Title: The Standard Model Experiment: Detectors

Date: Jul 15, 2015 10:15 AM

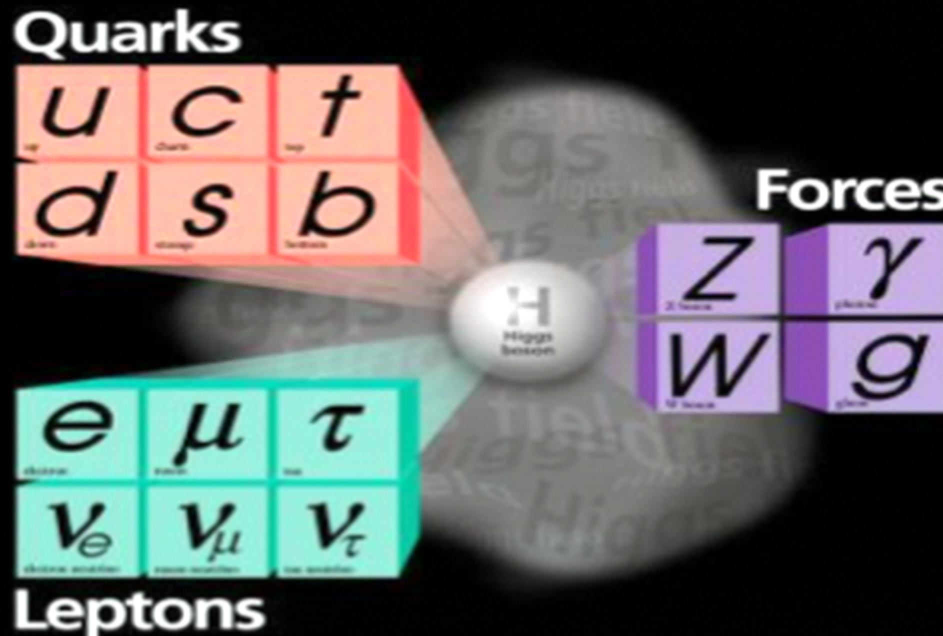
URL: http://pirsa.org/15070048

Abstract:

The Standard Model

Some important dates

1967:
  "A Model of Leptons"
  (Weinberg)
1971-73:
  Renormalizability of theory,
  Quantum Chromodynamics
  asymptotic freedom, weak neutral
  current observation
Mid-to-late 70s:
  Discoveries of c and b quarks,
  tau lepton
Early 80s:
  Discovery of the W and Z bosons
1995:
  Discovery of the top quark
2012:
  Discovery of the Higgs boson



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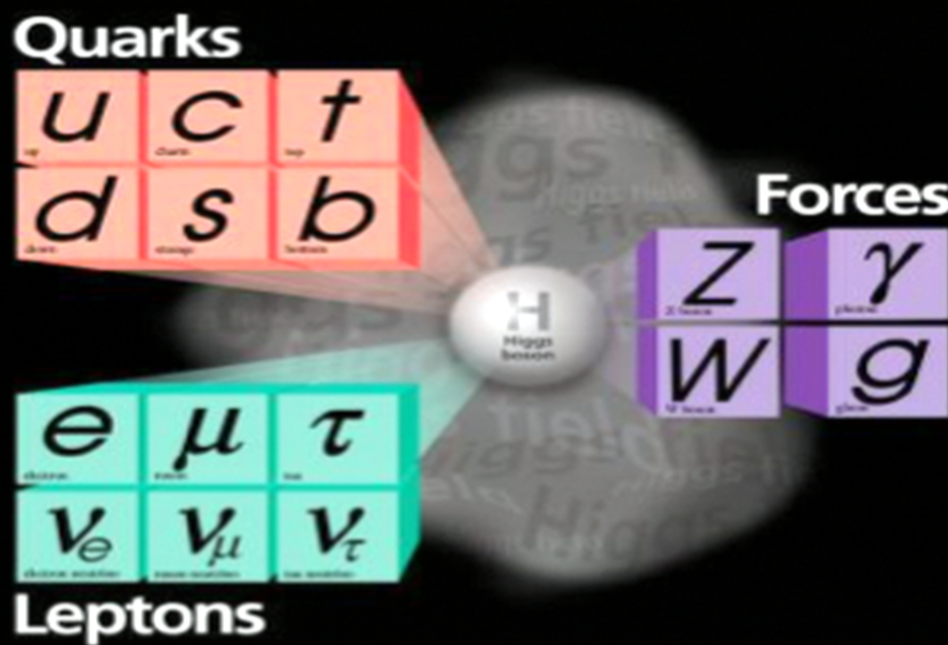

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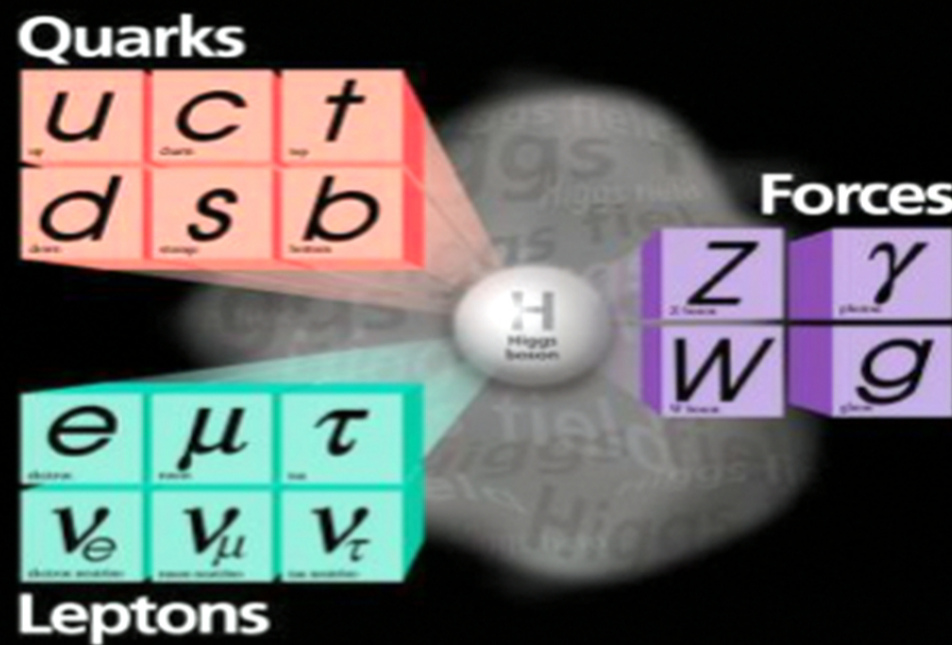
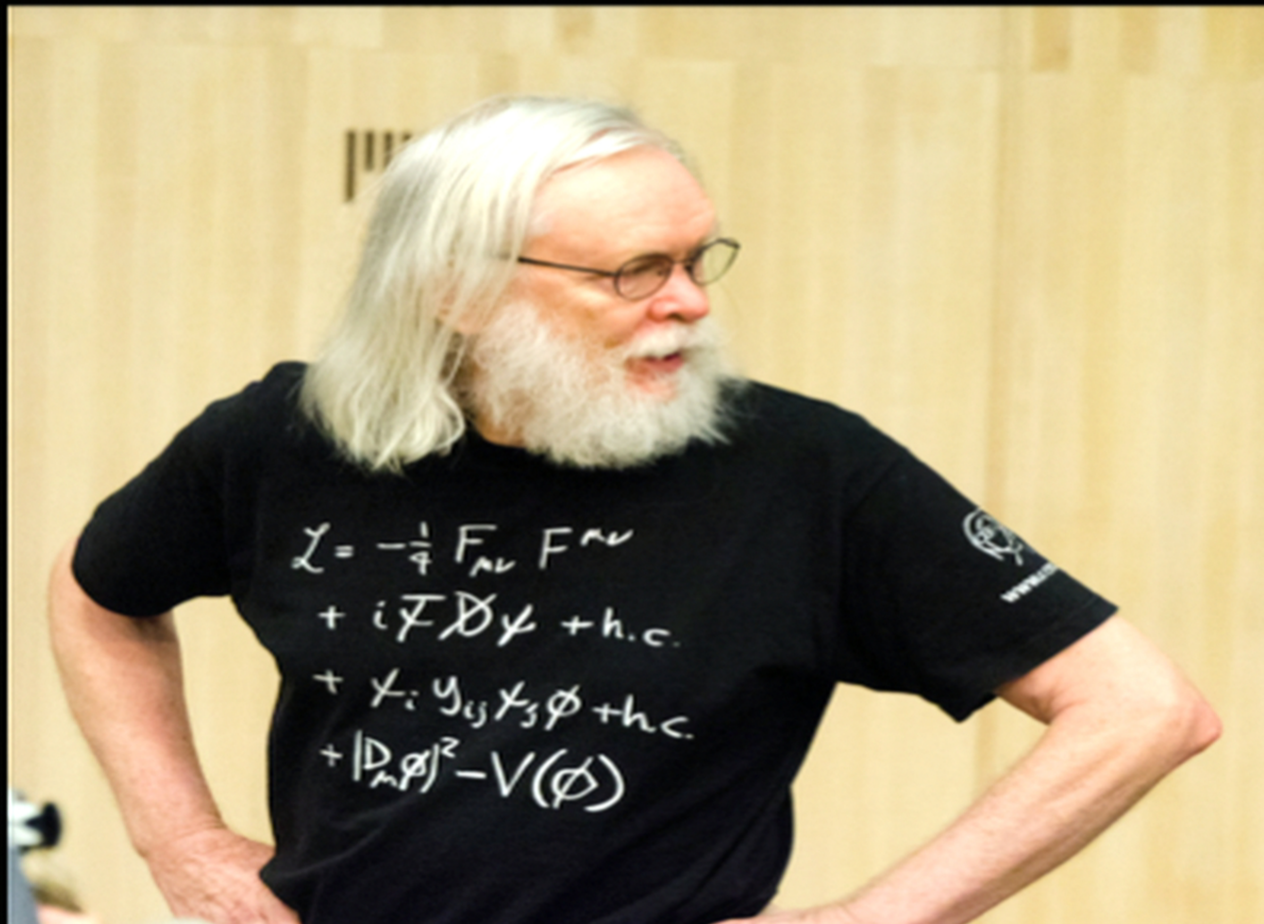


The Standard Model Lagrangian



The Standard Model

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R\sigma^\mu iD_\mu e_R + \bar{\nu}_R\sigma^\mu iD_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu iD_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R\sigma^\mu iD_\mu u_R + \bar{d}_R\sigma^\mu iD_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}
$$

where (h.c.) means Hermitian conjugate of preceeding terms, $\bar{\psi} = \text{(h.c.)}\psi = \psi^\dagger = \psi^{*T}$, and the derivative operators are

$$D_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad D_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix} u_L \\ d_L \end{pmatrix}. \quad (2)$$

$$D_\mu \nu_R = \partial_\mu \nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\, e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R, \quad (3)$$

$$D_\mu \phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi. \quad (4)$$

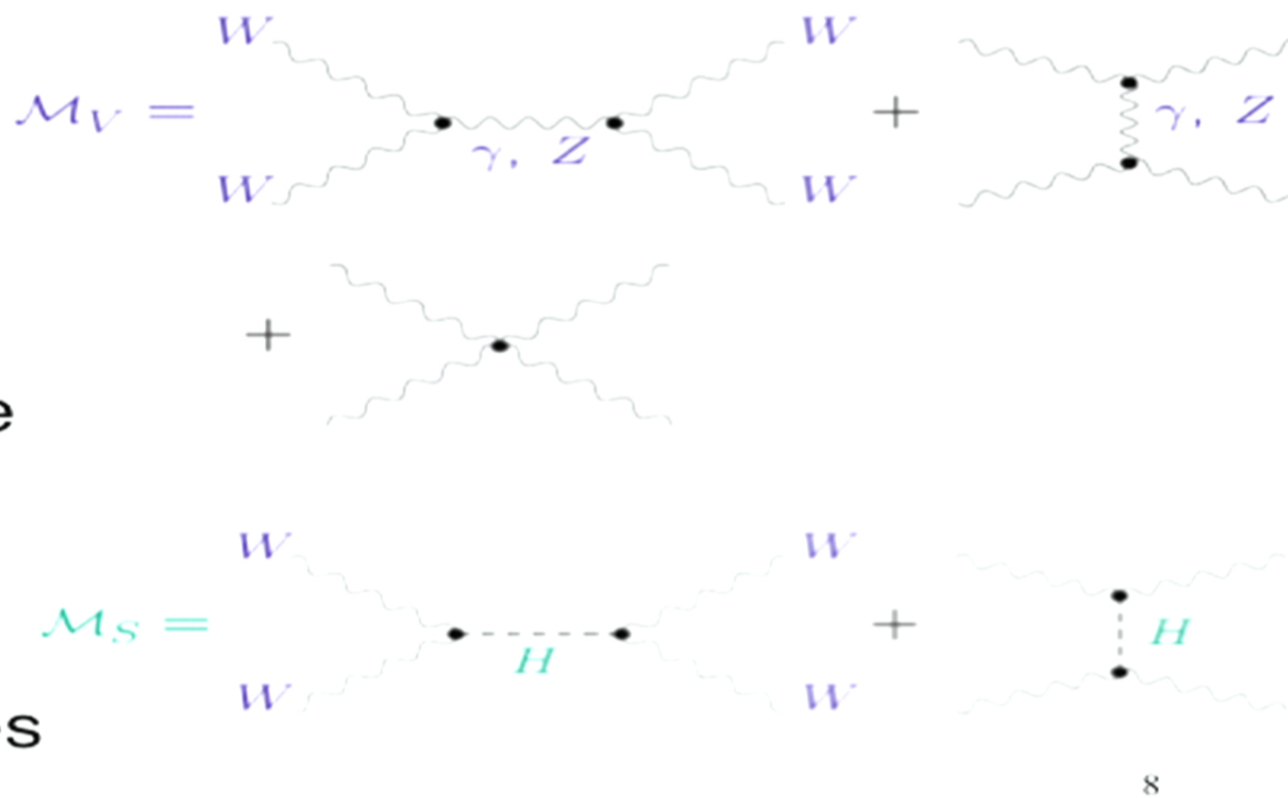
First Lecture

In this first lecture, I will focus on providing an overview of how modern detectors work by using the ATLAS and CMS detectors as examples

Normally, a full course is required to go into the details of how each part of the detector works. Here I will show you how the various pieces of the detectors look and give you an rough idea of how they work.

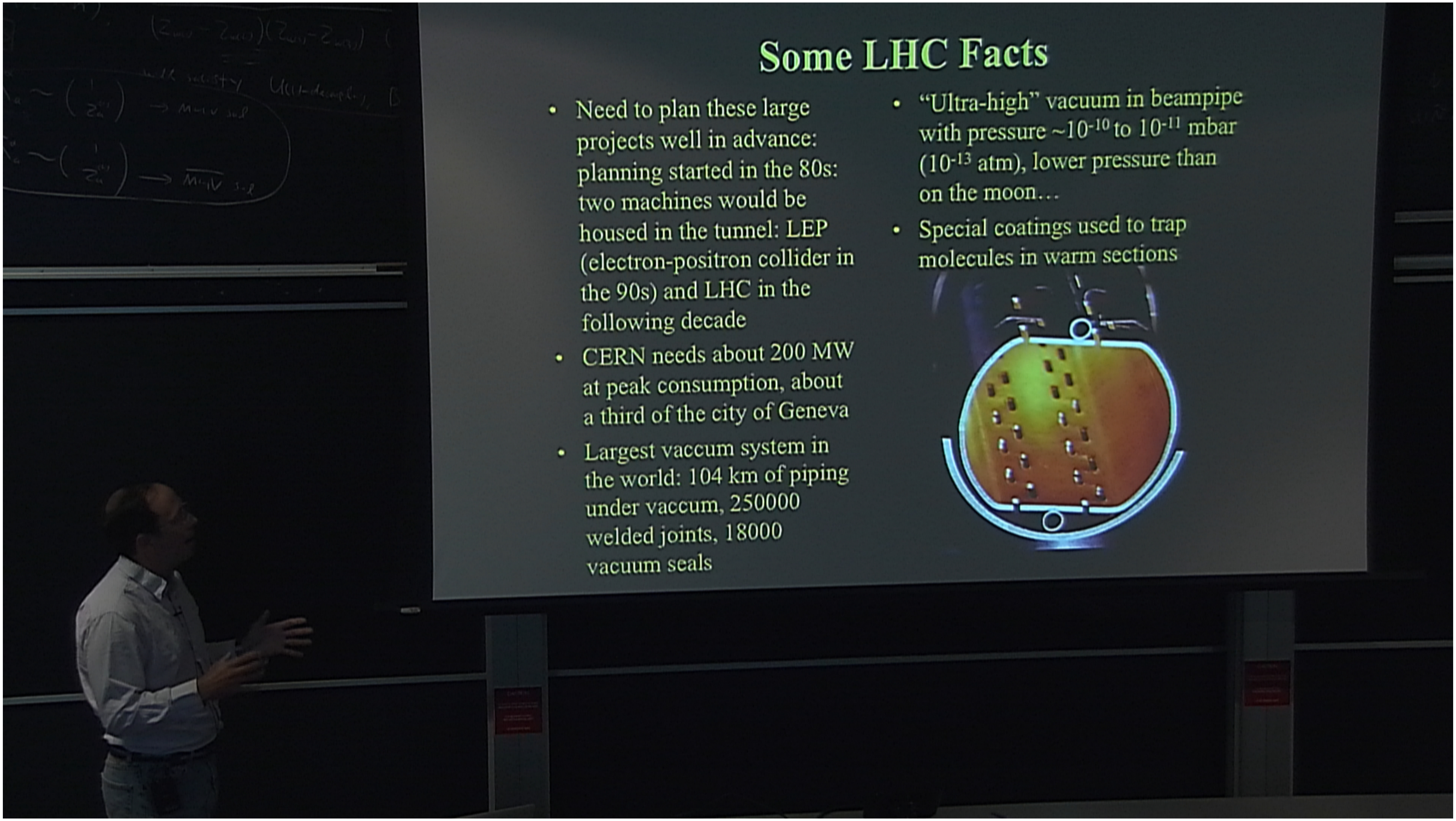
WW Scattering and the Higgs Boson

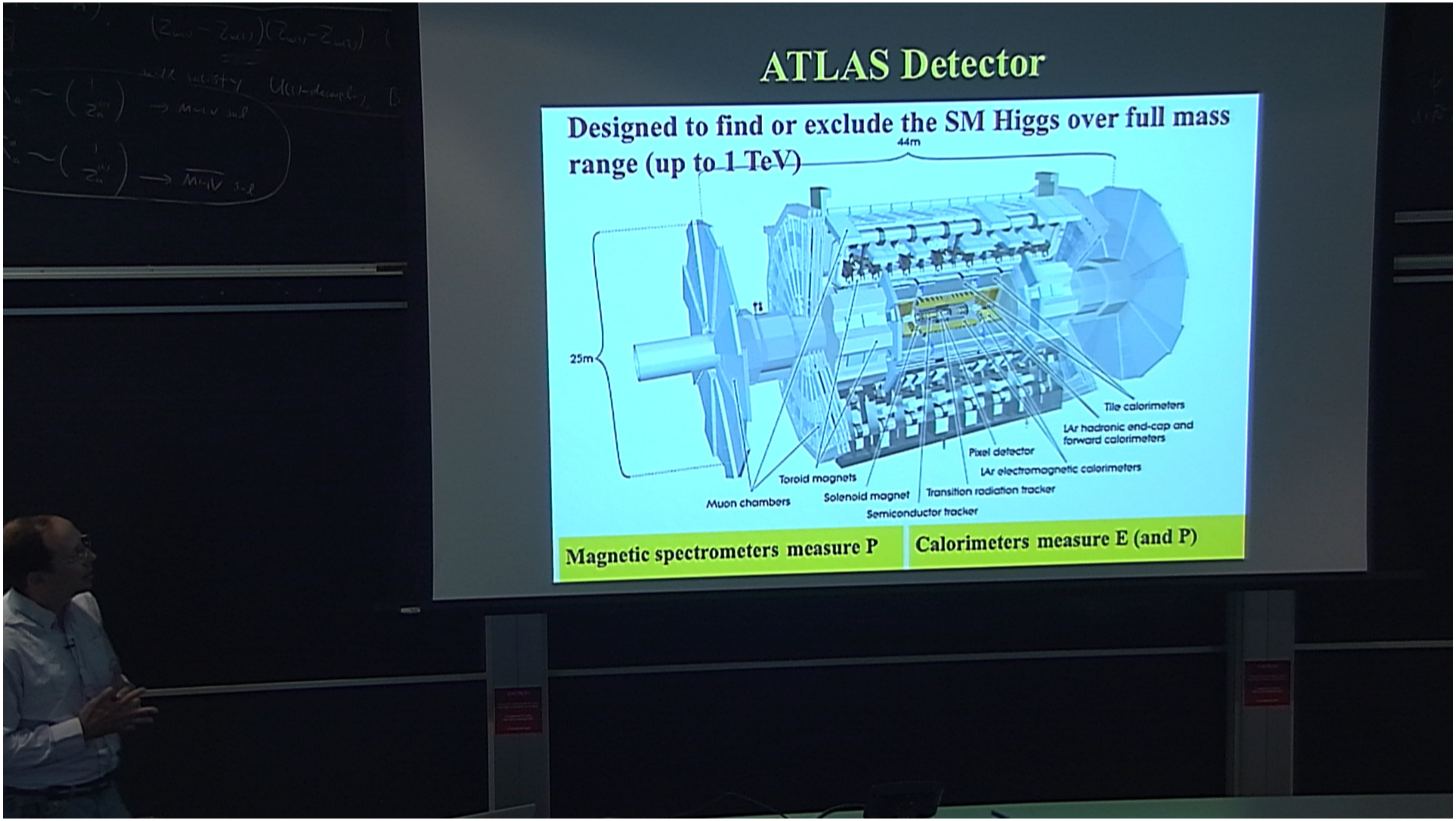
- WW scattering violates unitarity above ~1 TeV
- New diagrams needed to regulate the cross section
- Adding diagrams with a scalar solves the problem

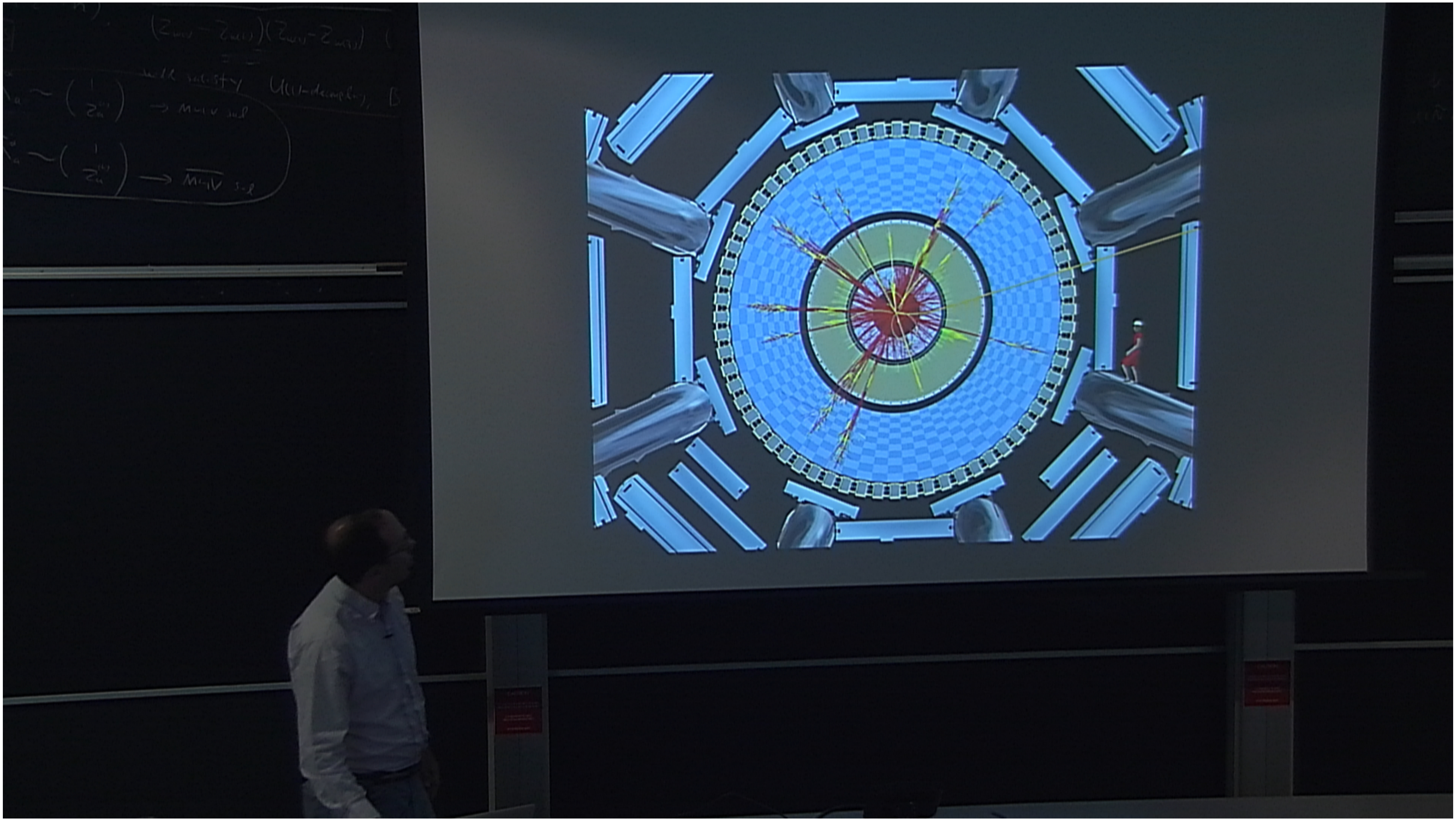


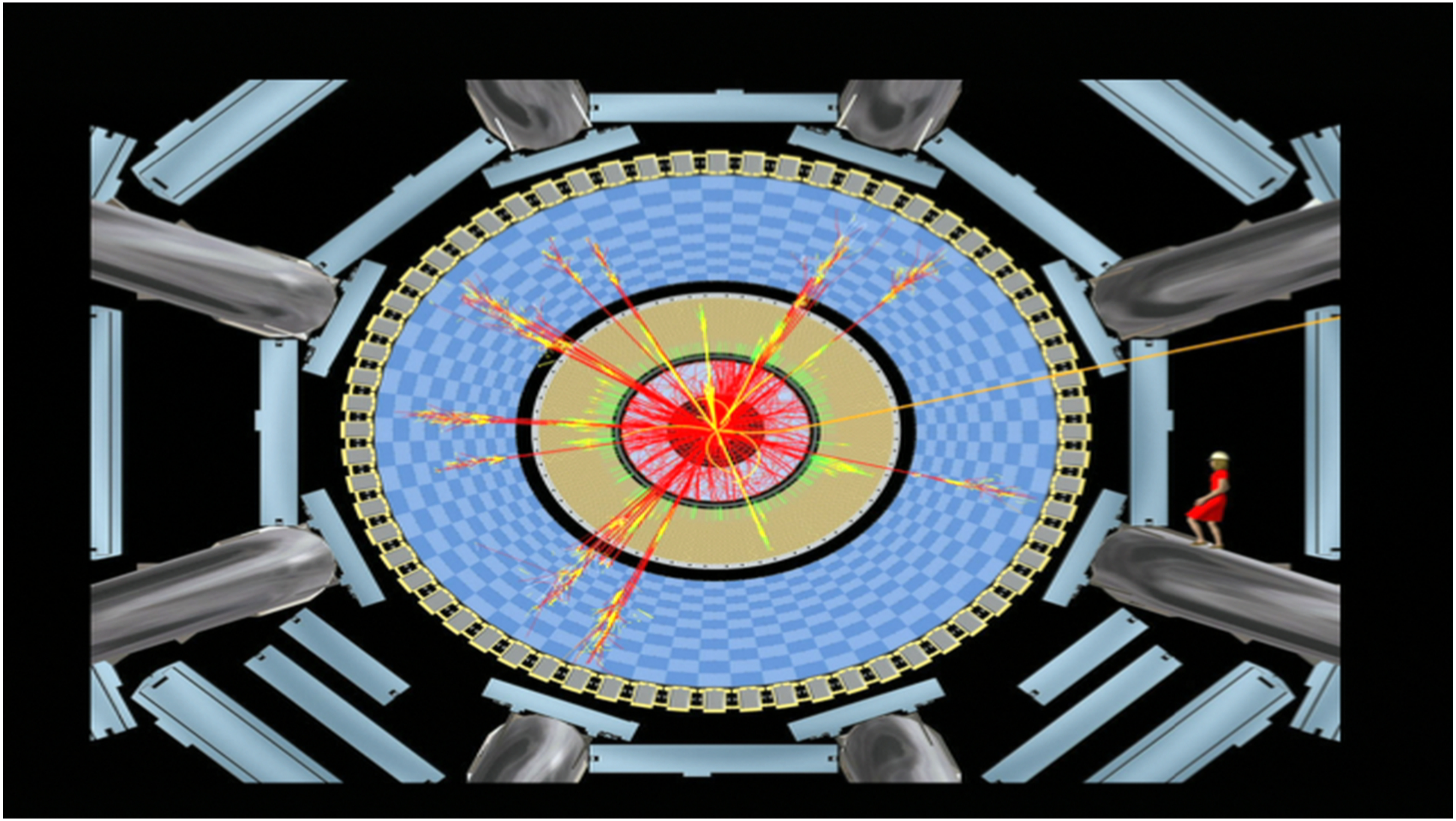
The Large Hadron Collider (LHC)

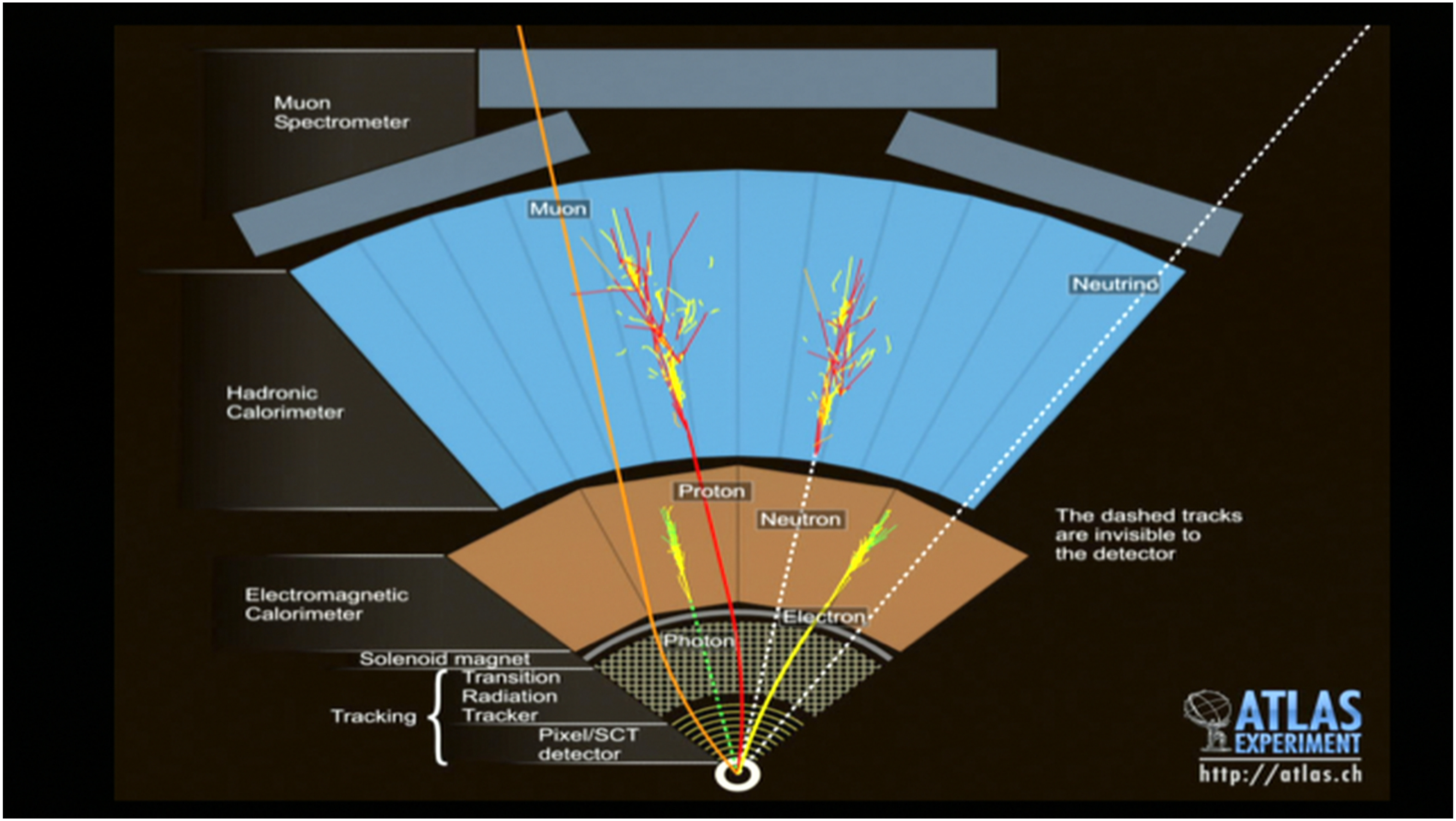
- A 27 km long circular collider at CERN near Geneva
- Collides bunches of protons on protons at every 25/50ns
- Produces up to ~800 million collisions per second
- Plan to reach ~design energy in 2015-2018

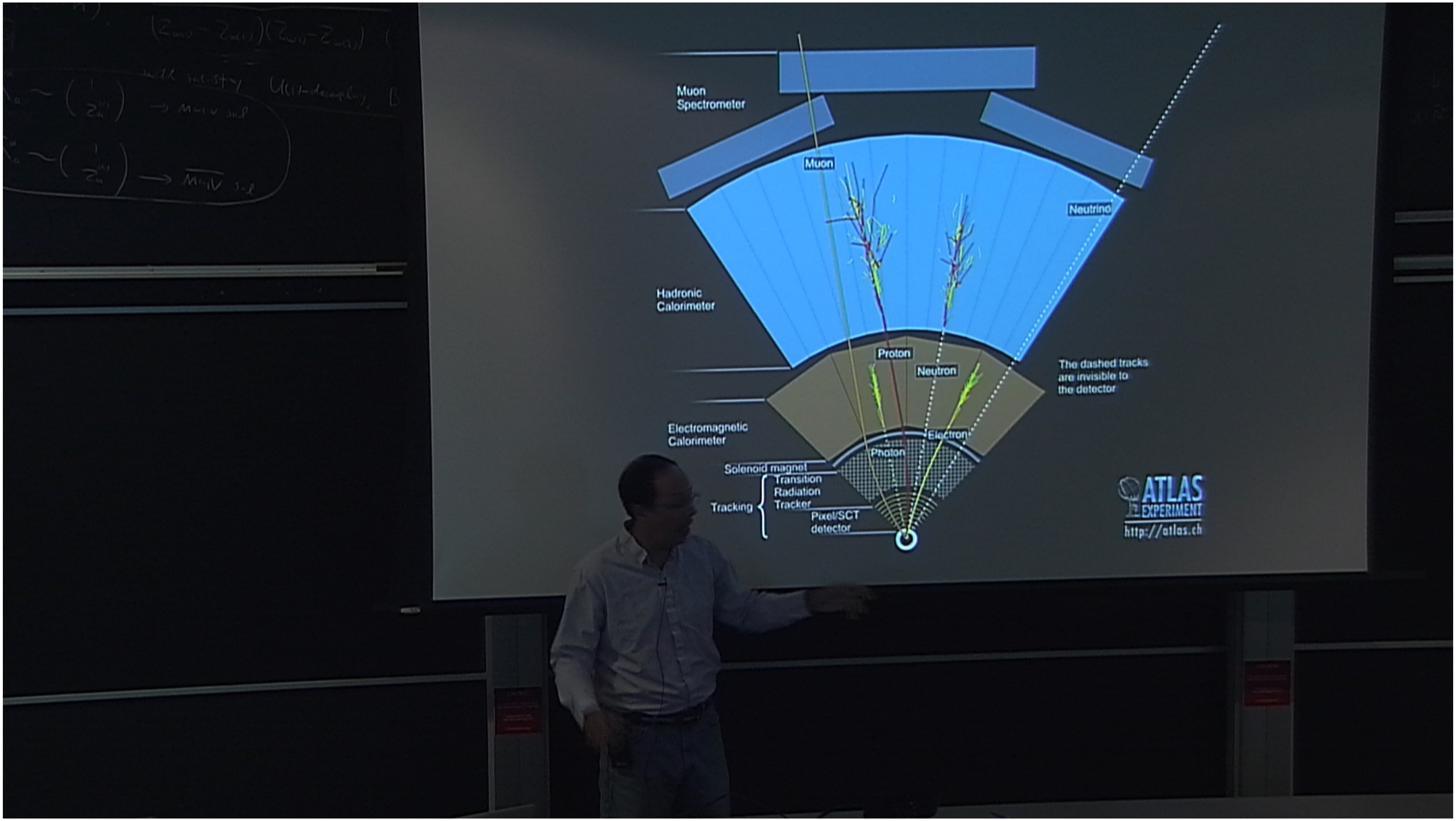

Some LHC Facts
Need to plan these large projects well in advance: planning started in the 80s: two machines would be housed in the tunnel: LEP (electron-positron collider in the 90s) and LHC in the following decade
CERN needs about 200 MW at peak consumption, about a third of the city of Geneva
Largest vaccum system in the world: 104 km of piping under vaccum, 250000 welded joints, 18000 vacuum seals
"Ultra-high" vacuum in beampipe with pressure ~10-10 to 10-11 mbar (10-13 atm), lower pressure than on the moon…
Special coatings used to trap molecules in warm sections


ATLAS Detector
Designed to find or exclude the SM Higgs over full mass range (up to 1 TeV)
44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker
Magnetic spectrometers measure P
Calorimeters measure E (and P)






Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch



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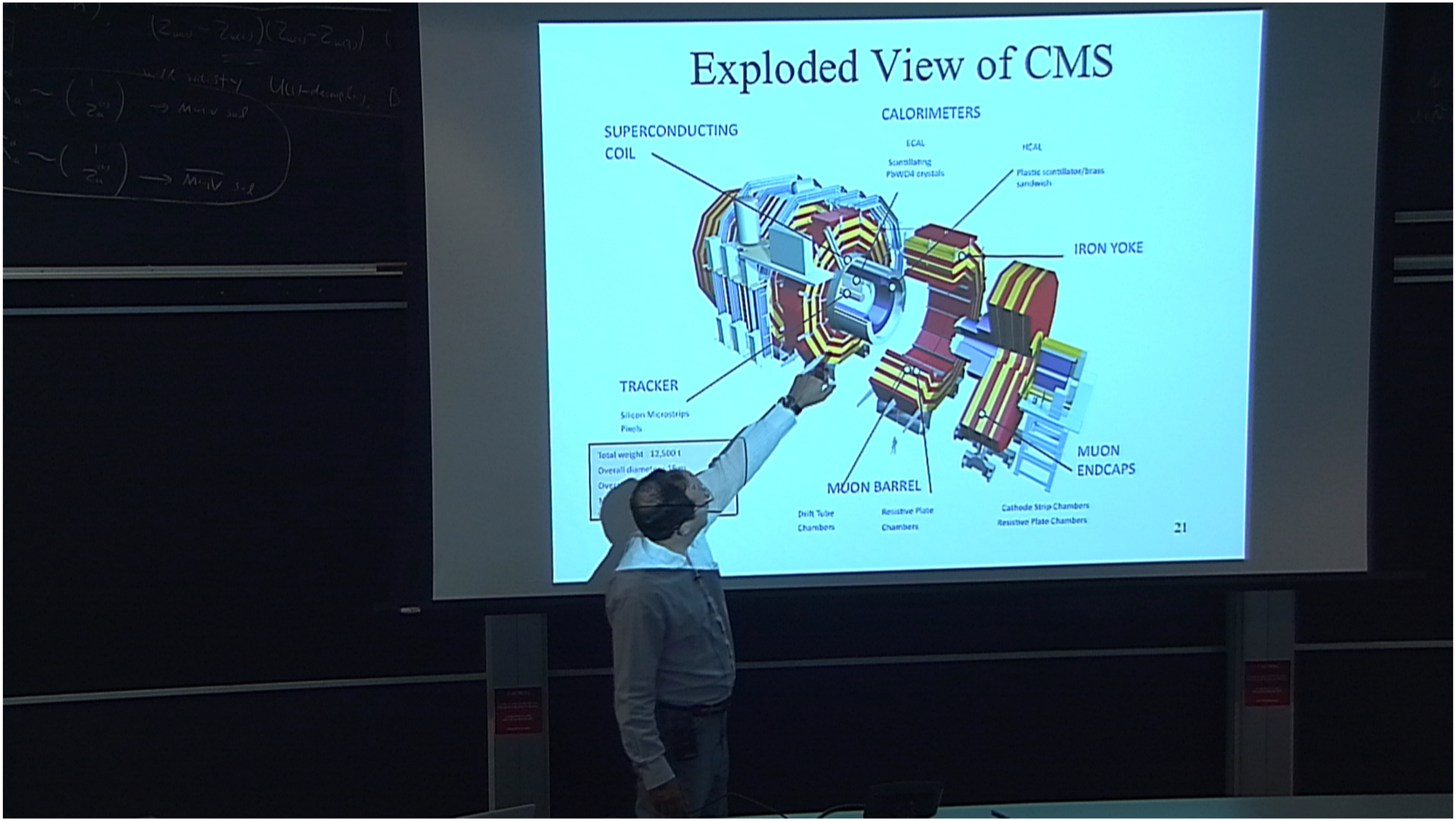
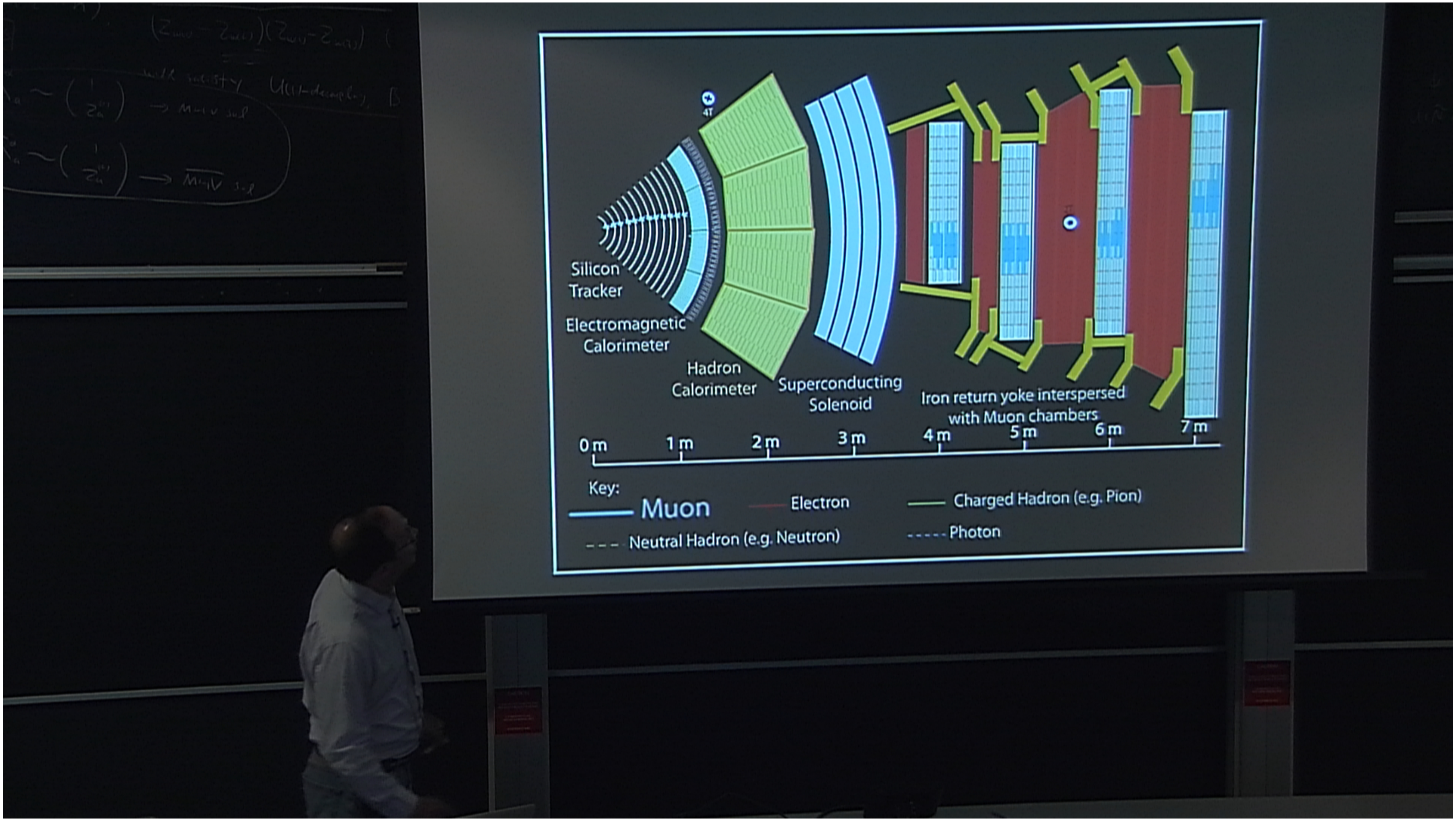

Exploded View of CMS
CALORIMETERS
SUPERCONDUCTING
COIL
ECAL
Scintillating
PbWO4 crystals
HCAL
Plastic scintillator/brass
sandwich
IRON YOKE
TRACKER
Silicon Microstrips
Pixels
Total weight : 12,500 t
MUON BARREL
Drift Tube
Chambers
Resistive Plate
Chambers
MUON
ENDCAPS
Cathode Strip Chambers
Resistive Plate Chambers
21



4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

Particle Interactions

- Electrically charged particles
  - Scattering
  - Ionization (liberating electrons from atoms)
    - Bethe-Bloch formula (next)
  - Atomic excitation
    - (leads to light emission (e.g. scintillation) when electrons go down to original levels)
  - Photon radiation
    - Bremsstrahlung (accelerated or decelerated charge emits photons)
    - Transition radiation (light emission (x-rays)) when particles goes through media with different indexes
    - Cherenkov light (faster than light in a medium)
- Strongly charged particles
  - Results in nuclear fragments, excited products that can emit photons
  - In general, results in less visible energy than em interactions (binding energy, neutrinos, muons)
- Photons
  - Compton Scattering
  - Photoelectric Effect
  - Pair production

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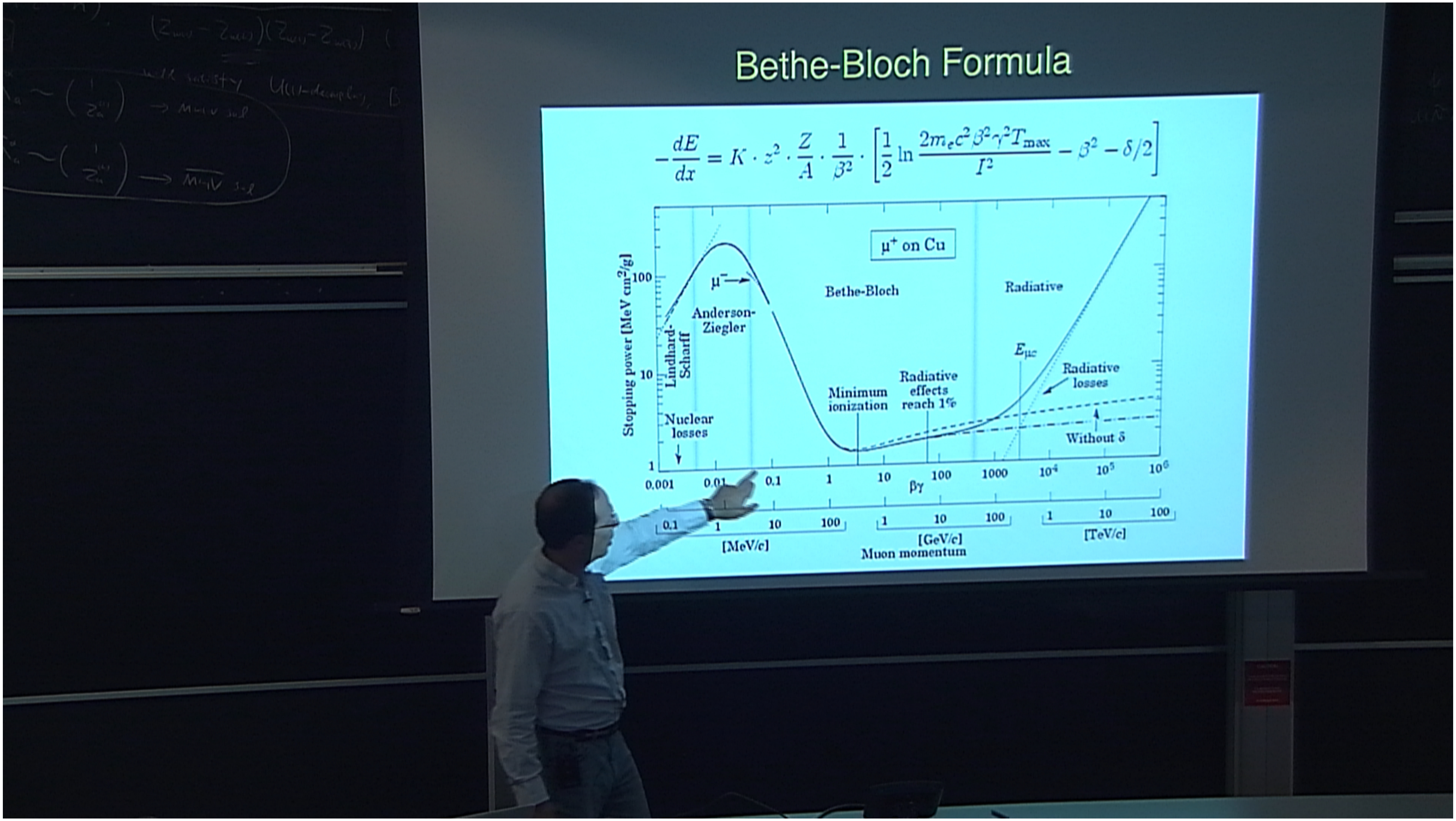
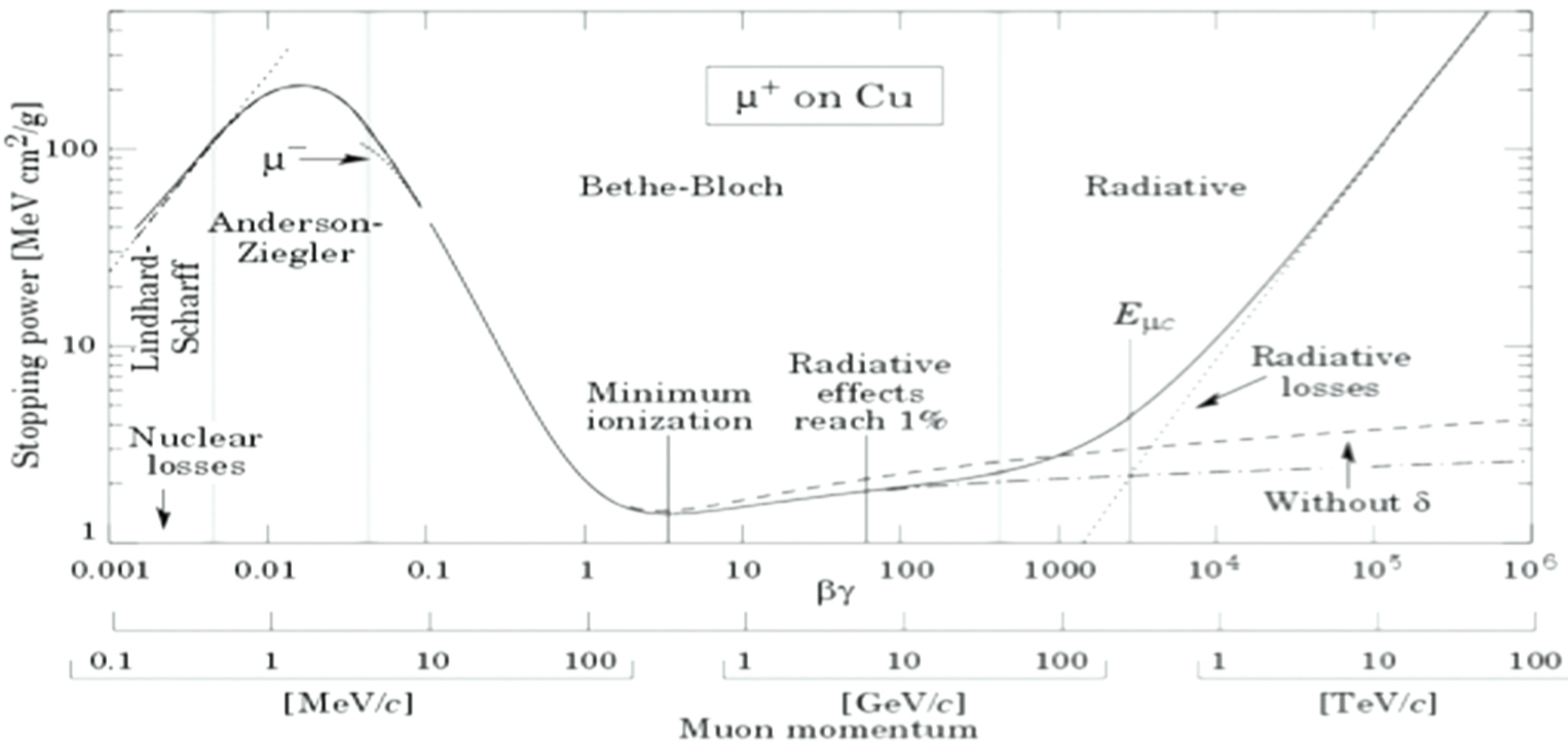
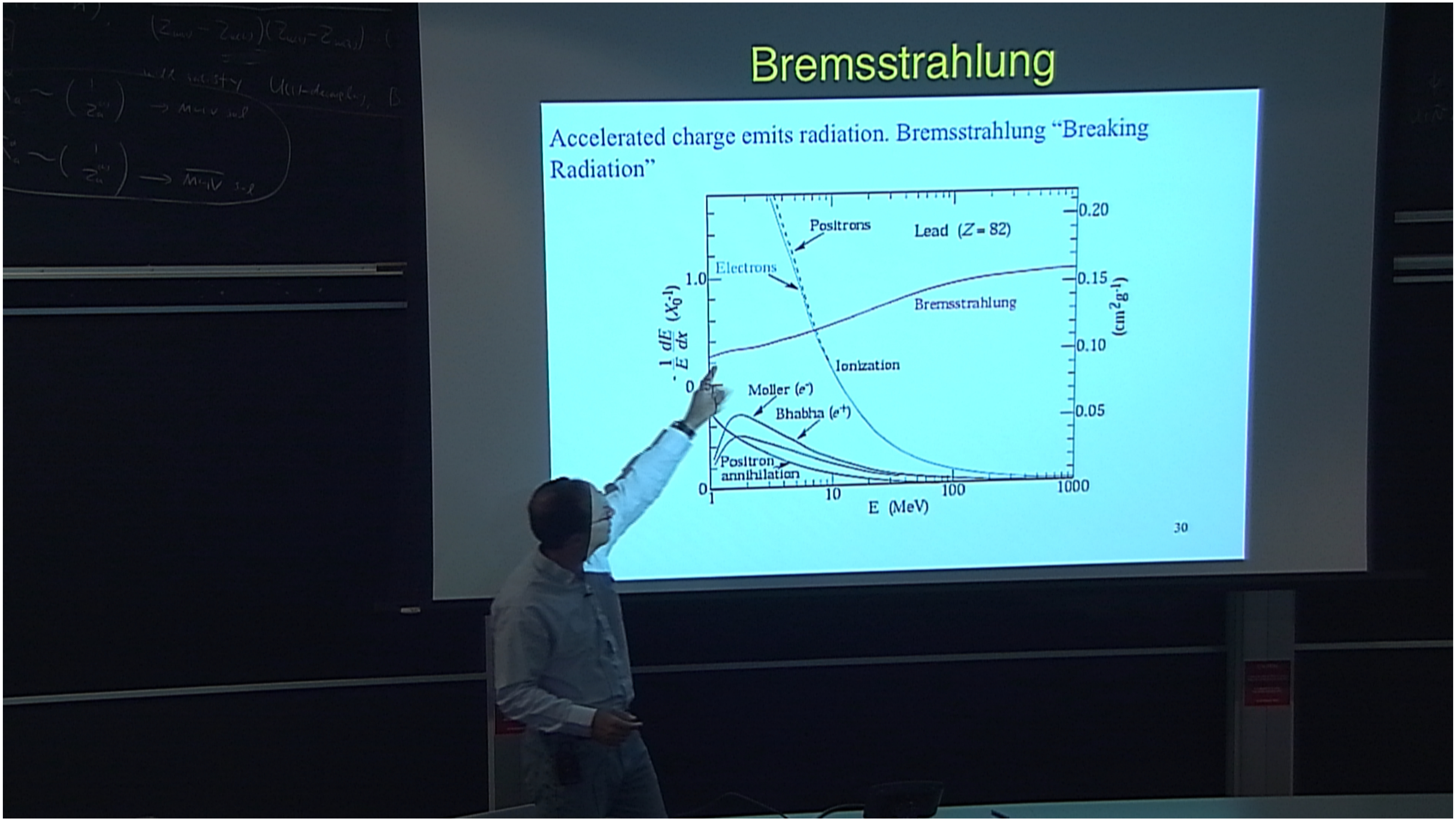


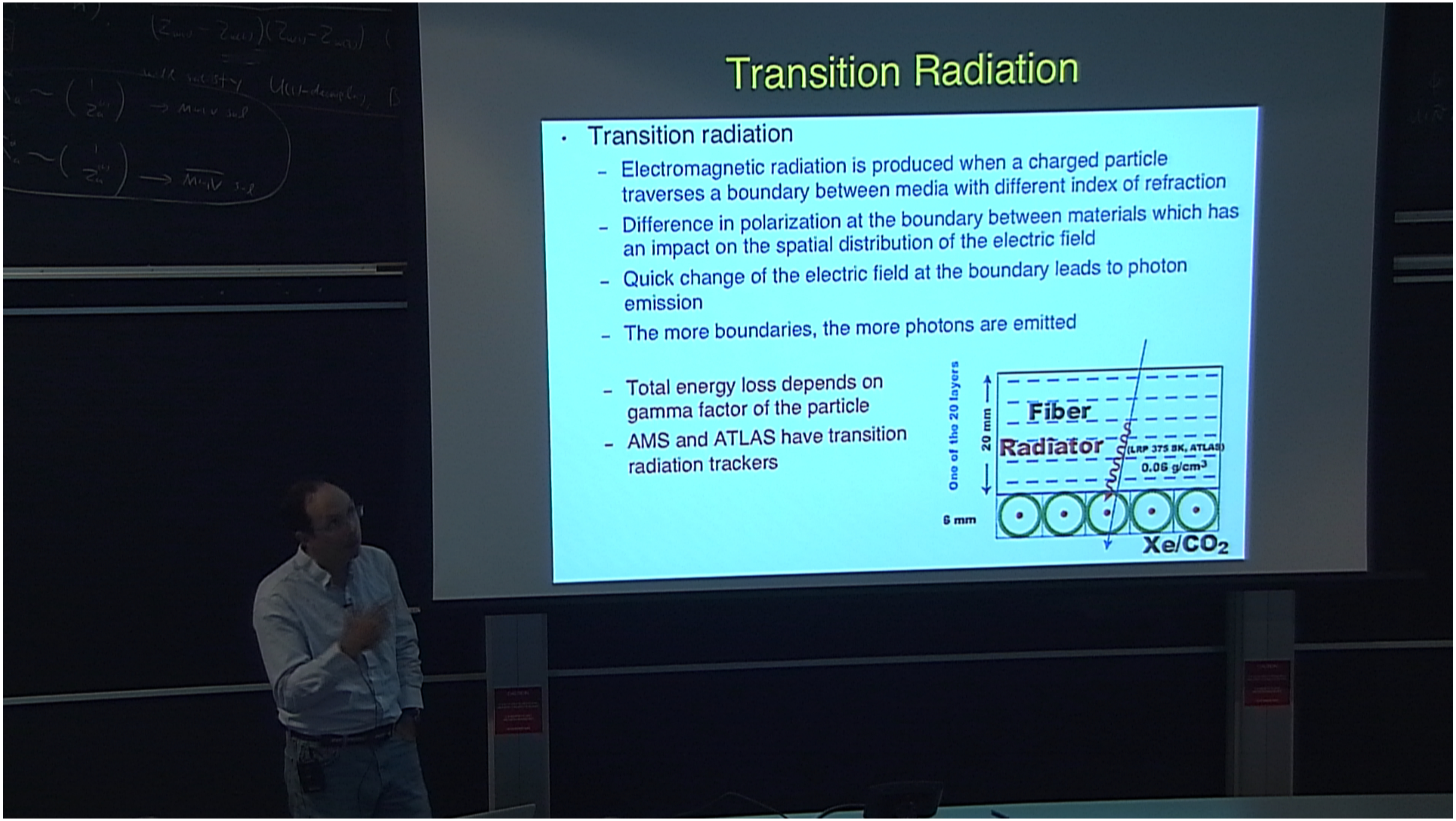
Bethe-Bloch Formula
$$-\frac{dE}{dx} = K \cdot z^2 \cdot \frac{Z}{A} \cdot \frac{1}{\beta^2} \cdot \left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2} - \beta^2 - \delta/2\right]$$
μ+ on Cu
Stopping power [MeV cm2/g]
Lindhard-Scharff
Anderson-Ziegler
μ−
Bethe-Bloch
Radiative
Nuclear losses
Minimum ionization
Radiative effects reach 1%
Eμc
Radiative losses
Without δ
βγ
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

Bethe-Bloch Formula

$$-\frac{dE}{dx} = K \cdot z^2 \cdot \frac{Z}{A} \cdot \frac{1}{\beta^2} \cdot \left[\frac{1}{2}\ln\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \delta/2\right]$$




Bremsstrahlung
Accelerated charge emits radiation. Bremsstrahlung "Breaking Radiation"
Positrons
Lead (Z = 82)
Electrons
Bremsstrahlung
Ionization
Moller (e⁻)
Bhabha (e⁺)
Positron annihilation
E (MeV)
1
10
100
1000
0.20
0.15
0.10
0.05
1.0
0
(cm²g⁻¹)
30



Transition Radiation
Transition radiation
Electromagnetic radiation is produced when a charged particle traverses a boundary between media with different index of refraction
Difference in polarization at the boundary between materials which has an impact on the spatial distribution of the electric field
Quick change of the electric field at the boundary leads to photon emission
The more boundaries, the more photons are emitted
Total energy loss depends on gamma factor of the particle
AMS and ATLAS have transition radiation trackers
One of the 20 layers
20 mm
Fiber
Radiator
(LRP 375 BK, ATLAS)
0.06 g/cm3
6 mm
Xe/CO2

Transition Radiation

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  - Electromagnetic radiation is produced when a charged particle traverses a boundary between media with different index of refraction
  - Difference in polarization at the boundary between materials which has an impact on the spatial distribution of the electric field
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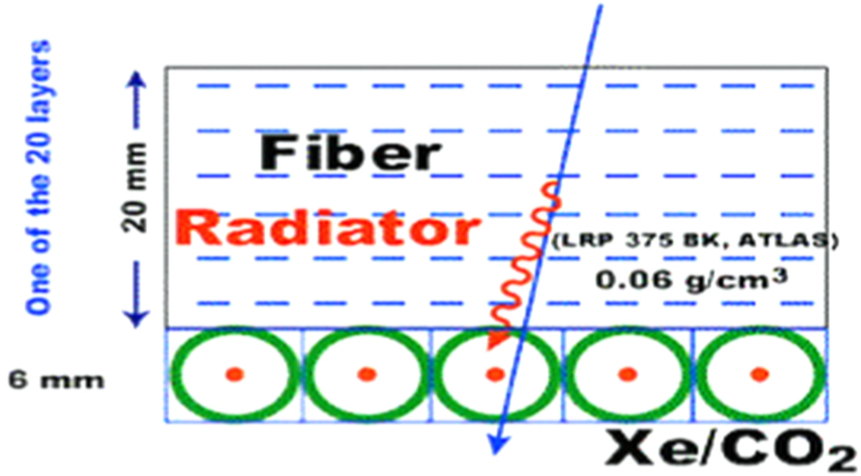
  - Total energy loss depends on gamma factor of the particle
  - AMS and ATLAS have transition radiation trackers



Magnetic Spectrometers

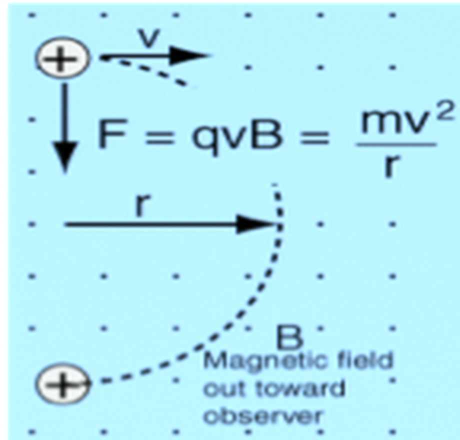
$$r = \frac{mv^2}{qvB} = \frac{mv}{qB}$$ Radius of path produced by magnetic field

If the velocity v is produced by an accelerating voltage V:

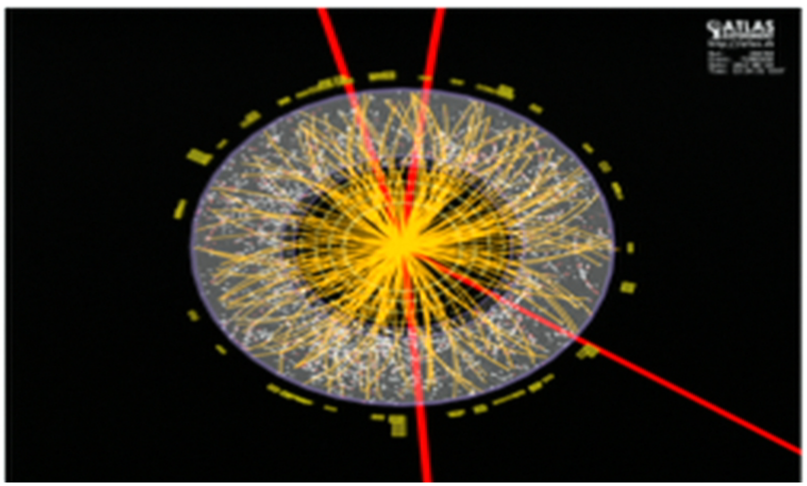
$$\frac{1}{2}mv^2 = qV\ ; \quad v = \sqrt{\frac{2qV}{m}}$$

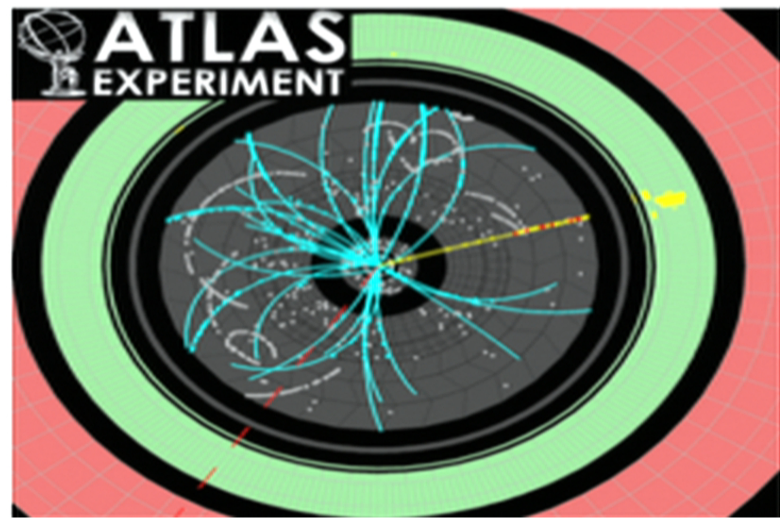
Substitution gives:

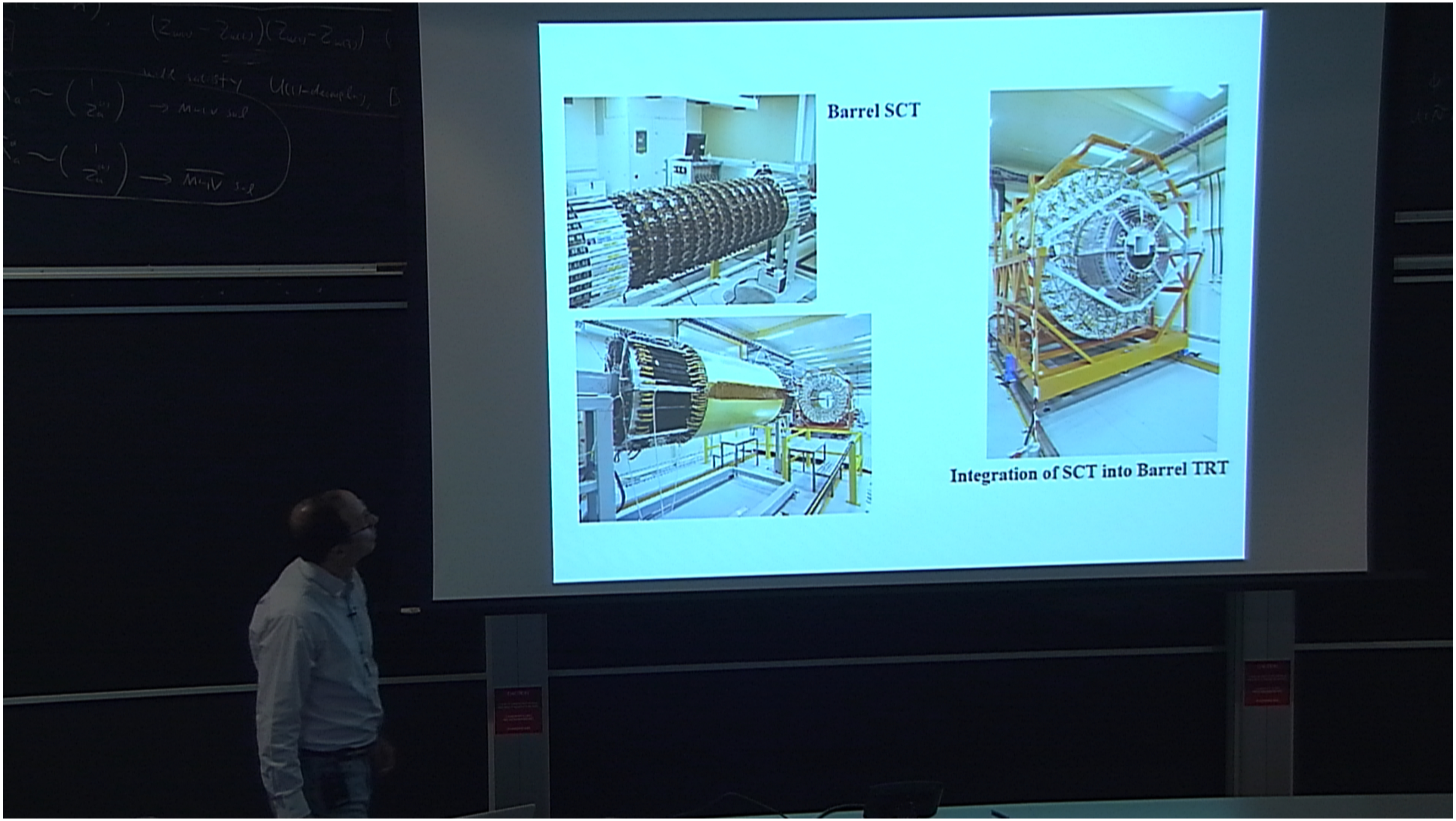
$$r = \frac{1}{B}\sqrt{\frac{2mV}{q}}$$

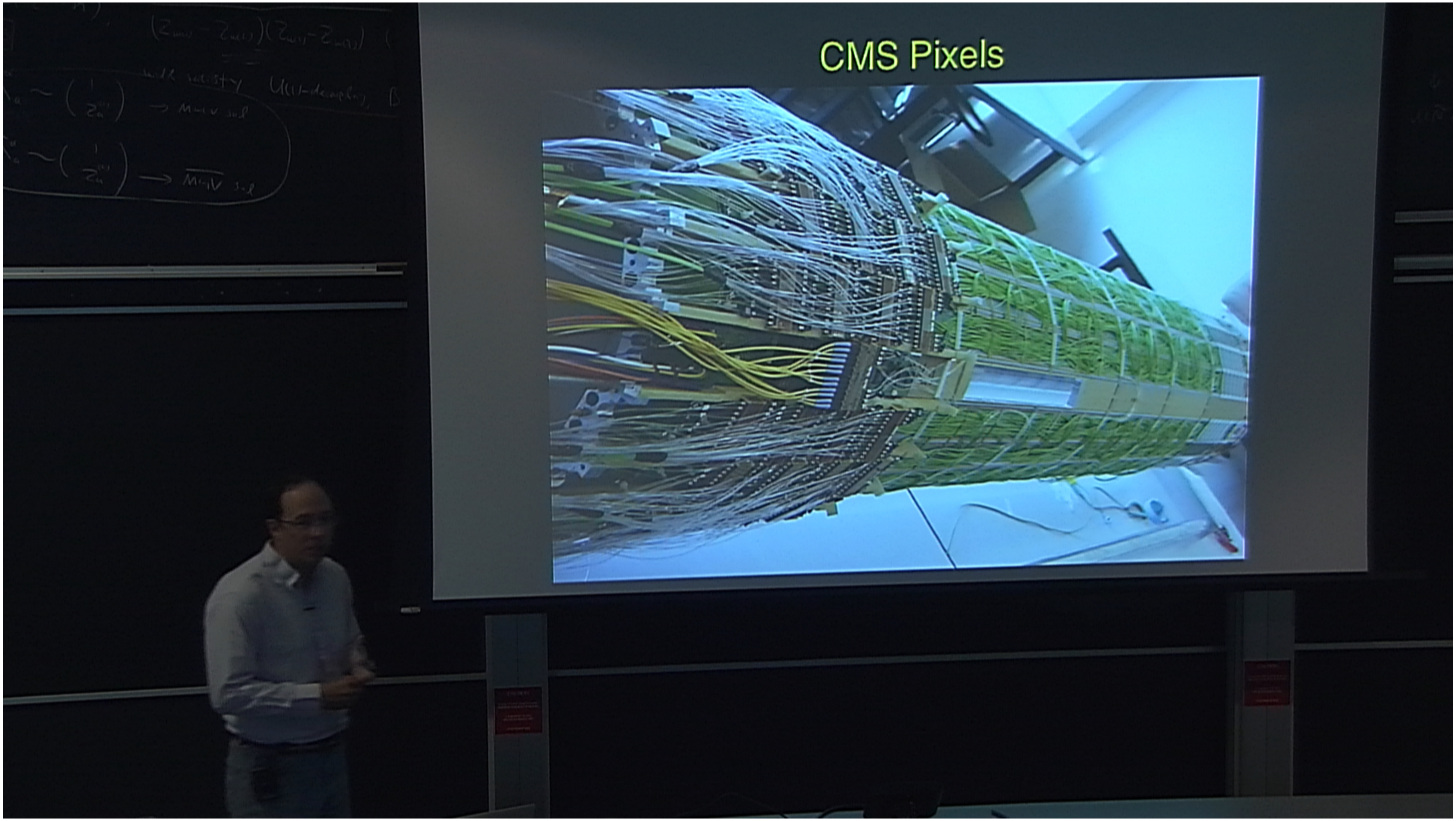


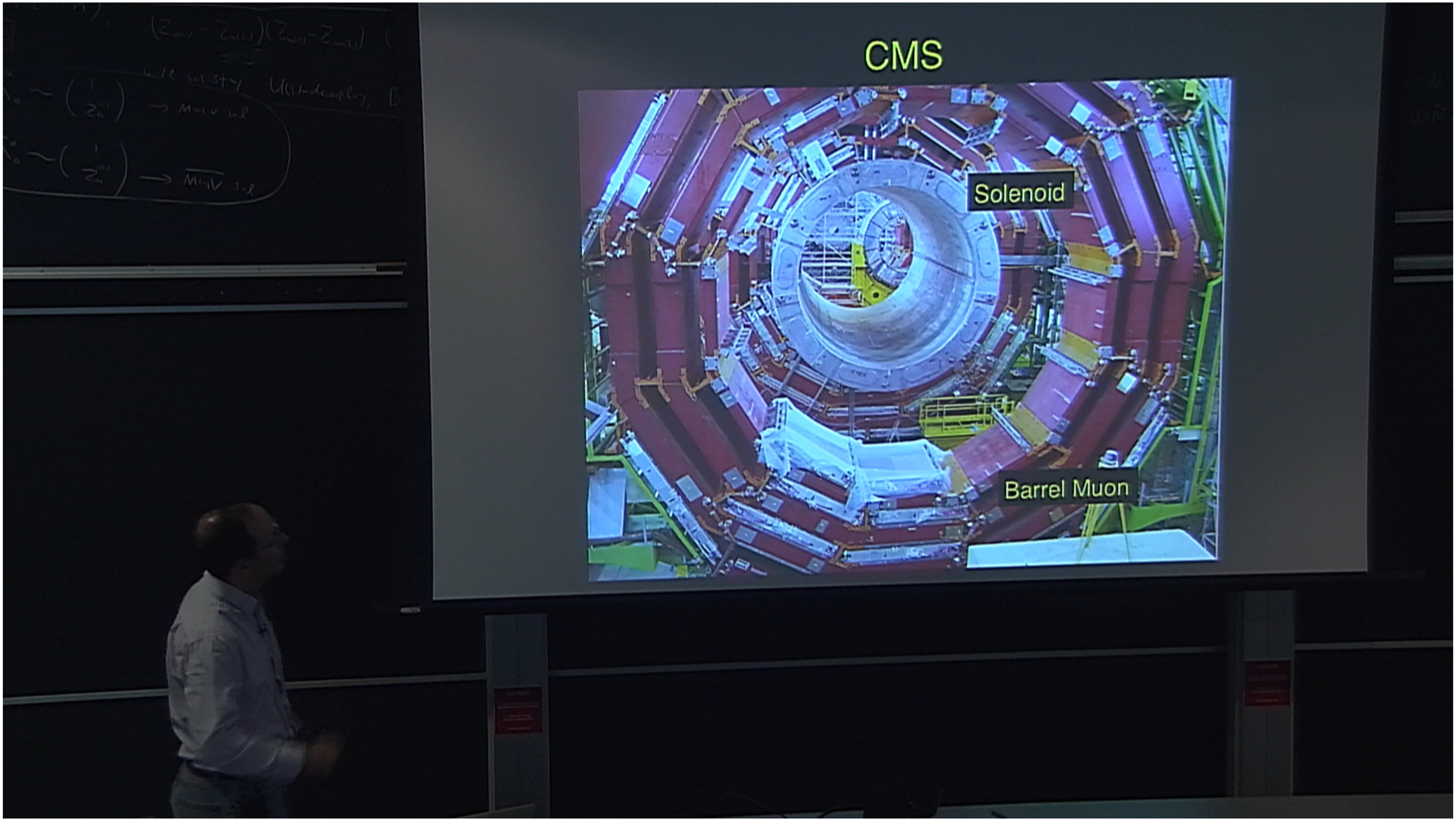
From Hyperphysics
Georgia State University

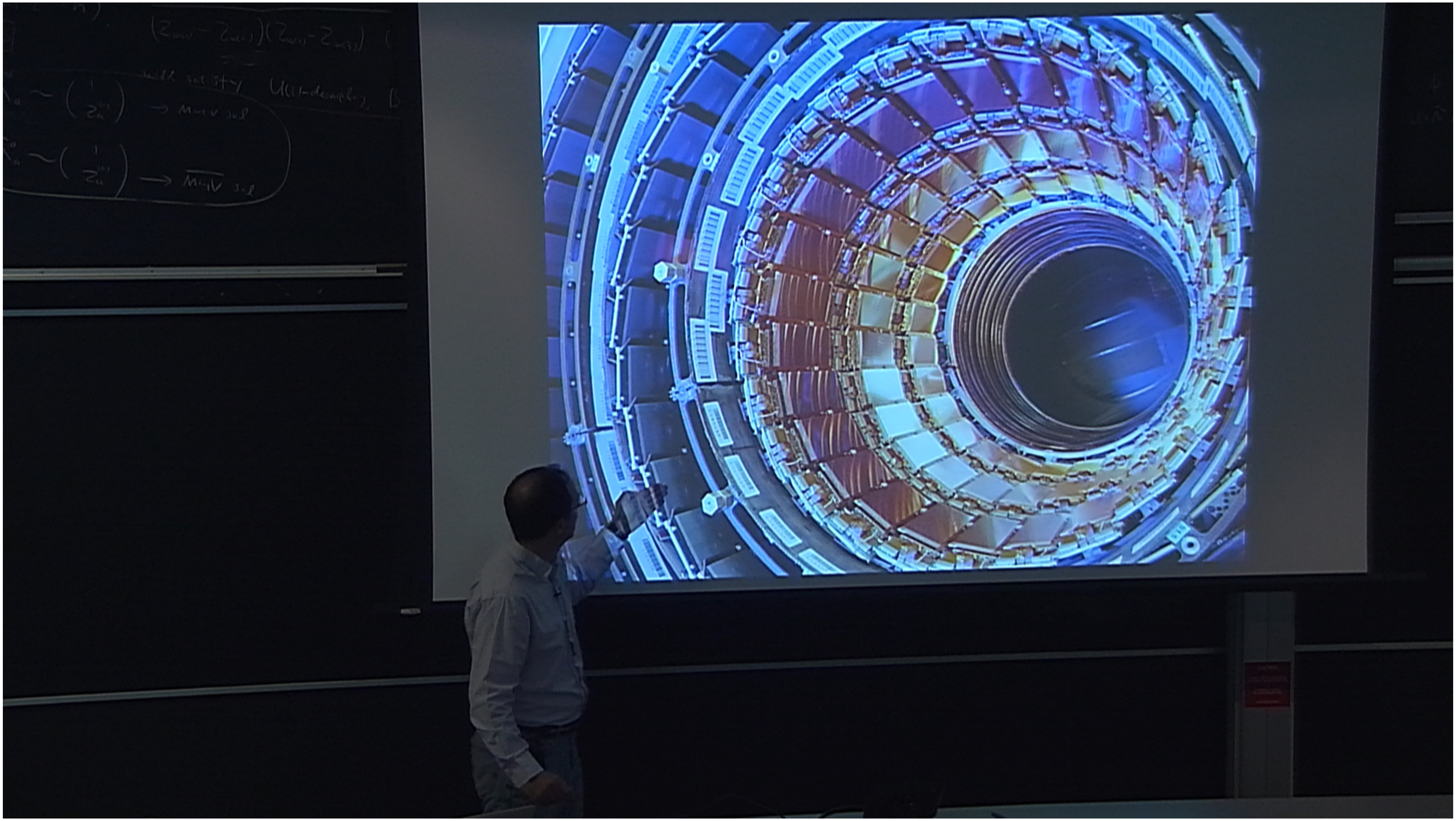


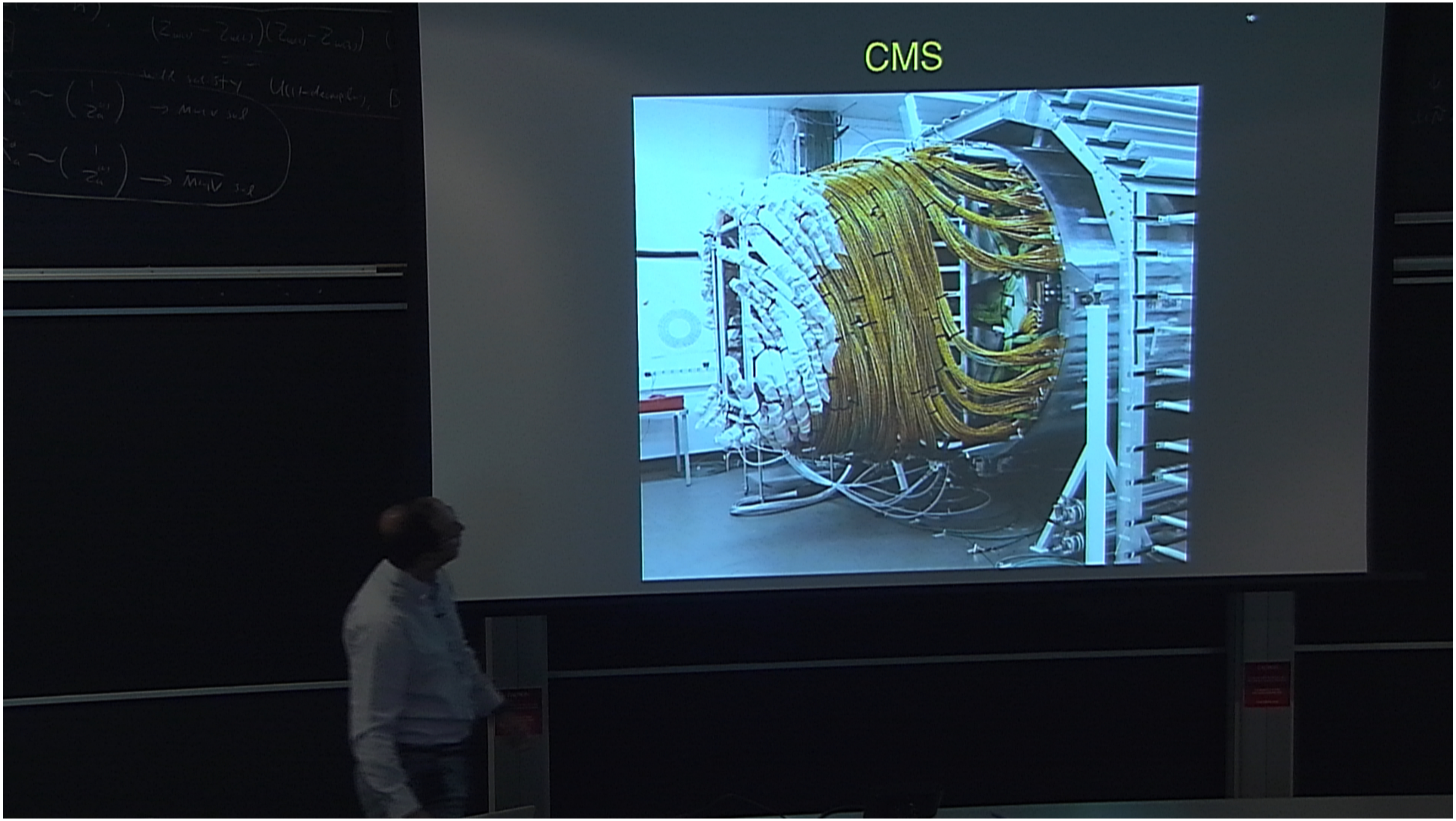



Barrel SCT
Integration of SCT into Barrel TRT

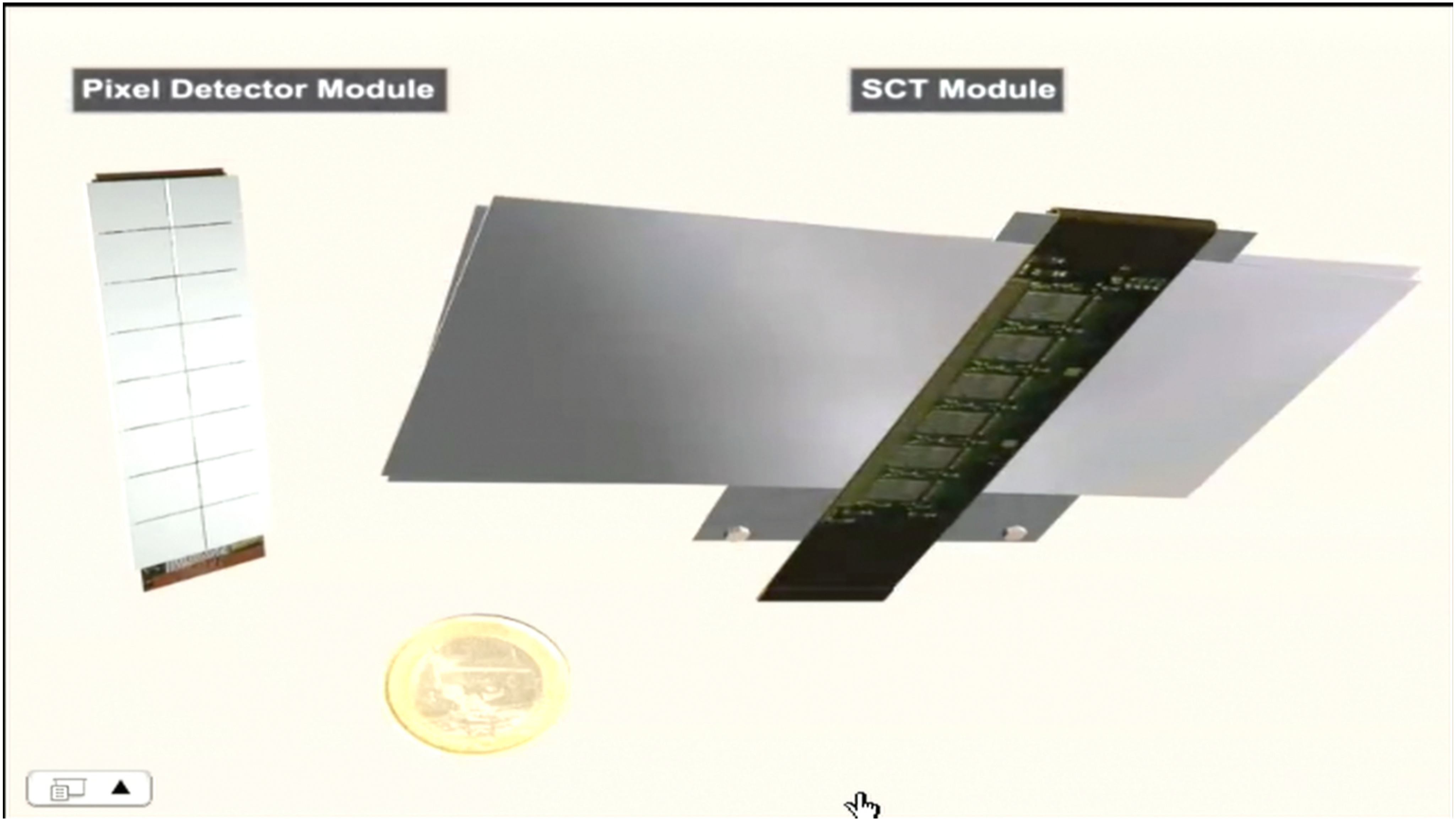

CMS Pixels


CMS
Solenoid
Barrel Muon

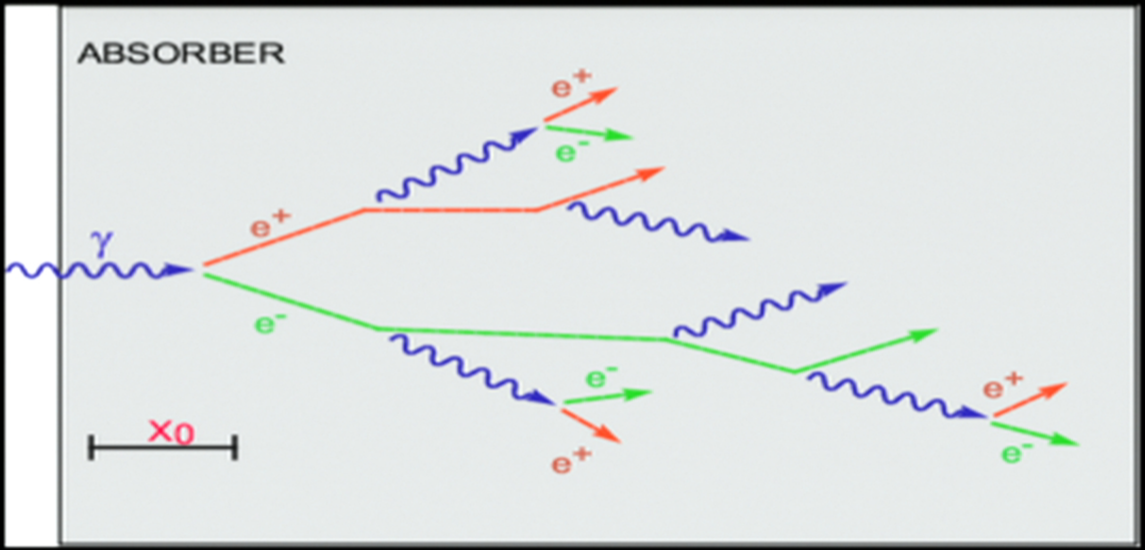


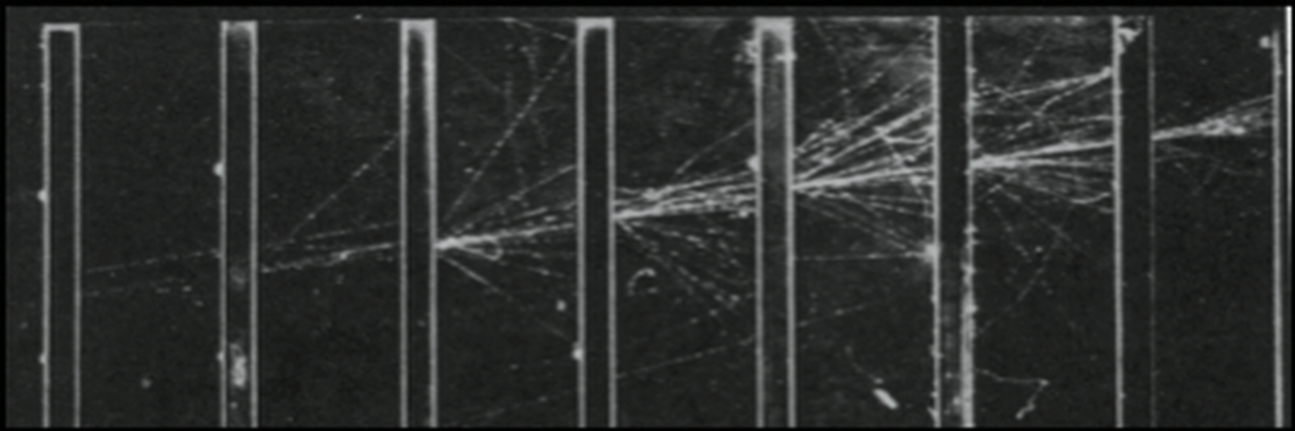

CMS


The ATLAS TRT
(Transition Radiation Tracker)
Clip excerpt from
ATLAS - Episode II
"The Particles Strike Back"
http://atlas.ch

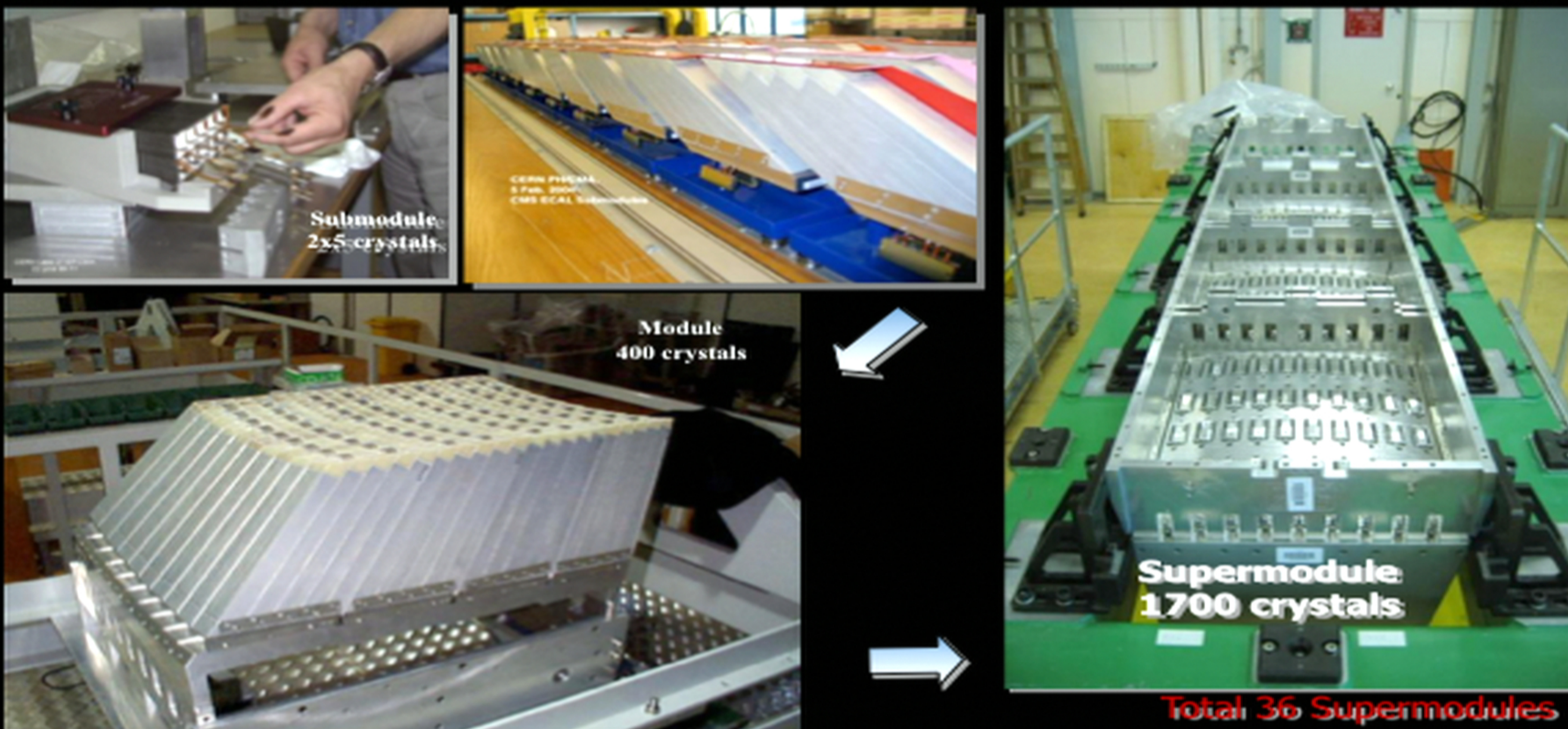

Pixel Detector Module
SCT Module

EM Shower



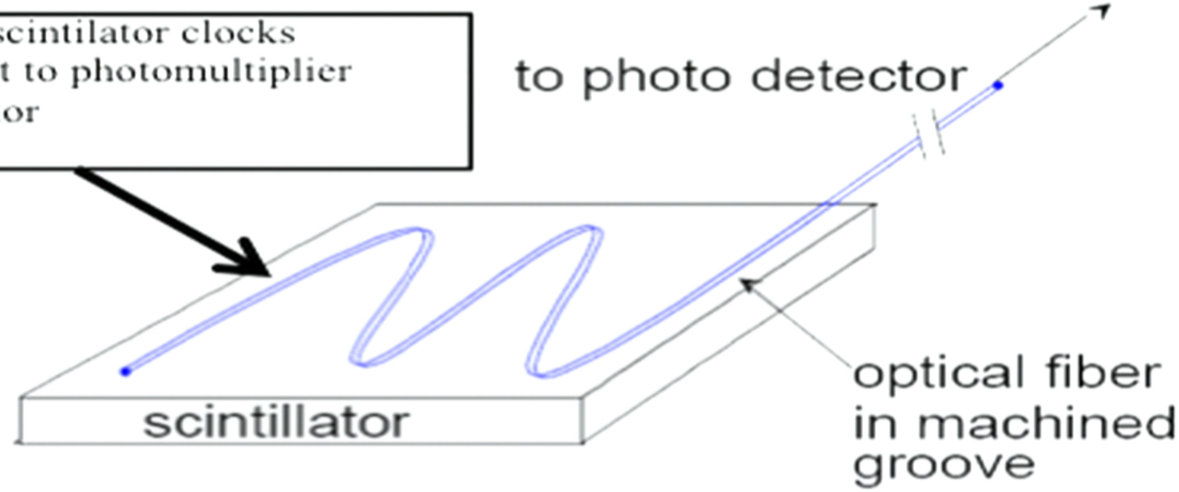


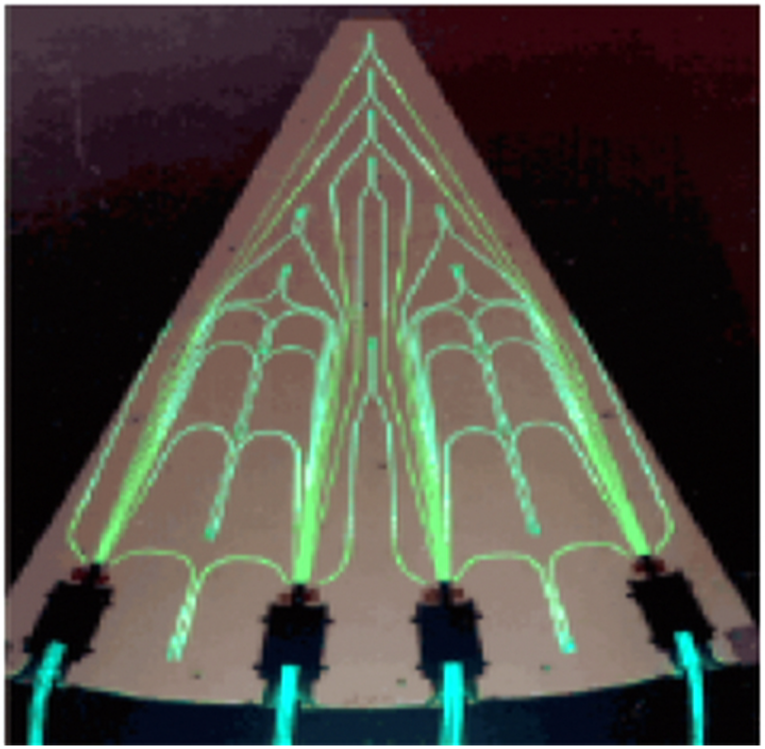
CMS EM Calorimeter

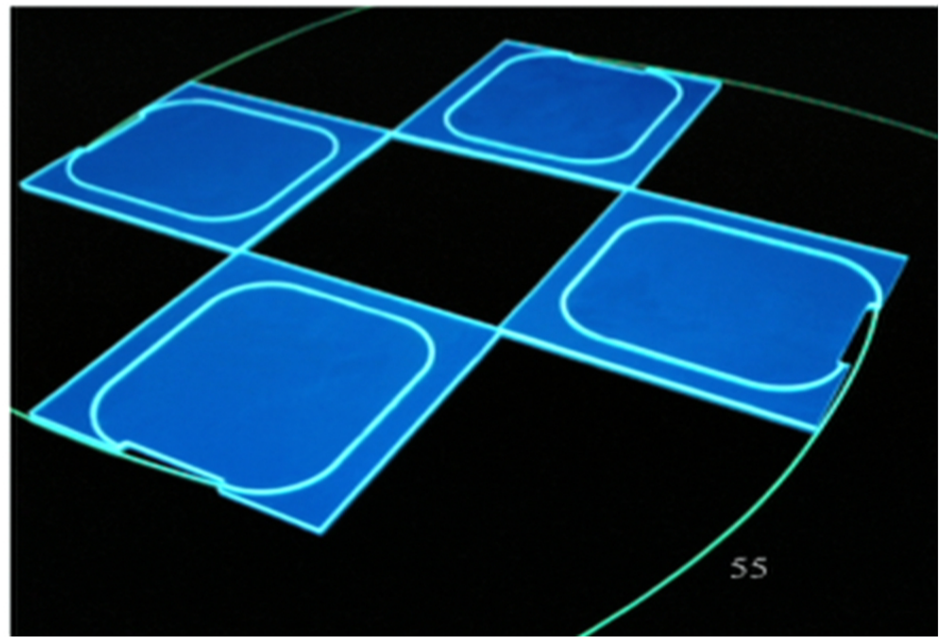


CMS Hadronic Calorimeter

Light guides in scintilator clocks
Guiding the light to photomultiplier
outside of detector







CMS Hadronic Calorimeter

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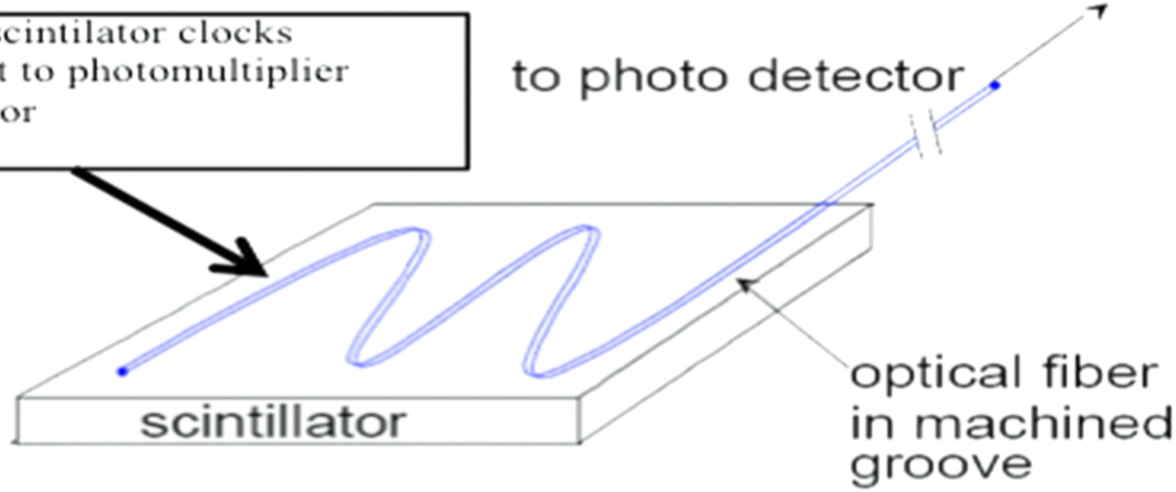
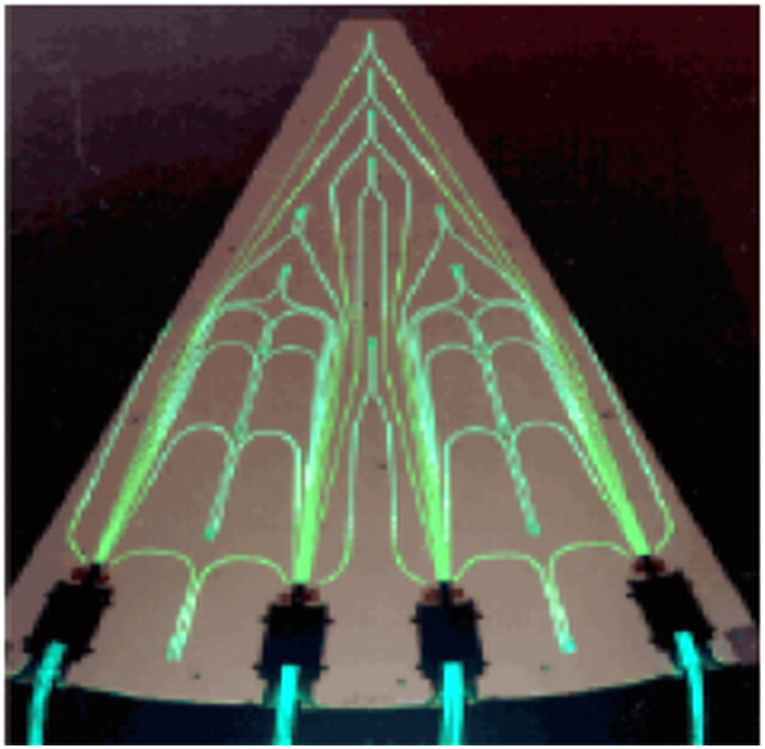
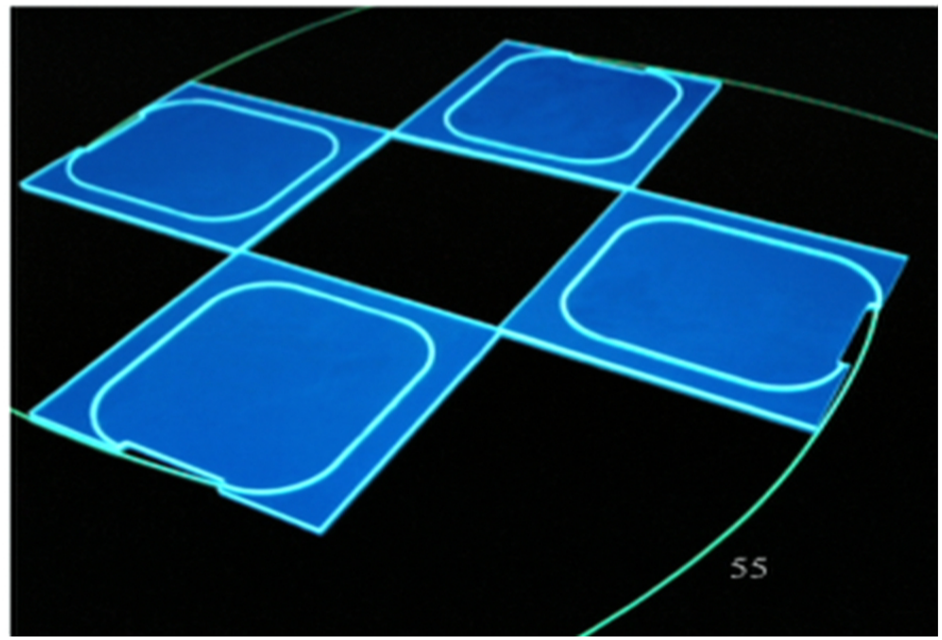
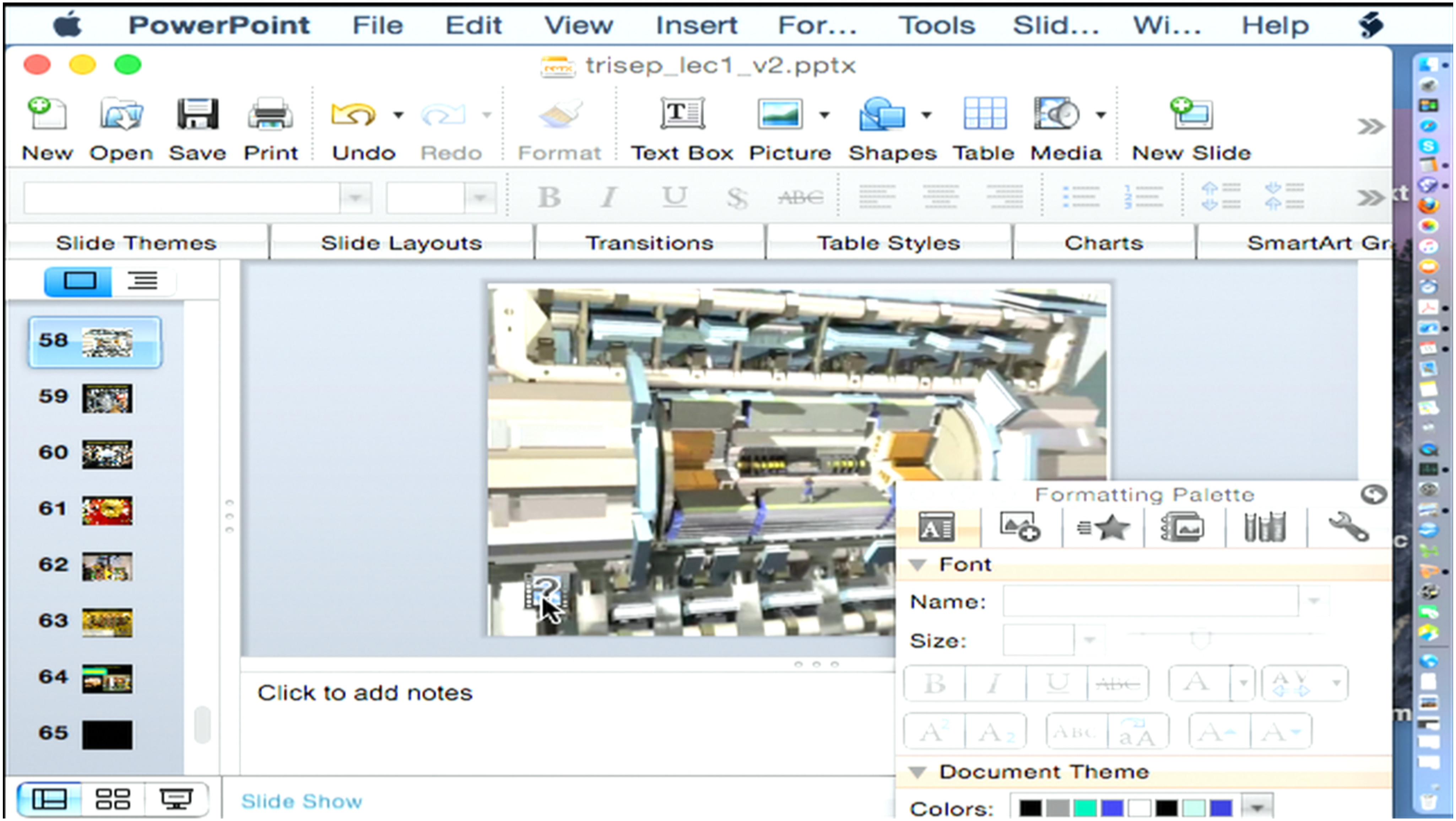






CMS Calorimeter



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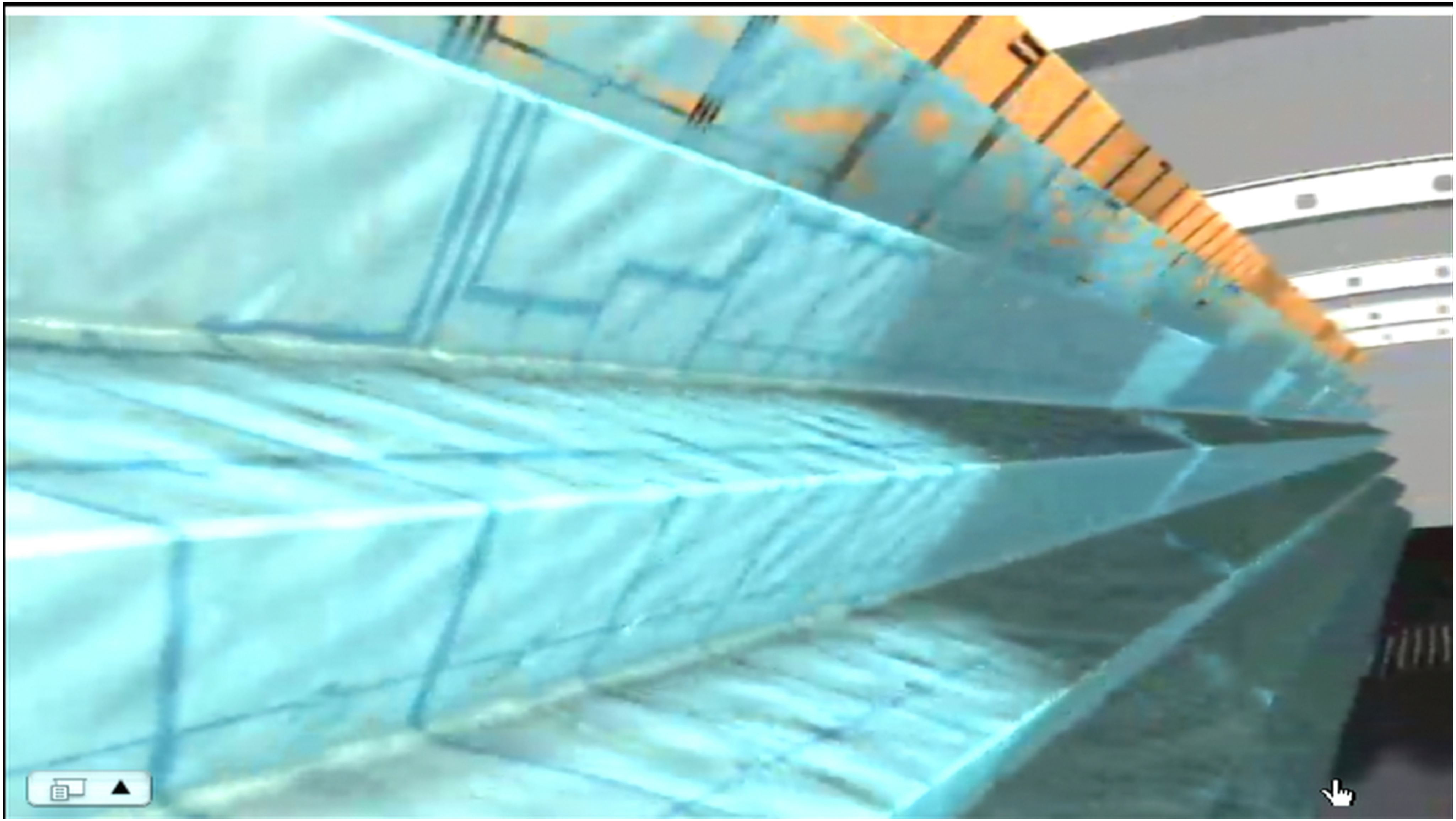
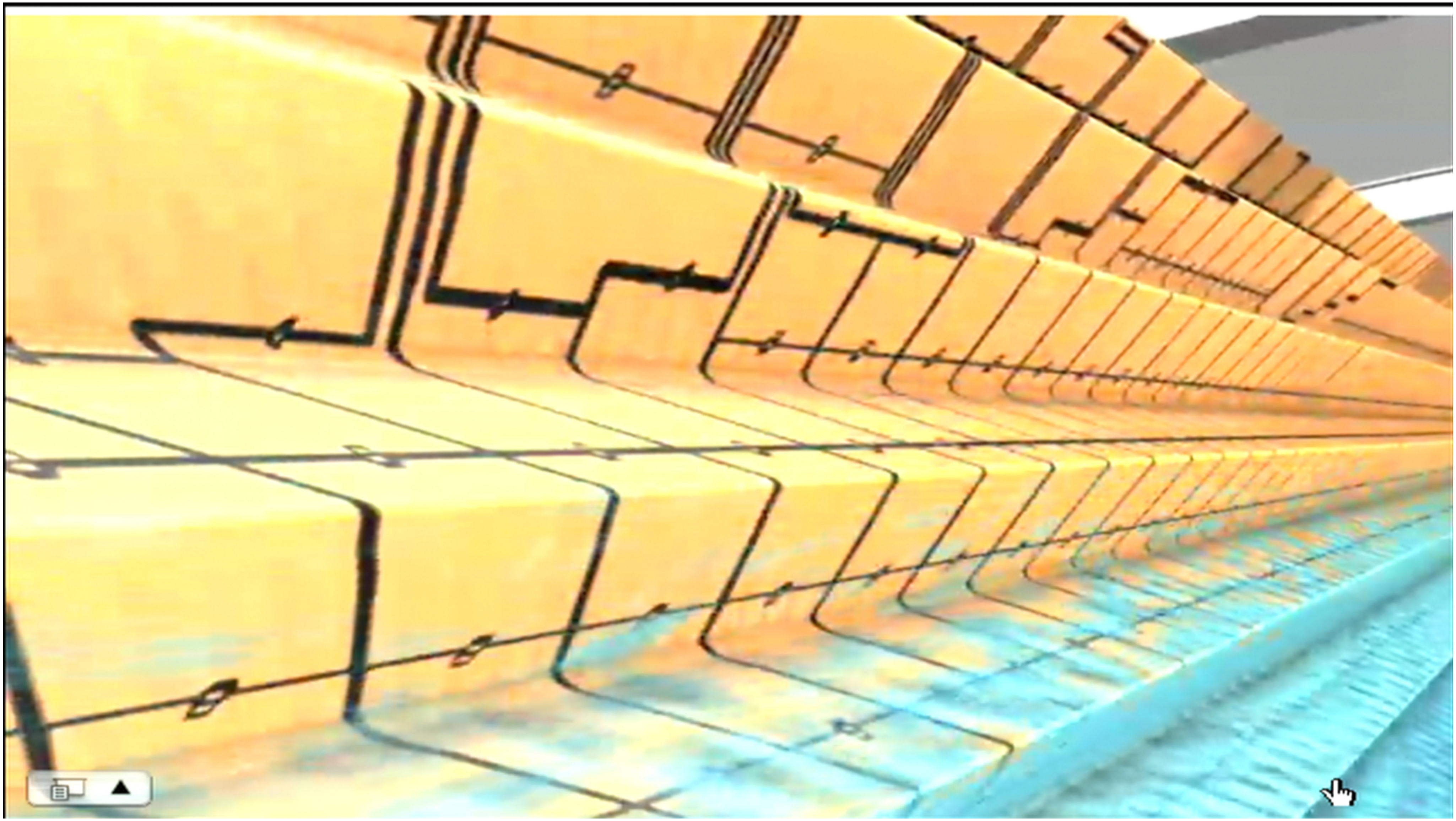
Slide Themes Slide Layouts Transitions Table Styles Charts SmartArt Gr
58
59
60
61
62
63
64
65
Click to add notes
Slide Show
Formatting Palette
Font
Name:
Size:
Document Theme
Colors:

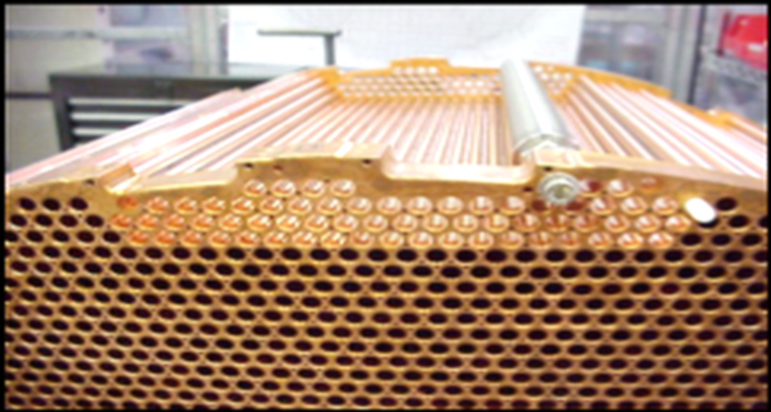




ATLAS Detector with Calorimeter

Forward Calorimeter

Design, Construction, Beam tests,
Installation & Commissioning:
Carleton, Toronto



Run 1 Trigger, Pileup, Data Acquisition

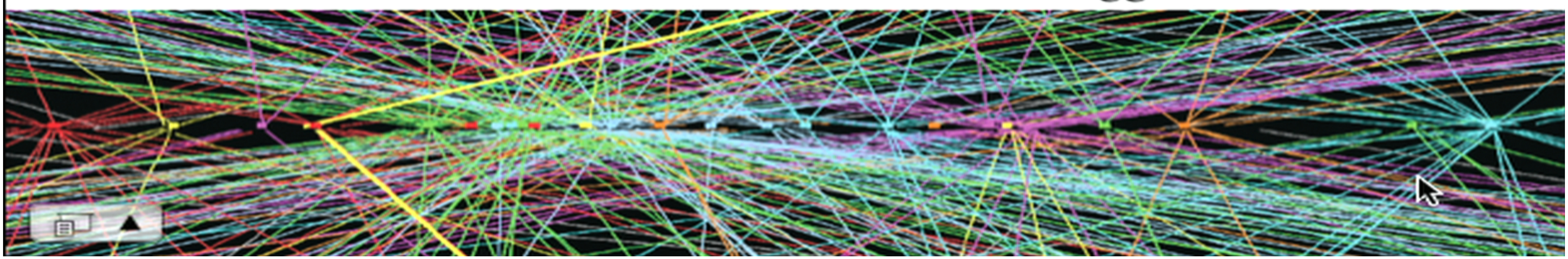
- Data/MC samples: 120 PB
- Over 30 collisions per event at high luminosity: increases event size and processing times for reconstruction
- Maintained good trigger and object reconstruction efficiency in high pileup environment
- Data taking/quality efficiency is 90% (from delivered to physics)

Example rates

Trigger	p_T Threshold	Rate (Hz) *
Inclusive e	24	70
Inclusive μ	24	45
ee	12	8
μμ	13	5
ττ	29,20	12
γγ	35,25	10
E_T^{mis}	80	18
5-jets	55	8

* At 5 10^{33} $cm^{-2}s^{-1}$

Total trigger rate: 400 Hz



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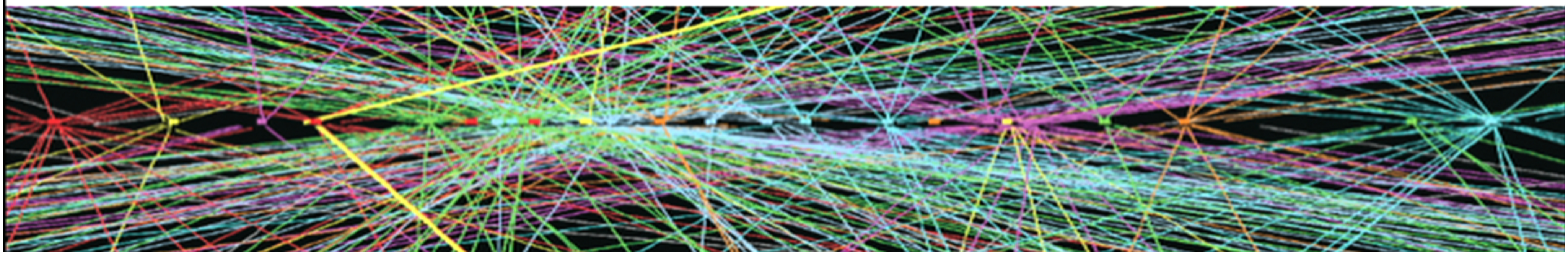

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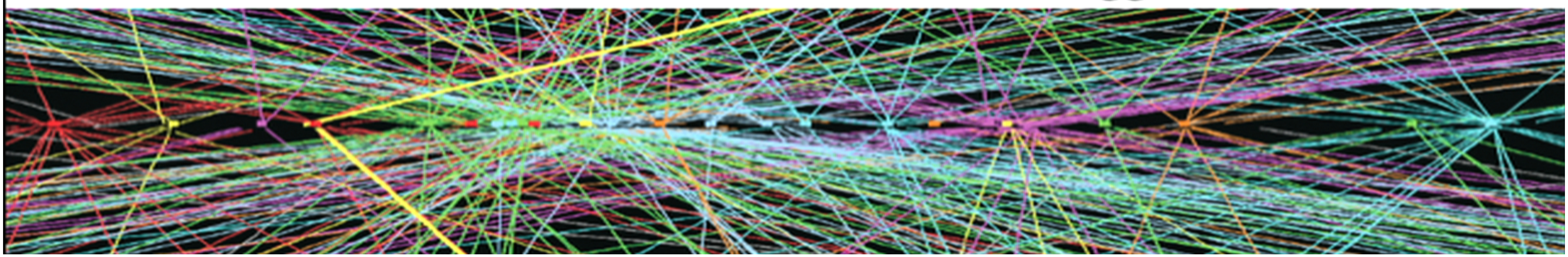
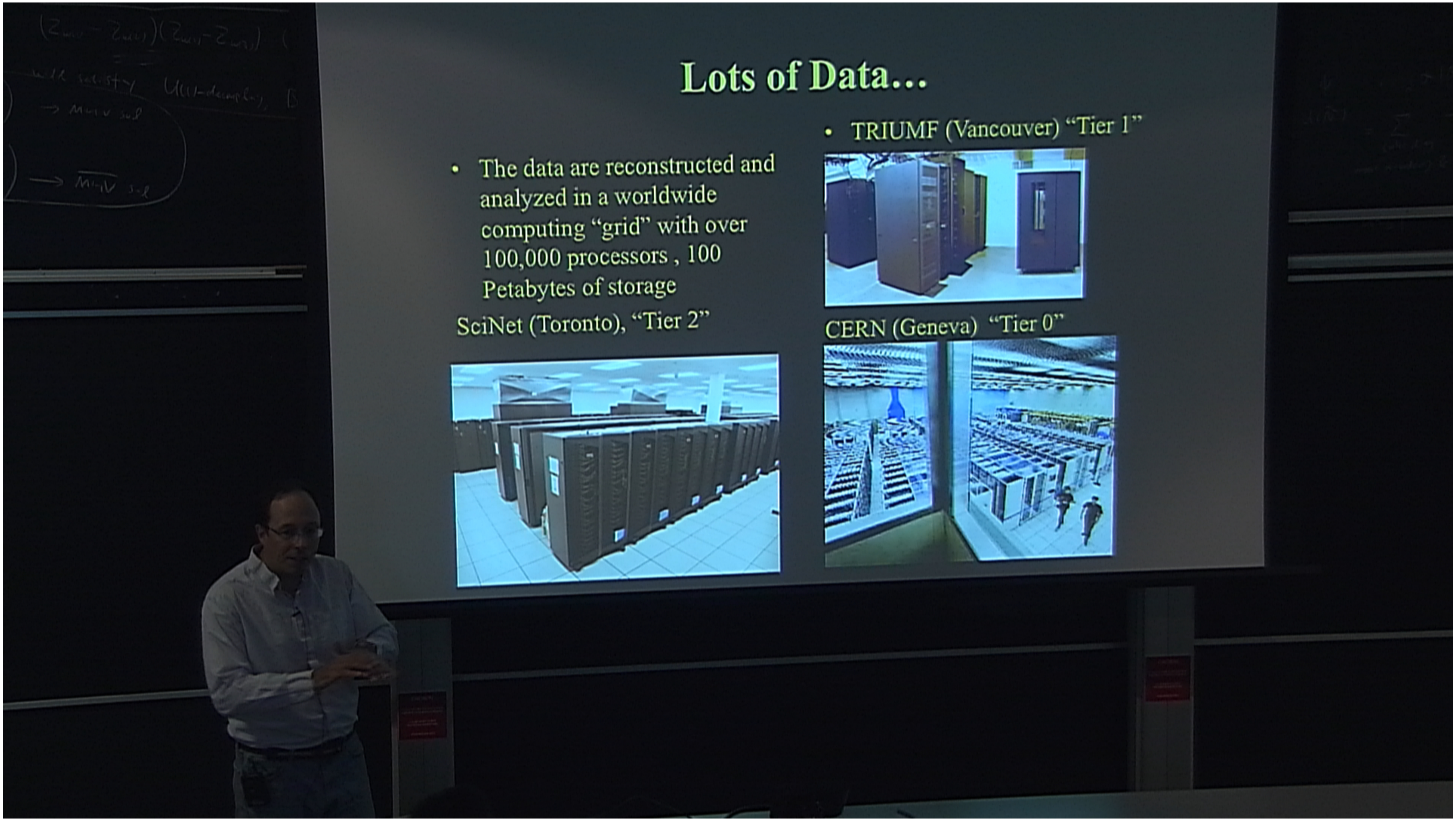
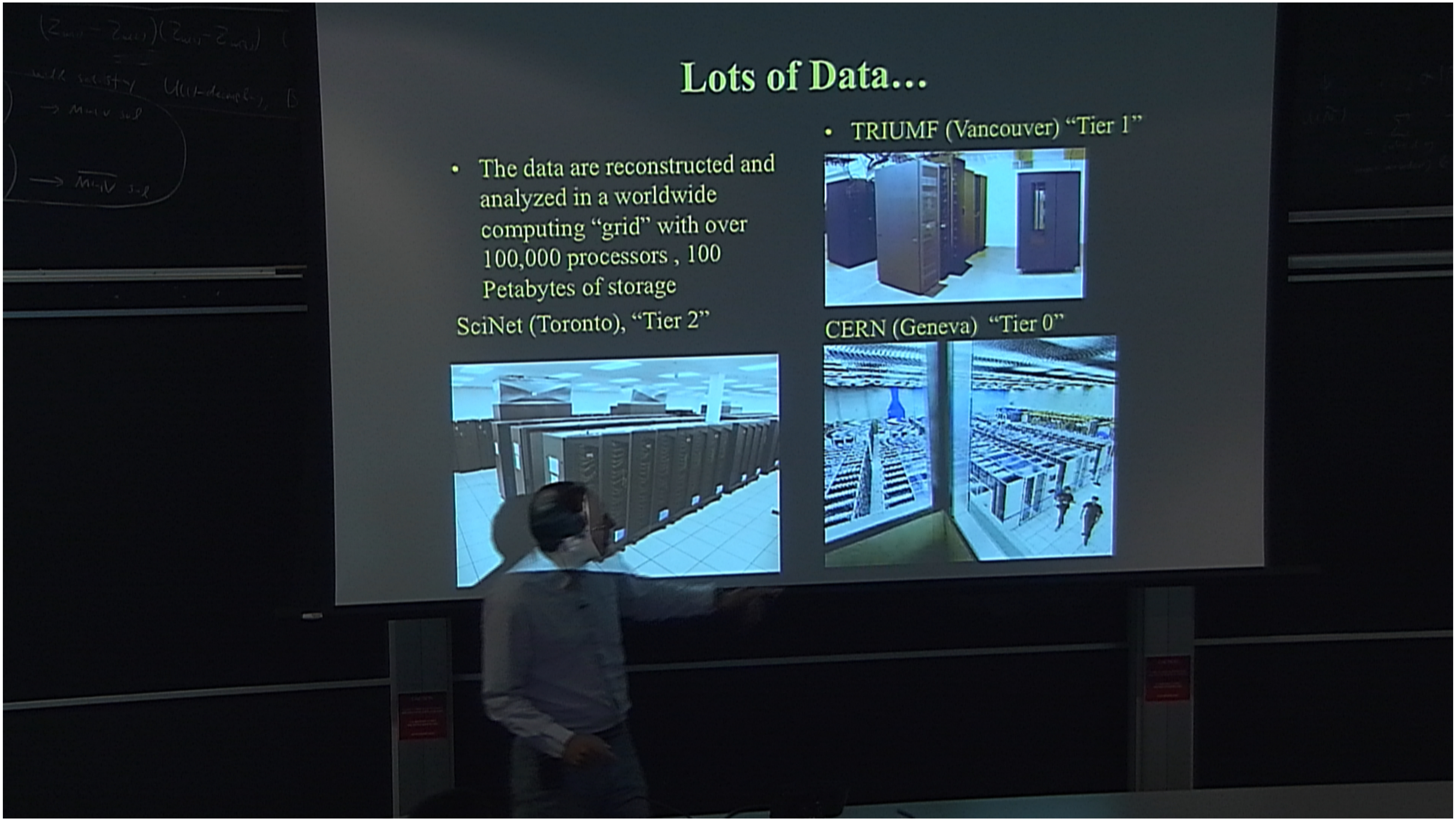



Lots of Data…
TRIUMF (Vancouver) "Tier 1"
The data are reconstructed and analyzed in a worldwide computing "grid" with over 100,000 processors , 100 Petabytes of storage
SciNet (Toronto), "Tier 2"
CERN (Geneva) "Tier 0"



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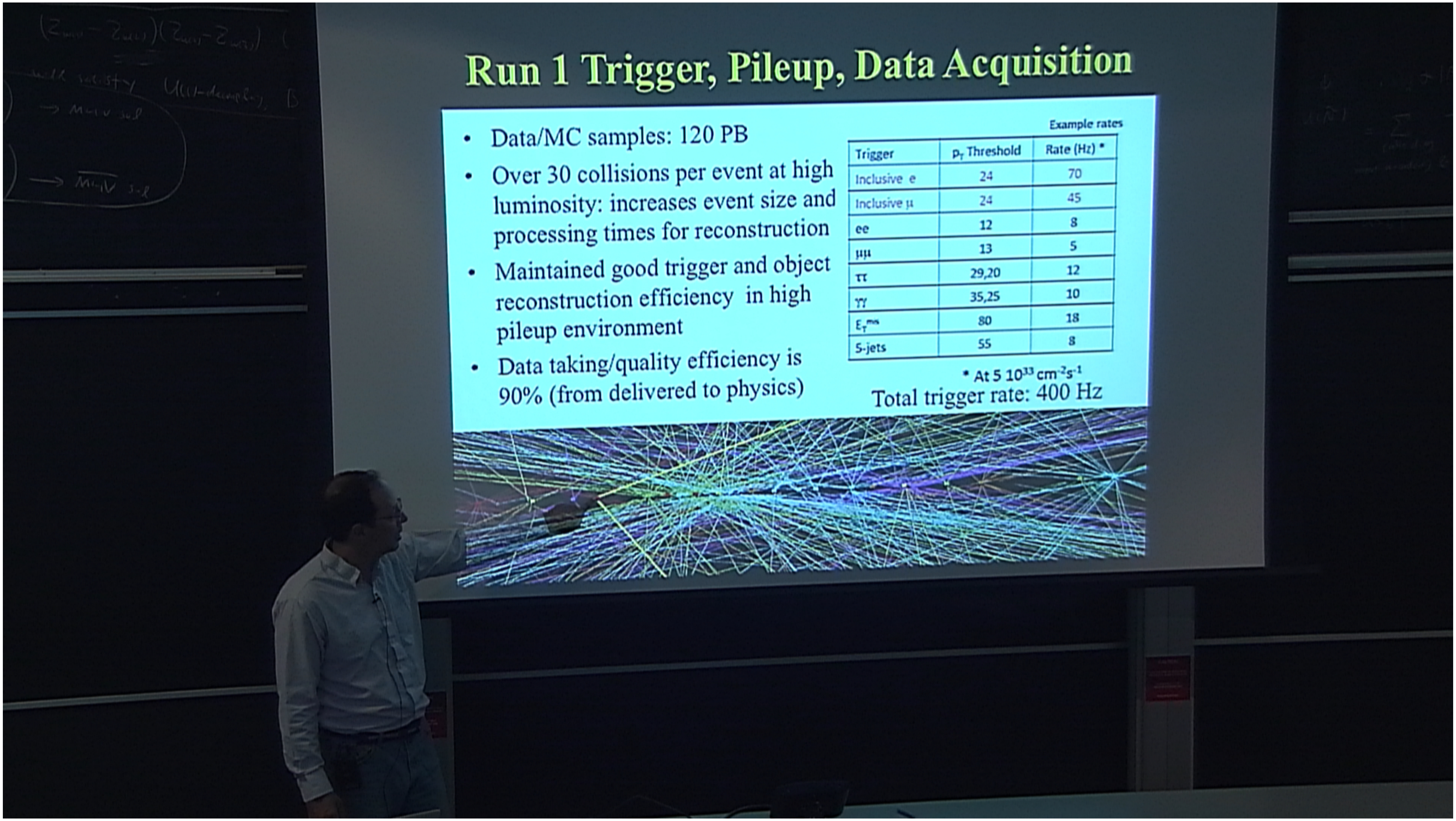
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ee | 12 | 8
μμ | 13 | 5
ττ | 29,20 | 12
γγ | 35,25 | 10
ET miss | 80 | 18
5-jets | 55 | 8
* At 5 10^33 cm^-2 s^-1
Total trigger rate: 400 Hz