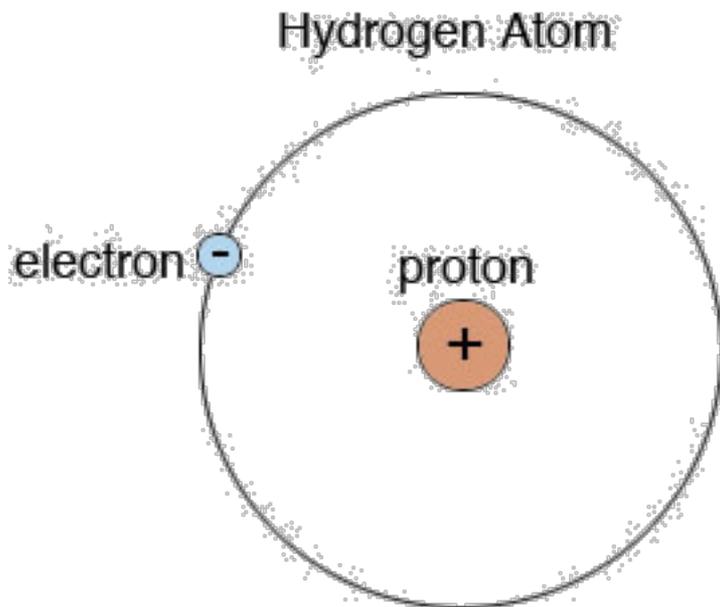


Let's define some units



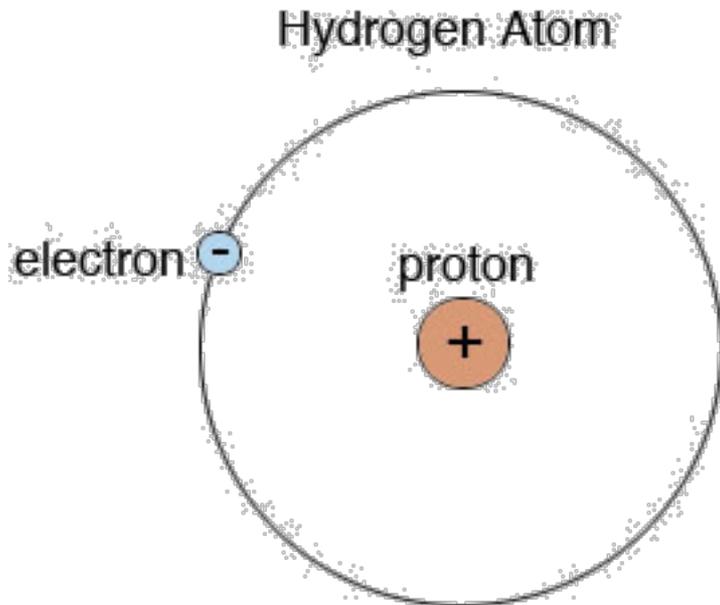
0.15 kg



Electron  
mass =  
 $9 \times 10^{-31}$  kg



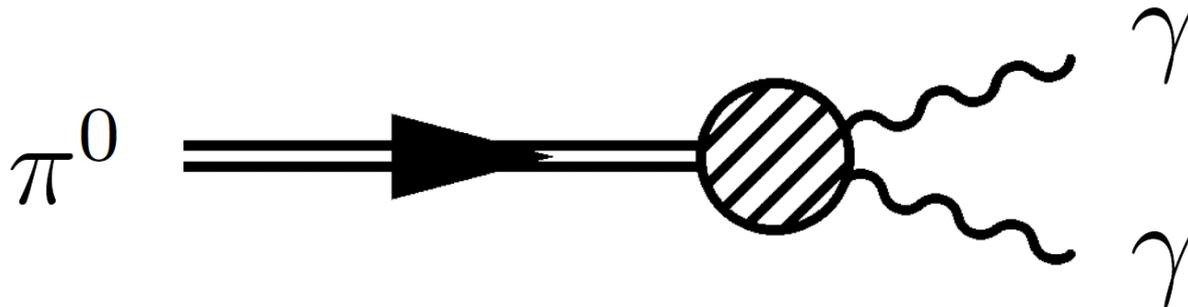
114 meters



Radius of  
electron orbit  
= 0.5  
angstroms =  
 $5 \times 10^{-11}$   
meters



This takes 0.4 seconds



Neutral pion  
lifetime =  
 $8 \times 10^{-17}$  s

**Do not use  
convenient  
particle physics  
units!**

## Other issues with SI units

$$\frac{-\hbar^2}{2m} \frac{\partial^2 u(x)}{\partial x^2} + V(x)u(x) = E u(x)$$

$\hbar$  are pesky and annoying!

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$E^2 = (pc)^2 + (mc^2)^2$$

so are factors of c everywhere!

# The units that we will use

$$\hbar = c = 1$$

$$c = 3 \times 10^8 \text{ m/s}$$

$$\hbar = 10^{-34} \text{ J s}$$

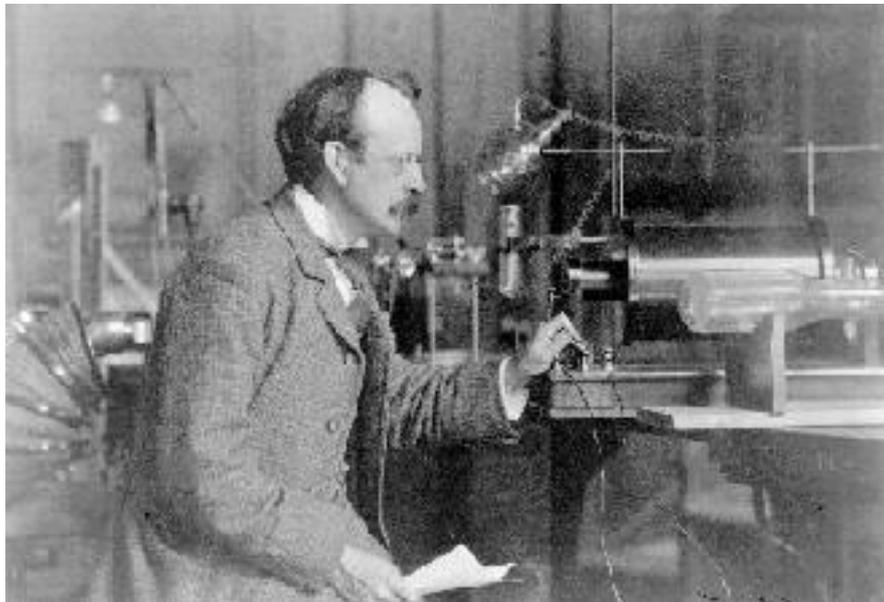
Natural units, with the above choices! Simplifies a lot of notation

$$1 \text{ GeV} = 10^9 \text{ eV} = 1.6 \times 10^{-10} \text{ J}$$

$$\hbar c = 0.2 \times 10^{-15} \text{ m} = 0.2 \times 10^{-15} \text{ fm}$$

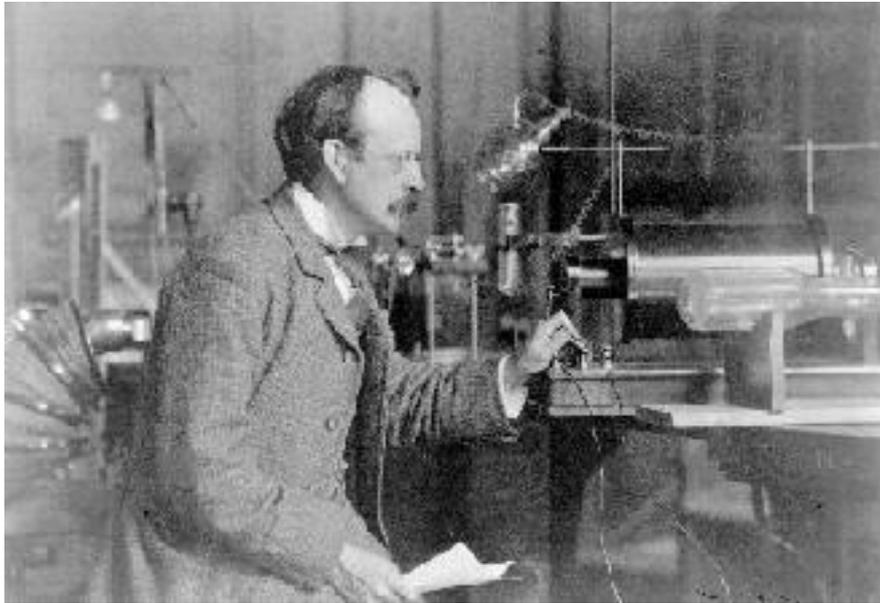
	Not our choice	In our choice of natural units
Energy	GeV	GeV
Momentum	GeV/c	GeV
Mass	GeV/c <sup>2</sup>	GeV
Time	$\hbar/\text{GeV}$	GeV <sup>-1</sup>
Length	$c \cdot \hbar/\text{GeV}$	GeV <sup>-1</sup>
Area	$(c \cdot \hbar/\text{GeV})^2$	GeV <sup>-2</sup>

Griffiths disagrees :)



JJ Thompson, who measured the charge to mass ratio of “cathode rays” (aka electrons). Any ideas how he found their velocity and, more importantly,  $q/m$ ? (1.1 in Griffiths)

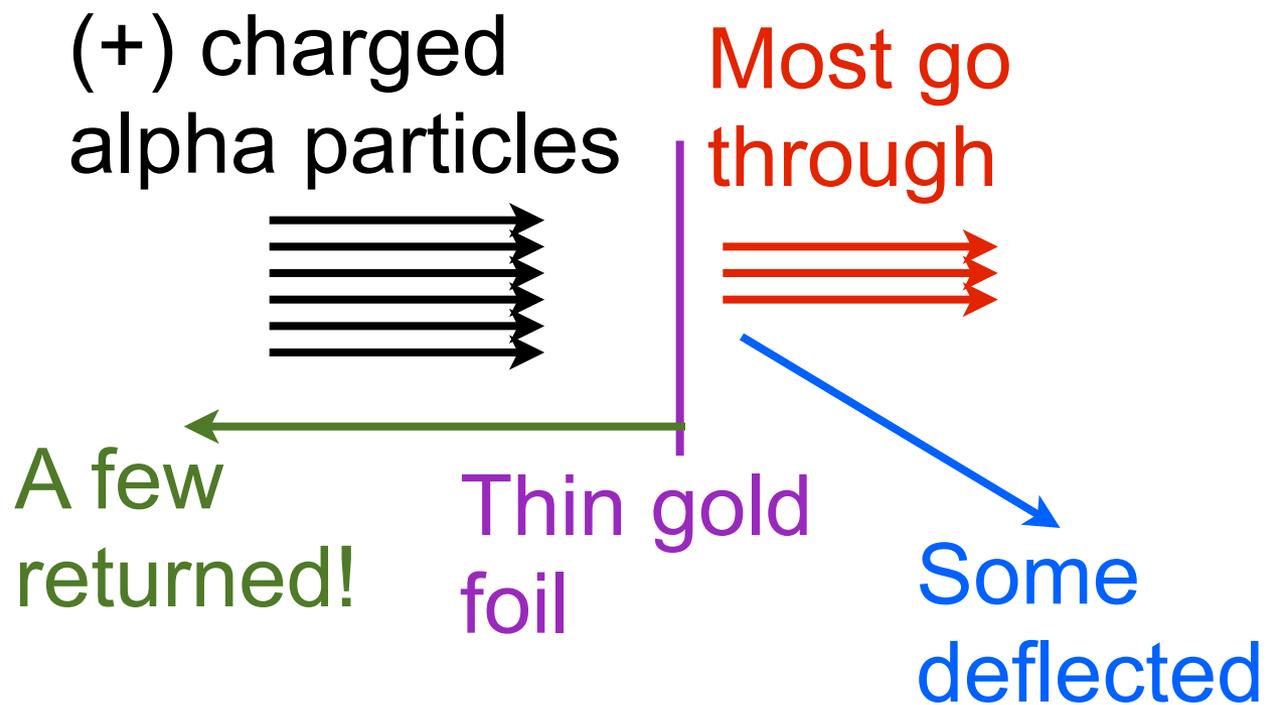
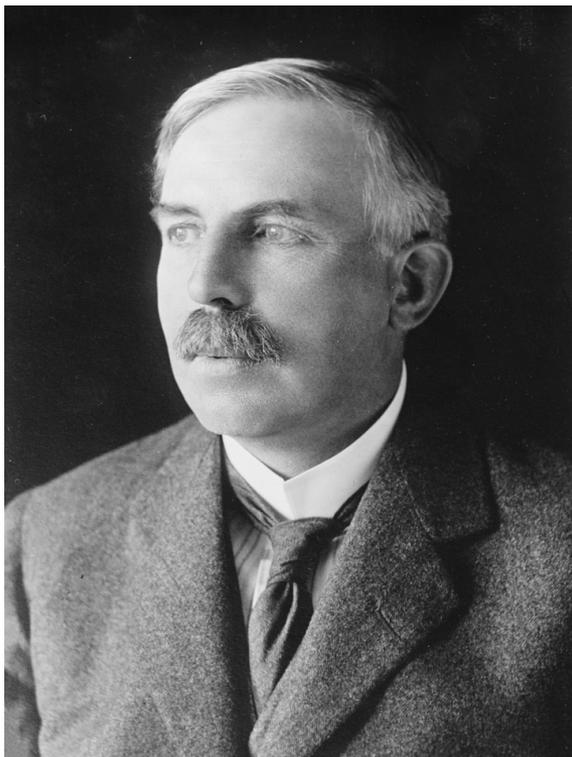
<http://www.phy.cam.ac.uk/history/electron/photos>



Undelected particle:  
 $qE = qvB, v=(E/B)$

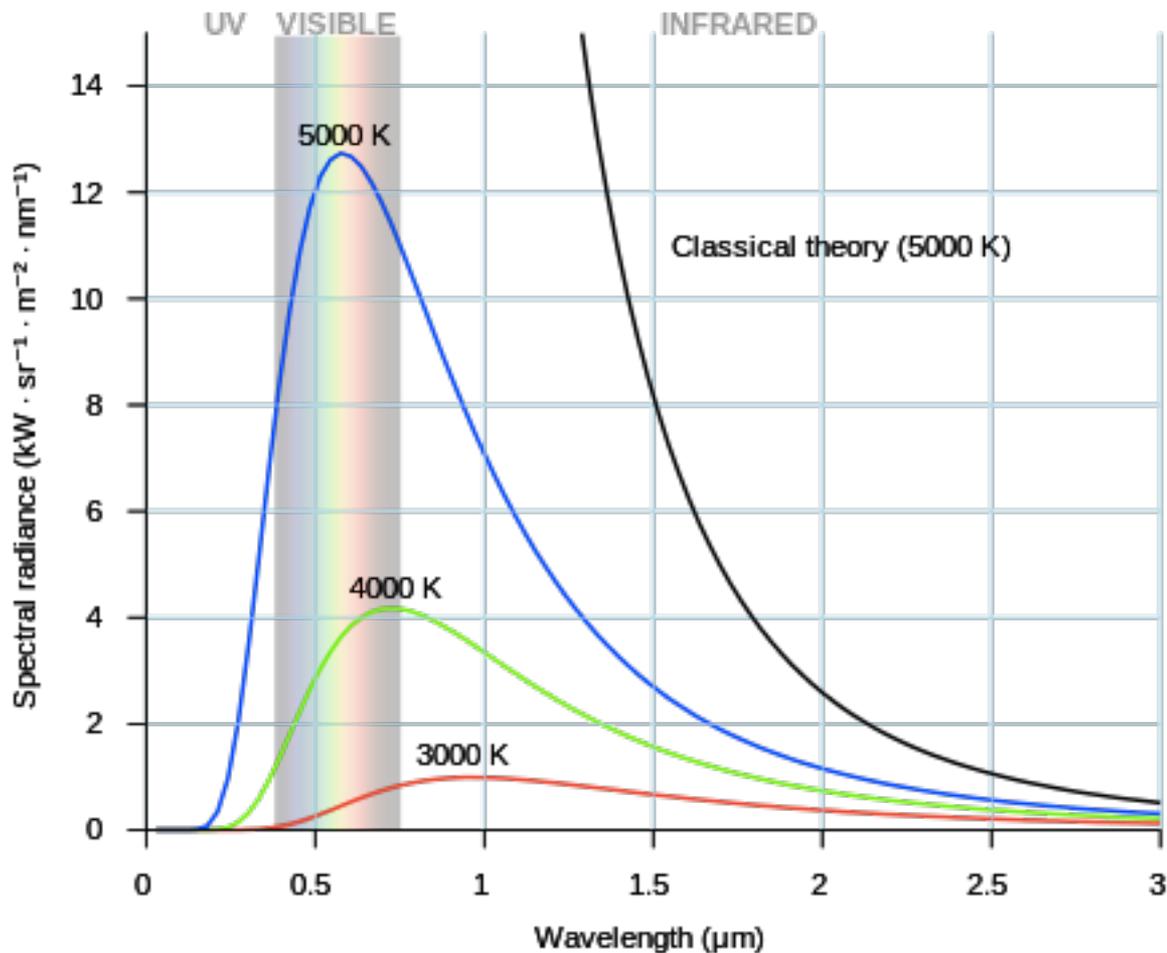
Just magnetic field:  
 $qvB = mv^2/R$   
 $(q/m) = v/(BR) = E/(B^2R)$

# On to Rutherford (1911)

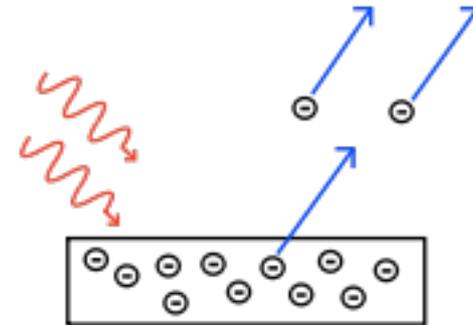
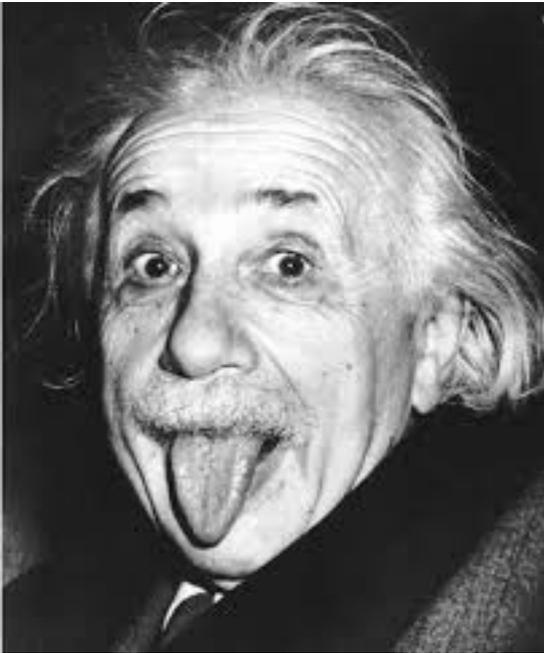


“It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.” - led to the idea that positive charge in atom must be concentrated in a small space

# Skipping to Max Planck

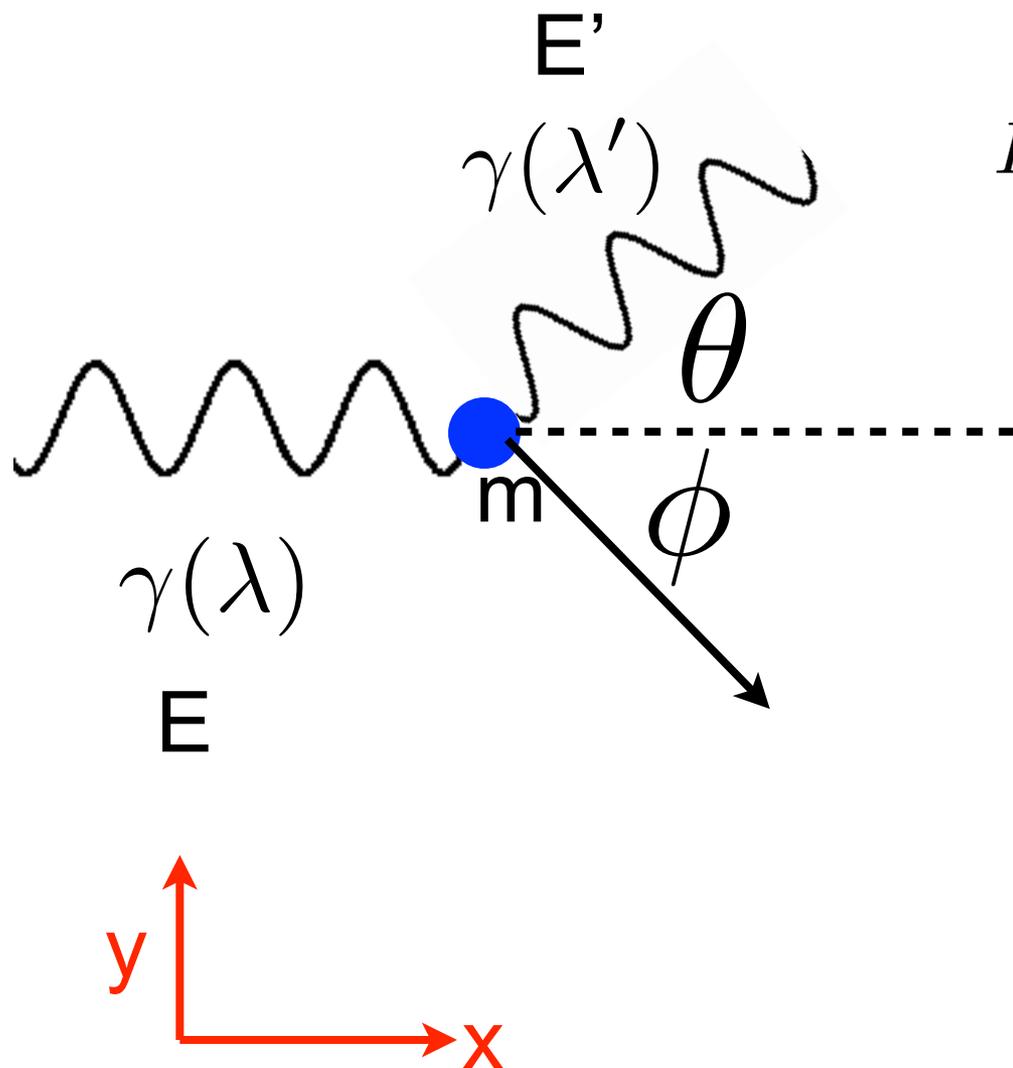


Quantization was “a purely formal assumption and I really did not give it much thought except that no matter what the cost, I must bring about a positive end.” (Turns out that Planck didn’t quite realize what he was doing)



A radical idea! The energy of a photon is quantized, and depends on its frequency (color). Higher intensity light will knock out more electrons, but always of the same energy! Isn't light a wave and not a particle?

# Compton scattering (1923)



Conservation of energy

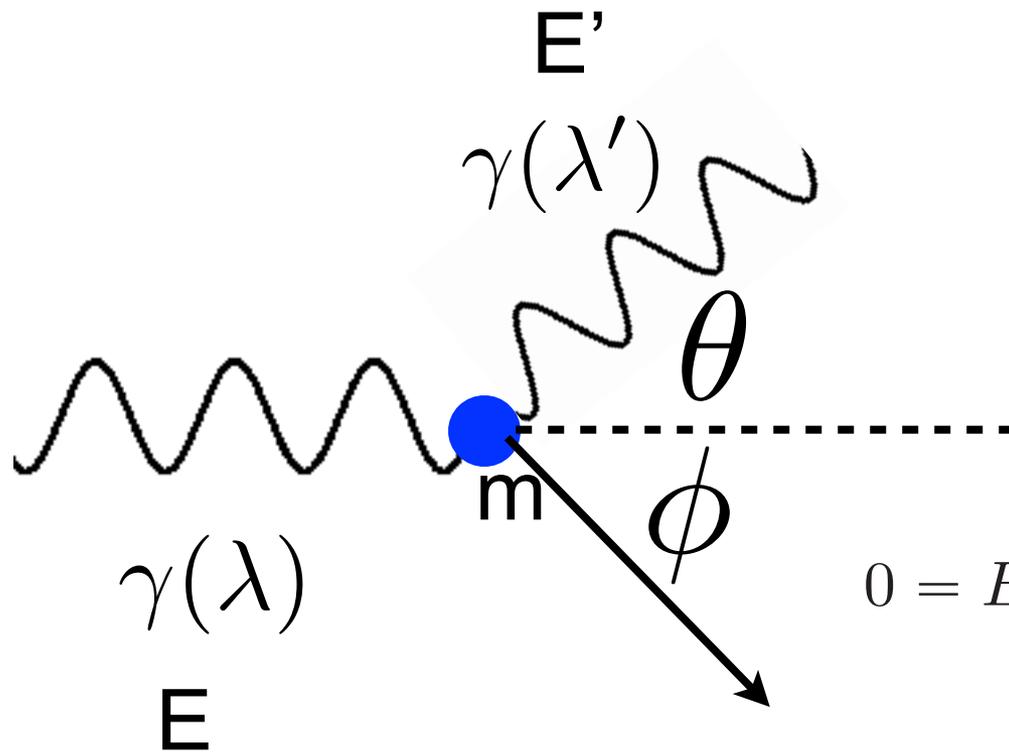
$$E + m = E' + \sqrt{p^2 + m^2}$$

Momentum conservation in x:

$$E = E' \cos \theta + p \cos \phi$$

Momentum conservation in y:

$$0 = E' \sin \theta - p \sin \phi$$



Momentum  
conservation in  $y$ :

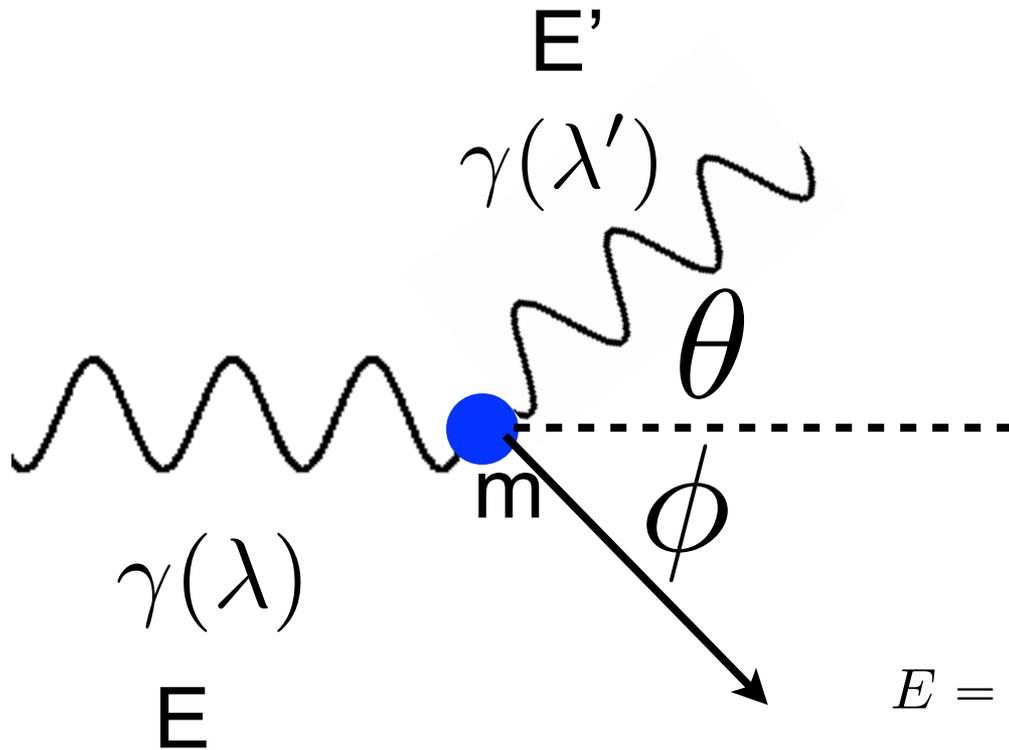
$$0 = E' \sin \theta - p \sin \phi \rightarrow p = \frac{E' \sin \theta}{\sin \phi}$$

$$p^2 \sin^2 \phi = E'^2 \sin^2 \theta$$

$$p^2 (1 - \cos^2 \phi) = E'^2 \sin^2 \theta$$

$$\cos \phi = \sqrt{1 - \frac{E'^2}{p^2} \sin^2 \theta}$$

Momentum  
conservation in x:



$$E = E' \cos \theta + p \cos \phi$$

$$E = E' \cos \theta + p \sqrt{1 - \frac{E'^2}{p^2} \sin^2 \theta}$$

$$(E - E' \cos \theta)^2 = p^2 \left( 1 - \frac{E'^2}{p^2} \sin^2 \theta \right)$$

$$E^2 + E'^2 \cos^2 \theta - 2EE' \cos \theta = p^2 - E'^2 \sin^2 \theta$$

$$p^2 = E^2 + E'^2 - 2EE' \cos \theta$$

## Conservation of energy again

$$E + m = E' + \sqrt{p^2 + m^2}$$

$$(E + m - E') = \sqrt{p^2 + m^2}$$

Plug in  $p^2$

$$(E + m - E')^2 = E^2 + E'^2 - 2EE' \cos \theta + m^2$$

$$E^2 + E'^2 + m^2 + 2mE - 2mE' - 2EE' = E^2 + E'^2 - 2EE' \cos \theta + m^2$$

$$2mE - 2mE' = 2EE'(1 - \cos \theta)$$

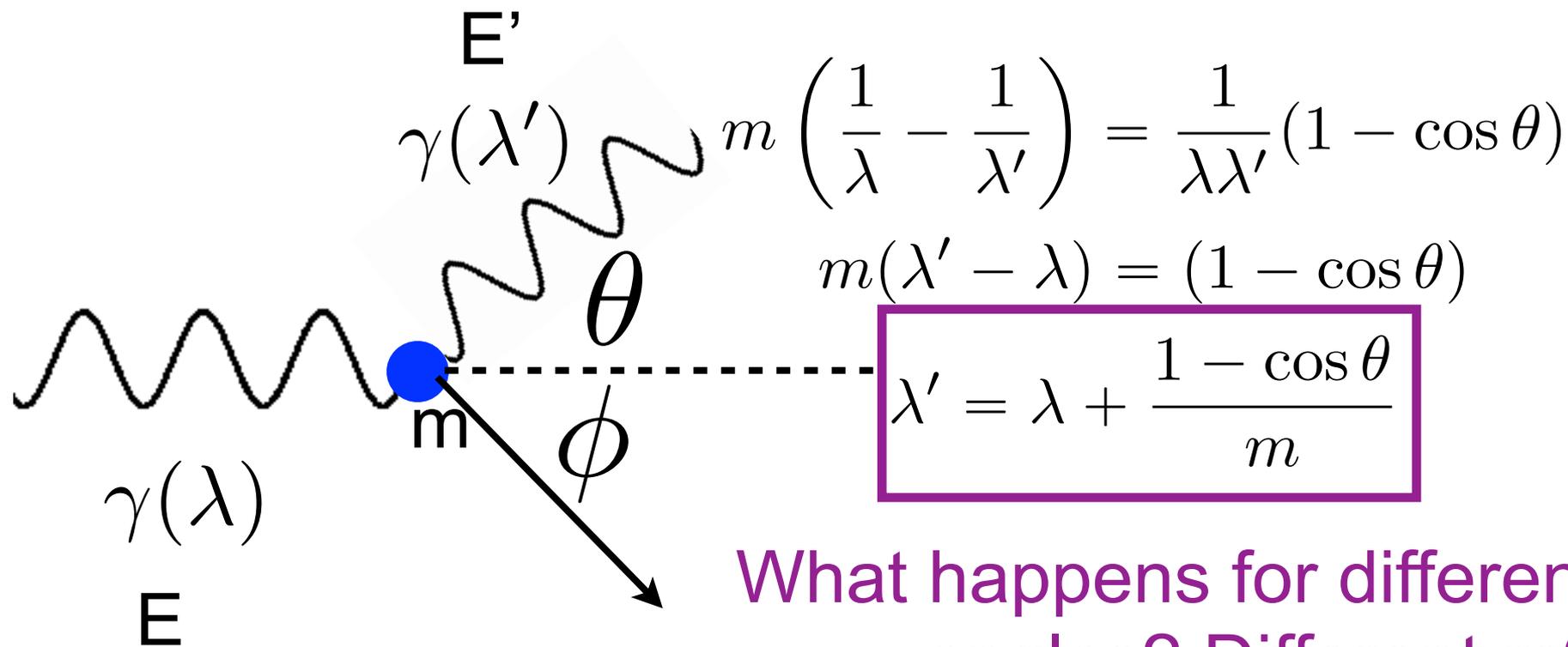
$$m \left( \frac{1}{\lambda} - \frac{1}{\lambda'} \right) = \frac{1}{\lambda \lambda'} (1 - \cos \theta)$$

$$E = \frac{1}{\lambda}$$

$$E' = \frac{1}{\lambda'}$$

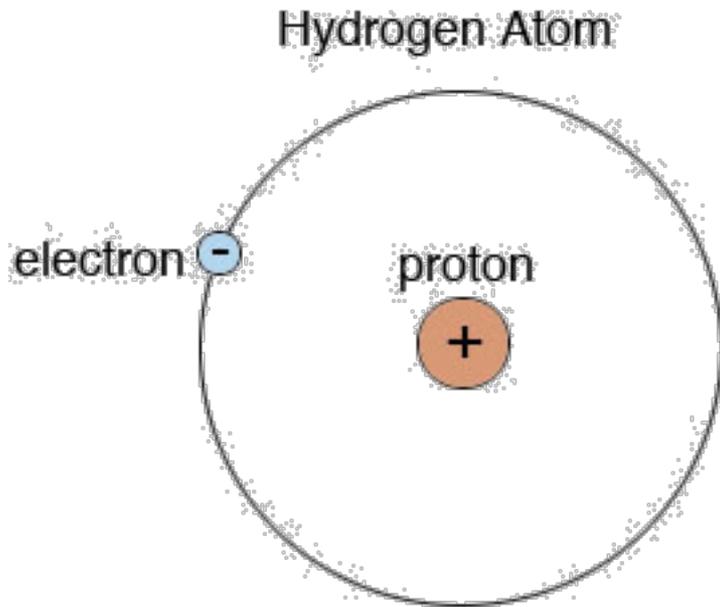
Nice to have these units

## Finishing up

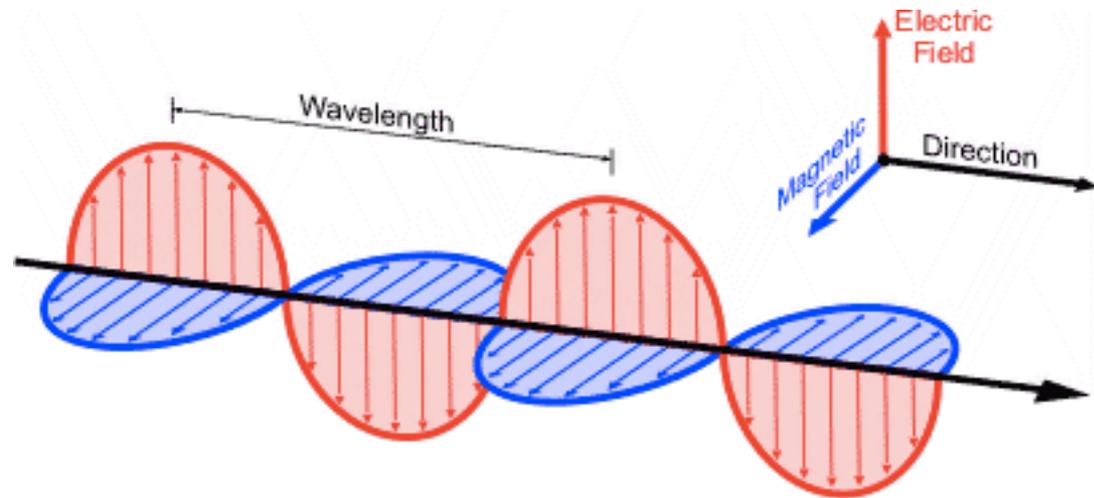


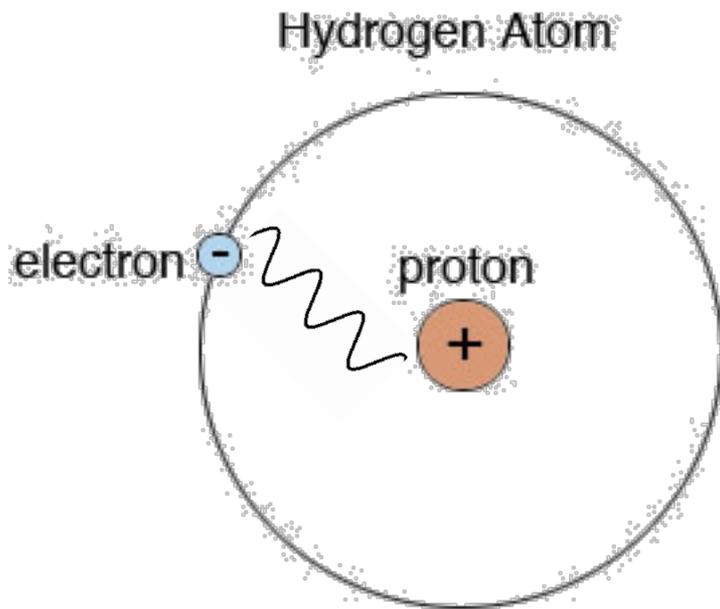
What happens for different angles? Different  $m$ ?

Note that this assumes particles of light, aka photons! No discussion of waves or interference



## Photon as a wave





**Photon** as a particle (classical). But what we really mean is that the field is quantized (here providing an attractive force), and the quantized unit of the field transmits some momentum from one object to another

# Early particle detectors - cloud and bubble chambers

A **cloud chamber** is a collection of supersaturated vapor of alcohol or water. A charge particle can ionize the vapor; the subsequent ions act as seeds for condensation.

Magnetic fields can give the charge and momenta of objects. Need to literally take pictures of the chambers!

**Bubble chamber** is similar, except it uses superheated liquid instead

What's happening?



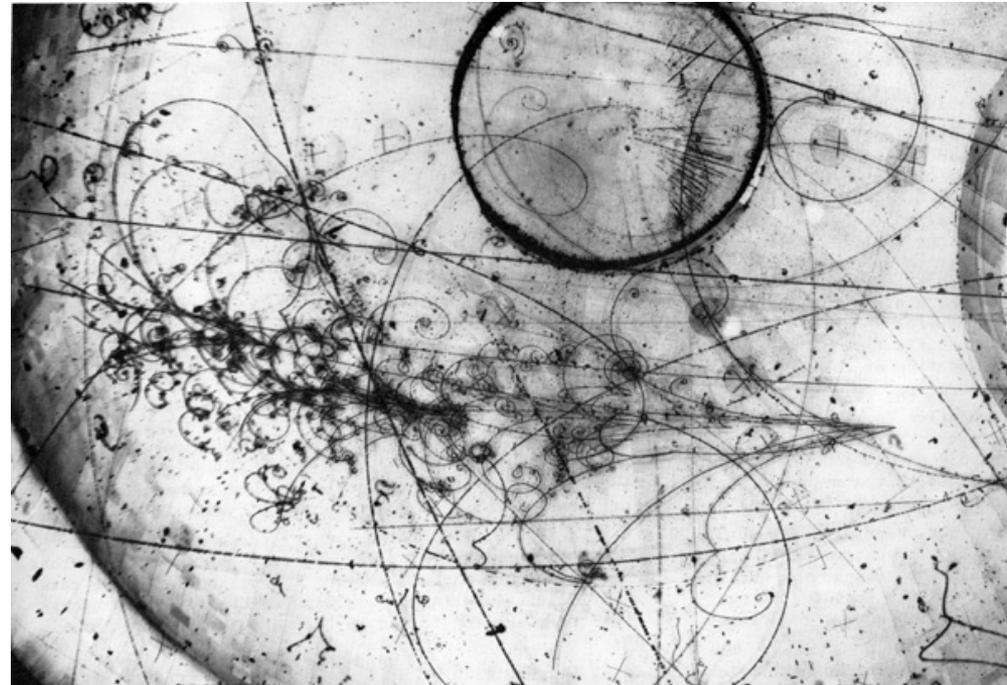
# Early particle detectors - cloud and bubble chambers

Glaser invented the bubble chamber (and won a Nobel prize for it).

“Legend has it that while he was on the faculty of the University of Michigan, Glaser was chilling with colleagues over a cold beer, observed the stream of bubbles in his glass, and was inspired to build a device that could track subatomic particles with bubbles. Glaser himself later refuted this story; beer was not his inspiration, although he did use it as a liquid in early prototypes.”

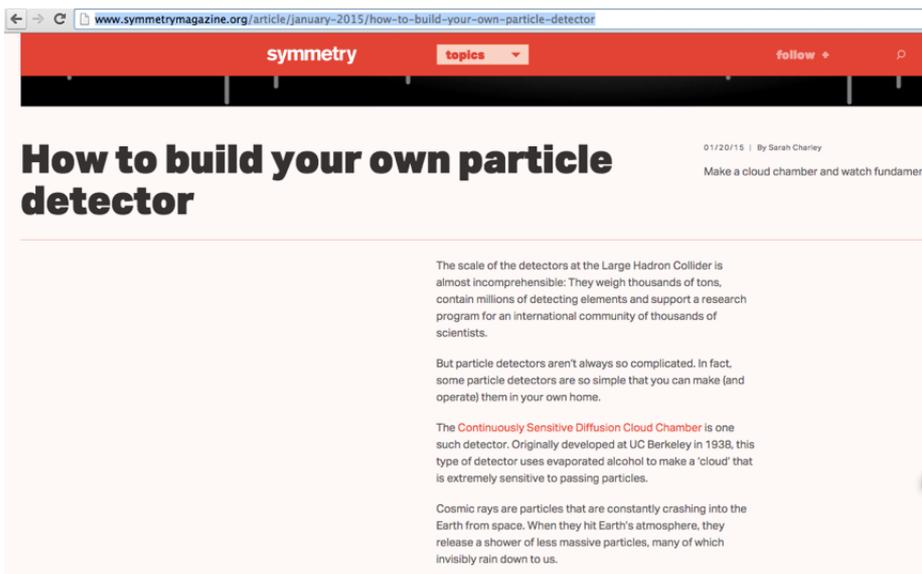
<http://www.aps.org/publications/apsnews/201001/physicshistory.cfm>

## FNAL bubble chamber photo



What's going on here?

<http://www.symmetrymagazine.org/article/january-2015/how-to-build-your-own-particle-detector>



If anyone knows any enterprising undergrads looking for work, we tried building one 2 years ago, but didn't really spend the time or effort. This would be a lot of fun



Strong meson (intermediate mass) must be the nuclear force carrier with mass  $\sim 150$  MeV. See Griffiths HW 1.2 for why this was only a vague estimate - any ideas how he got it (if you haven't read the textbook?)

# 1946 mesons

There are two such mesons observed in cosmic rays:

$$\pi, \mu$$

VERY different interactions with atomic nuclei (why feels the strong nuclear force, the other does not)

From Griffiths

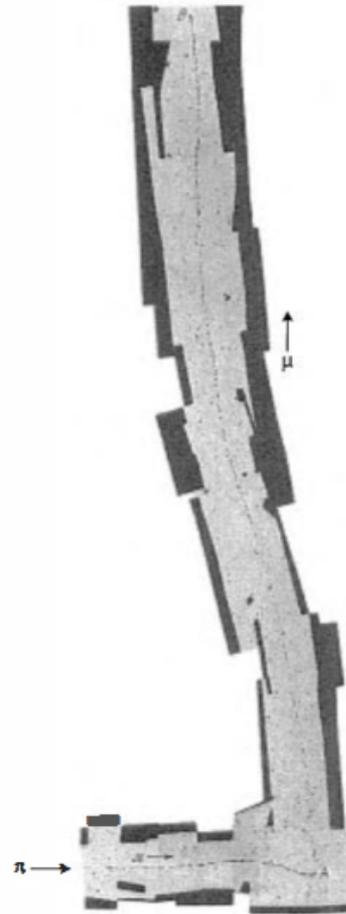


Fig. 1.3 One of Powell's earliest pictures showing the track of a pion in a photographic emulsion exposed to cosmic rays at high altitude. The pion (entering from the left) decays into a muon and a neutrino (the latter is electrically neutral, and leaves no

track). (Source: Powell, C. F., Fowler, P. H. and Perkins, D. H. (1959) *The Study of Elementary Particles by the Photographic Method* Pergamon, New York. First published in (1947) *Nature* 159, 694.)

# 1931 Anderson discovers antiparticles

## From Griffiths

Hypothesized  
by Dirac  
(we'll see  
why in a few  
chapters)

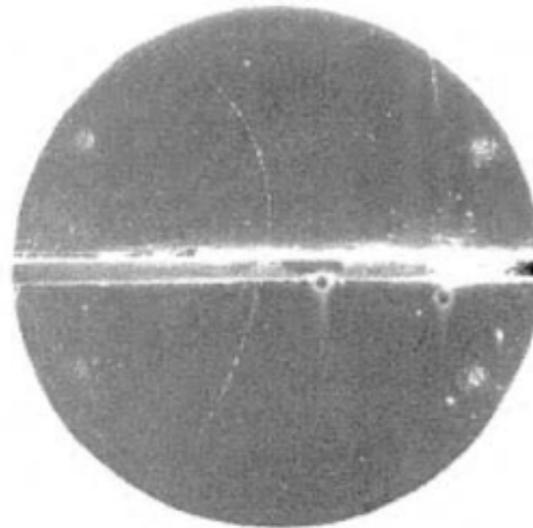
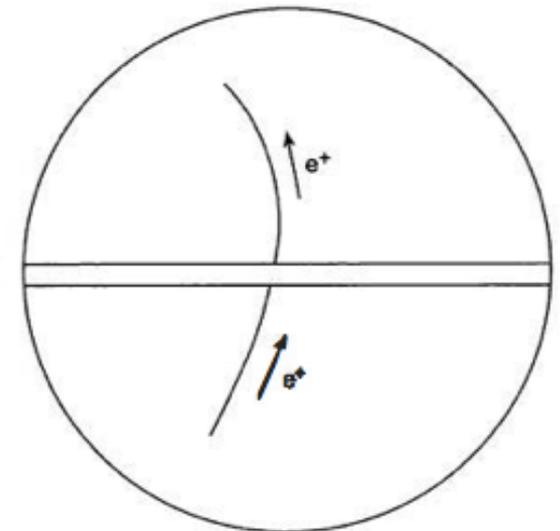


Fig. 1.4 The positron. In 1932, Anderson took this photograph of the track left in a cloud chamber by a cosmic ray particle. The chamber was placed in a magnetic field (pointing into the page), which caused the particle to travel in a curve. But was it a negative charge traveling downward or a positive charge traveling upward? In order to distinguish, Anderson had placed a lead plate across the center of the chamber (the thick horizontal line in the photograph). A



particle passing through the plate slows down, and subsequently moves in a tighter circle. By inspection of the curves, it is clear that this particle traveled upward, and hence must have been positively charged. From the curvature of the track and from its texture, Anderson was able to show that the mass of the particle was close to that of the electron. (Photo courtesy California Institute of Technology.)

Protons vs  
anti-proton

$$p = (uud)$$

$$\bar{p} = (\bar{u}\bar{u}\bar{d})$$

Neutron vs anti-  
neutron (note:  
neutron has no net  
electric charge!)

$$n = (udd)$$

$$\bar{n} = (\bar{u}\bar{d}\bar{d})$$

$$e^+ \text{ vs } e^-$$

$$\gamma = \bar{\gamma}$$

# Crossing symmetry

$A + B \rightarrow C + D \rightarrow$  If this then  
also...

$$A \rightarrow \bar{B} + C + D$$

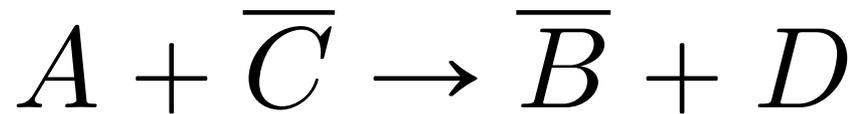
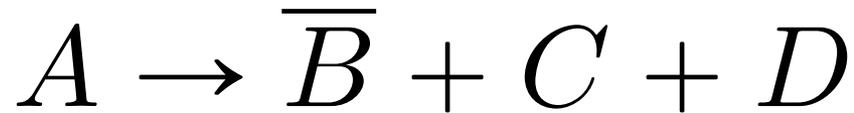
$$A + \bar{C} \rightarrow \bar{B} + D$$

$\gamma + e^- \rightarrow \gamma + e^-$  Implies

$$e^+ + e^- \rightarrow \gamma + \gamma$$

$$\gamma + \gamma \rightarrow e^+ + e^-$$

$A + B \rightarrow C + D \rightarrow$  If this then  
also...

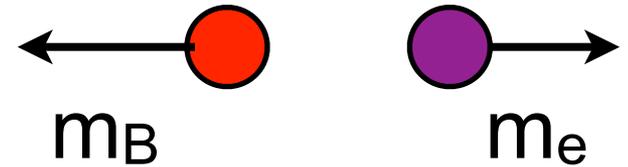


All that it tells us is whether there are any symmetry rules or conservation laws forbidding such a reaction (ie whether the **dynamics** are possible). Says nothing about the **kinematics**

$$A \rightarrow B + e^{-}$$

$$n \rightarrow p + e^{-}$$

What is the energy of the electron in this decay?



Initially, in center  
of mass frame, everything  
is at rest,  $p = 0$

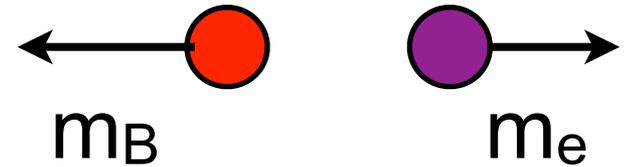
After decay

$$E = m_A$$

$$p = 0$$

$$E = \sqrt{m_B^2 + p_B^2} + \sqrt{m_e^2 + p_e^2}$$

Conservation of momentum:  $p_B = p_e = p$



Initially, in center  
of mass frame, everything  
is at rest,  $p = 0$

After decay

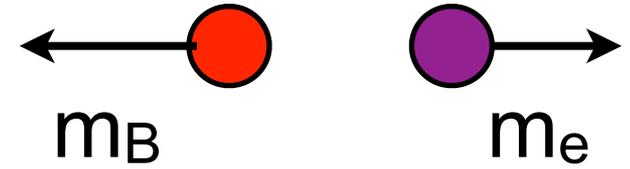
$$E = \sqrt{m_B^2 + p^2} + \sqrt{m_e^2 + p^2} = m_A$$

$$m_B^2 + p^2 + m_e^2 + p^2 + 2\sqrt{(m_B^2 + p^2)(m_e^2 + p^2)} = m_A^2$$

$$2\sqrt{(m_B^2 + p^2)(m_e^2 + p^2)} = m_A^2 - m_B^2 - m_e^2 - 2p^2$$

$$4(m_B^2 + p^2)(m_e^2 + p^2) =$$

$$m_A^4 + m_B^4 + m_e^4 + 4p^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 + 2m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2$$



Initially, in center  
of mass frame, everything  
is at rest,  $p = 0$

After decay

$$4m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2 + 4p^4 =$$

$$m_A^4 + m_B^4 + m_e^4 + 4p^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 + 2m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2$$

$$m_A^4 + m_B^4 + m_e^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 - 2m_B^2 m_e^2 = 0$$

$$p^2 = \frac{1}{4} (m_A^2 + (m_B^4 + m_e^4 - 2m_B^2 m_e^2)/m_A^2 - 2m_B^2 - 2m_e^2)$$

Energy of electron is completely specified, but we observe a range of energies in neutron decay! Must be missing some object: neutrinos!

$$\begin{aligned}
 & 4m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2 + 4p^4 = \\
 m_A^4 + m_B^4 + m_e^4 + 4p^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 + 2m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2 \\
 & m_A^4 + m_B^4 + m_e^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 - 2m_B^2 m_e^2 = 0 \\
 & p^2 = \frac{1}{4} (m_A^2 + (m_B^4 + m_e^4 - 2m_B^2 m_e^2)/m_A^2 - 2m_B^2 - 2m_e^2)
 \end{aligned}$$

Energy of electron is completely specified, but we observe a range of energies in neutron decay! Must be missing some object: neutrinos!

From  
Griffiths

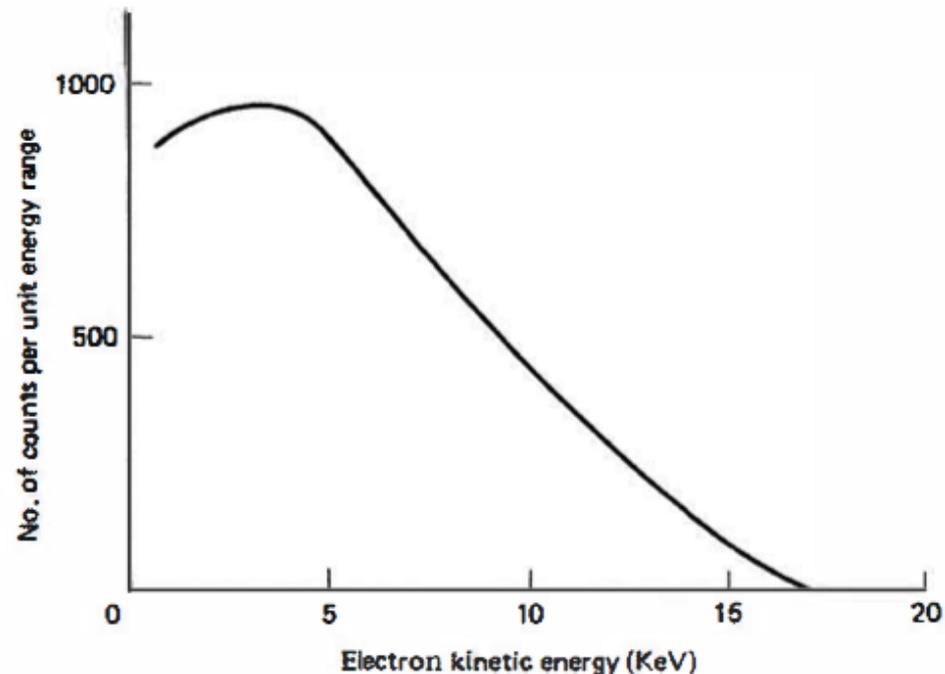


Fig. 1.5 The beta decay spectrum of tritium ( ${}^3_1\text{H} \rightarrow {}^3_2\text{He}$ ).  
(Source: Lewis, C. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

“Little neutral one” to distinguish from the neutron. Physicists really cling to the idea of conservation of energy

From  
Griffiths

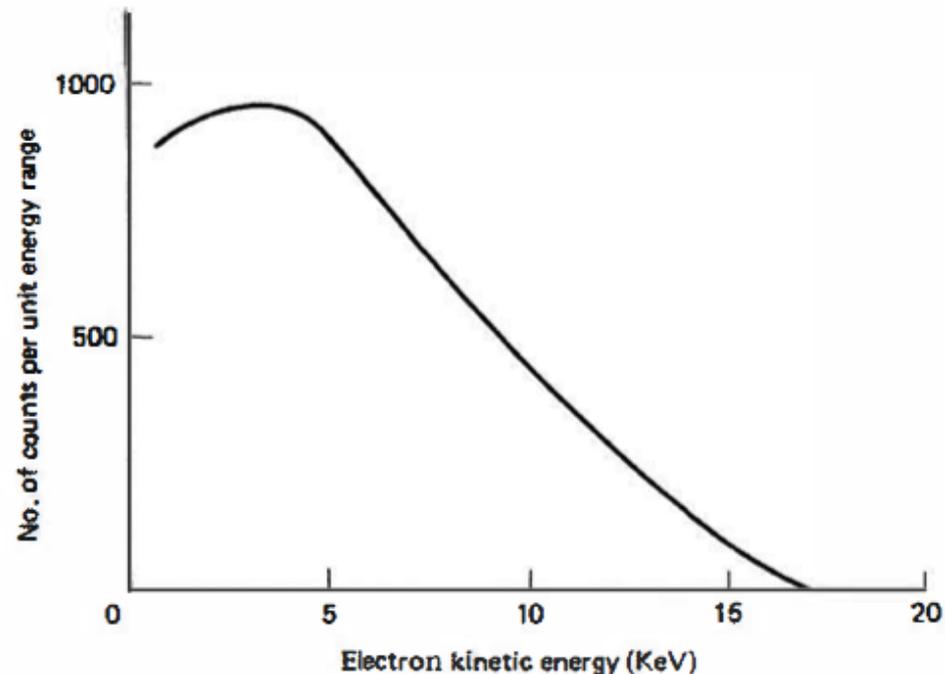
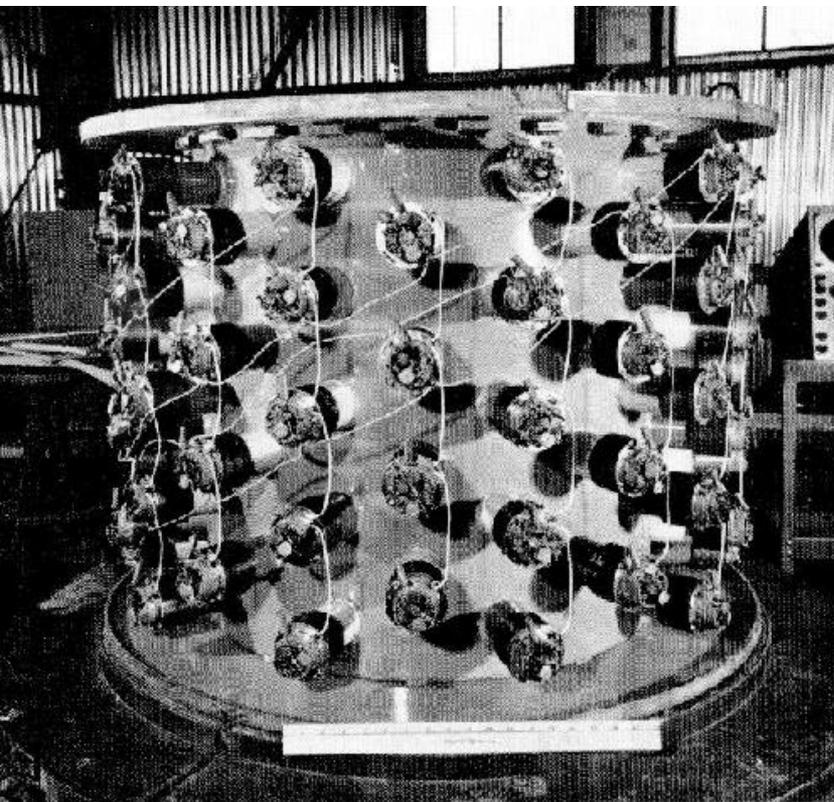
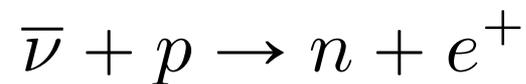


Fig. 1.5 The beta decay spectrum of tritium ( ${}^3_1\text{H} \rightarrow {}^3_2\text{He}$ ).  
(Source: Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)



Large tank of water  
mixed with cadmium  
chloride near a nuclear  
reactor to look for



What about the neutron?  
It gets captured by  
cadmium, which then  
emits pairs of photons  
shortly thereafter

# Tests with anti-neutrinos?

$$n + \nu \rightarrow p + e^{-}$$

$$n + \bar{\nu} \nrightarrow p + e^{-}$$

$$\gamma + \gamma \nrightarrow \mu^{+} + e^{-}$$

$$\mu^{-} \nrightarrow e^{-} + \gamma$$

Be careful  
about what is  
+1 and what  
is -1!

Why not? Well, neutrinos and anti-neutrinos are not the same thing. But also... this violates a conservation law known as conservation of electron number.

Electrons and electron neutrinos carry electron number = +1, and anti-electrons and anti-electron neutrinos = -1

Define in the same way a  
“muon number”. Muons  
and muon neutrinos carry  
muon number = +1, and  
anti-muons and anti-  
muon neutrinos = -1

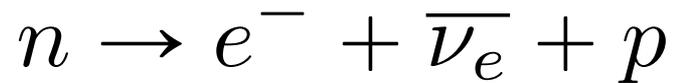
And yet the same thing for  
taus (which we haven't  
seen quite yet but we will  
soon)

## Checks to make sure your neutrinos are in the right place

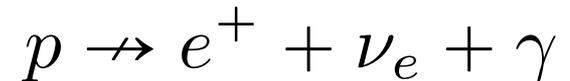
	Before		After	
	e	mu	e	mu
$\bar{\nu}_e + p \rightarrow n + e^+$	-1	0	-1	0
$\pi^+ \rightarrow \mu^+ + \nu_\mu$	0	0	0	1-1=0
$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$	0	0	0	1-1=0
$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$	0	1	1-1=0	1
$n \rightarrow p + e^- + \bar{\nu}_e$	0	0	1-1=0	0

# Conservation of baryon number

## Neutron decay



## No proton decay



Proton decay is not observed! Why not?

Propose conservation of baryon number

$B = +1$  for neutrons and protons,  $-1$  for anti-neutrons and anti-protons

Proton is lightest baryon, so it cannot decay (well, not in the Standard Model!)

No “conservation of meson” number

## From Griffiths

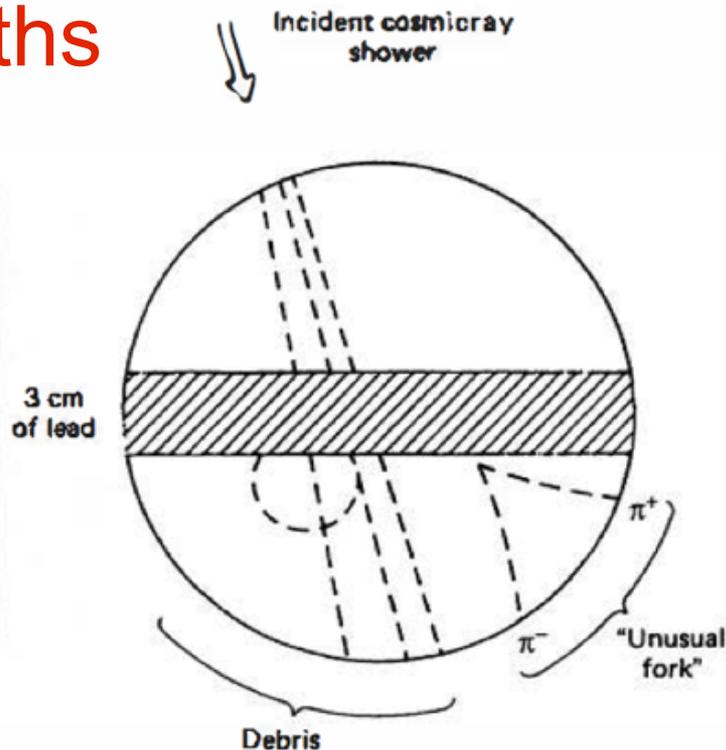
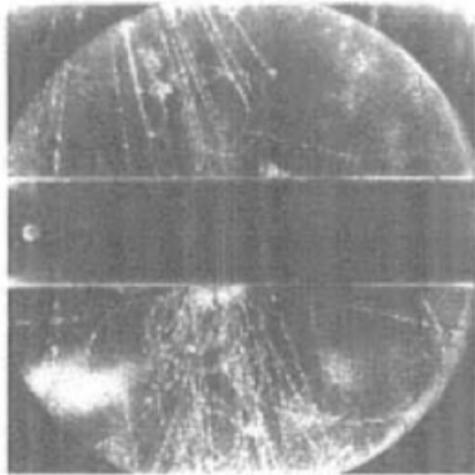
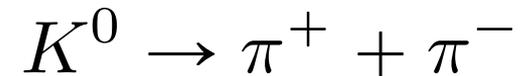


Fig. 1.7 The first strange particle. Cosmic rays strike a lead plate, producing a  $K^0$ , which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. Rochester, G. D. (© 1947). *Nature*, 160, 855. Copyright Macmillan Journals Limited.)

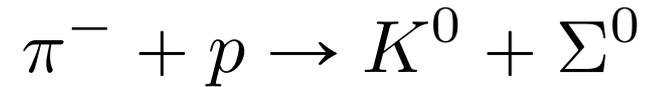
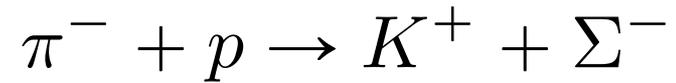


What is this neutral kaon? Can produce them in accelerators, but they decay 13 orders of magnitude slower than expected! Strange...

# How to account for these strange particles?

What if kaons are produced by the strong force, but decay typically via the weak force?

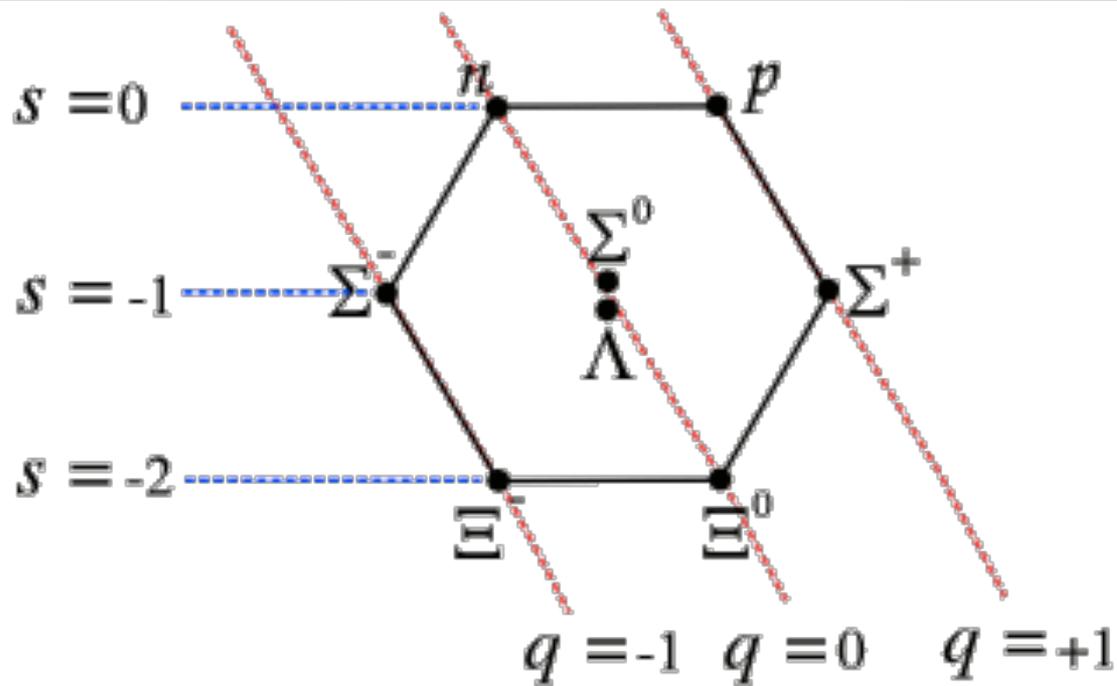
Strangeness is conserved in strong interactions but not in weak interactions



Initially, have zero strangeness. Assign  $S=+1$  to  $K^{+}$  and  $K^{0}$  and  $S=-1$  to  $\Lambda$  and  $\Sigma$ ,  $S$  remains 0. What does this say about how the above are produced?

Note: strangeness not conserved in the decay.

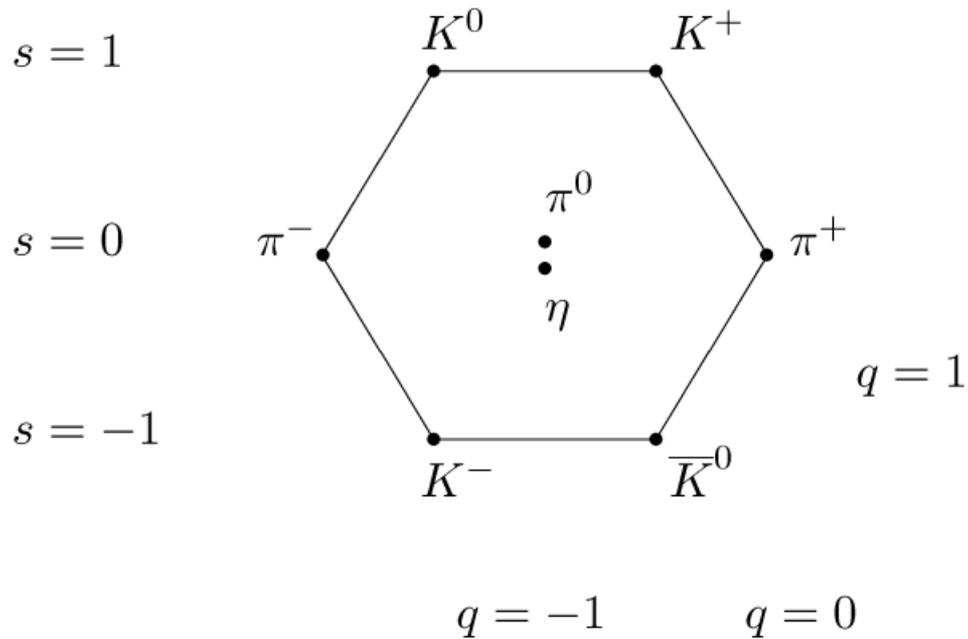
And how to start organizing all of this?



Murray Gell-Mann proposed his “Eightfold way” (apparently a slight reference to the Noble Eightfold path of Buddhism)



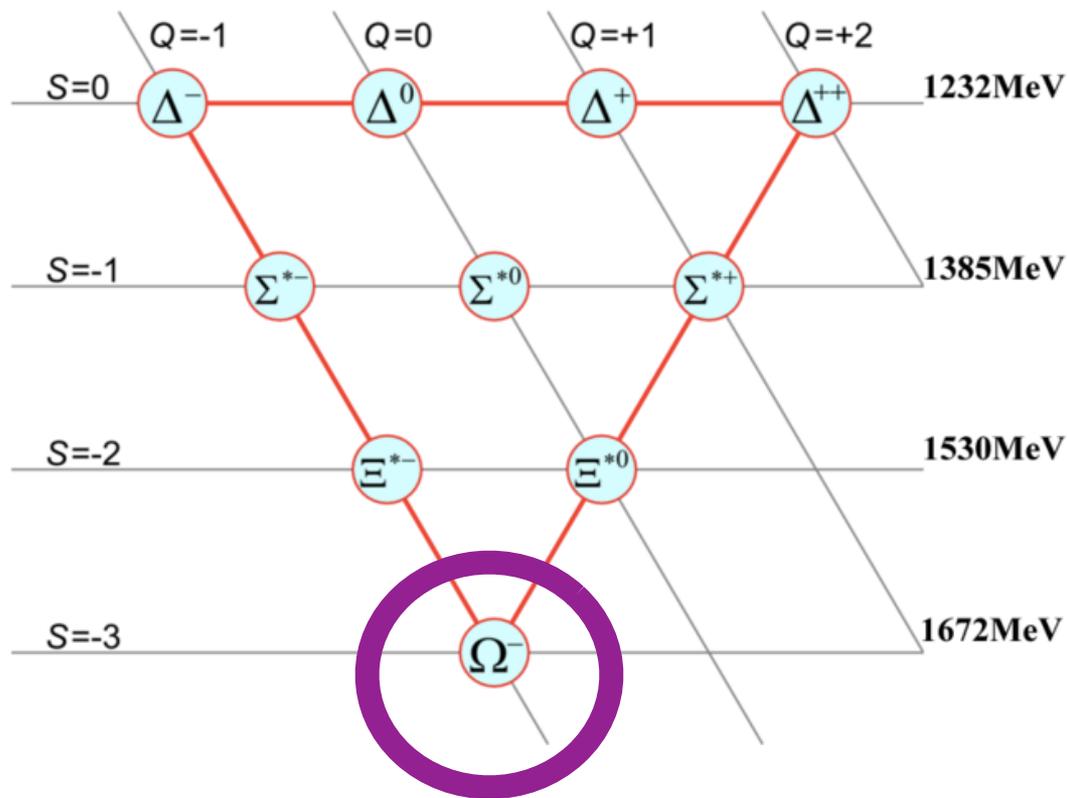
# Moving from baryons to mesons



Similar periodic structure  
(remind you of anything)?



# How was this verified?



This was predicted (including its mass and lifetime!)



The particle ... zoo  
was becoming a big  
mess to keep track  
of

Wolfgang Pauli: "Had I  
foreseen that, I would  
have gone into botany"



## We've skipped over some of the fun history

The particle ... zoo was becoming a big mess to keep track of (for some reason, physicists don't like botanists, apparently)

Fermi to Lederman:  
“Young man, if I could remember the names of these particles, I would have been a botanist”



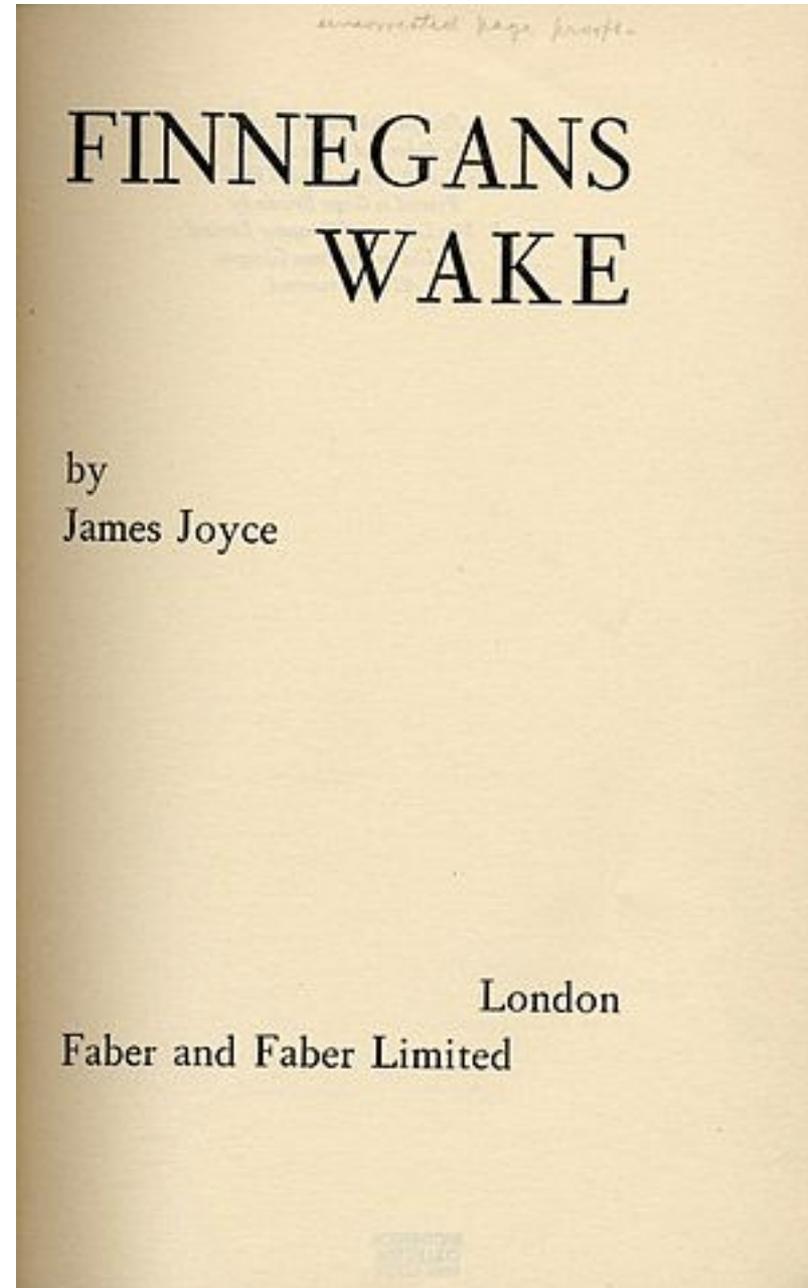
# The quark model (Gell-Man and Zweig)

Three quarks for Muster Mark!  
 Sure he has not got much of a bark  
 And sure any he has it's all beside  
 the mark.

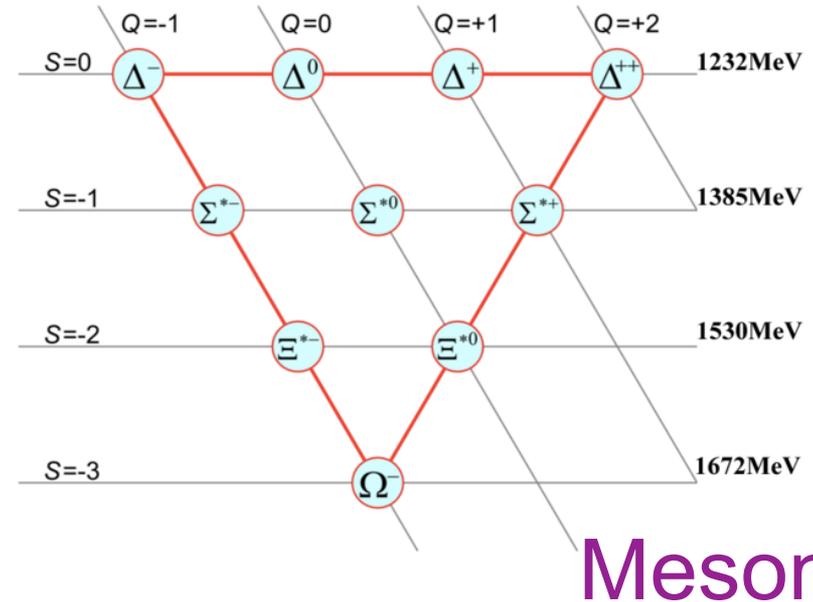
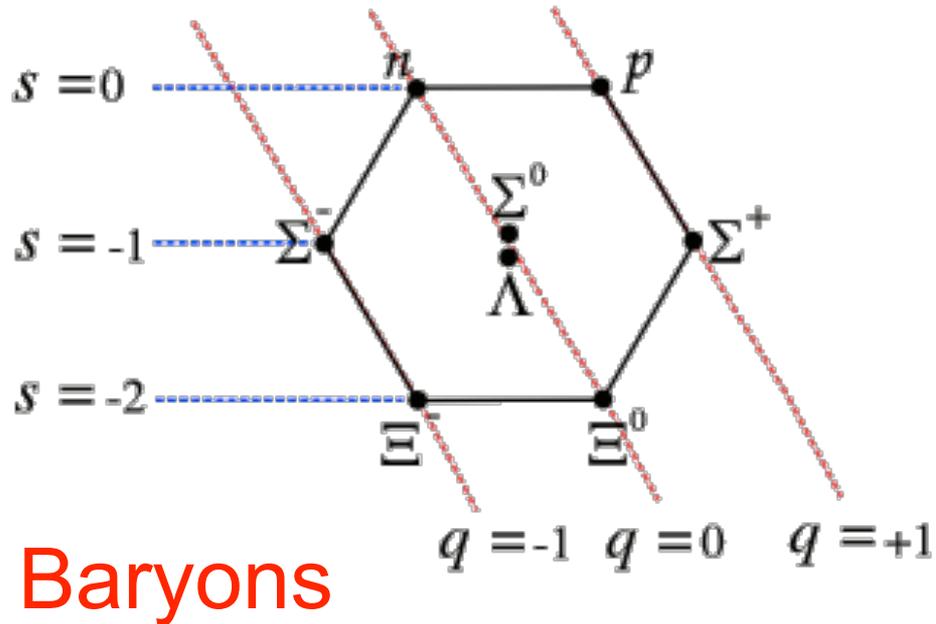
—James Joyce, *Finnegans Wake*

Quark and not  
 kwork!

Wikipedia: *Finnegans Wake* is a novel by Irish writer James Joyce. It is significant for its experimental style and reputation as one of the most difficult works of fiction in the English language.



## Hadrons



All hadrons (baryons and mesons) are made themselves of smaller pieces called quarks

# The quark model (so far)

	Charge (units of e)	Strangeness
u	+2/3	0
d	-1/3	0
s	-1/3	1
ubar	-2/3	0
dbar	+1/3	0
sbar	+1/3	-1

Mesons = one quark and one anti-quark

Baryons = three quarks

Anti-baryons = three anti-quarks

# Example of the baryon decuplet

	Q	S	Baryon	B number
uuu	2	0	$\Delta^{++}$	1
uud	1	0	$\Delta^+$	1
udd	0	0	$\Delta^0$	1
ddd	-1	0	$\Delta^-$	1
uus	1	-1	$\Sigma^{*+}$	1
uds	0	-1	$\Sigma^{*0}$	1
dds	-1	-1	$\Sigma^{*-}$	1
uss	0	-2	$\Xi^{*0}$	1
dss	-1	-2	$\Xi^{*-}$	1
sss	-1	-3	$\Omega^-$	1

Note that this fills in nicely and makes predictions, but we have yet to account for different energy levels and spin



Quarks are **confined** to hadrons, and cannot be observed as bare objects. In other words, they are social beasts, and don't like to exist on their own. We'll discuss them more later on

# What about Pauli exclusion principle?

sss hadron ( $\Omega^-$ )  
 should violate Pauli  
 exclusion principle  
 (multiple times!)  
 There needs to be  
 some fundamental  
 difference between  
 the quarks for this to  
 be allowed: QCD  
 color charge (beware  
 comparisons to real  
 "color")

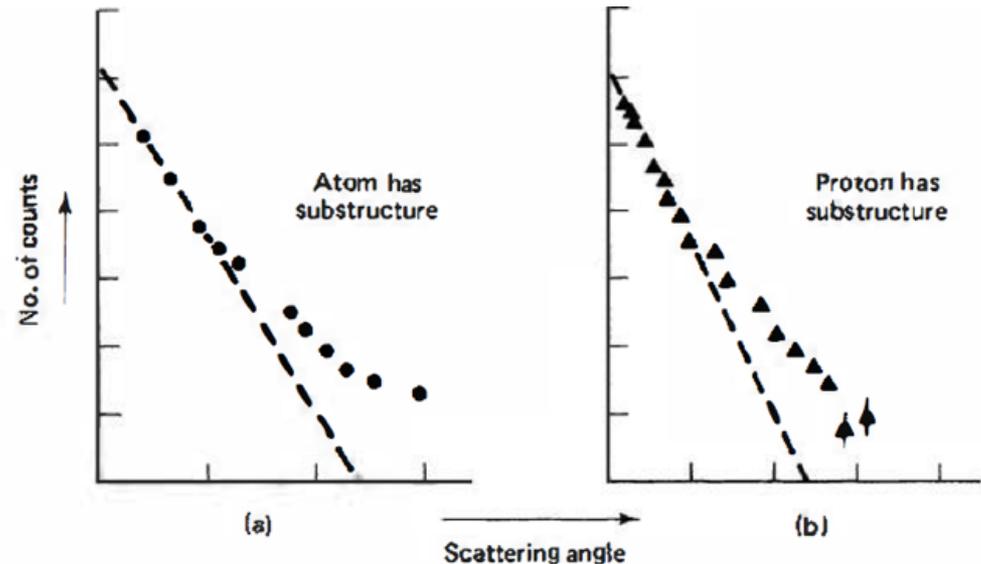


Fig. 1.11 (a) In Rutherford scattering, the number of particles deflected through large angles indicates that the atom has internal structure (a nucleus). (b) In deep inelastic scattering, the number of particles deflected through large angles indicates that the proton has internal structure (quarks). The dashed lines show what you would expect

if the positive charge were uniformly distributed over the volume of (a) the atom, (b) the proton. (Source: Halzen, F. and Martin, A. D. (1984) *Quarks and Leptons*, John Wiley & Sons, New York, p. 17. Copyright © John Wiley & Sons, Inc. Reprinted by permission.)

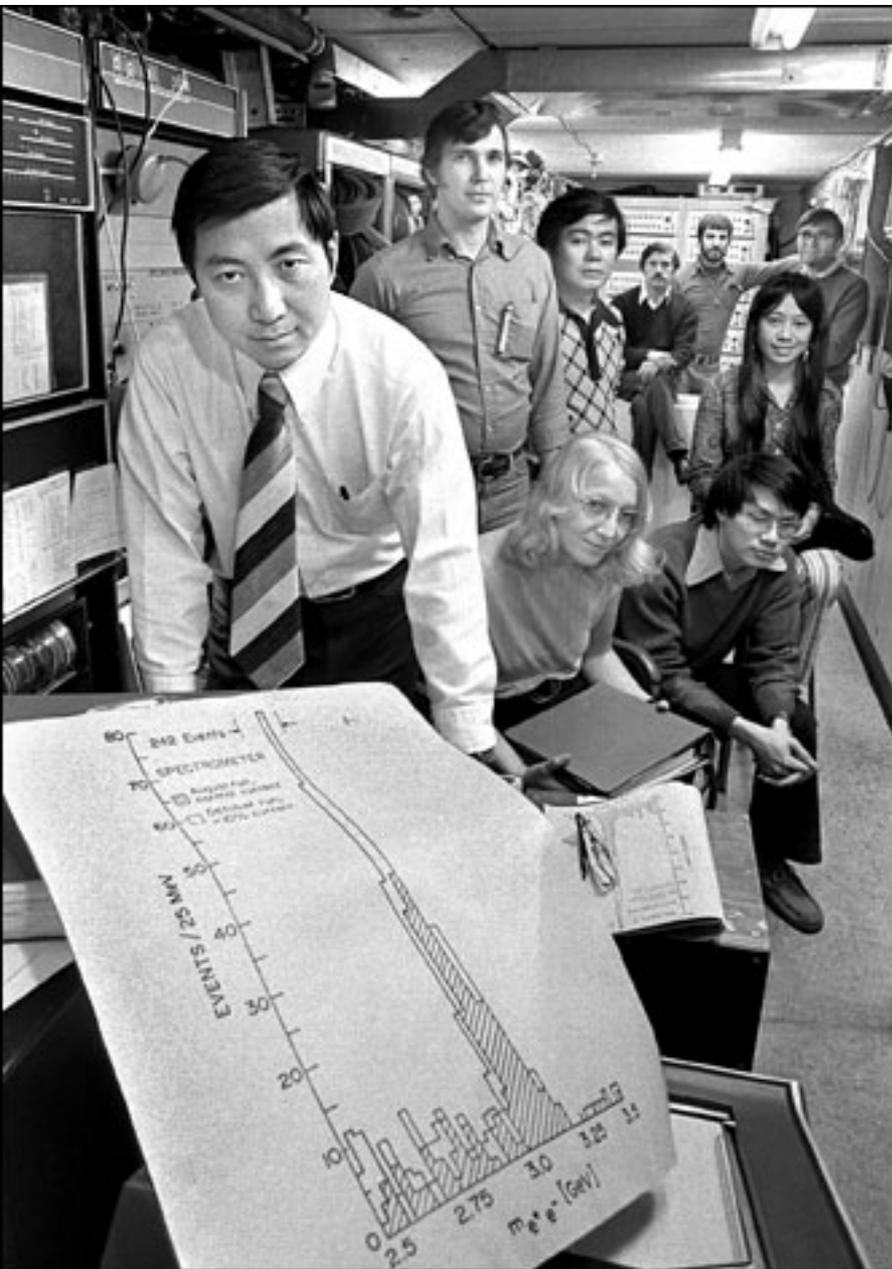
Colorless objects only:  
 Explains why we don't  
 have qq (or q) final states

November 1974,  $\psi$  meson discovered at SLAC, J meson at Brookhaven. Hence the name  $J/\psi$ , a new, electrically neutral particle with a long lifetime. Began the “November revolution”



**¡Viva la Revolución!**

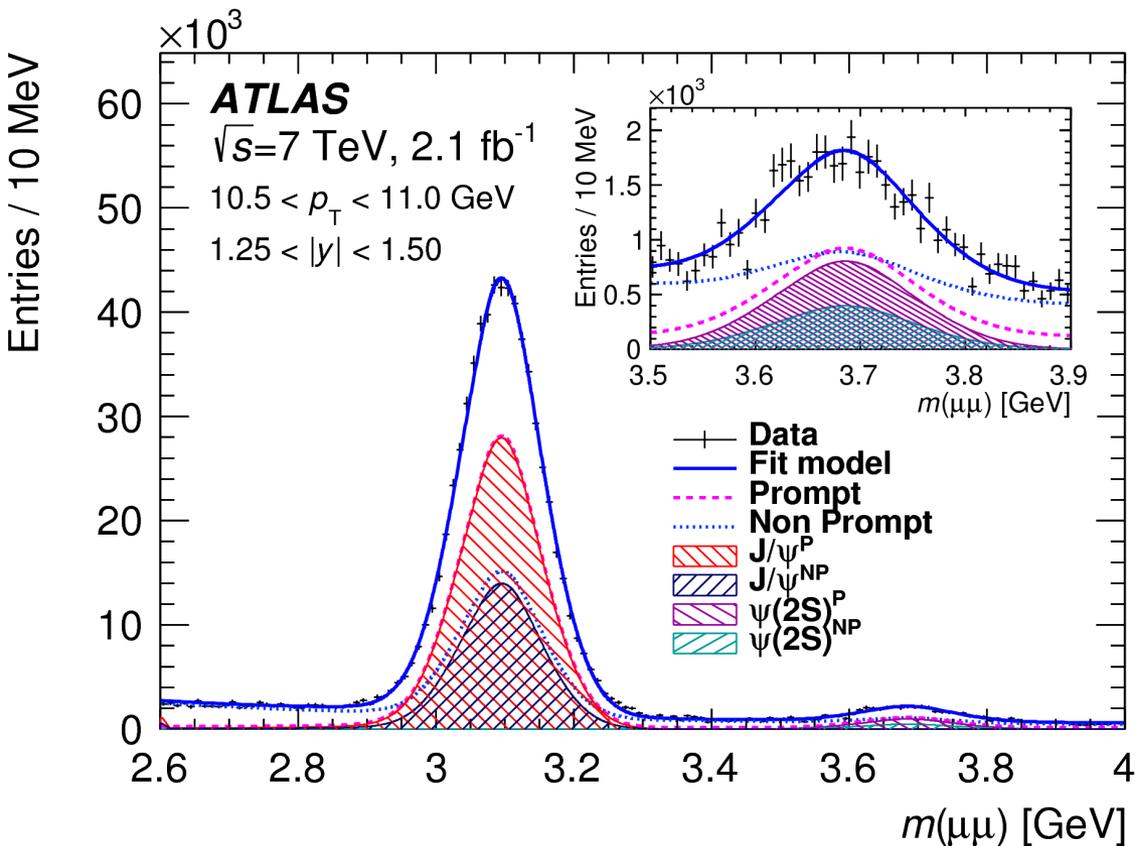
## How was it discovered?



[https://www.bnl.gov/bnlweb/history/nobel/nobel\\_76.asp](https://www.bnl.gov/bnlweb/history/nobel/nobel_76.asp)

Sam Ting and his team, showing a plot of mass of  $e^+e^-$  pairs. As we will see shortly, the mass of objects is an invariant even after decay, so we see a bump at 3.1 GeV =  $J\psi$  mass

And these days



We know that  
 the  $J\psi$  is a  
 charm-  
 anticharm  
 bound state  
 with spin = 1

This is a tiny fraction of the  
 data available to ATLAS

arXiv: 1612.02950

# Add in the third generation

**Table I.** From Perl (1975). A table of 2-charged-particle events collected at 4.8 GeV in the Mark I detector. The table, containing 24  $e\mu$  events with zero total charge and no photons, was the strongest evidence at that time for the  $\tau$ . The caption read:

“Distribution of 513, 4.8 GeV, 2-prong, events which meet the criteria:  
 $p_e > 0.65 \text{ GeV}/c$ ,  $p_\mu > 0.65 \text{ GeV}/c$ ,  $\theta_{\text{copl}} > 20^\circ$ .”

Number photons =	Total Charge = 0			Total Charge = $\pm 2$		
	0	1	> 1	0	1	> 1
$cc$	40	111	55	0	1	0
$e\mu$	24	8	8	0	0	3
$\mu\mu$	16	15	6	0	0	0
$eh$	18	23	32	2	3	3
$\mu h$	15	16	31	4	0	5
$hh$	13	11	30	10	4	6
Sum	126	184	162	16	8	17

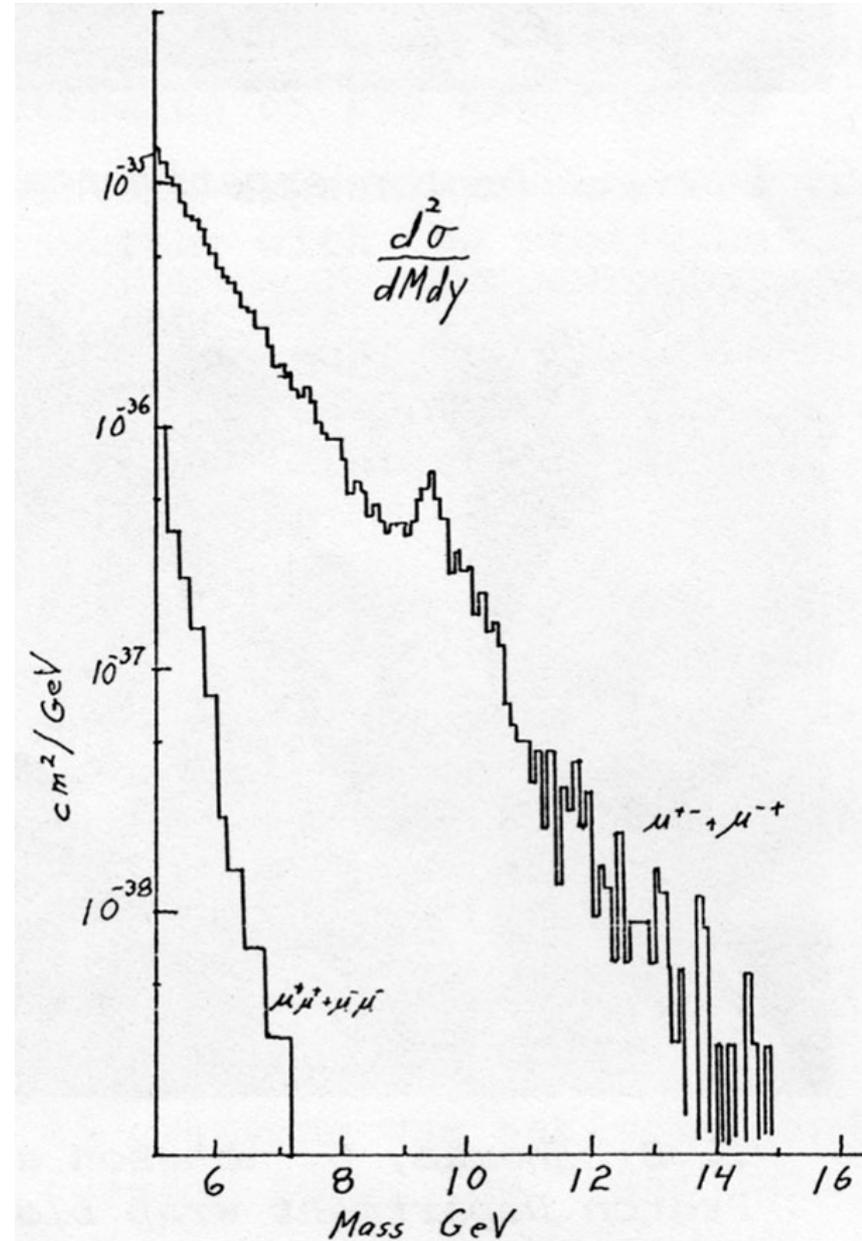


Martin Perl (1975) discovery of tau lepton (tau neutrino not until 2000!)

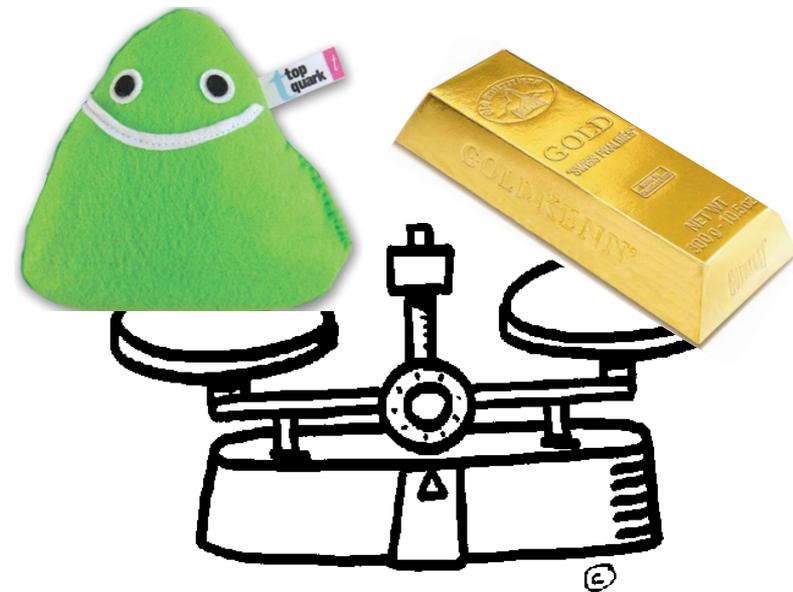
# Add in the third generation

Lederman and E288  
collaborators - discovery of  
the bottom quark at nearby  
Fermilab:

$$\Upsilon = b\bar{b}$$



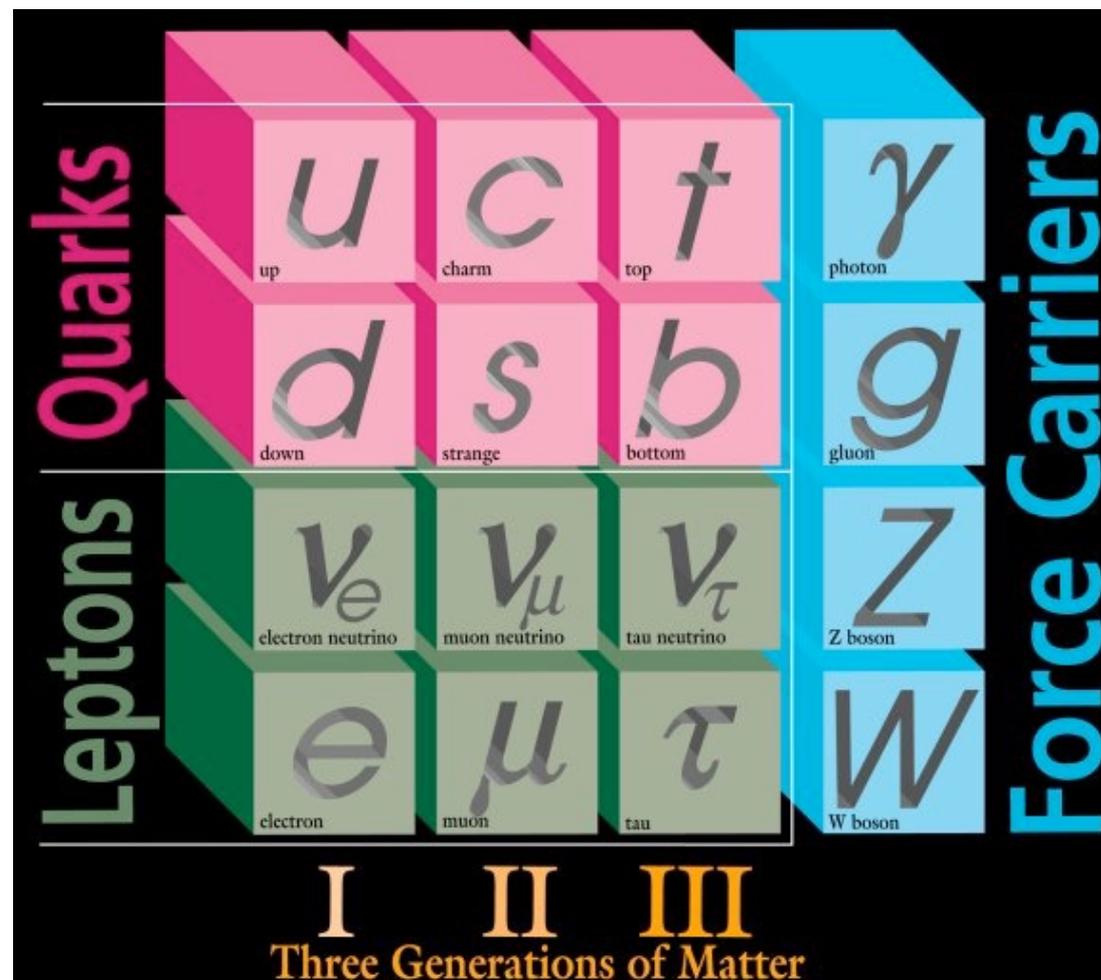
Announced jointly  
1994-1995 by DZero and  
CDF (at Fermilab) in  
proton-antiproton collisions,  
but top quarks decay so  
quickly that they do not  
form stable/metastable  
bound states. Mass of top  
quark  $\sim 173$  GeV!



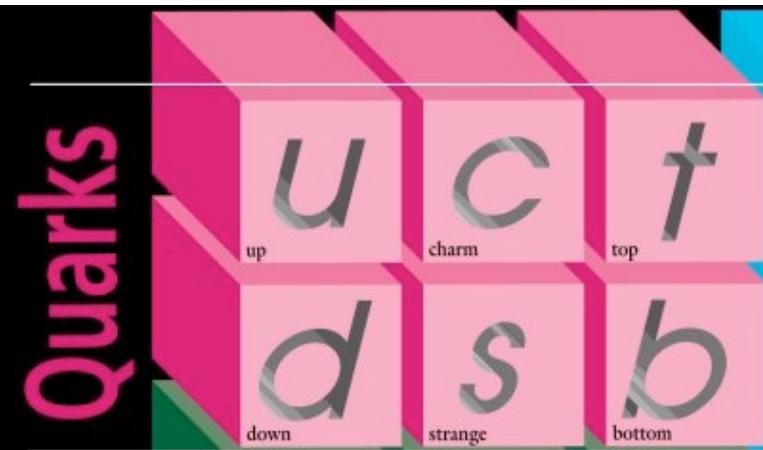
Fun aside: UA1 at  
CERN made a  
“discovery” of the  
top quark in 1984  
with a mass of  
 $40 \pm 10$  GeV

## Fermions

## Bosons



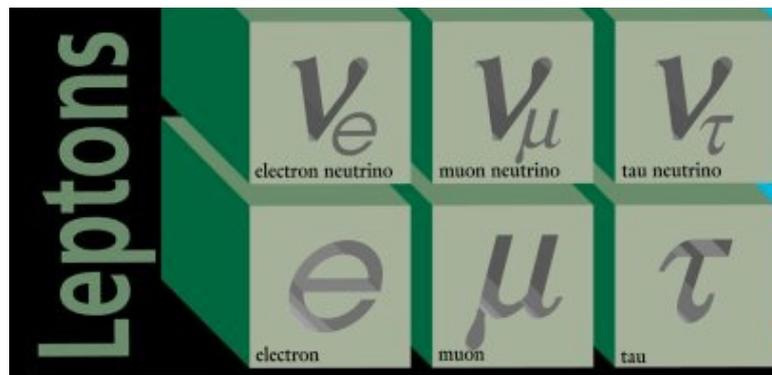
This is really the full Standard Model (modulo the Higgs boson,  $h$ ), though it of course ... hides some details



Three generations of quarks, with each generation getting more massive. Each quark carries electric charge ( $+2/3, -1/3$ ), and also QCD color (**rgb**). Quarks are confined, and do not exist alone in nature, but rather only in **hadrons**: **baryons** and **mesons**. Quarks also contain “**flavor**” (strangeness, topness, etc) that is conserved in QCD, but not in weak interactions. **Anti-quarks** not shown

Are there additional generations of quarks? We've been looking for them

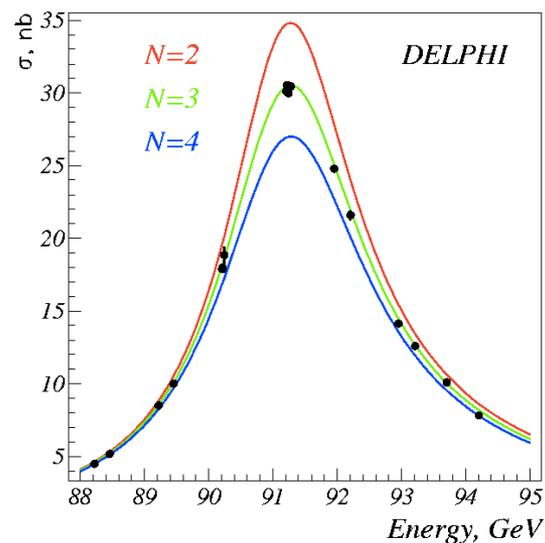
# The leptons



Are there additional leptons? We've been looking for them, though, though extra neutrinos have to be very massive or rarely interact. Masses of observed neutrinos unknown, but are very small

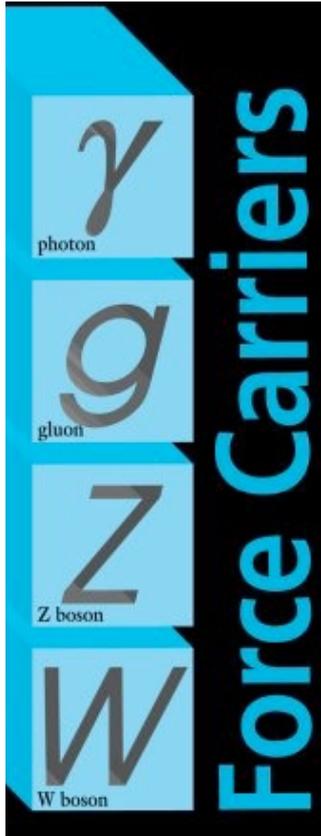
Three generations of **leptons**, with each generation (at least of charged leptons) getting more massive. Charged leptons carry electric charge, neutrinos do not. All leptons carry electron, muon and tau number, which is conserved.  
**Anti-particles** not shown

Study number of light neutrinos with Z production at  $e^+e^-$  machines



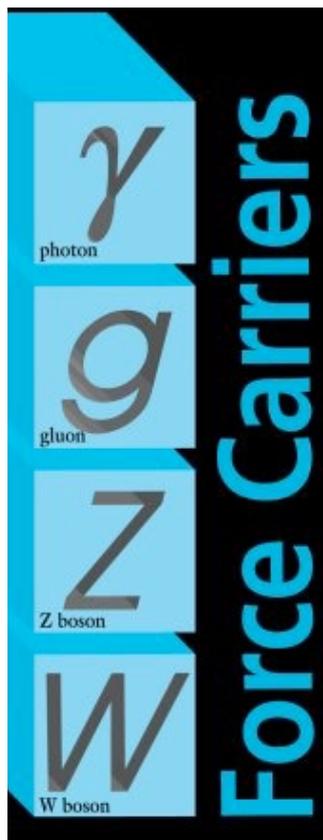
## Photon never changes matter flavor

Force carriers are bosons with integer spin. The **photon** is the force carrier from E&M, and has spin-1 (it's a vector boson) and zero mass. Interacts only with electrically charged particles

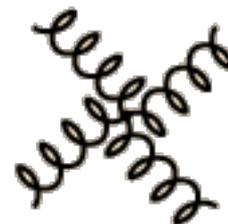
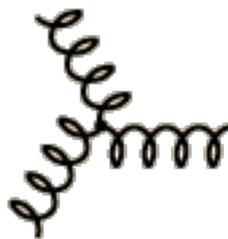


# The bosons

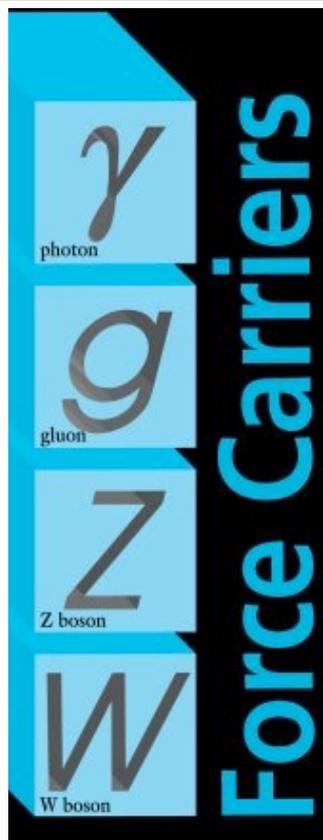
## Gluon never changes matter flavor



The **gluon** is the force carrier of QCD, and has spin 1 (it's a vector boson) and zero mass. It has no electric charge, but it carries **QCD color charge** (there are 8 types of gluons). Hence, it couples not only to quarks, but also to itself and other gluons (but not leptons)



# The bosons

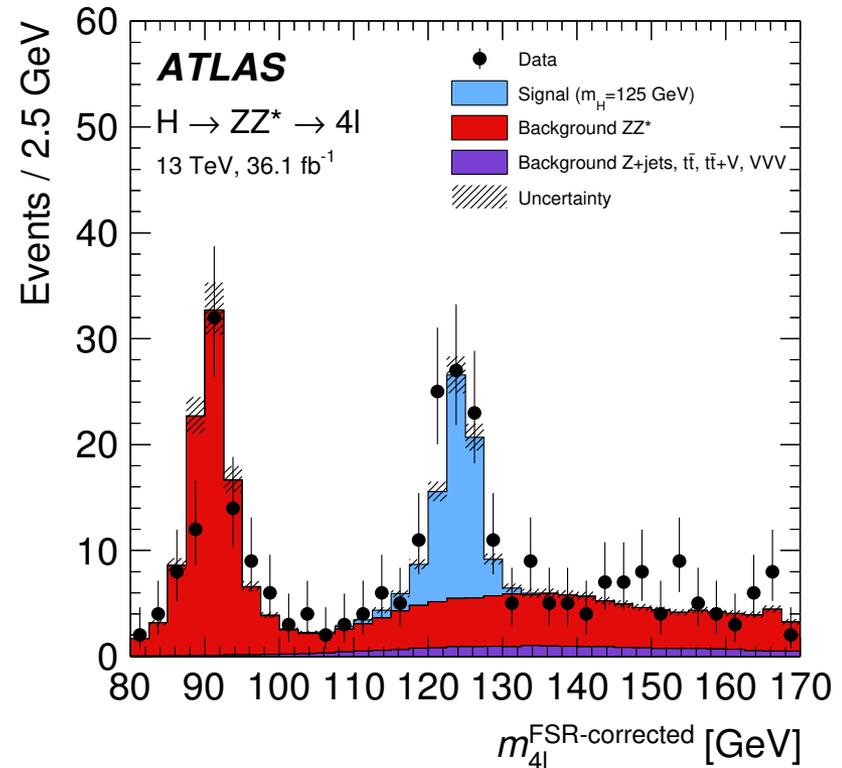


**W bosons**  
**always change**  
**matter flavor,**  
**Z bosons do not**

The  $W^\pm$  and  $Z^0$  bosons are the **weak force carriers**, with spin-1 (vector bosons) and both having large, non-zero mass ( $W \sim 80$  GeV,  $Z \sim 91$  GeV). The weak force is called exactly that due to their large mass. Weak force carriers are special - they are the only way to change one quark generation into another (see JPsi lifetime!), and have other special properties that we'll get to. Responsible for **nuclear  $\beta$ -decay and fusion**

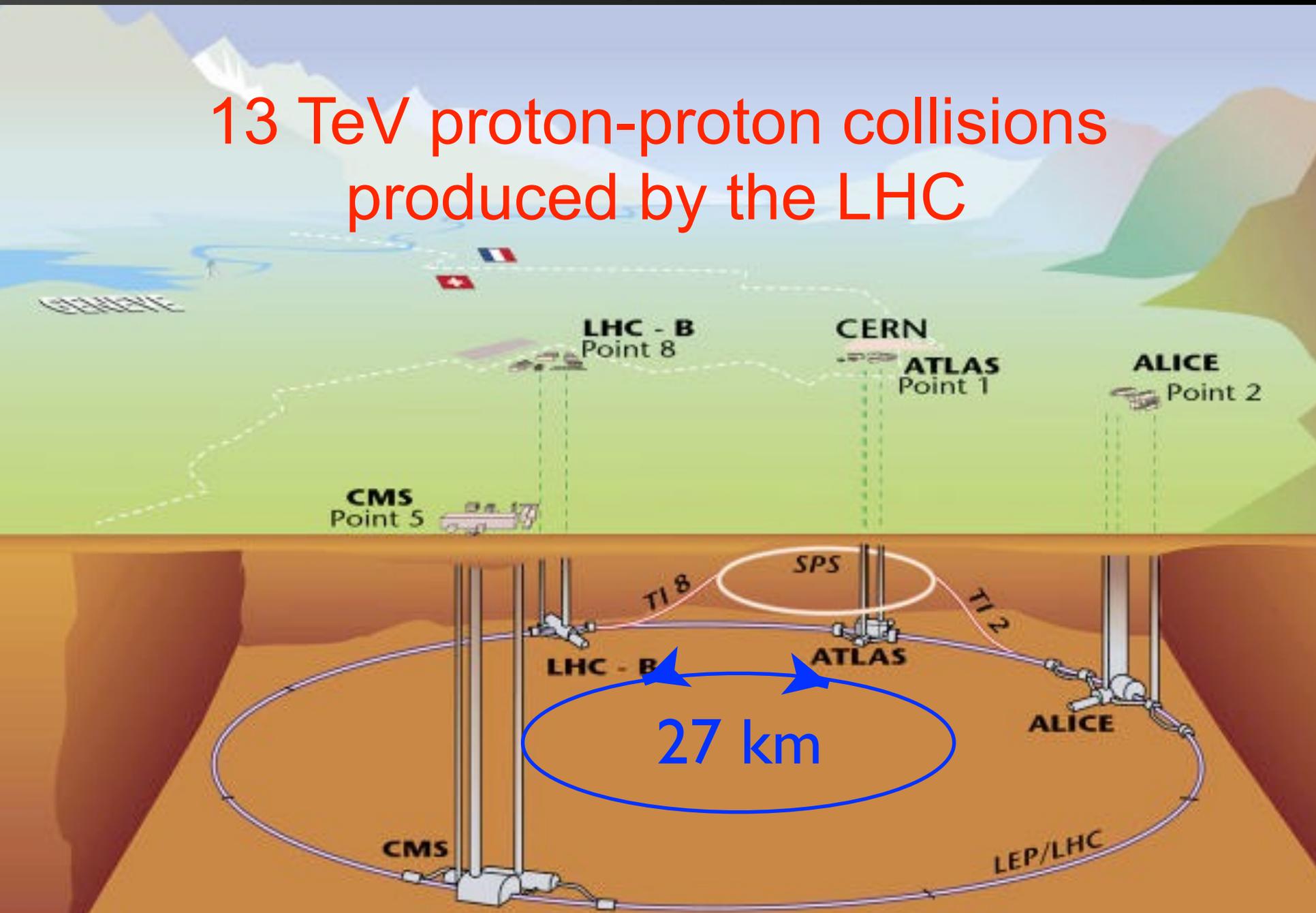
# The Higgs boson

The Higgs boson ( $h$ ) was hypothesized in 1960s, but was not discovered until July 2012. Long timeline! We'll see later in the course how the **Higgs mechanism** explains why the weak force carriers are so weak/massive, and why the fermions have mass



[arXiv:1708.02810](https://arxiv.org/abs/1708.02810)

# 13 TeV proton-proton collisions produced by the LHC



# ATLAS (I can talk about my experiment for.. awhile)

7000 tons

Muon Detectors

Tile Calorimeter

Liquid Argon Calorimeter

25 m

44 m



ATLAS

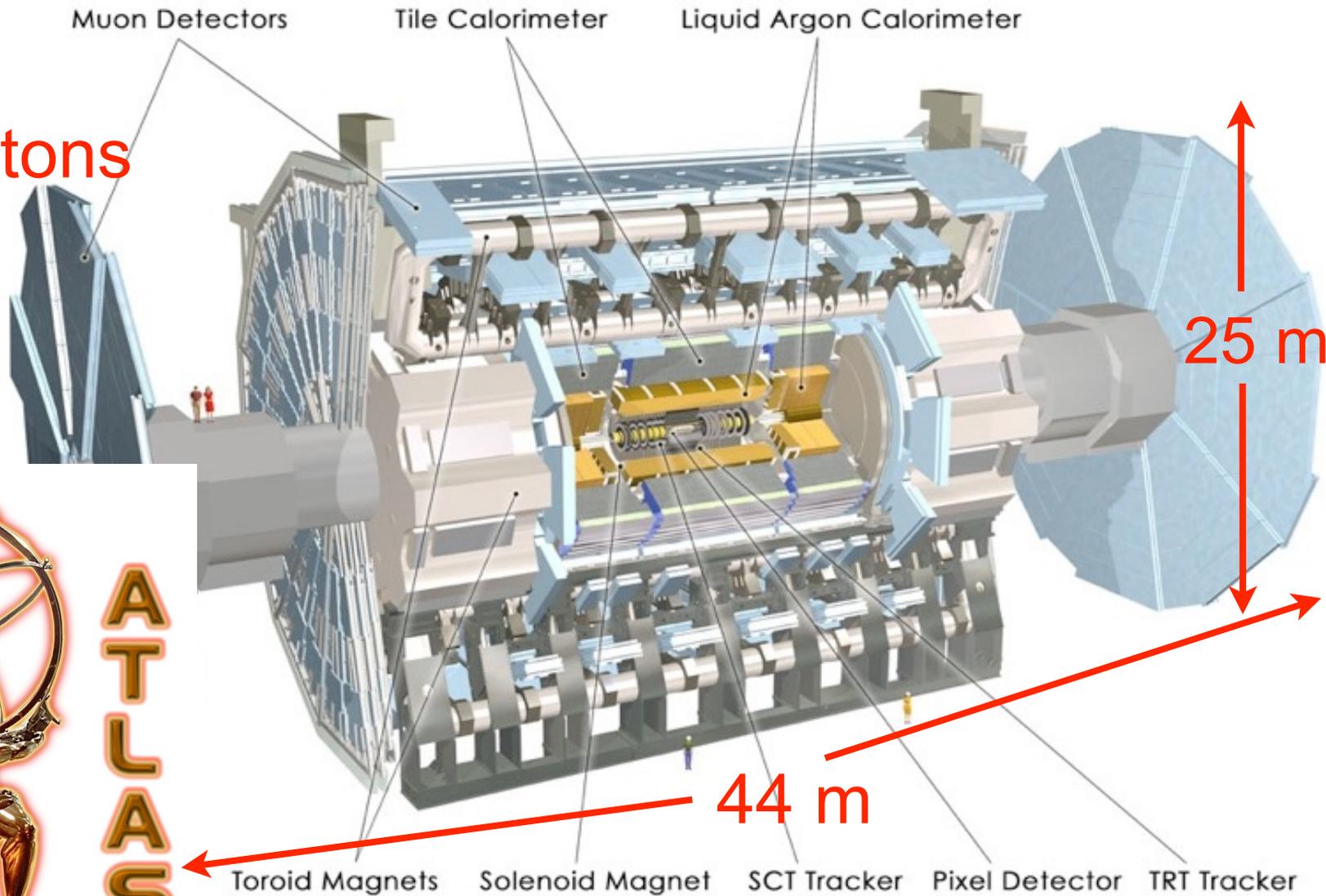
Toroid Magnets

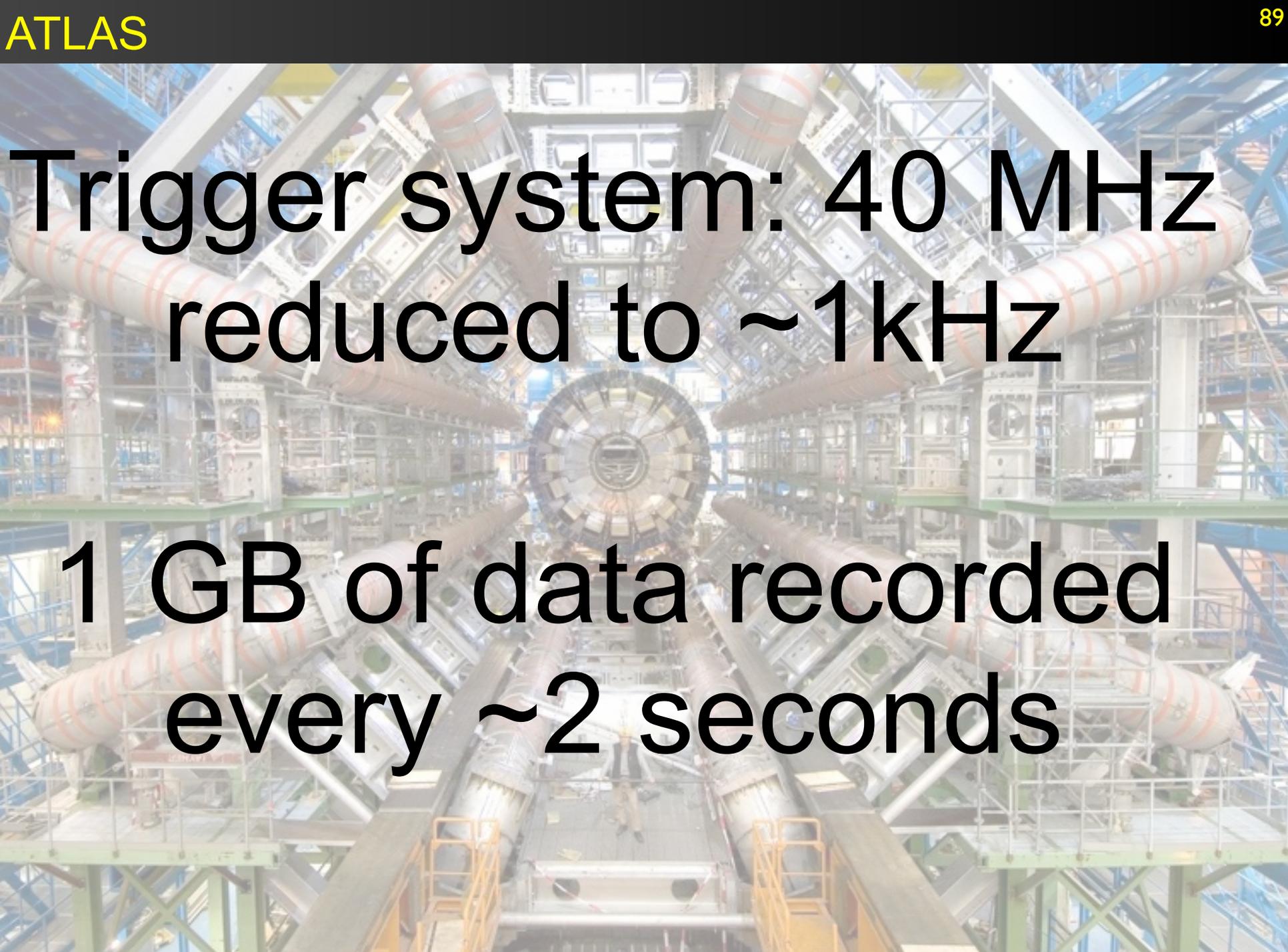
Solenoid Magnet

SCT Tracker

Pixel Detector

TRT Tracker



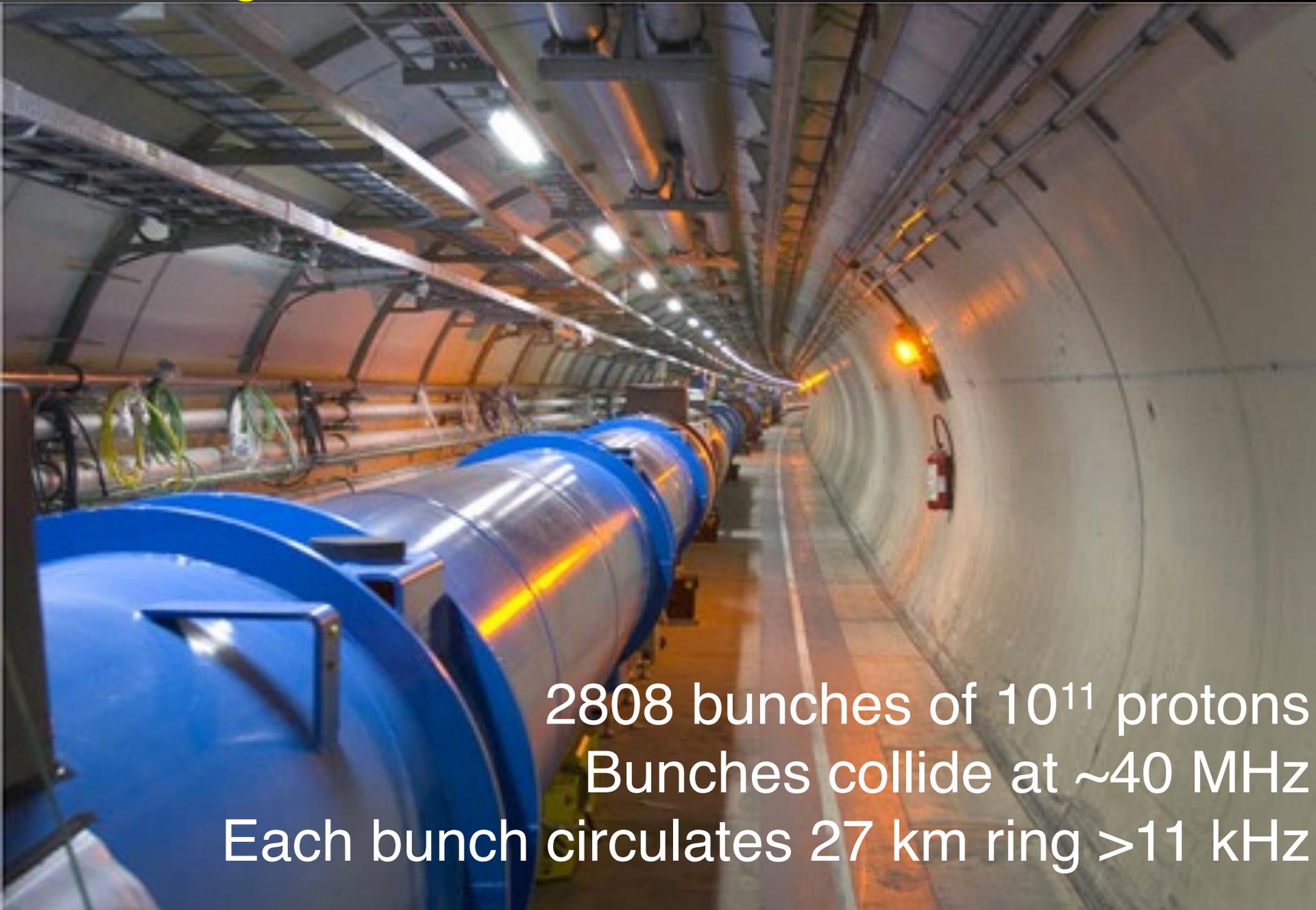
The background image shows the interior of the ATLAS detector, a large cylindrical structure with multiple layers of detector components. The central part is a circular structure, likely the calorimeter, surrounded by various pipes, cables, and structural elements. The lighting is bright, highlighting the metallic surfaces and the complex geometry of the detector.

**Trigger system: 40 MHz  
reduced to  $\sim 1$  kHz**

**1 GB of data recorded  
every  $\sim 2$  seconds**

# Life as a particle physicist





2808 bunches of  $10^{11}$  protons  
Bunches collide at  $\sim 40$  MHz  
Each bunch circulates 27 km ring  $> 11$  kHz

# Other sorts of modern experiments

g-2  
mu2e  
neutrino expts (nuclear, solar, accelerator...)  
nuclear physics  
astroparticle physics  
dark matter searches  
dark energy surveys  
...

Not to mention all the accelerator physics  
that goes along with much of the above

## How do modern particle detectors work?

Want to see the effect of a particle, usually in the form of radiation or energy transfer that we can observe. **Goal is to infer as much about the original particle/object as possible.**

Problem is of course that we cannot just put things inside of a microscope for careful, lengthy study: **typically traveling close to speed of light, often very short-lived, occasionally produced with many other nearby objects, sometimes have no electric charge and can look like other, similar particles**

# What can we take advantage of?

Charged particles bend in a magnetic field (can measure electric charge and momentum)

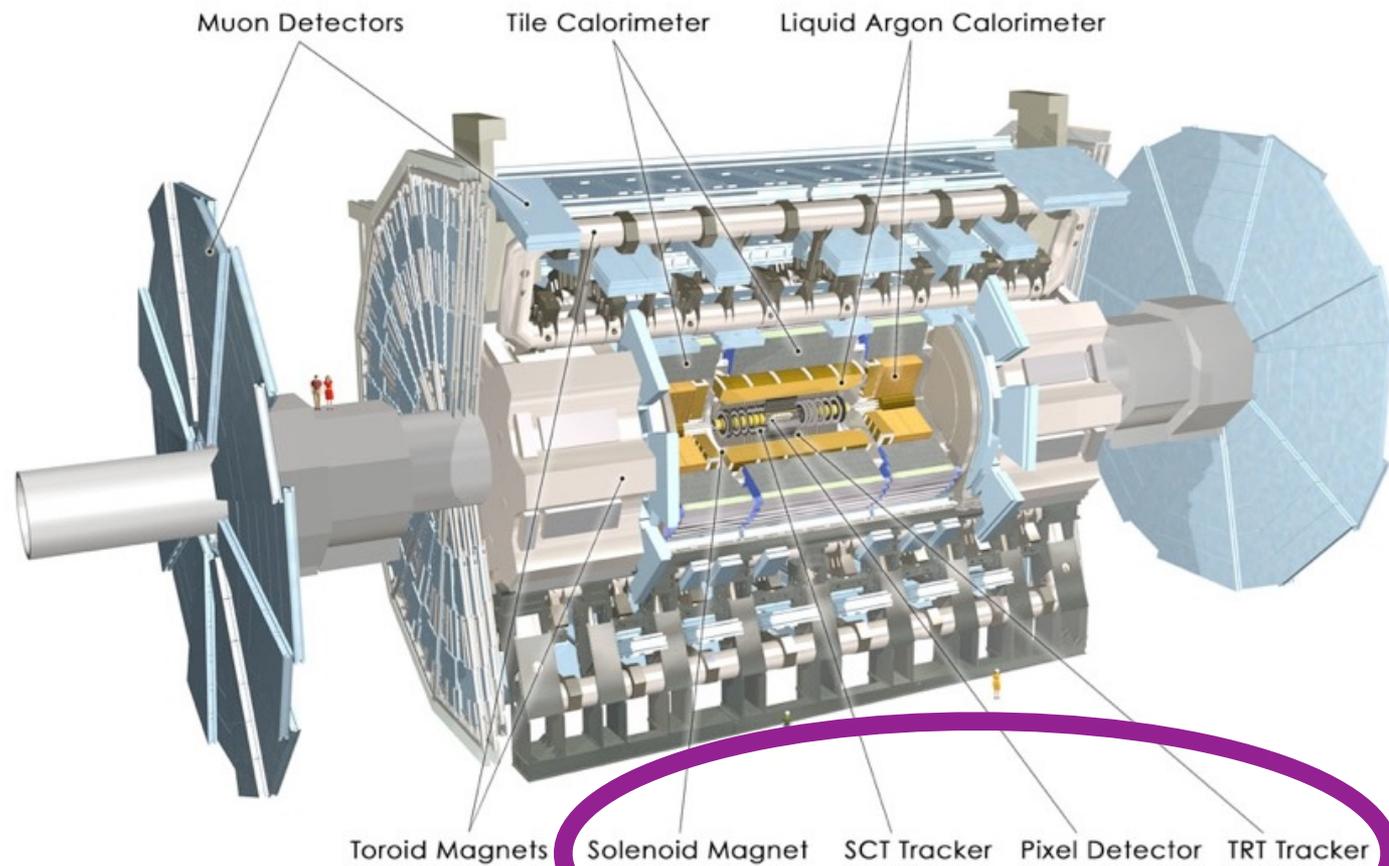
Careful timing measurements can give us particle velocity and other information (useful not only for the original particle, but also secondary particles it produce)

Calorimeter measurements give particle energy (different types of particles deposit energy electromagnetically vs via strong force, and at different rates)

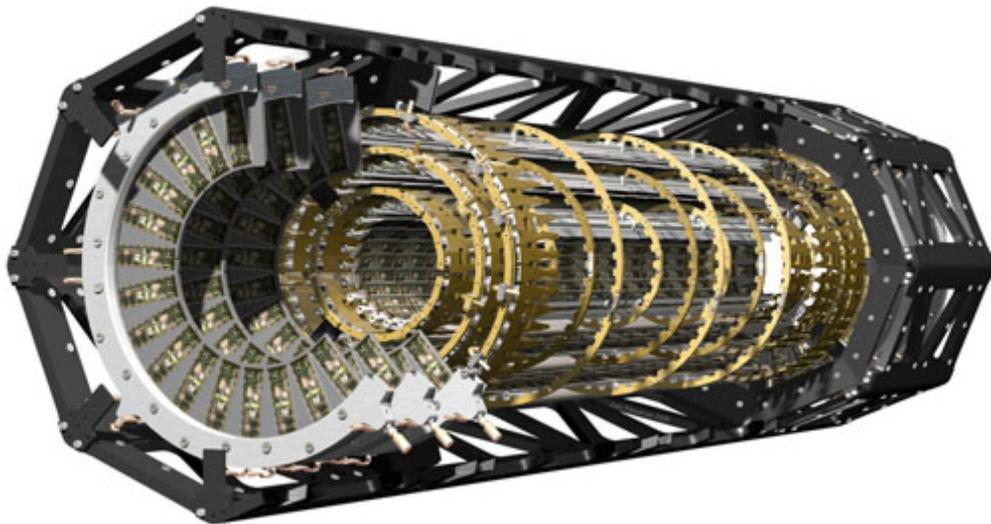
Neutrinos escape ~undetected, leading to imbalance of momentum in detector

Muons are highly penetrating and minimally ionizing

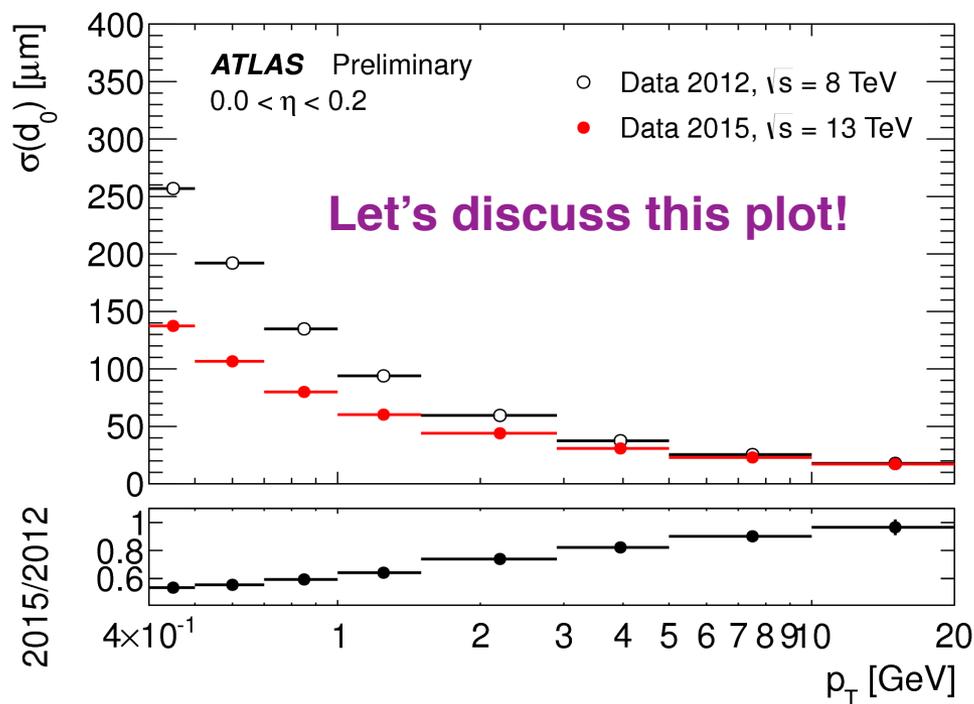
Other tricks like Cherenkov radiation, measurements of  $dE/dx$ , looking for transition radiation at material boundaries, ...



Inner tracking system nearest collision point immersed in 2T solenoid magnetic field: measure  $p$  and  $q$



100 million readout channels (recently upgraded for an extra layer) to measure precise location of charged particle trajectory

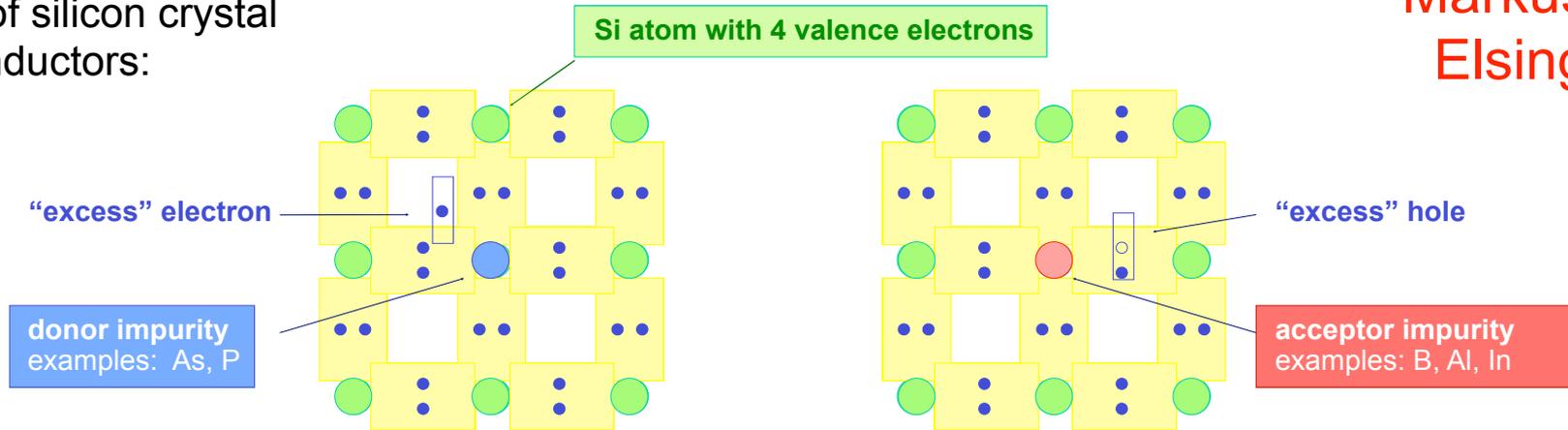


<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2015-007/>

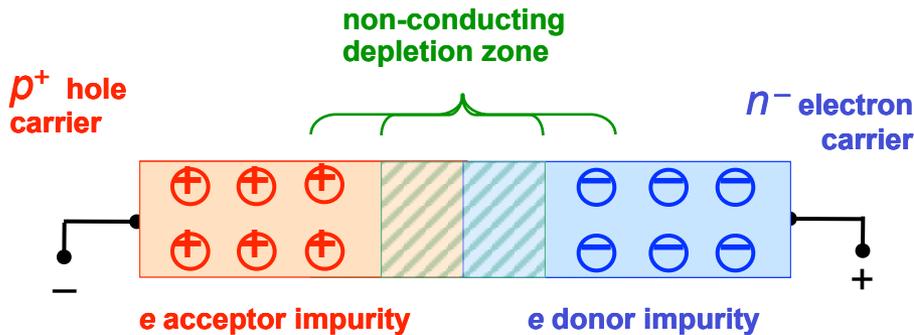
# Semiconductors

Slide  
from  
Markus  
Elsing

doping of silicon crystal  
semiconductors:



$p-n$  junction  $p-n$  junction



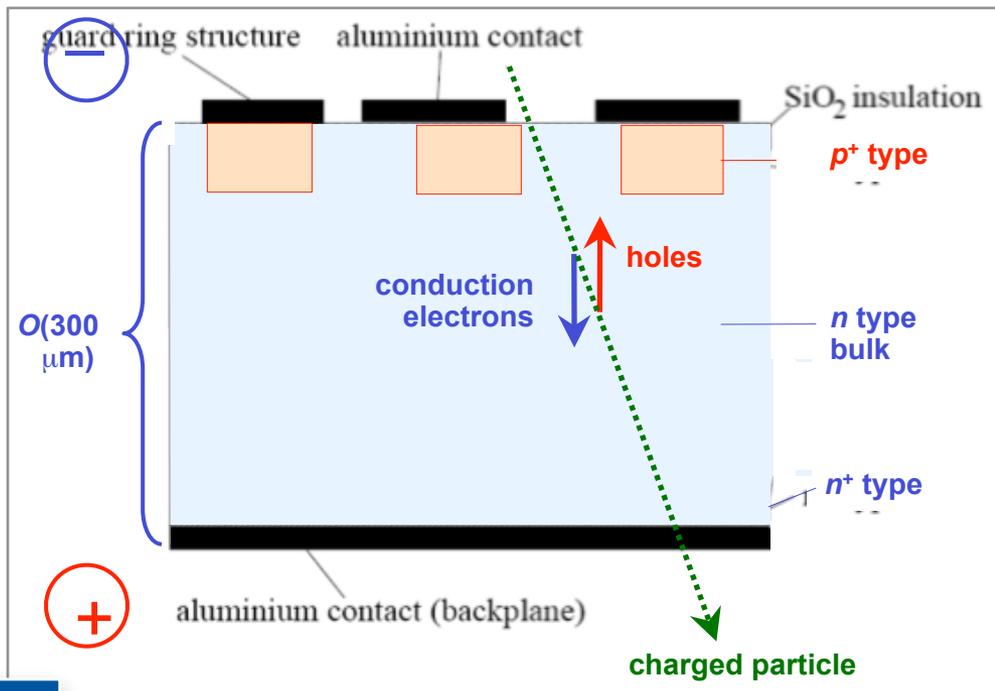
- the p-region is doped with acceptor atoms, the potential barrier in the depletion zone, n doping adds electro-phobe atoms enhancing its resistance
- the potential barrier in the junction
- counter-weights the loss of the potential



# The $p-n$ Junction as a Tracking Detector

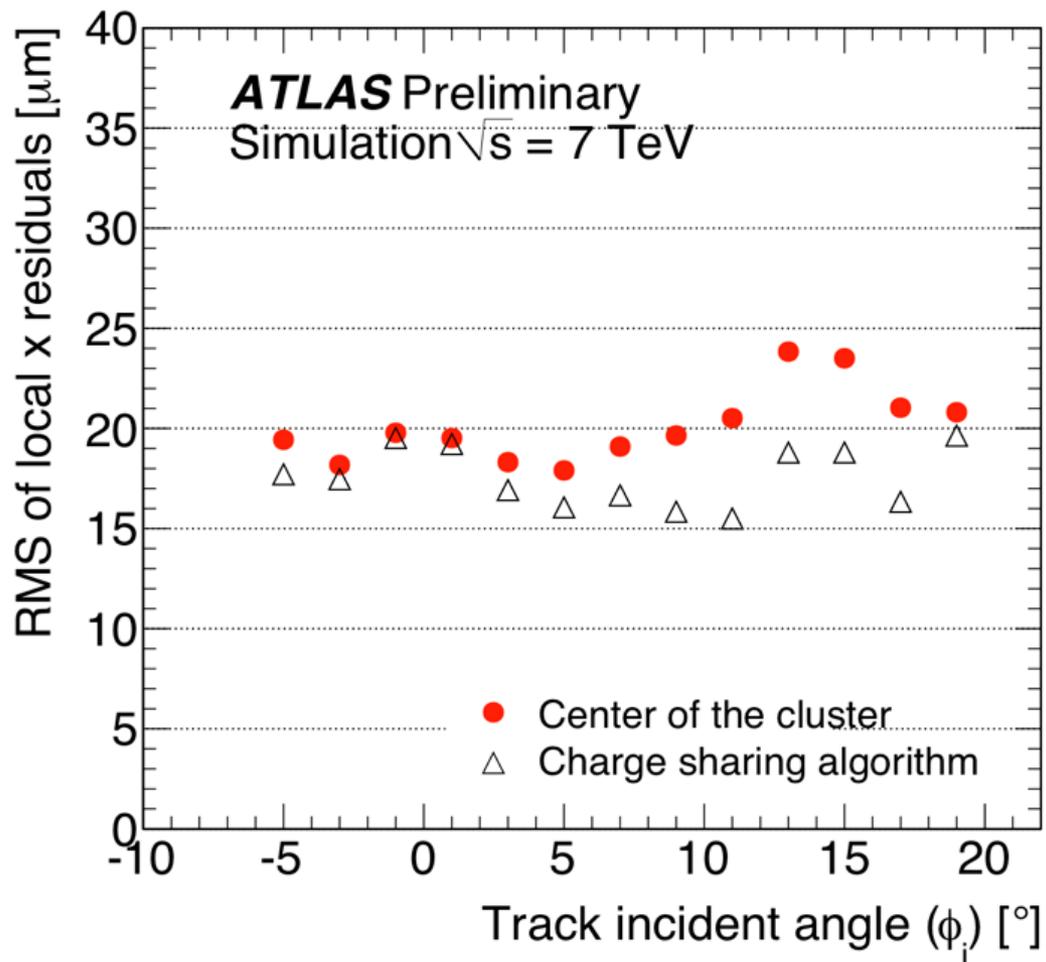
- thin ( $\sim\mu\text{m}$ ), highly doped  $p^+$  ( $\sim 10^{19}\text{ cm}^{-3}$ ) layer on lightly doped  $n$  ( $\sim 10^{12}\text{ cm}^{-3}$ ) substrate
- high mobility of charge carriers in Si allows fast charge collection ( $\sim 5\text{ ns}$  for electron)
- high Si density & low electron-hole creation potential (3.6 eV compared to  $\sim 36\text{ eV}$  for gaseous ionization) allows use of very thin detectors with reasonable signal

Slide  
from  
Markus  
Elsing



## schema of silicon microstrip sensor

- reverse bias: backplane set to positive voltage ( $< 500\text{ V}$ )
- a traversing charged particle ionizes silicon, creating conduction electrons and holes that induce a measurable current by drifting to electrodes
- metal-semiconductor transition forms charge (Schottky) barrier similar to  $p-n$  junction. Highly doped  $n^+$  layer reduces width of potential barrier and hence resistance

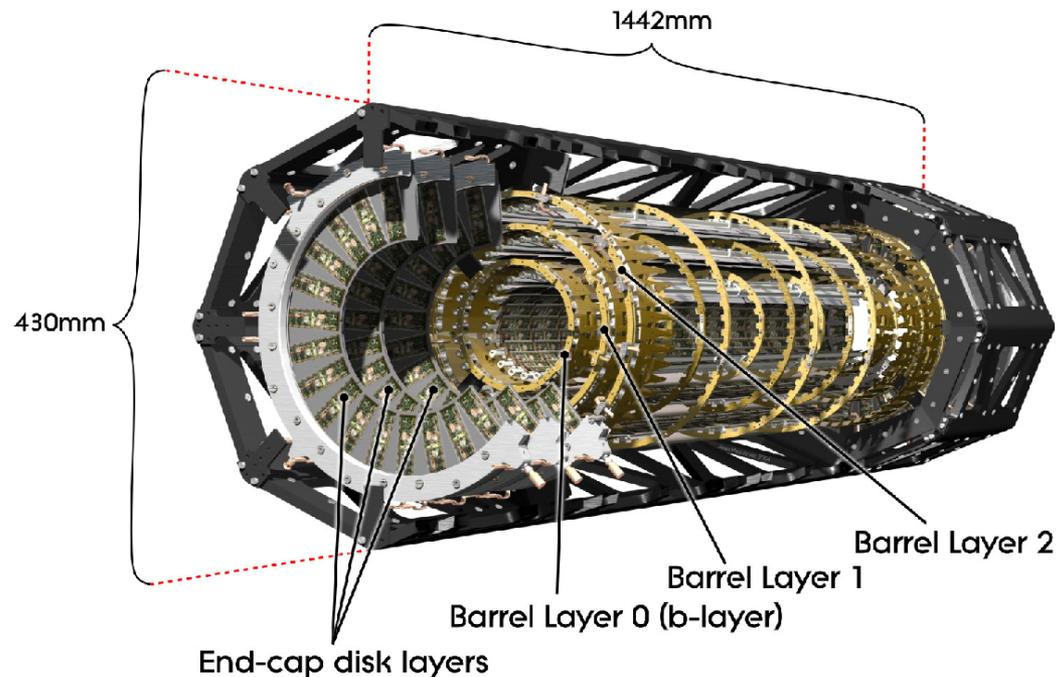


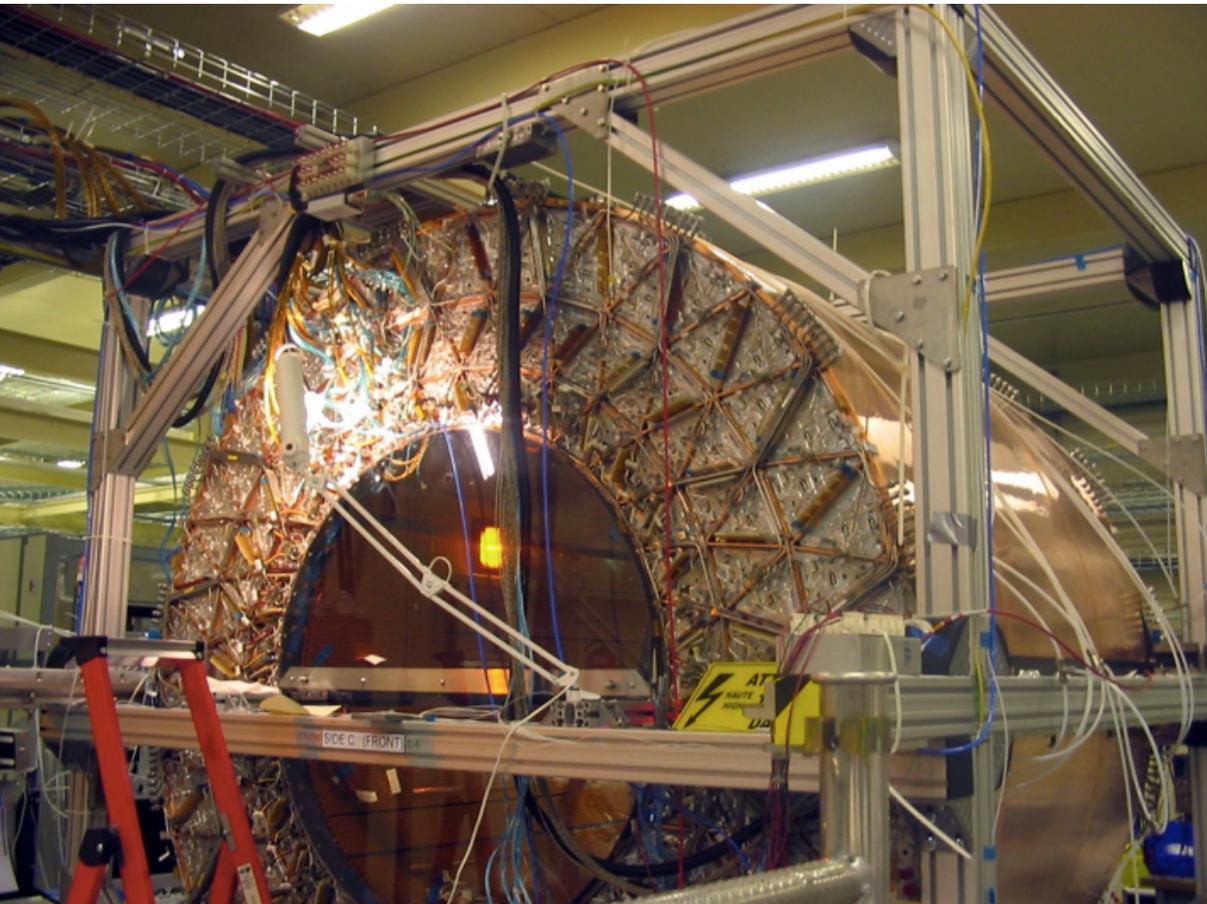
Tens of micron resolution from single hits! The alignment for all the modules gets quite ... tricky

# Challenges for silicon systems at the LHC

Just like your digital camera - except more directional, ie pointing in different directions (why?)... and we have to read out data a lot faster!

Not to mention dealing with intense radiation environments. Why might this be a problem? How can we mitigate the problem?



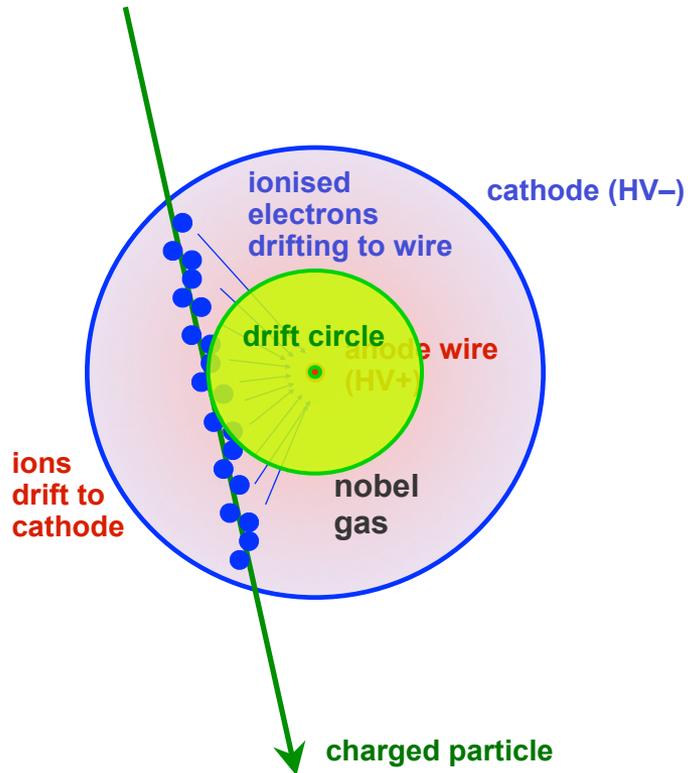


300,000 straws  
(4 mm in  
diameter) at  
larger track  
radius, ~35  
measurements  
per track. Also  
helps with  
particle  
identification

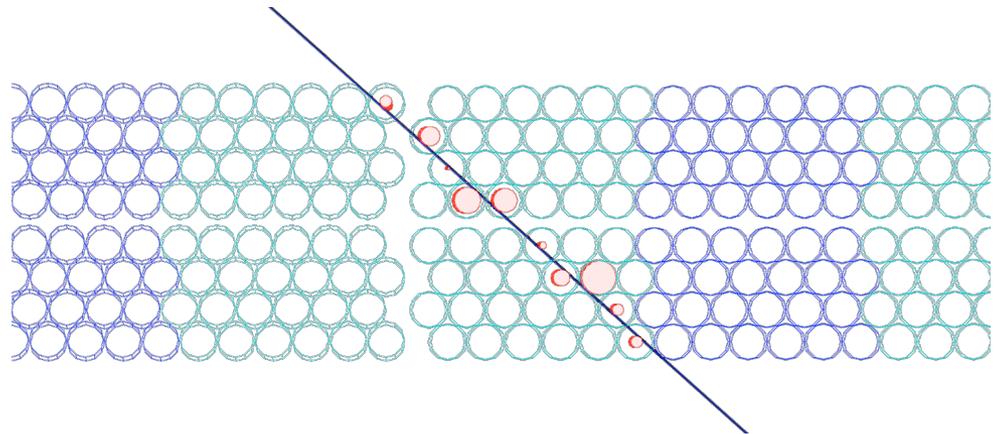
This is being removed for future LHC operations with larger numbers of collisions. Any guesses why?

# Drift Tubes in ATLAS: Inner Detector and Muon Spectrometer

- classical detection technique for charged particles based on gas ionization and drift time measurement



example: segment in muon drift tubes reconstruction from measured drift circles (left-right ambiguity)

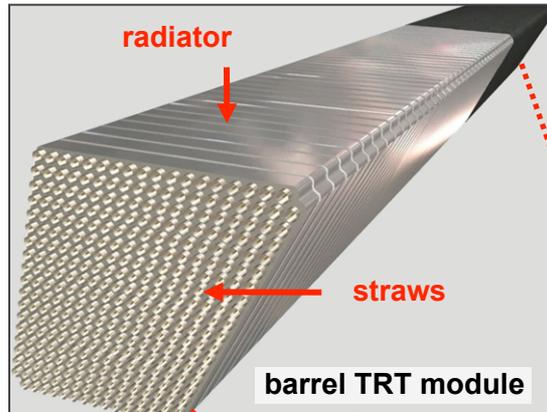
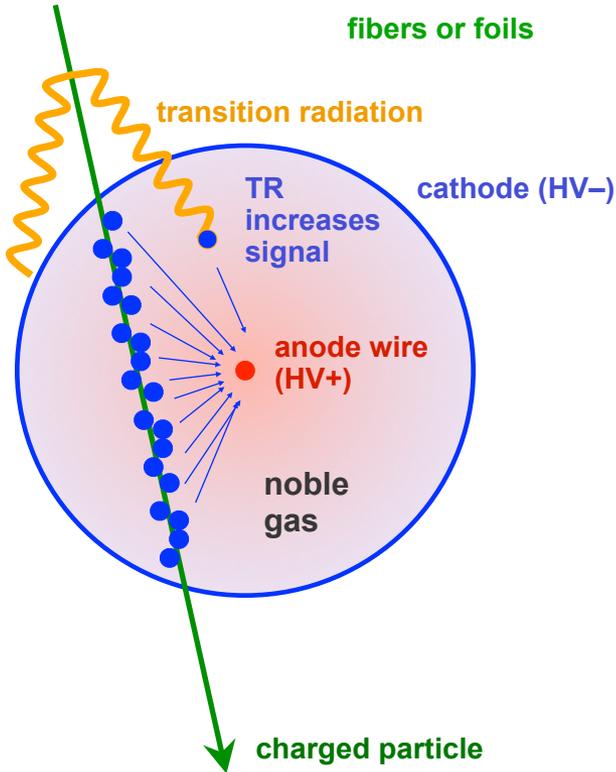


TRT: Kapton tubes,  $\varnothing = 4$  mm  
MDT: Aluminium tubes,  $\varnothing = 30$  mm

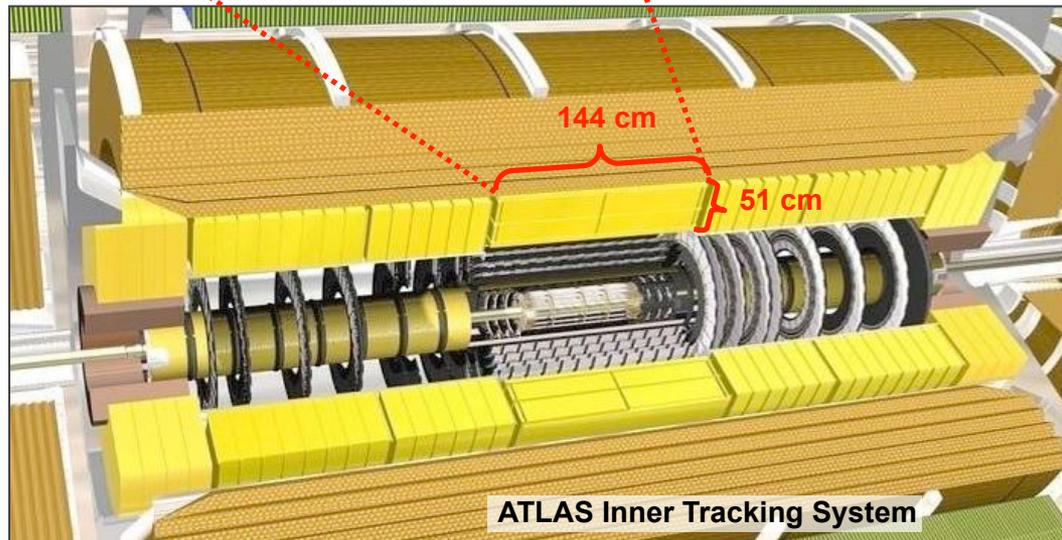
Slide from  
Markus Elsing

# Combining Tracking with PID: the ATLAS TRT

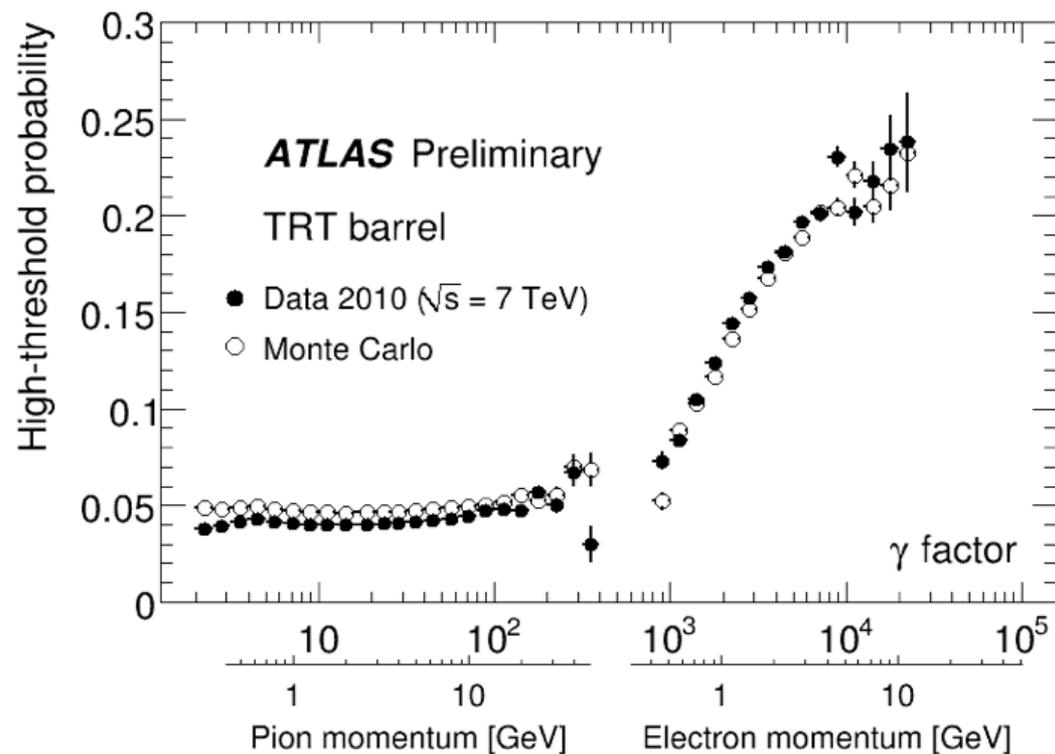
- $e/\pi$  separation via transition radiation: polymer (PP) fibers/foils interleaved with drift tubes



total: 370k straws  
barrel ( $|\eta| < 0.7$ ):  
36  $r-\phi$  measurements / track  
resolution  $\sim 130 \mu\text{m}$  / straw  
14 end-cap wheels ( $|\eta| < 2.1$ ):  
40 or less  $z-\phi$  points



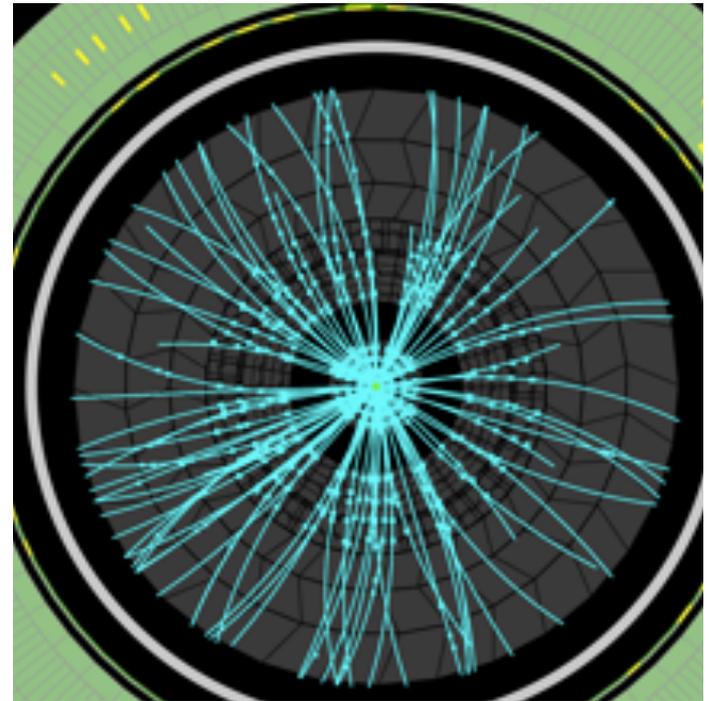
electrons radiate  $\rightarrow$  higher signal  
PID info by counting  
high-threshold hits



Given  $\sim 30$  hits per track, small difference in probability to measure hits with a higher threshold can give significant particle identification/background rejection for electron ID

$$p \propto B \cdot R$$

For precise measurement of  $p$ , want precise measurement of radius of curvature. 100 GeV object at ATLAS has  $R = 166\text{m}$ ! A 1 TeV pion will have  $R$  close to 1 km... need precision in silicon systems order ( $\sim 10$  microns per measurement)



Particle travels  $\sim c\tau$  before decaying **in its own rest frame** but in lab frame,  $\sim \gamma c\tau$ . Typically interested in objects with substantial Lorentz gamma factors, so muons, neutrons and charged pions and kaons travel and decay in the detector

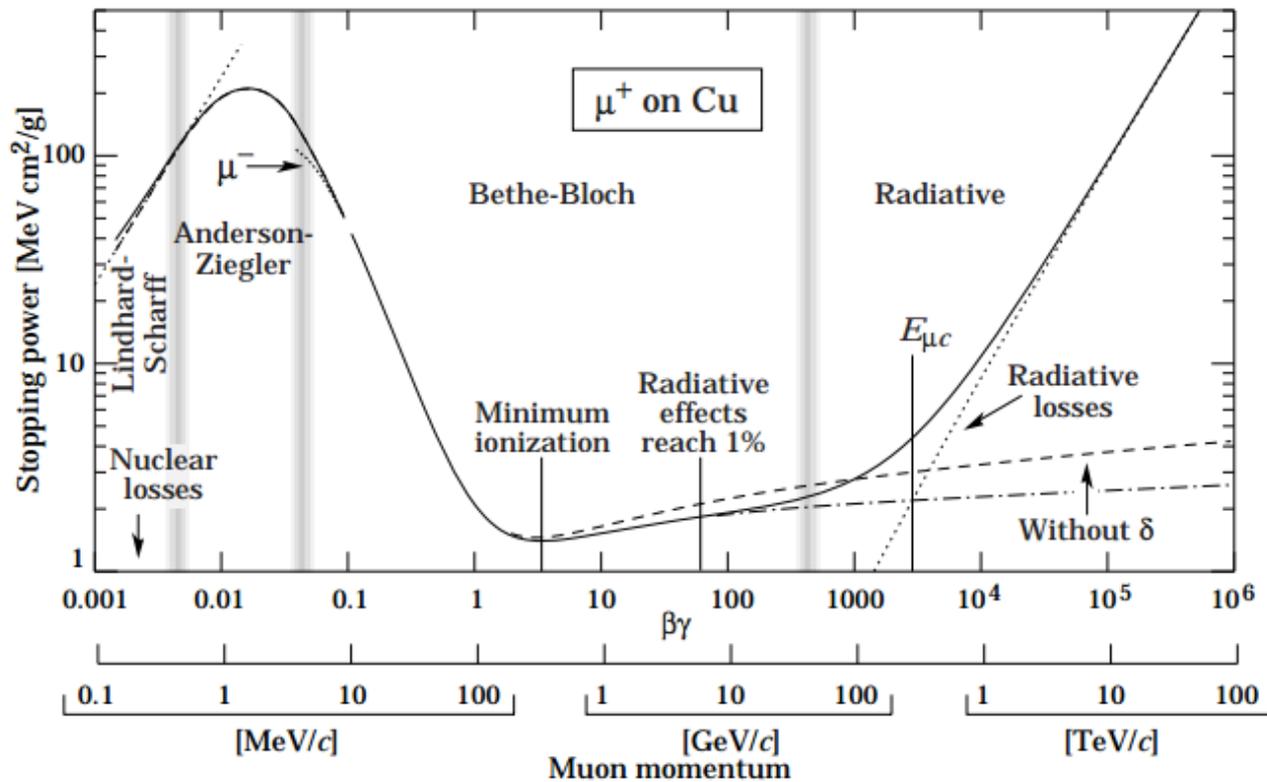
## Bethe-Bloch equation

When a relativistic charged particle passes through some material with atomic number  $Z$  and electron density  $n$ , it ionizes the atoms and thus loses energy.  $I$  is the mean excitation energy in the material  $\sim 10 Z$  [eV]

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left( \frac{e^2}{4\pi\epsilon_0} \right)^2 \cdot \left[ \ln \left( \frac{2m_e c^2 \beta^2}{I \cdot (1 - \beta^2)} \right) - \beta^2 \right]$$

Not very intuitive :)

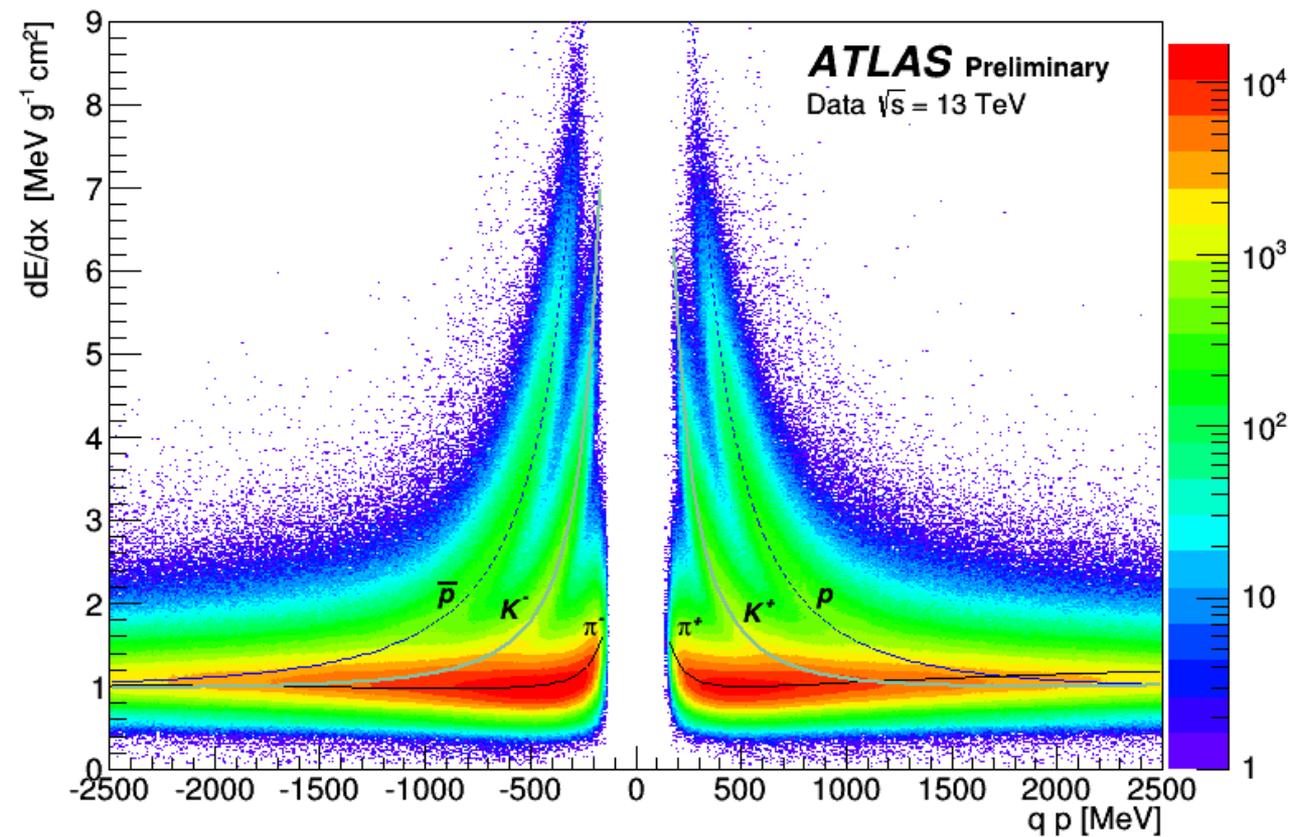
# Bethe-Bloch equation



**Fig. 27.1:** Stopping power ( $= \langle -dE/dx \rangle$ ) for positive muons in copper as a function of  $\beta\gamma = p/Mc$  over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at  $\beta\gamma \approx 0.1$  are taken from ICRU 49 [4], and data at higher energies are from Ref. 5. Vertical bands indicate boundaries between different approximations discussed in the text. The short dotted lines labeled “ $\mu^-$ ” illustrate the “Barkas effect,” the dependence of stopping power on projectile charge at very low energies [6].

From PDG.  
 Particles with  $\beta\gamma \sim 3$  lose the least amount of energy as they travel, and are referred to as “minimum ionizing” particles

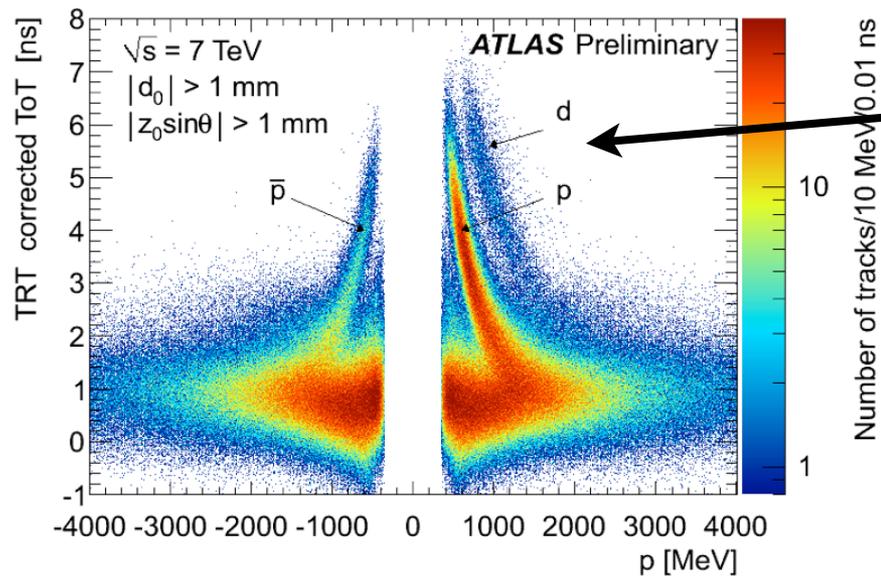
# Using $dE/dx$ in the pixel system of ATLAS



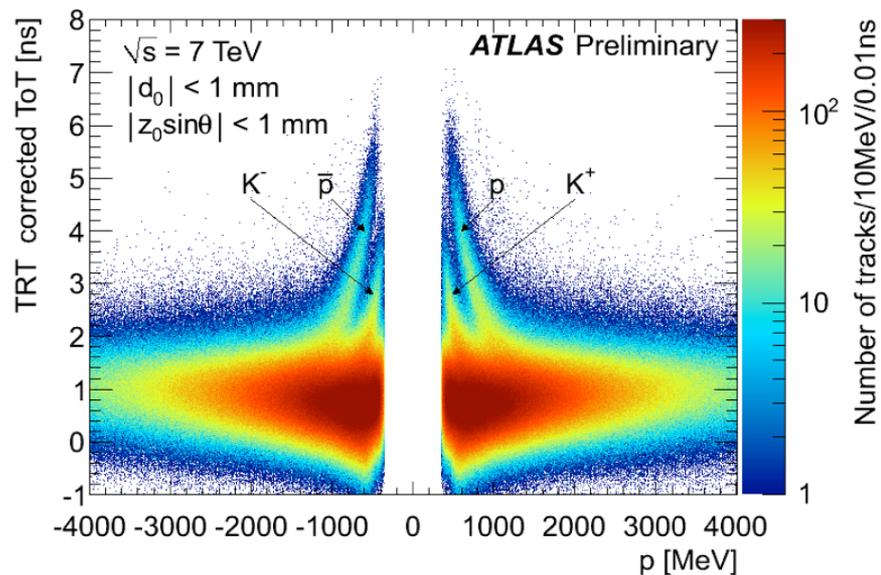
Can see  
pions, kaons  
and protons!

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/PIX-2015-002/>

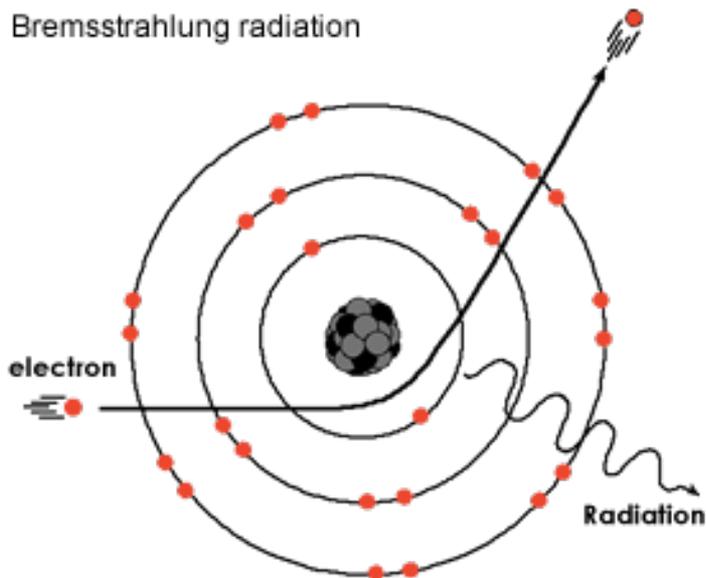
# Using $dE/dx$ in the TRT system of ATLAS



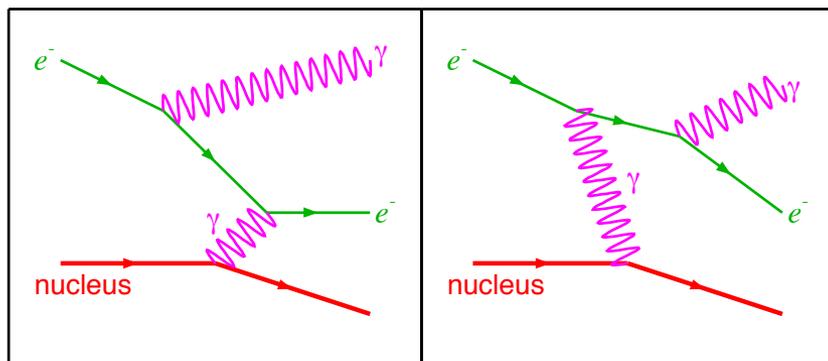
Asymmetry! Why?



Using “time over threshold”, we can also do particle identification with straw detectors



Bremsstrahlung



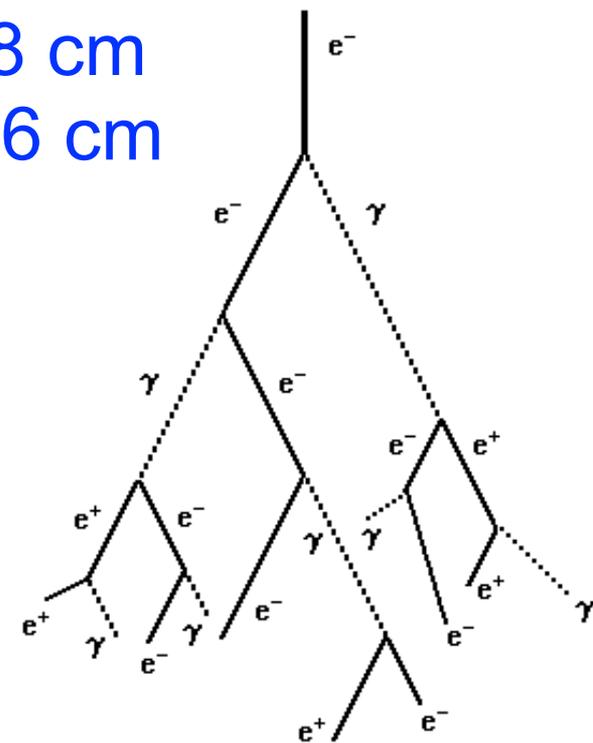
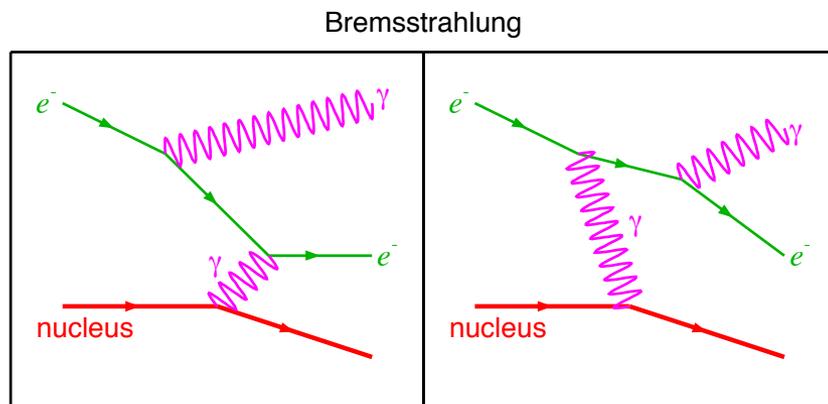
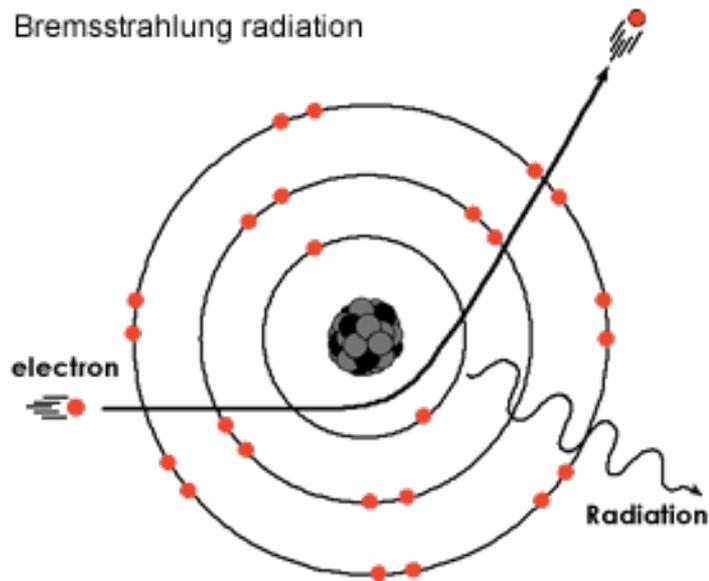
Literally “braking radiation” in German, **bremsstrahlung** is the main way that electrons of interest at ATLAS lose energy. In EM you might have seen that the amount of energy radiated away goes as  $1/\text{mass}^2$ , which is why one reason why ee accelerators need to be so big, and why muons don't lose much energy in the detector

# Radiation length for high-energy electrons/photons

Radiation length  $X_0$  is the average distance over which the energy of an electron is reduced by  $1/e$  (characteristic distance scale for material effects)

$$X_0(\text{iron}) = 1.8 \text{ cm}$$

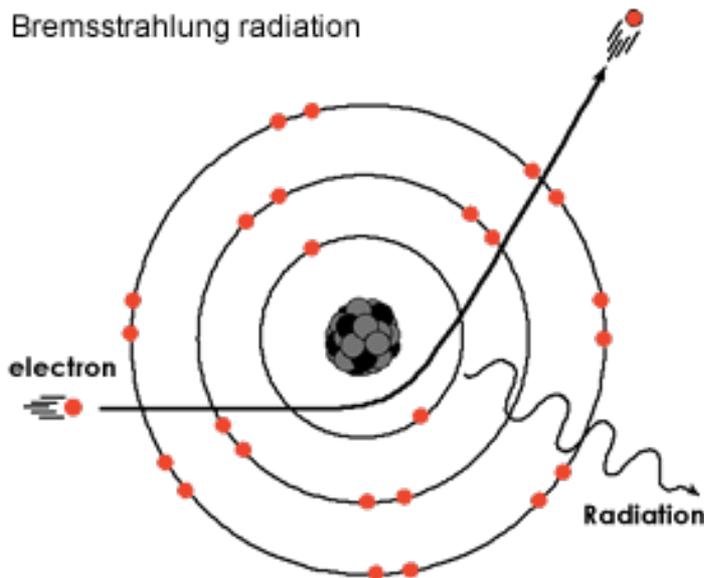
$$X_0(\text{lead}) = 0.6 \text{ cm}$$



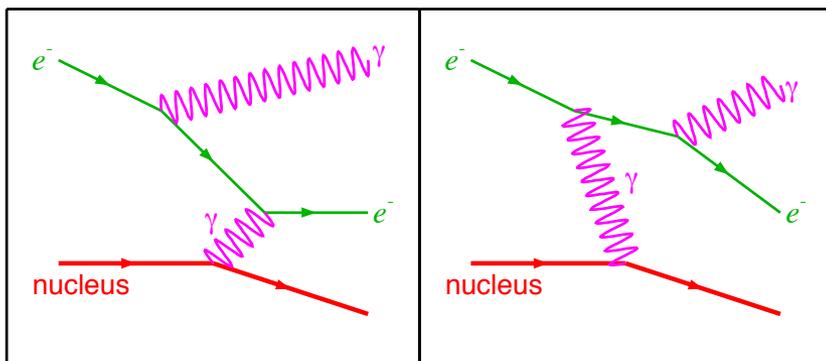
Very similar for photons

# Radiation length for high-energy electrons/photons

Bremsstrahlung radiation



Bremsstrahlung



After 1  $X_0$  we have roughly twice as many particles, with half the original energy

After 2  $X_0$ , we have  $\sim 4x$  as many particles, with  $1/4$  the original energy

After  $n$   $X_0$ , we have  $\sim 2^n$  as many particles, and the energy of each is  $\sim 2^{-n}$  of the original value

At some critical energy  $E_c$ , the Brem process stops

$$\langle E \rangle_n = \frac{E}{2^n} = E_c$$

$$\ln E - \ln 2^n = \ln E_c$$

$$\ln E - n \ln 2 = \ln E_c$$

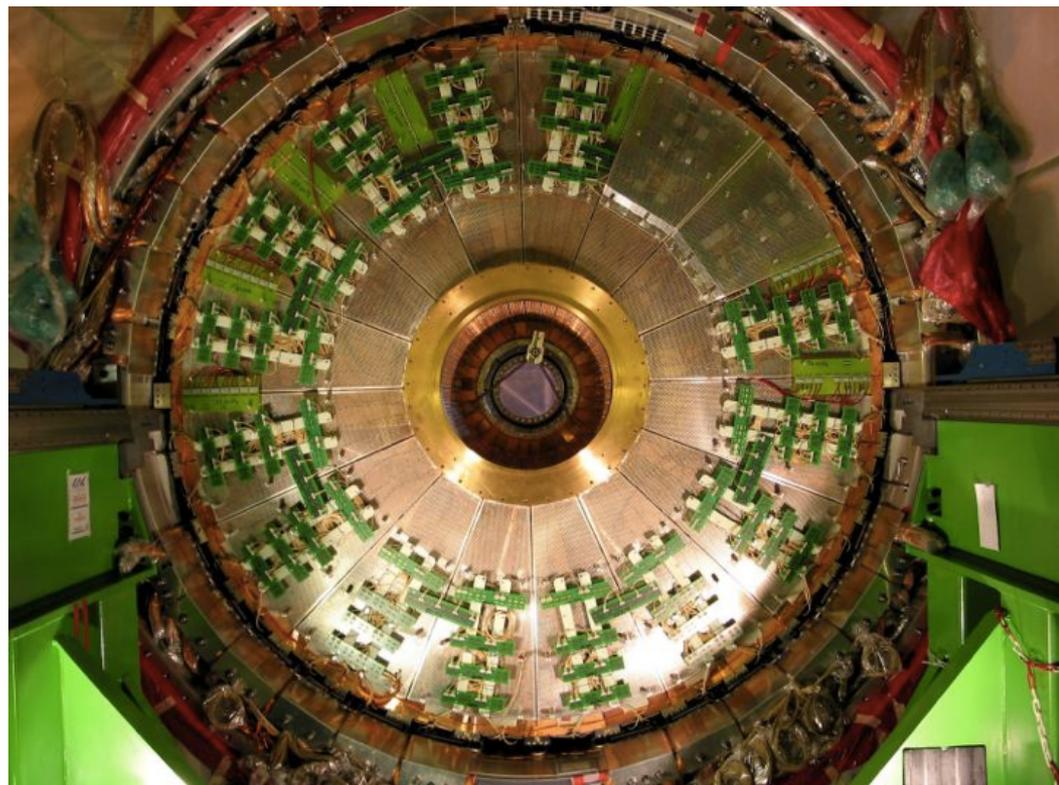
$$n \ln 2 = \ln(E/E_c)$$

$$n = \frac{\ln(E/E_c)}{\ln 2}$$

Here  $n$  is the number of radiation lengths where the maximum number of particles is observed, aka where Brem stops (for lead, 100 GeV electron gives 13  $X_0$ , which is just a few cm)

Need some dense material to absorb energy, and some active material to notice this and produce an output signal. Can be the same material, often is not.  
ATLAS EM calorimeter is lead-liquid argon

A view inside the ATLAS LAr calorimeter



# Hadronic calorimeters

Trickier, as hadrons can be electrically neutral but even then the constituents (quarks) have electric charge.

And many hadrons have an overall electric charge

Defined by the nuclear interaction length ( $\lambda_{\text{I}}$ ), which is the mean distance between hadronic interactions.

$\lambda_{\text{I}}(\text{lead}) = 17 \text{ cm}$  (compare with  $X_0(\text{lead}) = 0.6 \text{ cm}$ )

Also tricky because neutral pions decay 99% of the time to a pair of photons

# ATLAS tile calorimeter

Intersperse steel absorber with plastic scintillator tiles, plastic doped with organic material. When charged secondary particles emerge from the steel, they excite the doped material, and emit UV light that can be re-emitted as one color by a dye

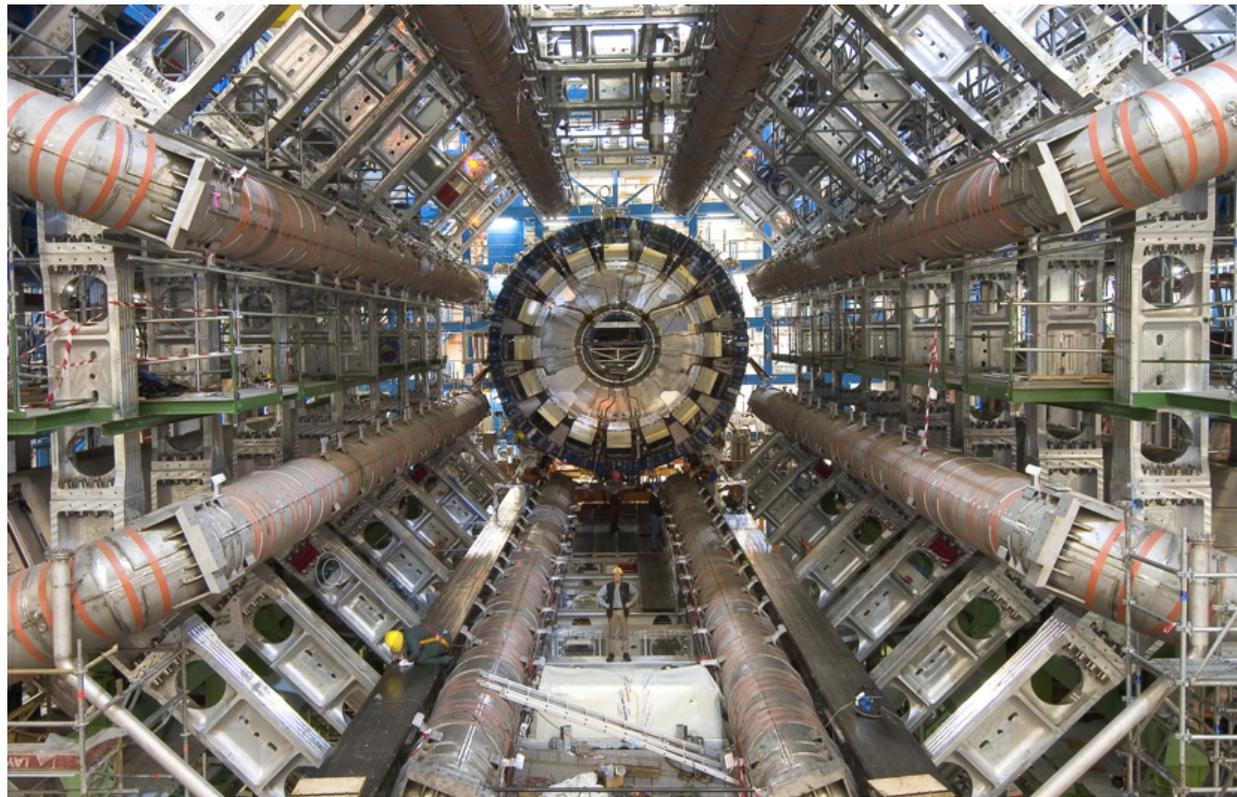
## The ATLAS tile calorimeter



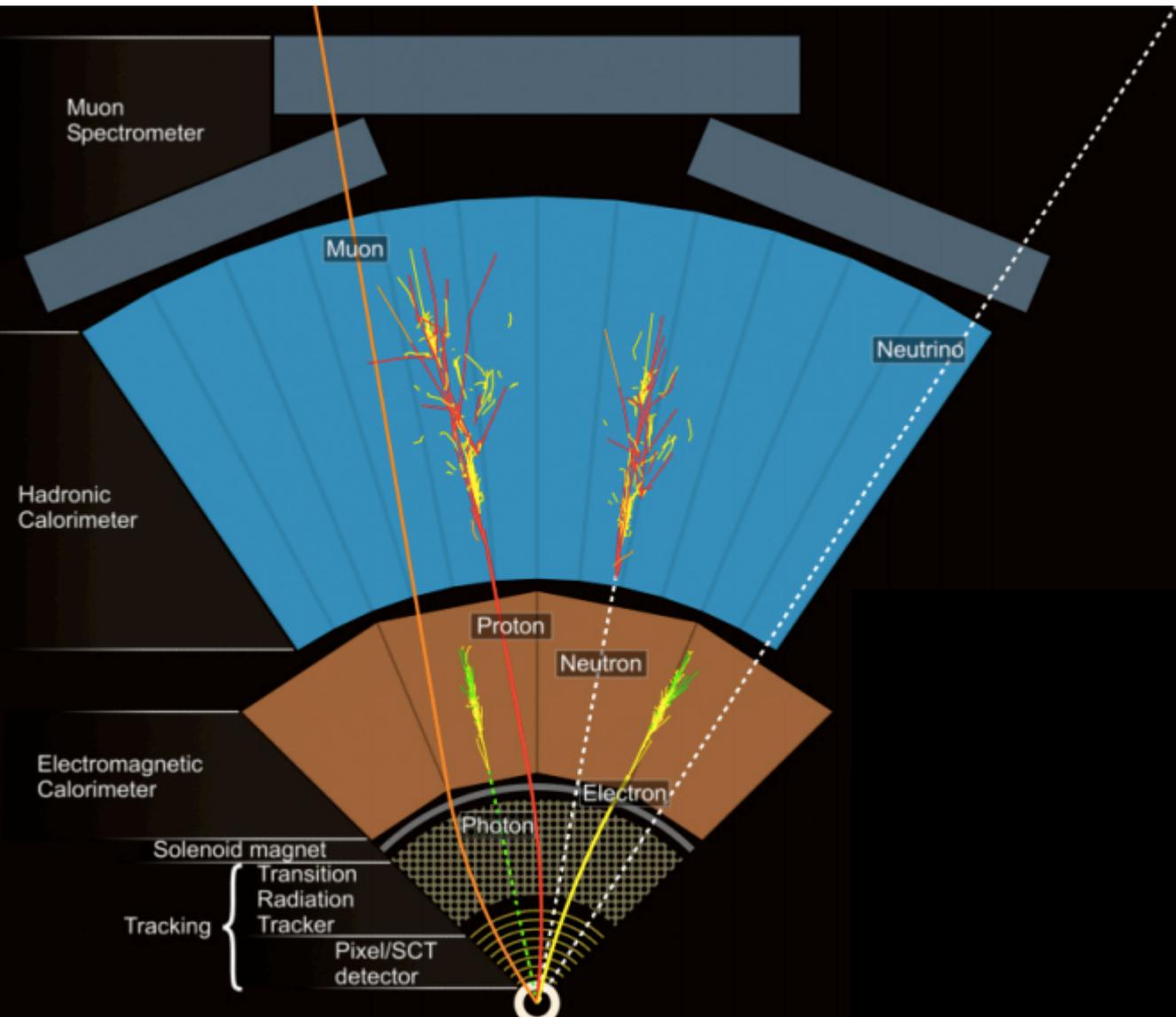
# What emerges from the calorimeters?

Neutrinos... we “detect” them (indirectly) by applying momentum conservation in the plane perpendicular to the beam

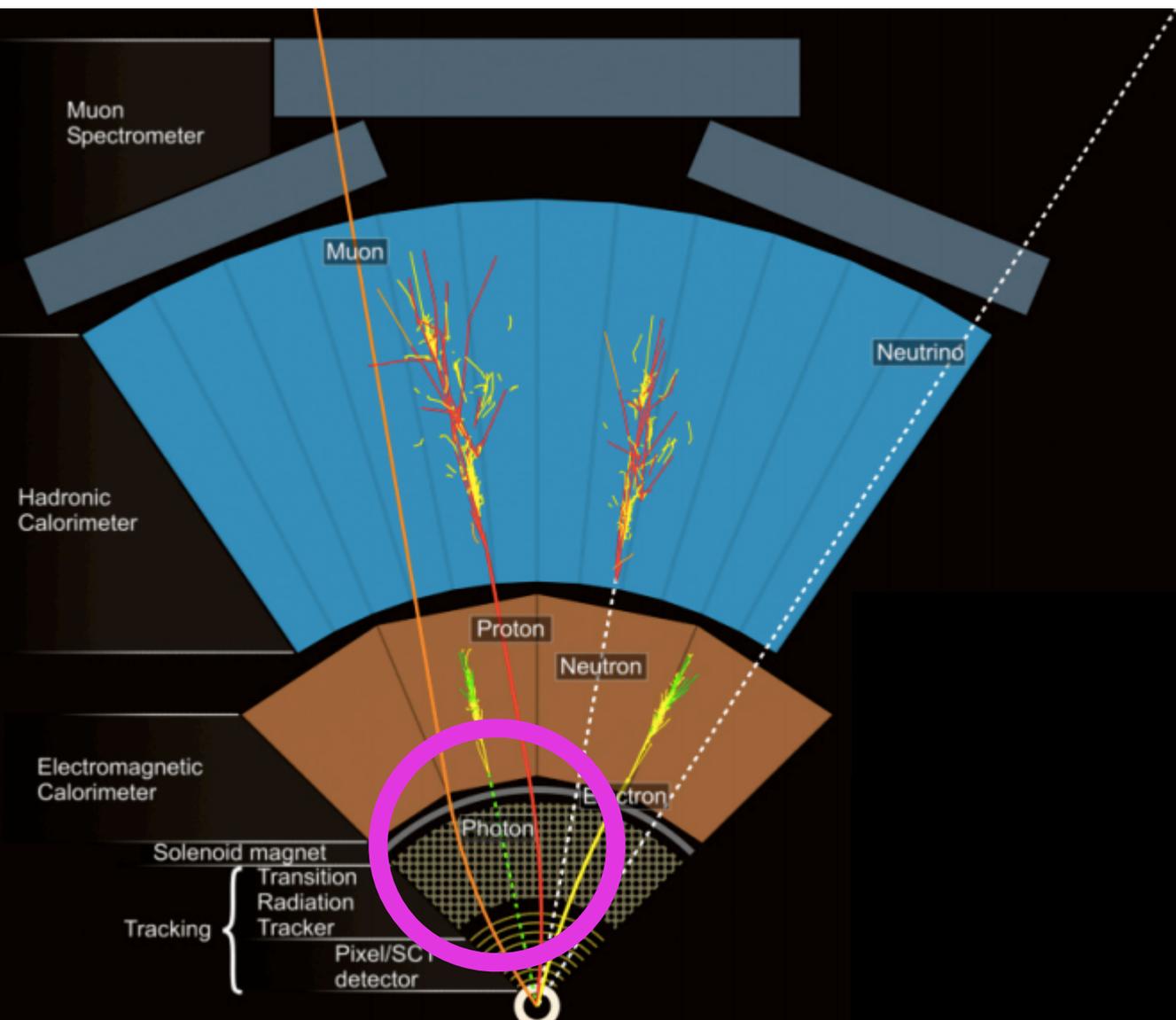
And muons! Have a set of toroidal magnets (giving ATLAS its shape and name) and more muon systems on outside of detector



Highly non-trivial B field. Need to monitor not just alignment but also field itself



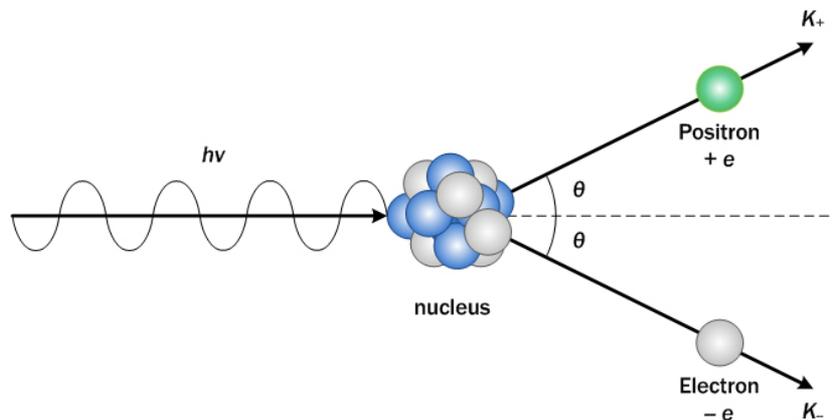
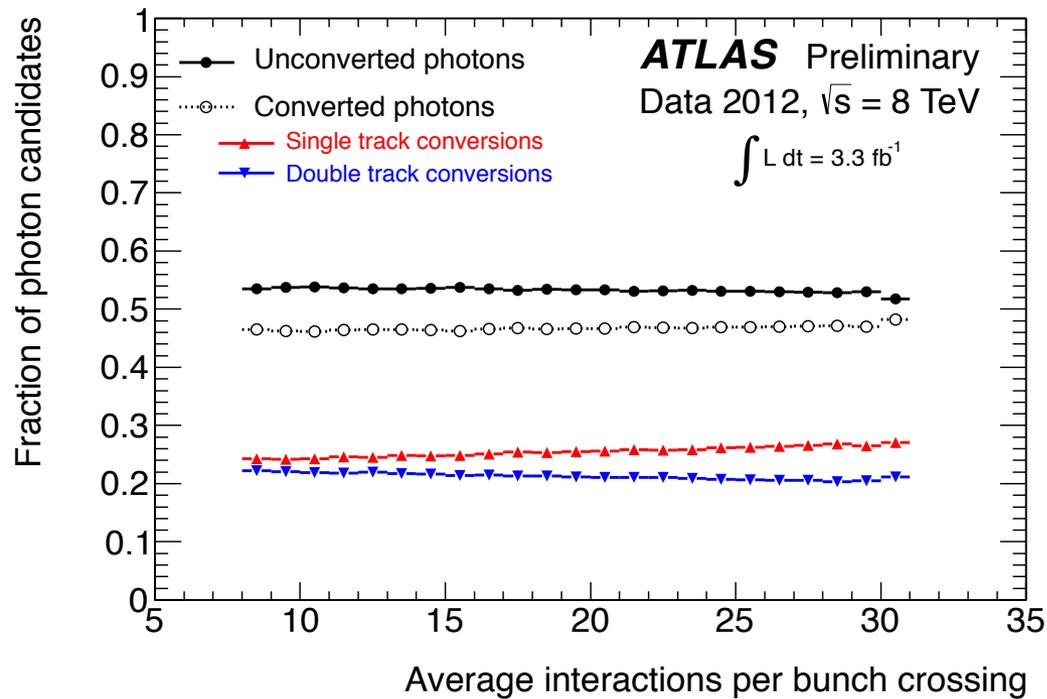
# Putting it all together



Photon can appear as isolated cluster in the EM calorimeter with nothing in hadronic calorimeter behind it and nothing else nearby. NO charged track pointing at calorimeter. Careful: lots of neutral pions!

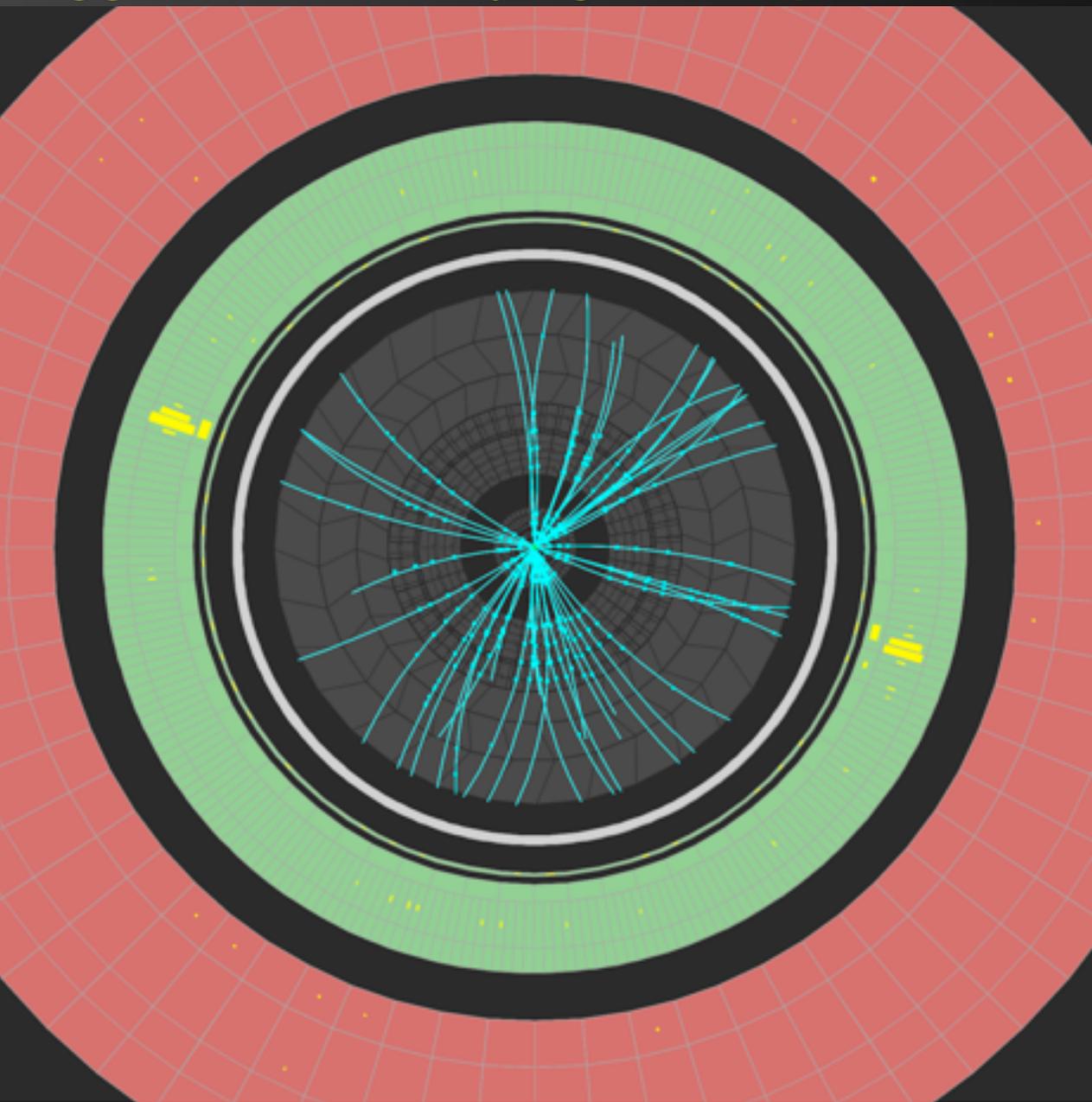
# Putting it all together

<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ElectronGammaPublicCollisionResults>



Need to be careful because almost half of the photons at ATLAS interact with material in the detector before reaching the calorimeter! These photons look similar, except there are one or two clusters of energy with charged tracks not coming from the original interaction. How can there be only one track? Other one can be very **soft** (low momentum)

# Higgs boson decaying to two photons

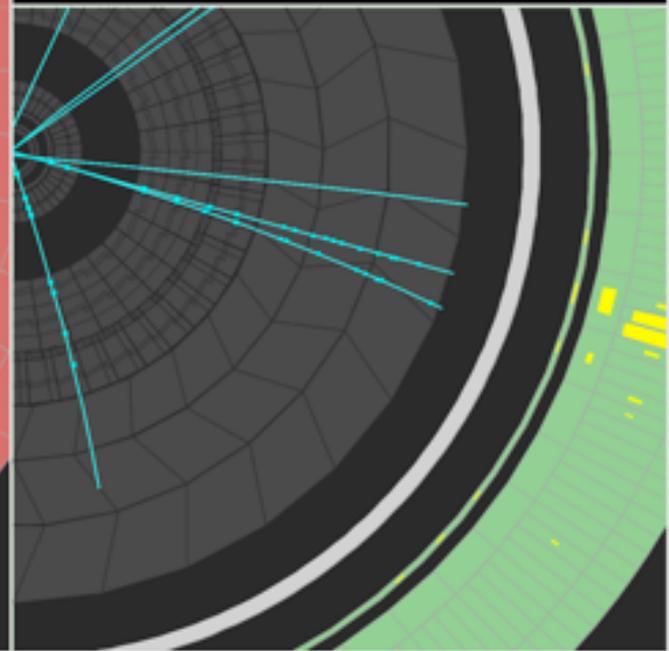


# ATLAS EXPERIMENT

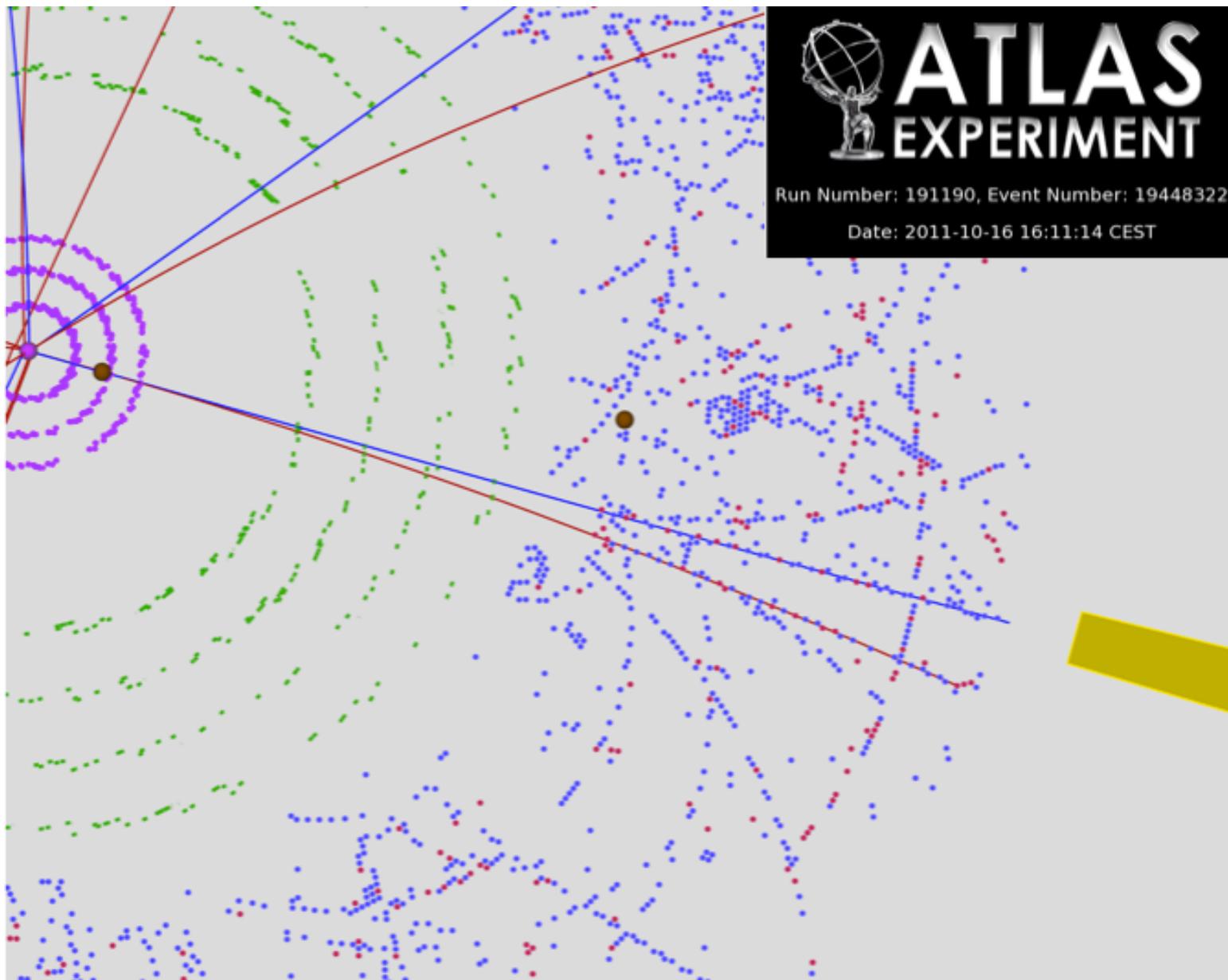
Run Number: 191190, Event Number: 19448322

Date: 2011-10-16 16:11:14 CEST

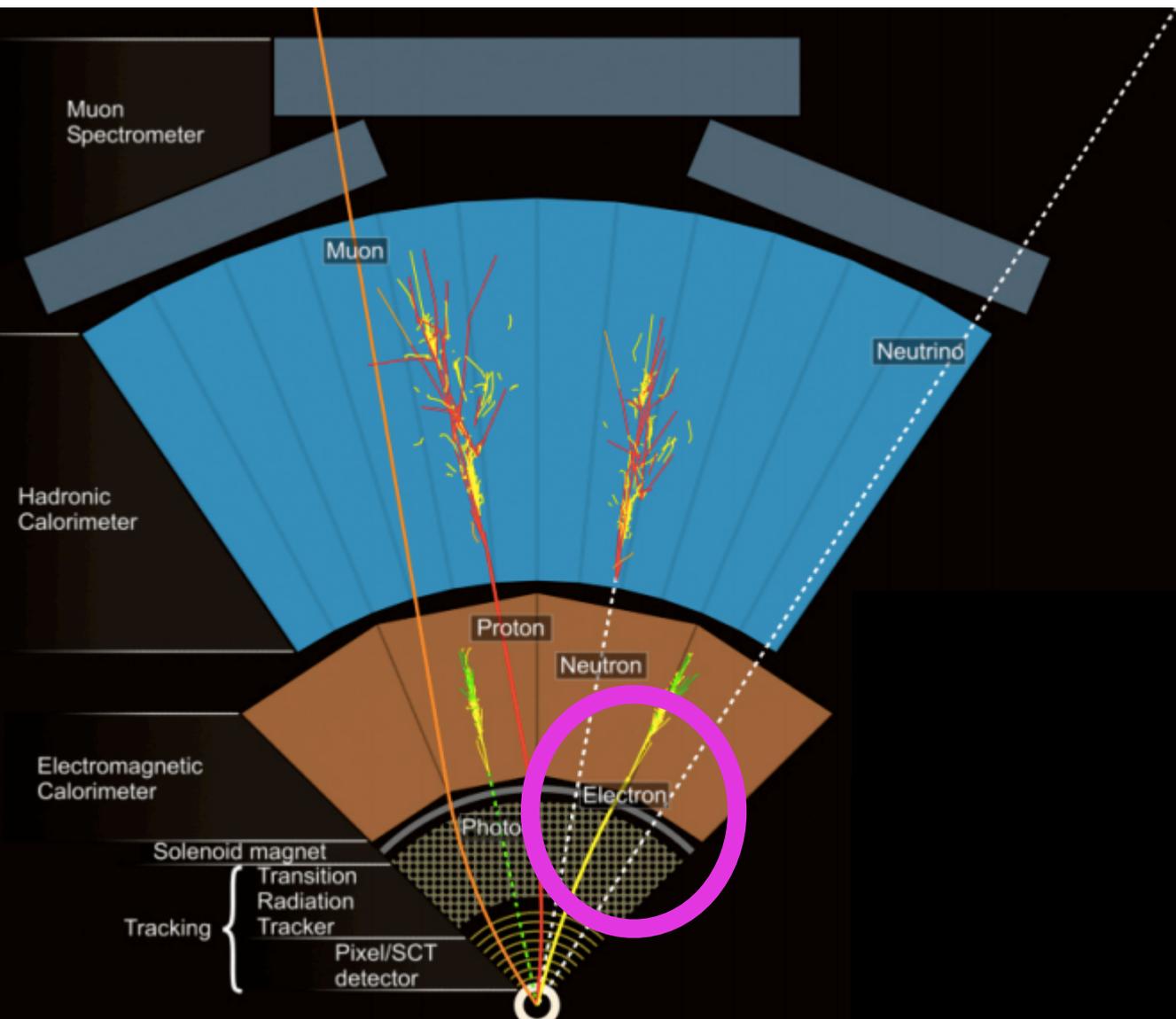
$$m_{\gamma\gamma} = 125.8 \text{ GeV}$$



# Zooming in on a converted photon

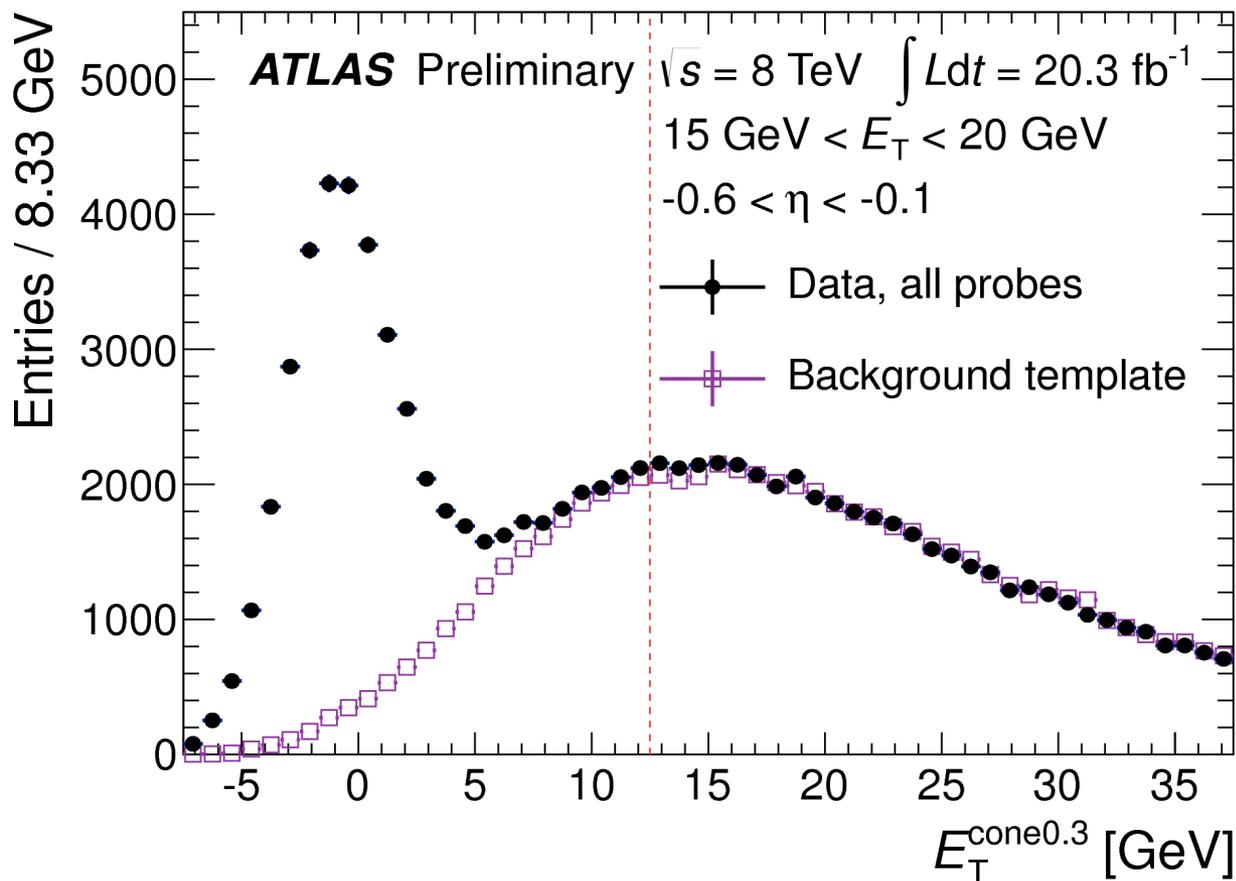


# Putting it all together



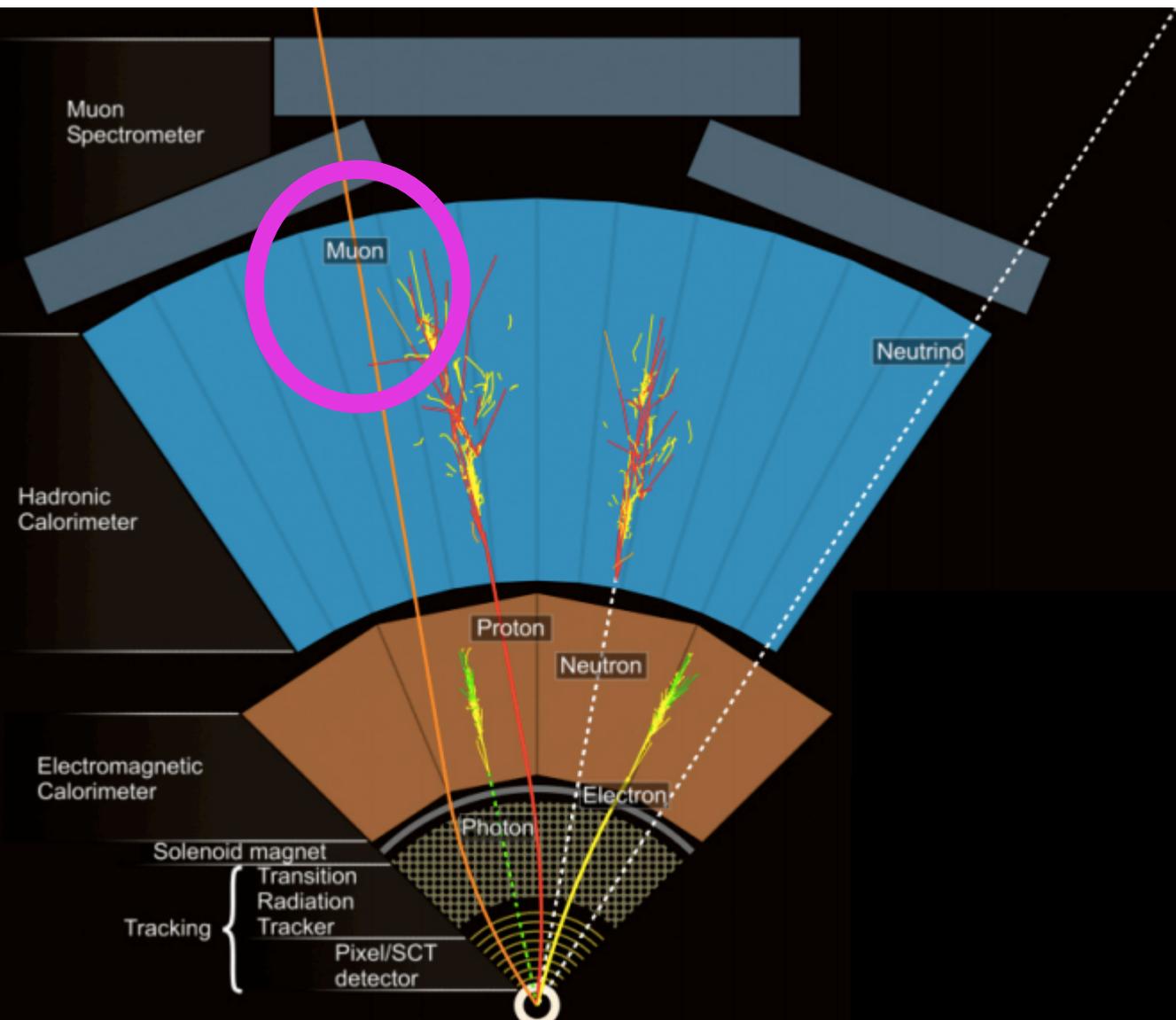
Electron appears as isolated cluster in the EM calorimeter with nothing in hadronic calorimeter behind it and a charged track. Photons and charged hadrons look like this too!

# Electron ID at ATLAS



“Isolation” of nearby activity (in calorimeters and also tracking system) can help us to distinguish real electrons from fake electrons

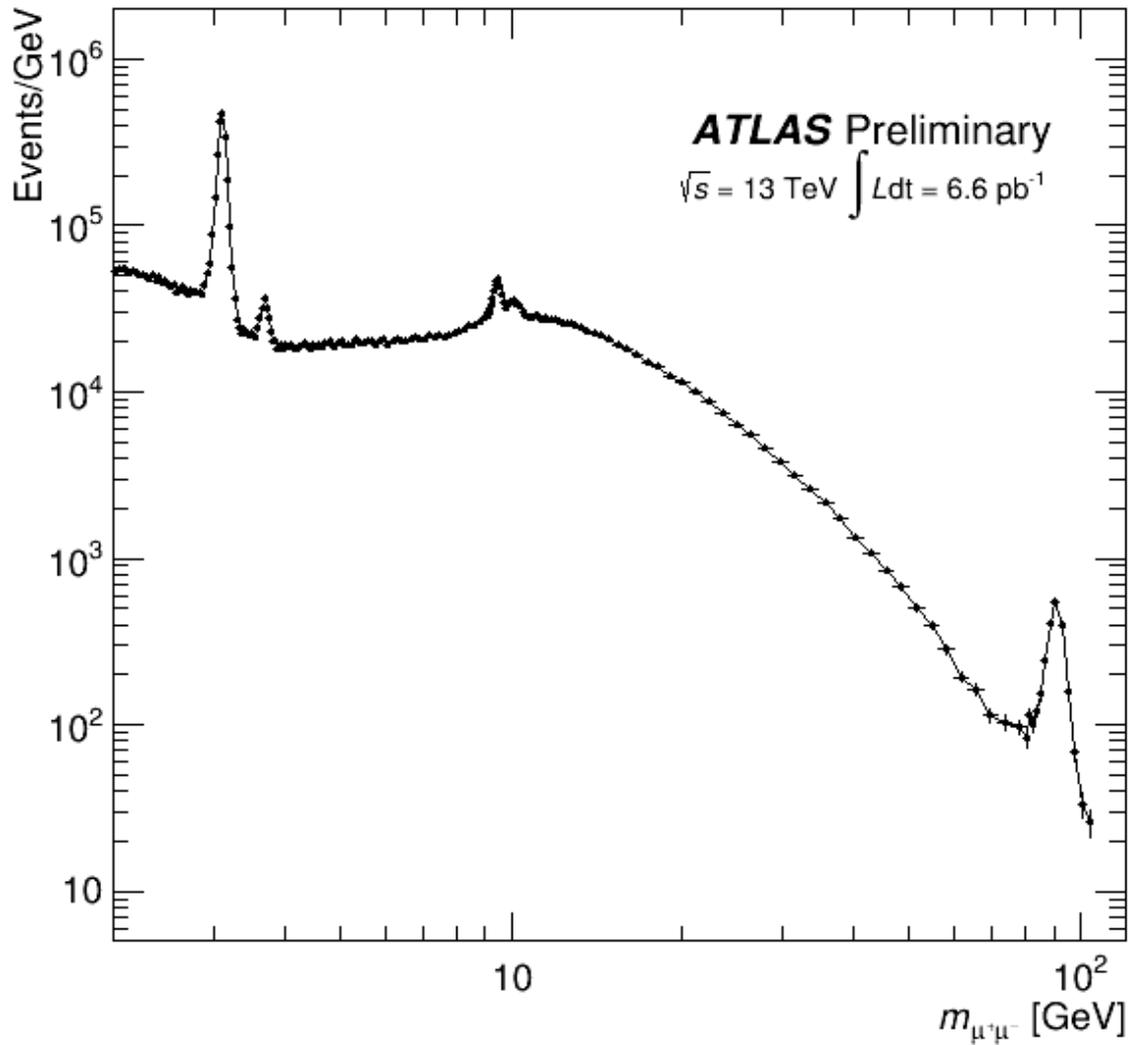
# Putting it all together



Muons appear as isolated, minimally ionizing particles in the calorimeter, with charged tracks in both the inner detector and also the muon spectrometer. Typically not so many fake muons, but can have **non-prompt** muons from hadron decays

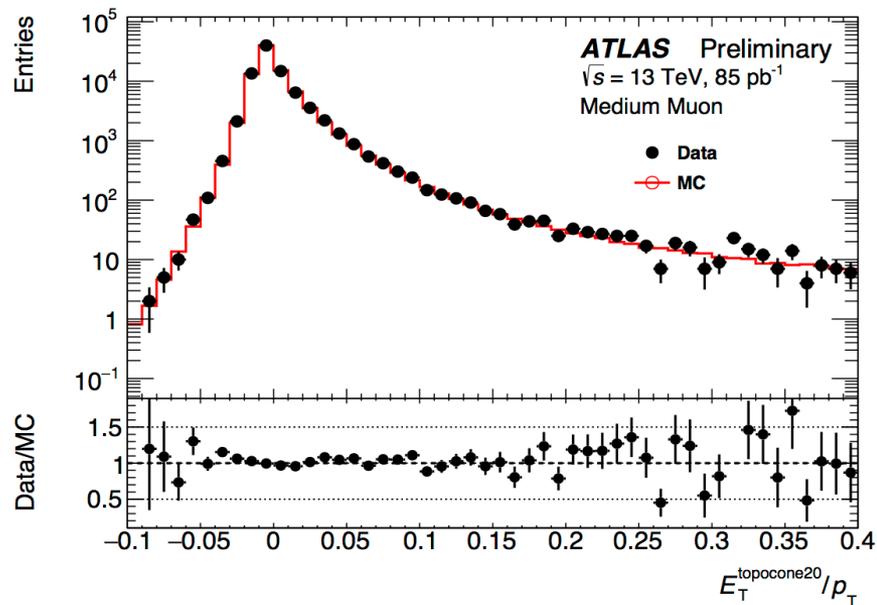
# Muon ID at ATLAS

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/MUON-2015-001/index.html>

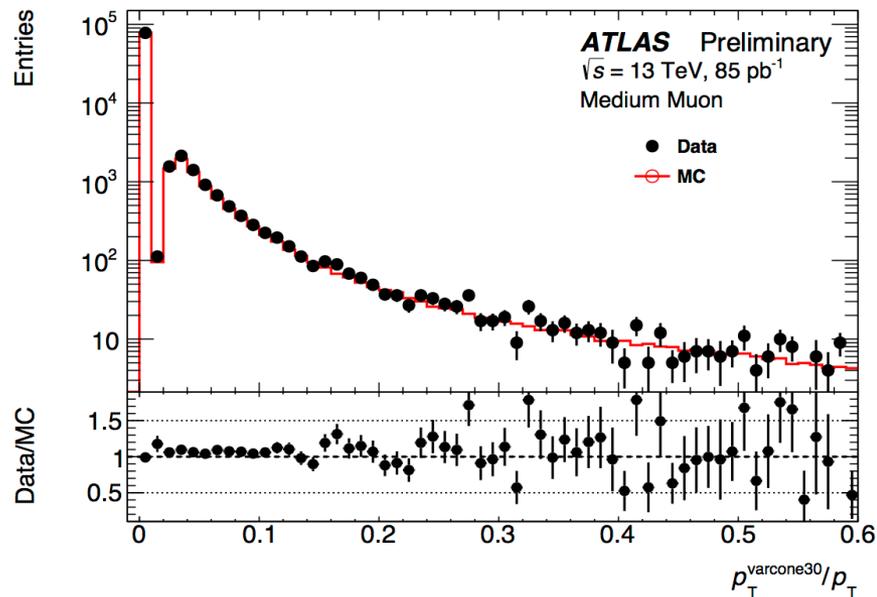


Beautiful  
invariant mass  
plot with early  
Run 2 ATLAS  
data

# Muon isolation

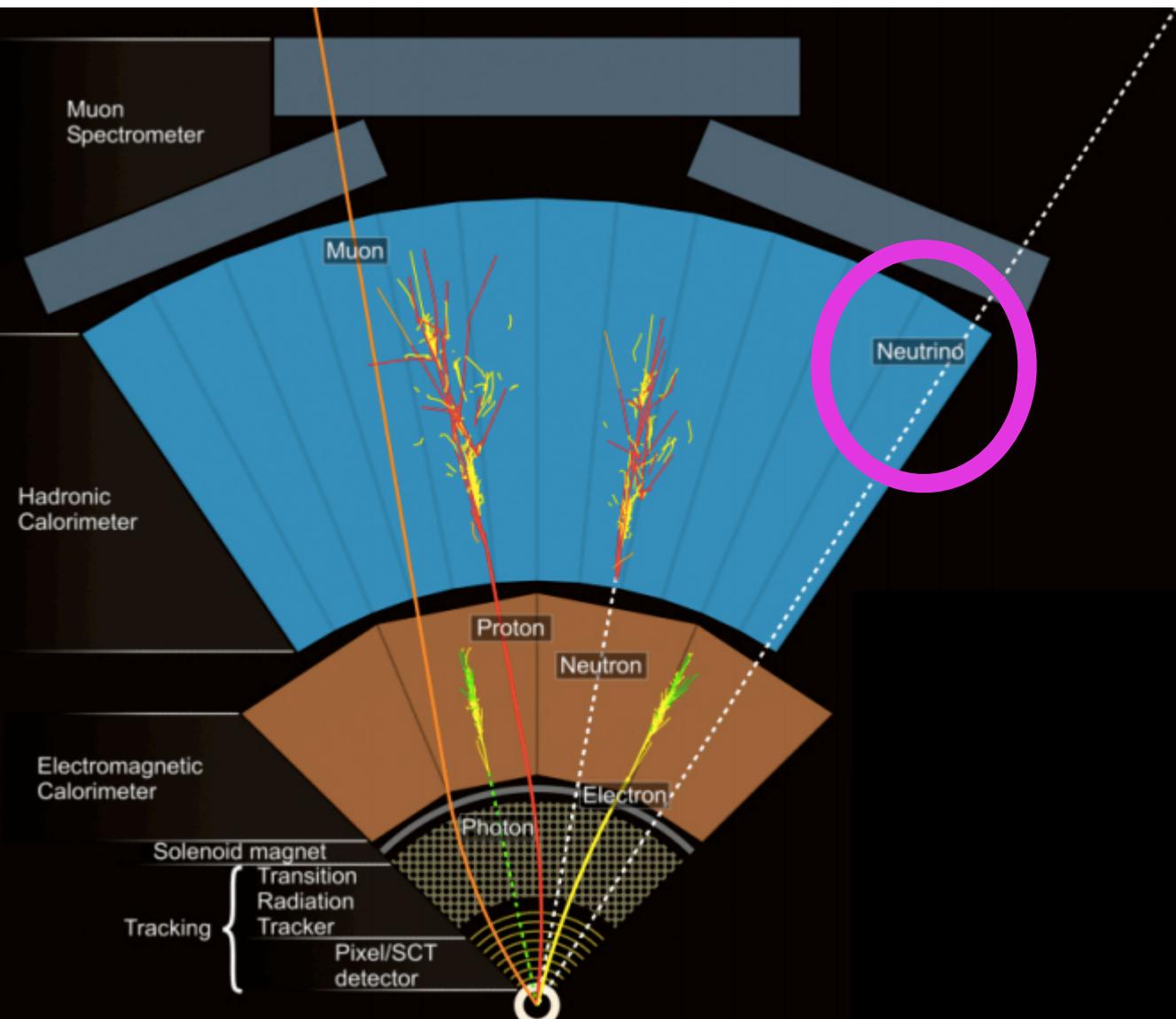


Let's look at these two isolation plots (from muons inside the Z boson mass window)

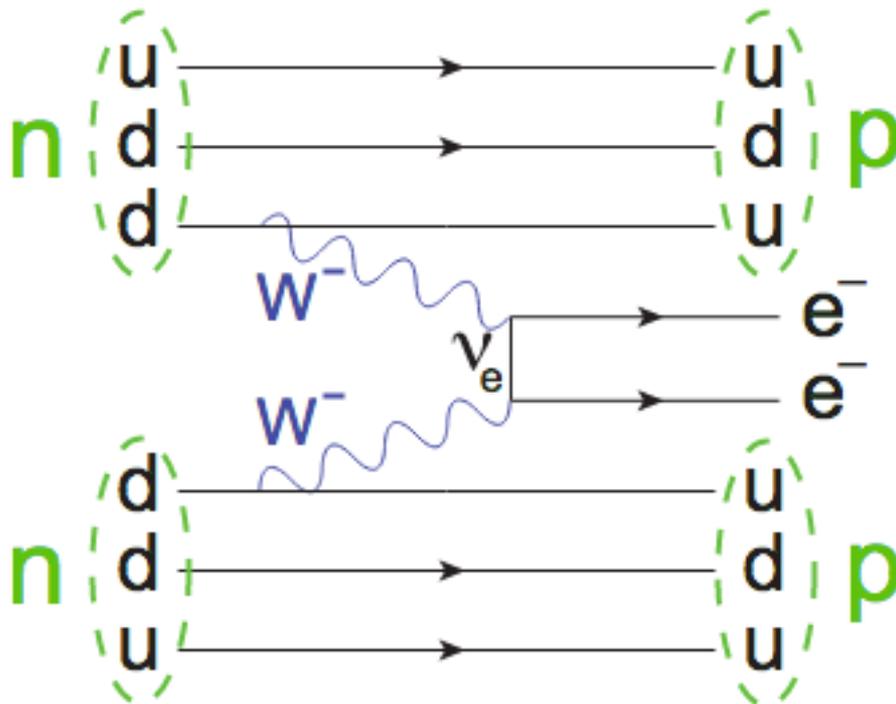


<http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2015-037/>

# Putting it all together



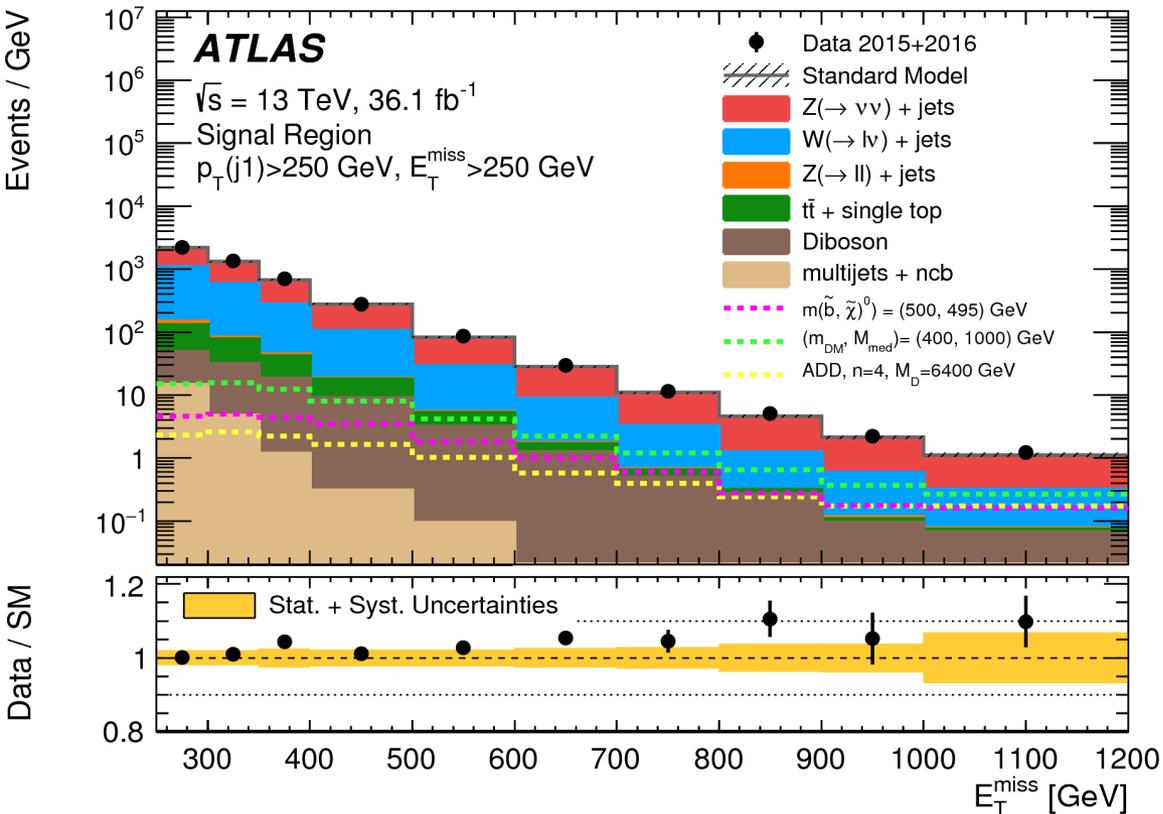
Neutrinos are not measured directly but inferred by applying the conservation of momentum to all measured objects



Any guesses?!

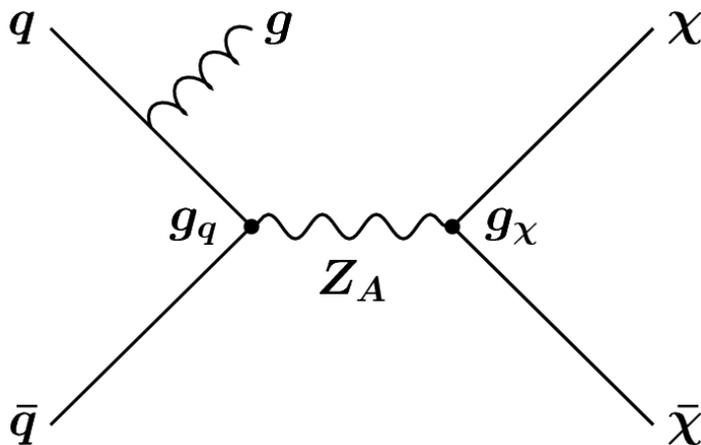
Are neutrinos Majorana particles (ie their own anti-particles)? Different than Dirac particles (not their own anti-particles). Would violate electron flavor number! How to observe this?

# Using “MET” at ATLAS



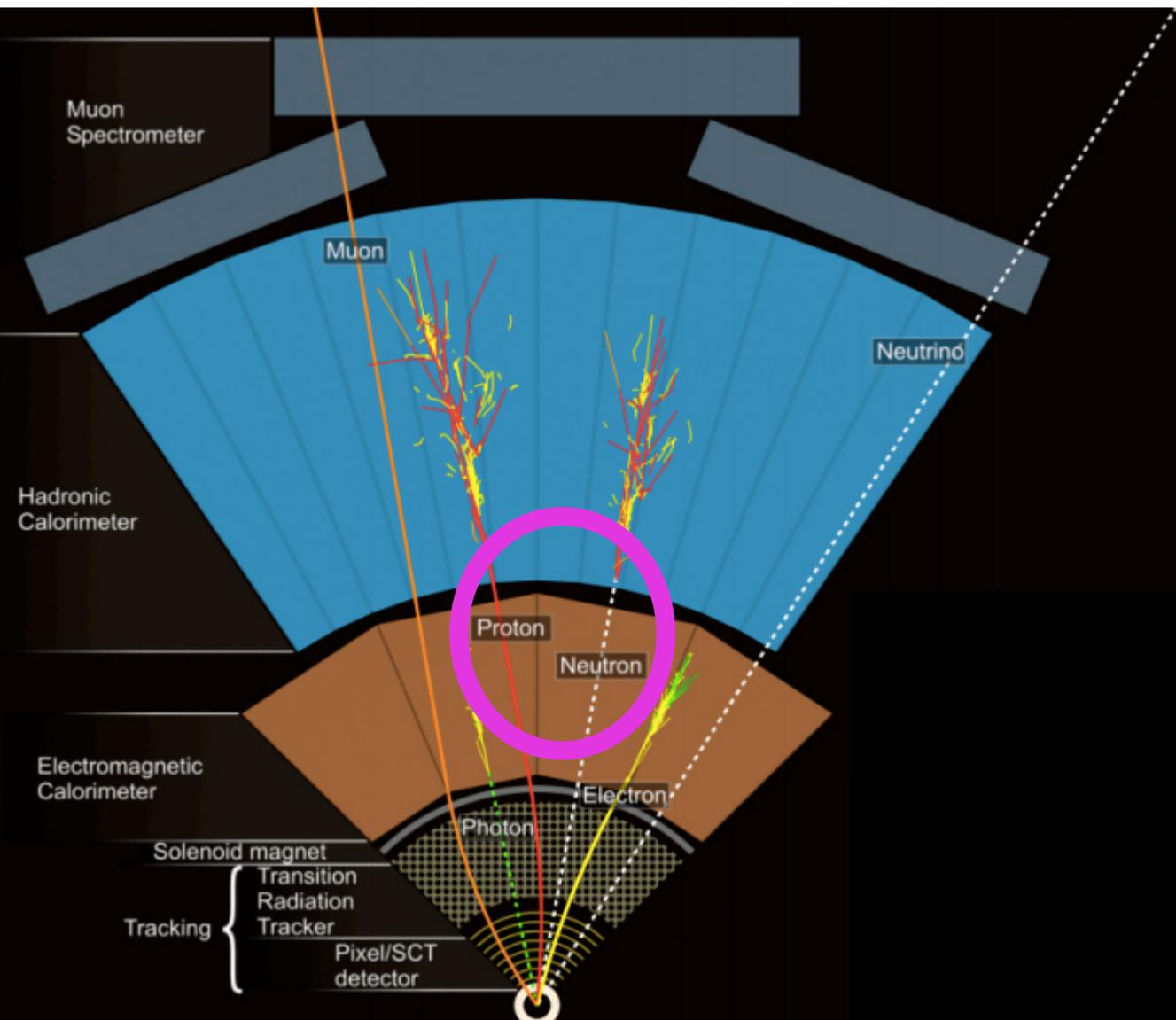
Note the nomenclature of “Missing energy” as part of “MET” even though energy is a scalar. Physicists are lazy!

Using momentum imbalance to look for dark matter production

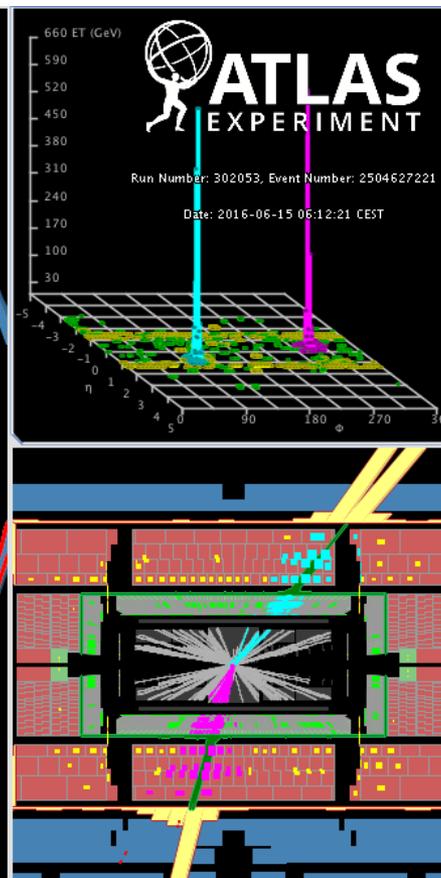
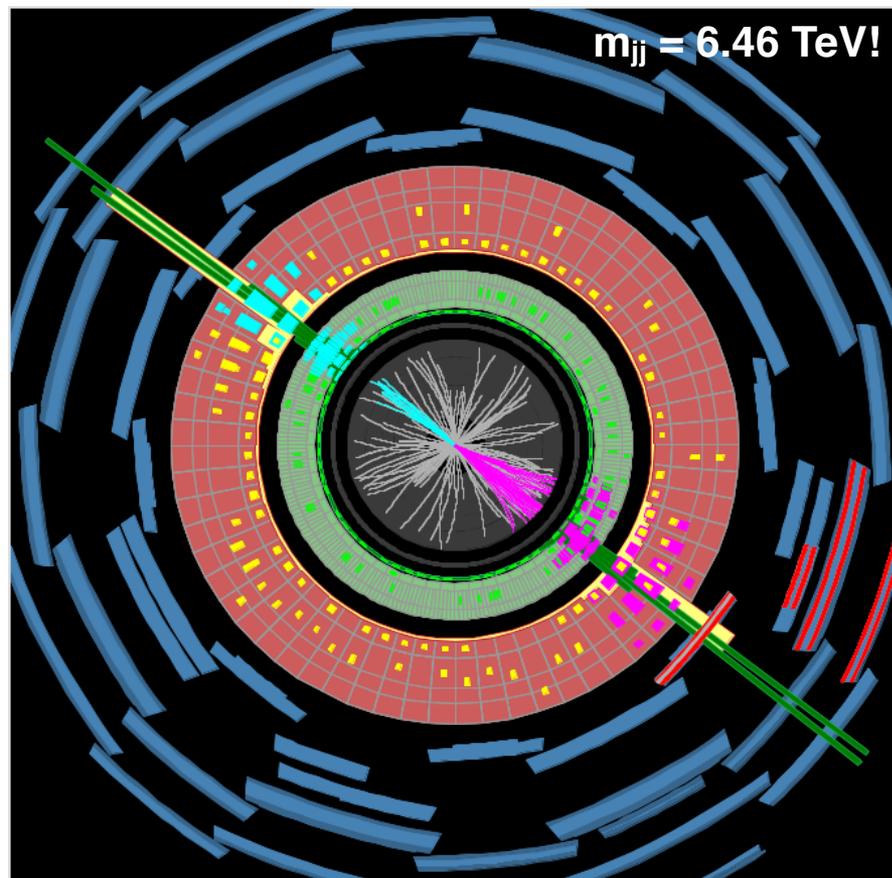


arXiv:1711.03301

# Putting it all together



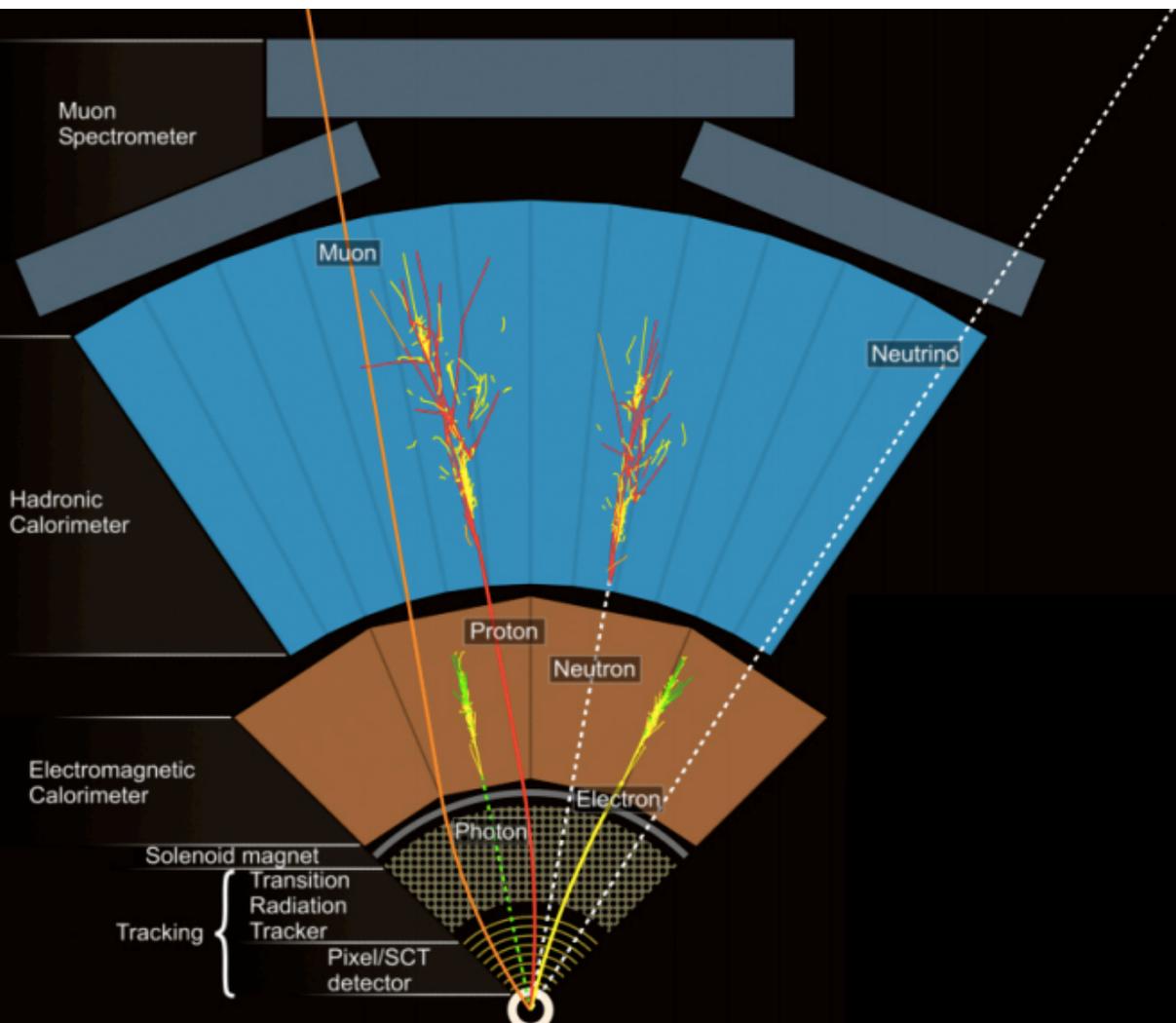
Protons leave charged tracks, neutrons do not. Both deposit energy in both the electromagnetic and hadronic calorimeters. Both typically not produced on their own but with lots of other particles nearby inside of a **jet**



Typical jet has ~60% of energy in charged particles (mostly pions), ~30% in photons from neutral pion decay, and 10% neutrals. On average, of course

In a process like  $pp \rightarrow qq\bar{q}$ , quarks are flying apart in opposite directions. They do not form a bound state together, but the energy pulling them apart leads to radiation of gluons and lots of other quarks, which decay to other objects with QCD color charge, which decay, etc into a collection of particles called a **jet**

# Putting it all together



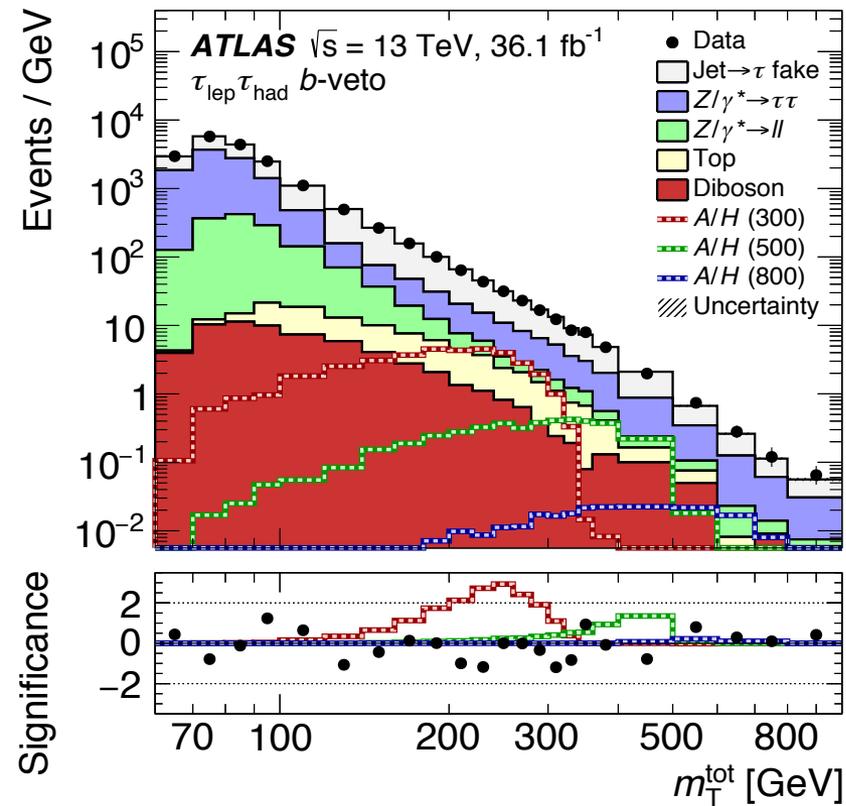
Taus can decay to

- an electron (18%);
- a muon (17%);
- a single charged pion and extra neutral pions decaying to photons (48%);
- three charged pions plus extra neutral pions decaying to photons (15%)

Taus are often reconstructed as a narrow collimated jet of 1 or 3 tracks

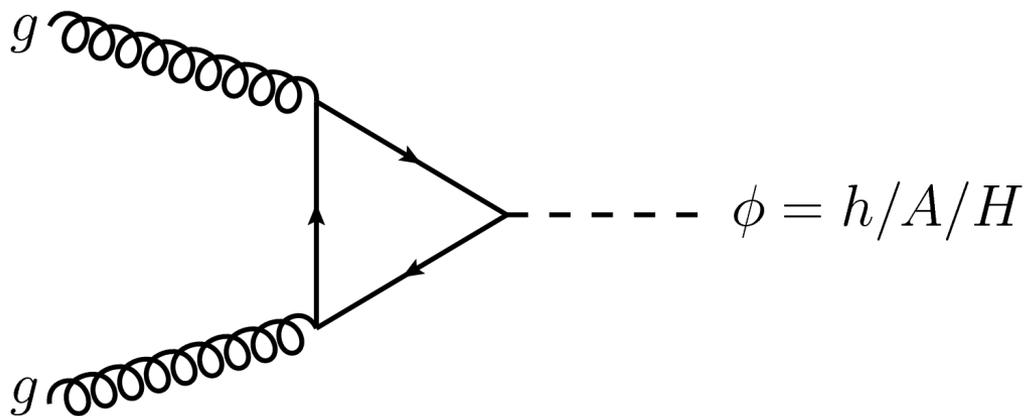
(Ignoring neutrinos)

# Using taus at ATLAS

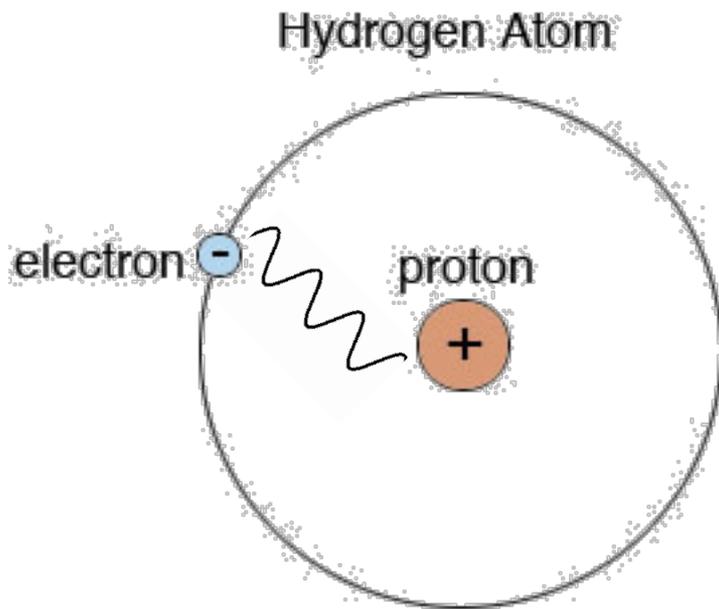


arXiv:1709.07242

In many models of Beyond Standard Model physics, new Higgs-like particles prefer to decay to heavy objects. Can have such objects decay to a pair of taus

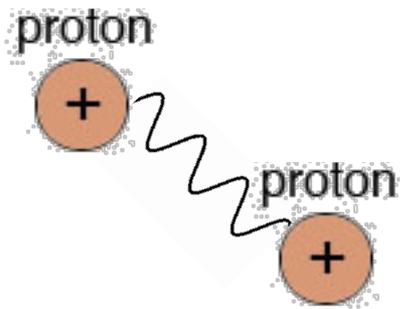






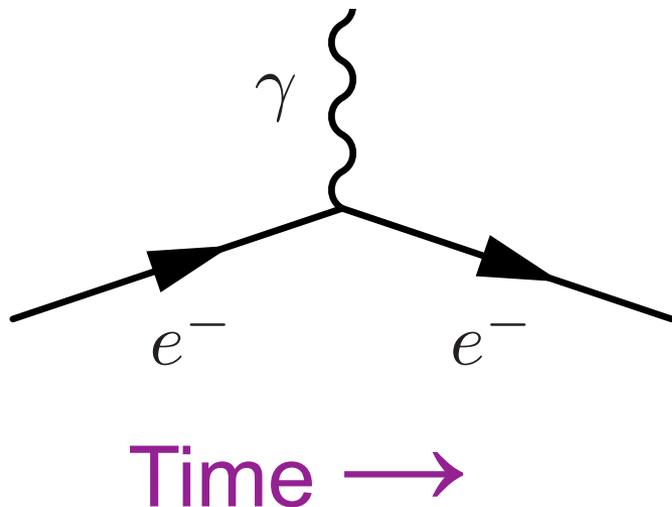
**Photon** as a particle (classical). But of course, what we really mean is that the field is quantized (here providing an attractive force), and the quantized unit of the field transmits some momentum from one object to another

But these forces can also be repulsive (more intuitive, actually)



**Photon** are still exchanged here, but now they transmit a repulsive force. It's a bit counterintuitive to think of forces being transmitted (or even better, '**mediated**') by particles, especially on a macroscopic scale, but we are anyway talking about single particles

# Feynman diagram

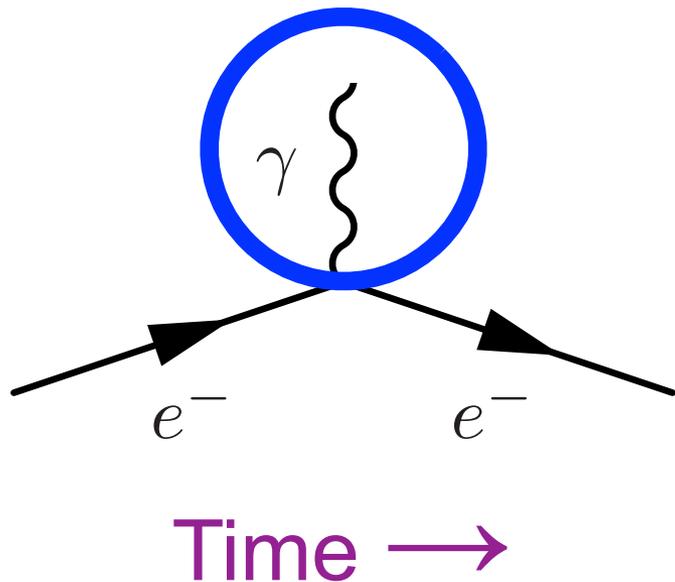


Think of time “passing” to the right, so initially (the “initial state”), we start with an electron. And at the end (in the “final state”), we also have an electron.,

At some intermediate time, there is a photon interacting with this electron (whether it emits it or absorbs it). We can combine multiple such diagrams

# Feynman diagram

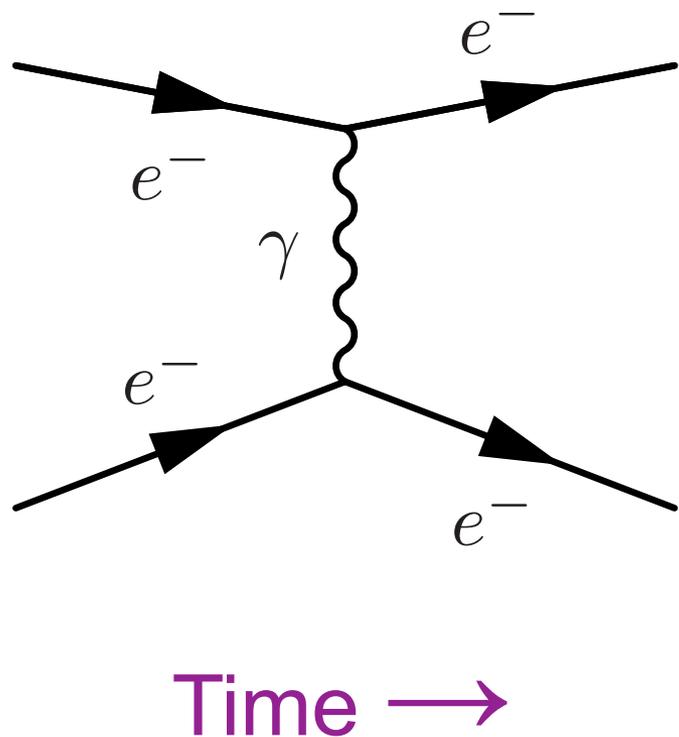
Note: Photon gets a squiggly line!



Think of time “passing” to the right, so initially (the “initial state”), we start with an electron. And at the end (in the “final state”), we also have an electron.,

At some intermediate time, there is a photon interacting with this electron (whether it emits it or absorbs it). We can combine multiple such diagrams

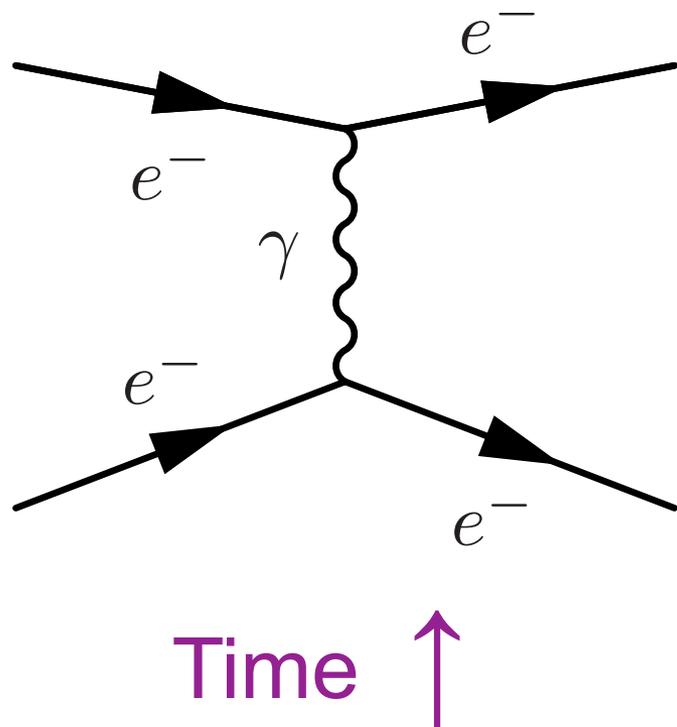
# Feynman diagram



At some initial time, there were two separate electrons. At a later time, there were also two electrons. At an intermediate time, they were exchanging a photon between them (repulsive force)

Møller scattering

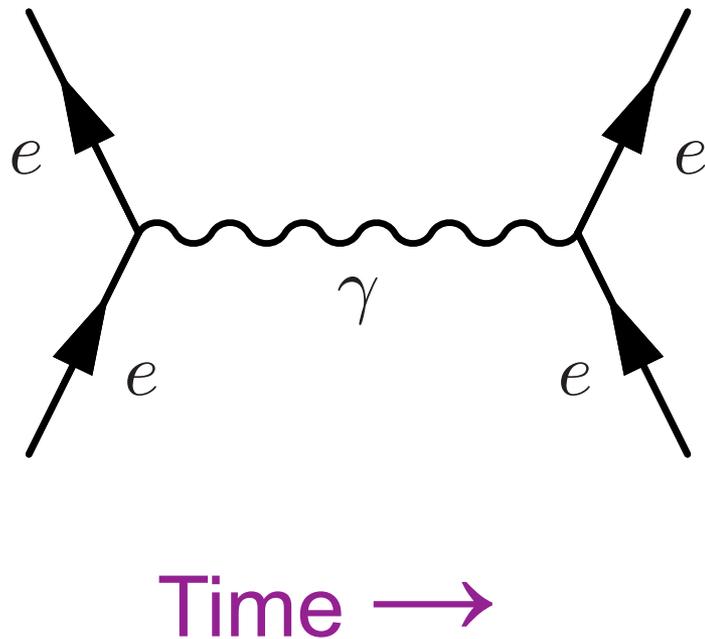
# Feynman diagram



What happens if we just change the direction of time? Everyone turn your heads now :)

Does this remind you of anything from earlier in the course?

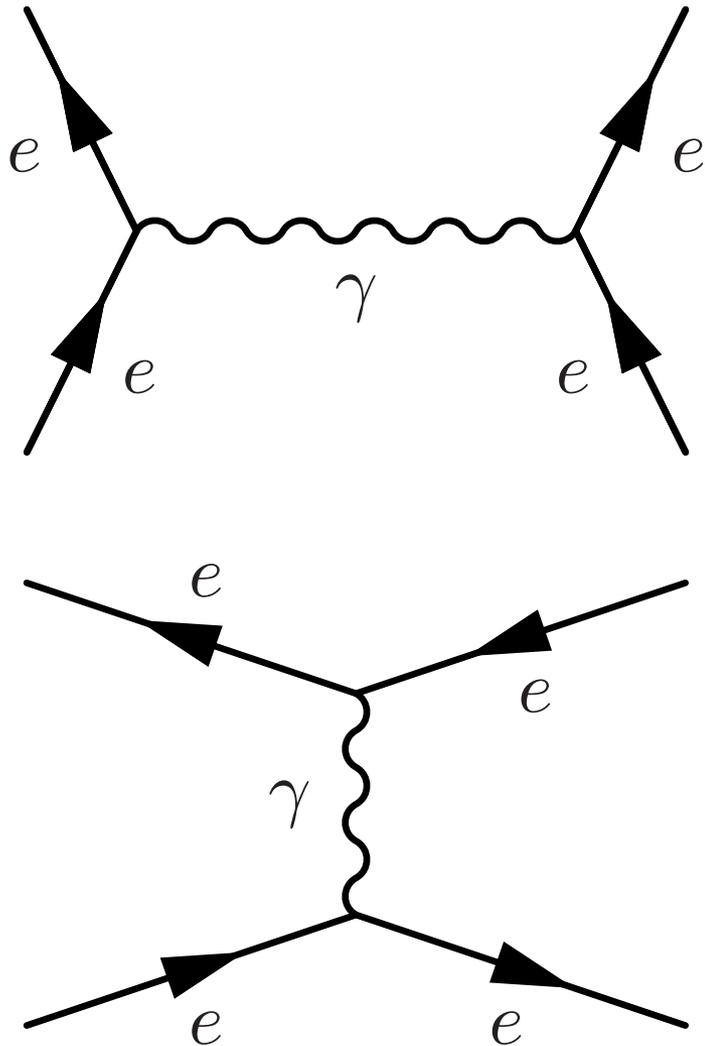
# Feynman diagram (I turned things for you)



Electron vs positron  
should now be more  
obvious/automatic

Here I put things back such that time moves to the right. Note that in the initial time (on left) there is a fermion line moving backwards! This is an antiparticle moving forwards in time. And on the right there is a fermion line also going backwards, this is again an anti-particle

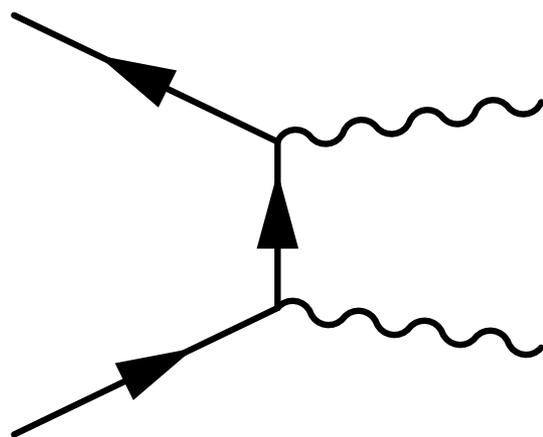
## Bhabha scattering



Note the second diagram below... start with  $e^+e^-$  and end with  $e^+e^-$  ... these two diagrams are both needed (same initial and same final states, so they must interfere quantum mechanically!)

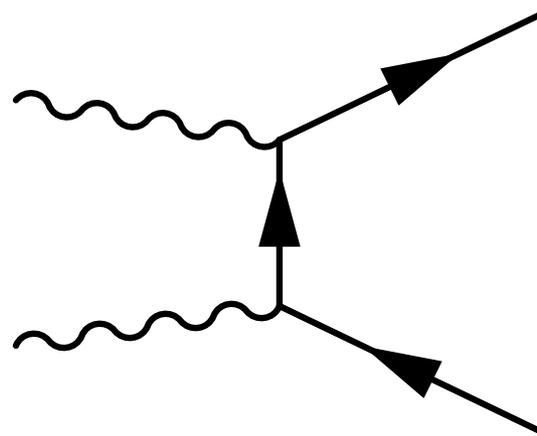
# Feynman diagrams (note crossing symmetry again!)

## Pair annihilation



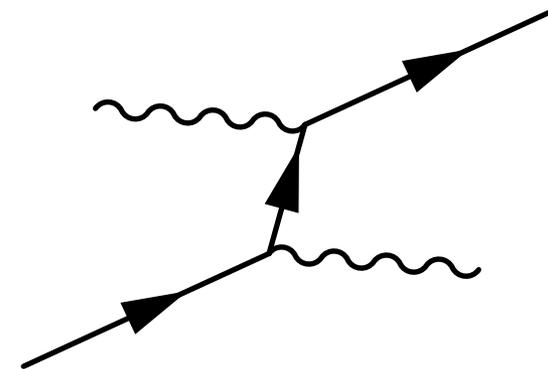
$$e^-e^+ \rightarrow \gamma\gamma$$

## Pair production



$$\gamma\gamma \rightarrow e^-e^+$$

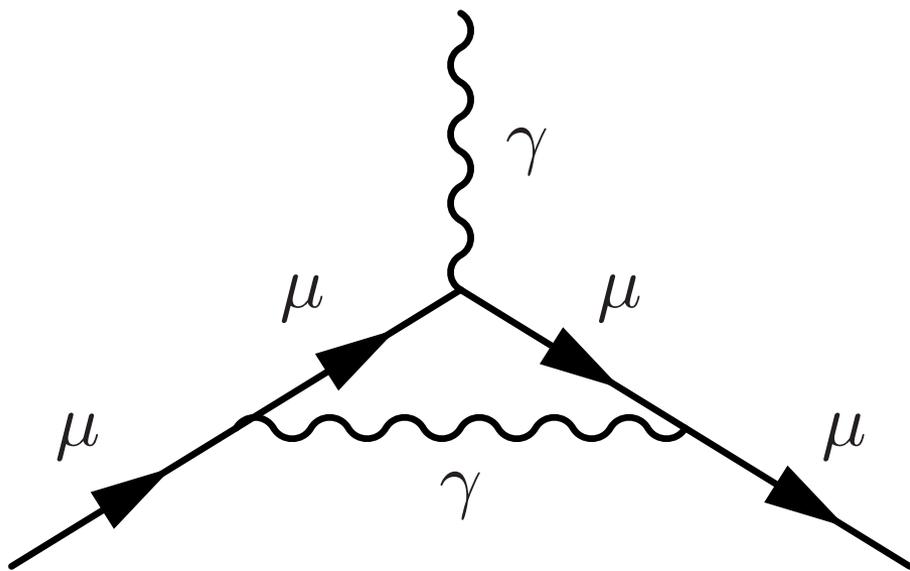
## Compton scattering



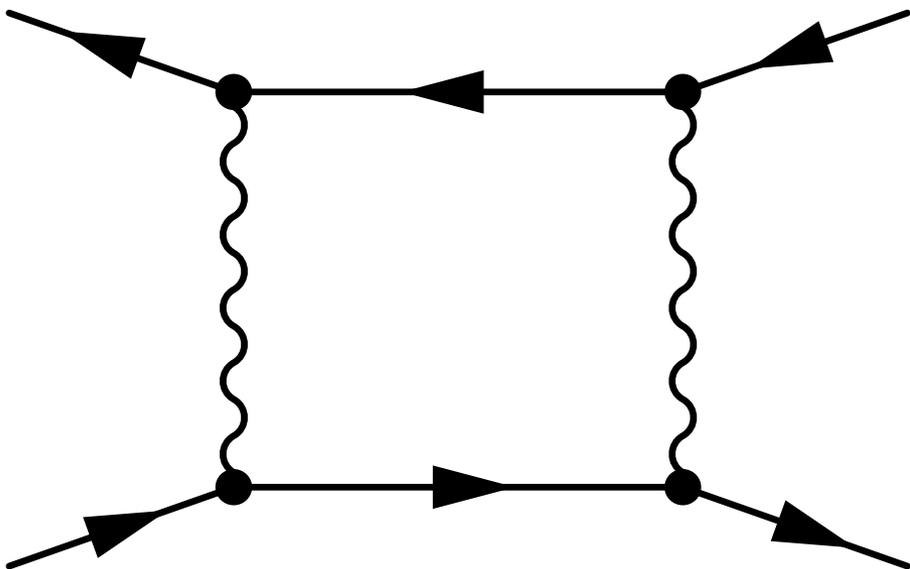
$$e^-\gamma \rightarrow \gamma e^-$$

Electrons here could be replaced by other objects with electric charge. Note that Feynman diagrams so far just look like pictorial ways to represent processes, but they can be used for much more, as we'll see

We can start to combine these...

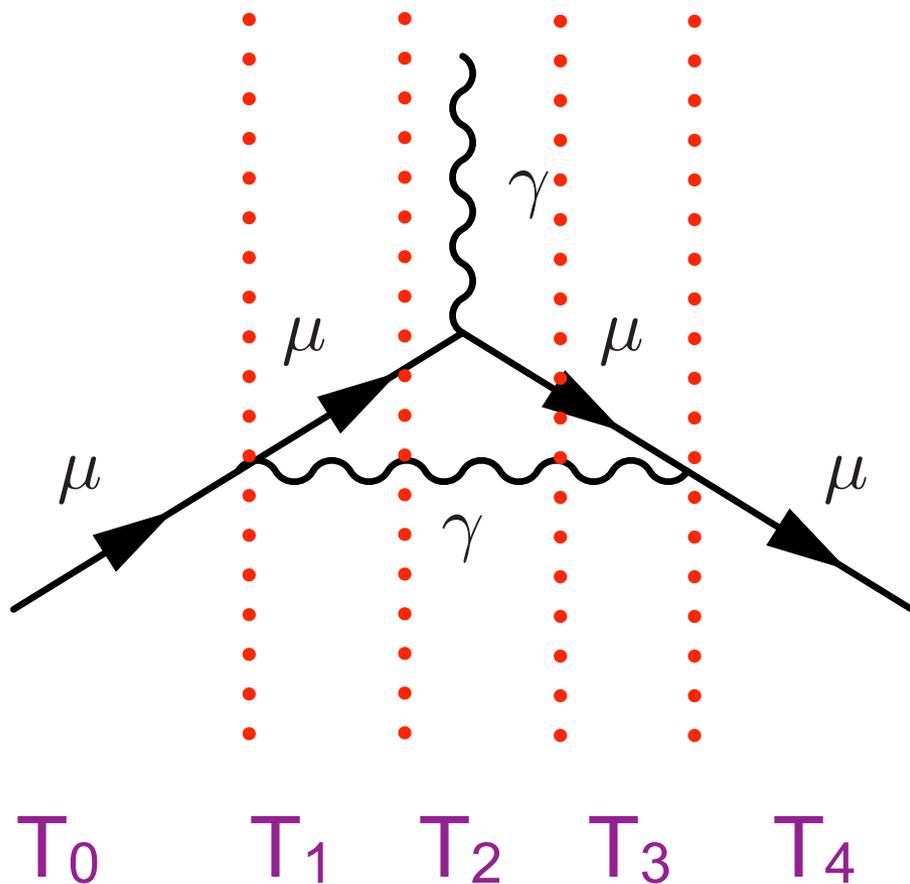


What is this? Does it remind you of any experiment that NIU works on? :)



Modification to Møller scattering (same initial and final states, different diagram)

# Let's take a closer look at these diagrams

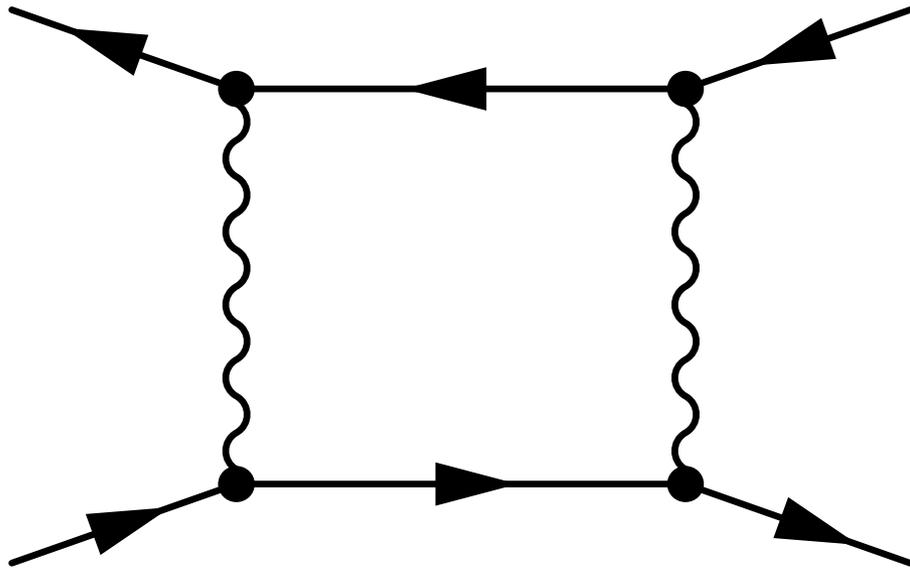


- $T_0$ : Single initial muon
- $T_1$ : Muon after interaction with photon, and that photon
- $T_2$ : Some external photon, muon after interaction with one or two photons, the internal photon
- $T_3$ : Muon after interaction with external photon, before reabsorbing the internal photon
- $T_4$ : Single final muon

Let's slice this up into different time bins

Can cleanly divide into **internal** and **external** particles

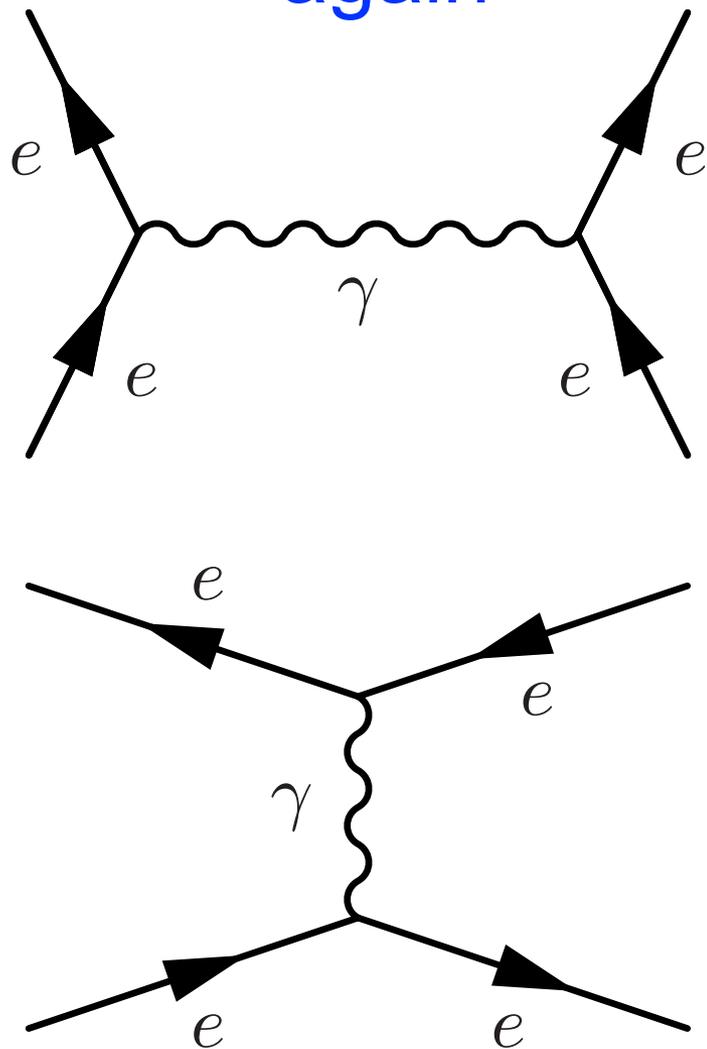
# Let's take a closer look at these diagrams



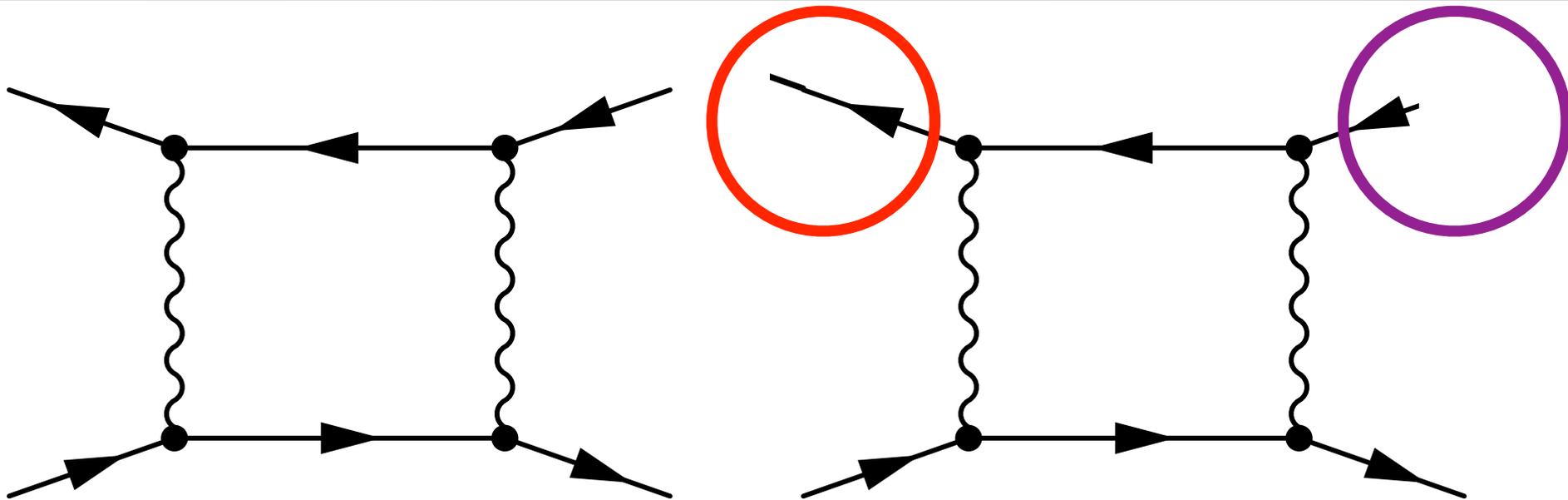
There are eight different particles in this diagram. Four of them are **external** to the diagram and **can be observed**.

The other four are **internal** to the diagram and are called **virtual particles** and do **not** have to have on-shell mass

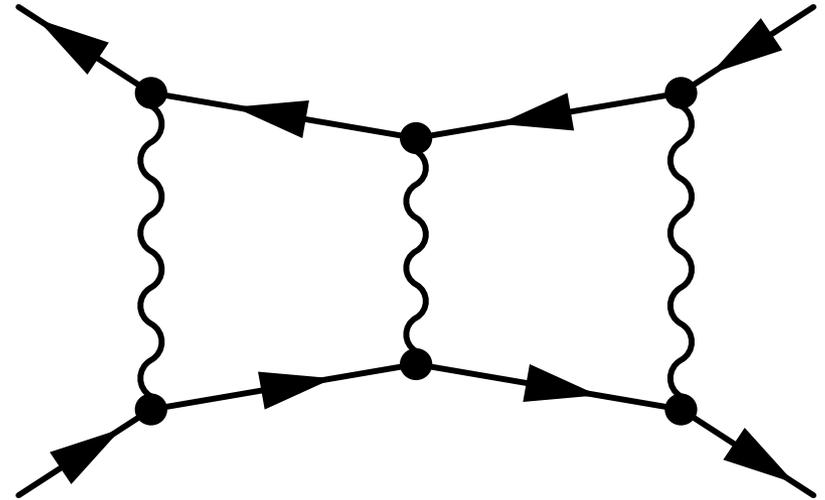
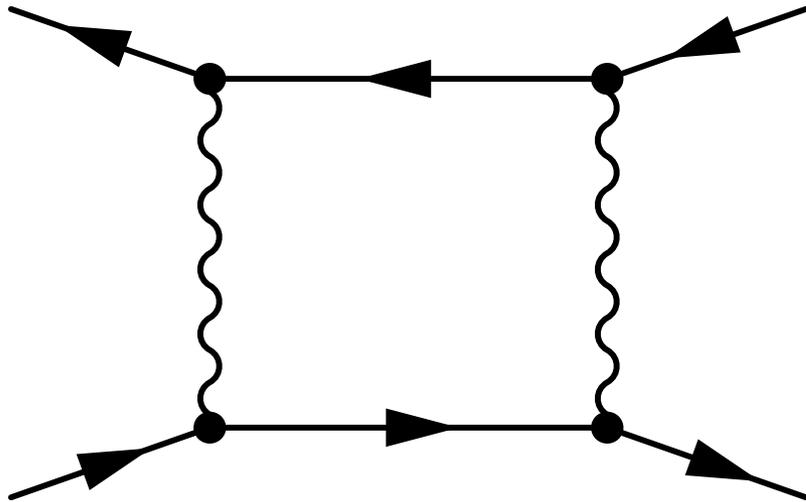
## Bhabha scattering again



Virtual particles here (the photon in each diagram) cannot be observed, since the initial and final states are the same, so these much have interfering matrix elements

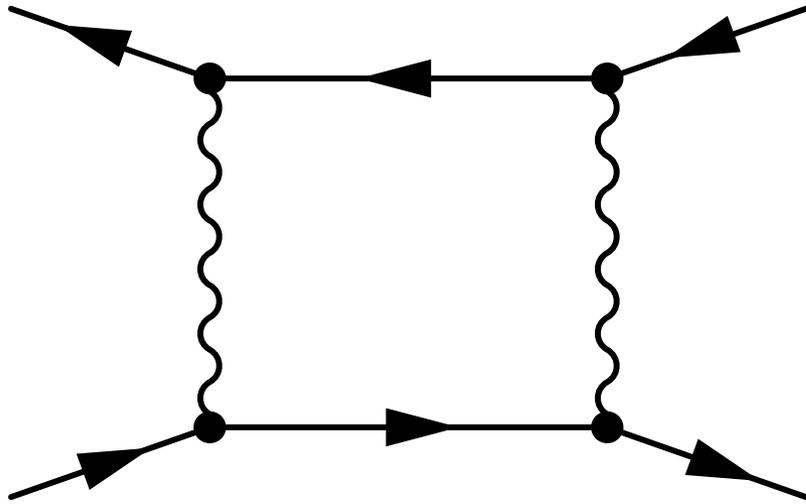


Have **extended one line** and **shrunk another**. Could have spaced things further apart or closer together - we do not differentiate between these sorts of things, nor the angle of the lines (**we are not artists, here, or at least, I am not**)

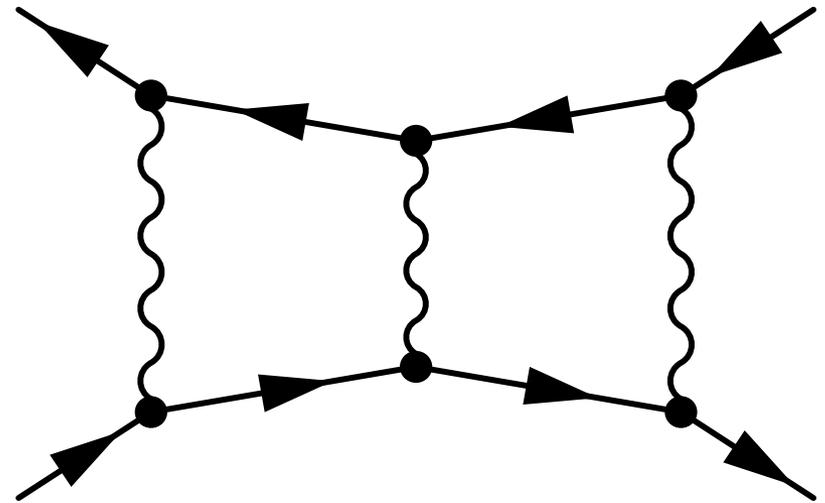


Again, can't distinguish these diagrams.  
So the observable scattering amplitude  
must be due to the sum of all such  
diagrams ... but there are an infinite  
number of them! Let's draw another few

# On diagrams

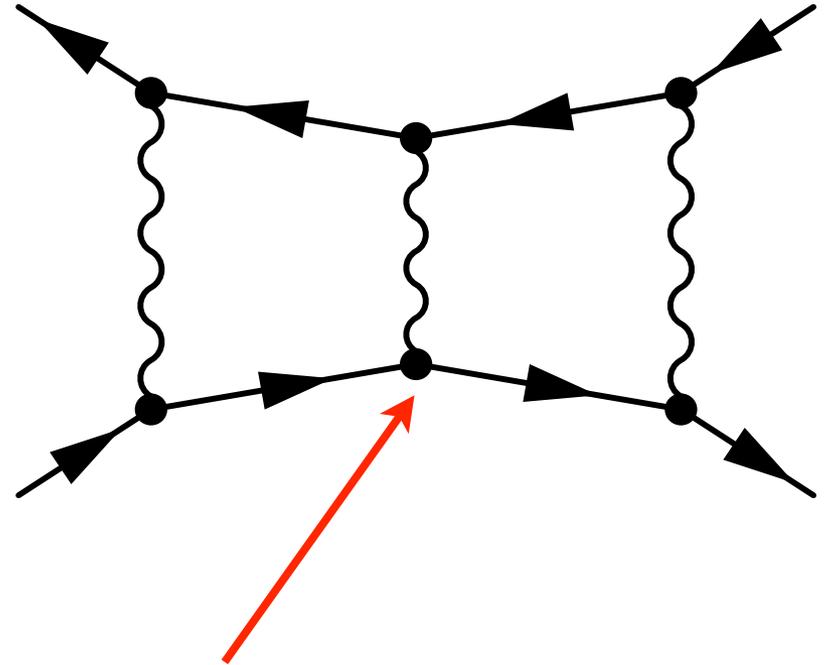
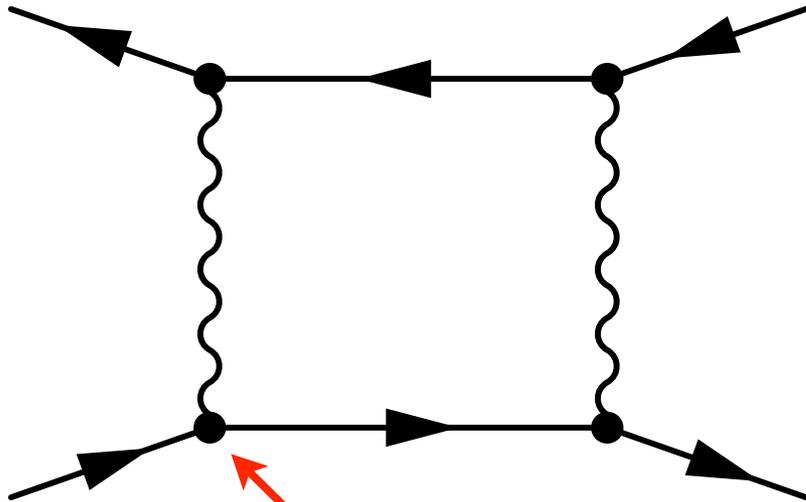


$$e^+e^- \rightarrow e^+e^- \rightarrow e^+e^-$$



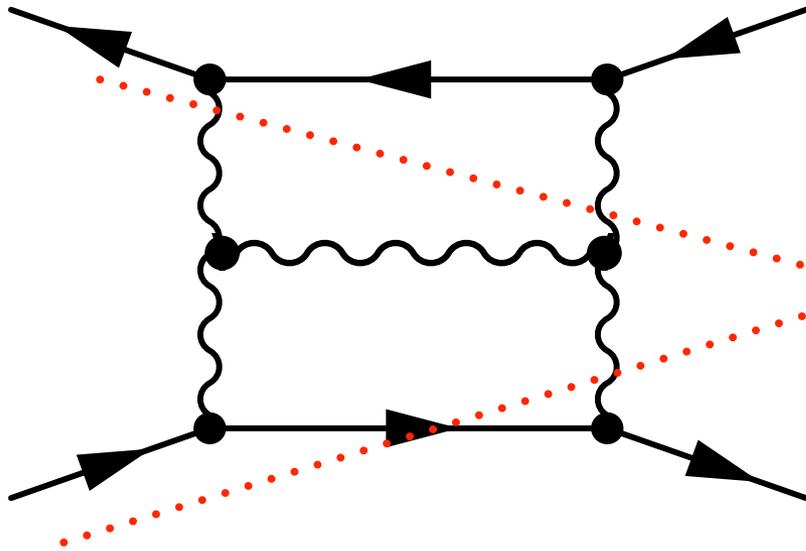
$$e^+e^- \rightarrow e^+e^- \rightarrow e^+e^- \rightarrow e^+e^-$$

$e^+e^- \rightarrow e^+e^-$  in both cases, since intermediate states are not observable. You might ask why we're bothering to draw such pictures, but they will shortly become an invaluable computation tool. Each of these represents a single number!

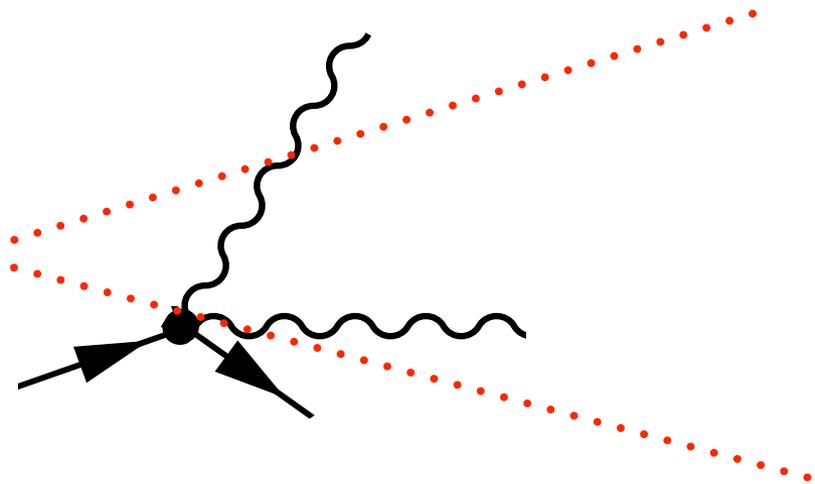


You may have noticed that I started putting circles at each interaction point - these are **vertices** and describe a point in space-time where an interaction occurs.

# NOT valid

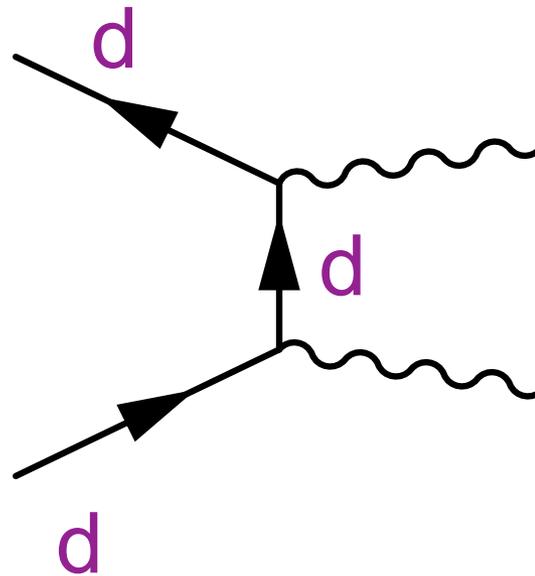
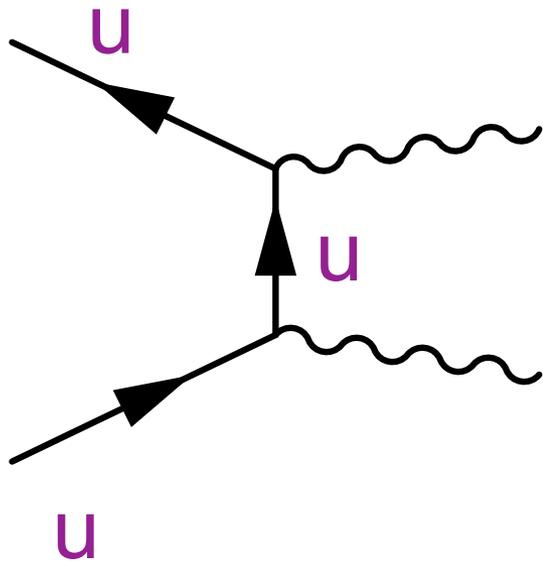


There is no such photon-photon-photon vertex in the SM (of course, you should know that already - the photon does not carry electric charge)



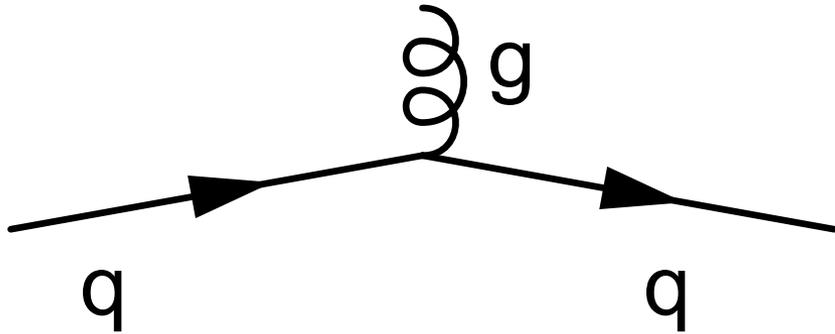
Muons can emit multiple photons, but not at the same vertex (note that the solid lines here represent any particle with electric charge)

## Pair annihilation again, with quarks

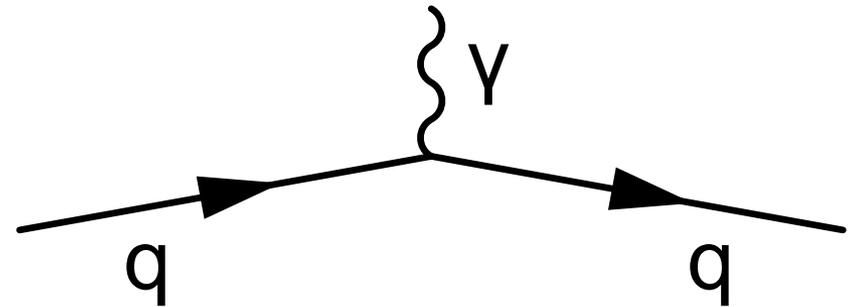


Now we can see why neutral pions decay 99% of the time to a pair of photons, and also why this happens so quickly (any good answers?)

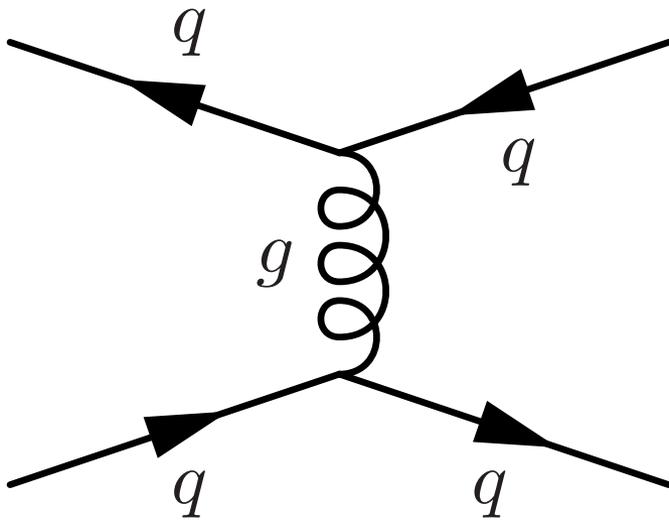
Start with common building block:



Note the similarity with the common building block of QED:

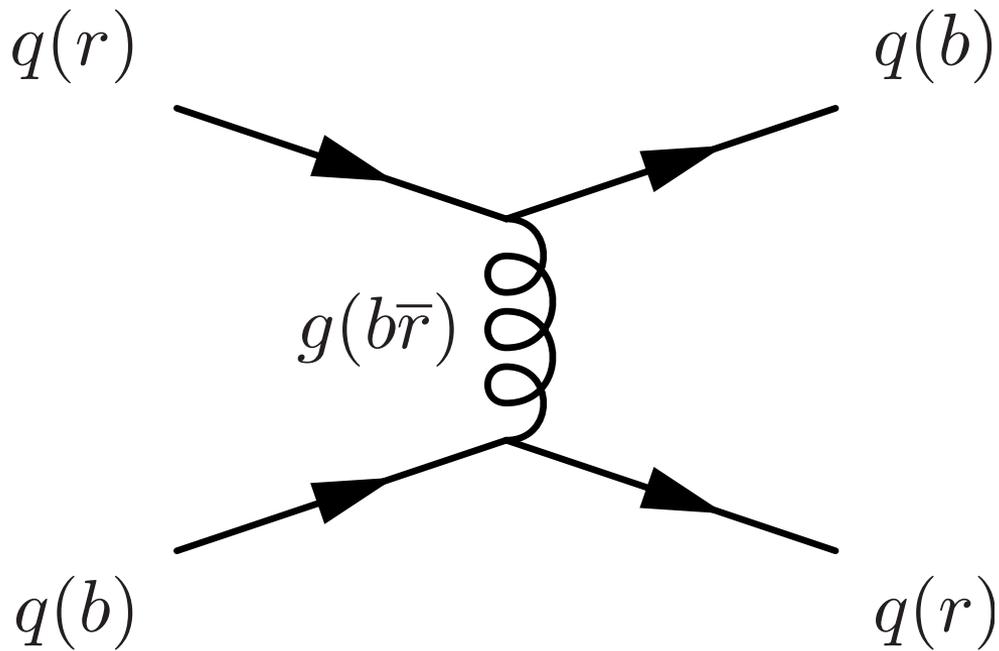


## Glueon exchange between quark and anti-quark:



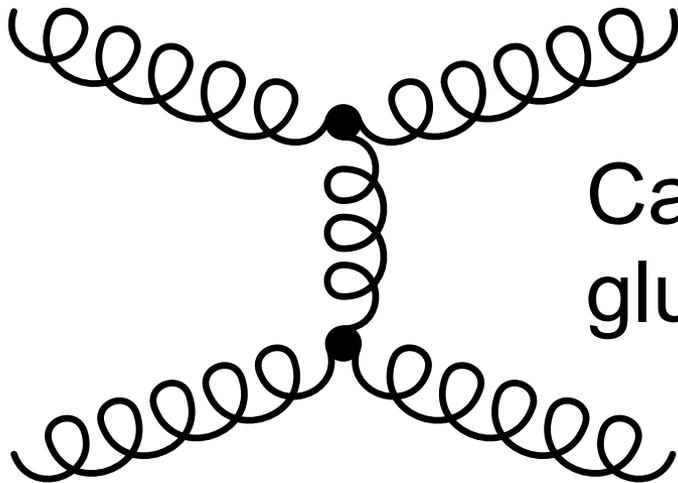
A few  
fundamental  
differences,  
though, between  
QED and QCD...

## Gluon exchange between quarks:



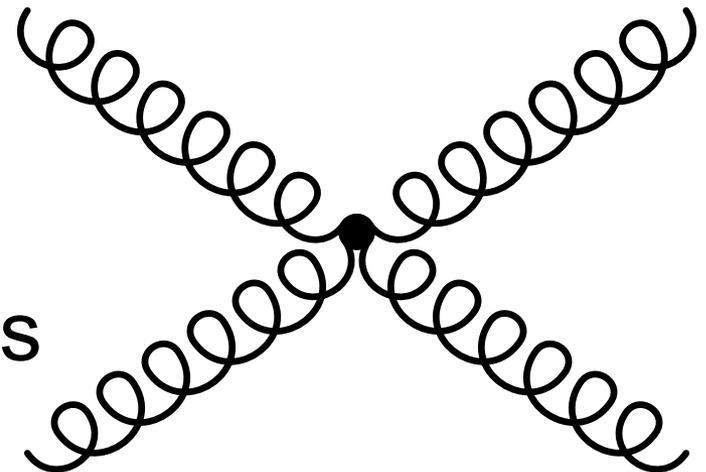
Remember that quarks have color (and so do gluons!) Try and follow the color lines (always a good thing to check)

Remember that gluons themselves have QCD color, so they self-couple!



Can have three-gluon vertices

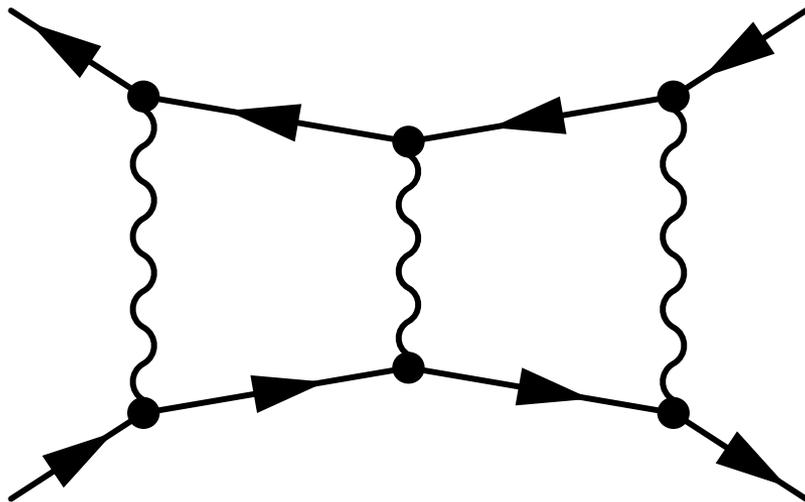
And four-gluon vertices



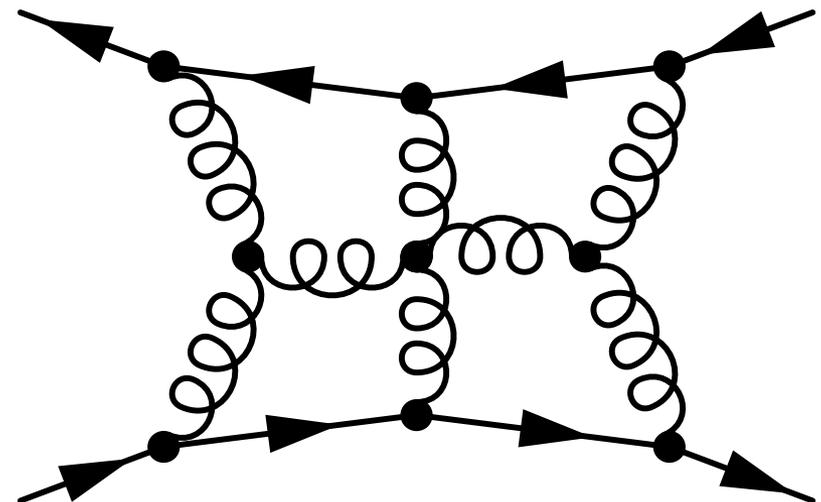
# One other QED vs QCD differences

Each vertex describes an emission/absorption of a force carrier.

In QED, the probability of this is governed by the unit-less number  $\alpha=1/137$ , which is good, since it means the probability for many of these is small



In QCD, the probability of this is governed by the unit-less number  $\alpha_s > 1$ , which means the diagrams with more vertices contribute ... more!

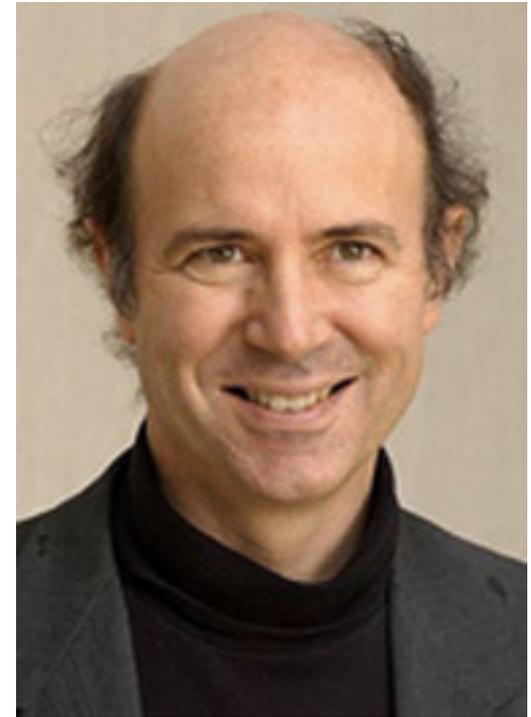




# Running of the coupling constant

The value of the coupling constant is indeed strong, but only at large distances. At small distances (such as inside of a proton), the strong coupling constant gets very small and we can calculate quantities

The property that the coupling gets weaker at smaller distances (aka at larger energies) is known as **asymptotic freedom**



Nobel prize for  
Wilczek, Gross and  
Politzer

# As Griffiths points out...

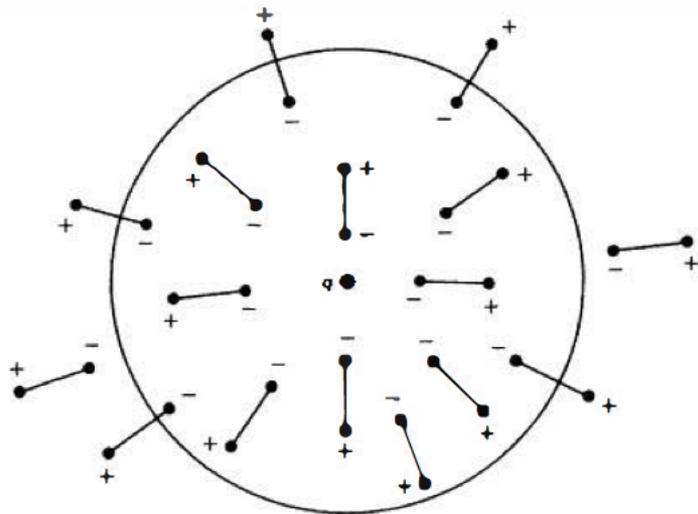


Fig. 2.1 Screening of a charge  $q$  by a dielectric medium.

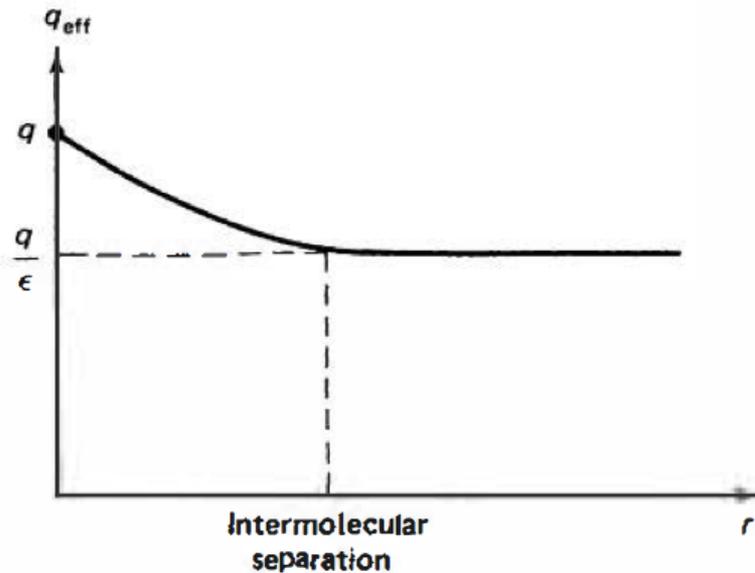
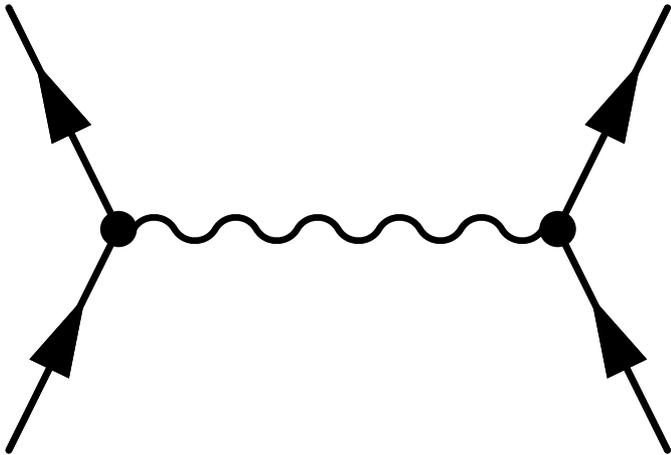


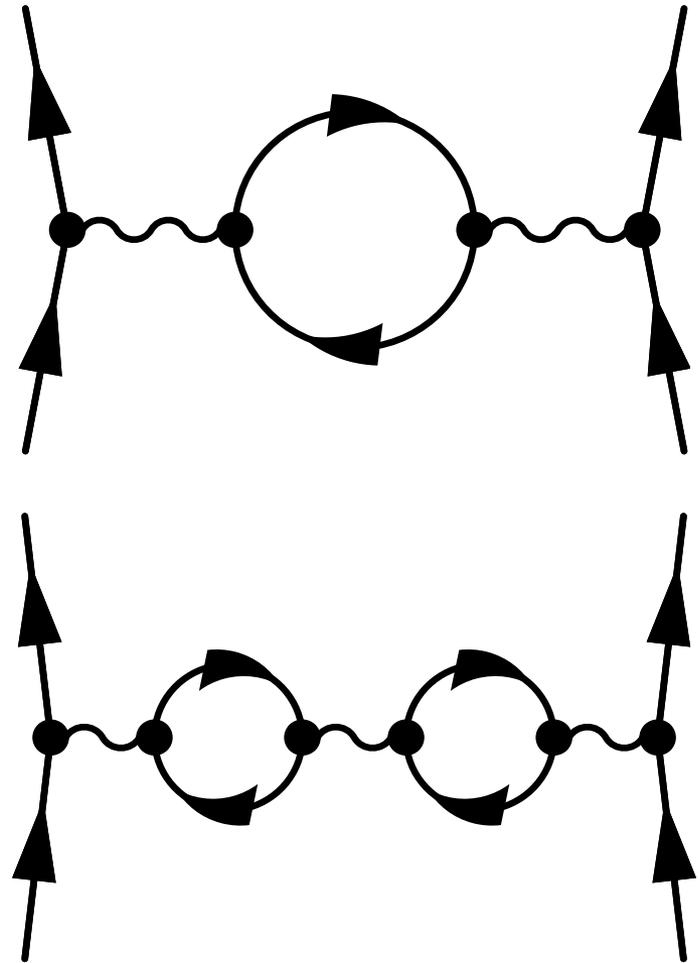
Fig. 2.2 Effective charge as a function of distance.

In classical E&M, the coupling is given by the charge  $q$ , and this is reduced at large distances by a dielectric

Bhabha  
scattering again



Virtual diagrams  
contributing



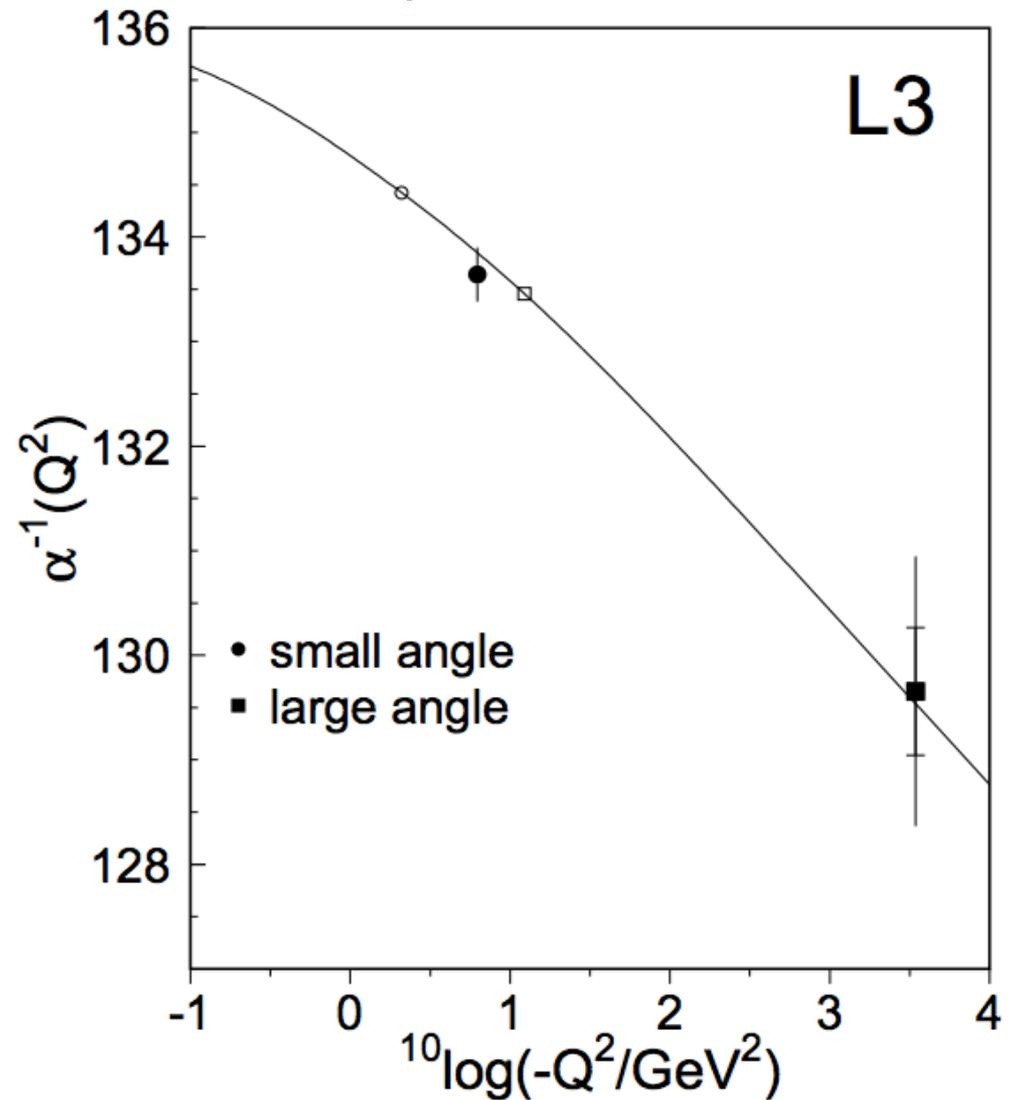
# Running of the E&M fine structure constant

~1/137 at zero  
momentum transfer

~1/127 at the Z  
boson mass!

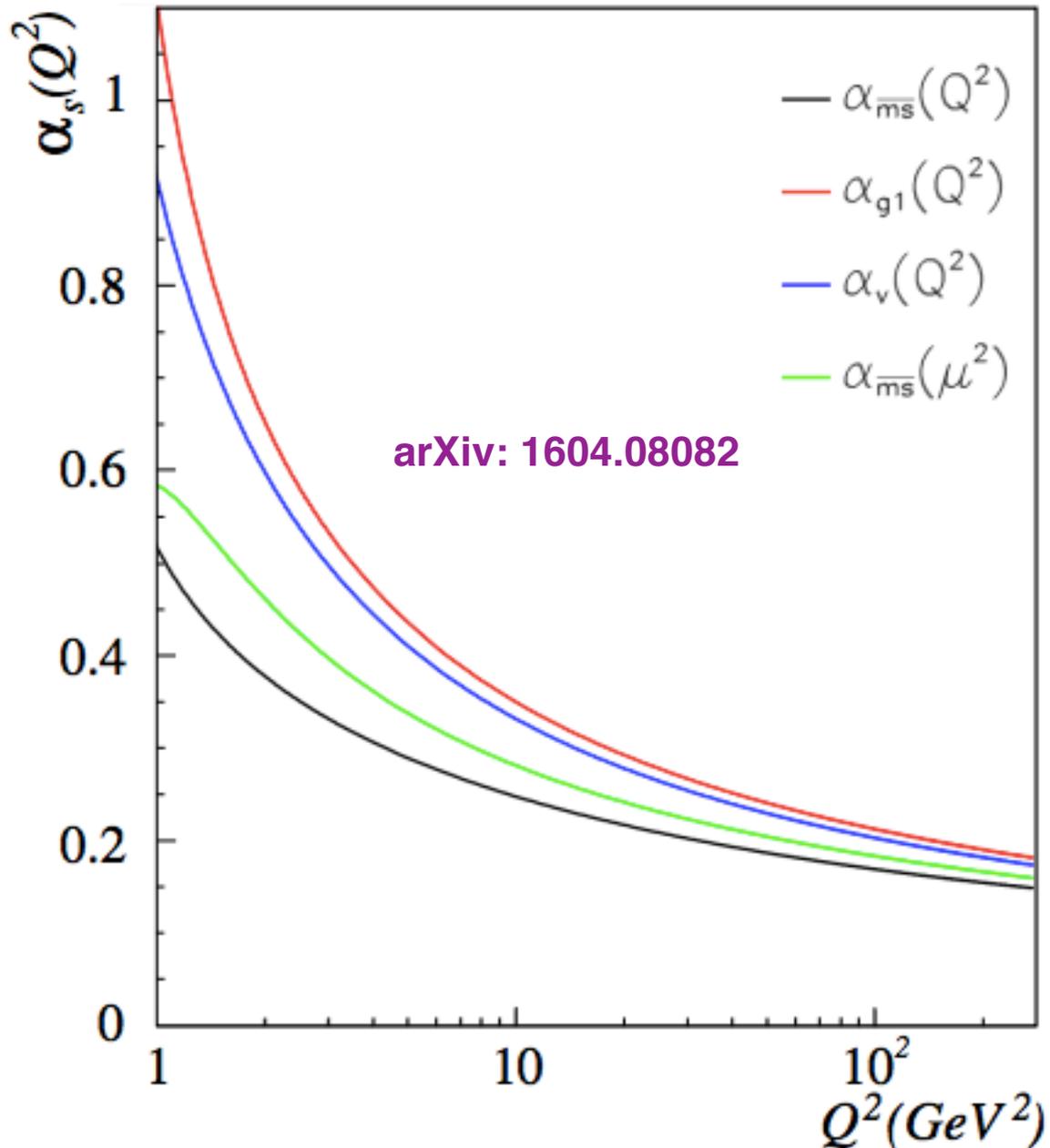
These are **vacuum  
polarization** effects

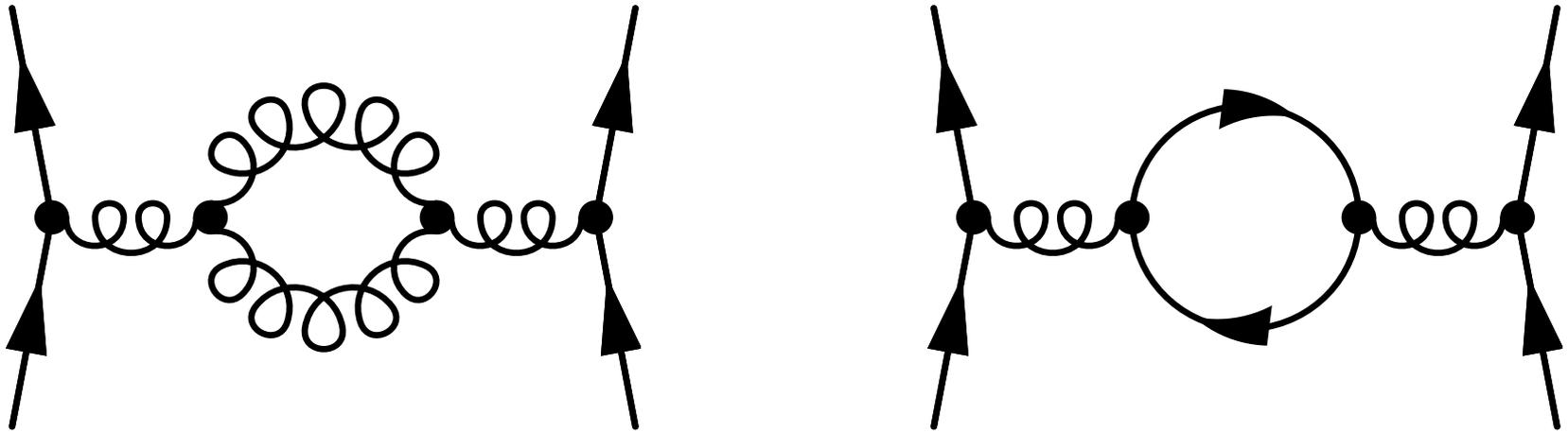
hep-ex/0002035v1



# Running of the QCD strong coupling constant

Large “running” of the coupling quite evident. Different colors are different “renormalization schemes” - we’ll get to that in a little bit, but consider it different coupling definitions



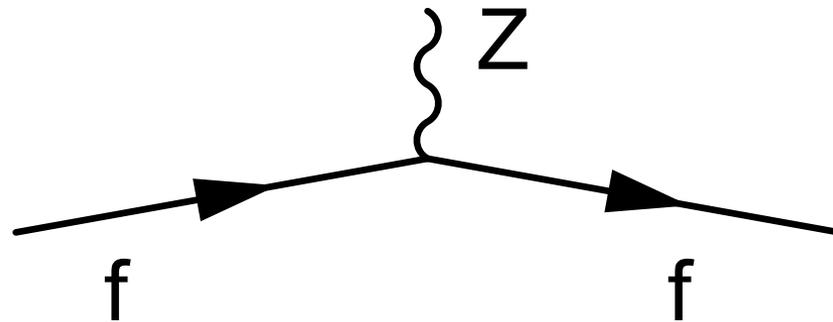


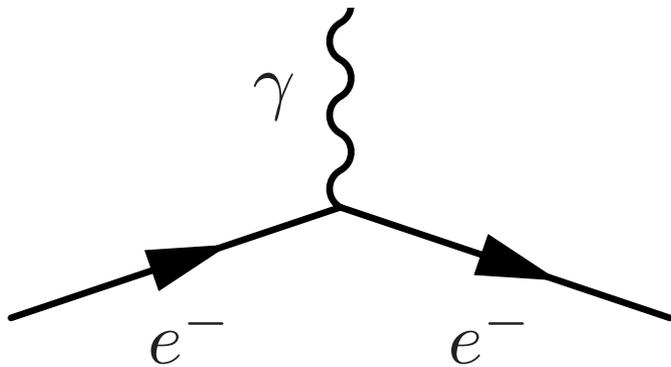
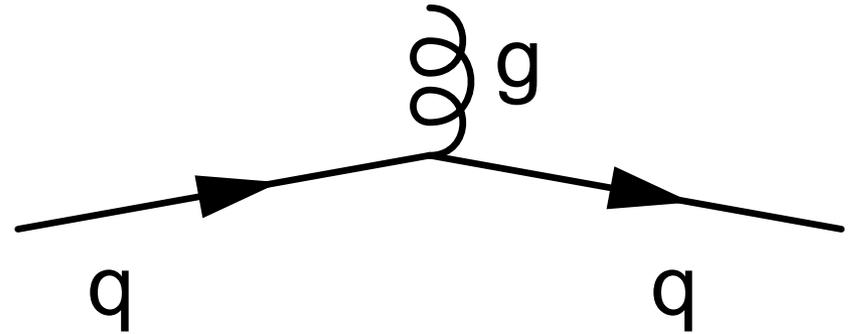
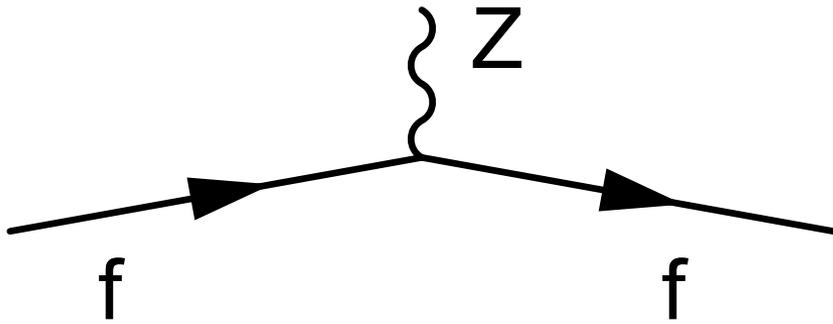
Effects from quark polarization and gluon polarization give opposite effects!

$a = 2f - 11n$  ( $f$ =number of flavors,  $n$ =number colors)  
 defines whether coupling increases or decreases  
 at short distances

$f=6, n=3 \rightarrow a < 0 \rightarrow$  asymptotic freedom (upper limit  
 on no more than 17 generations of quarks)

where  $f$  here  
is any fermion ( $Z$  boson couples to all quarks,  
charged leptons and neutral leptons)

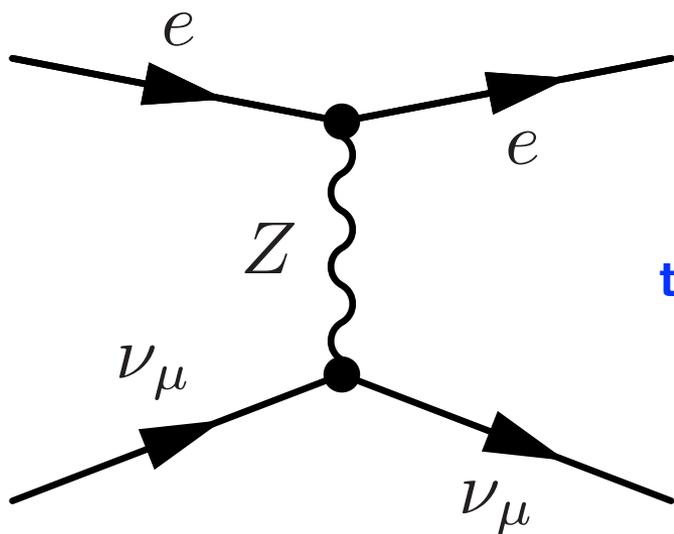




Griffiths uses a jagged straight line for EW bosons, but I will not. Just be careful, regardless of your choice!

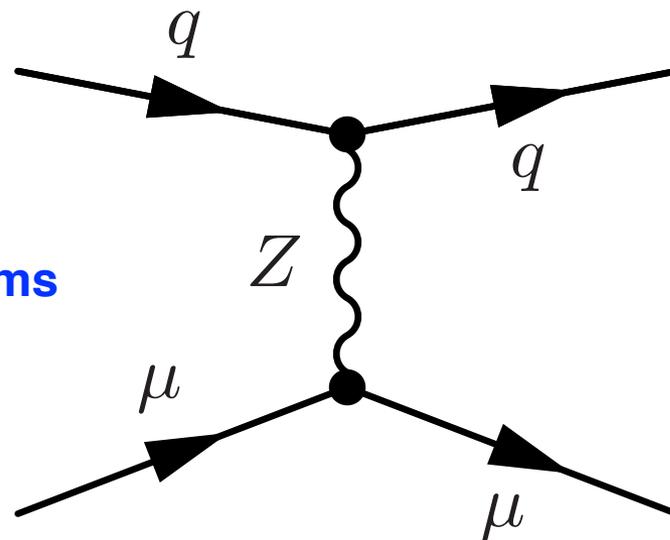
# What processes can the Z boson mediate?

$e^- \nu_e \rightarrow e^- \nu_e$

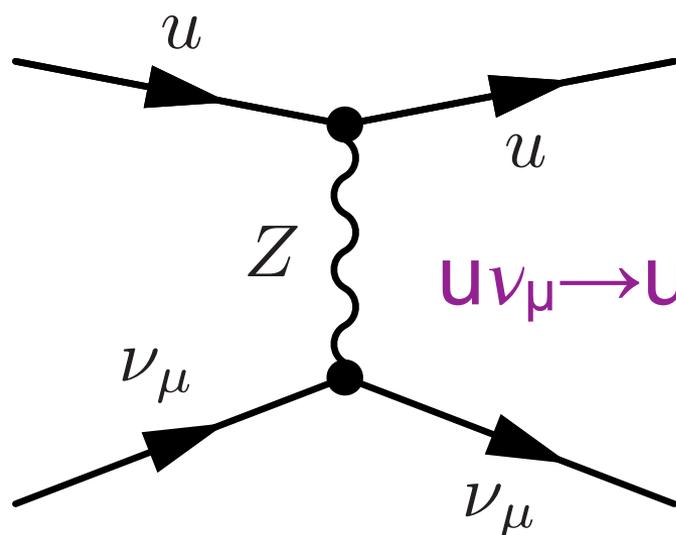


t channel diagrams

$\mu^- q \rightarrow \mu^- q$

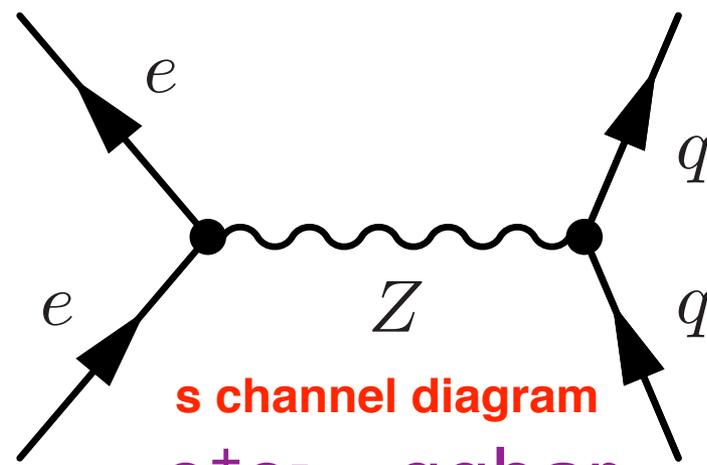


$U \nu_\mu \rightarrow U \nu_\mu$

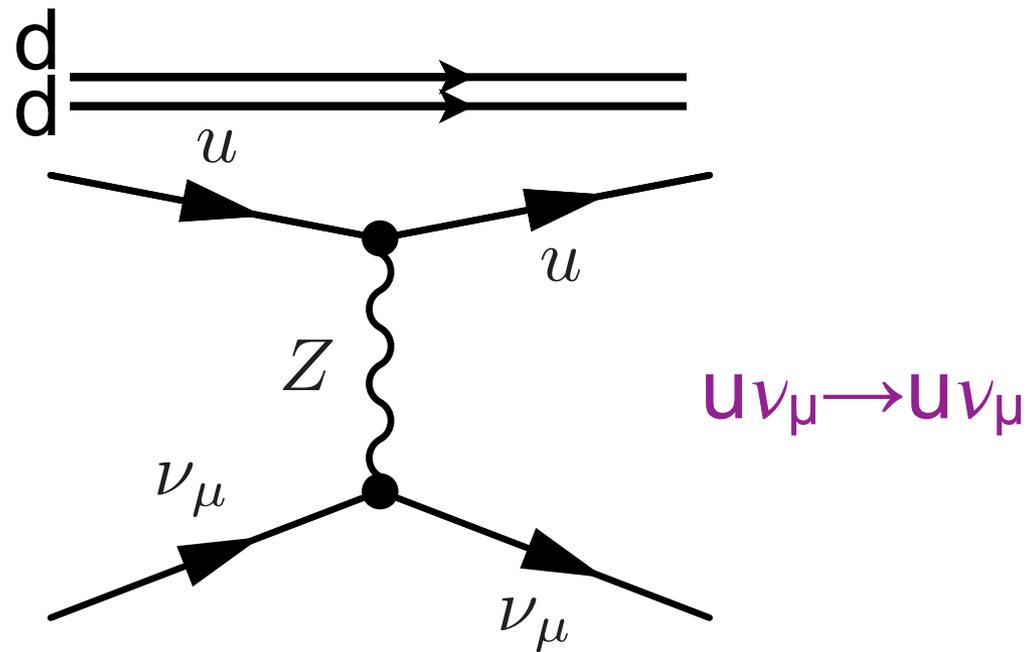


s channel diagram

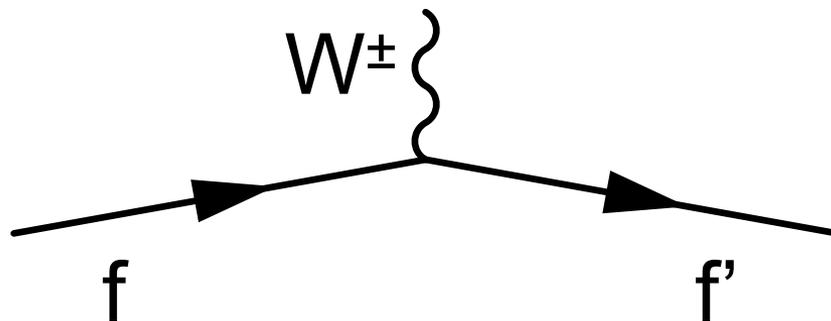
$e^+ e^- \rightarrow q \bar{q}$



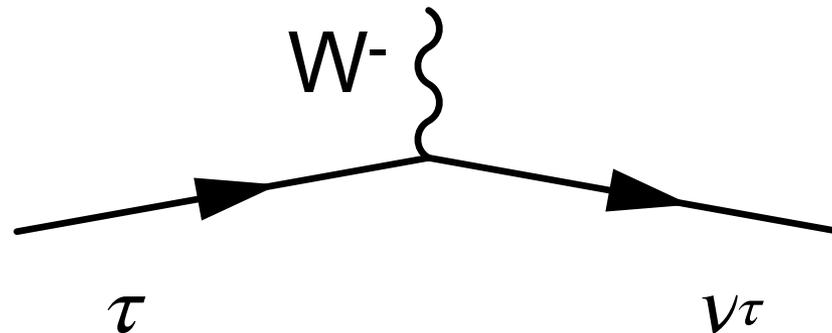
We of course don't scatter the bare quarks, but quarks inside hadrons (here inside a neutron)



Remember that  $W$  bosons are the only ones involved in change of flavor or type of matter



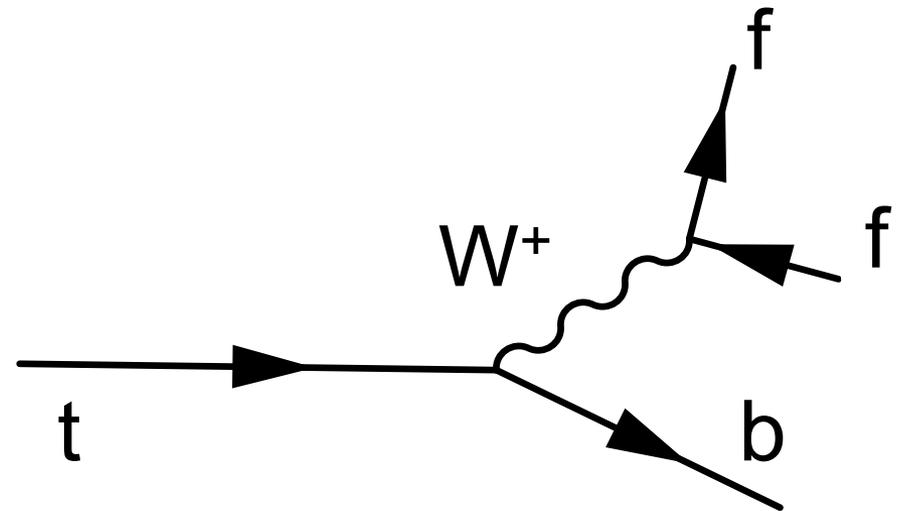
Remember that  $W$  bosons are the only ones involved in change of flavor or type of matter. Example, a tau converts into a tau neutrino and a  $W$  boson:



# Charged weak interactions

Top quarks decay nearly  $\sim 100\%$  of the time to a  $W$  boson and a bottom quark. The  $W$  boson can decay to a quark-antiquark pair, or to a charged lepton and a neutrino

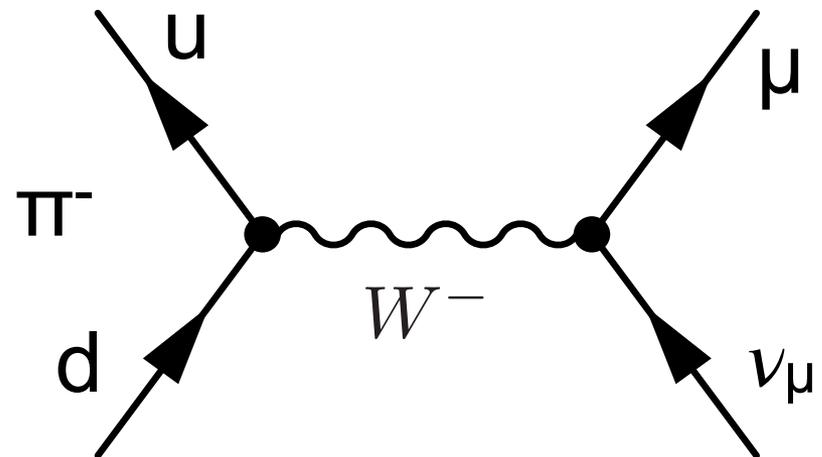
Check lepton  
flavor numbers  
and EM  
charge!



# Charged weak interactions

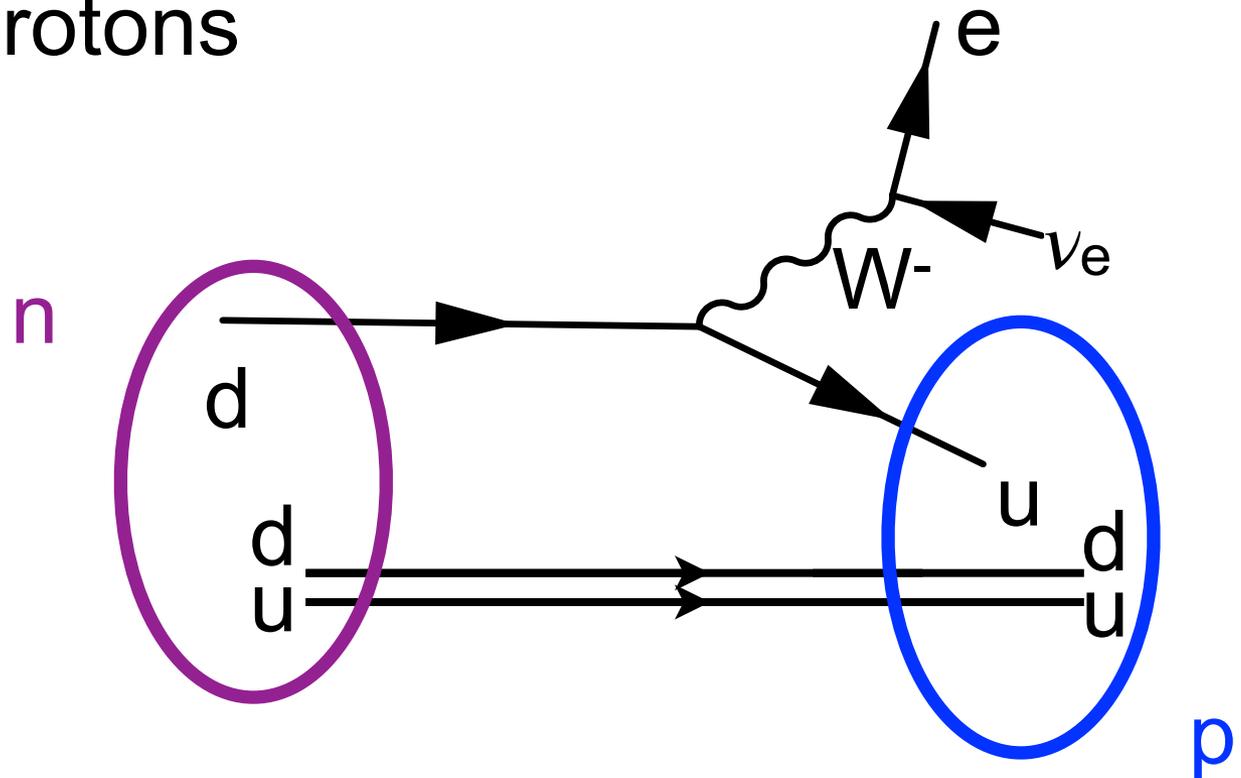
This is how a charged pion can decay to a muon (and an anti-muon neutrino). Could have guessed  $W$  boson involvement, because it involves a change of flavor (here charged pion decay is much slower than neutral pion decay)

Check lepton flavor numbers and EM charge!



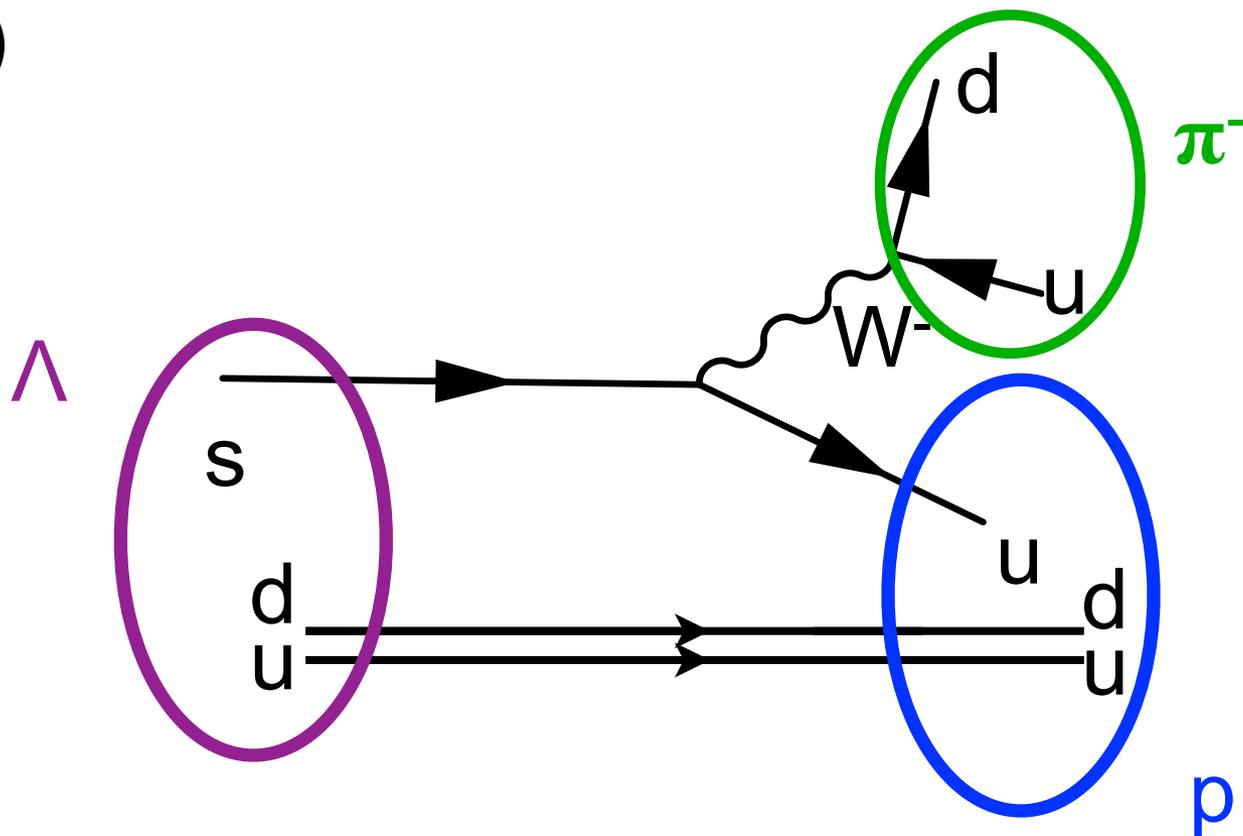
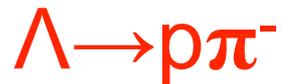
# What processes can the W boson mediate?

We of course don't scatter the bare quarks, but quarks inside hadrons (here inside a neutron)  
This is how neutrons beta-decay to protons



# The important question...

How do we account for strangeness-changing weak interactions? (We know they have to come via the weak force, but so far we have only seen decays within a matter generation)



# The Kobayashi-Maskawa matrix

The weak force couples not to eigenstates of quarks that we observe, but to a slightly skewed set instead:

What we observe

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

What weak force couples to

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

What we observe

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

What weak force  
couples to

$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

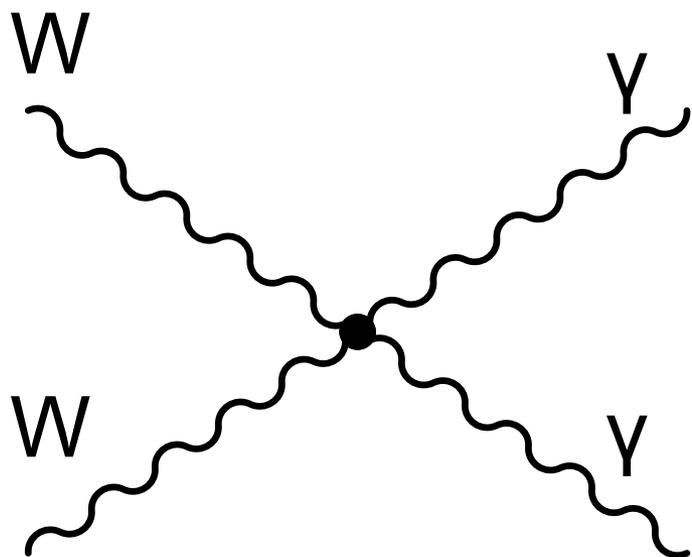
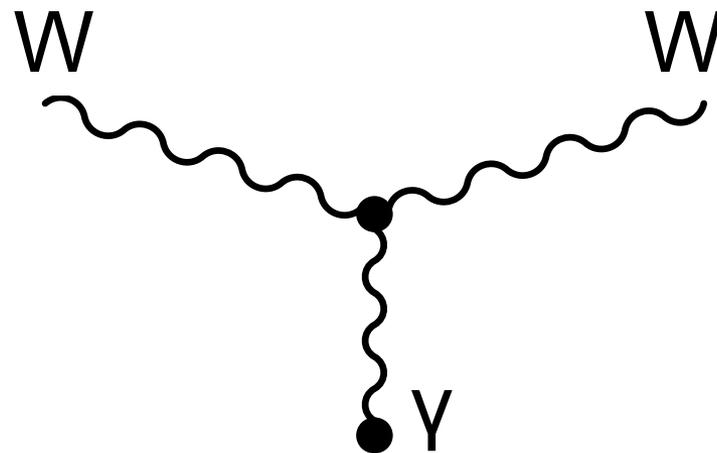
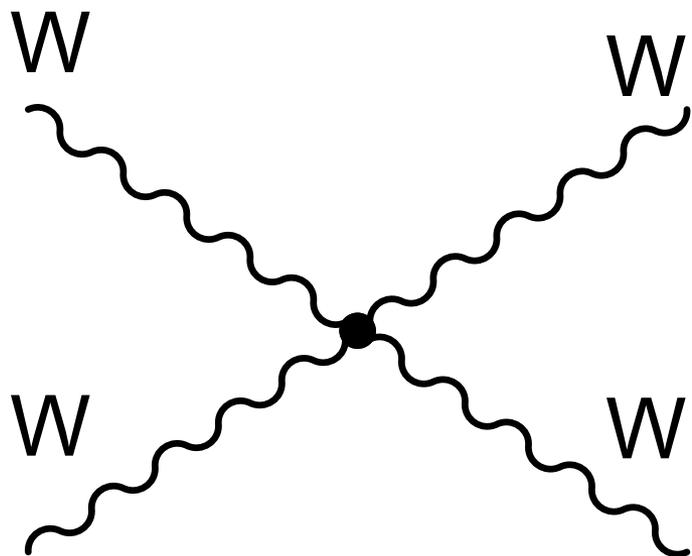
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.97434 & 0.22506 & 0.00357 \\ 0.22492 & 0.97351 & 0.0411 \\ 0.00875 & 0.0403 & 0.99915 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

2017  
PDG

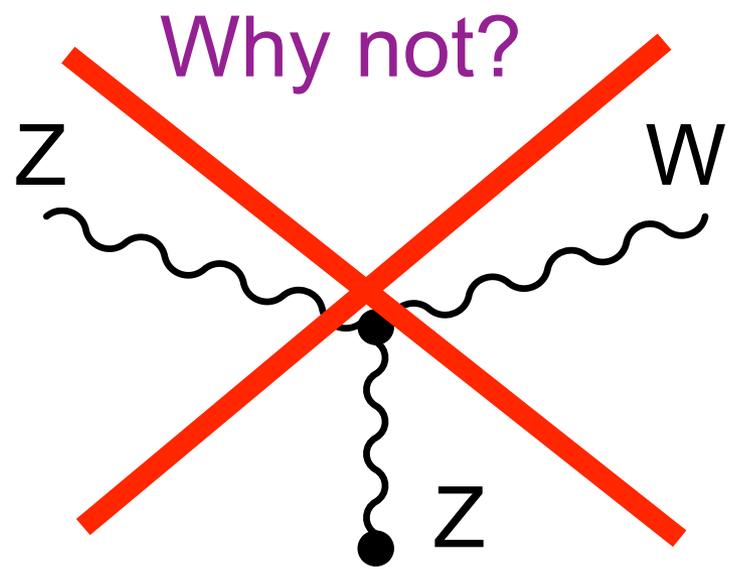
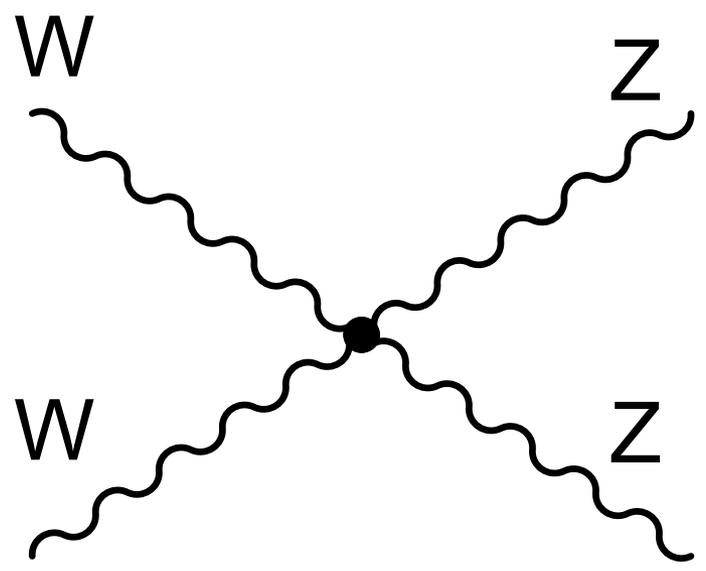
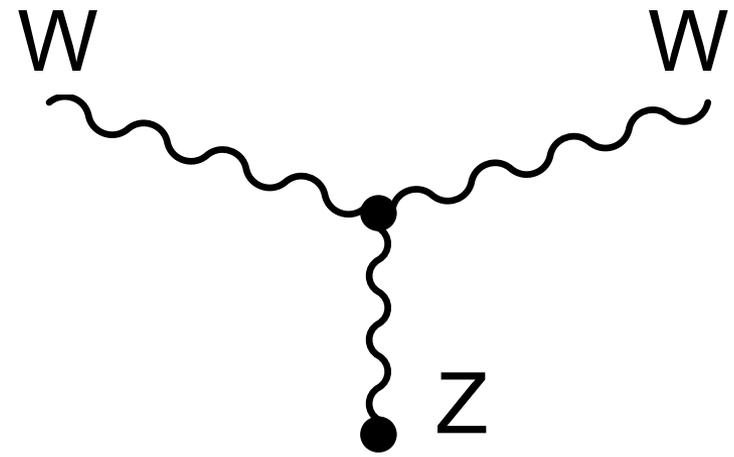
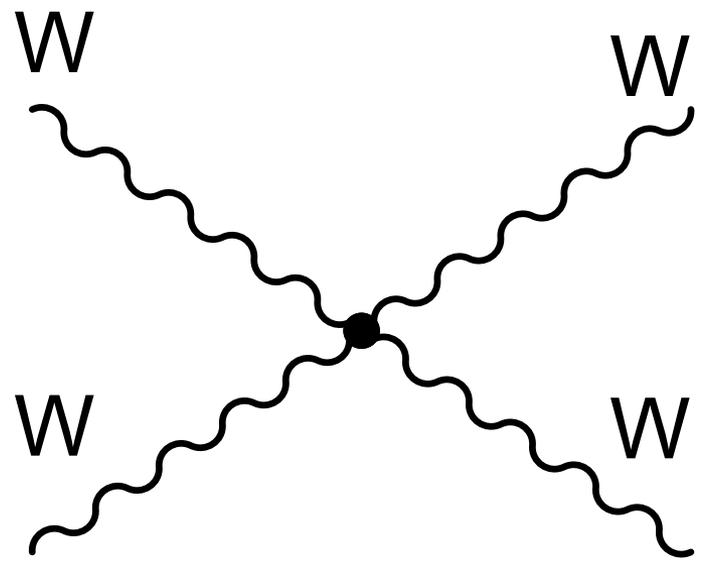
Off-diagonal numbers are small, which has implications for which decays happen more/less frequently. **The matrix has to be unitary.** Note that I've cheated a bit, because there are phases in the matrix that I have ignored so far

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.97434 & 0.22506 & 0.00357 \\ 0.22492 & 0.97351 & 0.0411 \\ 0.00875 & 0.0403 & 0.99915 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \begin{matrix} 2017 \\ \text{PDG} \end{matrix}$$

# Boson couplings in weak theory



In general, can always replace a photon by a Z boson in a diagram.  
What about the reverse?



What are the s-channel and t-channel diagrams for  $e^+e^- \rightarrow W^+W^-$ ? Which way do arrows go? Why? What about  $e^+e^- \rightarrow \mu^+\mu^-$ ? What diagrams are there?

Particles... like to decay to lighter objects, unless there is a reason that they can't decay (such as a conservation law)

What is the most obvious reason for non-decay?

$$p^+ \rightarrow n e^+ \nu_e$$

Hint, look at the energy in the  
rest frame

Momentum conservation

Angular momentum conservation

Conservation of charge

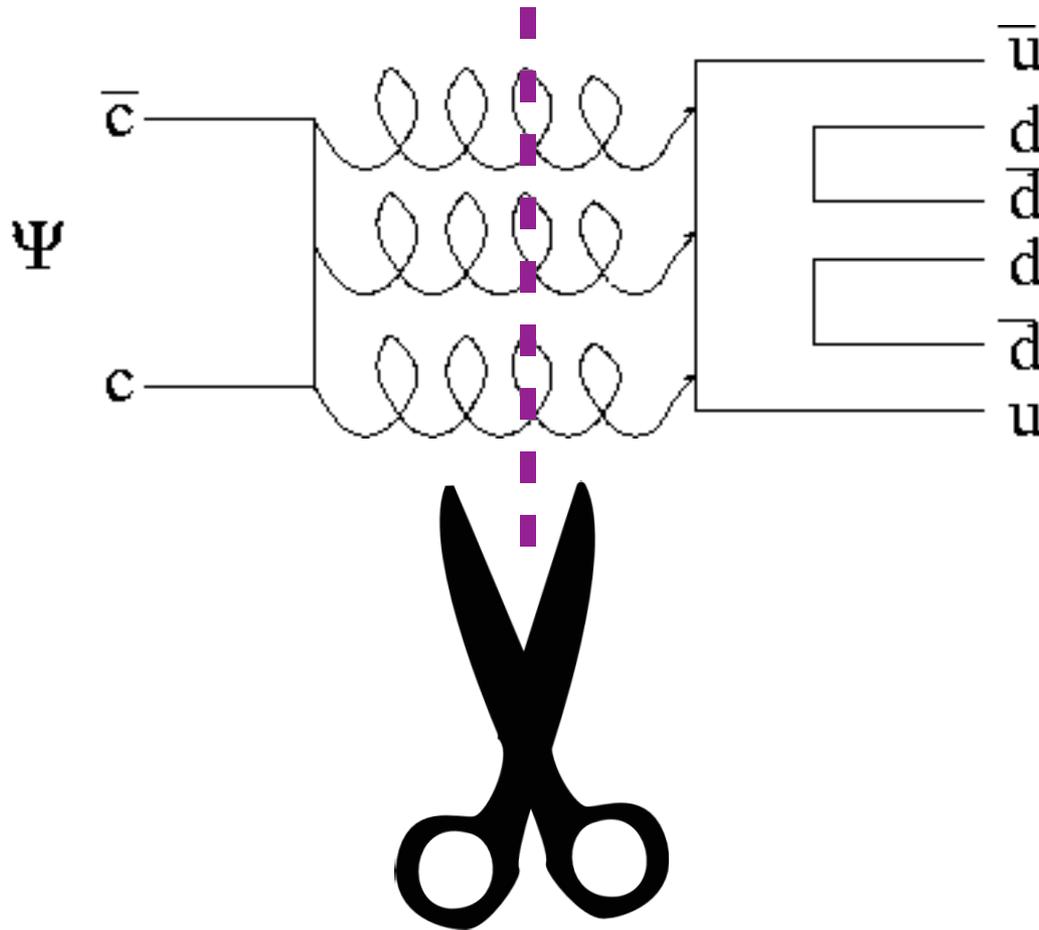
Conservation of color

Conservation of baryon number

Conservation of lepton (electron/muon/tau)  
number

Quark flavor (not quite conserved)

<http://www.ippp.dur.ac.uk/~krauss/Lectures/QuarksLeptons/QCD/Equations/jpsidecay.gif>



OZI rule explains why the J/Psi takes so long to decay.  
 What does this have to do with **asymptotic freedom**?

Photons can't decay (they already have zero mass - nothing lighter to decay into)

Protons are the lightest baryon, so baryon conservation tells us that they are stable

This is why the world is made up of protons, neutrons (which are stable inside nuclei), electrons and neutrinos

Decays are probabilistic - you never know when an object will decay, but you can say on average how long a type of object will take to decay

$$\mu: 2.2 \times 10^{-6} \text{ s}$$

$$\pi^+: 2.6 \times 10^{-8} \text{ s}$$

$$\pi^0: 8.3 \times 10^{-17} \text{ s}$$

$$\tau: 2.9 \times 10^{-13} \text{ s}$$

$$n \text{ (free)}: 880 \text{ s}$$

$$\text{top quark}: 4 \times 10^{-25} \text{ s}$$

Many of these objects will decay to multiple final states with different, predicted **branching ratios**

Why so different?

Strong decays:  $10^{-23}$  s (top quark)

EM decays:  $10^{-16}$  s ( $\pi^0$ )

Weak decays: longer (neutron and muon)

The more (less) phase space for a decay, the faster (slower) it will occur.

See the free neutron



Photos: Internet screengrabs



OK, not a real physics explanation, but a good way to remember things

Griffiths  
problems  
1.19, 2.1, 2.2,  
2.5, 2.6, 2.7,  
2.8