pp physics, RWTH, WS 2003/04, T.Hebbeker

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1. Accelerators and Detectors

In the following, we concentrate on the three machines SPS, Tevatron and LHC with the experiments UA1, UA2, CDF, D0, ATLAS and CMS, representing the past, present and future of high energy p p physics[1].

The accelerators are treated as ‘black boxes’: the parameters relevant for the experimenters are reviewed, but the physics and technical aspects are not covered.

The detector design is discussed first in general terms, then the six detectors are presented and compared in some detail.

1.1. Accelerators

parameter	SPS	Tevatron	LHC
time	1981-1990	1987-2009	2007-2020
particles	$p+\bar{p}$	$p+\bar{p}$	$p+p$
c.m. energy / GeV	630	1960	14000
circumference l/km	6.91	6.28	26.66
peak lumi / $10^{30}/\mathrm{cm}^2/\mathrm{s}$	6	50	10000
average lumi / $\mathrm{fb}^{-1}/\mathrm{year}$	0.05	0.5	100
number of bunches	6 + 6	36 + 36	2808 + 2808
particles $(p,\bar{p})$ / bunch / 10^{10}	15, 8	25, 3	11
bunch separation $\Delta t/\mathrm{ns}$	3800	396	25
beam crossing angle	0	0	$300\,\mu\mathrm{rad}$
inelastic collisions / crossing	0.1	2	20
inelastic collisions / s	$5\cdot 10^5$	$4\cdot 10^6$	$8\cdot 10^8$
particle production / s	$2\cdot 10^7$	$3\cdot 10^8$	$1\cdot 10^{11}$
bunch size $\sigma_x,\sigma_y/\mu\mathrm{m}$	~ 50	30	16
bunch length σ_z/cm	20	38	7.5

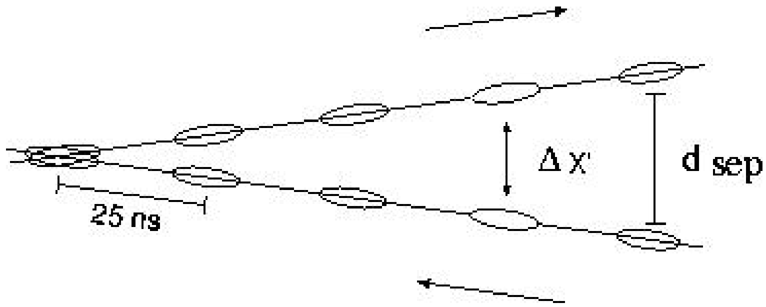
Note: The figures for the SPS refer to the best performance reached; the Tevatron parameters are those expected for the data taking period 2004 of ‘run IIa’; the LHC numbers are design values which will probably not be reached before the end of the decade.

Reference: Review of Particle Physics 2002 (Phys. Rev. D 66 (2002) 1).

Some comments:

i) The beam crossing angle in the LHC (in which two separate beams circulate!) avoids unwanted parasitic collisions:

[1] the generic expression p p physics covers both $p\,p$ and $p\,\bar{p}$ collisions



Note: $25\,\mathrm{ns} = 7.5\,\mathrm{m}$.

ii) The number $\tilde{n}$ of inelastic collisions per bunch crossing can be calulated this way:

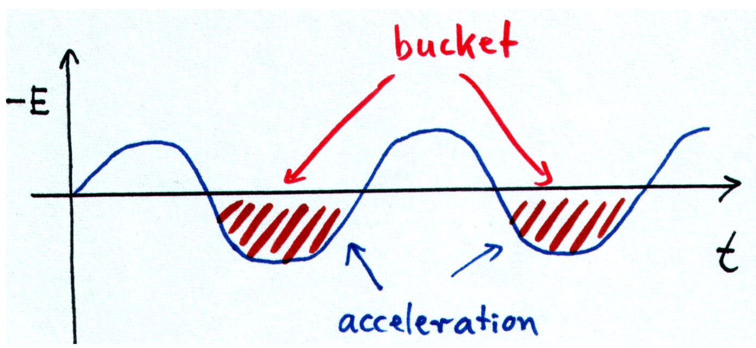
$$\tilde{n} = \dot{N}\Delta t = L\,\sigma_{inel}\,\Delta t \qquad\qquad \sigma_{inel} \sim 50\,\mathrm{mb} \tag{1}$$

where Δt denotes the (average) bunch spacing.

iii) The *particle* production rate is given by the average particle multiplicity per inelastic collision (increases from 40 at SPS to 140 at LHC[2]) and the event production rate.

iv) In general the bunch spacing is not uniform in time:

Example Tevatron:
Radiofrequency = $\mathrm{RF} = 53\,\mathrm{MHz}$. This corresponds to $\tau = 1/\mathrm{RF} = 19\,\mathrm{ns}$ and $d = \tau\, c = 5.7\,\mathrm{m}$. But not all ‘buckets’ can be filled in this accelerator scheme, only every seventh, resulting in a smallest bunch separation of $7 \cdot 19\,\mathrm{ns} = 132\,\mathrm{ns}$.



Every $132\,\mathrm{ns}$-clock-signal is called a ‘tick’. This operating mode was originally foreseen for Run IIb, but it might never be realised. It would also require a nonzero beam crossing angle for the reasons explained above.

Currently, in run IIa, only every third tick is filled, that is $\Delta t = 396\,\mathrm{ns}$. However, the timing is more complicated: Along the Tevatron circumference of about $l = 6.3\,\mathrm{km}$ one can fit exactly 153 ticks, which are divided into 3 groups of 53 ticks, since the Tevatron has a threefold symmetry[3]. But 53 is not a multiple of 3, so that some ‘adjustment’ is necessary, resulting in 12 bunches (= 36 ticks):

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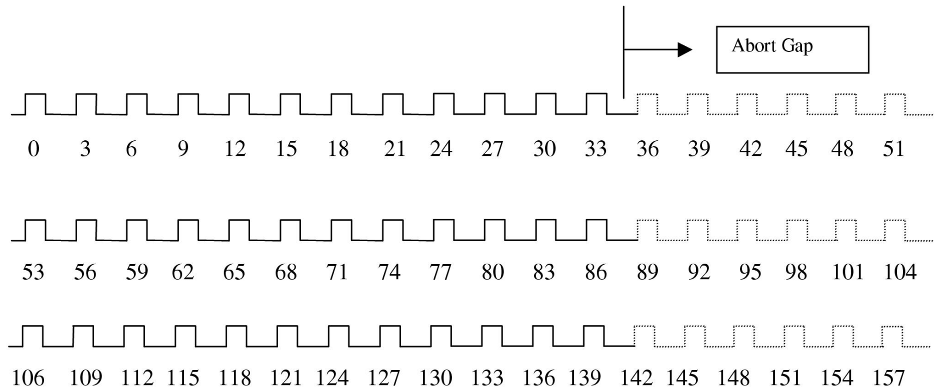
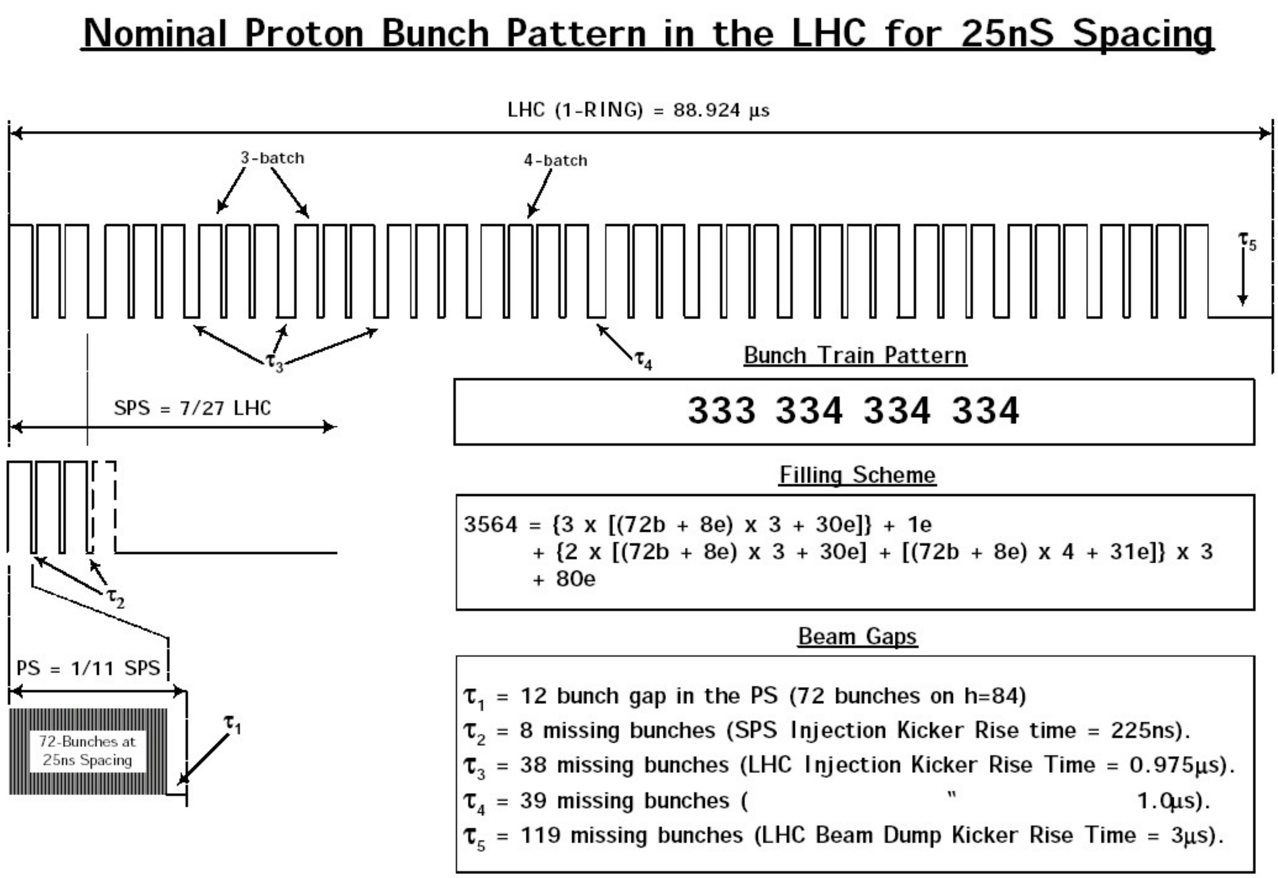
[2] Pythia simulation: all ‘stable’ particles

[3] so that CDF and D0, at a distance of $l/3$, get the same luminosity



Example: LHC[4]*:*
Radiofrequency = $\mathbf{RF = 400.8\,MHz}$. This corresponds to $\boldsymbol{\tau = 1/\mathrm{RF} = 2.5\,\mathrm{ns}}$ and $\boldsymbol{d = \tau\, c = 75\,\mathrm{cm}}$. Only every 10th bucket is used, resulting in a bunch spacing of $\mathbf{25\,ns}$:



Here 'glitches' are unavoidable due to the transfers between the different accelerators: PS $\longrightarrow$ SPS $\longrightarrow$ LHC. Sometimes bunches remain empty, up to 119 in a row! This results in a total of 2808 bunches

[4]for pp operation; in heavy ion mode the bunch separation will be even smaller

per LHC ring/beam. The 'empty crossings' can be used to measure backgrounds (electronic noise, cosmics).

v) The transverse beam size is given by the 'squeezing' in the nearest quadrupoles. The total longitudinal beam size can not exceed half the 'wavelength' d; here we quote the r.m.s of the distribution, σ_z, which is then limited by $d/(4\sqrt{3})$. The bunch length might be substantially shorter than this limit, if stable beam acceleration is limited to a smaller phase interval.

Beyond the parameters listed in the table, the experimenter is interested in background rates (e.g. proton halo scraping collimators upstream[5]) and - related - the mimimum radius of the beam tube (in order to place vertex detectors as close to the interaction region as possible).

1.2. Detectors

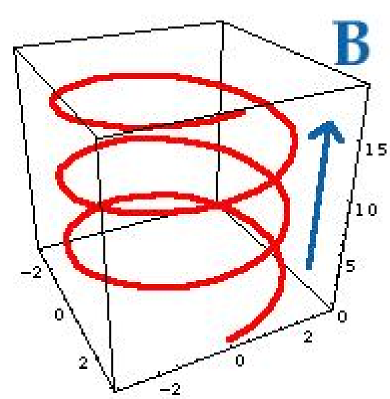
Since the magnet choice has a major impact on the design of all the other detector parts, the different types of magnets are described first in this chapter.

1.2.1. Magnets

A good momentum measurement requires precise detectors and 'thick' magnetic fields with a large B field. The track curvature radius grows with particle energy/momentum, so that at high energy colliders this task becomes particularly difficult.

Some formulae:

i) Trajectory inside magnetic field



A charged particle describes a helix inside a homogeneous magnetic field; the radius of curvature for a particle with charge ± 1 is given by

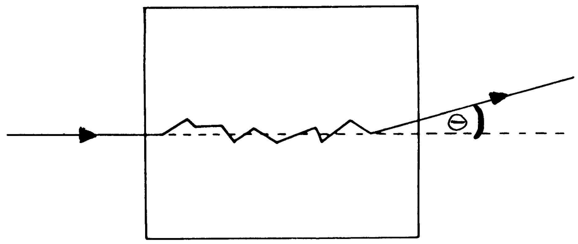
$$R = \frac{p_B}{e\,B} = 3.3\,\mathrm{m} \cdot \frac{p_B/\mathrm{GeV}}{B/\mathrm{T}} \tag{2}$$

where p_B denotes the component of $\vec{p}$ perpendicular to $\vec{B}$.

Example: The Tevatron superconducting dipole magnets produce $B = 4.4\,\mathrm{T}$. For $1\,\mathrm{TeV}$ particles this implies a radius of $R = 750\,\mathrm{m}$. This number is smaller than the geometrical Tevatron radius of $1\,\mathrm{km}$, since the magnets do not cover all the circumference!

[5] this is not the most important background source at the LHC, see section 1.2.2

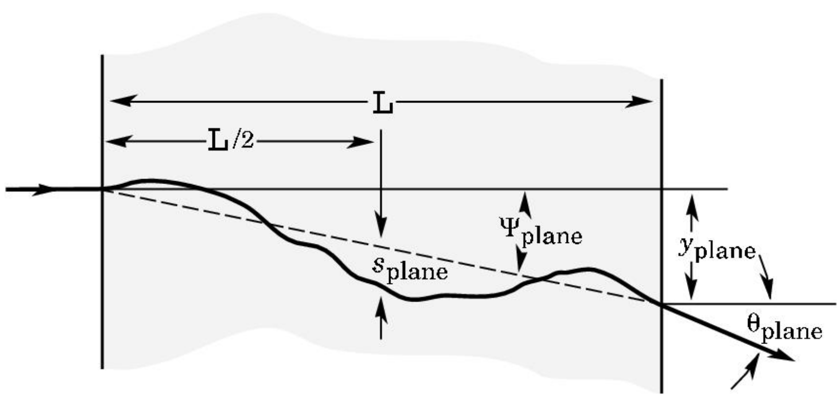
ii) Multiple scattering
Multiple deflections in the Coulomb field of nuclei result in both a spatial and an angular displacement:



The overall scattering angle is Gaussian distributed. In one projection the width is given by

$$\theta_{MS} = \frac{13.6\,\mathrm{MeV}}{p}\sqrt{\frac{L}{X_0}}\,(1 + 0.038\,\ln\frac{L}{X_0}) \tag{3}$$

for relativistic particles with unit charge. The last factor is close to 1 and can often be ignored. L is the traversed matter thickness and X_0 the radiation length of the material.



The track displacement is (approximately)

$$y_{MS} = \frac{1}{\sqrt{3}}\,L\,\theta_{MS} \tag{4}$$

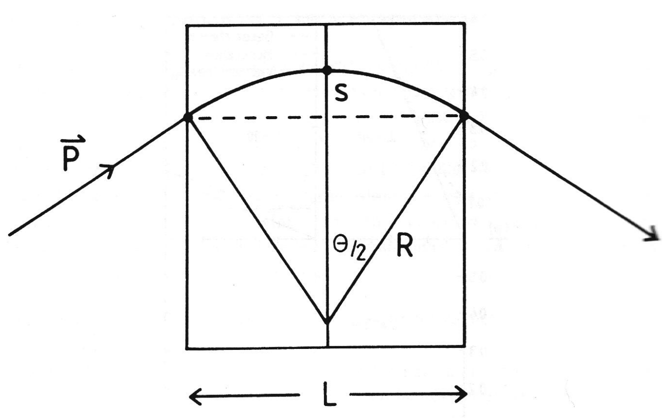
and

$$s_{MS} = \frac{1}{4\sqrt{3}}\,L\,\theta_{MS} \tag{5}$$

Reference: Review of Particle Physics 2002 (Phys. Rev. D 66 (2002) 1).

Example: A muon of $p = 1\,\mathrm{GeV}$ is deflected by typically $\theta_{MS} = 0.6^0$ (in one projection) when passing through $L = 1\,\mathrm{cm}$ of iron ($X_0 = 1.8\,\mathrm{cm}$).

iii) Curvature measurement
The momentum resolution depends on the detector precision, on the amount of material the particle has to traverse, and on the measurement principle. In collider experiments often the sagitta s is measured inside the magnet region:



At least three coordinate measurements are necessary. It is also possible to measure the track direction inside and/or outside the magnet area and to include the collision point as a constraint in the momentum determination - but we will not discuss these points here.

The sagitta is given by (⟶ tutorial)

$$s = \frac{e\,B\,L^2}{8\,p_B} = 0.3\,\mathrm{m}\,\frac{B/\mathrm{T}\,(L/\mathrm{m})^2}{8\,p_B/\mathrm{GeV}} \tag{6}$$

Obviously, the more precise the s measurement, the better the momentum resolution. The quadratic dependence on L is very important! Some comments on this dependence:

- intuitive explanation: trajectory in homogeneous field (angle $\vec{p} - \vec{B}$ approx. constant) = parabola: transverse momentum $\sim L$, spatial deviation $\sim L^2$.
- doubling the radius of an inner tracking detector = fourfold improvement in momentum resolution! Difficult to reach by increasing B or by improving detector resolution!
- If a detector is subdivided into two independent identical halves, each of thickness $L/2$: Measuring the sagitta twice and combining the momentum measurements yields a resolution which is worse by a factor $4/\sqrt{2}$ compared to the full detector's resolution. To avoid this degradation a common track fit through both detector parts is mandatory, implying: no material (MS) in between, negligible alignment uncertainties.

Example: A muon of $p = 100\,\mathrm{GeV}$ traversing a magnetic field $B = 1\,\mathrm{T}$ (at right angles) of thickness $L = 1\,\mathrm{m}$ results in a sagitta of only $s = 0.4\,\mathrm{mm}$.

A sagitta measurement requires three coordinate measurements, for example the measurement of y_1, y_2 and y_3 at the coordinates $x_1, x_2 = x_1 + L/2, x_3 = x_1 + L$ along the trajectory:

$$s = y_2 - \frac{y_1 + y_3}{2}. \tag{7}$$

The formula implies that the central point should be measured more precisely than the outer ones. This can be realized by using *four* identical coordinate detectors, which measure independently with a resolution of Δy at $x = 0, x = L/2, x = L/2$ (!) and $x = L$:

$$s = \frac{y_{2a} + y_{2b}}{2} - \frac{y_1 + y_3}{2}. \tag{8}$$

In this case the sagitta error is

$$\Delta s = \Delta y \cdot \sqrt{1/4 + 1/4 + 1/4 + 1/4} = \Delta y \tag{9}$$

Example: A detector resolution of $\Delta y = 0.1\,\mathrm{mm}$ *yields* $\Delta s = \sqrt{1.5}\,\Delta y = 0.12\,\mathrm{mm}$ *using three detectors and* $\Delta s = \Delta y = 0.1\,\mathrm{mm}$ *with four detectors.*

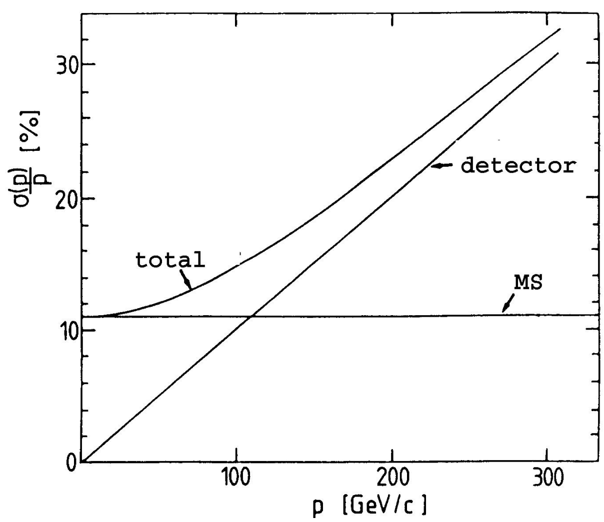
iv) Momentum resolution
In many cases the relative momentum resolution can be parametrised as follows:

$$\frac{\Delta p}{p} = \frac{\Delta p_{det}}{p} \oplus \frac{\Delta p_{MS}}{p} = c_{det} \cdot \frac{p}{\mathrm{GeV}} \oplus c_{MS} \tag{10}$$

where $a \oplus b$ stands for $\sqrt{a^2 + b^2}$.

Here $\vec{p} \perp \vec{B}$ was assumed, the more general case is discussed below. This formula applies for example when a muon track through an iron yoke is measured several times in ‘holes’ inside the material along the trajectory.

Note that the detector resolution contribution is growing with p, while the MS part is independent of momentum:



From the sagitta formula (6) we can calculate the detector term c_{det}:

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = 8 \cdot \frac{\Delta y}{eL^2\,B} \cdot p = 26.4 \cdot \frac{\Delta y/\mathrm{m}}{L^2/\mathrm{m}^2\;B/\mathrm{T}} \cdot p/\mathrm{GeV} \tag{11}$$

assuming $\Delta s = \Delta y$, thus

$$c_{det} = 0.026 \cdot \frac{\sigma/\mathrm{mm}}{L^2/\mathrm{m}^2\;B/\mathrm{T}} \tag{12}$$

All these formulae assume $\vec{B} \perp \vec{p}$!

The multiple scattering term can be calculated in a similar way from the fake sagitta (equation 5):

$$c_{MS} = \frac{\Delta p}{p} = \frac{s_{MS}}{s} = \frac{1}{4\sqrt{3}}\,L\,\frac{13.6\,\mathrm{MeV}}{p}\sqrt{\frac{L}{X_0}} \cdot 8\,\frac{1}{L^2\,B} \cdot p = \frac{16\,\mathrm{MeV}}{L\,B}\sqrt{\frac{L}{X_0}} \tag{13}$$

$$= \frac{0.052}{L/\mathrm{m}\;B/\mathrm{T}}\sqrt{\frac{L}{X_0}} \tag{14}$$

Example: *We assume a magnetic field of* $\mathbf{2\,T}$ *and an iron layer of* $\boldsymbol{L = 1\,\mathrm{m}}$ *thickness. For the 4 chamber model with* $\boldsymbol{\Delta y = 0.1\,\mathrm{mm}}$ *we get*

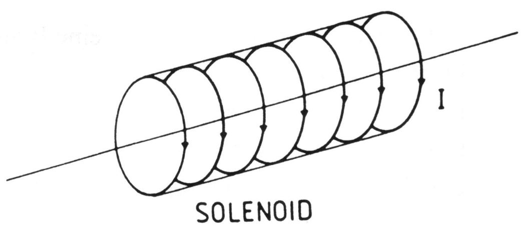
$$c_{det} = 0.13\% \qquad\qquad c_{MS} = 19\% \tag{15}$$

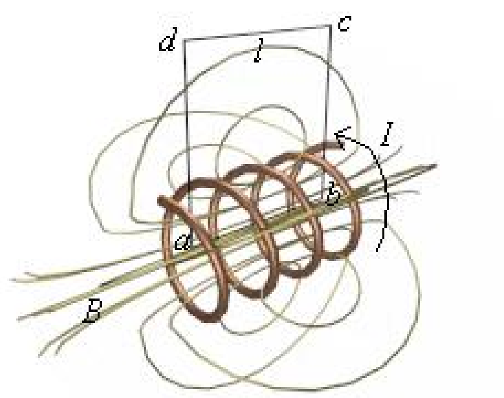
Thus the detector contribution becomes relevant only for momenta above $\sim \mathbf{100\,GeV}$.

v) Magnetic field configurations

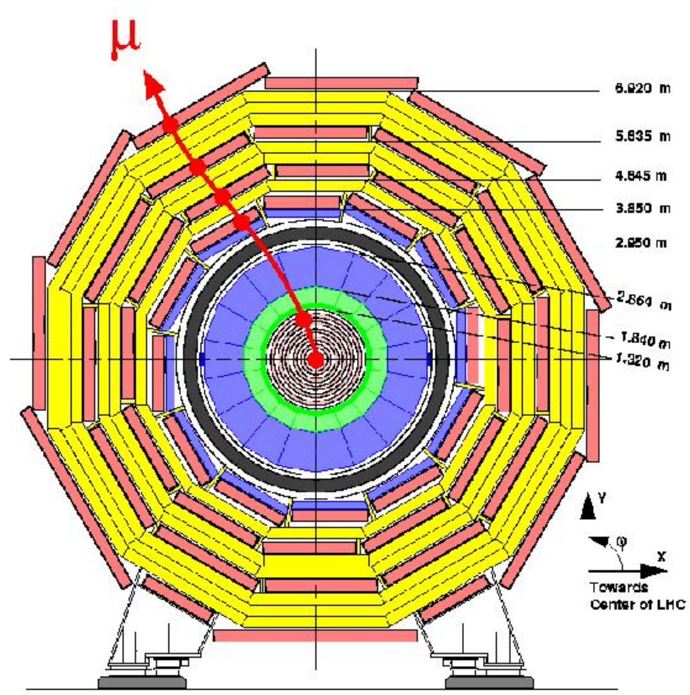
Since the beam must not be disturbed by the detector's magnetic field only two field configurations seem possible:

a) Solenoid

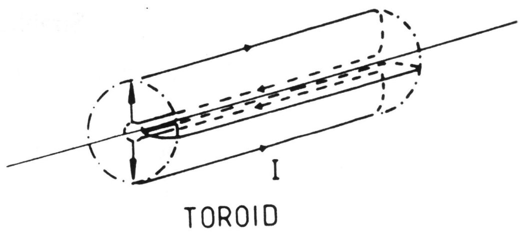


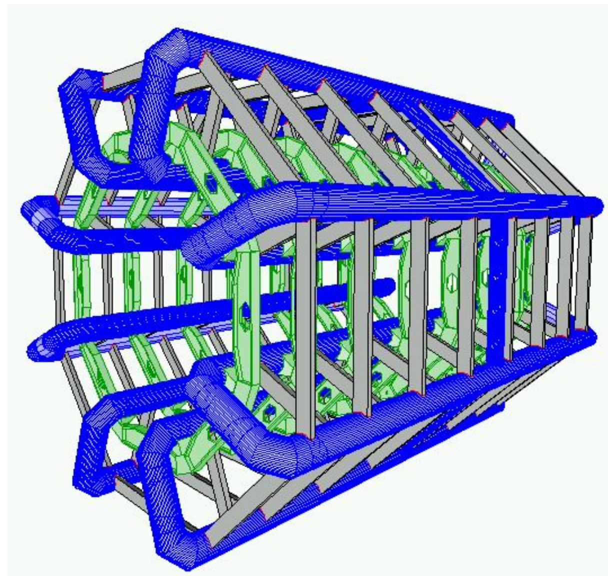


The symmetry axis of the solenoid coincides with the beam line, so $\vec{v} \times \vec{B} = \vec{0}$. The cross section of the coil can be circular, but also a rectangular design will work. The field lines extend far outside the magnet; to avoid related problems one can capture the field in a cylindrical magnet yoke outside the solenoid and feed it back. Another advantage of the yoke is the extra field that can be used to (re)measure track momenta.



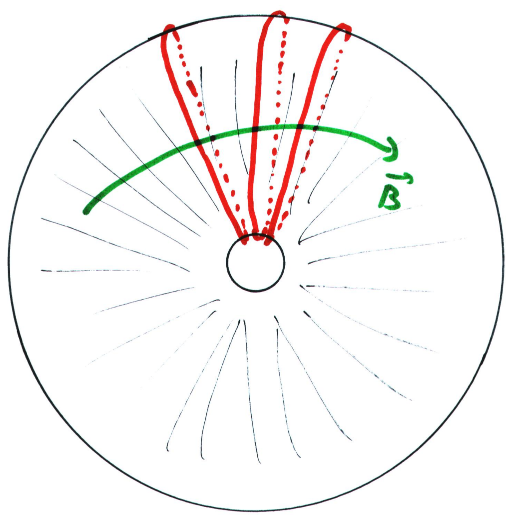
b) Toroid



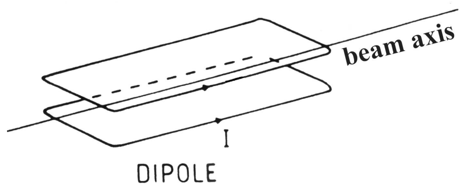


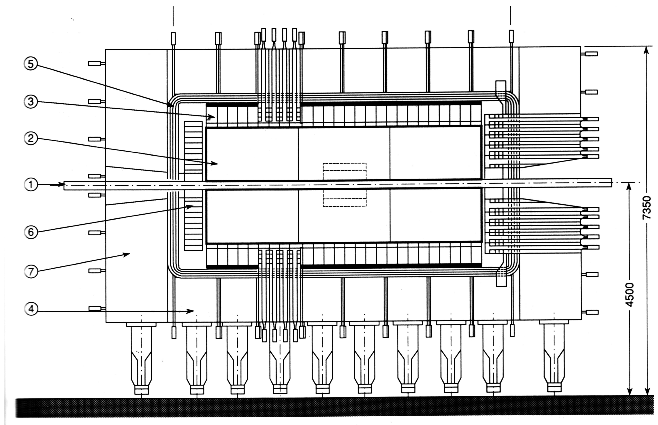
Toroids contain closed B field lines, thus there is no need for extra yokes, avoiding the resulting multiple scattering!

In the endcap regions often iron toroids are used:



c) There is a notable exception to the rule $\vec{v} \times \vec{B} = \vec{0}$: the UA1 detector used a horizontal dipole field (generated by a ‘rectangular solenoid’) which was oriented perpendicular to the beam:





Of course this requires another magnetic field outside the detector to compensate. A dipole magnet can never be used in electron accelerators, due to the induced synchrotron radiation.

<u>Some general comments on magnet technology:</u>

- The magnetic fields can be generated by 'conventional' or by superconducting coils, the latter type is used in all modern experiments. The resulting field strengths are in the range $\mathbf{0.7\,T}$ (UA1 dipole) to $\mathbf{4\,T}$ (CMS sc. solenoid). These values are limited by the power dissipation (conventional) and the breakdown of superconductivity for high $\boldsymbol{B}$ fields. The field strength inside an iron magnet is normally close to the saturation value, i.e. $\boldsymbol{B = 1.5 - 1.9\,\mathrm{T}}$.

- Superconducting magnets need a cryostat, thus complicating the detector design.

- Mechanical forces can be important. *<u>Example:</u> the CMS iron yoke can move by $\mathcal{O}(cm)$ when the coil is turned on/off.*

- The energy stored is huge. Quenches must be avoided. *<u>Example</u>: ATLAS toroid = 1500 MJ.*

- An iron filled magnet needs substantially lower currents than an air magnet. *<u>Examples:</u> D0 central toroid: each coil: $\boldsymbol{n\,I}$ = 25 kA, ATLAS barrel toroid: each coil = 3 MA.*

<u>Comparison of 'physics performance':</u>

The two main aspects are:

* <u>multiple scattering</u>: dominated by iron yoke (if existing); severe limitation for momentum resolution, see above.

* <u>field geometry</u>:

a) barrel toroid: bending in plane containing beam
+ $\vec{\boldsymbol{p}} \perp \vec{\boldsymbol{B}}$, in barrel toroid $\boldsymbol{B\,L^2}$ largest at small angles!
- no vertex constraint (long collision region)
- no field in central detector part

b) barrel solenoid: axial field, bending in plane perpendicular to beam
o $\vec{\boldsymbol{p}}_\perp$ is measured, resolution indep. of angle (without MS)
+ vertex constraint (small beam diameter)
+ B field inside and close to beam pipe

c) barrel dipole: bending in plane containing beam, ϕ dependent!

+ $B\,L^2$ largest at small angles, works even for $\eta \pm \infty$.
- no vertex constraint (long collision region)
- no bending for tracks || $\vec{B}$
- needs compensation

In the forward region there is less choice: only toroids make sense ($\vec{P} \approx\perp \vec{B}$).

Above the momentum resolution formulae were given for barrel magnets at $\theta = 90^0, \eta = 0$. For other polar angles the following modifications have to be taken into account for cylindrical magnets:
- solenoids measure p_T ($\rightarrow p = p_T/\sin\theta$).
- toroids measure p, effective track length $L = L_0/\sin\theta$, resolution $\sim 1/L^2$ (sagitta method).
- similar for dipole, but additional ϕ dependence.
- multiple scattering increases: effective thickness $= L_0/\sin\theta$.

Summary of the magnet configurations of the six pp detectors:

experiment	UA1	UA2	CDF	D0	ATLAS	CMS
solenoid	-	-	1.6 T sc	2.0 T sc	2.0 T sc	4.0 T sc
solenoid yoke	-	-	iron	-	yes	1.6 T iron
barrel toroid	-	-	-	1.9 T iron	4 T sc air	-
endcap toroid	-	yes	iron	2.0 T iron	4 T sc air	-
endcap yoke	-	yes !	-	-	-	2 T iron
dipole	0.7 T	-	-	-	-	-
dipole yoke	1.8 T iron	-	-	-	-	-

Some (expected) performance figures (depend of course on position resolution) for $\eta = 0$:

CMS central tracker:

$$\frac{\Delta p}{p} = 0.012\% \cdot p/\mathrm{GeV} \oplus 0.5\% \tag{16}$$

ATLAS toroid:

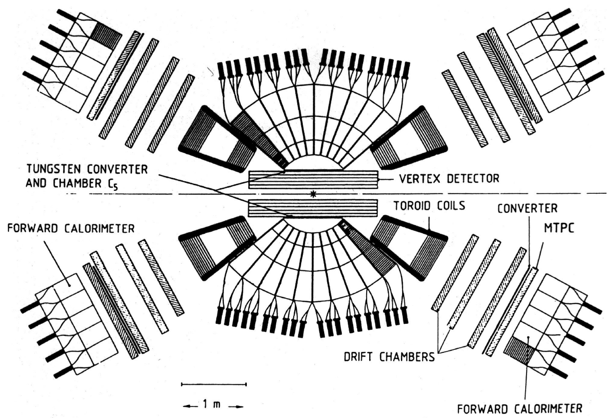
$$\frac{\Delta p}{p} = 0.01\% \cdot p/\mathrm{GeV} \oplus 1.5\% \tag{17}$$

D0 toroid:

$$\frac{\Delta p}{p} = 0.3\% \cdot p/\mathrm{GeV} \oplus 18\% \tag{18}$$

Finally a few pictures:

UA2 detector:


TUNGSTEN CONVERTER
AND CHAMBER C_5
VERTEX DETECTOR
TOROID COILS
CONVERTER
MTPC
FORWARD CALORIMETER
DRIFT CHAMBERS
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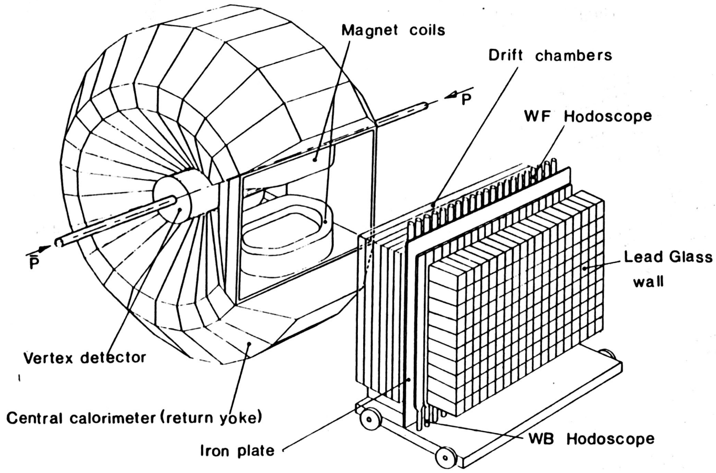
FORWARD CALORIMETER


Magnet coils
Drift chambers
P
WF Hodoscope
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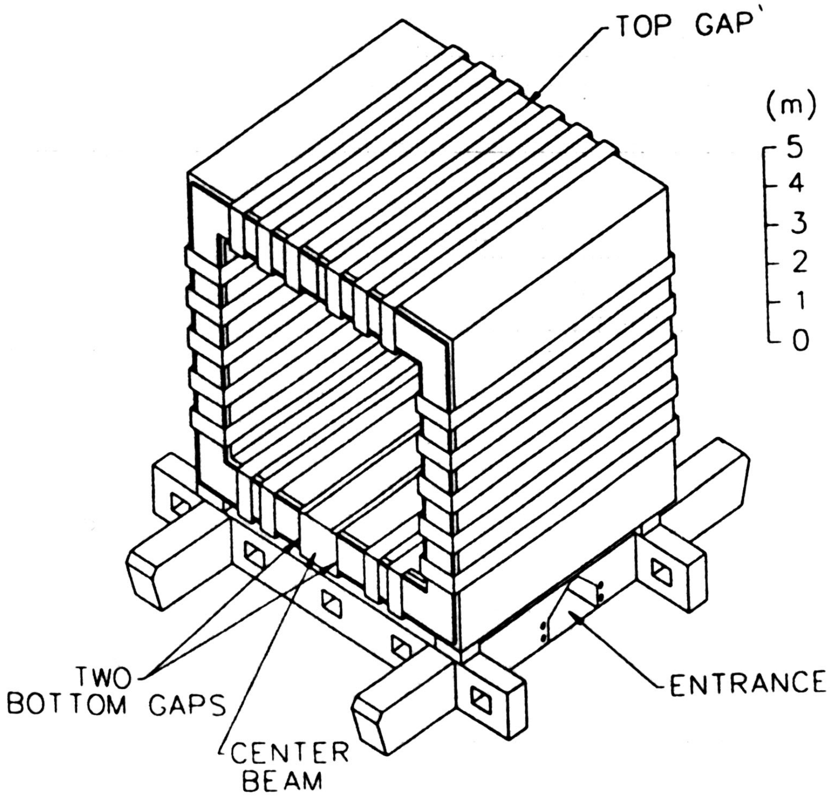
Lead Glass
wall
Vertex detector
Central calorimeter (return yoke)
Iron plate
WB Hodoscope

D0 toroid:


TOP GAP
(m)
5
4
3
2
1
0
TWO
BOTTOM GAPS
CENTER
BEAM
ENTRANCE

Note: here no sagitta measurement, but determination of track direction before and after traversing magnet.

Atlas toroid coil:

CMS magnetic field: