Standard Model at the LHC
(Lecture 2: Particle Detectors)

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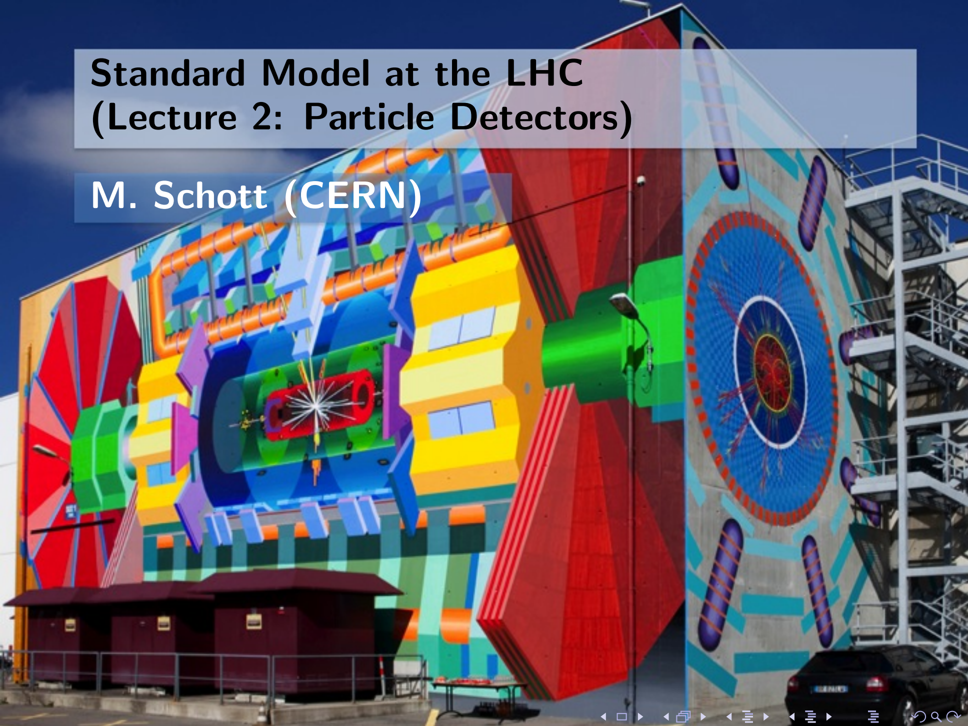


Content

Why colliding protons

Electron-Positron Collider

- \- interactions of point-like particles
- \- exact energy known
- \- QED processes 'easy' to calculate

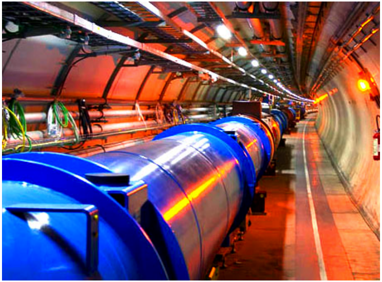
Proton-Proton Collider

- \- only a fraction of the beam energy 'used' in collisions
- \- 'messy' QCD environment
- \+ negligible synchrotron radiation: $\Delta E_s \sim \frac{E^4}{m^4}\frac{1}{R} \rightarrow$ high energies
- \+ high luminosities
- → good for discovering something new

The Large Hadron Collider (1/2)

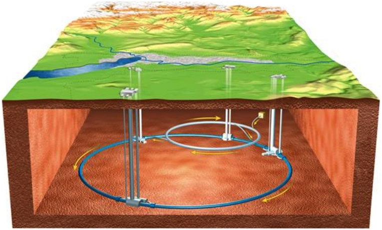
The Large Hadron Collider is

- 27km in circumference
- 100m underground (old LEP tunnel)
- a proton-proton collider with a center of mass energy of currently $\sqrt{s} = 8\,TeV$



Design Parameters

- 2835×2835 proton-bunches
- distance: 7.5m (25ms)
- per bunch 10^{11} proton
- per bunch-crossing: ~ 25 proton-proton collisions



The Large Hadron Collider (2/2)

The LHC consists of

- 1232 supraconducting dipol magnets
- field-strength 8.6 T with liquid helium

Design luminosity

- $L = 10^{34} cm^{-2} s^{-1}$
- high luminosity important as cross-sections for new physics are small
  - $\dot{N} = L \cdot \sigma$

Stable Particles

Relevant particles for the interaction with matter:

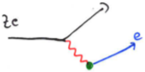
- stable particles: protons, anti-protons, electrons, anti-electrons, photons, atomic-cores, neutrinos
- long-lived particles (= do not decay within the detector): neutrons, myons, $\pi^{\pm}$, $K^{\pm}$

Hence we have here leptons and hadrons which interact via

- weak force (leptons): : $\approx 10^{-5}$
- electromagnetic force (leptons, hadrons): $\approx 1/137$
- strong force (hadrons): ≈ 1

Electromagnetic Interaction of heavy particles (1/3)

The electromagnetic interaction is described by the exchange of virtual photons



- ionization
- excitation of atoms
- polarization, cerenkoc-effect, transition radiation

Simplify the interaction of particles with matter to interactions of photons with matter

Electromagnetic Interaction of heavy particles (2/3)

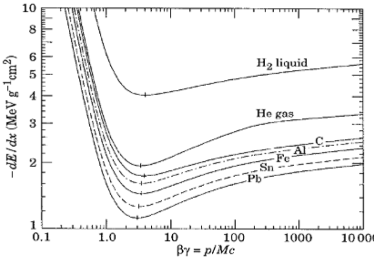
Within this model we can calculate the differential energy loss dE/dx via the famous Bethe-Bloch formulae

$$-<\frac{dE}{dx}>=2\pi r_e^2 m_e c^2 \rho \frac{N_0 Z z^2}{A\beta^2}[ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I}-\beta^2]$$

with

- r_e : classical electron radius
- N_0 : Avogado-number
- ρ : density of matter
- I : Ionisation potential of the atom
- T_{max} : max. kin. energy which an electron at rest can get by a central impact

Electromagnetic Interaction of heavy particles (3/3)

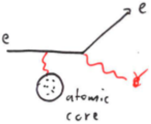


- Typical order of magnitude keV/cm
- Plateau : Saturation through energy loss via ionisation

Electrons and Positrons (1/2)

So far: heavy particles which ionize matter (atoms). We need some modifications for electrons and positrons

- Mass of impact-partners is the same
- Impact-partners cannot be distinguished
- Annhiliation process ($e^+e^- \rightarrow 2\gamma$)
- Bremsstrahlung
    - Dominating process when energies are $E \gg 10MeV$, i.e. at the LHC



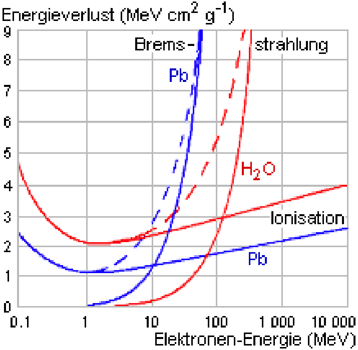
Electrons and Positrons (2/2)

Cross-Section for this process is $\sigma \sim \frac{1}{m^2}$,

- important for $e^\pm$ but not for $\mu^\pm$.

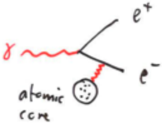
Note that $< \frac{dE}{dx} >_{rad} \sim E \rightarrow -\frac{dE}{E} \sim dx$

- Hence the energy of a particle that is transversing a detector is $E(x) = E_0 \cdot exp(-x/X_0)$
- After a distance of X_0 (= radiation length), the initial energy is reduced to 37%.
- Important for detector dimensions ($X_0^{H2O} = 36.1cm, X_0^{Pb} = 0.56cm$)



Photons

Pair-production is the dominant process for photons with an energy above $E_\gamma > 2MeV$



This is very similar to Bremsstrahlung.
As a rule of thumb: A high energetic photon converts after X_0 with a probability of $\sim 54\%$.

Summary of interactions

Summary

- electrons@LHC: Bremsstrahlung
- photons@LHC: Pair-production
- muons@LHC: Ionisation
- hadron@LHC: Ionisation, Nuclear-Interactions
- neutrinos@LHC: No signature in the detector

What do we want to measure?

- Ultimate goal is particle identity and 4-Momentum (Lorentz-Momentum Vector)
- particle identification via detector design
- 4-momentum measurement: Measure $|\vec{p}| \approx E$ and the flight direction w.r.t to collision point

Momentum Measurement: Basic Concept (1/2)

- Idea: Use magnetic field to bend trajectory with charged particle. Momentum is given by

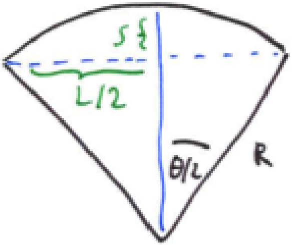
$$p = e \cdot E \cdot R$$

  - where R is the bending radius and B is the magnetic field.

- Measurement via Sagitta

$$S = R - \sqrt{R^2 - (L/2)^2} \approx R\frac{\theta^2}{8}$$

$$p = e \cdot B \cdot \frac{L}{2sin\frac{\theta}{2}} \rightarrow S \approx \frac{e \cdot B \cdot L^2}{8p}$$

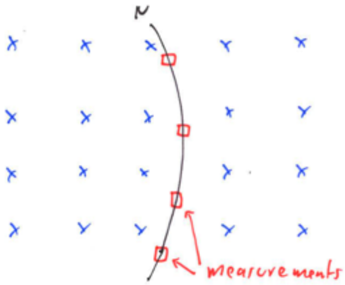


Momentum Measurement: Basic Concept (2/2)

- Trajectory of particle in magnetic field is measured at N (equidistant) points
- Momentum resolution (for soleniod magnetic field) is given by

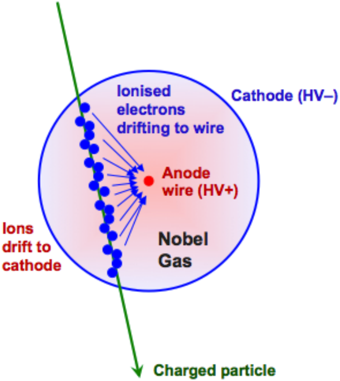
$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma_{pos}}{0.3 \cdot B \cdot L^2}\sqrt{\frac{720}{N+4}} \cdot p_T$$

- Consequences
  - Larger Magnetic field → better resolution
  - Even better to have longer measurement distance!
  - Rel. resolution worsens with increasing p_T



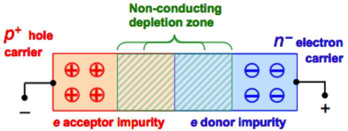
Gas Based Detectors

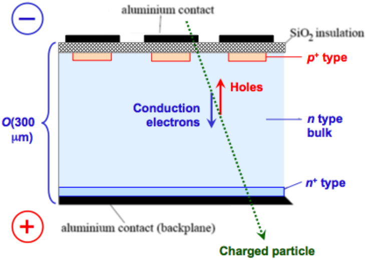
- Idea: Use ionisation of gas-atoms by incident particles
  - Primary Ionisation: $x + A \rightarrow x + A^* + \delta_e$
  - Secondary Ionisation: $\delta_e + A \rightarrow \delta_e + A^* + e^-$
  - Typical value for producing one ion-pair: $\approx 30eV$.
- Measurement: Voltage in gas
  - electrons/ions drift to cathode/anode
  - When the E-field gets strong (close to wire): Ionisation electrons can cause new ionisations
  - $\rightarrow$ electron-avalanche $\rightarrow$ measureable signal



Semi Conductor Detectors

- Using the pâ“n junction as a tracking detector
- enhance depletion zone with external voltage
- High Si density low electronâ“hole creation potential (3.6 eV compared to 36 eV for gaseous ionisation) allows use of very thin detectors with reasonable signal
- Very high spatial resolution ($\approx 10\mu m$)





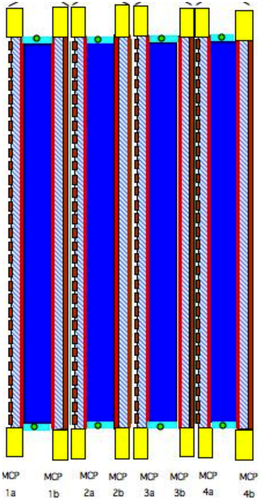
Basic Concept of Energy Measurements (1/2)

Energy-measurements are destrutive, i.e. the particles deposit their full energy in the detector

- cannot be used for further measurements

Detectos for the energy measurement are called calorimeters

- homogenous calorimeters: Absorber material is also detection material
- sampling calorimeter: Absorber material is passiv and placed in layers. In between active detection layers for ionisation measurements



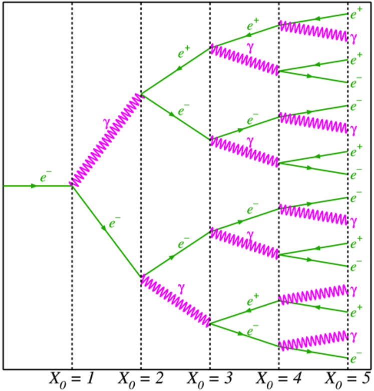
Basic Concept of Energy Measurements (2/2)

Calorimeter and Material have to be designed such that the particles leave their full energy inside → depends on interaction

- Electromagnetic calorimeter: mainly energy of e^+, e^-, γ
- Hadronic calorimeter for particles which interact mainly which hadronic interactions with the atomic cores of the absorber material: $\pi^\pm, p^\pm, n, ...$

Electromagnetic Calorimeters (1/3)

- High energetic electrons and photons create showers in the absorber-material:
  - pair-production, bremsstrahlung, pair-production, ...
- until critical energy E_C is reached
- The number of particles doubles in each step X_0 as long as EE_C:
  - $N(t) \approx 2^t$, where t is the numbner of steps in X_0
- with an average energy per particle of
- $\mathrm{E(t)} = \mathrm{E}_0/N(t) = E_0 \cdot 2^{-t}$



Electromagnetic Calorimeters (2/3)

The maximum of the shower is reached at $t_{max} \approx In(E_0/E_C)$. The total number of particles S in the shower can the be calculated by

$$S = \sum_{t=0}^{t_{max}} N(t) = \sum 2^t = 2^{t_{max}+1} - 1 \approx 2^{t_{max}+1}$$

this gives

$$S = 2\frac{E_0}{E_S} \sim E$$

Therefore we just have to measure the number of particles in the shower to determine the initial energy. Since S is a large number and its uncertainty is given by $\sqrt(S)$, we expect for the relative energy resolution

$$\frac{\sigma}{E} \sim \sqrt{\frac{t}{E_0}}$$

i.e. it gets more precise for higher energies!

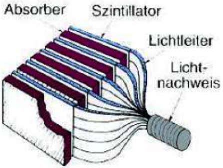
Electromagnetic Calorimeters (3/3)

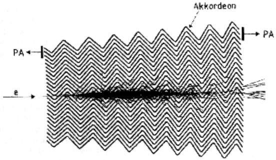
How does it work? Lets look at a sampling calorimeter:
Periodic structure of passive absorber material (Keep in mind: Bremsstrahlung cross-section goes with $\sigma \sim Z^2$)

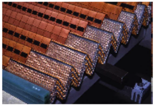
- lead
- copper
- ...

And active materials for the detection of the shower particles

- plastic scintillators
- liquid argon (as 'ionisation chamber')
- ...



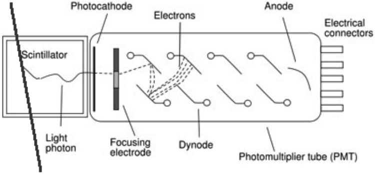




Scintillators

Scintillators are particle detectors, in which ionizing particles cause light emissions in a transpartent medium.

- Anorganic Scintillators
  - cristal structure, doped with activators
  - Ionizing particles create free electron-hole pairs
  - excitations travel in the lattice to an activator which gets excited and emitts light to get back into its ground state
  - → just count photons with the help of a photo-multiplier
- Organic Scintillators



Hadronic Calorimeters (1/2)

Hadronic calorimeter are designed for the energy measurement of hadrons

- Similar principle as electromagentic calorimeters, but showers are produced via strong interaction
  - incoming hadrons interact with atomic nuclei → $n, p, \pi^0, \pi^\pm$
  - $\pi^0 \rightarrow \gamma\gamma$: also electromagnetic shower
  - $\approx 20\%$ of energy needed to break up nuclear binding energy
- nuclear absorption lengths λ instead of radiation length X_0
  - Typical values for λ: $\lambda_{Fe} \approx 17.1cm$, $\lambda_{Pb} \approx 18.5cm$
  - Typical values for $_0$: $_{0,Fe} \approx 1.76cm$, $\lambda_{0,Pb} \approx 0.56cm$
  - → hadronic calorimeters must be much larger

Hadronic Calorimeters (2/2)

Energy Resolution

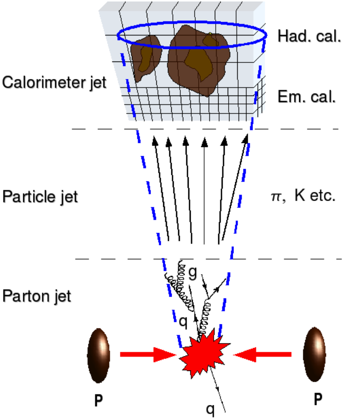
- EC: $\frac{\sigma}{E} = \frac{3\text{–}5\%}{\sqrt{E[GeV]}}$
- HC: $\frac{\sigma}{E} = \frac{50\text{–}90\%}{\sqrt{E[GeV]}}$

Worse resolution of HC due to:

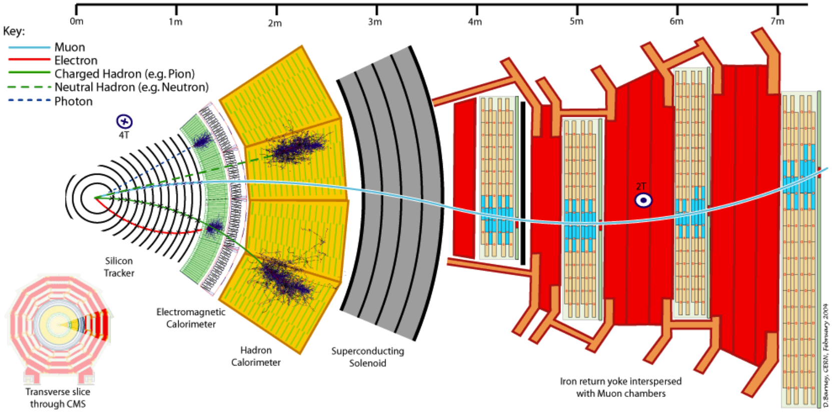
- leakage
- some shower-particles (ν, μ) escape the calorimeter
- breaking up binding energies

Important

HC do not measure directly quarks/gluons but **Particle Jets**



Basic Principle of an LHC Detector



What do we measured?

We measure

- energy / momentum of particles
- the 'initial' position (separate primary vertex and secondary vertex)
- trajectory / direction
- → 4-momentum: $P = (E, -\vec{p})$
- Note: $P^2 = E^2 - |\vec{p}|^2 = m^2$. @LHC: $E^2 >> m^2$

We distinguish

- electrons
- photons
- muons
- jets (from quarks, gluons,): uds-jet? b-jet? c-jet?

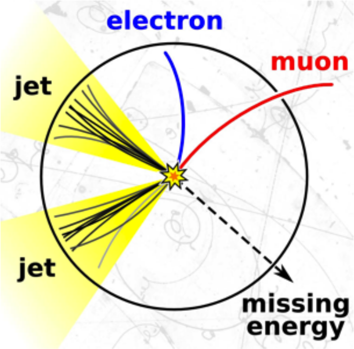
How to detect neutrinos

Neutrinos leave detector 'unseen', but carry away energy

- total momentum in z-direction of interacting partons not known
    - Different to e^+/e^- collisions
- But $\sum E_T^{initial} = 0 = \sum_{all} E_T^{final}$
- Hence we define

$$\vec{E}_T^{miss} = -\sum_i \vec{E}_T^i$$

- Use $\vec{E}_T^{miss}$ as estimate for neutrinos
    - No z-information!



The ATLAS Detector (1/2)

ATLAS and CMS are 4π detectors

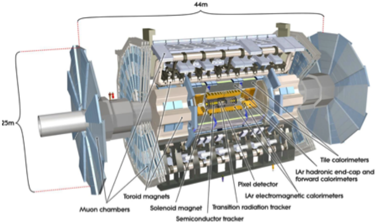
- Barrel- and Endcap-Regions

Inner Detector

- $|\eta| < 2.5$, solenoid $B = 2T$
- Si Pixels, Si strips, TRT
- Tracking and vertexing
- Resolution: $\sigma/p_T \sim 3.8 \times 10^{-4} p_T[GeV] \oplus 0.015$

EM calorimeter

- $|\eta| < 3.2$
- LAr/Pb accordion structure e/γ
- E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$



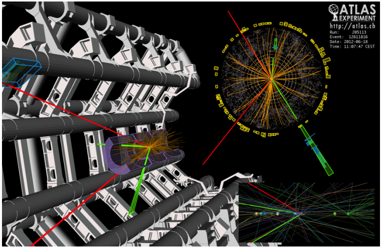
The ATLAS Detector (2/2)

HAD calorimeter

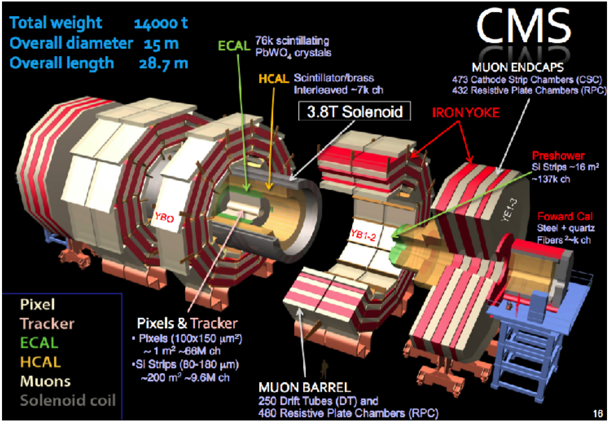
- $|\eta| < 3.2$
- Forward Calo. $|\eta| < 4.8$
- Scint./Fe tiles in the central, W(Cu)/LAr in fwd region
- Trigger, jets + missing Et
- E-resolution: $\sigma/E \sim 50\%/sqrtE \oplus 0.03$

Muon Spectrometer

- $|\eta| < 2.7$
- Toroid B-Field ($0.5T$)
- Muon Momentum resolution $< 10\%$ up to $\sim 1TeV$



The CMS Detector



(stolen from a fantastic CMS talk)

ALICE and LHCb Detector

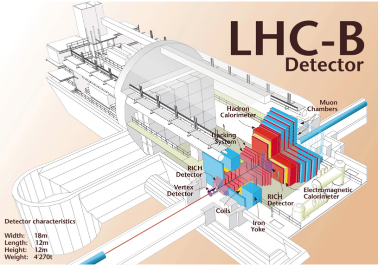
ALICE Detector

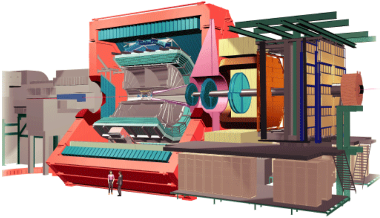
- designed to study the quark-gluon plasma during the ion-ion collisions at the LHC

LHCb Detector

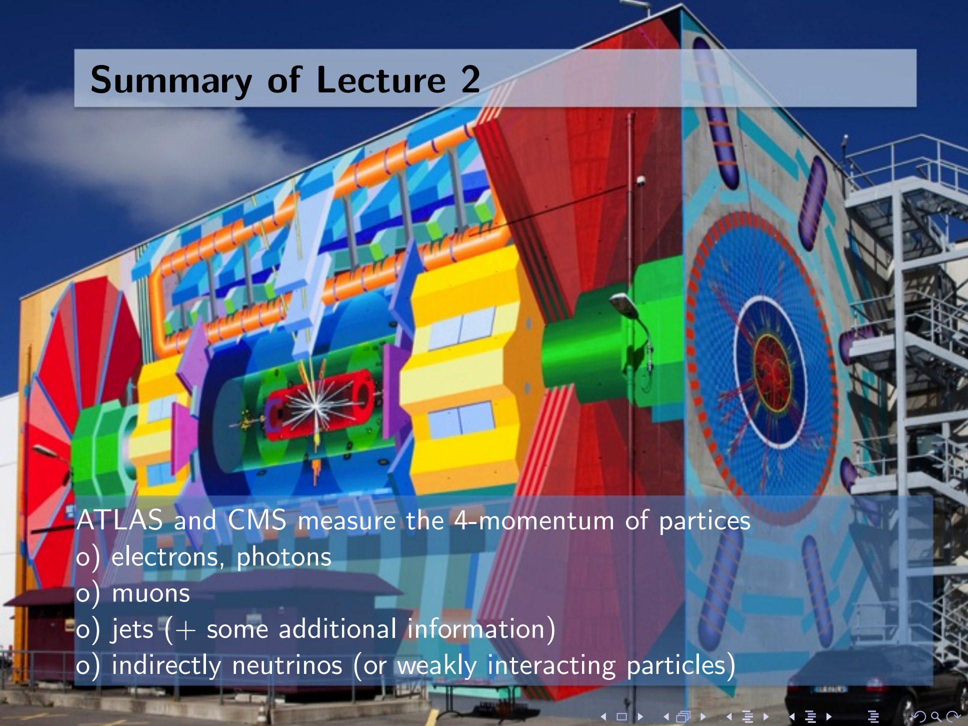
- designed to study the CP-Violation in b-hadrons
- understand the Matter-Antimatter asymmetry of the universe?
- study and measure the

Both highly interesting physic programs - maybe a lecture in 2013?





Summary of Lecture 2



ATLAS and CMS measure the 4-momentum of partices
o) electrons, photons
o) muons
o) jets (+ some additional information)
o) indirectly neutrinos (or weakly interacting particles)