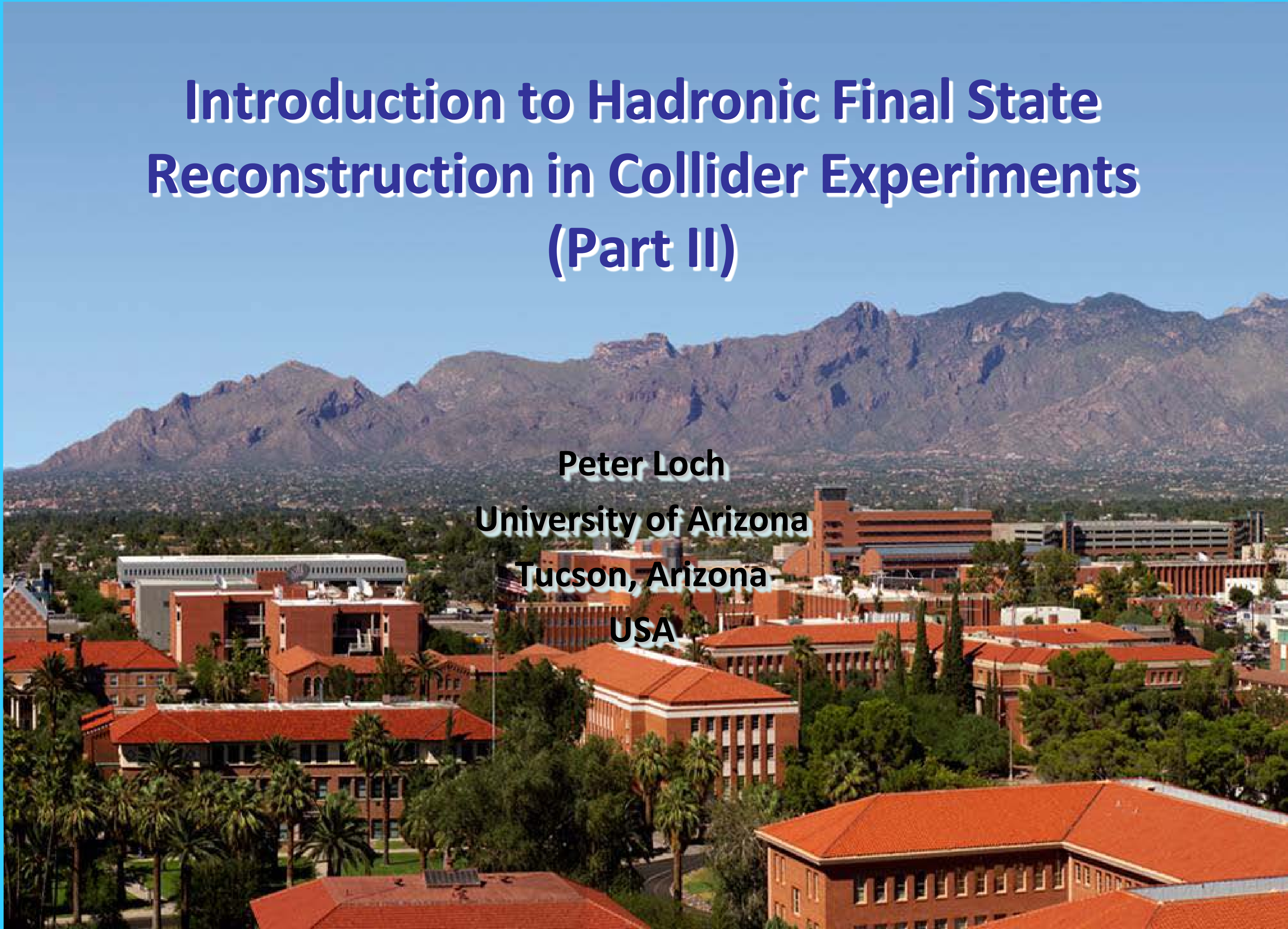


Introduction to Hadronic Final State Reconstruction in Collider Experiments (Part II)

Peter Loch
University of Arizona
Tucson, Arizona
USA

Principles of Calorimetry

Detector needs for multi-purpose collider experiments

- Tracking for charged particle momentum measurement
- Calorimeters for charged and neutral particle energy measurement
- Muon spectrometers (tracking) for muon momentum measurements

Underlying physics for calorimetry: particle interaction with matter

- Electromagnetic cascades
- Hadronic cascades
- Muon energy loss

Calorimetric principles in particle detection

- Conversion of deposited energy into an extractable signal in homogeneous and sampling calorimeters
- Minimum ionizing particles and muons
- General signal features of electromagnetic and hadronic showers

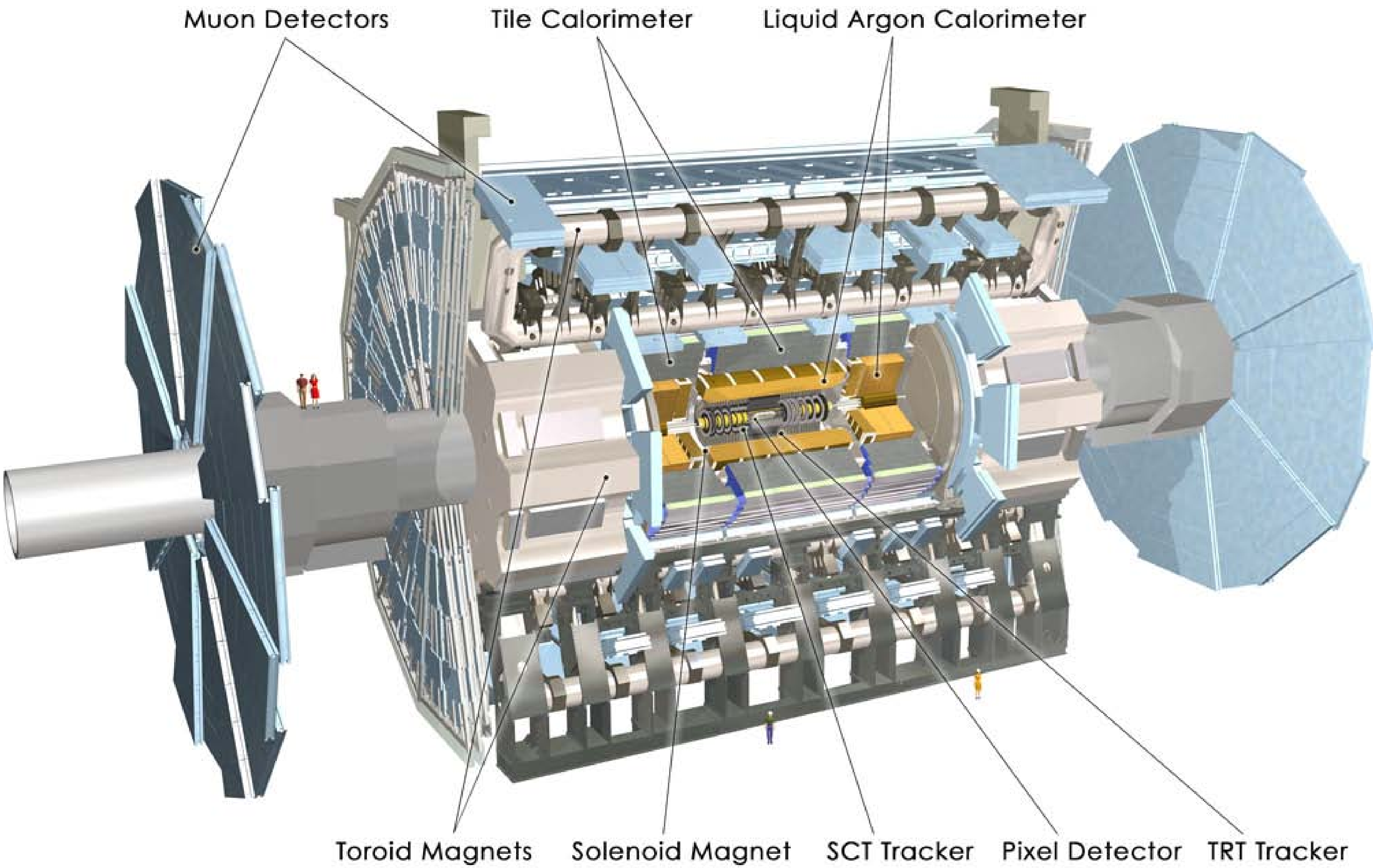
Calorimeter characteristics in sampling calorimeters

- Sampling fraction
- Signal linearity and relative resolution
- Non-compensation

Signal extraction

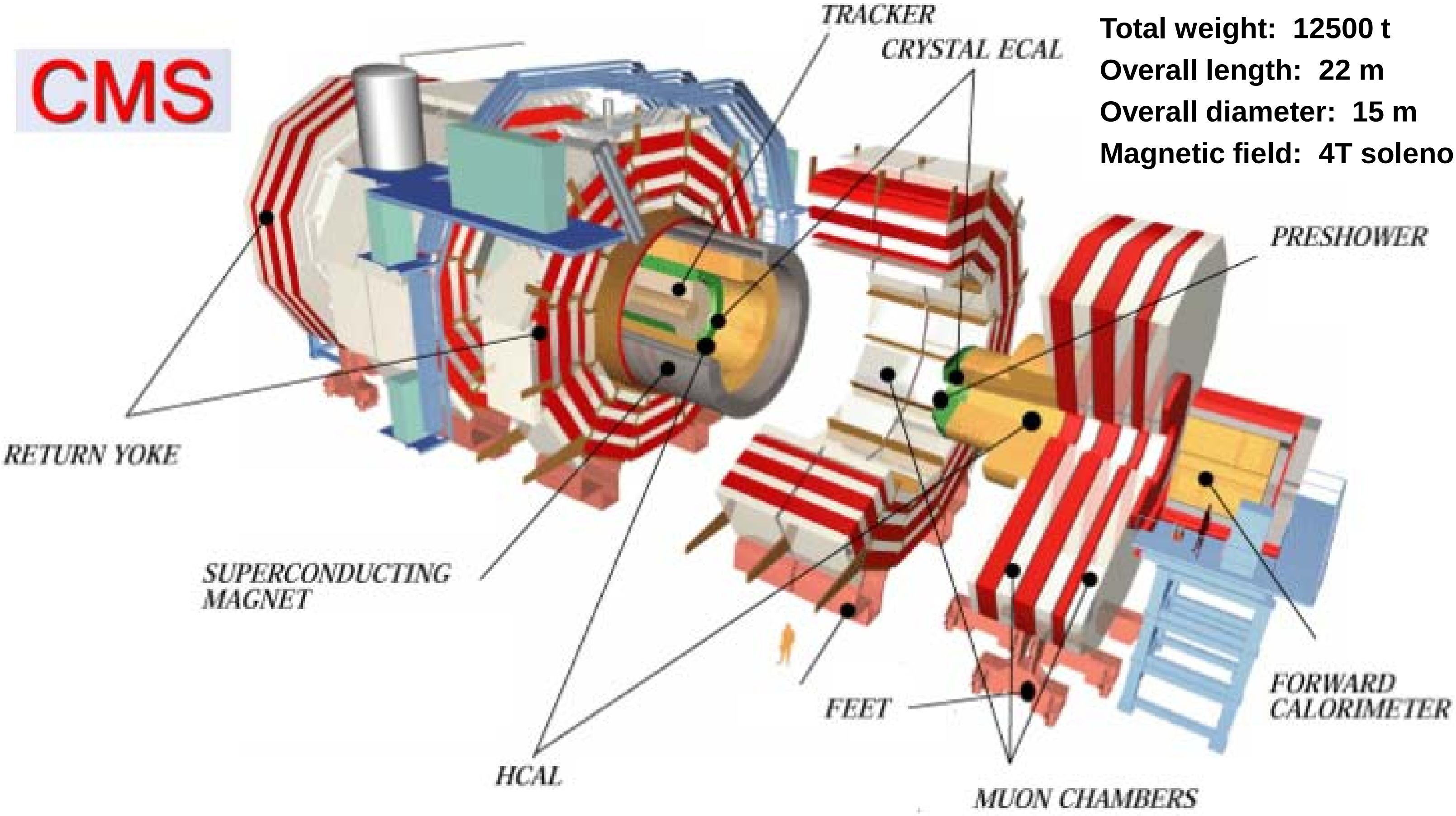
- Charge collection
- Current measurement
- Pulse shapes

ATLAS – Multipurpose LHC Detector



Total weight : 7000 t
Overall length: 46 m
Overall diameter: 23 m
Magnetic field: 2T solenoid
+ toroid

CMS – Multipurpose LHC Detector



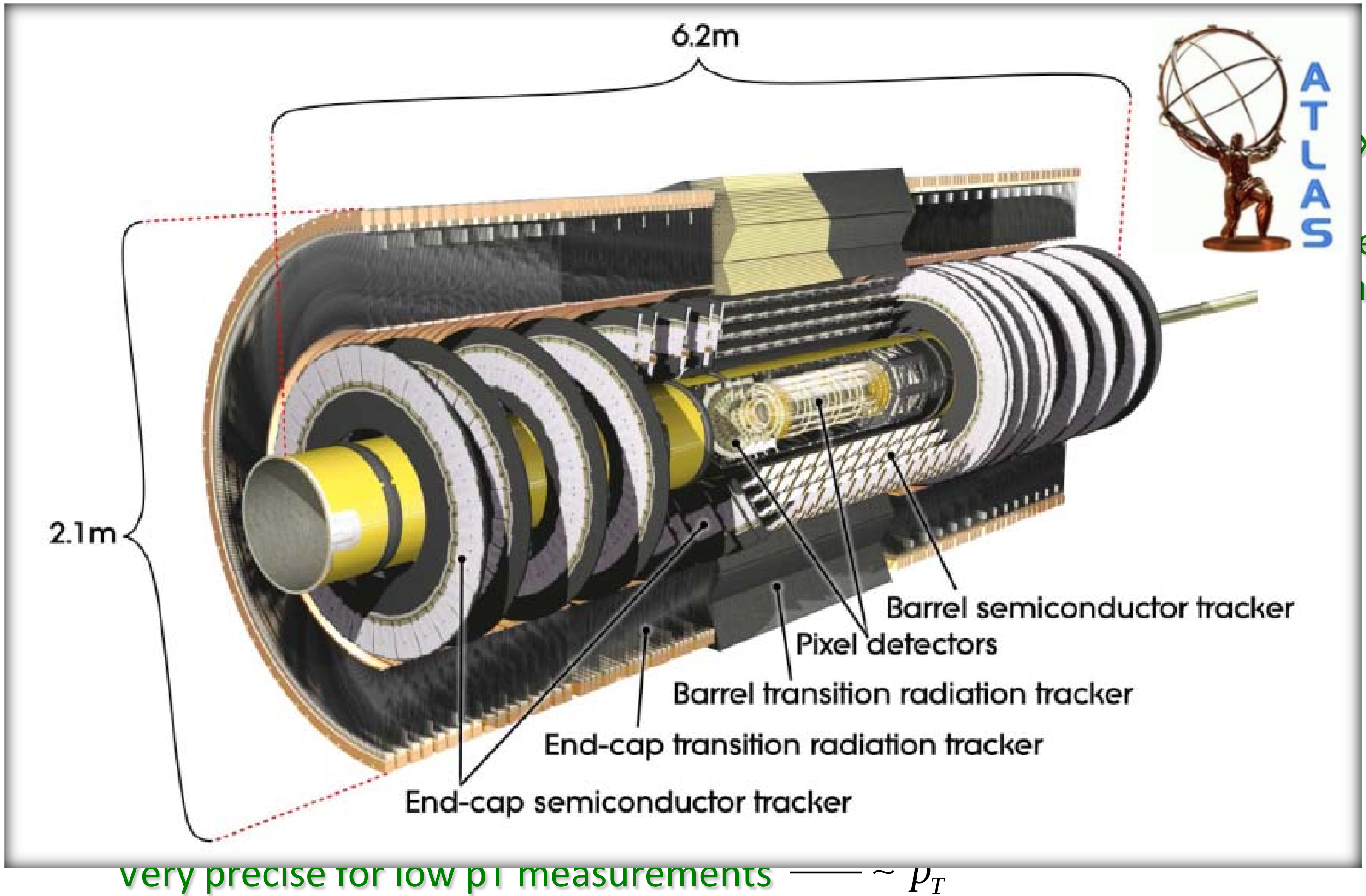
Total weight: 12500 t
Overall length: 22 m
Overall diameter: 15 m
Magnetic field: 4T solenoid

Tracking (inner detector)

- Closest to the interaction vertex
- Reconstructs charged particle tracks in magnetic field
    - Charged particles generate current Silicon pixel elements → fit tracks to (x,y,z) space points defined by hit sensor location
    - Collect secondary charges from gas ionizations by passing charged particles on wires in electric fields → fit tracks to space point in (x,y) plane and z from pulse timing
    - Solenoid field allows very precise pT reconstruction and less precise p reconstruction
- Reconstructs interaction vertices
    - Vertex reconstructed from track fits
    - More than one vertex possible
        - B-decays
        - Multiple proton interaction (pile-up)
    - Primary vertex defined by $\sum_{\text{tracks}} p_T = \max$ or $\sum_{\text{tracks}} p_T^2 = \max$
- Advantages and limitations
    - Very precise for low pT measurements $\frac{\Delta p_T}{p_T} \sim p_T$
    - Only sensitive to charged particles
    - Limited polar angle coverage
        - Forward region in experiment excluded

Detector Systems in Multi-purpose Collider Experiments (1)

Tracking (inner detector)



x,y,z)

es on

pulse

Very precise for low pT measurements $\frac{\quad}{p_T} \sim p_T$

Only sensitive to charged particles

Limited polar angle coverage

- Forward region in experiment excluded

Detector Systems in Multi-purpose Collider Experiments (2)

Calorimeters

- Usually wrapped around inner detector
- Measures the energy of charged and neutral particles
  - Uses the energy deposited by particles to generate signal
  - Collects light or electric charges/current from this energy deposit in relatively small volumes
  - Only works if particle energy can be fully absorbed
- Signals are space points with energy
  - Reconstructs direction and energy from known position of energy deposit
  - Needs assumption for “mass” to convert signal to full four momentum
    - ATLAS: $m = 0$
- Advantages and limitations
  - Gets more precise with increasing particle energy
  - Gives good energy measure for all particles except muons and neutrinos
    - Muons not fully absorbed!
  - Large coverage around interaction region
    - “4 π” detector – except for holes for beam pipes
  - Relation of incoming (deposited) energy and signal is particle type dependent
    - Also need to absorb all energy – large detector system
  - Does not work well for low energies
    - Particles have to reach calorimeter
    - Noise in readout
  - Slow signal formation in LHC environment

Detector Systems in Multi-purpose Collider Experiments (2)

Calori

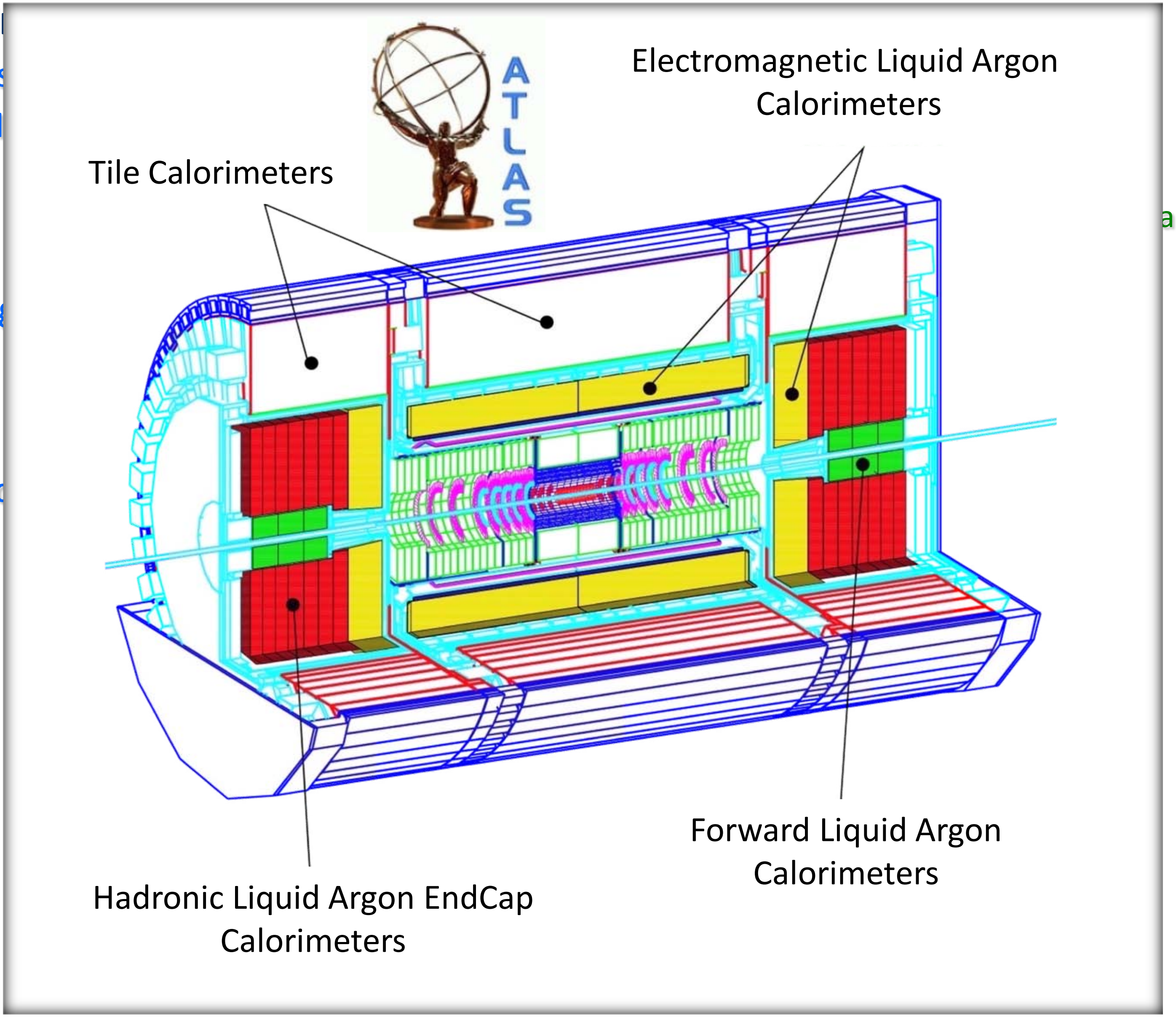
Us

M

all volumes

Si

Ac



Particle Interaction with Matter

Cascades or showers

- Most particles entering matter start a shower of secondary particles
  - Exception: muons and neutrinos
- The character of these cascades depends on the nature of the particle
  - Electrons, photons: cascades are formed by QED processes
  - Hadrons: cascades are dominantly formed by QCD processes
- Extensions/size of these showers
  - Again depends on particle type
  - Electromagnetic showers typically small and compact
  - Hadronic showers much larger
  - Common feature: shower depths scales approximately as log(E)
    - Higher energies do not require much deeper detectors!

Shower development and age

- Shower maximum
  - Depth at which energy of shower particles is too small to continue production of secondaries
- Age of shower
  - Depth of shower
- Shower width
  - Extend of shower perpendicular to direction of flight of incoming particle

Electromagnetic Showers

QED drives cascade development

- High energetic electrons entering material emit photons in the electric field of the nuclei
  - Bremsstrahlung
- High energetic photons produce e+e- pairs in the electric field of the nuclei
  - Pair production

Rossi’s shower model (1952!)

- Simple model of interplay of electron energy loss and photon pair production
  - Uses critical energy as cutoff for shower development

Electron energy loss through bremsstrahlung after 1 radiation length (X_0) in matter: $E_0/2$

Assume this energy is taken by 1 photon, meaning the energy of each shower particle after $t\ X_o$ is: $E(t) = E_0/2^{N(t)}$, with $N(t) = 2^t$

The shower develops until $E(t) = E_c$ (critical energy - ionization loss becomes large and suppresses further radiation) at the shower maximum $t_{\max} = \dfrac{\ln(E_0/E_c)}{\ln 2}$

Electromagnetic Showers

QED drives cascade development

- High energetic electrons entering material emit photons in the electric field of the nuclei
  - Bremsstrahlung
- High energetic photons produce e+e- pairs in the electric field of the nuclei
  - Pair production

Rossi's shower model (1952!)

- Simple model of interplay of electron energy loss and photon pair production
  - Uses critical energy as cutoff for shower development

Electron energy loss through bremsstrahlung after 1 radiation length (X_0) in matter: $E_0/2$

Assume this energy is taken by 1 photon, meaning the energy of each shower particle after $t\ X_o$ is: $E(t) = E_0/2^{N(t)}$, with $N(t) = 2^t$

The shower develops until $E(t) = E_c$ (critical energy - ionization loss becomes large and suppresses further radiation) at the shower maximum $t_{\max} = \dfrac{\ln(E_0/E_c)}{\ln 2}$

Electromagnetic Showers

QED drives cascade development

- High energetic electrons entering material emit photons in the electric field of the nuclei
  - Bremsstrahlung
- High energetic photons produce e+e- pairs in the electric field of the nuclei
  - Pair production

Rossi's shower model (1952!)

- Simple model of interplay of electron energy loss and photon pair production
  - Uses critical energy as cutoff for shower development

Electron energy loss through bremsstrahlung after 1 radiation length (X_0) in matter: $E_0/2$

Assume this energy is taken by 1 photon, meaning the energy of each shower particle after $t\ X_o$ is: $E(t) = E_0 / 2^{N(t)}$, with $N(t) = 2^t$

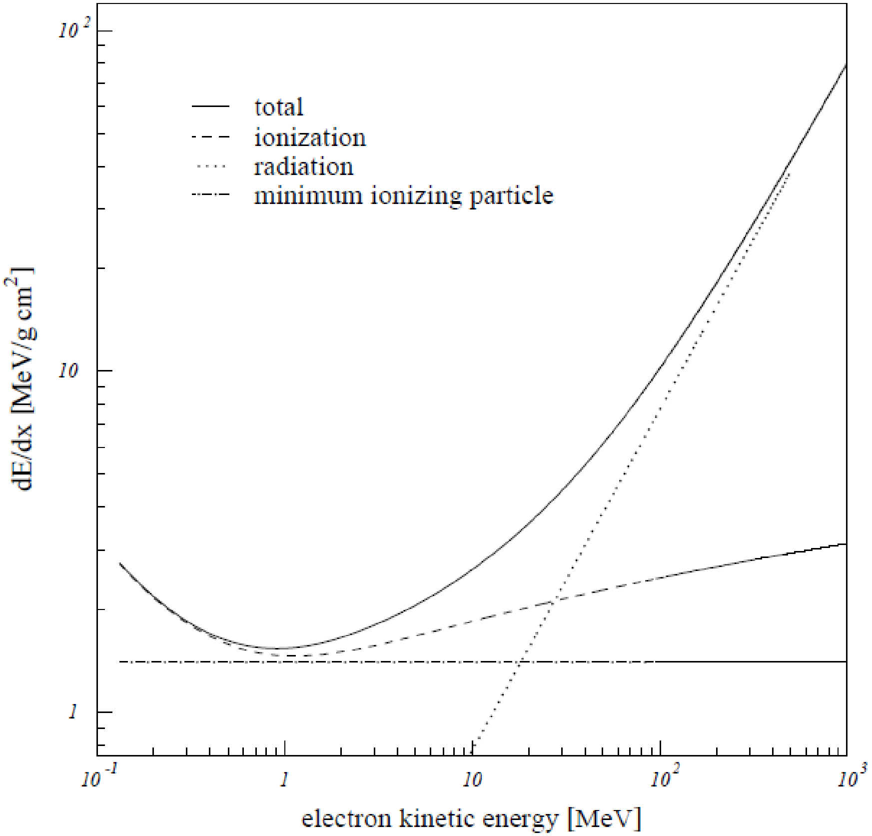
The shower develops until $E(t) = E_c$ (critical energy - ionization loss becomes large and suppresses further radiation) at the shower maximum $t_{\max} = \dfrac{\ln(E_0/E_c)}{\ln 2}$

Electromagnetic Showers

- **QED drives cascade development**
  - High energetic electrons entering material emit photons in the electric field of the nuclei
    - Bremsstrahlung
  - High energetic photons produce e+e- pairs in the electric field of the nuclei
    - Pair production
- **Rossi's shower model (1952!)**
  - Simple model of interplay of electron energy loss and photon pair production
    - Uses critical energy as cutoff for shower development

Electron energy loss through bremsstrahlung after 1 radiation length (X_0) in matter: $E_0/2$

Assume this energy is taken by 1 photon, meaning the energy of each shower particle after $t\ X_0$ is: $E(t)=E_0/2^{N(t)}$, with $N(t)=2^t$



Electromagnetic Showers

QED drives cascade development

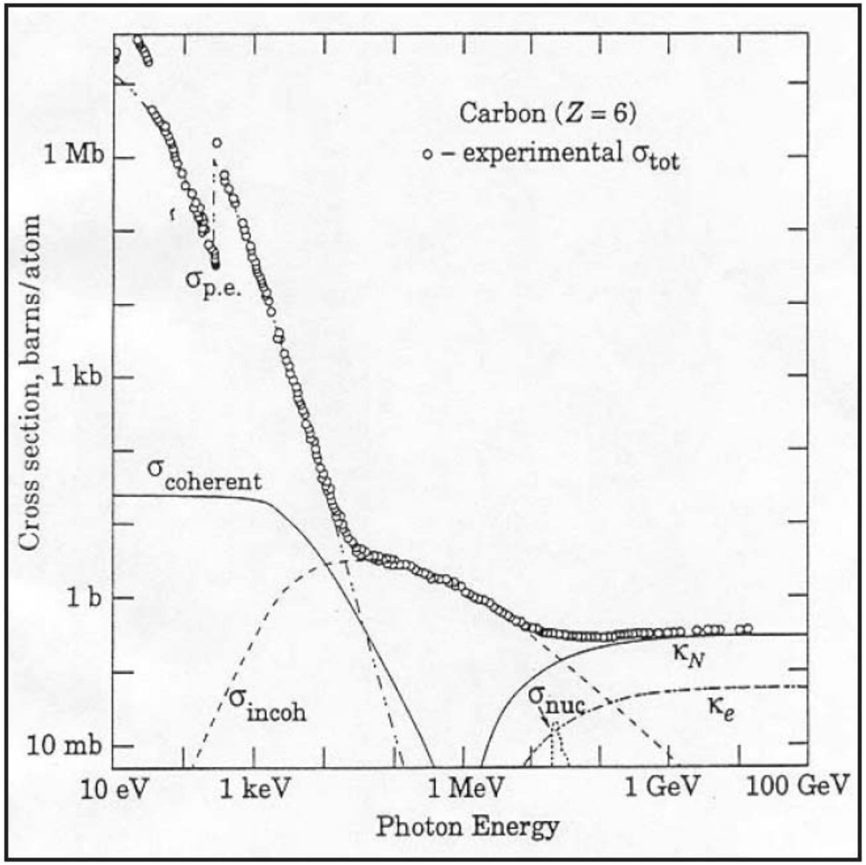
- High energetic electrons entering material emit photons in the electric field of the nuclei
  - Bremsstrahlung
- High energetic photons produce e+e- pairs in the electric field of the nuclei
  - Pair production

Rossi's shower model (1952!)

- Simple model of interplay of electron energy loss and photon pair production
  - Uses critical energy as cutoff for shower development

Electron energy loss through bremsstrahlung after 1 radiation length (X_0) in matter: $E_0/2$

Assume this energy is taken by 1 photon, meaning the energy of each shower particle after $t\ X_0$ is: $E(t)=E_0/2^{N(t)}$, with $N(t)=2^t$



Hadronic Showers

QCD drives fast shower development

- Hadron interacts with nucleon in nuclei
  - Like a fixed target collision
  - Develops intra-nuclear cascade (fast)
- Hadron production
  - Secondary hadrons escape nucleus
  - Neutral pions decay immediately into 2 photons → electromagnetic cascade
  - Other hadrons can hit other nucleons → internuclear cascade

Slow de-excitation of nuclei

- Remaining nucleus in excited state
  - Evaporates energy to reach stable (ground) state
  - Fission and spallation possible
- Binding energy and low energetic photons

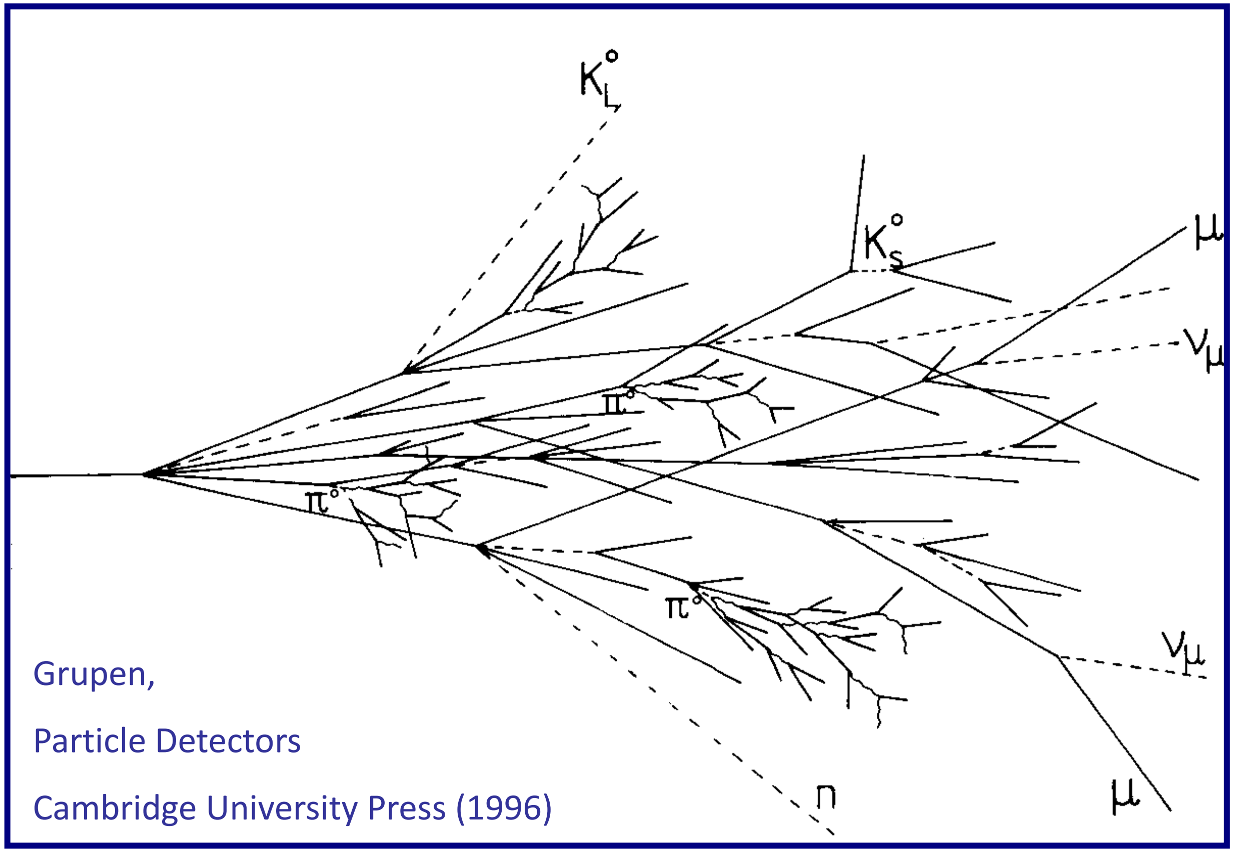
Large process fluctuations

- ~200 different interactions
- Probability for any one of those < 1%!

Hadronic Showers

QCD drives fast shower development

- Hadron interacts with nucleon in nuclei



Grupen,

Particle Detectors

Cambridge University Press (1996)

- Had

etic cascade

Slow d

- Rem

- Binc

Large p

- ~200 different interactions
- Probability for any one of those < 1%!