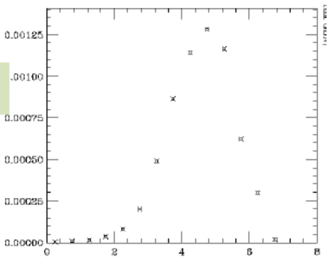
Physics moving forward …

VBF jets acceptance





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)

Concepts for Detector Magnets for a 100 TeV proton-proton collider

Herman ten Kate and Jeroen van Nugteren
following discussions with D. Fournier, F. Gianotti, A. Henriques, L. Pontecorvo

14 February 2014

Content

1. Requirements, design drivers

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

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

BL^2 has to be increased by factor 7!

---> 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!

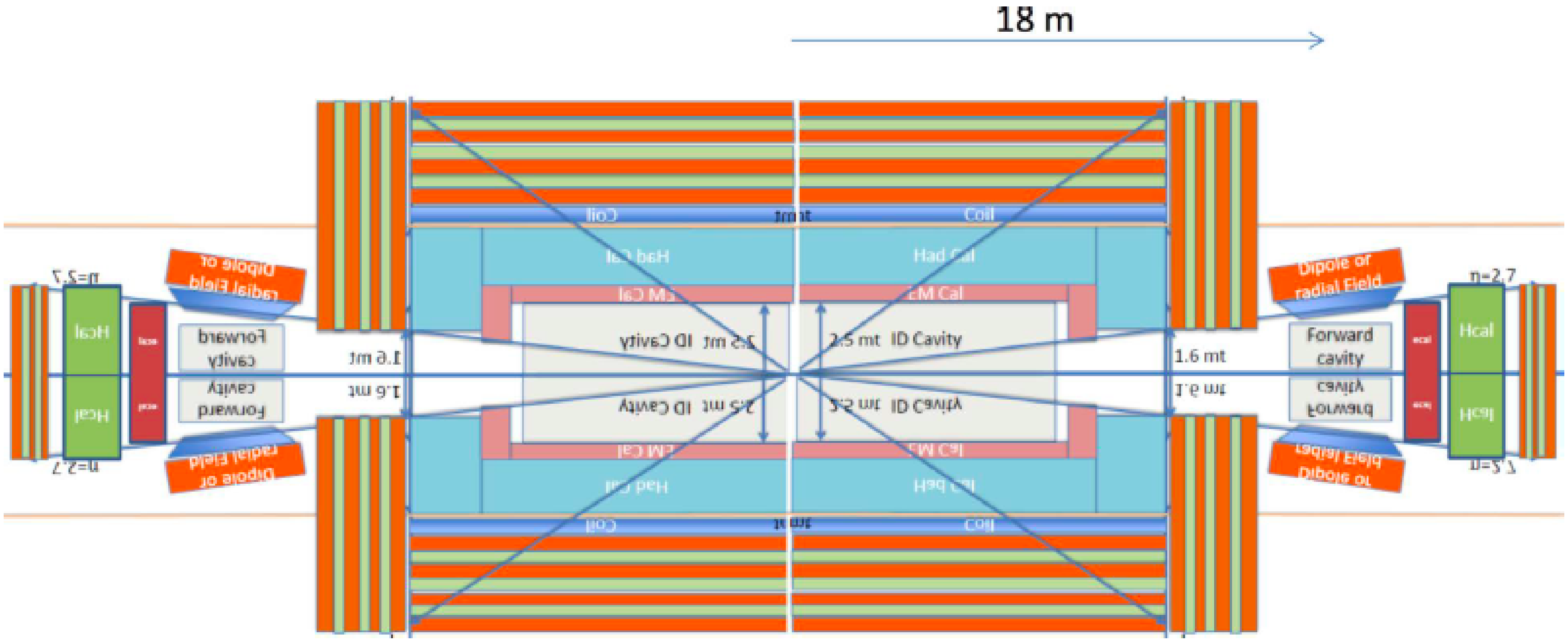
HCAL depth from 10 λ to 12λ (iron) radial thickness some 3.0 m!

---> 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.

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



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

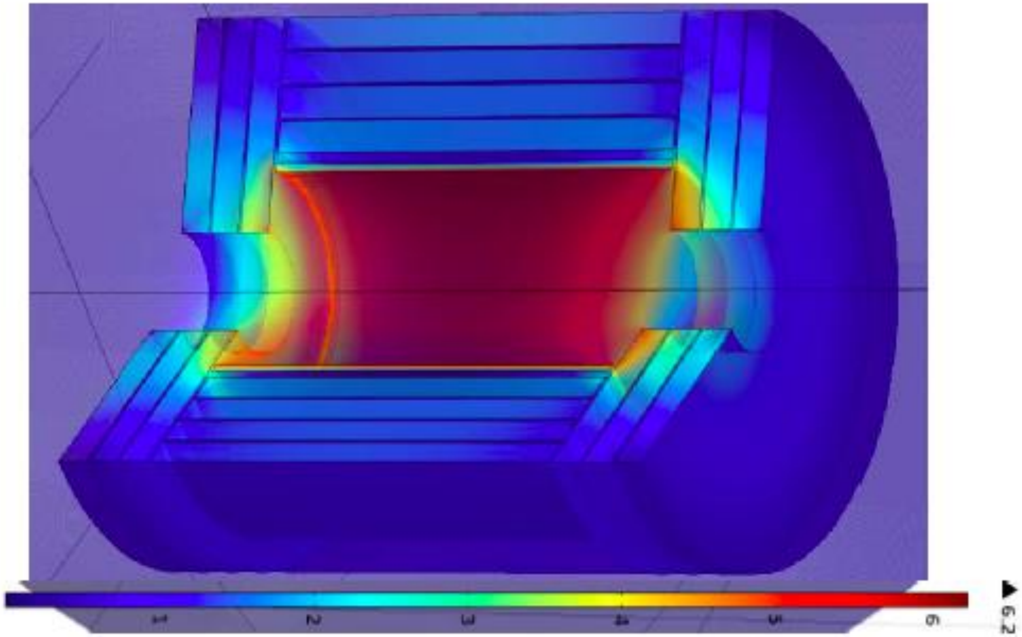
+ massive Iron yoke for flux return (shielding) and muon tagging.

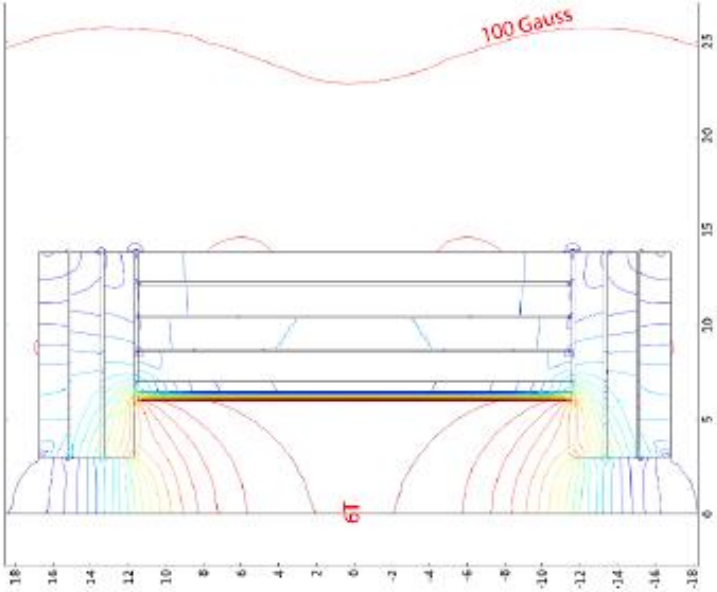
Dipoles: 10 Tm with return yoke placed at 18 m.

Practically no coupling between dipoles and solenoid.

They can be designed independently at first.

Option 1: Solenoid-Yoke + Dipoles

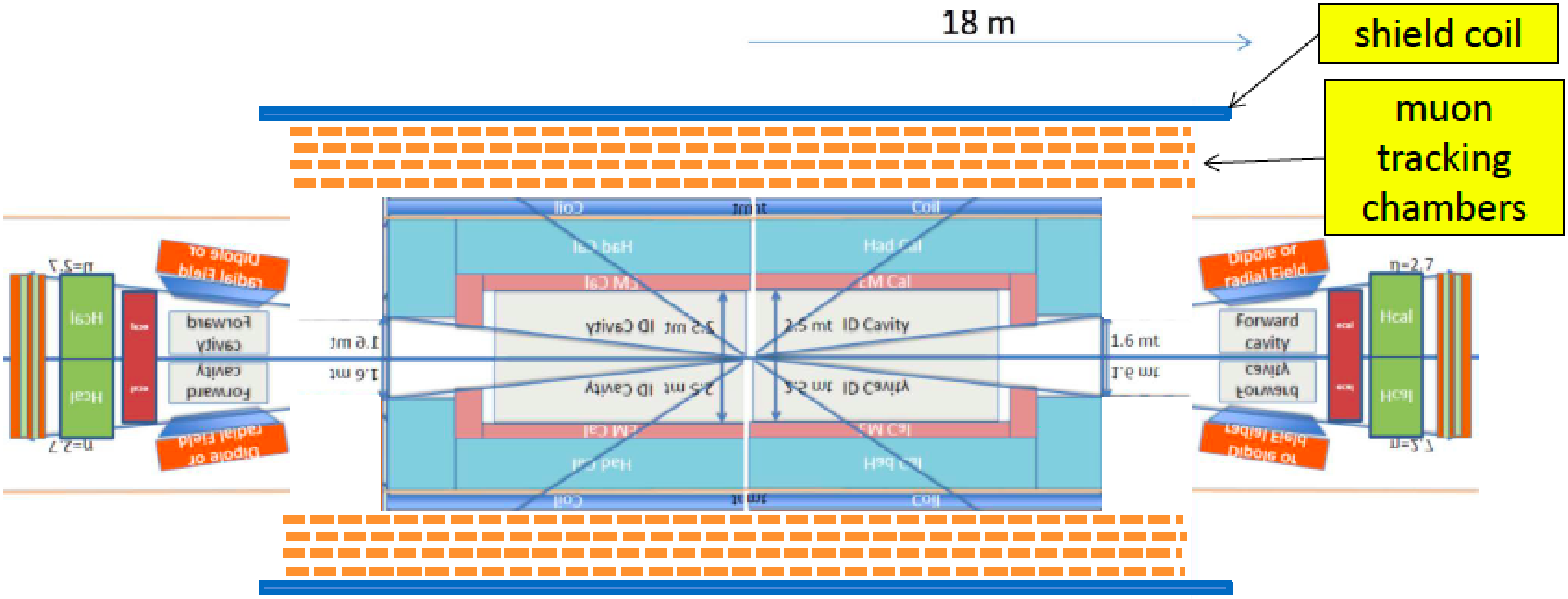




6 T in a 12 m bore, 23 m long, 28 m outer diameter.

- Stored energy 54 GJ, 6.3 T peak field.
- Yoke: 6.3 m thick iron needed to have 10 mT line at 22 m , 15 m^3, **mass ≈120,000 ton** (>200 M€ raw material).
- Note this huge mass! Realize consequences for cavern floor, installation, opening -closing system ---> bulky, not an elegant design.

Option 2: Twin Solenoid + Dipoles


18 m

shield coil

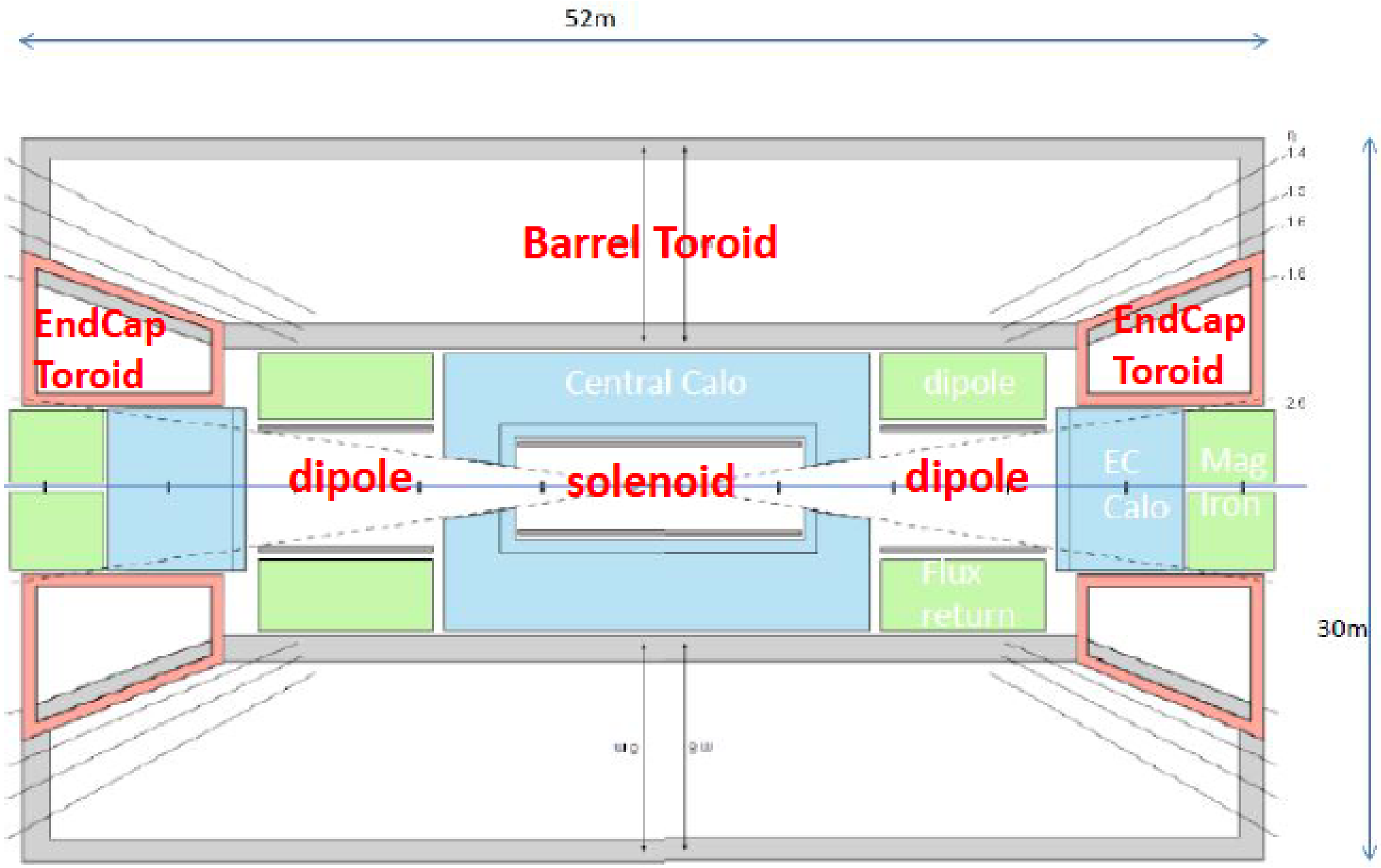
muon tracking chambers

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 .

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

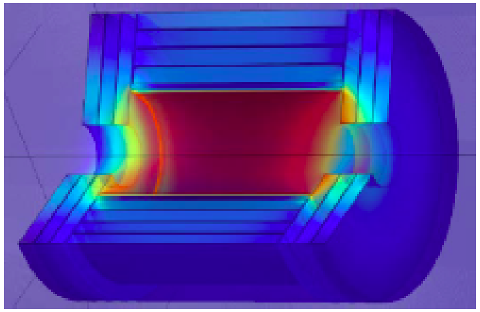
Sizes: 12m bore, 30m diameter, 30-50m length……

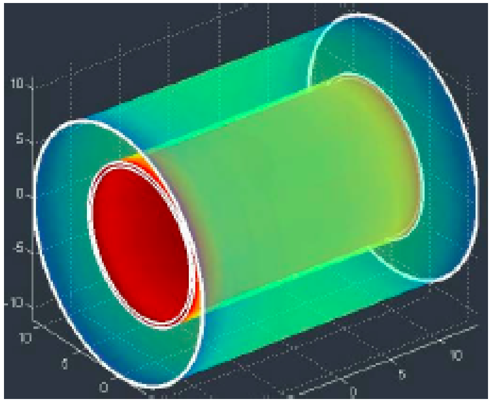
- It looks gigantic but similar sized magnets are being made these days (ITER PF coils, 26m).
- Production is required on site, in smaller modules, but very well possible.

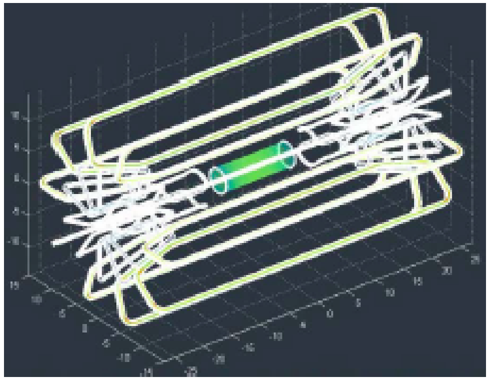
Stored Energy: 50 - 100 GJ……

- 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………







2nd Approach:

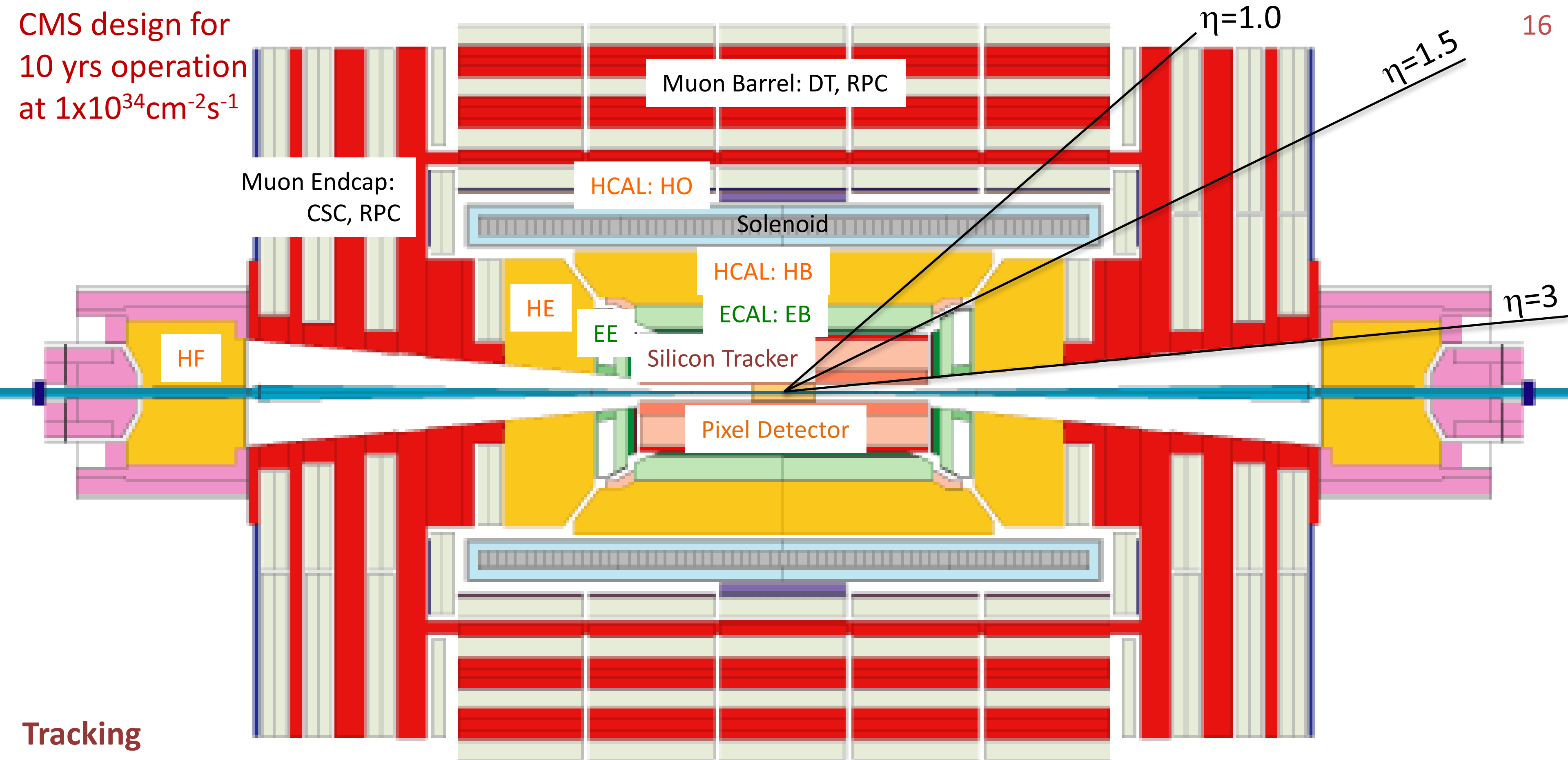
Use a present magnet system (ATLAS/CMS, LHCb) and understand possible improvement of detector resolution.

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

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

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

CMS design for 10 yrs operation at $1\times10^{34}\mathrm{cm^{-2}s^{-1}}$



Tracking

More than 220m^2 surface and 76M channels (pixels & strips)

6m long, ~2.2m diameter

Tracking to $|\eta|<2.4$

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.

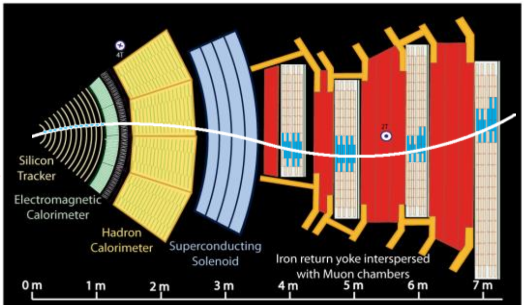
HO: Plastic scintillator “tail catcher”

Muon System

Muon tracking in the return field

Barrel: Drift Tube & Resistive Plate Chambers

Endcap: Cathode Strip Chambers & RPCs



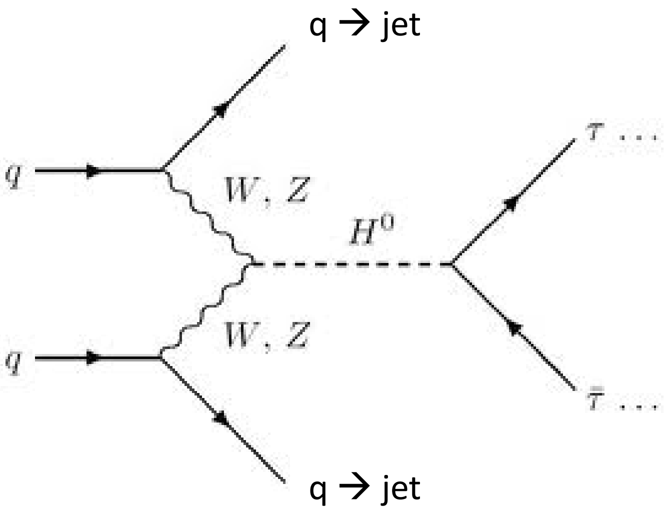
Trigger

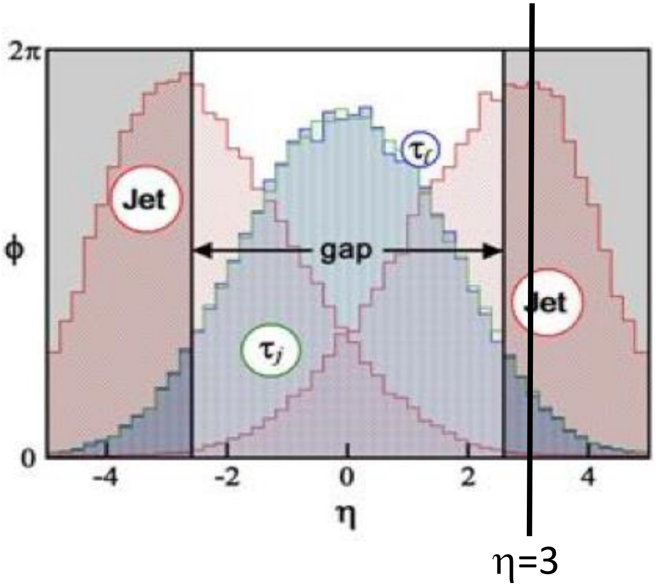
Level 1 in hardware, 3.2µs latency ,100 kHz

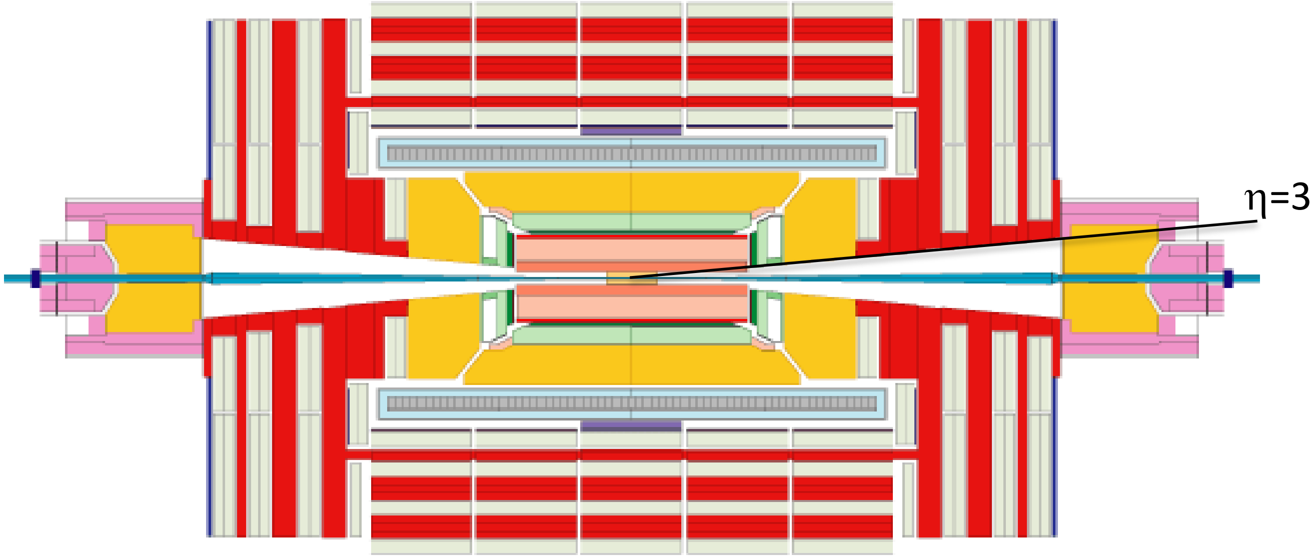
ECAL+HCAL+Muon

HLT Processor Farm,1 kHz: Tracking , Full reco

Vector Boson Fusion (VBF) -Jets







Very important channel to measure.

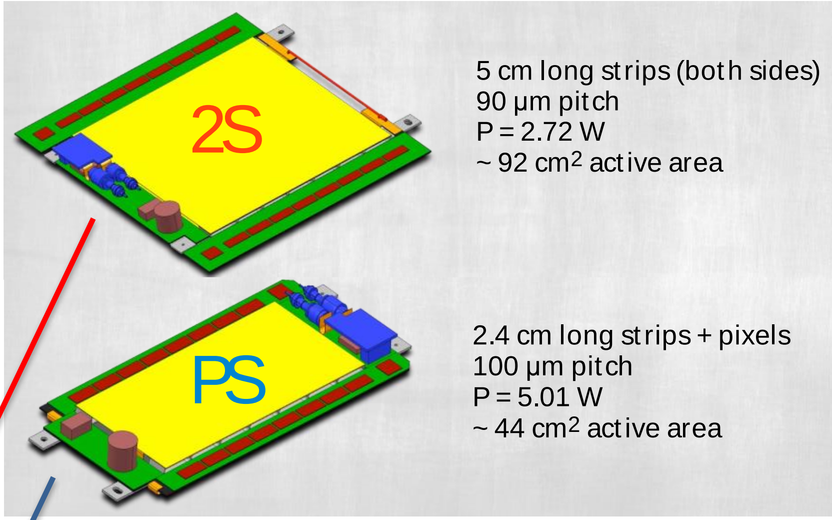
Quarks do not interact through color exchange i.e. the jets are peaked in forward direction at η=3.

Signature: high jet activity in forward region, little hadronic activity in the barrel.

η = 3 is exactly in the transition region of the endcap calorimeters !

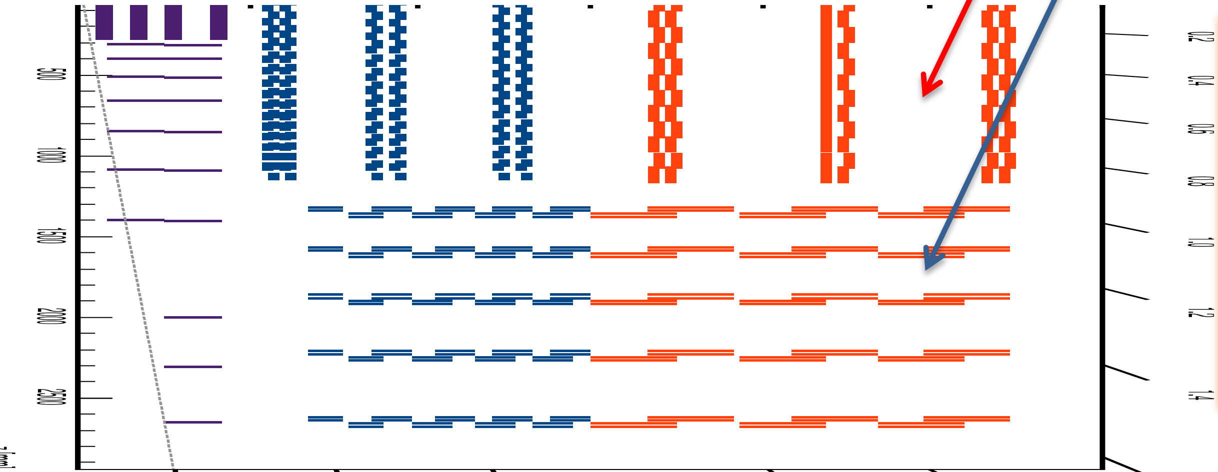
Phase 2 Tracker: conceptual design

- ○ Outer tracker
  - High granularity for efficient track reconstruction beyond 140 PU
  - Two sensor “Pt-modules” to provide trigger information at 40 MHz for tracks with Pt≥2GeV
  - Improved material budget
- ○ Pixel detector
  - **Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to |η|= 4**
  - Thin sensors 100 µm; smaller pixels 30 x 100 µm
- ○ R&D activities
  - In progress for all components - prototyping of 2S modules ongoing
  - BE track-trigger with Associative Memories

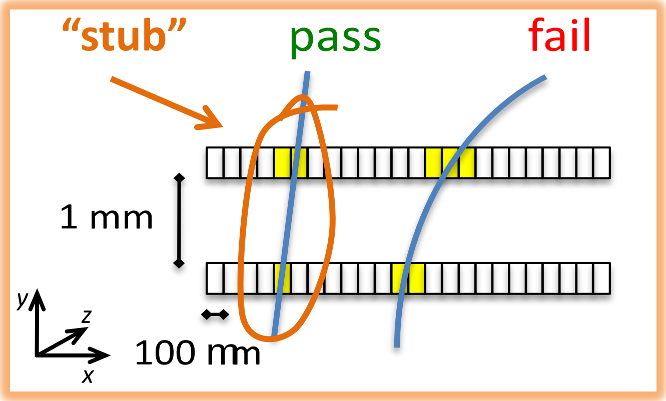


5 cm long strips (both sides)
90 µm pitch
P = 2.72 W
~ 92 cm^2 active area

2.4 cm long strips + pixels
100 µm pitch
P = 5.01 W
~ 44 cm^2 active area



Trigger track selection in FE



3nd Approach:

Think about something crazy …

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‘.

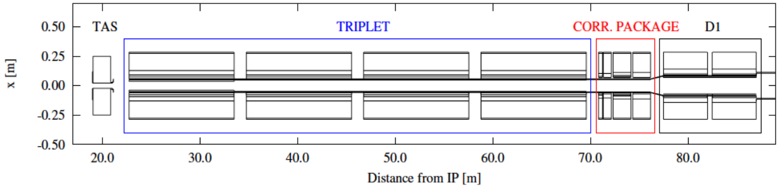
L* ... the disance between IP and triplet magnet, which determines the maximum size of the detector.

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.



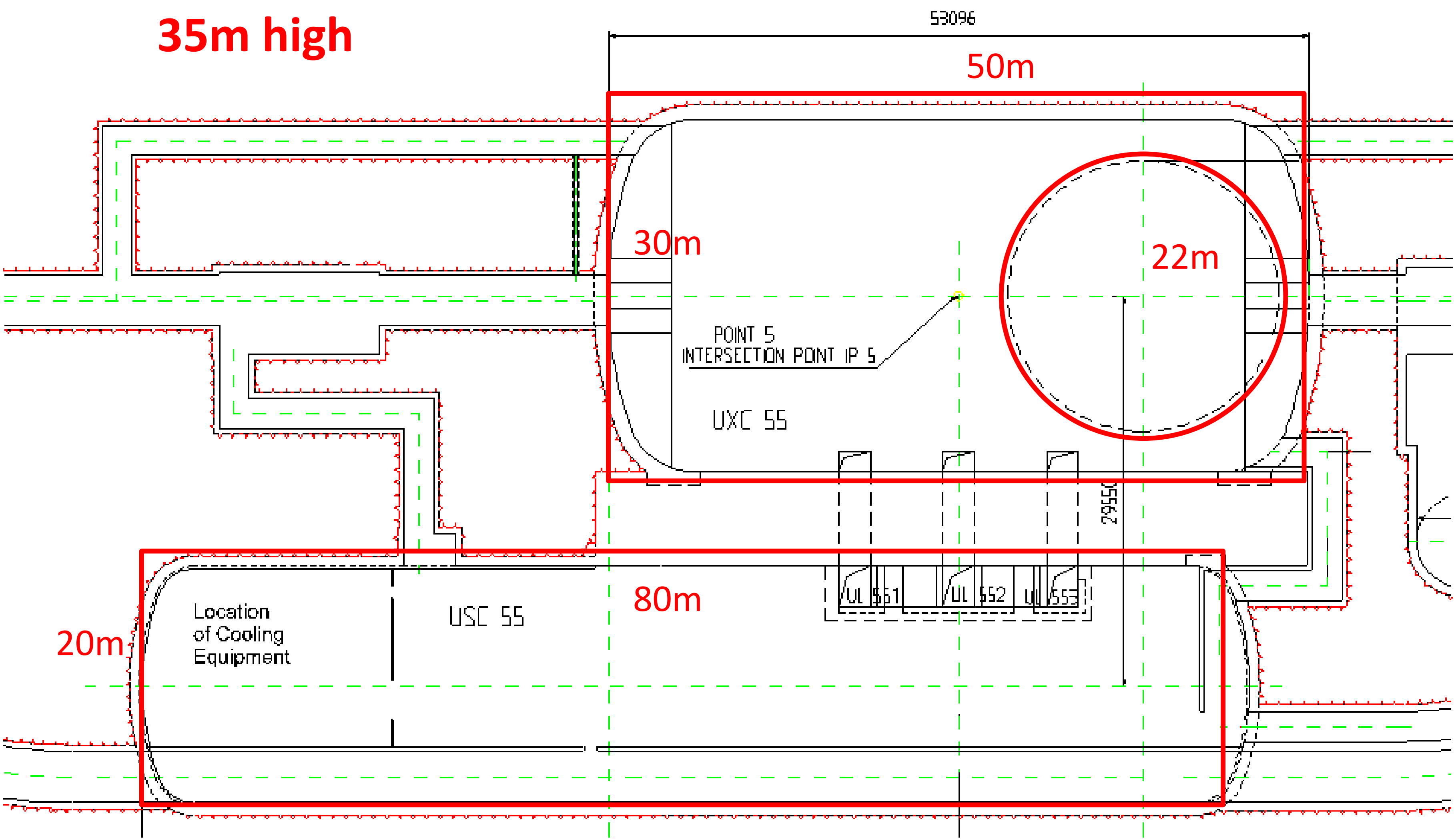
A large number of L* does of course allow some fantastic all in one ‚Nirvana' detector concepts.

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.

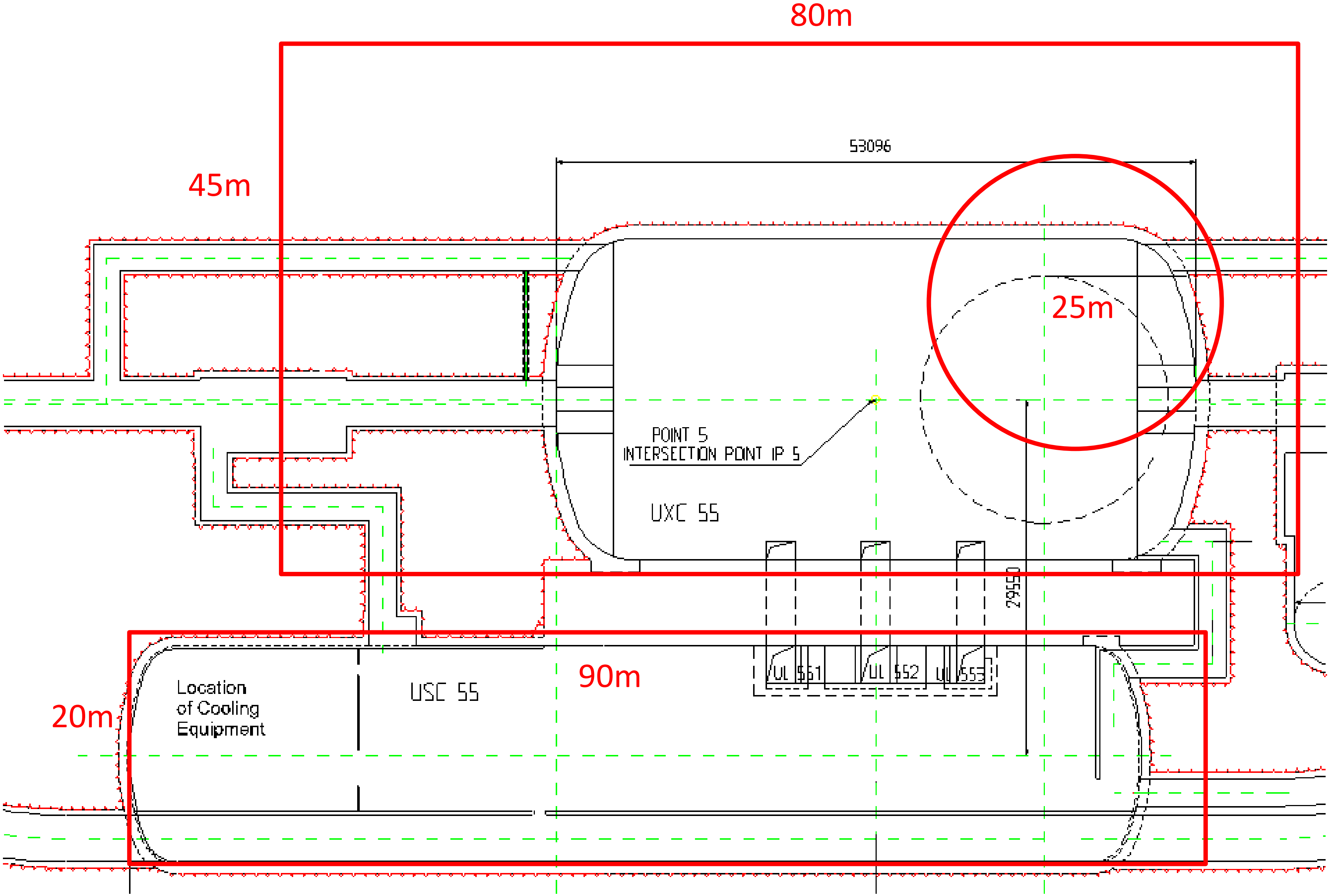
It also has to be seen whether such very large caverns are feasible at the very large cavern dephth and probably difficult terrain that are discussed at this moment (300-500m).

… 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



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

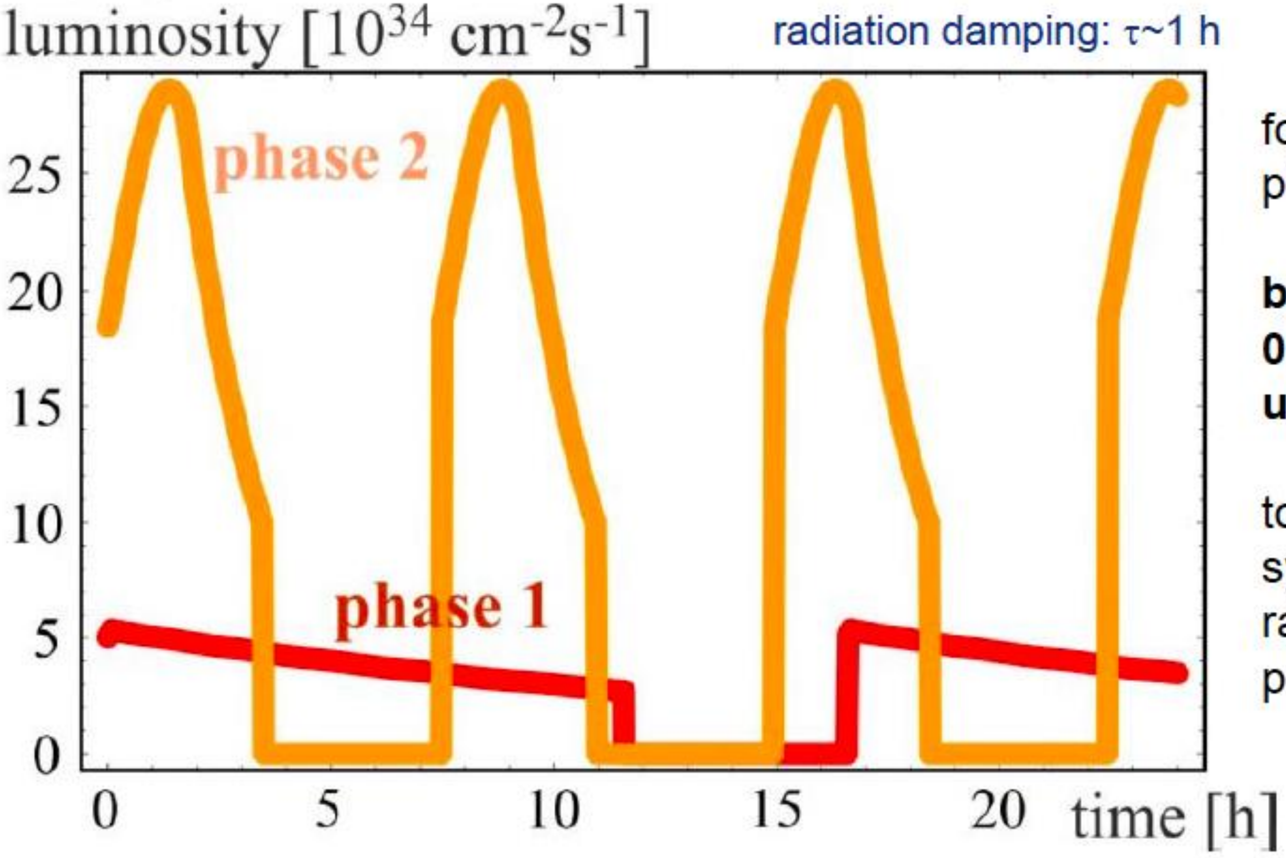
corresponds to an average pileup of

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

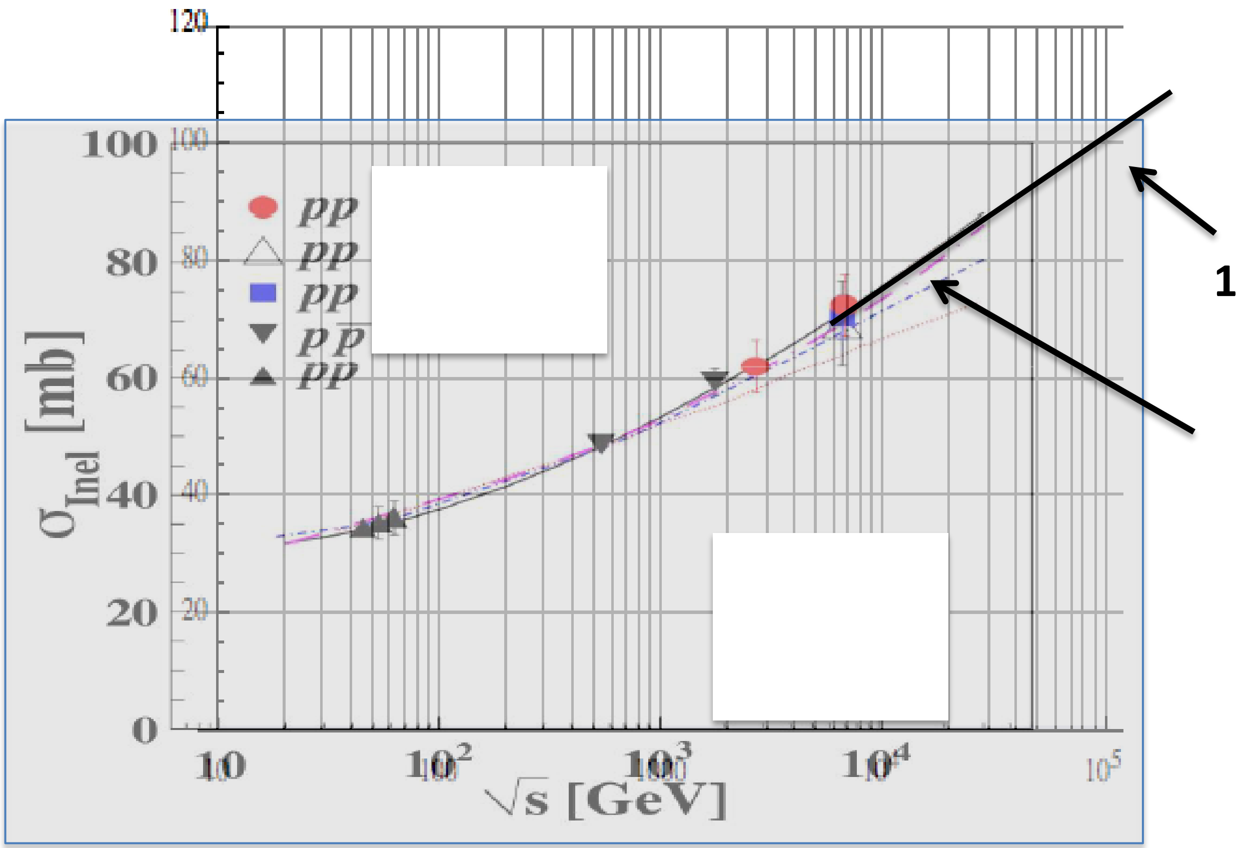
→ N_{pileup} [150, 900] at 25ns

→ N_{pileup} [30, 180] at 5ns

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

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

Inelastic pp crossection



100TeV

14TeV

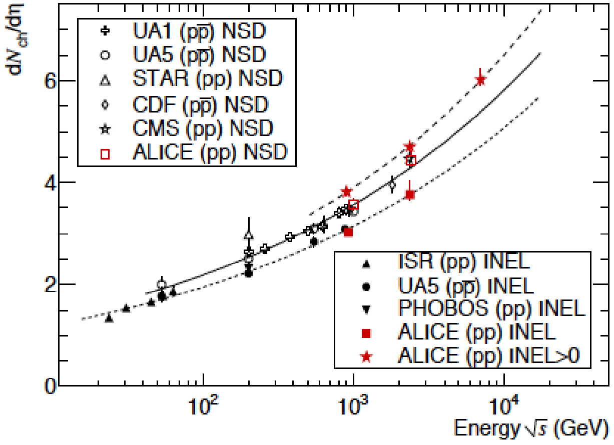
Inelastic pp crossection, hand extrapolation from data up to 7 TeV:

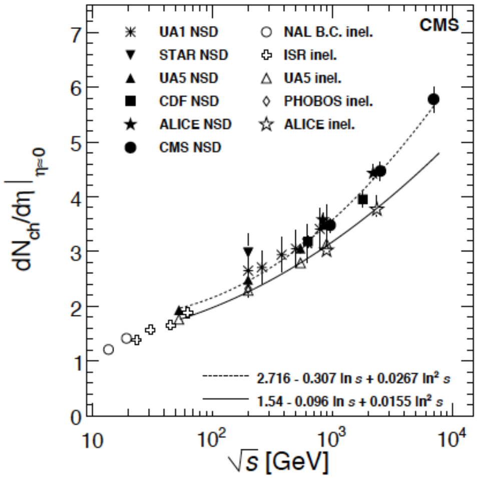
≈ 80mb at 14TeV

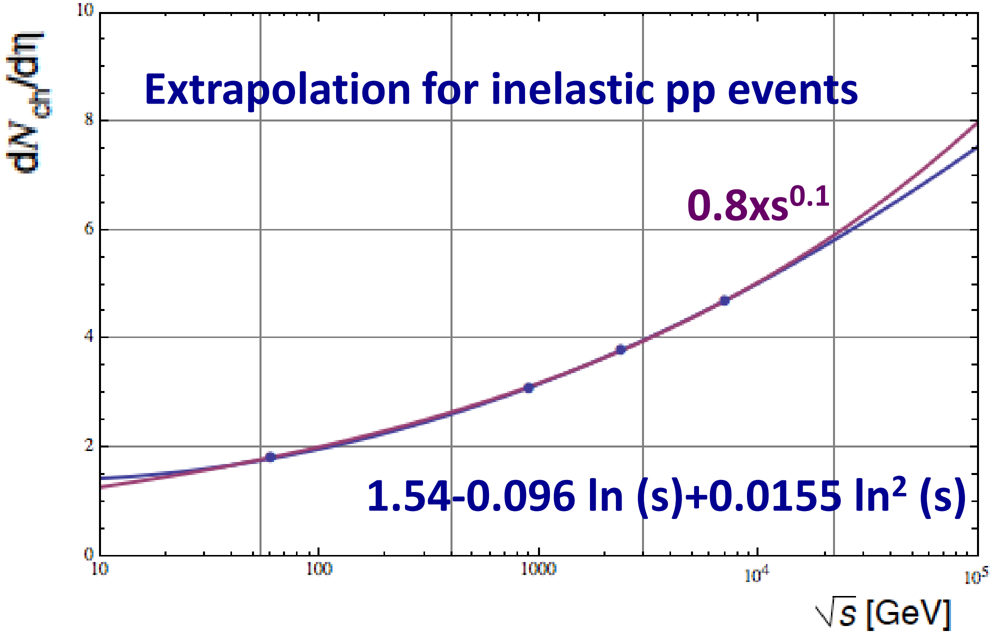
≈ 100mb at 100TeV

→ 25% increase

Multiplicities



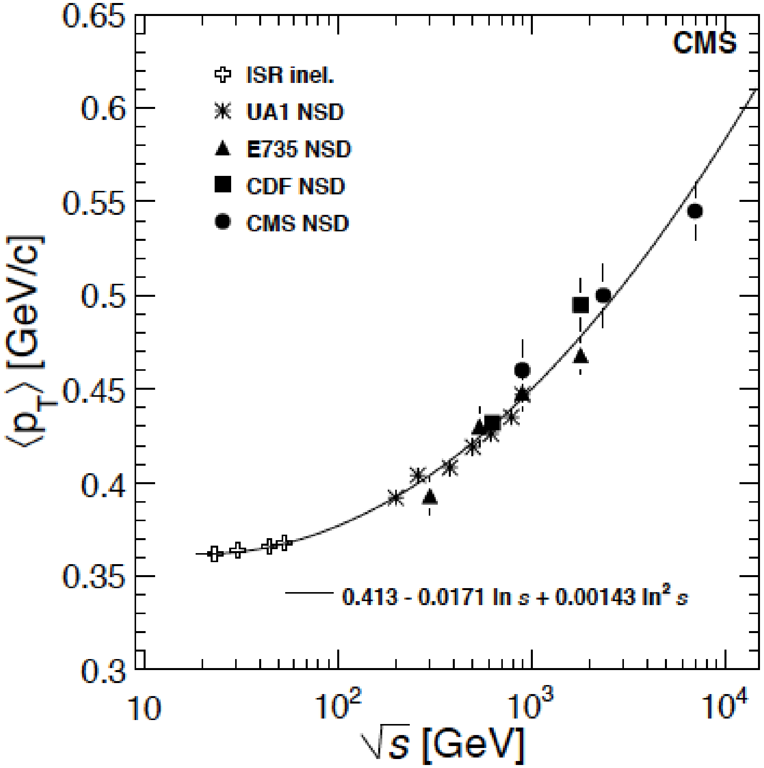


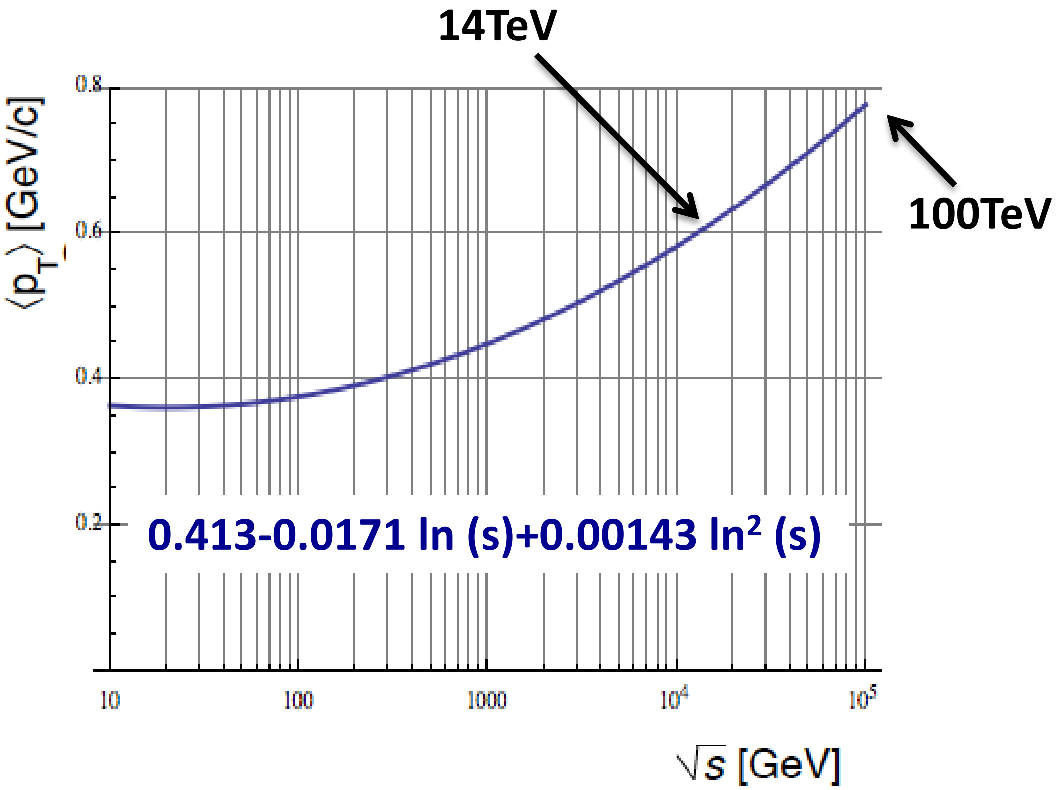


100TeV

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

Average Particle Momentum





14TeV

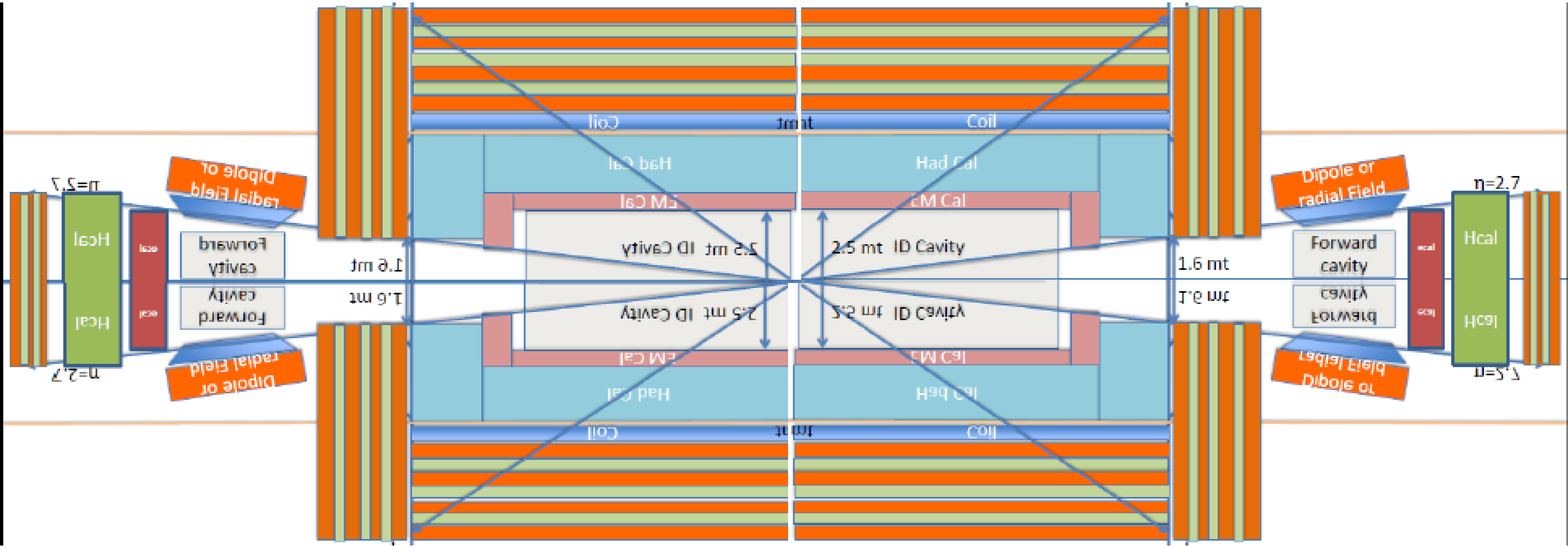
100TeV

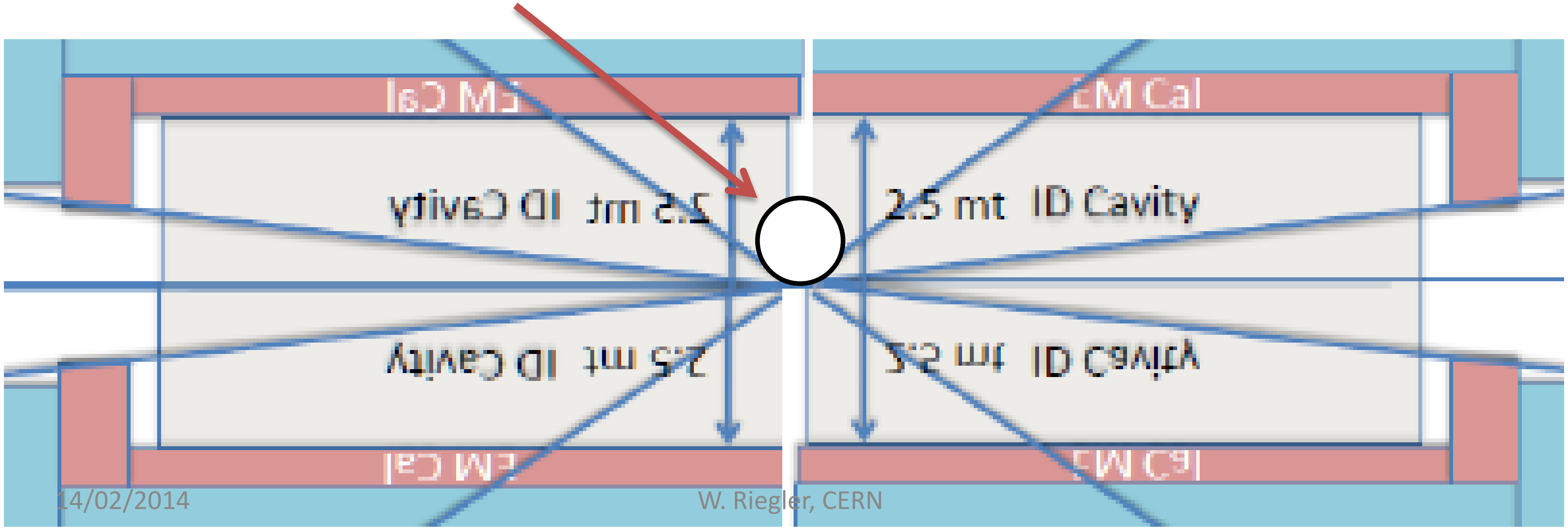
$0.413-0.0171 \ln(s)+0.00143 \ln^2(s)$

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

14TeV → 100TeV:

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

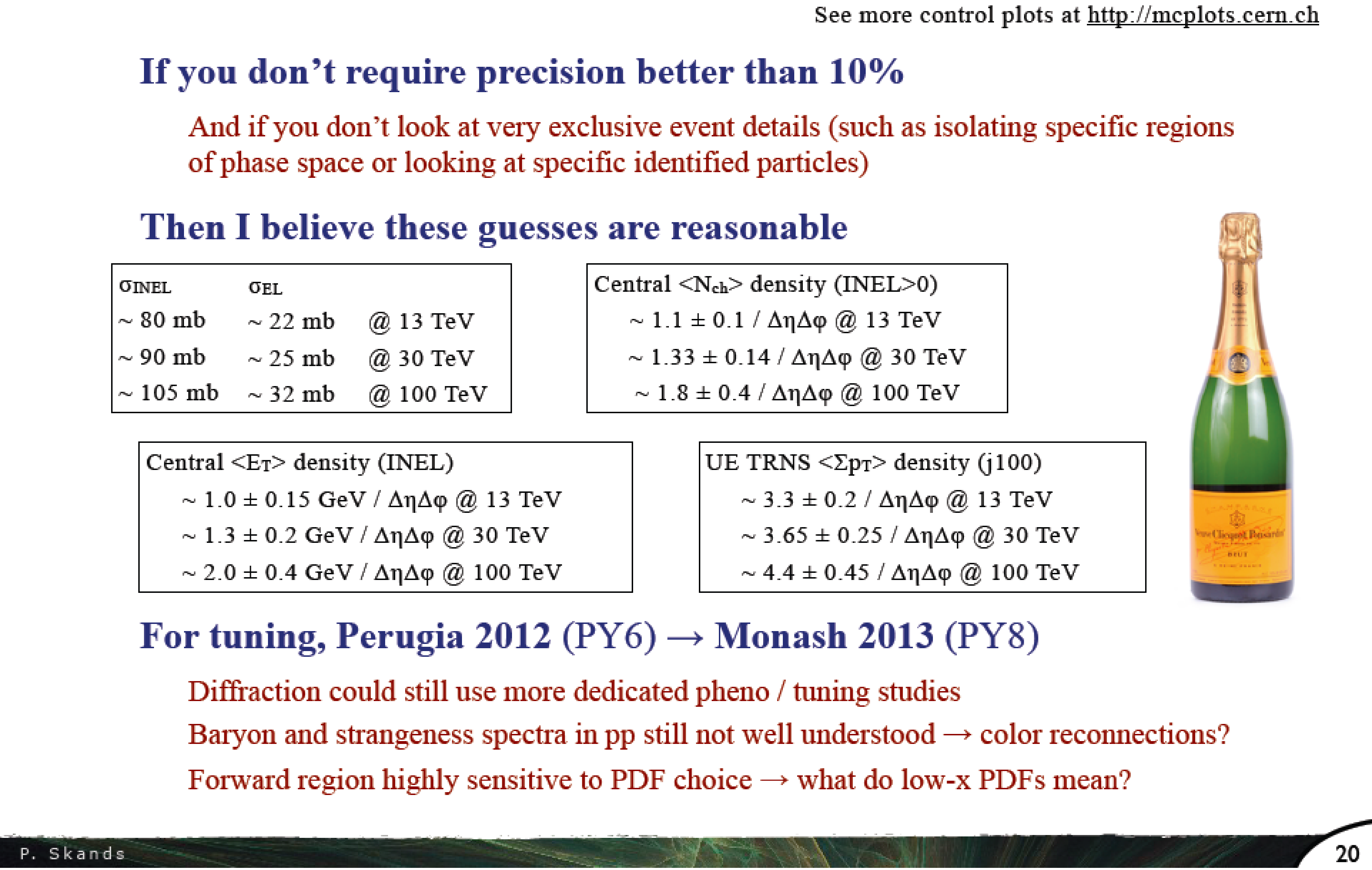
Multiplicity 14 →100TeV changes from 5.4 → 8 charged particles per rapidity unit.

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 $\langle N_{ch} \rangle$ 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 $\langle E_T \rangle$ 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 $\langle \Sigma p_T \rangle$ 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

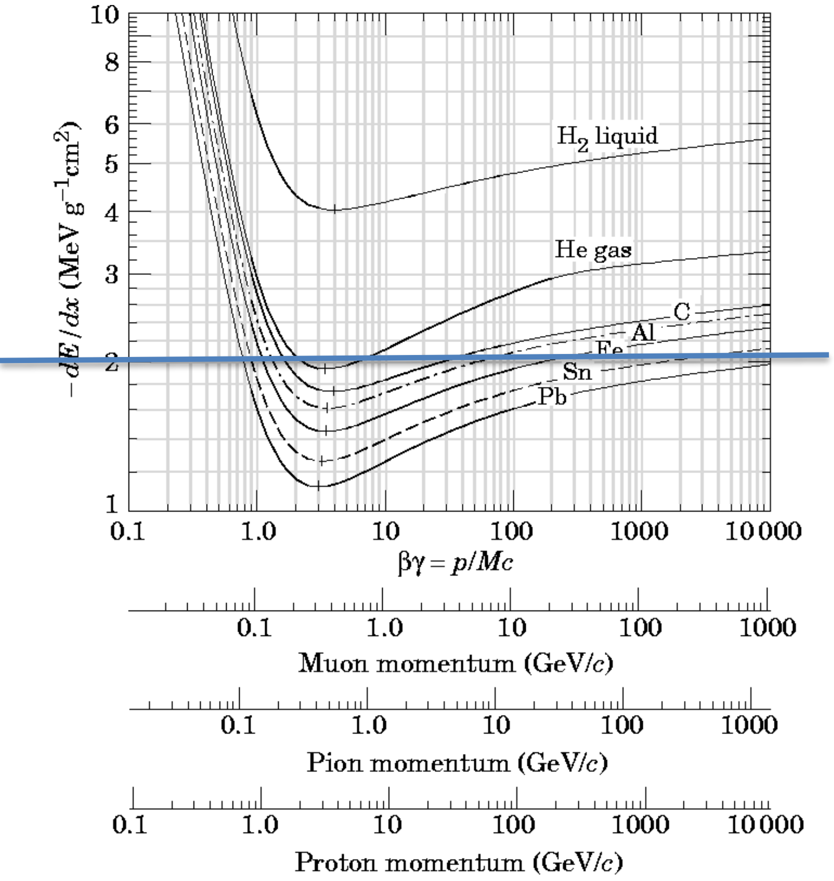
For tuning, Perugia 2012 (PY6) → Monash 2013 (PY8)

Diffraction could still use more dedicated pheno / tuning studies

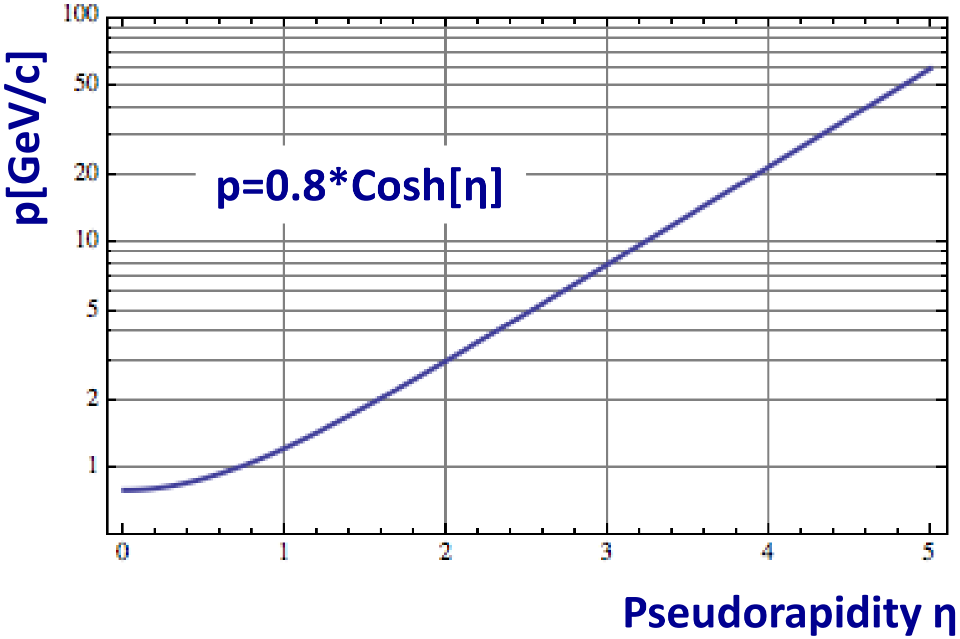
Baryon and strangeness spectra in pp still not well understood → color reconnections?

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

Energy Deposit in Tracker Elements



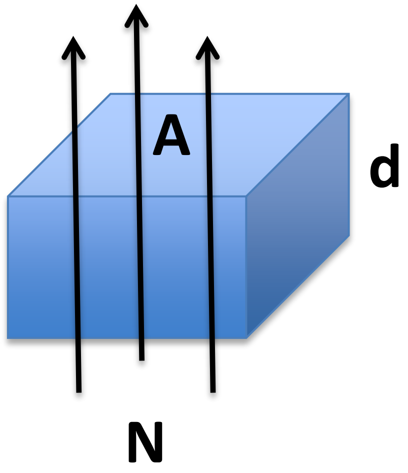
Momentum p for p_T of 0.8GeV/c



Pions are dominant particle species.
Close to MIP.

For Si, C i.e. detector materials let's assume
1/ρ * dE/dx = 2MeV cm^2/g

Ionizing Dose



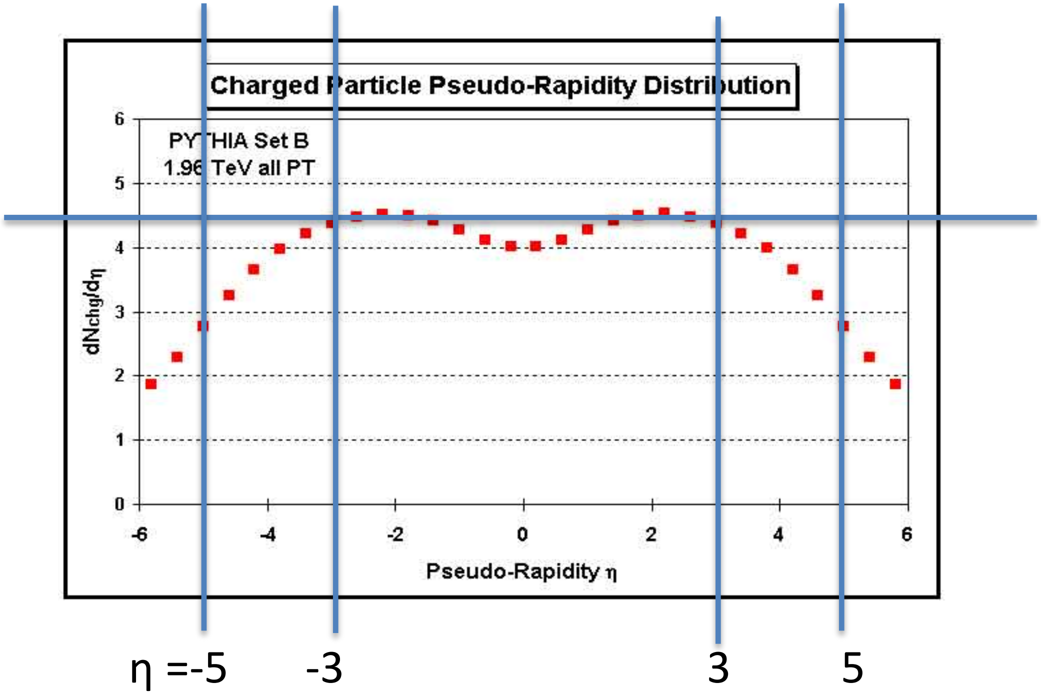
Assuming N ionizing particles per cm^2
there are N*A particles passing the volume.

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

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

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

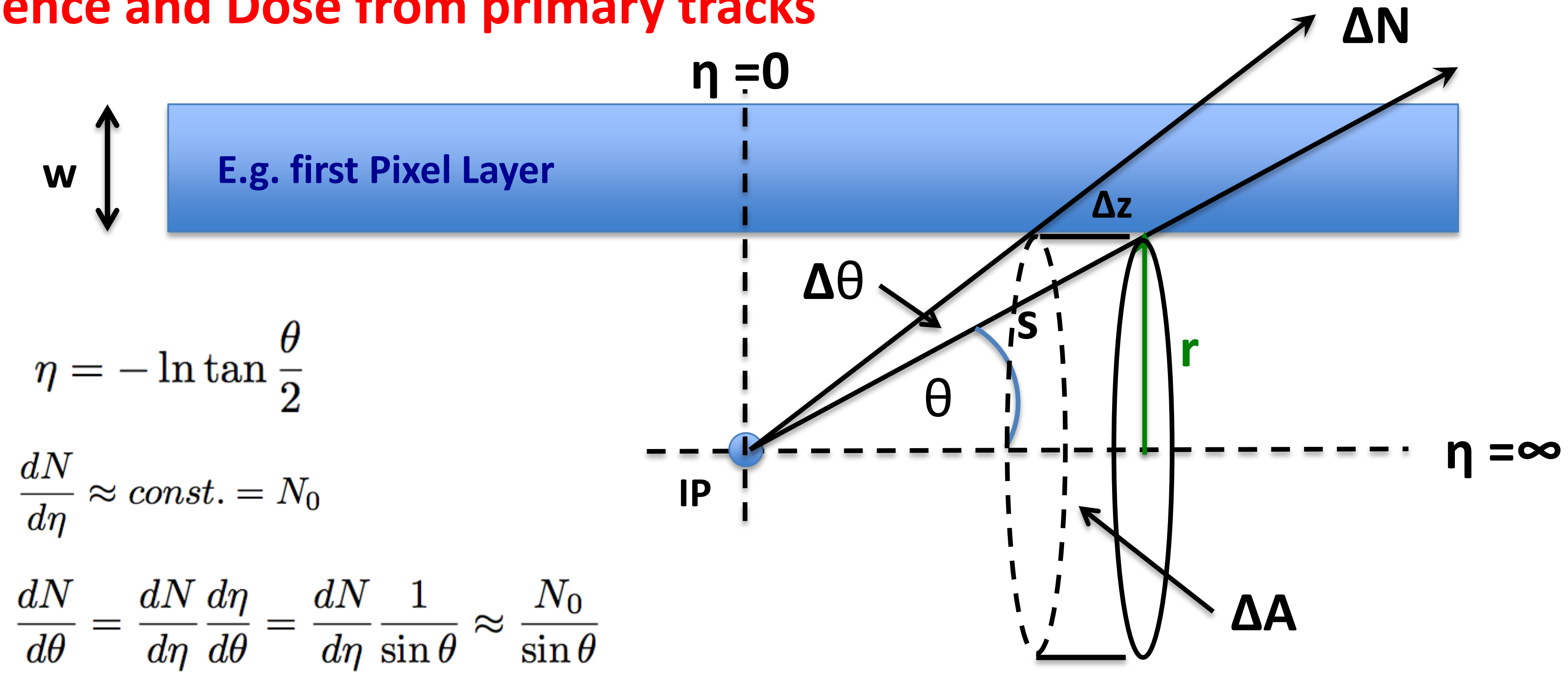
Multiplicities



In the pseudorapidity range of η ±3 (±5) the multiplicty varies only by about 10% (50%)
→ Boost Invariance of pp collisions.

→ Assuming a constant value equal to the central one gives a slightly conservative estimate of the particle multiplicity in the entire tracking range.

Fluence and Dose from primary tracks



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

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

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

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

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

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

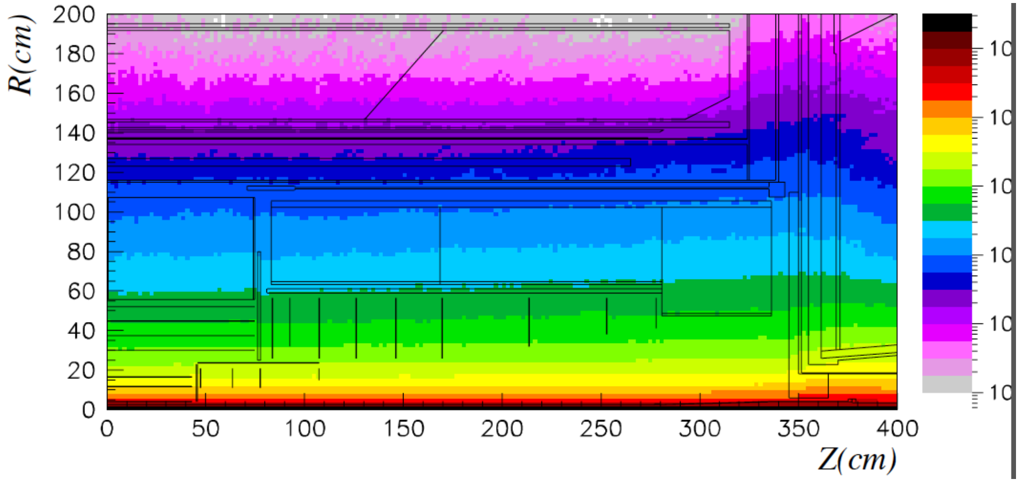
$$\text{Fluence} = \frac{\Delta N}{\Delta A}\frac{w}{w\sin\theta} = \frac{dN}{d\theta}\frac{\sin\theta}{2r^2\pi} \approx \frac{N_0}{2r^2\pi}$$

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

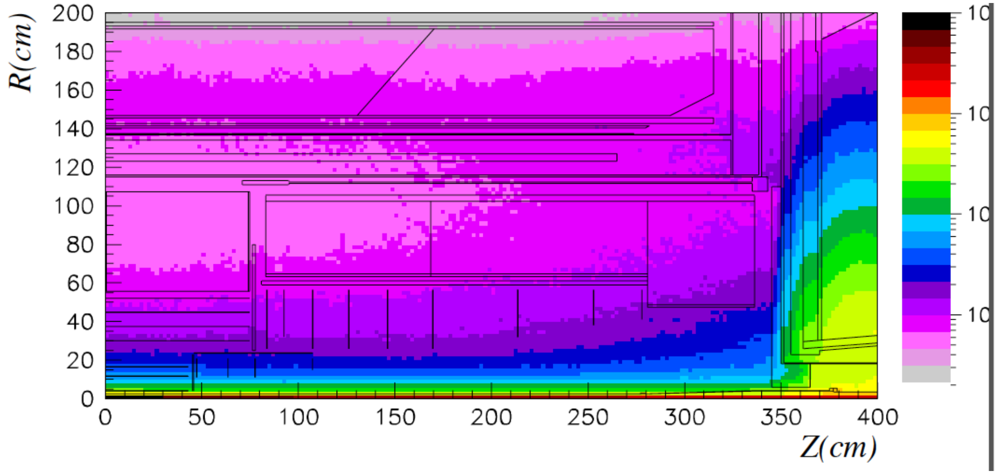
→ The hadron fluence due to primary particles is just a function of the distance from the beamline.

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

Crosscheck with original ATLAS ID TDR



Charged Hadron Fluence
Constant in parallels to beamline



1MeV-neq fluence,
Constant in parallels to the beamine.
However, close to absorbers, many neutrons escape – clearly different

From charged particle fluence to 1MeV neutron equivalent fluence

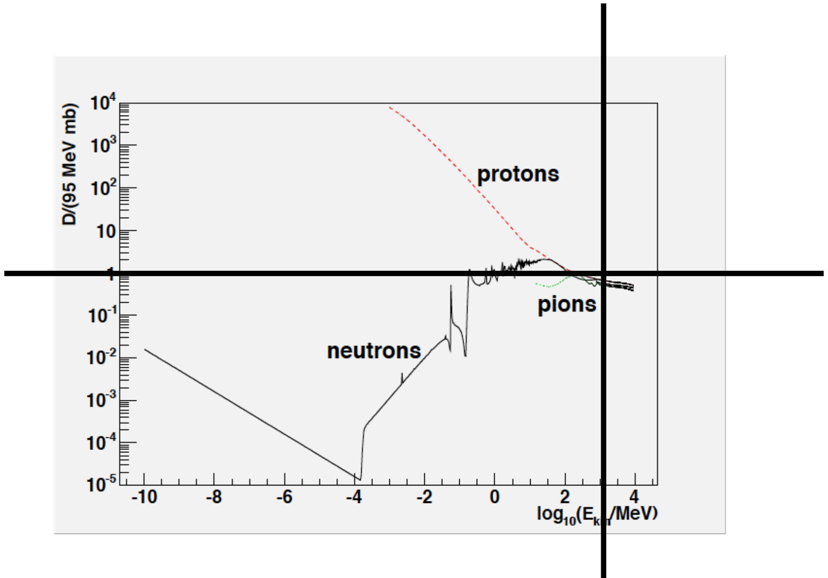


Figure 1: The damage function used for the calculation of 1 MeV n-equivalent fluences: neutrons (solid line), protons (dashed line), pions (dotted line)

Damage function for calculation of 1MeV n-equivalent fluence for the primary hadrons in the low GeV range is close to 1.

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

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

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

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

Crosscheck with ATLAS Phase II LOI

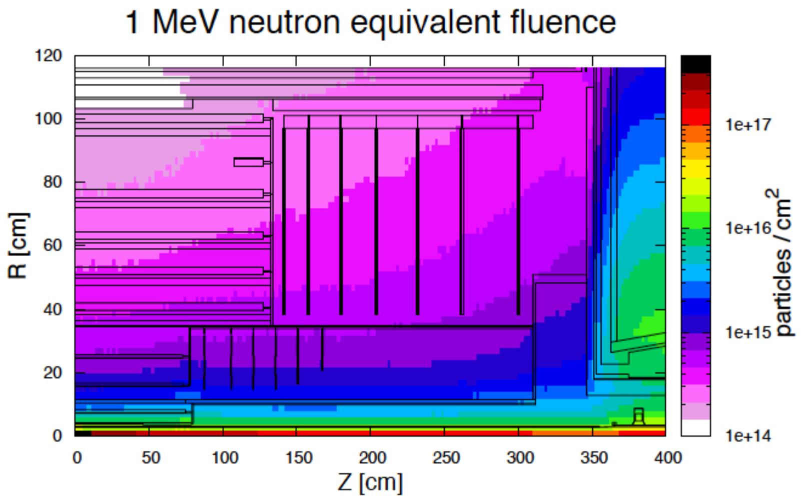
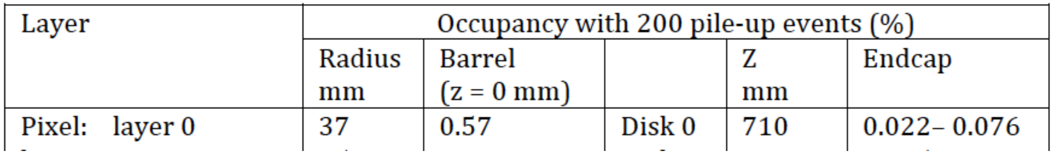


Figure 6.2: *RZ*-map of the 1 MeV neutron equivalent fluence in the Inner Tracker region, normalised to 3000 fb^{-1} of 14 TeV minimum bias events generated using PYTHIA8.

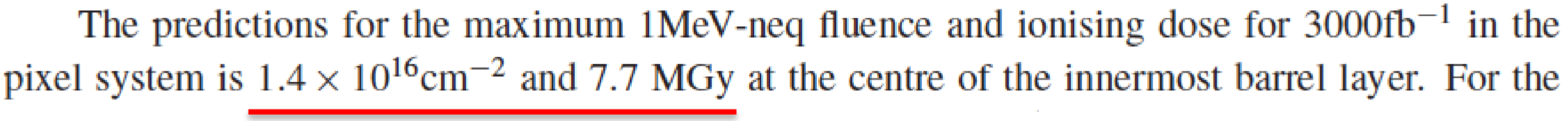
3000 fb^{-1}
80mb inelastic pp crossection
2.4 * 10^{17} events
dN/dη = N0=5.4 at 14 TeV
Pixel layer1 at r=3.7cm

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

Dose = $3.2\times10^{-8}*1.5*10^{16}$ =
4.8MGy

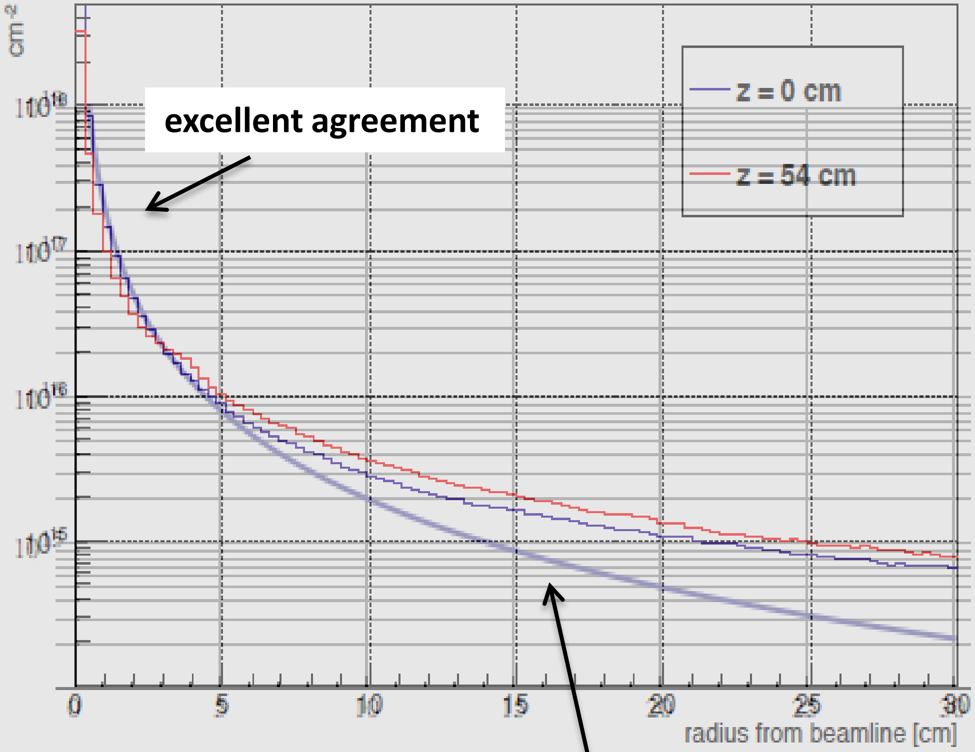


Layer	Occupancy with 200 pile-up events (%)				
	Radius mm	Barrel (z = 0 mm)		Z mm	Endcap
Pixel: layer 0	37	0.57	Disk 0	710	0.022– 0.076



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

Crosscheck with ATLAS Phase II LOI



excellent agreement

off by factor 4 at 30cm

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

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

Crosscheck with ATLAS Phase II LOI

ATL-UPGRADE-PUB-2012-003

excellent agreement

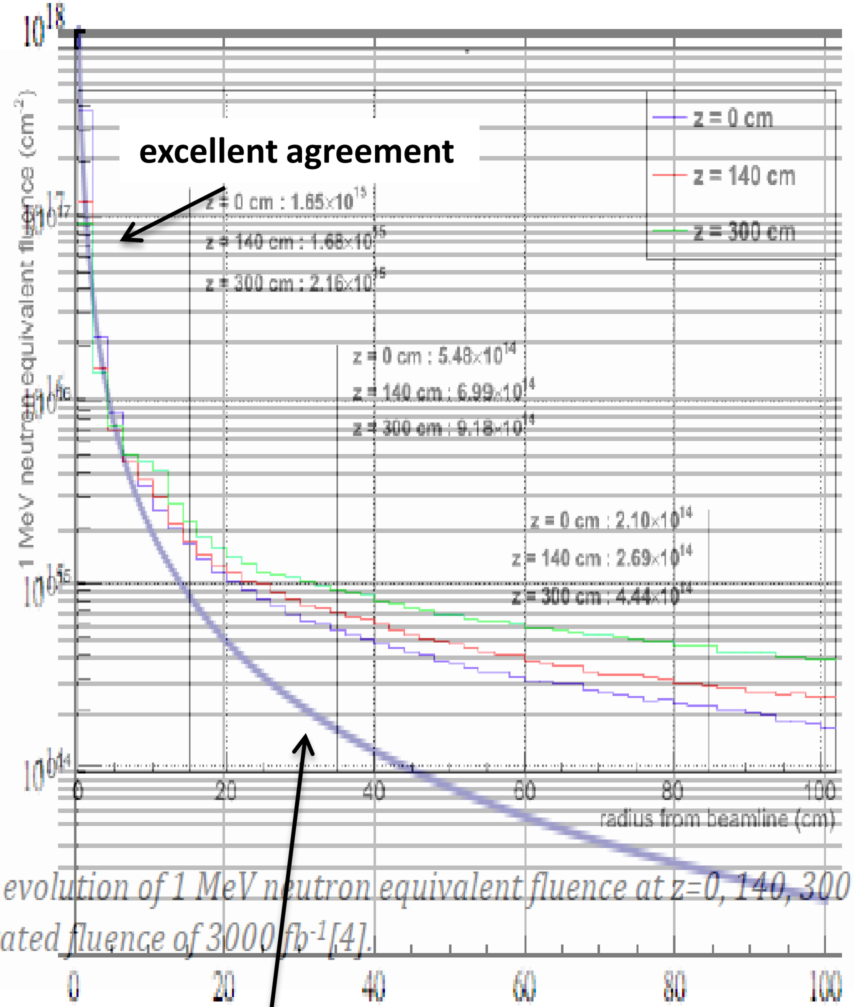


Figure 2. *Radial evolution of 1 MeV neutron equivalent fluence at z=0, 140, 300 cm for an integrated fluence of 3000 fb^{-1}[4].*

off by factor 10 at 100cm

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

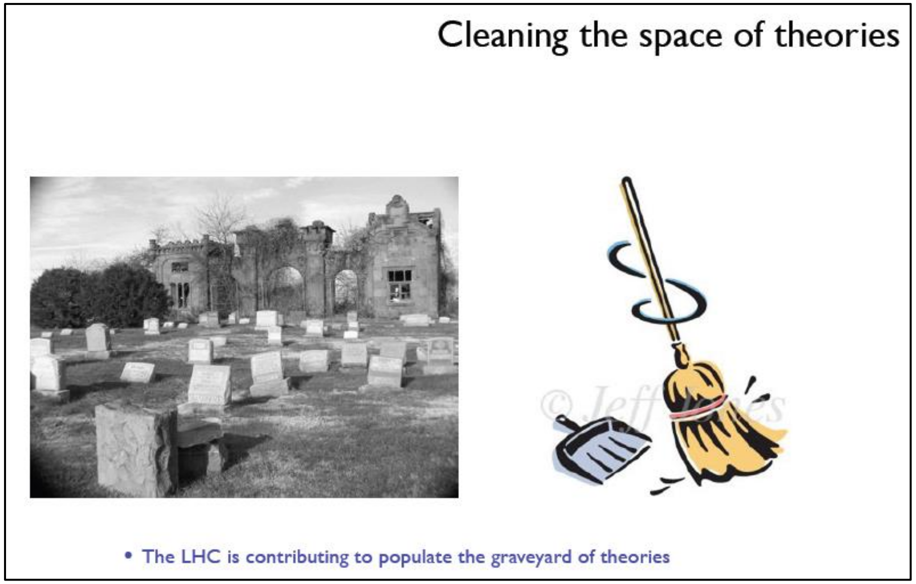
Radiation load of first Pixel Layer at r=3.7cm:

HL-LHC $3ab^{-1}$
1MeVneq Fluence = $1.5x10^{16}$ cm^{-2}
Dose = 4.8MGy

FCC $3ab^{-1}$
1MeVneq Fluence = $2.8x10^{16}$ cm^{-2}
Dose = 9MGy

FCC $30ab^{-1}$
1MeVneq Fluence = $2.8x10^{17}$ cm^{-2}
Dose = 90MGy

Detector Technologies



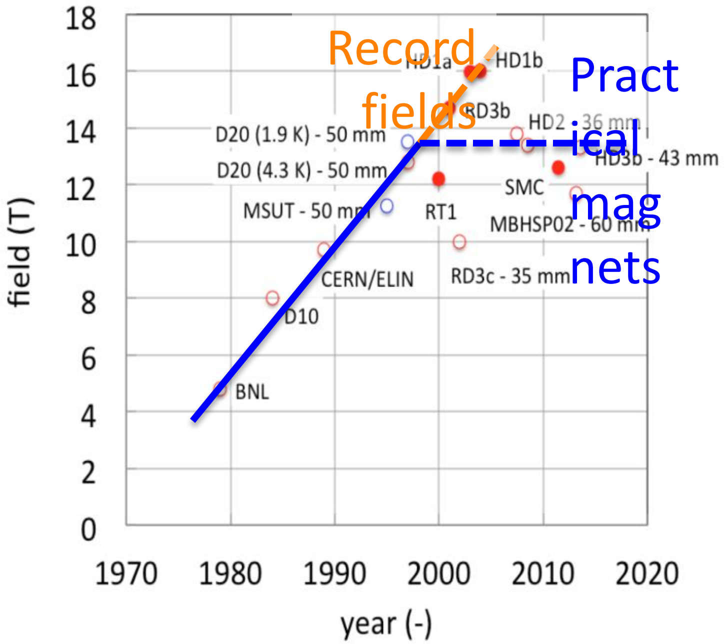
Cleaning the space of theories

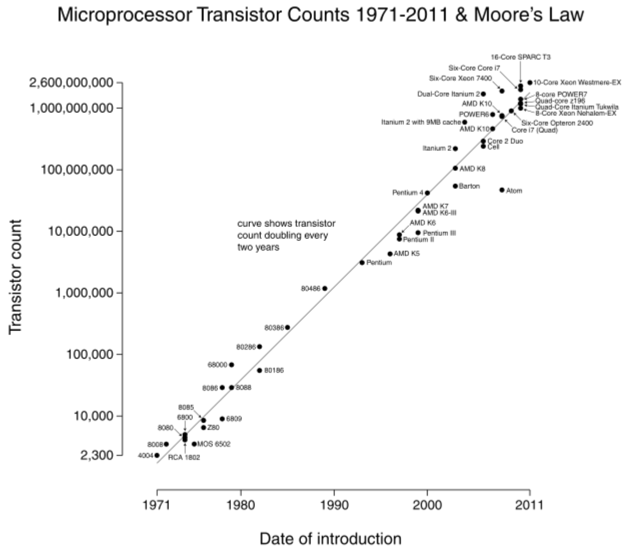
- The LHC is contributing to populate the graveyard of theories

Luis Alvarez-Gaume

The graveyard of invented detectors that never made it to a successful large scale application is also significant !

Detector Technologies

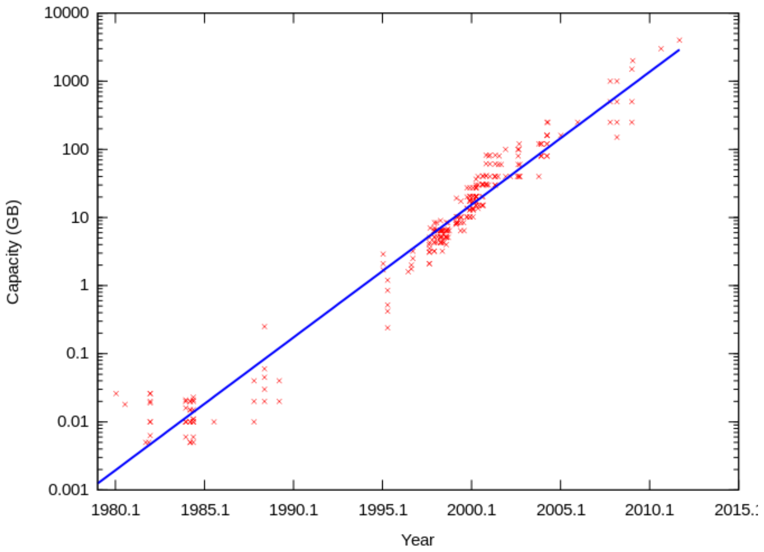




Magnets between 1980 to 2000: factor 3 with difficult prospects ...

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

Assume factor 2^{10} = 1024 from 2014 – 2034



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.

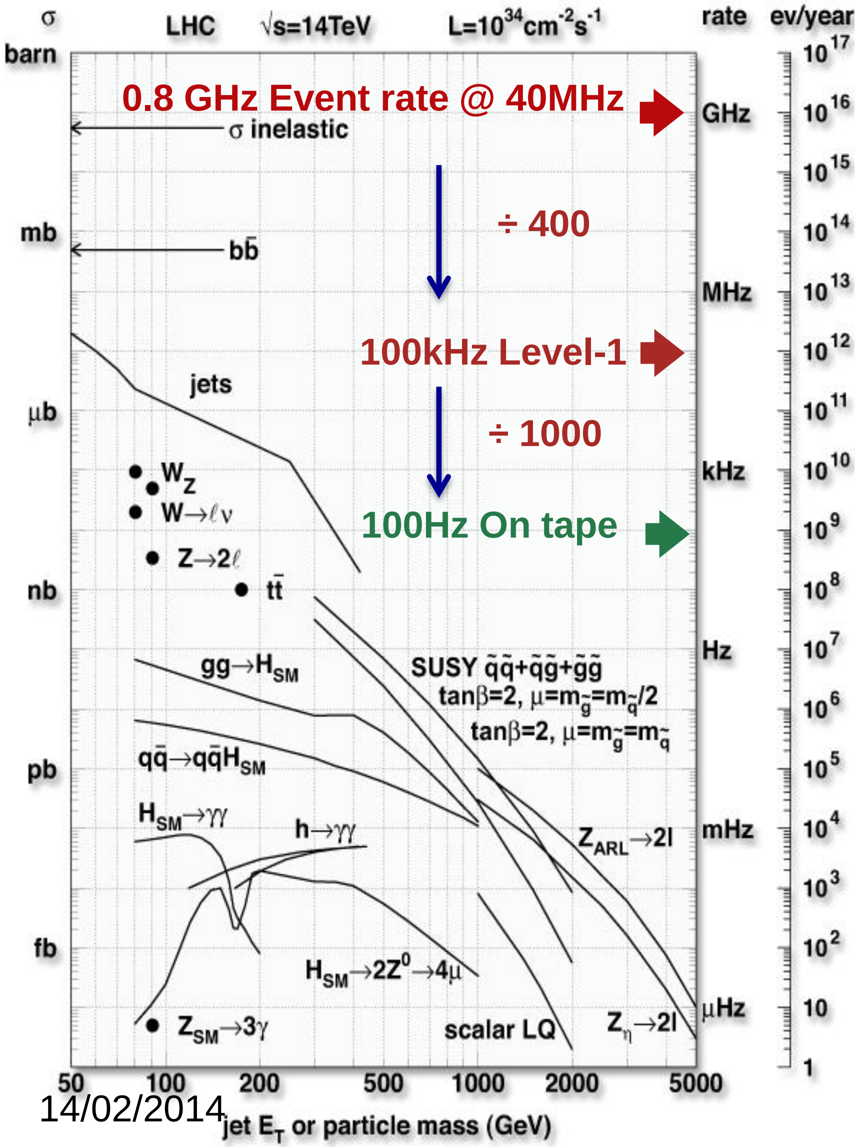
"Futurists believe that's what you need for artificial intelligence. At that point, the computer starts thinking for itself.“

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

Magnet system 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.

LHC to HL-HLC



0.8 GHz Event rate @ 40MHz

÷ 400

100kHz Level-1

÷ 1000

100Hz On tape

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

4 GHz Event Rate @ 40MHz

÷ 40

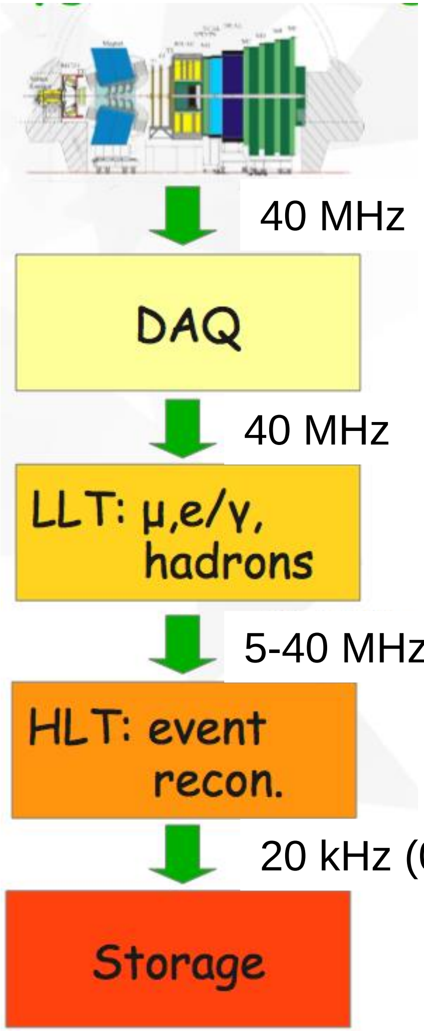
0.5-1 MHz Level-1 Rate

÷ 100

5-10kHz Rate to Tape

Increase in computing power, according to Moores Law doubling every 2 years, and related increase in storage capacity, makes it possible ...

LHCb & ALICE in 2018



40 MHz

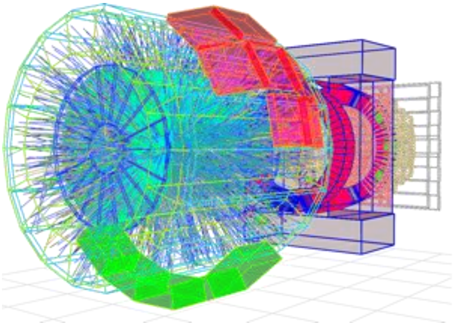
40 MHz

5-40 MHz

20 kHz (0.1 MB/event)

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 $5\text{x}10^{34}$.

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

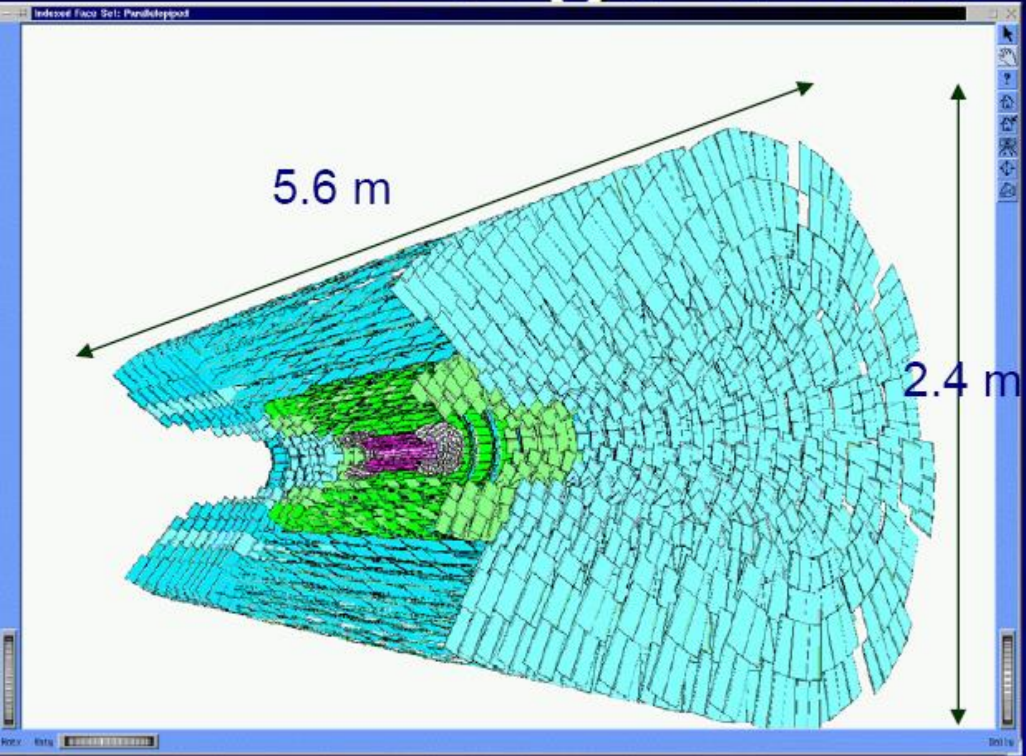
For 2022 this is considered too difficult.

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



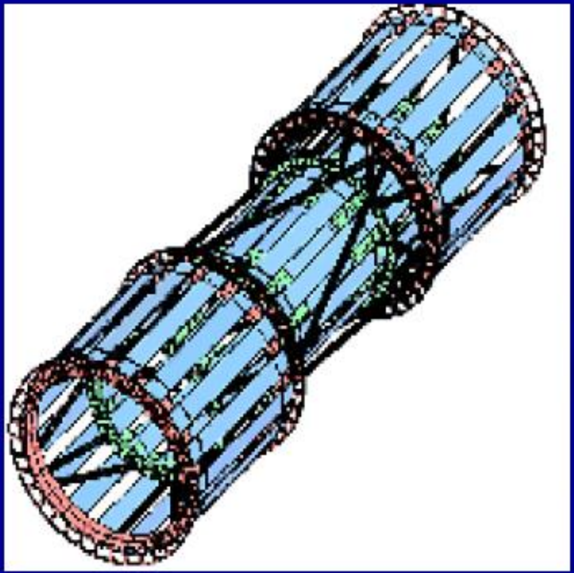
CMS tracker (~2007)

12000 modules

~ 445 m² silicon area

~ 24,328 silicon wafers

~ 60 M readout channels



CDF SVX IIa (2001-)

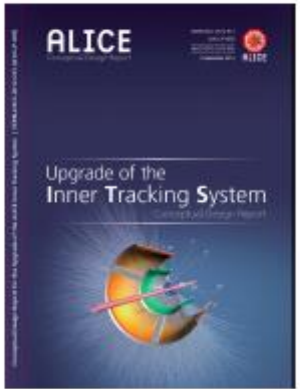
~ 11m² silicon area

~ 750 000 readout channels

ALICE 2018 upgrade, 20x20um monolithic pixels

New ITS Layout

25 G-pixel camera
(10.3 m^2)

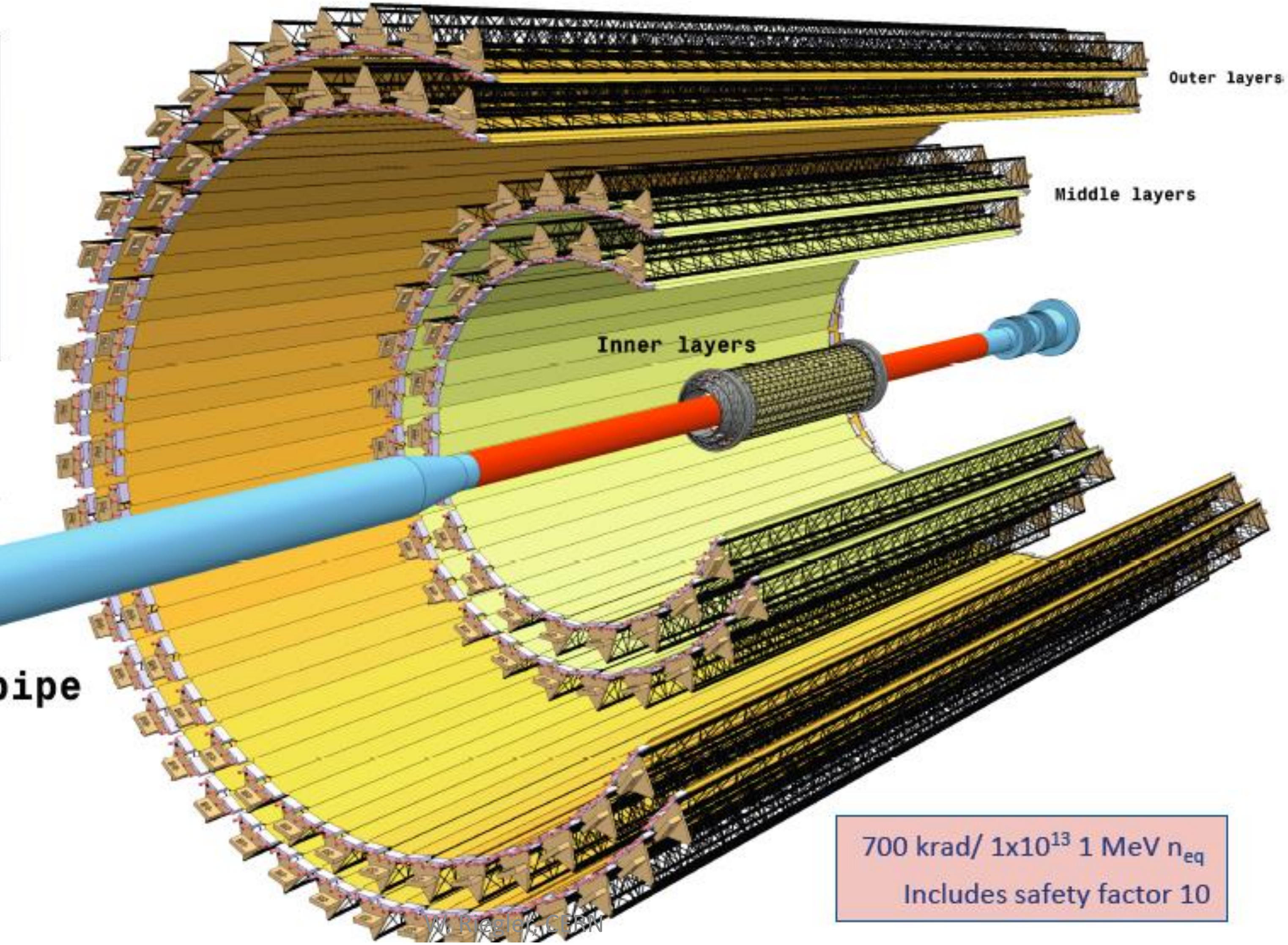


ALICE

Upgrade of the
Inner Tracking System

CERN-LHCC-2013-024

7 layers of MAPS



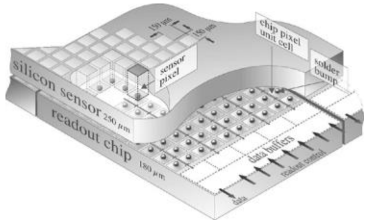
700 krad/ $1x10^{13}$ 1 MeV n_{eq}

Includes safety factor 10

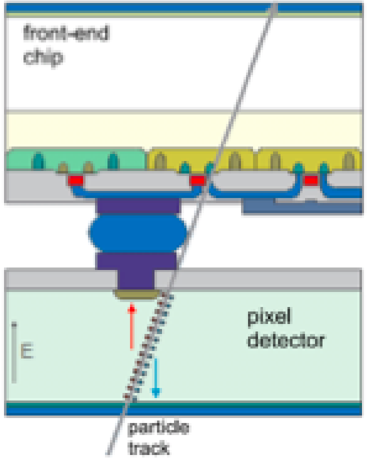
Radial coverage
22 – 406 mm

CMOS Sensors

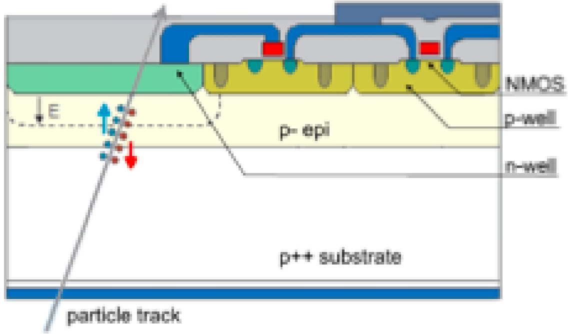
- CMOS sensors **contain sensor and electronics combined in one chip**
    - No interconnection between sensor and chip needed
- Standard CMOS processing
    - Wafer diameter (8")
    - Many foundries available
    - Lower cost per area
    - Small cell size – high granularity
    - Possibility of stitching (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)



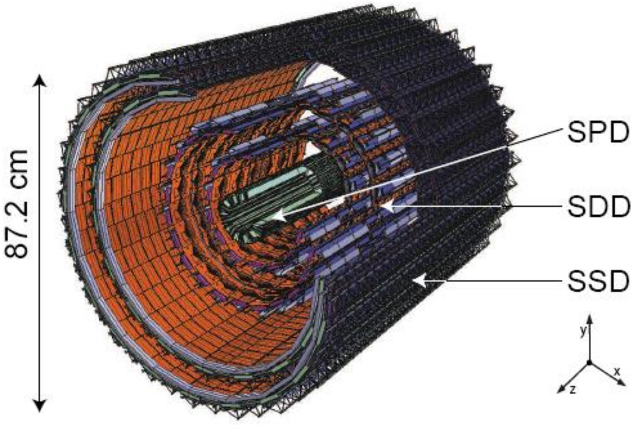
Hybrid Pixel Detector



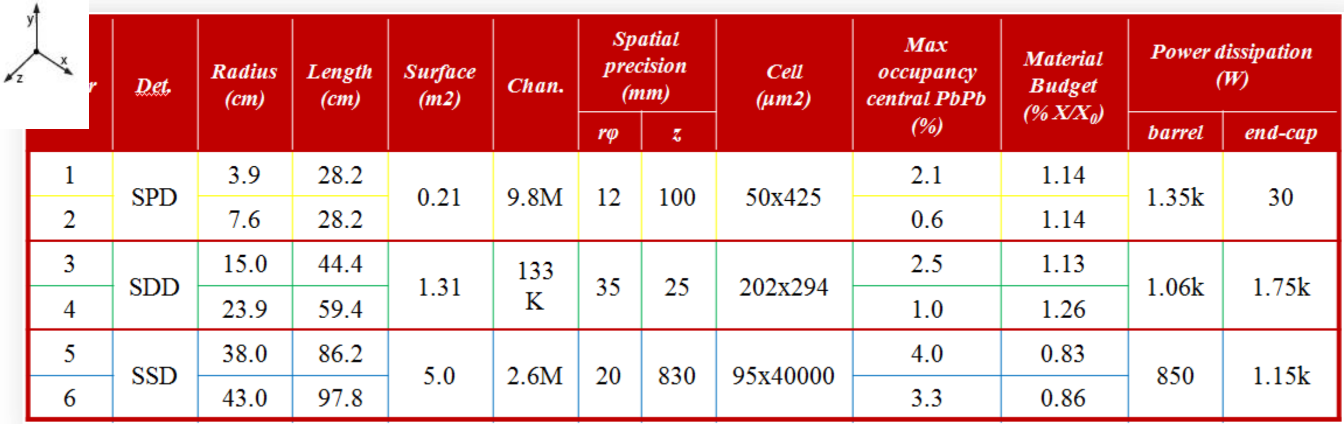
CMOS (Pixel) Detector



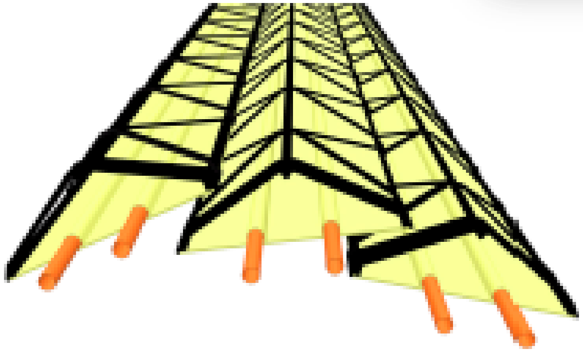
ALICE Silicon Tracker & Upgrade 2018 upgrade

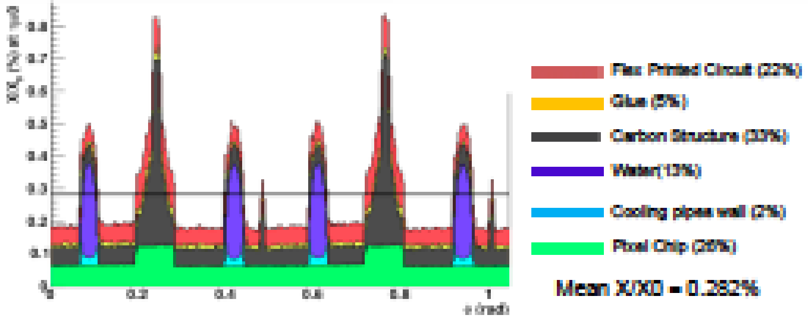


Go from 1.14% X_0 to 0.3% X_0 with monolithic pixels



r	*Det.*	*Radius (cm)*	*Length (cm)*	*Surface (m2)*	*Chan.*	*Spatial precision (mm)*		*Cell (μm2)*	*Max occupancy central PbPb (%)*	*Material Budget (% X/X$_0$)*	*Power dissipation (W)*	
						rφ	*z*				*barrel*	*end-cap*
1	SPD	3.9	28.2	0.21	9.8M	12	100	50x425	2.1	1.14	1.35k	30
2		7.6	28.2						0.6	1.14		
3	SDD	15.0	44.4	1.31	133 K	35	25	202x294	2.5	1.13	1.06k	1.75k
4		23.9	59.4						1.0	1.26		
5	SSD	38.0	86.2	5.0	2.6M	20	830	95x40000	4.0	0.83	850	1.15k
6		43.0	97.8						3.3	0.86		





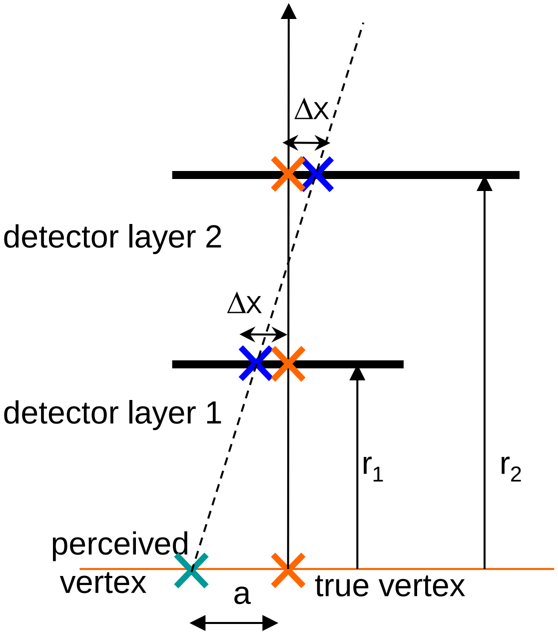
What determines the impact parameter resolution

Vertex projection from two points: a simplified approach (telescope equation)

pointing resolution = (a ⊕ b) μm

from
detector
position
error

from
coulomb
scattering



$$a = \Delta x \cdot \sqrt{\frac{r_2^2 + r_1^2}{(r_2 - r_1)^2}}$$

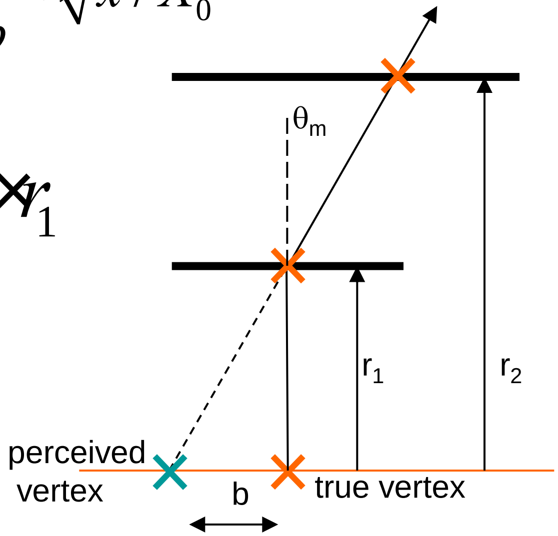
Detector Granularity, minimize Δx:

e.g. 50um pixel and r_2 very large compared to r_1

→ a=Δx=50/√12 = 15um

$$\theta_m = \frac{13.6 MeV}{\beta \cdot c \cdot p} \times \sqrt{x / X_0}$$

$$b = \theta_m \cdot r_1$$

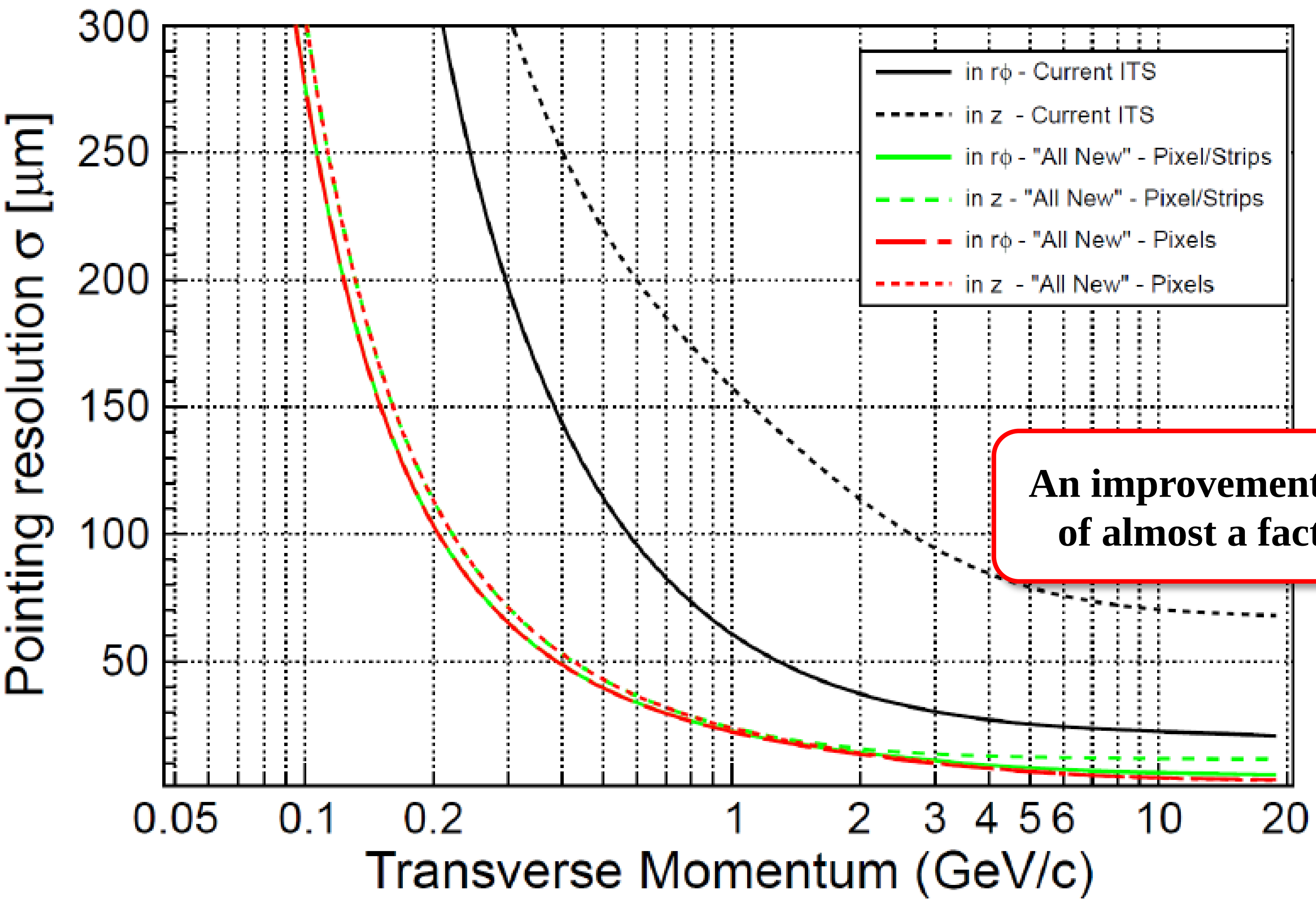


First layer as close as possible to the vertex and First layer with minimal amount of material.

e.g. x/X_0 = 0.0114, r_1= 39mm

→ b= 57um for p=1GeV/c

ALICE Silicon Tracker & Upgrade 2018 upgrade



An improvement in rφ of almost a factor 3

This will help a lot for pileup rejection for an FCC detector

PIXEL Chip - technology

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

Monolithic PIXEL chip using
Tower/Jazz 0.18 µm technology

- feature size 180 nm
- gate oxide < 4nm
- metal layers 6

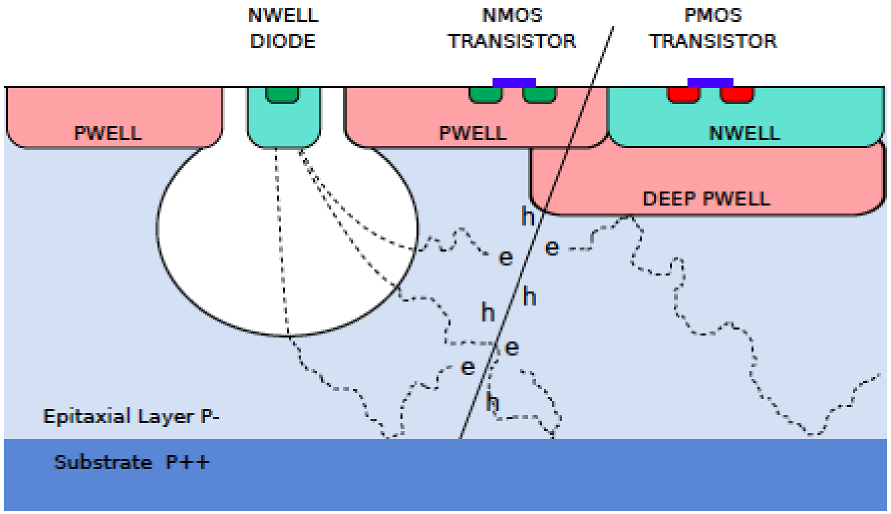
- high resistivity epi-layer
  - thickness 18-40 µm
  - resistivity 1-6 k Ω×cm

- “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

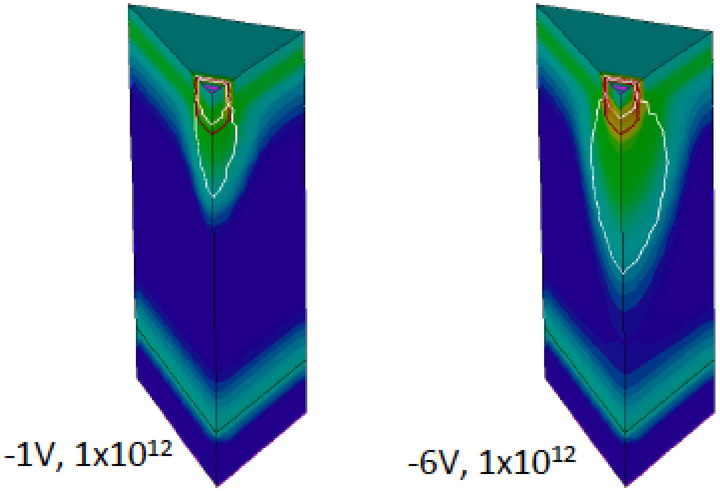
Standard processing, no bump bonding (>>50% of Pixel detector cost). Allows implementation of complex processing electronics inside the entire pixel area.

→ Revolution !



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

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

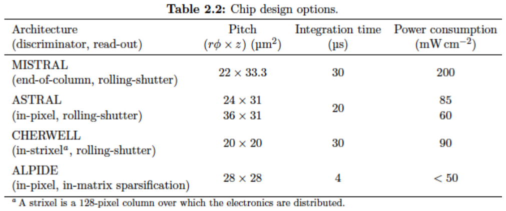


Table 2.2: Chip design options.

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.

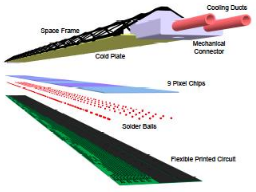
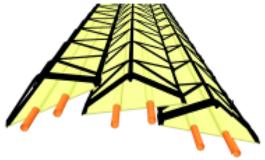
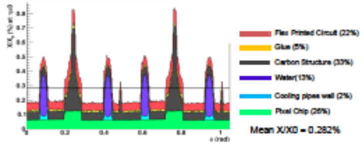
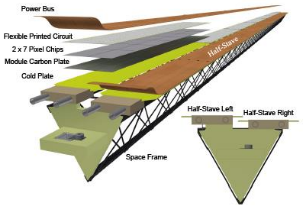
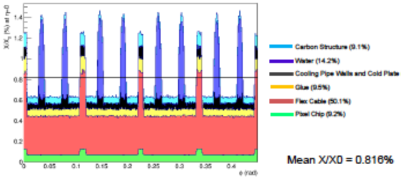


Figure 4.1: Schematic view of the Inner Barrel Stave.









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

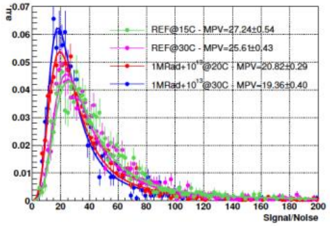


Figure 2.22: SNR of seed pixel measured with MIMOSA-32ter at the CERN-SPS, at two operating temperatures, before and after irradiation with the combined load of 1 Mrad and 10^{13} 1 MeV n_{eq}/cm^2.

Dramatic decrease in cost.

Very low power consumption, possibly <100mW/cm^2 i.e. simple water cooling

Ultra low material budget <0.3% for inner layers, <1% for outer layers.

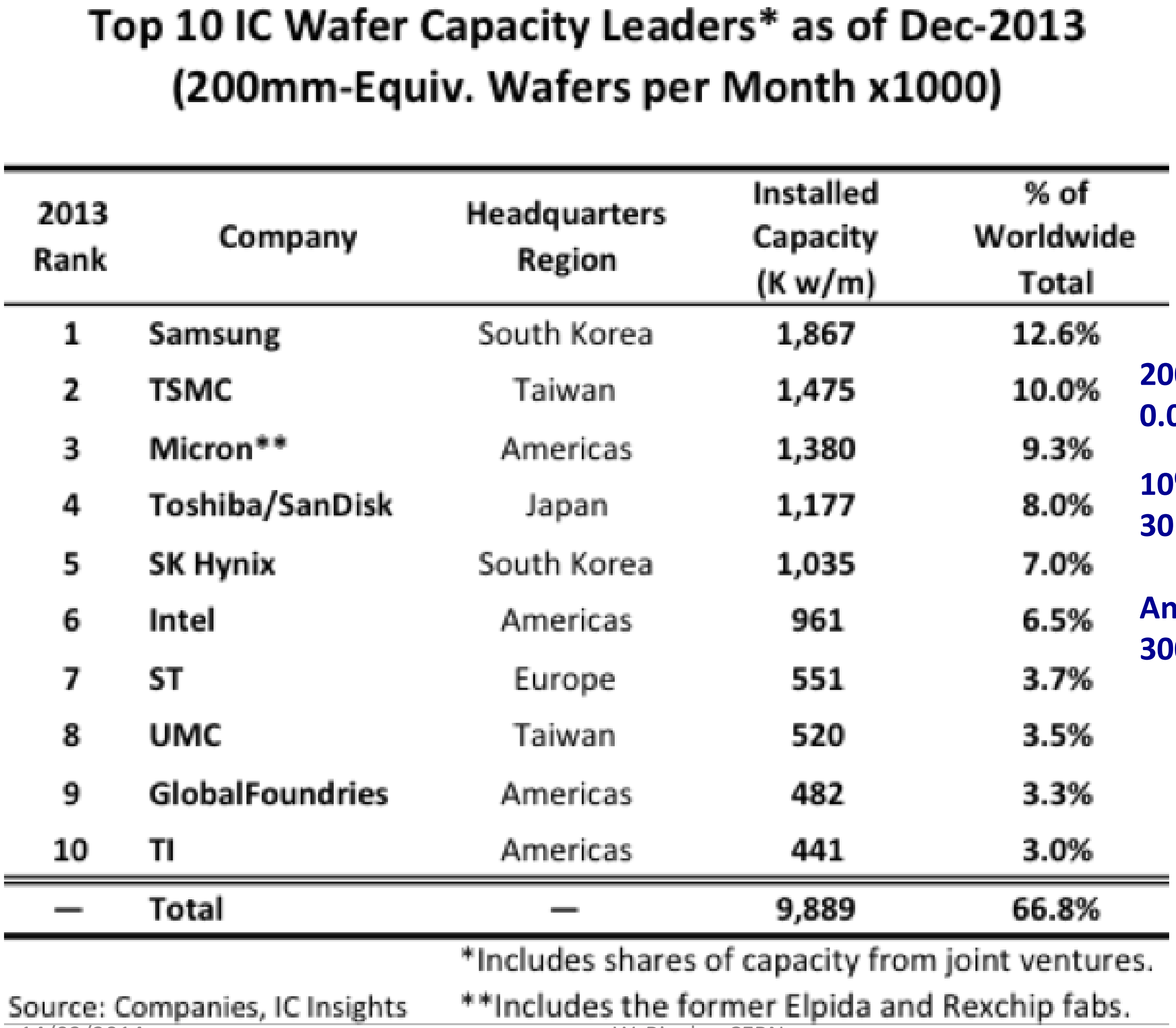
Question of speed and radiation hardness:

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.

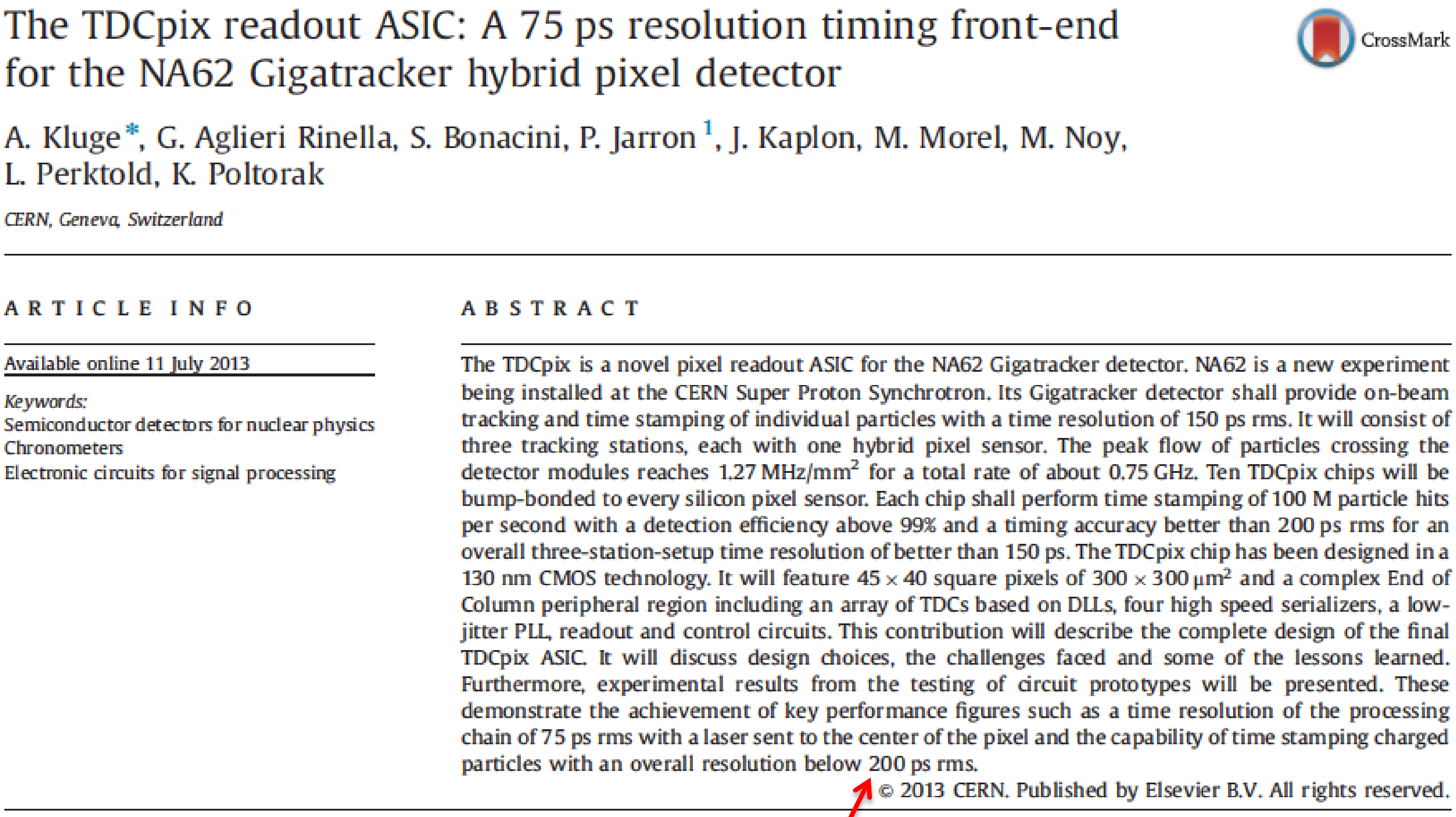
Source: Companies, IC Insights

200mm wafer = $0.03m^2$

10^6 wafers= 30 000 m^2

An FCC detector with $3000m^2$ = 3 days

Time stamping of charged particles with a silicon sensor



The TDCpix readout ASIC: A 75 ps resolution timing front-end for the NA62 Gigatracker hybrid pixel detector

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A R T I C L E I N F O

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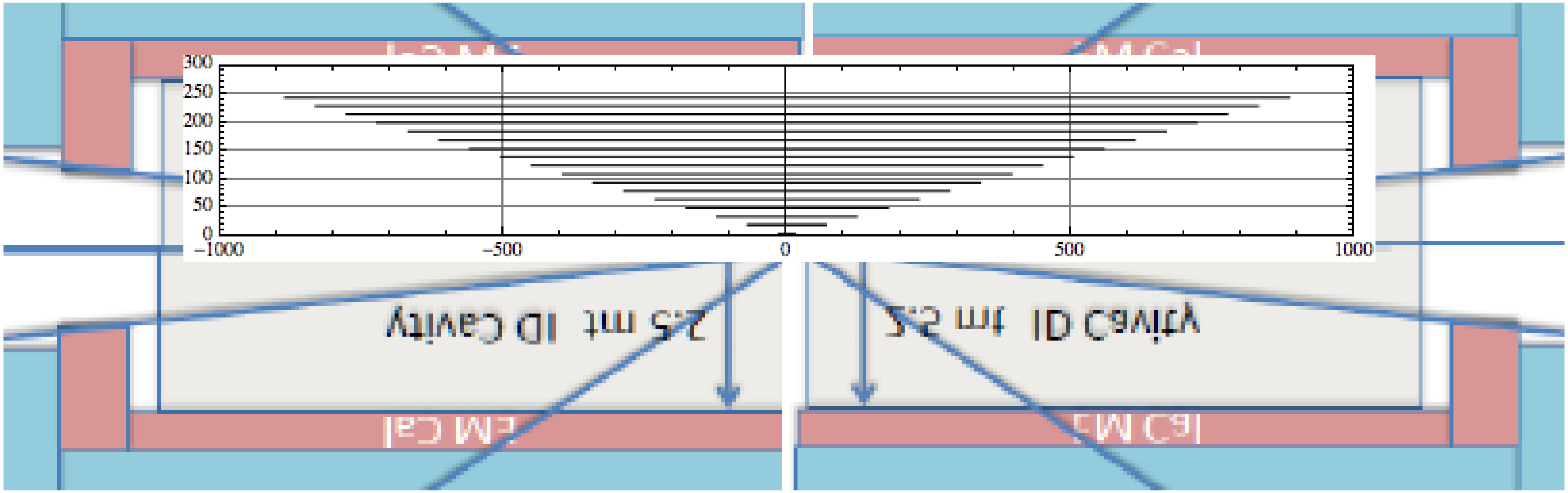
Keywords:
Semiconductor detectors for nuclear physics
Chronometers
Electronic circuits for signal processing

A B S T R A C T

The TDCpix is a novel pixel readout ASIC for the NA62 Gigatracker detector. NA62 is a new experiment being installed at the CERN Super Proton Synchrotron. Its Gigatracker detector shall provide on-beam tracking and time stamping of individual particles with a time resolution of 150 ps rms. It will consist of three tracking stations, each with one hybrid pixel sensor. The peak flow of particles crossing the detector modules reaches 1.27 MHz/mm^2 for a total rate of about 0.75 GHz. Ten TDCpix chips will be bump-bonded to every silicon pixel sensor. Each chip shall perform time stamping of 100 M particle hits per second with a detection efficiency above 99% and a timing accuracy better than 200 ps rms for an overall three-station-setup time resolution of better than 150 ps. The TDCpix chip has been designed in a 130 nm CMOS technology. It will feature 45 × 40 square pixels of 300 × 300 μm^2 and a complex End of Column peripheral region including an array of TDCs based on DLLs, four high speed serializers, a low-jitter PLL, readout and control circuits. This contribution will describe the complete design of the final TDCpix ASIC. It will discuss design choices, the challenges faced and some of the lessons learned. Furthermore, experimental results from the testing of circuit prototypes will be presented. These demonstrate the achievement of key performance figures such as a time resolution of the processing chain of 75 ps rms with a laser sent to the center of the pixel and the capability of time stamping charged particles with an overall resolution below 200 ps rms.

Time resolution below 200ps – makes BCID feasible even for 5ns FHC bunchcrossing.

Tracker Area



Tracker cylinders from $\eta = 0$ to 2
17 layers at radii 4+n*15cm (n=1 to 16)
First at 4cm, last at 244cm, total area = 1600m^2

First 4 layers ‚fast' pixels for BCID, 13 layers ‚slow e.g. 100ns' monolithic pixels (neq <10^{15}cm^{-2})

Including forwards discs around 3000m^2 = 6 times CMS = 300 times ALICE
ALICE 10m^2 with 20x20um pixels = 25GPixels
FHC Detector 3000m^2 with 20x20um pixels = 7500GPixel = 7.5TPixel

Tracker Data Rates

Assume a full pixel tracker:

- **L=5x10^{34} at 100TeV → 5x10^{9} pp collisions/second**
- **dN/dη = 8 i.e. 80 tracks inside η ±5**
- **Each track crosses 15 tracking stations**
- **In each station 5 pixels are fired.**
- **Each hit is encoded in 5 Bytes**
- **Factor 5 for background + curling etc.**

→750 TByte/second into online system

→ Not totally insane

(Fairly easy to simulate)

Tracker Data Rates For Heavy Ions

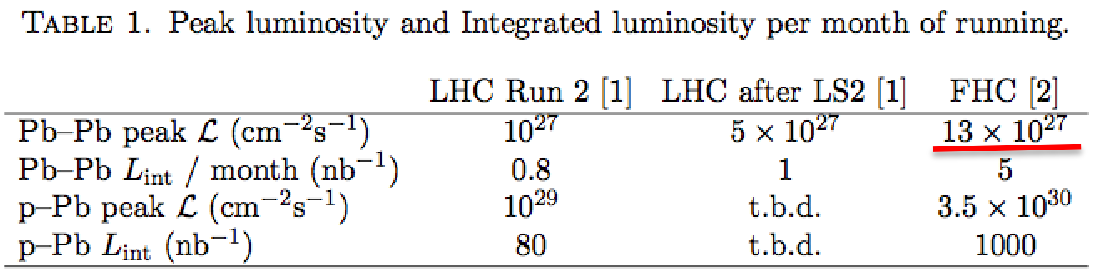


TABLE 1. Peak luminosity and Integrated luminosity per month of running.

	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

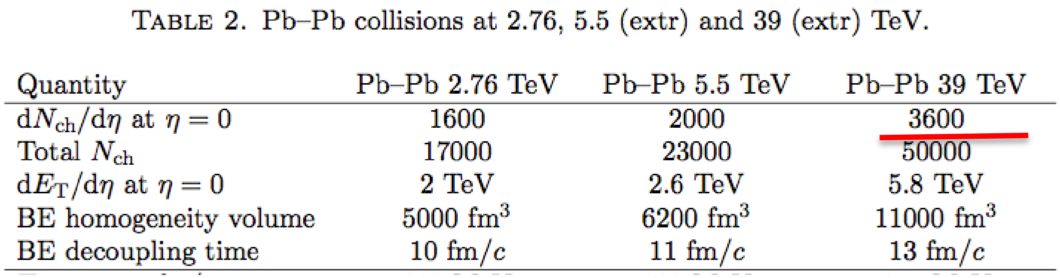


TABLE 2. Pb–Pb collisions at 2.76, 5.5 (extr) and 39 (extr) TeV.

Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta$ 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=5x10^{34}, σ=100mb, dN/deta = 8

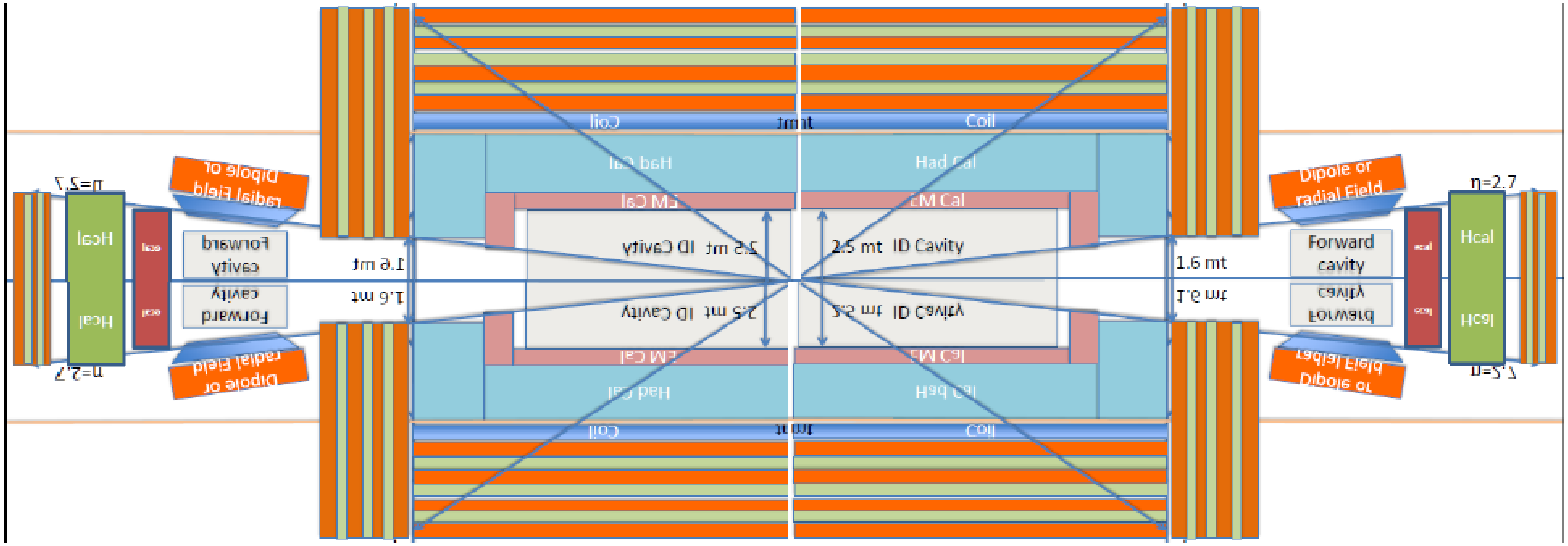
→ 40GHz of tracks per unit of rapidity

PbPb: L=13x10^{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

Tracker + Calorimetry



7.5 Terapixel Tracker with BCID capability down to 5ns bunchcrossing (or less), that pushes all data to the online computing (HLT) system at a data rate of around 1000 TByte/s.

What about calorimetry ?

→ Same pixel chip: Digital calorimetry, even EMCAL.

First results of beamtests of a MAPS based ElectroMagnetic calorimeter

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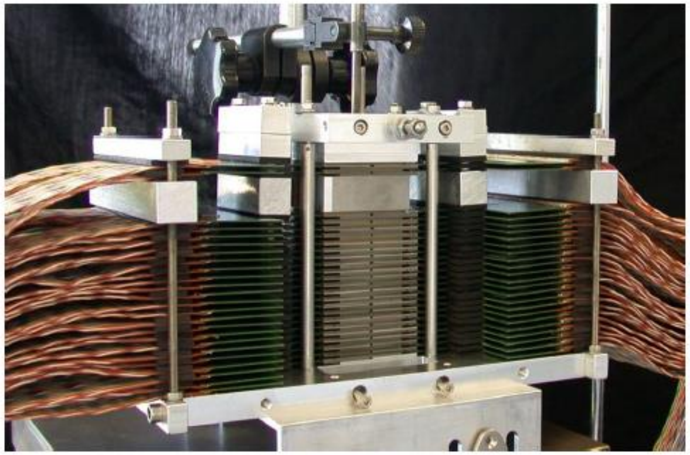
A prototype of a Si-W EM calorimeter was built with Monolithic Active Pixel Sensors as the active elements. With a pixelsize of 30 μm it allows digital calorimetry, i.e. the particles energy is determined by counting pixels, not by measuring the energy deposited. Although of modest size, only 4 Moliere radii wide, it has 39 million pixels and its calibration appears far from trivial. The calorimeter has been tested at DESY (electrons) and at CERN PS and SPS (mixed beams) with energies from 2 to 200 GeV. We present the shape of showers caused by electrons and pions, as well as tracks by pions and cosmic muons in unprecedented detail. Preliminary results for energy and position resolution will also be given.



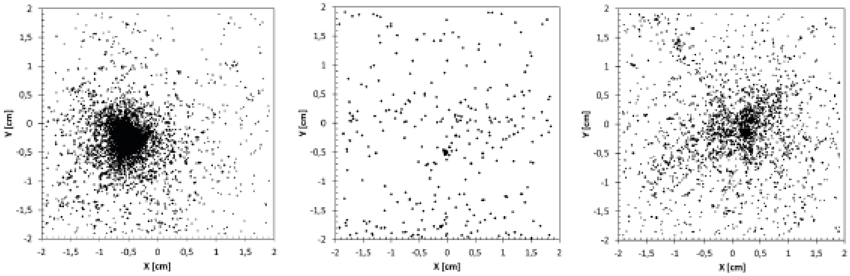


Figure 5: Projection of all hits generated by *left:* a 200 GeV/*c* positron, *centre:* a 200 GeV/*c* non showering pion and *right:* a 200 GeV/*c* showering pion.

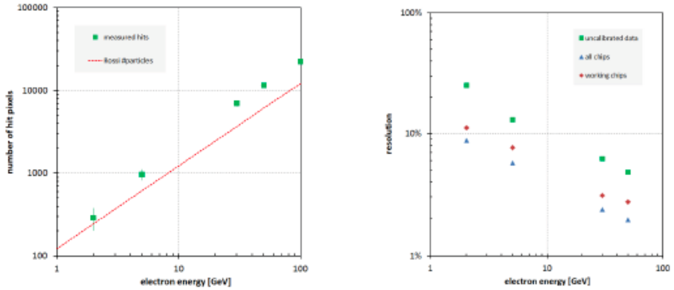
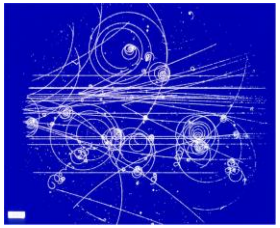
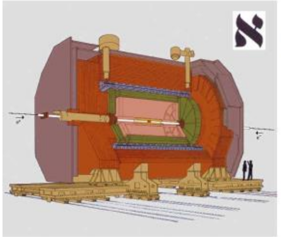
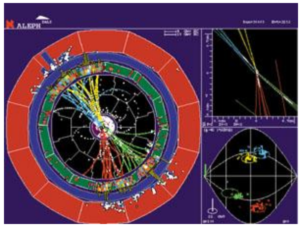


Figure 7: *Left:* The number of hits in the full detector, the line "Rossi" shows the theoretical number of particles. *Right:* Measured resolution of the uncalibrated detector (*squares*). The results of simulations of the ideal detector (*triangles*) and the real detector where only the signals from working chips were used (*diamonds*).

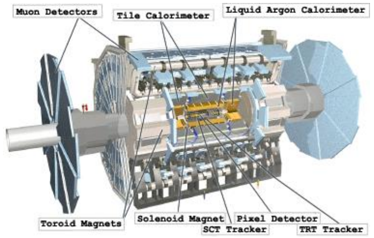


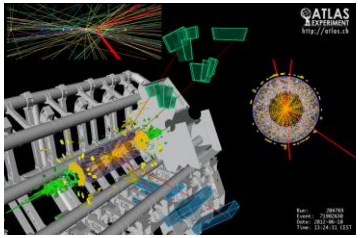
BEBC photopgraphs, untriggered



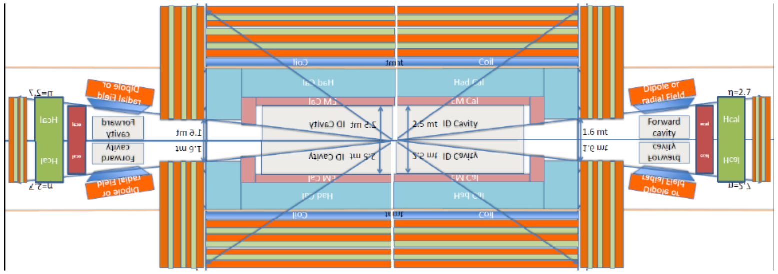


ALEPH triggered, only wire chamber readout.





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.