Basic principles of detector design

By C. D'Ambrosio (CERN)
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Outline

Lecture 1 - Introduction C. Joram, L. Ropelewski

Lecture 2 - Tracking Detectors L. Ropelewski, M. Moll

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5a – Particle Identification

5b – Detector Design

- **Basic connections between accelerator and detector**
- **Vertex and momentum measurements (in solenoid systems)**
- **Dose generated and occupancy**
- **A Decalogue**

Principles of Detector Design

Designing a detector is exciting

(one of the best part of the whole story!)

I shall try to give you a fade feeling of what a process lasting years is, and a few tools and basic principles, for a <u>"back of the envelope"</u> design.

Important before starting: Given an accelerator

Higgs → Gammas
Higgs → Leptons
Higgs → Hadr Jets

Sparticles…..

Rare mesons….

Etc

What we want to measure (signatures)
How we can measure (detector)

But a lot is simply not known, therefore, **stick to general assumptions and design for surprises.**

Introduction 2

The classic quantities to measure are:

Trajectory, Charge, Momentum, Velocity, Energy

In order to :

identify particle, calculate mass, recover intermediate processes, decays, etc.

Most basic for a detector design:

Cost of experiment goes with **~volume**

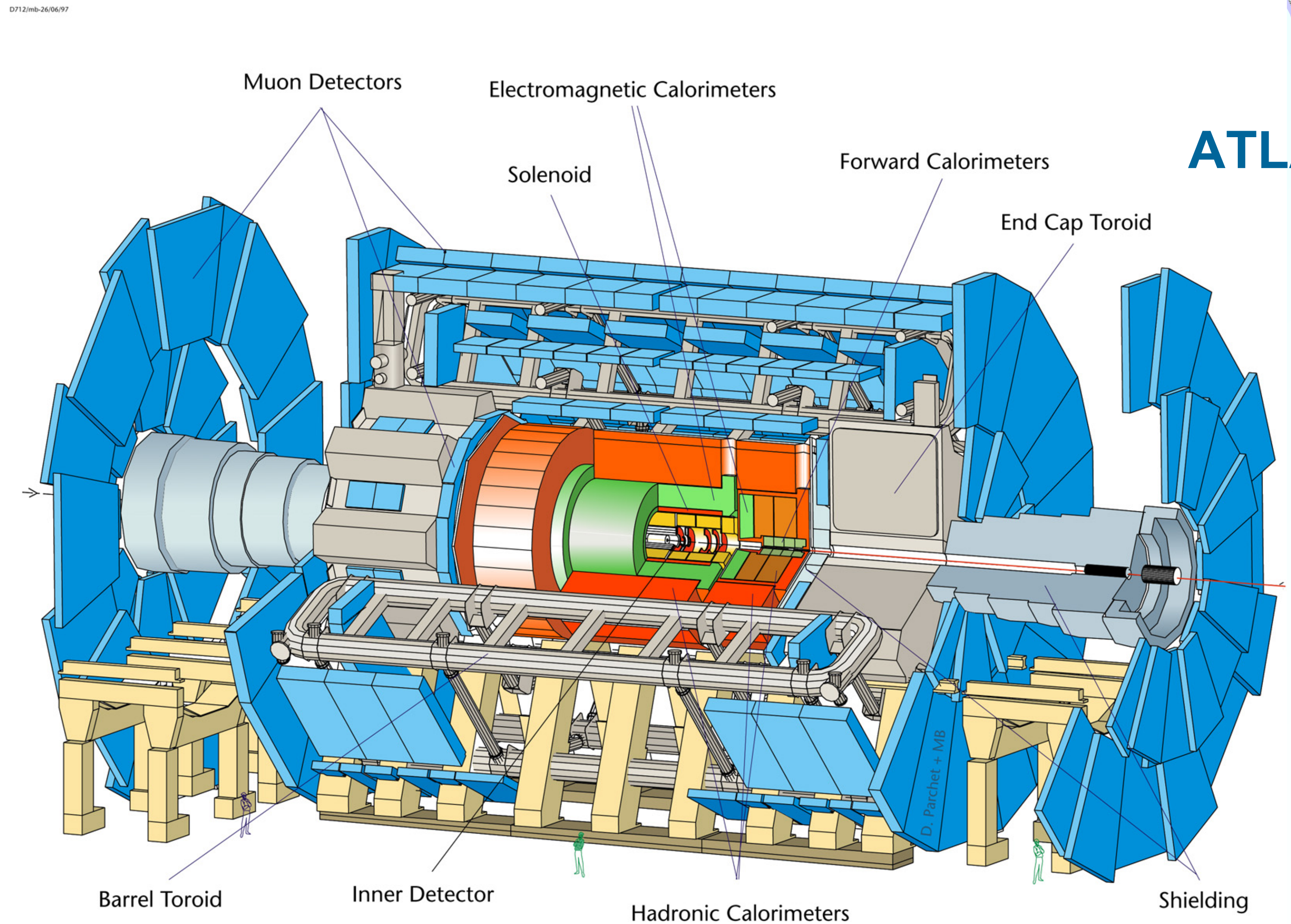
As little as possible material in front of the calorimeter

As much as possible in front of the muon chambers

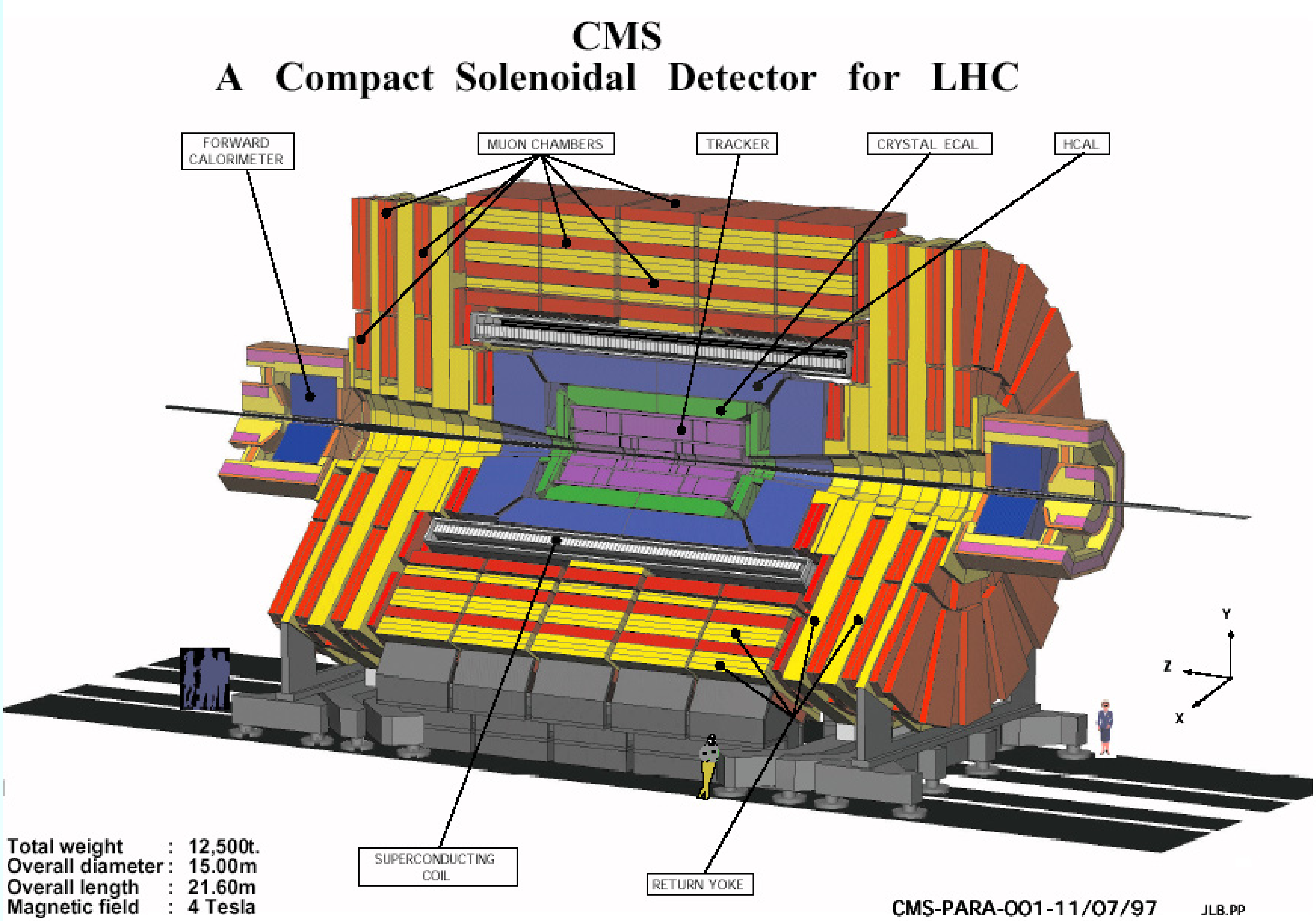
Hermetic but easy to dismount

Introduction

ATLAS



Introduction 1



List of relevant parameters, their units and symbols

Accelerator parameters		Symbol
Centre of mass energy	TeV	E_{CM}
Full beam crossing angle	µrad	α
Beam radius (68 % of particles)	µm	σ_x
Bunch length (68 % of particles)	m	σ_b
Time between two bunches	ns	t_b
Interaction parameters		
Standard luminosity	$cm^{-2}s^{-1}$	L_0
Length of luminous region	m	l^*
Inelastic cross-section	cm^2	σ_{inel}
Avr. Nr of charged part. per unit of rap. and per event		H
Distribution of vertices per mm		$n_v(z)$
Avr. Nr of vertices per bunch crossing		$\langle n_v \rangle$
Avr. Nr of vertices per mm (for 68 % of interaction)	mm^{-1}	$\langle n_v^* \rangle$
Momentum, trans. Mom. and avr. trans. Mom.	GeV/c	p, p_t, $\langle p_t \rangle$

Detector parameters		
Det. precision in (r,z)-plane	µm	σ_z
Det. precision in (r,φ)-plane	µm	σ_φ
Distance from the beam axis	m	r
Distance between outer- and inner det. shells	m	Δr_t
Number of hits		N
Multiple scattering angle	rad	θ_{ms}
Thickness of det. in unit of radiation length		t
Thickness of det. to achieve one hit in unit of rad. length		t_0
Det. precision on the beam axis (z-axis)	mm	δz
Total and transverse Mom. resolution		$\delta p/p$, $\delta p_t/p_t$

Disclaimer

- In this "walkthrough", we will concentrate mainly on the "central" trackers design: this is roughly the region up to η = 2, $\eta = -\ln \tan(\theta/2)$ (η is the pseudo rapidity and θ the polar angle with origin at the interaction point).
- Also, we will be talking mostly of charged particles. In principle, all the gammas produced are traversing the "inner region" (before the calorimeters) unconverted. Neutrons constitute an important source of noise and rad. Dose.
- Fraction of converted gammas or hadrons before the calorimeter

$$f_{conv} \sim 1 - e^{-t} \quad where \quad t \equiv material\ in\ units\ \ of\ \ X_0\ or\ \lambda_I$$

- Whenever we talk of "xxx-like detector", it means that our results may not coincide with the actual xxx detector.
- Nothing about calorimeter design and neither about trigger aspects.
- We will have to be short, therefore you will have to accept for good a lot of things that you should not to…

- Apologies…, I have given to the lecture a fairly personal cut. I trust the interested people will find the remaining information!

Layout

- **Basic connections between accelerator and detector**
  - Luminosity, interaction region and implications on the detector design
  - Scaling of physical quantities with the center of mass energy

- **Vertex and momentum measurements (in solenoid systems)**
  - Basic tools for the calculation of vertex and momentum resolutions in detector systems
  - The example of a CMS-like detector in a LHC-like accelerator

- **Dose generated and occupancy**
  - Charged and neutral particles
  - Detector Occupancy
  - Magnetic field effects on dose and occupancy

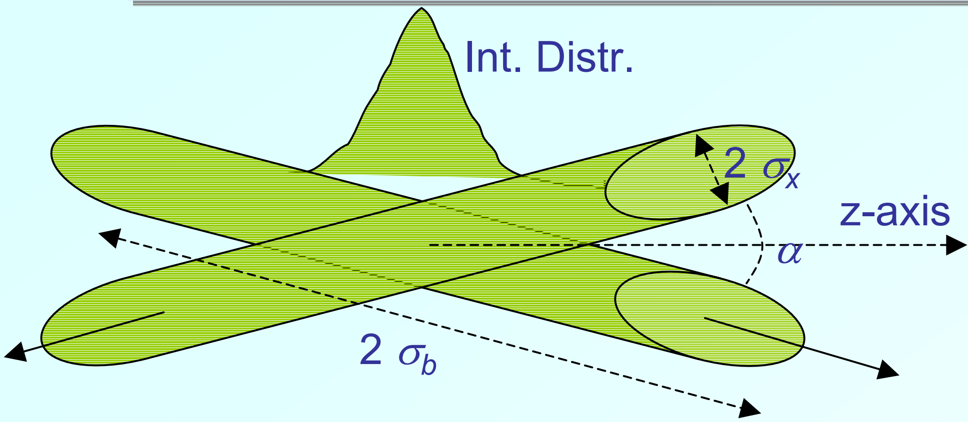
- **Conclusions**

http://ph-dep-dt2.web.cern.ch/ph-dep-dt2/lectures_PD_2005.htm or

http://user.web.cern.ch/User/Welcome.html

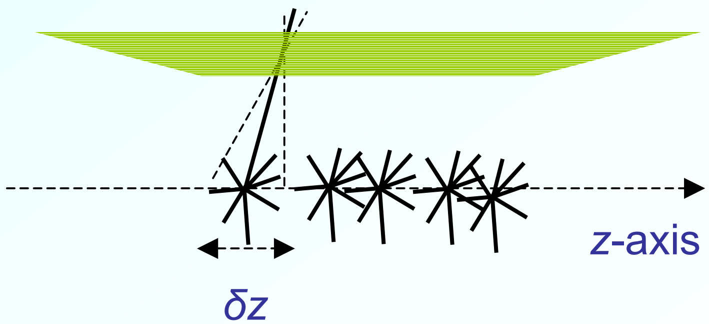
Luminosity and Interaction Region

Luminosity and Interaction Region



$$\langle n_v \rangle = \sigma_{inel} t_b L_0$$

$$\langle n_v^* \rangle = \frac{0.68 \langle n_v \rangle}{l^*} \quad [mm^{-1}]$$



$$L_0 = \frac{N^2}{4\pi\sigma_x^2 t_b} \frac{F^2}{q} \quad [cm^{-2}s^{-1}]$$

$$q = \sqrt{1 + \left(\frac{\alpha}{2}\frac{\sigma_b}{\sigma_x}\right)^2}$$

$$2.36\,\delta z \cdot \langle n_v^* \rangle < 0.5 \qquad (1)$$

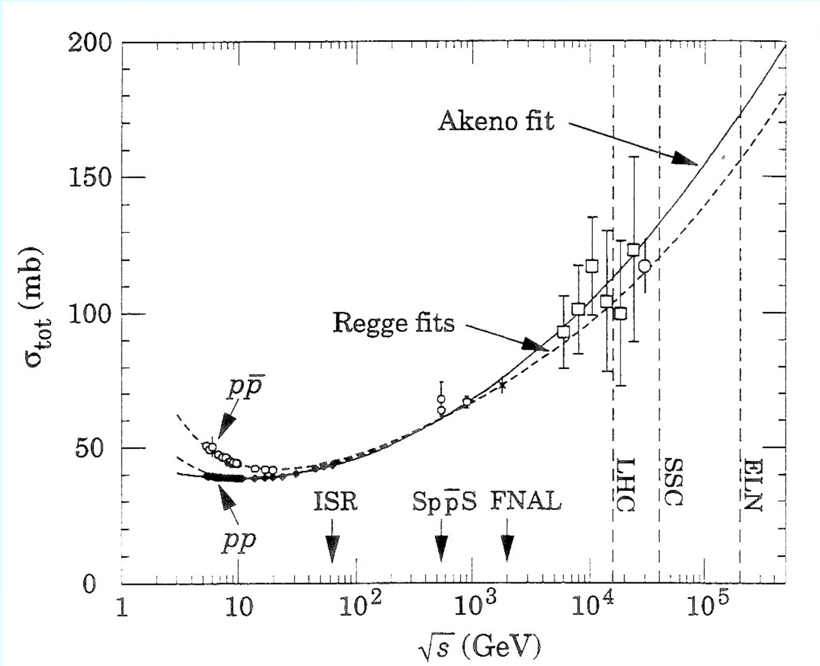
$$l^* = \frac{q}{\sqrt{2}\sigma_b}$$

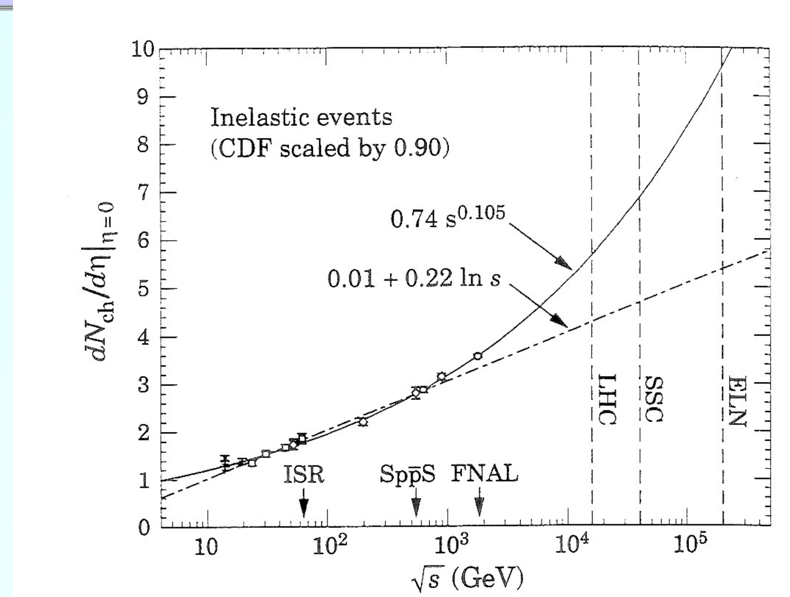
δz is the min. required detector precision on the beam axis. This inequality relates a collider quantity, $\langle n_v^* \rangle$,to a detector quantity, δz : it tells us, how good our tracking system has to be to distinguish adjacent interaction vertices.

Interaction Region Parameters

σ_b [m]	σ_x [μm]	α [μrad]	σ_{inel} [mb]	t_b [ns]	L_0 [cm^{-2}s^{-1}]	$\langle n_v \rangle$	**$\langle n^*_v \rangle$ [mm^{-1}]**	l^* [m]	**δz [mm]**	Collider E_{cm} [TeV]
0.38	30	0	56	400	$1\cdot10^{-32}$	2.24	**0.003**	0.54	**74.8**	Tevatron 1.8
0.076	15	300	80	25	$1\cdot10^{-34}$	20	**0.159**	0.085	**1.33**	LHC 14
75	15	500	80	25	$1\cdot10^{-35}$	200	**1.603**	0.085	**0.13**	SLHC 15
0.076	15	300	80	25	$1\cdot10^{-35}$	200	**1.59**	0.086	**0.13**	SLHC 15
0.06	5	50	130	20	$1\cdot10^{-34}$	26	**0.22**	0.081	**0.97**	VLHC 200

Scaling Relations

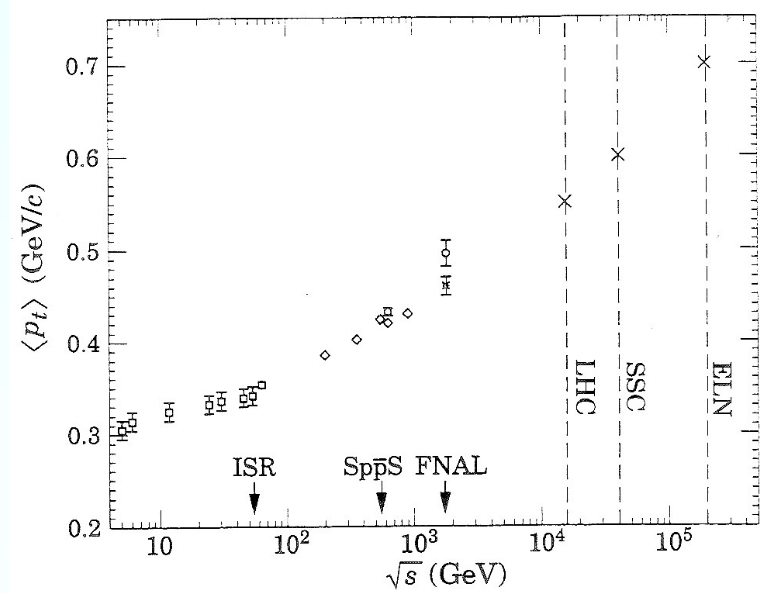




G. 2. Data and extrapolations of $dN_{ch}/d\eta|_{\eta=0}$.

Remember $\sigma_{tot} \sim 1/4\sigma_{elas} + 3/4\sigma_{inel}$

$$\langle p_t \rangle \approx 0.44 + 0.071 \log \sqrt{s}$$



From D. E. Groom, in *Supercolliders and Superdetectors: Proc. Of the 19th and 25th Workshops*, ed. W.A. Barletta and H. Leutz, Erice, 17-22 Nov. 1992

Table of scaled parameters

E_{cm} [TeV]	σ_{inel} [mb]	Integ. L_0 [fb^{-1}]]	L_0 [cm^{-2}s^{-1}]	$\langle p_t \rangle$ [GeV/c]	H_{ch}	$\langle n_v \rangle$	N_{ch}*	Collider
1.8	56	***	$1 \cdot 10^{-32}$	0.46	4	2.24	18	**Tevatron**
14	80	10 - 100	$1 \cdot 10^{-34}$	0.55	7	20	280	**LHC**
15	80	100 -1000	$1 \cdot 10^{-35}$	0.55	7	200	2800	**SLHC**
200	130	10 - 100	$1 \cdot 10^{-34}$	0.70	11	26	572	**VLHC (Elo)**

*for a coverage of $\eta_{max} = 2$

Meanwhile keep in mind that, other than the N_{ch} produced, we also have neutral particles and gammas. And that the vast majority of events represents NOISE for us.

A CMS-Like Detector

(mostly tracking)

Solenoidal detector system

Let us now get on with the **solenoidal system**

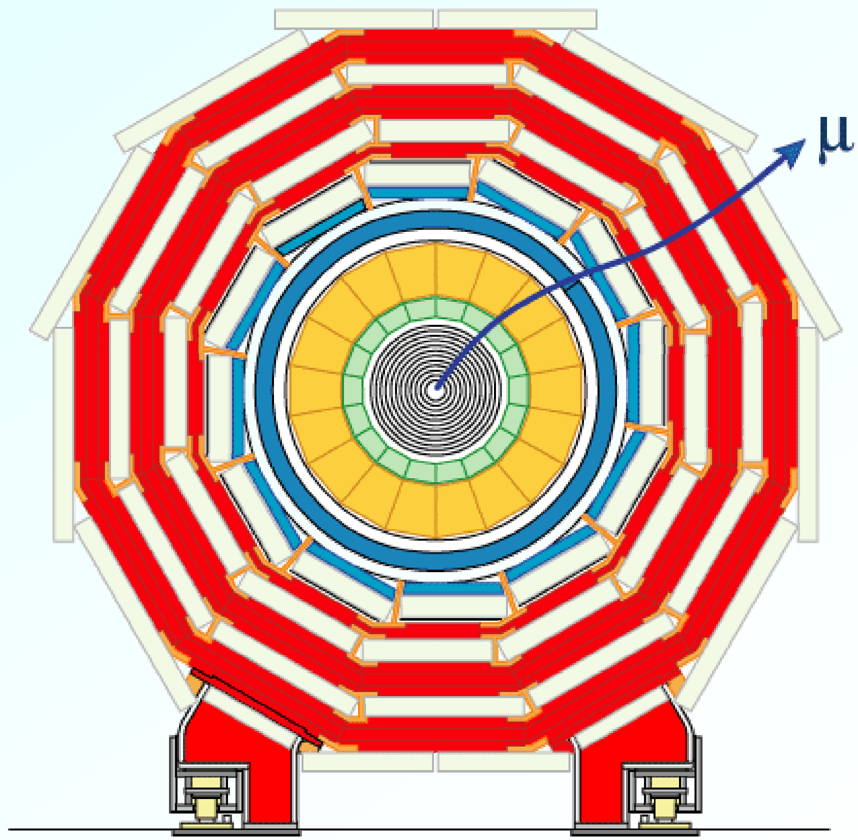
Of course, we need the magnetic field (***B***) to measure the **momentum** (of charged particles).

We also try to place the big solenoid after the calorimeter to preserve its energy resolution (see Christian's lecture 4a, CMS choice):

We like the Higgs to $\gamma\gamma$ signature

We also like the Higgs to ZZ to 4 muons signature:

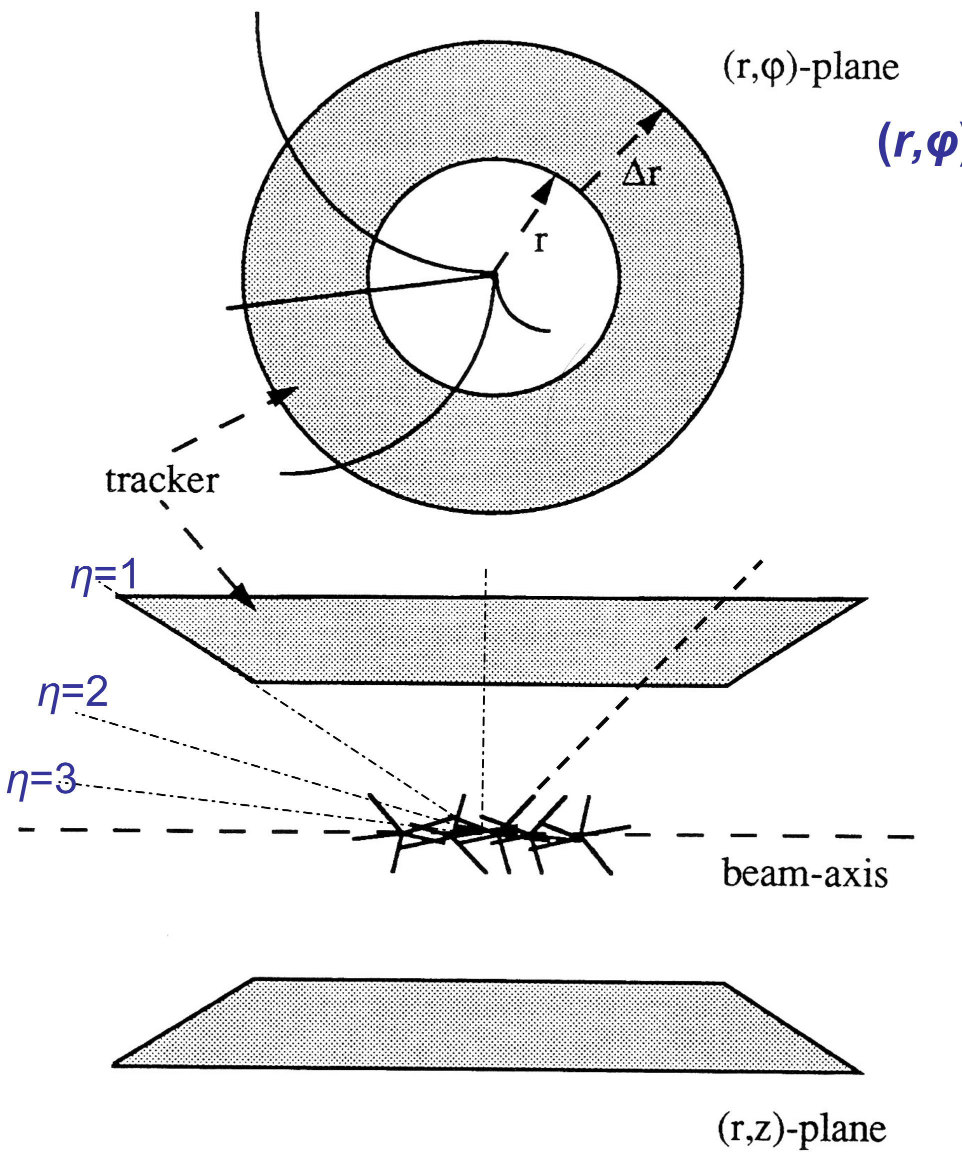
We build a robust muon detector outside the coil, with "integrated" return yoke, to have **transverse momentum** measurement from the **beam axis to the last muon chamber**.



CMS front view

(from CMS home page)

Vertex Resolution in solenoid systems 1



(*r,φ*)- and (*r,z*)- views of a schematic tracker:

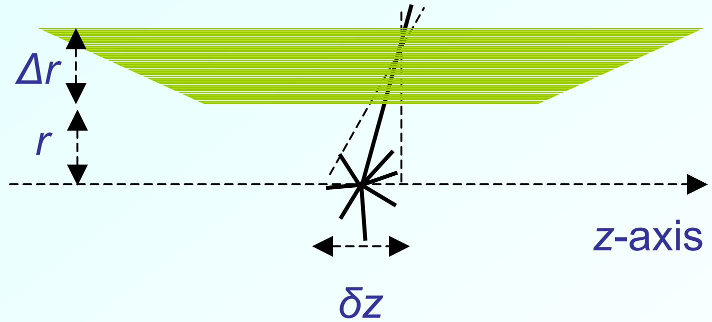
In the (*r,φ*)-plane, the beam constraint provides enough precision on the primary vertex position;

on the contrary, in the (*r,z*)-plane the production of multi-vertices in the luminous region asks for a high detector resolution (**2.36*δz***) in the z-coordinate.

Vertex Resolution in solenoid systems 2

If we follow an old work from Monsieur Gluckstern, we find that:

$$\delta z^2 \approx \frac{\sigma_z^2}{N}\left[\frac{5}{2}+6\frac{r}{\Delta r}+6\left(\frac{r}{\Delta r}\right)^2\right]+N\left(r\,\frac{0.0136}{p}\sqrt{t_0}\right)^2 \quad (2)$$



And, for a system where $r/\Delta r$ ~1, N=16, σ_z =1 mm and t_0 is the minimum layer thickness to achieve one hit (you will understand why I am taking these values in a moment)

$$\delta z \approx 1\,mm + mult.\,scatt.\,error$$

Sufficient for the LHC requirement on δz.

For a CMS-like det., this could be achieved with the muon chambers alone, if we manage to keep low the multiple scattering error….

By the way, if you are interested, here the complete formulas for the (r,z)-plane measuring error:

$$\delta z^2 = \frac{F_2}{F_0F_2 - F_1^2} \quad with \quad F_i = \sum_1^N \beta_n x_n^i$$

$$\sigma_{sl}^2 = \frac{F_0}{F_0F_2 - F_1^2} \quad and \quad \beta_n = \frac{\alpha_n}{\varepsilon_n^2}$$

Not difficult to calculate for the (r,φ)-plane

CERN Academic Training Programme 2004/2005

Vertex Resolution in solenoid systems 3

The δz is completely smeared by the mult. scatt. error due to the material of and in front of the muon system :

$$\delta z \approx (1\,mm) \oplus N\left(r\,\frac{0.0136}{p}\sqrt{t_0} \right) \oplus \left(r\,\frac{0.0136}{p}\sqrt{t_{inner}} \right) = (1\,mm) \oplus (11\,mm) \oplus (14\,mm)$$

Therefore, a good tracker is mandatory.

For a four shell tracker:

$$\delta z \approx (0.6\,mm) \oplus \left(\frac{3.4\,mm}{p} \right)$$

for $r/\Delta r$ ~0.35/1 ($r+\Delta r$ =1.35 m), N=16, σ_z =1 mm and t_0~2 % of X_0 , (see Eq. 2)

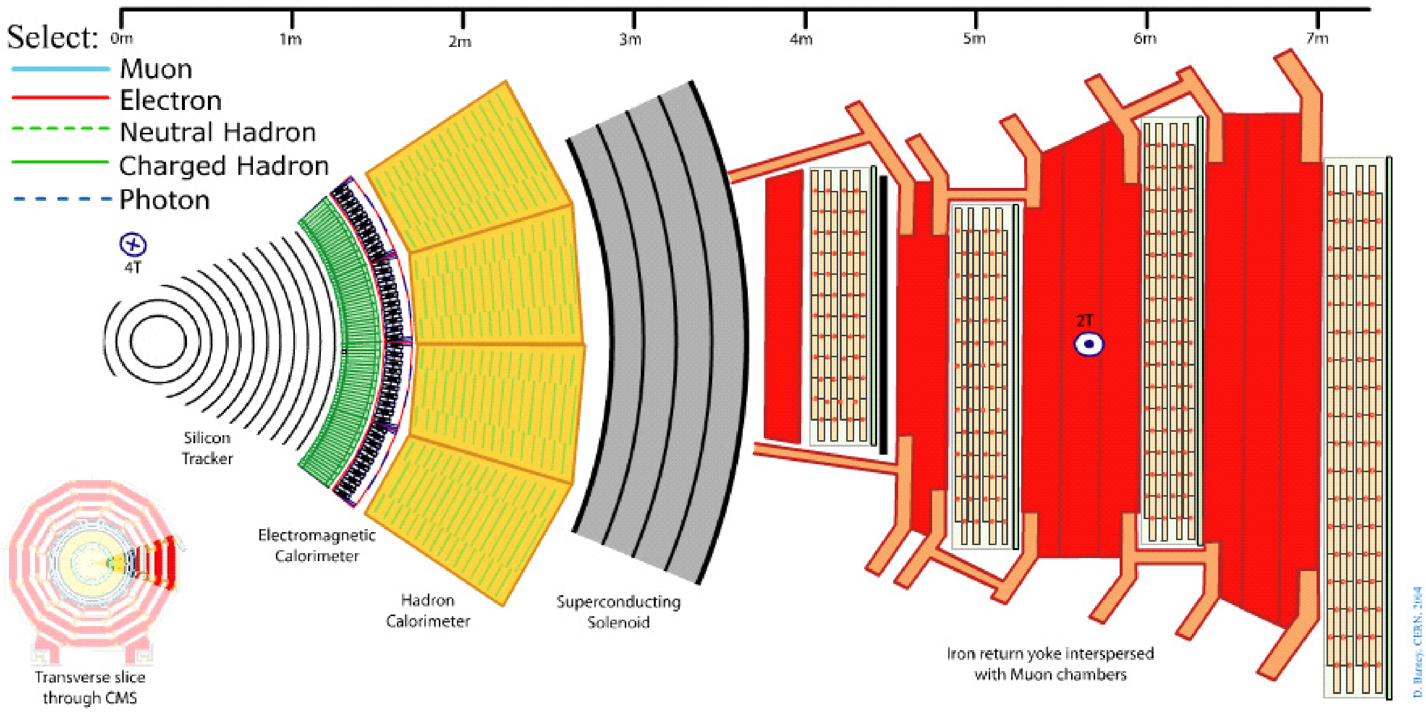
For SuperLHC, this would not be enough. Can we go closer ?
We must consider dose and occupancy.

Momentum Resolution in solenoid systems 1

Transverse slice through CMS detector

Click on a particle type to visualise that particle in CMS

Press “escape” to exit



From CMS home page

Momentum Resolution in solenoid systems 2

For H to ZZ to 4 muons, in a CMS-like system with only muon chambers, the mom. resolut. is:

In the (r,φ)-plane, p_t resolution* (remember Christian's lecture 1a),

$$\left(\frac{\delta p_t}{p_t}\right) = \left\{\left(\frac{363}{N}\right)^{1/2}\left(\frac{\sigma_\varphi}{\Delta r_m^2}\right)\left(\frac{p\sin\theta}{0.3B}\right)\right\}_{curv} \oplus \left\{10\cdot\left(\frac{0.016\sin\theta}{0.3B\Delta r_m}\right)\right\}_{ms}$$

For a 45° muon track at 50 GeV/c, B=2T, Δr_m =4 m, $\sigma_{\varphi,z}$=1 mm and N=16

$$\sim (1.8 \text{ x } 10^{-2}) \oplus (4.7 \text{ x } 10^{-2})$$

curvature error, plus ~100 X_0 of multiple scattering

In the (r,z)-plane, $p_{//}$ resolution*,

$$\left(\frac{\delta p_{//}}{p_{//}}\right) = \left\{\left(\frac{7.3}{N}\right)^{1/2}\left(\frac{\sigma_z\cos\theta}{\Delta r_m}\right)\right\}_{slope} \oplus \left\{\left(\frac{100}{\sin\theta}\right)^{1/2}\cdot\left(\frac{0.014}{p\tan\theta}\right)\right\}_{ms}$$

$$\sim (0.012 \text{ x } 10^{-2}) \oplus (0.028 \text{ x } 10^{-2})$$

slope error, plus ~100 X_0 of multiple scattering

*thanks again to M. Gluckstern, we can calculate the numerators of $(G_{c,sl}/N)^{1/2}$, for any disposition of our det. layers. They range from 256 to 720 for G_c and from 2 to 12 for G_{sl}, if the precisions are the same everywhere.

Momentum Resolution in solenoid systems 3

For the tracker alone, the momentum resolution is:

In the (r,φ)-plane, p_t resolution ,

$$\left(\frac{\delta p_t}{p_t}\right)=\left\{\left(\frac{250}{N+1}\right)^{1/2}\left(\frac{\sigma_\varphi}{(r+\Delta r)^2}\right)\left(\frac{p\sin\theta}{0.3B}\right)\right\}_{curv}\oplus\left\{0.56\cdot\left(\frac{0.016\sin\theta}{0.3B(r+\Delta r)}\right)\right\}_{ms}$$

For 45° tracks, B = 4 T,

$r/\Delta r$ ~ 0.35/1 ($r+\Delta r$ = 1.35 m),

$\sigma_{\varphi,z}$= 1 mm and N = 17,

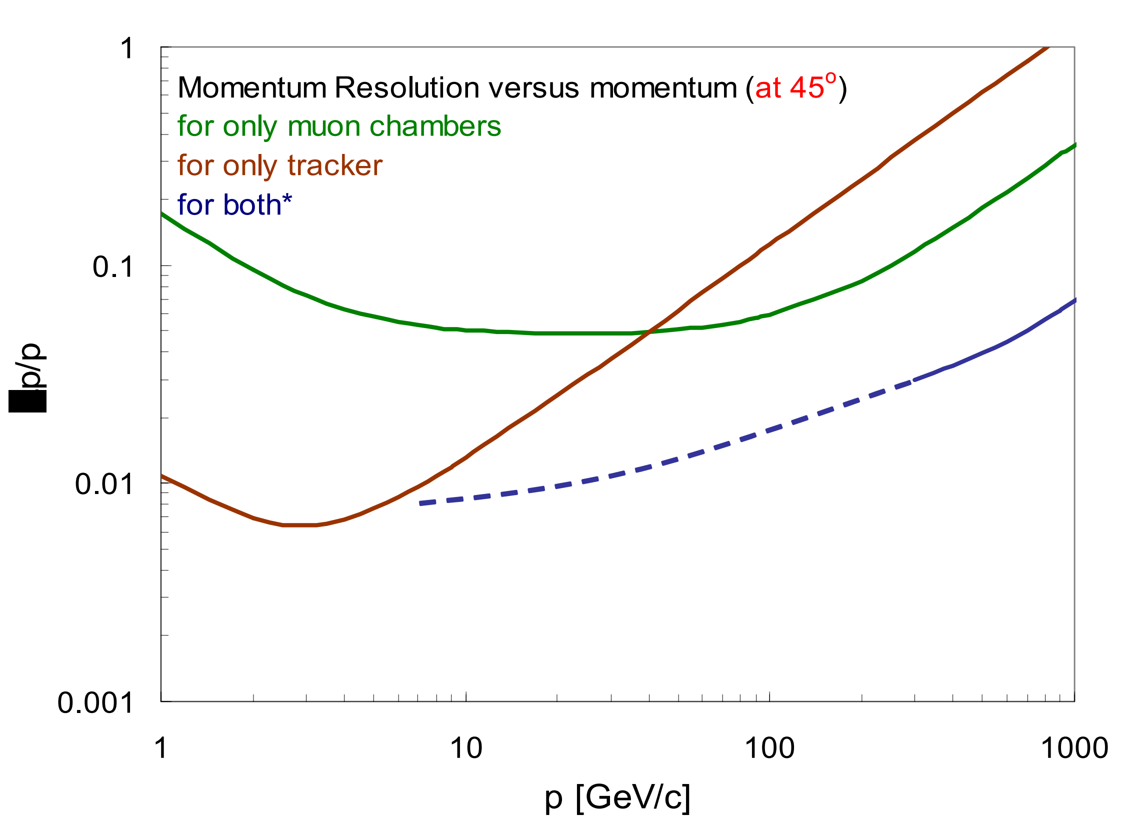
beam axes point ~ 0.020 mm

and t_0 ~ 2 % of X_0.

In the (r,z)-plane, $p_{//}$ resolution,

$$\left(\frac{\delta p_{//}}{p_{//}}\right)=\left\{\left(\frac{7}{N}\right)^{1/2}\left(\frac{\sigma_z\cos\theta}{\Delta r}\right)\right\}_{slope}\oplus$$

$$\oplus\left\{\left(\frac{0.3}{\sin\theta}\right)^{1/2}\cdot\left(\frac{0.014}{p\tan\theta}\right)\right\}_{ms}$$



- Given our solenoid, we have roughly defined:
  - our muon detection system (cell precision, number of hits, positions);
  - our inner tracker and calorimeters;
- We have calculated rough estimations for the values of δz, *dp/p.*

But, can our detectors cope with radioactivity dose ?

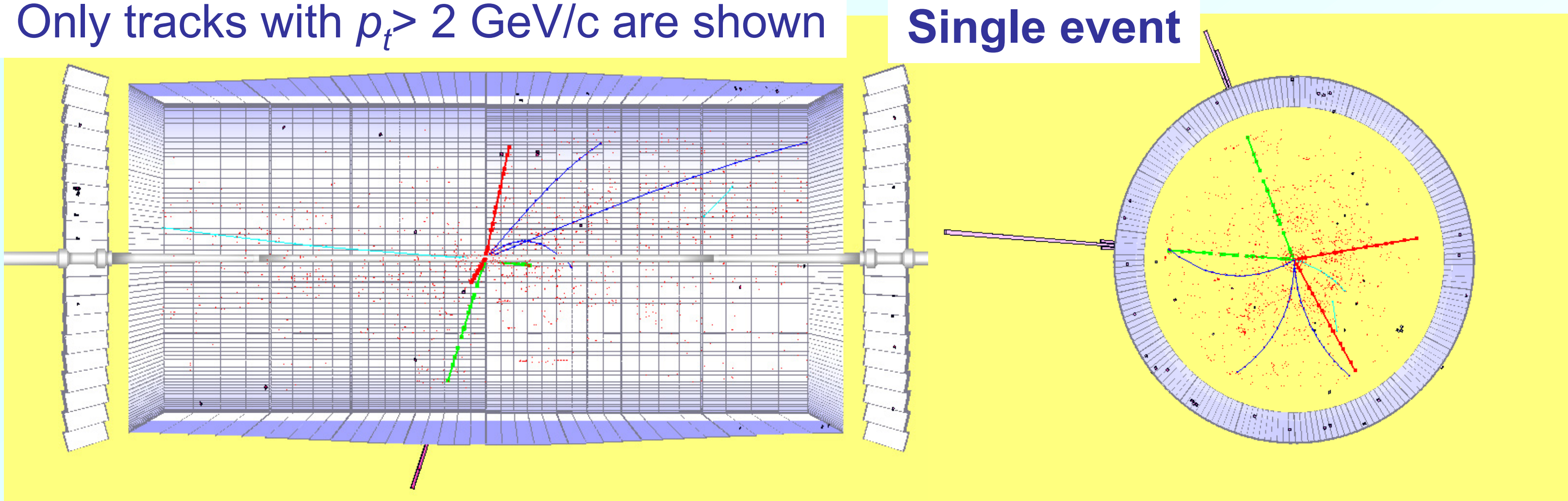
And will they not be flooded with particles ?

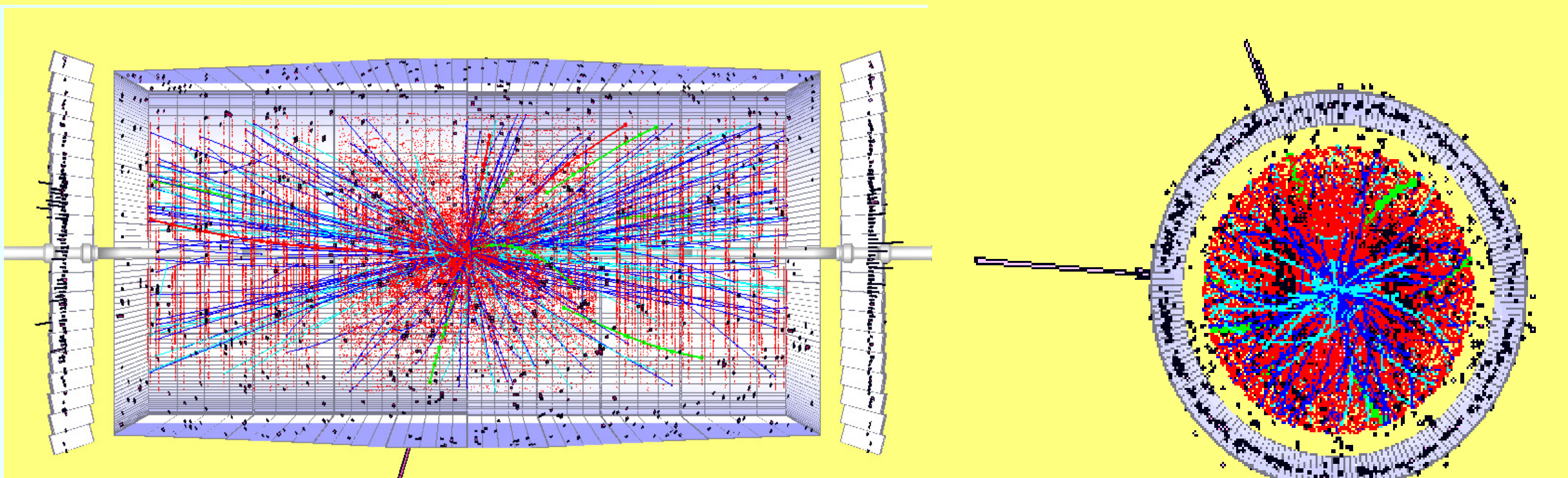
CMS: H → ZZ → 2e 2μ (from J. Virdee, HIP-27 Aug 03)

20 pileup events/crossing superposed on the one of interest

Only tracks with p_t> 2 GeV/c are shown

Single event





+ 20 pileup events i.e. L =10^{34} and 25 ns bunch spacing

Dose and Occupancy

Dose generated and occupancy 1

The dose experienced by a thin absorber, placed around the interaction point and due to charged particles, depends only on r^2 (r is the distance to the beam axes). Therefore, the average dose experienced by a thin cylindrical shell placed at distance r from the beam axis (central tracker arrangement) can be written as:

$$D_{ch}[Gy\ yr^{-1}] \approx \frac{C}{2\pi r^2} \quad where\ C = 3.2 \cdot 10^{-7}\ H\langle n_v \rangle t_b^{-1}$$

For a year of 10^7 s.

For LHC, $H\langle n_v \rangle t_b^{-1} = 5.6 \cdot 10^9$, therefore $C = 1800\,[m^{-2}]$.

The albedo neutron flux is roughly constant in the inner cavity and can be estimated between $10^{13} - 10^{14}$ $cm^{-2}yr^{-1}$. The dose induced will depend on the material, its thickness and neutron cross section (energy dep.). A rule of thumb would give a 100 – 1000 Gy/yr.

Dose generated and occupancy 2

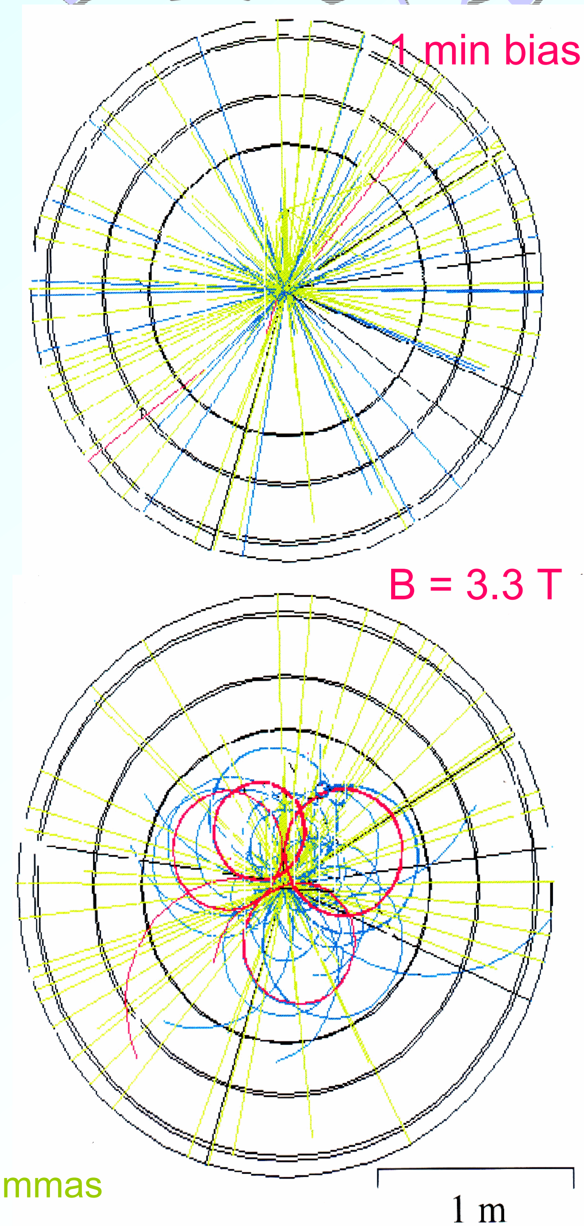
Adding a magnetic field, produces three major effects:

Charged particles start curling: Low p_t will curl and stay inside the inner region, while high pt will escape and continue to the calorimeter. Therefore the dose is increases at low radii and decreases at large radii (remember, $r = p_t / (0.15\,B)$).

Charged pions (half of the particles produced, considering double counts from neutral pions) will decay inside or outside the tracker acceptance η_{max}: contributing with a different weight to the dose, which will now depend also on η.

The calorimeter (or the magnet) position will influence the inner tracker dose.

$$D_{ch}[Gy\ yr^{-1}] \approx \frac{C}{2\pi r^2} \cdot F(x,\eta) \quad where\ x = 2\frac{p_t}{\langle p_t \rangle} = \frac{0.3Br}{\langle p_t \rangle}$$



Blue, charged hadrons Red, charged leptons Green, gammas

Dose generated and occupancy 3

$$D_{ch}[Gy\ yr^{-1}] \approx \frac{C}{2\pi r^2} \cdot F(x,\eta) \quad where\ x = 2\frac{p_t}{\langle p_t \rangle} = \frac{0.3Br}{\langle p_t \rangle}$$

$$\langle p_t \rangle \approx 0.44 + 0.07 \log E_{cm}$$

you already saw this one

$$F(x,\eta) = 2\langle n_c \rangle \int_{x_r}^{x_c} f(x')dx' + \int_{x_c}^{\infty} f(x')dx' =$$

$$= 2\langle n_c \rangle \left[(1+x_r)e^{-x_r} - (1+x_c)e^{-x_c}\right] + (1+x_c)e^{-x_c}$$

x_r and x_c are the x equivalent to the tracker inner radius and the calorimeter starting position

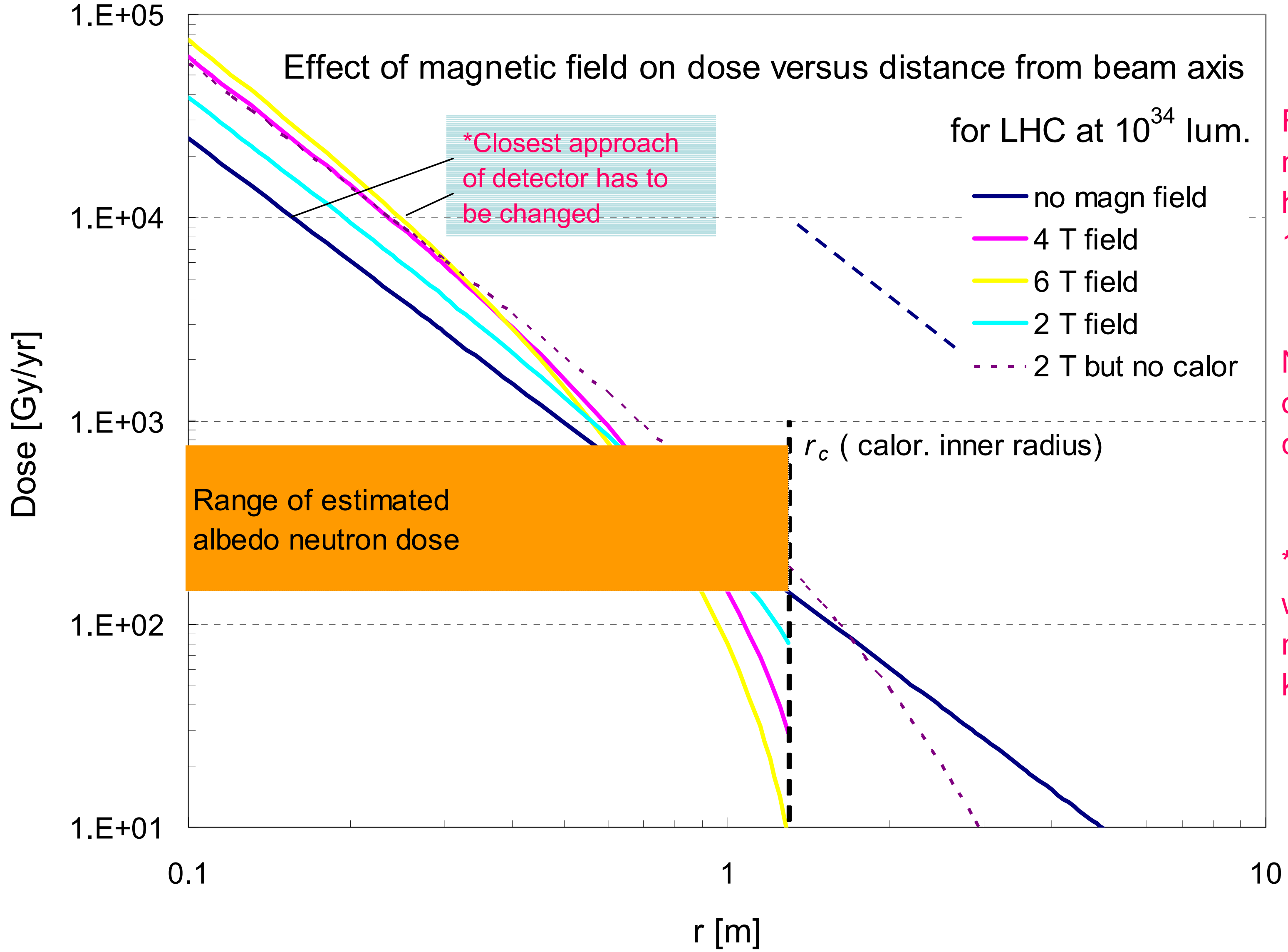
$f(x) = x\, e^{-x}$ is a rough distribution of p_t with $<p_t>$

$$\langle n_c \rangle = \frac{1}{\pi} \frac{\sinh \eta_{max}}{\eta_{max}} \left\{ \frac{\eta_0}{\sinh \eta_0} + \ln\left[\frac{\tanh\left(\frac{\eta_{max}}{2}\right)}{\tanh\left(\frac{\eta_0}{2}\right)} \right] \right\}$$

$<n_c>$ is the average number of curls per produced particle (note it is independent of p_t)

η_{max} is the max. coverage of the tracker shells and η_0 *is* the pseudorapidity, inside which particles decay in the tracker

Dose generated and occupancy 4



For SLHC, just multiply the left-hand scale by 10!

Note the effect of the calorimeter.

*for a detector withstanding a max. dose of 10 kGy/yr

Dose generated and occupancy 5

The occupancy (O_{ch}) of a detector with a cylindrical shell shape, placed at a distance r from the beam axis, is defined as the number of occupied detector cells divided by the their total number and multiplied by their time response in two-bunch crossing time units (t_b).

$$O_{ch} = \frac{\langle n_v \rangle H}{2\pi r^2} \frac{t_{dr}}{t_b} (\Delta\varphi \Delta z) \approx 3.1 \cdot 10^6 \; n \, t_b D_{ch} (\Delta\varphi \Delta z)$$

and it is proportional to the charged particle dose, for thin detector shells.

($\Delta\varphi$ Δz) – in mm^2 - is the detector cell segmentation.

For our detector (slide 5b/19):

$$O_{ch} \approx 3.1 \cdot 10^{-4}$$

At a distance of 0.35 m from the beam axes.

The decalogue of the detector designer:

If you want to have fun with your next collider detector (mostly trackers) design:

1) Check what signatures have significance (ask your preferred theoretician);
2) Have a look at the interaction region and estimate your minimal δz;
3) Fix your detector cell size (with precisions σ_φ, σ_z);
4) Go for a magnet (or none?) and decide which type;
5) Place your inner tracker and muon shells in order to satisfy your min. requests on $\delta p/p$ and δz (which you can calculate);
6) Decide what kind of calorimeter you need (study Christian's talk in detail!) and place it;
7) Calculate dose and occupancies and find your closest approach values to the interaction region (compatible with maximum allowed dose and cell size);
8) Go back to point 3) (only once) and re-adjust the values (if needed);
9) You might have learned something;
10) Start your simulations or your R&D (depends on your preference and money)!

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