Radiation issues and tracking concepts for a FHC detector

FCC kickoff meeting
Feb. 12th – 14th 2014

W. Riegler, CERN

Rough check on a few basic points

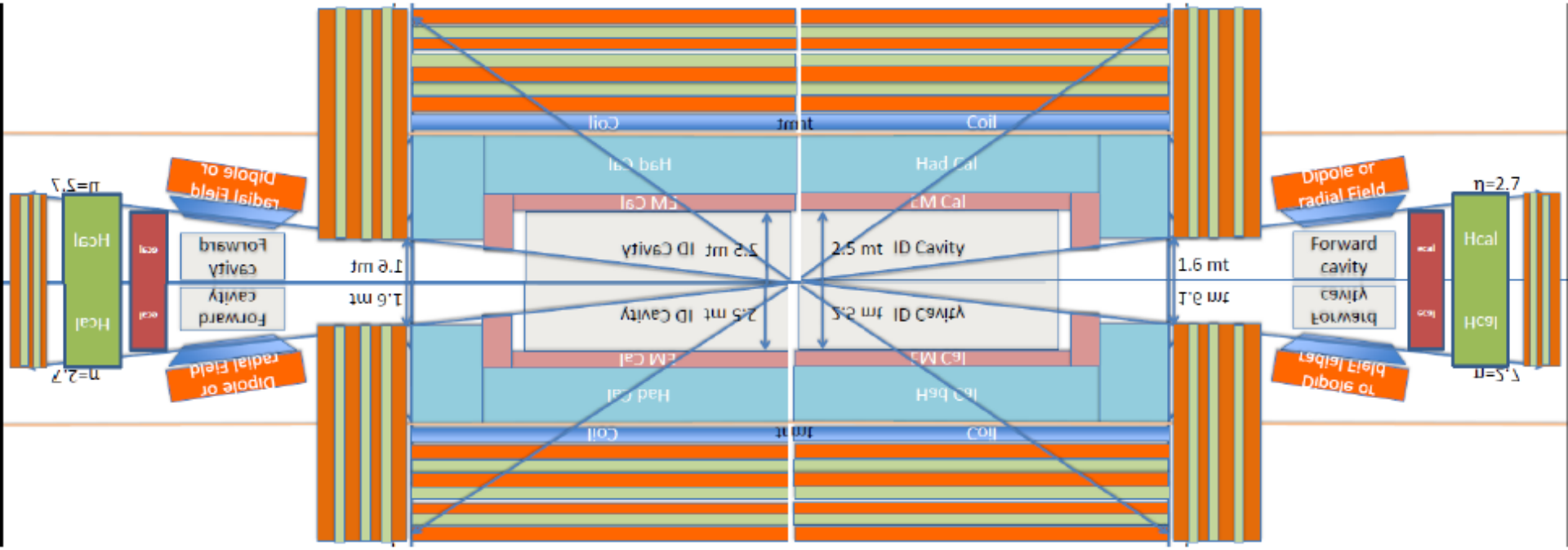
How do multiplicities, particle energy and radiation dose at a 100TeV FHC compare to 14 TeV HL-LHC ?

What could we expect from silicon sensors in 10-20 years from now ?

Are there issues with very short bunchcrossing times of 5ns ?

Will we be able to push the data from an FHC detector into the online systems, without the need for a hardware trigger level ?

Detector Layout

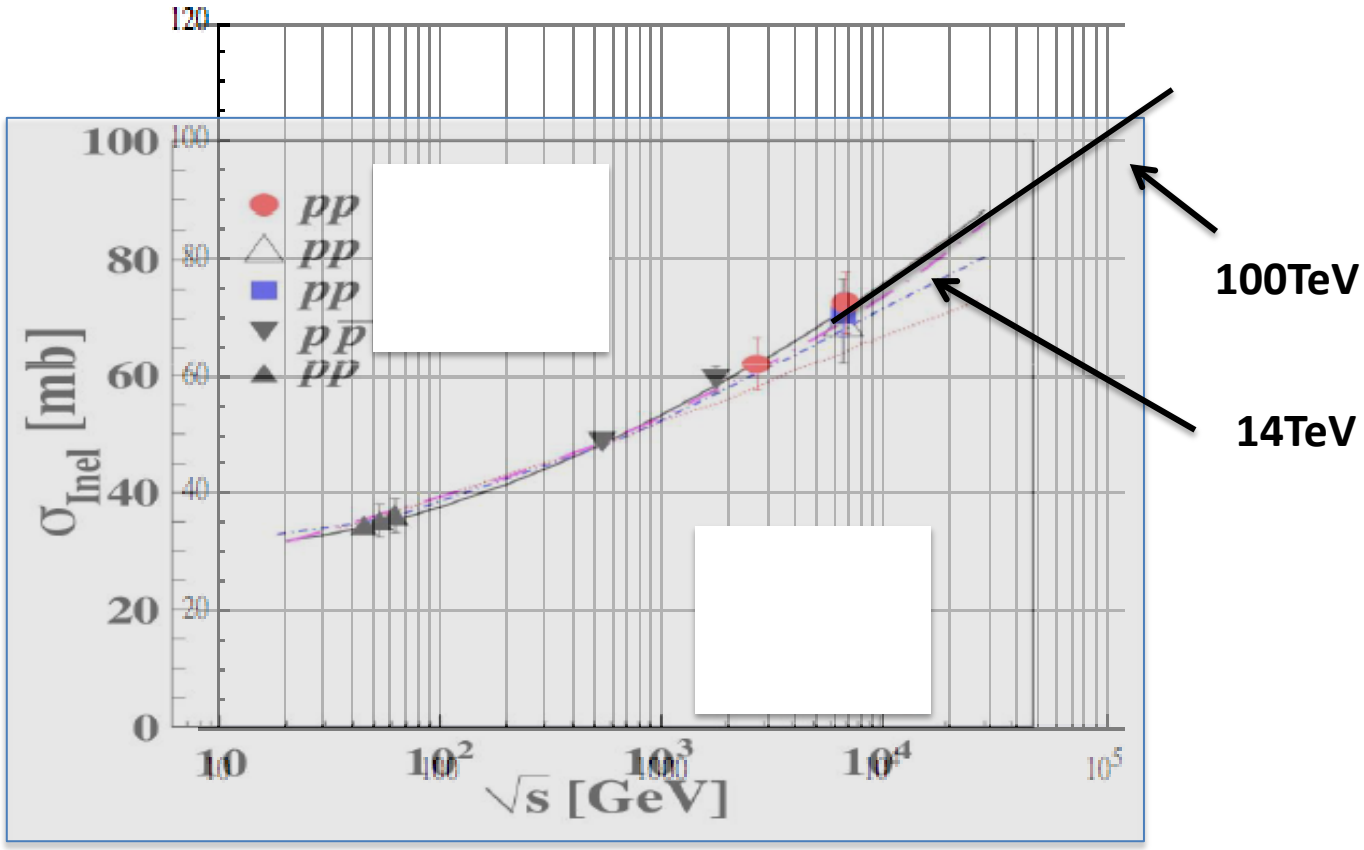


Will use one of the concepts from Daniel Fournier & Co

At η=0 assuming an overall error of 20 μm for the sagitta measurement

- the resolution at 1 TeV (only from the ID) should be 2 % and at 5 TeV about 10 %
- In comparison for the CMS Geometry the resolution at 1 TeV is about 12% at eta =0

Inelastic pp crossection



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

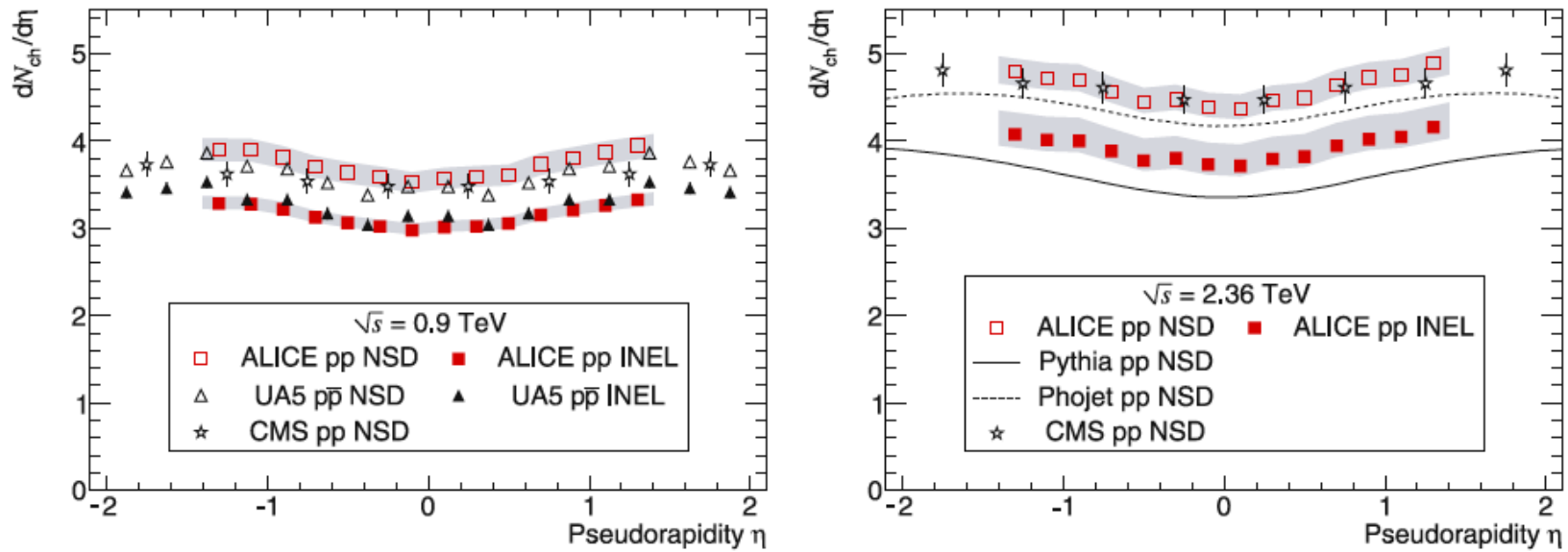
≈ 80mb at 14TeV

≈ 100mb at 100TeV

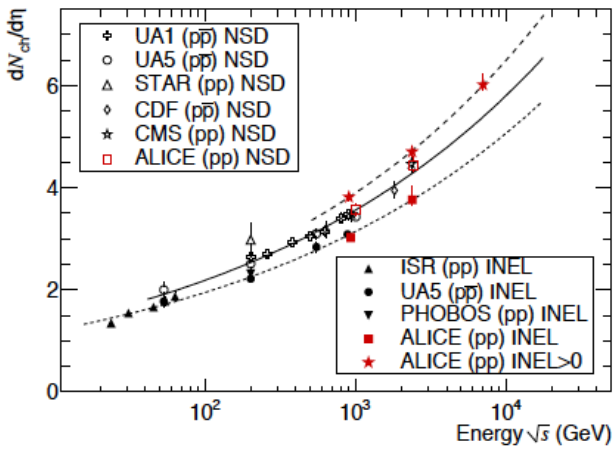
→ 25% increase

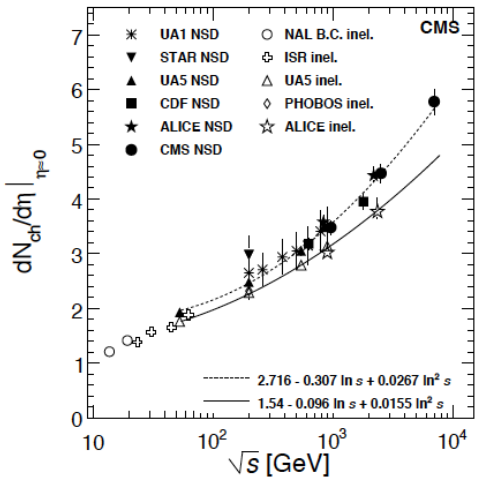
Multiplicities

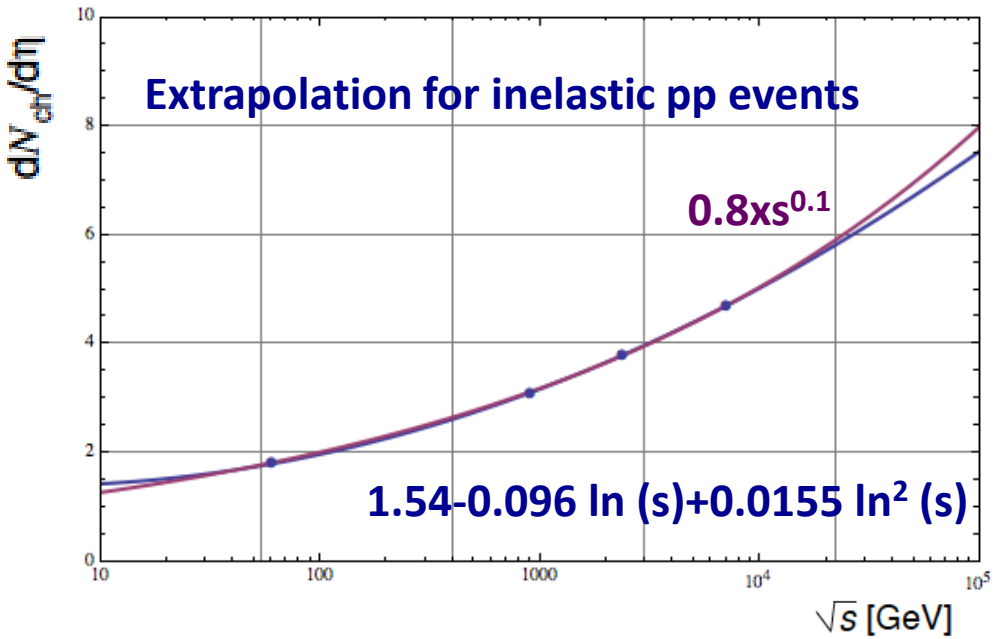
Eur. Phys. J. C (2010) 68: 89–108



Multiplicities



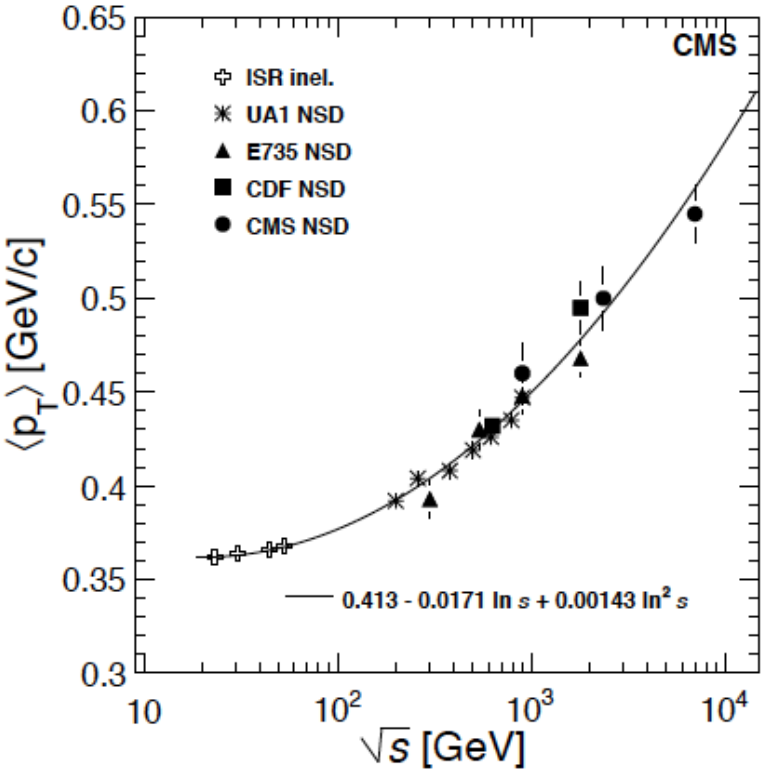


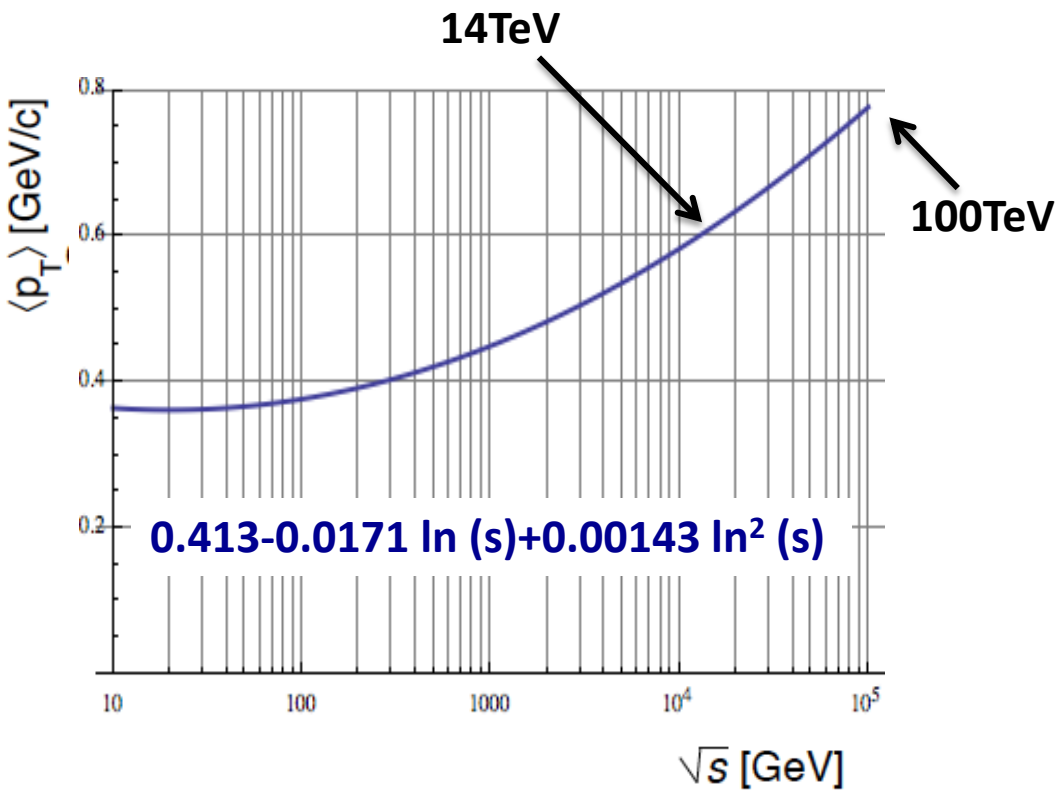


100TeV

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

Average Particle Momentum

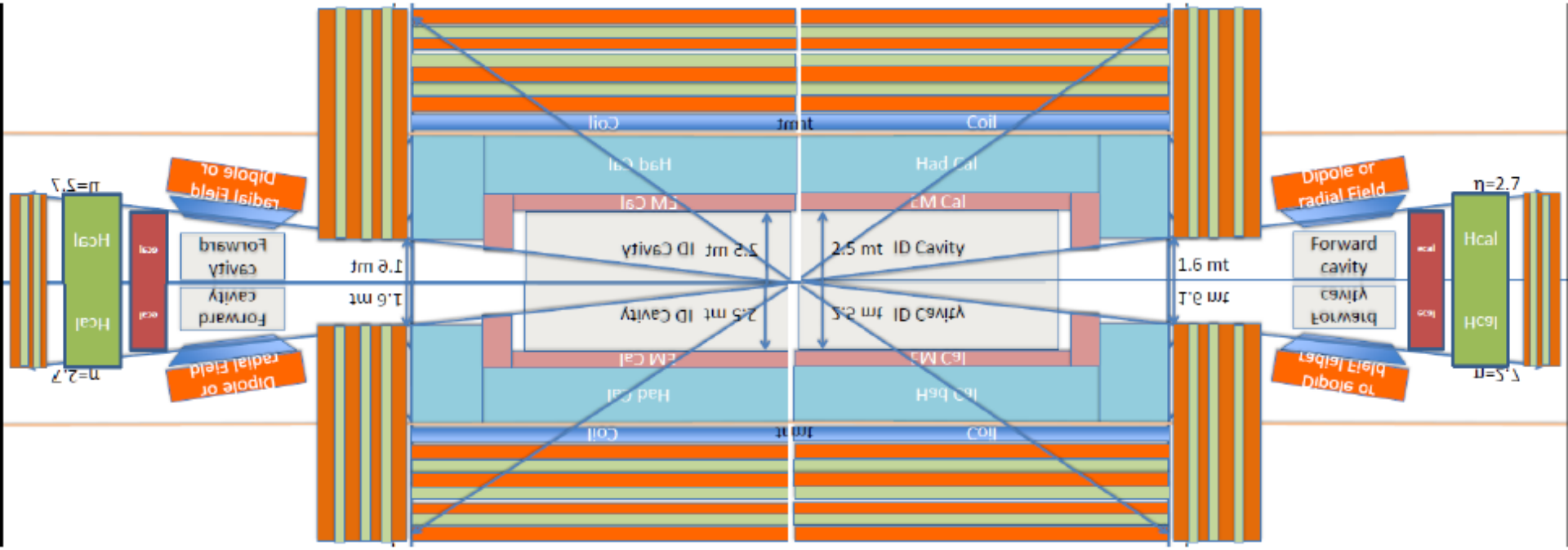




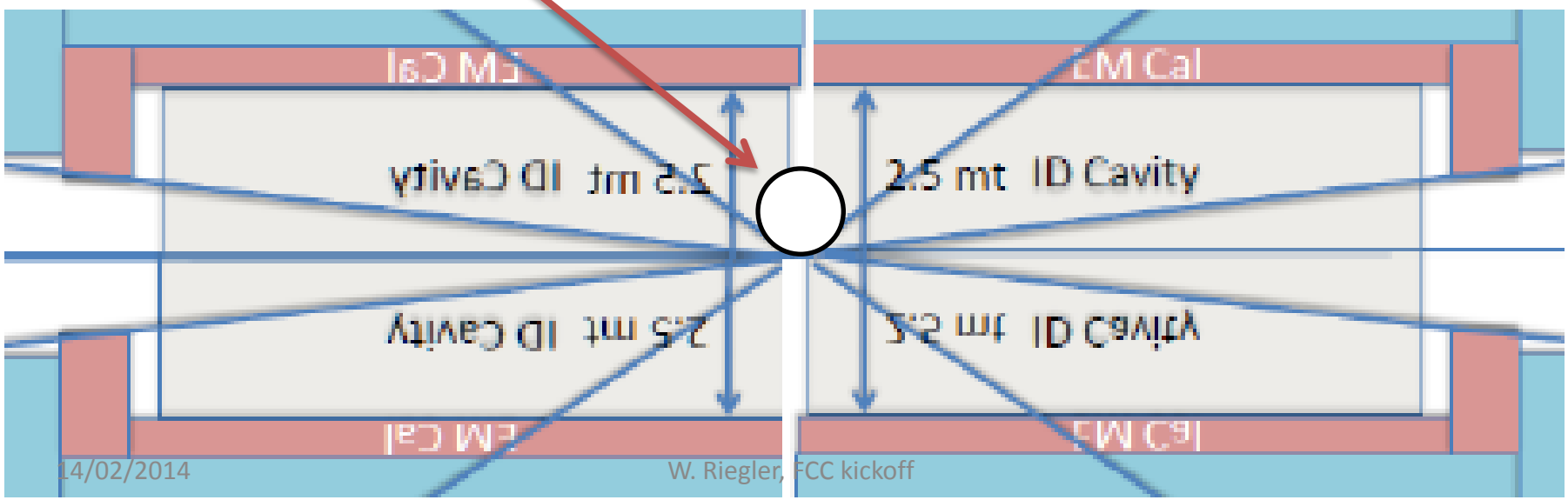
Average p_T approx. 0.6GeV/c for 14 TeV and 0.8GeV/c at 100TeV i.e. increase of 33%.

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

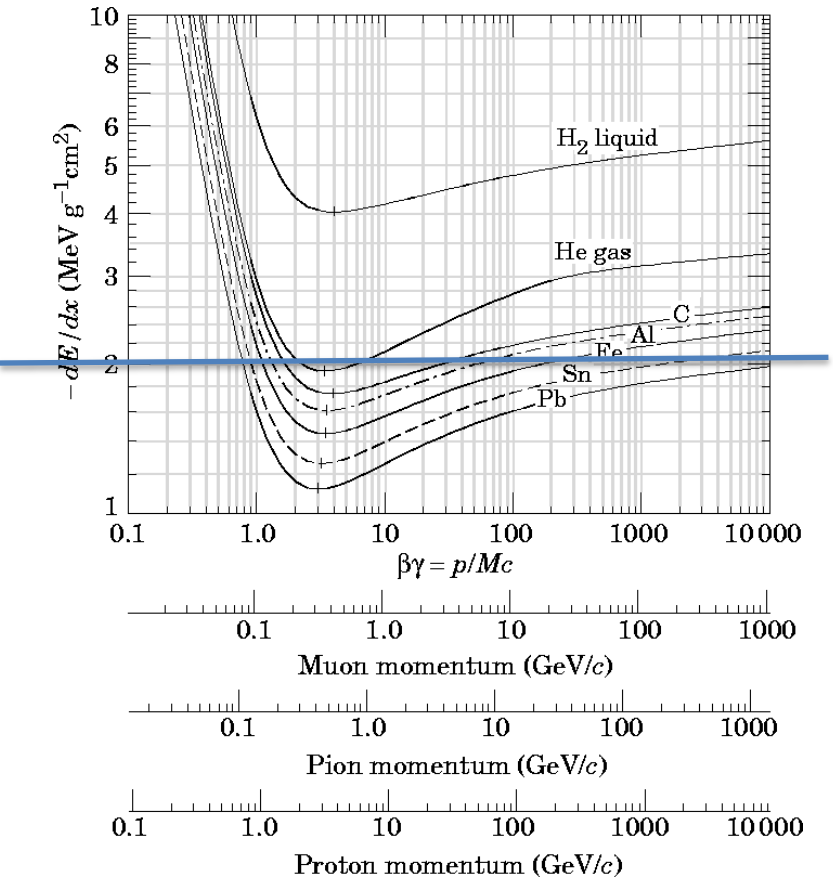
→ **Average particle will curl with 1.33m diameter inside the ID.**



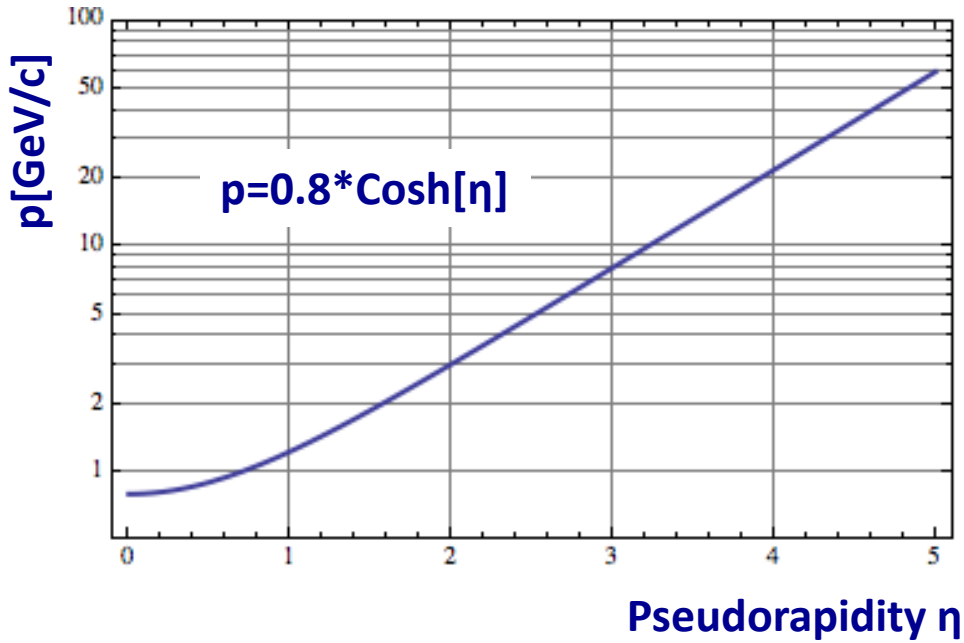
Curling circle of average p_T particle at B=4T



Energy Deposit in Tracker Elements



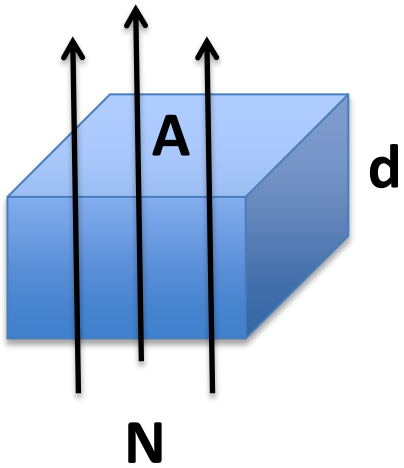
Momentum p for p_T of 0.8GeV/c



Pions are dominant particle species.
Close to MIP.

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

Ionizing Dose



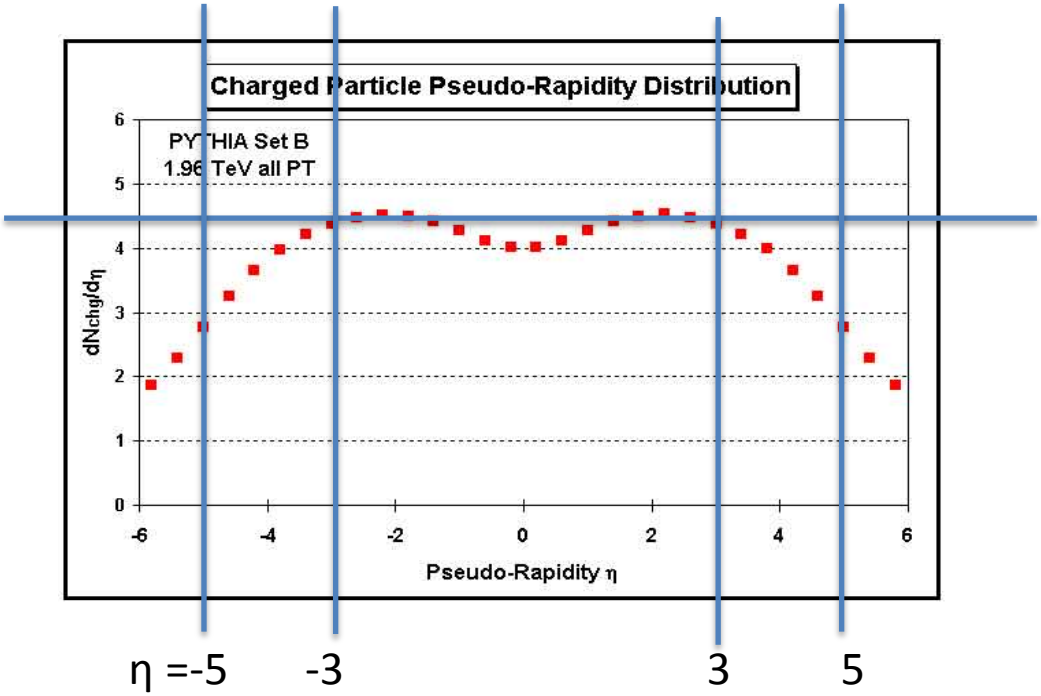
Assuming N ionizing particles per cm^2
there are N*A particles passing the volume.

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

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

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

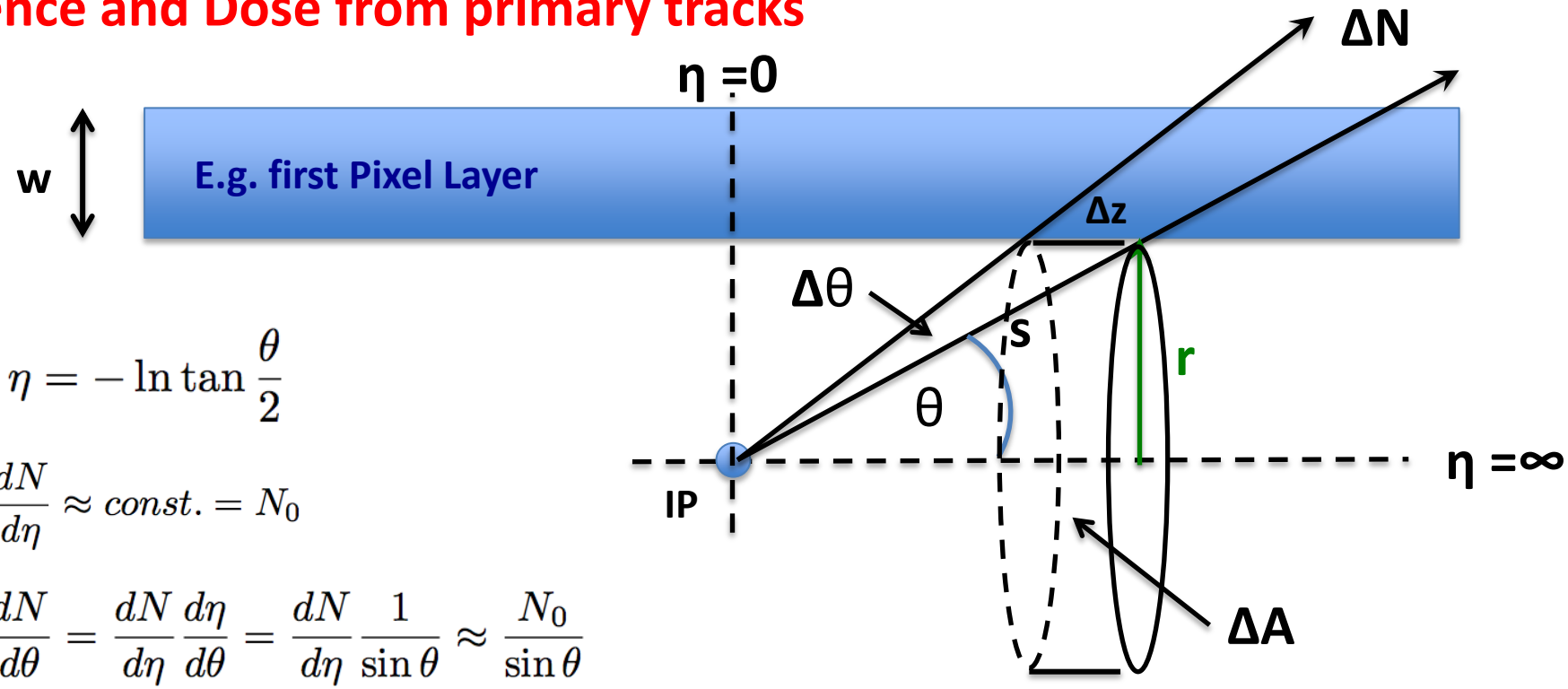
Multiplicities



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



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

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

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

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

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

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

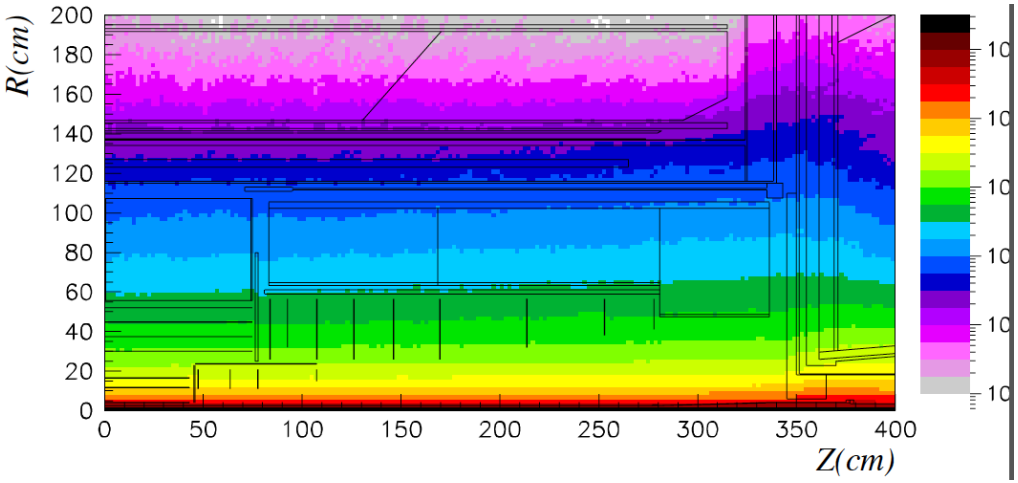
$$\text{Fluence} = \frac{\Delta N}{\Delta A}\frac{w}{w\sin\theta} = \frac{dN}{d\theta}\frac{\sin\theta}{2r^2\pi} \approx \frac{N_0}{2r^2\pi}$$

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

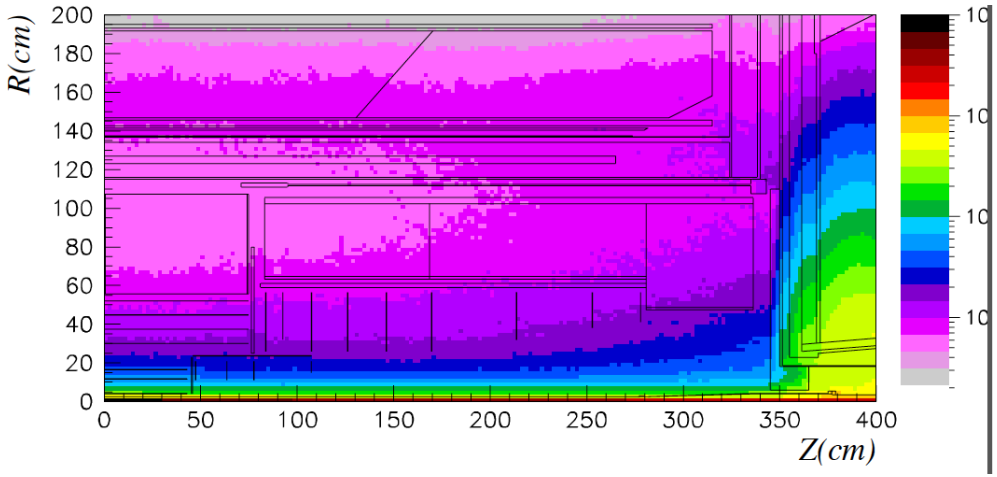
→ **The hadron fluence due to primary particles is just a function of the distance from the beamline.**

→ **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

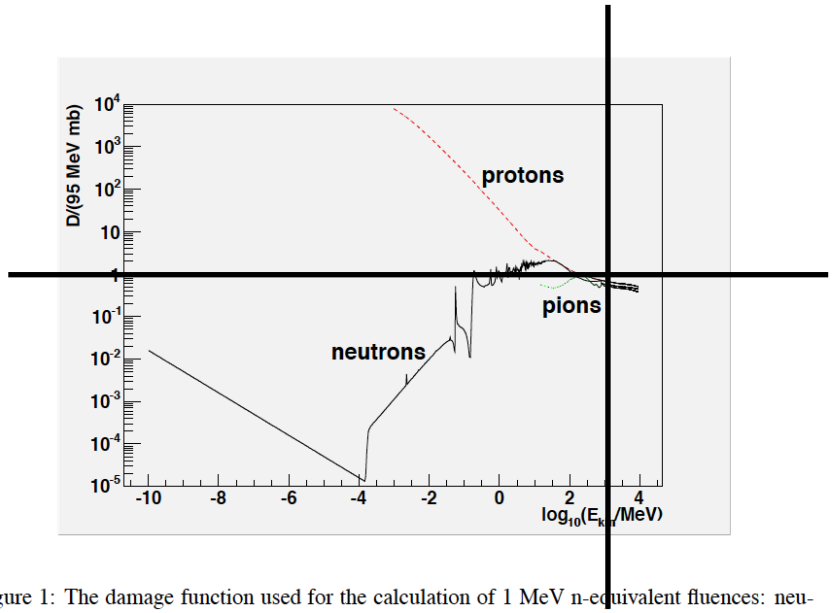


Figure 1: The damage function used for the calculation of 1 MeV n-equivalent fluences: neutrons (solid line), protons (dashed line), pions (dotted line)

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

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

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

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

Crosscheck with ATLAS Phase II LOI

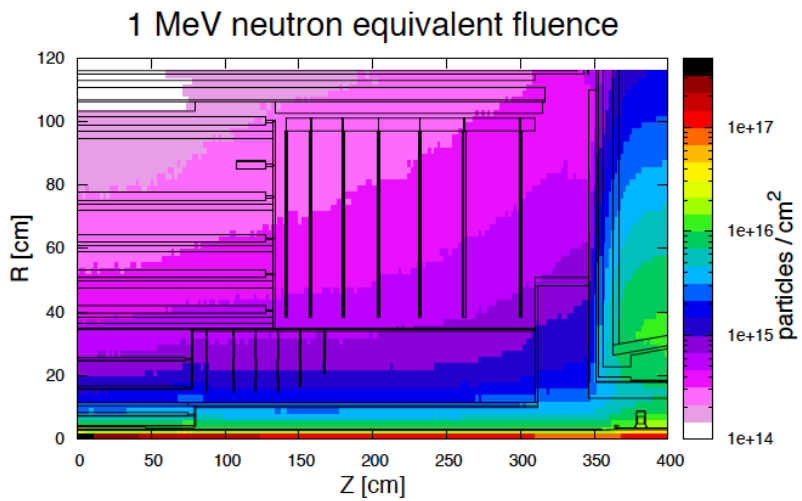


Figure 6.2: *RZ*-map of the 1 MeV neutron equivalent fluence in the Inner Tracker region, normalised to 3000 fb^{-1} of 14 TeV minimum bias events generated using PYTHIA8.

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*π*3.7^2) = 1.5*10^{16} cm^{-2}

Dose = 3.2x10^{-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 1.4×10^{16}cm^{-2} and 7.7 MGy at the centre of the innermost barrel layer. For the

Crosscheck with ATLAS Phase II LOI

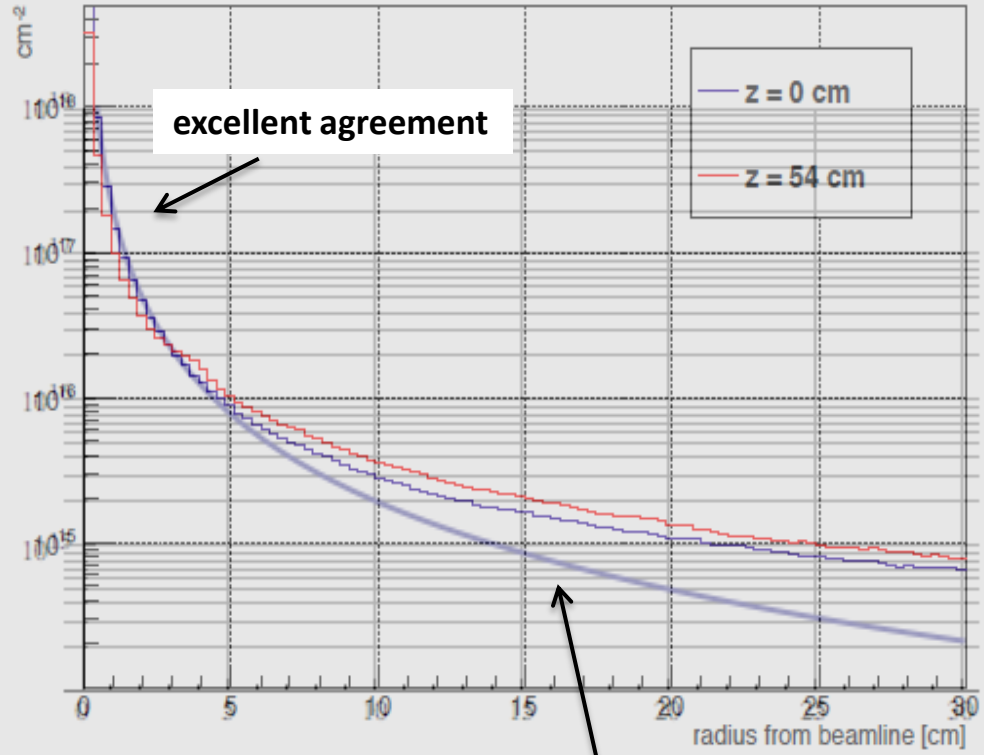


Figure 3. *Radial evolution of 1 MeV neutron equivalent fluence at z=0, 54 cm for an integrated fluence of 3000 fb⁻¹ [4].*

ATL-UPGRADE-PUB-2012-003

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

Crosscheck with ATLAS Phase II LOI

ATL-UPGRADE-PUB-2012-003

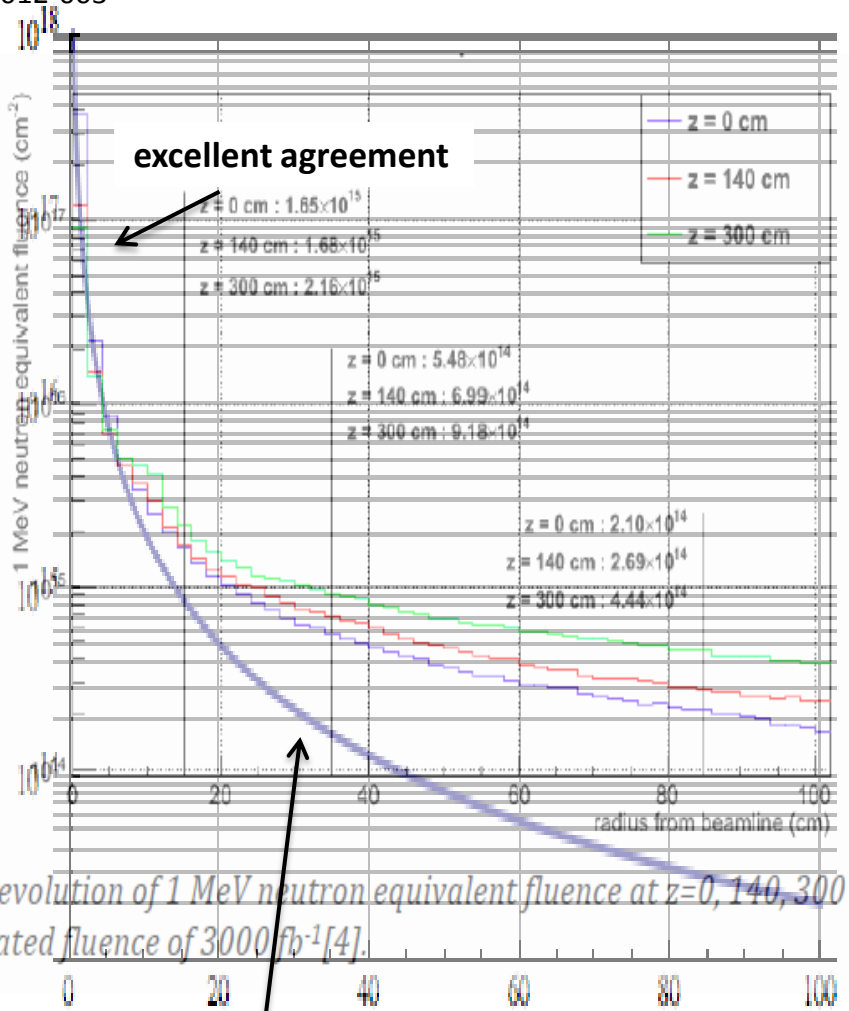


Figure 2. *Radial evolution of 1 MeV neutron equivalent fluence at z=0, 140, 300 cm for an integrated fluence of 3000 fb^{-1}[4].*

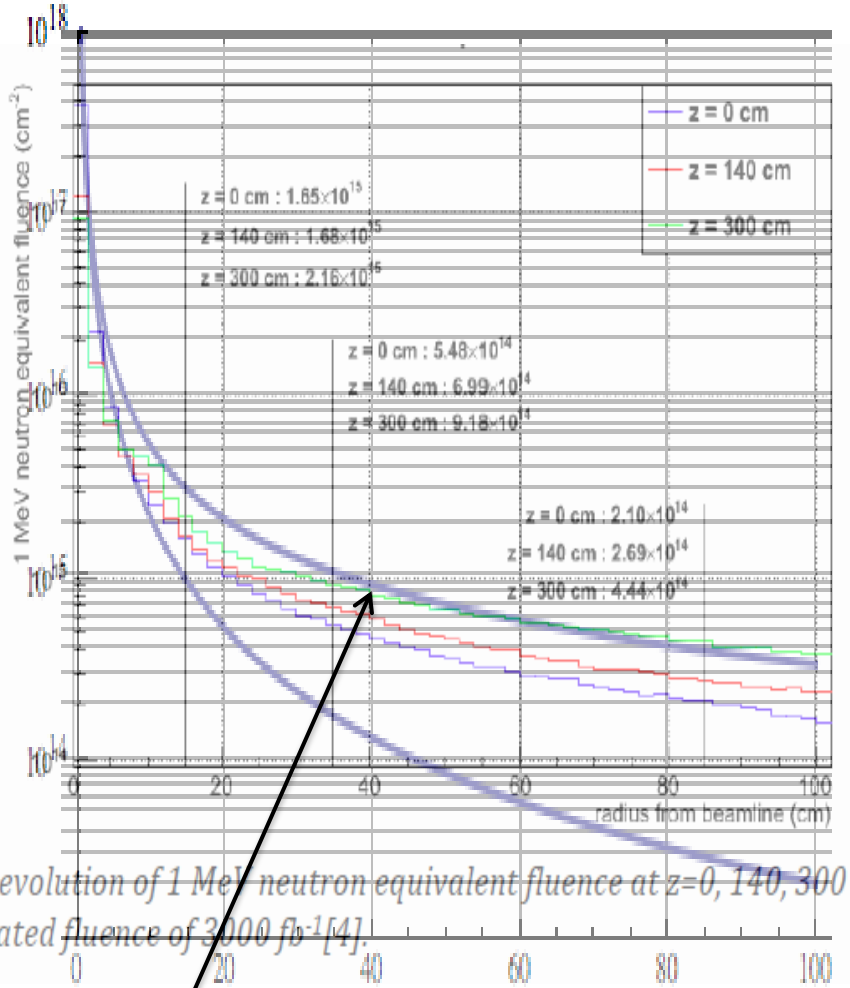
off by factor 10 at 100cm

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

Crosscheck with ATLAS Phase II LOI

Adding some 1/r component.

1/a= distance where direct and secondary particles are in same numbers.



1/a=6.7cm

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].*

$$1\text{MeV neq Fluence}[cm^{-2}] \approx \frac{N_0}{2\pi} \times N_{pp} \left(\frac{1}{r[cm]^2} + \frac{a[cm^{-1}]}{r[cm]} \right)$$

$$\text{Dose}[Gray] \approx 3.2 \times 10^{-10} \frac{N_0}{2\pi} \times N_{pp} \left(\frac{1}{r[cm]^2} + \frac{a[cm^{-1}]}{r[cm]} \right)$$

FHC 100TeV

Parameter	LHC	HL-LHC		HE-LHC	VHE-LHC
c.m. energy [TeV]	14			33	100
circumference C [km]	26.7				80
dipole field [T]	8.33			20	20
dipole coil aperture [mm]	56			40	≤ 40
beam half aperture [cm]	2.2 (x), 1.8 (y)			1.3	< 1.3
injection energy [TeV]	0.45			>1.0	>3.0
no. of bunches	2808	2808	1404	2808	8420
bunch population [10^{11}]	1.125	2.2	3.5	0.81	0.80
init. transv. norm. emit. [μm]	3.73,	2.5	3.0	1.07	1.70
initial longitudinal emit. [eVs]	2.5			3.48	13.6
no. IPs contributing to tune shift	3	2	2	2	2
max. total beam-beam tune shift	0.01	0.021	0.028	0.01	0.01
beam circulating current [A]	0.584	1.12	0.089	0.412	0.401
RF voltage [MV]	16			16	22
rms bunch length [cm]	7.55			7.55	7.55
IP beta function [m]	0.55	$0.73 \rightarrow 0.15$		0.3	0.9
init. rms IP spot size [μm]	16.7	$15.6 \rightarrow 7.1$	$24.8 \rightarrow 7.8$	4.3	5.3
Stored energy [MJ]	362	694		601	4573
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1	(7.4)		5	5

Average pile-up: ~140/xing

Assume:

Luminosity 5x10^{34} in 25ns or 5ns bunch spacing.

Integrate 3000fb-1.

FHC 100TeV

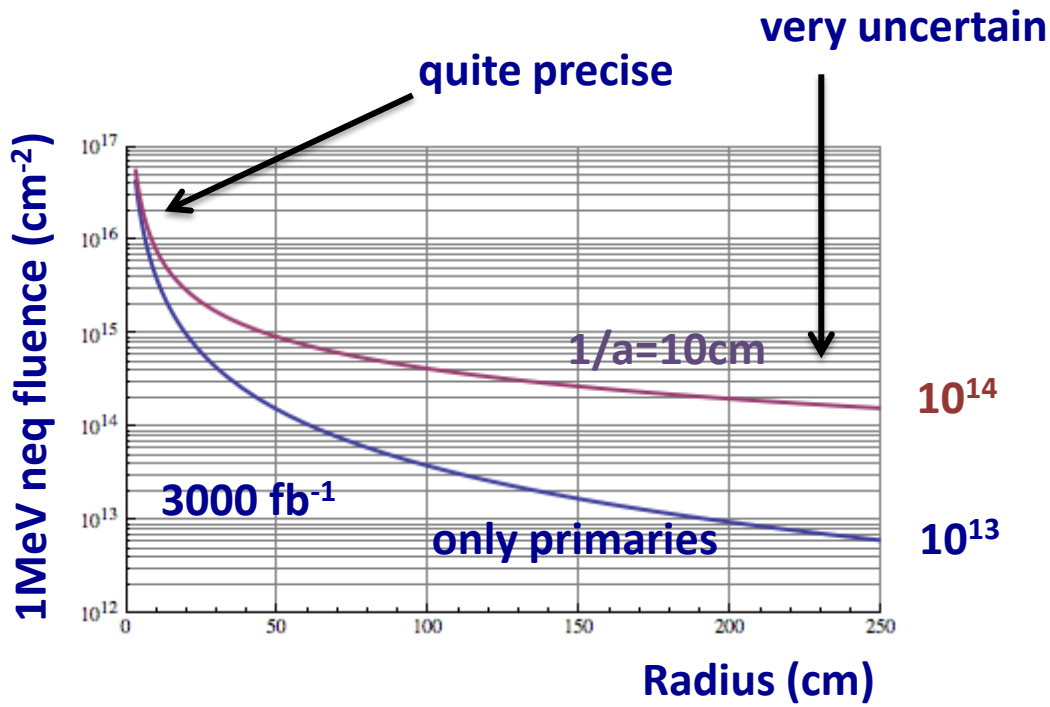
3000 fb^{-1}
100mb inelastic pp crossection
3 * 10^{17} events
dN/dη = N0 = 8
Pixel layer1 at r=3.7cm

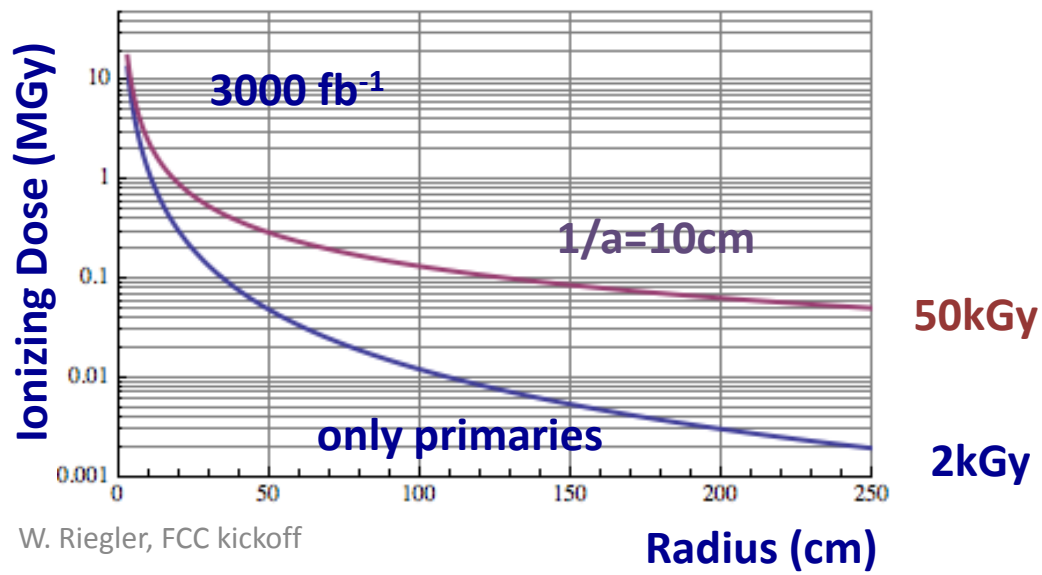
1MeVneq Fluence =
$3*10^{17}*8/(2*\pi*3.7^2)$ =
$2.8*10^{16}$ cm^{-2}

Dose = 3.2x10-8*2.8*1016 =
9MGy

→ Integrating 3000fb-1 of pp collisions with a FHC detector will result in 2x the HL-LHC fluence and dose numbers for the first pixel layer at r=3.7cm.

→ For 10000fb^{-1} i.e. 10 ab^{-1} the hadron fluence is close to $10^{17}cm^{-2}$





Conslusion 1/2

Inelastic crossection at 14(100)TeV is 80(100mb).

Multiplicity at 14(100)TeV is 5.4(8) charged particles per rapidity unit.

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

1MeV neq fluence and Dose are to a quite good approximation only depending on distance from beamline, independently of z.

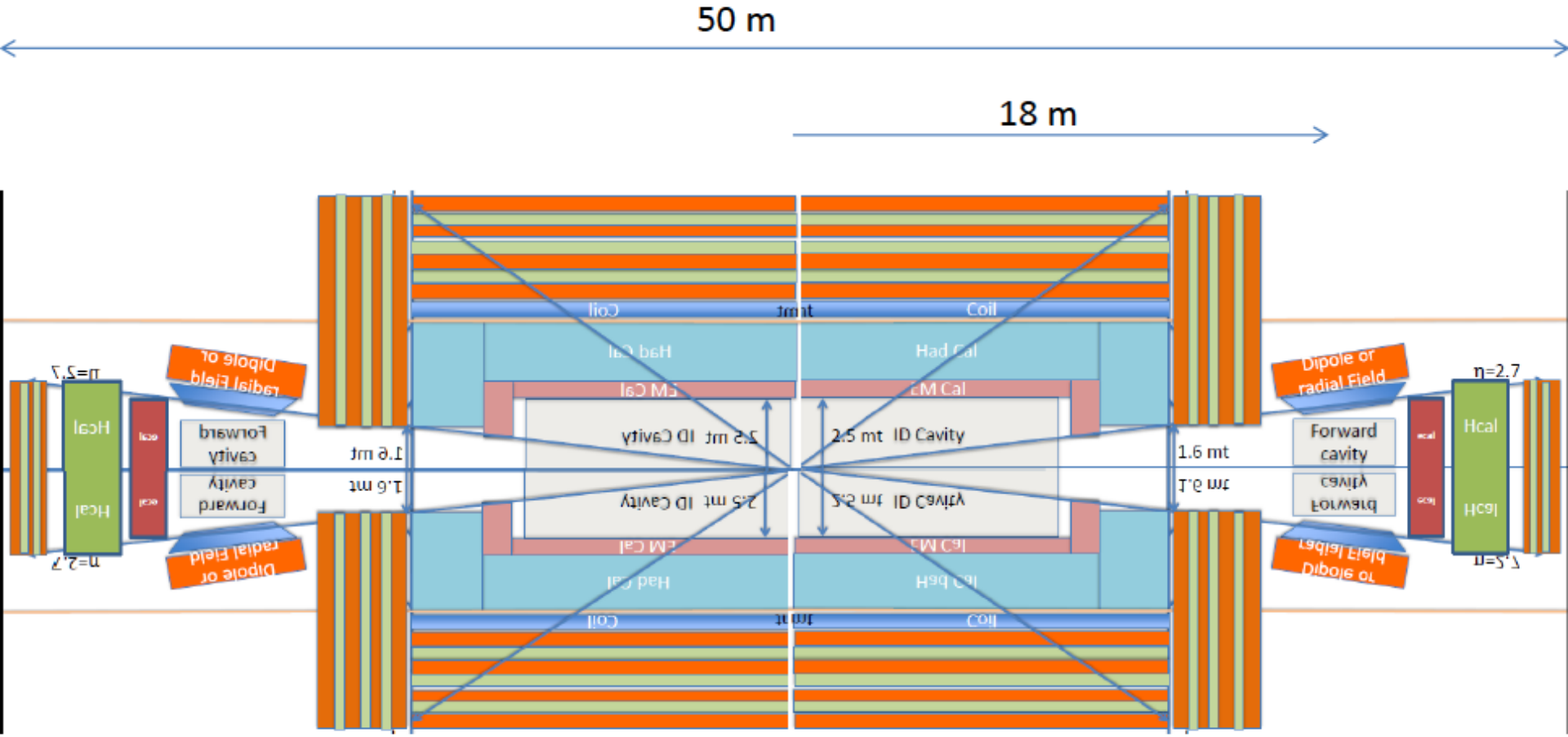
Radial dependence of fluence and dose due to primary straight charged tracks are given by

$$\text{1MeV neq Fluence}[cm^{-2}] \approx \frac{N_0}{2r[cm]^2\pi} \times N_{pp} \qquad \text{Dose}[Gray] \approx 3.2 \times 10^{-10} \frac{N_0}{2r[cm]^2\pi} \times N_{pp}$$

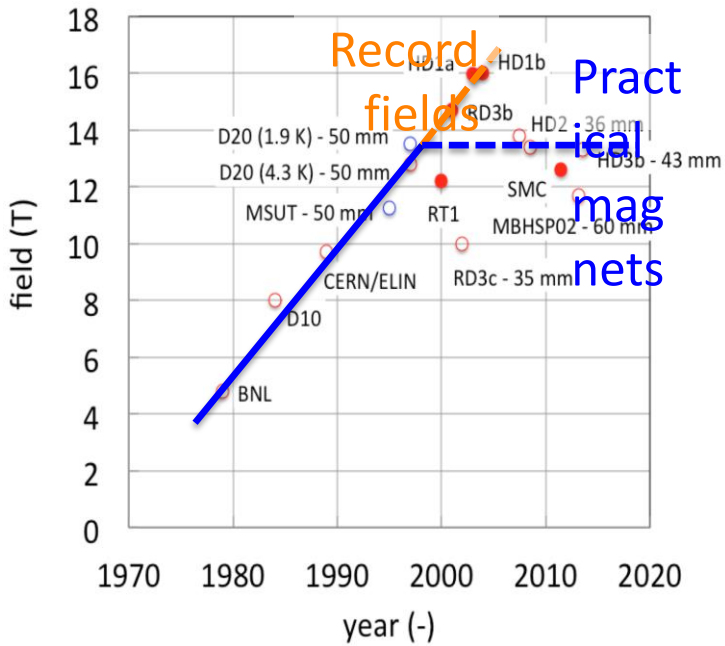
It is a very good approximation up to 10cm distance, but underestimates by up to factor 10 at 250cm due to curling particles and neutrons.

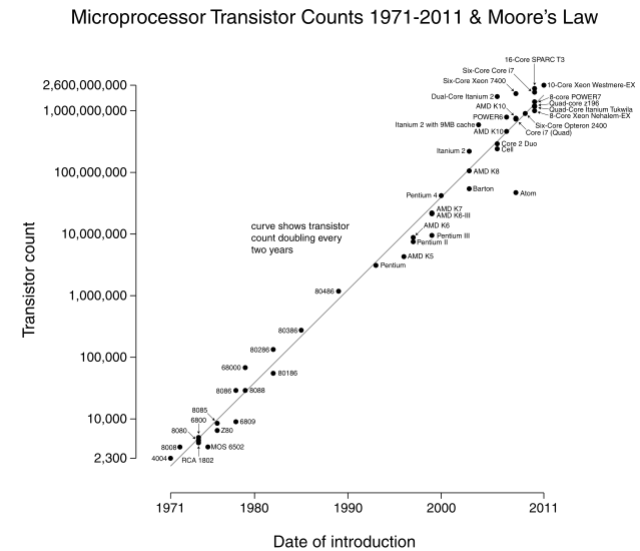
Assuming an integrated luminosity of 3000 fb^{-1} and the first pixel layer at r=3.7cm from the beampipe the fluence and dose for 14(100)TeV are 1.5(3)$10^{16}cm^{-2}$ and 5(10)MGy i.e. the numbers for an FHC detector are only about twice the HL-LHC numbers (unless one puts the first pixel closer).

The fluence and dose numbers for a distance of 2.5m from the IP for 3000 fb^{-1} of 100TeV collisions are between 10^{13} and 10^{14} cm^{-2} and 2-50 kGy.


50 m
18 m
Dipole or radial Field
Forward cavity
Hcal
ecal
η=2.7
Coil
1m
Had Cal
EM Cal
2.5 mt ID Cavity
1.6 mt

Detector Technologies

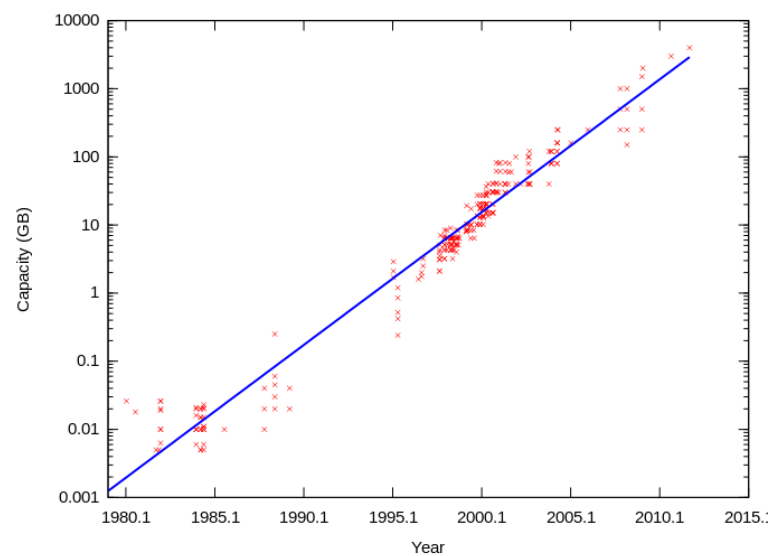




Magnets between 1980 to 2000: factor 3 with difficult prospects ...

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

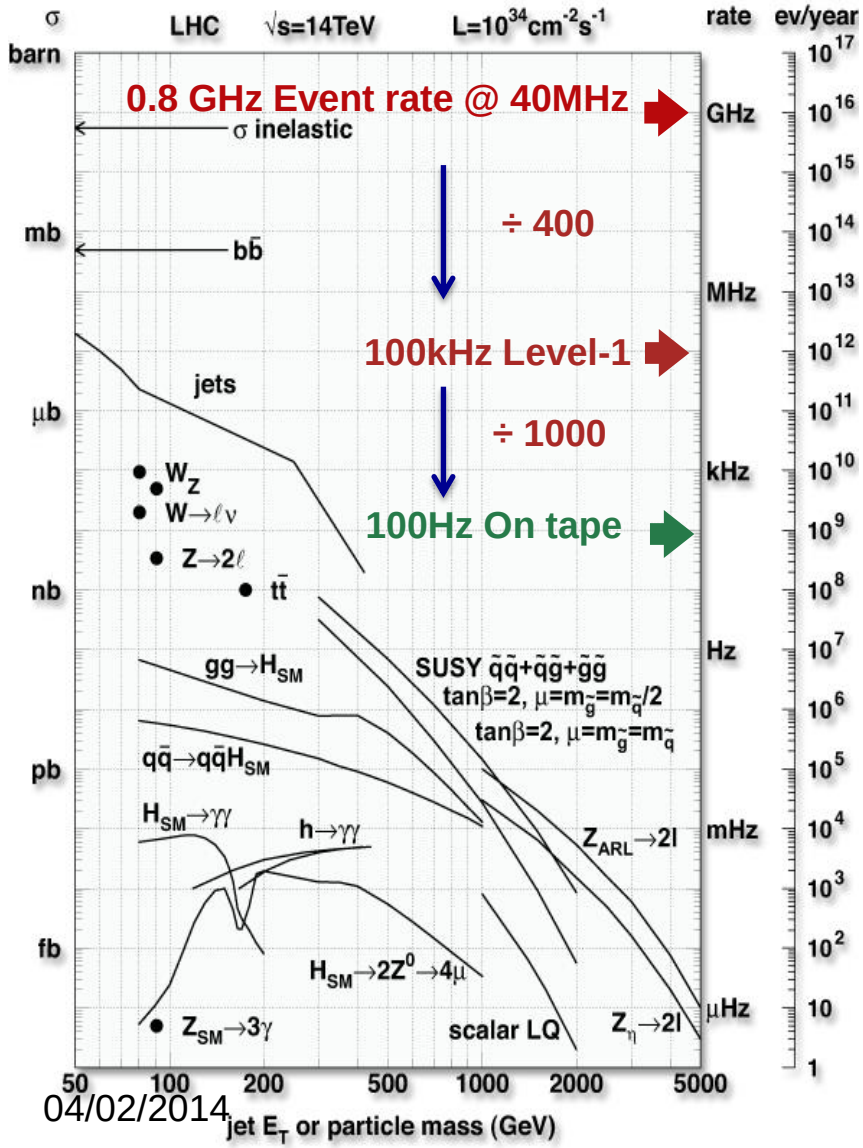
If the doubling of computing power every two years continues to hold, "then by 2030 whatever technology we're using will be sufficiently small that we can fit all the computing power that's in a human brain into a physical volume the size of a brain," explained Peter Denning, distinguished professor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



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

4 GHz Event Rate @ 40MHz

÷ 40

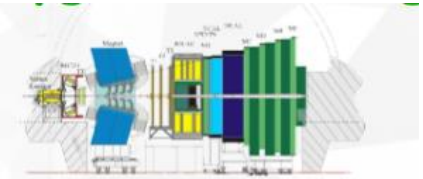
0.5-1 MHz Level-1 Rate

÷ 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

DAQ

40 MHz

LLT: μ,e/γ, hadrons

5-40 MHz

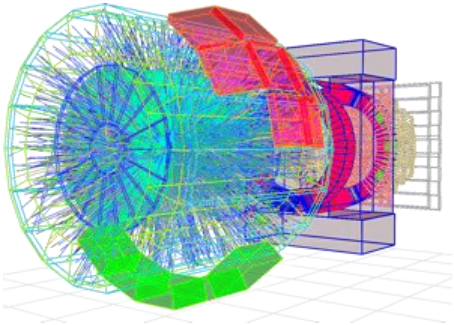
HLT: event recon.

20 kHz (0.1 MB/event)

Storage

2 GB/s

4 TByte/s into PC farm



1 TByte/s into PC farm

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 $5x10^{34}$.

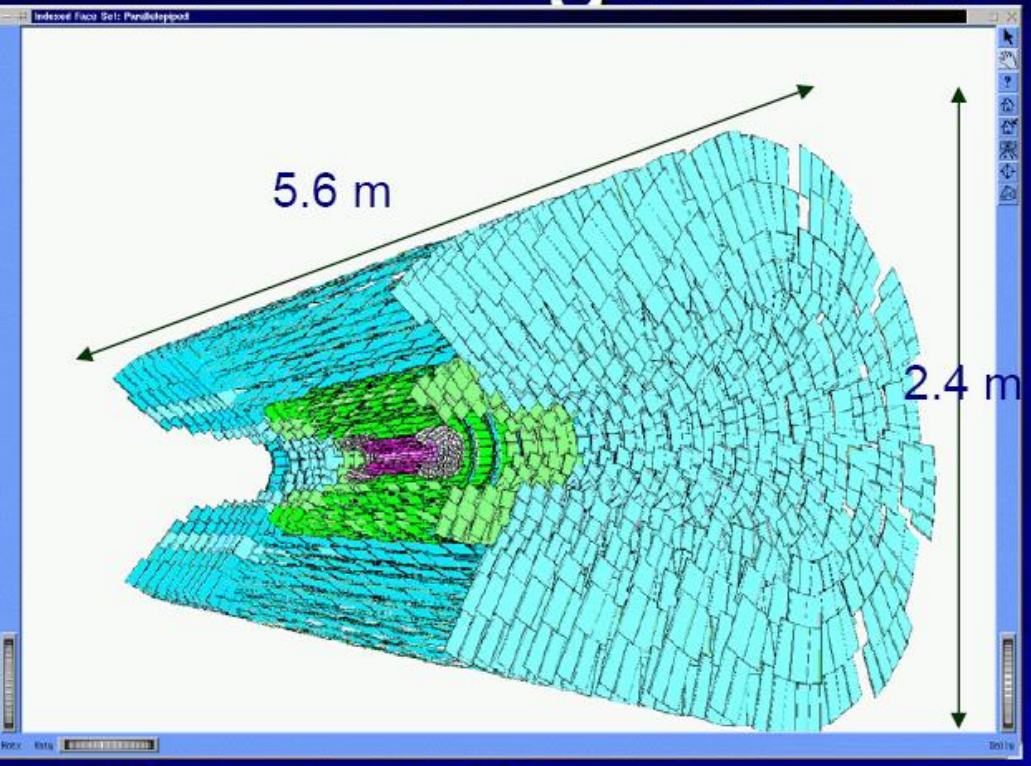
At 40MHz bunch crossing rate this results in 200TByte/s into the online system for a triggerless readout.

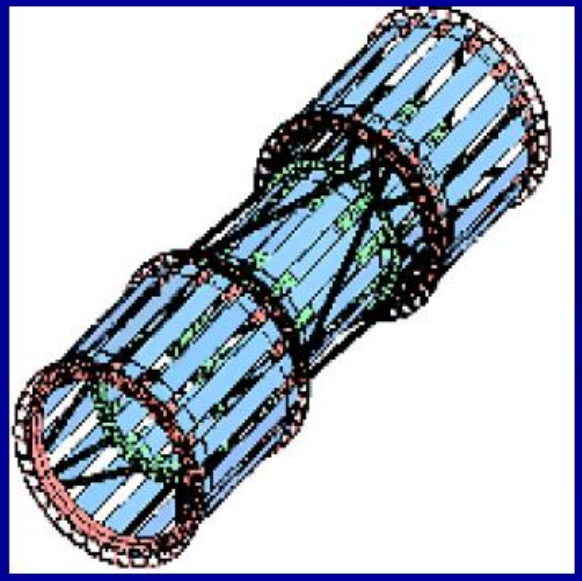
For 2022 this is considered too difficult.

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

In 2035 no trigger necessary ! All data to the online system, synchronous or asynchronous.

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

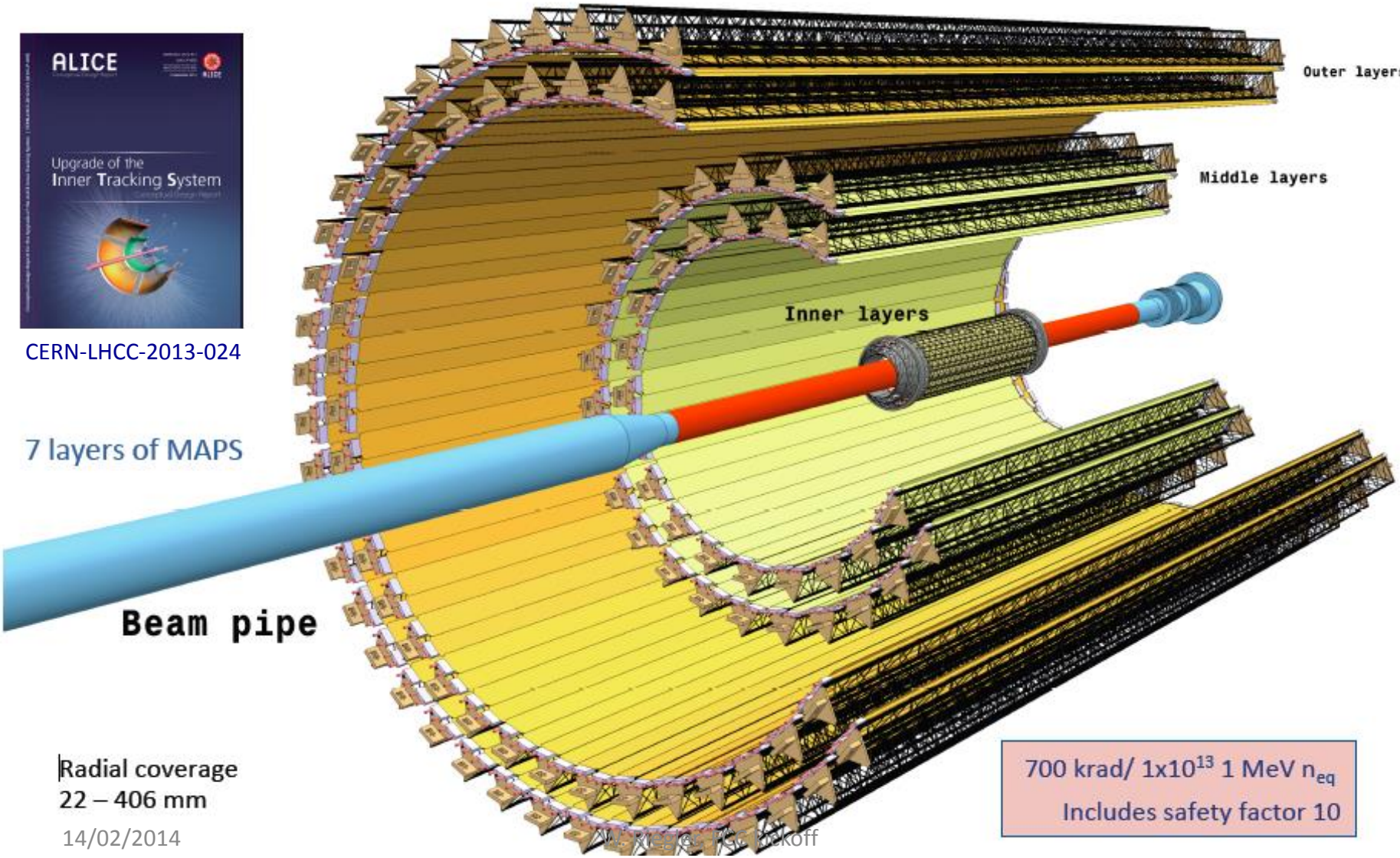
ALICE 2018 upgrade, 20x20um monolithic pixels

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

PIXEL Chip - technology

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

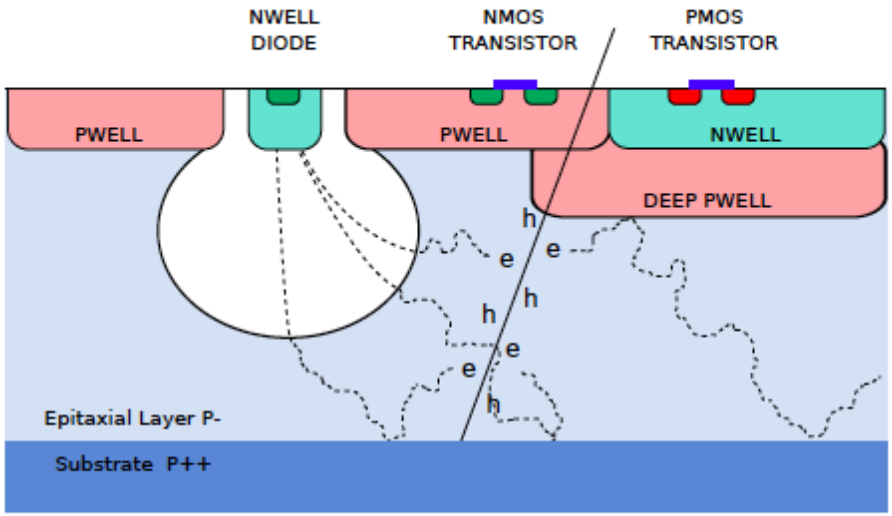
Monolithic PIXEL chip using Tower/Jazz 0.18 µm technology

- 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

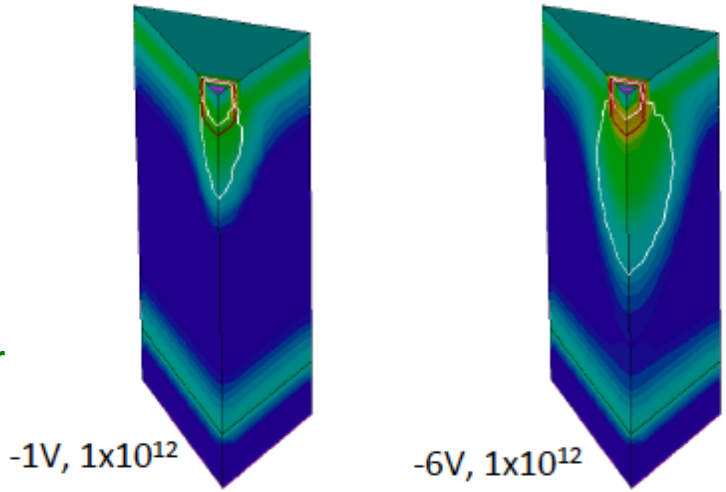
Standard processing, no bump bonding (>>50% of Pixel detector cost). Allows implementation of complex processing electronics inside the entire pixel area.

→ **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.

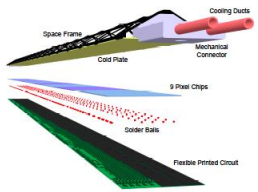
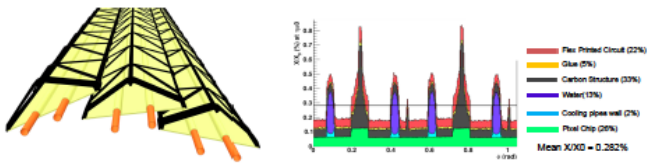
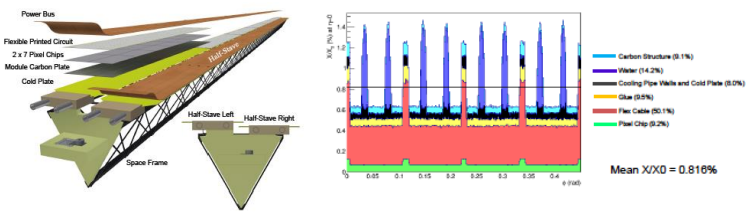


Figure 4.1: Schematic view of the Inner Barrel Stave.





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

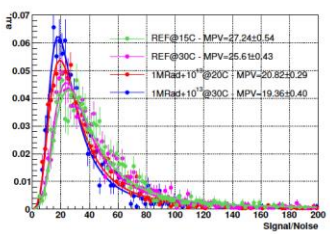


Figure 2.22: SNR of seed pixel measured with MIMOSA-32ter at the CERN-SPS, at two operating temperatures, before and after irradiation with the combined load of 1 Mrad and 10^{13} 1 MeV n_{eq}/cm^2.

Dramatic decrease in cost.

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

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

Question of speed and radiation hardness:

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

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

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

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

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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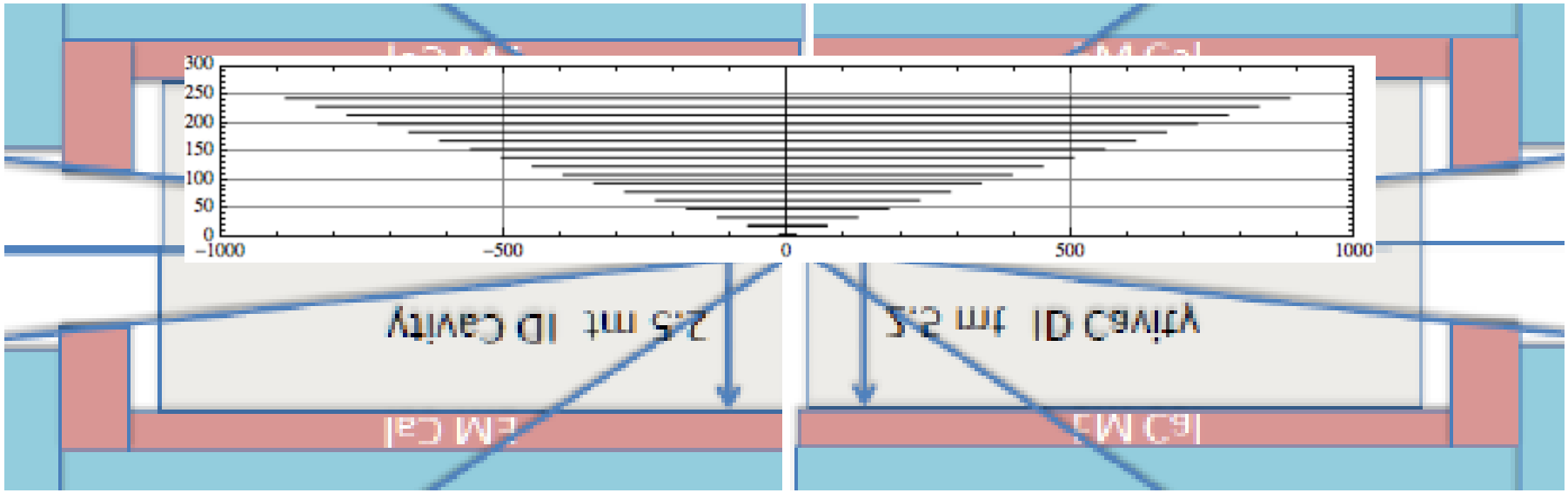
ABSTRACT

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 η = 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**
- **$dN/d\eta = 8$ i.e. 80 tracks inside $\eta \pm 5$**
- **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.

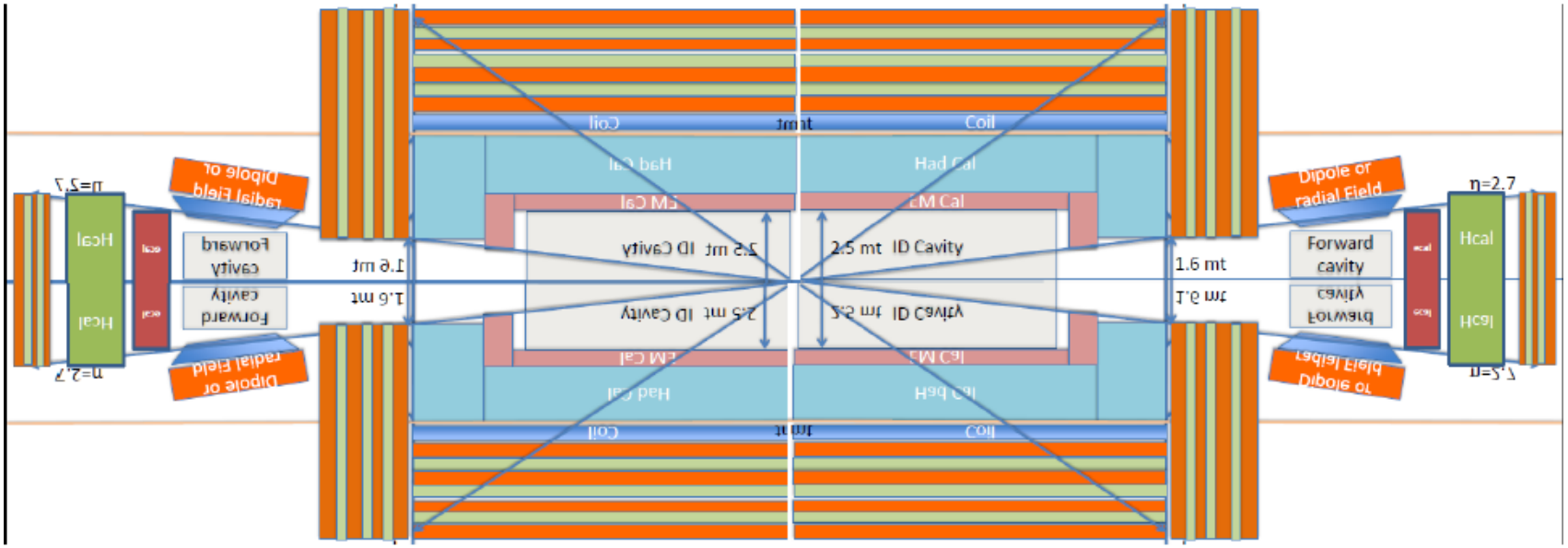
Quantity	Pb–Pb 2.76 TeV	Pb–Pb 5.5 TeV	Pb–Pb 39 TeV
$dN_{ch}/d\eta$ at $\eta = 0$	1600	2000	3600
Total N_{ch}	17000	23000	50000
$dE_T/d\eta$ at $\eta = 0$	2 TeV	2.6 TeV	5.8 TeV
BE homogeneity volume	5000 fm^3	6200 fm^3	11000 fm^3
BE decoupling time	10 fm/c	11 fm/c	13 fm/c

pp: L=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.

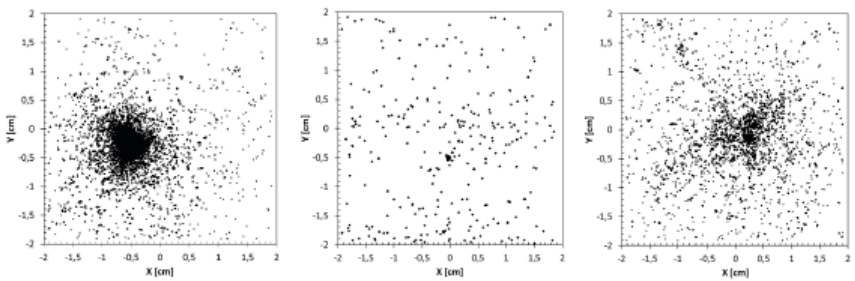
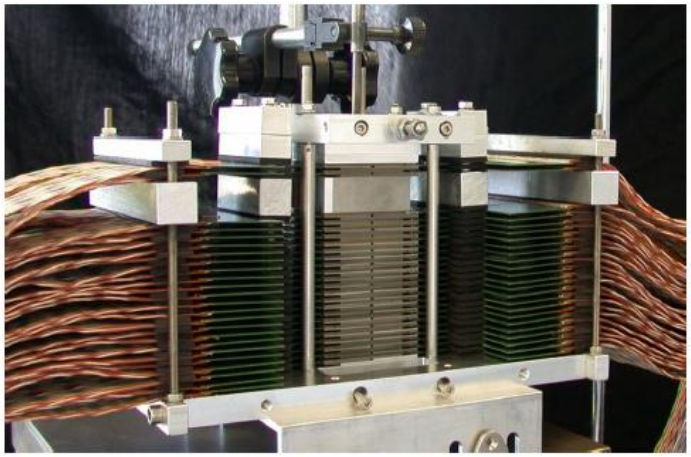


Figure 5: Projection of all hits generated by *left:* a 200 GeV/*c* positron, *centre:* a 200 GeV/*c* non showering pion and *right:* a 200 GeV/*c* showering pion.



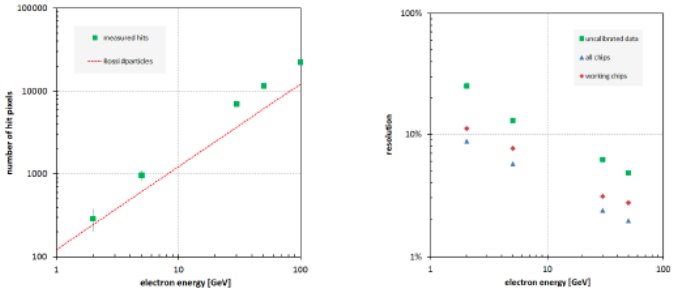


Figure 7: *Left:* The number of hits in the full detector, the line "Rossi" shows the theoretical number of particles. *Right:* Measured resolution of the uncalibrated detector (*squares*). The results of simulations of the ideal detector (*triangles*) and the real detector where only the signals from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

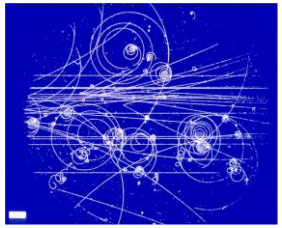
Conslusion 2/2

It is highly probable that by 2035 there is no need for a Hardware L1 trigger → All data are pushed into a PC farm.

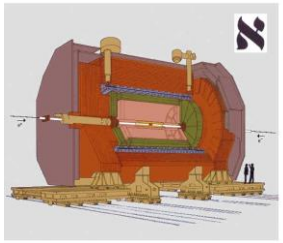
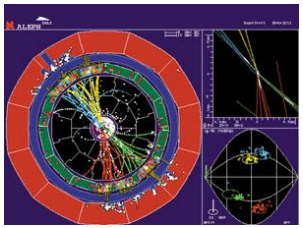
It is highly probable that monolythic silicon sensors will revolutionize our field and arrive at radiation hardness numbers of 10^{15} cm^{-2} neq or more and ‚charge collection times' of less than 100ns.

Maybe also calorimetry can be based on Silicon.

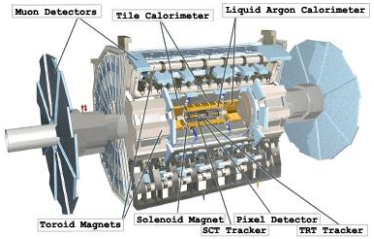
→ We should make sure that we do not put constraints on the FHC accelerator people. They should provide the maximum energy and maximum luminosity – we will for sure be able to make best use of it.

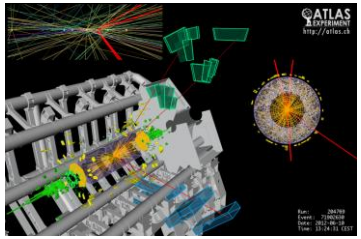



BEBC photopgraphs, untriggered

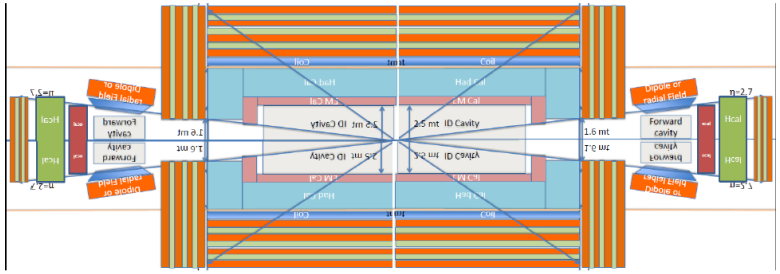



ALEPH triggered, only wire chamber readout.





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



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