Instrumentation for Flavor Physics - Lesson I

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Outline

Lesson I

Introduction

Basics for detector design

Vertex detectors

See also dedicated lecture at this school about vertexing and tracking

Lesson II

Tracking detectors

Particle identification (PID) detectors

Muon detectors

Prerequisites and references

Interaction of radiation with matter

Basics of particle detectors

Some references that I used in preparing these lectures:

Bichsel, Groom and Klein, “Passage of particles through matter”, PDG review

Chakraborty et. al., “Particle detectors for accelerators”, PDG Review

Grupen and Shwartz, “Particle detectors”, Cambridge

Leo, “Techniques for Nuclear and Particle Physics Experiments”, Springer Verlag

Spieler, “Semiconductor Detector Systems”, Oxford

Shultz-Colon, “The Physics of Particle Detectors”, Lecture notes

Brown, “Tracking in BaBar”, BaBar Analysis School Lectures

Forty, “Particle Identification”, ICFA Instrumentation School Lectures

Introduction

Disclaimer

Flavor Physics is a wide field of research studying the properties and interactions of leptons and quarks. In these lectures, which are not meant to be a review on the subject, I will try to give you the very basic ideas about the instrumentation required for detecting particles and reconstructing signal events.

I will focus these lectures on instrumentation used in *B* physics experiments at colliders. This is mostly because I am working in that field -:), but also because these techniques are quite general and are used also in other high energy physics experiments.

Particle Colliders definitions

E_{CM} = center-of-mass energy, available for particle creation

Assume beams with particle mass m and energy $E \gg mc^2$

Fixed target experiment: $E_{CM} = \sqrt{2mE}$

Collider: $E_{CM} = 2E$

Ex: calculate the beam energy for E_{CM}=14 TeV for a fixed target experiment

Luminosity $$\mathcal{L} = f \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$ [$cm^{-2}s^{-1}$]

number of particles per bunch (n_1, n_2)

bunch transverse size at the interaction point (σ_x, σ_y)

bunch collision rate (f)

Rate $$R = \mathcal{L}\sigma$$ [s^{-1}]

cross section of the physics process (σ)

Ex: $\mathcal{L} = 10^{34}\mathrm{cm}^{-2}s{-}1, \sigma = 1\mathrm{nb} \rightarrow R = 10\ \mathrm{Hz}$

How do we design a detector?

Start with the Physics

What is the physics measurement that is driving the experiment?

What reactions do we intend to study? What final state particles?

What level of precision do we want to achieve?

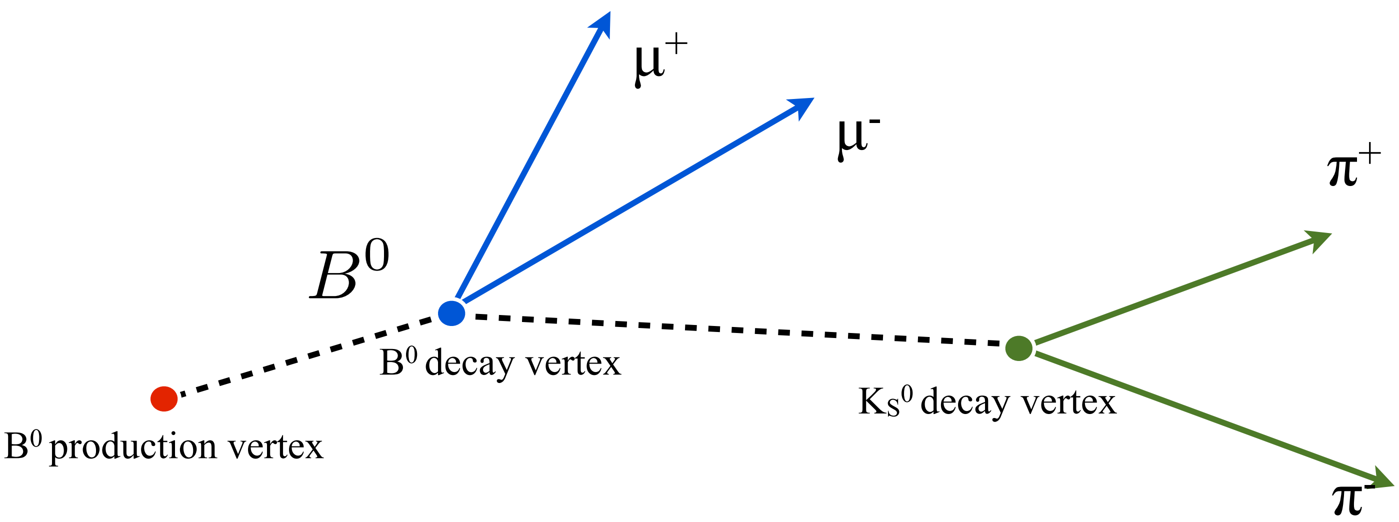
How do we select the signal events?

What is the expected event rate?

Start from a real example

Assume that we are interested in reconstructing the decay $B^0 \to J/\psi K^0_S$

$J/\psi \to \mu^+\mu^-$, $K^0_S \to \pi^+\pi^-$



What do we need to measure in order to reconstruct the signal (and distinguish it from the background)?

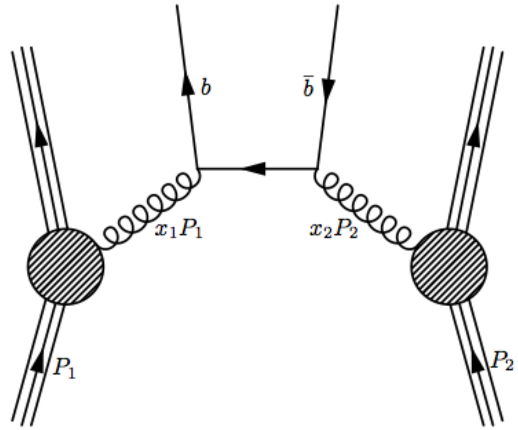
$b\bar{b}$ production mechanisms

Hadron colliders: *e.g.* Tevatron, LHC

$b\bar{b}$ from QCD mediated process

incoherent production of *b* hadrons

not defined hadron energy



gluon-gluon fusion is the leading mechanism at LHCb

Tevatron $\sigma(b\bar{b}) \sim 10\mu\text{b at } p\bar{p} \text{ collisions, } E_{CM} = 1.96 \text{ TeV}$

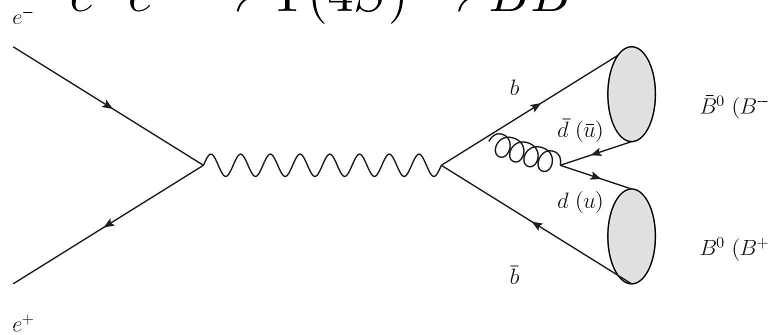
LHCb $\sigma(b\bar{b}) \sim 150\mu\text{b at } pp \text{ collisions, } E_{CM} = 14 \text{ TeV}$

Electron colliders: *e.g. B* factories

coherent production of $B\bar{B}$ at E_{CM}=10.58 GeV

well defined *B* meson energy

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$



$$\sigma(B\bar{B}) \sim 1.1\text{nb at } e^+e^- \text{ collisions, } E_{CM} = 10.58 \text{ GeV}$$

Signal reconstruction and background suppression

Signal reconstruction

Identify clean signal signature

final state particles ⇒ particle identification (PID) ⇒ e.g. Cherenkov detectors, time of flight detectors, muon chambers

topology ⇒ measurements of particle trajectories and decay vertex ⇒ e.g. gas detectors, silicon detectors

kinematical constraints ⇒ measurement of particle momentum, angle, energy ⇒ e.g. tracking detectors, calorimeters

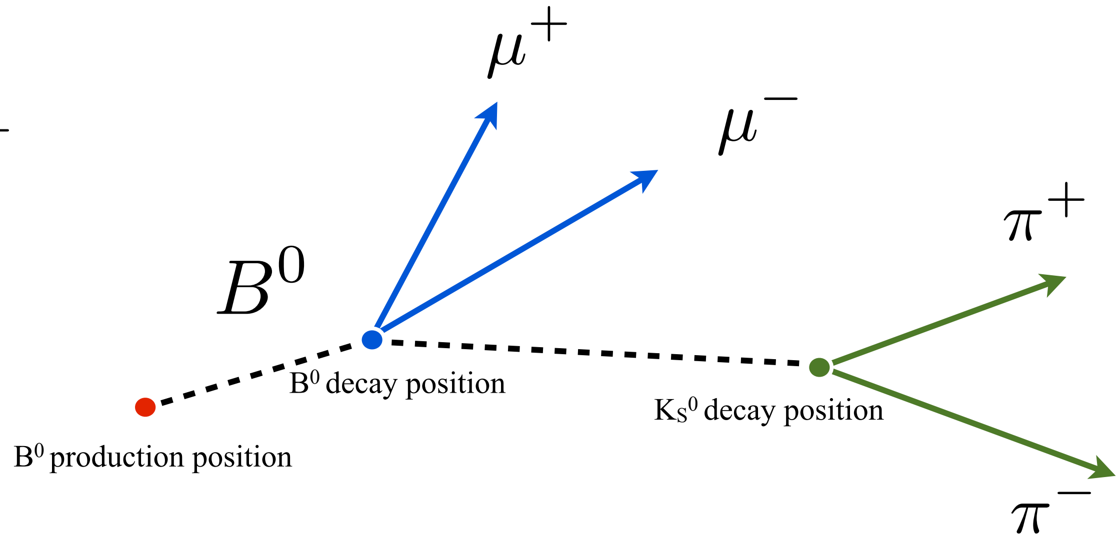
Background suppression

Identify background sources and exploit different signatures ⇒ event selection criteria ⇒ precise measurements of discriminating quantities ⇒ high performance detectors

Example of signal signature and constraints

$$B^0 \rightarrow J/\psi K_S^0$$

$J/\psi \rightarrow \mu^+\mu^-$, $K_S^0 \rightarrow \pi^+\pi^-$



PID: muons and pions

Topology: 2 displaced decay vertex (B^0, K_S^0)

Kinematical constraints:

$$(p_{\mu^+} + p_{\mu^-})^2 = m^2_{J/\psi}$$

$$(p_{\pi^+} + p_{\pi^-})^2 = m^2_{K_S^0}$$

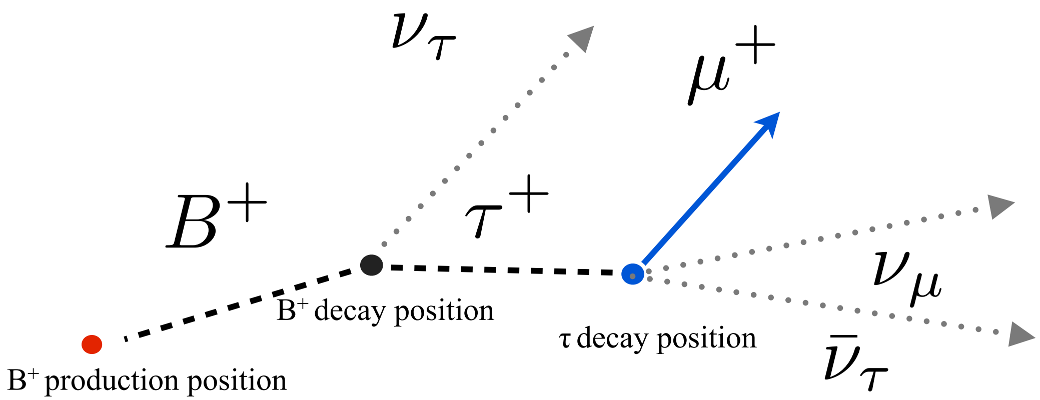
$$(p_{J/\psi} + p_{K_S^0})^2 = m^2_{B^0}$$

Invariant mass reconstruction requires measurements of particle momenta and angles

$$m^2 = m_1^2 + m_2^2 + 2(E_1E_2 - |\vec{p}_1||\vec{p}_2|\cos\theta_{12})$$

Example of signal signature and constraints (II)

$$B^+ \to \tau^+ \nu_\tau$$
$$\searrow$$
$$\mu^+ \nu_\mu \bar{\nu}_\tau$$



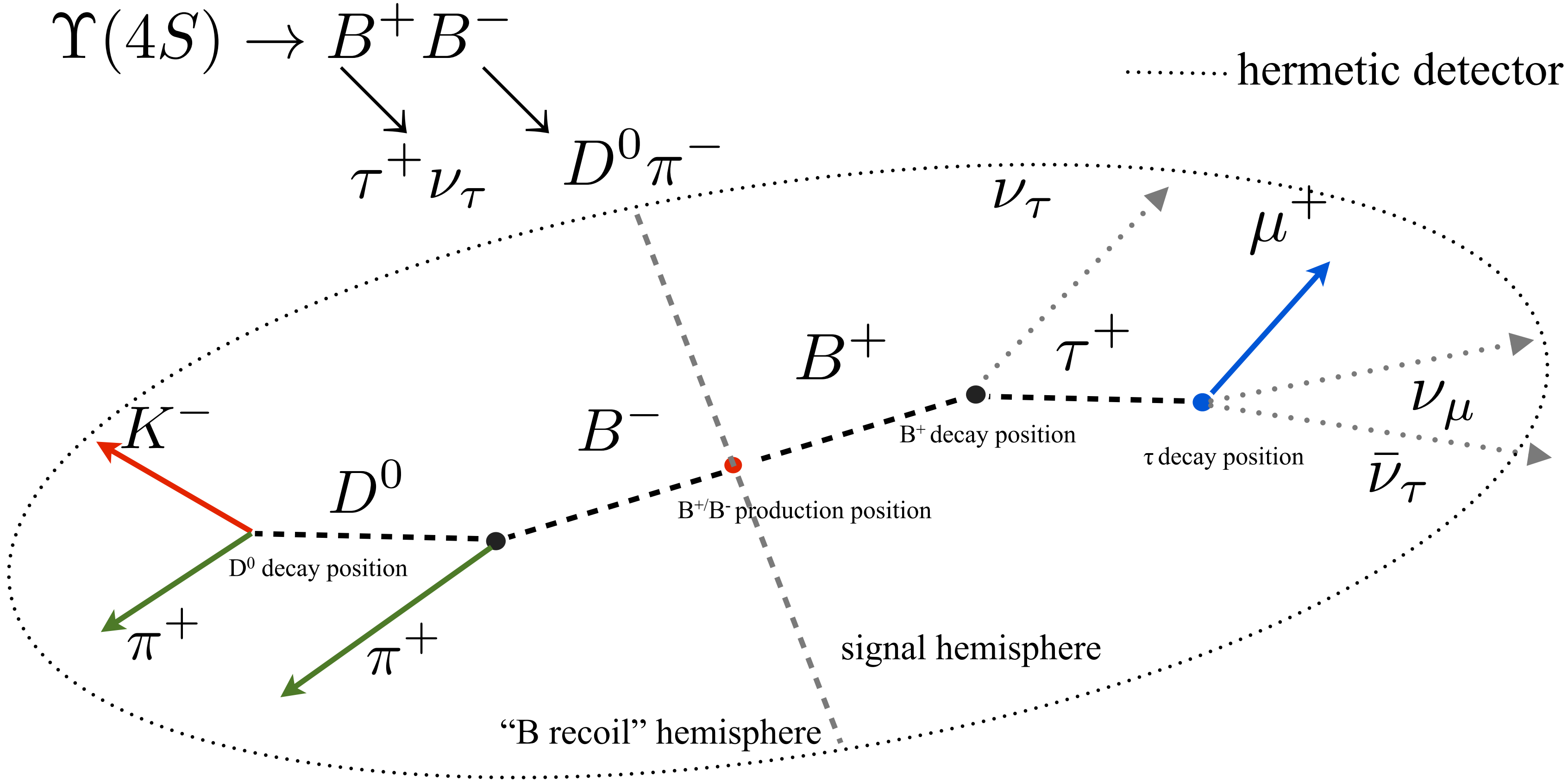
PID: muon

Topology: no displaced vertex

Kinematical constraints: no useful kinematical constraints (neutrino is not detected

Signal identification and background suppression are very challenging!

Nature helps sometimes... if you have an hermetic detector



Kinematical constraints: if we reconstruct the B^- decay, we know the B^+ momentum by imposing momentum conservation.

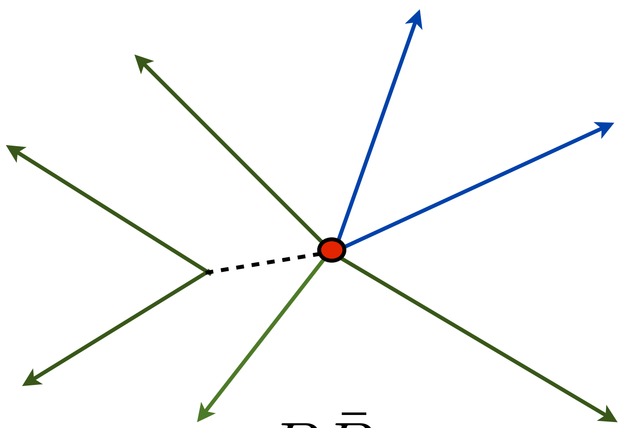
Signal signature: only one muon and no "extra signal" in the signal hemisphere (neutrinos are not detected). The signature is no "extra signal" or no "extra energy"!

Detector has to be hermetic (~4π solid angle coverage) to avoid events with missing particles that mimic the signal.

Physics and detector geometry

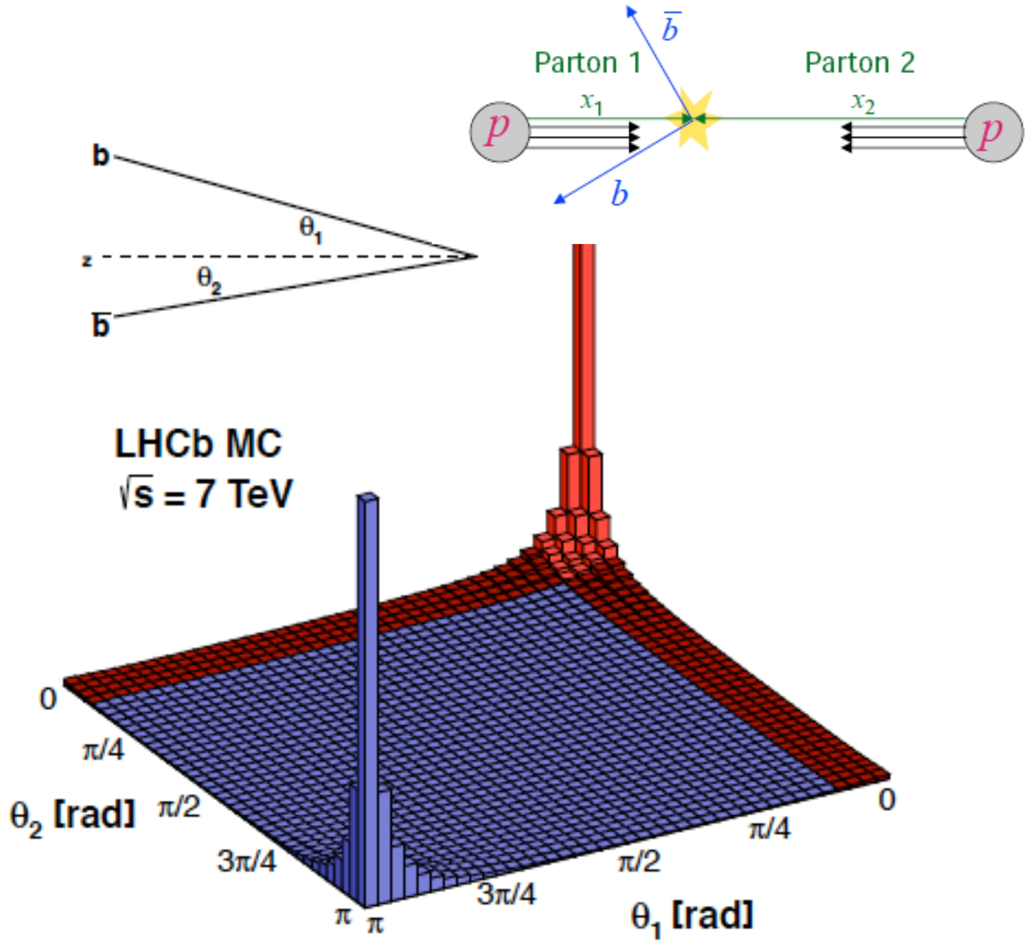
Detector geometry has to be optimized for the physics processes we intend to study

In e^+e^- collisions at E_{CM}=10.58 GeV, $B\bar{B}$ events are produced almost at rest in CM frame. The decay products are ~isotropically distributed.



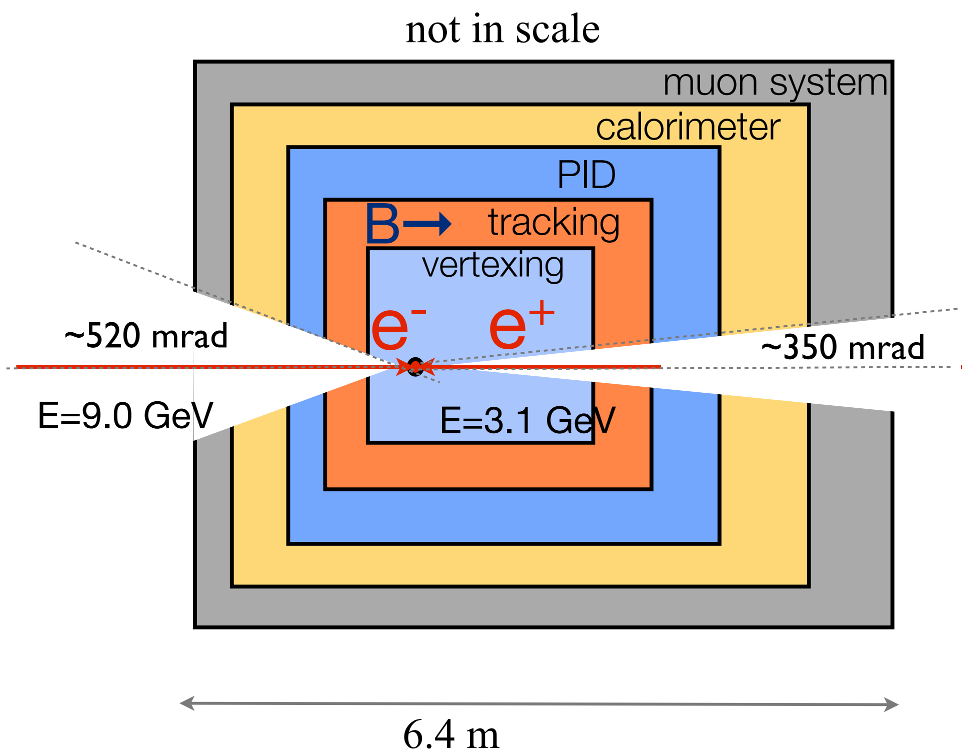
$B\bar{B}$ event

In high energy pp collisions $b\bar{b}$ events are produced in the forward and backward directions

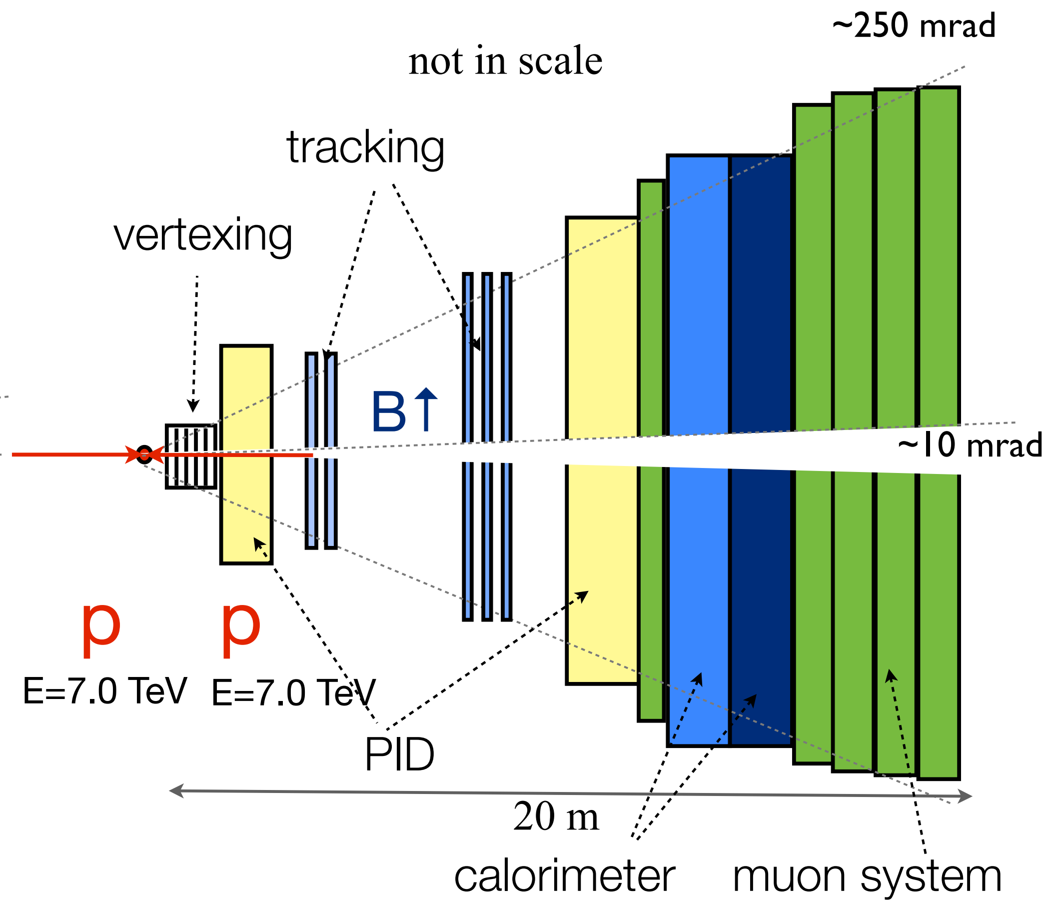


Detector geometry

BaBar onion-like geometry around the interaction point (IP). Solenoidal magnetic field B=1.5 T along e^- beam axis.



LHCb single arm magnetic spectrometer. Dipole magnetic field ∫B·dl=3.73 T·m, perpendicular to beam axis



Detector material

The measurement of the particle properties modifies the properties of that particle through the interaction with detector material: e.g. energy loss, multiple scattering, nuclear reactions.

Active material is the sensor material: e.g. silicon, gas, crystal, quartz, plastic.

Passive material: e.g. mechanical support, cooling, cables.

The "lightest" detectors, in term of radiation length (x/X_0), are positioned closer to the IP, where most particles are originated (x= detector thickness)

Measure particle properties using light detectors first ($x/X_0 <$ few %)

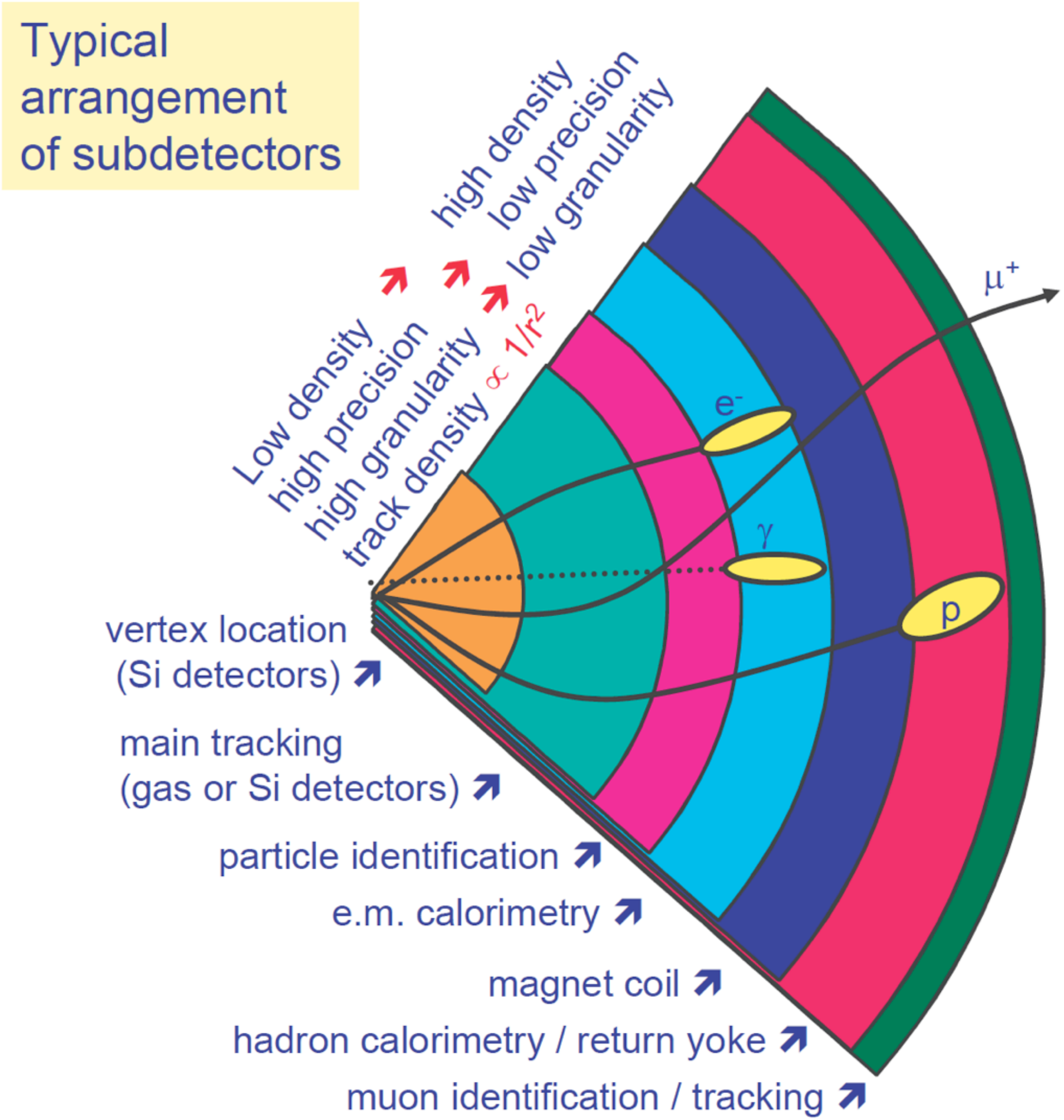
$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\left(183 Z^{-1/3}\right)} \quad [\mathrm{g/cm^2}]$$

$N_A = 6.022 \cdot 10^{23}$
[Avogardo's number]

$r_e = e^2/4\pi\varepsilon_0 m_e c^2 = 2.8$ fm
[Classical electron radius]

Z : Charge number of medium
A : Atomic mass of medium

Detector systems



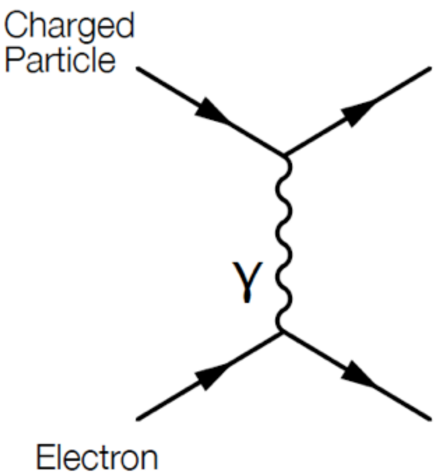
Particle detection

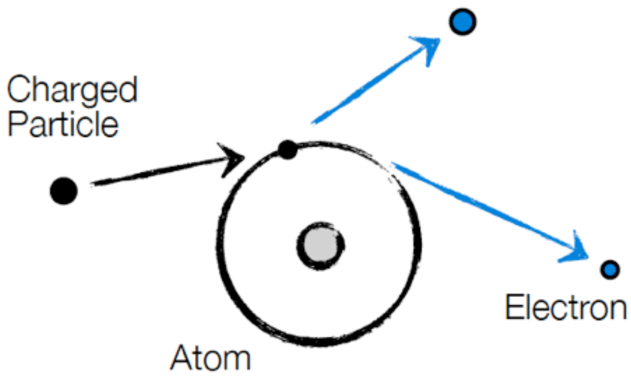
Particles can be detected through their interactions with matter

- Charged particles: energy loss by excitation or ionization of the medium, irradiation by bremsstrahlung, Cherenkov effect, deflection from the trajectory due to Coulomb multiple scattering
- Photons: photoelectric effect, Compton scattering, pair production
- Hadrons: nuclear interactions
- Neutrinos: weak interactions

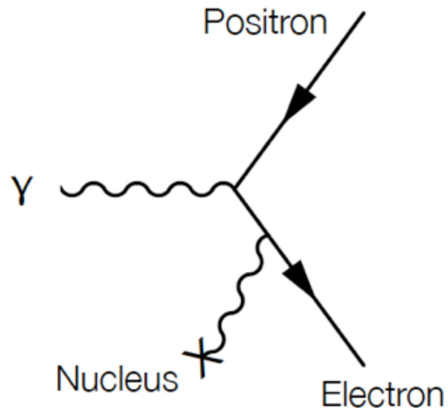
Examples of particle interactions

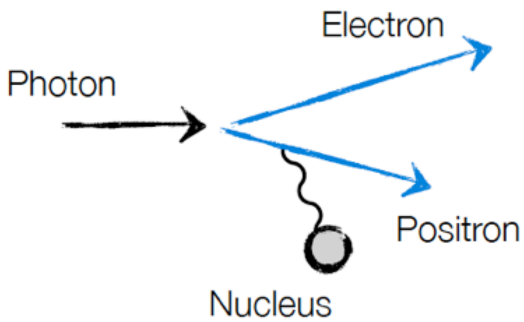
Ionization:



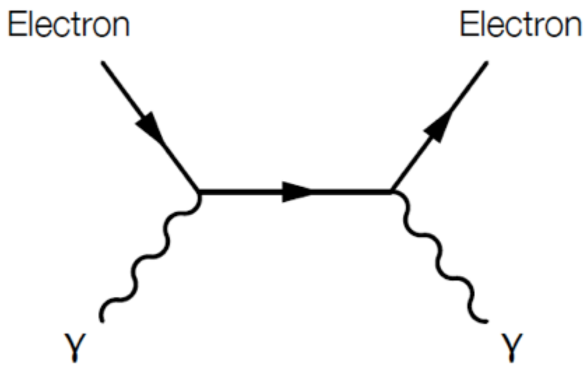


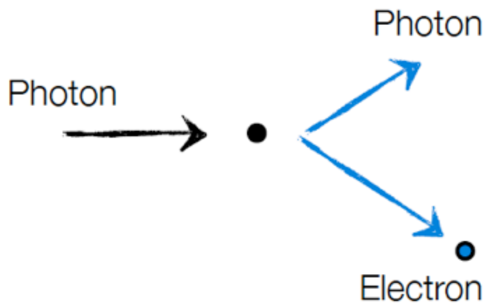
Pair production:





Compton scattering:





Exercises

1. At the LHC at CERN, two proton beams collide head on with energies E_{beam}=7 TeV. What energy would be needed to obtain the same CM energy with a proton beam on a fixed hydrogen target?
2. Estimate the resolution on the reconstructed invariant mass for a 3 GeV/c J/Ψ decaying into muons, assuming $\sigma_p/p=[0.1p(GeV/c)\oplus0.4]\%$, σ_θ= 1mrad.
3. Calculate the geometrical acceptance in the CM system for a detector with angular coverage in the lab, θ_{fw}=350mrad, θ_{bw}=-520mrad and $\beta\gamma_{CM}$=0.56 (see left figure in Pag. 15).
4. Calculate x/X_0 for a cylindrical beam pipe (1.5mm Be, 1.5 $H_2$0, 4μm Au), a 5 layer silicon detector (300μm thick) and for 80 cm Fe used as muon filter. Why Be is preferred on Al for a beam pipe?
5. A beam of negative muons can be stopped in matter? What about positive muons?
6. Definition of critical energy for a particle. Is it lower for an electron or a muon?

Detectors for b physics

Vertex detectors

Tracking detectors

PID detectors

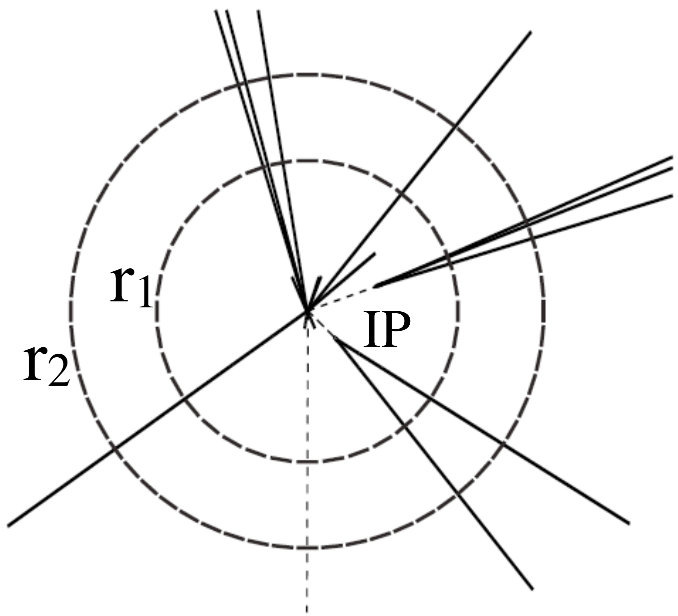
Calorimeters (not covered in these lectures)

Muon detectors

Vertex detectors

Impact parameter resolution - An example

Axial view of a collider event



Simple 2 layer tracking system

radius r_1 (r_2) and resolution σ_1 (σ_2)

Impact parameter resolution (geometry)

$$\sigma_b^2 \approx \left(\frac{\sigma_1 r_2}{r_2 - r_1}\right)^2 + \left(\frac{\sigma_2 r_1}{r_2 - r_1}\right)^2 = \frac{1}{(r_2 - r_1)^2}\left[(\sigma_1 r_2)^2 + (\sigma_2 r_1)^2\right]$$

if identical resolution $\sigma_1 = \sigma_2$

$$\left(\frac{\sigma_b}{\sigma}\right)^2 \approx \left(\frac{1}{1 - r_1/r_2}\right)^2 + \left(\frac{1}{r_2/r_1 - 1}\right)^2$$

Multiple scattering also affects resolution

$$\Theta_{rms} = \frac{0.0136[\mathrm{GeV/c}]}{p_\perp}\sqrt{\frac{x}{X_0}}\left[1 + 0.038 \cdot \ln\left(\frac{x}{X_0}\right)\right]$$

Good impact parameter resolution

first hit measurement close to the IP ➞ high particle flux, radiation damage

minimize material between IP and the first measurement point ➞ thin beam pipe (use Beryllium, large X_0 ➞small x/X_0) and thin detectors

Silicon vertex detectors

Possibility to produce highly segmented detectors (10 μm hit precision)

Fast signals (~ns) and small charge cloud (~μm) ➞ capable to cope with very high particle rates

Relatively large numbers of electron-hole pairs created per energy deposition. Low ionization energy:

Silicon : 3.6 eV per electron-hole pair

Gas: 20 - 40 eV for a single ion pair

Scintillators : 400 - 1000 eV depending on light yield [typical 1-10%]

Yield 80 e^{-}-hole pairs/μm for a minimum ionizing particle (MIP)

Relatively sensitive to radiation damage

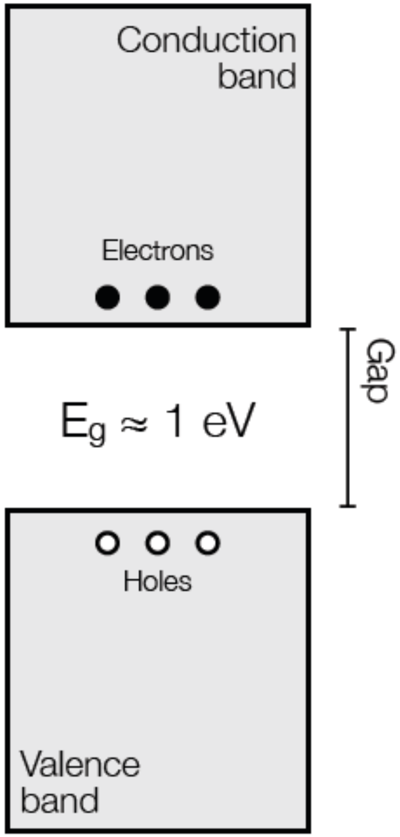
Basic semiconductor properties

Intrinsic semiconductor

Periodic potential ➞ Energy bands

very pure material; charge carriers provided by thermal excitation; high resistivity ρ~400 kΩ·cm

Silicon, Germanium; four valence electrons



Semiconductor

Doped semiconductor

Majority of carriers provided by donors (doping atoms); typical resistivity ρ~1-10 kΩ·cm in Si

n-type : majority carriers are electrons (pentavalent dopants P, As, Sb). Electrons easily excited in conduction band.

p-type : majority carriers are positive holes (trivalent dopants Al, B, Ga, In). Doping atom easily accepts valence electron leaving hole.

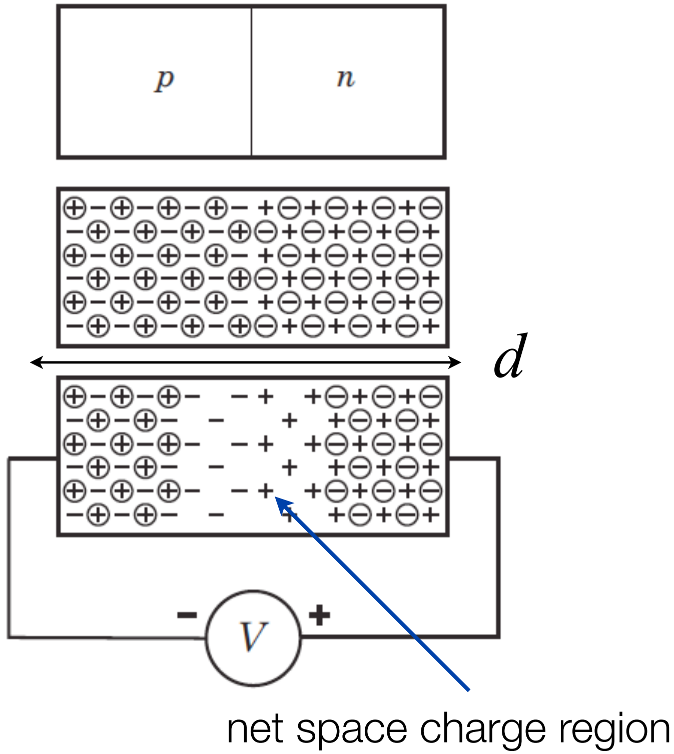
pn junction operated at reverse bias V

Sensitive region depleted of mobile charge

Thickness of depleted region

$$W = \sqrt{2\rho\mu\epsilon(V + V_{bi})}$$

$\epsilon =$ dielectric constant $= 11.9\ \epsilon_0 \approx 1$ pF/cm in Si
$\rho =$ resistivity (typically 1–10 kΩ cm in Si)
$\mu =$ charge carrier mobility
$V_{bi} =$ "built-in" voltage ~0.5 V

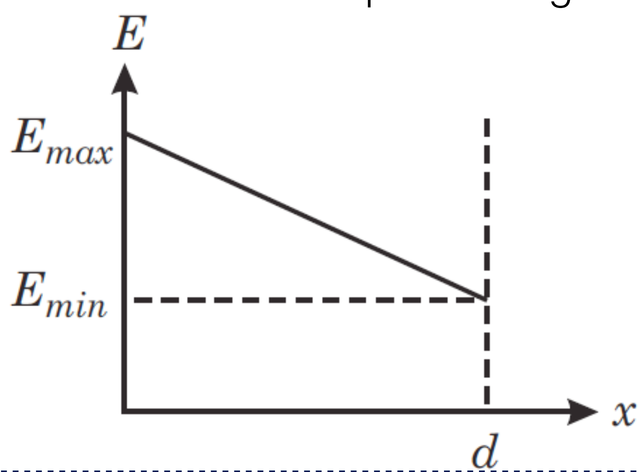


Electric field in sensitive region

Detector often operated with "overbias": $V>V_d$

depletion voltage $|E(x)| = \frac{2V_d}{d}\left(1 - \frac{x}{d}\right) + \frac{V - V_d}{d}$

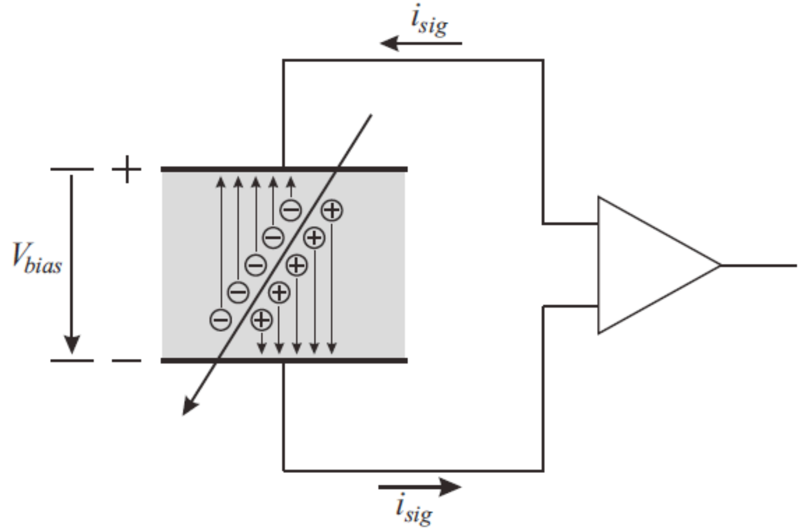
Collection time $t_c \approx \frac{d}{v} = \frac{d}{\mu \overline{E}} = \frac{d^2}{\mu V}$



Basic sensor

Semiconductor detectors are basically ionization chambers

moving charges induce signal on electrodes



Average signal charge
80e-hole pair/μm in Si

$$Q_s = \frac{E}{E_i} e \ ,$$

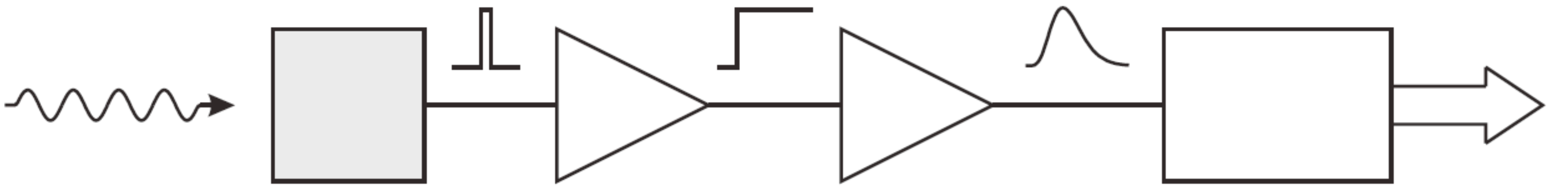
E = absorbed energy
E_i = 3.6eV, energy to form a charge pair

Carrier velocity

$$\vec{v}(x) = \mu \vec{E}(x) \ ,$$

μ = mobility 1350 (450) V/cm·s^2 for electrons (holes)
E = electric field.
Ex: V_{bias}=30 V in 300μm Si then E=10^3 V/cm. v_e=1.4·10^6 cm/s and t_c=20 ns to transverse 300μm silicon sensor

Basic detector functions



Preamplifier

signal charge is small ~4fC for MIPs in 300 μm Si

electronic noise is proportional to input capacitance C_{in}, to be minimized

Pulse shaping

improves signal to noise ratio, typically by transforming a short sensor pulse into a broader pulse with peaking time $T_{p.}$ Use CR-RC high pass - low pass filters.

Identical shape for all signal magnitudes ➞ pulse height spectrum = energy spectrum

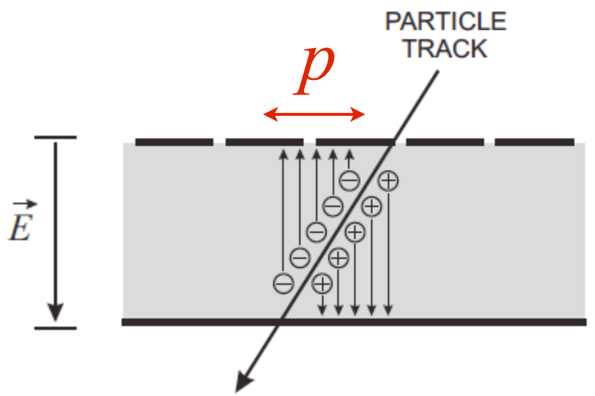
Digitizer

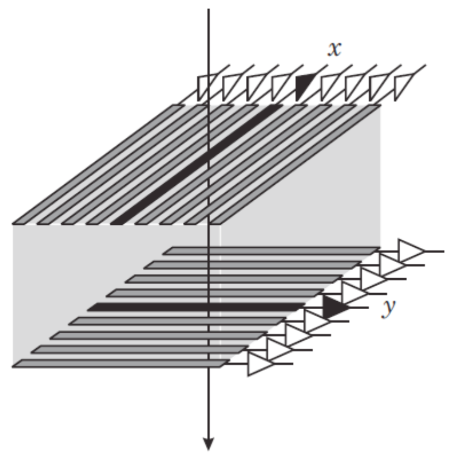
Analog to digital conversion of pulse height. Convenient format for data transmission.

Position resolution

Electrode segmentation allows position measurement.
Strip pitch p typically 25-100 μm

2d information
double sided detector

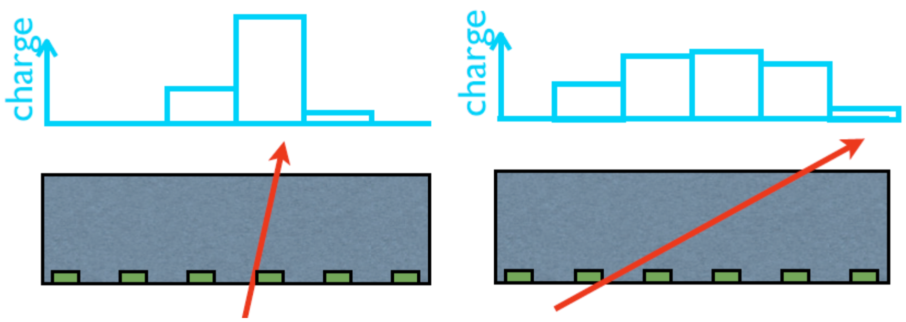




Cluster of adjacent strips above threshold

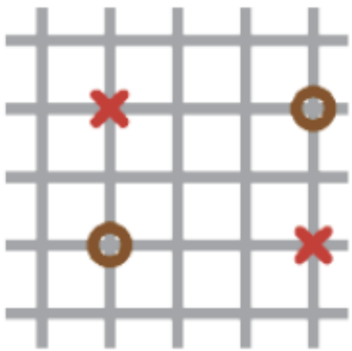
Cluster position from charge distribution

Better resolution than $\sigma = \dfrac{p}{\sqrt{12}}$

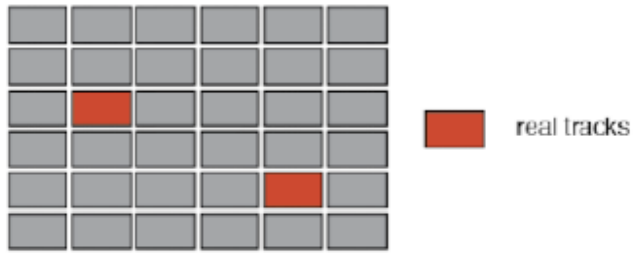


Sensor geometry: pixel vs strips

Pixel detectors produce unambiguous hits



crossed strips detector
n tracks generate
n^2-n ghost hits



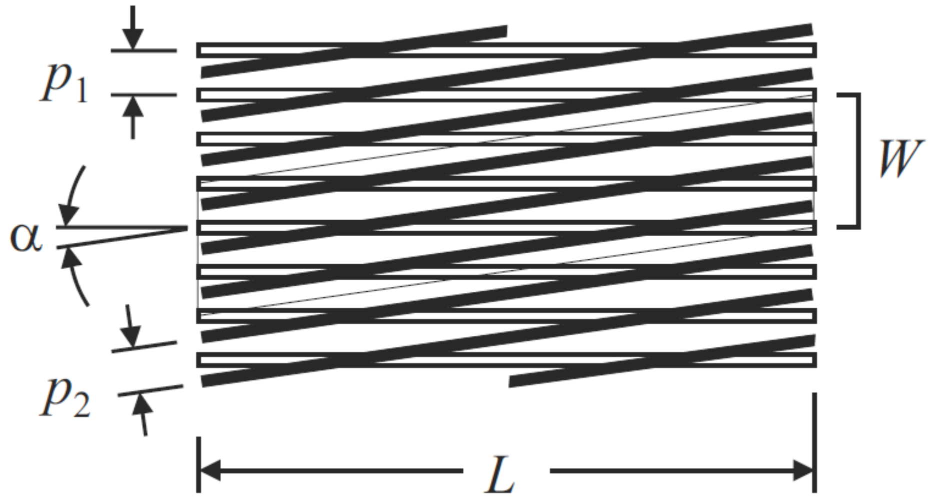
Pixel:

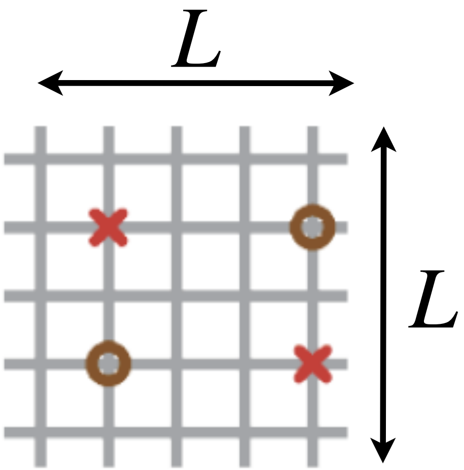
small pixel area ➞ low detector capacitance ➞ high signal/noise ratio

Large number of readout channels ➞ large power consumption, bandwidth, electrical connections

Ghost hits and small-stereo angle strips

Reduce probability of producing ghost hits at the expense of resolution in the longitudinal coordinate





$A \sim L^2$

$$W = L(p_2/p_1)\tan\alpha + p_2$$

$$A \approx L^2 \frac{p_2}{p_1} \tan\alpha + L p_2$$

A = area subjected to creation of ghost hits

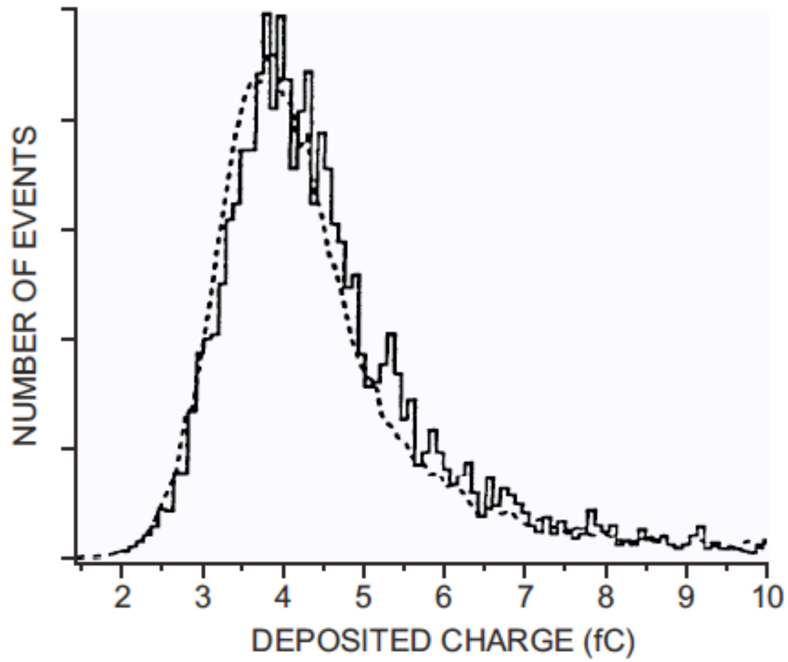
Energy resolution

Fano factor: multiple excitation mechanisms reduce the statistical spread (F=0.1 for Si)

Electron-holes pairs (E_i~eV) and lattice vibrations/phonons (E_i~meV)

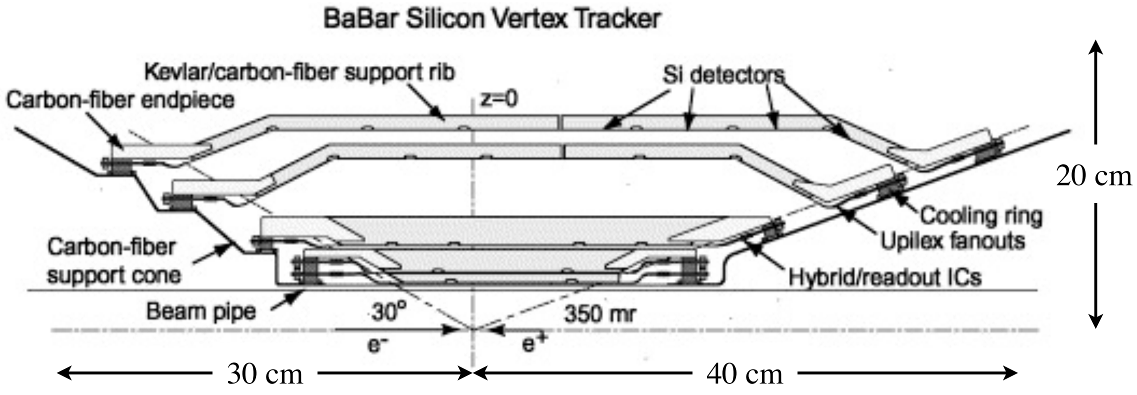
$$\frac{\Delta E}{E} = \frac{\Delta N}{N} = \frac{\sqrt{FN}}{N} \qquad N = \frac{E}{E_i}$$

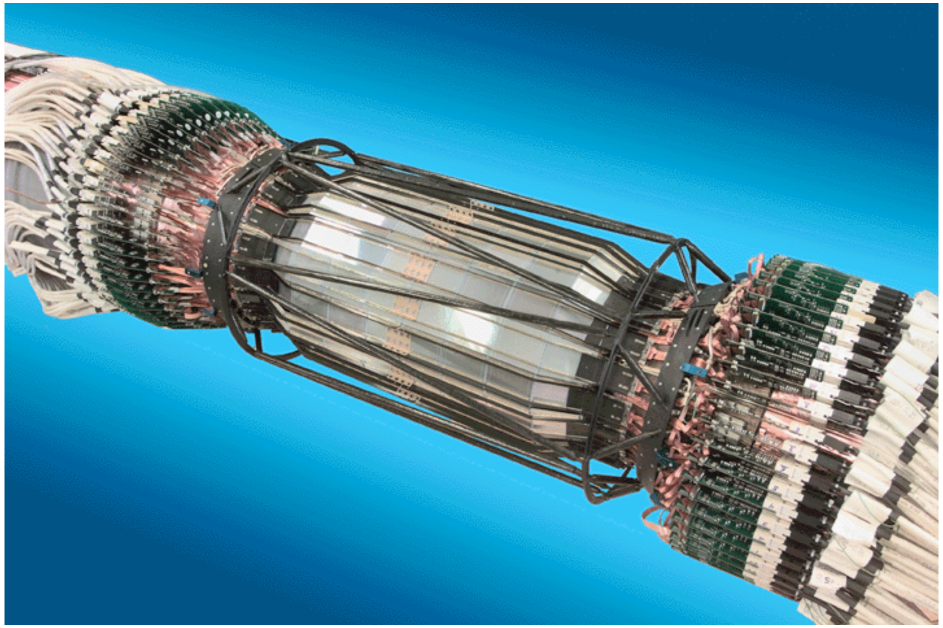
For MIPs, σ_Q/Q~0.2 in 300 μm of Si (Landau-Vavilov energy loss distribution). Inherent detector energy resolution is negligible



Measured energy loss distribution of 1.5 MeV/c electrons in a silicon detector and compared with the Landau-Vavilov calculation (dashed line)

Silicon Vertex Tracker (SVT) - BaBar





5 layers detector: independent tracker

Double-sided Si wafers, 300 μm thickness, ~1 m^2 Silicon

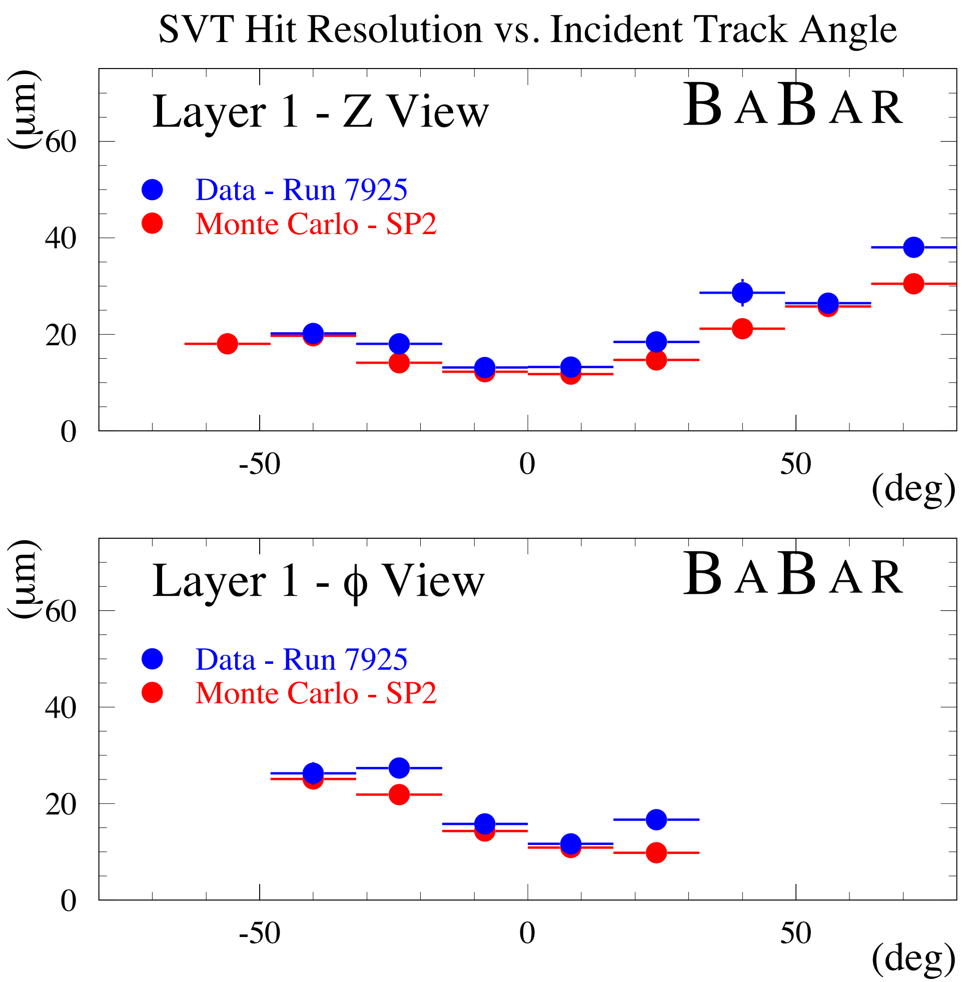
~90% geometrical acceptance in center-of-mass system

Material 4% x/X_0 total

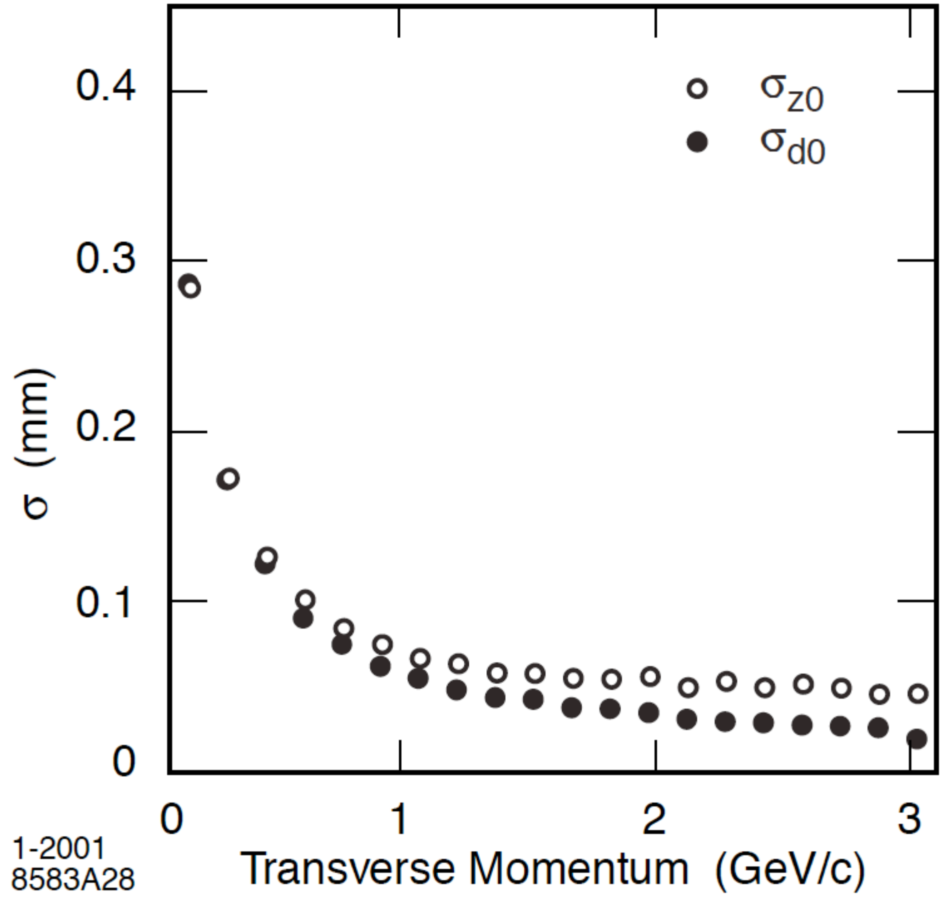
Hit resolution: ~10-15 μm inner layers

dE/dx resolution ~14%

SVT performance

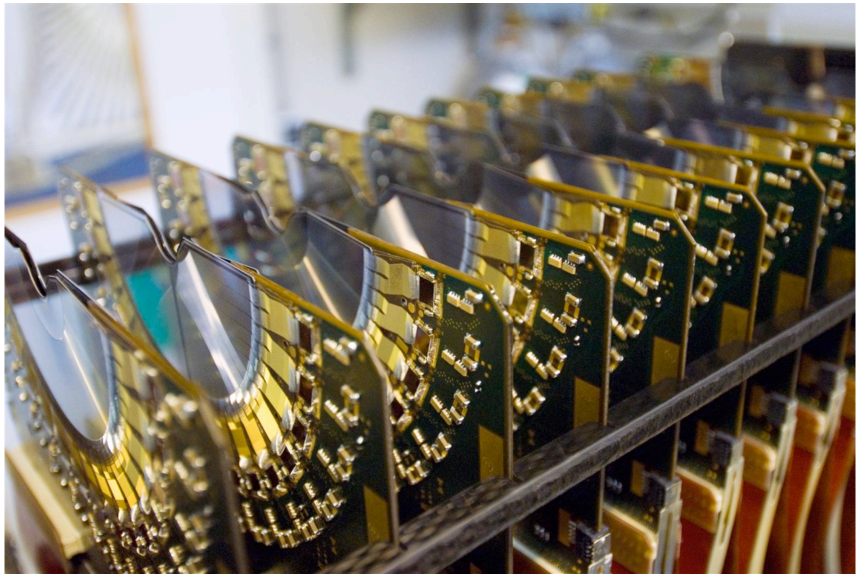


Position (Vertex) resolution

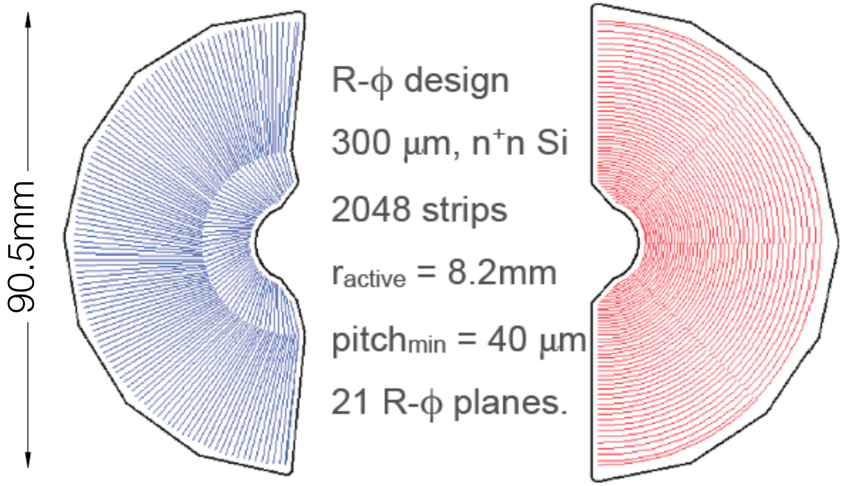


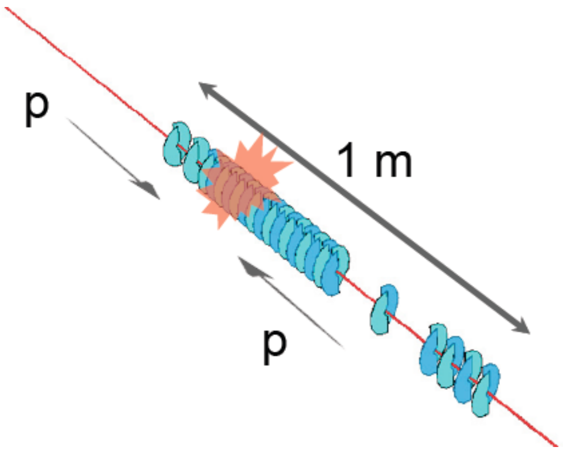
$$\sigma_{ms} \propto \frac{\sqrt{\frac{x}{X_0}}}{p} \qquad \sigma_{pos} \propto R \cdot \sigma_{ms}$$

Vertex Locator (VELO) - LHCb



Semicircular silicon strip detector



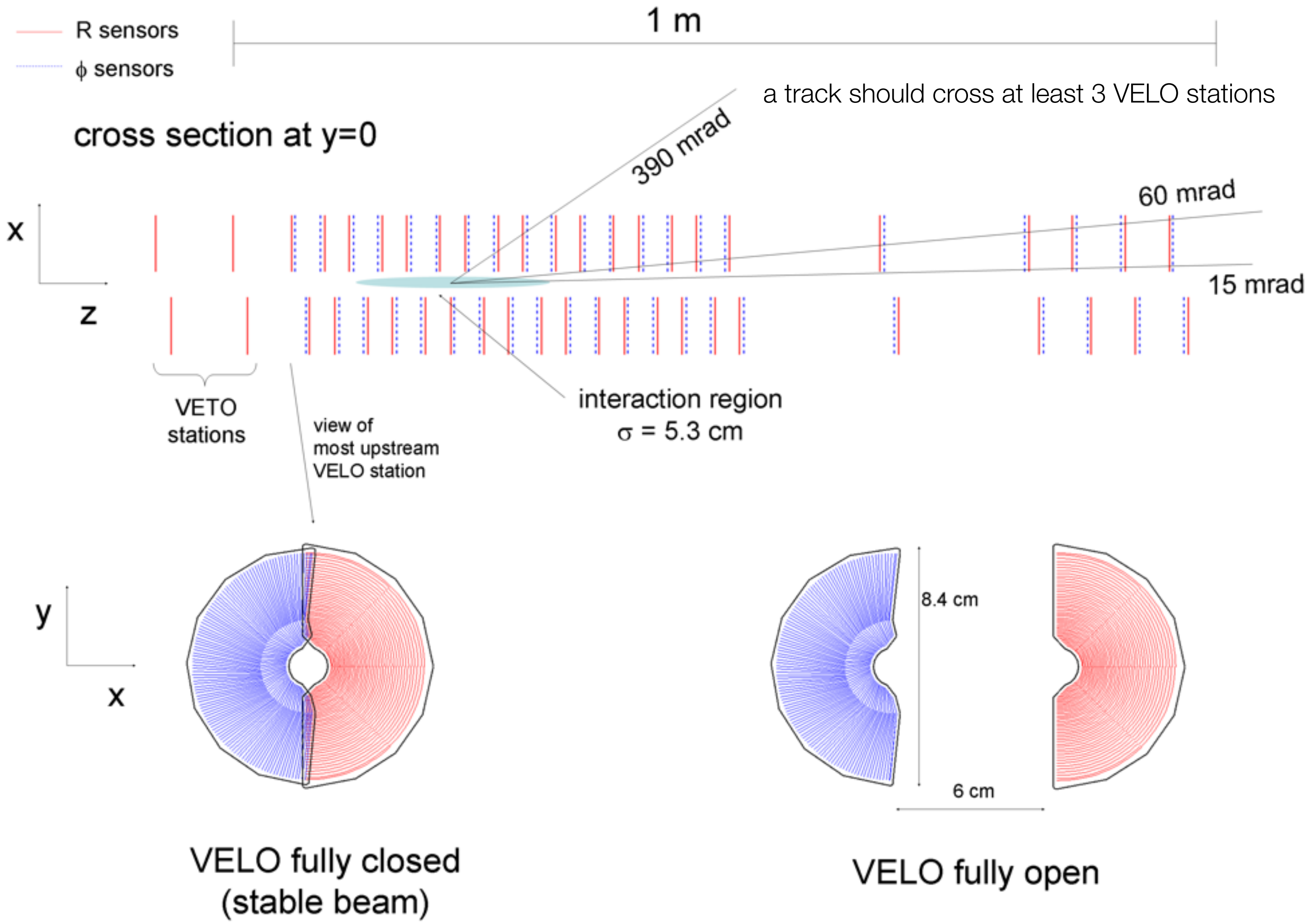


Vertex detector has silicon microstrips with rϕ geometry approaches to 8 mm from beam (inside complex secondary vacuum system)

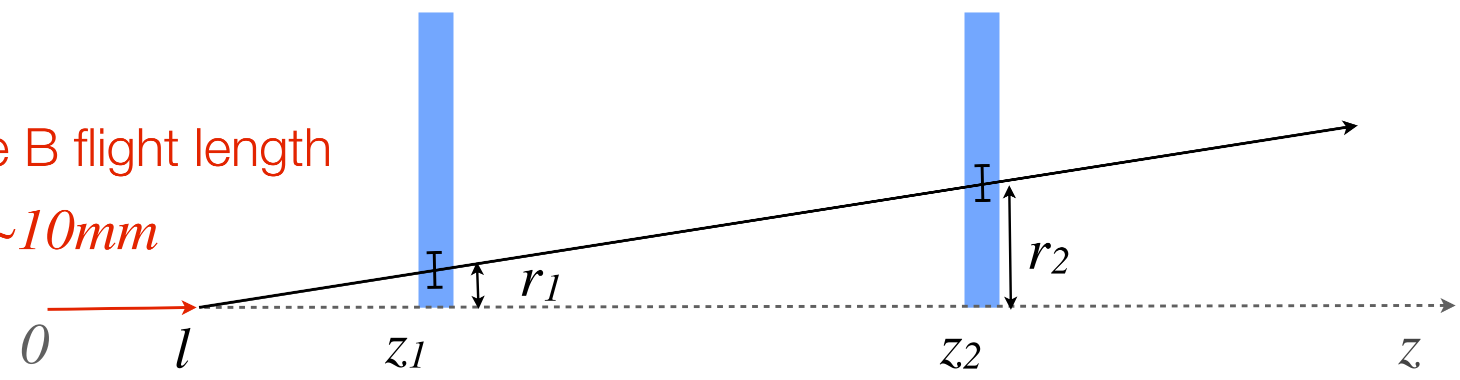
The VELO sits back ~3cm from the beam line if there are no stable beams

Performance: 30 μm impact parameter resolution for high momentum tracks and 40 fs proper time resolution for B mesons

VELO Geometry



B proper time resolution - simple calculation



$\left[p_t/p_z = (r_2 - r_1)/(z_2 - z_1)\right]$

$$l = \frac{r_1 z_2 - r_2 z_1}{r_2 - r_1} \qquad \sigma_l^2 \sim (r_2^2\sigma_{r_1}^2 + r_1^2\sigma_{r_2}^2)\frac{(z_1-z_2)^2}{(r_1-r_2)^4} = (r_2^2\sigma_{r_1}^2 + r_1^2\sigma_{r_2}^2)\frac{(p_z/p_t)^4}{(z_1-z_2)^2}$$

Using typical values: z_2-z_1~ 0.5m; p_t=2.5 GeV/c; p_z~50 GeV/c; r_2~3cm; σ_r~15μm and assuming a two body decay (two tracks)

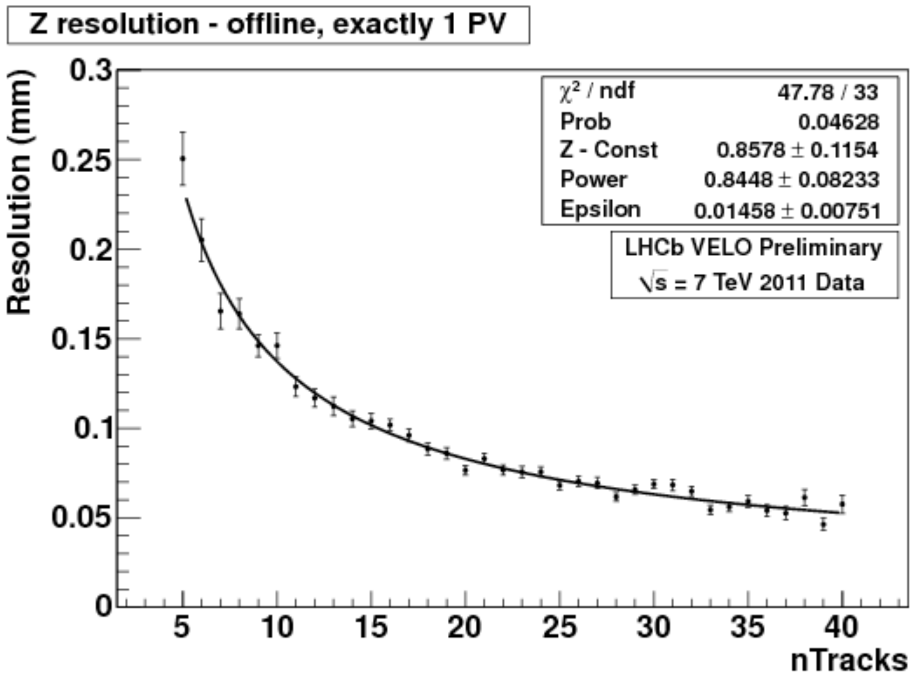
$$\sigma_l \sim 360\mu m \rightarrow \sigma_l/\sqrt{2} \sim 250\mu m$$

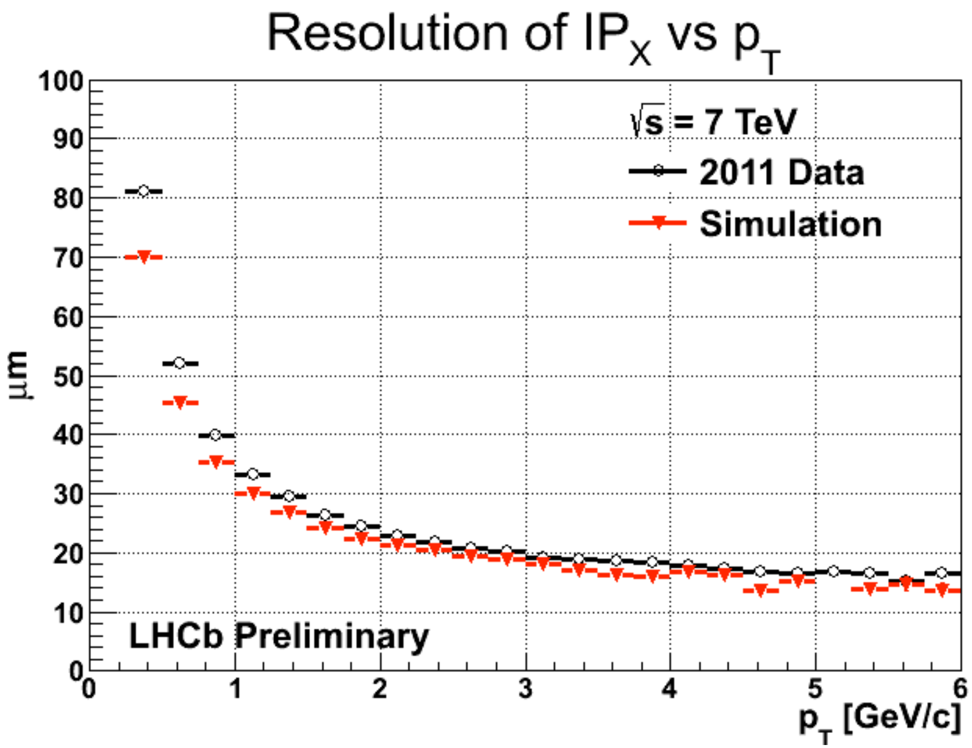
1 track 2 tracks

$$\sigma_l/l = \sigma_\tau/\tau \sim 2.5\% \rightarrow \sigma_\tau \sim 40\text{fs} \quad (\tau \sim 1.5\text{ps})$$

Not accounted for multiple scattering and uncertainty on primary vertex

VELO performance





Exercises

1. Why $E_{e/h}$=3.6eV while E_{gap}~1.1eV for Silicon?
2. Plot diode capacitance as a function of reverse bias voltage ($1/C^2$ vs V)
3. What happens if a silicon detector is not fully depleted? Does it still work? What about signal over noise ratio?
4. Which is the spatial resolution for a silicon strip detector with 50μm pitch and no charge sharing among different electrodes?
5. A strip detector ($5x5cm^2$) with 50μm pitch has occupancy 10% (number of strips fired over total number of strips). What would be the occupancy for a pixel detector with cell $50x50\ \mu m^2$?
6. Can you estimate the improvement on the position (track impact parameter) resolution if the inner radius of the SVT would be reduced from 3 cm to 1.5 cm? What would be the drawbacks?

Questions received by students

1. Why the noise for the preamplifier is proportional to C_{in}?
2. Why S/N improves when transforming the fast detector signal to a broader signal with peaking time T_p? How does S/N depend on T_p?
3. Provide a simple explanation for the Fano factor
4. Is the resolution on flight length independent of z_1 at LHCb?
5. Germanium detectors can be used for tracking?
6. Can you detect τ^+ as a particle (energy loss) in a detector?
7. What is an “indirect bandgap” semiconductor?