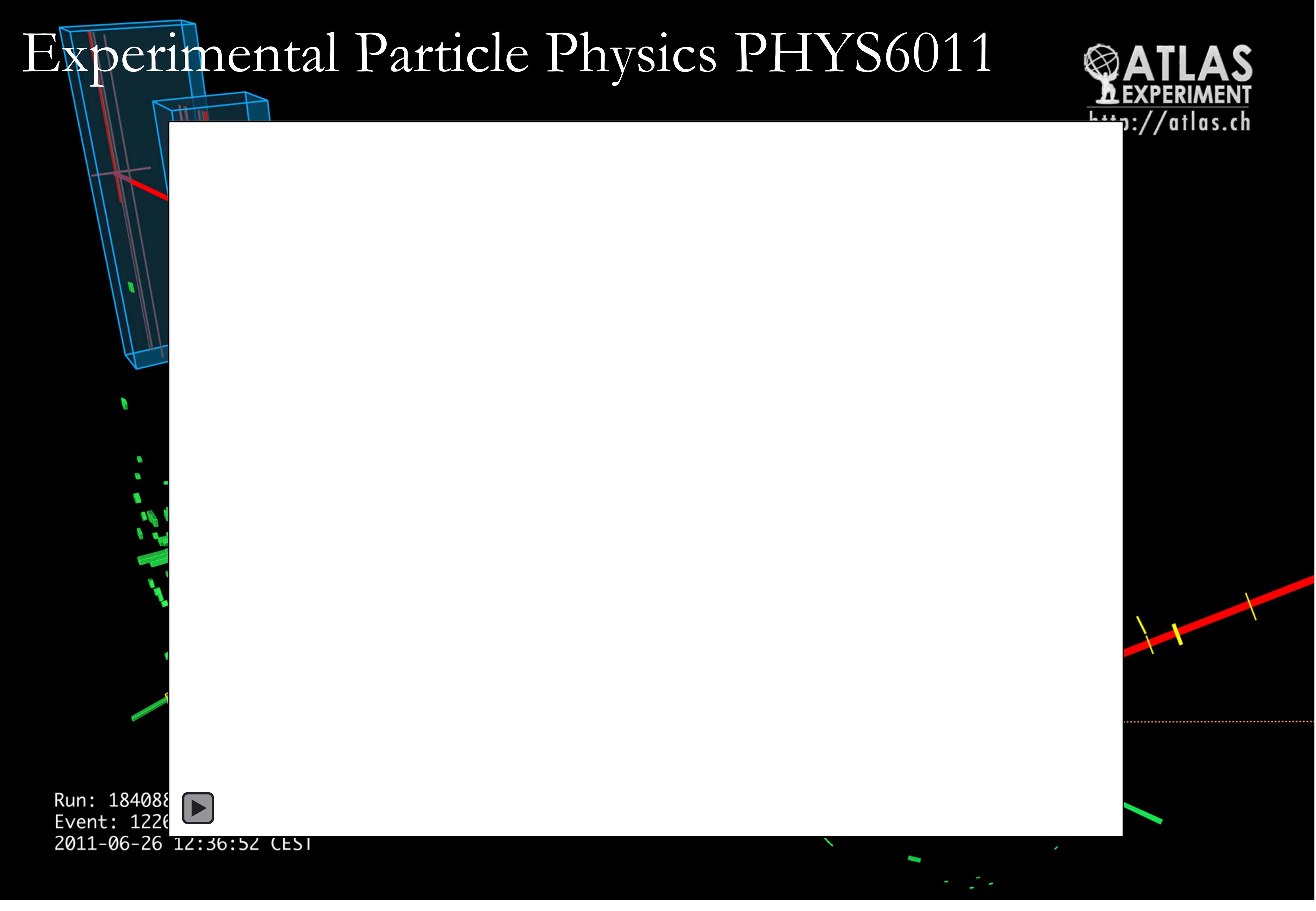
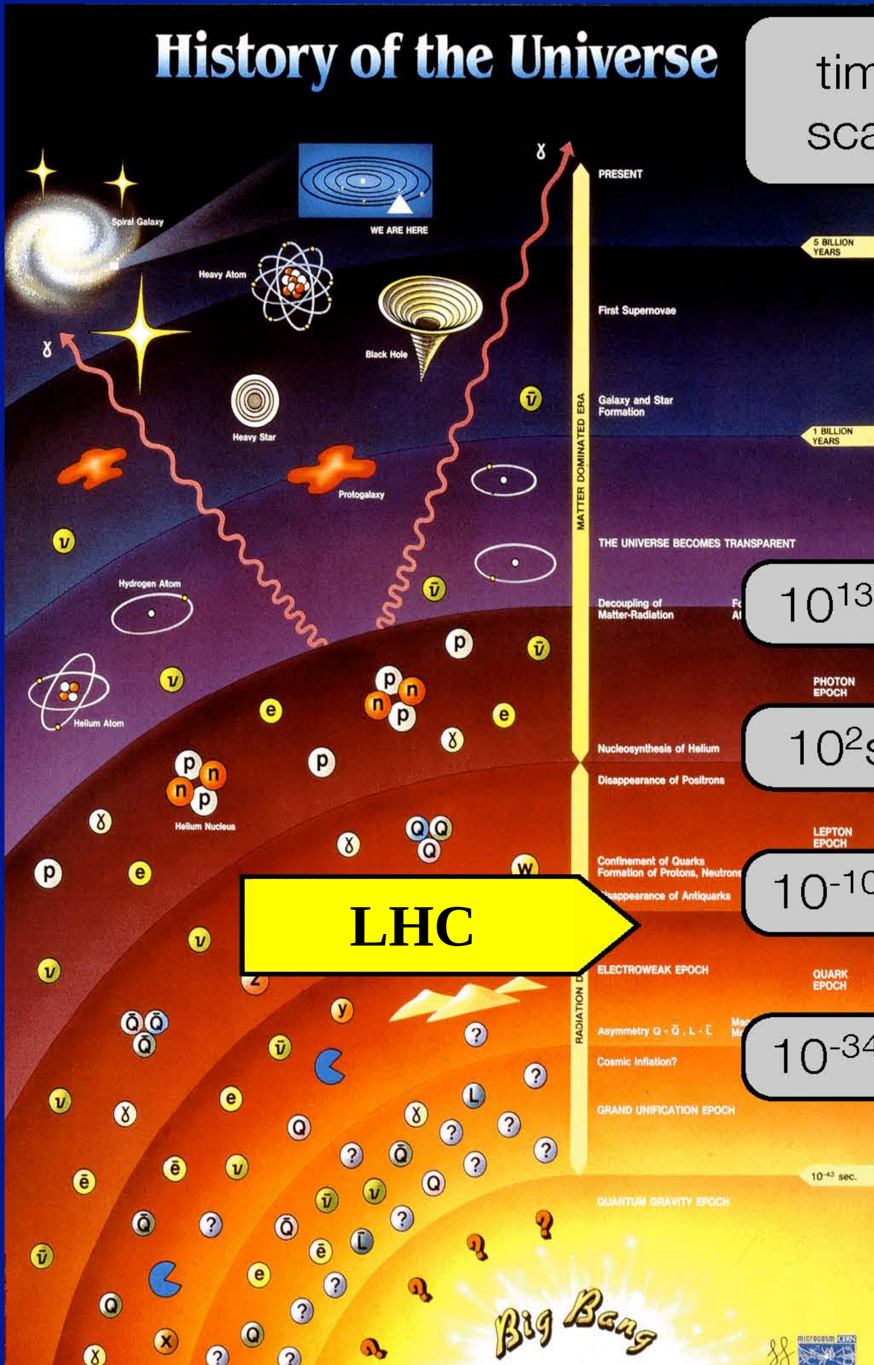
Experimental Particle Physics PHYS6011



Administrative Points

- 3 lectures:
  - Wednesday 12:00-13:00: 6th May : 1) Radiation and Accelerators
  - Friday 11:00-13:00: 8th May : 2) Particle Interactions, and Detectors; 3) Search for the Higgs and Supersymmetry.
- Course Objectives, Lecture Notes, Problem examples:
  - http://www.phys.soton.ac.uk/module/PHYS6011/
  - http://hepwww.rl.ac.uk/fwilson/Southampton/
- Resources:
  - K. Wille, "The Physics of Particle Accelerators"
  - D. Green, "The Physics of Particle Detectors"
  - K.Kleinknecht, "Detectors for Particle Radiation"
  - I.R. Kenyon, "Elementary Particle Physics" (chap 3).
  - Martin and Shaw, "Particle Physics"
  - Particle Data Group, http://pdg.lbl.gov

Fergus Wilson, Email: Fergus.Wilson at stfc.ac.uk



time scale	energy scale
10^{13} sec	10^{-9} GeV
10^{2} sec	10^{-3} GeV
10^{-10} sec	10^{2} GeV
10^{-34} sec	10^{16} GeV
	10^{19} GeV

Electroweak Epoch (10^{2} GeV)

- Higgs particles
- Supersymmetry

Unification Epoch (10^{16} GeV)

- Grand unification of fundamental forces
- Origin of Neutrino mass (RH neutrino)
- Leptogenesis (baryogenesis)

Quantum Gravity Epoch (10^{19} GeV)

- Superstrings

Universe energy

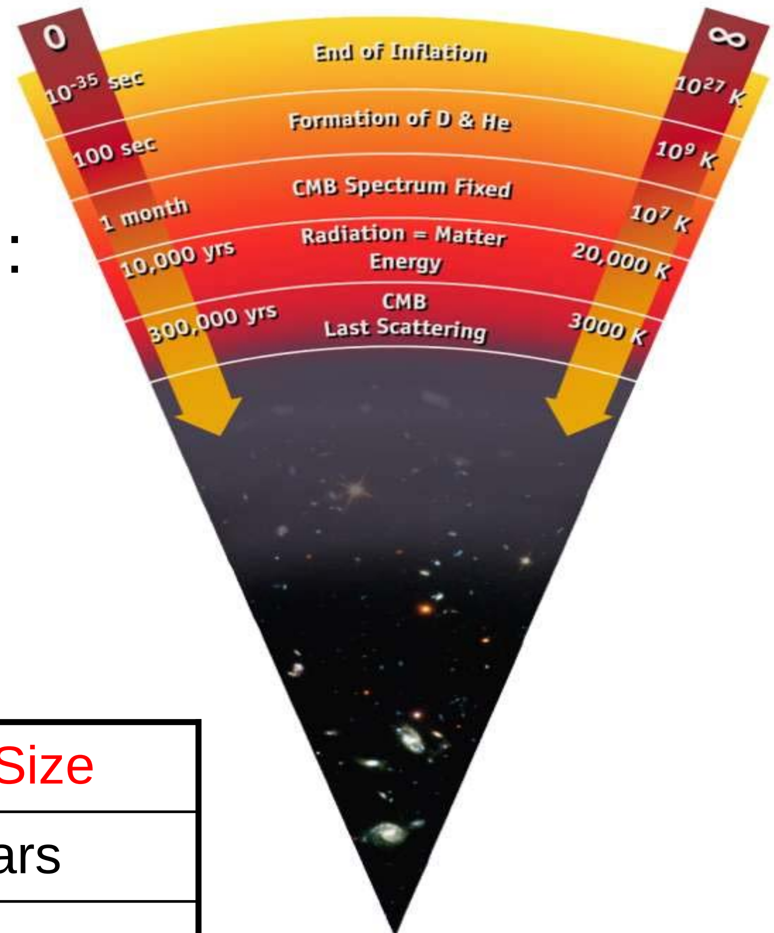
- Time, energy (temperature) and distance are related.
- High momentum : small distance : short wavelength : high temperature : early Universe

$$T_{univ}(K) = 1.5\times10^{12}\, t^{-2/3} \quad t<10^{11}\text{secs}$$

$$T_{univ}(K) = 2\times10^{10}\, t^{-1/2} \quad t>10^{11}\text{secs}$$

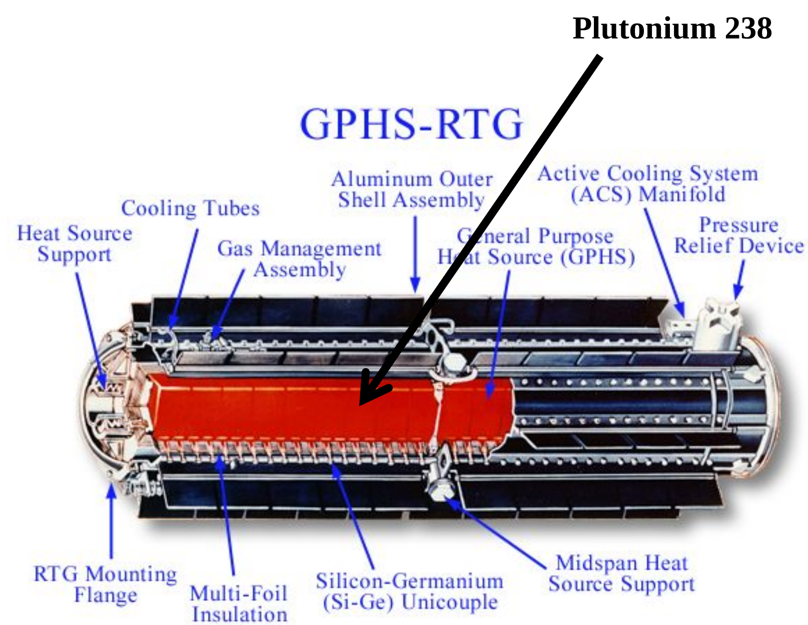
$$\text{Boltzmann constant, } k = 8.619\times10^{-5}\,\text{eV K}^{-1}$$

Energy	Age (secs)	Temp. (K)	Observable Size
1 eV	10^{13}	10^{4}	10^{6} Light Years
1 MeV	1	10^{10}	10^{6} km
10 TeV	10^{-14}	10^{17}	10^{-2} mm



Natural Radioactivity

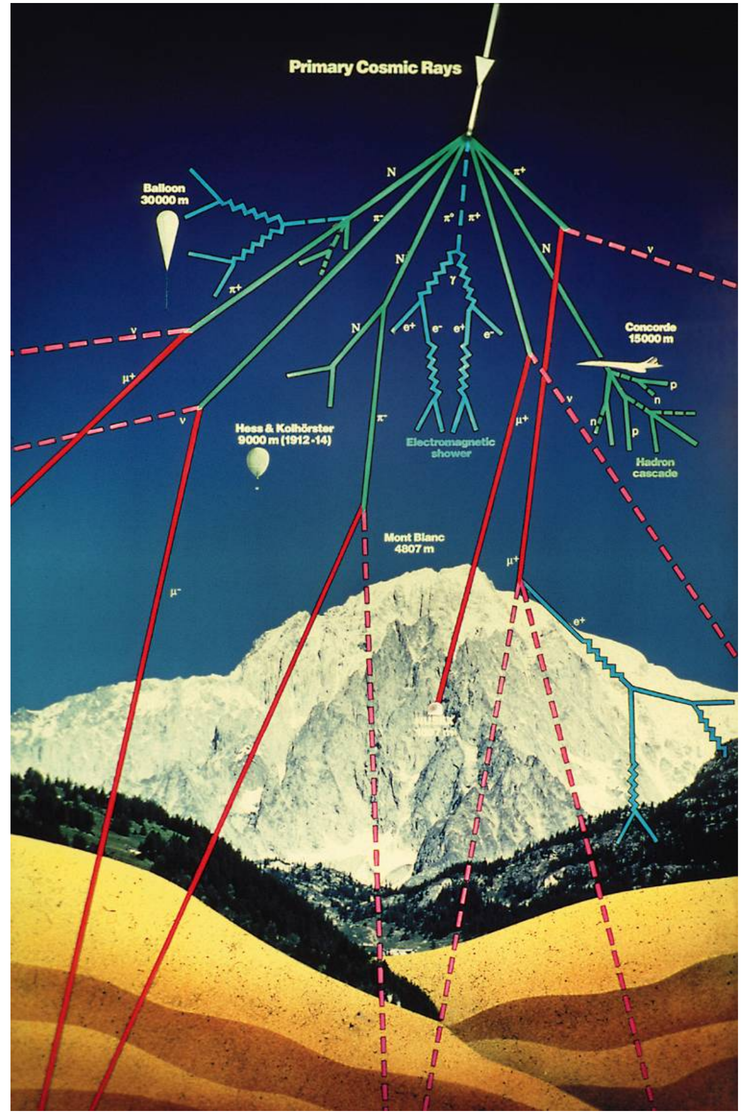
- First discovered in late 1800s (X-rays Becquerel 1896)
- Used as particle source in many significant experiments
  - Rutherford's 1906 experiment: elastic scattering α+N$\rightarrow$ α+N
  - Rutherford's 1917 experiment: inelastic scattering α+N$\rightarrow$ p+X
- Common radioisotopes include
  - ^{55}Fe: 6 keV γ, $\tau_{1/2}$ = 2.7 years (1938)
  - ^{90}Sr: 500 keV β, $\tau_{1/2}$ = 28.9 years (1790)
  - ^{241}Am: 5.5 MeV α, $\tau_{1/2}$ = 432 years (1944)
  - ^{210}Po: 5.41 MeV α, $\tau_{1/2}$ = 137 days (1898)
- Radioactivity of food
  - Bananas : 3500 pCi/Kg
  - Beer: 400 pCi/Kg
- Easy to control, predictable flux but low energy
- Still used for calibrations and tests



Cassini probe: **http://saturn.jpl.nasa.gov/index.cfm**

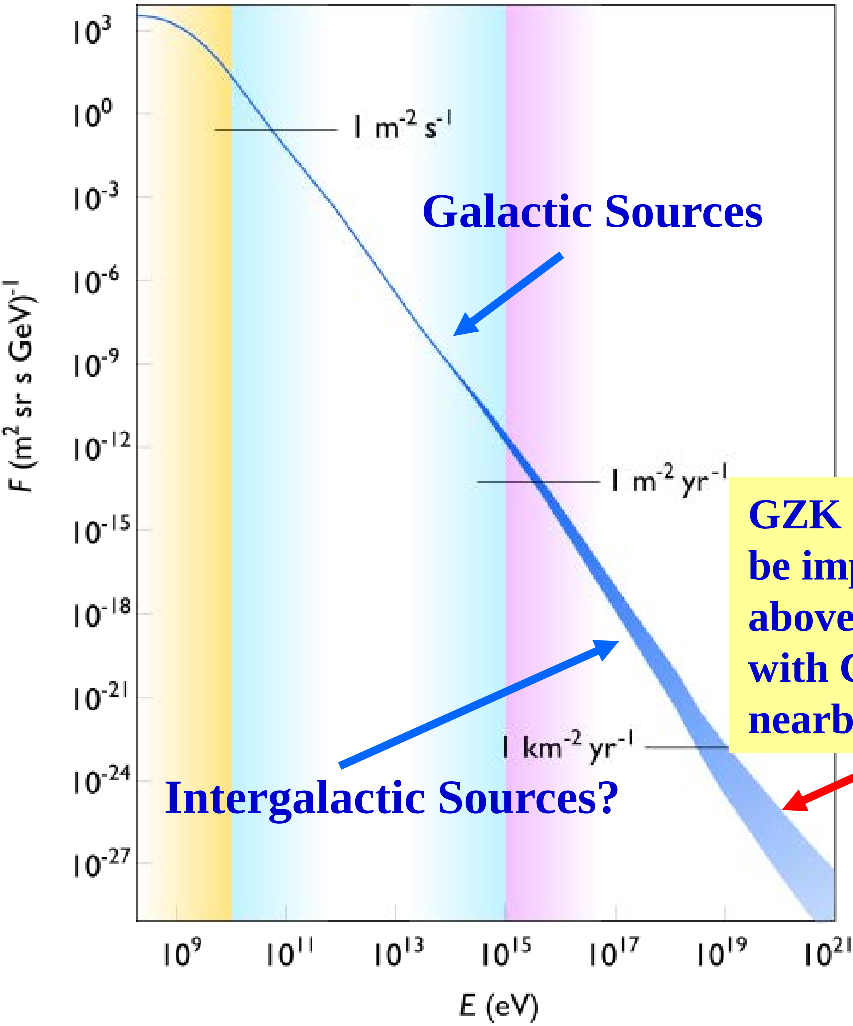
Cosmic Rays

- History
  - 1912: First discovered (Hess)
  - 1927: First seen in cloud chambers
  - 1962: First 10^{20} eV cosmic ray seen
- Low energy cosmic rays from Sun
  - Solar wind (mainly protons)
  - Neutrinos
- High energy particles from sun, galaxy and perhaps beyond
  - Primary: Astronomical sources.
  - Secondary: Created in atmosphere.
  - Neutrinos pass through atmosphere and earth
  - Low energy charged particles trapped in Van Allen Belt
  - High energy particles interact in atmosphere.
  - Flux at ground level mainly muons: 100-200 s^{-1} m^{-2}
- Highest energy ever seen ~10^{20}eV



Cosmic Rays

$$I_N(E) \approx 1.8E^{-2.7} \frac{nucleons}{\text{cm}^2\text{s sr GeV}} \quad E < 100\text{TeV}$$



GZK cutoff 10^{20} eV. Should be impossible to get energies above this due to interaction with CMB unless produced nearby => Black Holes?

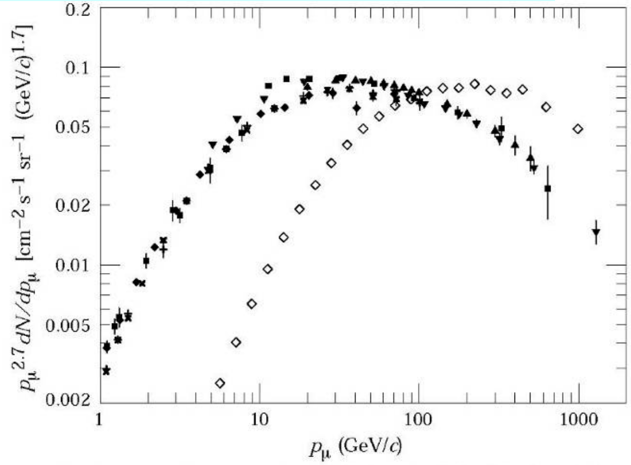
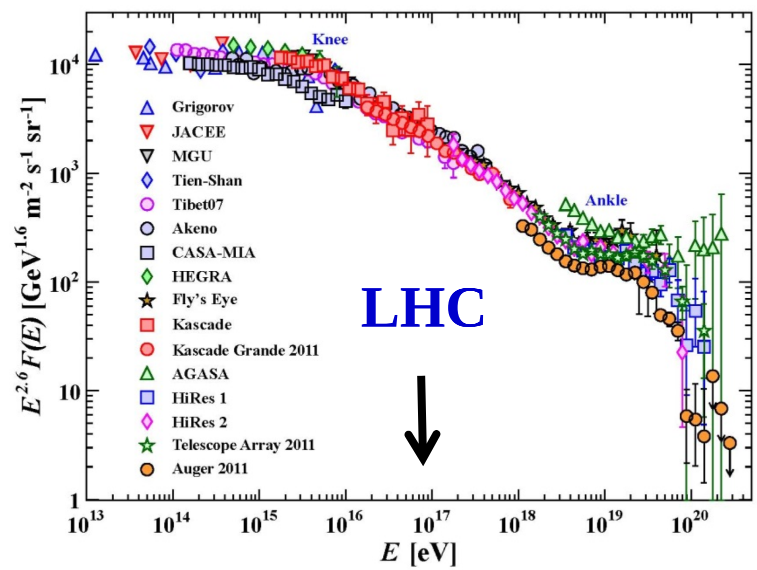


Figure 24.4: Spectrum of muons at $\theta = 0°$ (♦ [29], ■ [34], ▾ [35], ▲ [36], × and + [31], and $\theta = 75°$ ◊ [37]) .



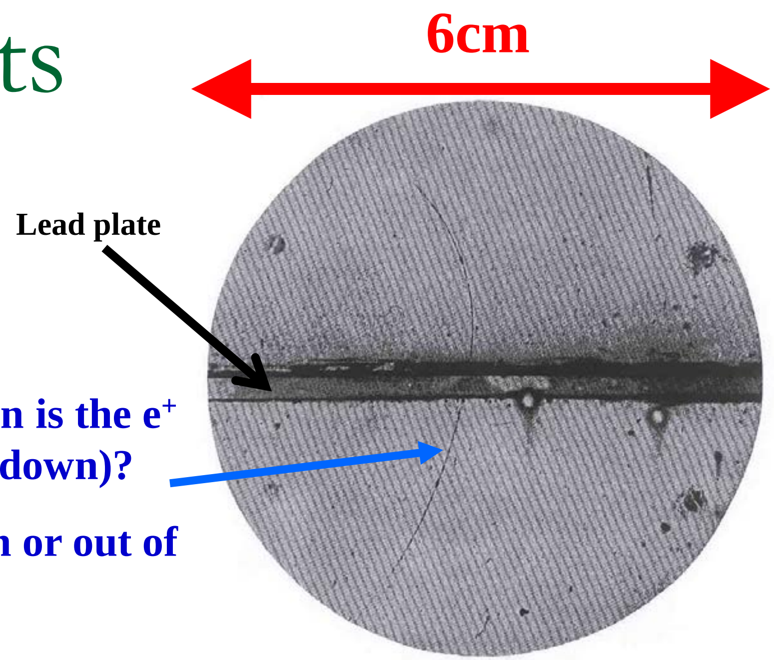
Cosmic Ray Experiments

- Primary source for particle physics experiments for decades
- Detectors taken to altitude for larger flux/higher energy
- Positron (1932) and many other particles first observed

Modern experiments include:

- Particle astrophysics
  - Space, atmosphere, surface, underground
- Neutrino
  - Solar, atmospheric
- “Dark Matter” searches

Still useful for calibration and testing

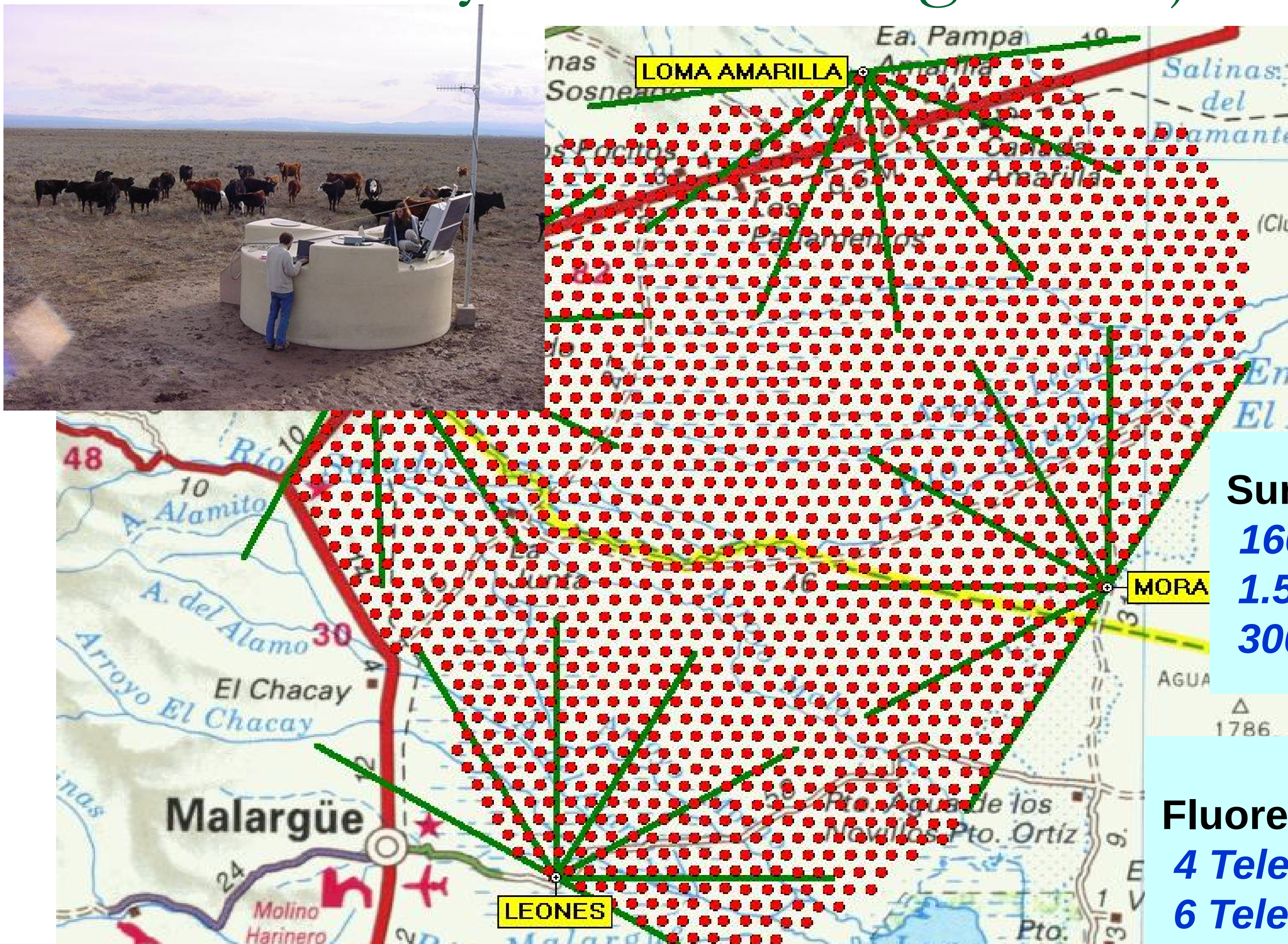


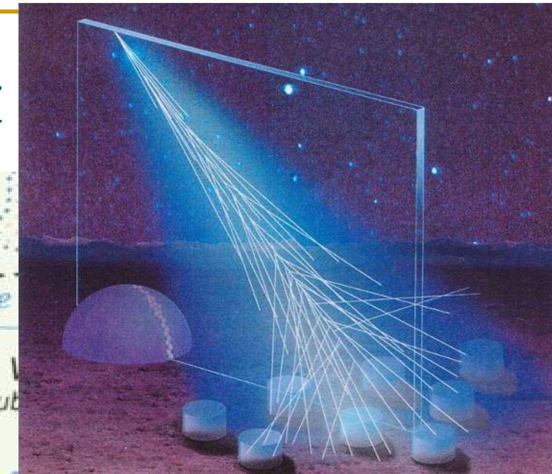
Which direction is the e^+ moving (up or down)?

Is the B-field in or out of the page?

1912 CTR Wilson Cloud Chamber

Cosmic Rays - Pierre Auger Project





Surface Array

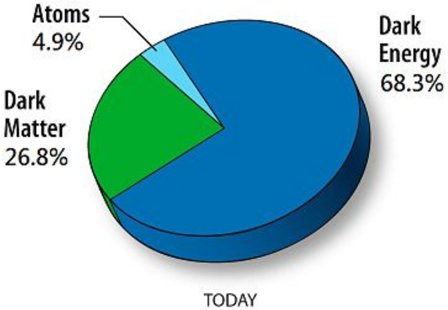
1600 detector stations
1.5 km spacing
3000 km²

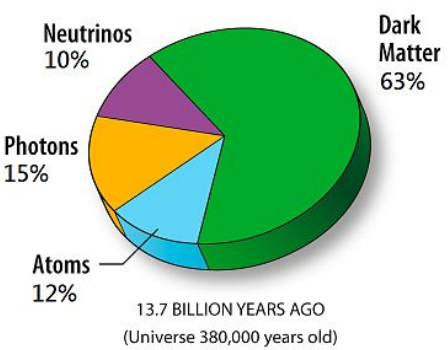
Fluorescence Detectors

4 Telescope enclosures
6 Telescopes per enclosure
24 Telescopes total

Dark Energy and Dark Matter

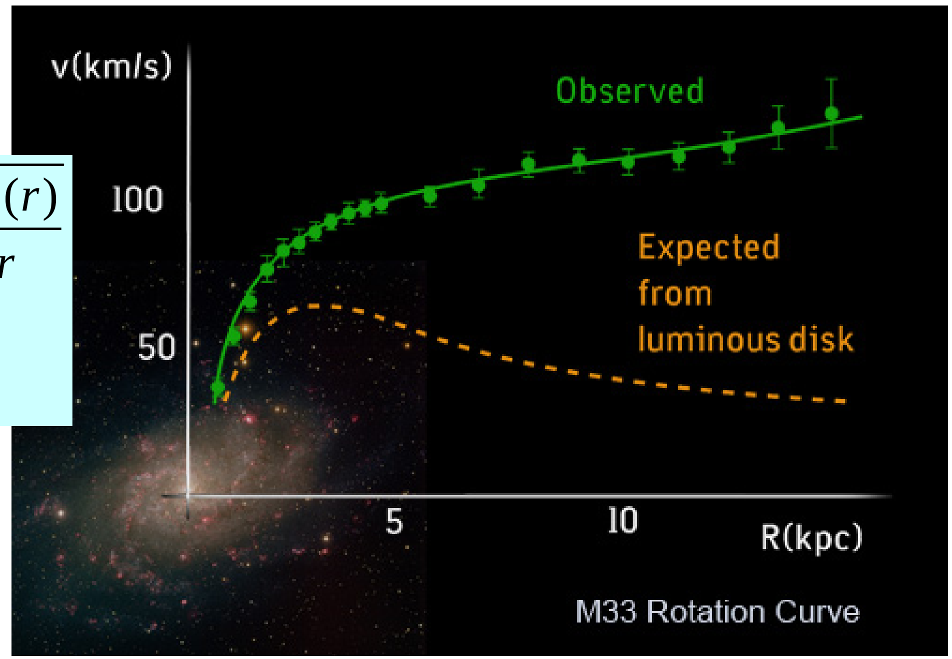
- Most of the Universe is invisible.
- Dark Energy:
  - Exerts a negative pressure on the Universe
  - Increases the acceleration of the galaxies.
- Dark Matter:
  - Just like ordinary matter but not visible (does not give off light).
- *1: Baryonic Dark Matter*
  - *~2% of the Universe*
  - *MACHOS, dwarf stars, etc…*
- *2: Non-Baryonic Dark Matter*
  - *~24% of the Universe*
  - *Hot (neutrinos) and Cold (WIMPS, axions, neutralinos).*
  - *Expected to be mostly Cold*



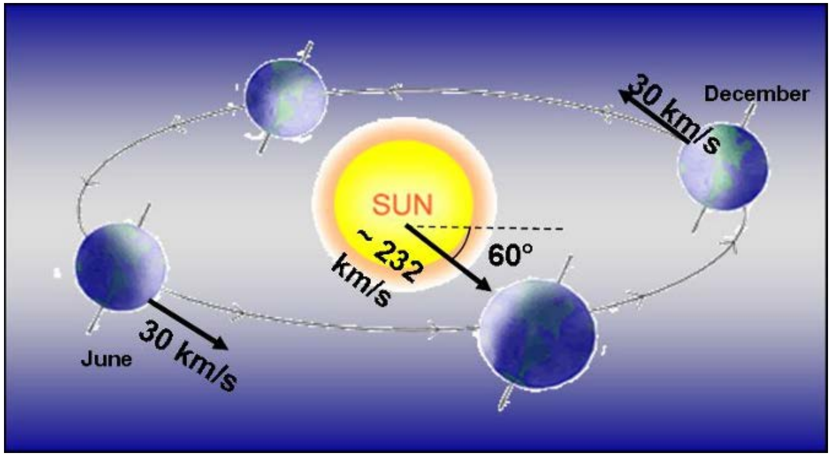


Rotation Velocity $v(r) = \sqrt{\frac{M(r)}{r}}$

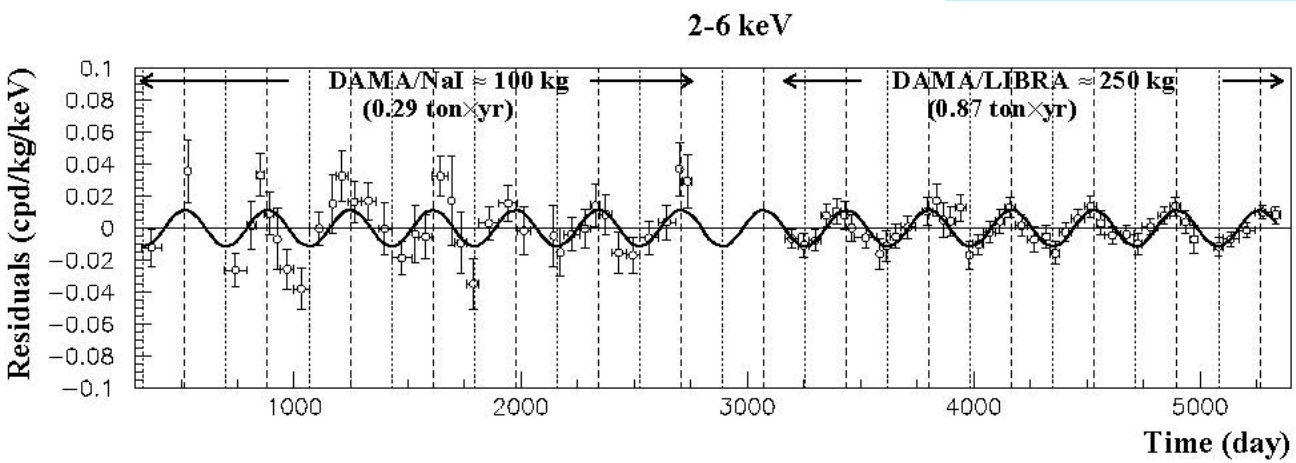
Outside Galaxy $v(r) \propto \frac{1}{\sqrt{r}}$



Dark Matter – DAMA/LIBRA



1. As the earth goes round the sun, its velocity relative to the galaxy changes by +/-30 km
2. Look for nuclear recoil in NaI as nucleus interacts with "dark matter" particle.
3. Expect to see a change in the rate of interactions every six months.
4. But is there really a pattern? and is it really dark matter?



http://arxiv.org/abs/1301.6243

Neutrino Oscillation

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}|\nu_i\rangle \qquad P_{\alpha\to\beta} = |<\nu_\beta|\upsilon_\alpha(t)>|^2$$

α = neutrino with definite flavour (e,μ,τ)

i = neutrino with definite mass (1,2,3)

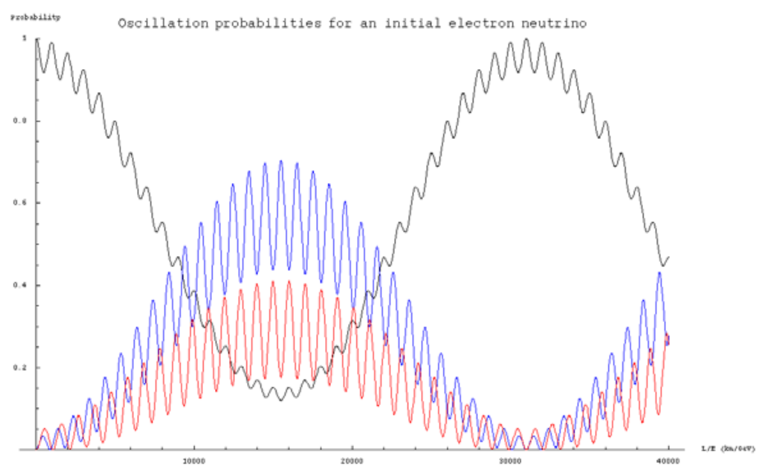
$U_{\alpha i}$ = PMNS mixing matrix

$$P_{\nu_\alpha\to\nu_\beta} = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2 L}{E}\frac{GeV}{eV^2 km}\right)$$

- Neutrinos “Oscillate”:
  - Can change from one type to another.
  - Implies ν have mass.
  - Oscillation experiments can only measure difference in squared mass Δm^2

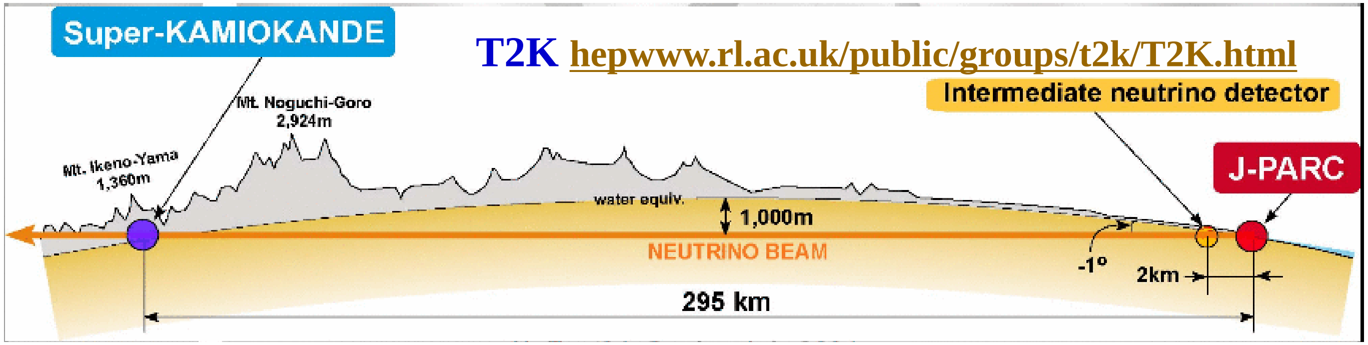
$$\begin{bmatrix}\upsilon_e & \upsilon_\mu & \upsilon_\tau\end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{bmatrix}\begin{bmatrix}\upsilon_1 \\ \upsilon_2 \\ \upsilon_3\end{bmatrix}$$

$i \leftrightarrow j$	Source	$\Delta m^2_{ij}(eV^2)$	$\theta_{ij}(^0)$
$1 \leftrightarrow 2$	Solar	$8.0^{+0.6}_{-0.4}\times 10^{-5}$	$33.4^{+0.81}_{-0.78}$
$2 \leftrightarrow 3$	Atmospheric	$2.4^{+0.6}_{-0.5}\times 10^{-3}$	45 ± 7
$1 \leftrightarrow 3$	Nuclear	2.32×10^{-3}	8.7 ± 0.5



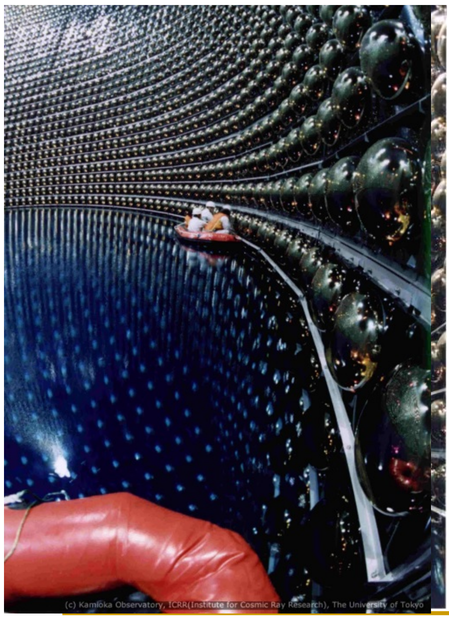
L/E (km/GeV)

Some Neutrino Detectors – Present and Future

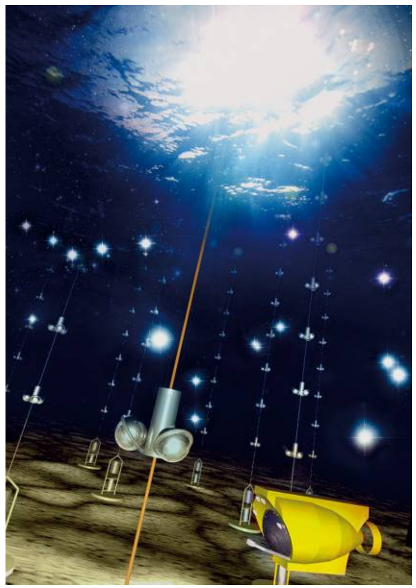


T2K hepwww.rl.ac.uk/public/groups/t2k/T2K.html

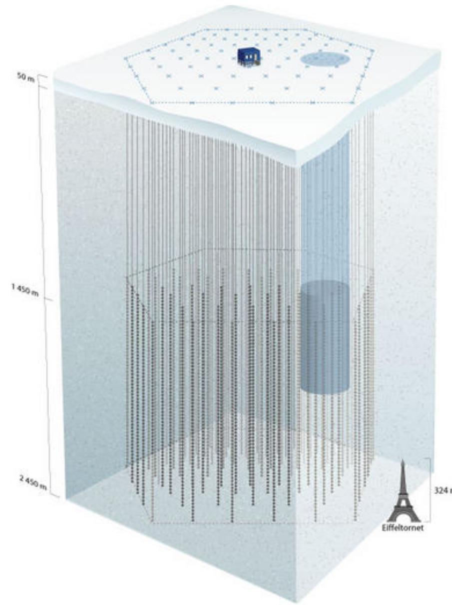
Super-Kamiokande
http://www-sk.icrr.u-tokyo.ac.jp/



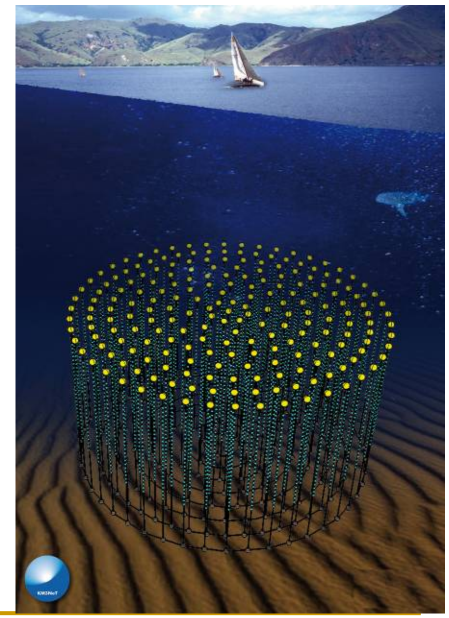
Antares
http://antares.in2p3.fr



Ice Cube
http://icecube.wisc.edu/



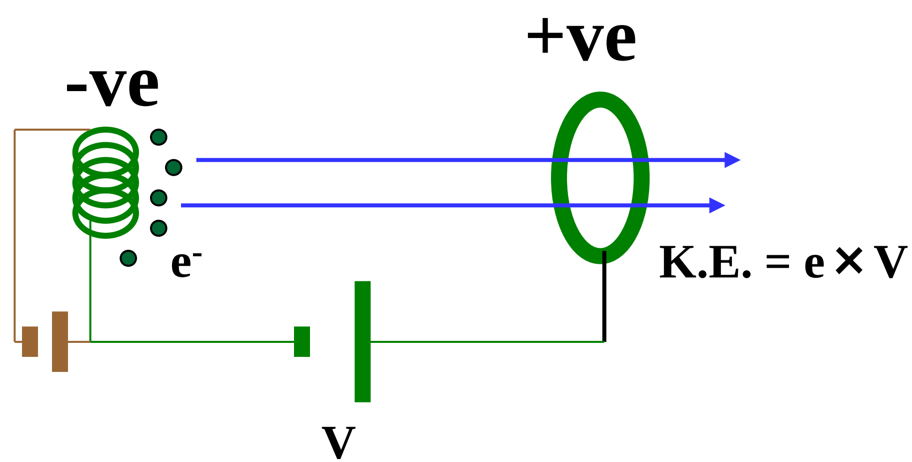
KM3NeT
http://www.km3net.org



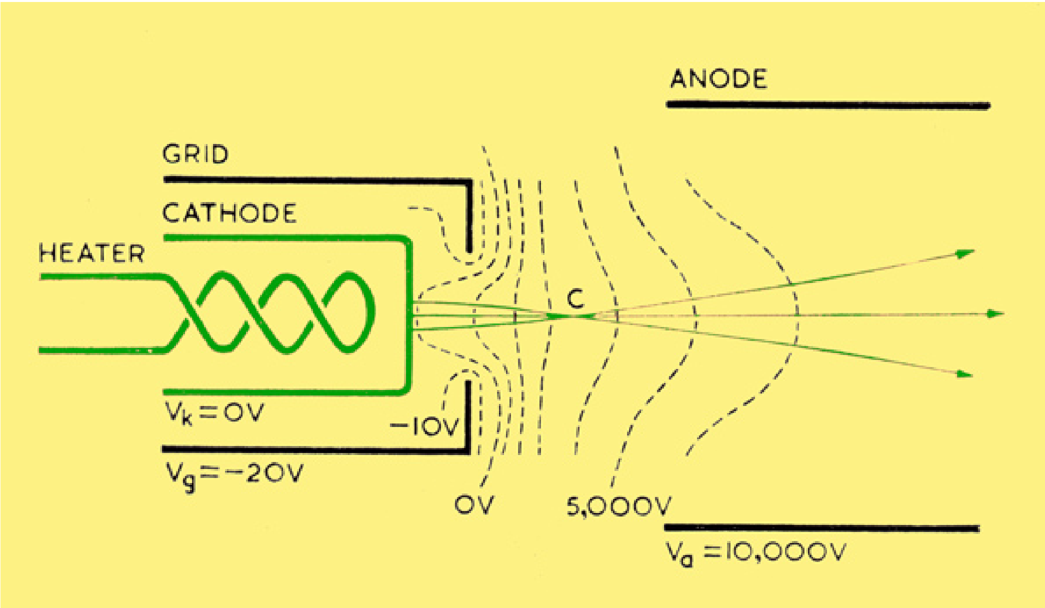
Particle Sources

Want intense monochromatic beams on demand:

1. Make some particles
   - Electrons: metal + few eV of thermal energy
   - Protons/nuclei: completely ionise gas
2. Accelerate them in the lab

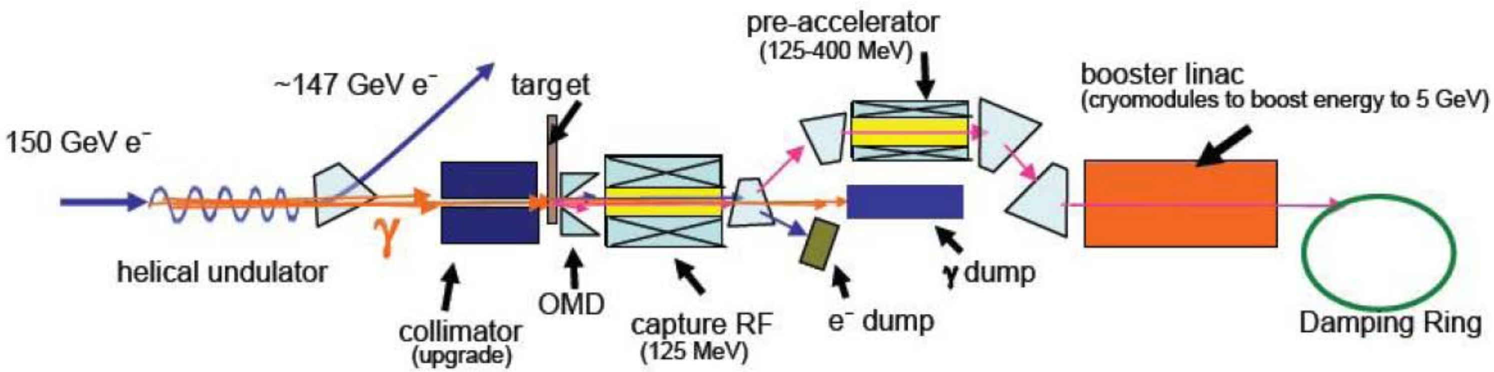


Creating Electrons



- Triode Gun
- Current: 1 A
- Voltage: 10 kV
- The grid is held at 50V below cathode (so no electrons escape).
- When triggered, grid voltage reduced to 0V. Electrons flow through grid.
- Pulse length: ~1ns

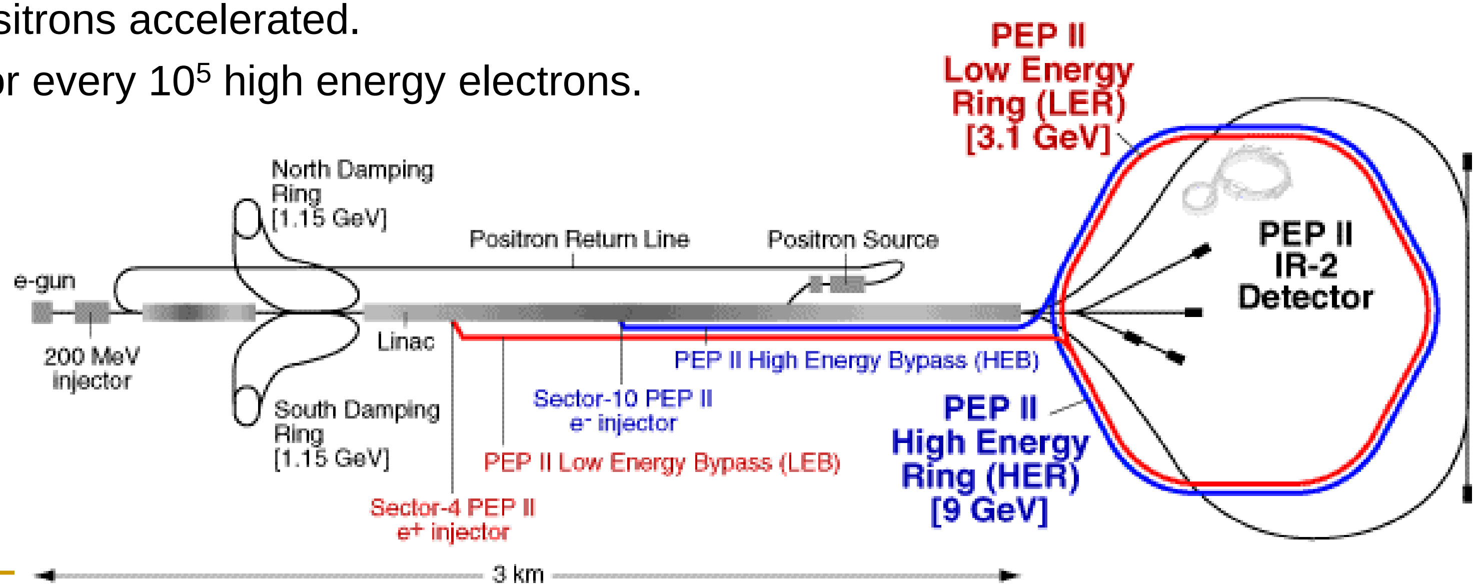
Creating Positrons



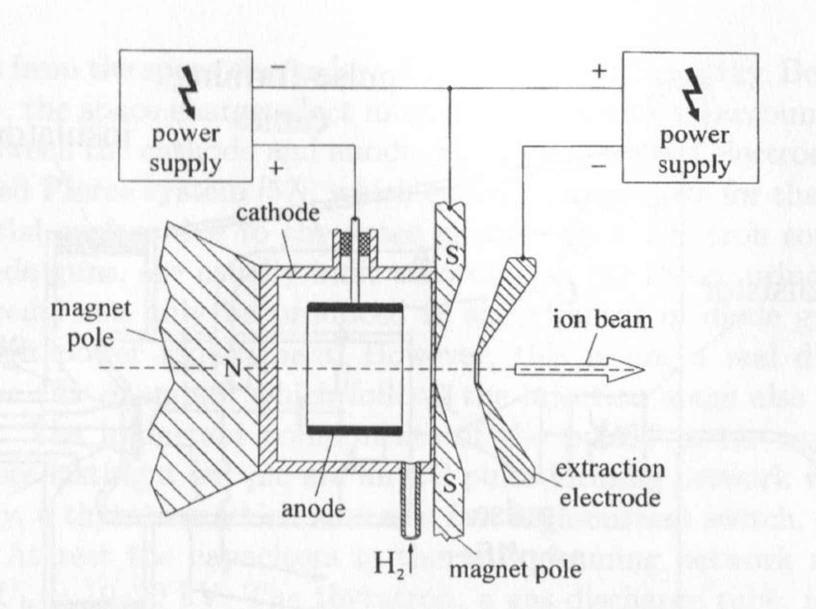
Example of how it will be done at the ILC (2027?)

- High energy e- emit photons in undulator.
- Photons hit target (tungsten)
- Positrons and electrons emitted by pair-production.
- Electrons removed, positrons accelerated.
- Inefficient: 1 positron for every 10^5 high energy electrons.

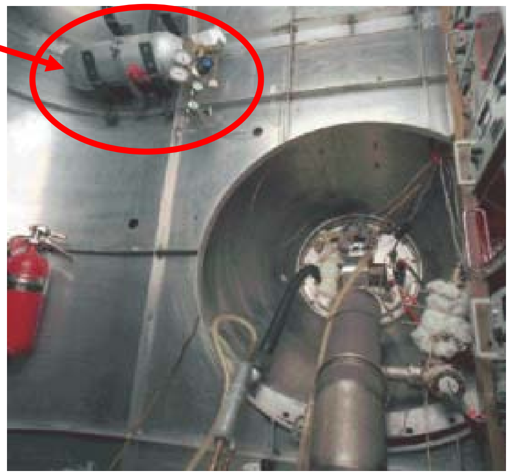
Example of how it is done at SLAC (2005)



Creating Protons – PIG (Penning Ion Gauge)



Hydrogen gas bottle

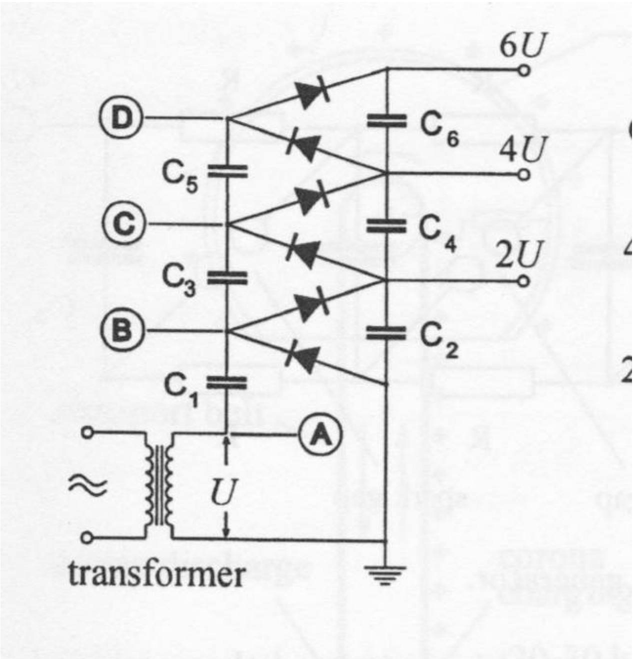


Tevatron

- Ion source (e.g. H_2) introduced as a gas and ionised.
- Magnetic field 0.01T perpendicular to E-field causes ions to spiral along B-field lines.
- Low pressure needed to keep mean-free path long (10^{-3} Torr).
- Modern methods are more complicated.
- http://www-bdnew.fnal.gov/tevatron/

DC Accelerators – Cockcroft Walton

How it works



Cockcroft and Walton's Original Design (~1932)

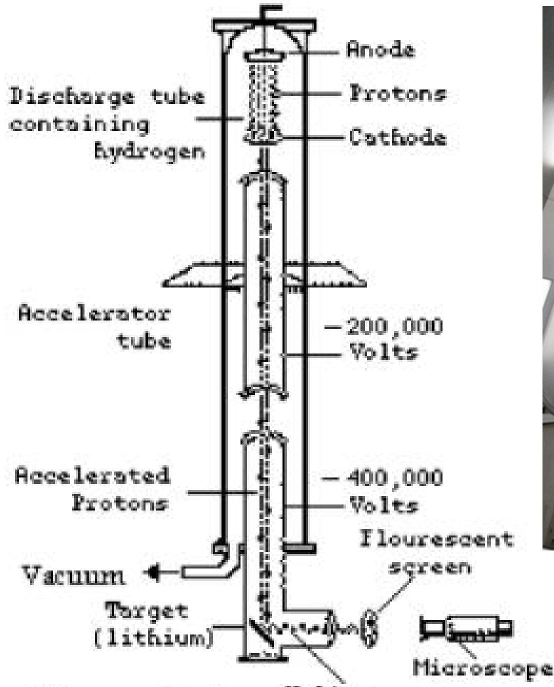


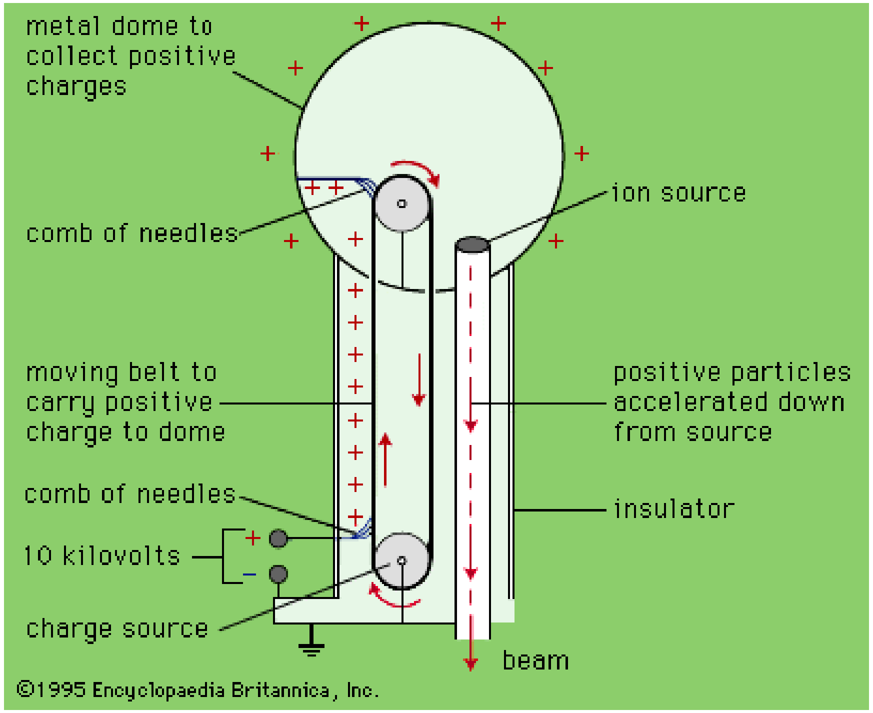
Figure 1.2

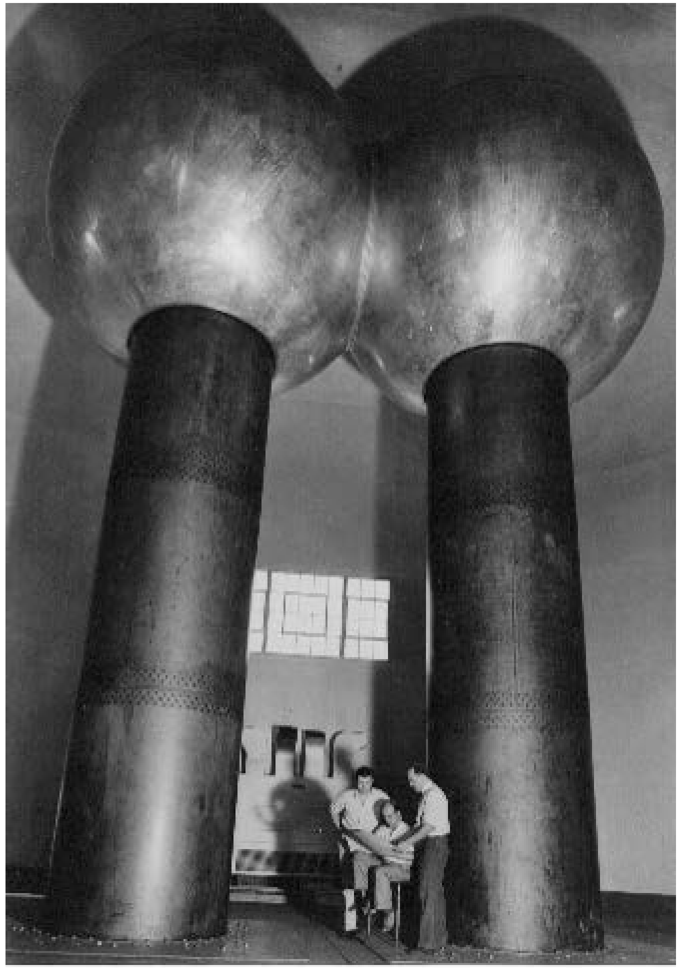
Fermilab's 750kV Cockroft-Walton

- DC accelerators quickly become impractical
- Air breaks down at ~1 MV/m

DC Accelerators – Van der Graff

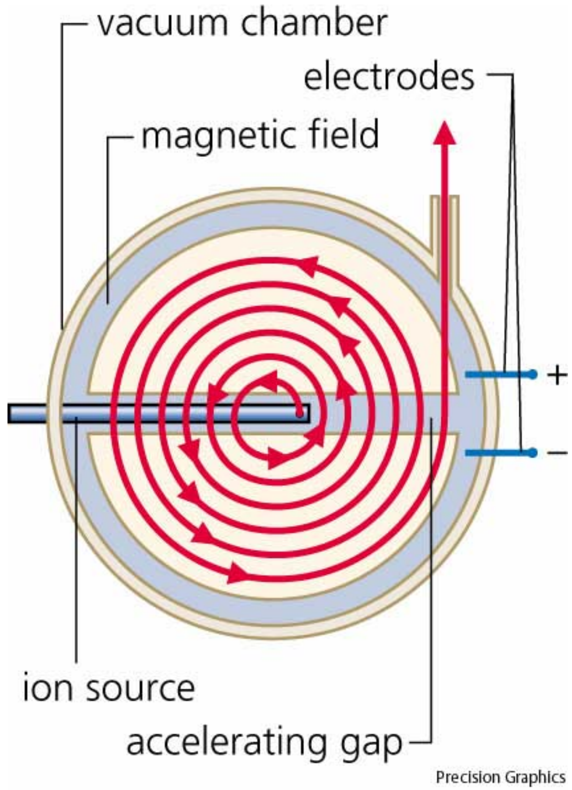
Van de Graaf at MIT (25 MV)



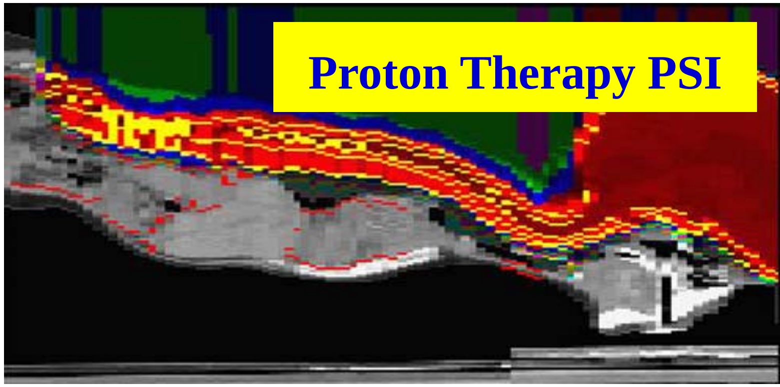


Cyclotrons

- Utilise motion in magnetic field:
  p (GeV/c) = 0.3 q B R
- Apply AC to two halves
- Lawrence achieved MeV particles with 28cm diameter
- Magnet size scales with momentum



$$\omega = \frac{qB}{m}$$



Cyclotrons - Variations

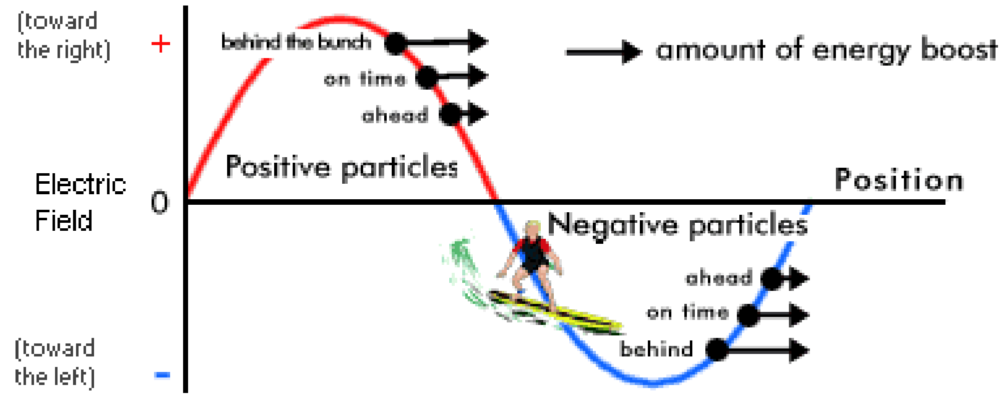
- Cyclotron limitations:
  - Energy limit is quite low: 25 MeV per charge
  - Non-relativistic velocity v < 0.15c
- Alternatives:
  - Syncro-cyclotron
    - Keep magnetic field constant but decrease RF frequency as energy increases to compensate for relativistic effects.
  - Iso-cyclotron
    - Keep RF frequency the same but increase the radial magnetic field so that cyclotron frequency remains the same:
    - Can reach ~600 MeV
  - Synchrotron
    - For very high energies. See later…

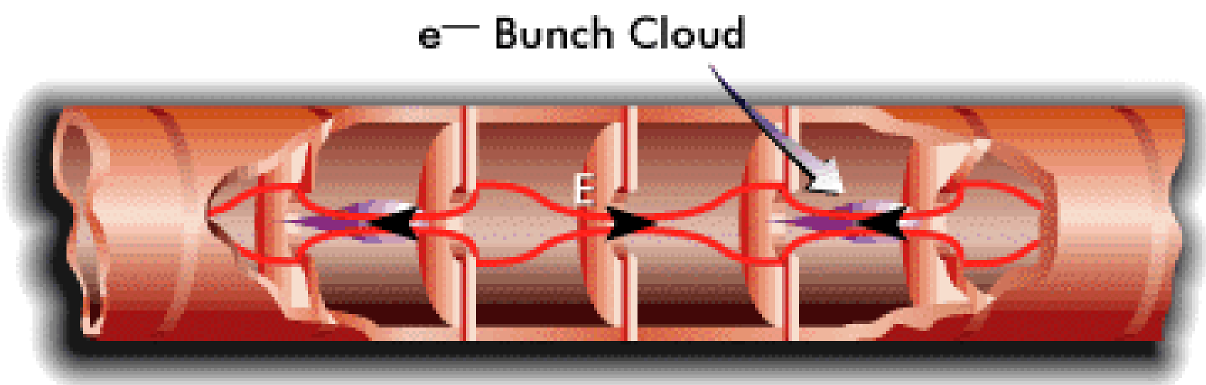
$$\omega = \frac{qB(r(E))}{m(E)} = const.$$

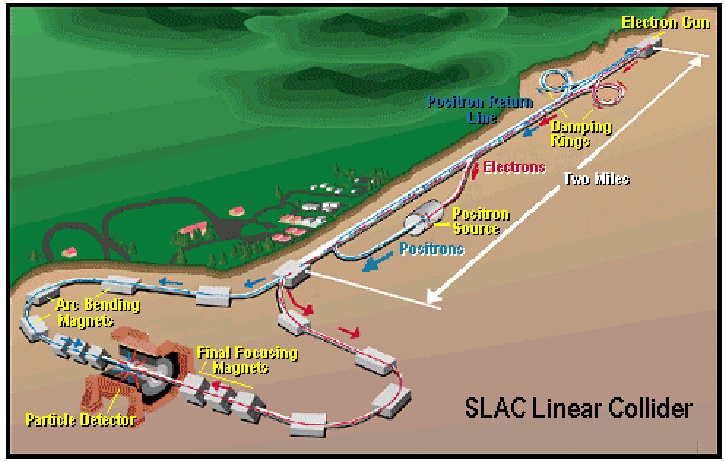
Linear Accelerators

For energies greater than few MeV:

- Use multiple stages
- RF easier to generate and handle
- Bunches travel through resonant cavities
- Spacing and/or frequency changes with velocity
- Can achieve 10MV/m and higher
- 3km long Stanford Linac reached 45 GeV
- 30km Linear Collider would reach 250 GeV.

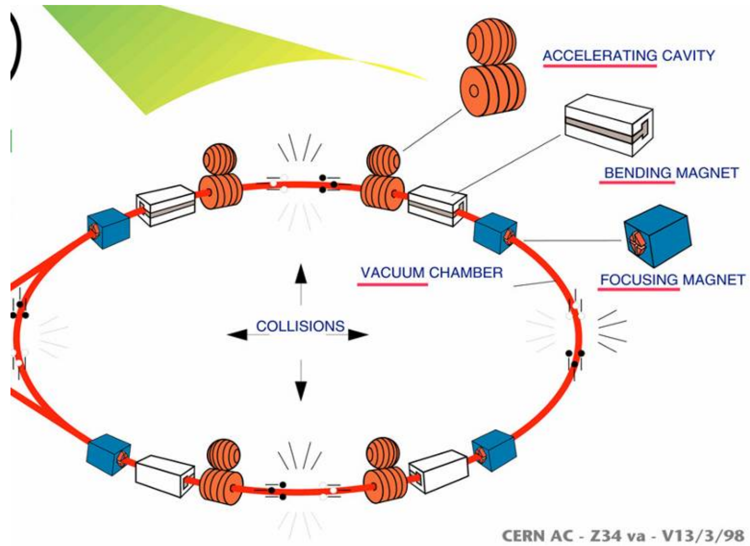






Synchrotrons

- *p (GeV/c) = 0.3 q B R*
- Cyclotron has constant *B*, increasing *R*
- Increase *B* keeping *R* constant:
  - variable current electromagnets
  - particles can travel in small diameter vacuum pipe
  - single cavity can accelerate particles each turn
  - efficient use of space and equipment
- Discrete components in ring
  - cavities
  - dipoles (bending)
  - quadrupoles (focusing)
  - sextuples (achromaticity)
  - diagnostics
  - control



$$mv^2 = Bqv$$

$$\omega = \frac{v}{r} = \frac{Bq}{m}$$

$$f = \frac{Bq}{2m\pi}\frac{m_0}{m_0 + T}$$

Synchrotron Radiation

- Accelerated charges radiate
- Average power loss per particle:
- Quantum process → spread in energy
- For a given energy ~ $1/\text{mass}^4$
  - (this comes from γ in the power loss equation)
- Electron losses much larger than proton
  - High energy electron machines have very large or infinite *R (i.e. linear).*
- Pulsed, intense X-ray source may be useful for some things....

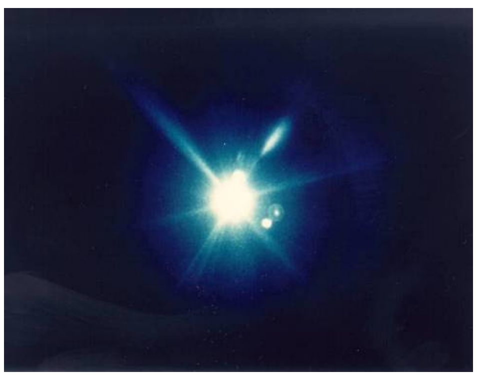
Power loss (Watts) $= \dfrac{1}{6\pi\varepsilon_0}\dfrac{e^2a^2}{c^3}\gamma^4 \quad a = \dfrac{v^2}{R} \quad \gamma = \dfrac{E}{m_o}$

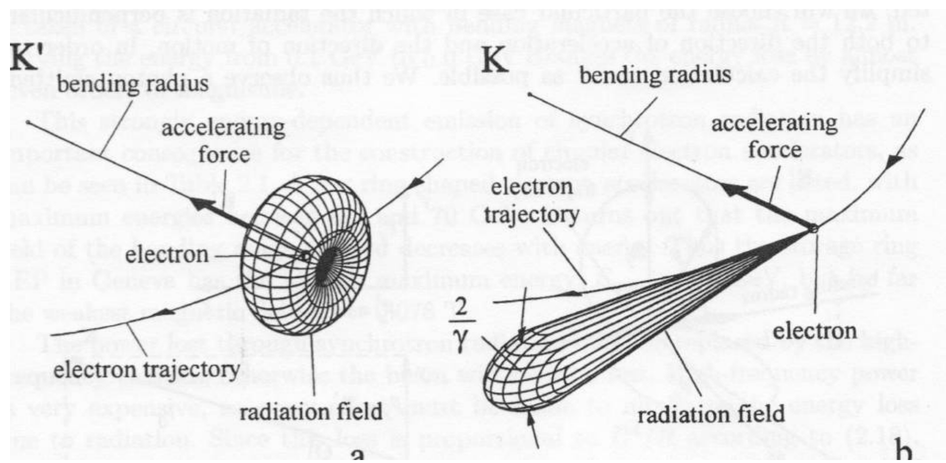
$\Rightarrow$ Electron Power Loss per turn $= \dfrac{8.85\times10^{-5}E^4}{R}$ MeV/turn

E in GeV, R in km.

$\Rightarrow$ Proton Power Loss per turn $= \dfrac{7.78\times10^{-3}E^4}{R}$ keV/turn

E in TeV, R in km.



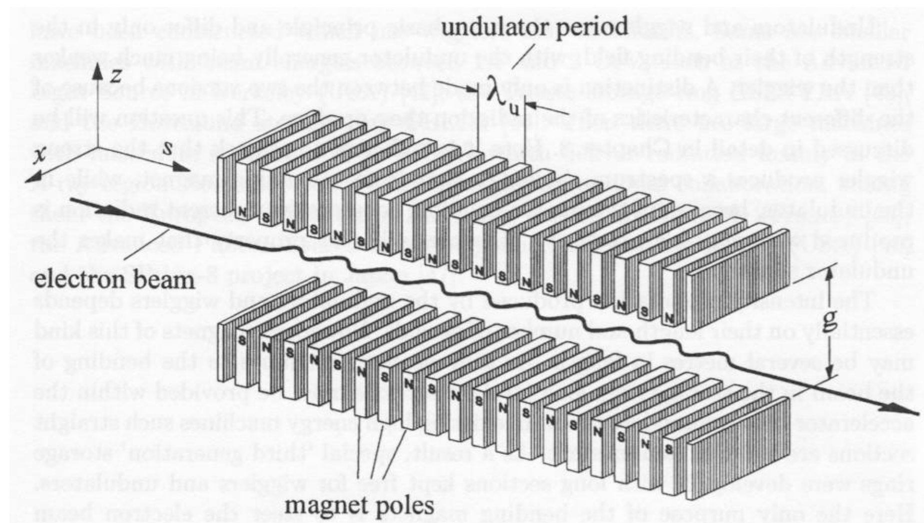


Real Synchrotrons

Bevatron, LBNL, USA (1954)

Grenoble, France

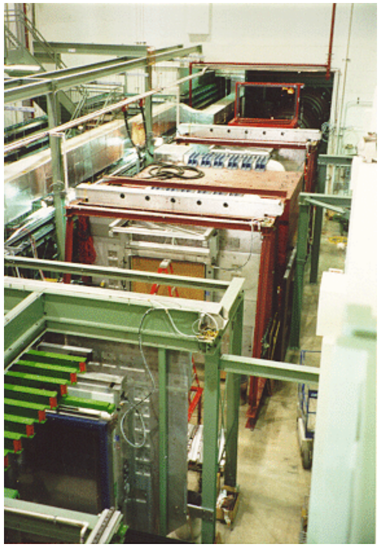
DIAMOND, RAL, UK



Fixed Target Experiments

Beam incident on stationary target

- Interaction products have large momentum in forward direction
- Large "wasted" energy ⇔ small $\sqrt{s}$
- Intense beams/large target ⇒ high rate
- Secondary beams can be made.

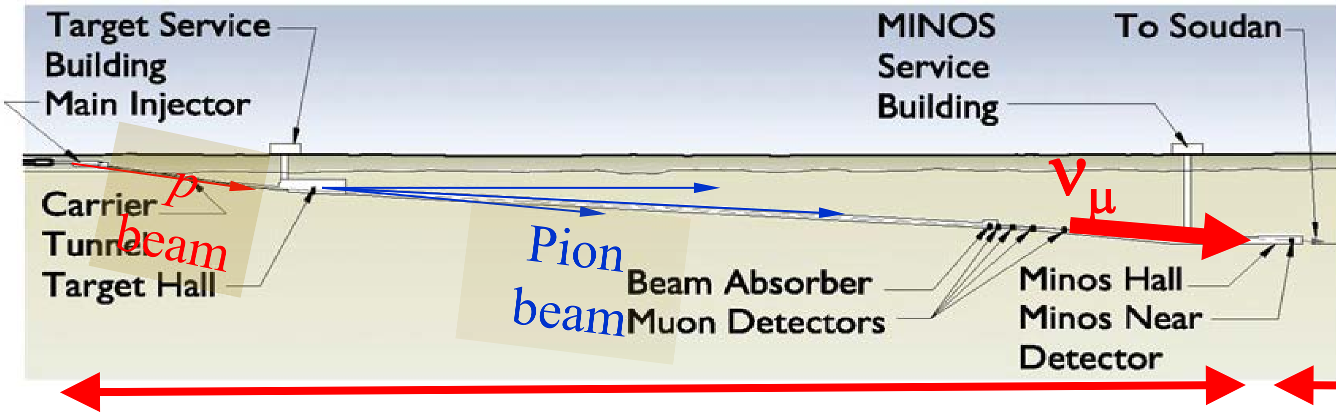


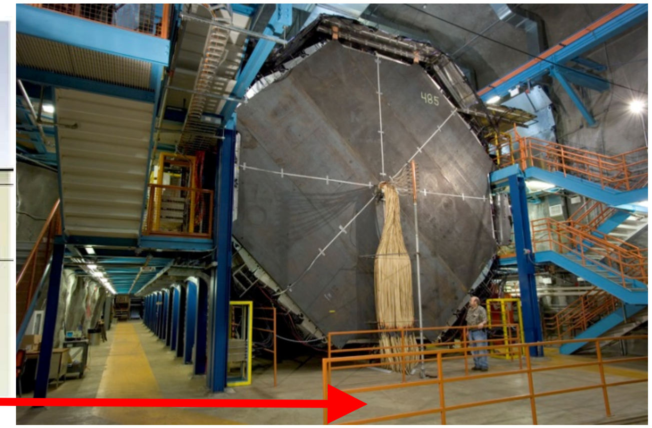
$$p_1 = (E_1, \overline{p}_1) \quad p_2 = (E_2, \overline{p}_2) \quad E^2 = p^2 + m_0^2$$

Centre of Mass energy squared $s = E_{cm}^2 = (p_1 + p_2)^2$

$$\Rightarrow E_{cm} = \left[\left(E_1 + E_2\right)^2 - \left(\overline{p}_1 + \overline{p}_2\right)^2 \right]^{1/2}$$

Fixed Target - Neutrino Beams

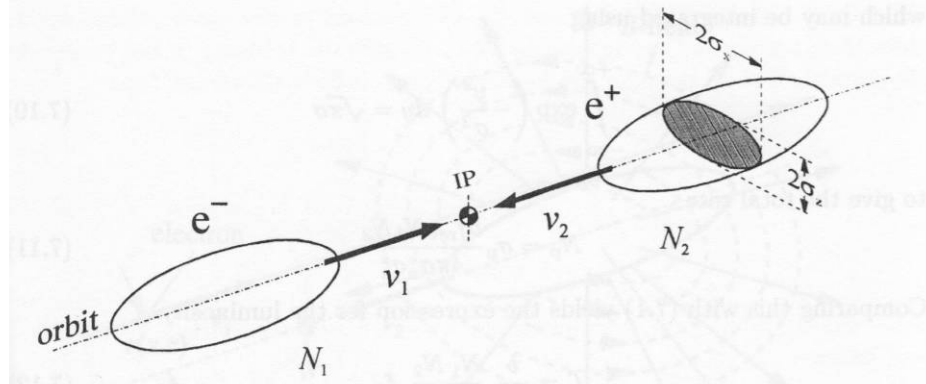




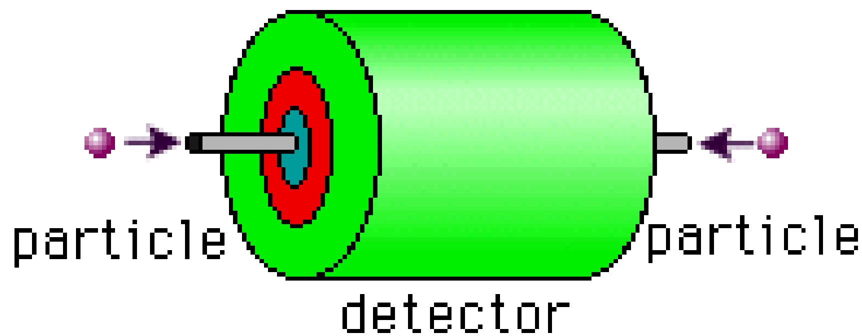
700 m **700 km**

- Fermilab sends a ν_μ beam to Minnesota
- Looking for oscillations
- Detector at bottom of mine shaft

Colliders



- Incoming momenta cancel
- $\sqrt{s} = 2E_{beam}$
- Same magnetic field deflects opposite charges in opposite directions ⇒ *Antiparticle accelerator for free!*
  - particle/antiparticle quantum numbers also cancel
- *Technically challenging*



Event Rate R = $L\sigma$

Current $I_i = n_i e f N_b$

particles per bunch

$$\text{Luminosity} = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y} = \frac{I_1 I_2}{4\pi\, f N_b e^2 f\, \sigma_x \sigma_y}$$

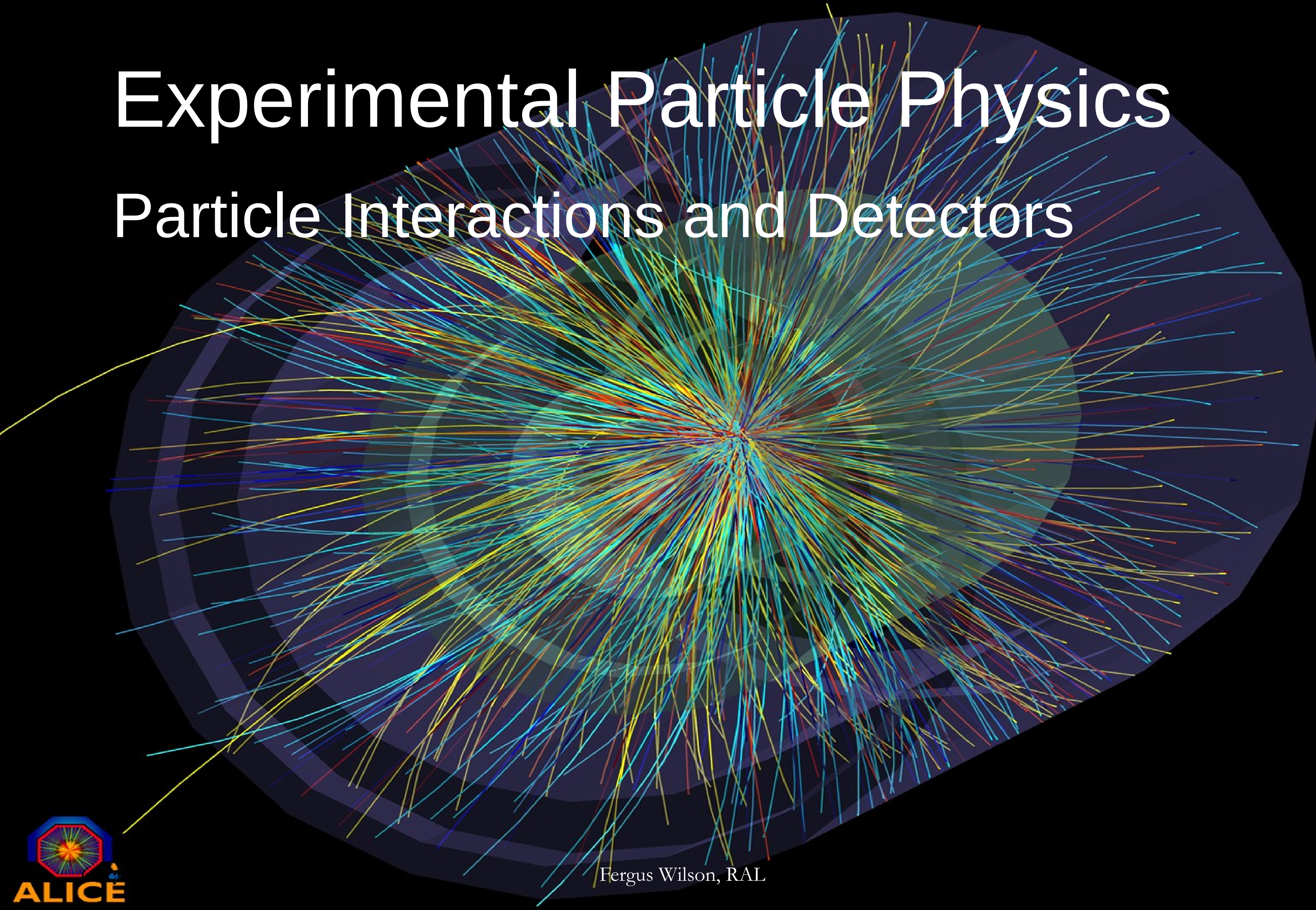
frequency

bunch size

#bunches

Experimental Particle Physics

Particle Interactions and Detectors

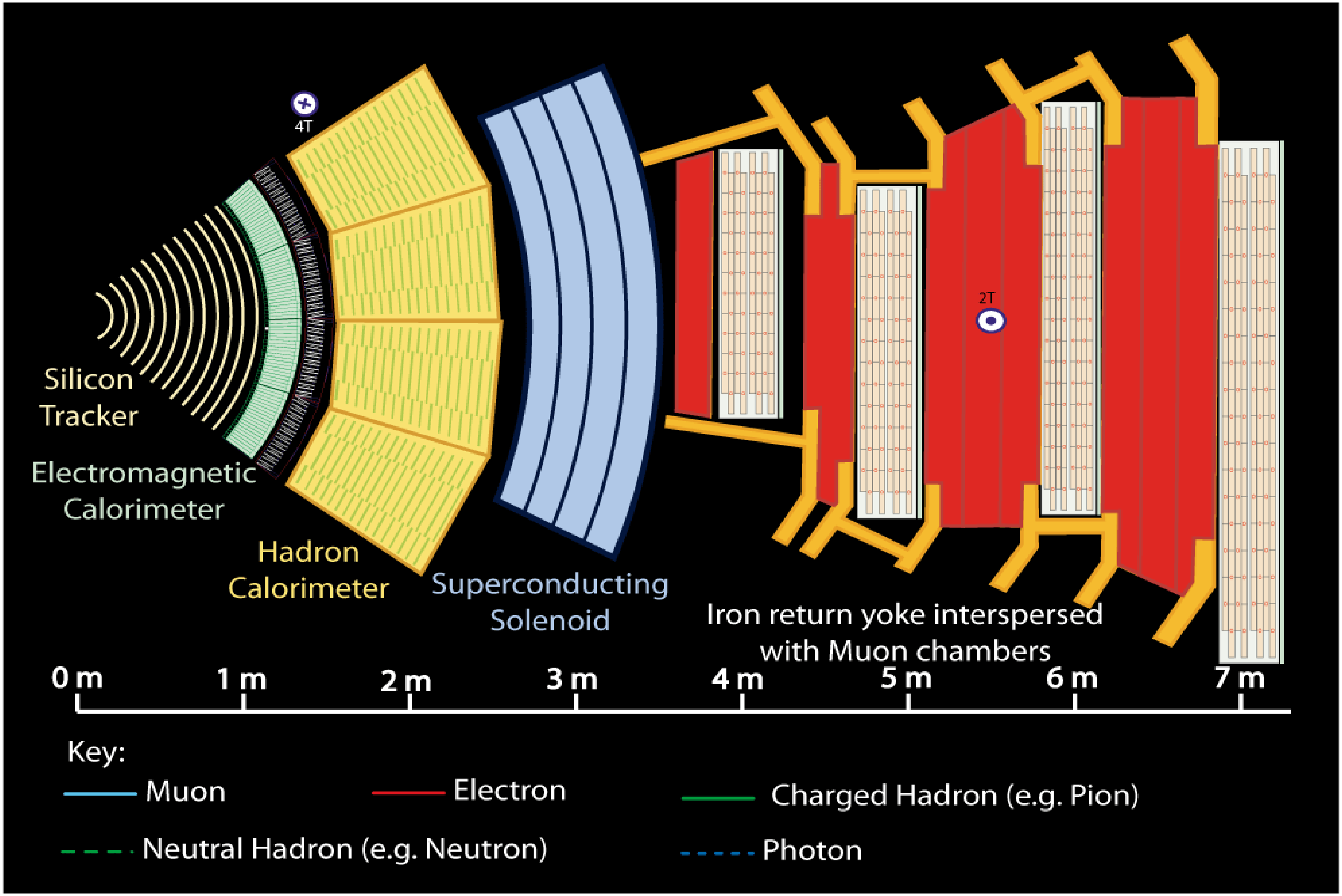


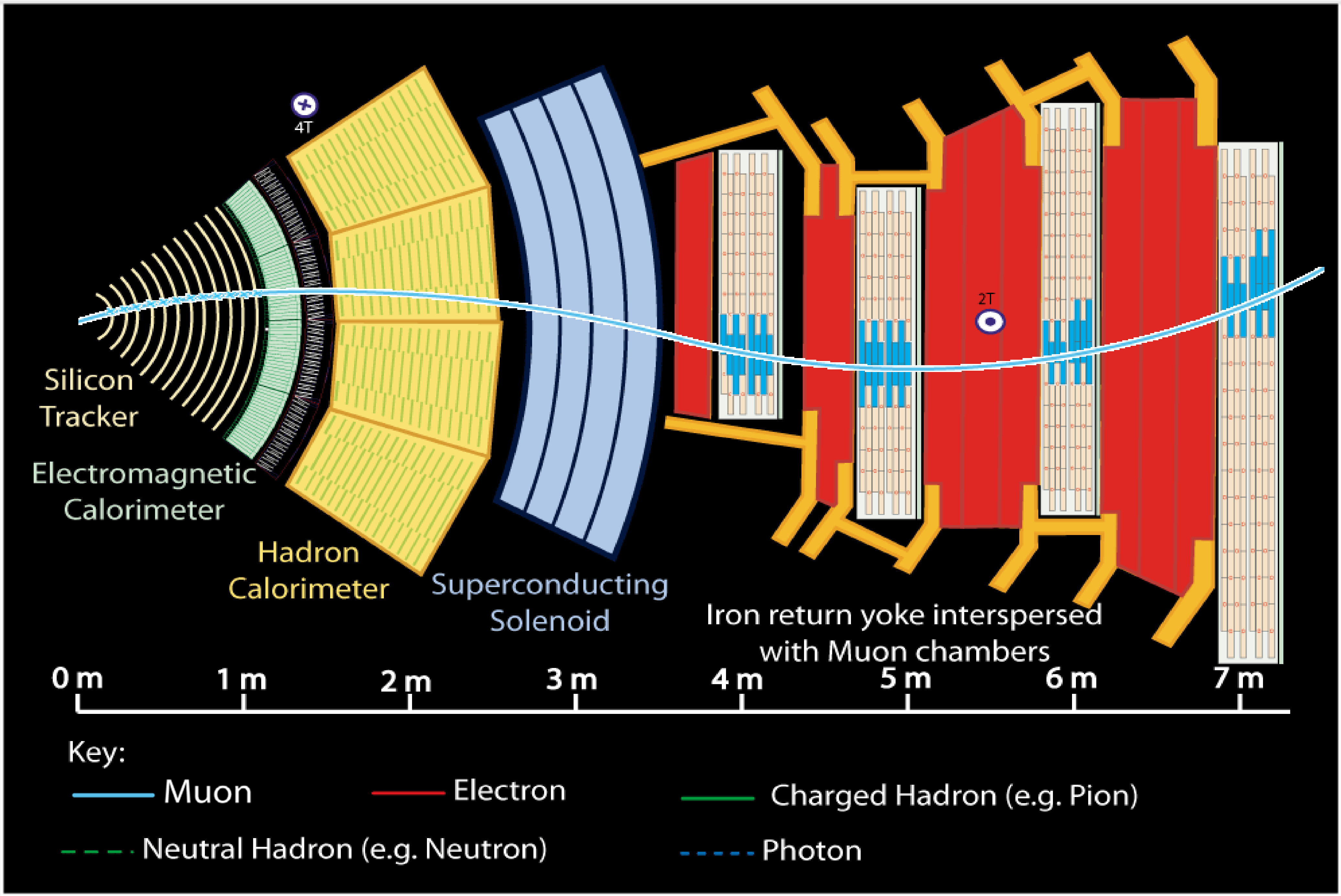
Fergus Wilson, RAL

How do we detect particles?

- Particle Types
  - Charged ($e^-/K^-/\pi^-$)
  - Photons (γ)
  - Electromagnetic (e^-)
  - Hadronic ($K^-/\pi^-/\mu^-$)
  - Muonic (μ^-)
  - Gravitons !
- Interaction with matter
  - Ionisation Loss
  - Radiation Loss
  - Photon Absorption
  - Electromagnetic Showers
  - Hadronic Showers
  - Cherenkov Radiation
  - Transition Radiation

In general, we measure the energy lost as the particle passes through a medium.


4T
2T
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



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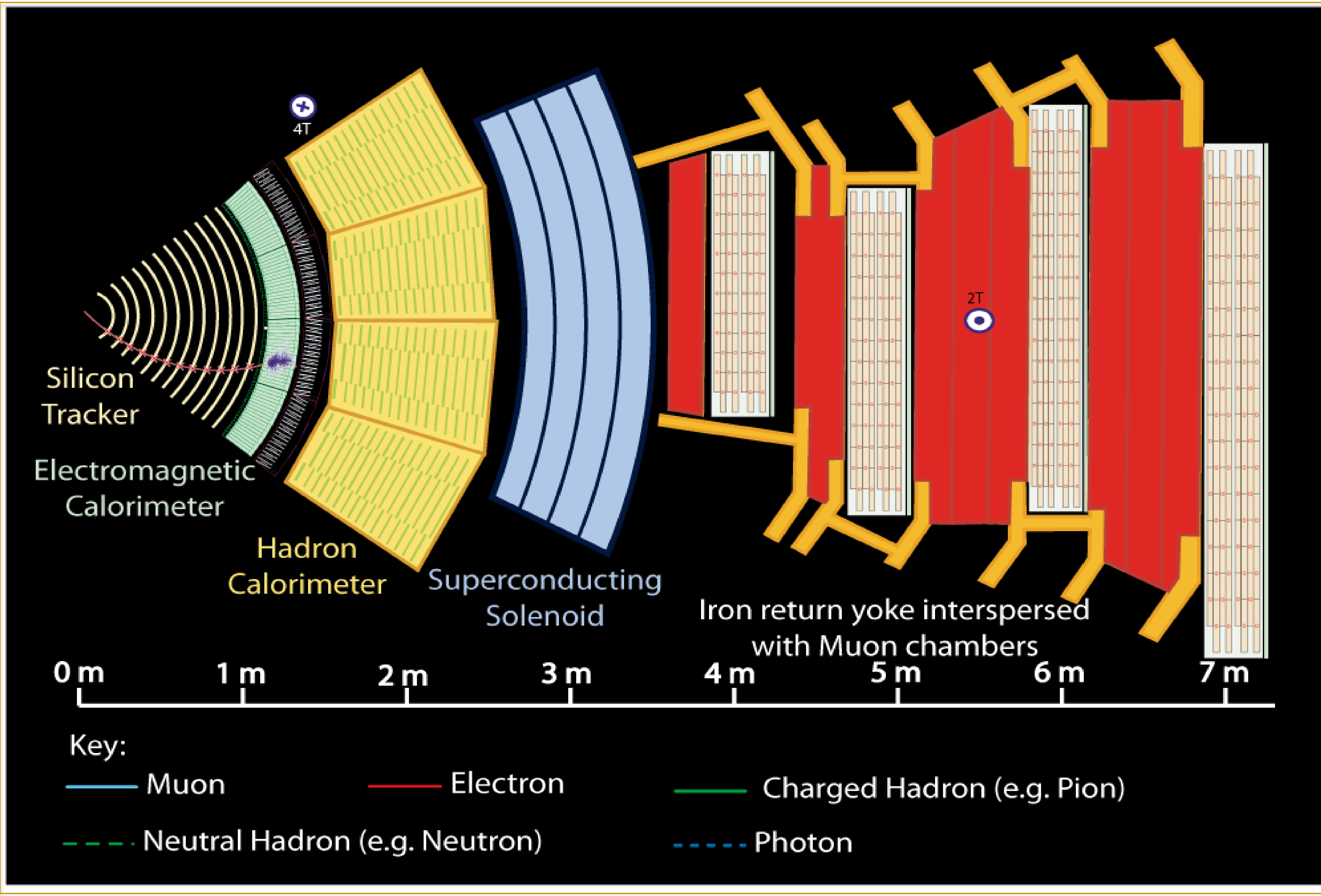
Photon



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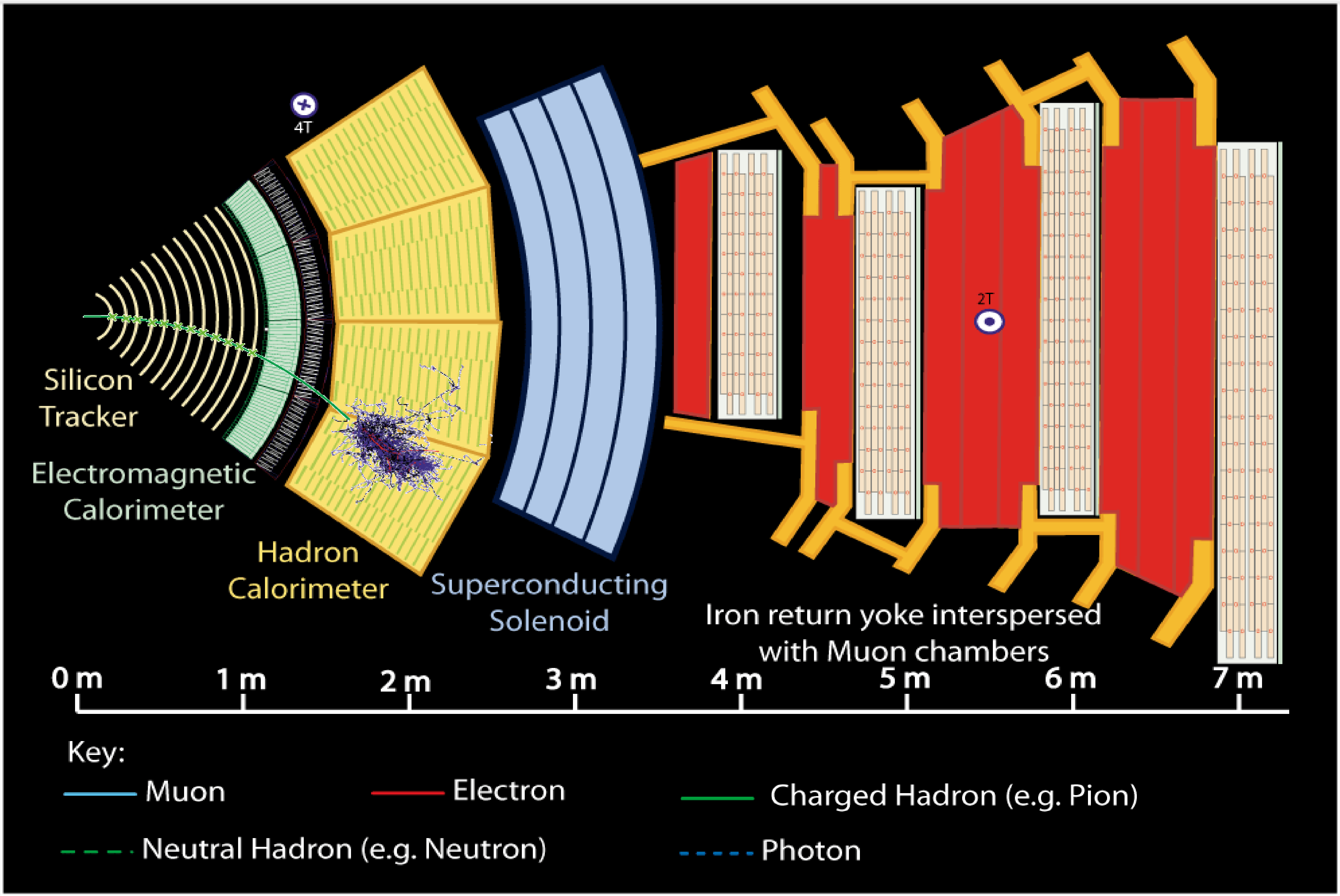
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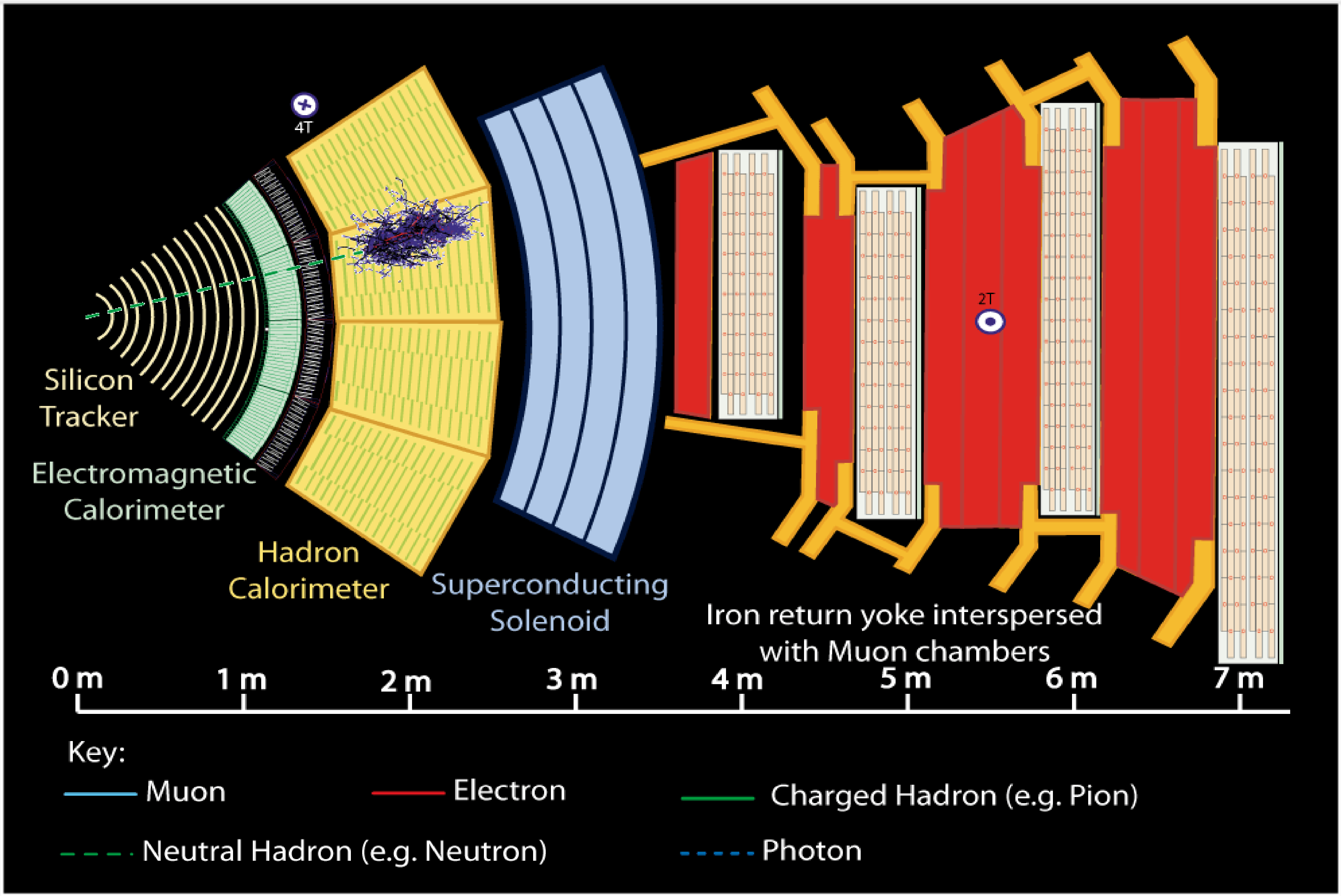
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
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Iron return yoke interspersed with Muon chambers
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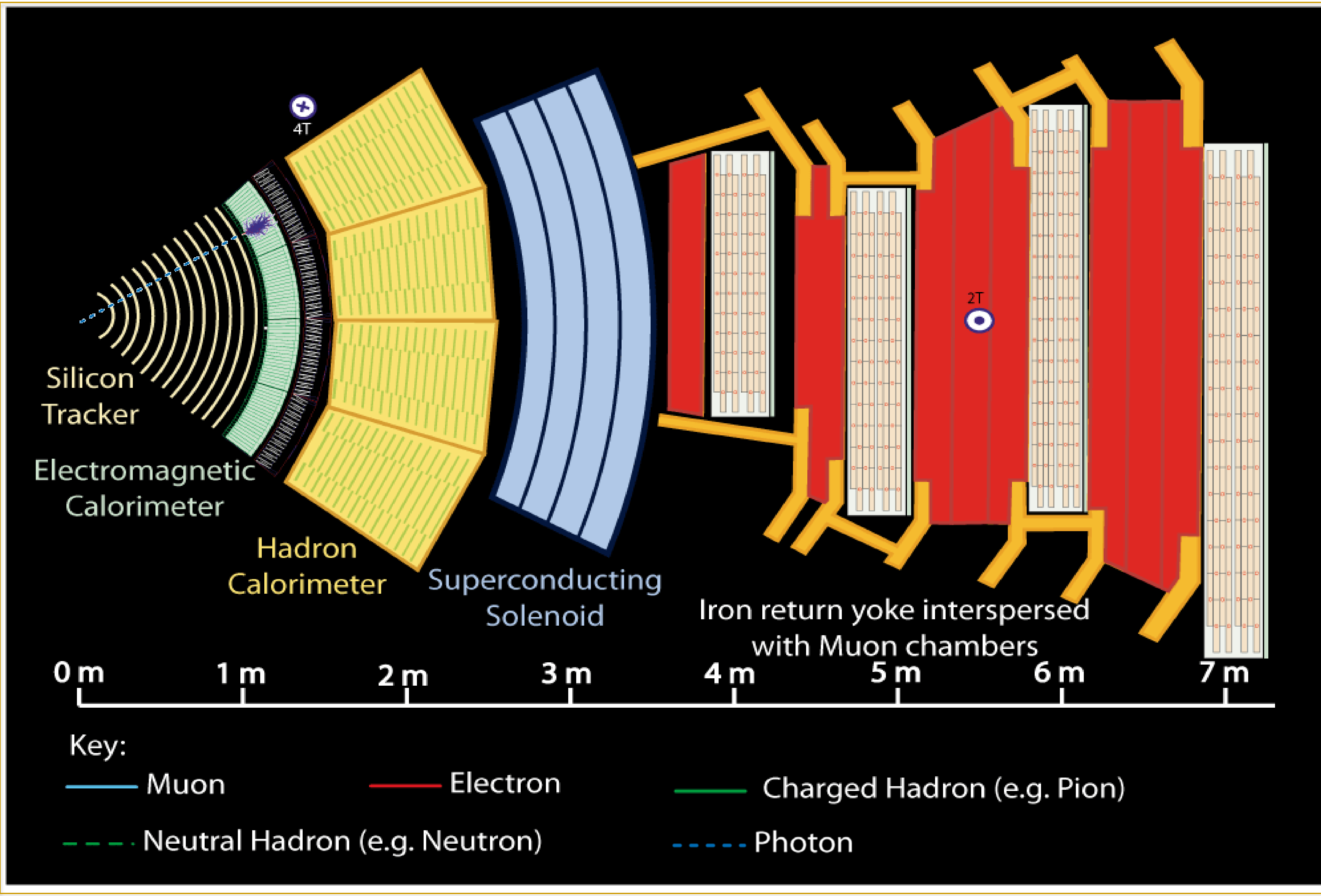
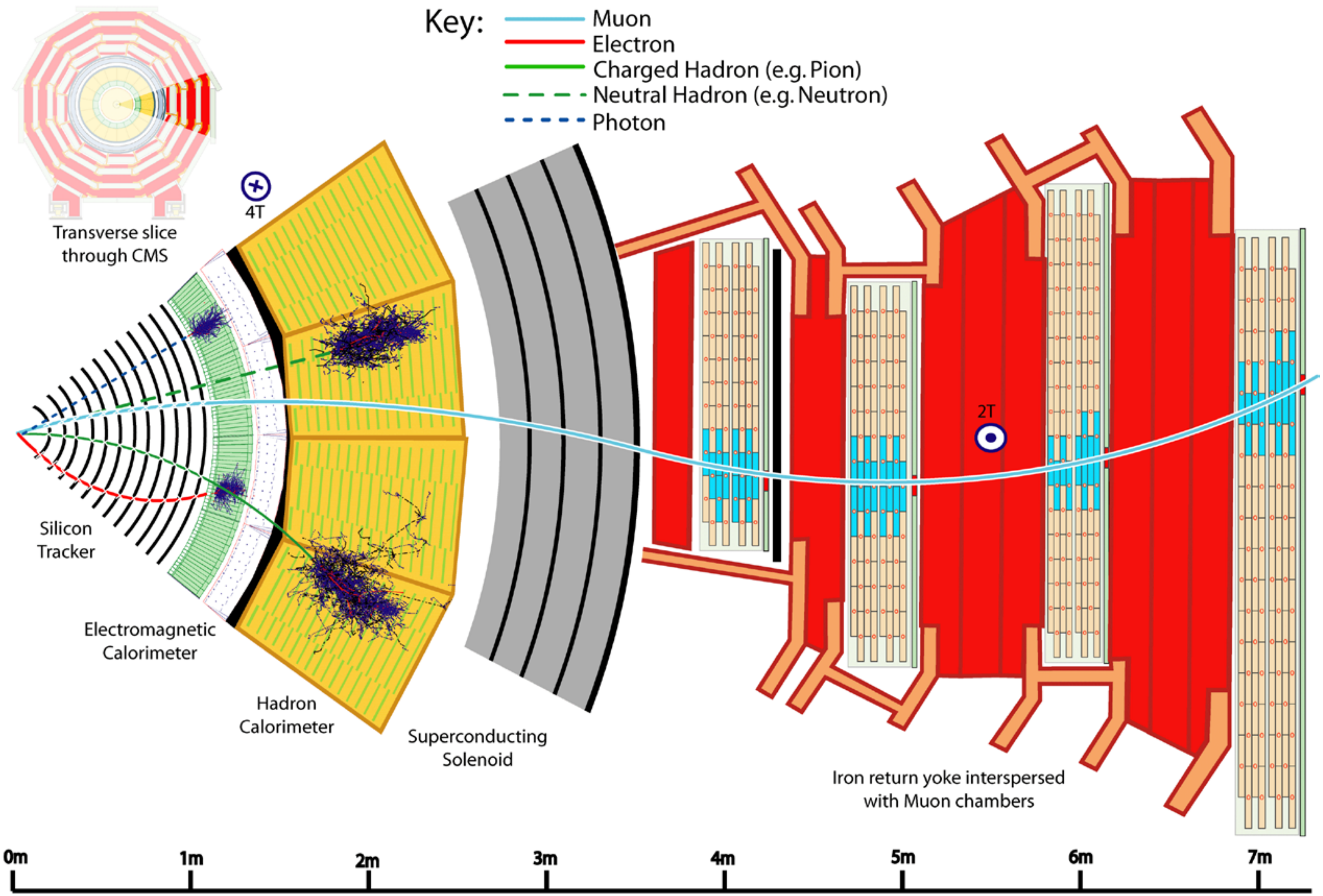
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



4T
2T
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



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

Which particles interact with which subdetector?

(caveat: some particles leave a small signal in a subdetector e.g. muon in EM calorimeter)

Detector	Electron	Charged Hadron (K^+/π^+)	Muon	Neutral Hadron (π^0)	Photon
Tracking	Yes	Yes	Yes		
Cherenkov		Yes			
Transition Radiation	Yes	Yes			
EM Calorimeter	Yes				Yes
Hadronic Calorimeter		Yes		Yes	
Muon Detector			Yes		

Charged Particle Detectors

- Physics
  - Ionisation
  - Mean Energy Loss
  - Fluctuations
  - Cherenkov Light
  - Transition Radiation

- Detectors
  1. Emulsion
  2. Bubble Chambers
  3. Scintillation Detectors
  4. Wire Chambers
  5. Multi Wire Proportional Chambers (MWPC)
  6. Geiger Muller
  7. Solid State Devices
  8. Time Projection (TPC)
  9. Resistive Plate Counters (RPC)
  10. Limited Streamer Tubes (LST)
  11. Cherenkov
  12. Transition Radiation (TRD)

Ionisation and Atomic Excitation

- Heavy Charged particles interact with electrons in material as they pass
- Energy loss can be calculated: *The Bethe-Bloch Equation*
- *Works for energies between 6 MeV and 6 GeV*
- *Function only of β (approximately)*

Maximum energy loss in single collision

$$T_{\max} \approx 2m_e c^2 \beta^2 \gamma^2$$

Stopping Power

Constant

$$-\frac{dE}{dx}(\mathrm{eV cm^2 g^{-1}}) = Kq^2 \frac{Z}{A\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\beta^2\gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

$$x = \frac{\text{distance (cm)}}{\text{density (g/cm}^3\text{)}}$$

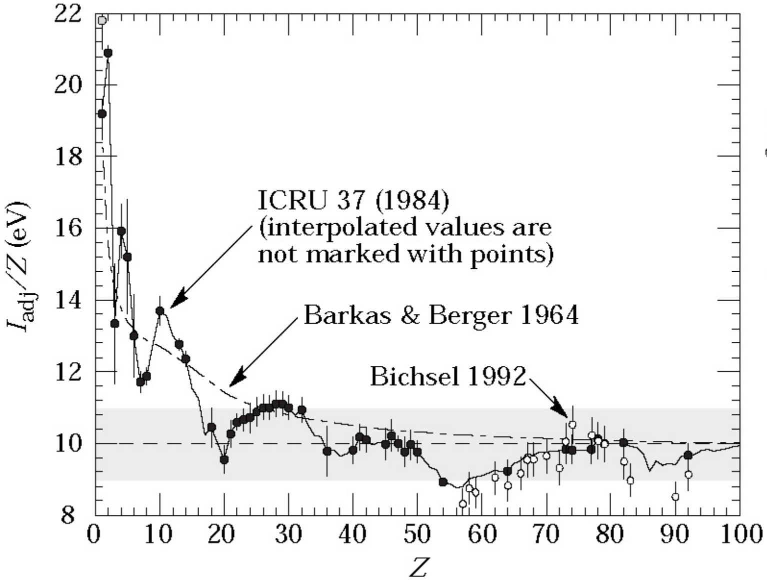
≈1/2

Ionisation Constant for material

Density correction

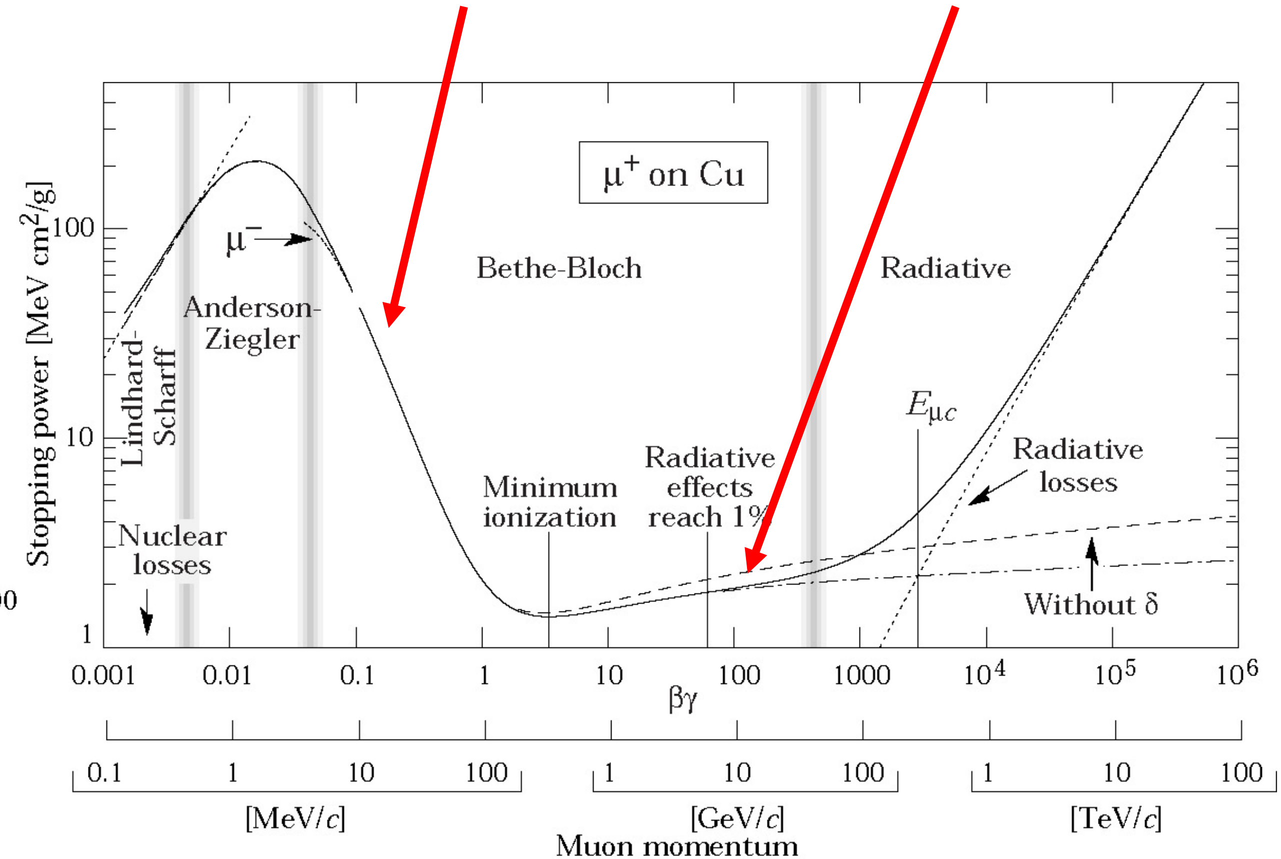
Stopping Power

Ionisation Constant

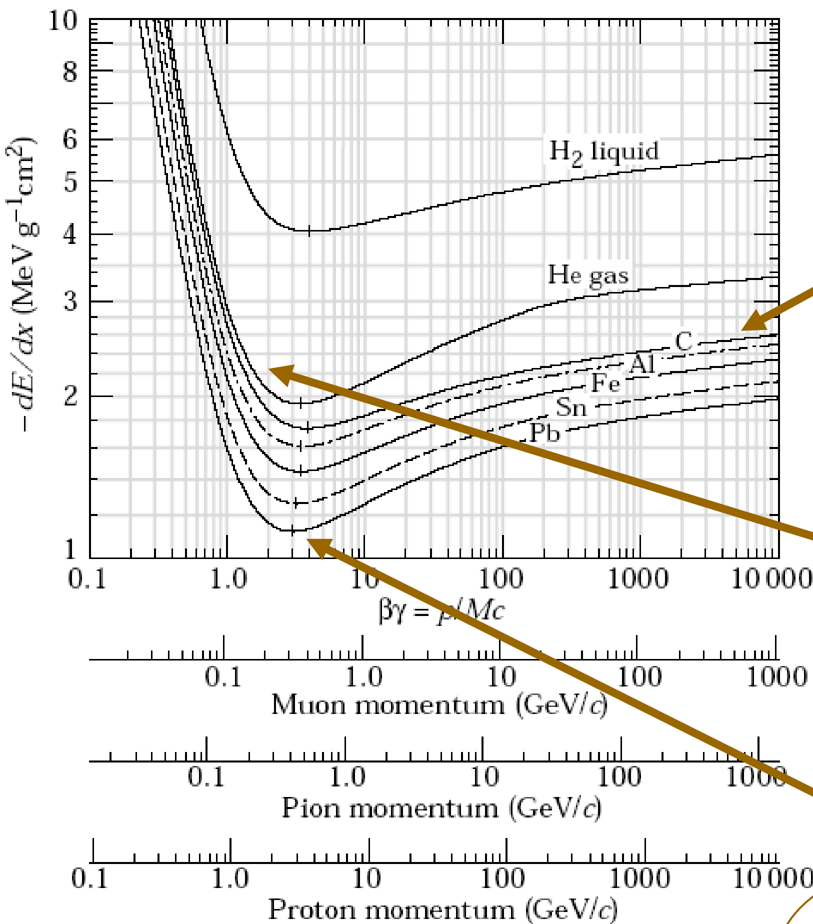


$1/\beta^2$

$\ln(\beta^2)$



Mean Energy Loss in different materials



High energy ~ ln γ

$$-\frac{dE}{dx} \approx Kq^2 \frac{Z}{A\beta^2}\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I^2} - \beta^2\right]$$

Low energy ~ 1/β²

Minimum at γ≈3

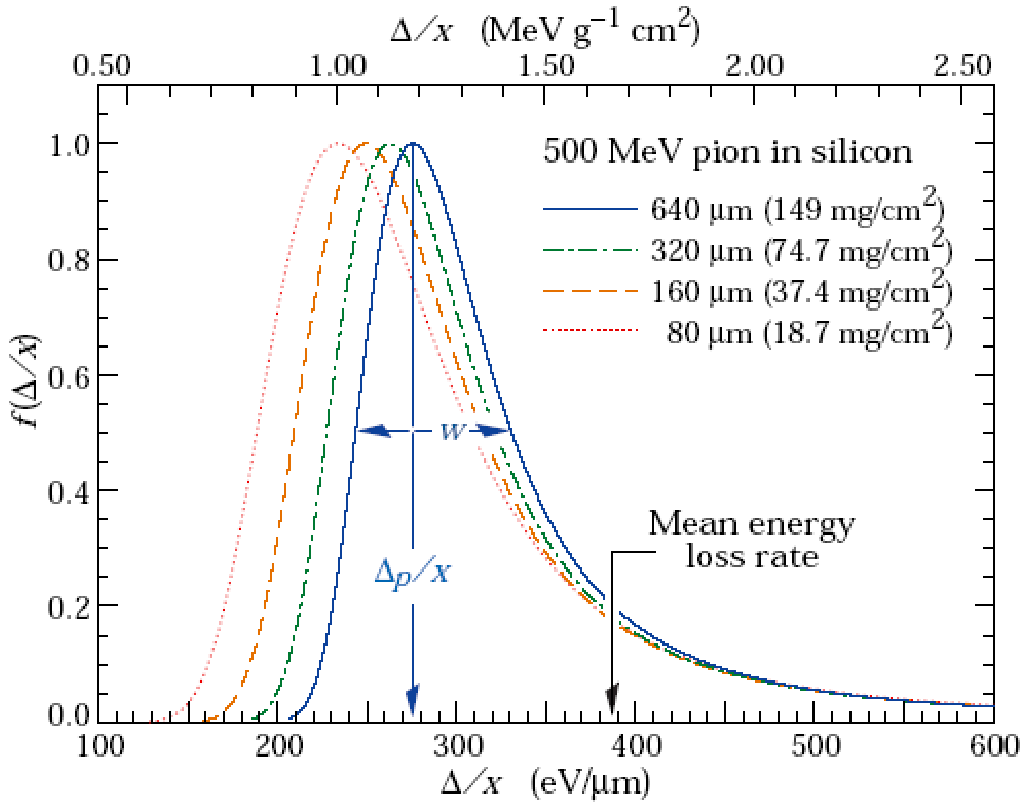
Distance units (x):

- **g cm^{-2}**

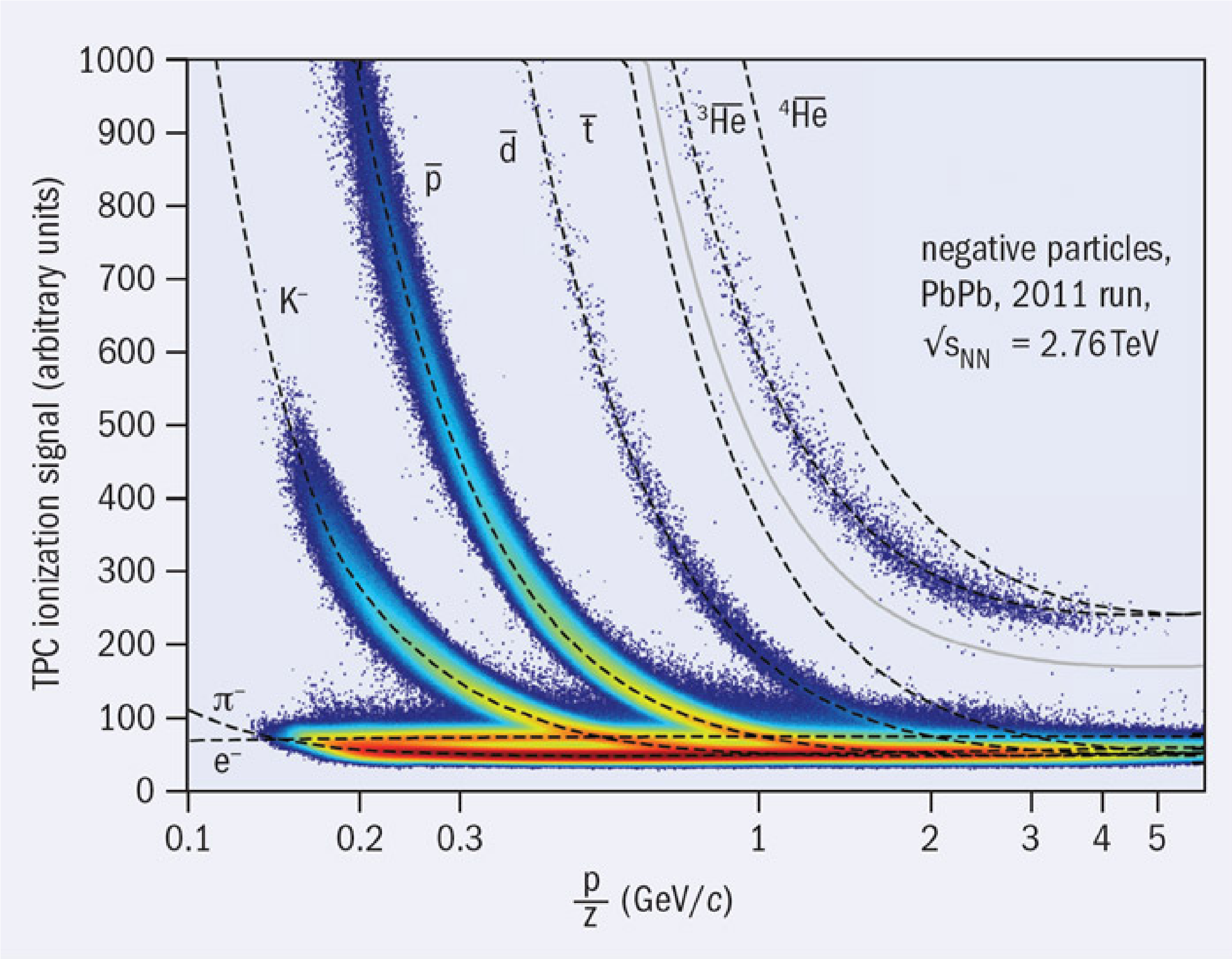
Energy Fluctuations

- Bethe-Block only gives mean, *not* most probable
- Large high energy tail – δ rays ("delta rays")
- Landau distribution:

δ-rays : electrons produced by the Bethe-Block equation that have sufficient energy to ionize further atoms through subsequent interactions on their own.

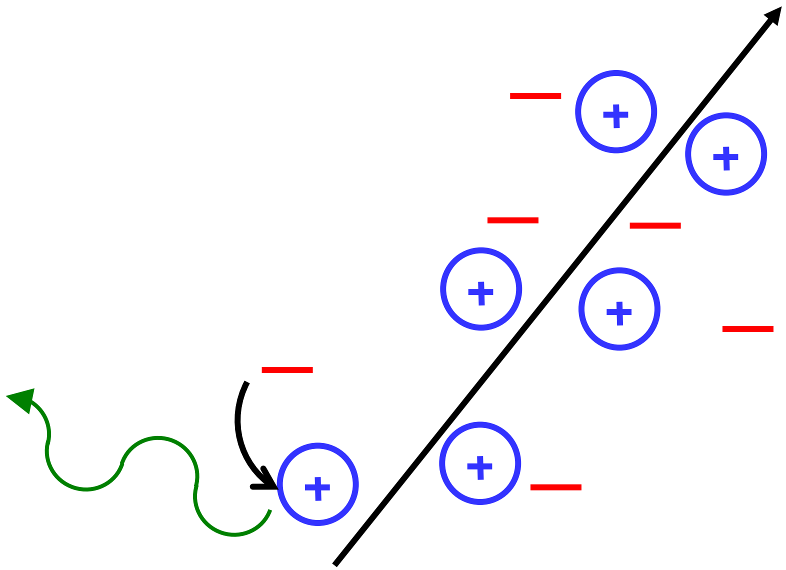


Particle Identification by Energy Loss (dE/dx)



Results from ALICE at LHC

Ionisation Detectors

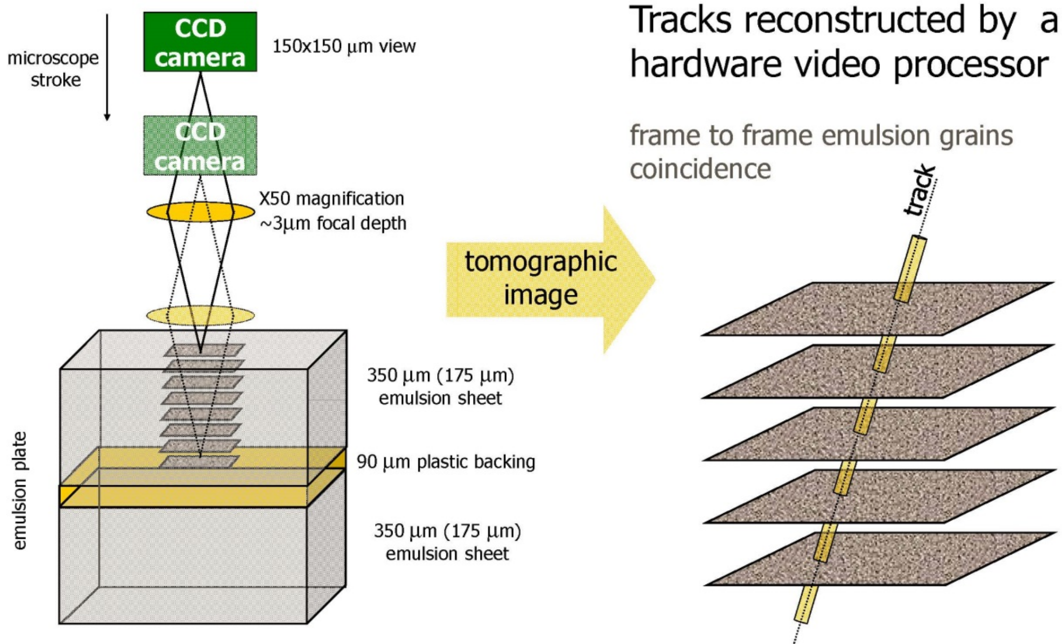


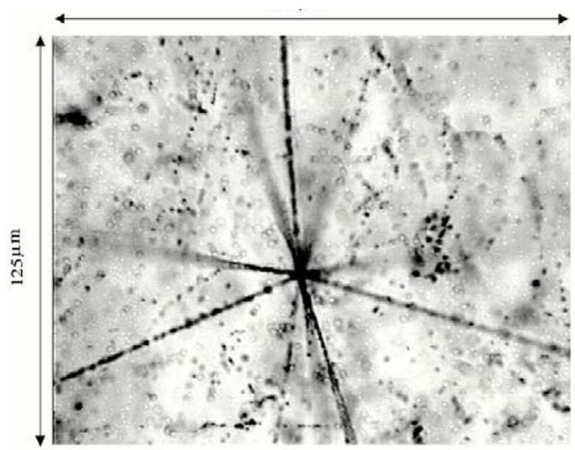
Ionisation used to detect particles in different ways:

1. Observe physical or chemical change due to ions
2. Detect energy from recombination - scintillation
3. Collect and measure free charges - electronic

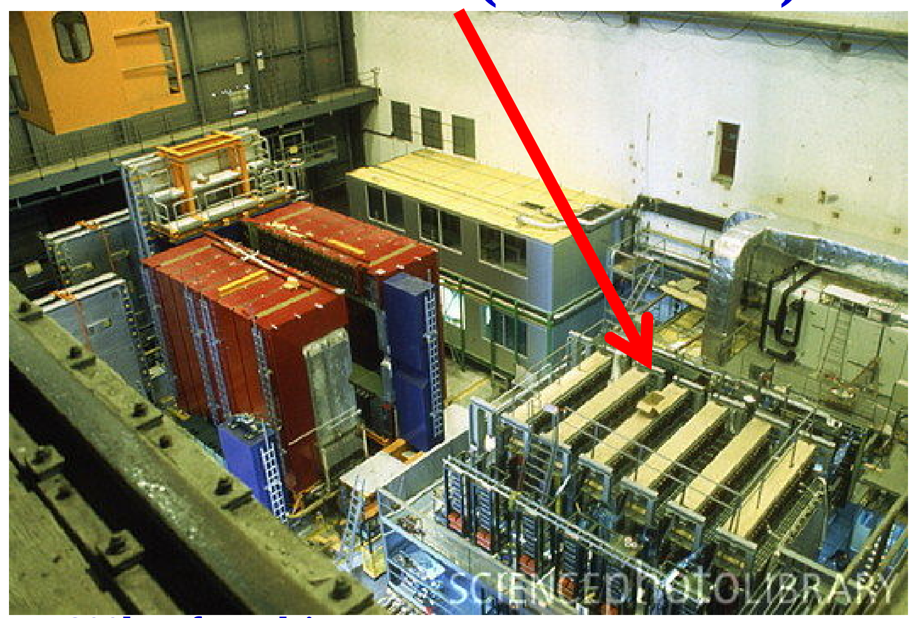
Emulsions

- Expose film to particles and develop
- Natural radioactivity was discovered this way
- Still occasionally used for very high precision, low rate experiments
- Similar technique in etched plastics





CHORUS (neutrinos)

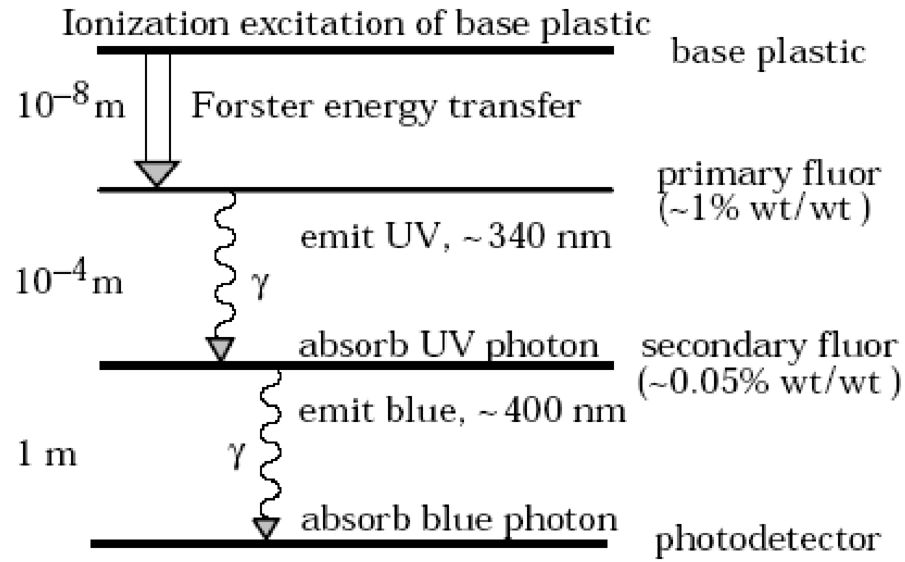


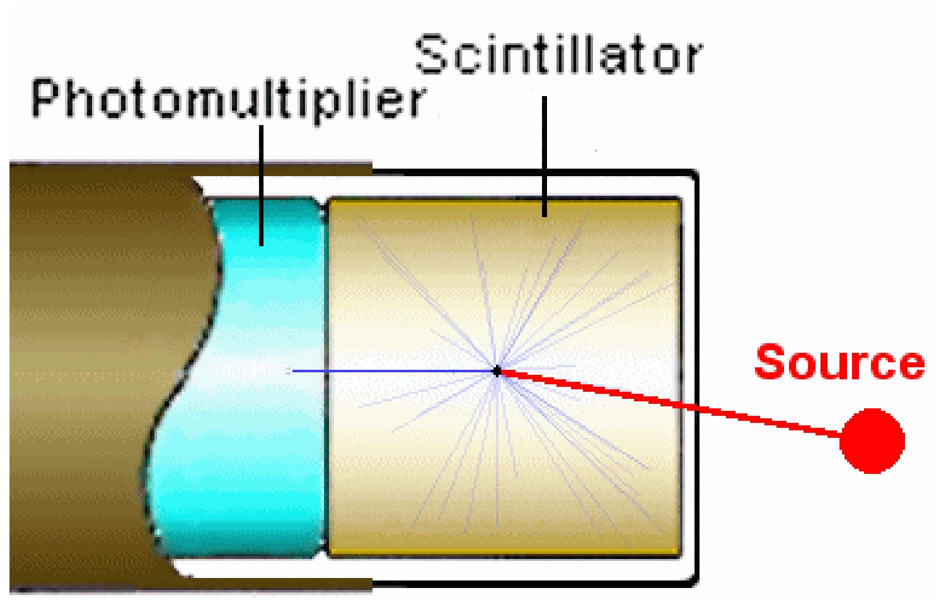
800kg of emulsion

4 stacks of 8 modules each 35 x 70 x 2.9 cm^3

Scintillation Detectors

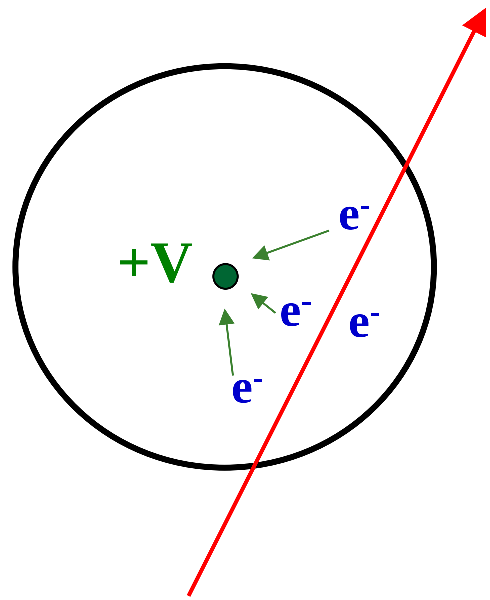
- Detect photons from electronic recombination of ions
- Organic (plastic)
- Inorganic (crystal or glass)
  - doping normally required
- Not very efficient ~ 1 photon/100eV
- Light carried to sensitive photo-detectors
- Fast, cheap and flexible

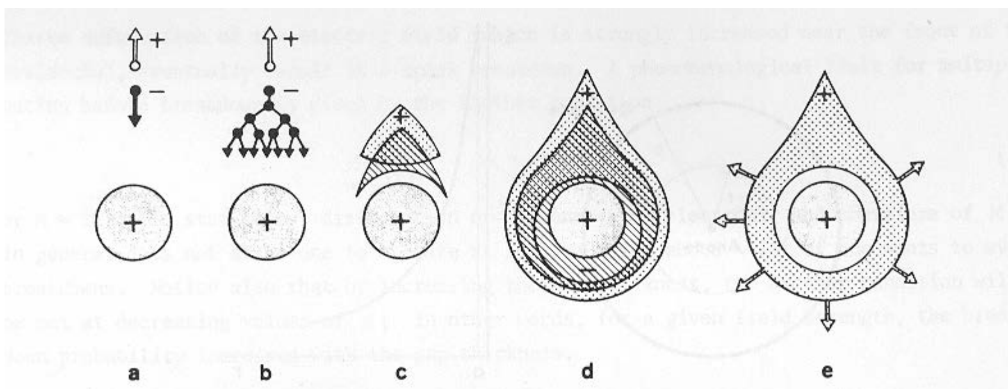




Wire and Drift Chambers

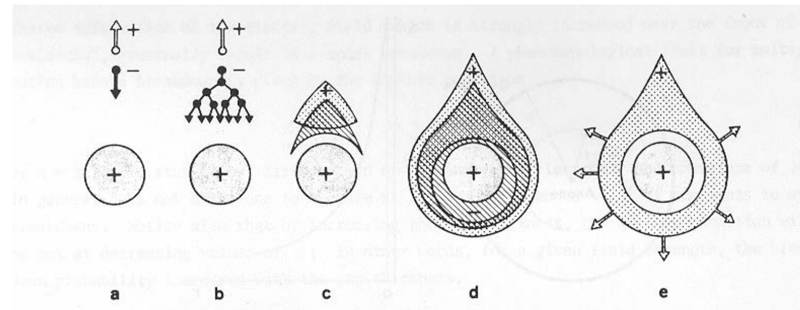
- Charged particle ionises atoms along its path
  - "Primary ionisation": around 20 primary ions per cm (in a gas)
- Free electrons will be attracted to anode
- Electric field near thin wire increases
  - Electrons are accelerated towards wire
- Accelerated electrons ionise more atoms.
  - *"Secondary ionisation"*
  - *More electrons released → more ionisation*
- *Avalanche!*

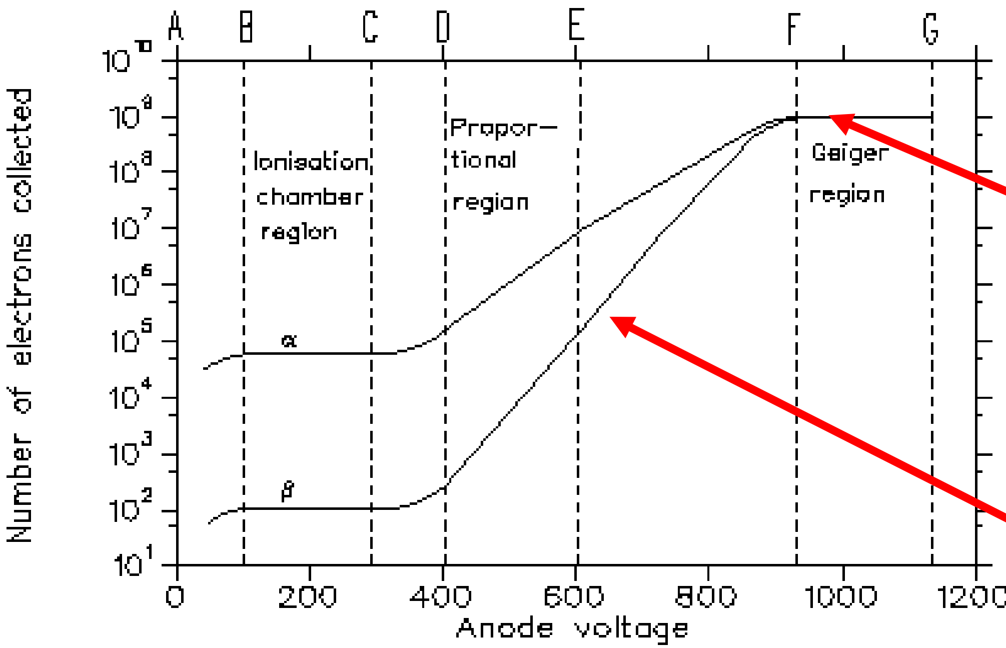




Gas Amplification

- Charged particle ionises atoms along its path
  - "Primary ionisation": around 20 primary ions per cm (in a gas)
- Free electrons will be attracted to anode
- Electric field near thin wire increases
  - Electrons are accelerated towards wire
- Accelerated electrons ionise more atoms.
  - *"Secondary ionisation"*
  - *More electrons released → more ionisation*





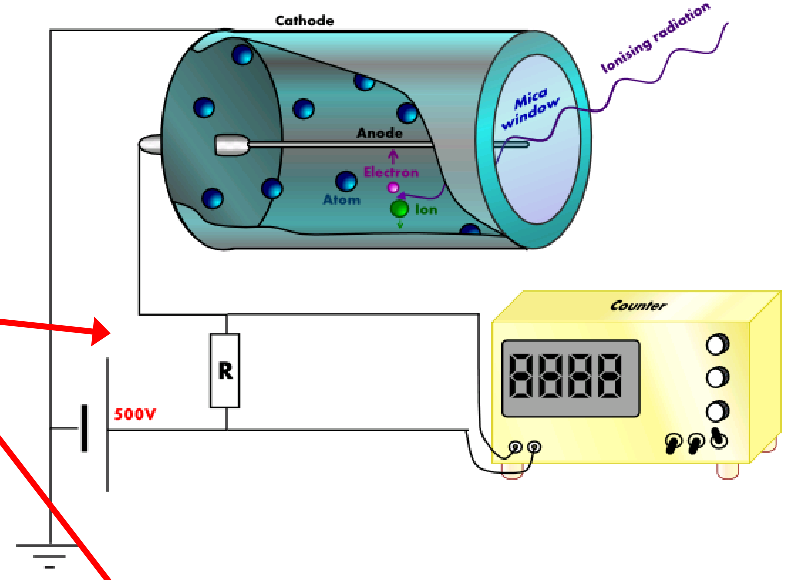
Maximum gain ~10^7

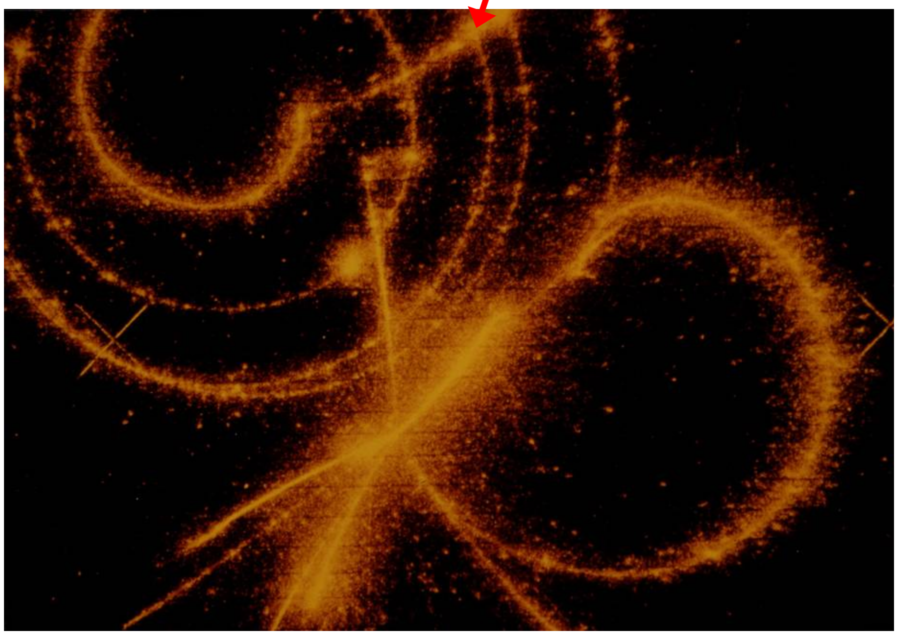
- **Geiger Muller Tube**
- **Resistive Plate Chambers**

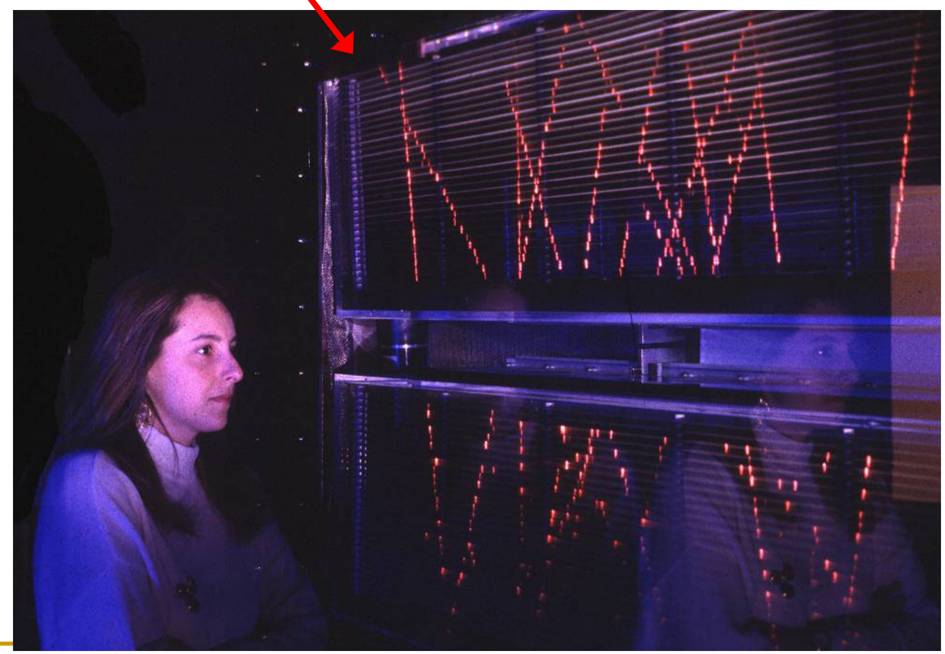
Proportional Chambers

Geiger Region

- Geiger Counter
- Spark Chamber
  - short bias pulse->localise breakdown
- Streamer Chamber
  - Large volume, transparent electrodes

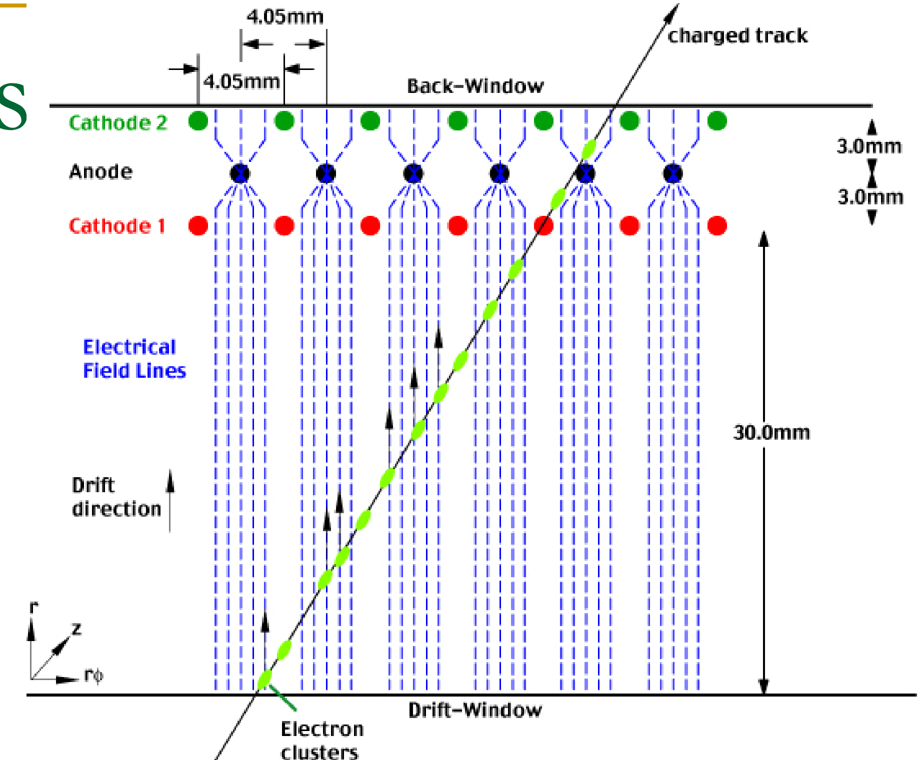


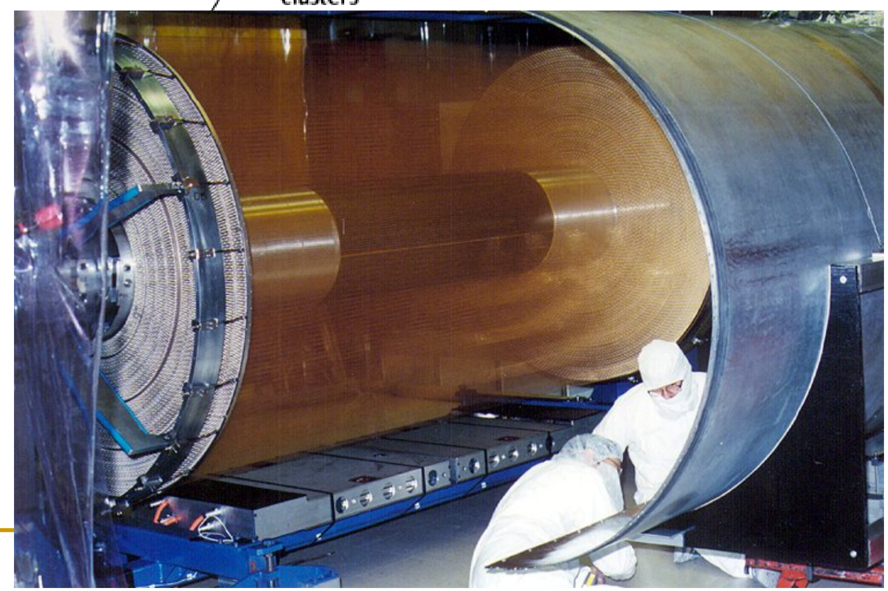




Wire & Drift Chambers

- Electron drift speed depends on electric field and gas
- Time delay of hit gives distance from sense anode
- Extra wires can be used to separate drift and avalanche regions
- Typical values:
  - drift distance ~cm
  - drift velocity ~ 50 km/s (50 μm/ns)
  - drift time ~μs
  - precision ~100 μm

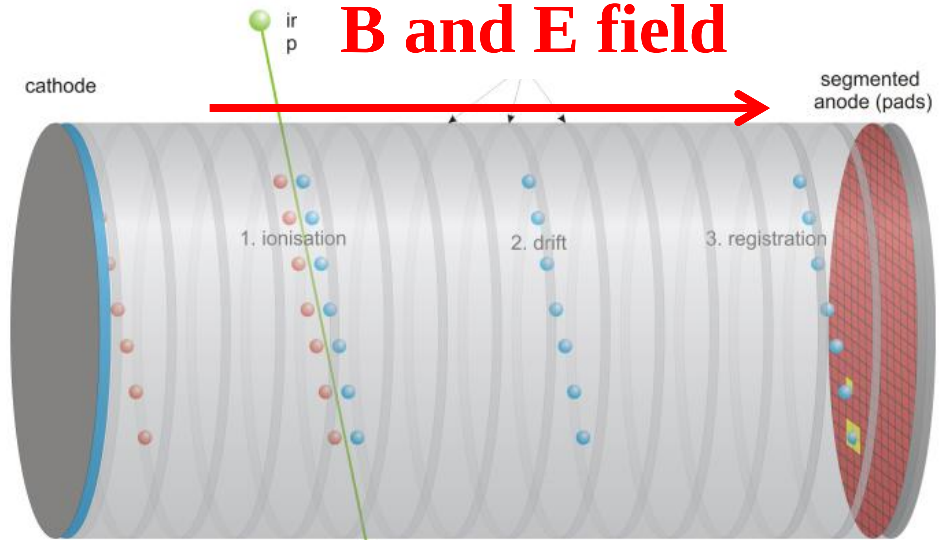


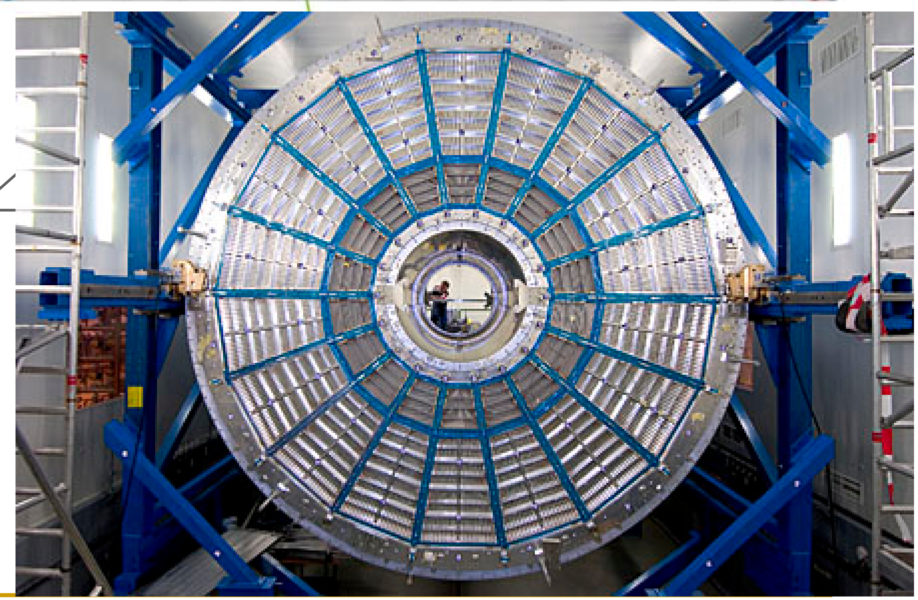


Time Projection Chamber

What if you get rid of all the wires?

- Gas
  - E.g.: Ar + 10 to 20 % CH_4
- E-field
  - **E** ~ 100 to 200 V/cm
- B-field
  - as big as possible to measure momentum and to limit electron diffusion
- Wire chamber at ends
  - To detect projected tracks
  - Timing gives z measurement
- Long drift distances (many metres)



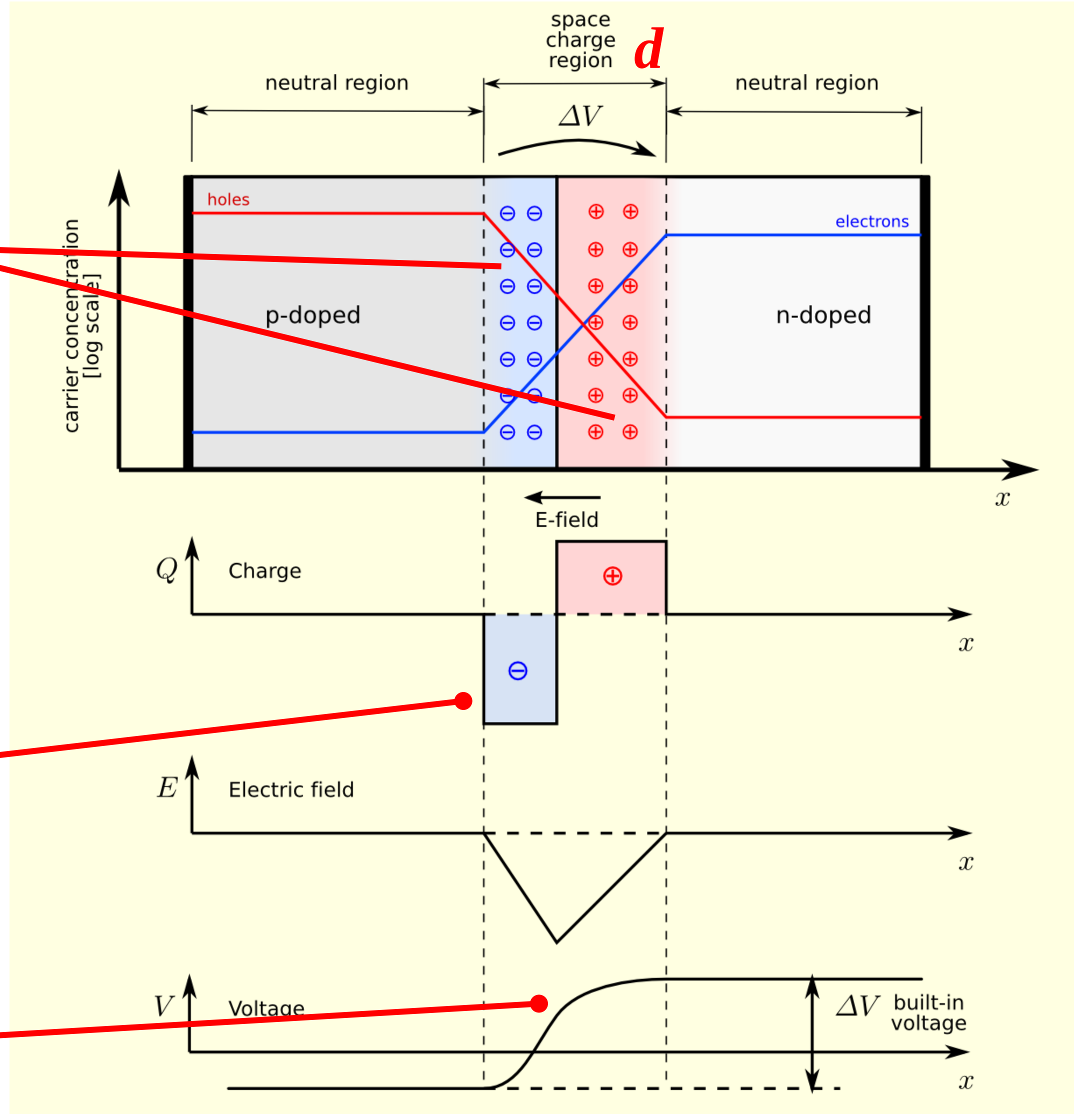


Reminder: p-n Junctions

http://britneyspears.ac/physics/basics/basics.htm

Silicon doped to change electrical properties

Charge carriers diffuse out of depletion region



Net space charge -> electric field

Intrinsic depletion can be increased by reverse bias

Space Charge Region, d

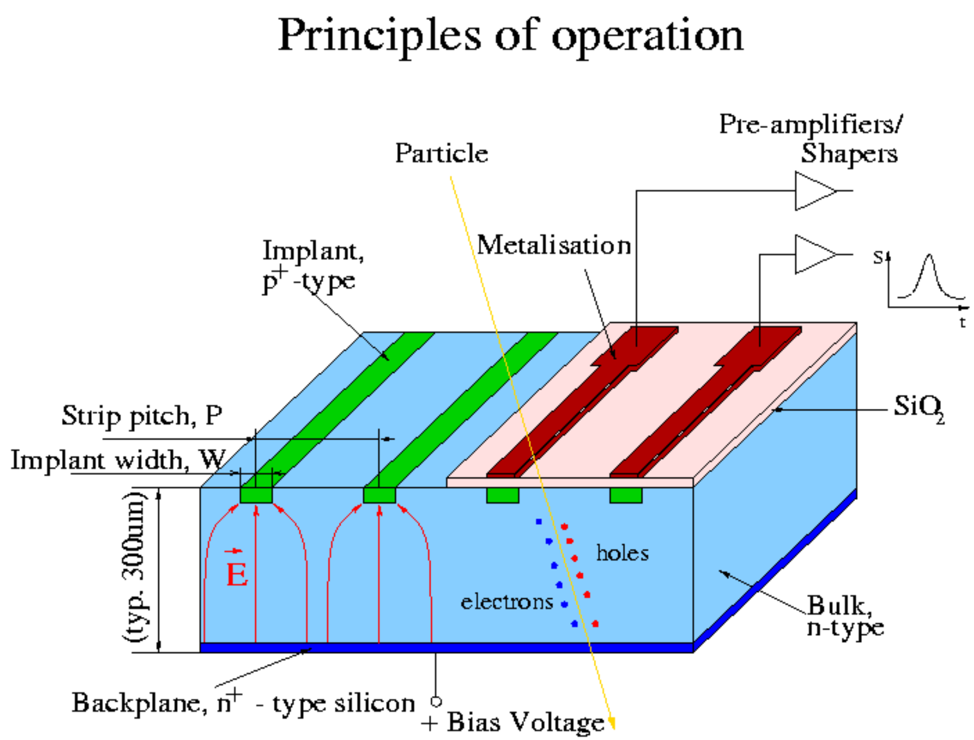
$$d \approx 0.5\left[\mu\text{m}/\sqrt{\Omega\text{cm.V}}\right]\sqrt{\rho(V+0.5)}\ \mu\text{m}$$

Solid State Detectors

- Detect ionisation charges in solids
  - high density → large *dE/dx* signal
  - mechanically simple
  - can be very precise
- Semiconductors
  - small energy to create electron-hole pairs
  - silicon extremely widely used
    - *band gap 1.1 eV*
    - *massive expertise and capability in electronics industry*
- Resistors
  - Plastic – cheap
  - Diamond – robust, rad. hard
  - Germanium – can be made thick

Implanted p-strips 50-150 μm pitch

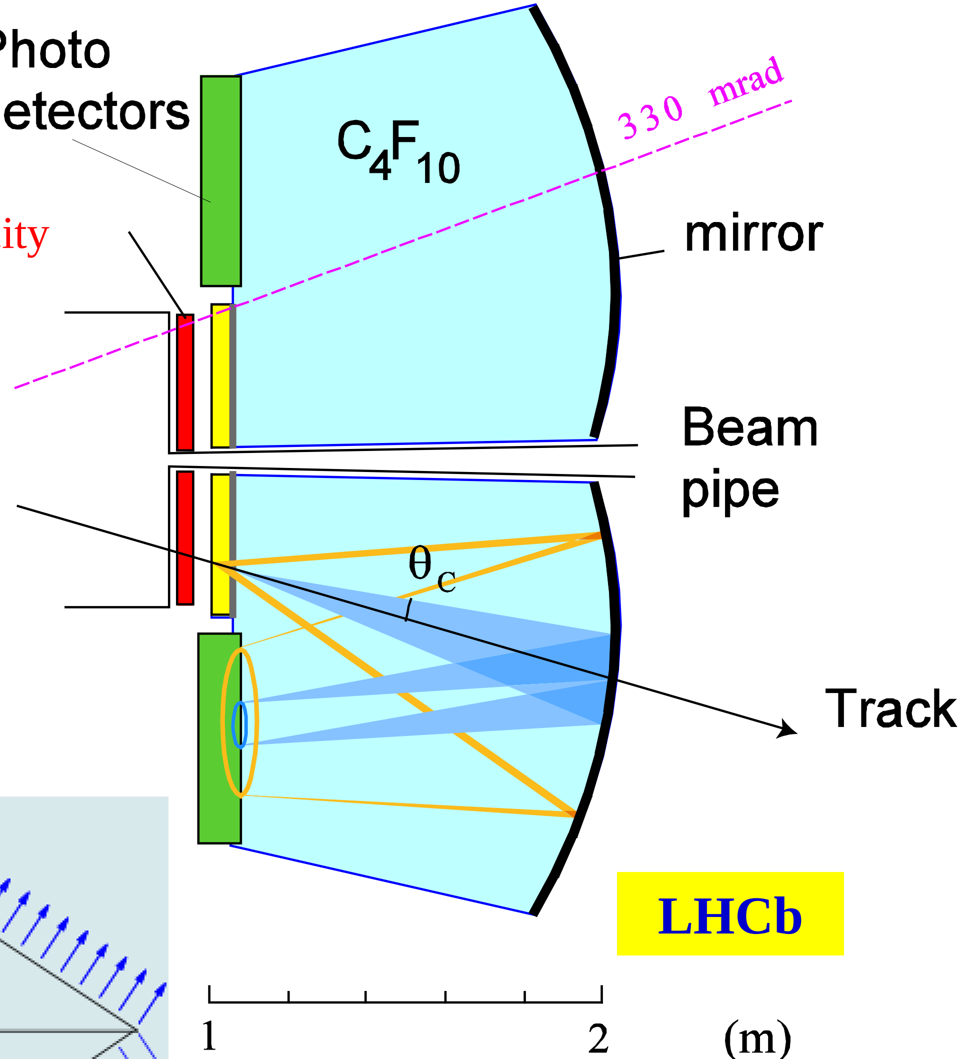
Resolution = pitch/√12



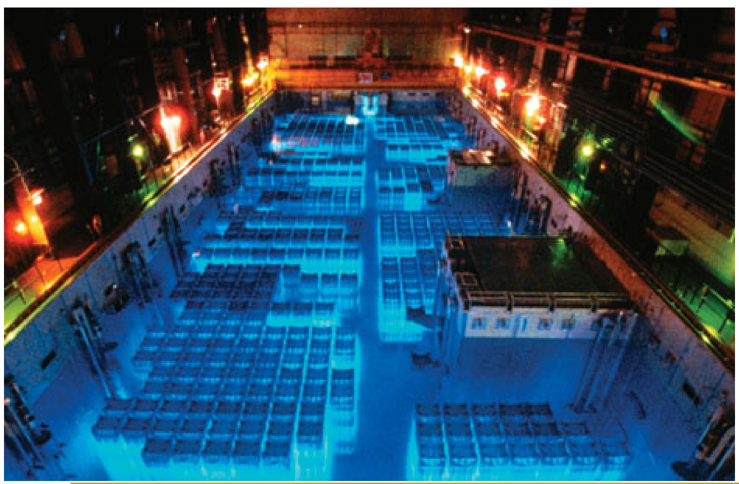
~22,000 electron-hole pairs per MIP
(most probable) in 300μm

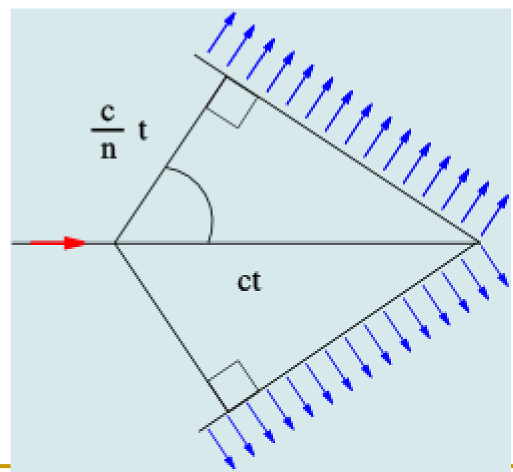
Cerenkov Detector

- Cerenkov Radiation
  - A charged particle will radiate energy if its velocity is greater than the local phase velocity of light
  - speed of light in medium = c/n
  - n = refractive index
  - charged particles produce light "shock waves" if v>c/n
  - light cone cosθ = c/vn = 1/(nβ)
  - "eerie blue glow"
  - Useful for separating pions and kaons



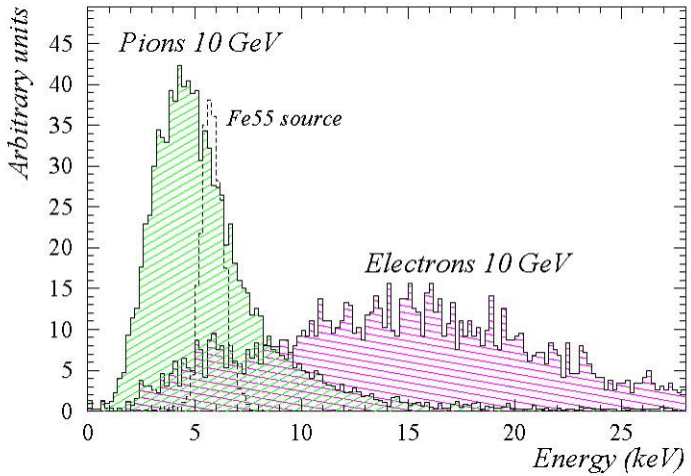
$$\cos\theta = \frac{c}{vn} = \frac{1}{n\beta}$$





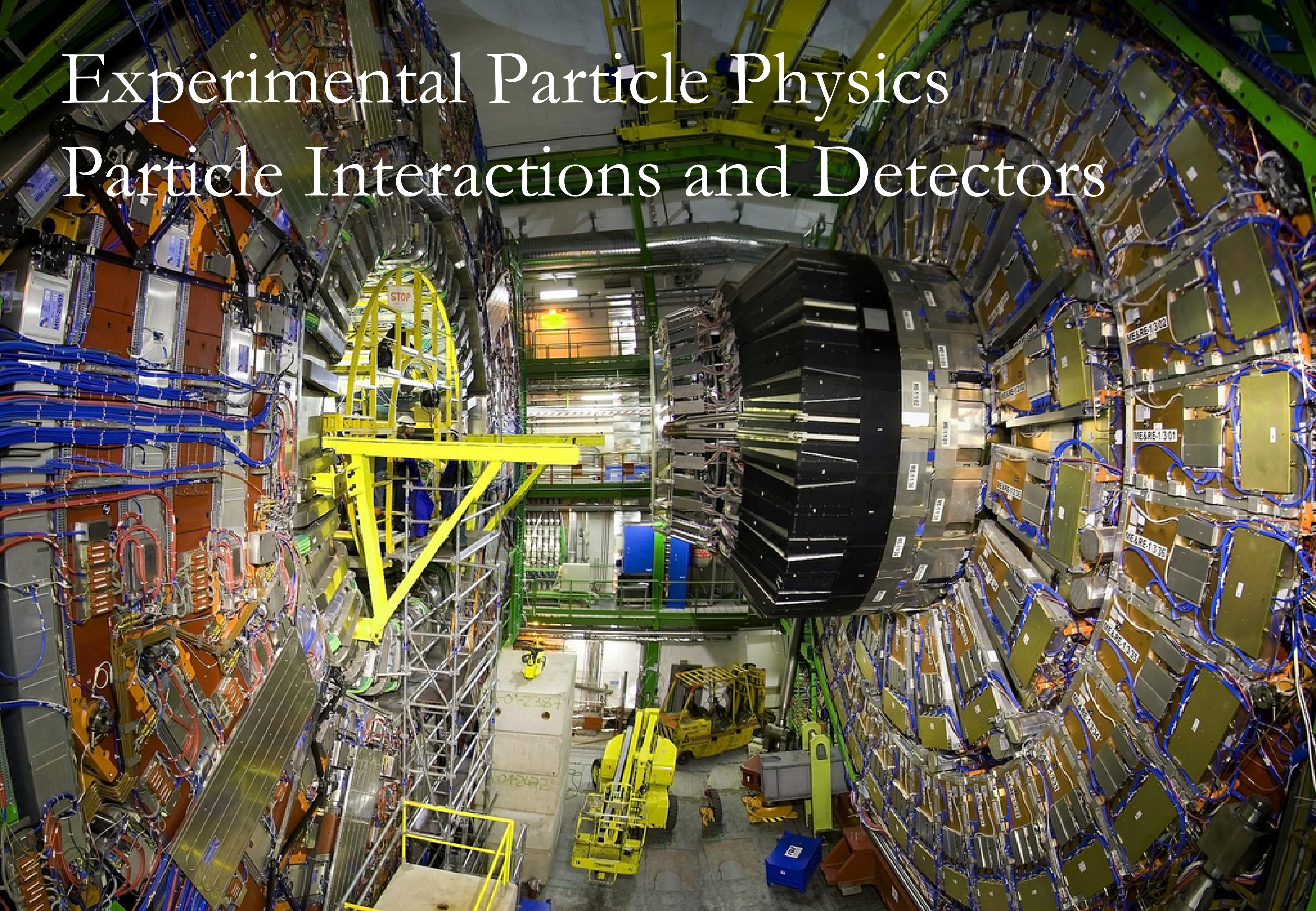
Transition Radiation Detector

Launched May 26th 08
http://www.nasa.gov/glast

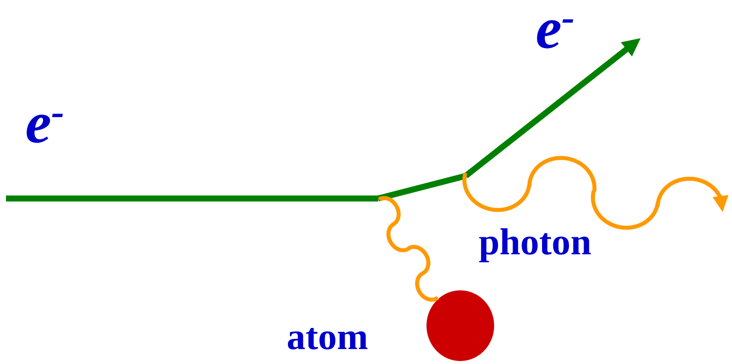


- An energetic charged particle moving through matter momentarily polarizes the material nearby. If the particle crosses a boundary where the index of refraction changes, the change in polarization gives rise to the emission of electromagnetic transition radiation.
- About one photon is emitted for every 100 boundaries crossed. Transition radiation is emitted even if the velocity of the particle is less than the light velocity of a given wavelength, in contrast to Cerenkov radiation. Consequently, this radiation can take place in the x-ray region of the spectrum where there is no Cerenkov radiation, because the index of refraction is less than one.
- At each interface between materials, the probability of transition radiation increases with the relativistic gamma factor. Thus particles with large γ give off many photons, and small γ give off few. For a given energy, this allows a discrimination between a lighter particle (which has a high γ and therefore radiates) and a heavier particle (which has a low γ and radiates much less).
- Useful for separating pions and electrons

Experimental Particle Physics
Particle Interactions and Detectors



Radiation Loss for electrons

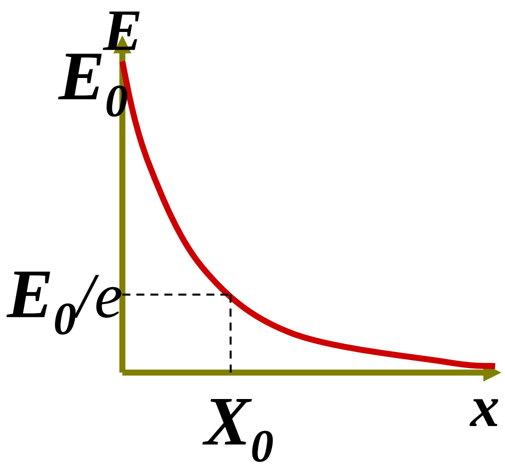


- Bremsstrahlung: electromagnetic radiation produced by the deceleration of a charged particle, such as an electron, when deflected by another charged particle, such as an atomic nucleus.
- Photon can be very energetic.

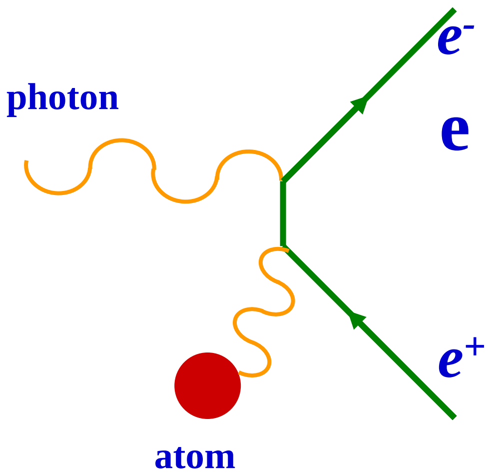
$$-\frac{dE}{dx} = \frac{E}{X_0}$$

***Radiation Length* (*gcm*$^{-2}$)**

$$\Leftrightarrow E = E_0 e^{-x/X_0}$$



Photon Absorption



- Electron-positron pair production
- Exponential absorption
- Length scale $9/7 \times X_0$

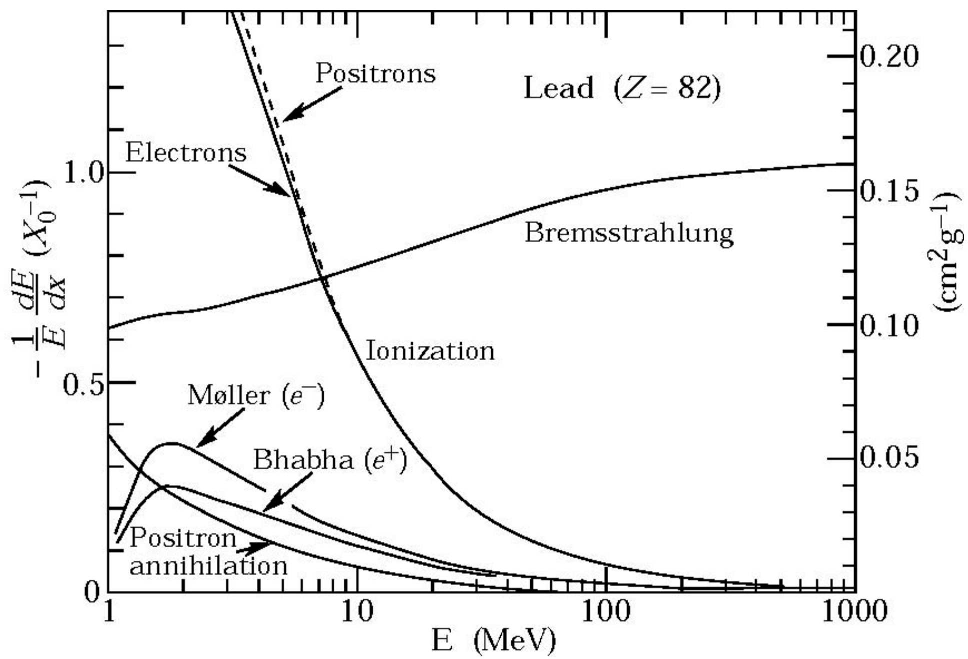
$$-\frac{dE}{dx} = \frac{7E}{9X_0}$$

Radiation Length for electrons and photons

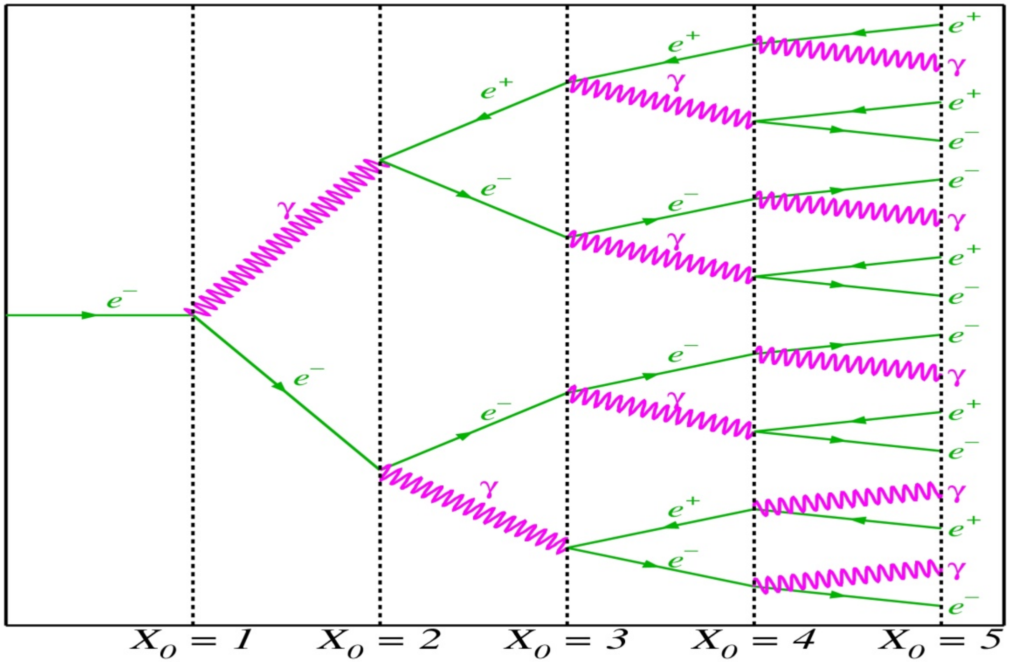
- Radiation Length X_o has 2 definitions:
  - "Mean distance over which high-energy electron loses all but 1/e of its energy by Bremsstrahlung."
  - "7/9ths of the mean free path for pair production by a high-energy photon."

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \quad (\text{gcm}^{-2})$$

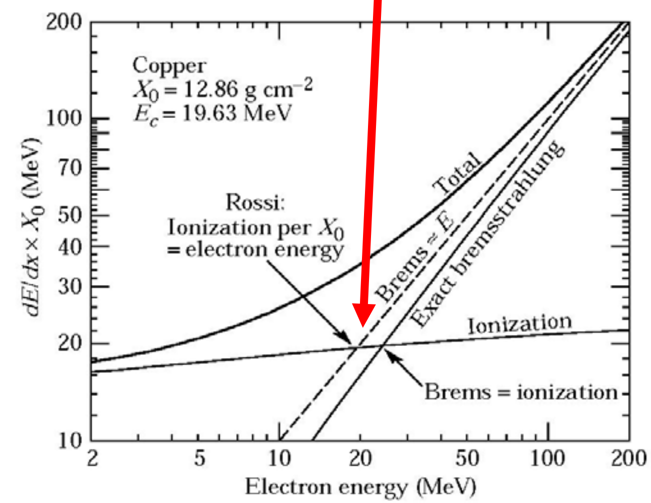
	X_0 (g cm^{-2})	X_0 (cm)
Air	37	30,000
Silicon	22	9.4
Lead	6.4	0.56



Simple Electromagnetic (EM) Shower



E_c Critical Energy



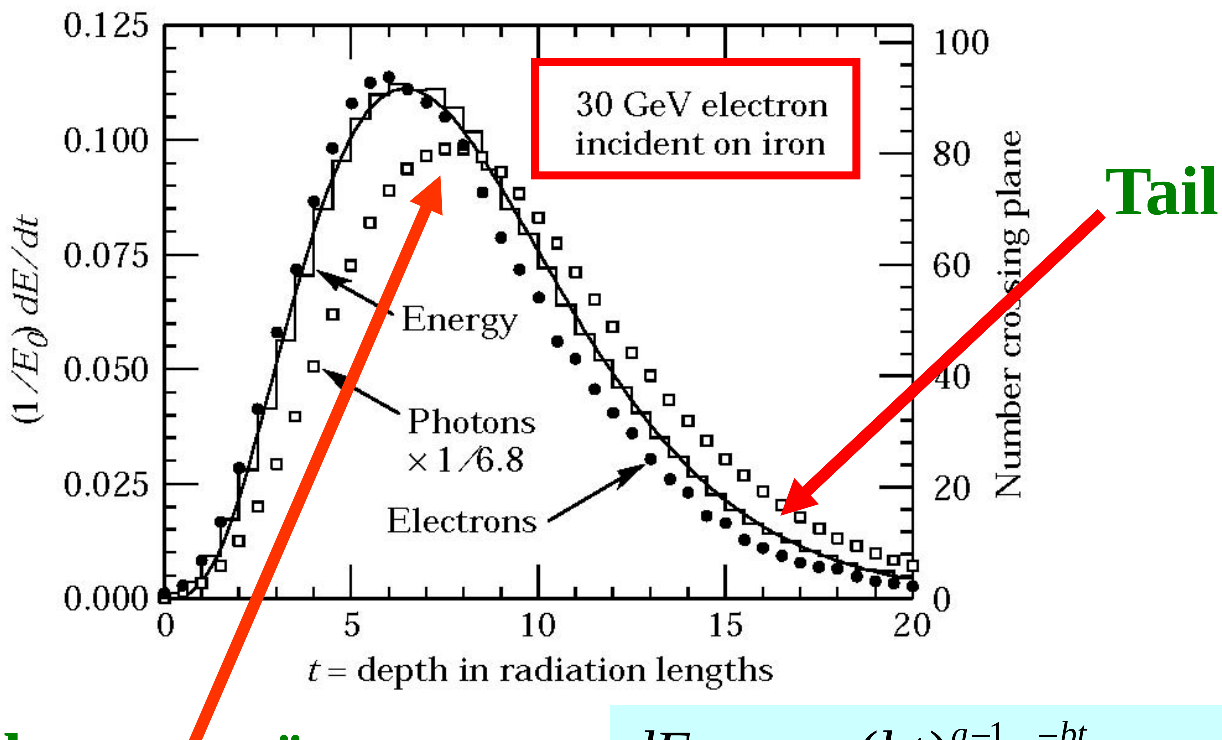
x	0	X_0	$2X_0$	$3X_0$	$4X_0$	
N	1	2	4	8	16	0
<E>	E_0	$E_0/2$	$E_0/4$	$E_0/8$	$E_0/16$	<E_c

- Start with electron or photon
- Depth ~ $\ln(E_0)$
- Most energy deposited as ionisation.

Real Electro-magnetic Shower

- Shape dominated by fluctuations

As depth of shower increases more energy is carried by photons



Maximum close to naïve depth expectation

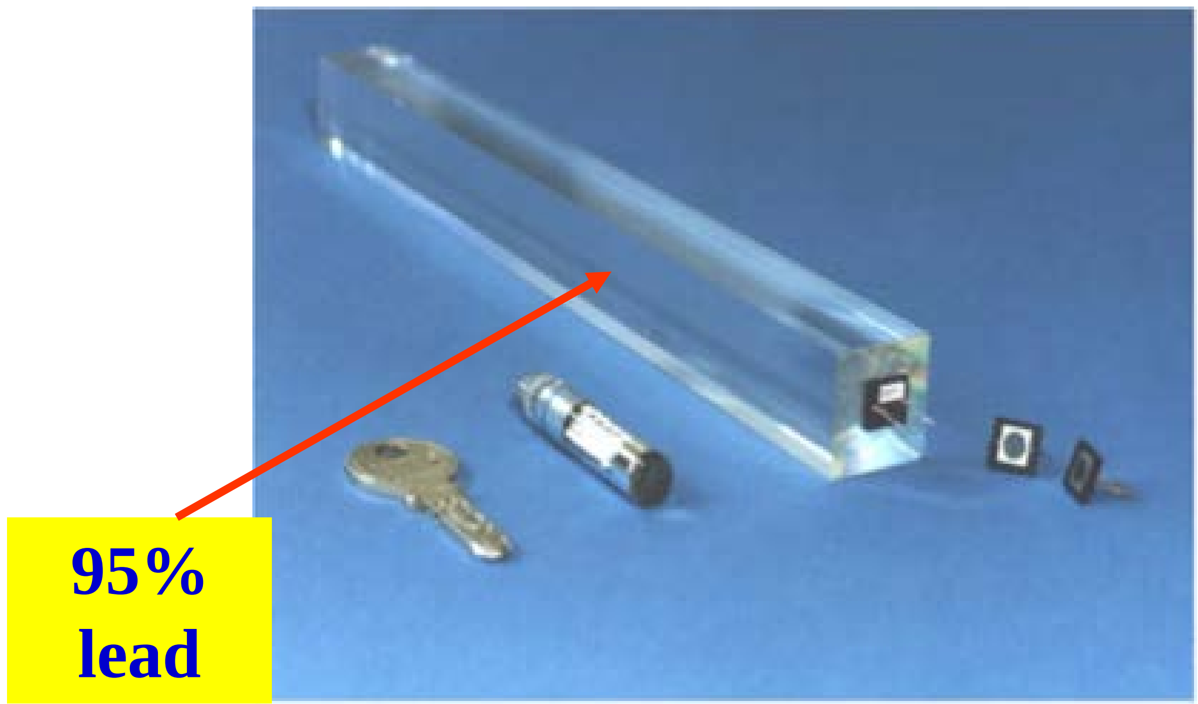
$$\frac{dE}{dt} \approx E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}, \quad t = \frac{x}{X_0}$$

Calorimetry 1 - Homogeneous

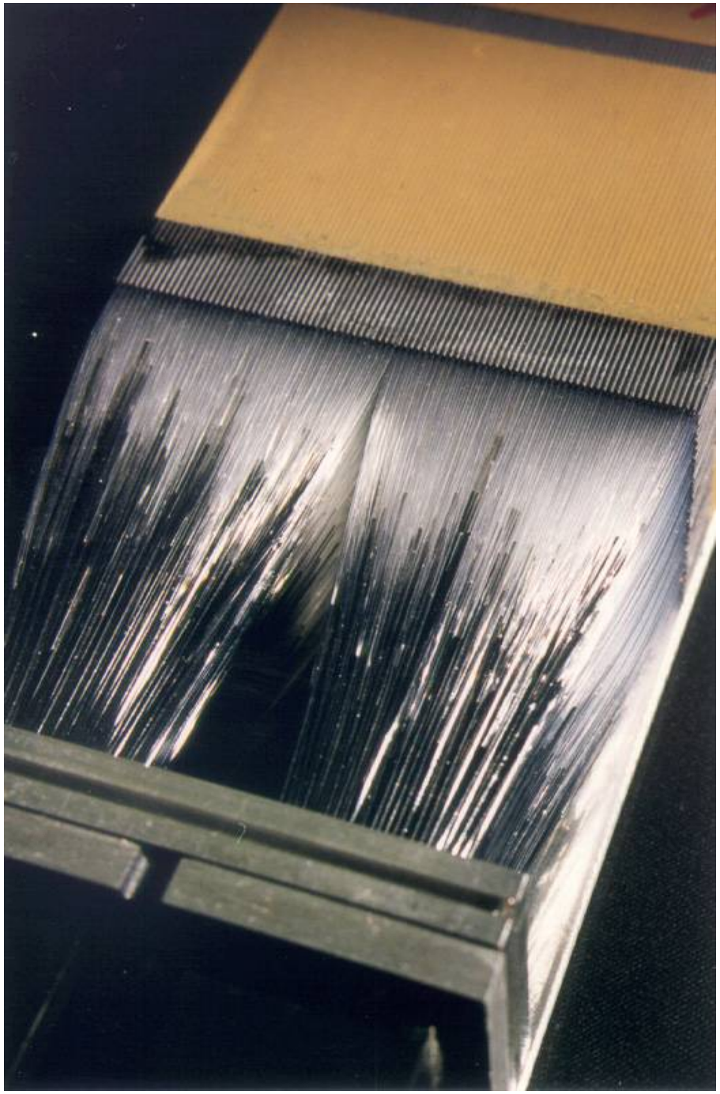
In homogeneous calorimeters the functions of passive particle absorption and active signal generation and readout are combined in a single material. Such materials are almost exclusively used for electromagnetic calorimeters, e.g. crystals, composite materials (like lead glass, $PbWO_4$) or liquid noble gases.

- Crystal, glass, liquid
- Acts as absorber and scintillator
- Light detected by photodetector
- E.g. $PbWO_4$

  ($X_0 \approx 0.9$ cm)



Calorimetry 2 – Sampling



- In sampling calorimeters the functions of particle absorption and active signal readout are separated. This allows optimal choice of absorber materials and a certain freedom in signal treatment.
- Heterogeneous calorimeters are mostly built as sandwich counters, sheets of heavy-material absorber (e.g. lead, iron, uranium) alternating with layers of active material (e.g. liquid or solid scintillators, or proportional counters).
- Only the fraction of the shower energy absorbed in the active material is measured.
- Hadron calorimeters, needing considerable depth and width to create and absorb the shower, are necessarily of the sampling calorimeter type (see next slide).

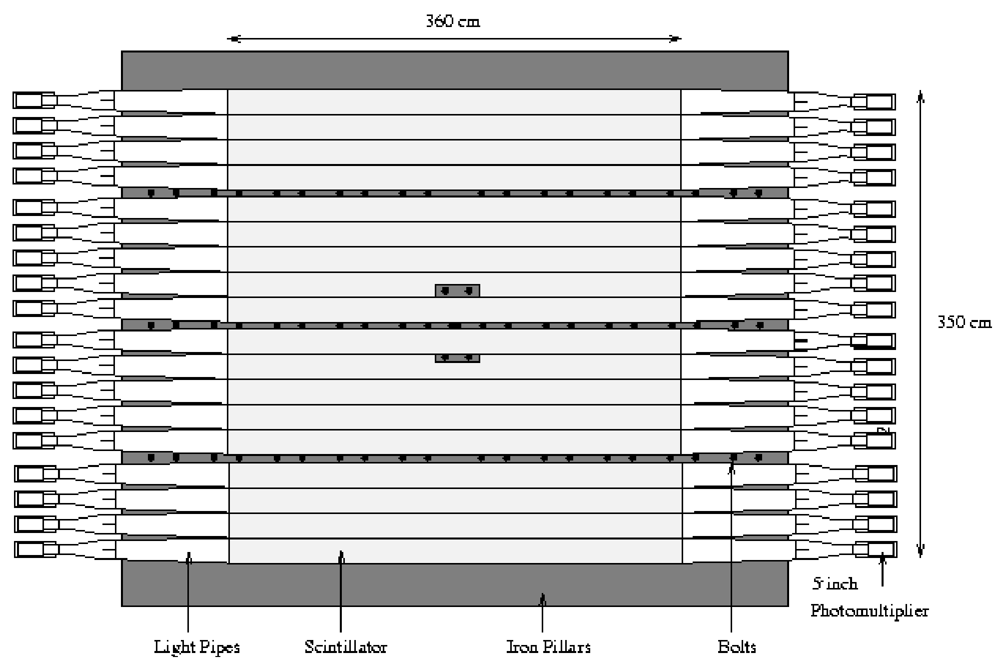
Hadronic Showers

- Nuclear interaction length >> radiation length

$$\lambda \approx 35\mathrm{g.cm}^{-2} A^{1/3}$$

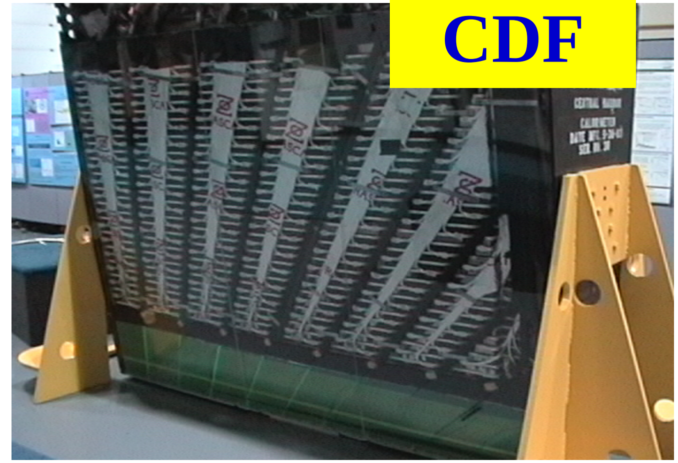
e.g. Lead: X_0 = 0.56 cm, λ = 17 cm

- Hadron showers wider, deeper, less well understood
- Need much larger calorimeter to contain hadron shower
  - Always sampling
  - Dense metals still good as absorbers
  - Mechanical/economic considerations often important
  - Uranium, steel, brass…



Hadronic Calorimeter from NOMAD experiment

Hadronic Calorimeter

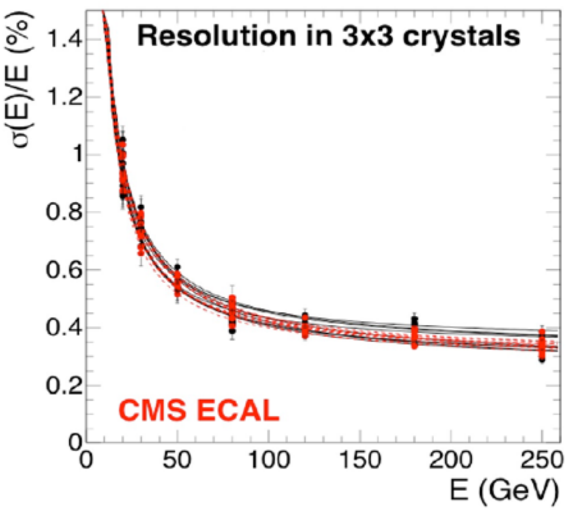


Alternating layers of steel and readout

Energy Resolution Limitations

- EM Calorimeter
  - the intrinsic limitation in resolution results from variations in the net track length of charged particles in the cascade.
  - Sampling Fluctuations
  - Landau Distribution

$$\frac{\sigma(E)}{E} \approx \frac{1\% - 3\%}{\sqrt{E}}$$

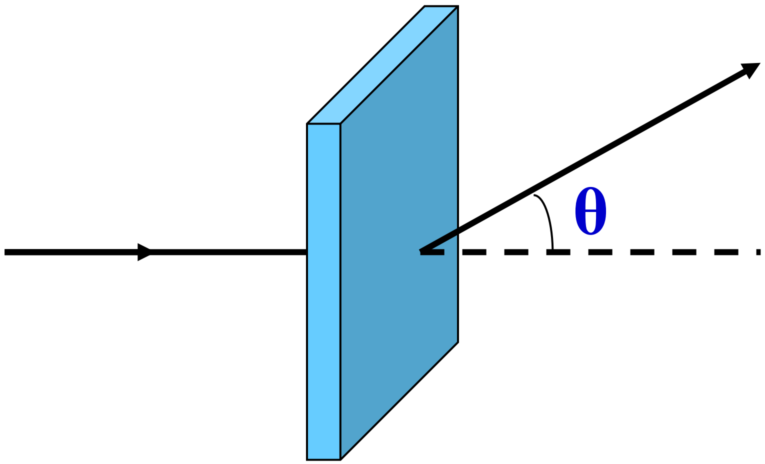


- Hadronic Calorimeter
  - A fluctuating π^0 component among the secondaries which interacts electromagnetically without any further nuclear interaction ($\pi^0 \rightarrow \gamma\gamma$). Showers may develop with a dominant electromagnetic component.
  - A sizeable amount of the available energy is converted into excitation and breakup of nuclei. Only a small fraction of this energy will eventually appear as a detectable signal and with large event-to-event fluctuations.
  - A considerable fraction of the energy of the incident particle is spent on reactions which do not result in an observable signal. Such processes may be energy leakage of various forms, like:
    - Backscattering
    - Nuclear excitation
    - slow neutrons, neutrinos

$$\frac{\sigma(E)}{E} \approx \frac{30\%}{\sqrt{E}}$$

Multiple Scattering

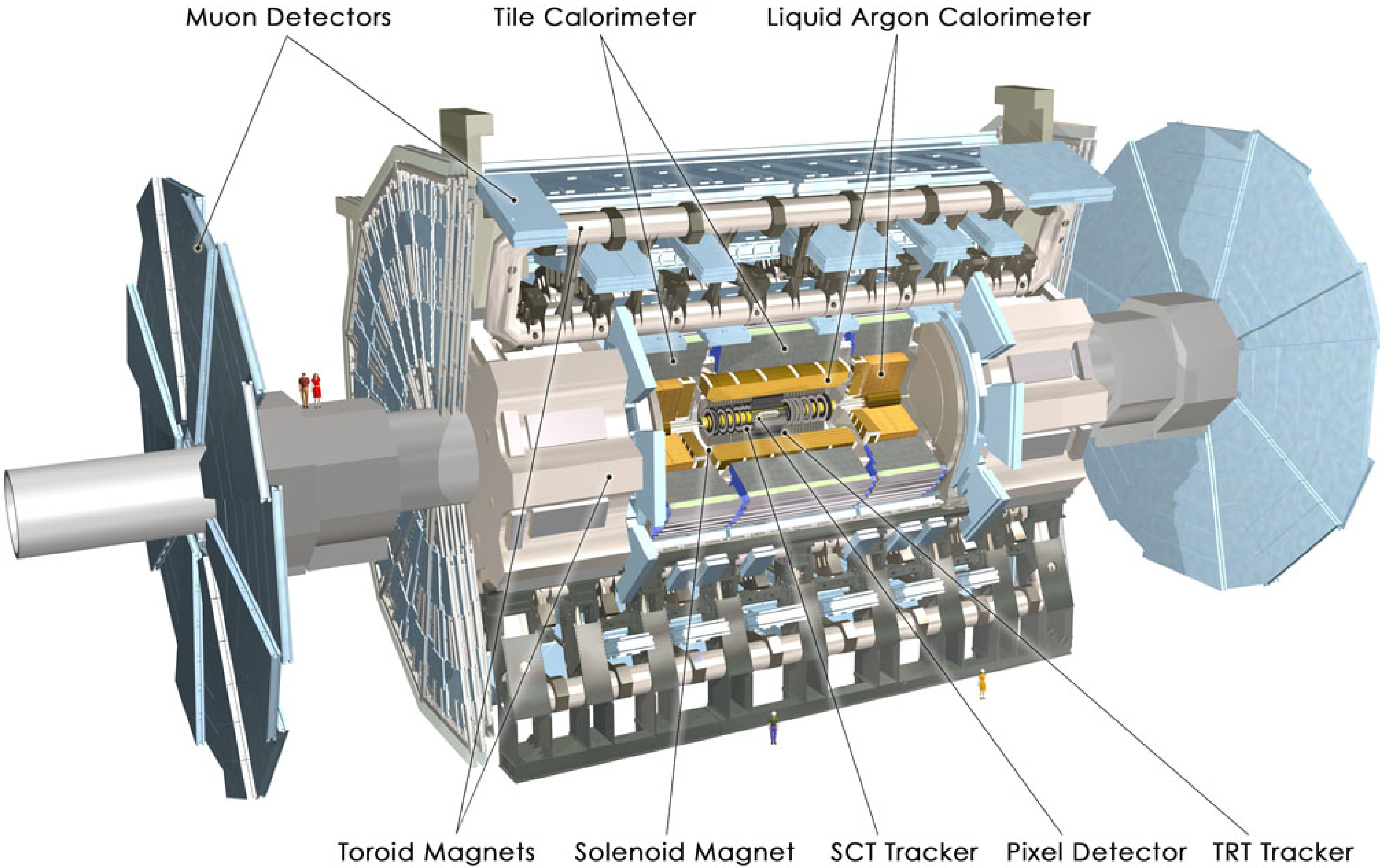
- Elastic scattering from nuclei causes angular deviations:

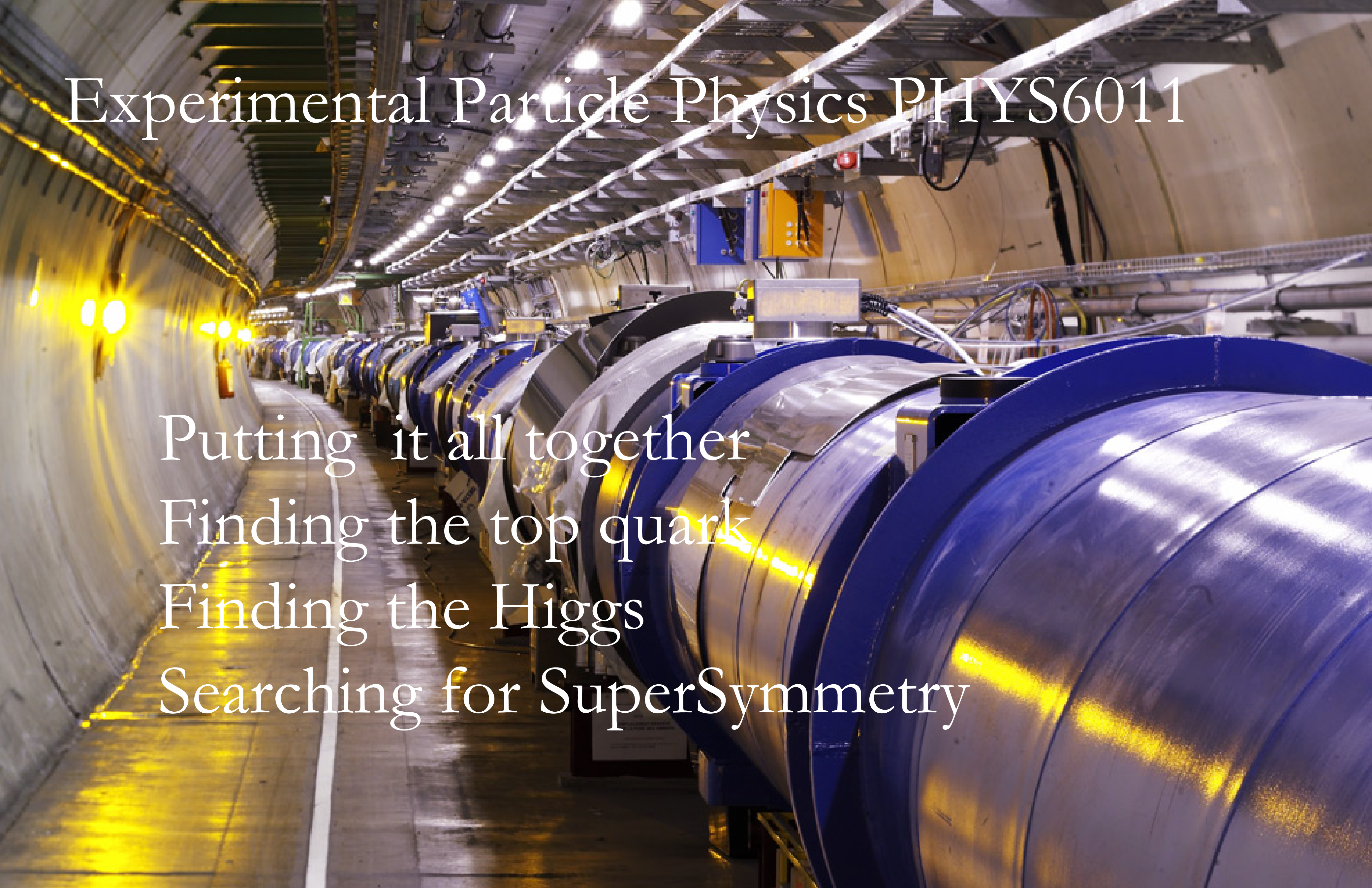


$$\theta_{RMS} \approx \frac{13.6\text{MeV}}{\beta c p} q \sqrt{x / X_0}$$

- Approximately Gaussian
- Can disrupt measurements in subsequent detectors
- If you want to:
  - Measure momentum : make detector as light as possible
  - Measure energy: make detector as heavy as possible
- Measure momentum before energy!

Putting them all together





Experimental Particle Physics PHYS6011

Putting it all together

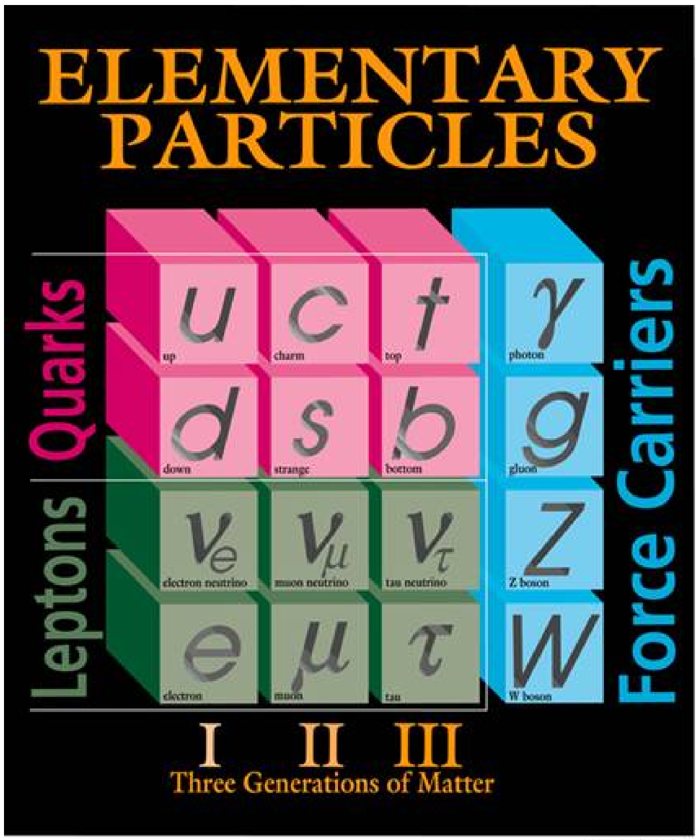
Finding the top quark

Finding the Higgs

Searching for SuperSymmetry

What do we measure?

In principle:



Fermilab 95-759

But in reality:

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u}-d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

Quark content

$\pi^\pm$ $\qquad I^G(J^P) = 1^-(0^-)$

Spin

Mass

Lifetime

Mass $m = 139.57018 \pm 0.00035$ MeV $\quad (S = 1.2)$
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s $\quad (S = 1.2)$
$c\tau = 7.8045$ m

$\pi^\pm \to \ell^\pm \nu \gamma$ form factors [a]

$F_V = 0.017 \pm 0.008$
$F_A = 0.0115 \pm 0.0005 \quad (S = 1.2)$
$R = 0.059^{+0.009}_{-0.008}$

Form factor

π^- modes are charge conjugates of the modes below.

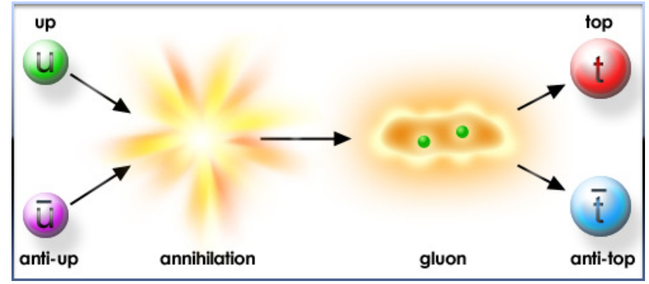
For decay limits to particles which are not established, see the appropriate Search sections (Massive Neutrino Peak Search Test, A^0 (axion), and Other Light Boson (X^0) Searches, etc.).

Decay Modes

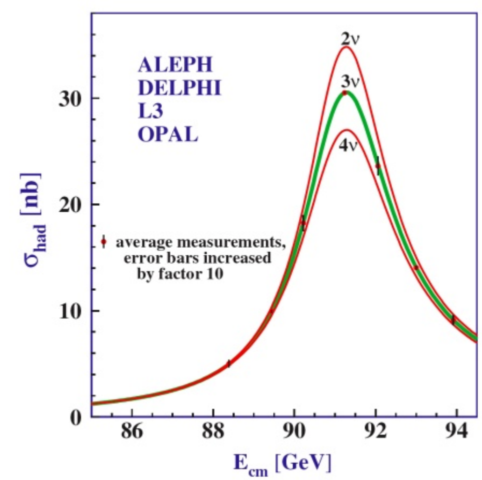
Branching Fraction

π^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+\nu_\mu$	[b]	(99.98770 ± 0.00004) %		30
$\mu^+\nu_\mu\gamma$	[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+\nu_e$	[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$	[c]	$(1.61 \pm 0.23) \times 10^{-7}$		70
$e^+\nu_e\pi^0$		$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$		$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\bar{\nu}$		$< 5 \times 10^{-6}$	90%	70
Lepton Family number (LF) or Lepton number (L) violating modes				
$\mu^+\bar{\nu}_e$	L [d]	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+\nu_e$	LF [d]	$< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	LF	$< 1.6 \times 10^{-6}$	90%	30

What should we collide?

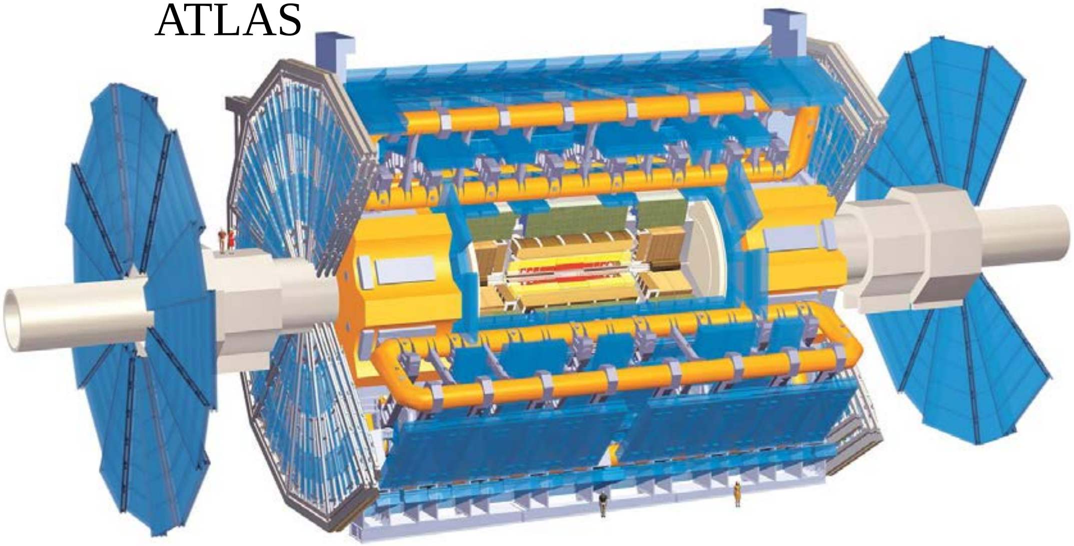


- Generally want to collide particles and anti-particles:
  - They annihilate into energy
  - But anti-particles can be expensive to produce.
- Electron / Positron colliders (e.g. LEP):
  - Point-like with well-known initial energy.
  - All the energy goes into the collision.
  - All decays have roughly the same cross-section so there are no large backgrounds.
  - Lose lots of synchrotron radiation in circular colliders.
  - Need to have good idea of the mass of the particles you want to produce e.g. e+e- $\rightarrow Z^0$
- Proton / Anti-proton colliders (e.g. Tevatron):
  - Composite particles so initial energy not known
  - Not all the energy goes into the collision so need to accelerate to higher energies
  - Large cross-sections but large QCD backgrounds
  - Heavy so do not lose lots of energy via synchrotron radiation
  - Useful if you don't know the mass of the particles you want to produce e.g. gg$\rightarrow$H
- Proton / Proton colliders (e.g. LHC)
  - At high energies, most interactions involve gluons and sea-quarks so little difference in proton/proton and proton/anti-proton cross-section.
- Neutrino / Nucleon colliders (e.g. T2K)
  - Need a lot of mass to stop neutrinos
- Electron / Proton (e.g. ZEUS and H1 at DESY)
  - A giant electron microscope to probe the structure of the proton.

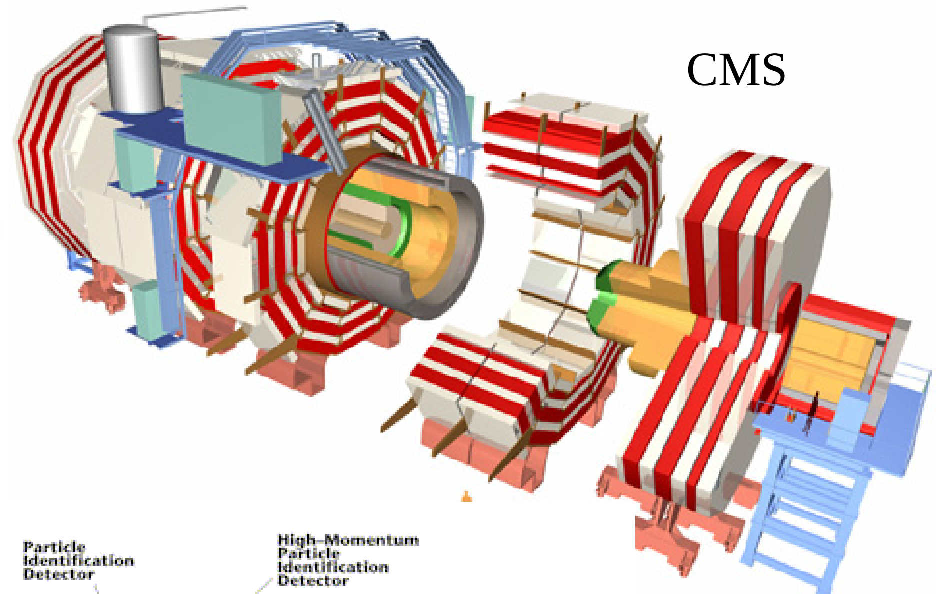


The (4 out of 6) LHC Experiments

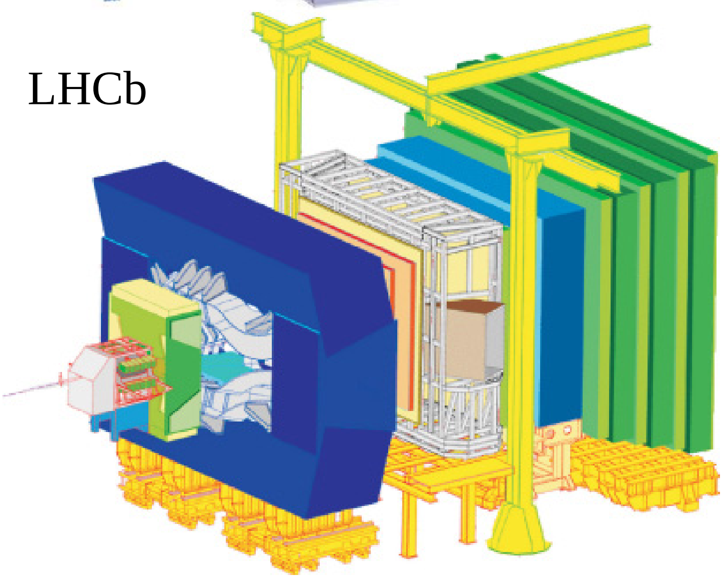
ATLAS

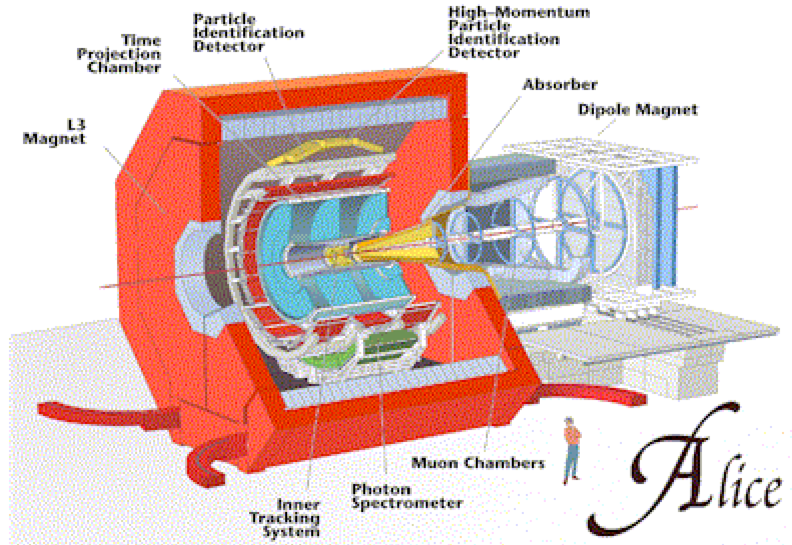


CMS



LHCb



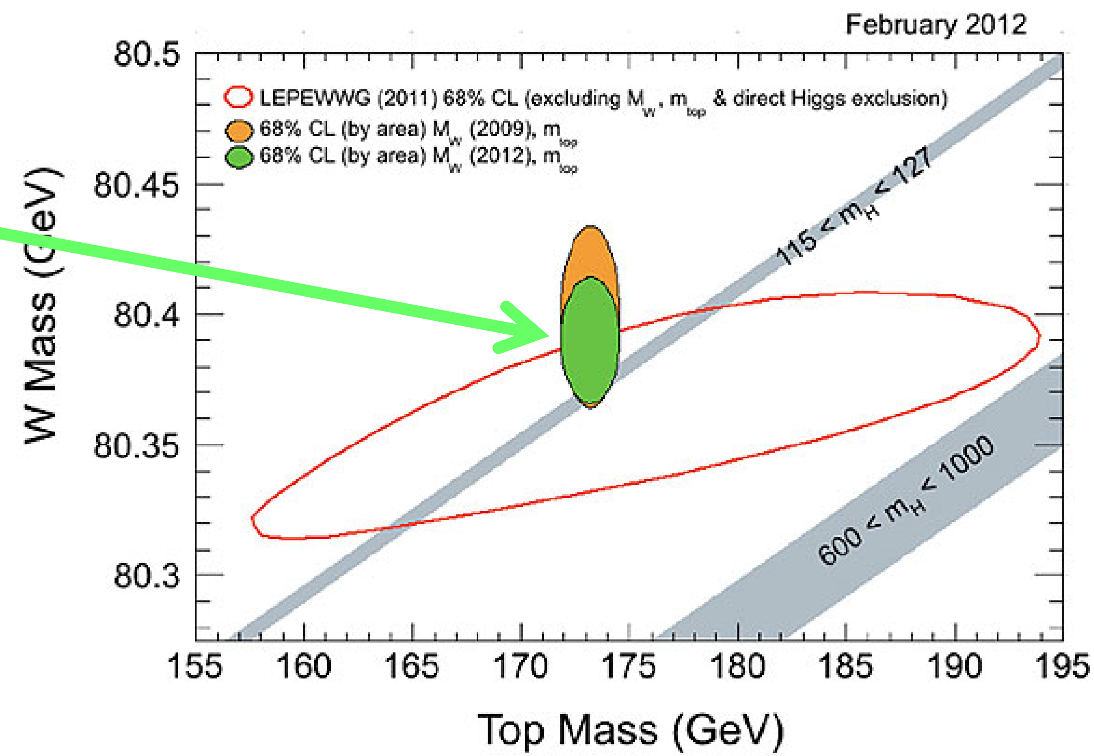


Why look for the top quark?

- The top quark and W boson are very heavy
- Their mass is influenced by the Higgs mass
- If we measure both we can “predict” Higgs mass

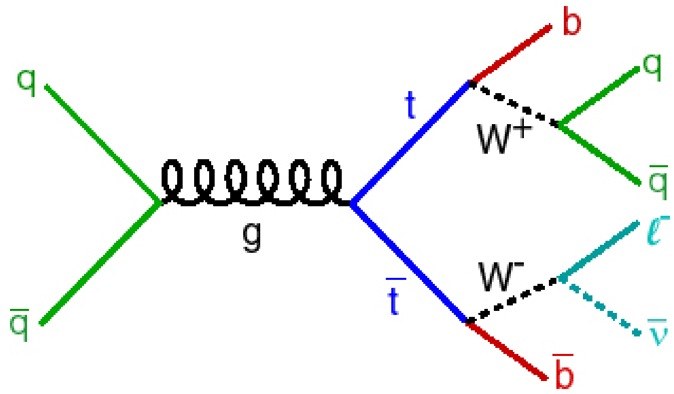
Top mass : 172.6 ± 1.4 GeV

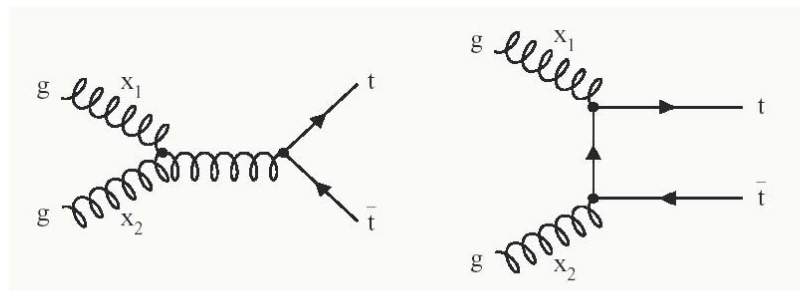
W mass : 80.385 ± 0.0021 GeV



Top Pair Production and decay

- Tevatron
- LHC





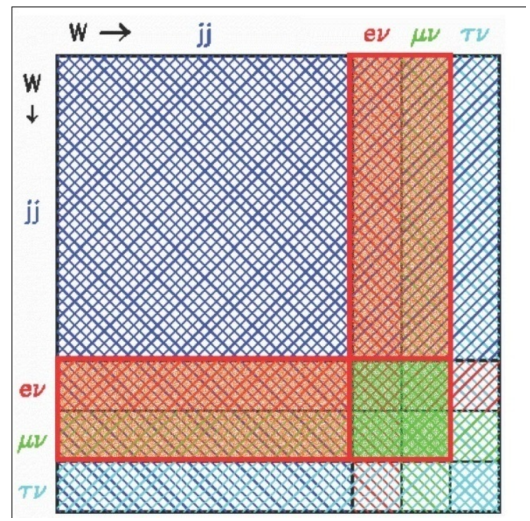
$t \to W^+ b \quad (100\%)$

$W^+ \to q\bar{q} \quad (70\%)$

$W^+ \to l^+ \nu \quad (10\%\ \text{per lepton})$

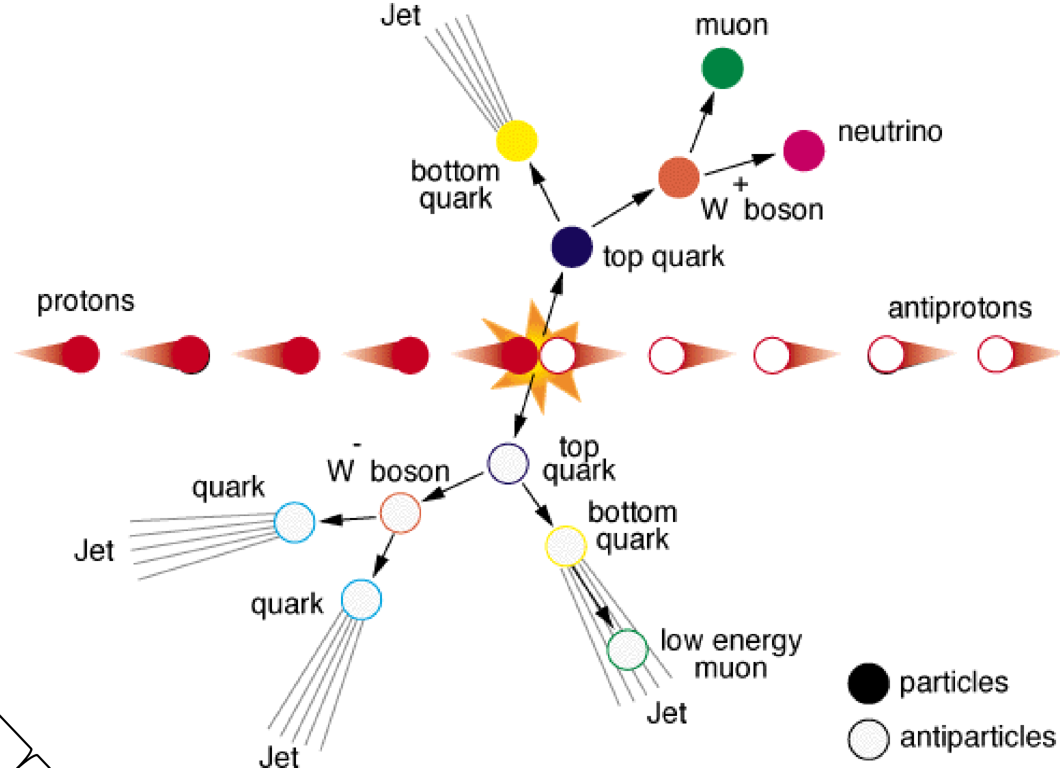
Semi-leptonic ($l^+ \upsilon$) channel is best

- l^+ is an electron or muon
- l^+ is easy to identify
- Only one neutrino
- Each b quark decays into a jet
- Each q quark decay into another 2 jets



Best decay channel to look for

- Semi-leptonic mode (lepton+neutrino)
- Electron or muon 20% of the time
- Signature:
  - 2 light quark jets
  - 2 bottom jets
  - One electron or muon
  - Missing transverse momentum (because of the neutrino)
- Extras:
  - Underlying event
  - Higher order processes
  - Multiple interactions



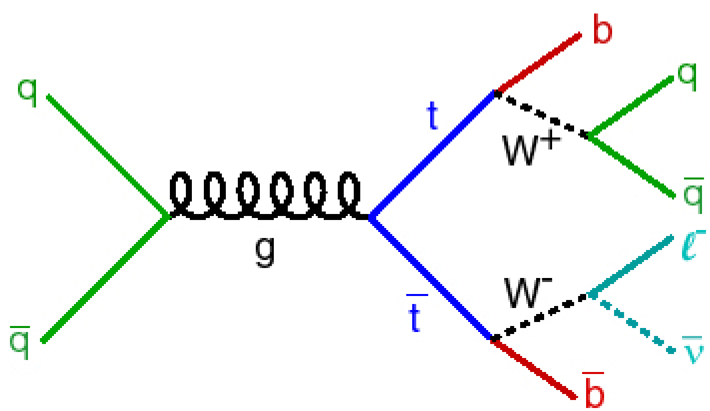
A Top Antitop Quark Event from the D-Zero Detector at Fermilab

These two jets have W^- mass

These three jets have top mass

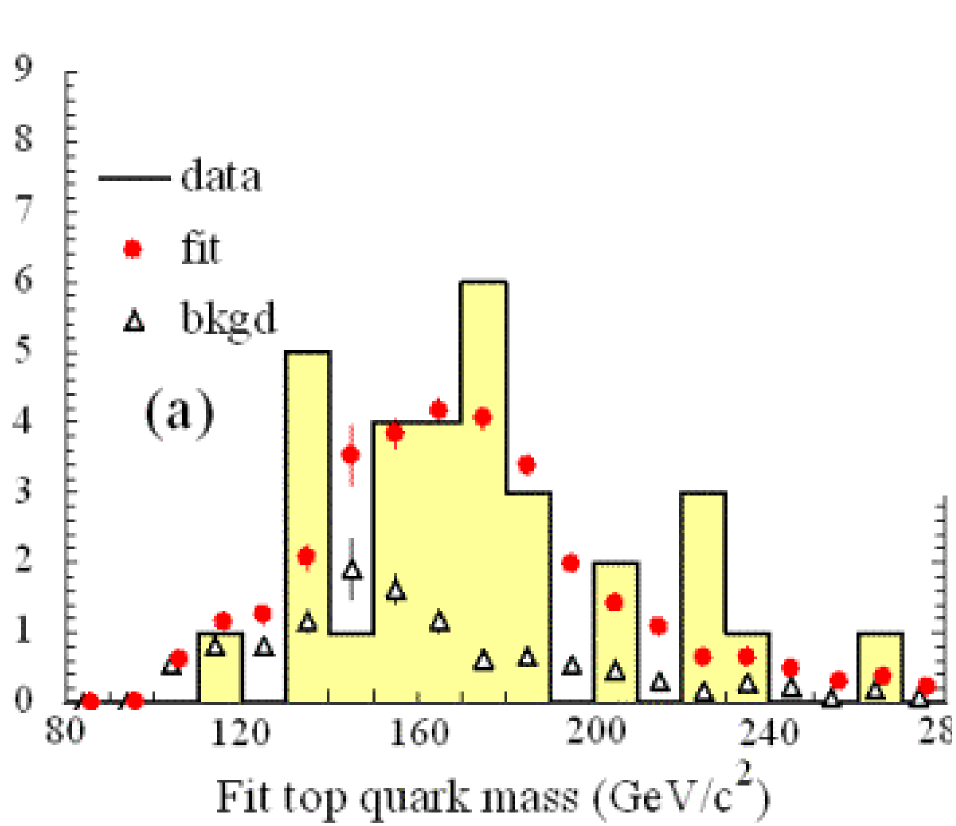
The Top mass

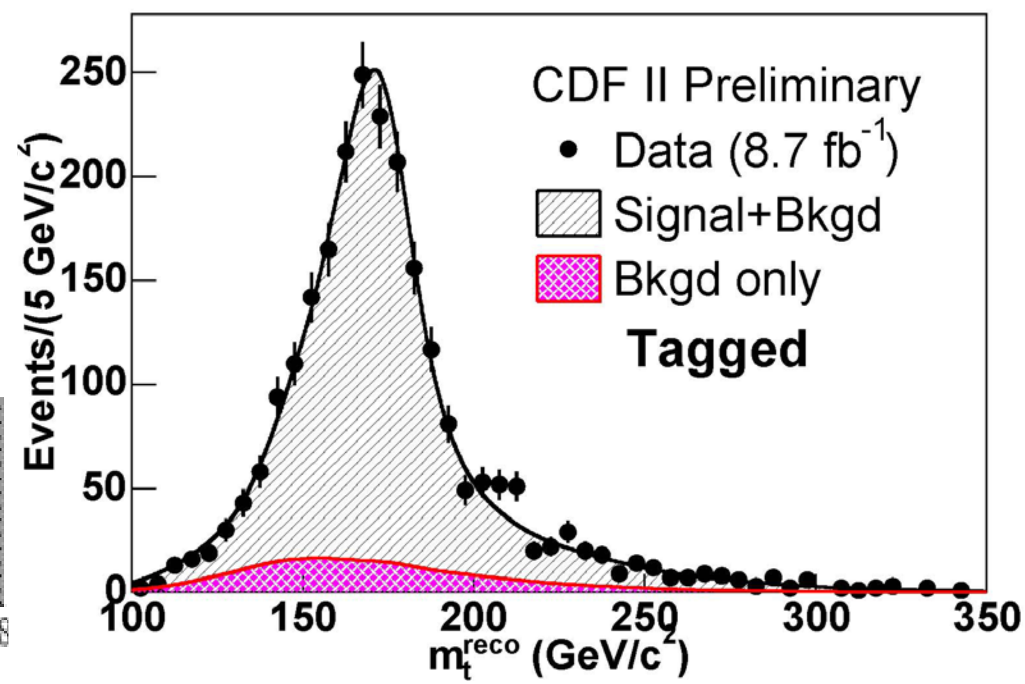
- How do we find the top mass



- Add together the q and anti-q jets to form W^+ mass
- If this is okay, add the b quark jet to get the top mass

An example of the top mass



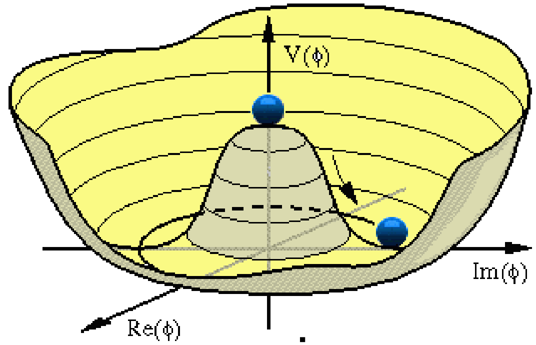


~1999 **2011**

Search for the Higgs Boson

- Missing piece of Standard Model
- Standard Model Higgs theory well understood:
  - Mass is only free parameter
  - Clear predictions to test
- Most "New Physics" models have something equivalent to a Higgs boson ("MSSM Higgs", "little Higgs", etc…).
- Could be more than one type of Higgs boson
- Particle masses are generated by interactions with the scalar (Higgs) field.
- Couplings are fixed by the masses.
- Once M_H is known everything is predicted.
- So by measuring the coupling of the Higgs to particles of known mass we can test theory.

Higgs Mechanism in the Standard Model



- Need to accommodate massive gauge bosons
  - Strong and electromagnetism ok (photon, gluon)
  - Weak force has two massive W and a Z

Modified potential $V = \mu^2 |\phi|^2 + \lambda |\phi|^4$ $\qquad \phi_{min} = \upsilon = \sqrt{\frac{-\mu^2}{\lambda}}$

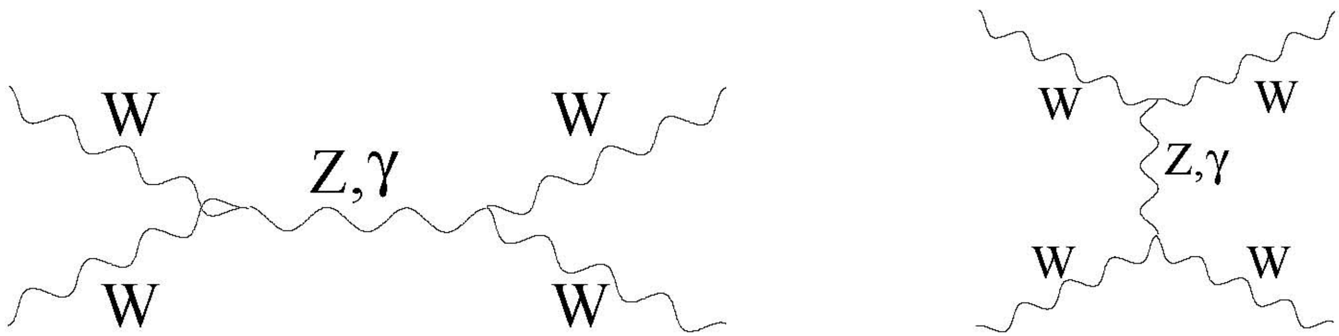
- Step 1: Spontaneous Symmetry Breaking produces one massive and one massless gauge boson (Goldstone Boson).
- Step 2: Introduce local gauge invariance : massive Higgs particle, three massive vector bosons (W/Z) and one massless boson (γ).
- Higgs mass a free parameter $\qquad M_H = \sqrt{-2\mu^2}$
- Gauge couplings of Higgs doublet give gauge boson masses:

$$M_W = g_W \nu / 2 \quad M_Z = M_W \cos\theta_W \quad \cos\theta_W = 0.8810$$

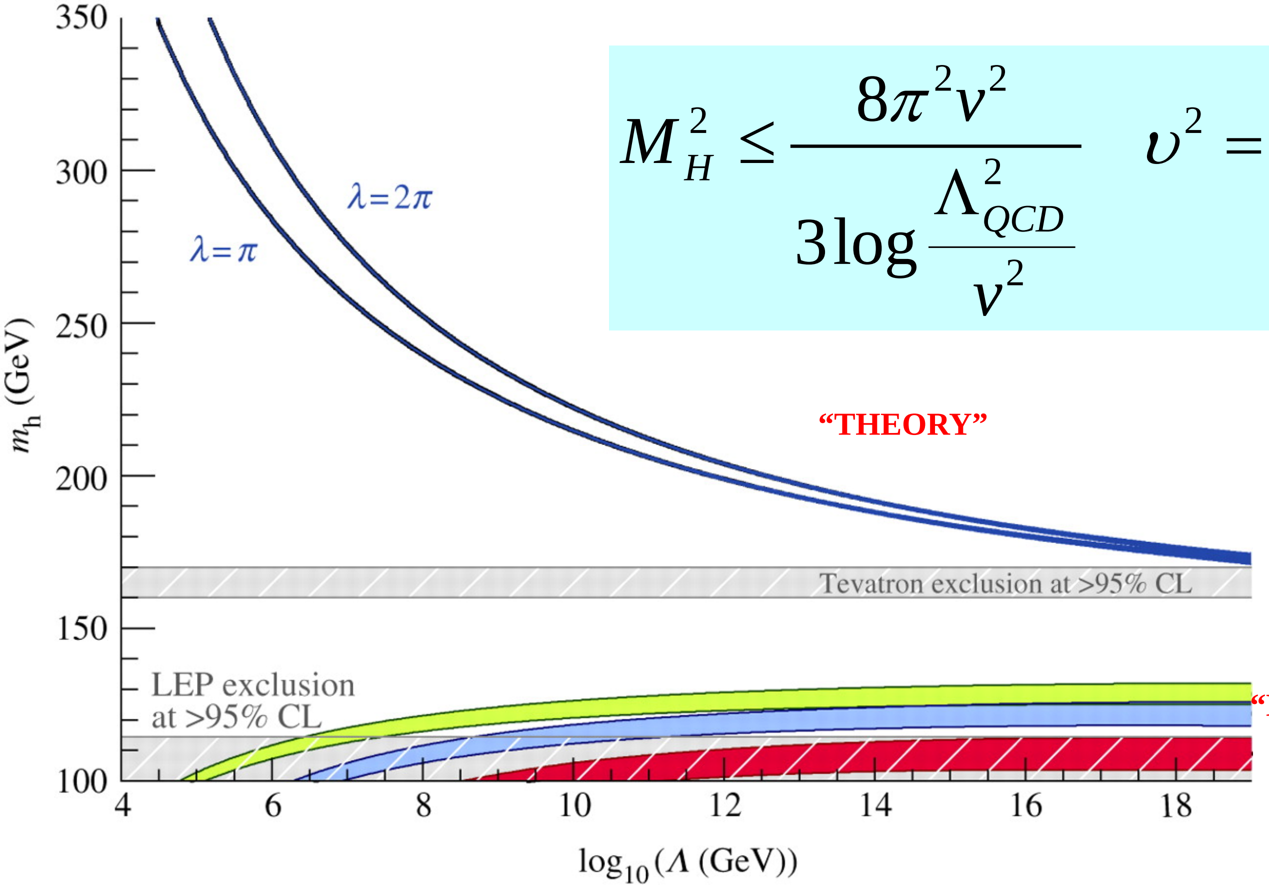
- Can calculate υ (=246GeV) but not λ before measuring Higgs mass.
- Higgs couplings to fermions depends on their mass and unique coupling for each fermion: $\qquad M_f \propto M_H g_f$

What did we know about the Higgs before 2012?

- No useful lower limit from theory.
- Lower limit from experiments.
- Upper limit from WW scattering calculations
  - Above ~1TeV cross-section $\rightarrow \infty$
  - Need Higgs to "regularise" cross-section



What did we know about the Higgs before 2012?



$$M_H^2 \leq \frac{8\pi^2 v^2}{3\log\frac{\Lambda_{QCD}^2}{v^2}} \qquad \upsilon^2 = 246\,\mathrm{GeV}$$

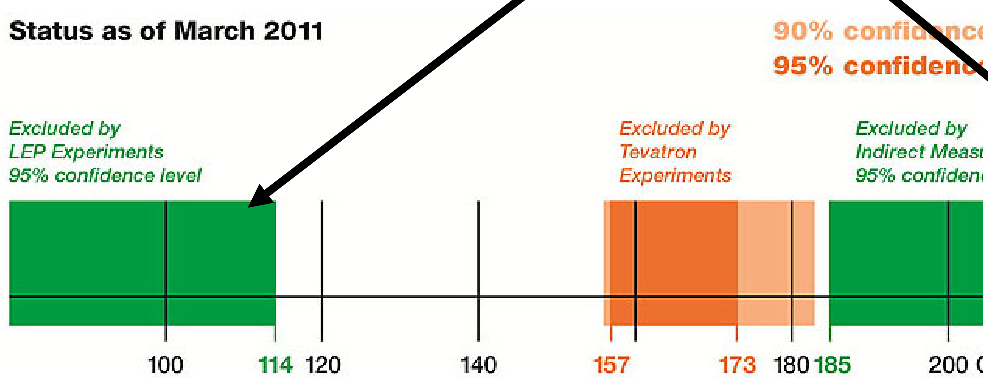
"THEORY"

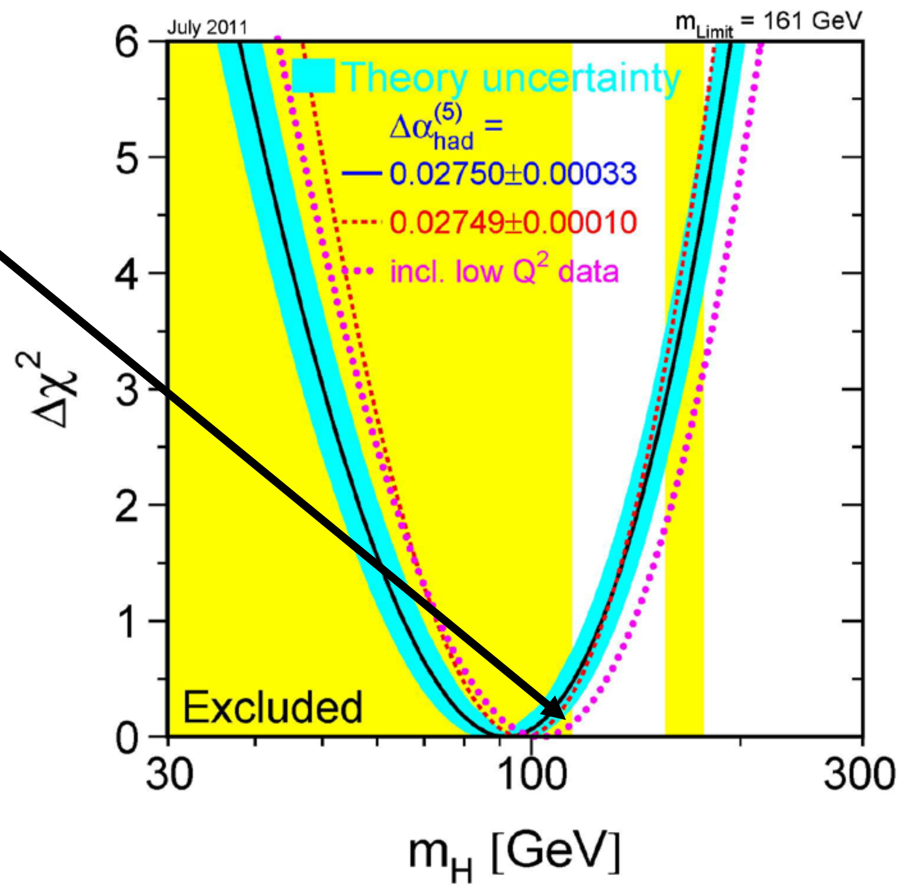
"EXPERIMENT"

If no new physics up to Planck scale (~10^{19}GeV) small mass range for Higgs: 130 < M_H < 190 GeV

What did we know about the Higgs before 2012?

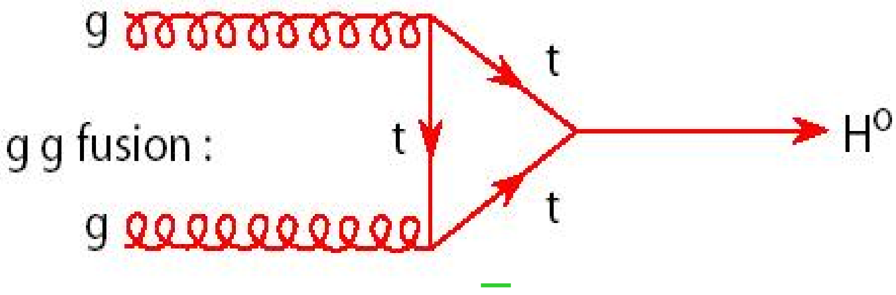
Direct searches
$M_H > 114.4$ GeV
@ 95% C.L.

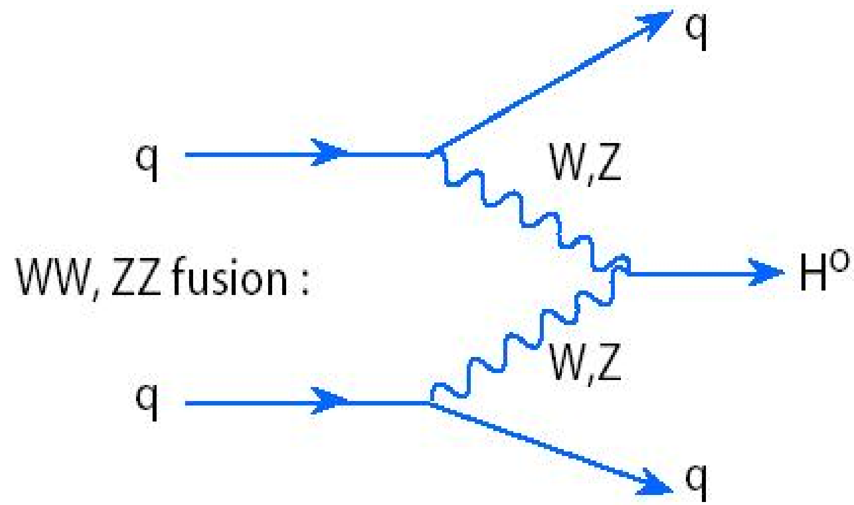




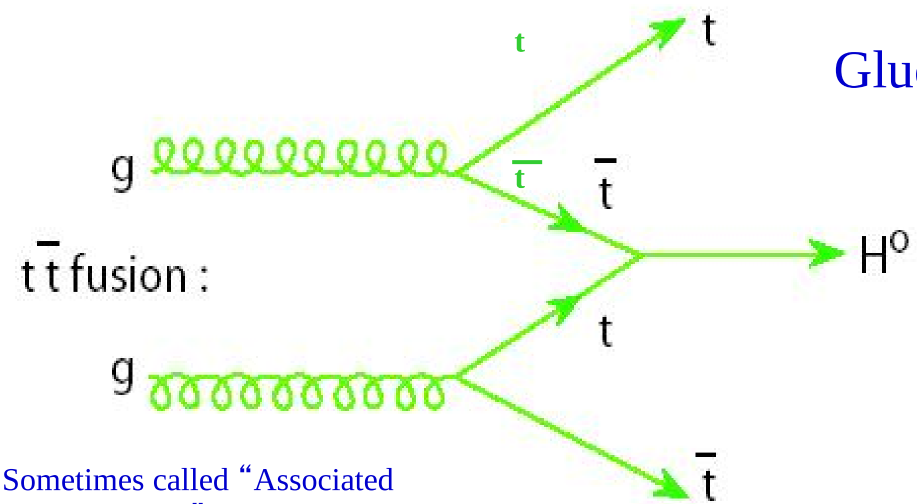
http://lepewwg.web.cern.ch/LEPEWWG

Higgs Production Mechanisms

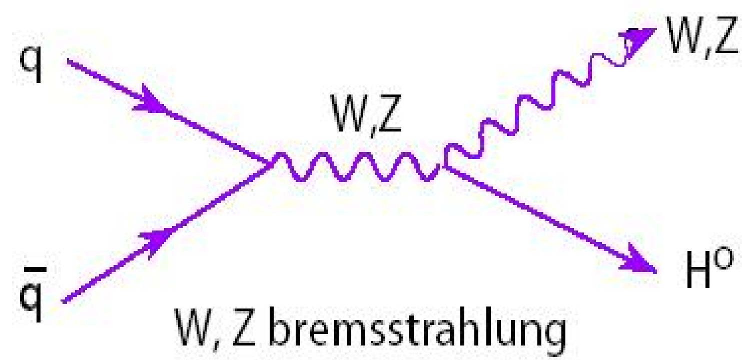




Gluon fusion looks most promising



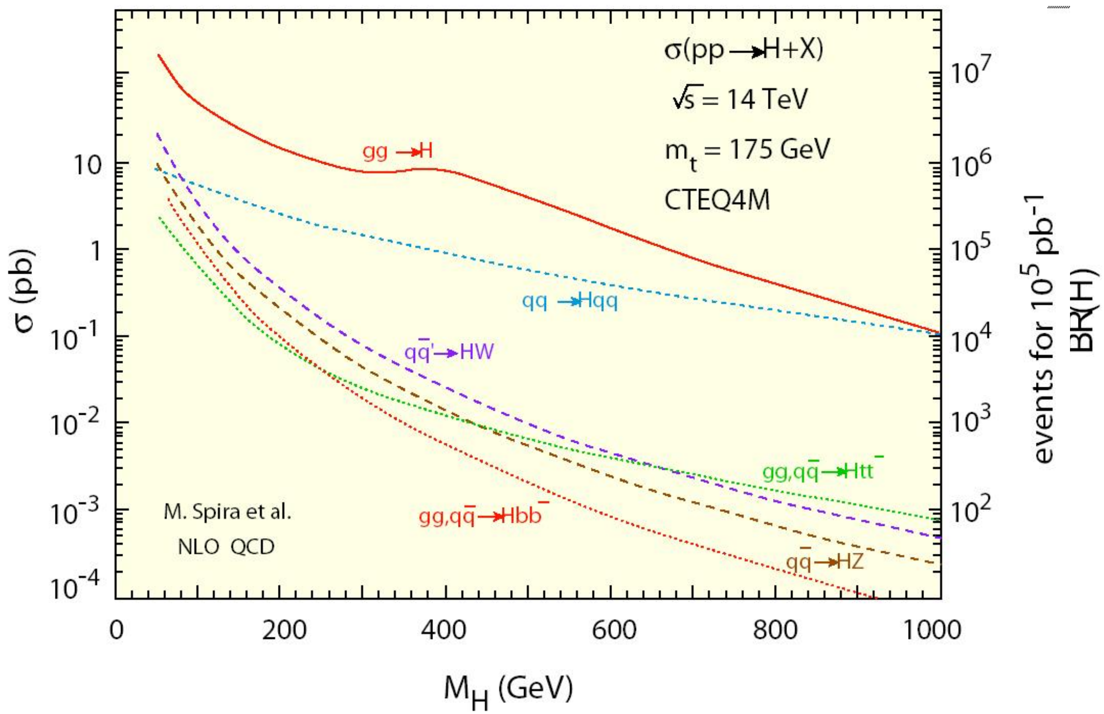
Sometimes called "Associated ttH production"



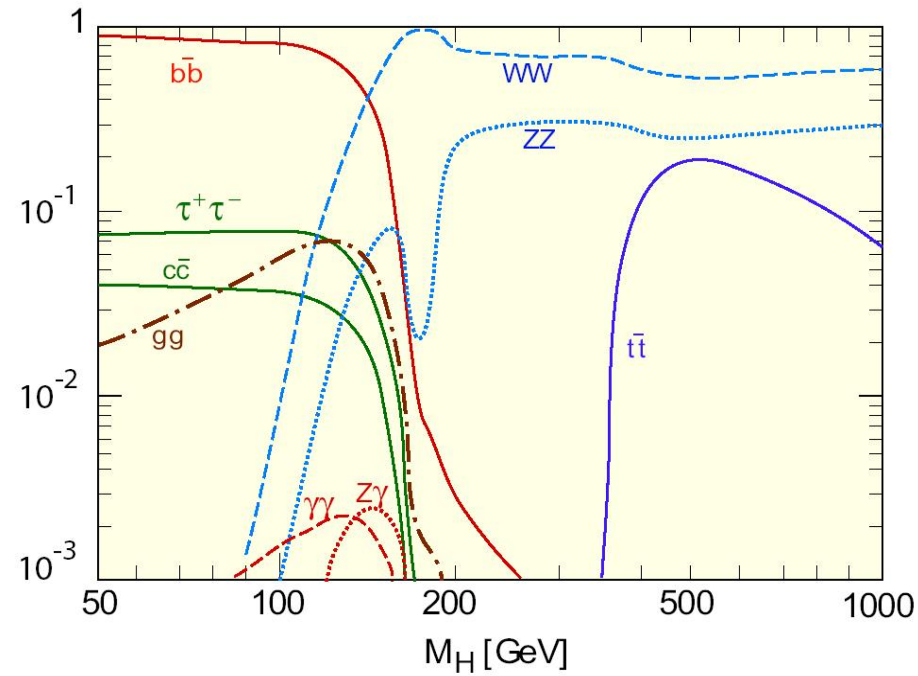
Sometimes called "Associated WH,ZH production"

Higgs production and decay

How often is it produced?



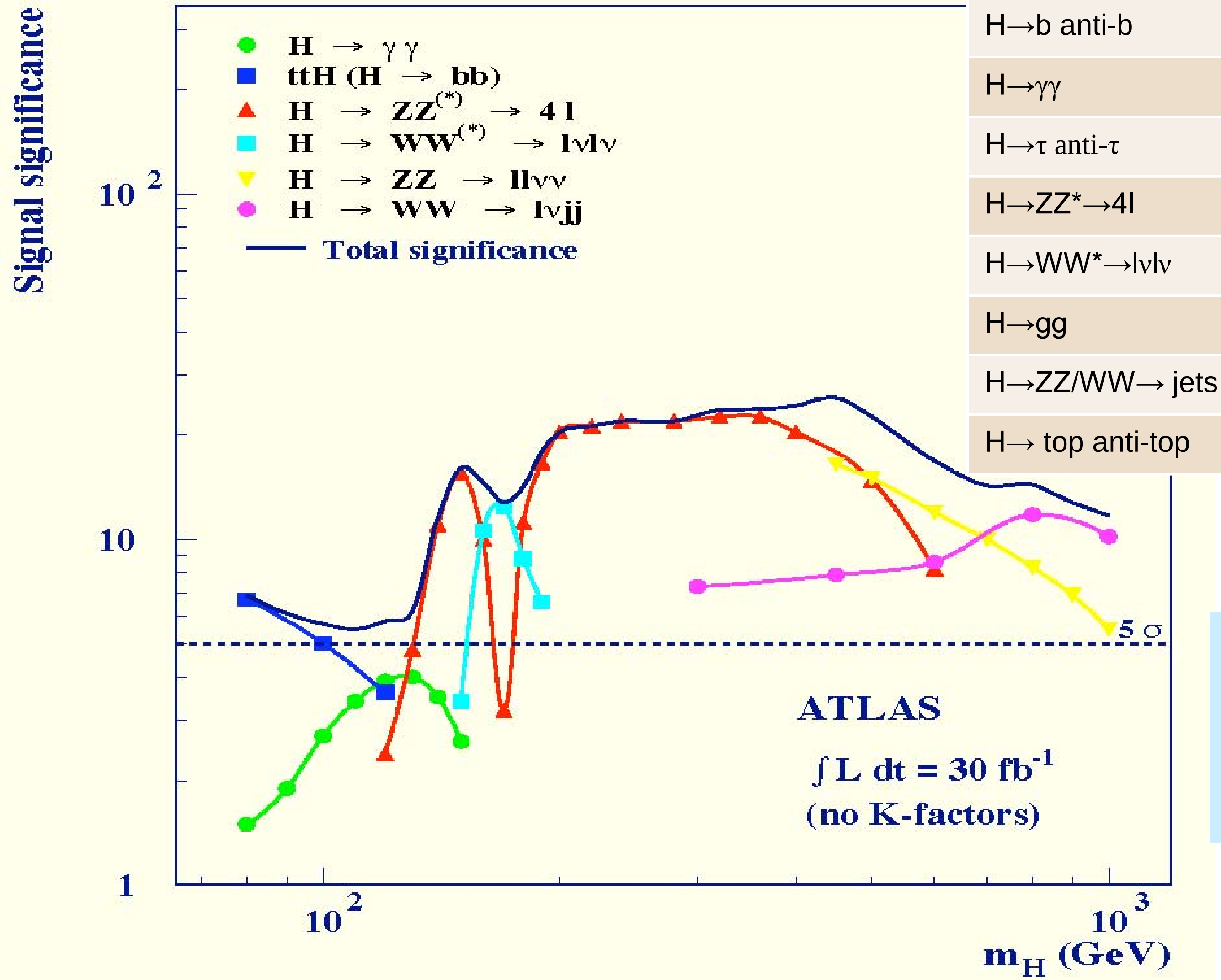
What does the Higgs decay into?



Process	Events/s	Events/year
$W \to e\nu$	40	$4 \cdot 10^8$
$Z \to ee$	4	$4 \cdot 10^7$
$t\bar{t}$	1.6	$1.6 \cdot 10^7$
$b\bar{b}$	10^6	10^{13}
$\tilde{g}\tilde{g}$ (m = 1 TeV)	0.002	$2 \cdot 10^4$
Higgs (m= 120 GeV)	0.08	$8 \cdot 10^5$
Higgs (m= 120 GeV)	0.08	$8 \cdot 10^5$
Higgs (m= 800 GeV)	0.001	10^4
QCD jets $p_T > 200$ GeV	10^2	10^9

Best Modes to look at

Decay	Signal Rate	Background Rate	Best for Higgs mass
H→q anti-q	Low	Large	~100 GeV
H→b anti-b	Large	Large	~100 GeV
H→γγ	Low	Low	~100 GeV
H→τ anti-τ	Low	Large	~100 GeV
H→ZZ*→4l	Large	Low	~250 GeV
H→WW*→lνlν	Large	Low	~150 GeV
H→gg	Low	Large	~100 GeV
H→ZZ/WW→ jets	Large	Large	~500 GeV
H→ top anti-top	Low	Large	~500 GeV



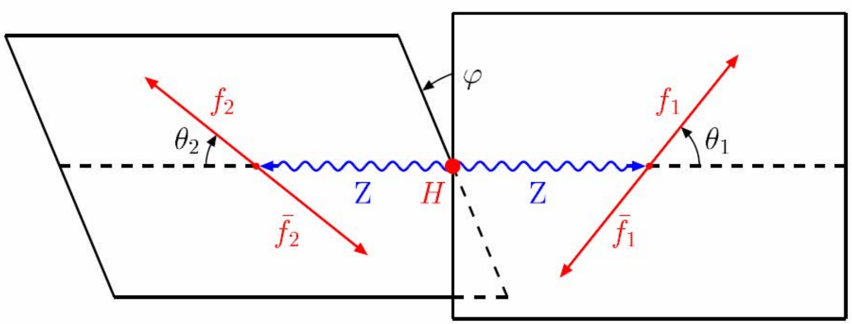
The amount of background affects our ability to see the Higgs.

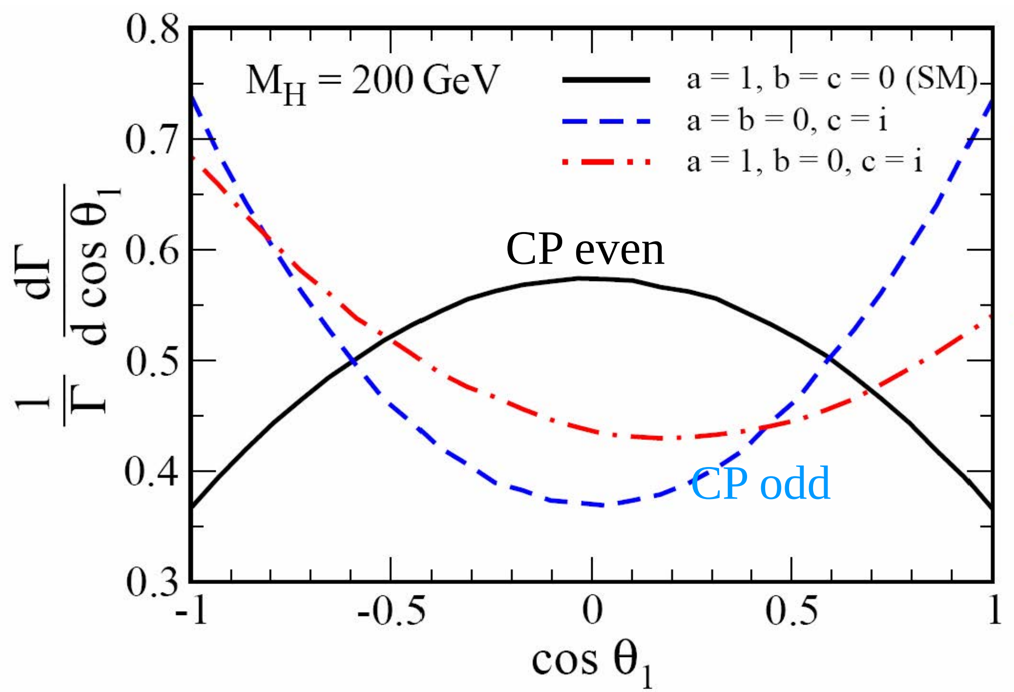
Reconstructing the Higgs properties

- 1) Mass
  - Add up all the 4-moment of its decay particles e.g. $H\rightarrow\gamma\gamma$, $H \rightarrow ZZ^* \rightarrow l^+l^-l^+l^-$ (4 leptons)
  - But sometimes miss particles e.g. $H\rightarrow W^+W^-\rightarrow l\nu l\nu$
    - Just use 4-momenta in transverse direction "transverse mass" i.e. ignore momentum p_z along beam direction.
- 2) Spin
  - Look at the angle between one of the decay products and the direction of the Higgs in the Higgs centre of mass
    - E.g. $H\rightarrow\gamma\gamma$

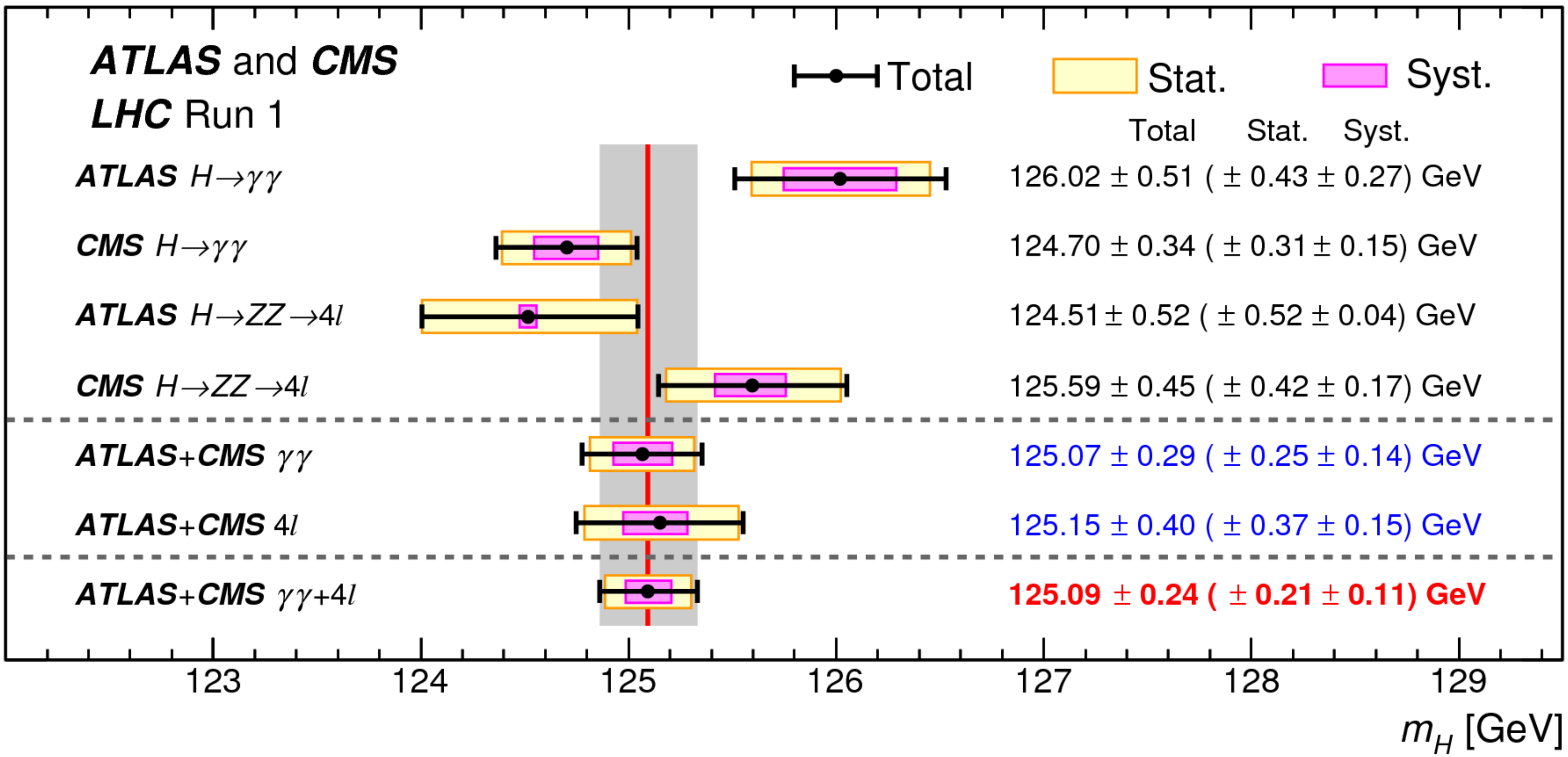
Reconstructing the Higgs properties

- 3) Charge Parity (CP)
  - Look at angles defined by leptons in $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$
  - SM CP=+1 (even); some SUSY models CP=-1 (odd)

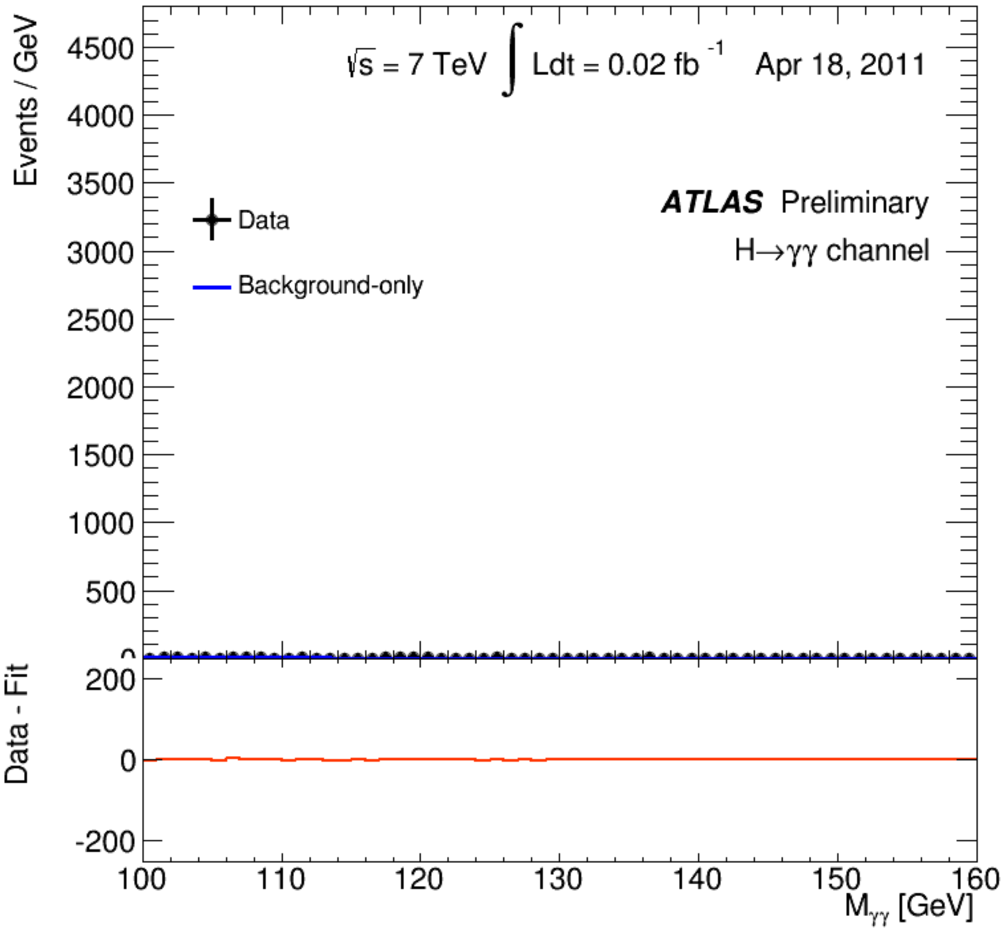


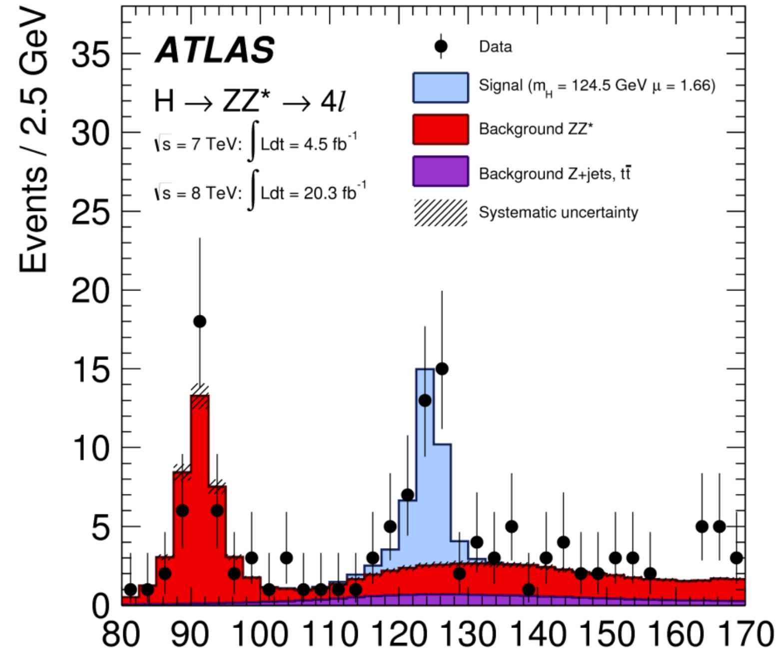


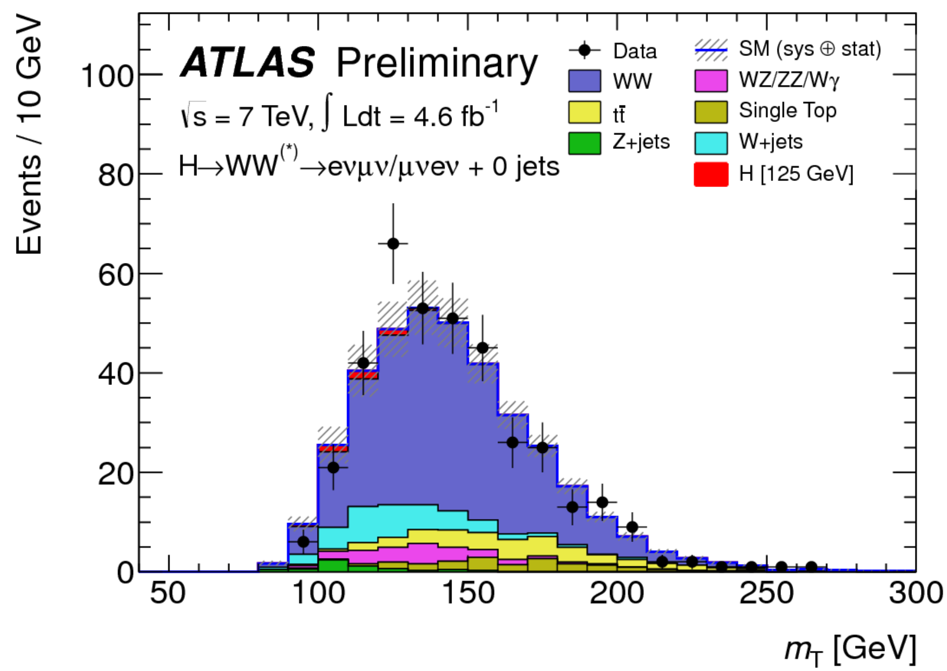
The Higgs Mass (March 2015)



Some Higgs masses



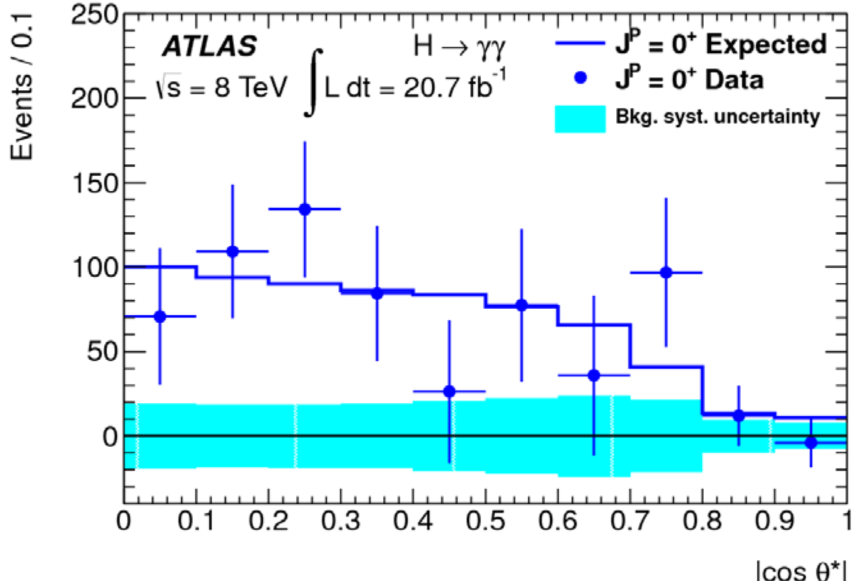


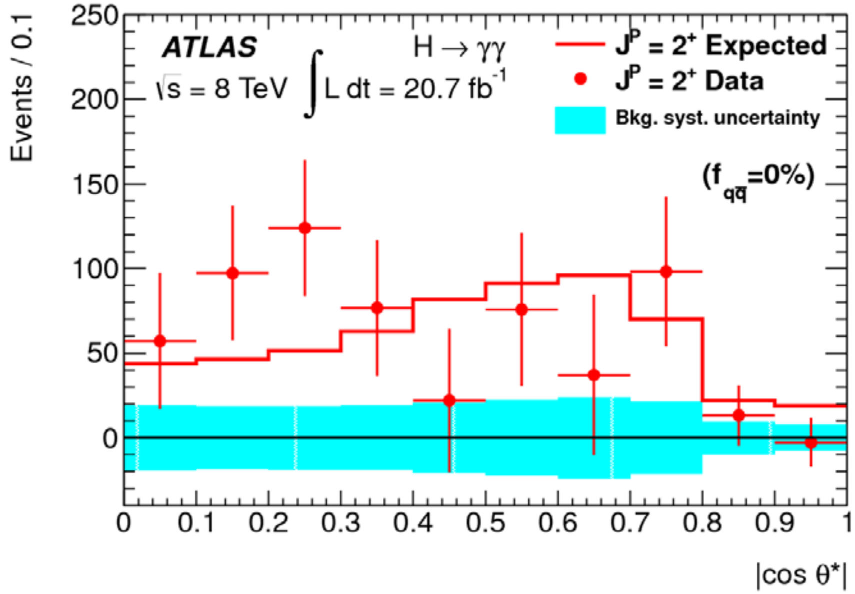


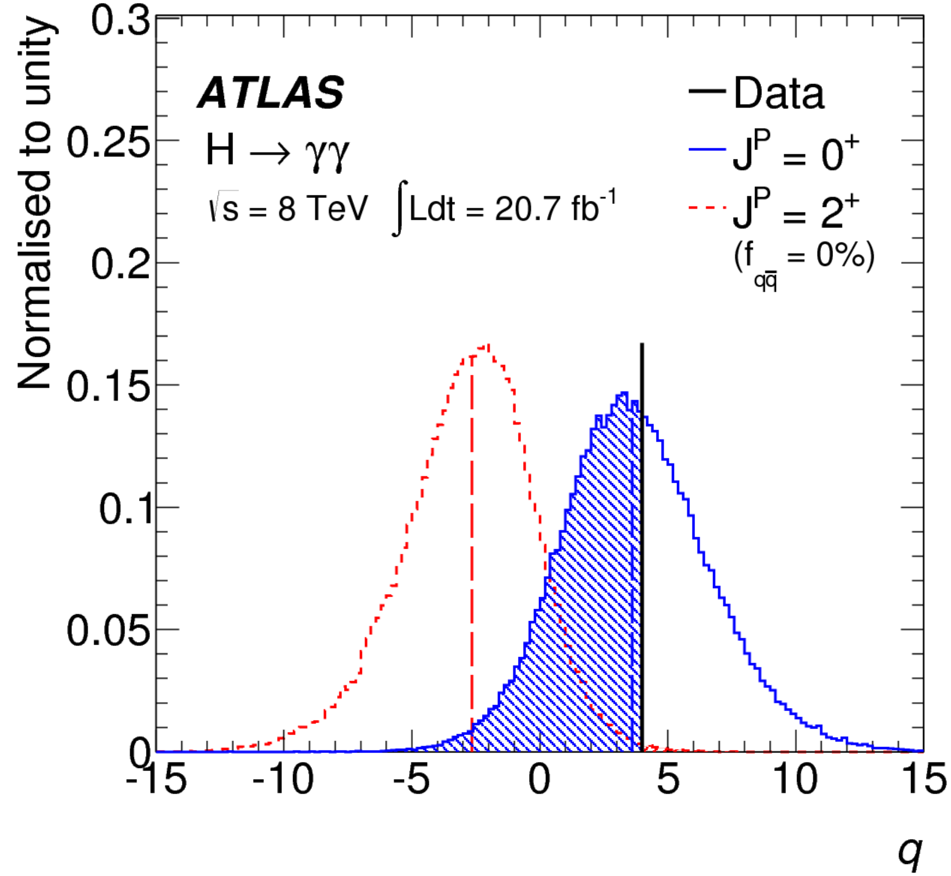
Higgs Spin

Best fit suggests Higgs is a scalar (J=0) particle.

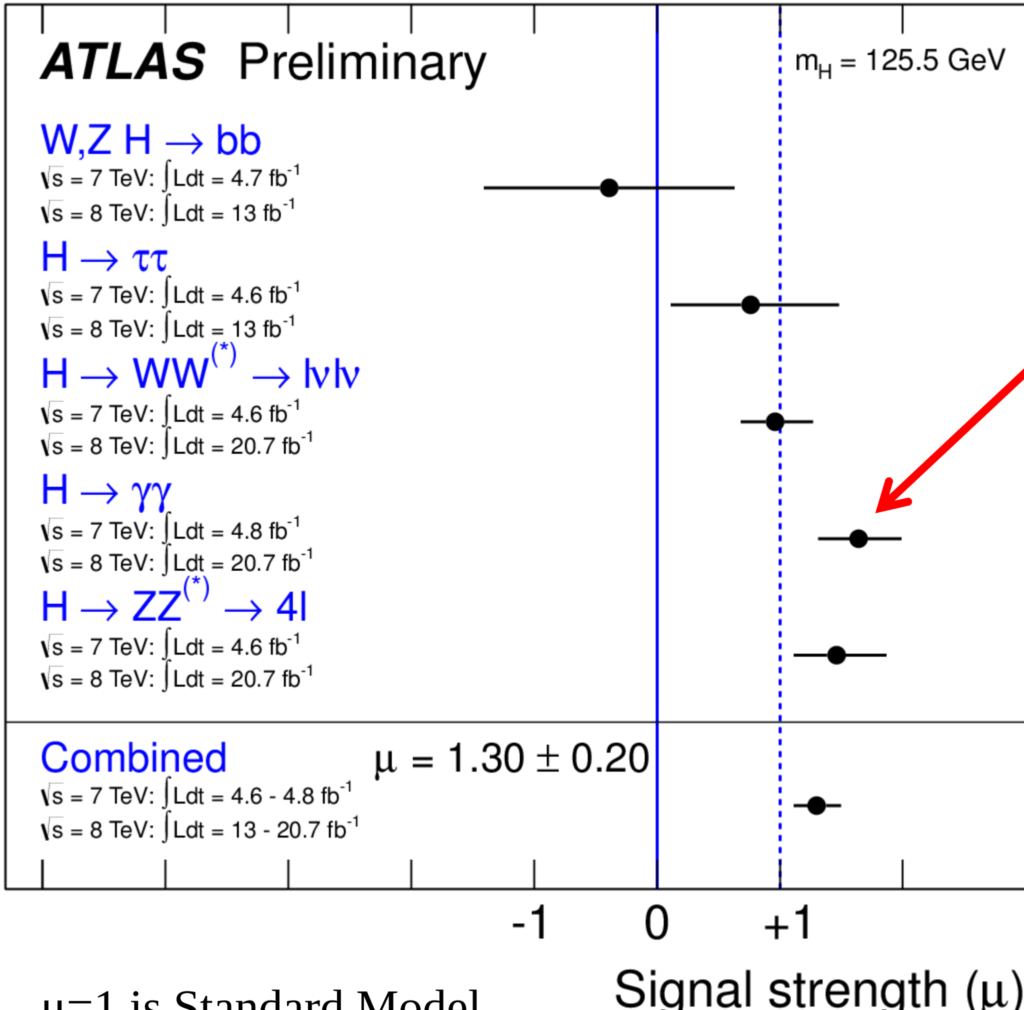
Don't yet know CP values but CP=+1 is preferred.







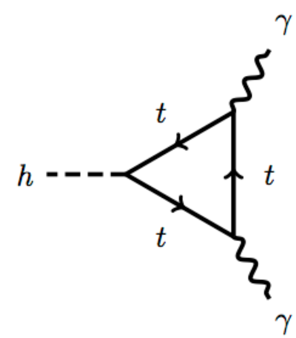
Higgs coupling to different particles

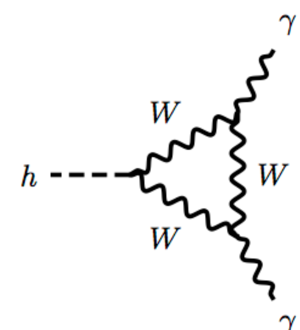


μ=1 is Standard Model

Is this rate too high? Is it a signal of new physics?

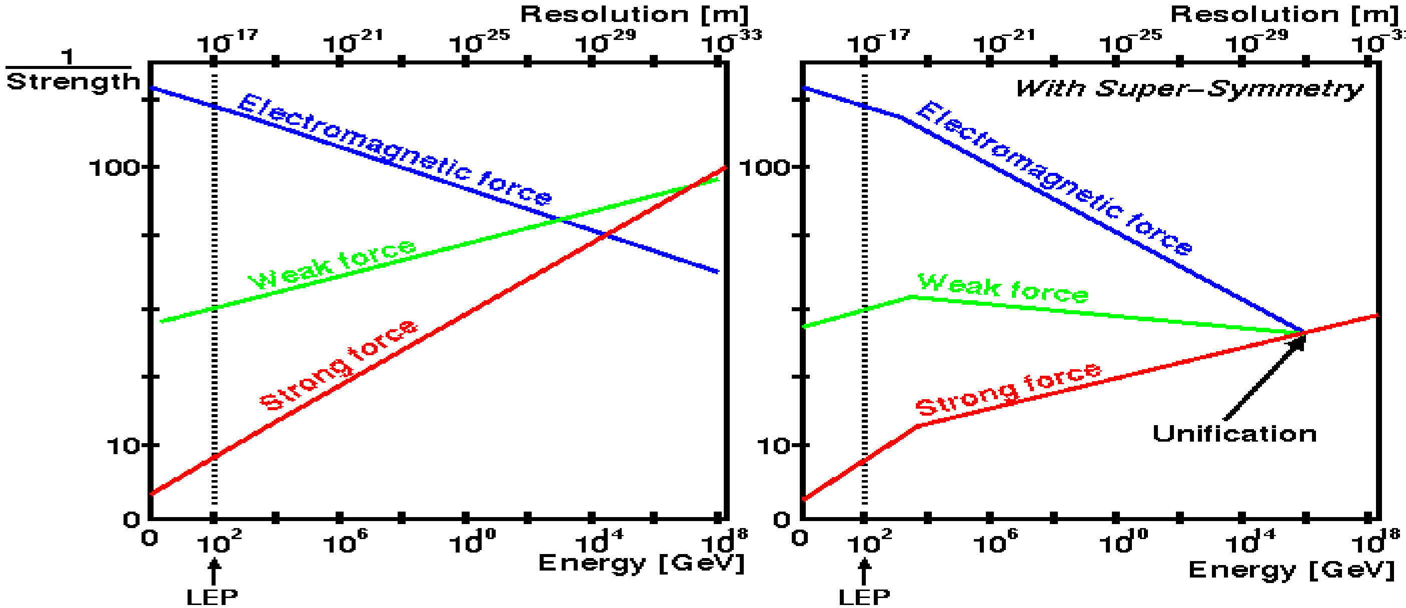
- Could be new fermions in the decay or production.
- Could be new charged bosons in the decay loop.
- Could just be statistics !



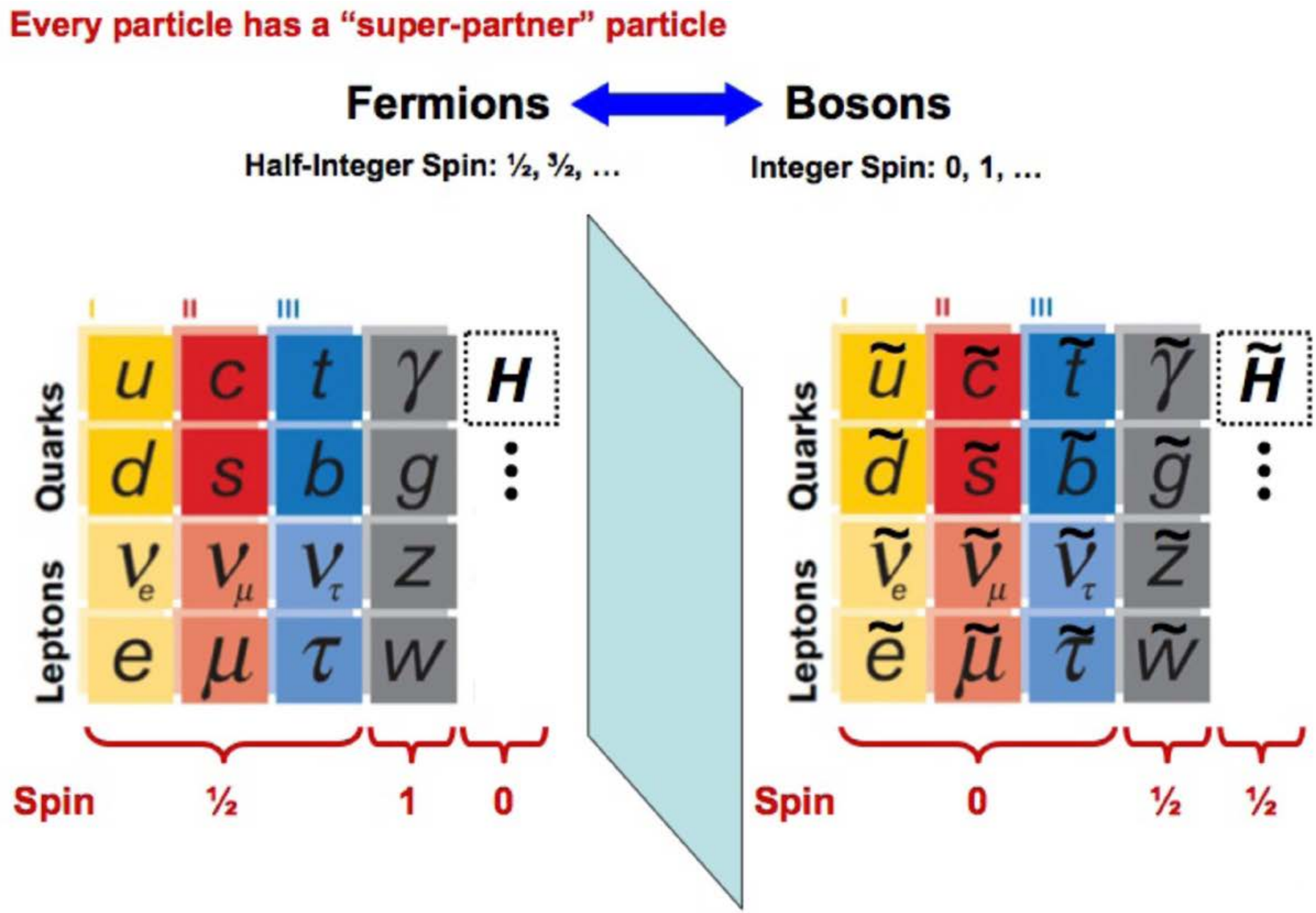


Is the Standard Model all there is?

- So far we have assumed a Standard Model Higgs but...
  - Does not explain Dark Matter
  - Does not unify electromagnetism, weak and strong forces at high-energies (10^{16} GeV, Planck mass).
- Need models beyond the Standard Model



Supersymmetry



Supersymmetric Higgs

- Need at least two Higgs doublets (H_1,H_2) to generate down- and up-type particles.
- Physical particles:

$$h = H_2 \cos\alpha - H_1 \sin\alpha \quad (m_h < m_Z)$$
$$H = H_2 \sin\alpha - H_1 \cos\alpha \quad (m_H > m_Z)$$
$$A = \text{CP-odd Higgs}$$
$$\text{H}^{\pm} = \text{charged Higgs} \quad (m_{H^{\pm}} = m_A^2 + m_W^2)$$

- Radiative corrections can change masses.
- Higgs sector now described by two free parameters (m_h and $\tan\beta = \upsilon_2/\upsilon_1$).
- However, the exact SUSY symmetry has to be broken to reconcile the theory with experiment (i.e. the standard model and SUSY particles have different masses).
- The minimal extension to SUSY (MSSM) has 105 parameters!
- Have to assume a specific model e.g. mSUGRA
  - Modifies Higgs mechanism
  - 5 free parameters:
    - tanβ (as before)
    - m_0 (universal scalar mass, includes Higgs)
    - $m_{½}$(gaugino mass)
    - plus two others

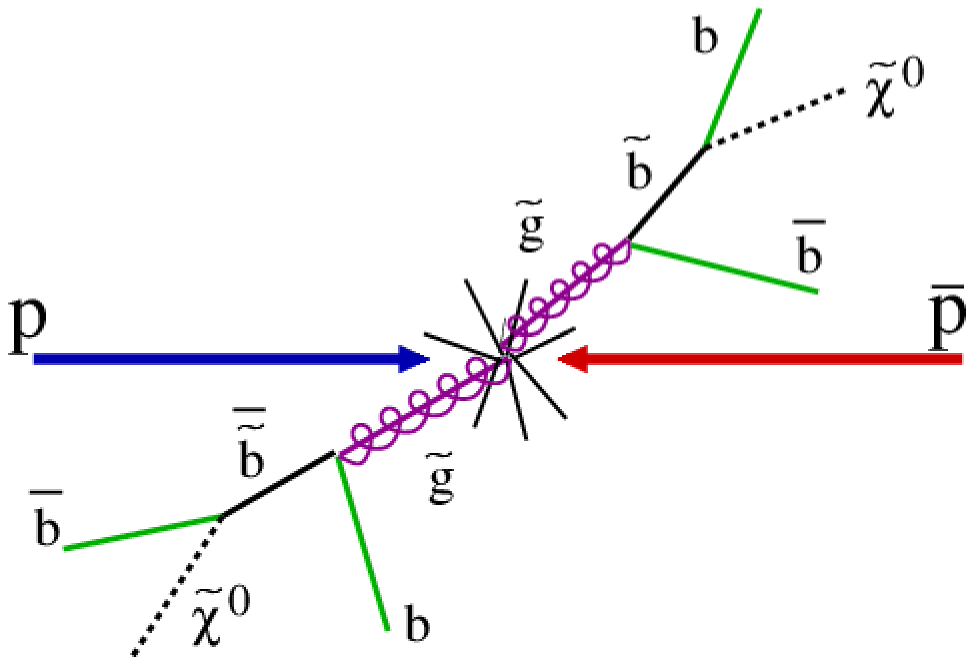
Looking for SUSY Higgs at the LHC

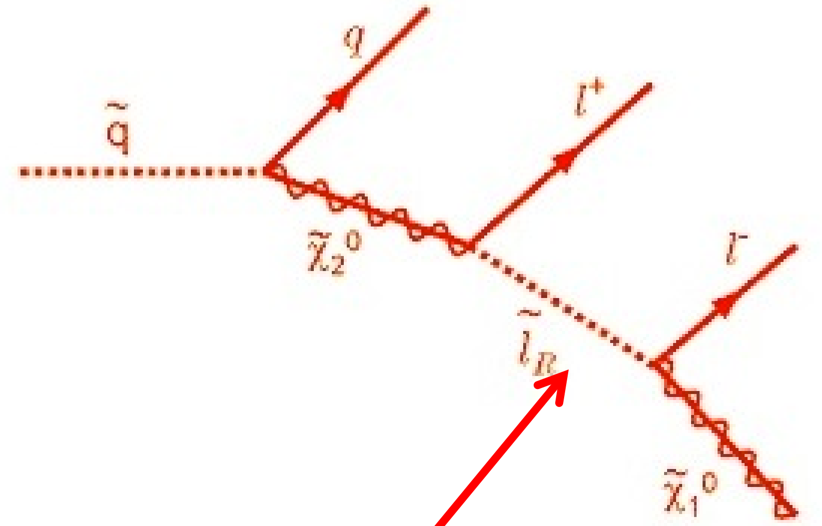
- Small tanβ
  - gg→H,A production is enhanced due to stronger $t\bar{t}$H coupling.
  - H,A →$t\bar{t}$ decay gets enhanced.
- Large tanβ
  - H, A production is enhanced in $b\bar{b}$-fusion
  - H →$\tau^+\tau^-$ has a large branching ratio
- Medium tanβ
  - Only SM-like h visible. We could see a Higgs and not realise we have seen SUSY!
- Charged Higgs
  - Clear signal for new physics (not predicted in Standard Model)

Looking for other SUSY particles

- SUSY predicts that every Standard Model particle has a Super-Symmetric partner
  - Electron ↔ selectron, quark ↔ squark,W ↔ wino, etc...
  - But masses not the same → SUSY not exact symmetry
  - But they can not be too massive.
- SUSY can be a new source of CP-Violation
  - Explain matter/anti-matter asymmetry of the Universe
- A SUSY particle will quickly decay to the Lightest Supersymmetric Particle (LSP).
  - Neutral (no charge)
  - LSP is a candidate for Dark Matter
- LSP will leave detector without interacting
  - Large Missing energy, momentum (because LSP is massive)
- What is the LSP?
  - Don't really know
  - Likely to be a neutralino

What a SUSY decay looks like

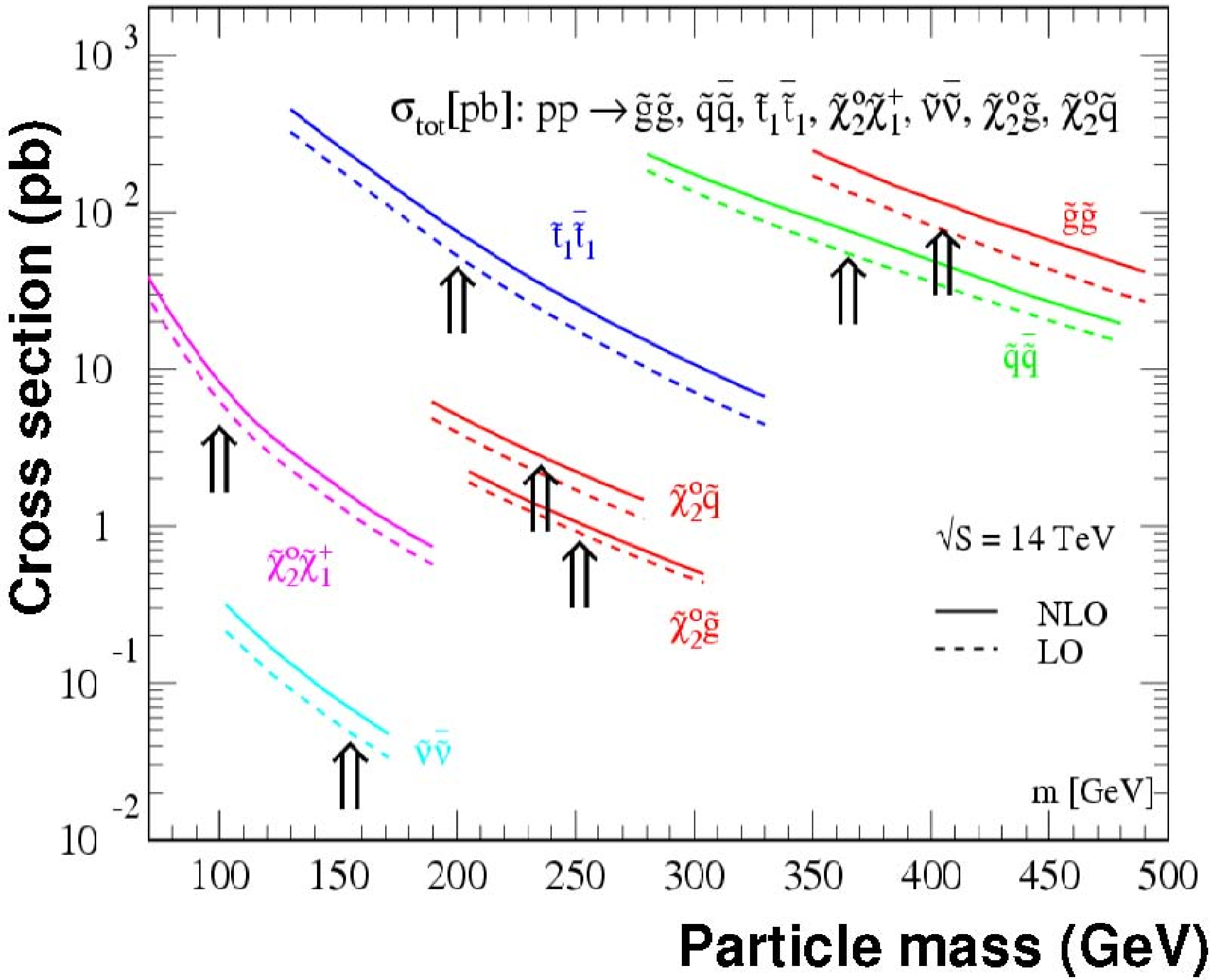




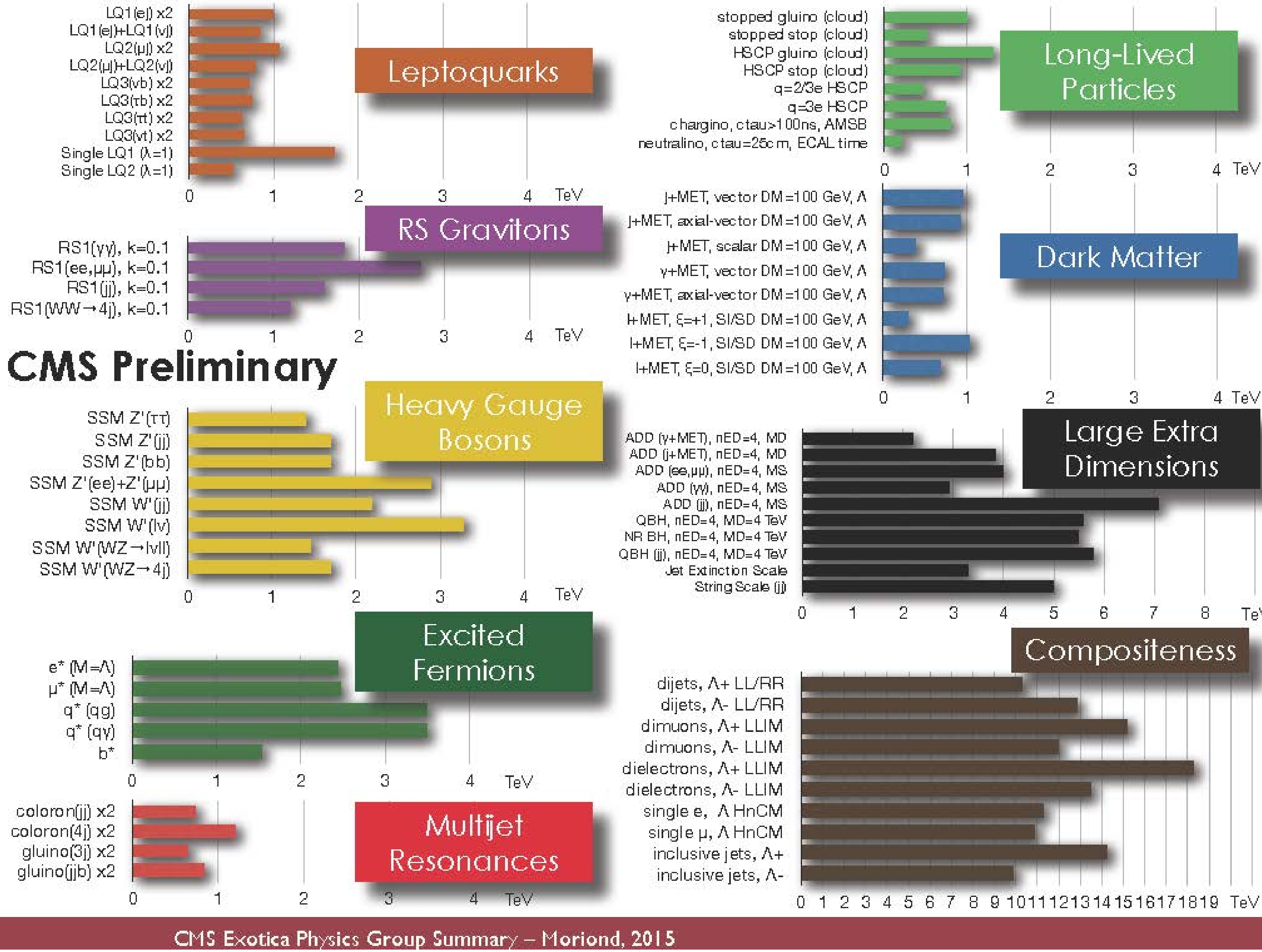
Lots of missing energy

Lots of leptons produced. Easy to see and not produced in background events

What theory predicts for SUSY at LHC



What we currently (don't) see (March 2015)



Status of the LHC today

- Higgs
  - Mass ~125 GeV
  - Spin = 0
  - CP probably not -1.
  - Could be a Standard Model Higgs (good).
  - Could be a SUSY Higgs (also good).
  - No sign yet of any other Higgs below ~600 GeV.
- SUSY
  - No particles found below 1 TeV
  - If no SUSY particles found below 1 TeV SUSY models are "wrong" (bad) but theorists always have a back up plan.

The LHC is due to start data-taking in June at 14 TeV and run for another 4 years before being upgraded