LHC Phenomenology (Part I)

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Outline

- Motivations
- LHC Machine
- Phenomenology of p-p collisions
- Overview of detectors & trigger

LHC Motivation

- The last 20 years has seen a remarkable synthesis. The "Standard Model" has triumphed in explaining a host of data.

- This very success enables more fundamental questions to be posed and better defines them:
  - Mass
    - What is the origin of the mass of the particles? Is it the Higgs Boson? Why are they so mall compared to Planck Mass?
  - Unification
    - Why are they 4 interactions? Can they be unified?
  - Flavour
    - Why are there so many quarks and leptons? Why are flavour mixed?

LHC Motivation

- The Standard Model is probably a low-energy approximation of a more general theory

- There are a host of theoretical ideas (Supersymmetry, extra-dimensions, composite quarks, etc.)

  one might even be right ...

- Many theories predict new physics at the TeV scale

- The case for the LHC is even stronger now than when the LHC was first suggested 20 years ago.

  We need its Experimental discoveries to progress

- Power of LHC is its enormous mass reach relative to current facilities..

LHC parameters

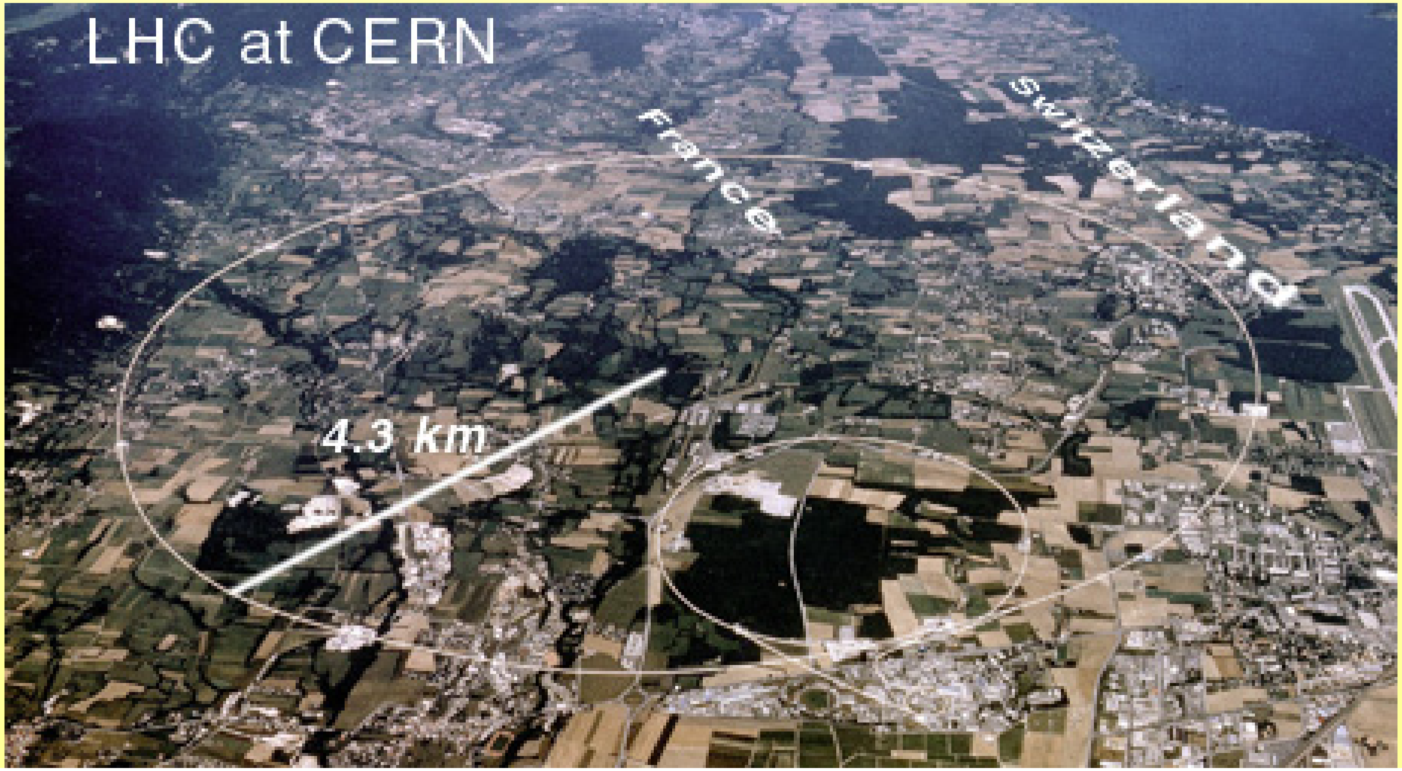
Limiting factor for √s:

bending power needed to fit ring in 27 km LEP tunnel

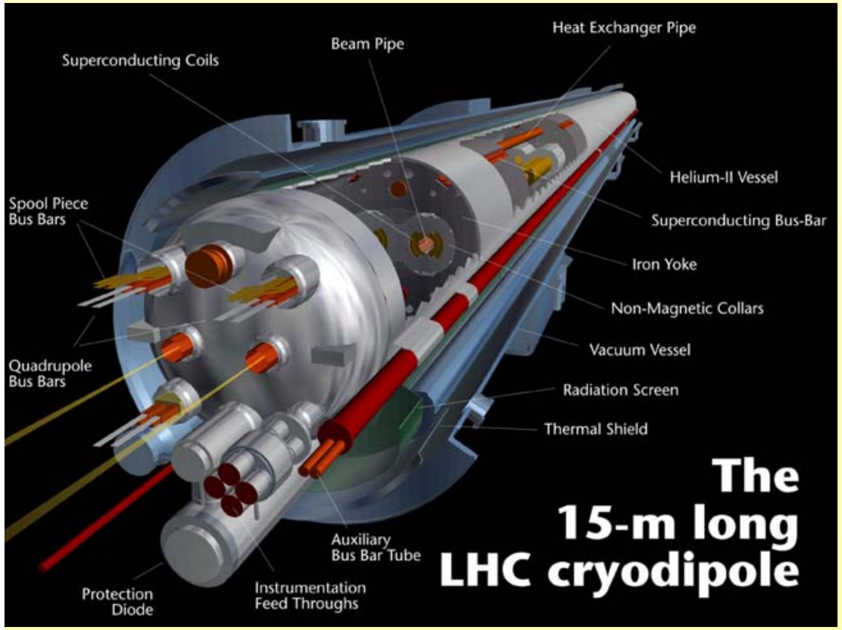
p(TeV) = 0.3 B(T) R(km)

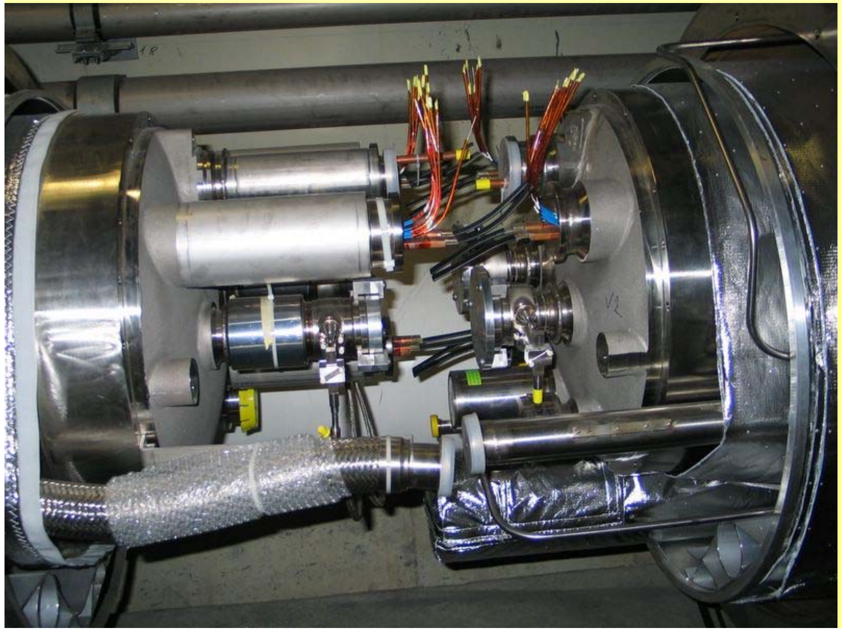
7 TeV 4.3 km → **B = 8.4 T**

~1300 superconducting dipoles working at 1.9 K



LHC status


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs



LHC Operation

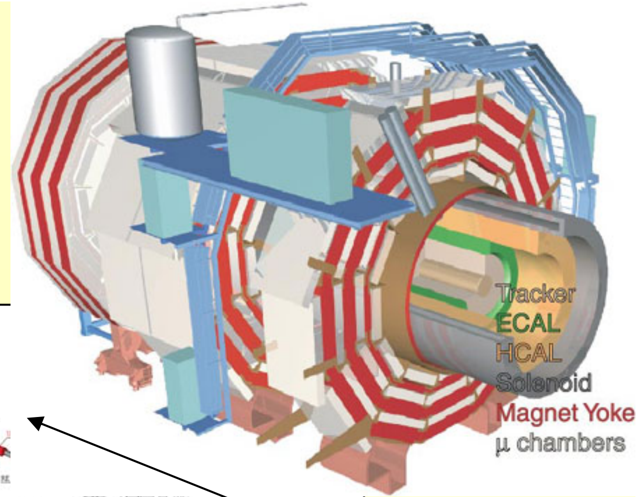
- Single Beam operation – Spring/Summer 2007
- Collisions – Fall 2007

  followed by shutdown 6 months?
- Operation in "low luminosity mode" for 3 years at ~2×10^{33} $cm^{-2}sec^{-1}$ (ramping-up?)
- 1 month per year of heavy ion running.
- Full luminosity in 2010, 10^{34} $cm^{-2}sec^{-1}$

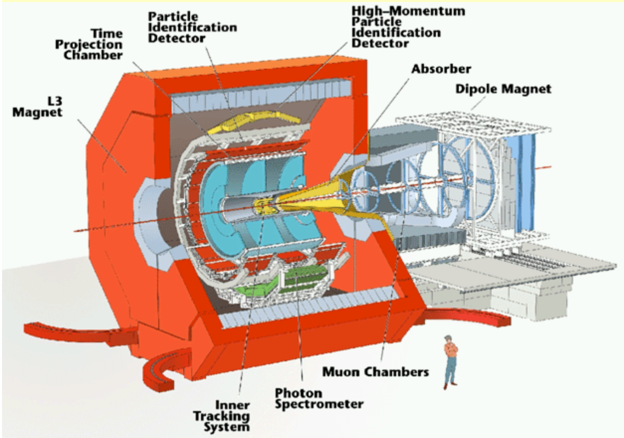
  multiple interactions per crossing cause some degradation in performance e.g. b-tagging
- Serious planning for a further factor of 10 in luminosity is underway: physics studies are being carried out.

  Higher energy very difficult ⇔ dipoles magnet

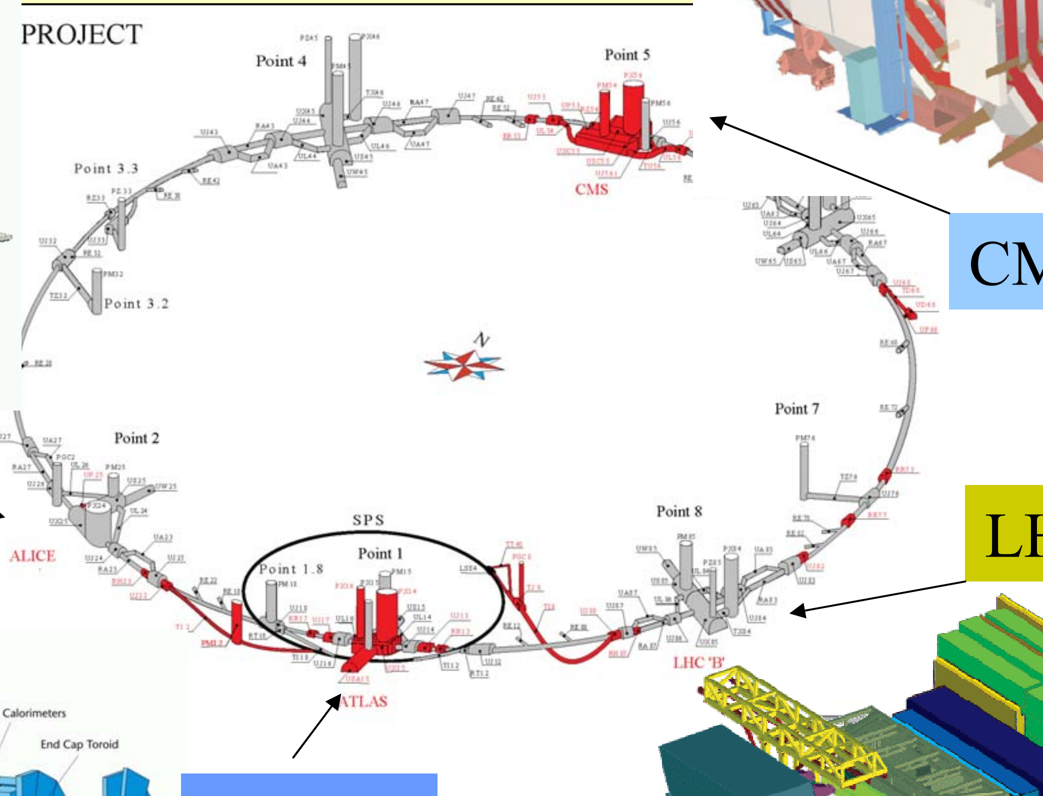
LHC experiments



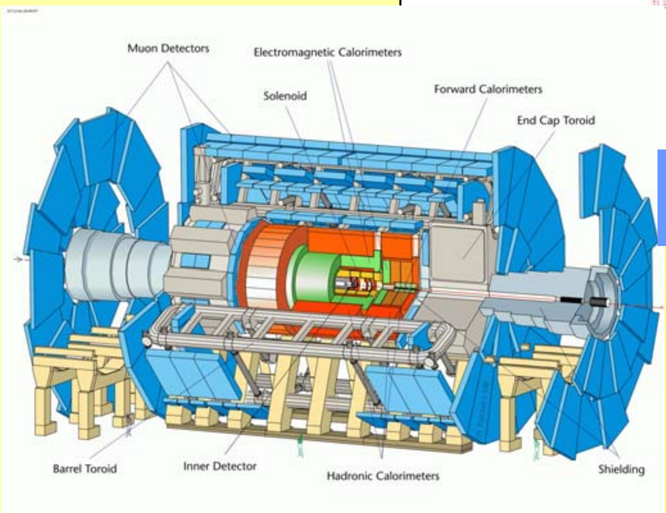
CMS



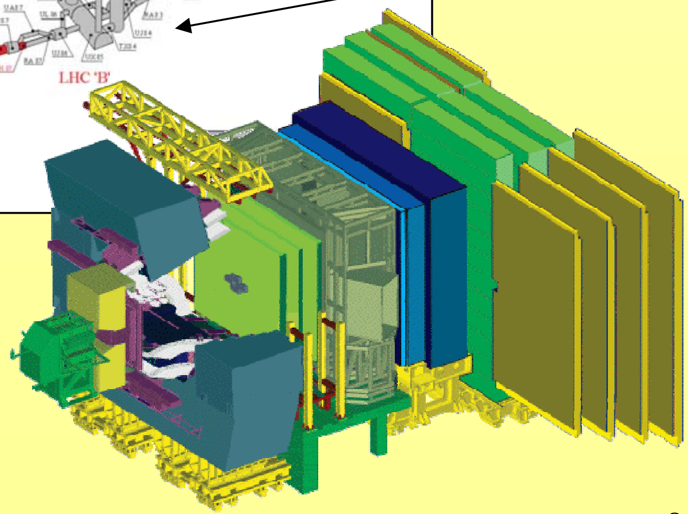
ALICE



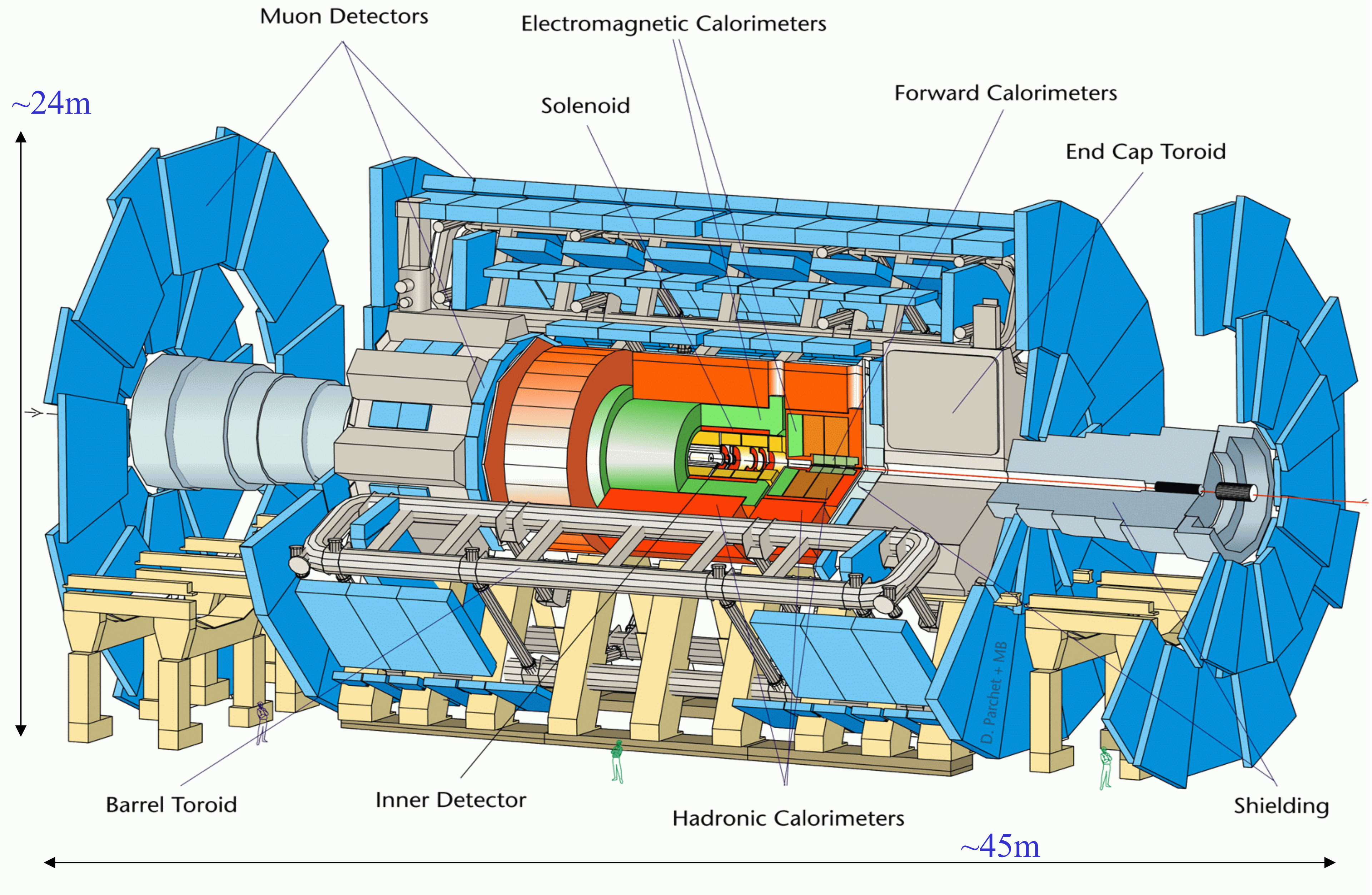
LHCb



ATLAS



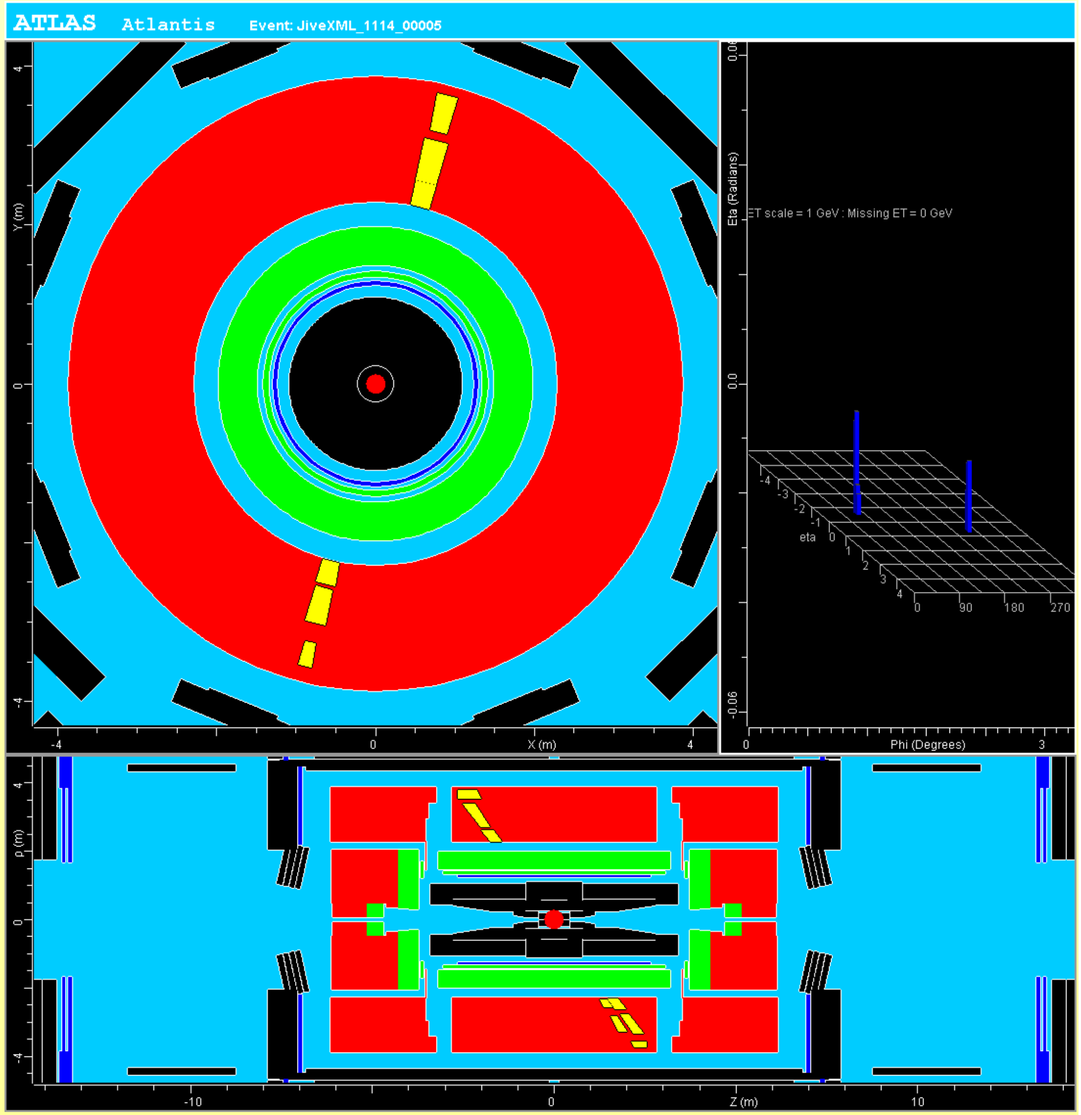
ATLAS detector



ATLAS detector

Not just science fiction ...

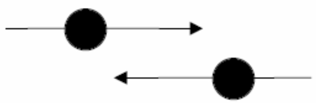
First Cosmic rays observed by the ATLAS Tile calorimeter in the underground cavern in mid-June

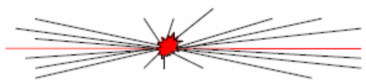


Phenomenology of p-p collisions

Class 1:

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole " → small momentum transfer ($\Delta p \approx \hbar / \Delta x$) → particles in final state have large longitudinal momentum but small transverse momentum (scattering at large angle is small)





$< p_T > \approx$ 500 MeV of charged particles in final state

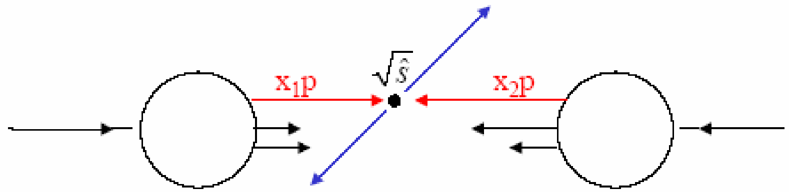
$\frac{dN}{d\eta} \cup 7$ charged particles uniformly distributed in ϕ

Most energy escapes down the beam pipe.

These are called minimum-bias events (" soft " events).
They are the large majority but are not very interesting.

Class 2:

Monochromatic proton beam can be seen as beam of quarks and gluons with a wide band of energy. Occasionally hard scattering (" head on") between constituents of incoming protons occurs.

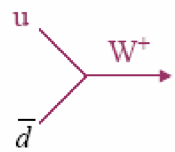


p ≡ momentum of incoming protons = 7 TeV

Interactions at small distance → large momentum transfer → massive particles and/or particles at large angle are produced.

These are interesting physics events but they are rare.

Ex. $u + \bar{d} \rightarrow W^+$



σ (pp → W) ≈ 150 nb ≈ $10^{-6}\, \sigma_{tot}$ (pp)

Phenomenology of p-p collisions

Coordinates at LHC: pp collisions

most of the energy goes down the beam pipe (spectator partons)

for "visible" products $\Sigma\, p_{//} \neq 0$; for hard collisions $\Sigma\, \vec{p}_T = 0$

→ p_T, E_T , E_T^{miss} variables that express the physics

Z along the beam; R radial; φ azimuth

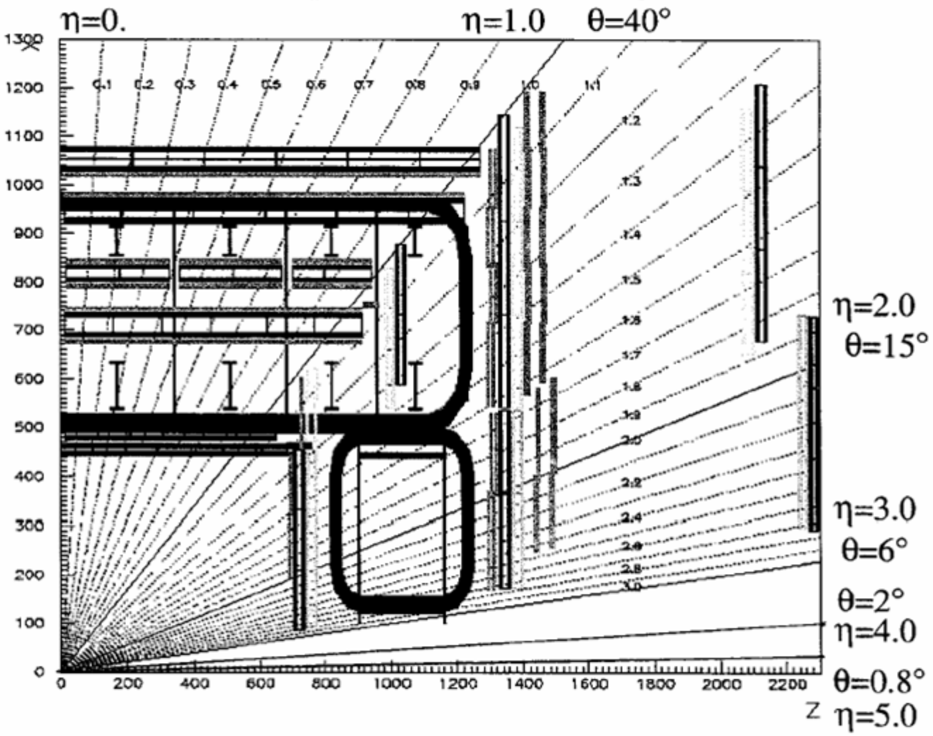
....

pseudo-rapidity η (rather than polar angle θ)

$\eta \equiv -\ln \tan(\theta/2) \approx$ rapidity(y) $\equiv 1/2 \ln(E+p_{//} / E-p_{//})$

longitudinal boost $y' = y + y^0$

jet cone shape invariant under a longitudinal boost



Minimum bias events at the LHC

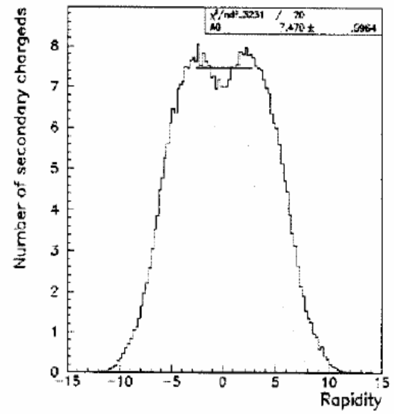
$\frac{dn_{ch}}{d\eta d\varphi} \approx 1$ for $|\eta| < 5$

at $\mathcal{L}$ = 10^{34} $cm^{-2}s^{-1}$, in each bunch crossing:

~ 1900 charged particles

~ 1600 neutral particles

in the region |η|<5

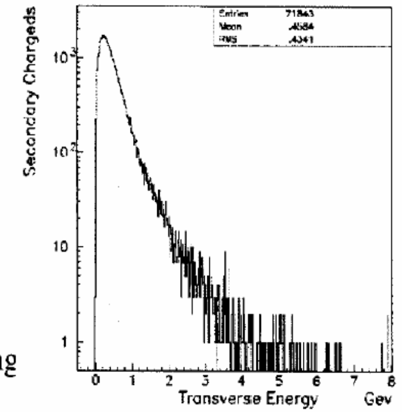


very steep P_T dependence affects more inner region

$\langle E_T \rangle$ photon = 0.3 GeV

$\langle E_T \rangle$ charged = 0.45 GeV

! Detectors may be sensitive to more than one bunch crossing



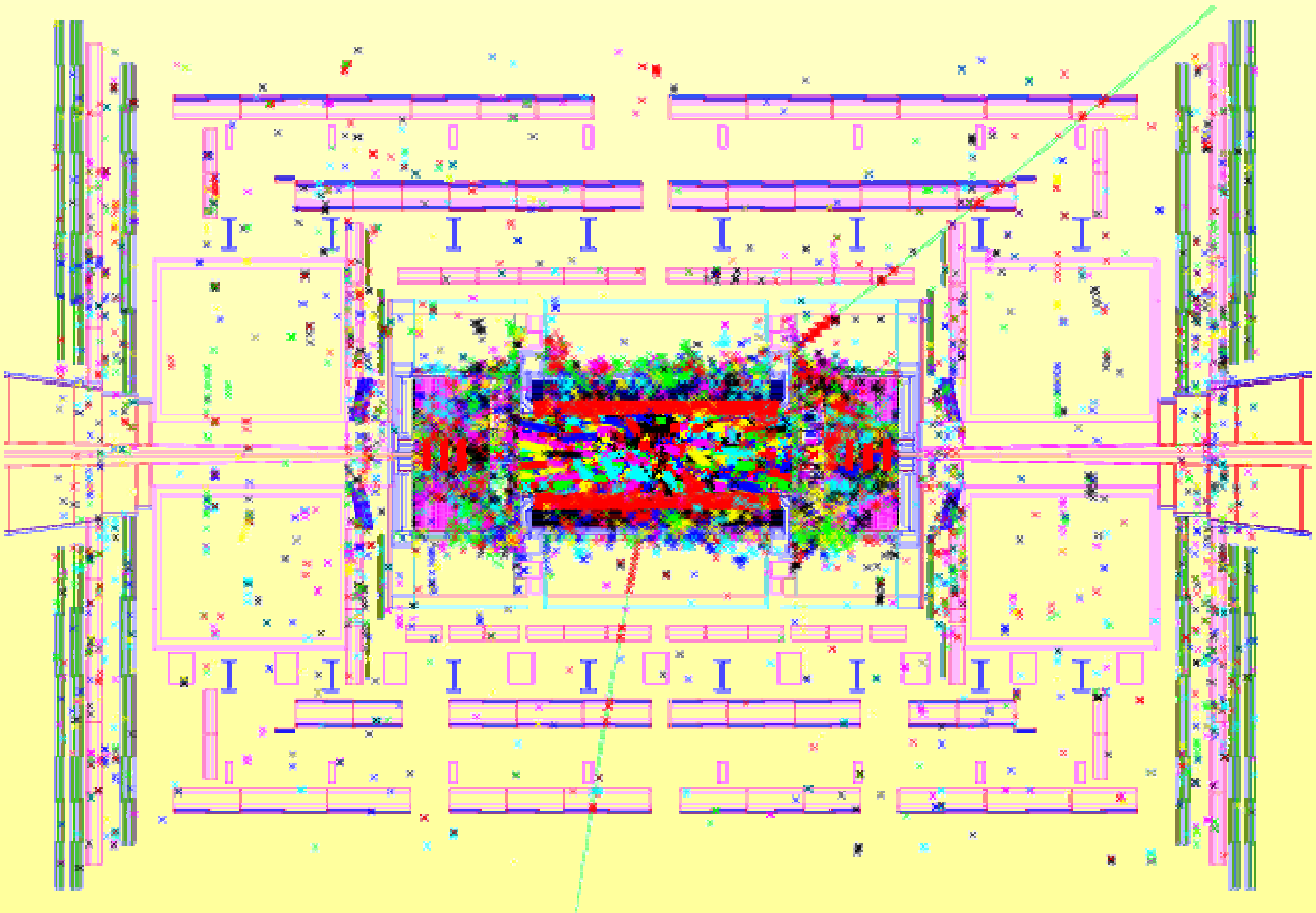
Typical E_T from pile-up noise in calorimeters :

EM cluster ~ 300 MeV Jet cone ΔR=0.4 ~ 7.5 GeV

ΔR=0.7 ~ 18 GeV

Total energy in the central region |η|<3 ~ 200 GeV

Looking for Interesting Events

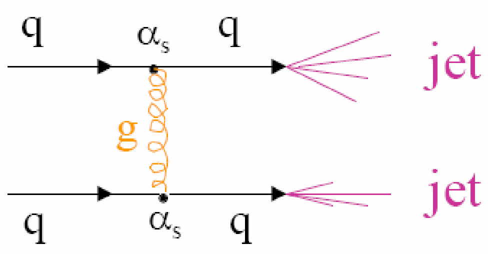


Higgs → ZZ → 2e+2μ

23 min bias events

- Common to all hadron colliders:

  high-p_T events dominated by QCD jet production:

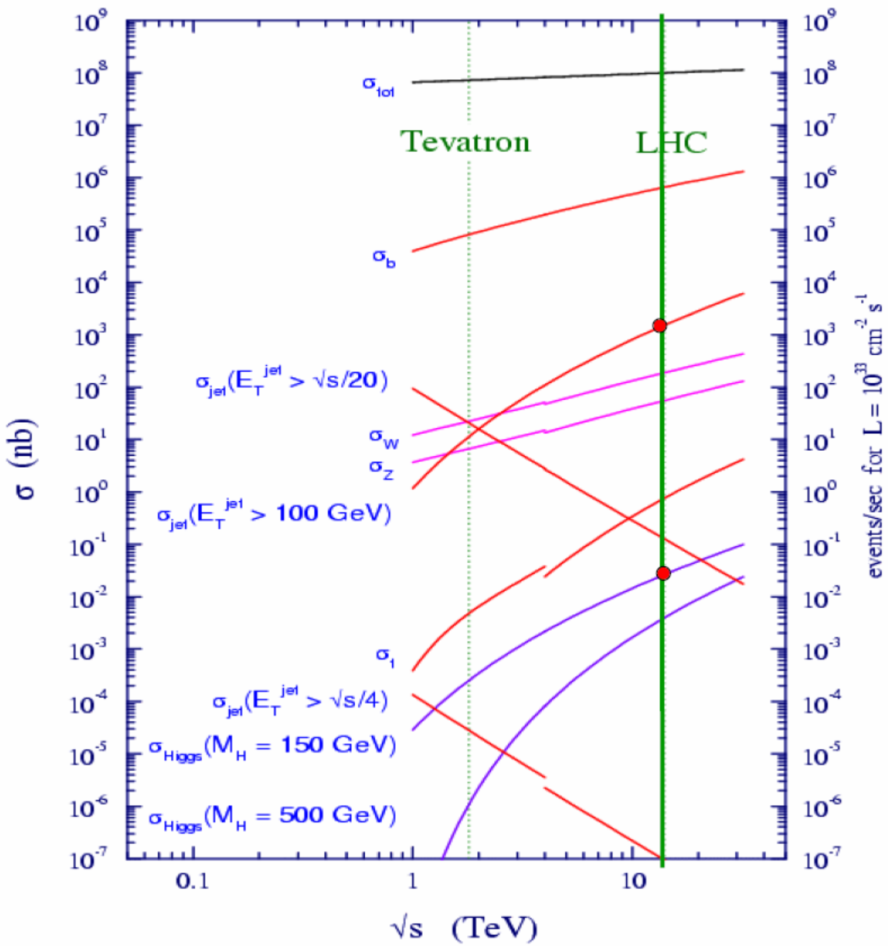


- Strong production → large cross-section
- Many diagrams contribute: qq → qq, qg → qg, gg → gg, etc.
- Called " QCD background "

Most interesting processes are rare processes:

- involve heavy particles
- have weak cross-sections (e.g. W production)

Proton - (anti) proton cross-section



To extract signal over QCD jet background must look at decays to photons and leptons → pay a prize in branching ratio

Ex. BR (W → jet jet) ≈ 70%
BR (W → ℓν) ≈ 30%

Detector requirements

Reconstruct, measure energy, identify

- electrons
- muons
- taus
- photons
- Jets (+ tag b quark jets)
- neutrinos via $p_T$miss

In pseudorapidity region [-5,5.]

In E_T range ~ 20 GeV to ~ 4 TeV

(down to p_T of ~ 0.5 GeV for tracks)

How to discover a signal?

$$S = \frac{N_S}{\sqrt{N_B}}$$

Significance > 5 → Discovery

Probability for background to fluctuate by more than 5σ : 10^{-7}

- energy resolution

  $S \approx 1/\sqrt{N_B} \approx 1/\sqrt{\sigma_m}$

  better resolution, better discovery potential

- particle identification

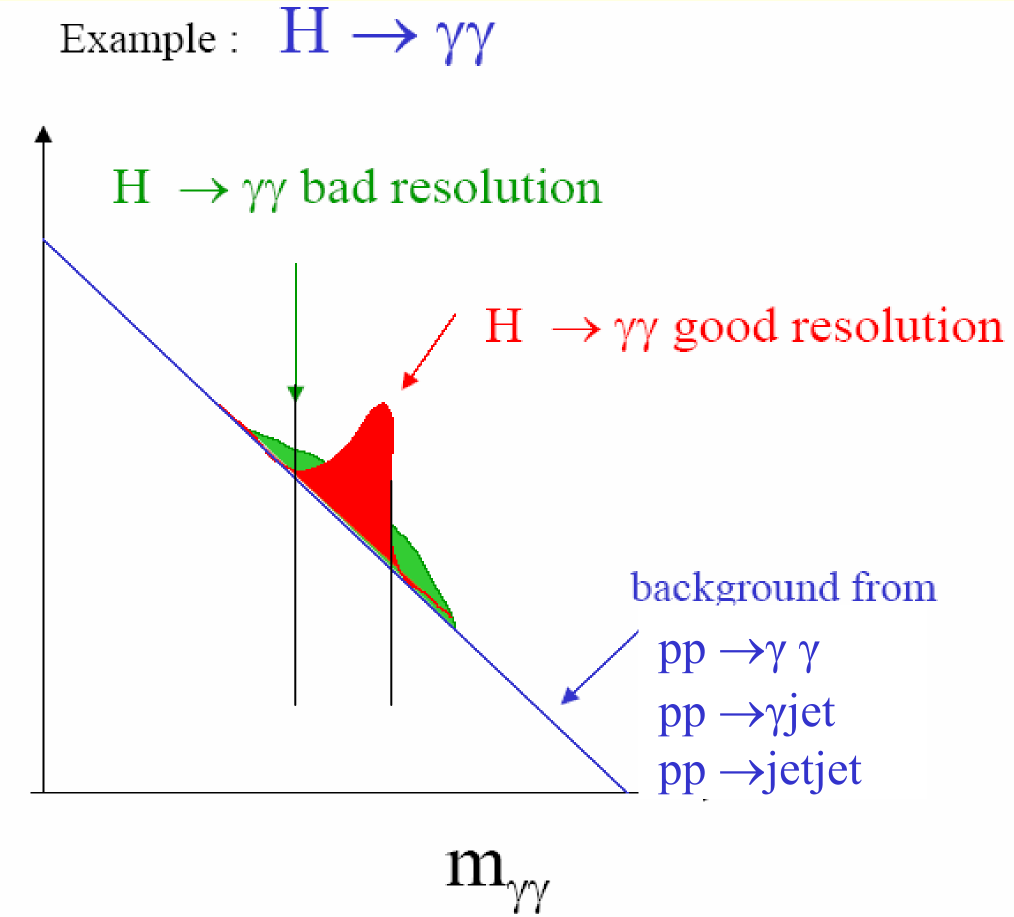
  Efficiency for signal (ε)

  background rejection (R)

  $S \approx \varepsilon$; $S \approx 1/\sqrt{R}$ or $S \approx 1/\sqrt{R^2}$

  maximize ε and R

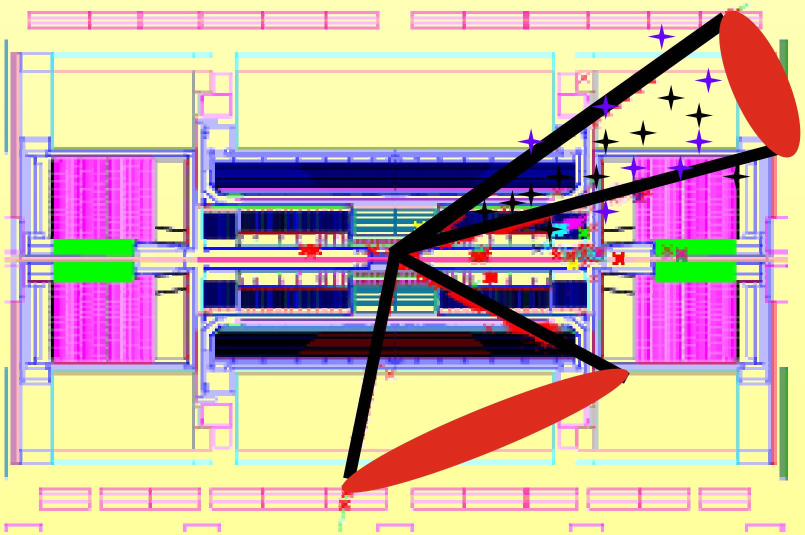
  but, usually trade-off between ε and R

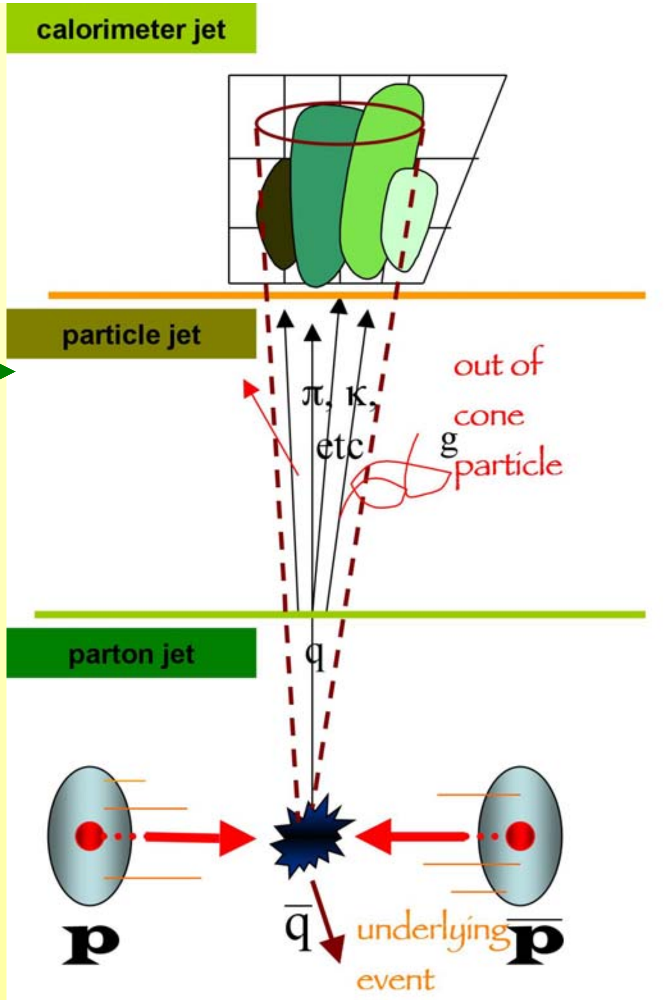


JETS

The Problem of Jet Measurement

- Jets are complicated objects
  - initiated by quark and gluon that spray in a jet of hadrons
- Jets cannot be defined in isolation to the event.
  in addition to hard scattering
  Underlying events + 23 interactions in a crossing





Different detector sections have different particle response (e,pi) , dead material, cracks & gaps.

Experimental goal:
Jet energy scale: 1.0 %
Jet resolution: 50%/√E ⊕ 2%

Difficult!!

Electrons

&

Photons

Physics motivations w.r.t performance requirements

- **energy resolution**

  $\sigma_E / E = 10\%/\sqrt{E} \oplus 25\%/E \oplus 0.7\%$

  linearity better than 0.5% up to 300 GeV

- **electron identification**
  - isolated electrons – e/jet separation

    R_{jet} ~10^5 in the range p_T>20 GeV (ε_e~80%)

    R_{jet} ~10^6 for a pure electron inclusive sample (ε_e~70%)
  - soft electron identification – e/π separation

    B physics studies (J/ψ)

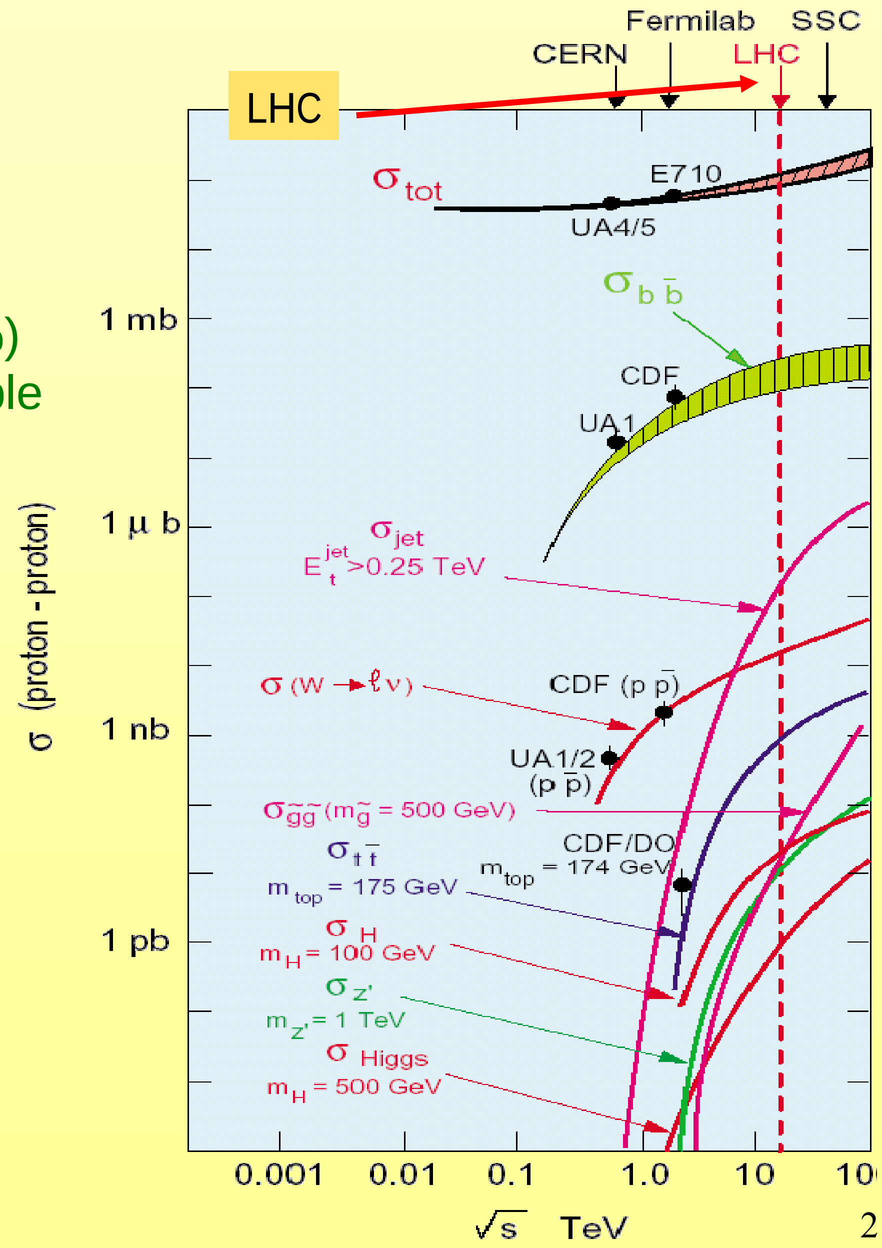
    soft electron b-tagging (WH, ttH)

- **photon identification**
  - γ/jet separation

    main reducible background to H→γγ comes from jet-jet and is ~2x10^6 more important than signal

    R_{jet} ~5000 in the range E_T >25 GeV

    R (isolated high p_T π^0) ~3 (ε_γ~80%)
  - conversion identification



Basics of e/jet and γ/jet separation

Identification of electromagnetic object (same for e/γ):

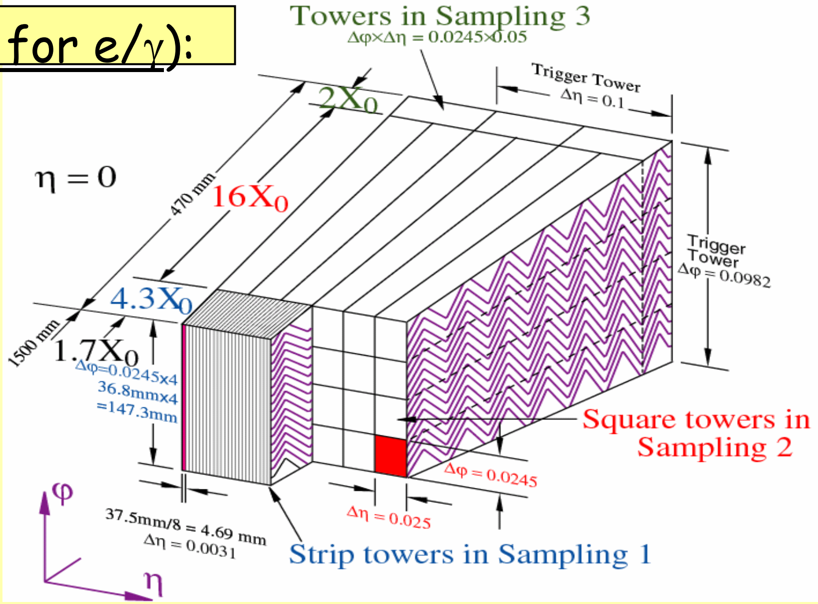
Leakage in Hadronic calorimeter

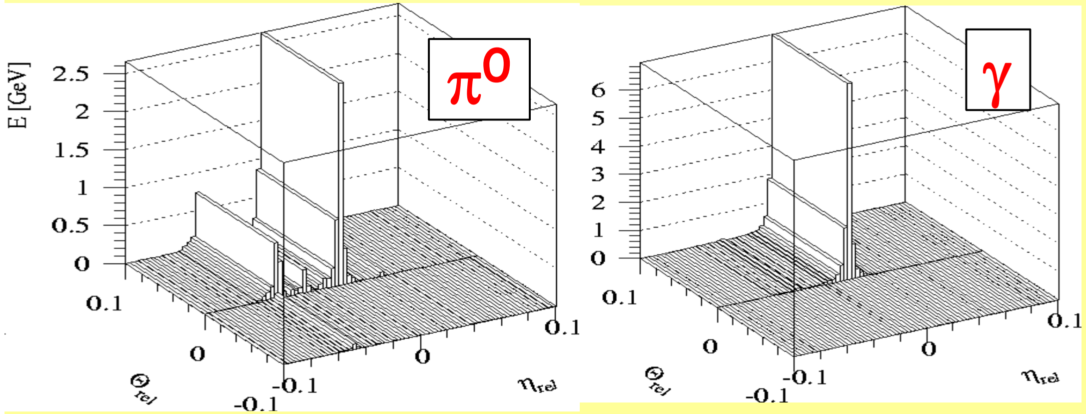
EM sampling 2 : different transverse development of electromagnetic and hadronic showers.

- shower shapes in η and φ
- shower width in η direction

EM sampling 1 : only jets with a little hadronic activity survive. Fine segmentation of the strips :

- look for substructures in strips
- shower width in η





Use of the Inner Detector:

Electron identification :

- track matching ($\Delta\eta$, $\Delta\phi$), E/p
- use of transition radiation
- identification of conversions