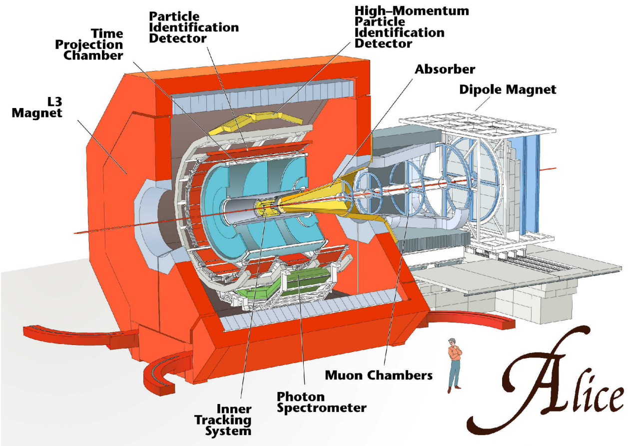

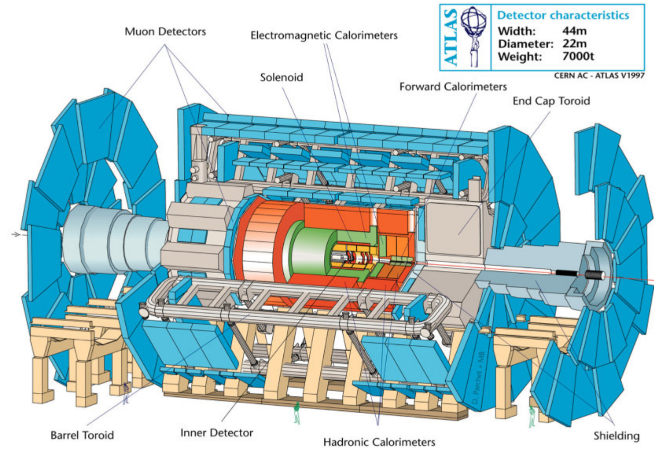

LHC Detectors and their Physics Potential

Nick Ellis

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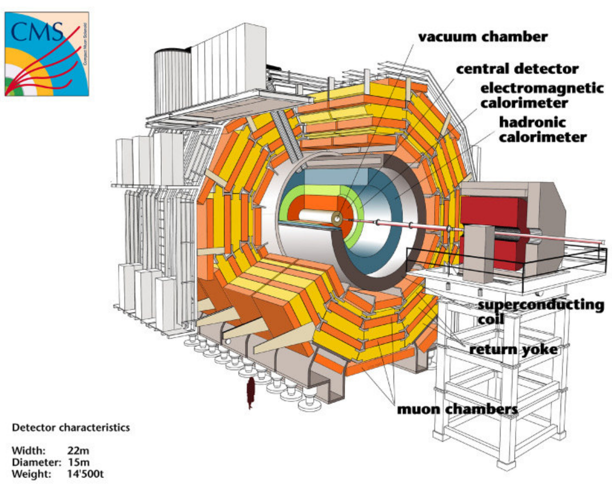
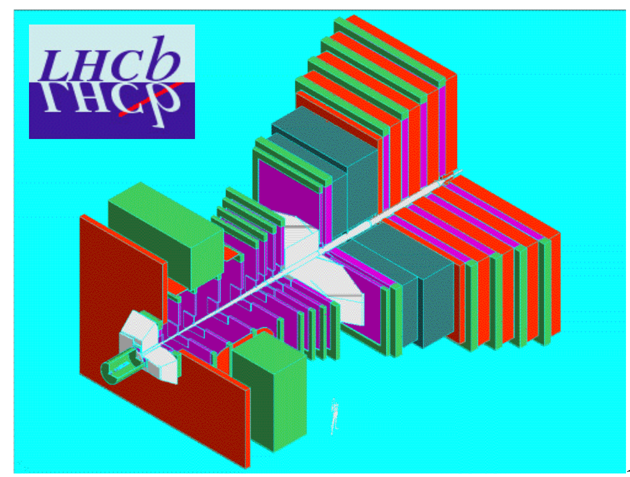




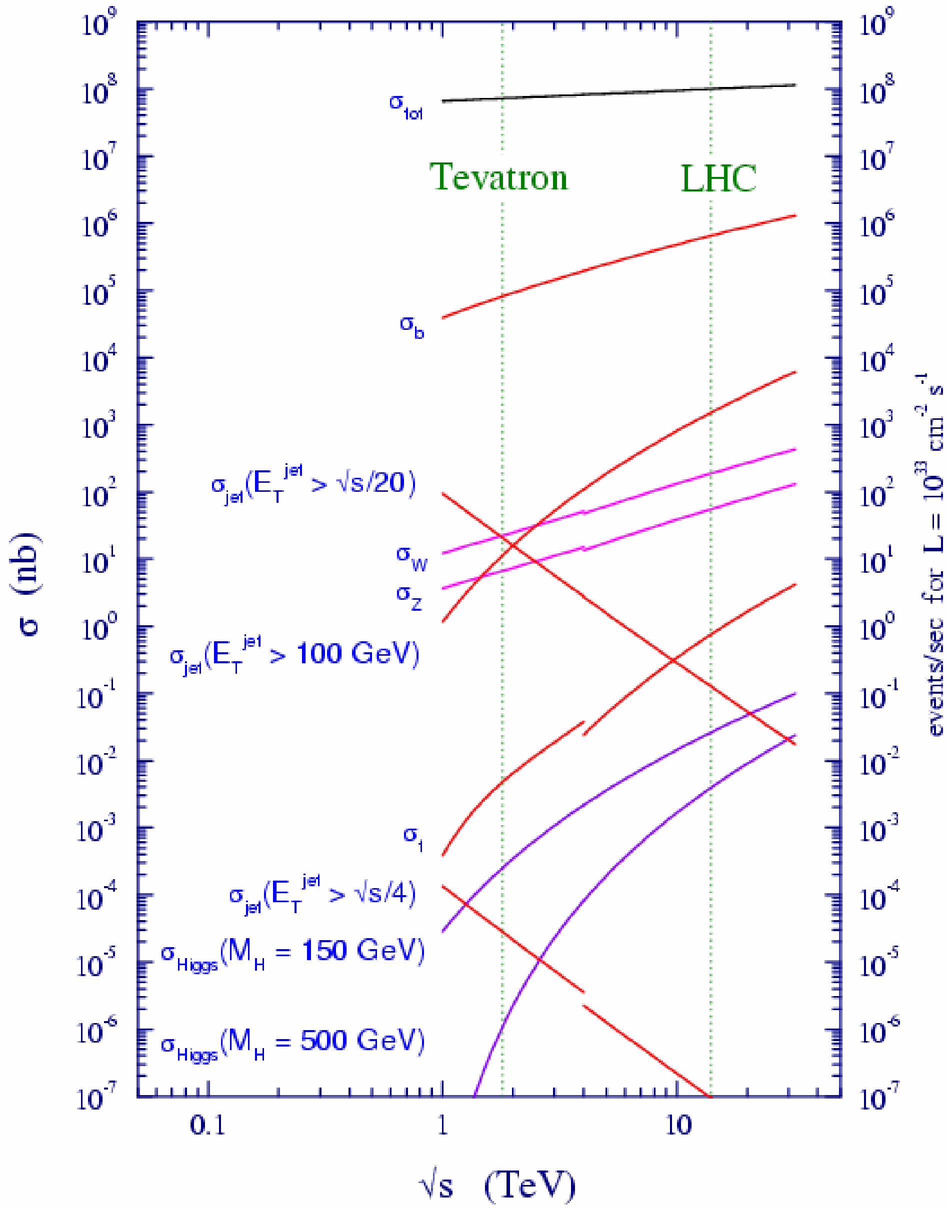
Part 1
Introduction to the LHC
Detector Requirements & Design Concepts

What is the Large Hadron Collider?

- Circular proton-proton collider under construction at CERN
  - Collide counter-rotating beams of protons head-on
    - Centre-of-mass energy
      $\sqrt{s} = 2\times E_{beam} \cong 2\times p_{beam}$
    - Compare to fixed-target
      $\sqrt{s} \cong \sqrt{(2\times m\times E_{beam})}$
      $m \cong 1$ GeV for proton target
- Will also operate some of the time with heavy-ion beams
  - e.g. Pb-Pb collisions
- First proton-proton collisions expected in Summer 2007

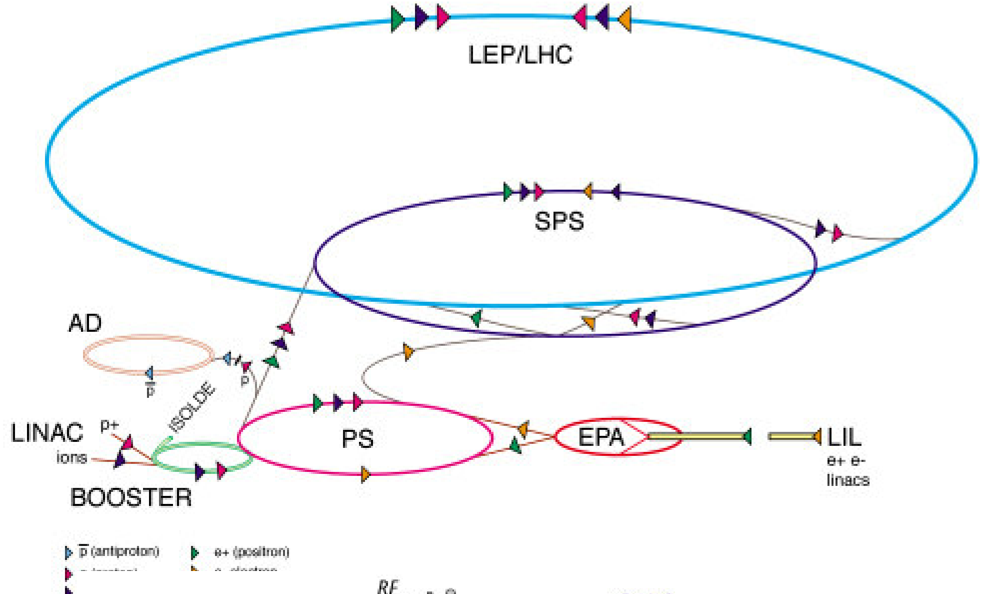
Energy and intensity

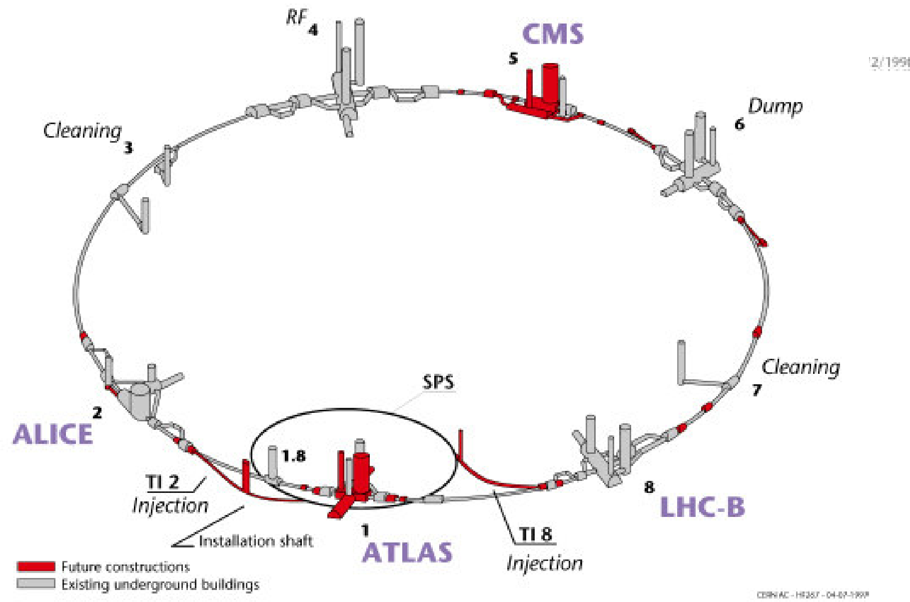
- Want very high ***energy*** and very high ***intensity*** to maximize the sensitivity to new physics
  - Energy needed to produce new massive particles such as the Higgs boson
  - Intensity needed because some of the processes that one would like to study are very rare (e.g. small σ.*B* for decay modes visible above background)



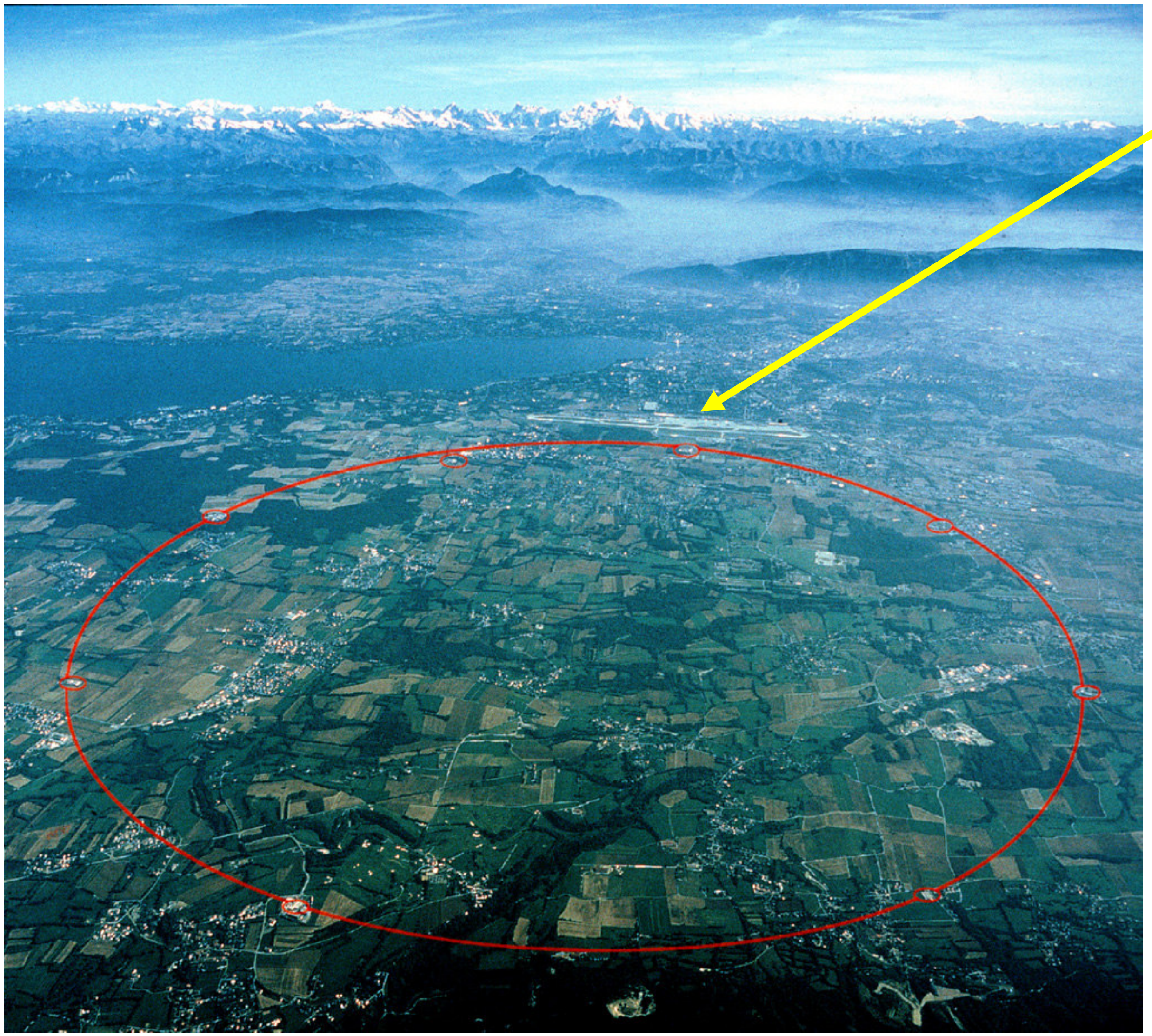
LHC uses existing CERN complex

- LHC is being built in the existing tunnel previously used for LEP
  - Circumference = 27 km
    - Radius = 4.3 km
- Use existing accelerators as injection system
- Four major “experiments”
  - ATLAS and CMS are “general-purpose” detectors optimised for exploring new physics in pp collisions
  - LHC*b* is a specialized detector optimised for B-physics studies
  - ALICE is a specialized detector optimised for heavy-ion physics





Path of the CERN LEP/LHC tunnel



Airport

Circumference of ring ~ 27 km

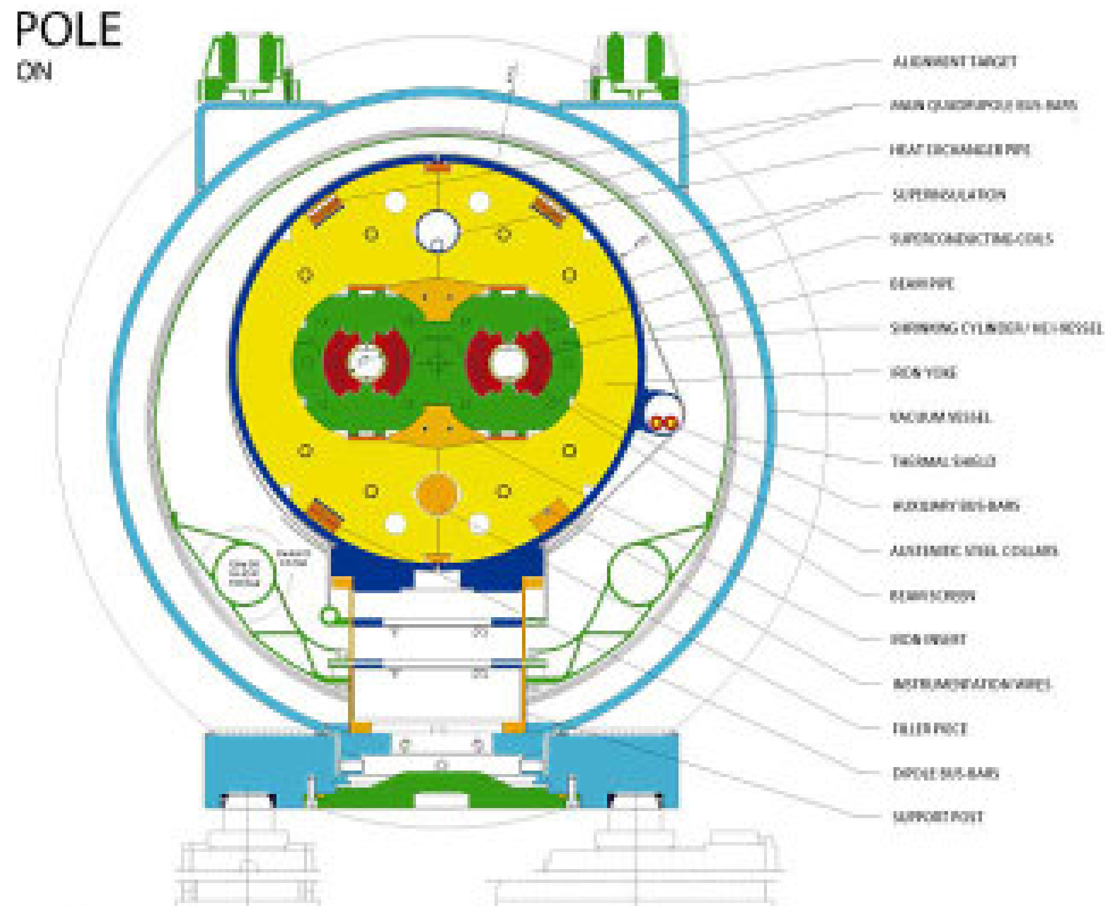
Illustration with ATLAS detector

Beam Energy

- Energy of protons is limited by the magnets that guide the beams on circular path
    - Beam energy ≅ momentum:
      $p = 0.3 \times B \times r$
      p = momentum [GeV],
      B = magnetic field [Tesla],
      r = radius [metres]
- Since the radius of the ring is fixed, one has to use very high-field magnets to reach high energy...
  - and fill as large a fraction as possible of the circumference with magnets
    - Achieve ~ 2/3 of ring with dipole magnets
    - Need other magnets for focusing, etc
    - Need straight sections for acceleration, detectors
    - Also require space for beam injection and ejection systems

Need very high-field "two-in-one" magnets

- Use 15-meter long super-conducting magnet coils cooled to 1.9 K with super-fluid Helium
  - Field > 8 Tesla
    - Compared to 4–5 Tesla at Tevatron and HERA
- Since LHC collides beams of protons (not proton-antiproton as at Tevatron), one needs double magnets
  - Note: Use two proton beams because antiprotons cannot be produced, accumulated and cooled in sufficient numbers to reach desired beam intensity

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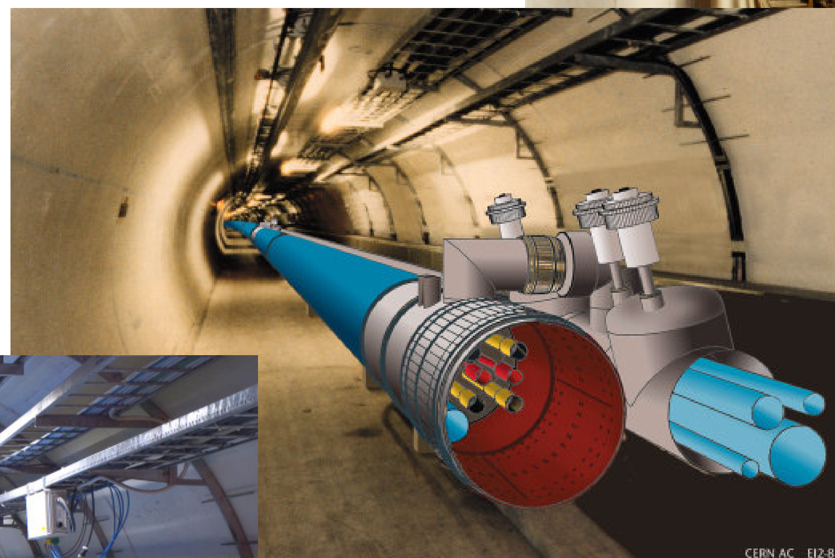

CERN AC _ EI2-8


Luminosity

- Want highest ***luminosity*** possible: *Rate* ≡ σ×*L*
  - Access to rare (i.e. low cross-section) processes

Bunch intensities

Number of bunches

Beam-beam offsets (horizontal & vertical)

$$\mathcal{L} = \frac{N_{b1}\, N_{b2}\, f_{rev}\, k_b}{2\pi\sqrt{(\sigma_{x_1}^2 + \sigma_{x_2}^2)(\sigma_{y_1}^2 + \sigma_{y_2}^2)}} \cdot \exp\left\{-\frac{(\overline{x}_1 - \overline{x}_2)^2}{2(\sigma_{x_1}^2 + \sigma_{x_2}^2)} - \frac{(\overline{y}_1 - \overline{y}_2)^2}{2(\sigma_{y_1}^2 + \sigma_{y_2}^2)}\right\}$$

Beam sizes at the IP (horizontal & vertical)

- Beam parameters at LHC
  - $N \cong 10^{11}$; σ ≅ 15 μm in ATLAS and CMS; $f = 11$ kHz; $k = 2808$

Some LHC parameters

- Centre-of-mass energy
  - $\sqrt{s}$ = 14 TeV for proton-proton collisions
    - c.f. 2 TeV at Tevatron collider
    - Equivalent to ~100,000 TeV or 10^{17} eV fixed-target beam energy
  - $\sqrt{s}$ = 6 TeV ***per nucleon*** for Pb-Pb collisions
- Luminosity
  - $L = 10^{34}$ $cm^{-2}s^{-1}$ for proton-proton collisions in ATLAS and CMS
    - c.f. $L = 10^{32}$ $cm^{-2}s^{-1}$ at Tevatron
  - $L = 10^{27}$ $cm^{-2}s^{-1}$ for Pb-Pb collisions (in ALICE and also ATLAS+CMS)
- Note: enormous energy stored in proton beams
  - 331 MJ/beam (enough to melt 500 kg of copper)!
    - Rely on safe ejection of beams into beam dumps at end of coast
    - Most of the protons used up in beam-beam collisions in experimental areas

More LHC parameters

- Protons circulate in bunches (i.e. not continuous beam)
  - Bunch spacing is 25 ns in time (i.e. 7.5 meters in distance)
    - Bunch-crossing rate is 40 MHz
- Total proton-proton cross-section $\sigma \sim 100$ mb
  - Interaction rate at $L = 10^{34}$ cm^{-2}s^{-1} is $R \sim 10^9$ Hz
    - On average ~ 25 interactions per bunch crossing
      - Background activity that complicates analysis of what happened in the interaction of interest
  - LHC*b* uses $L = 2\times10^{32}$ cm^{-2}s^{-1} to maximize rate of single-interaction bunch crossings
    - Different focussing of beams to ATLAS and CMS
  - Rate much lower for heavy-ion case
    - $R \sim 10^4$ Hz for Pb-Pb (low luminosity)
      - Much less than bunch-crossing rate (BC period = 125 ns for Pb ions)

Luminosity for LHC*b* $L = 2\times10^{32}$ cm^{-2}s^{-1}

- LHC*b* can operate concurrently with ATLAS and CMS
  - Different "optics" – less focussed beams – larger σ

$$\mathcal{L} = \frac{N_{b1}\, N_{b2}\, f_{rev}\, k_b}{2\pi\sqrt{(\sigma^2_{x_1}+\sigma^2_{x_2})(\sigma^2_{y_1}+\sigma^2_{y_2})}} \cdot \exp\left\{-\frac{(\overline{x}_1-\overline{x}_2)^2}{2(\sigma^2_{x_1}+\sigma^2_{x_2})} - \frac{(\overline{y}_1-\overline{y}_2)^2}{2(\sigma^2_{y_1}+\sigma^2_{y_2})}\right\}$$

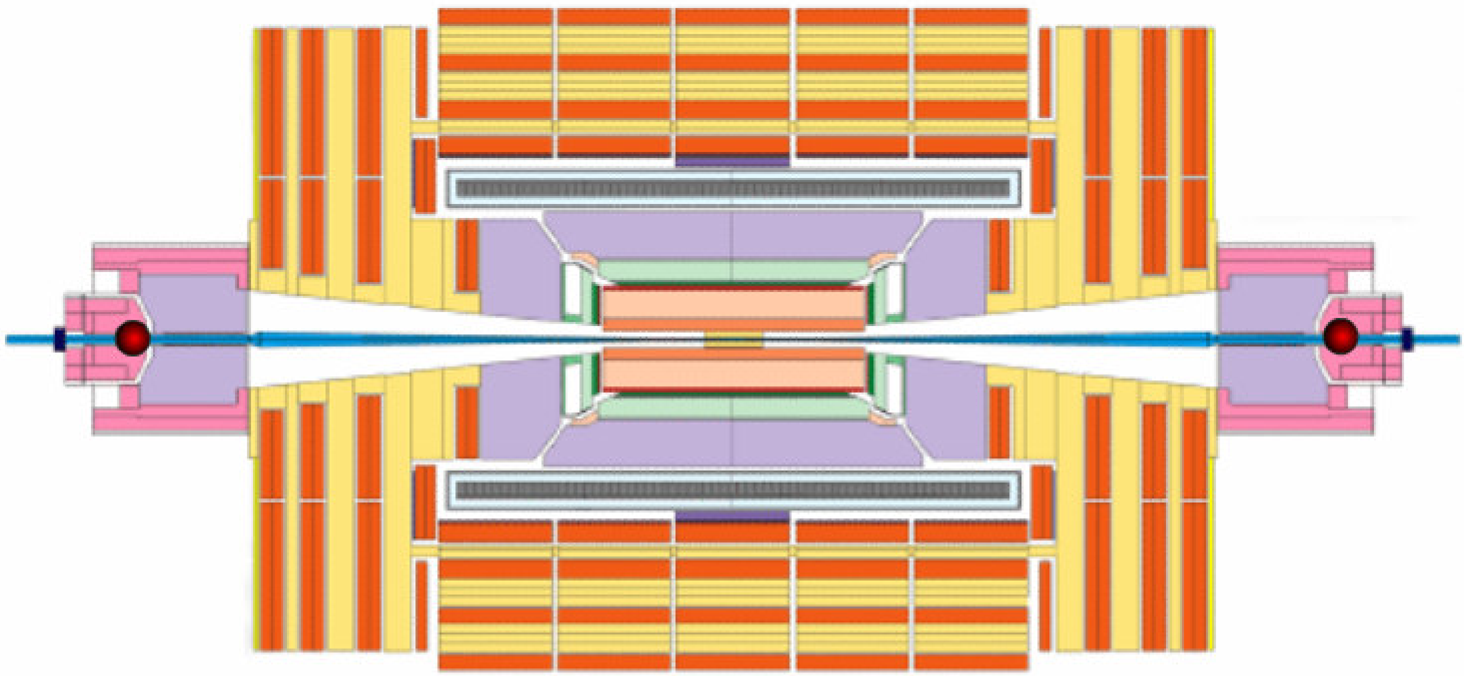
Bunch intensities

Number of bunches

Beam-beam offsets (horizontal & vertical)

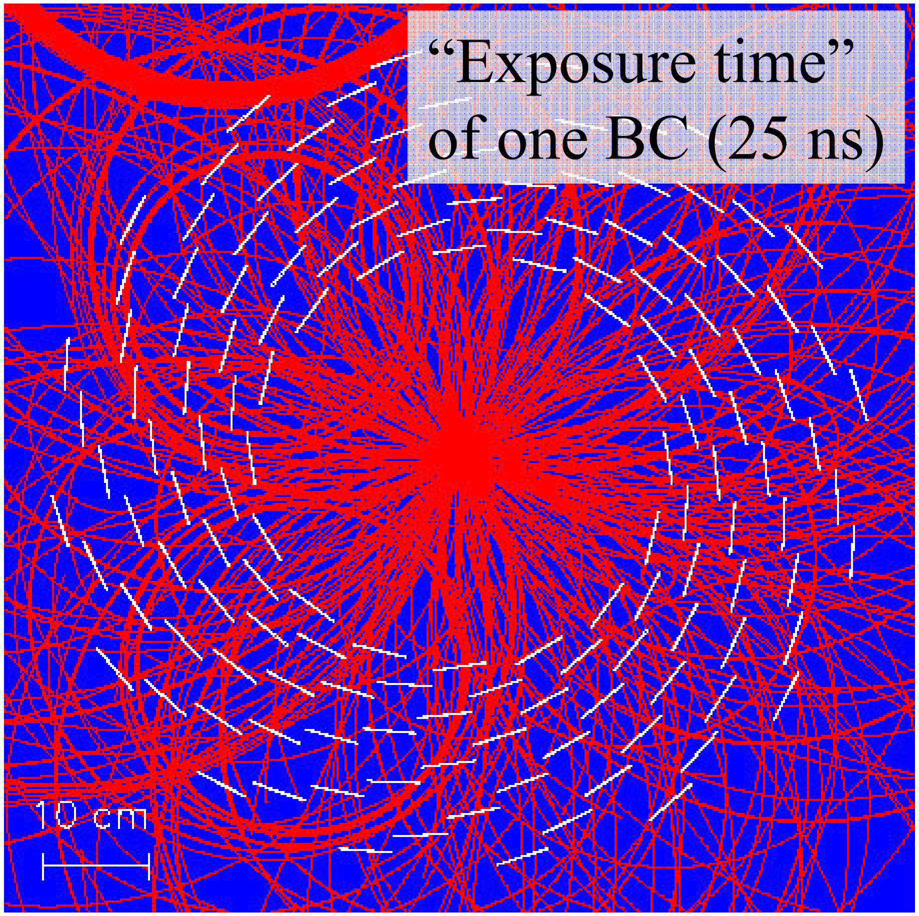
Beam sizes at the IP (horizontal & vertical)

Illustration with CMS detector



Multiple interactions per BC = “pile-up” Has strong impact on detector designs

18 superimposed pp collisions,
as seen by internal part of CMS silicon central tracker.
Among them 4 muons from a higgs decay.



- Need detectors with fast time response ~ “exposure time”
  - Pile up in a single bunch crossing already presents a challenge!
  - Except in the case of ALICE where the rate of heavy-ion collisions is much less than the bunch-crossing frequency
- Need fine detector granularity to be able to reconstruct the “event”
  - Minimize the probability of pile-up in the same detector element as an interesting object
    - E.g. probability for energy from the “pile-up” interactions being deposited in the calorimeter cell hit by a photon in an $H \rightarrow \gamma\gamma$ decay

Physics Objectives (ATLAS and CMS)

(see lectures of Michelangelo)

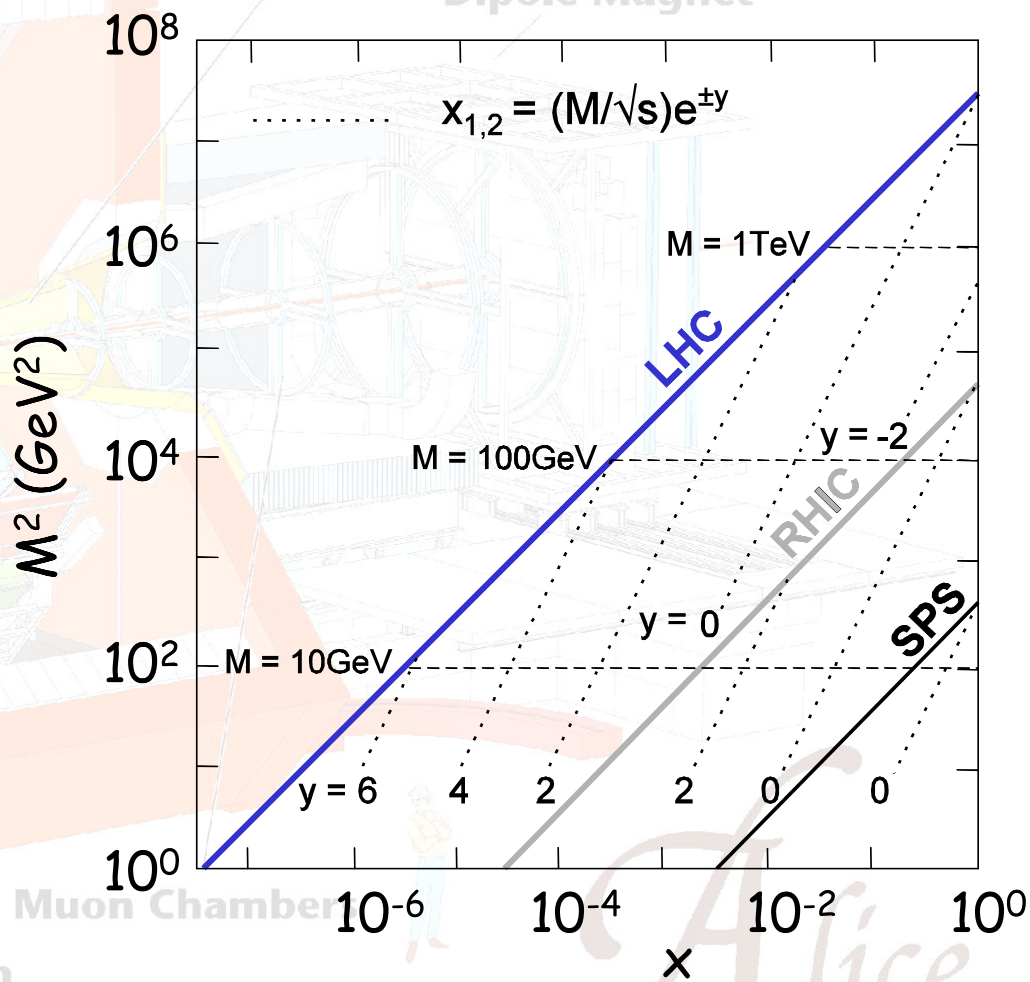
- Search for and study of new physics in ATLAS and CMS
  - Origin of electro-weak symmetry breaking (m_W and m_Z)
    - Higgs boson (or bosons)
    - Alternative schemes
  - SUSY
    - squark and gluinos have large cross sections
  - Compositeness
  - Leptoquarks
  - W' and Z'
  - Extra dimensions
    - KK excitations, black holes
  - ***The unpredicted!***
    - Very important to be open to this in our event selection and analysis
      - LHC has an order of magnitude more centre-of-mass energy and two orders of magnitude more luminosity compared to today's most powerful machine

Physics Objectives (ATLAS and CMS)

- Standard Model production processes
  - W, Z, direct-photon production
  - Jet production (including multi-jet production)
  - Interesting in their own right
  - Must be understood as backgrounds to new physics
  - Can be done with comparatively very little integrated luminosity
    - It will take some time before the LHC is tuned to reach its full luminosity
- Precision measurements
  - W mass and top mass
    - Important for consistency checks with Higgs studies

Physics Objectives (ALICE)

- Heavy-ion programme
  - Heavy-ion collisions will produce extremely high energy density
    - Search for evidence of quark-gluon plasma using simultaneous signatures
  - ALICE experiment is dedicated to this activity
    - ATLAS and CMS will also contribute in a few areas



Physics Objectives (LHC*b*)

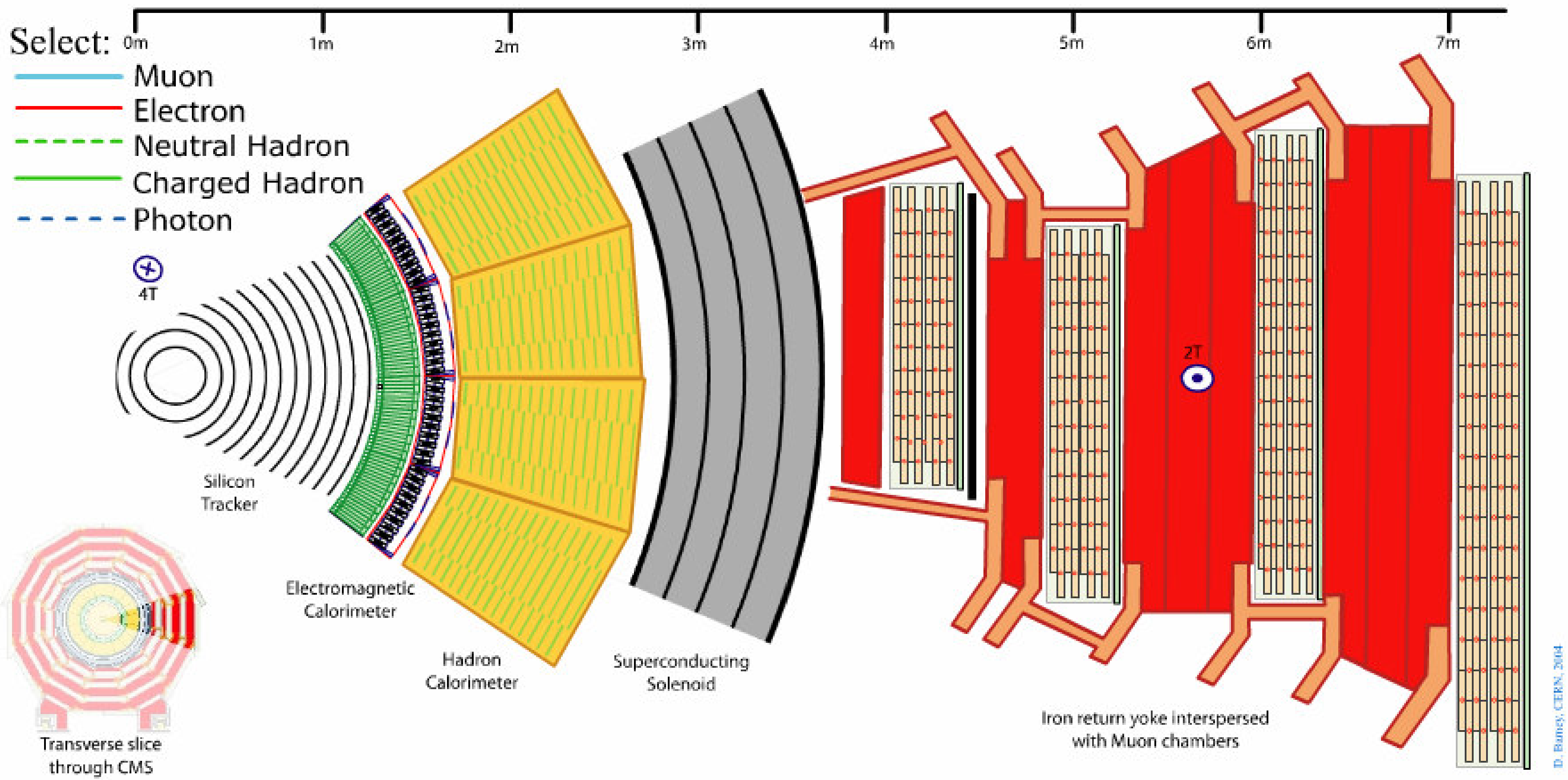
- LHC*b* aims to perform a broad programme of B-physics studies
  - ATLAS and CMS will also contribute significantly in some areas, although this is not their top priority and the detectors are not optimised for these studies
- *CP* violation in many channels with very high statistics
  - Extend precision beyond e^+e^- B factories
  - Including B_s decays
- B_s mesons
  - Precise measurement of oscillation period and lifetime difference between mass eigenstates
- Measurements of rare decays
  - Provide indirect tests on physics beyond the Standard Model

What do we actually measure?

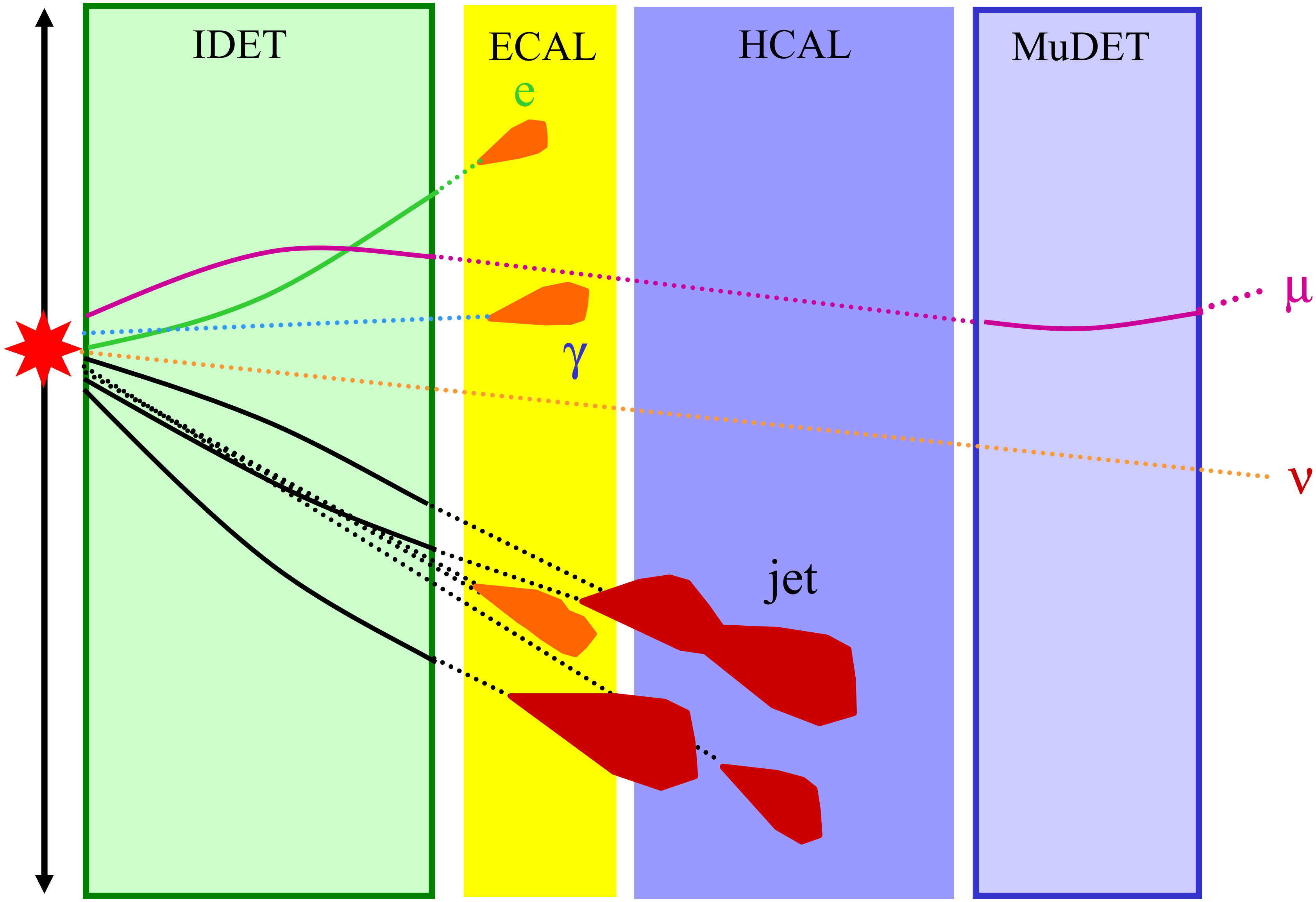
- The detectors give information on comparatively long-lived particles that are generally the decay products of the fundamental objects that we wish to study
  - We do not directly "see":
    - Up, down, charm, strange and beauty quarks, and gluons (that manifest themselves as jets of hadrons)
    - Top quarks that decay rapidly (e.g. $t \to bW$)
    - W and Z bosons that decay rapidly to quarks or leptons
    - Higgs bosons
    - Etc
  - We do "see" somewhat more directly:
    - Electrons
    - Muons
    - Photons
    - Long-lived charged and neutral hadrons (which may form jets)
    - Missing transverse momentum (e.g. due to high transverse momentum neutrinos)

Generic concept of detector

- Collisions take place in centre of detector
  - Collision products move outwards from the centre
- Trajectories of charged particles are measured
  - Solenoid magnetic field, so particles follow helical paths
    - $p = 0.3 \times B \times r \times Q$ used to determine momentum from radius of curvature (assuming charge $Q = 1$)
- Calorimeters measure energy deposited by electrons, photons, and hadrons
  - Calorimeters are sufficiently thick that almost all energy is absorbed, apart from muons (only minimally ionising) and neutrinos [and possibly other particles beyond those of the Standard Model]
- Trajectories of remaining charged particles (= muons) are measured
  - Provides muon identification and additional information on momentum


Select:
0m
1m
2m
3m
4m
5m
6m
7m
Muon
Electron
Neutral Hadron
Charged Hadron
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D. Barney, CERN, 2004

Generic detector (simplified)

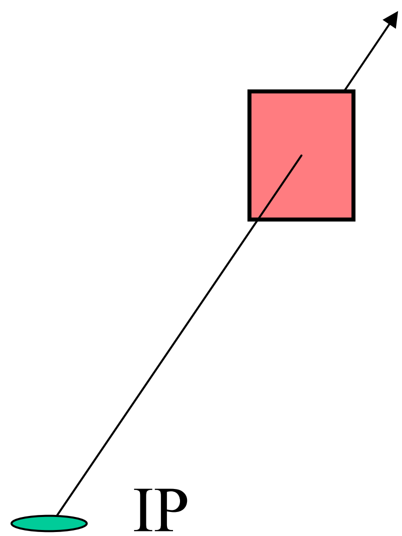


Additional information

- The inner tracking detectors may provide additional information for particle identification
  - Hadron identification by Cerenkov or time-of-flight techniques
    - Important in LHC*b*, e.g. for K/π separation in B decays
    - Important in ALICE, e.g. for strangeness-enhancement studies
  - Electron identification via transition-radiation signature
    - Used in ATLAS to enhance purity of electron selection
  - Particle identification from ionisation (d*E*/d*x*) measurements
- Reconstructed tracks can be extrapolated to search for primary and secondary vertices
  - Determine time of decay of short-lived particles
    - Important for B-physics studies (e.g. time-dependent *CP* violation)
  - Separate b-quark jets from light-quark and gluon jets
    - Important in top and Higgs physics studies

Particle identification: Time of Flight

- Charged particles can be identified from their mass that can be determined by measuring their velocity in addition to their momentum
- A rather direct way to measure velocity is to measure the time taken by the particles to move between two points



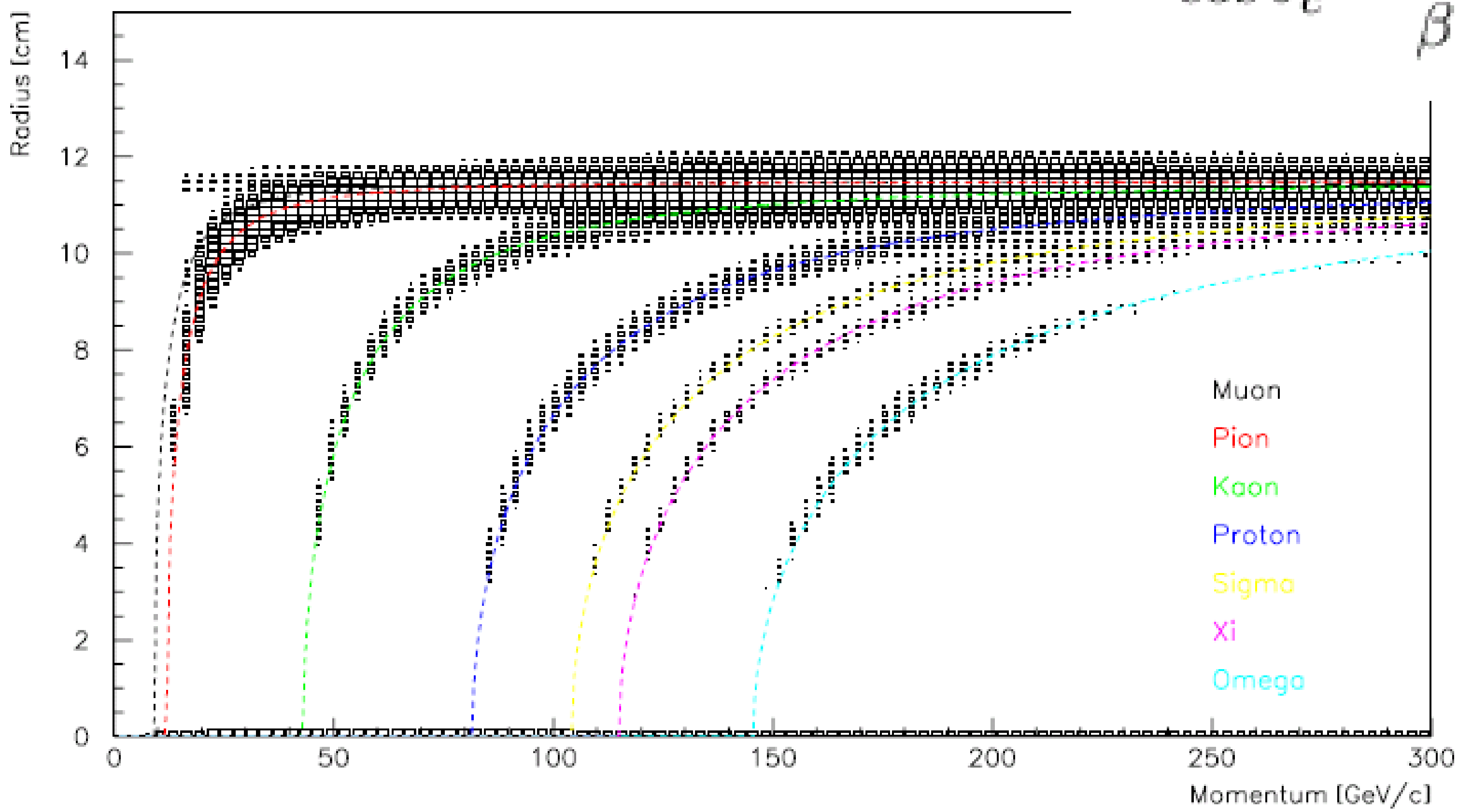
E.g. multi-gap RPC detectors

Technique used in ALICE

Particle identification: Cerenkov light

- Charged particles that traverse a medium with a velocity higher than the speed of light in that medium radiate Cerenkov light
  - Determine velocity from Cerenkov angle
  - Technique used in ALICE and in LHC*b*

$$\cos\theta_c = \frac{1}{\beta n} = \frac{1}{\frac{v}{c} n}$$



Particle identification: Transition Radiation

- When an ultra-relativistic charged particle (i.e. electron with $\beta\gamma > 1000$) traverses boundaries between materials of different refractive indices, they emit transition radiation
- The TR X-rays can be detected and used to identify electrons
- This technique is used in ALICE and ATLAS

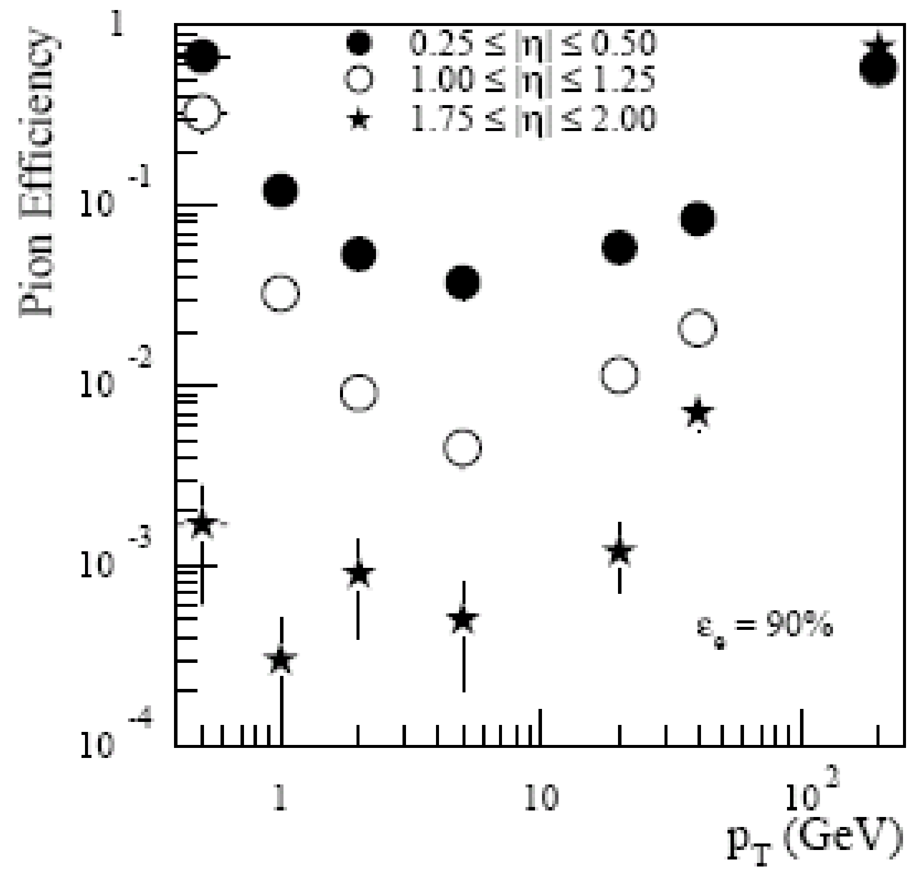
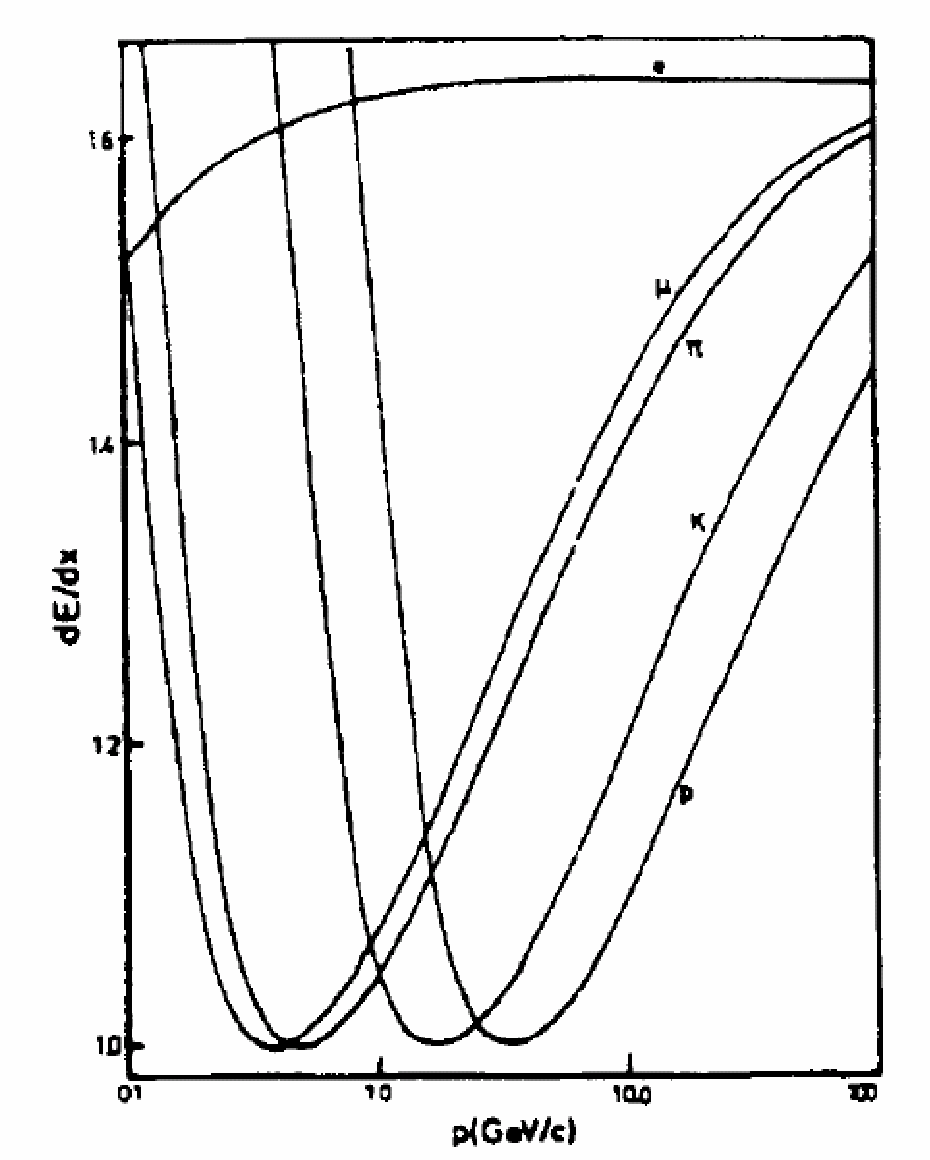


Figure 3-25 Pion efficiency as a function of p_T in various pseudorapidity intervals for 90% electron efficiency.

Particle identification: *d*E/d*x*



Definition of term "event"

- In high-energy particle colliders (Tevatron, HERA, LEP, LHC), the particles in the counter-rotating beams are bunched
  - Bunches cross at regular intervals
    - Interactions only occur during the bunch-crossings
  - The "trigger" (an on-line system of electronics and computers – see later) has the job of selecting the bunch-crossings potentially of interest for physics analysis, i.e. those containing interactions of interest
- I will use the term "event" to refer to the record of all the products of a given bunch-crossing (plus any activity from other bunch-crossings that gets recorded along with this)
  - Be aware (beware!): the term "event" is not uniquely defined!
    - Some people use the term "event" for the products of a single interaction between the incident particles
      - People sometimes unwittingly use "event" interchangeably to mean different things!

Transverse momentum and pseudo-rapidity

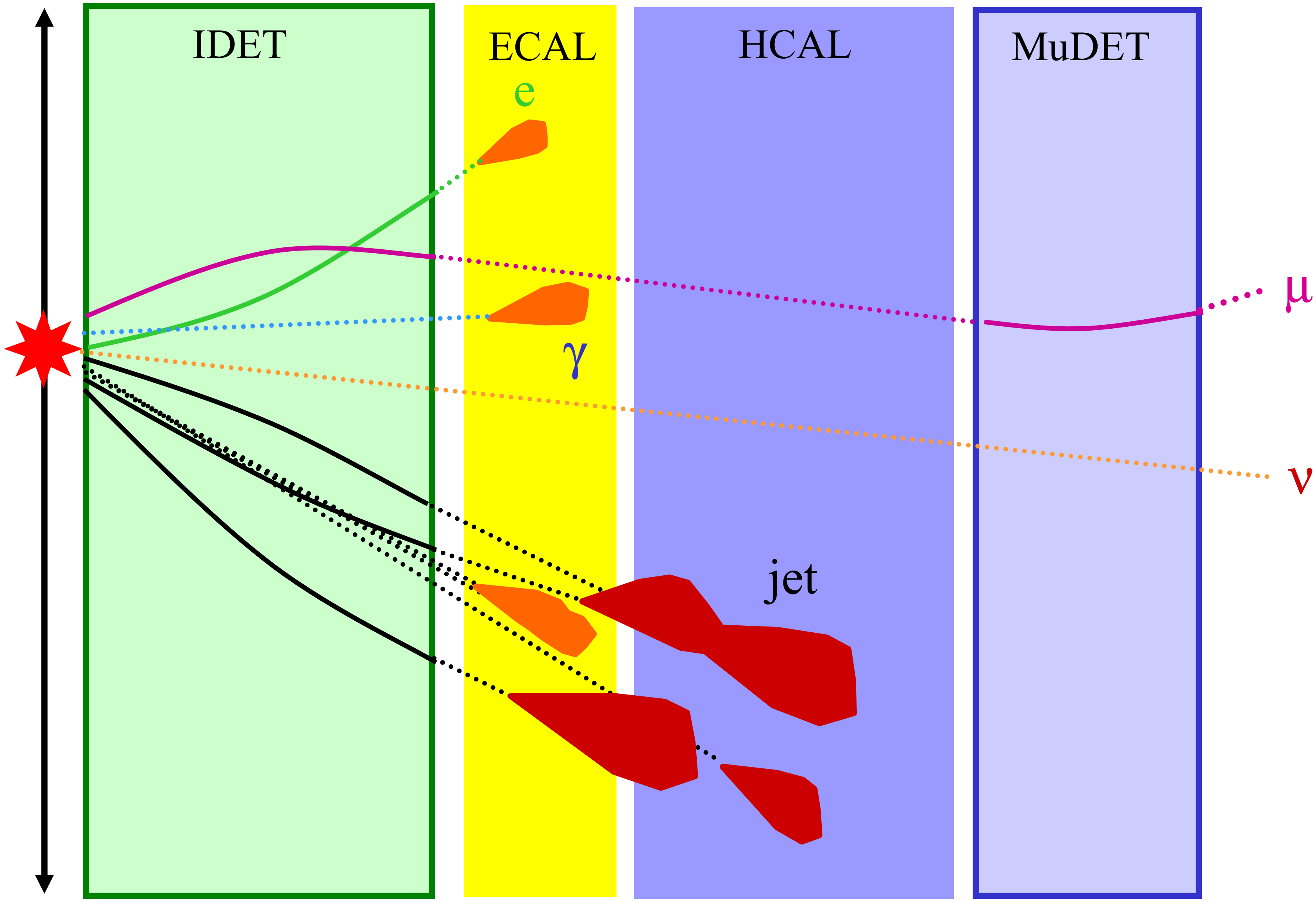
- Very often use transverse momentum (p_T) and pseudo-rapidity (η) as variables in hadron-collider physics
  - p_T is momentum transverse to the ***beam*** direction
    - Not same definition as in e^+e^- experiments

  $\eta \equiv -\,ln(\tan(\theta/2)) \cong y \equiv ½\, ln((E+p_z)/(E-p_z))$
    - In central region, hadron η distribution is approximately flat at fixed p_T
- Considering particle distribution in polar angle θ, there is a high concentration of high-momentum (but low- p_T) particles at small angles relative to the two proton beams
  - The high flux of particles originating from proton-proton collisions creates a challenging radiation environment for detectors and electronics
    - Radiation-resistant detectors
    - Radiation-hard (or tolerant) electronics
    - Need to consider "noise" signals induced in detectors by the radiation as well as conventional noise signals

How do we reconstruct an "event"...

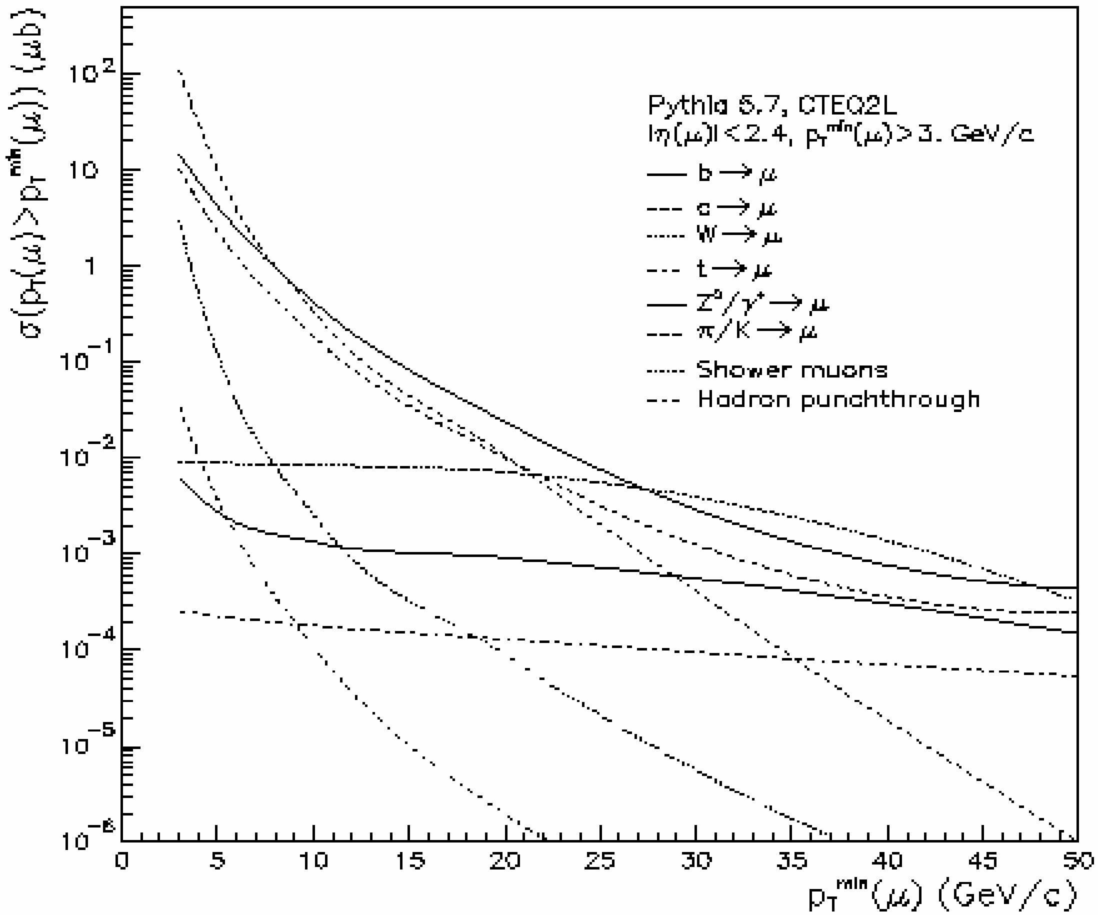
- Start with signals seen in the detectors
  - Points in space along charged particle trajectories
  - Energies measured in calorimeter cells
  - Signals from particle-identification detectors
- Reconstruct quantities more closely related to particles
  - Parametrize trajectory of charged-particle "tracks" in the inner tracking detectors and in the external muon detectors
    - Position and direction at some "start point"; radius of curvature
      - Infer charge sign and momentum (assuming $|Q| = 1$)
  - Parametrize energy deposits in the calorimeters in terms of "clusters"
    - Energy
    - Longitudinal and lateral shape
      - Can (e.g.) test consistency with shower from isolated electron or photon
    - Direction of energy flow

Generic detector (simplified)



Reconstruction of muons

- Combine information from muon detection system and the inner tracking detectors to get information on muon candidates
  - Muon charge sign and momentum vector at a given point in space
- Know with some confidence that this is really a muon, but there are backgrounds at some level
  - E.g. decays in flight of charged pions and kaons (π→μν, K→μν)
- Small probability to match the wrong inner-detector track to the muon-spectrometer track
  - Very small probability for fake muon-spectrometer tracks due to spurious hits

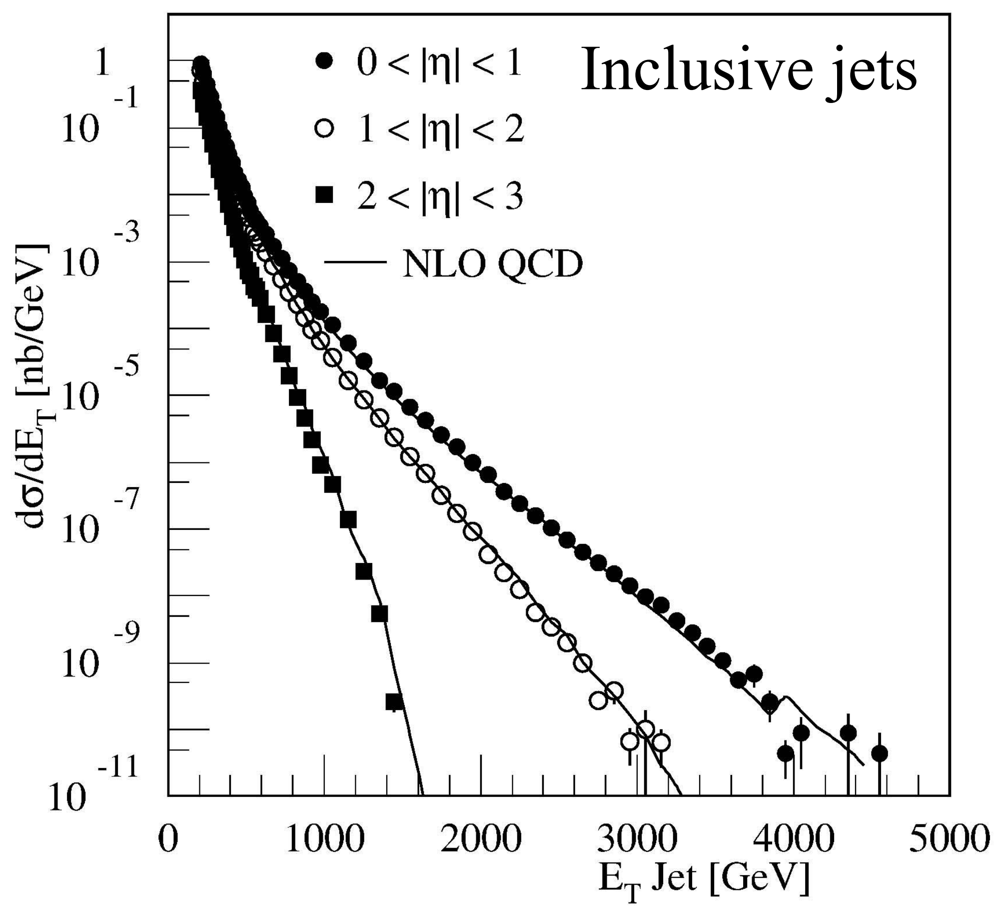


Reconstruction of electrons and photons

- Reconstruct electrons and photons
  - Combine information from the calorimeters and the inner tracking detectors
    - Electrons and photons identified as narrow clusters in electromagnetic calorimeters
    - Electrons have associated track; can check consistency of parameters between cluster and track (p / E, impact point / cluster centre, etc.)
    - Photons have no associated track
  - For many interesting processes, the electrons and photons are "isolated", whereas the candidates are often in jets for background processes
    - Genuine electrons from charm and beauty decays
    - Photons from π^0 decays (which may "convert" to given electrons)
    - Misidentified hadrons
  - Background comes from misidentified jets (dominant high-p_T process)
    - Also electrons may be misidentified as photons and vice versa

Reconstruction of jets

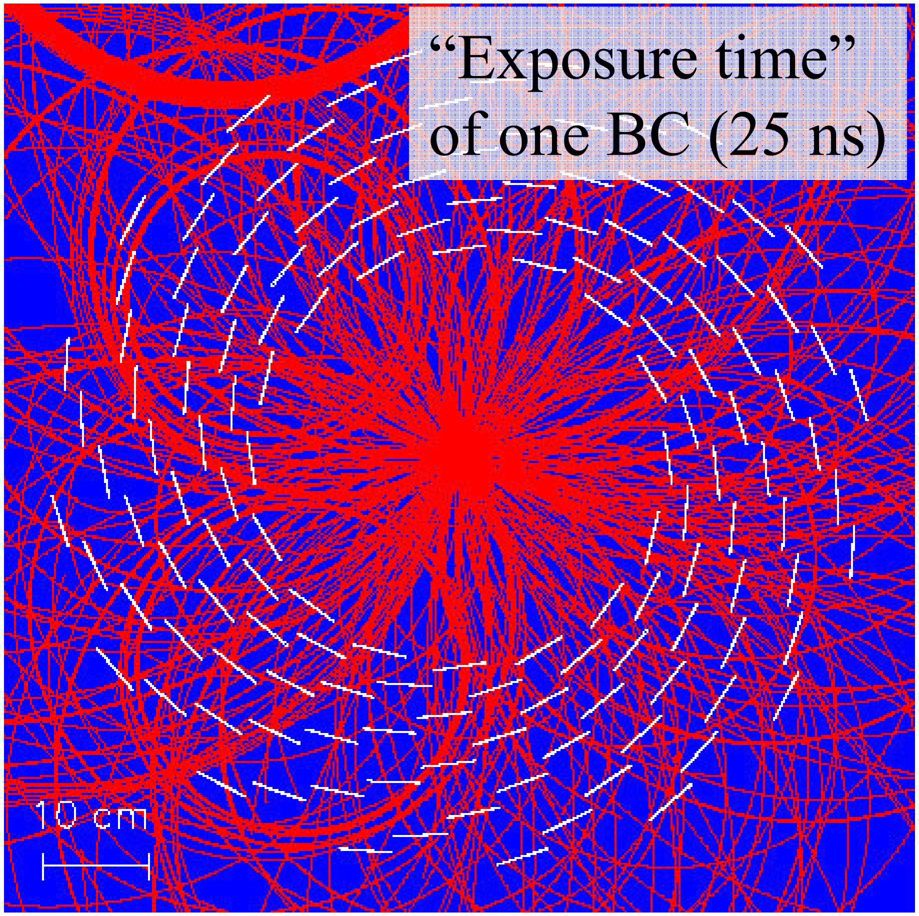
- Jets are the dominant high-p_T process at LHC
  - Interesting in their own right
  - Important source of background when searching for other physics processes
- Reconstruction is rather straightforward in principle
  - Comparatively broad clusters of energy in the calorimeters
  - Associated tracks in the inner detectors for the charged hadrons
- Very high rate of jets extending to extremely large transverse momentum



Features that distinguish interesting processes from pile-up and background

- Most of the particles from random ("minimum-bias") proton-proton interactions are low-p_T hadrons
  - Applying a cut on the reconstructed tracks / clusters of $p_T \sim 2$ GeV eliminates almost all of the activity
  - Concentrating on electrons, muons and photons gives particularly clean signatures for extracting physics signals
    - Requiring "isolation" reduces the background from hadronic jets
  - Missing transverse energy (i.e. momentum imbalance in the transverse plane) is also a very powerful signature
- Extensive studies of the physics potential of the experiments have demonstrated that in many cases the most important remaining backgrounds to new physics will involve events with genuine W or Z bosons, or top quarks

18 superimposed pp collisions,
as seen by internal part of CMS silicon central tracker.
Among them 4 muons from a higgs decay.



Reconstructed tracks of $p_t > 2$ GeV.

Among them well visible 4 muons from the higgs decay