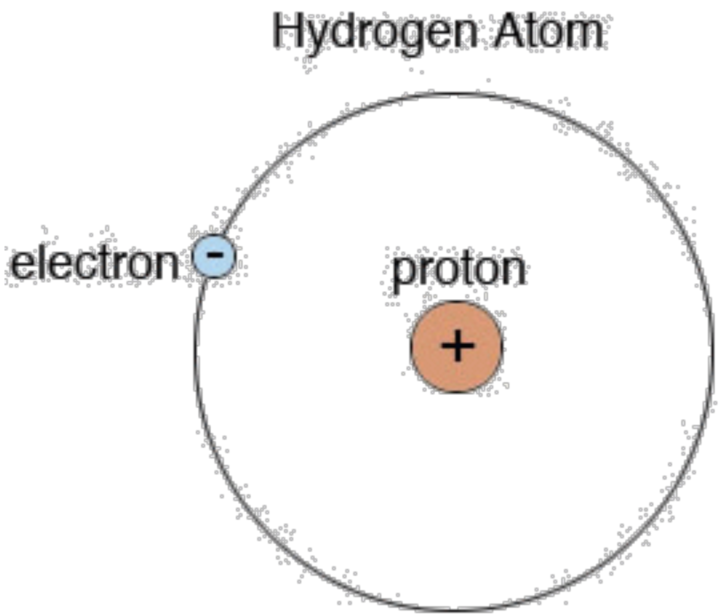
Let’s define some units

SI Units

0.15 kg

SI Units

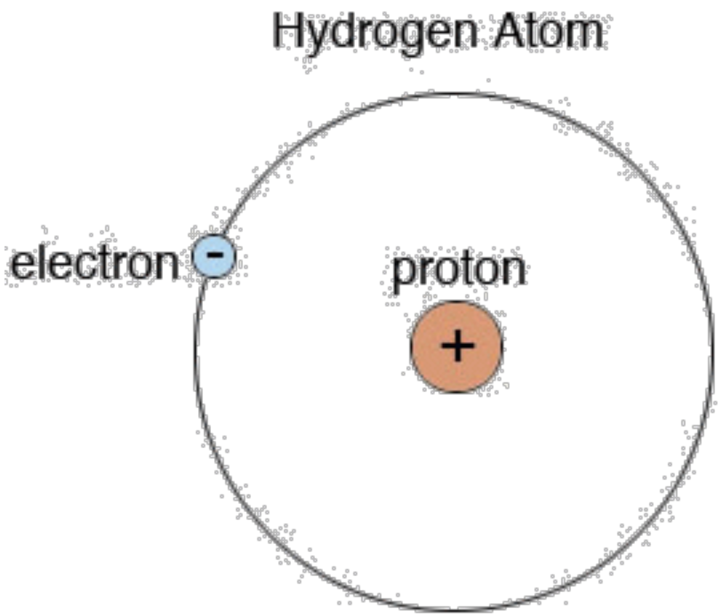


Electron mass = $9x10^{-31}$ kg

Units

114 meters

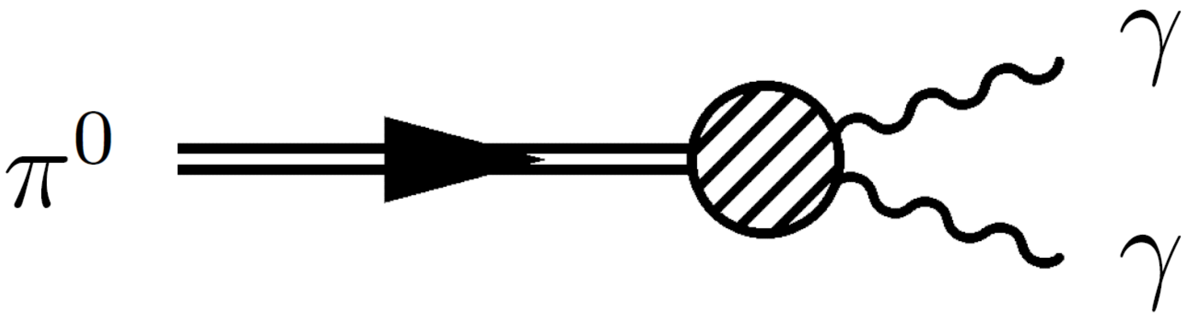
Units



Radius of electron orbit = 0.5 angstroms = 5×10^{-11} meters

Units

This takes 0.4 seconds

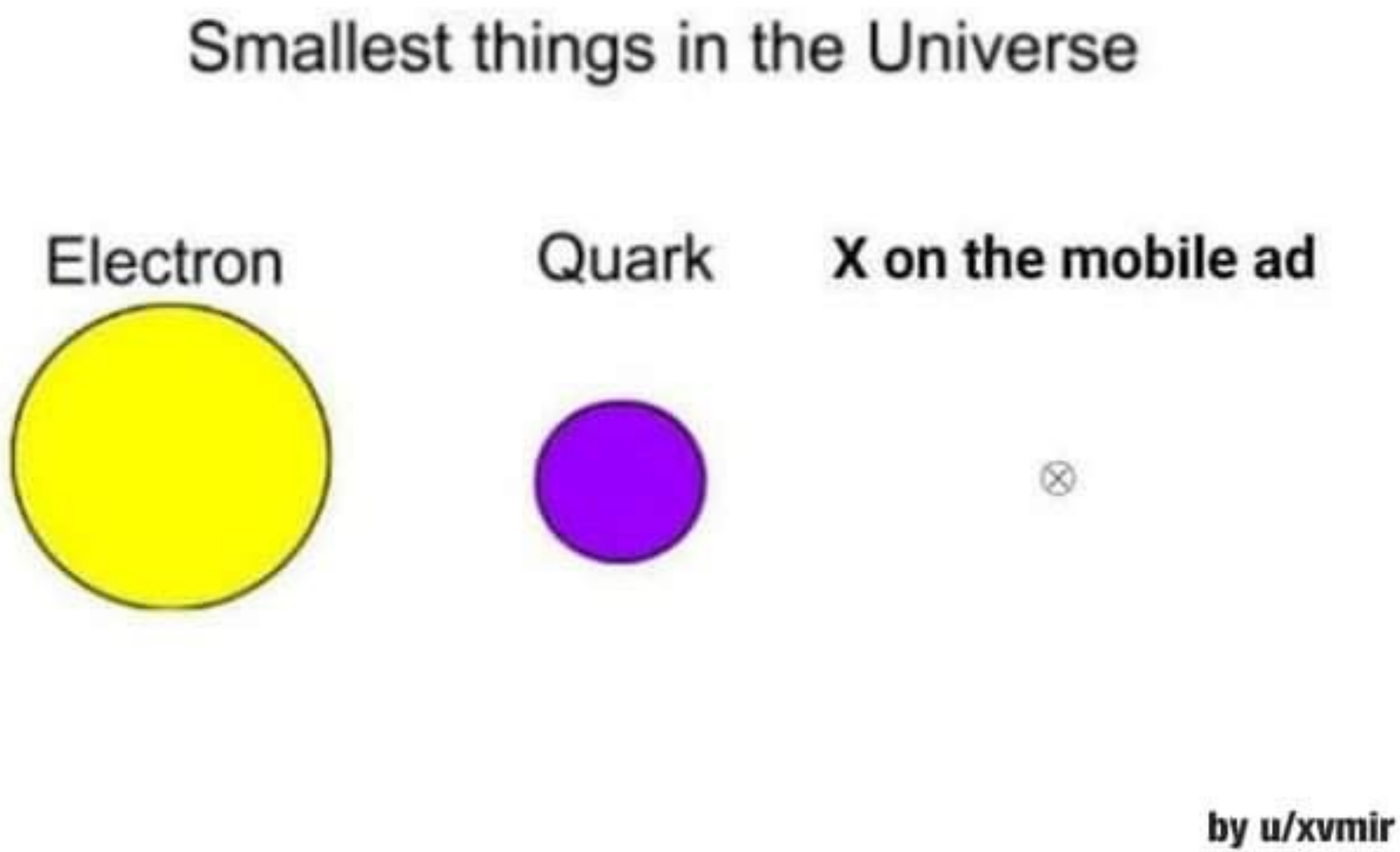


Neutral pion lifetime = 8×10^{-17} s

Our everyday experiences...

Do not use convenient particle physics units!

On length scales



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

$$\hbar = c = 1$$

Natural units. Simplifies a lot of notation!

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

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

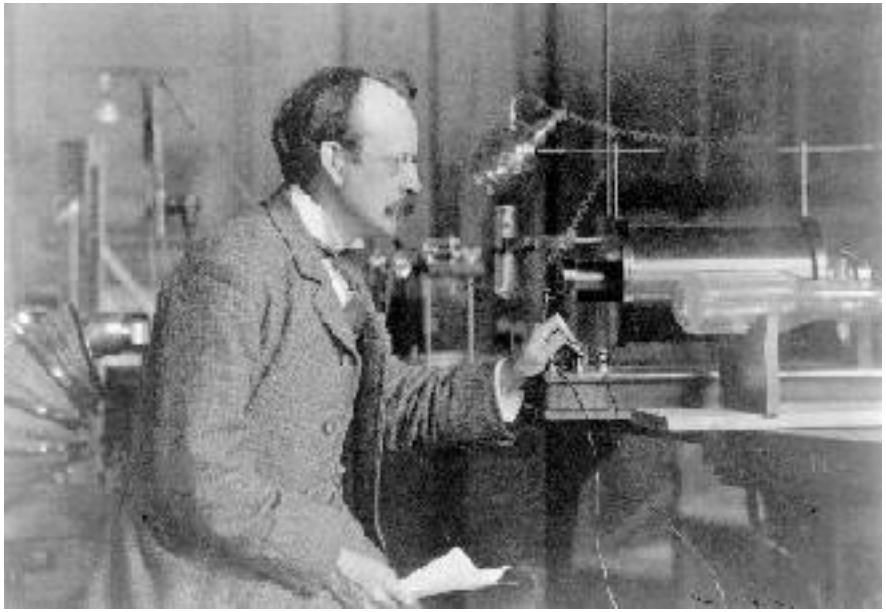
$$\boxed{1\text{GeV} = 10^9 \text{ ev}} = 1.6 \times 10^{-10} \text{J}$$

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

	Not our choice	In our choice of natural units
Energy	GeV	GeV
Momentum	GeV/c	GeV
Mass	GeV/c^2	GeV
Time	hbar/GeV	GeV^{-1}
Length	c*hbar/GeV	GeV^{-1}
Area	(c*hbar/GeV)^2	GeV^{-2}

Griffiths disagrees :)

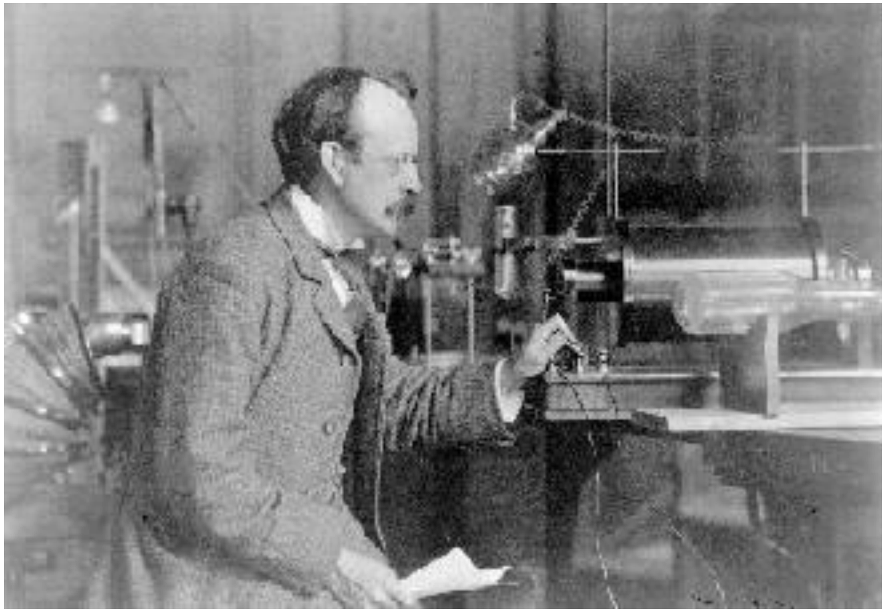
Let's take a step back in time, now (1897)



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

Let's take a step back in time, now (1897)



Undeflected particle:

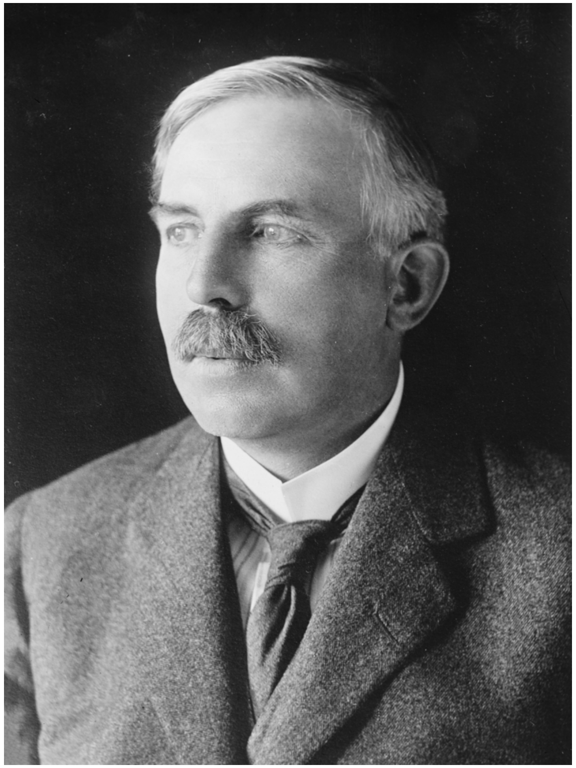
$qE = qvB$, $v=(E/B)$

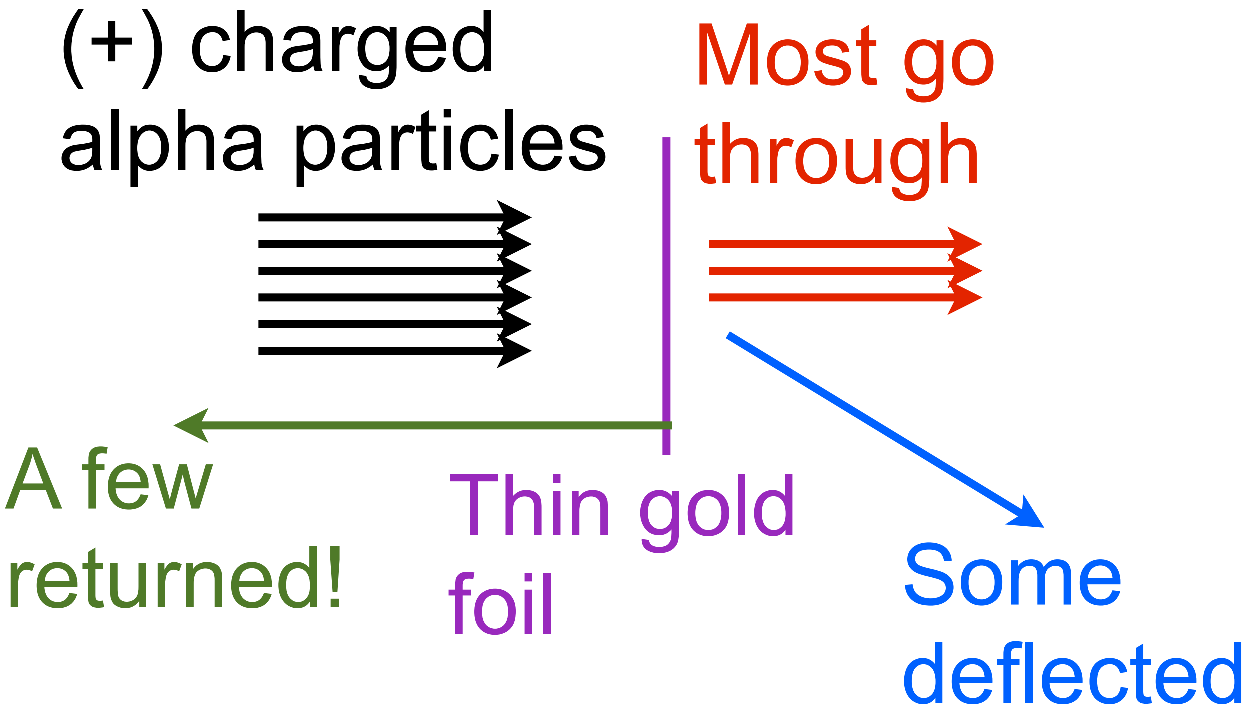
Just magnetic field:

$qvB = mv^2/R$

$(q/m) = v/(BR) = E/(B^2R)$

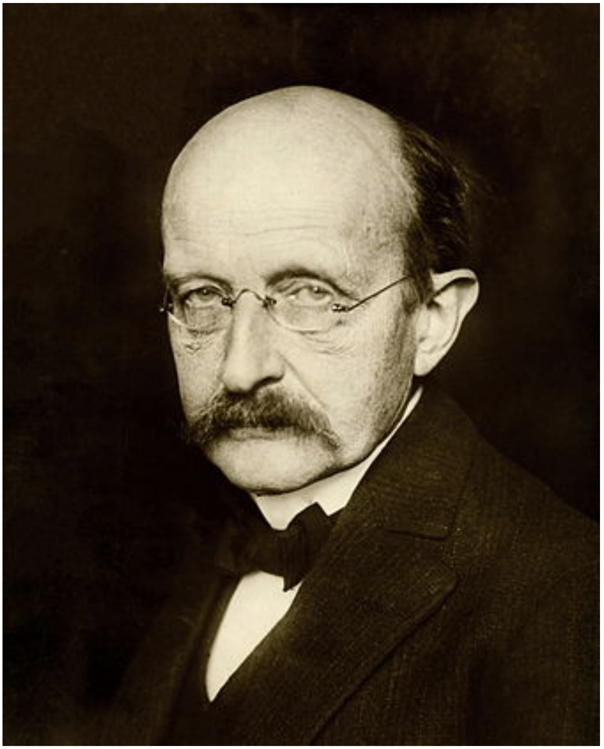
On to Rutherford (1911)

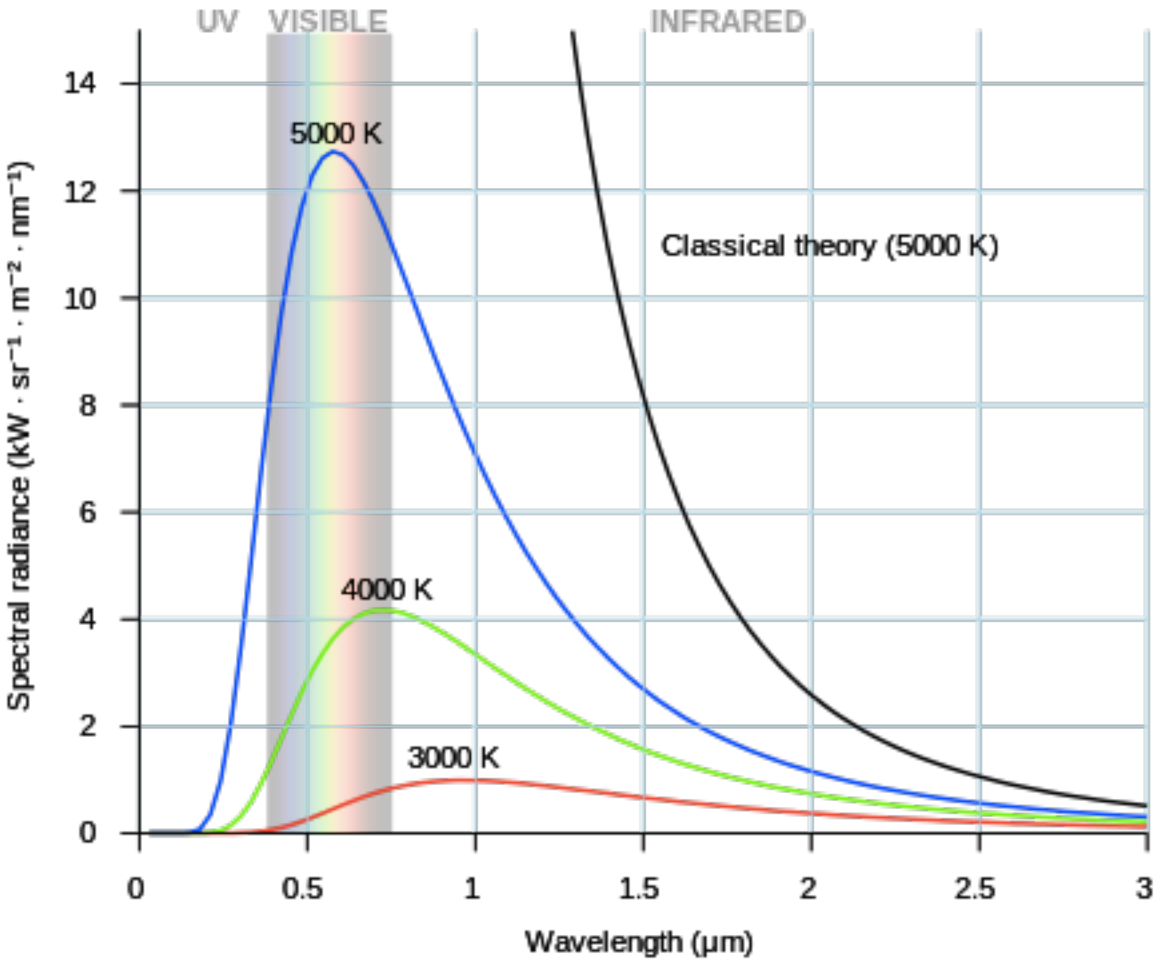




"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." - let to the idea that positive charge in atom must be concentrated in a small space

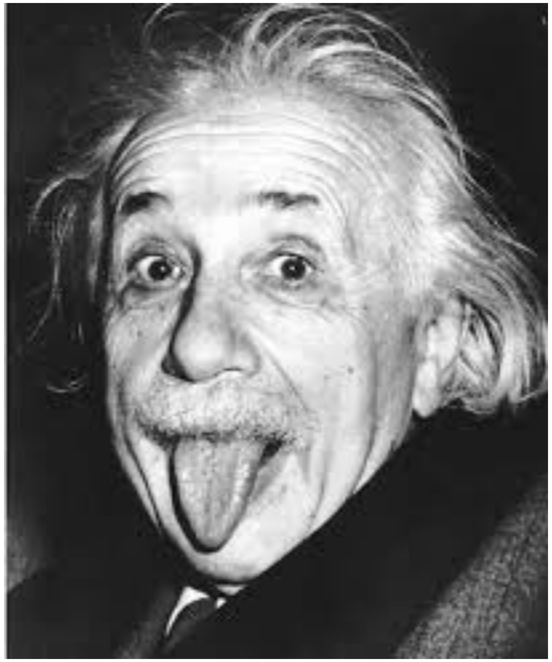
Skipping to Max Planck

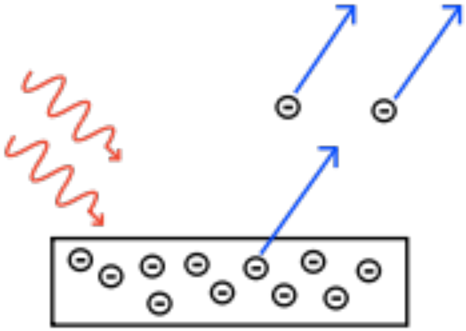




Quantization was "a purely formal assumption and I really did not give it much thought except that no matter what the cost, I must bring about a positive end." (Turns out that Planck didn't quite realize what he was doing)

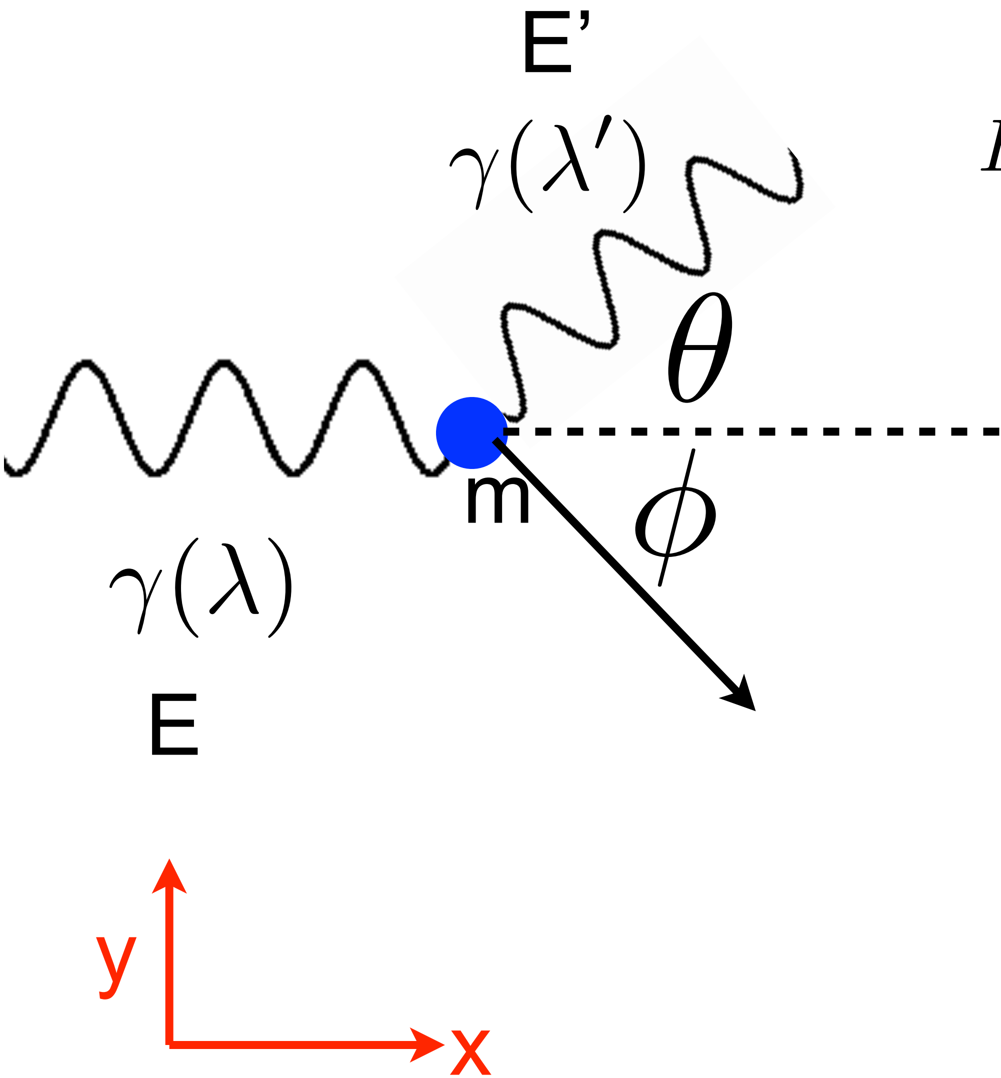
Einstein and the photoelectric effect (1905)





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

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

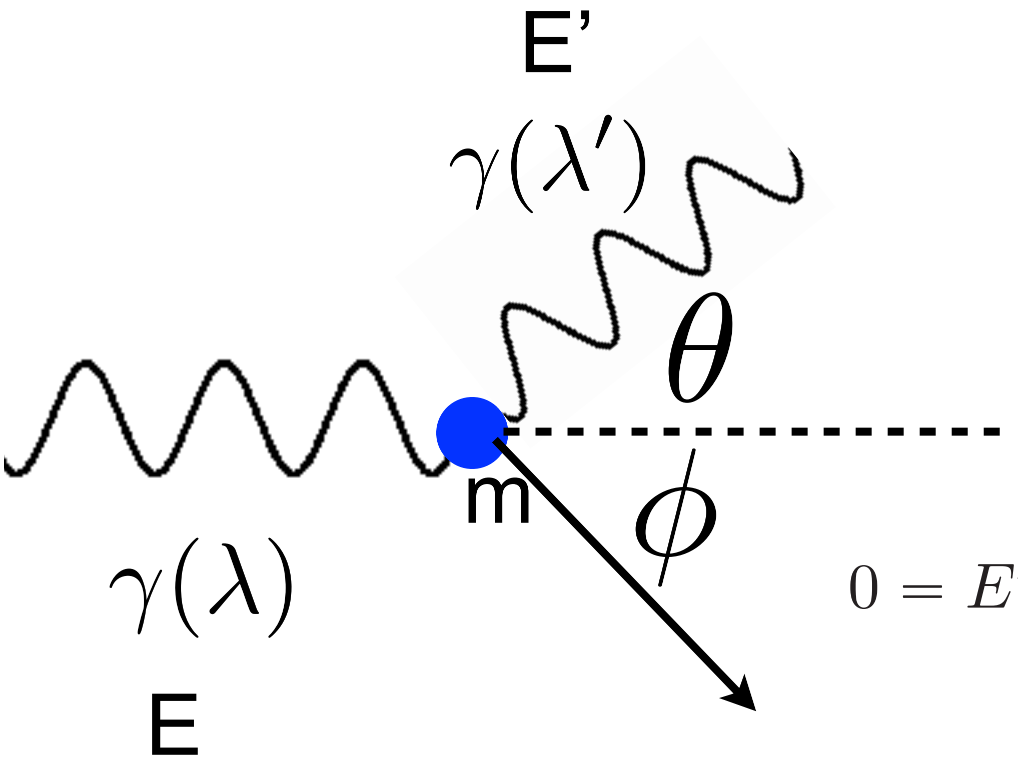
Momentum conservation in x:

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

Momentum conservation in y:

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

Compton scattering (1923)



Momentum conservation in y:

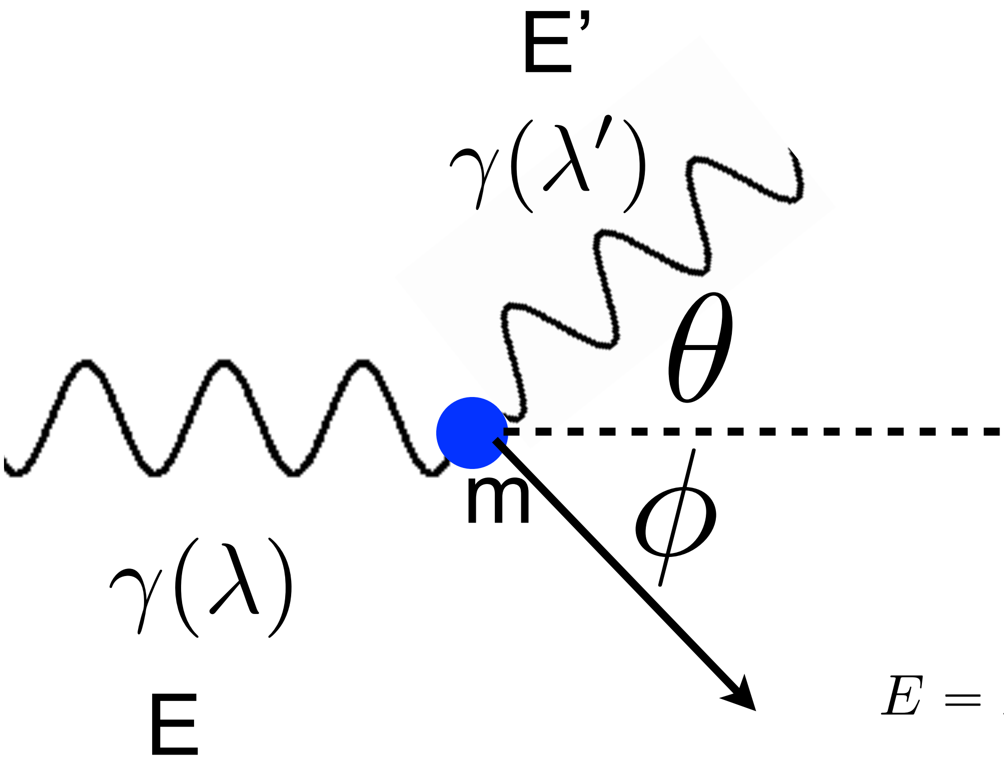
$$0 = E' \sin\theta - p \sin\phi \rightarrow p = \frac{E' \sin\theta}{\sin\phi}$$

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

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

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

Compton scattering (1923)



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 p²

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

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

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

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

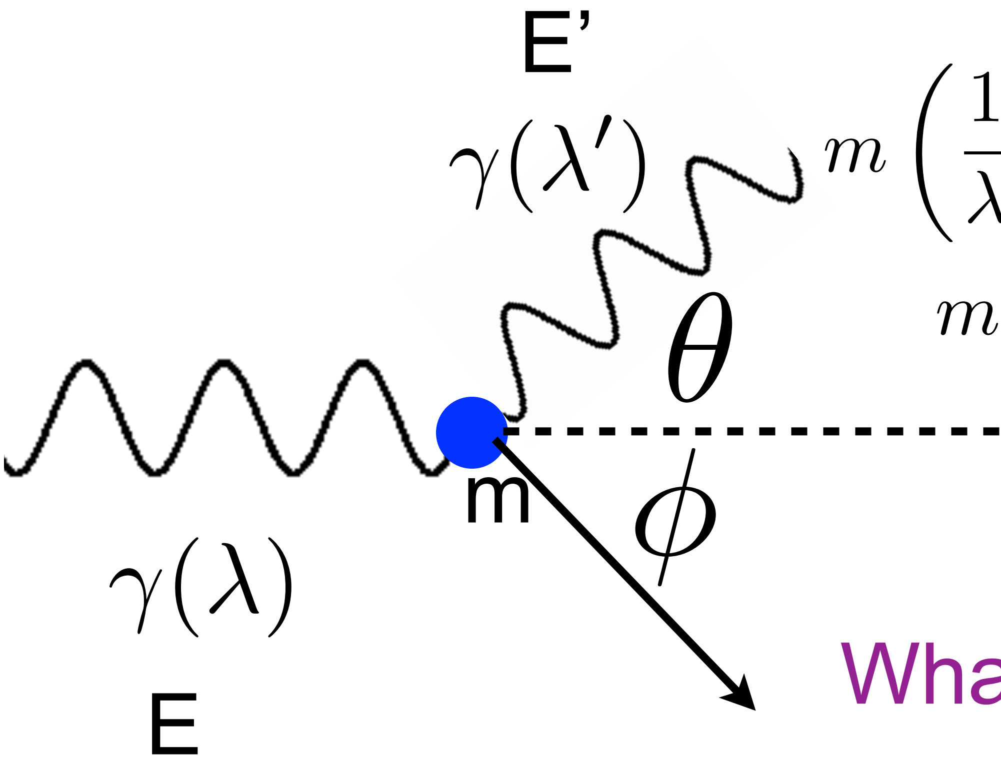
$$E = \frac{1}{\lambda}$$

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

Nice to have these units

Compton scattering (1923)

Finishing up



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

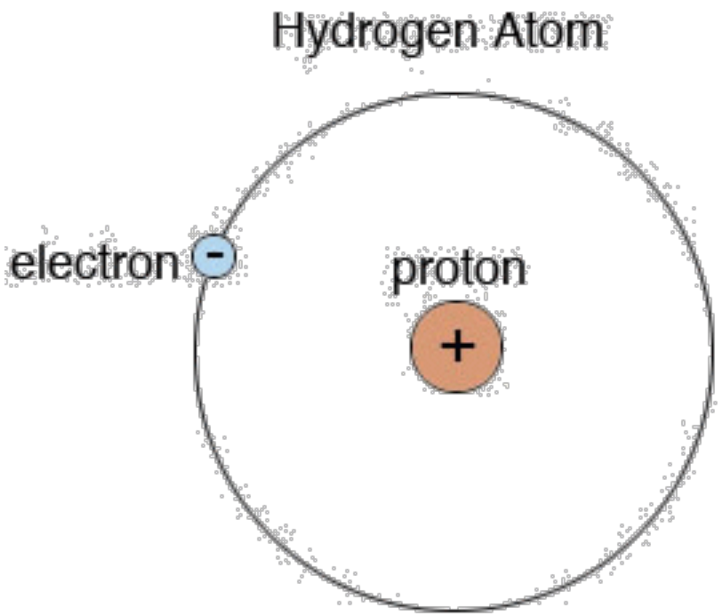
$$m(\lambda' - \lambda) = (1 - \cos\theta)$$

$$\boxed{\lambda' = \lambda + \frac{1 - \cos\theta}{m}}$$

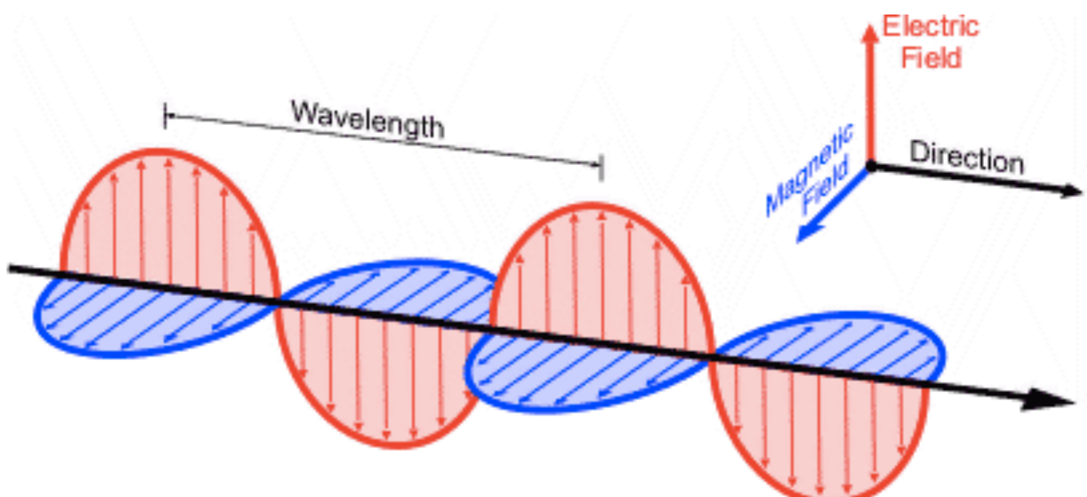
What happens for different angles? Different m?

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

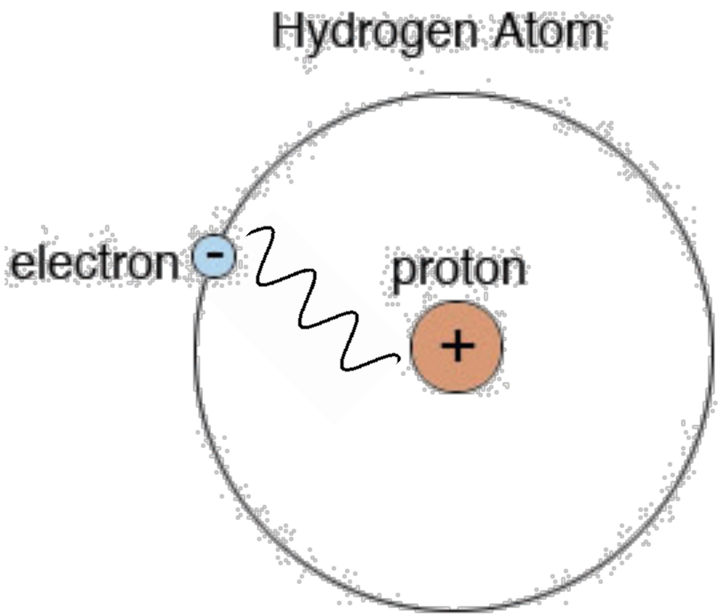
On force carriers



Photon as a wave



On force carriers



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

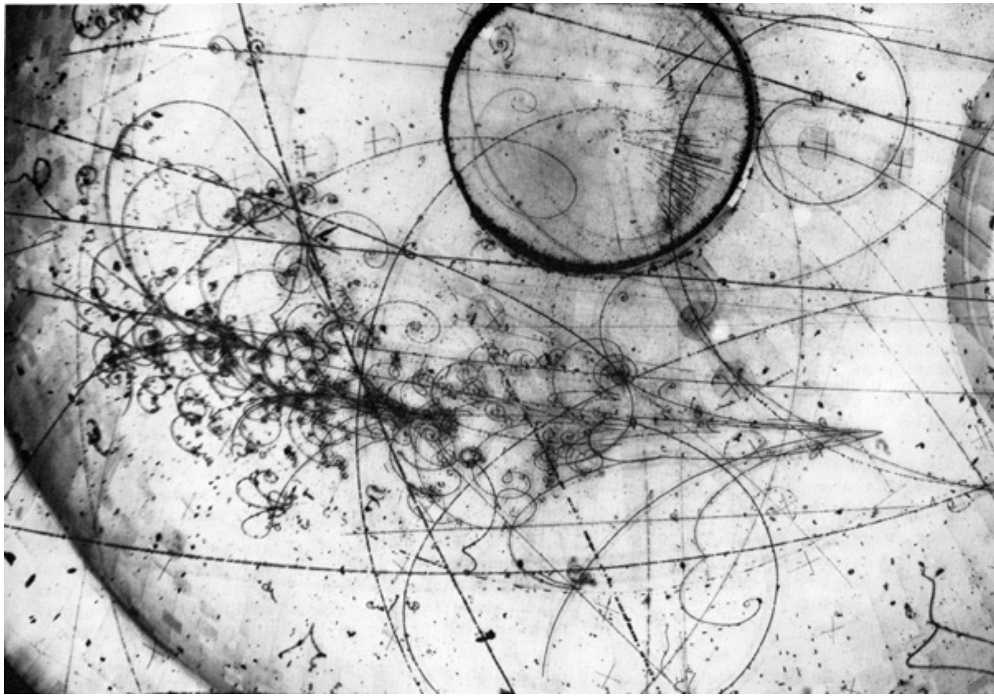
Early particle detectors - cloud and bubble chambers

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

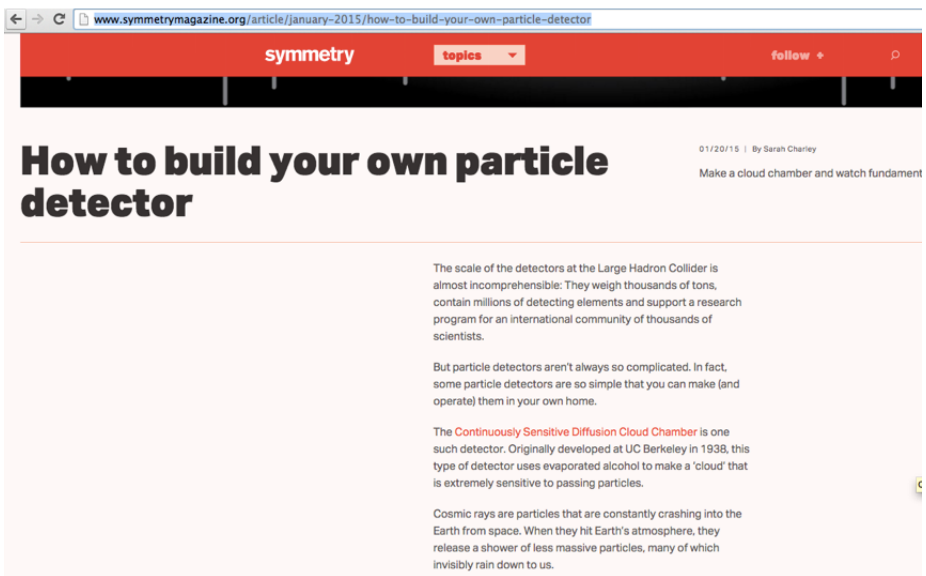
FNAL bubble chamber photo



What's going on here?

Early particle detectors - cloud and bubble chambers

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



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

symmetry topics follow +

How to build your own particle detector

01/20/15 | By Sarah Charley

Make a cloud chamber and watch fundament

The scale of the detectors at the Large Hadron Collider is almost incomprehensible: They weigh thousands of tons, contain millions of detecting elements and support a research program for an international community of thousands of scientists.

But particle detectors aren't always so complicated. In fact, some particle detectors are so simple that you can make (and operate) them in your own home.

The Continuously Sensitive Diffusion Cloud Chamber is one such detector. Originally developed at UC Berkeley in 1938, this type of detector uses evaporated alcohol to make a 'cloud' that is extremely sensitive to passing particles.

Cosmic rays are particles that are constantly crashing into the Earth from space. When they hit Earth's atmosphere, they release a shower of less massive particles, many of which invisibly rain down to us.

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

The strong meson (Yukawa, 1934)

Strong meson (intermediate mass) must be the nuclear force carrier with mass ~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 (one feels the strong nuclear force, the other does not)

From Griffiths

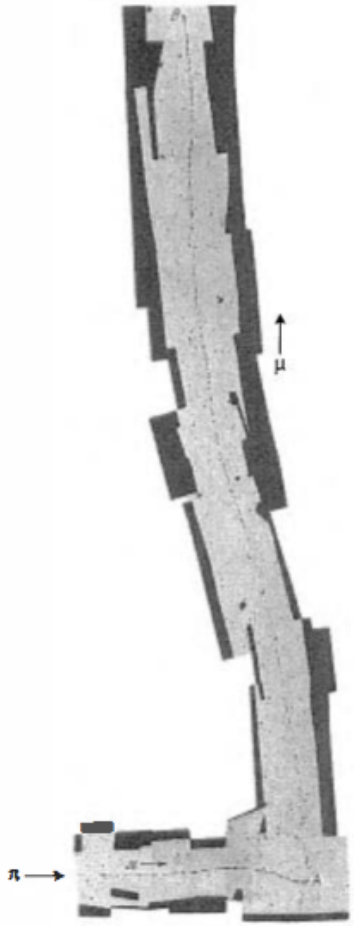


Fig. 1.3 One of Powell's earliest pictures showing the track of a pion in a photographic emulsion exposed to cosmic rays at high altitude. The pion (entering from the left) decays into a muon and a neutrino (the latter is electrically neutral, and leaves no track). (*Source:* Powell, C. F., Fowler, P.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

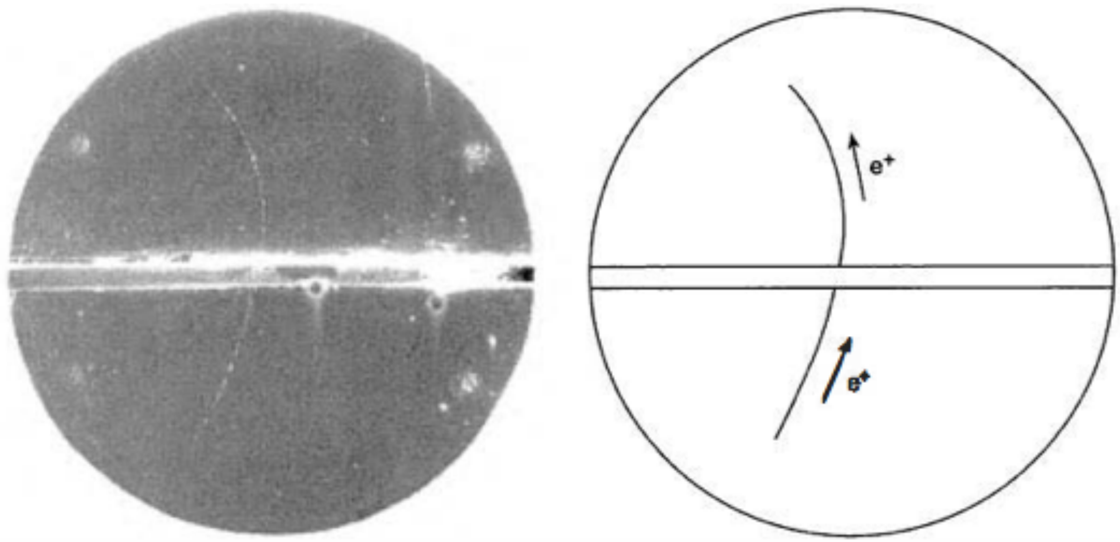


Fig. 1.4 The positron. In 1932, Anderson took this photograph of the track left in a cloud chamber by a cosmic ray particle. The chamber was placed in a magnetic field (pointing into the page), which caused the particle to travel in a curve. But was it a negative charge traveling downward or a positive 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.)

Antiparticles

Protons vs anti-proton

$$p = (uud)$$

$$\overline{p} = (\overline{uu}\,\overline{d})$$

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

$$n = (udd)$$

$$\overline{n} = (\overline{u}\,\overline{dd})$$

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

$$\gamma = \overline{\gamma}$$

Crossing symmetry

$$A + B \to C + D \to$$

If this then also...

$$A \to \overline{B} + C + D$$

$$A + \overline{C} \to \overline{B} + D$$

$$\gamma + e^- \to \gamma + e^-$$

Implies

$$e^+ + e^- \to \gamma + \gamma$$

$$\gamma + \gamma \to e^+ + e^-$$

Let's talk about what the "arrows" mean

On crossing symmetry

$$A + B \rightarrow C + D \rightarrow$$

If this then also...

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

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

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

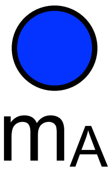
Neutrinos

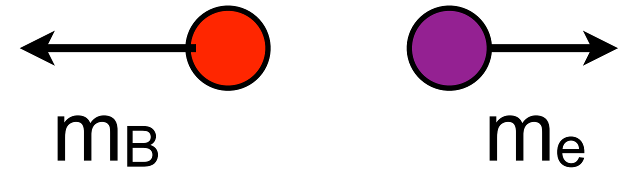
$$A \to B + e^-$$

$$n \to p + e^-$$

What is the energy of the electron in this decay?

Neutrinos





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

After decay

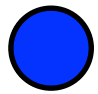
$$E = m_A$$

$$p = 0$$

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

Conservation of momentum: $p_B = p_e = p$

Neutrinos



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

After decay

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

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

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

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

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

Neutrinos

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

After decay

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

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

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

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

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

$$4m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2 + 4p^4 =$$
$$m_A^4 + m_B^4 + m_e^4 + 4p^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 + 2m_B^2 m_e^2 + 4m_B^2 p^2 + 4m_e^2 p^2$$
$$m_A^4 + m_B^4 + m_e^4 - 2m_A^2 m_B^2 - 2m_A^2 m_e^2 - 4m_A^2 p^2 - 2m_B^2 m_e^2 = 0$$
$$p^2 = \frac{1}{4}\left(m_A^2 + (m_B^4 + m_e^4 - 2m_B^2 m_e^2)/m_A^2 - 2m_B^2 - 2m_e^2\right)$$

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

From Griffiths

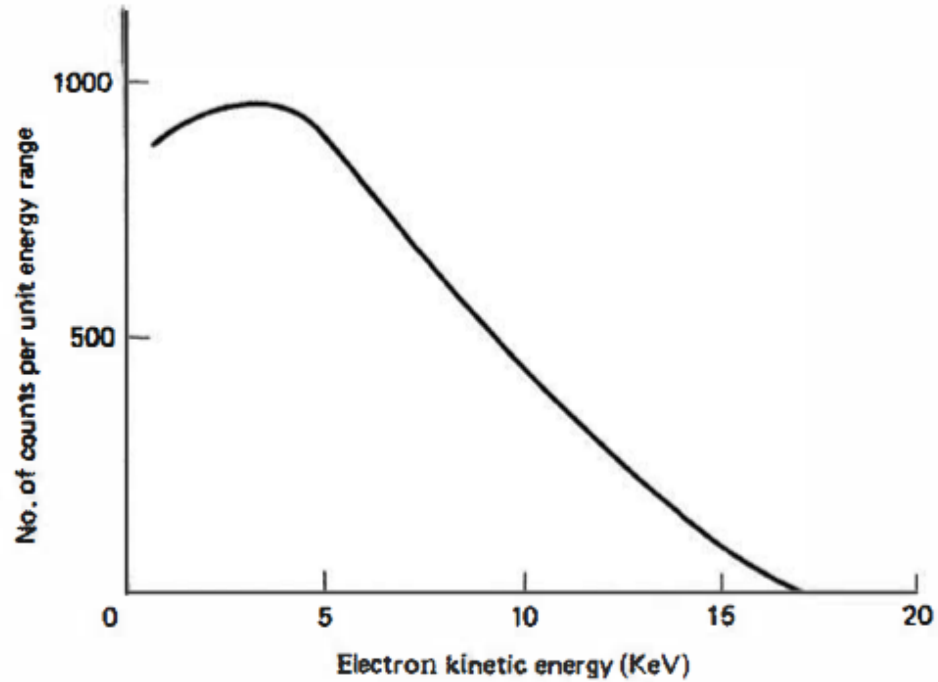


Fig. 1.5 The beta decay spectrum of tritium ($^3_1H \rightarrow ^3_2He$). (*Source*: Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

Neutrinos

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

From Griffiths

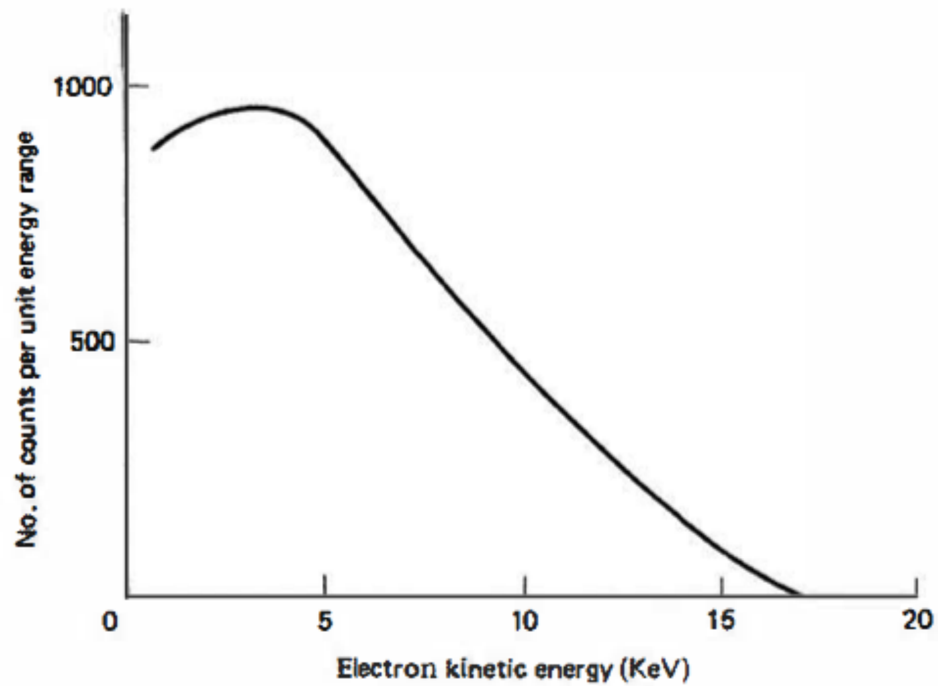
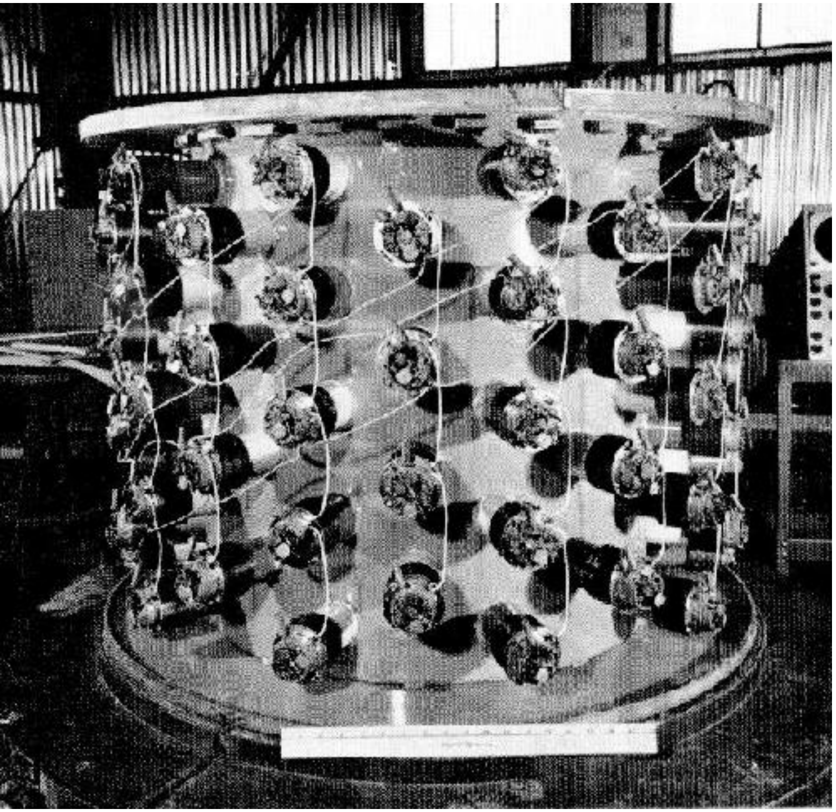


Fig. 1.5 The beta decay spectrum of tritium ($^3_1H \rightarrow {}^3_2He$). (*Source*: Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

Neutrinos, Cowan and Reines



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

$$\overline{\nu} + p \to n + e^+$$

$$e^+ + e^- \to \gamma\gamma$$

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

Tests with anti-neutrinos?

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

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

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

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

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

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

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

Similarly

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 e	Before mu	After e	After mu
$\overline{\nu_e} + p \rightarrow n + e^+$	-1	0	-1	0
$\pi^+ \rightarrow \mu^+ + \nu_\mu$	0	0	0	1-1=0
$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$	0	0	0	1-1=0
$\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$	0	1	1-1=0	1
$n \rightarrow p + e^- + \overline{\nu_e}$	0	0	1-1=0	0

Conservation of baryon number

Neutron decay

$$n \longrightarrow e^- + \overline{\nu_e} + p$$

No proton decay

$$p \nrightarrow e^+ + \nu_e$$

$$p \nrightarrow e^+ + \nu_e + \gamma$$

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

Strange things

$$K^0 \rightarrow \pi^+ + \pi^-$$

From Griffiths

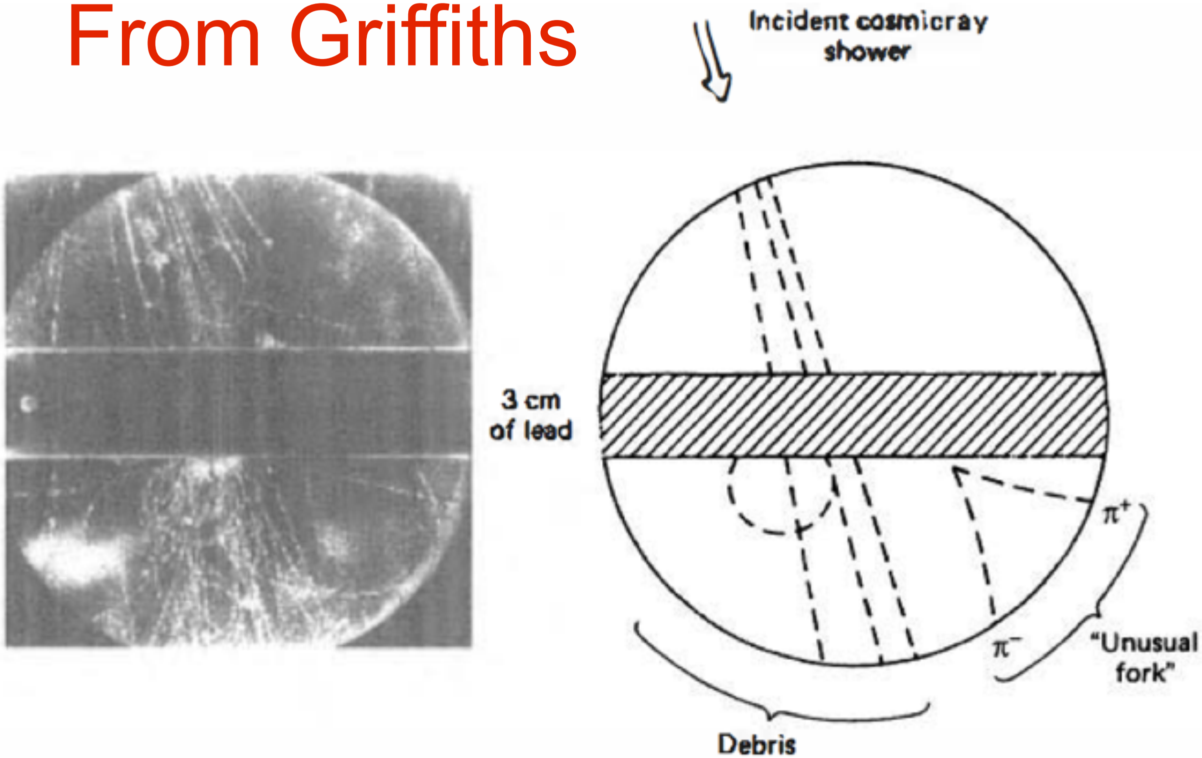


Fig. 1.7 The first strange particle. Cosmic rays strike a lead plate, producing a K^0, which subsequently decays into a pair of charged pions. (Photo courtesy of Prof. Rochester, G. D. (© 1947). *Nature*, **160**, 855. Copyright Macmillan Journals Limited.)

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?

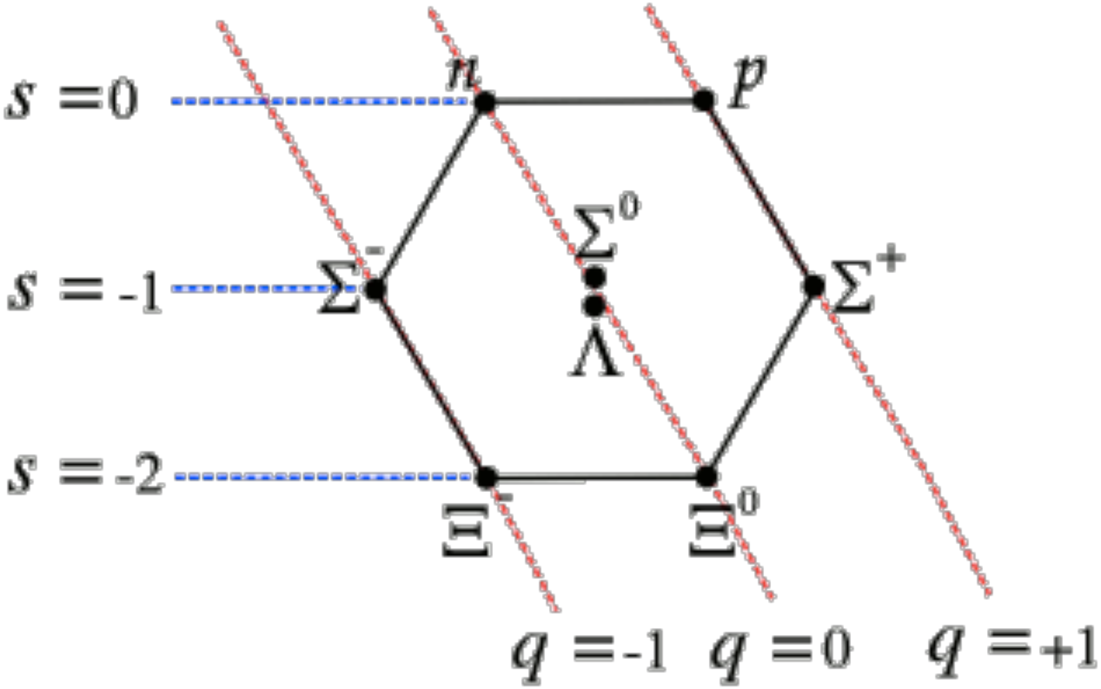
What if kaons are produced by the strong force, but decay typically via the weak force?

Strangeness is conserved in strong interactions but not in weak interactions

$$\pi^- + p \to K^+ + \Sigma^-$$
$$\pi^- + p \to K^0 + \Sigma^0$$
$$\pi^- + p \to K^0 + \Lambda$$

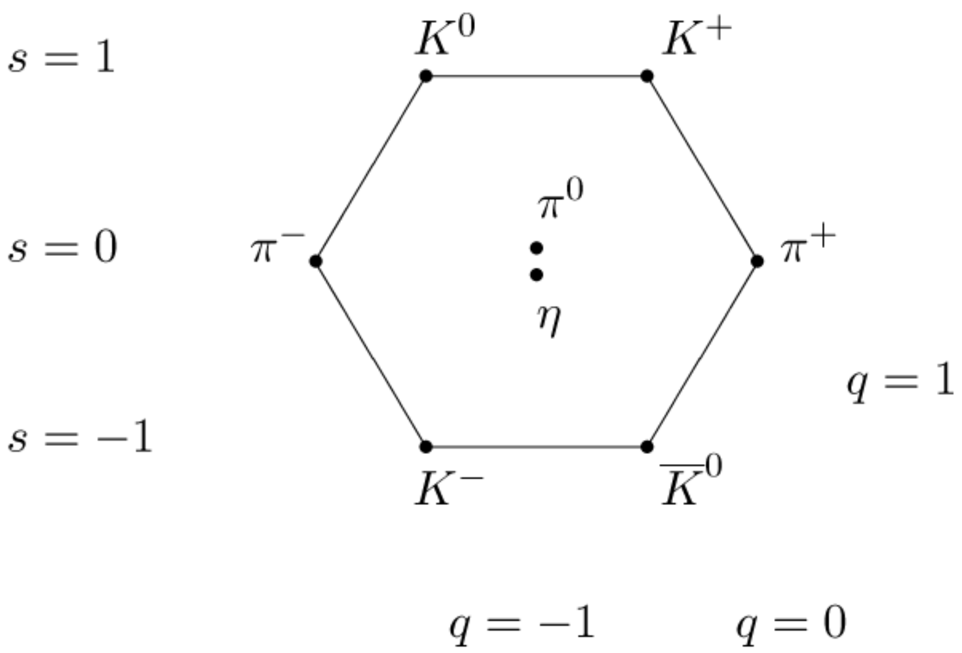
Initially, have zero strangeness. Assign S=+1 to K^+ and K^0 and S=-1 to Λ and Σ, S remains 0. What does this say about how the above are produced? Note: strangeness not conserved in the decay.

And how to start organizing all of this?



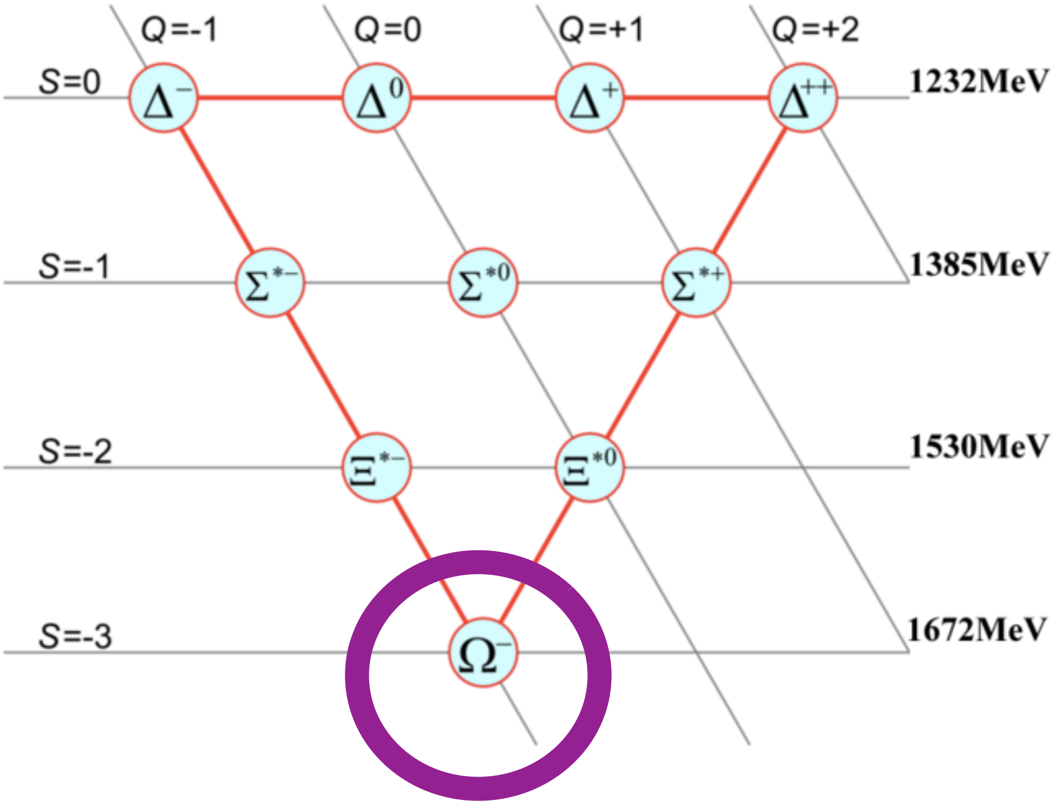
Murray Gell-Man proposed his "Eightfold way" (apparently a slight reference to the Noble Eightfold path of Buddhism)

Moving from baryons to mesons



Similar periodic structure (remind you of anything)?

How was this verified?



This was predicted (including its mass and lifetime!)

We’ve skipped over some of the fun history

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"

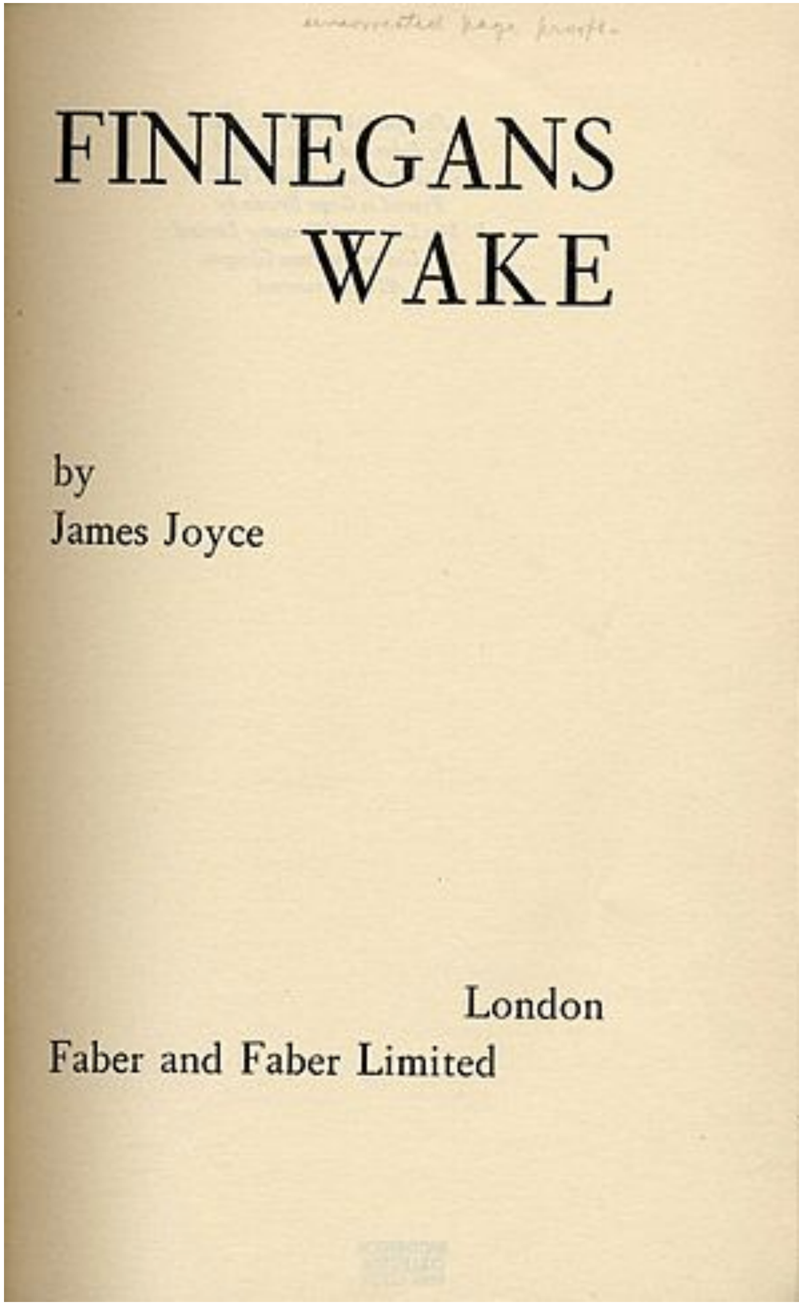
The quark model (Gell-Man and Zweig)

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!

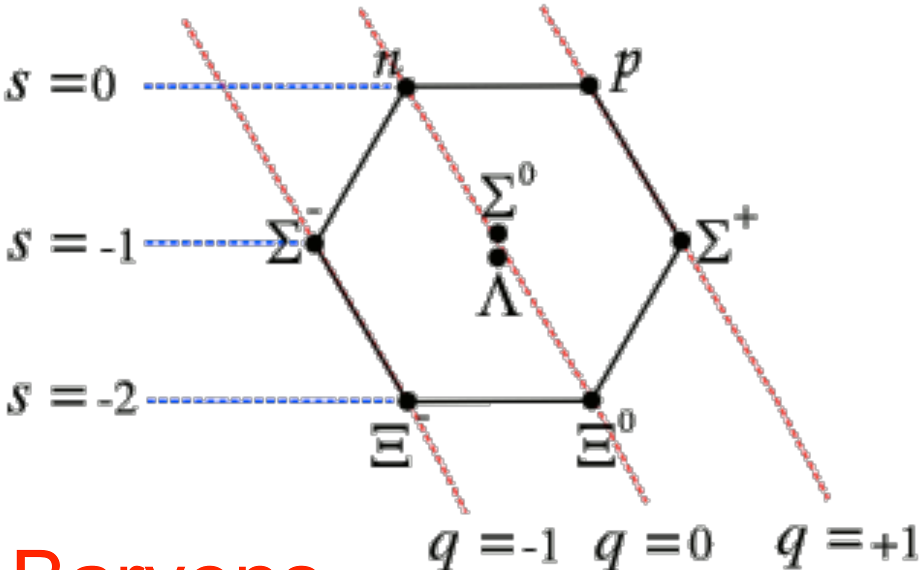
Wikipedia: ***Finnegans Wake*** is a novel by Irish writer James Joyce. It is significant for its experimental style and reputation as one of the most difficult works of fiction in the English language.


FINNEGANS WAKE

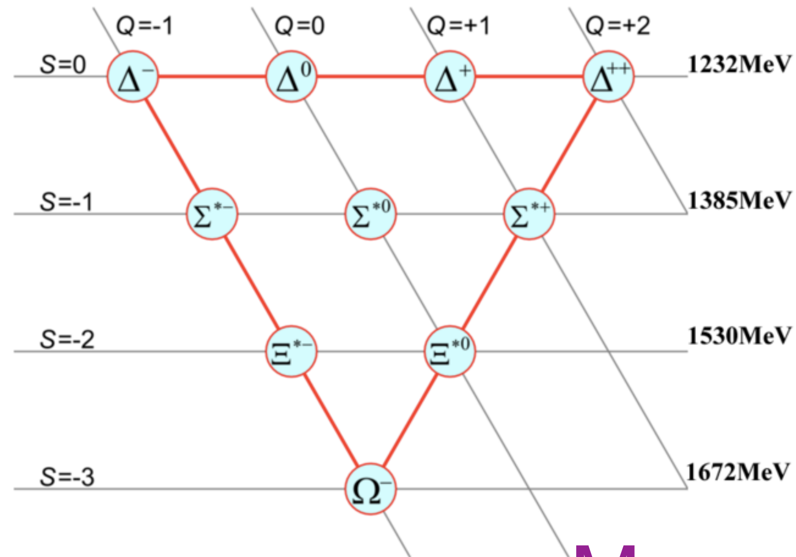
by
James Joyce

London
Faber and Faber Limited

Hadrons



Baryons



Mesons

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

The quark model (so far in our course)

	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	Δ^{++}	1
uud	1	0	Δ^{+}	1
udd	0	0	Δ^{0}	1
ddd	-1	0	Δ^{-}	1
uus	1	-1	Σ^{*+}	1
uds	0	-1	Σ^{*0}	1
dds	-1	-1	Σ^{*-}	1
uss	0	-2	Ξ^{*0}	1
dss	-1	-2	Ξ^{*-}	1
sss	-1	-3	Ω^{-}	1

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

It really is a particle zoo (from the PDG)

Meson Summary Table

See also the table of suggested $q\overline{q}$ quark-model assignments in the Quark Model section.

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.

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

	$I^G(J^{PC})$
• $\pi^{\pm}$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(500)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$
• $f_2'(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
$\rho(1570)$	$1^+(1^{--})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
$a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$
• $\pi_2(1670)$	$1^-(2^{-+})$

	$I^G(J^{PC})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
$a_2(1700)$	$1^-(2^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$\eta(1760)$	$0^+(0^{-+})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$?^?(?^{-+})$
$X(1840)$	$?^?(?^{??})$
• $\phi_3(1850)$	$0^-(3^{--})$
$\eta_2(1870)$	$0^+(2^{-+})$
• $\pi_2(1880)$	$1^-(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
• $f_2(1950)$	$0^+(2^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
• $f_2(2010)$	$0^+(2^{++})$
$f_0(2020)$	$0^+(0^{++})$
• $a_4(2040)$	$1^-(4^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
• $\phi(2170)$	$0^-(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2^{++}$ or $4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
$f_0(2330)$	$0^+(0^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$a_6(2450)$	$1^-(6^{++})$
$f_6(2510)$	$0^+(6^{++})$

OTHER LIGHT

Further States

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^{\pm}$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K_0^*(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K_0^*(1430)$	$1/2(0^+)$
• $K_2^*(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K_3^*(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K_0^*(1950)$	$1/2(0^+)$
$K_2^*(1980)$	$1/2(2^+)$
• $K_4^*(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K_5^*(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

	$I(J^P)$
• $D^{\pm}$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^{\pm}$	$1/2(1^-)$
• $D_0^*(2400)^0$	$1/2(0^+)$
$D_0^*(2400)^{\pm}$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^{\pm}$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D_2^*(2460)^0$	$1/2(2^+)$
• $D_2^*(2460)^{\pm}$	$1/2(2^+)$
$D(2550)^0$	$1/2(0^-)$
$D(2600)$	$1/2(?^?)$
$D^*(2640)^{\pm}$	$1/2(?^?)$
$D(2750)$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

	$I(J^P)$
• $D_s^{\pm}$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D_{s0}^*(2317)^{\pm}$	$0(0^+)$
• $D_{s1}(2460)^{\pm}$	$0(1^+)$
• $D_{s1}(2536)^{\pm}$	$0(1^+)$
• $D_{s2}(2573)$	$0(?^?)$
• $D_{s1}^*(2700)^{\pm}$	$0(1^-)$
$D_{sJ}^*(2860)^{\pm}$	$0(?^?)$
$D_{sJ}(3040)^{\pm}$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I(J^P)$
• $B^{\pm}$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^{\pm}/B^0$ ADMIXTURE	
• $B^{\pm}/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B_J^*(5732)$	$?(?^?)$
• $B_1(5721)^0$	$1/2(1^+)$
• $B_2^*(5747)^0$	$1/2(2^+)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

	$I(J^P)$
• B_s^0	$0(0^-)$
• B_s^*	$0(1^-)$
• $B_{s1}(5830)^0$	$0(1^+)$
• $B_{s2}^*(5840)^0$	$0(2^+)$
$B_{sJ}^*(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

	$I(J^P)$
• $B_c^{\pm}$	$0(0^-)$

$c\overline{c}$

	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
$X(3823)$	$?^?(?^{?-})$
• $X(3872)$	$0^+(1^{++})$
• $X(3900)^{\pm}$	$?(1^+)$
$X(3900)^0$	$?(?^?)$
• $\chi_{c0}(2P)$	$0^+(0^{++})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$X(4020)^{\pm}$	$?(?^?)$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^{\pm}$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^{\pm}$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^{\pm}$	$?(1^+)$
• $X(4660)$	$?^?(1^{--})$

$b\overline{b}$

	$I^G(J^{PC})$
$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $h_b(1P)$	$?^?(1^{+-})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
$\eta_b(2S)$	$0^+(0^{-+})$
• $\Upsilon(2S)$	$0^-(1^{--})$
• $\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
$h_b(2P)$	$?^?(1^{+-})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\chi_b(3P)$	$?^?(?^{?+})$
• $\Upsilon(4S)$	$0^-(1^{--})$
$X(10610)^{\pm}$	$1^+(1^+)$
$X(10610)^0$	$1^+(1^+)$
$X(10650)^{\pm}$	$?^+(1^+)$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the table are not established baryons. The names with masses are of baryons that decay strongly. The spin-parity J^P (when known) is given with each particle. For the strongly decaying particles, the J^P values are considered to be part of the names.

p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	**
$N(1895)$	$1/2^-$	**
$N(1900)$	$3/2^+$	***
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2300)$	$1/2^+$	**
$N(2570)$	$5/2^-$	**
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1710)$	$1/2^+$	*
$\Lambda(1800)$	$1/2^-$	***
$\Lambda(1810)$	$1/2^+$	***
$\Lambda(1820)$	$5/2^+$	****
$\Lambda(1830)$	$5/2^-$	****
$\Lambda(1890)$	$3/2^+$	****
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2050)$	$3/2^-$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	*
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1730)$	$3/2^+$	*
$\Sigma(1750)$	$1/2^-$	***
$\Sigma(1770)$	$1/2^+$	*
$\Sigma(1775)$	$5/2^-$	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(1900)$	$1/2^-$	*
$\Sigma(1915)$	$5/2^+$	****
$\Sigma(1940)$	$3/2^+$	*
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	$3/2^-$	***
$\Xi(1950)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
$\Lambda_b(5912)^0$	$1/2^-$	***
$\Lambda_b(5920)^0$	$3/2^-$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
$\Xi_b(5945)^0$	$3/2^+$	***
Ω_b^-	$1/2^+$	***

**** Existence is certain, and properties are at least fairly well explored.

*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.

** Evidence of existence is only fair.

* Evidence of existence is poor.

Let's pause and discuss the PDG a bit here. Who knows anything about the PDG?

So why can't we observe quarks directly?

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 (Ω^-) 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")

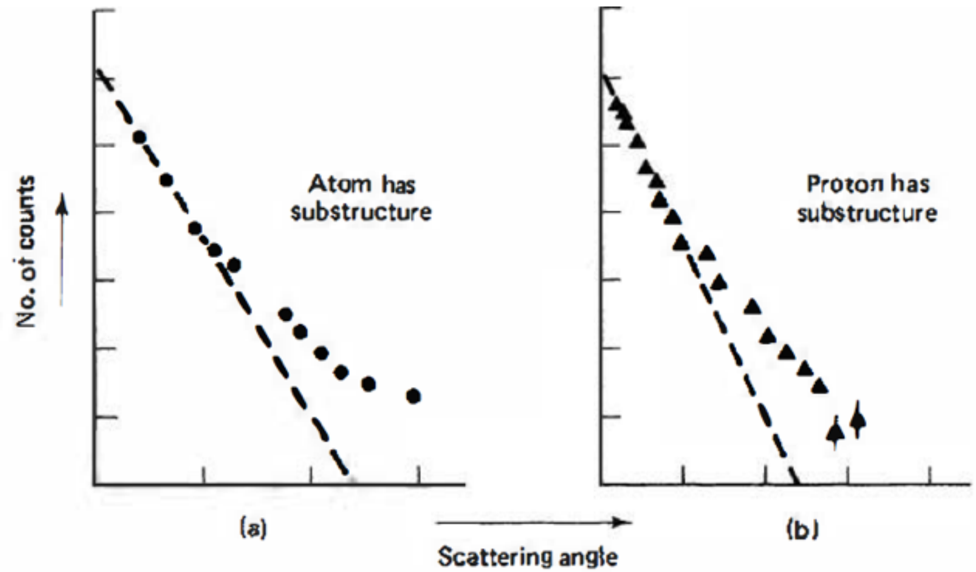
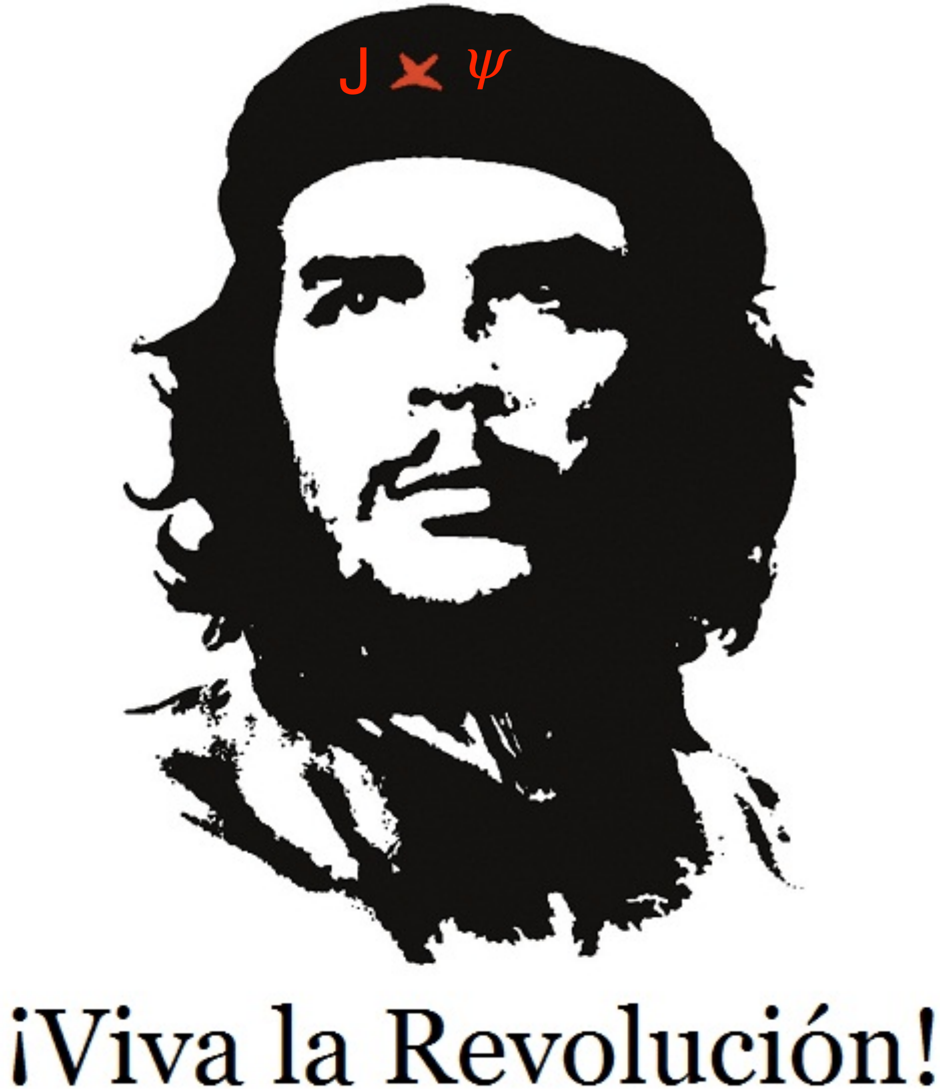


Fig. 1.11 (a) In Rutherford scattering, the number of particles deflected through large angles indicates that the atom has internal structure (a nucleus). (b) In deep inelastic scattering, the number of particles deflected through large angles indicates that the proton has internal structure (quarks). 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.)

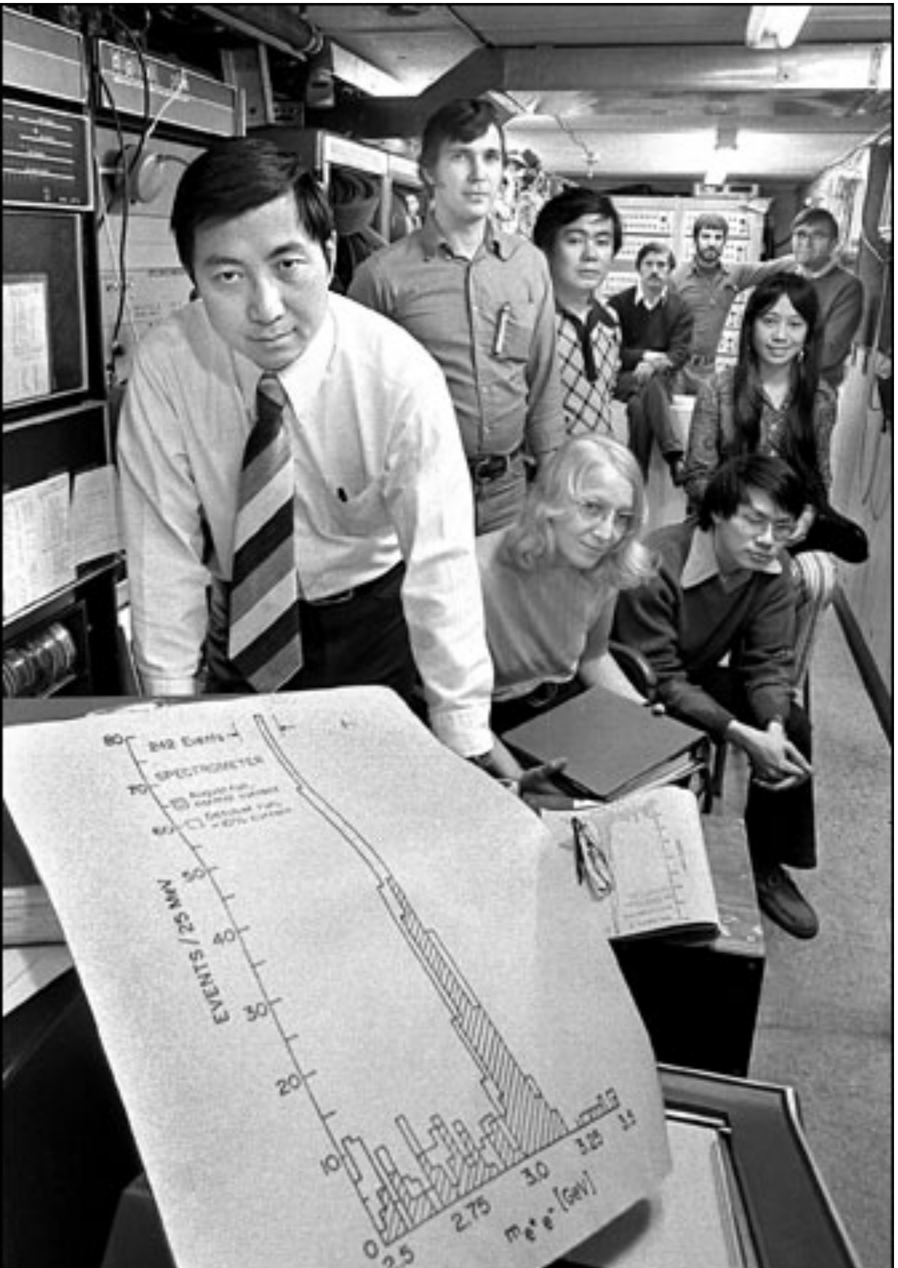
Colorless objects only: Explains why we don't have qq (or q) final states

November revolution

November 1974, ψ meson discovered at SLAC, J meson at Brookhaven. Hence the name J/ψ, a new, electrically neutral particle with a long lifetime. Began the "November revolution"



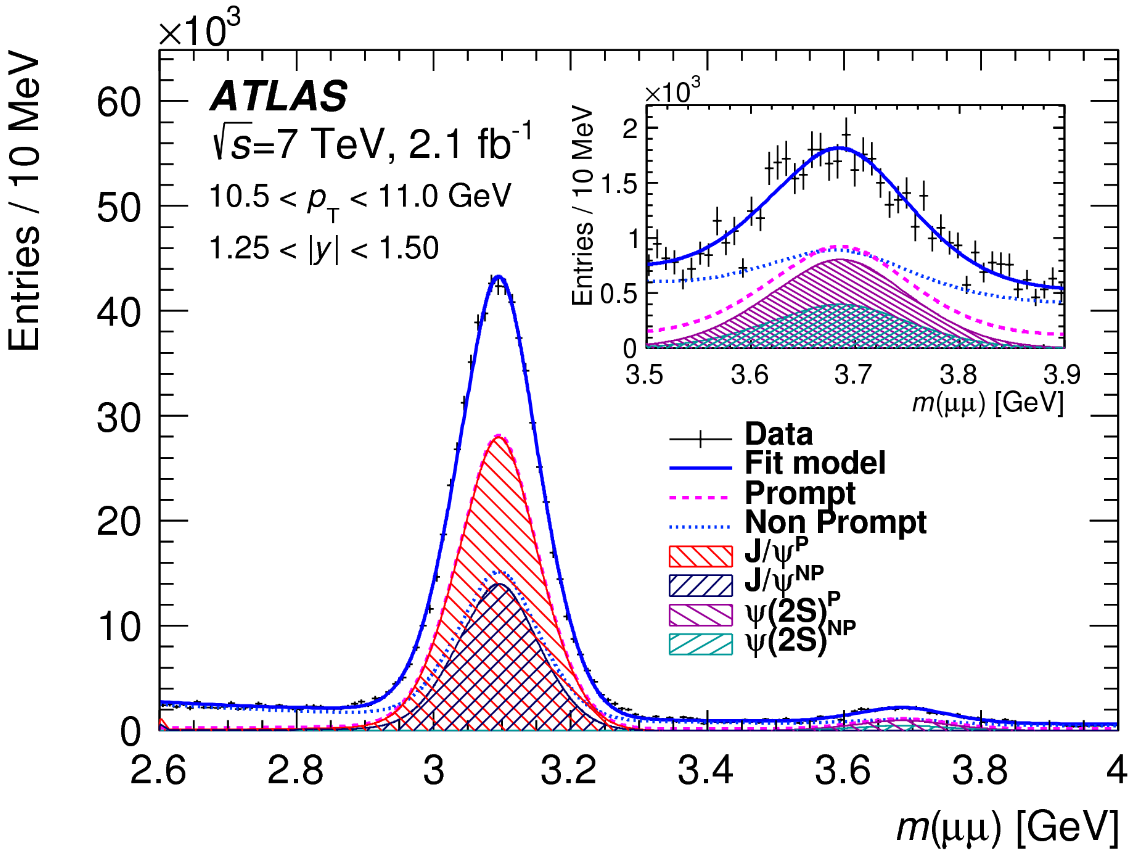
How was it discovered?



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 = JPsi mass

And these days

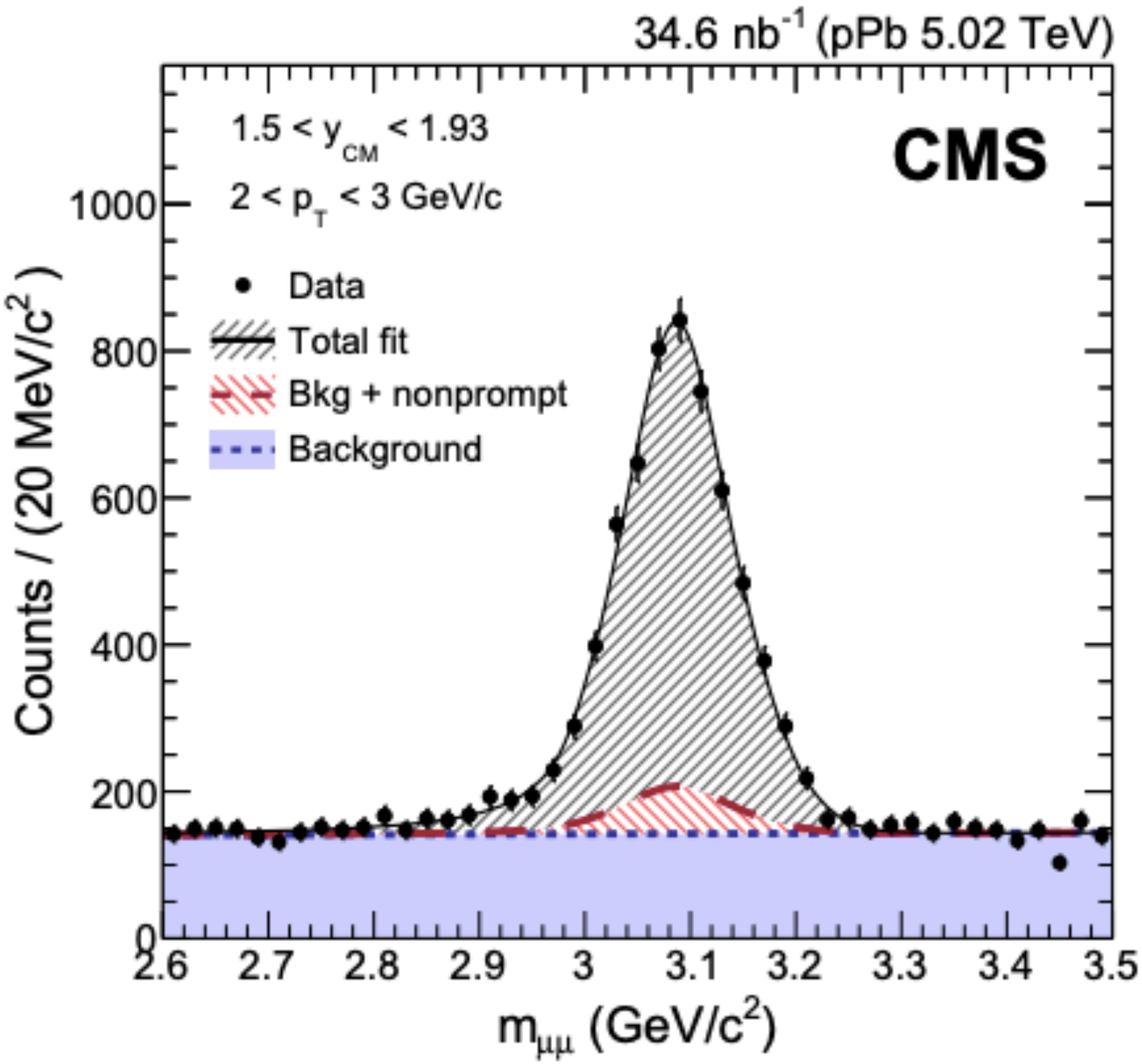


We know that the JPsi is a charm-anticharm bound state with spin = 1

This is a tiny fraction of the data available to ATLAS and CMS, and a large fraction of the JPsi that we produced are not even recorded

arXiv: 1612.02950

JPsi elsewhere



Proton-lead collisions!

arXiv: 1702.01462

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 τ. The caption read:

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

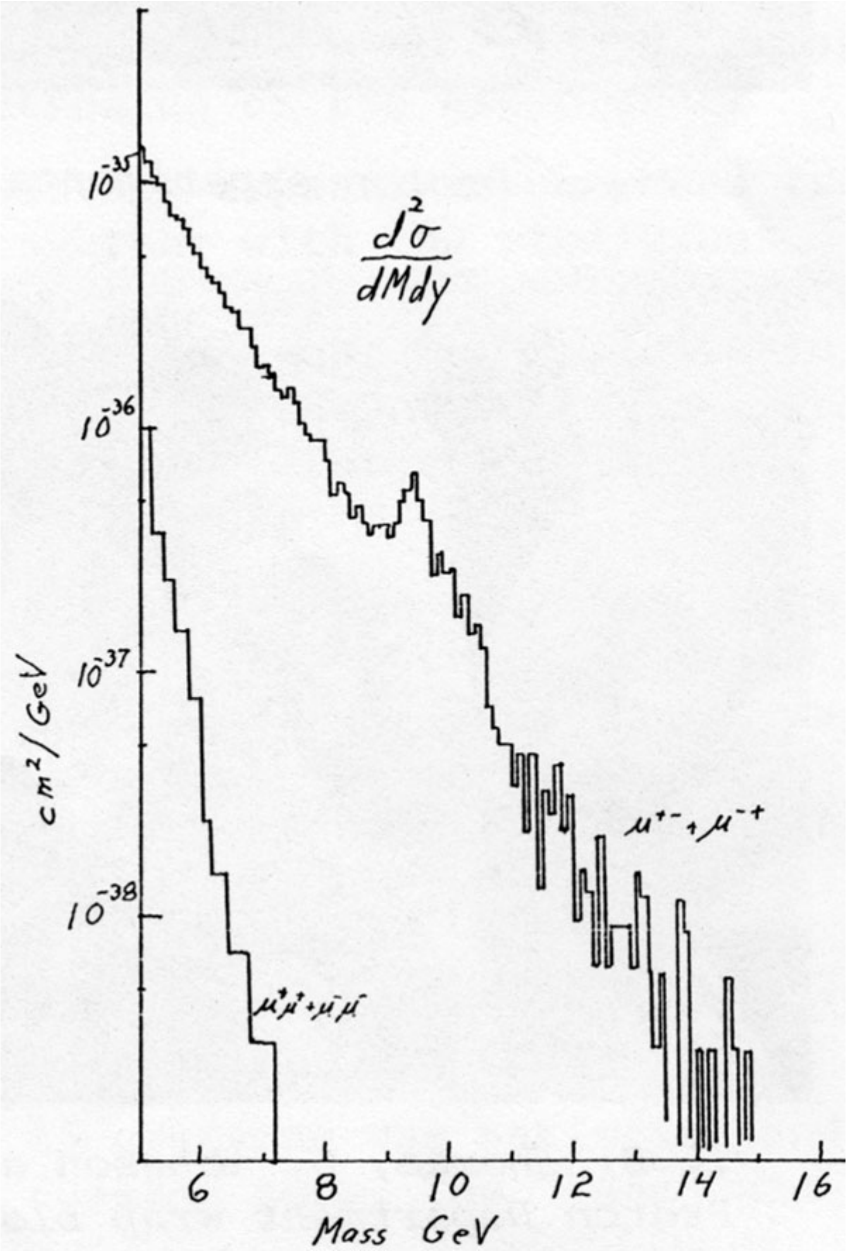
	Total Charge = 0			Total Charge = ±2		
Number photons =	0	1	> 1	0	1	> 1
cc	40	111	55	0	1	0
$e\mu$	24	8	8	0	0	3
$\mu\mu$	16	15	6	0	0	0
eh	18	23	32	2	3	3
μh	15	16	31	4	0	5
hh	13	11	30	10	4	6
Sum	126	184	162	16	8	17

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:

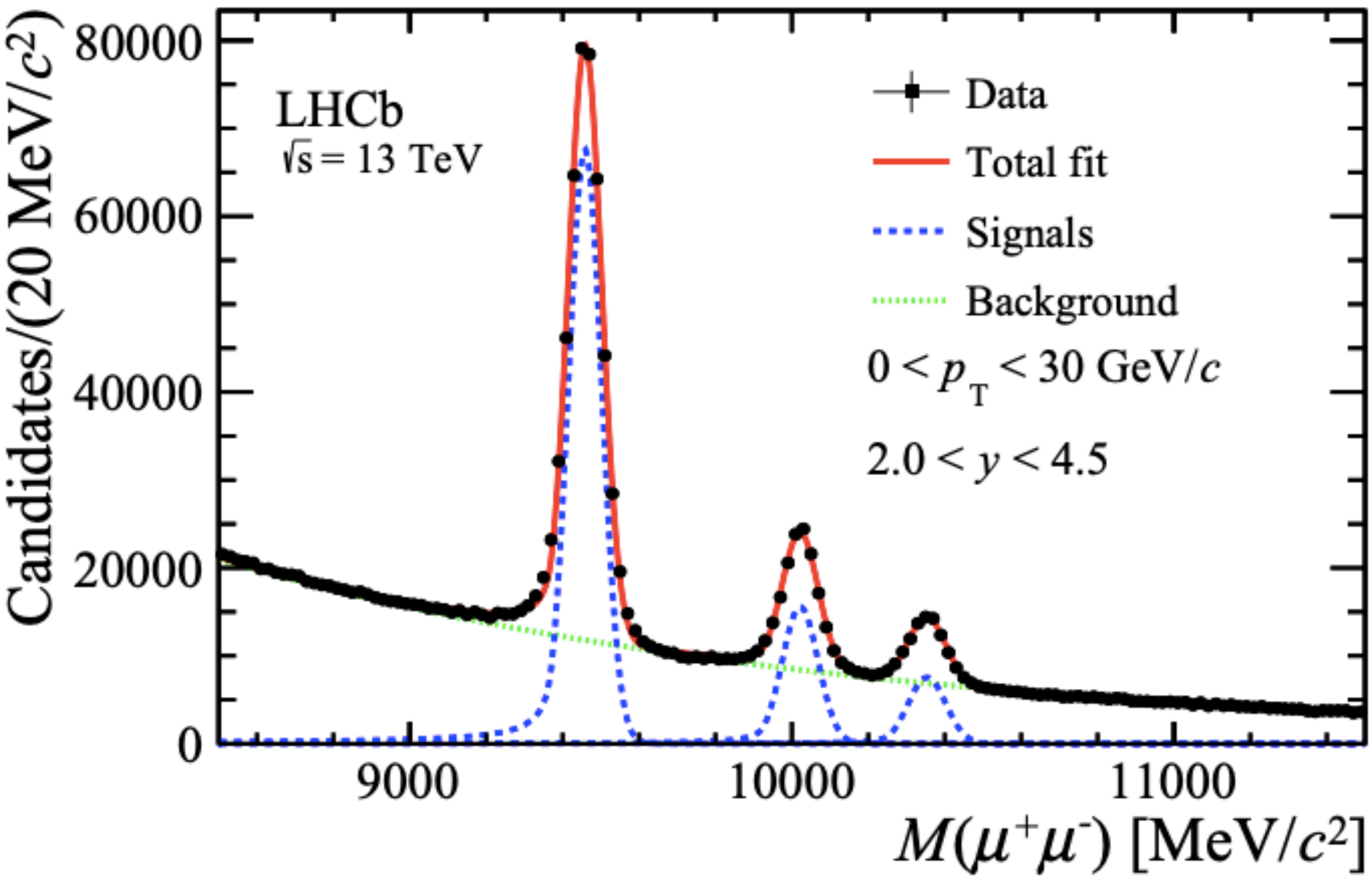
$$\Upsilon = b\bar{b}$$



Lots of upsilons everywhere, too

arXiv: 1804.09214

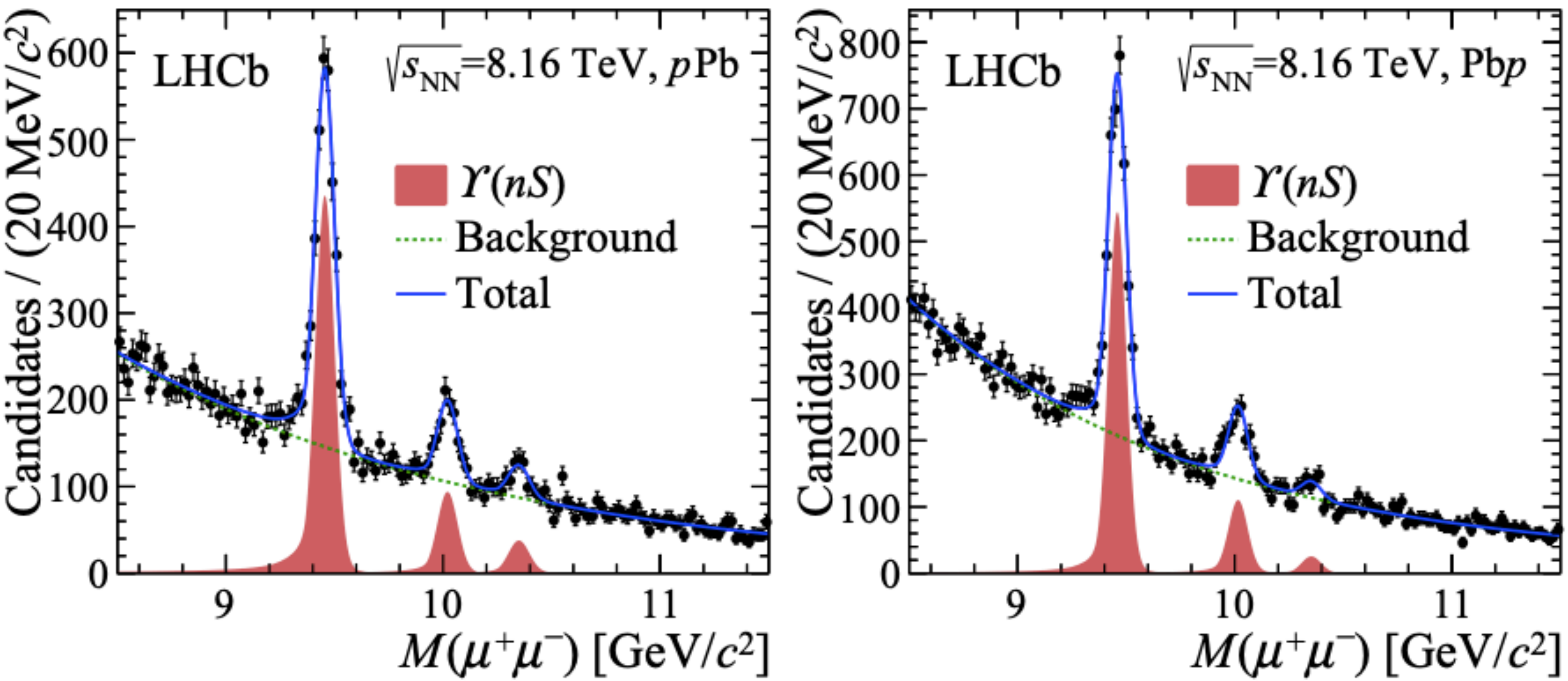
We'll talk about the 3 signal peaks in a few chapters!



Upsilons in proton-lead

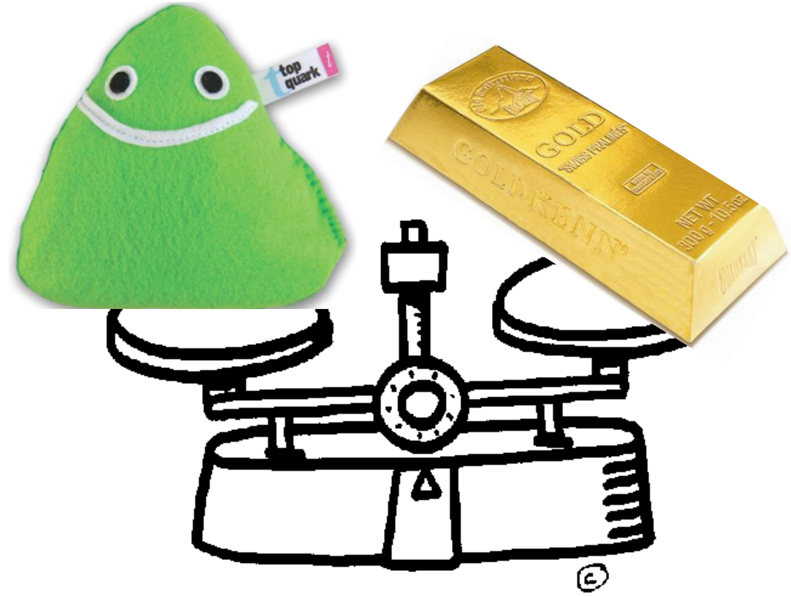
LHCb-PAPER-2018-035

LHCb is an asymmetric detector (any guesses why?). Difference between the two is which beams moves toward the detector at the interaction region



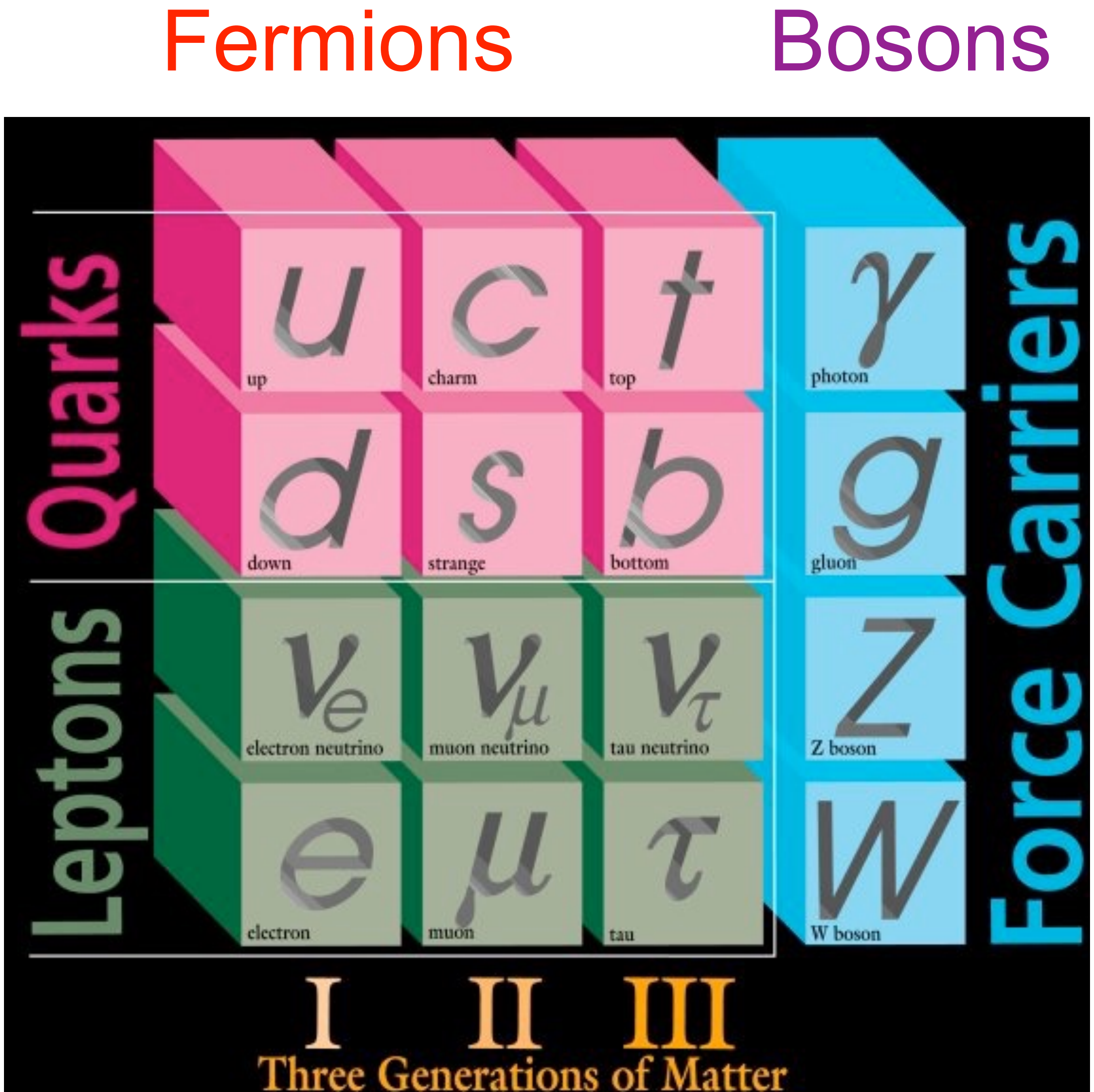
Top quark discovery

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 ~173 GeV!



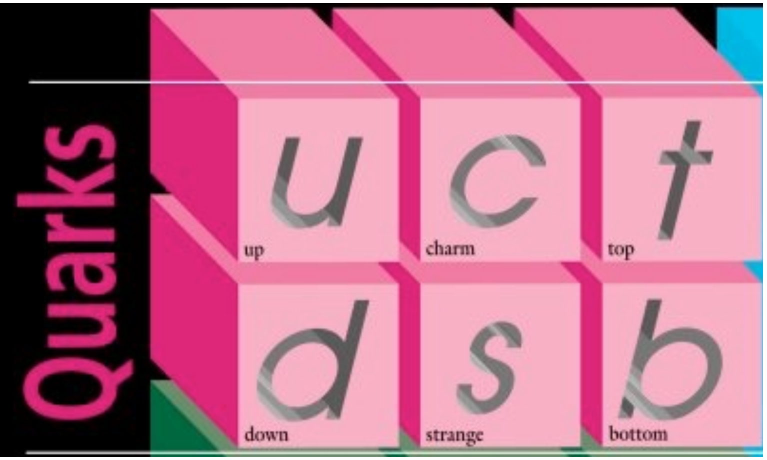
Fun aside: UA1 at CERN made a "discovery" of the top quark in 1984 with a mass of 40 +/- 10 GeV

Putting it all together, aka the Standard Model (SM)



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

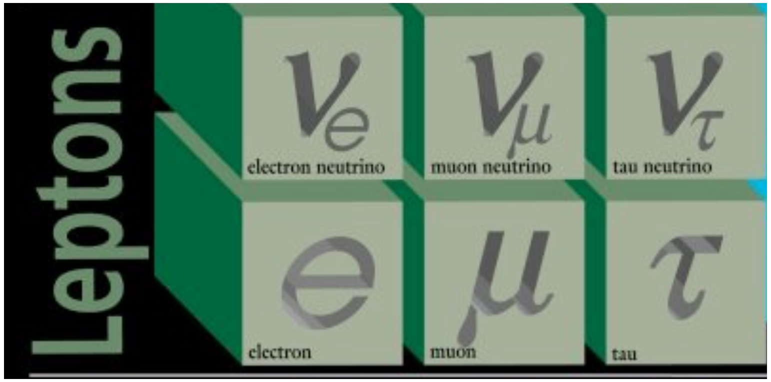
The quarks



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

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

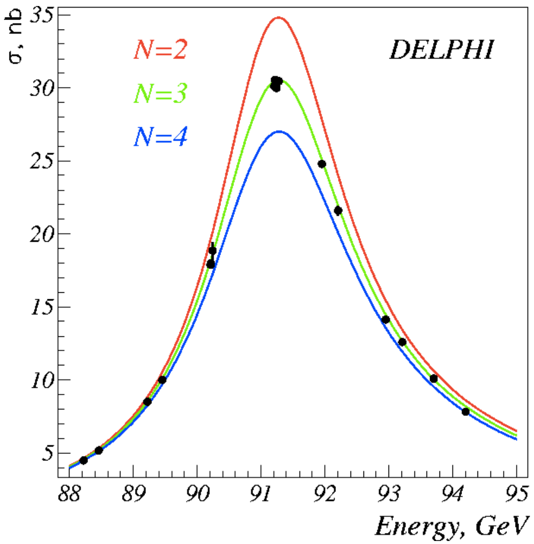
The leptons



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

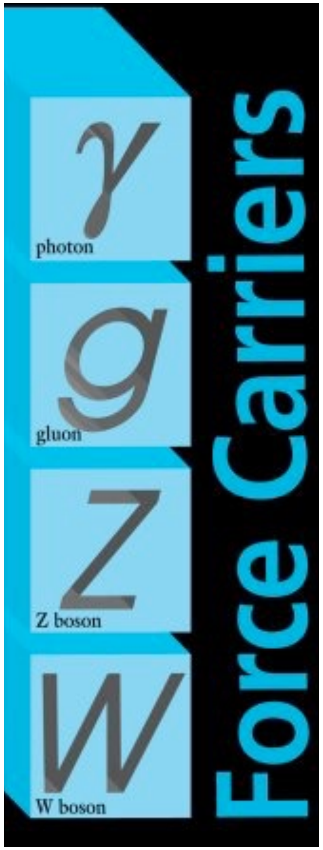
Are there additional leptons? We've been looking for them, though, though extra neutrinos have to be very massive or rarely interact. Masses of observed neutrinos unknown, but are very small

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



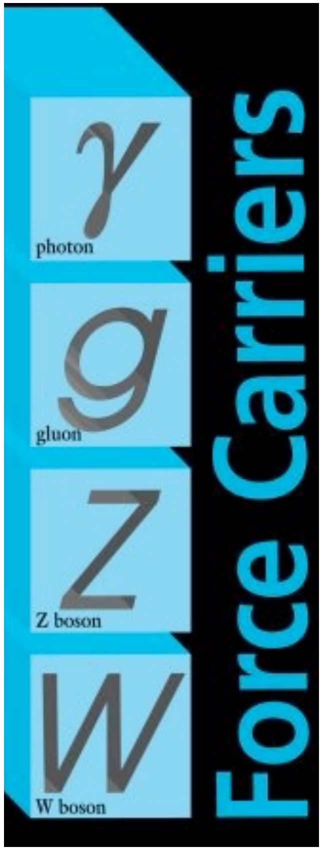
The bosons

Photon never changes matter flavor

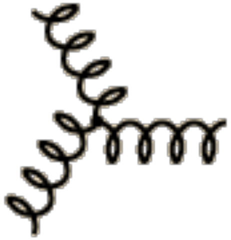


Force carriers are bosons with integer spin. The photon is the force carrier from E&M, and has spin-1 (it's a vector boson) and zero mass. Interacts only with electrically charged particles

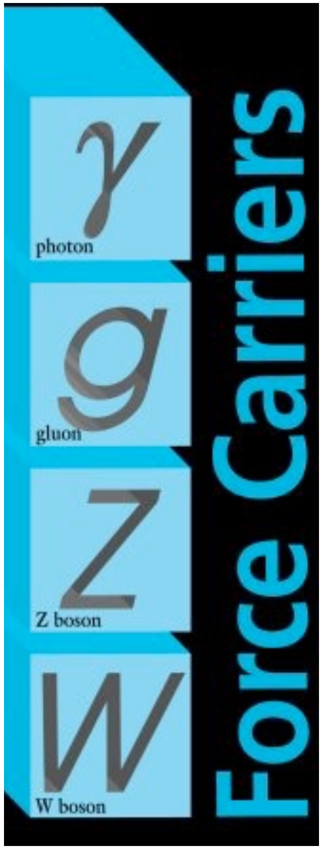
Gluon never changes matter flavor



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

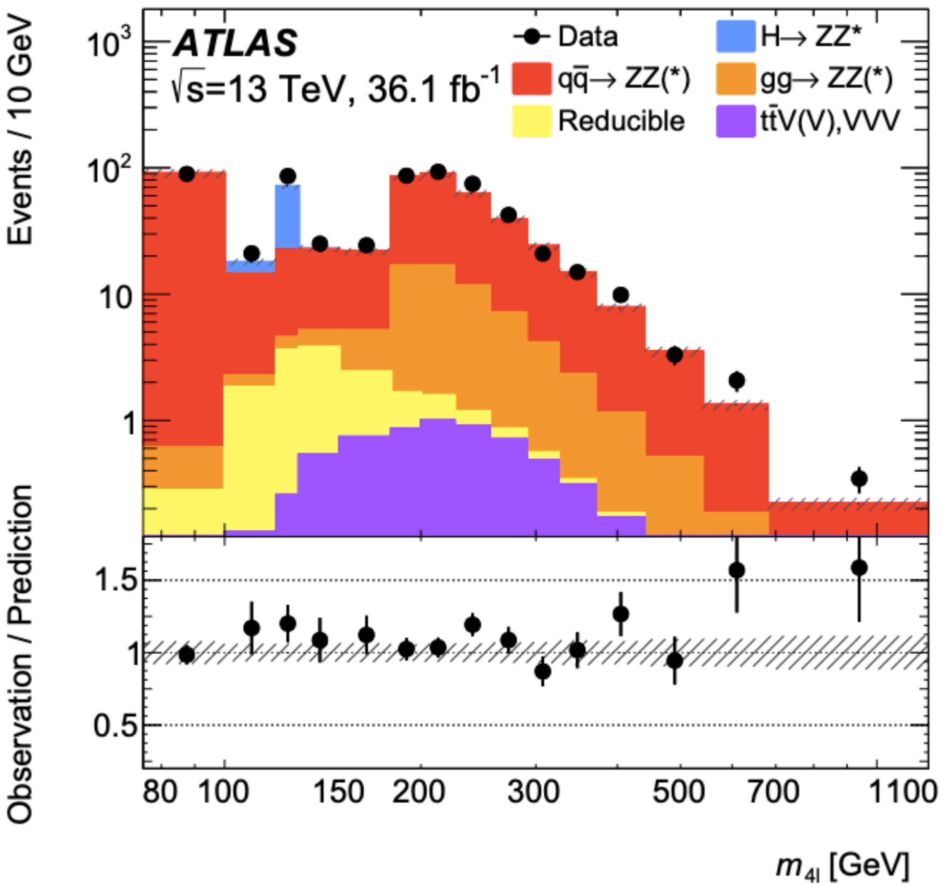


W bosons always change matter flavor, Z bosons do not

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~80 GeV, Z~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 β-decay and fusion

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

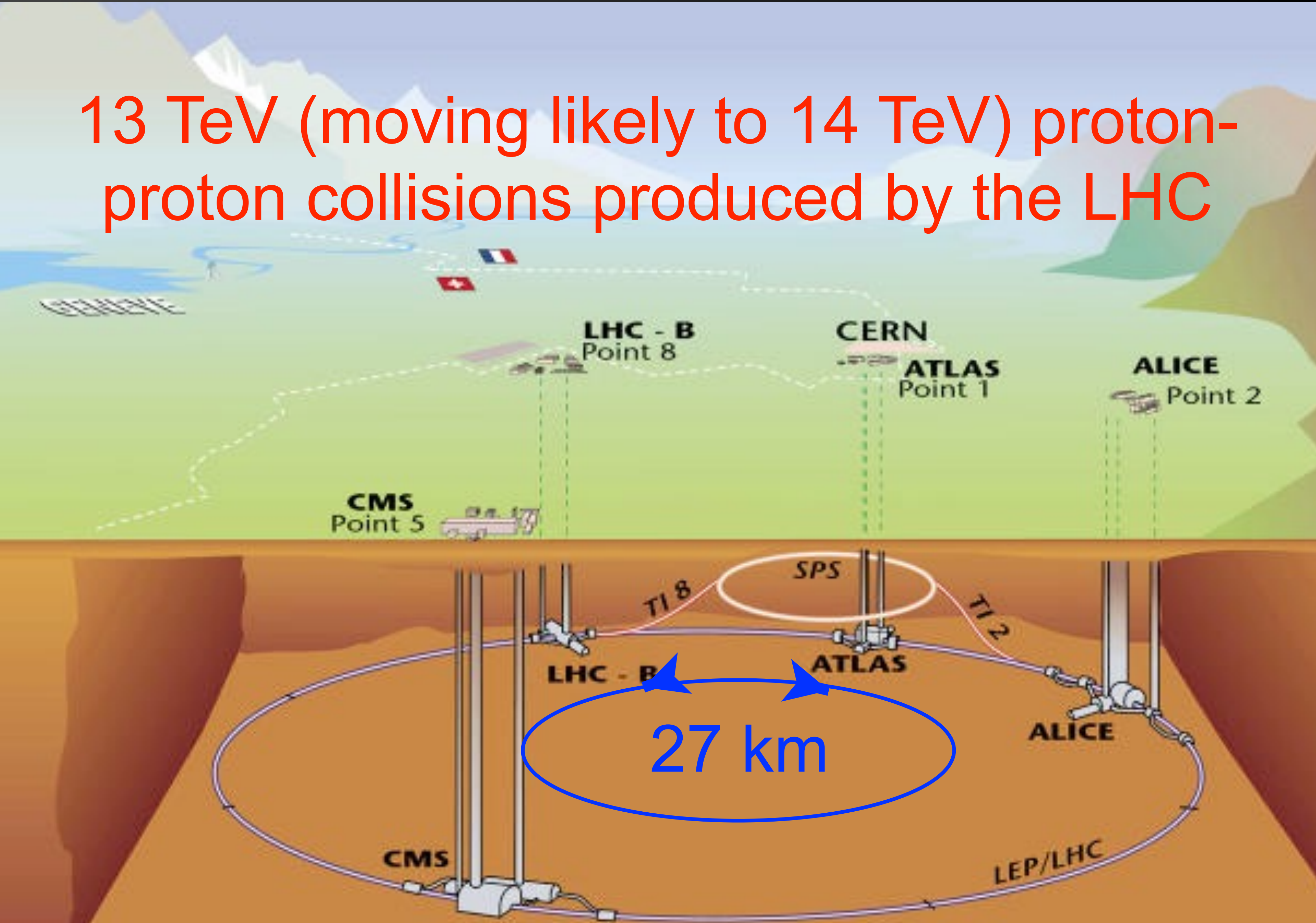
mH ~ 125 GeV



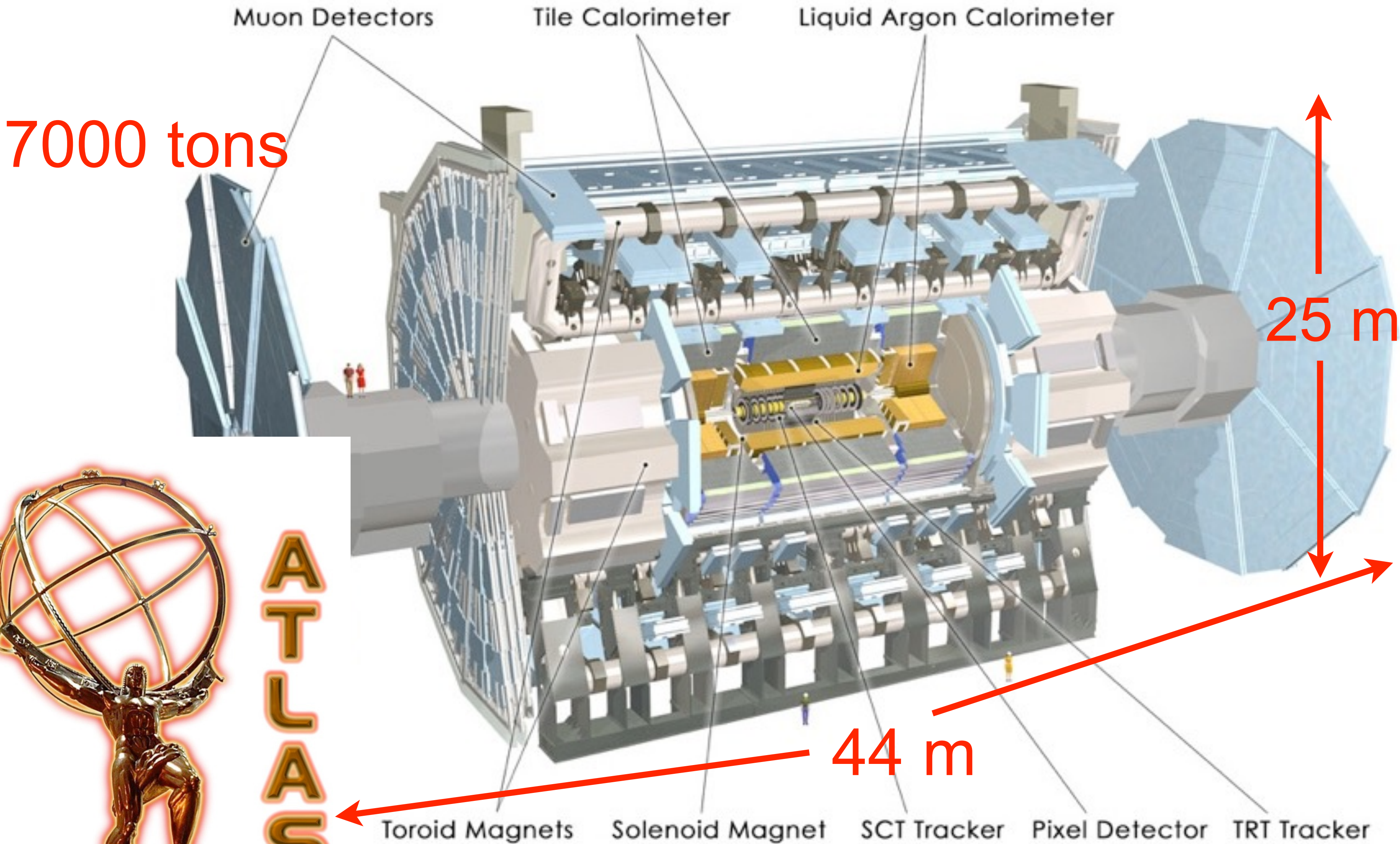
arXiv: 1902.05892

Collisions give us interesting physics (we'll see why)

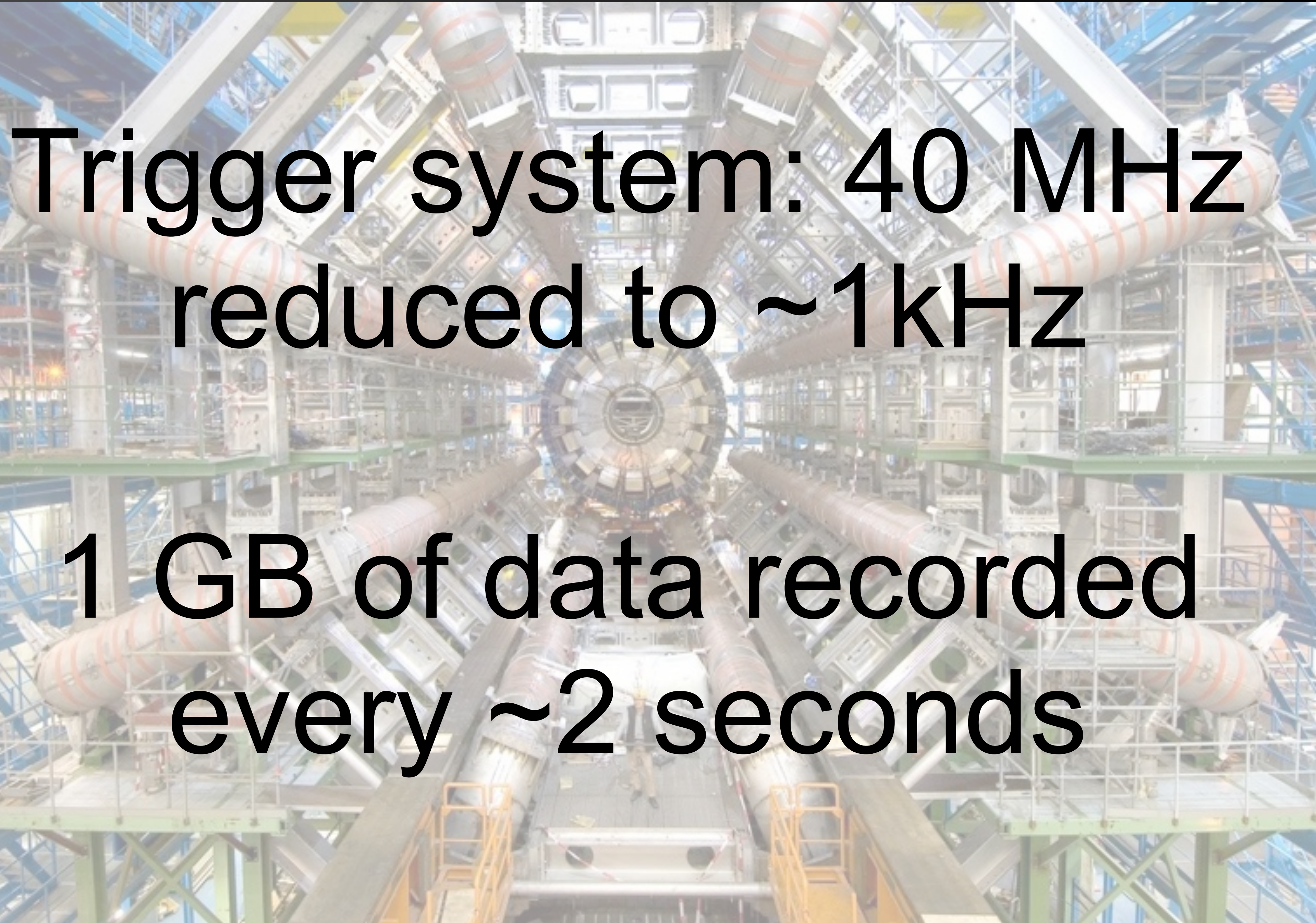
13 TeV (moving likely to 14 TeV) proton-proton collisions produced by the LHC



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



ATLAS



Trigger system: 40 MHz reduced to ~1kHz

1 GB of data recorded every ~2 seconds

Life as a particle physicist

Producing collisions

2808 bunches of 10^{11} protons

Bunches collide at ~40 MHz

Each bunch circulates 27 km ring >11 kHz

Other sorts of modern experiments

g-2
mu2e
neutrino experiments (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

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)

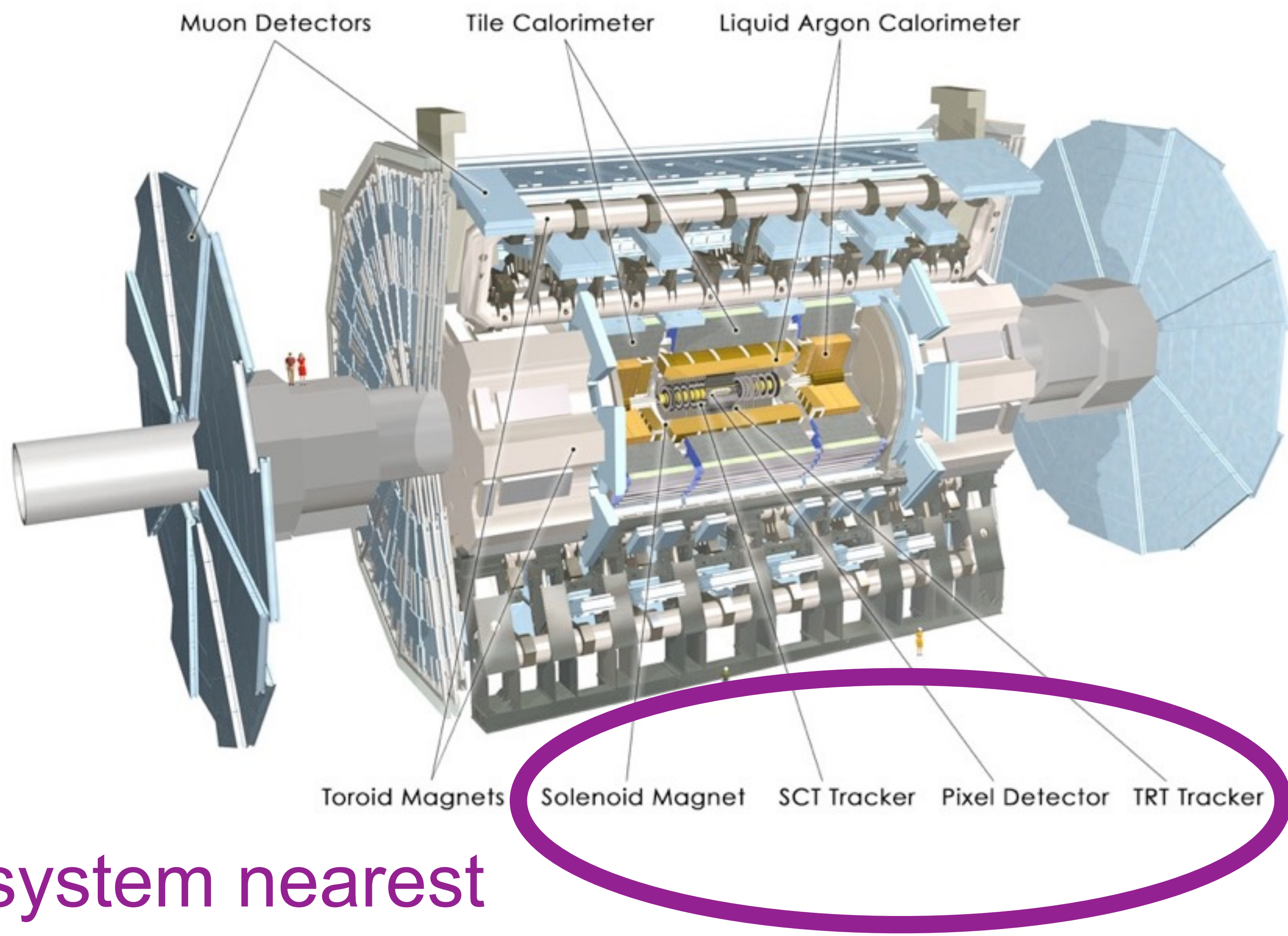
Calorimeter measurements give particle energy (different types of particles deposit energy electromagnetically vs via strong force, and at different rates)

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

Muons are highly penetrating and minimally ionizing

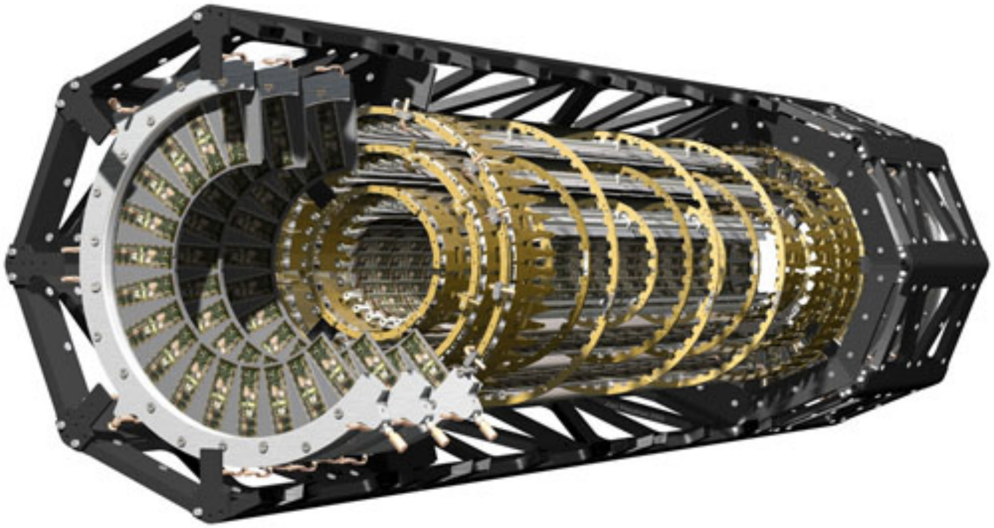
Other tricks like Cherenkov radiation, measurements of dE/dx, looking for transition radiation at material boundaries, ...

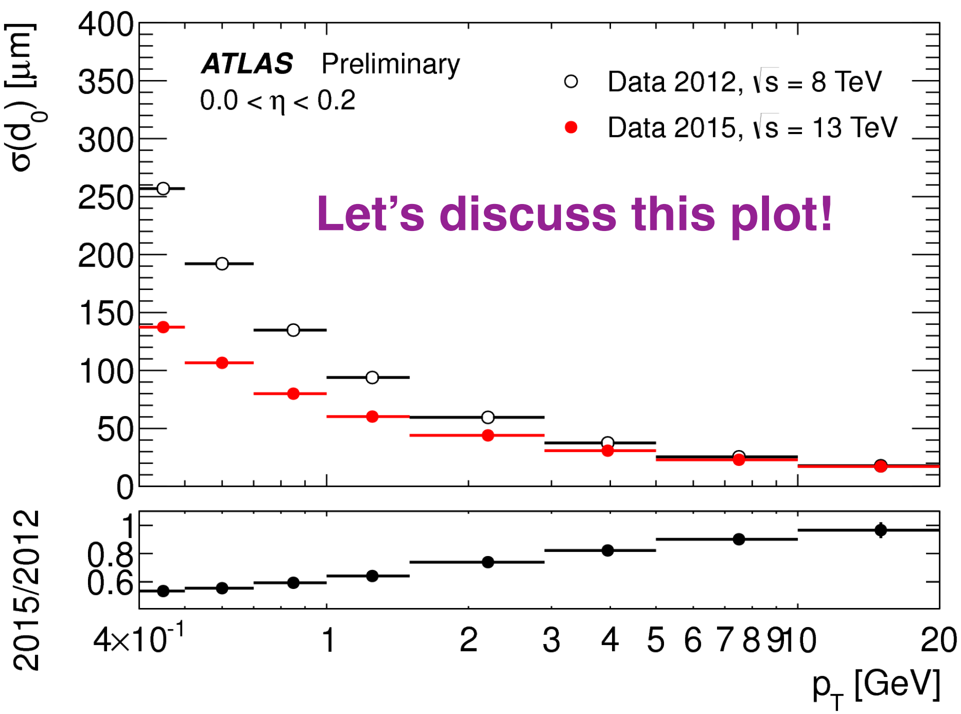
Back to ATLAS



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

ATLAS pixel subsystem





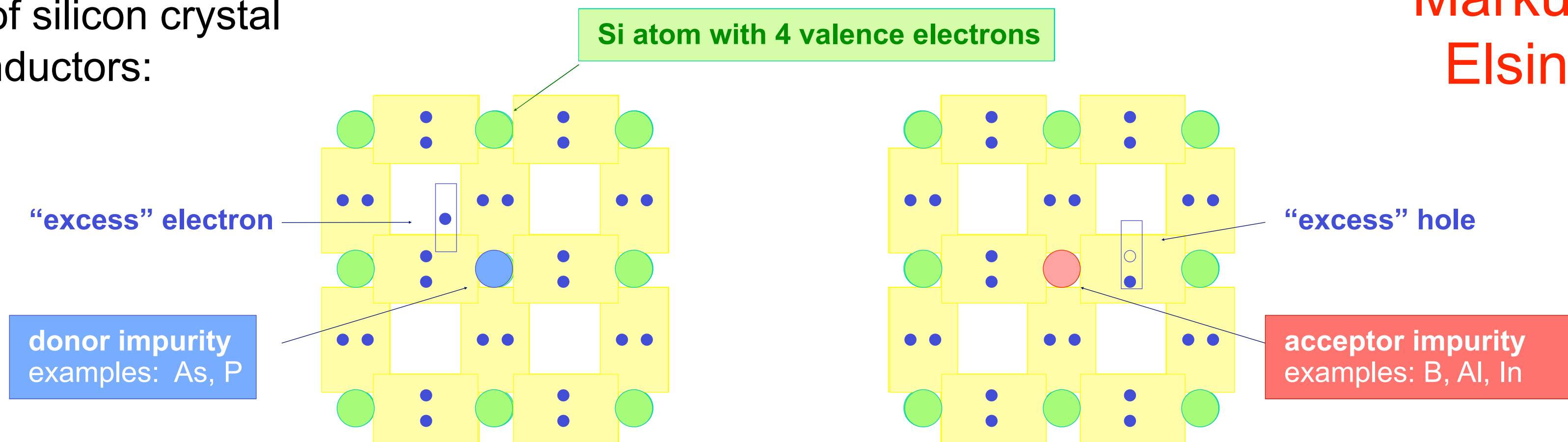
100 million readout channels (upgraded between the two data-taking years on the plot for an extra layer) to measure precise location of charged particle trajectory

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

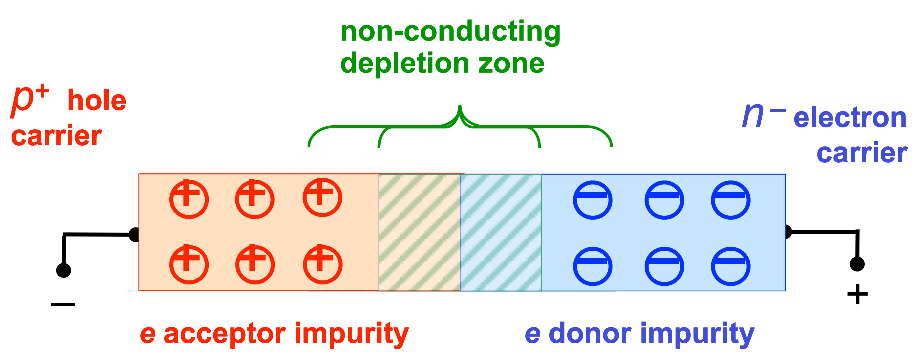
Semiconductors

Slide from Markus Elsing

- doping of silicon crystal semiconductors:



p–n junction *p–n* junction

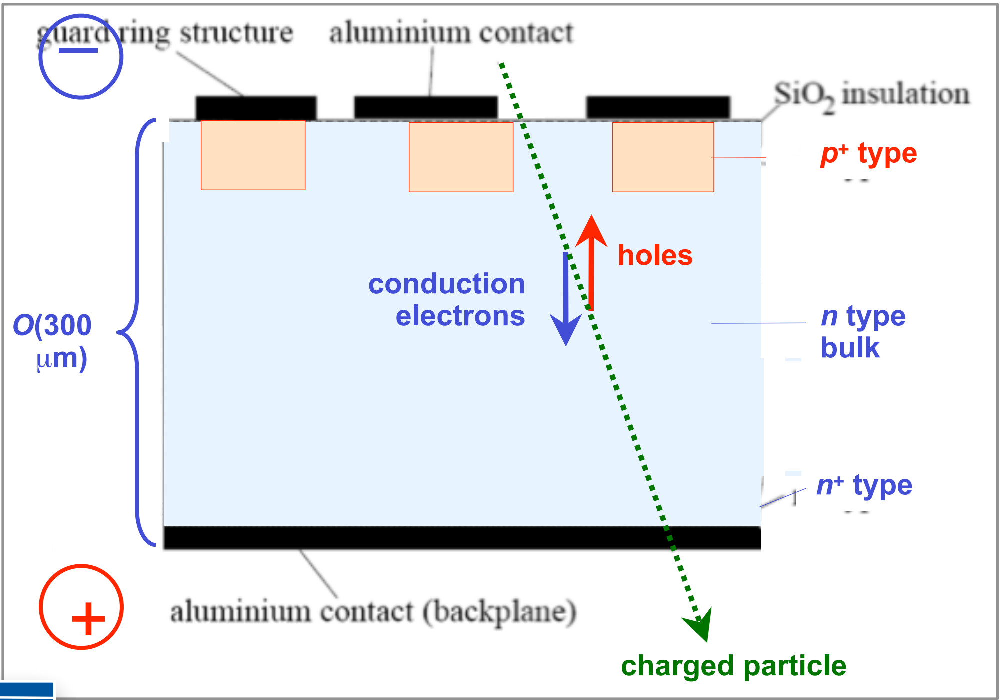


- *n* doping adds electro-phobe atoms
- enhancing its resistance
- the potential barrier in the junction

The *p–n* Junction as a Tracking Detector

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

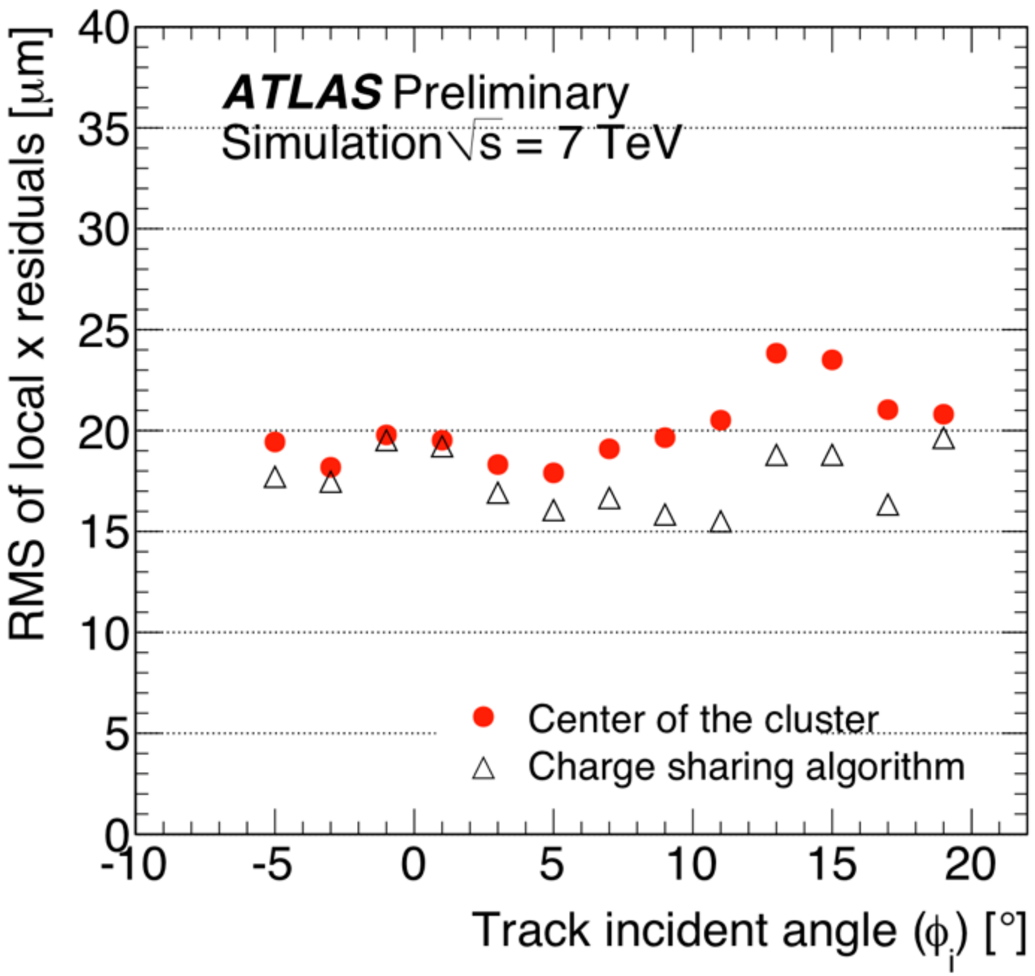
Slide from Markus Elsing



schema of silicon microstrip sensor

- reverse bias: backplane set to positive voltage (< 500 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

ATLAS pixel system

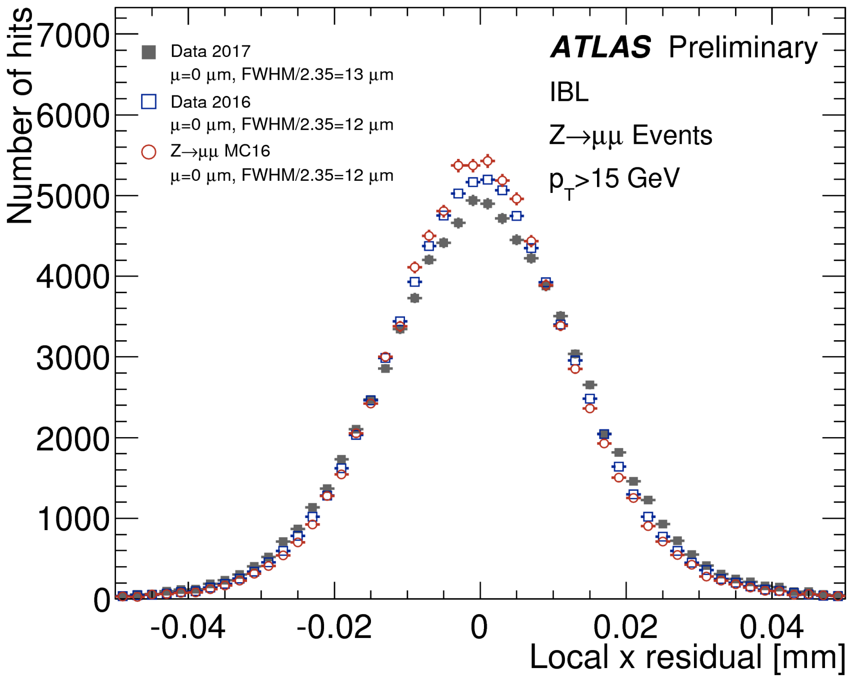


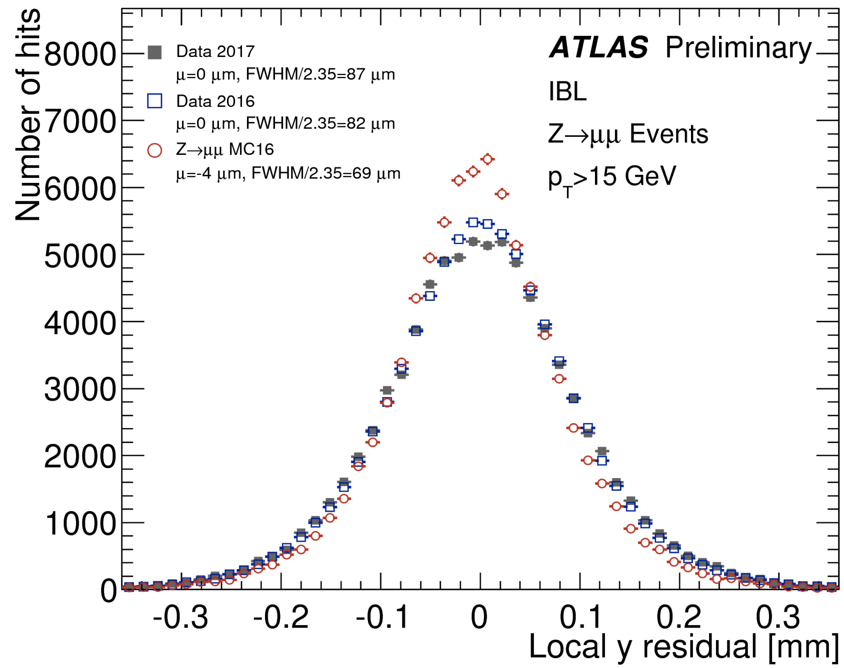
Tens of micron resolution from single hits! The alignment for all the modules gets quite ... tricky

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/InDetTrackingPerformanceApprovedPlots#Run_2

ATLAS IBL pixel system

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/IDTR-2017-004/



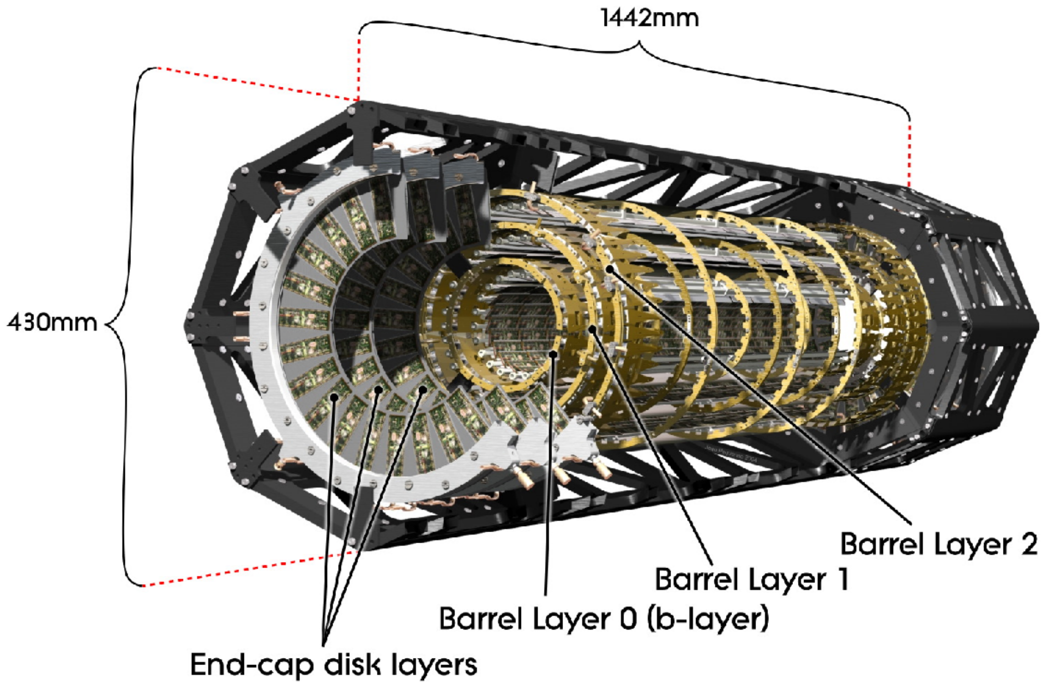


Let’s look very carefully at these plots together

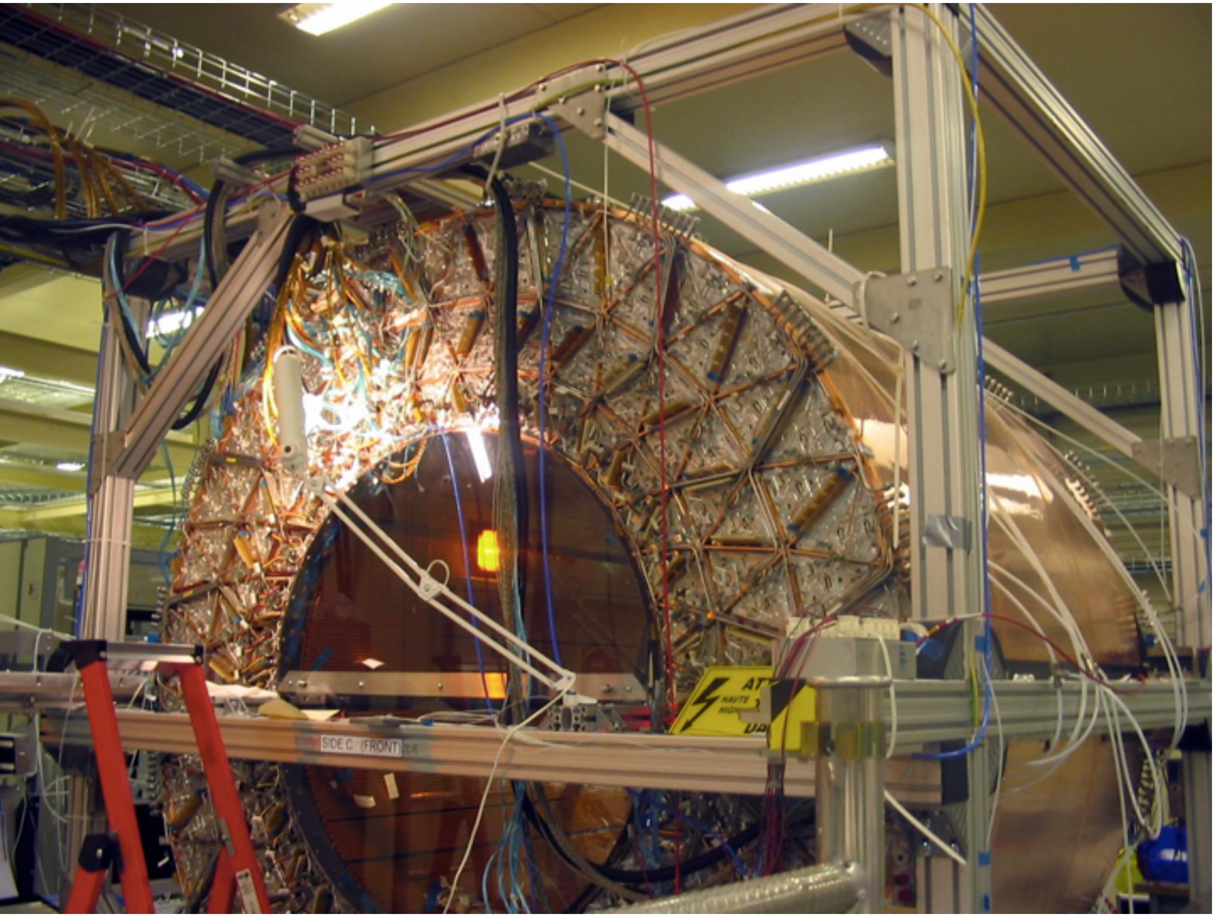
Challenges for silicon systems at the LHC

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?



ATLAS TRT (Transition Radiation Tracker)

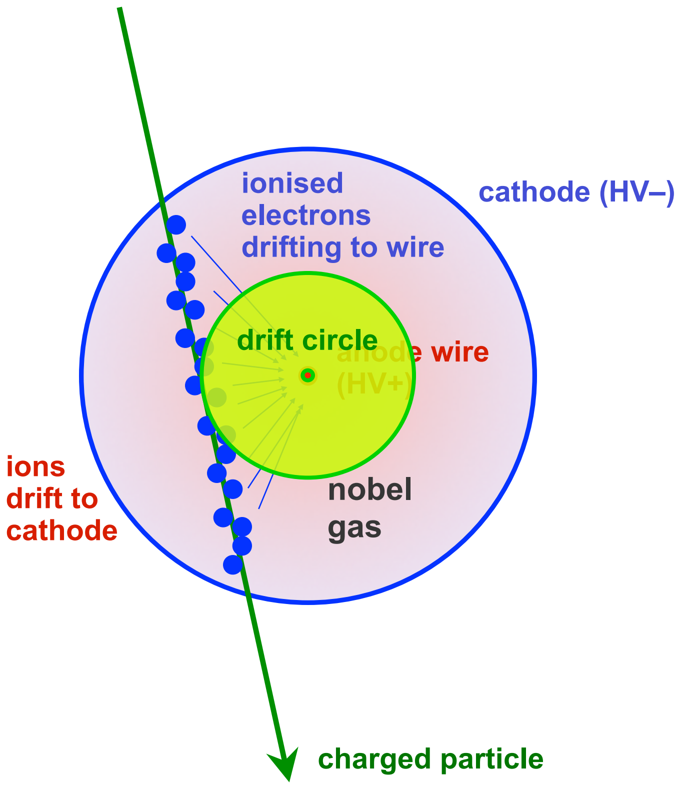


300,000 straws (4 mm in diameter) at larger track radius, ~35 measurements per track. Also helps with particle identification

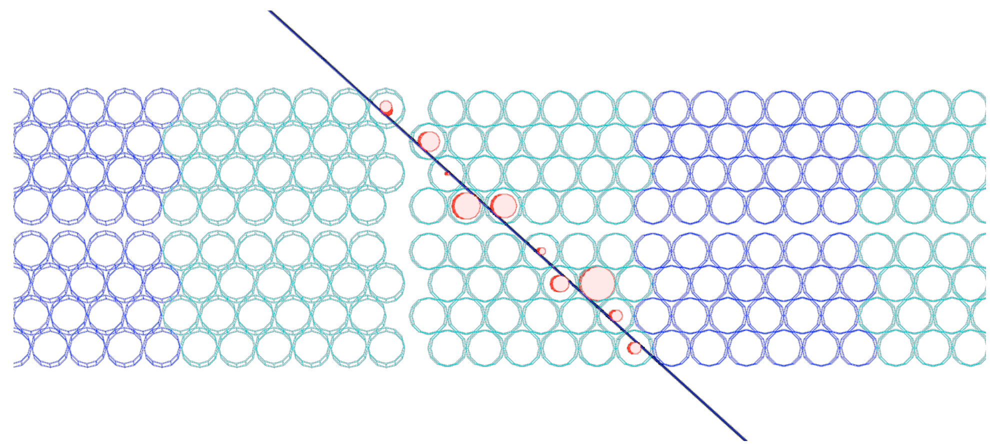
This is being removed for future LHC operations with larger numbers of collisions. Any guesses why?

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)

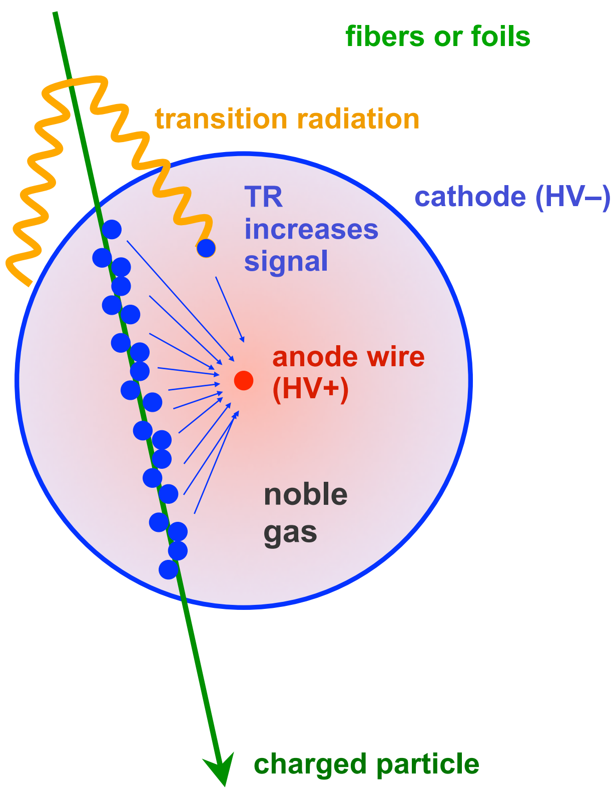


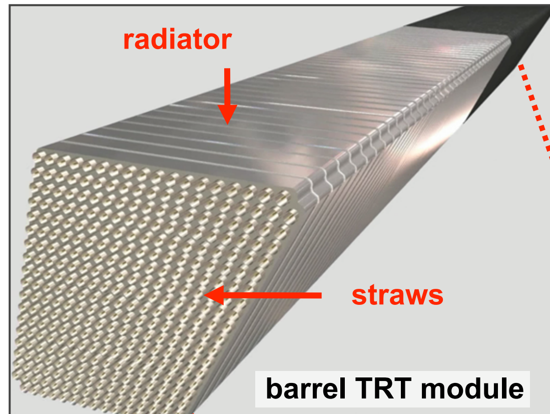
TRT: Kapton tubes, ∅ = 4 mm
MDT: Aluminium tubes, ∅ = 30 mm

Slide from
Markus Elsing

Combining Tracking with PID: the ATLAS TRT

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

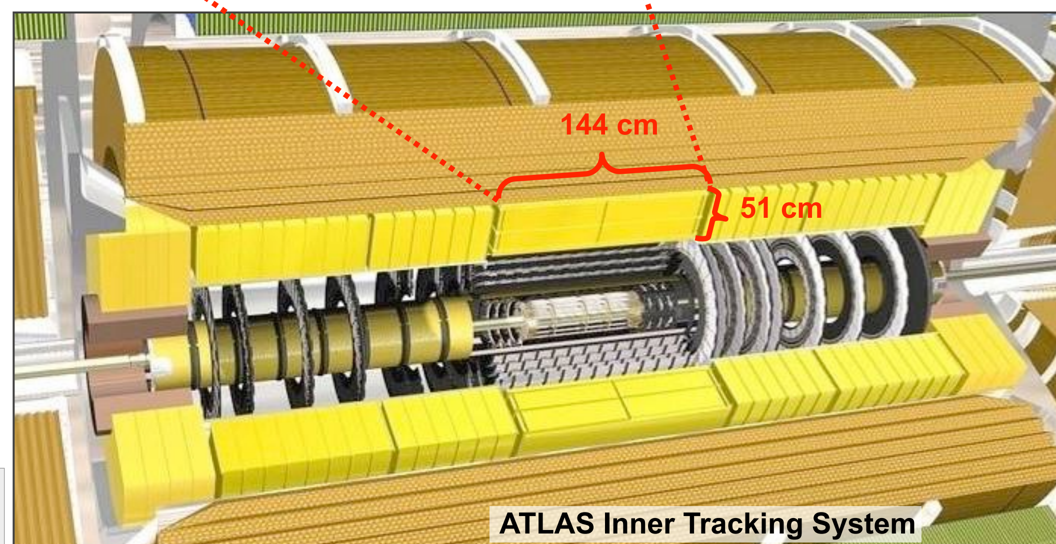




total: 370k straws

barrel ($|\eta| < 0.7$):
36 r-ϕ measurements / track
resolution ~130 μm / straw

14 end-cap wheels ($|\eta| < 2.1$):
40 or less z-ϕ points

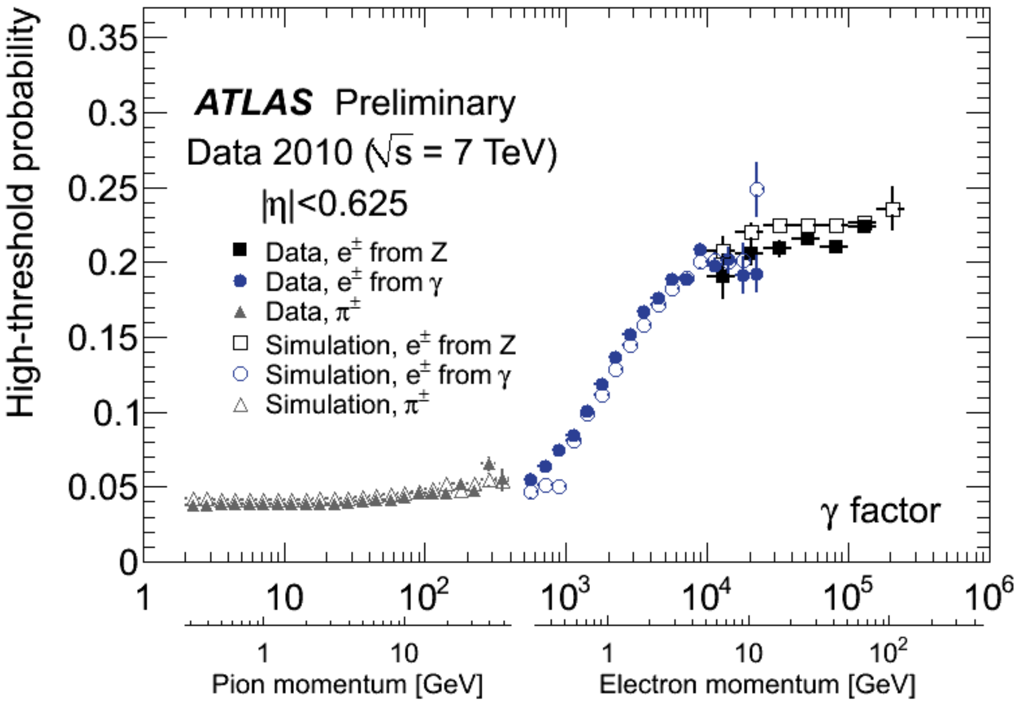


electrons radiate → higher signal
PID info by counting
high-threshold hits

Slide from Markus Elsing

ATLAS TRT (Transition Radiation Tracker) PID

ATLAS-CONF-2011-128

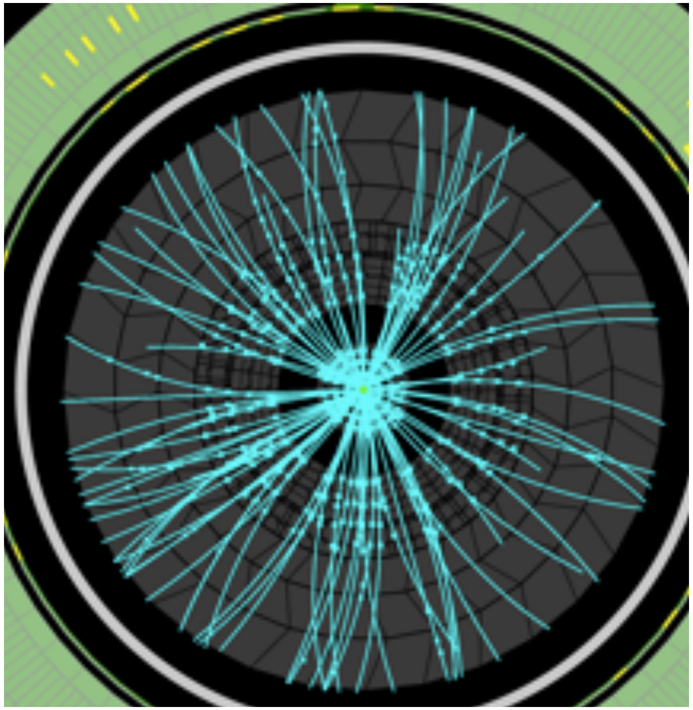


Given ~30 hits per track, small difference in probability to measure hits with a higher threshold can give significant particle identification/ background rejection for electron ID

Charged particle tracking

$$p \propto B \cdot R$$

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



Stable particles?

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

Bethe-Bloche 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 ~10 Z [eV]

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{n z^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

Not very intuitive :)

Bethe-Bloche equation

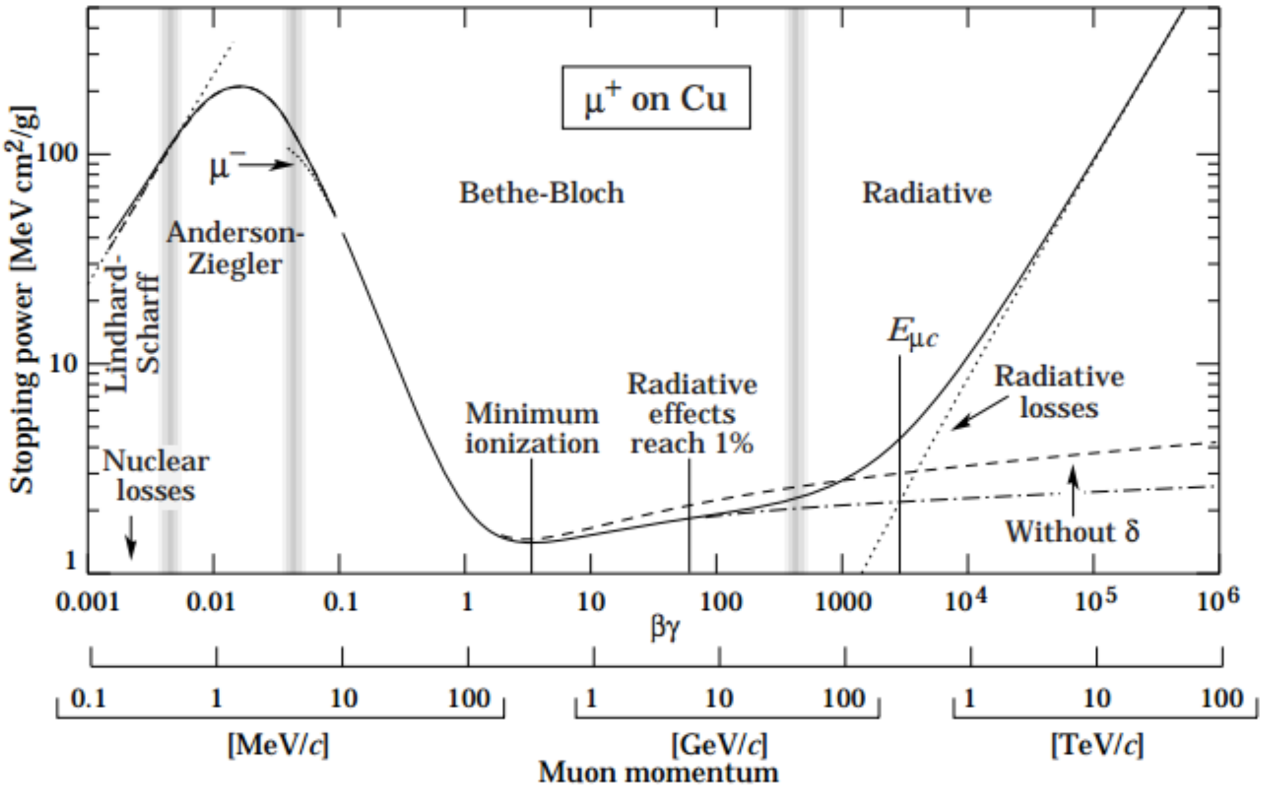
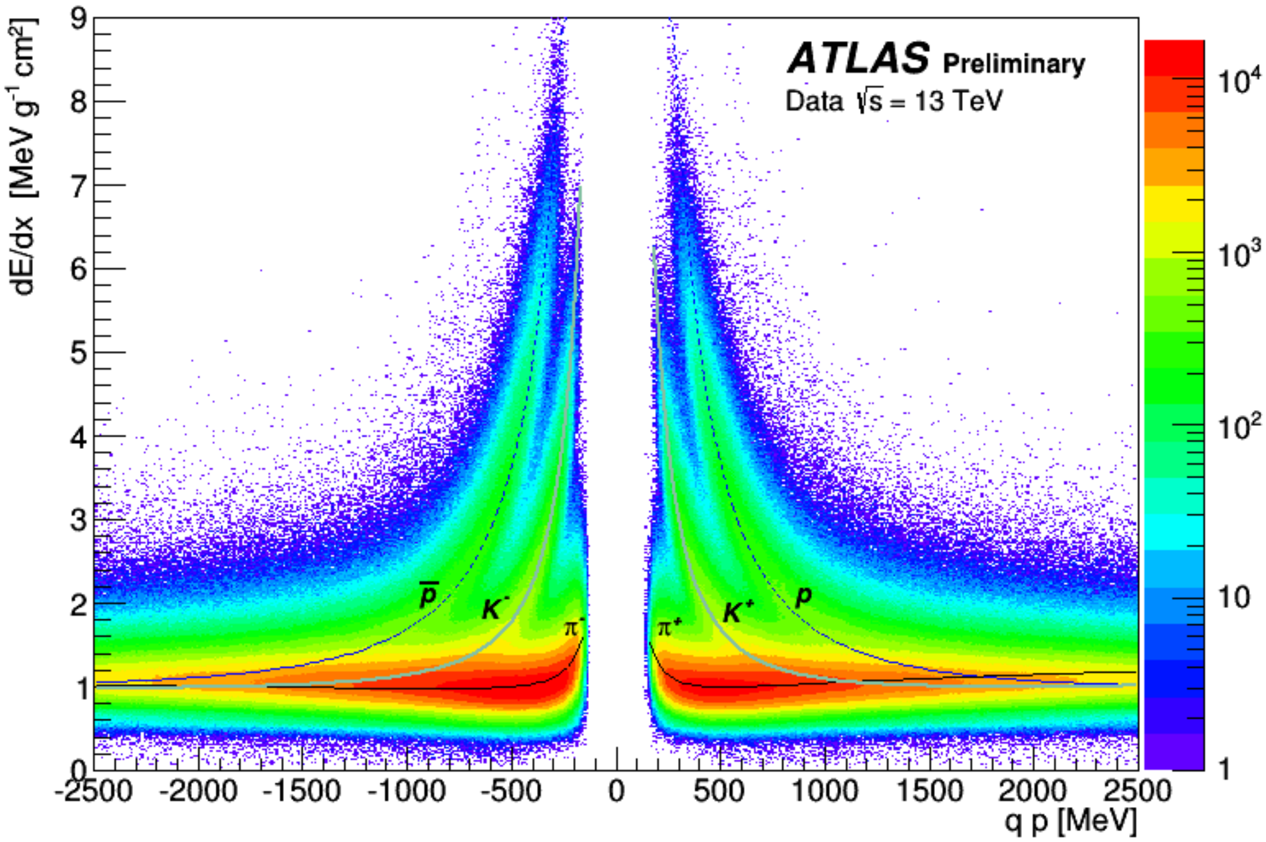


Fig. 27.1: Stopping power ($= \langle -dE/dx \rangle$) for positive muons in copper as a function of $\beta\gamma = p/Mc$ over nine orders of magnitude in momentum (12 orders of magnitude in kinetic energy). Solid curves indicate the total stopping power. Data below the break at $\beta\gamma \approx 0.1$ 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 "μ^-" illustrate the "Barkas effect," the dependence of stopping power on projectile charge at very low energies [6].

From PDG. Particles with βγ~3 lose the least amount of energy as they travel, and are referred to as "minimum ionizing" particles

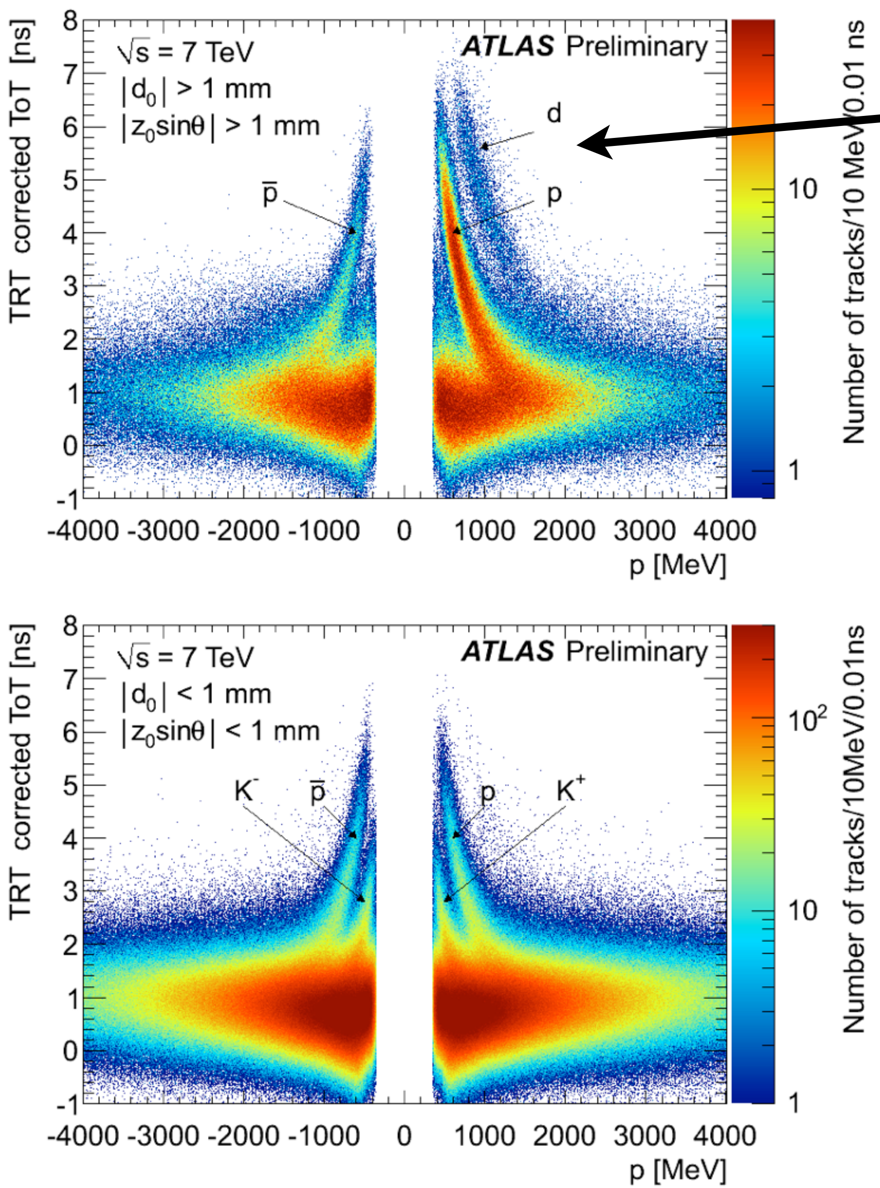
Using dE/dx in the pixel system of ATLAS



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

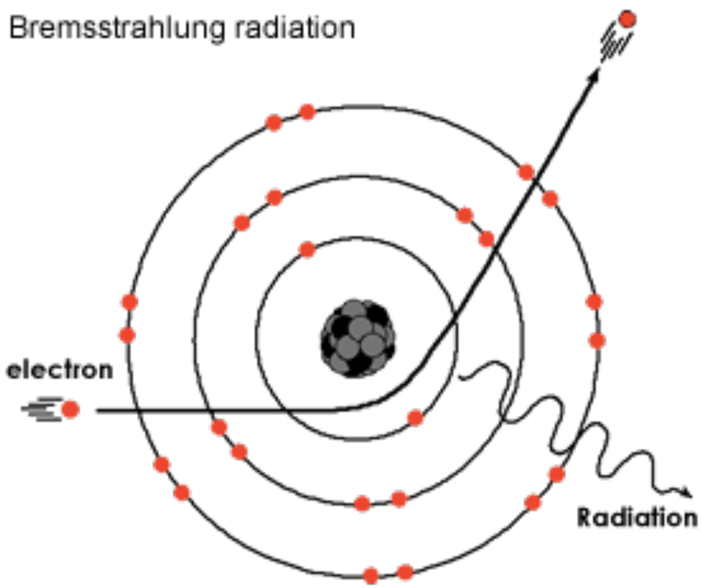


Asymmetry! Why?

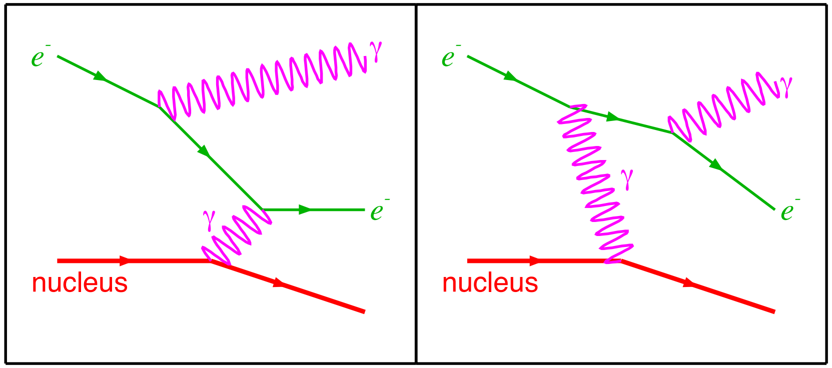
Using "time over threshold", we can also do particle identification with straw detectors

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TRTPublicResults

Bremsstrahlung

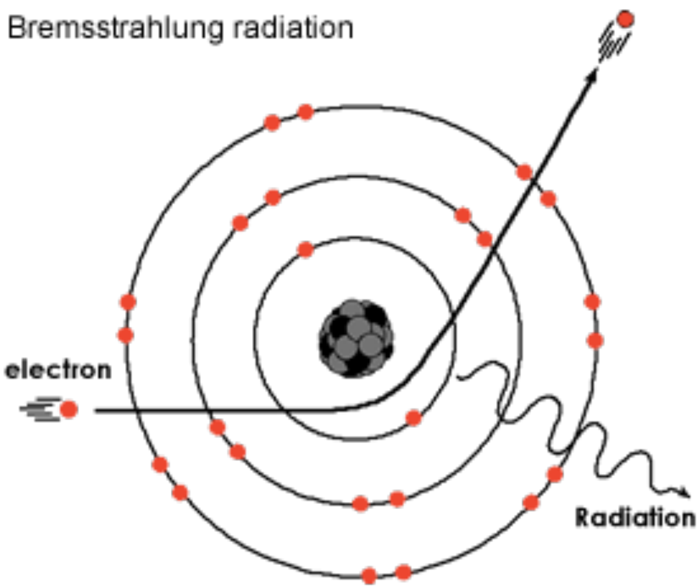


Bremsstrahlung



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/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

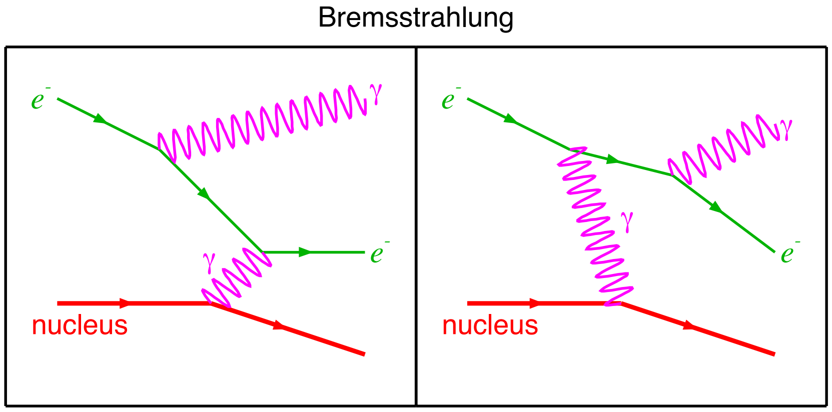
Radiation length for high-energy electrons/photons

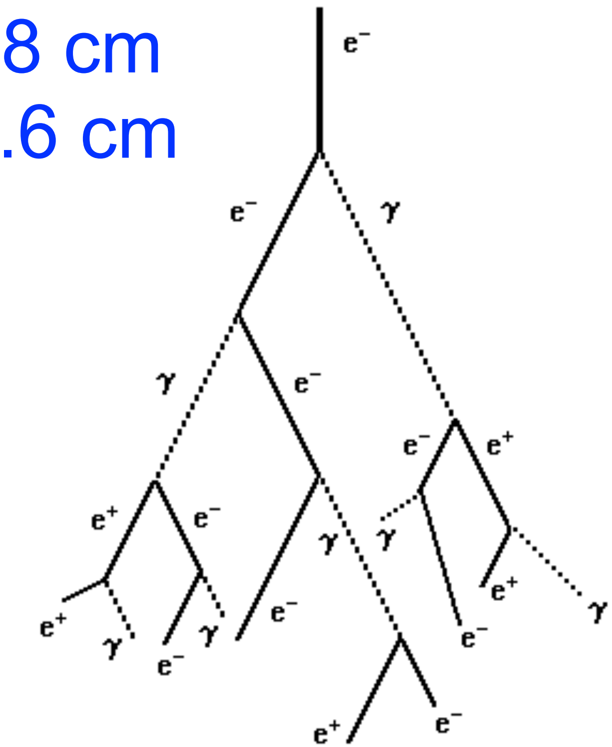


Radiation length X_0 is the average distance over which the energy of an electron is reduced by 1/e (characteristic distance scale for material effects)

X_0(iron) = 1.8 cm

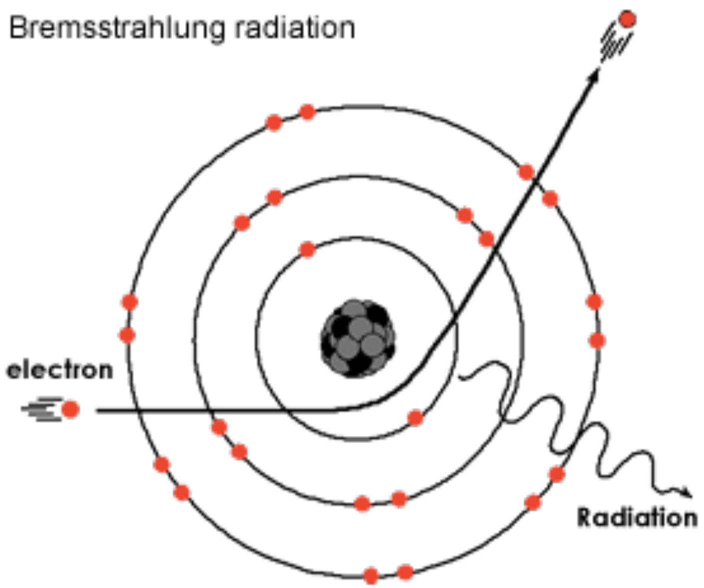
X_0(lead) = 0.6 cm

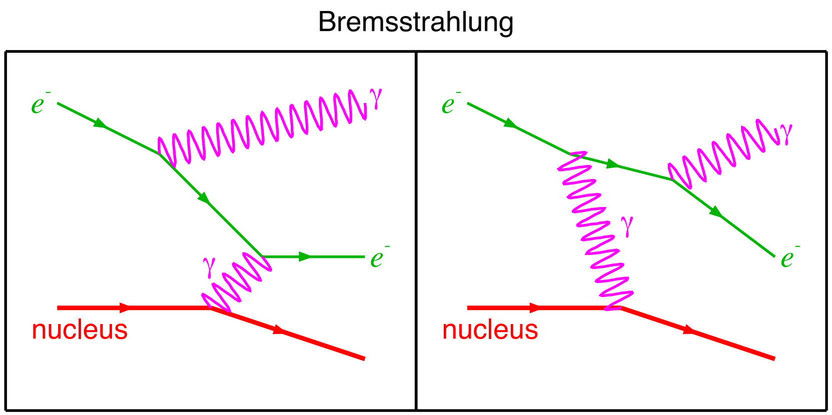




Very similar for photons

Radiation length for high-energy electrons/photons





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

After 2 X_0, we have ~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

Radiation length for high-energy electrons/photons

$$< E >_n = \frac{E}{2^n} = E_c$$

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

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

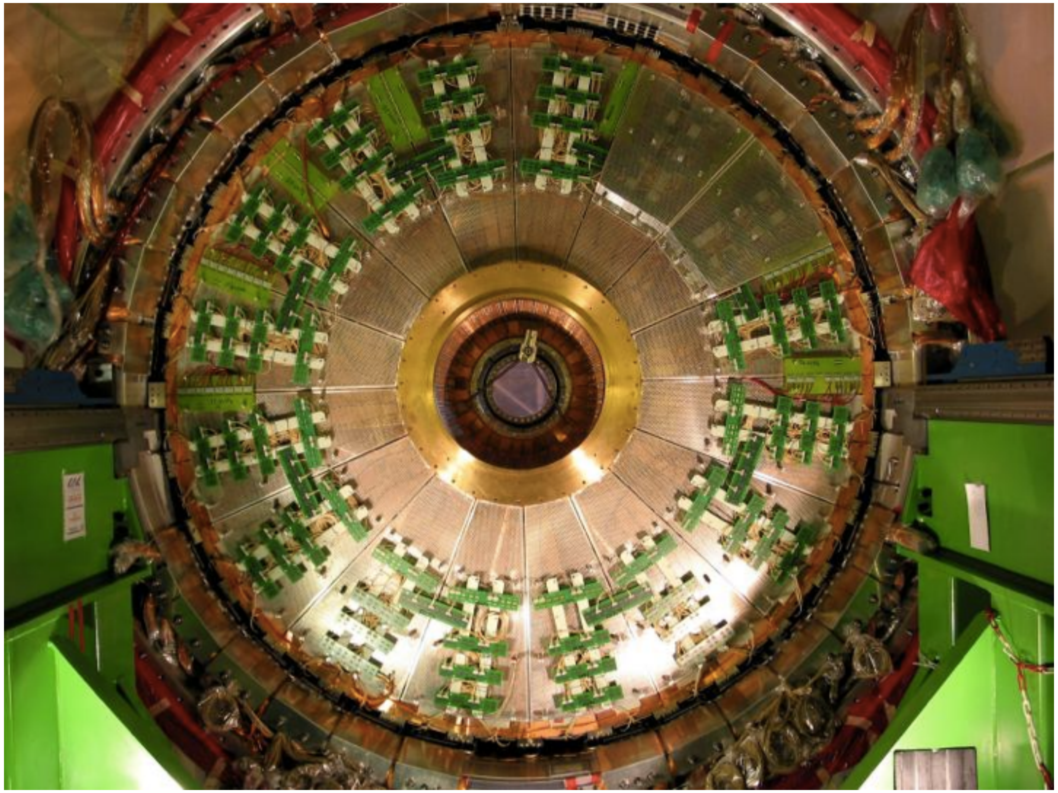
$$n \ln 2 = \ln(E/E_c)$$

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

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 (λ_I), which is the mean distance between hadronic interactions.
λ_I(lead) = 17 cm (compare with X_0(lead) = 0.6 cm)

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

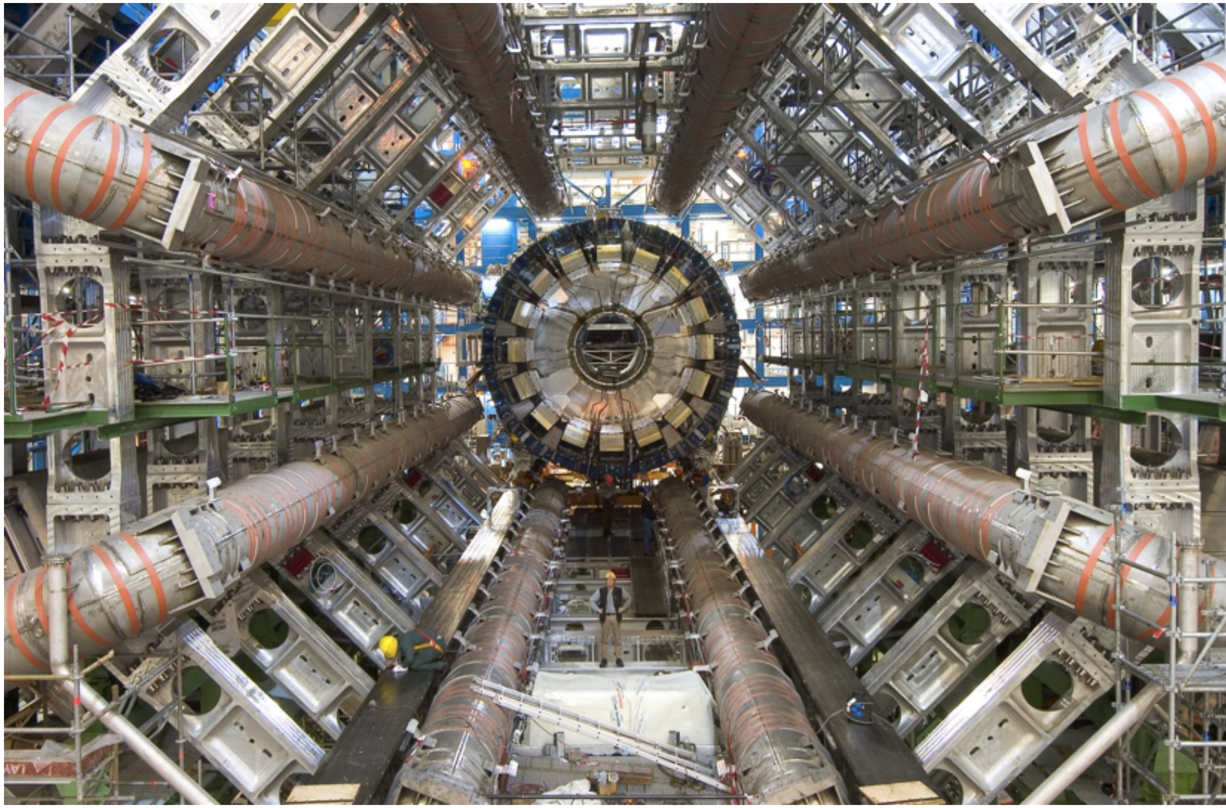
ATLAS tile calorimeter

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?

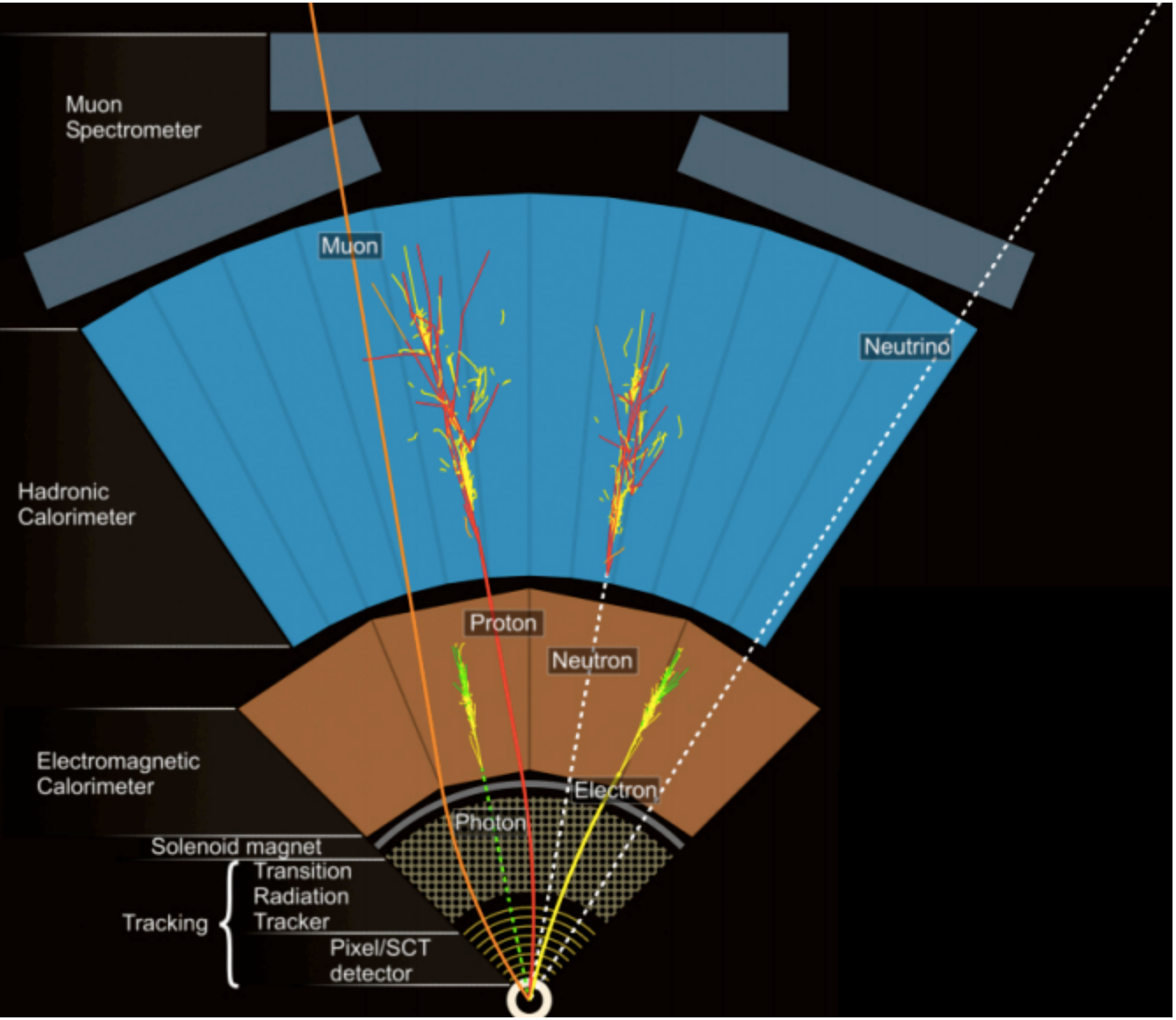
Neutrinos... we "detect" them (indirectly) by applying momentum conservation in the plane perpendicular to the beam



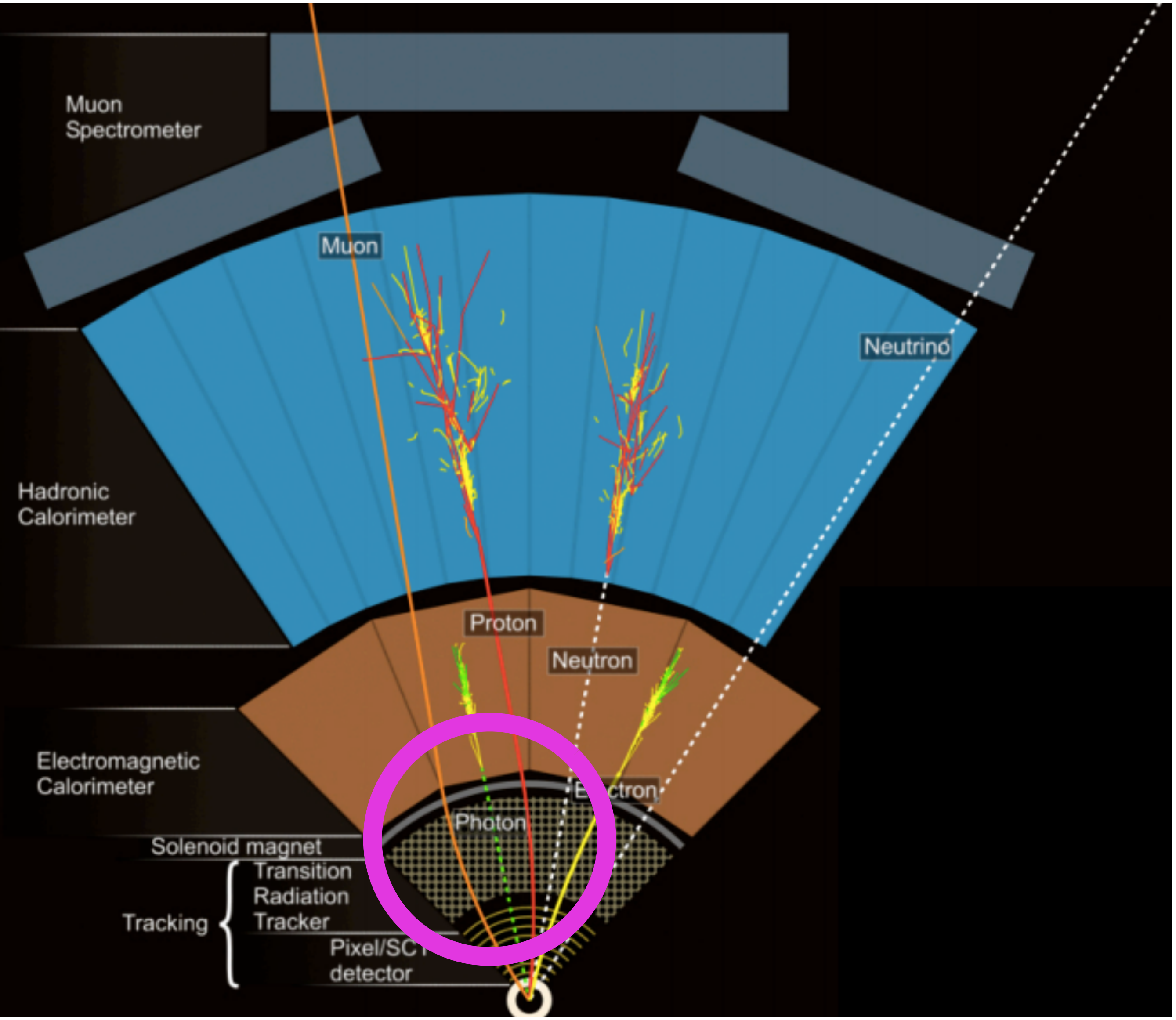
And muons! Have a set of toroidal magnets (giving ATLAS its shape and name) and more muon systems on outside of detector

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

Putting it all together



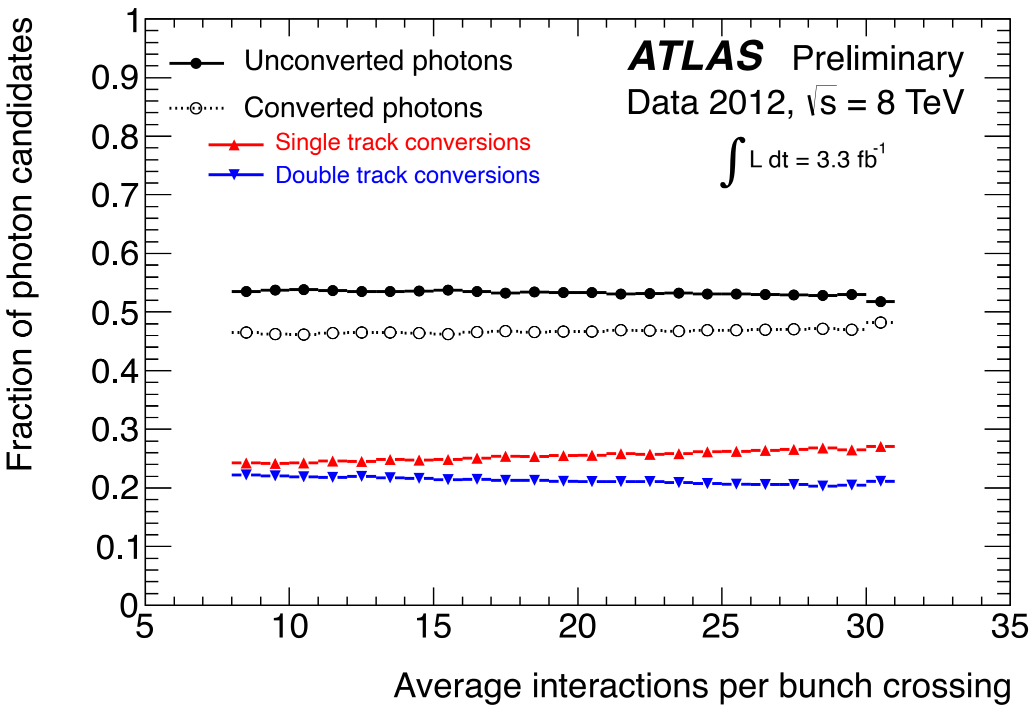
Putting it all together

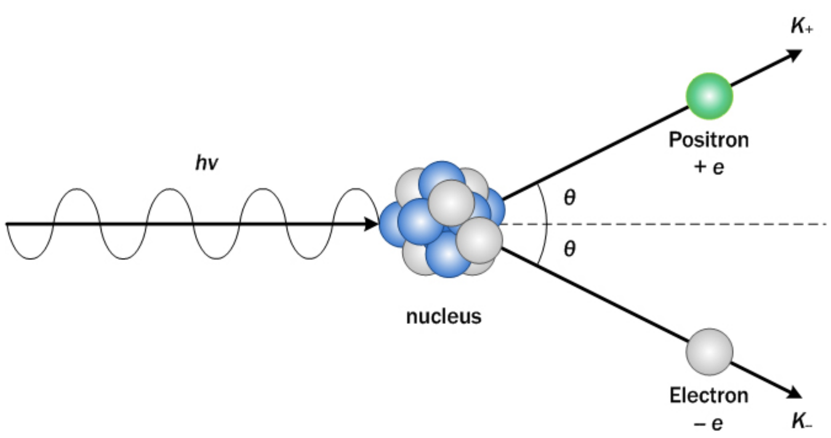


Photon can appear as isolated cluster in the EM calorimeter with nothing in hadronic calorimeter behind it and nothing else nearby. NO charged track pointing at calorimeter. Careful: lots of neutral pions!

Putting it all together

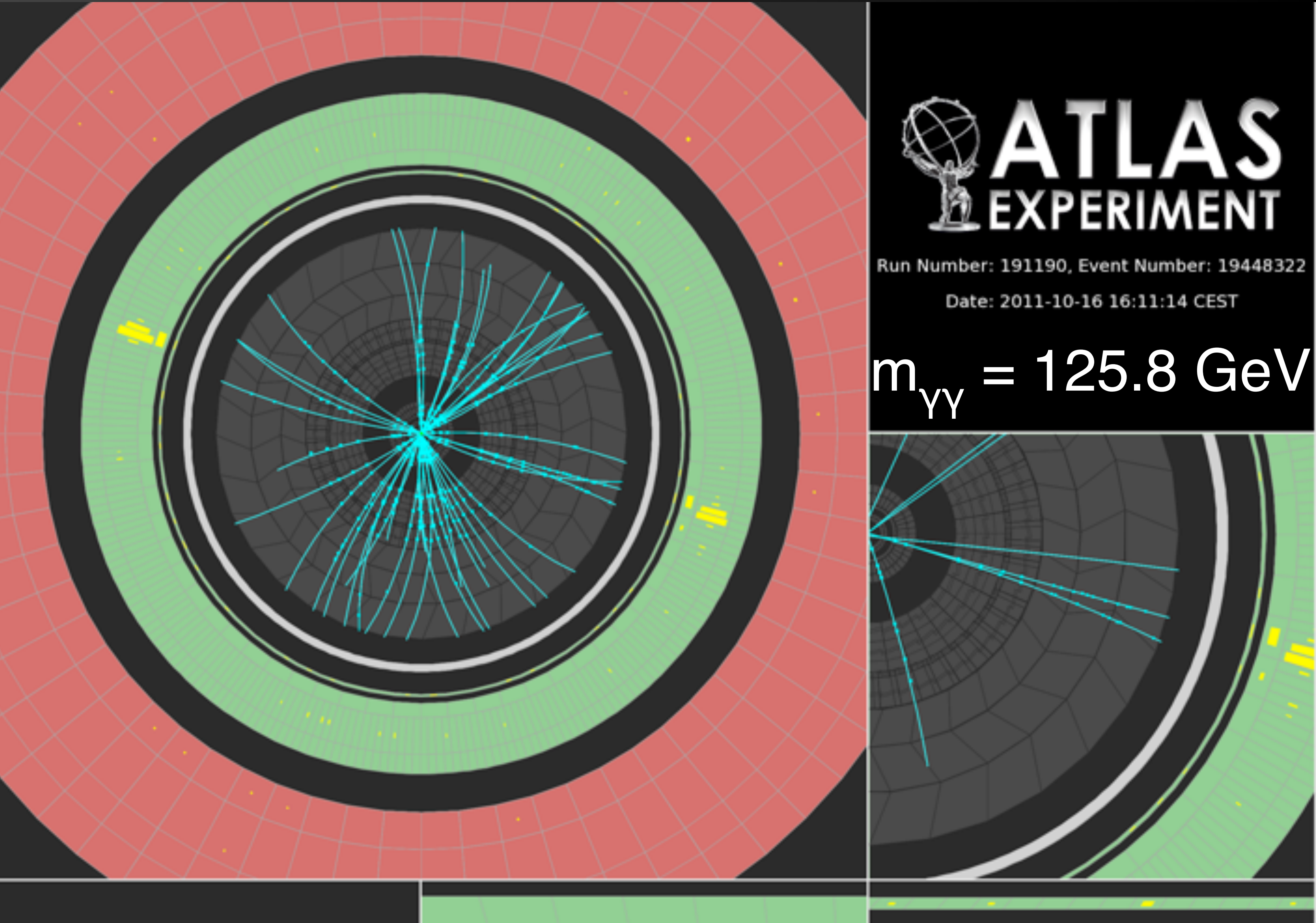
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ ElectronGammaPublicCollisionResults



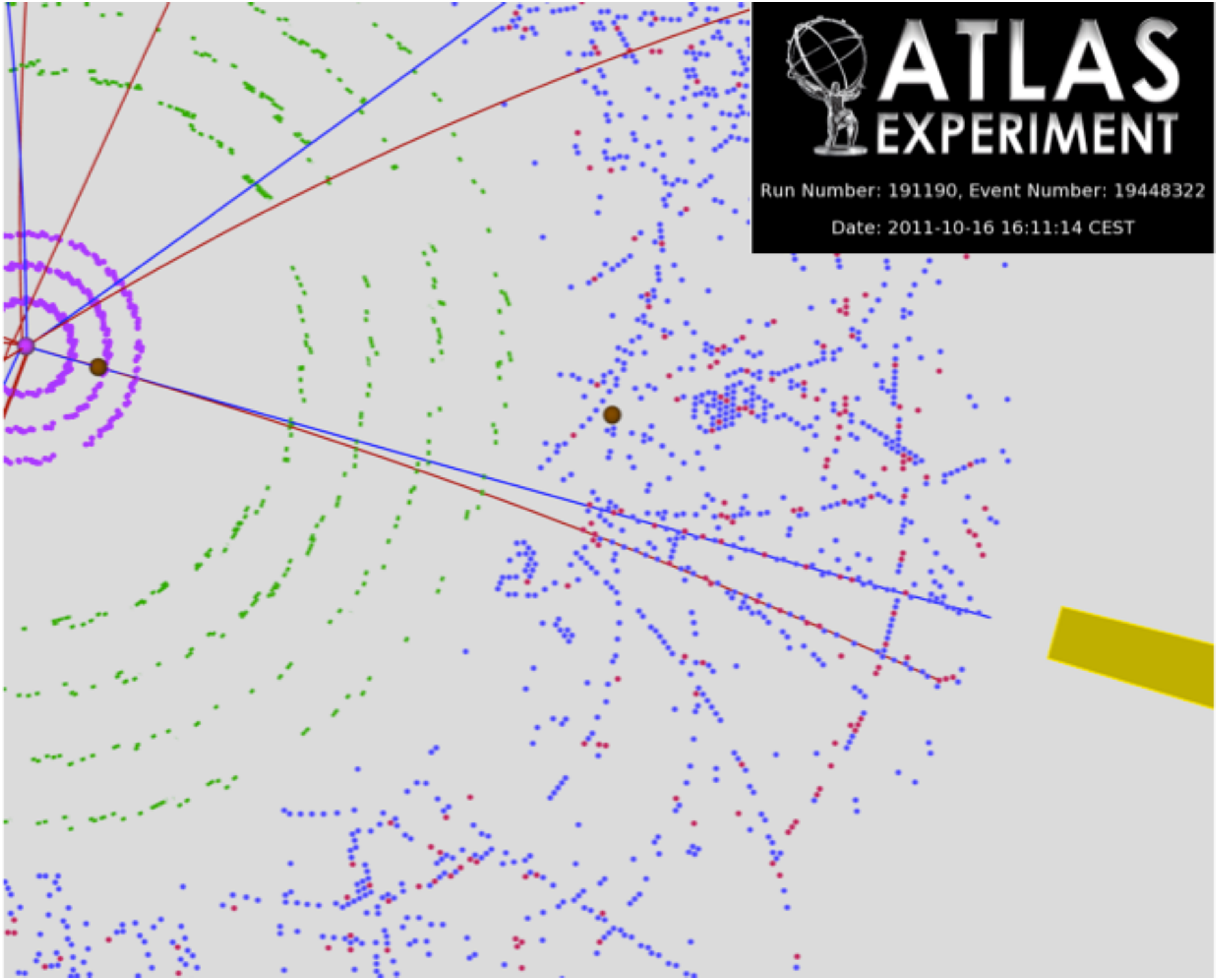


Need to be careful because almost half of the photons at ATLAS interact with material in the detector before reaching the calorimeter! These photons look similar, except there are one or two clusters of energy with charged tracks not coming from the original interaction. How can there be only one track?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

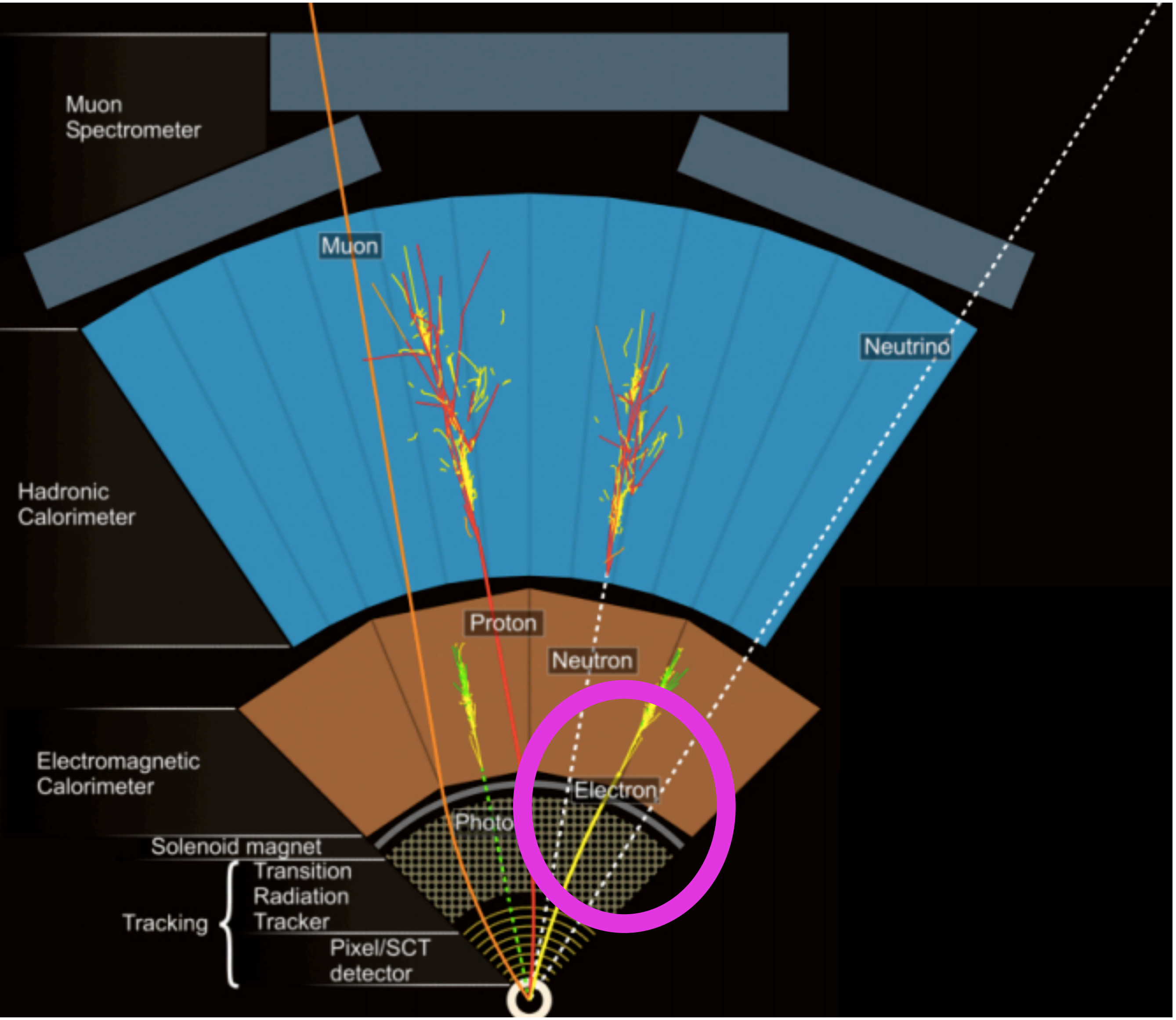
Higgs boson decaying to two photons



Zooming in on a converted photon

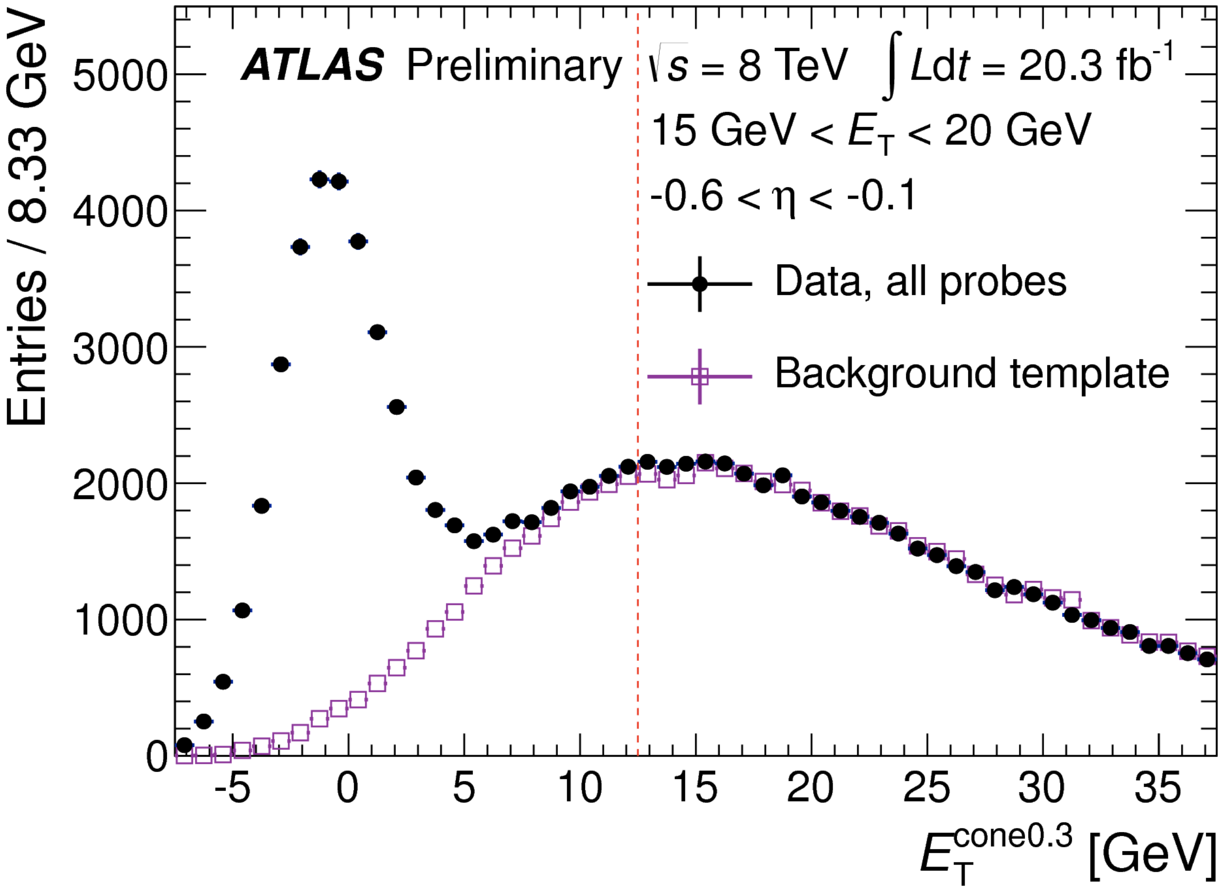


Putting it all together



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!

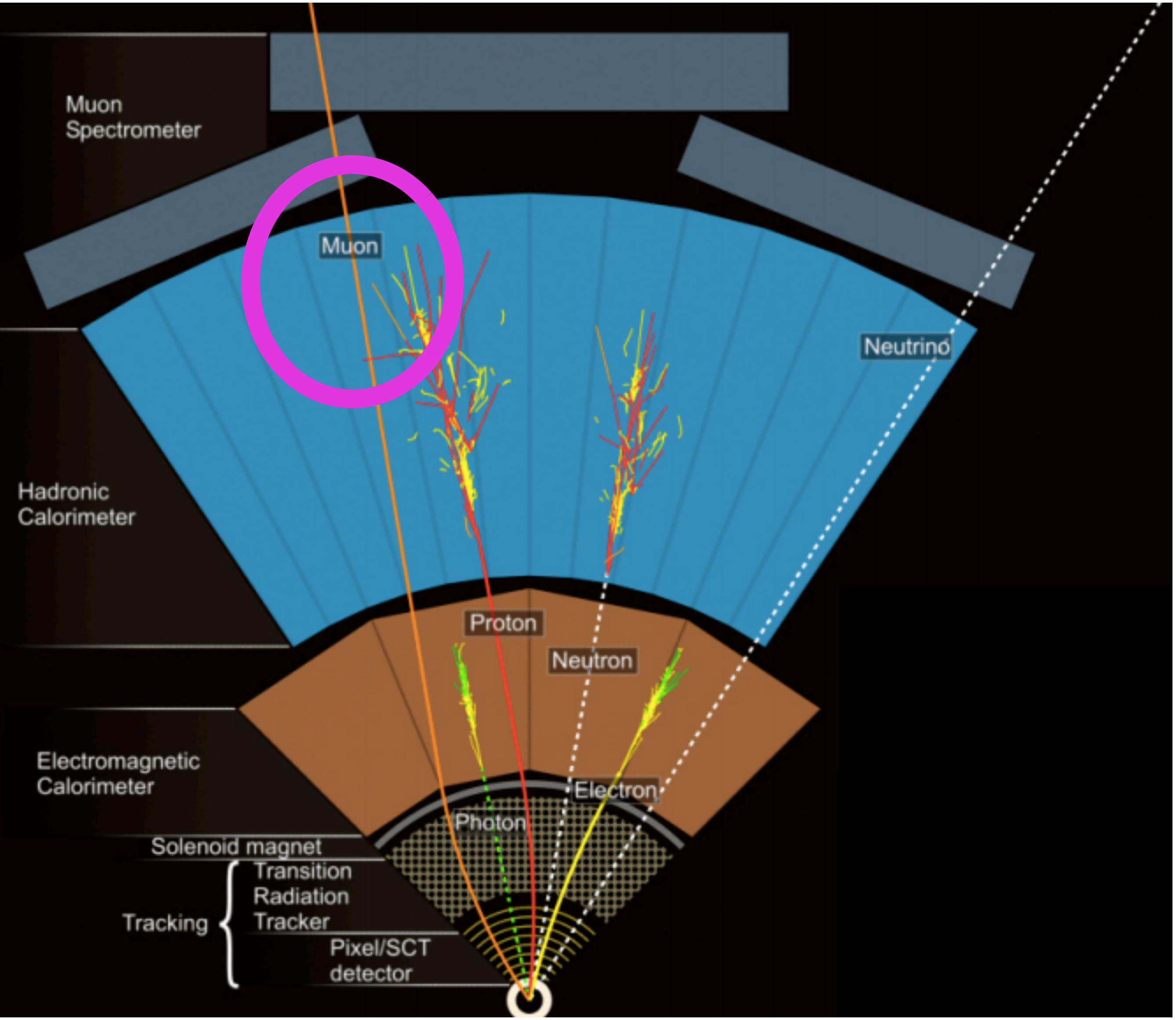
Electron ID at ATLAS



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

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2014-032/

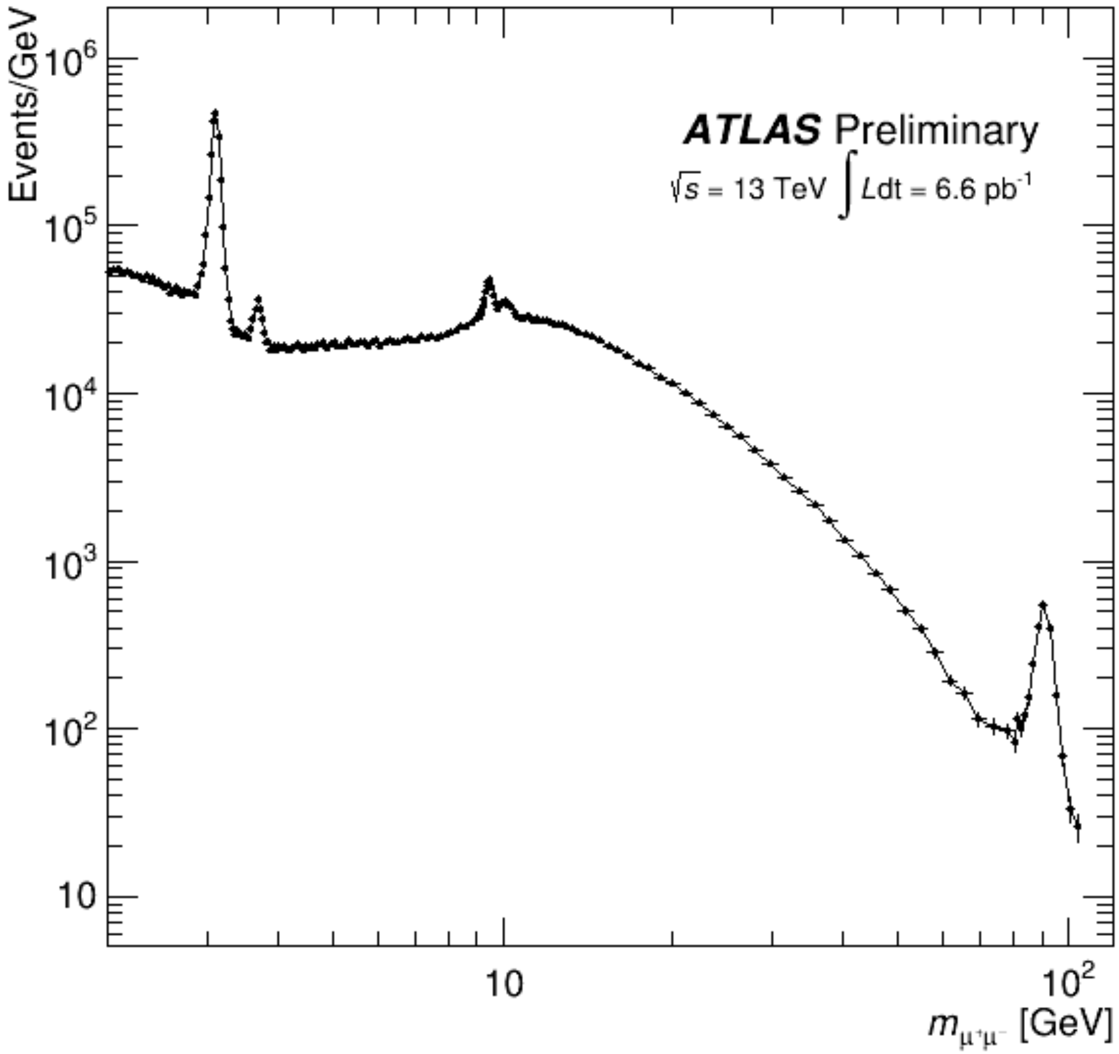
Putting it all together



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

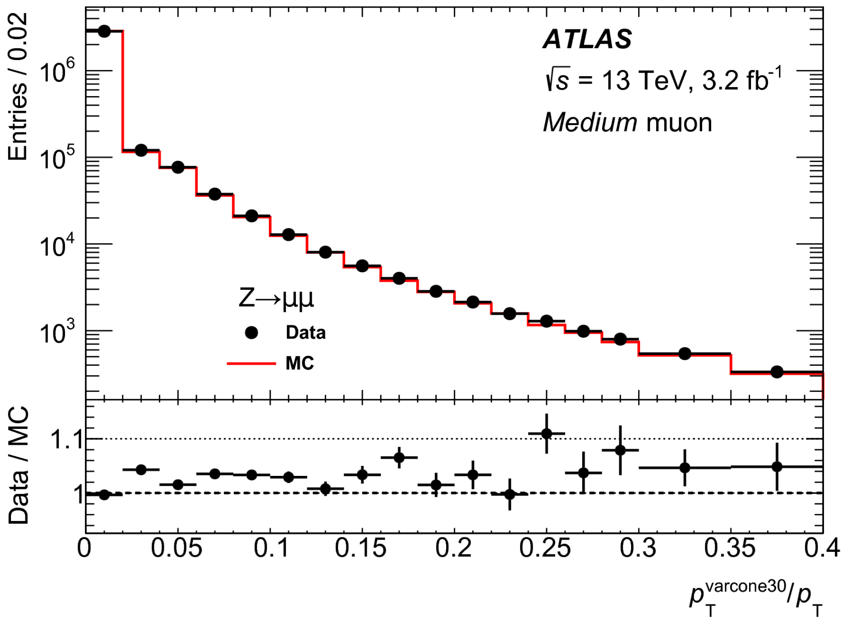
Muon ID at ATLAS

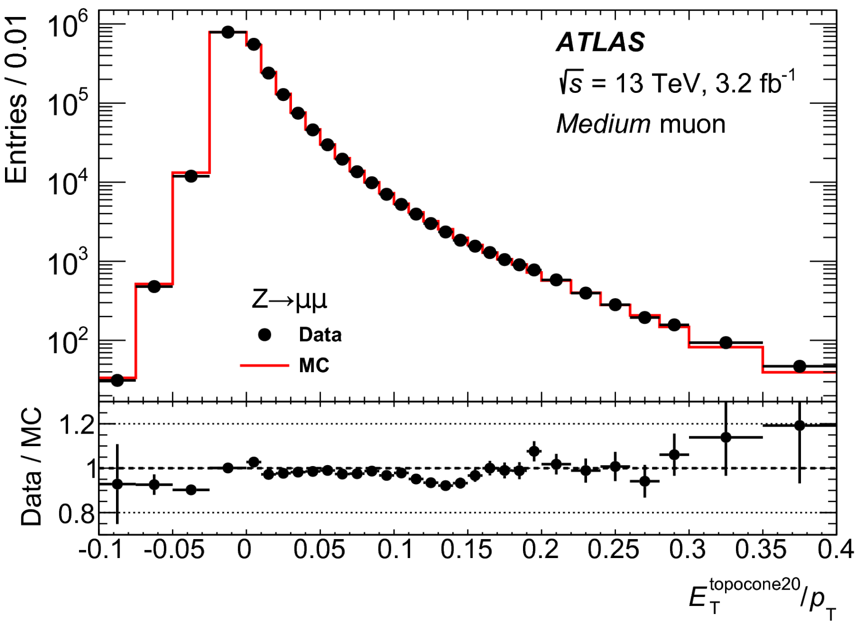
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/MUON-2015-001/index.html



Beautiful invariant mass plot with early Run 2 ATLAS data

Muon isolation

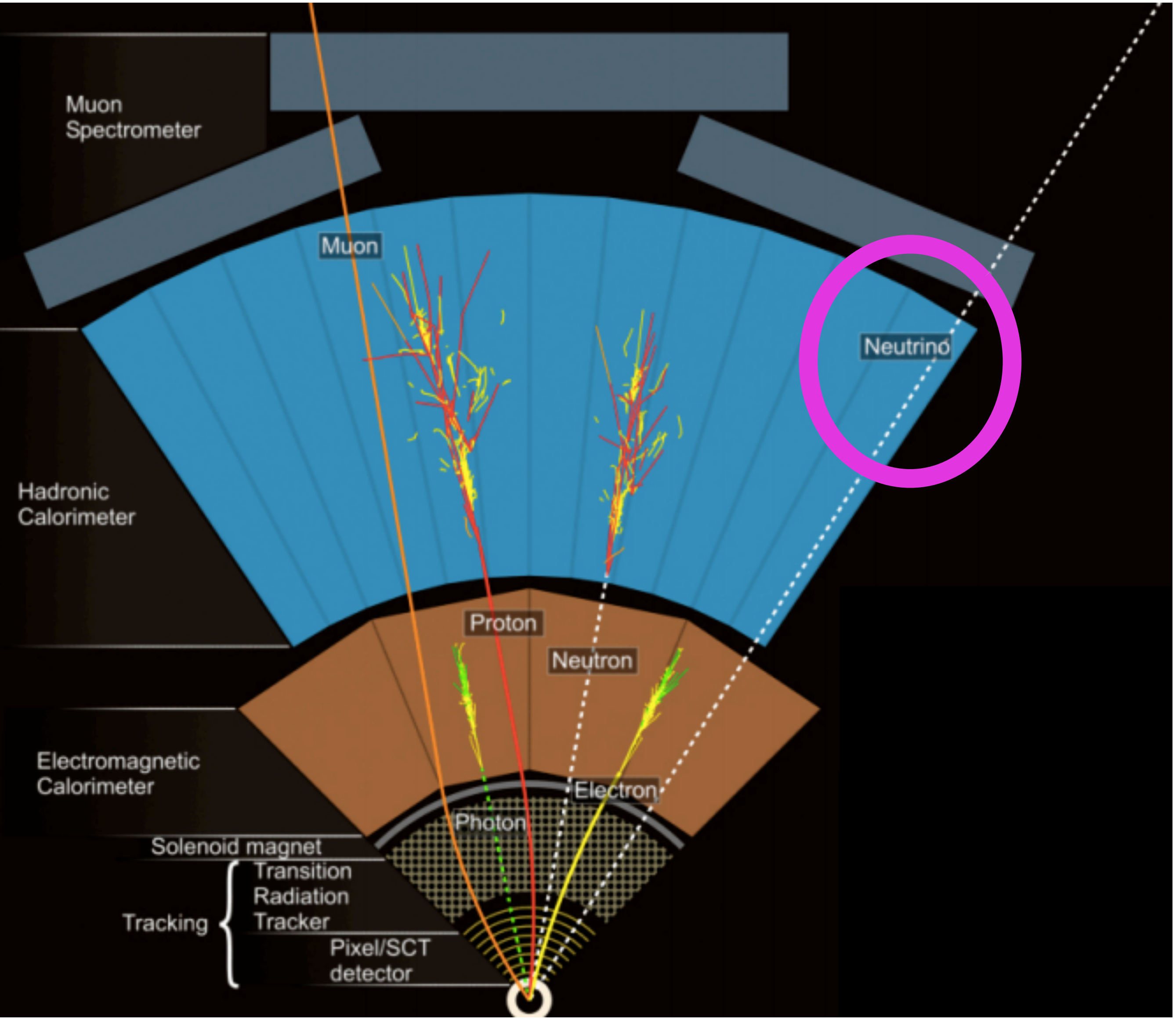




Let's look at these two isolation plots (from muons inside the Z boson mass window)

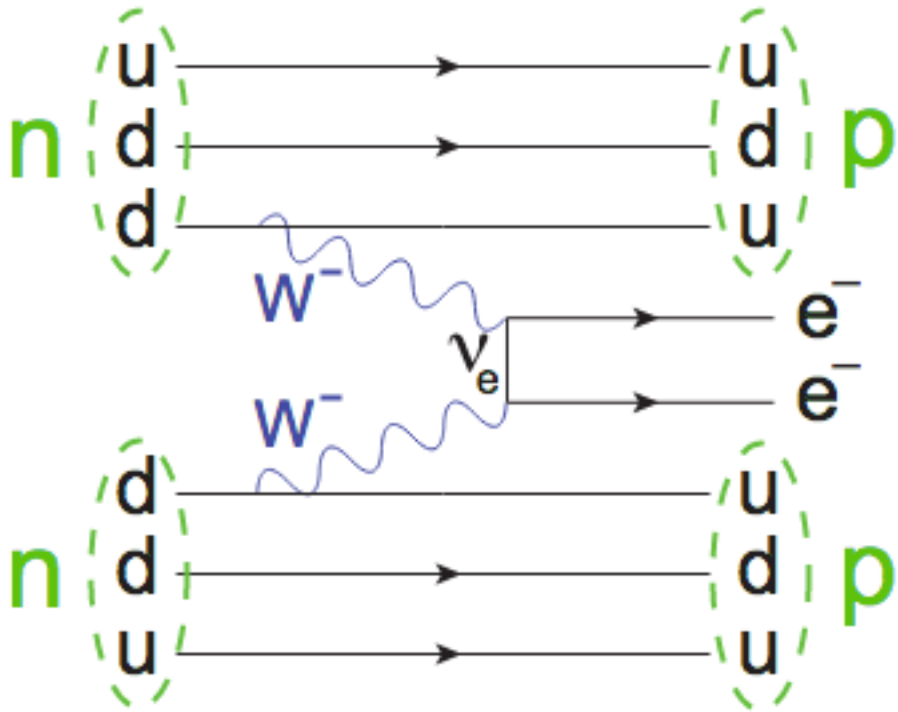
arXiv:1603.05598

Putting it all together



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

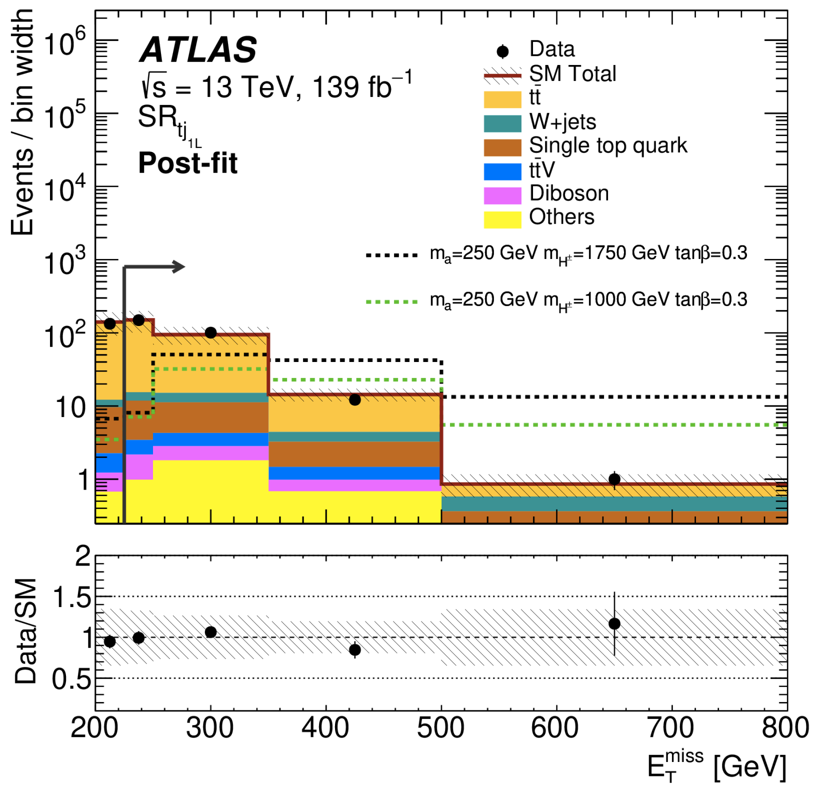
Aside about neutrinos

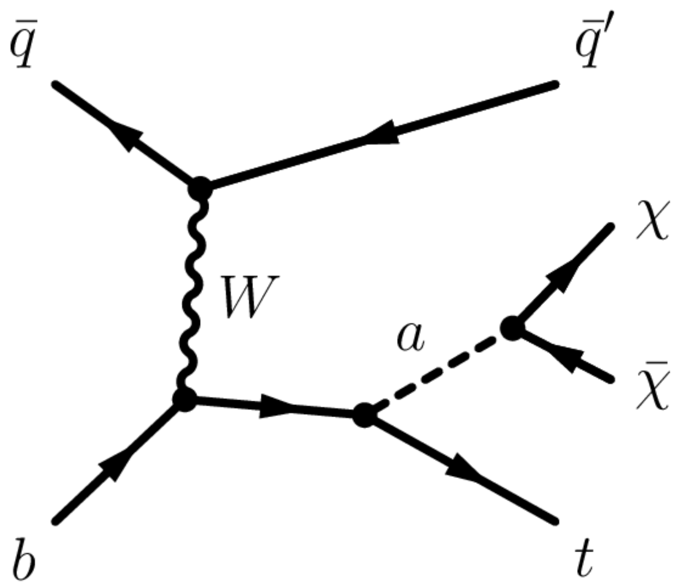


Any guesses?!

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



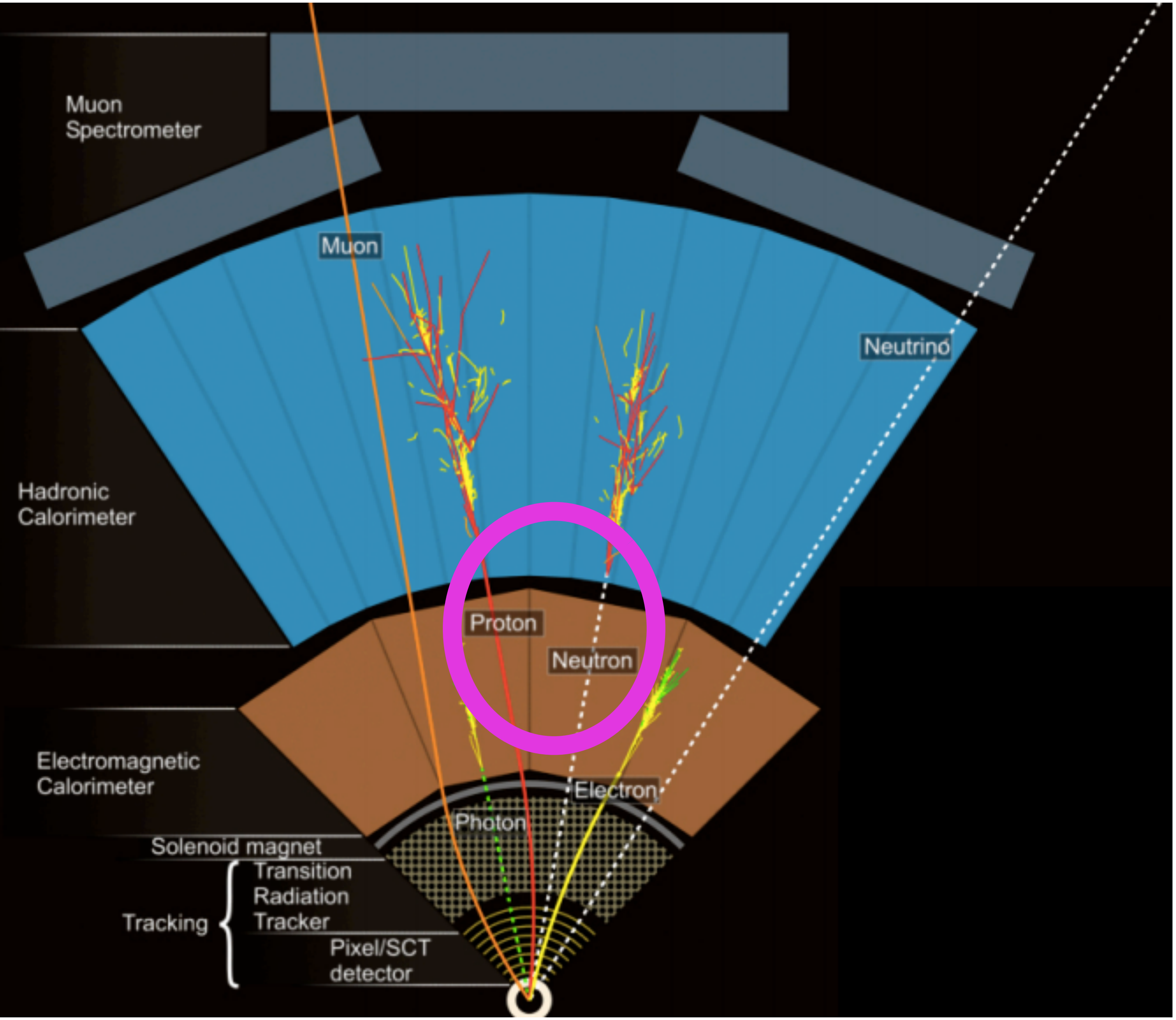


Using momentum imbalance to look for dark matter production

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

arXiv:2011.09308

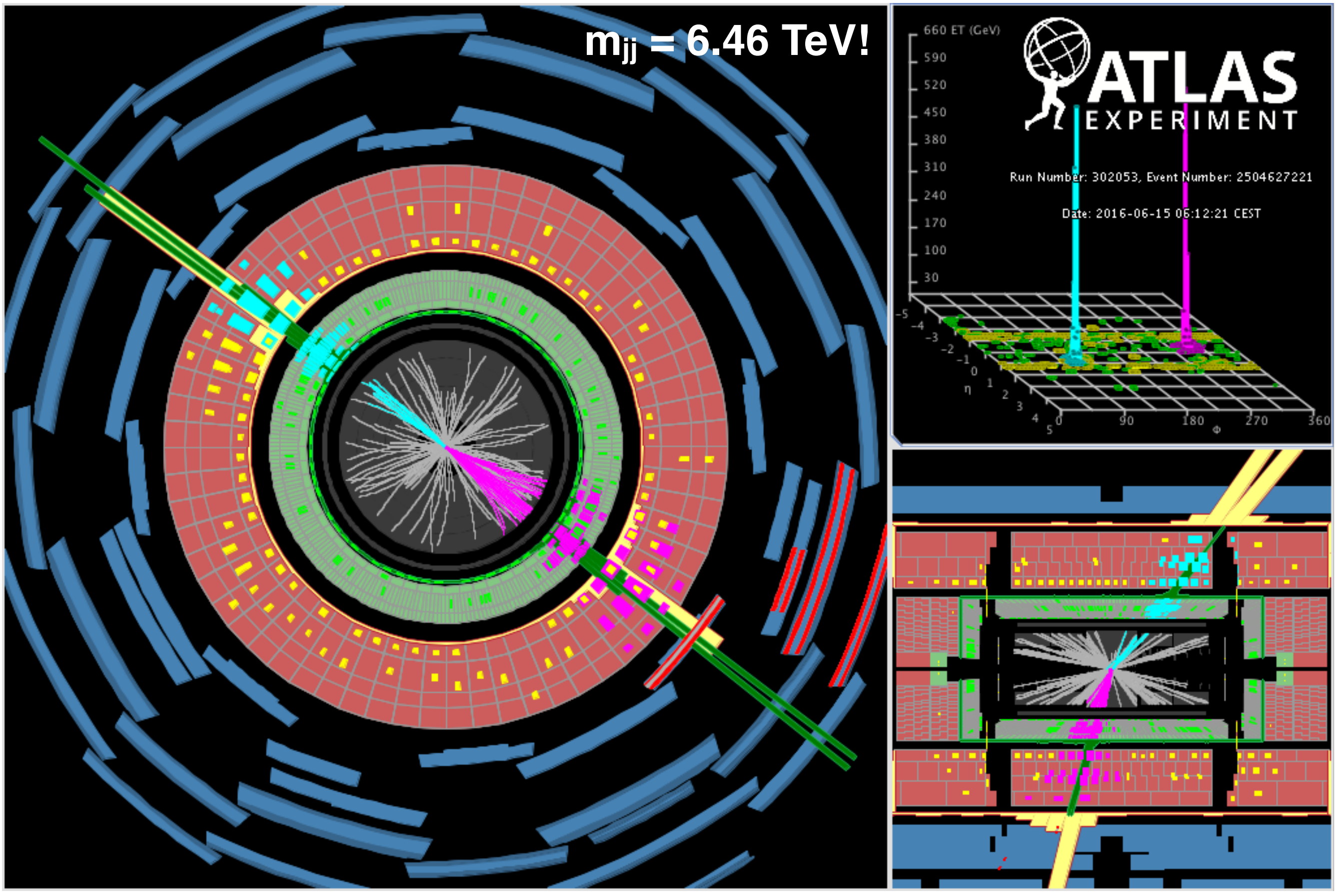
Putting it all together



Protons leave charged tracks, neutrons do not. Each 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

Jets

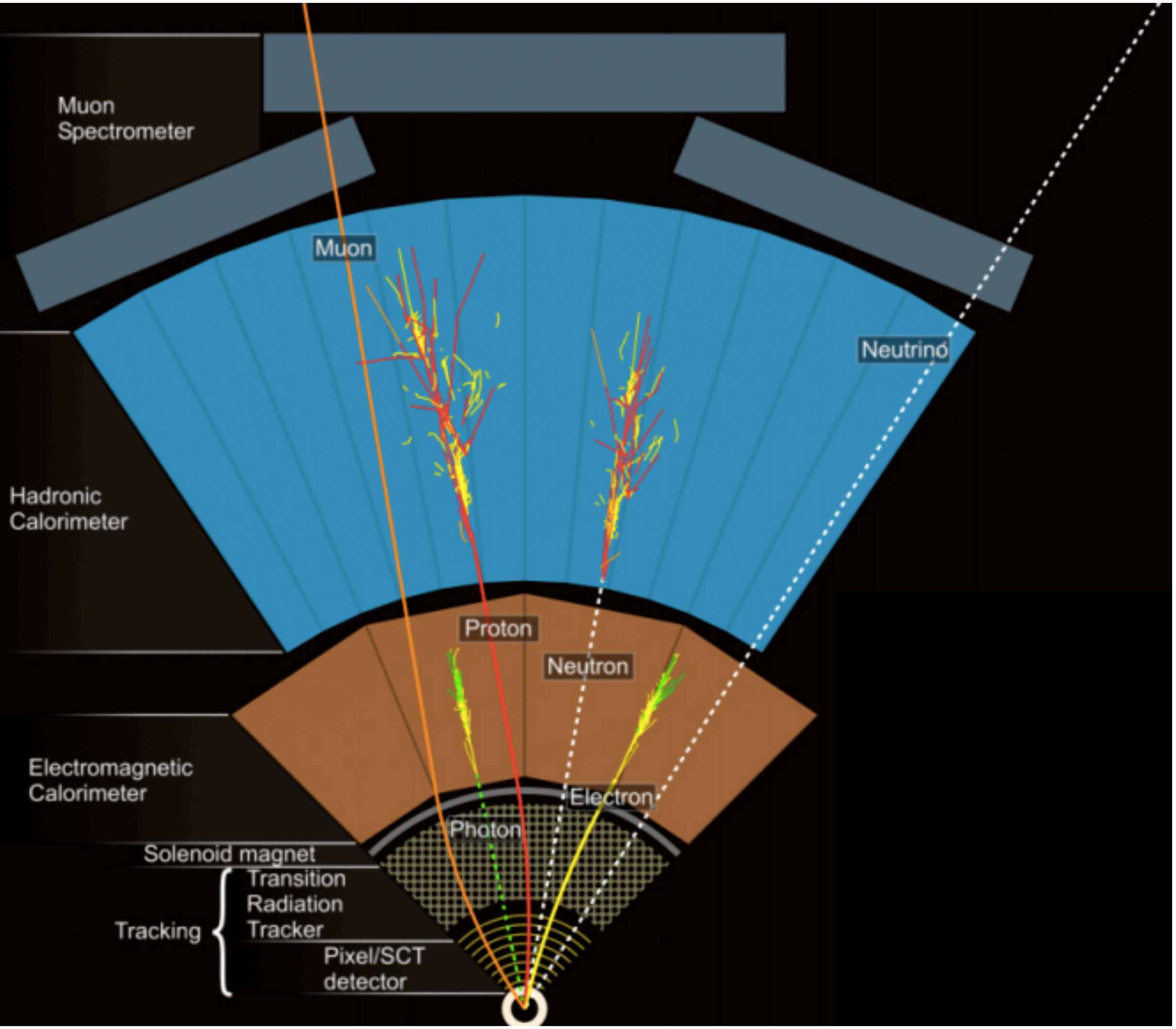
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsDisplayRun2#Highest_mass_central_dijet_event



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→qqbar, 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%);

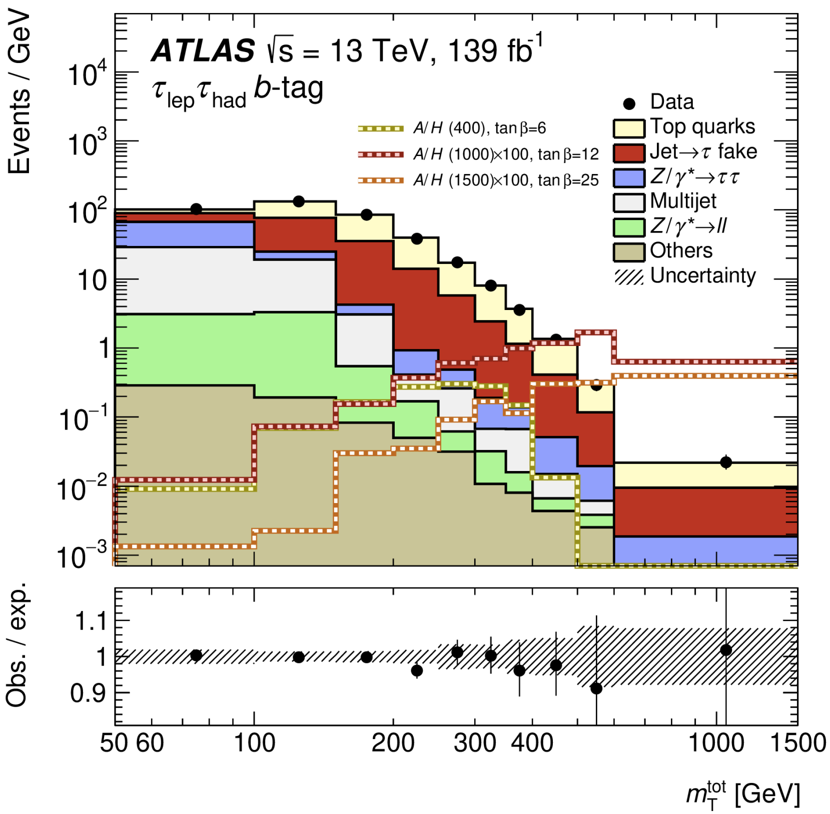
a single charged pion and extra neutral pions decaying to photons (48%);

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

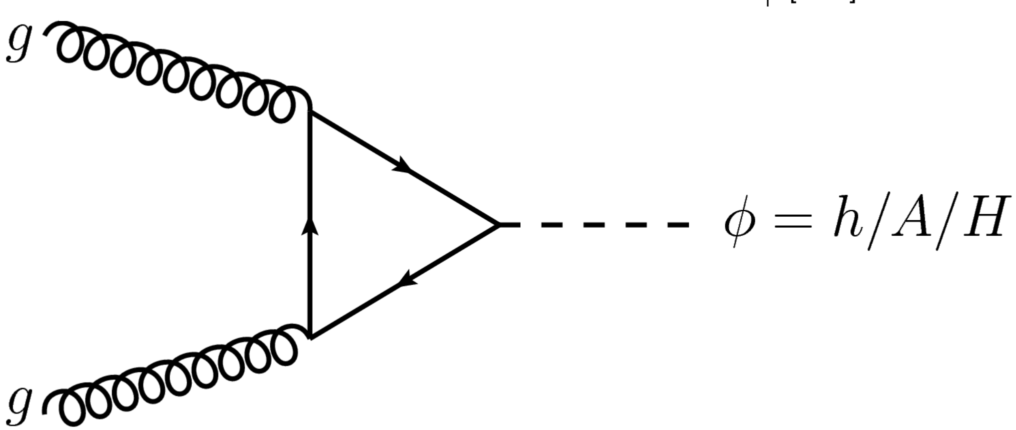
(Ignoring neutrinos)

Using taus at ATLAS



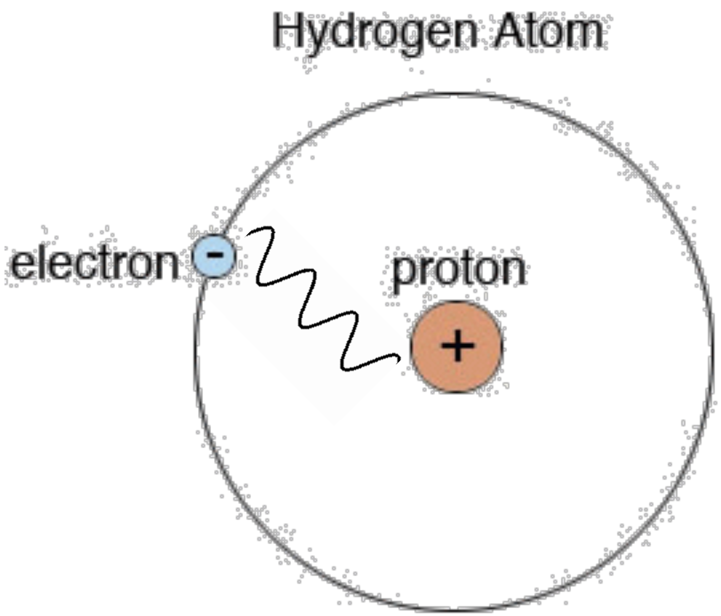
arXiv:2002.12223

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



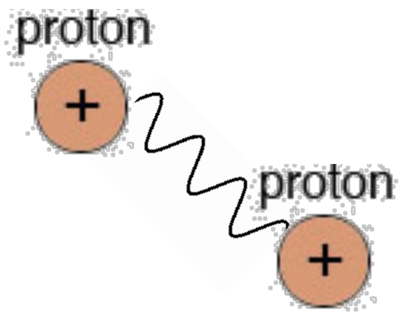
On to Feynman diagrams

Reminder of what we mean by force carriers



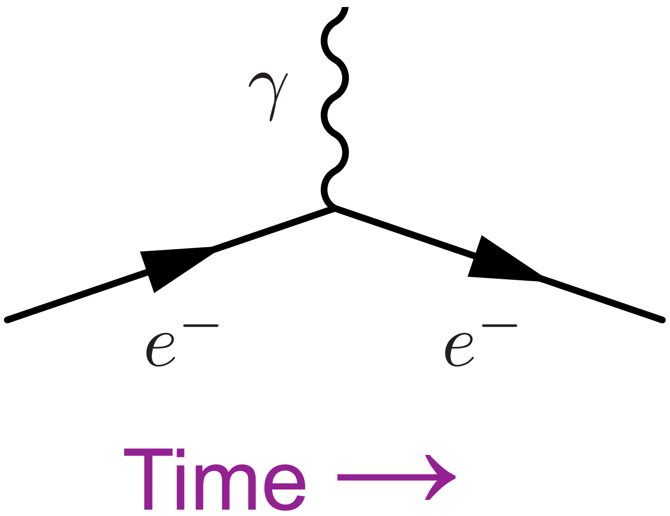
Photon as a particle (classical). But of course, what we really mean is that the field is quantized (here providing an attractive force), and the quantized unit of the field transmits some momentum from one object to another

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

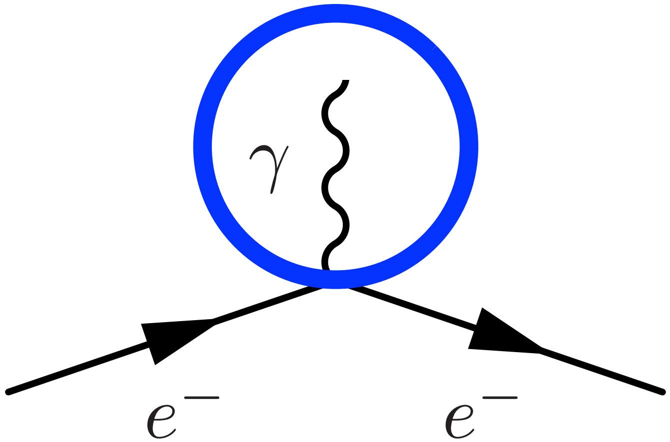


Think of time "passing" to the right, so initially (the "initial state") we start with an electron. And at the end (in the "final state"), we also have an electron.

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!

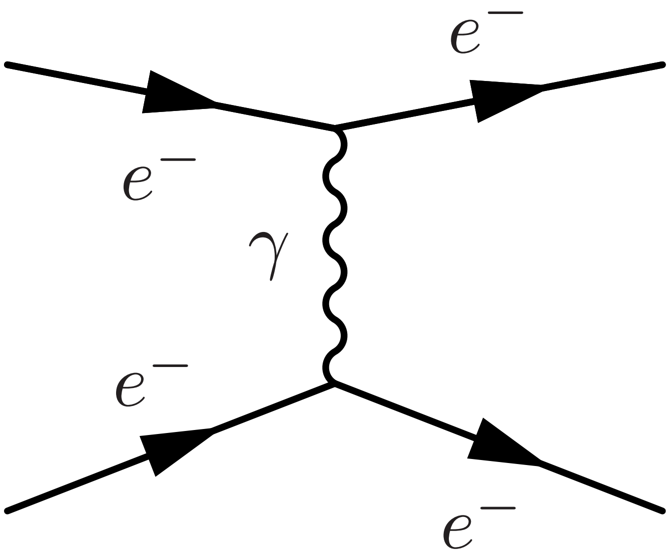


Time $\longrightarrow$

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

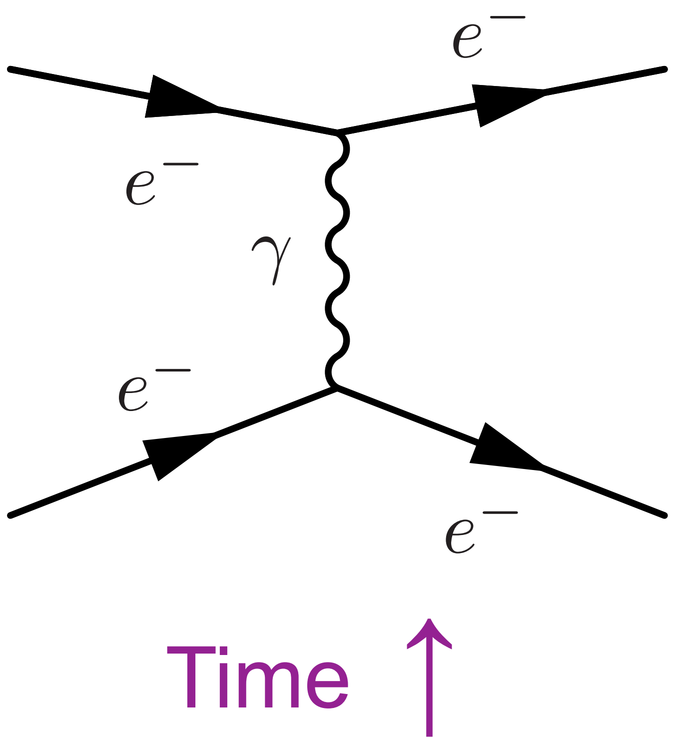


Time ⟶

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

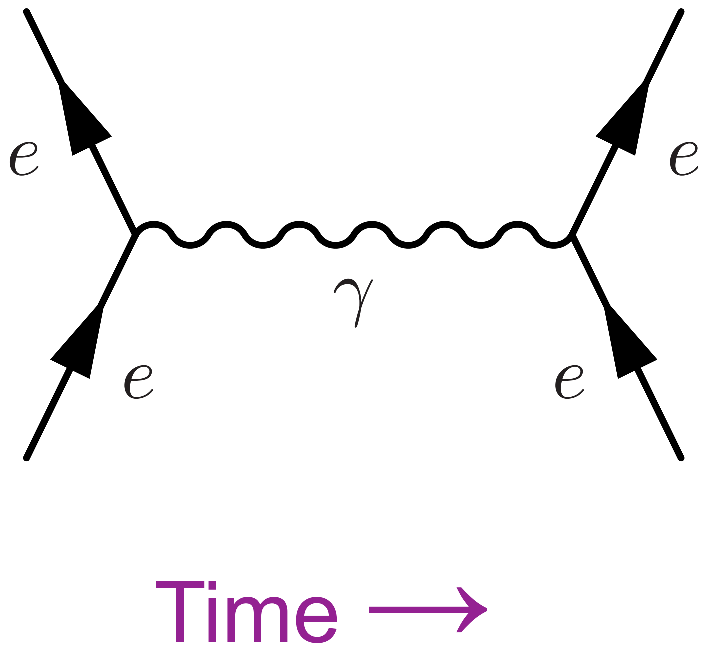
Feynman diagram



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?

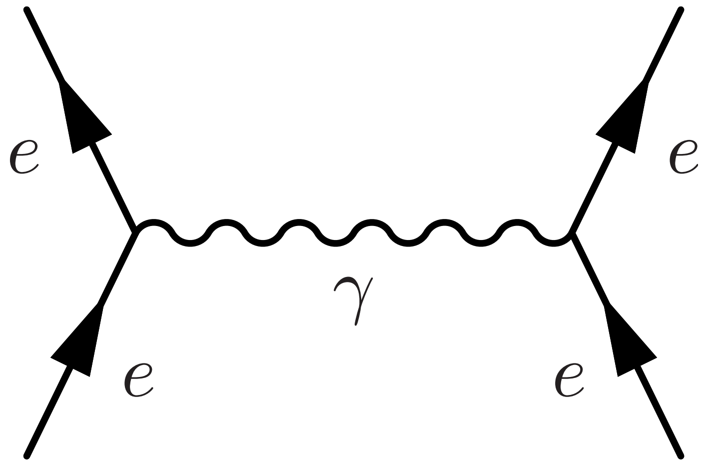
Feynman diagram (I turned things for you)

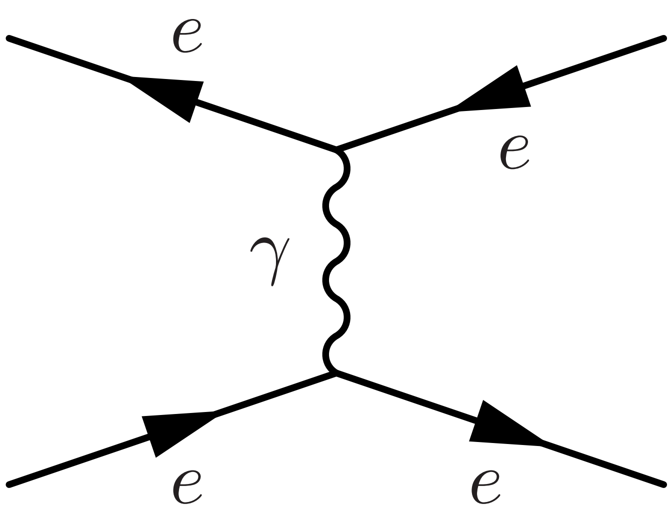


Here I put things back such that time moves to the right. Note that in the initial time (on left) there is a fermion line moving backwards! This is an antiparticle moving forwards in time. And on the right there is a fermion line also going backwards, this is again an anti-particle

Electron vs positron should now be more obvious/automatic

Bhaba scattering

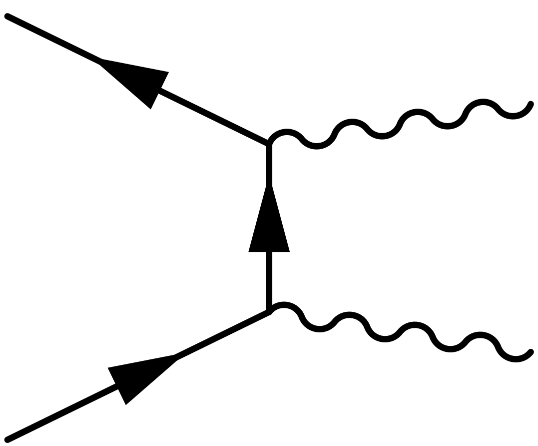




Note the second diagram below... start with e^+e^- and end with e^+e^- ... these two diagrams are both needed (same initial and same final states, so they must interfere quantum mechanically!)

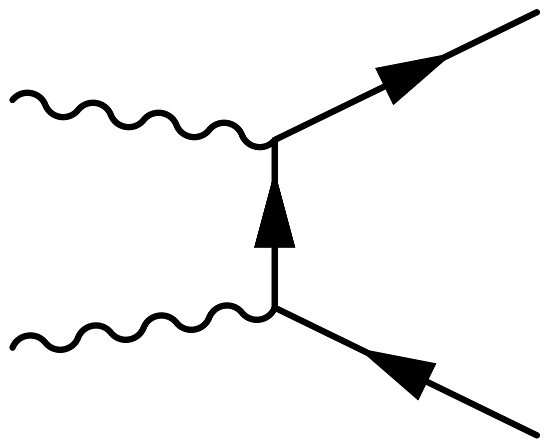
Feynman diagrams (note crossing symmetry again!)

Pair annihilation



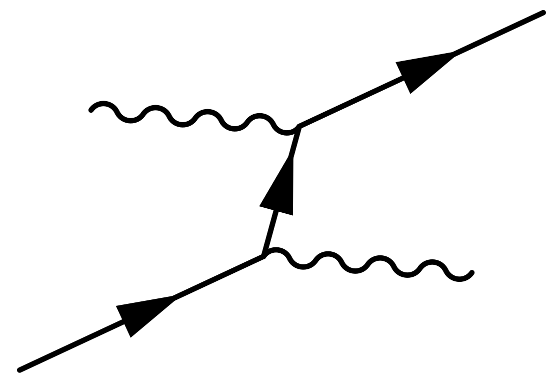
$e^- e^+ \rightarrow \gamma\gamma$

Pair production



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

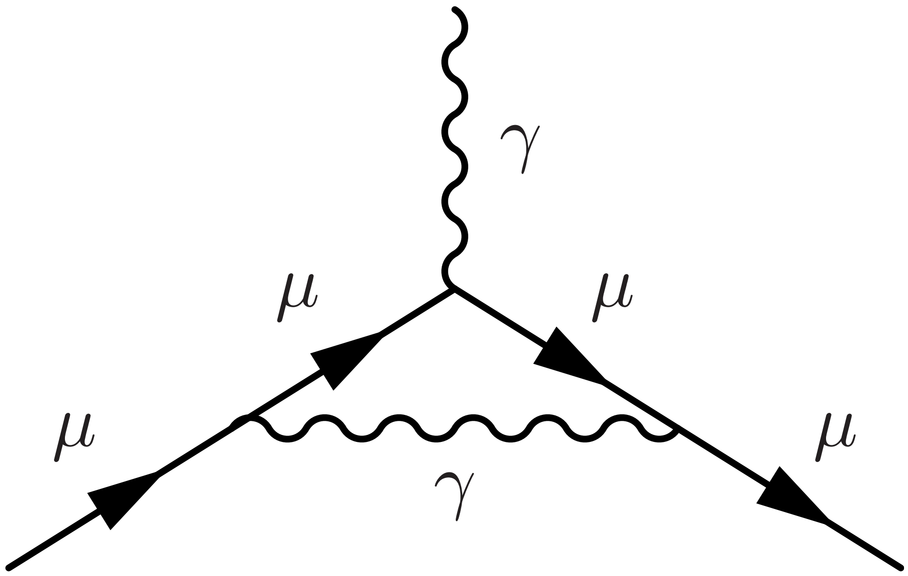
Compton scattering



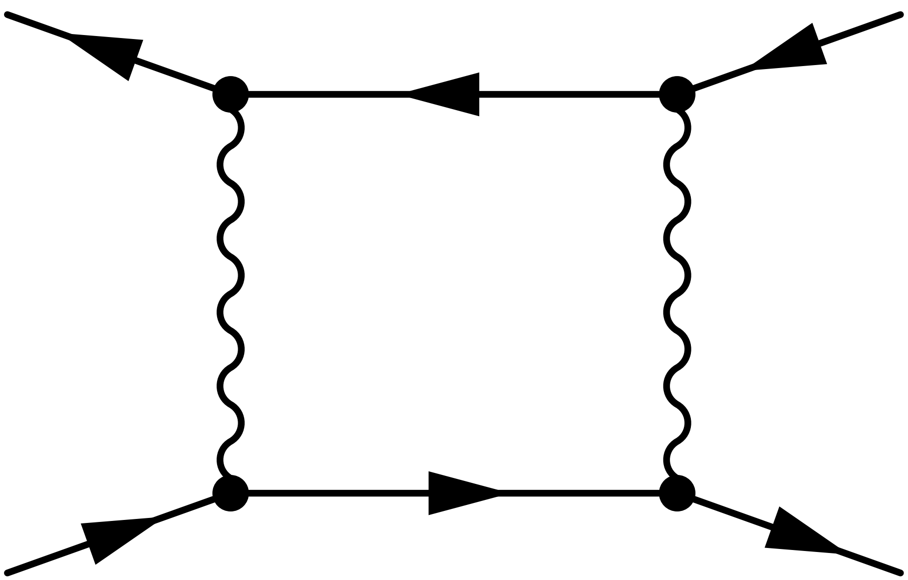
$e^- \gamma \rightarrow \gamma e^-$

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...

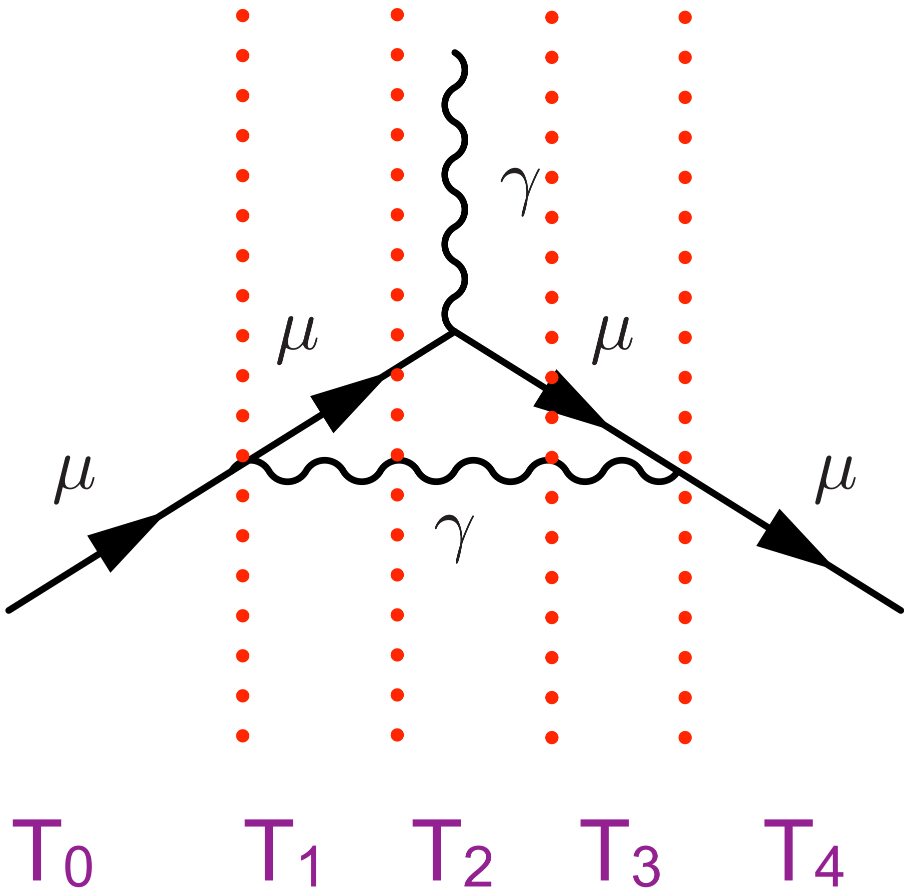


What is this? Does it remind you of any experiment that NIU works on? :)



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

Let’s take a closer look at these diagrams

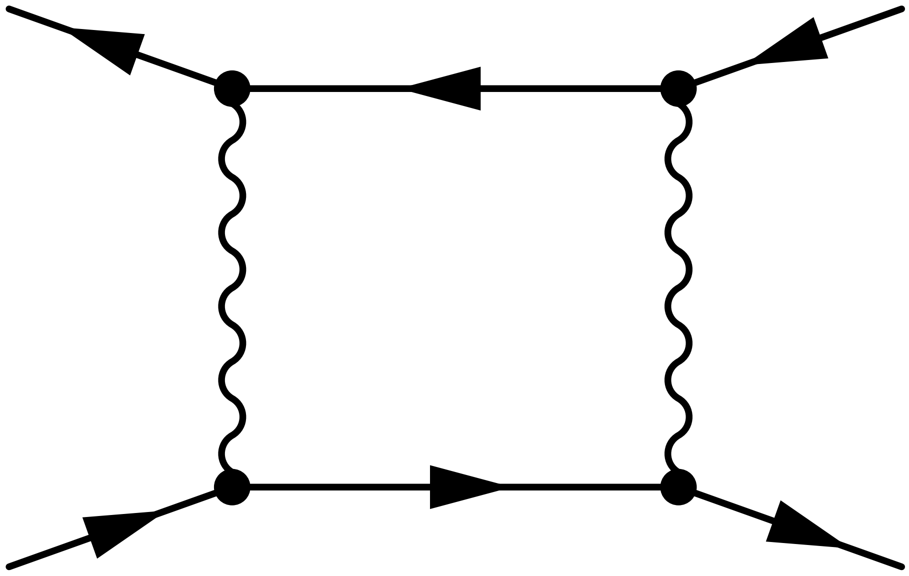


T_0: Single initial muon
T_1: Muon after interaction with photon, and that photon
T_2: Some external photon, muon after interaction with one or two photons, the internal photon
T_3: Muon after interaction with external photon, before reabsorbing the internal photon
T_4: Single final muon

Let’s slice this up into different time bins

Can cleanly divide into internal and external particles

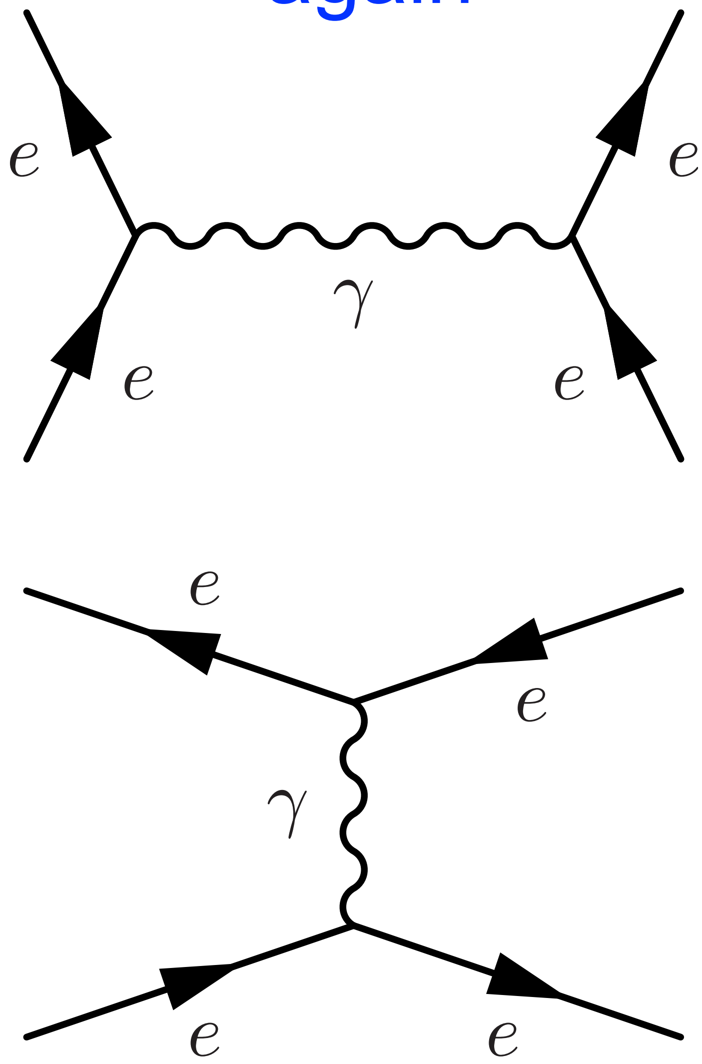
Let's take a closer look at these diagrams



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

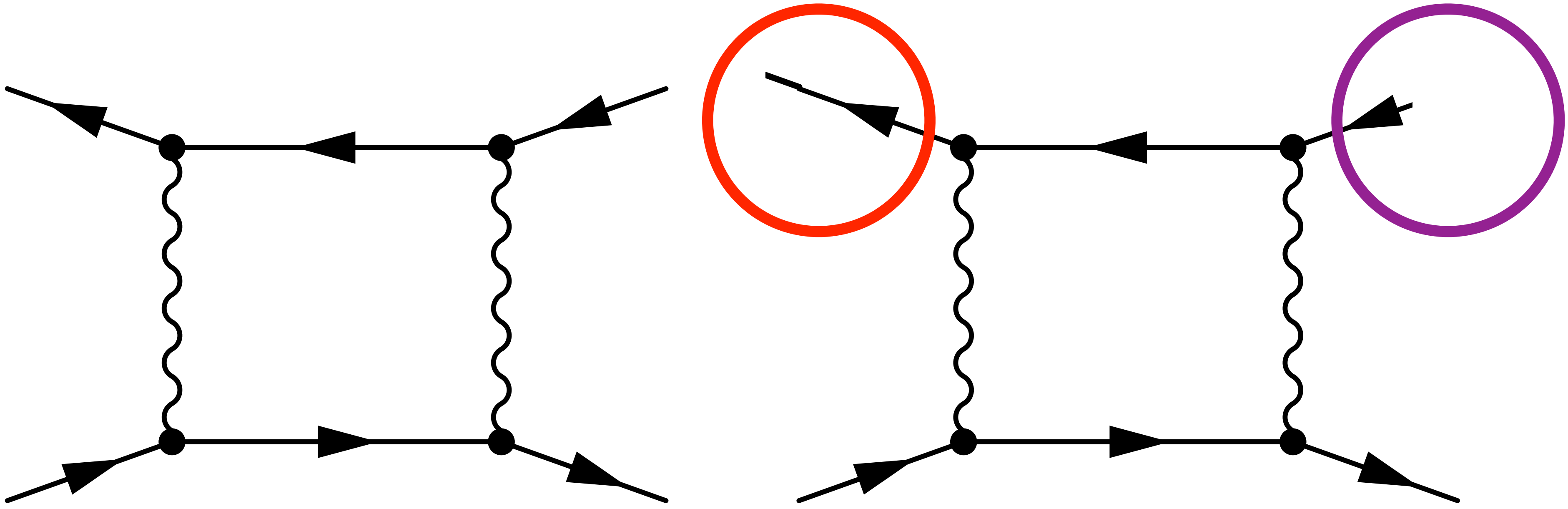
The other four are internal to the digram and are called virtual particles and do **not** have to have on-shell mass

Bhaba scattering again

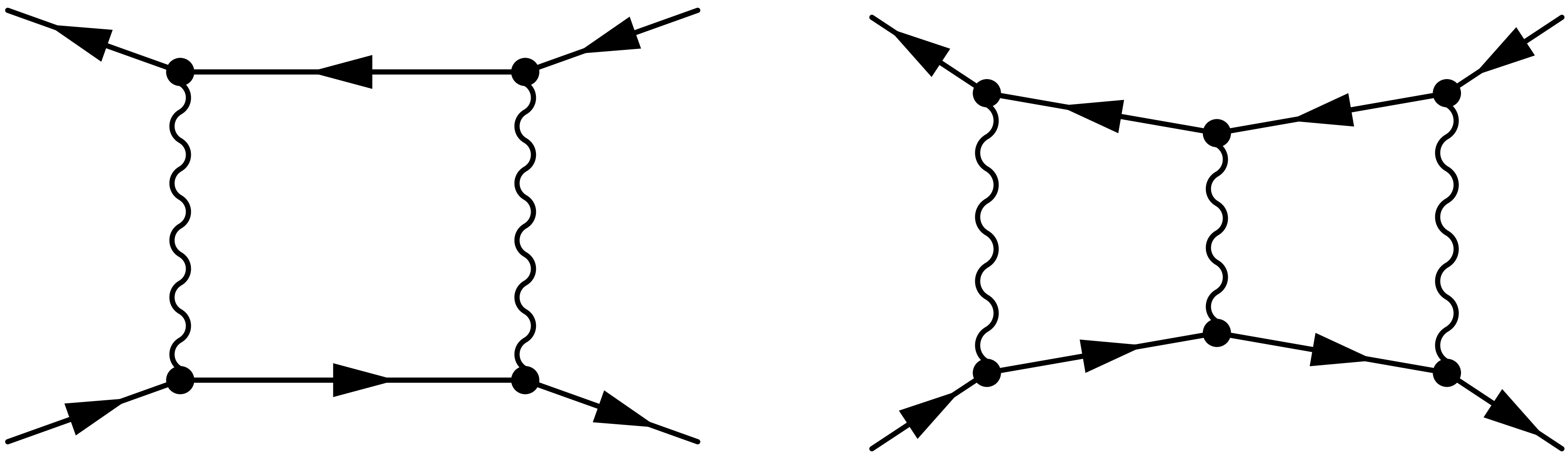


Virtual particles here (the photon in each diagram) cannot be observed, since the initial and final states are the same, so these much have interfering matrix elements

On diagrams

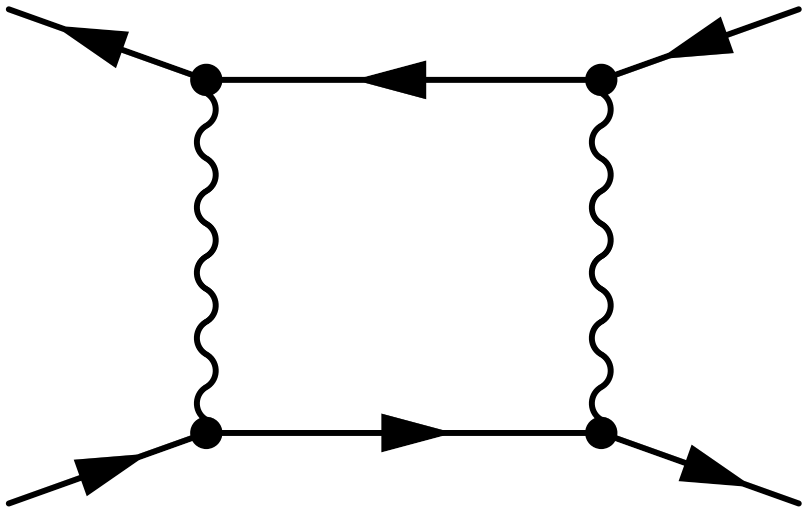


Have extended one line and shrunk another. Could have spaced things further apart or closer together - we do not differentiate between these sorts of things, nor the angle of the lines (we are not artists, here, or at least, I am not)

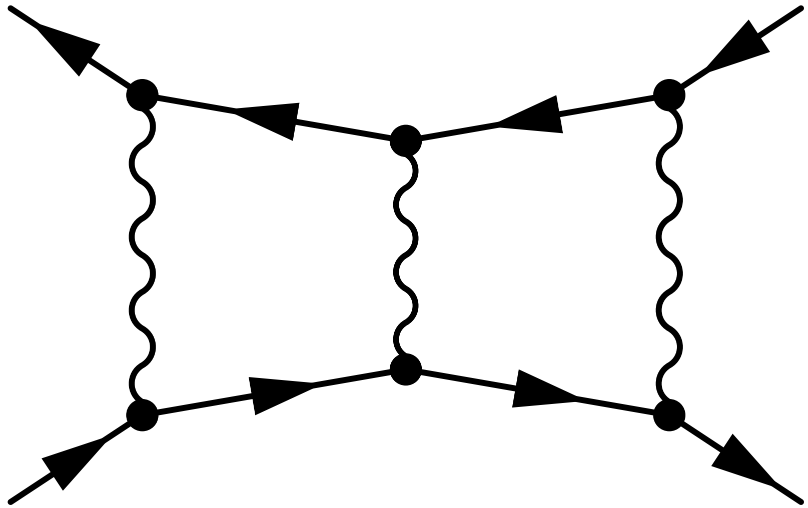


Again, can't distinguish these diagrams. So the observable scattering amplitude must be due to the sum of all such diagrams … but there are an infinite number of them! Let's draw another few

On diagrams



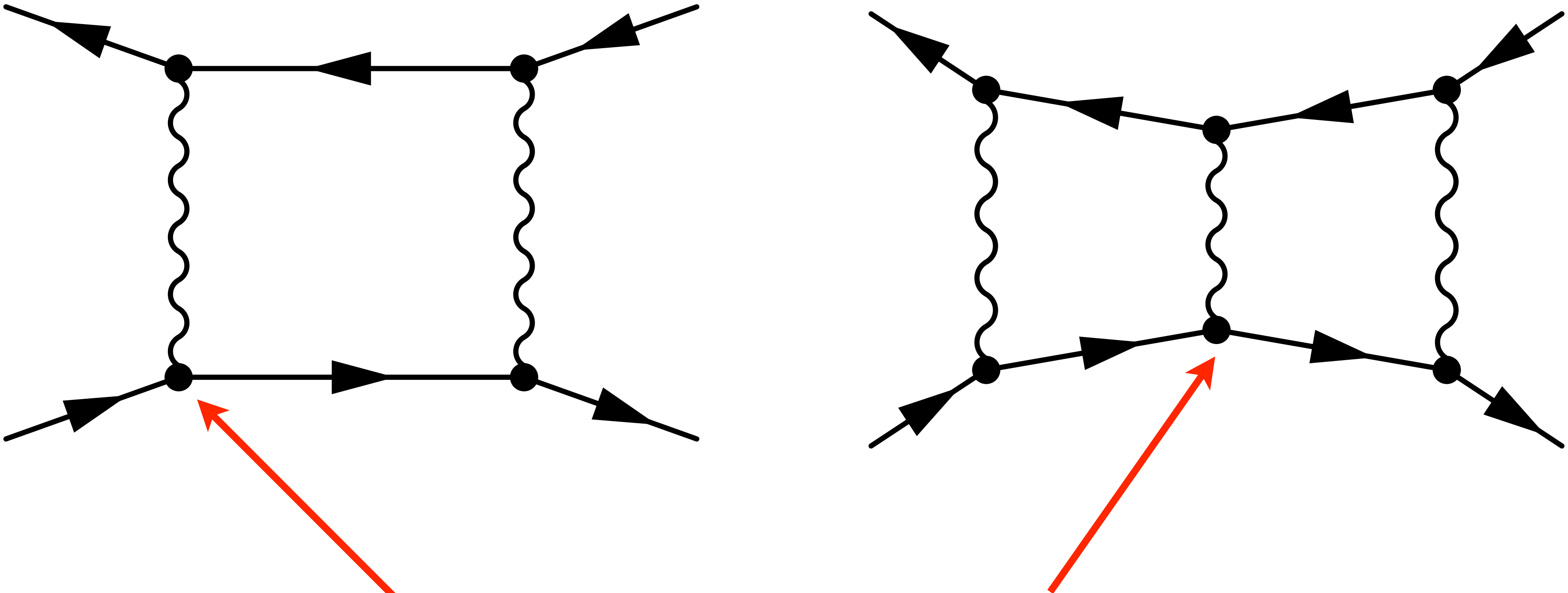
$e^+e^-\rightarrow e^+e^-\rightarrow e^+e^-$



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

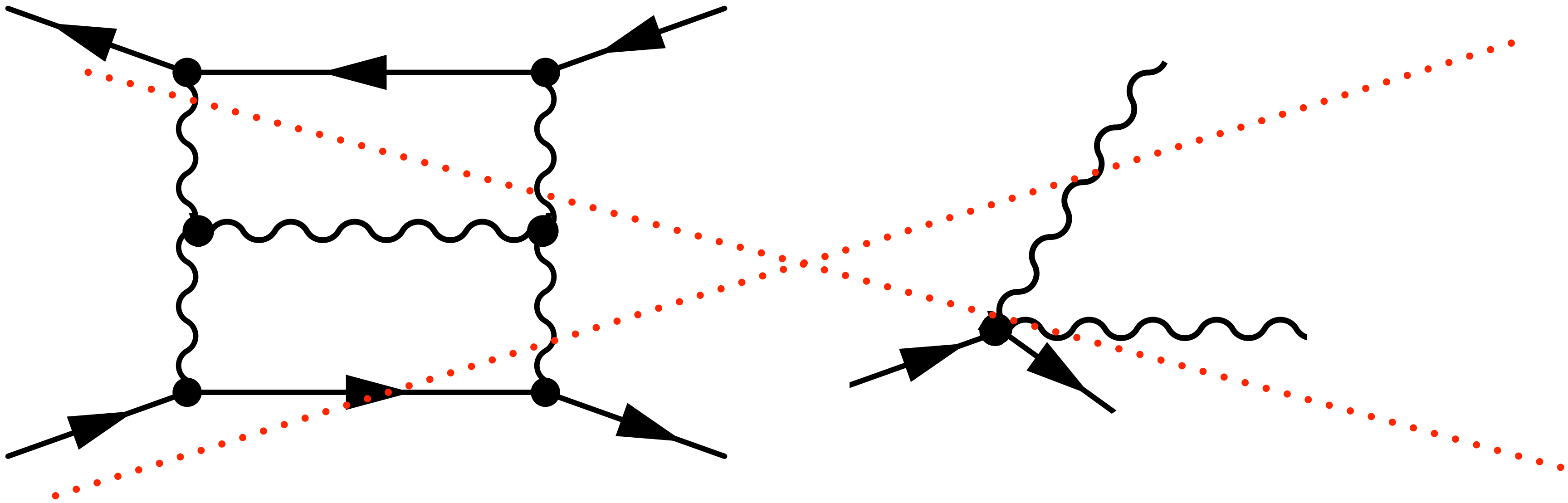
$e^+e^-\rightarrow e^+e^-$ in both cases, since intermediate states are not observable. You might ask why we're bothering to draw such pictures, but they will shortly become an invaluable computation tool. Each of these represents a single number!

On diagrams



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.

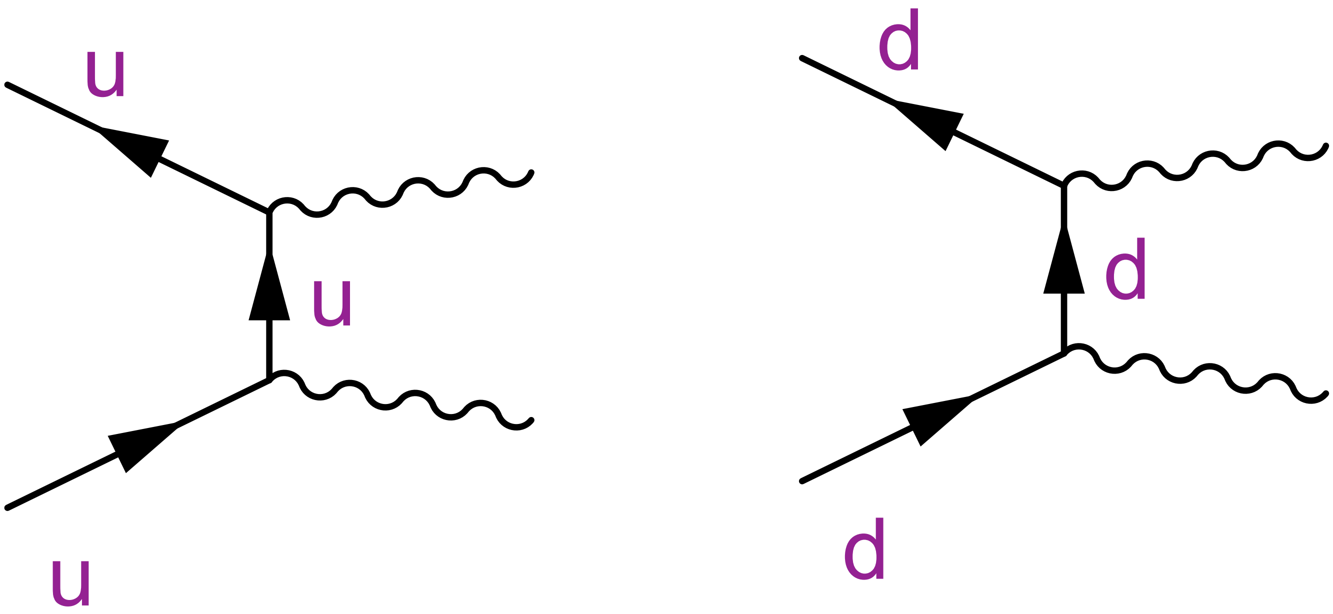
NOT valid



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)

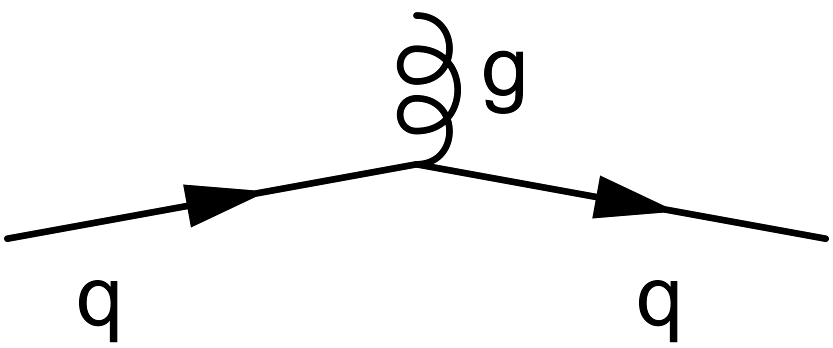
Muons can emit multiple photons, but not at the same vertex (note that the solid lines here represent any particle with electric charge)

Pair annihilation again, with quarks

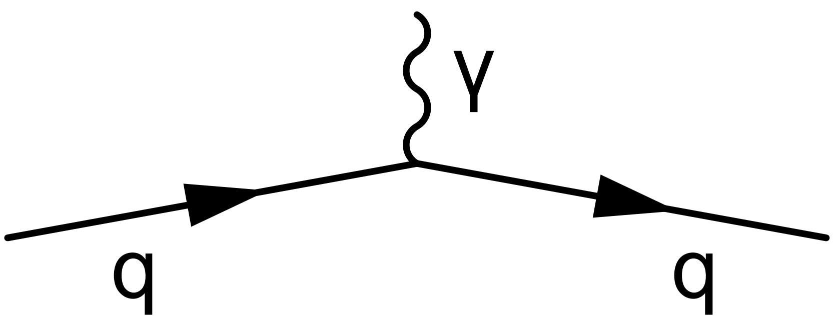


Now we can see why neutral pions decay 99% of the time to a pair of photons, and also why this happens so quickly (any good answers?)

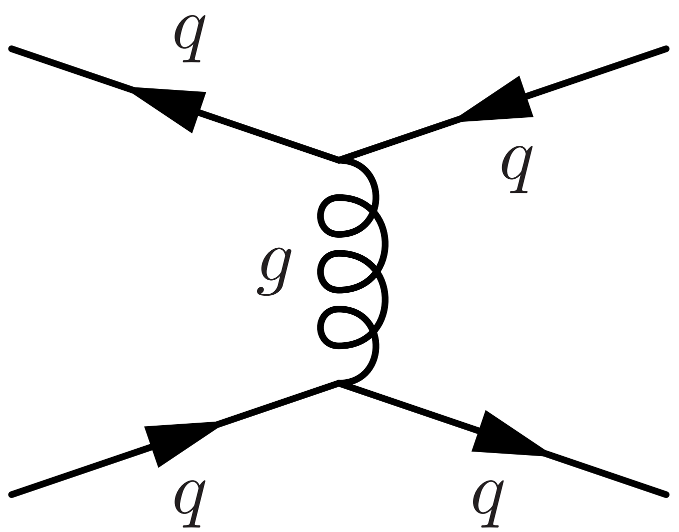
Start with common building block:



Note the similarity with the common building block of QED:

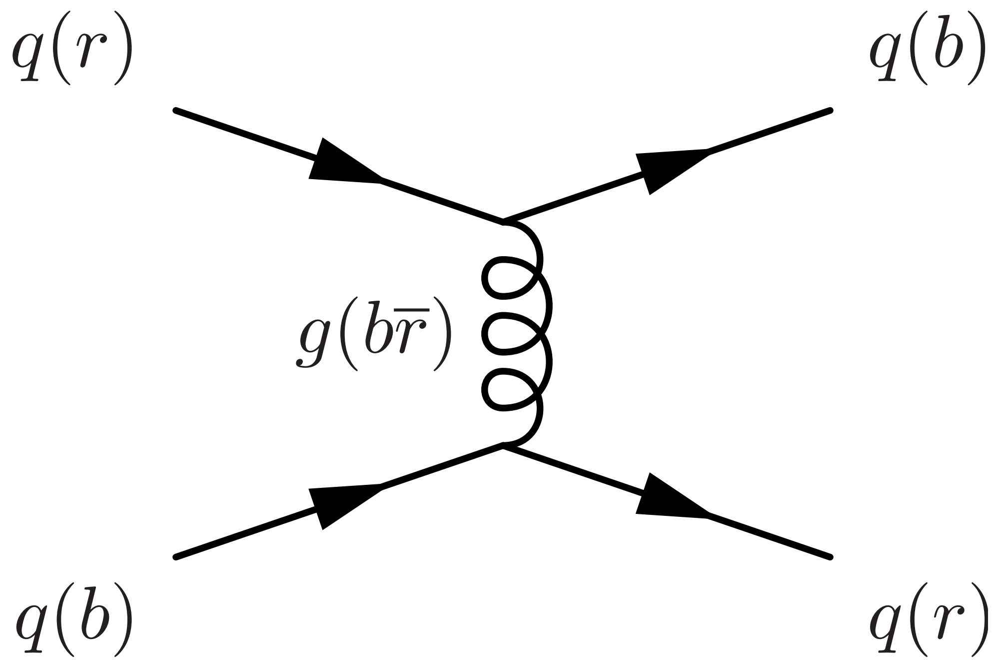


Gluon exchange between quark and anti-quark:



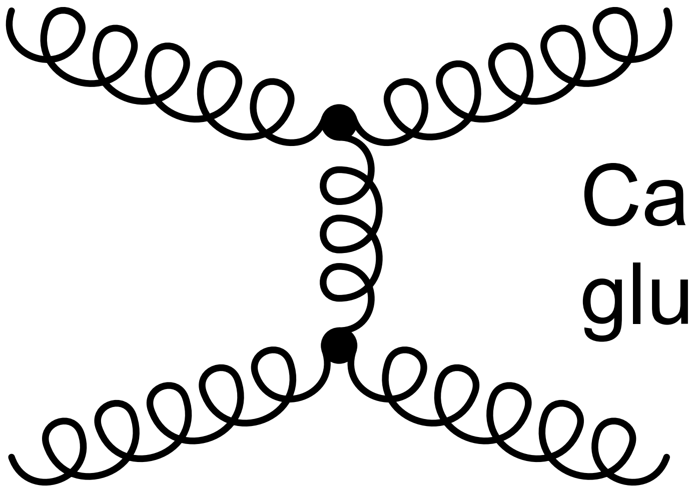
A few fundamental differences, though, between QED and QCD...

Gluon exchange between quarks:



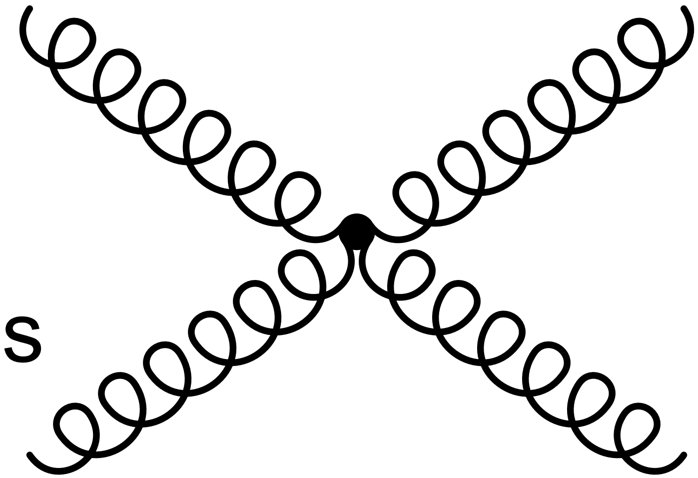
Remember that quarks have color (and so do gluons!) Try and follow the color lines (always a good thing to check)

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



Can have three-gluon vertices

And four-gluon vertices

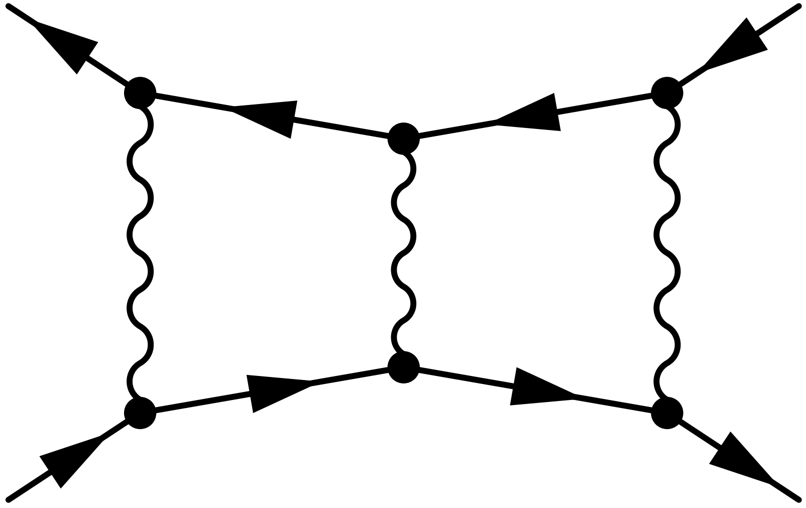


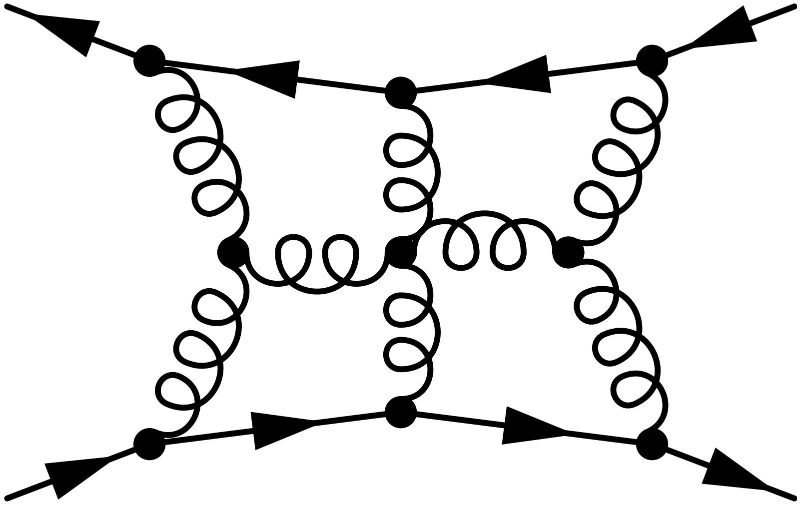
One other QED vs QCD differences

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

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...

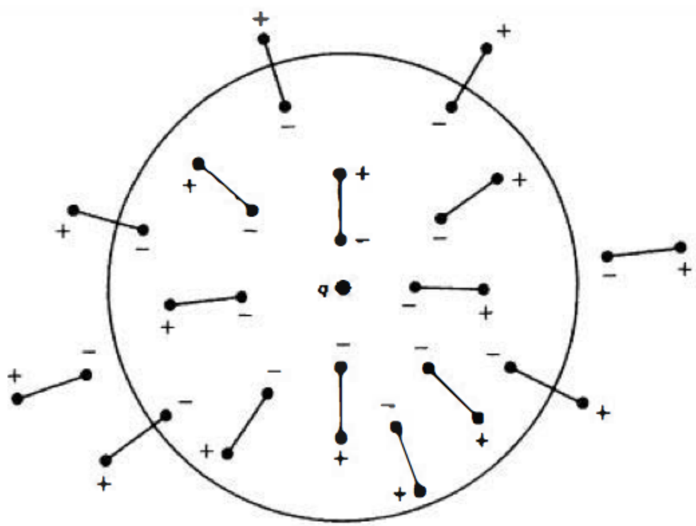


Fig. 2.1 Screening of a charge q by a dielectric medium.

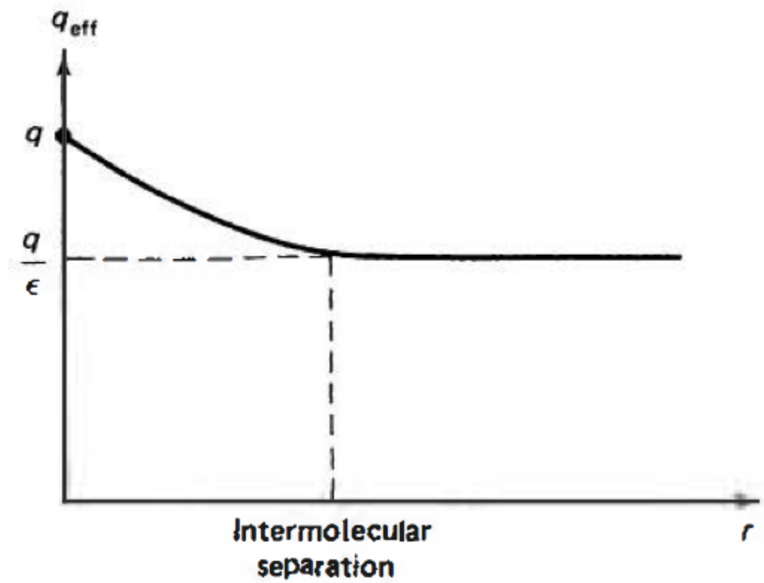
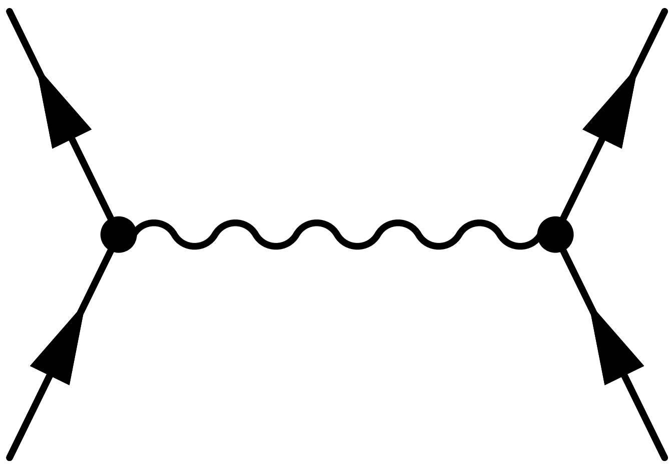


Fig. 2.2 Effective charge as a function of distance.

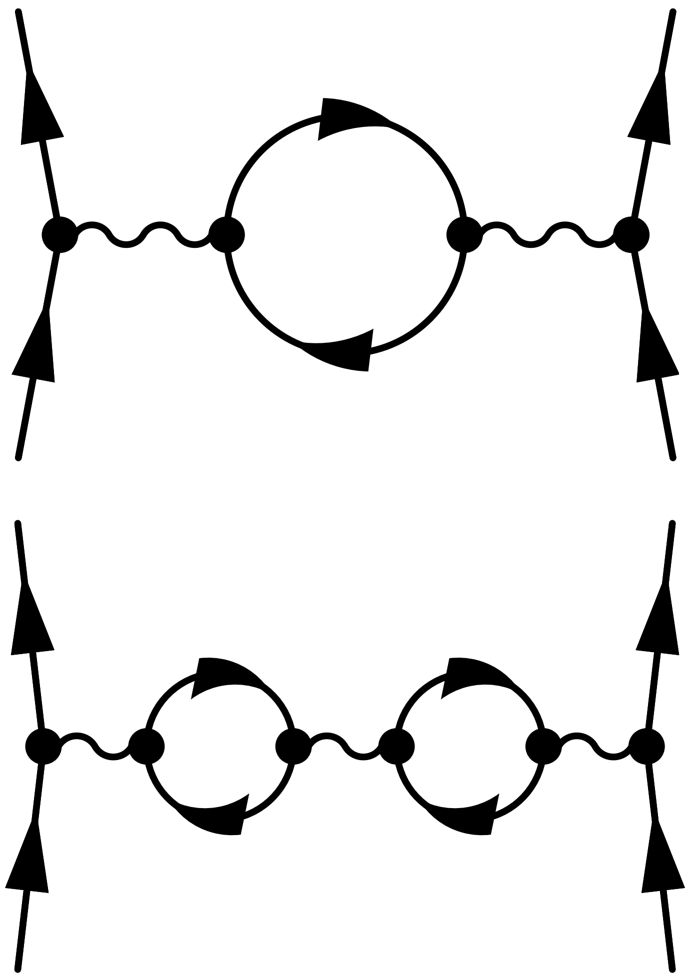
In classical E&M, the coupling is given by the charge q, and this is reduced at large distances by a dielectric

QED and screening effects

Bhaba scattering again



Virtual diagrams contributing



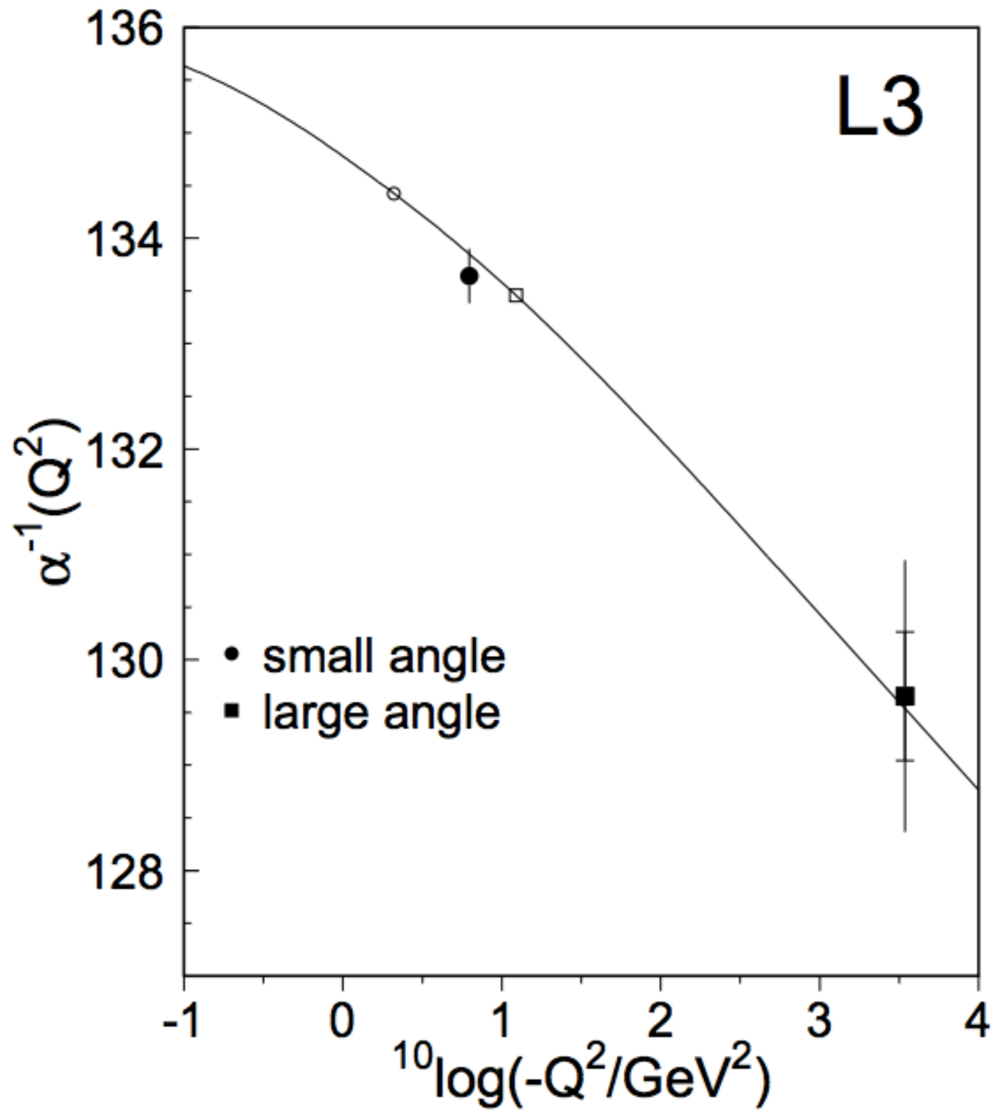
Running of the E&M fine structure constant

~1/137 at zero momentum transfer

~1/127 at the Z boson mass!

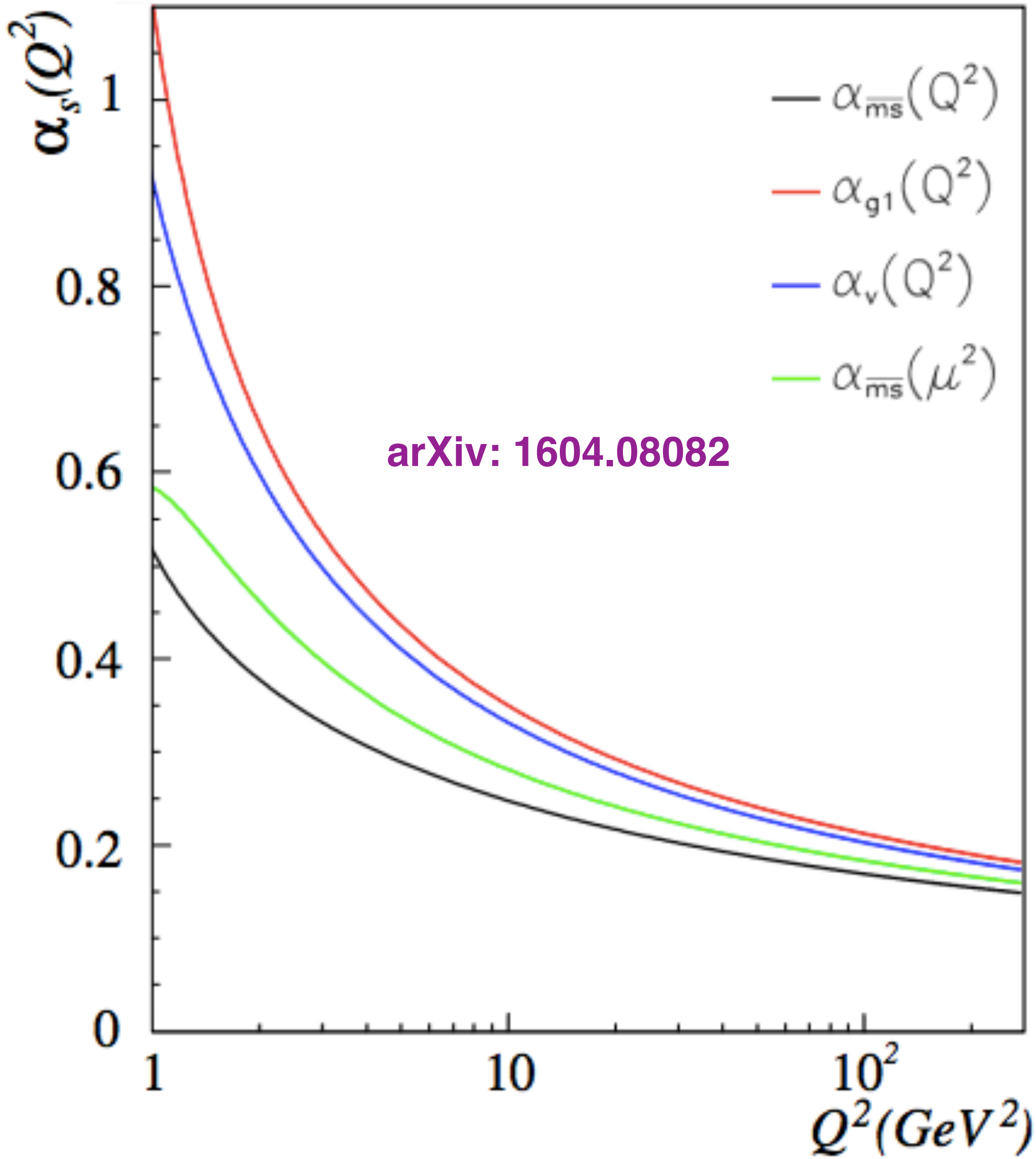
These are **vacuum polarization** effects

hep-ex/0002035v1



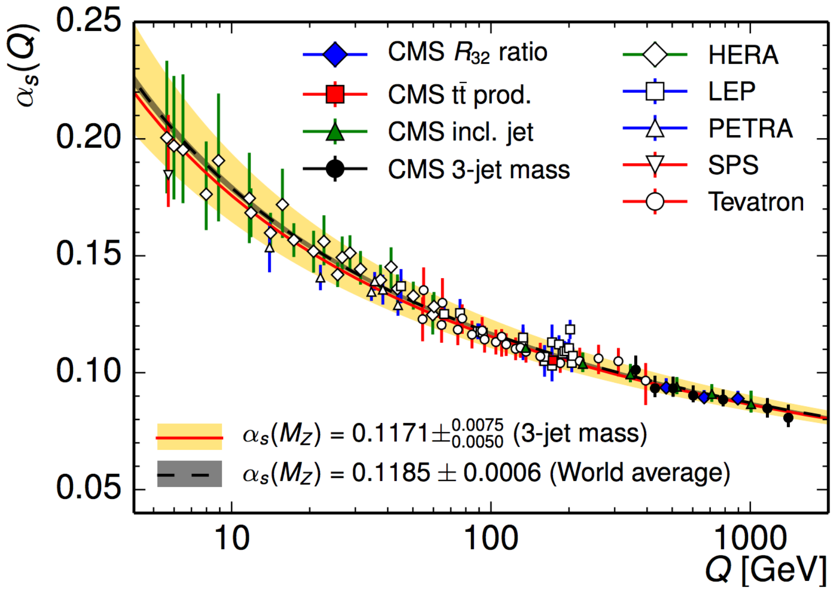
Running of the QCD strong coupling constant

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

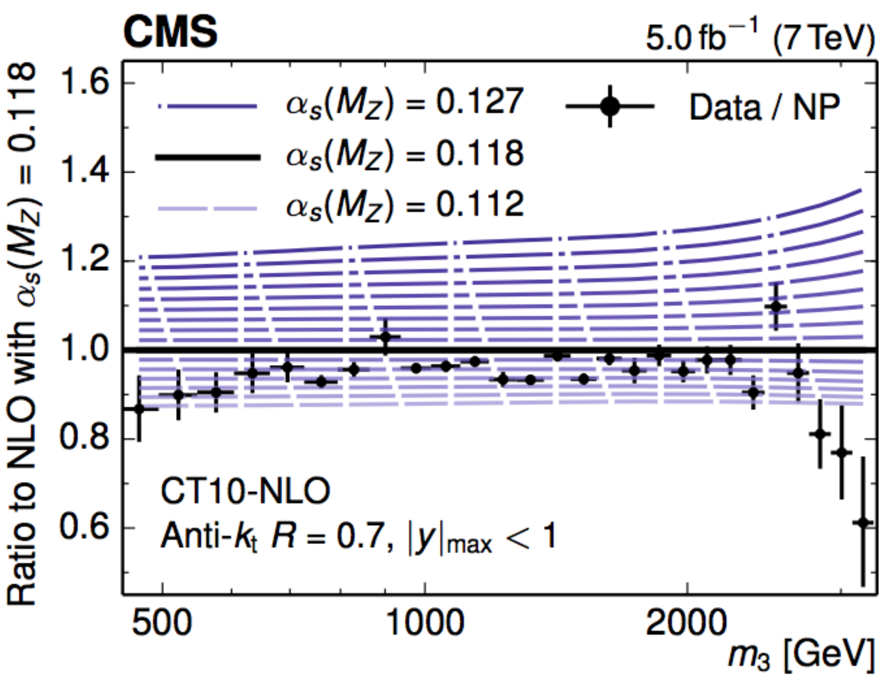


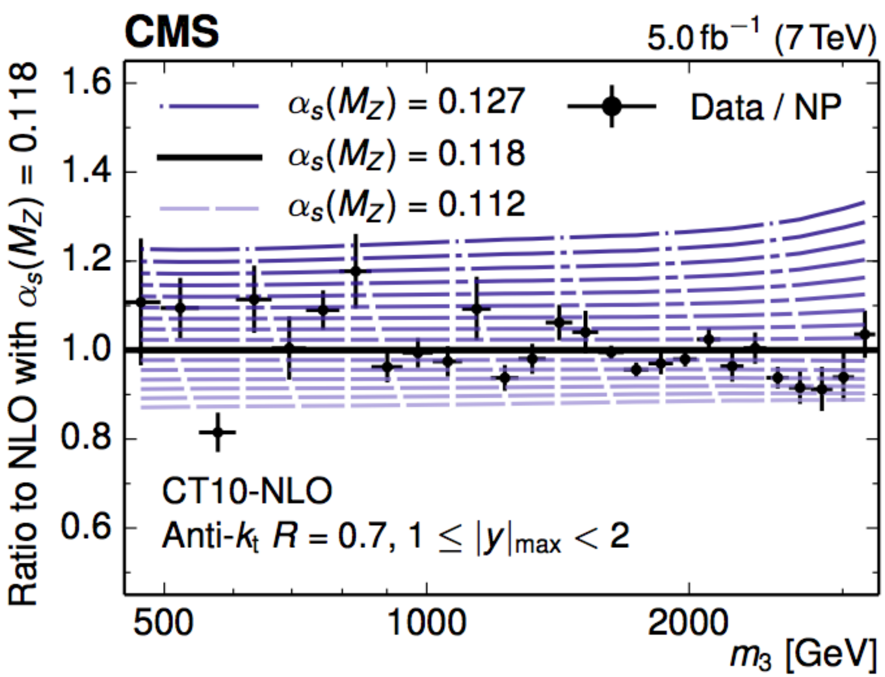
Can measure this in a variety of ways

Use trijet mass to determine the strong coupling constant!



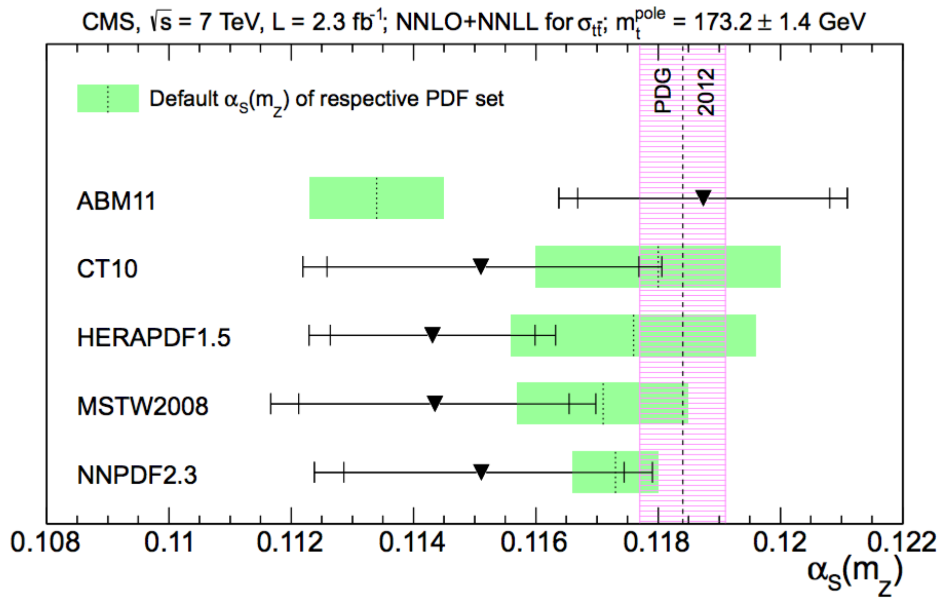
arXiv: 1412.1633



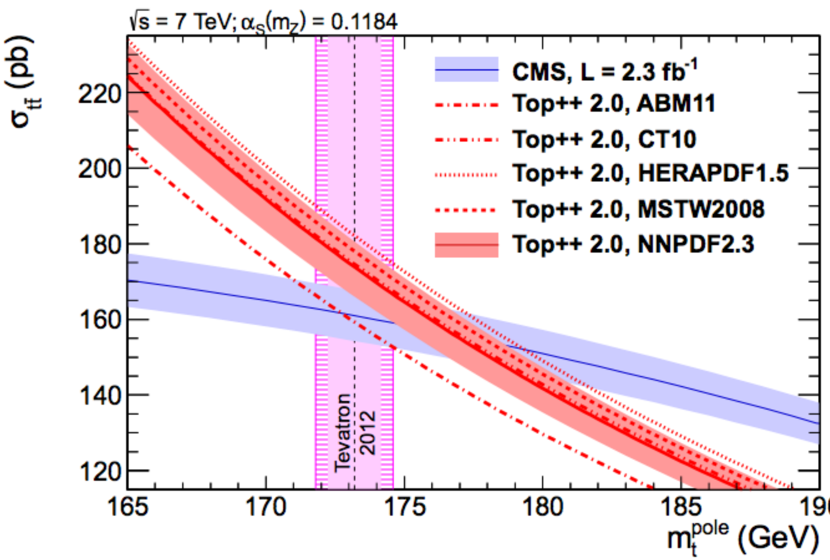


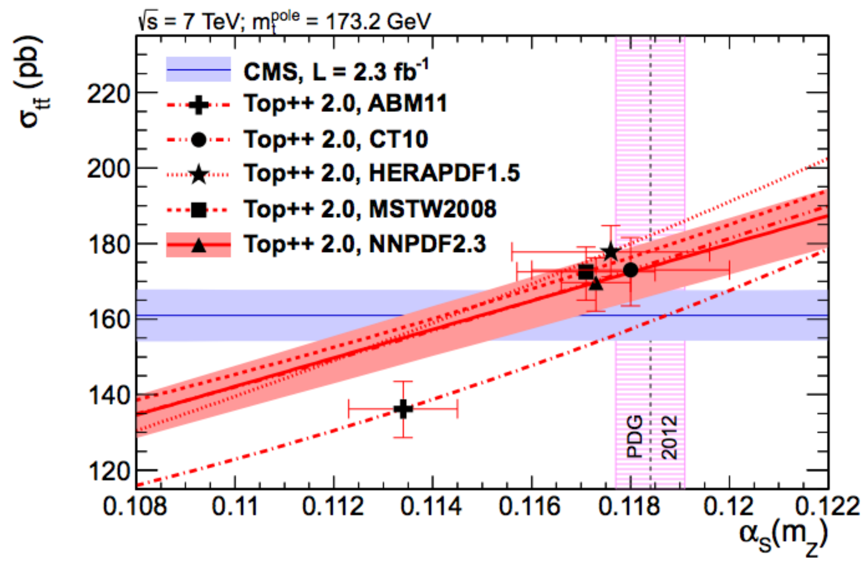
Can measure this in a variety of ways

Use ttbar production cross section instead!



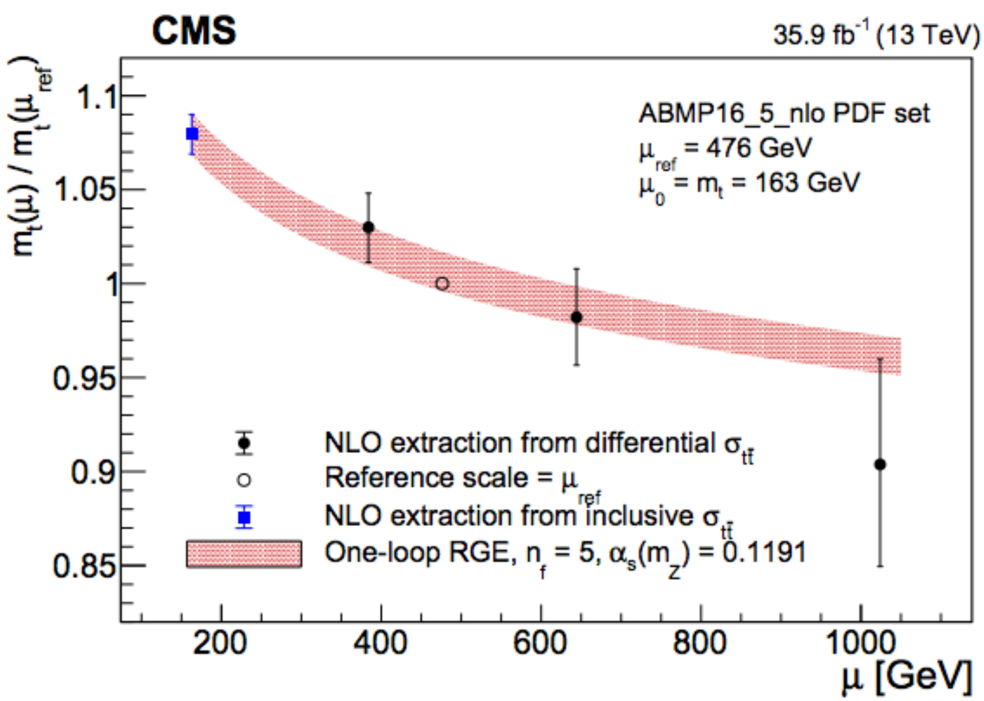
arXiv: 1307.1907





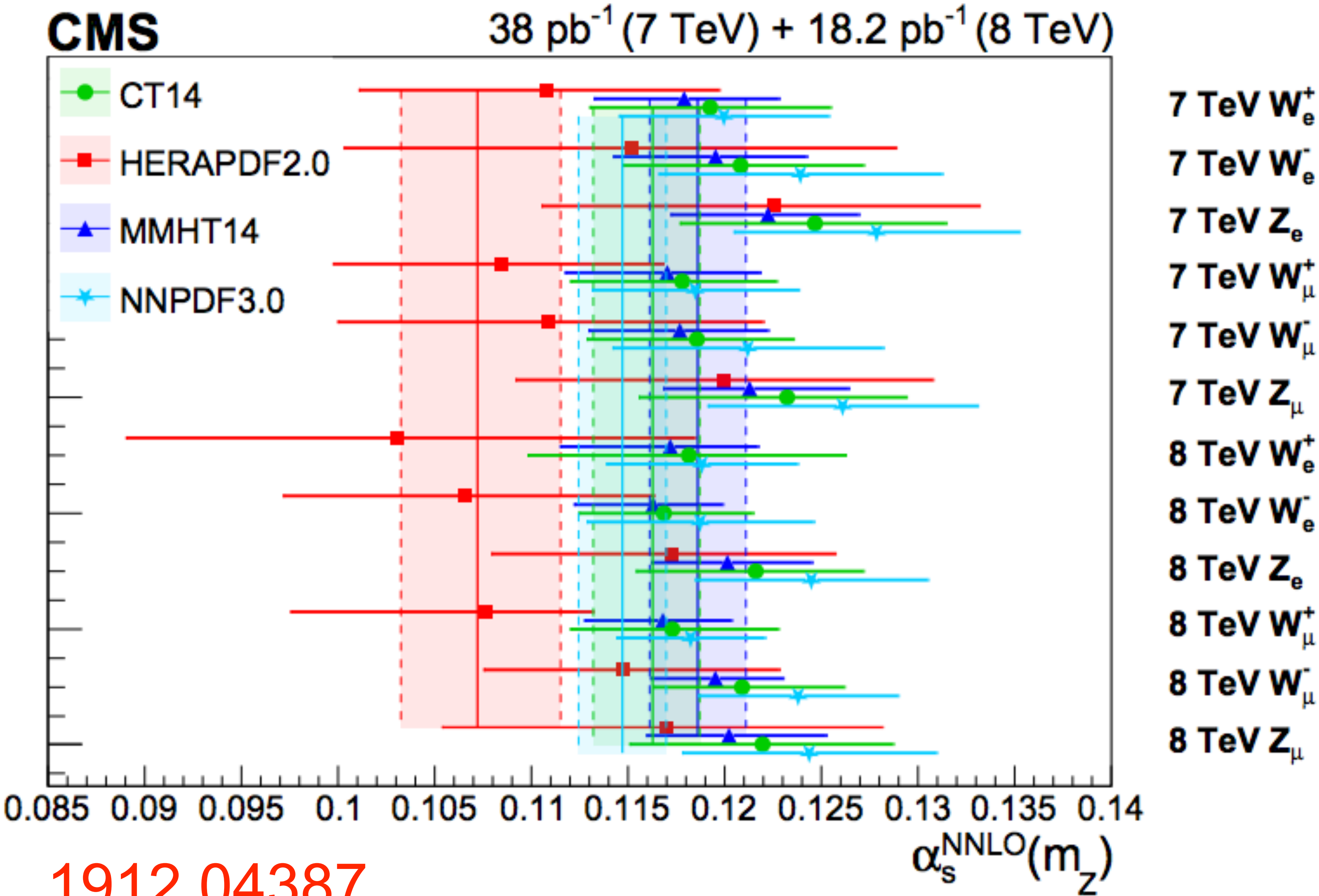
Masses of objects are also not single numbers!

The “mass” of the top quark depends on the energy scale of the collision! Use the differential cross section vs m_{tt} as a proxy for this



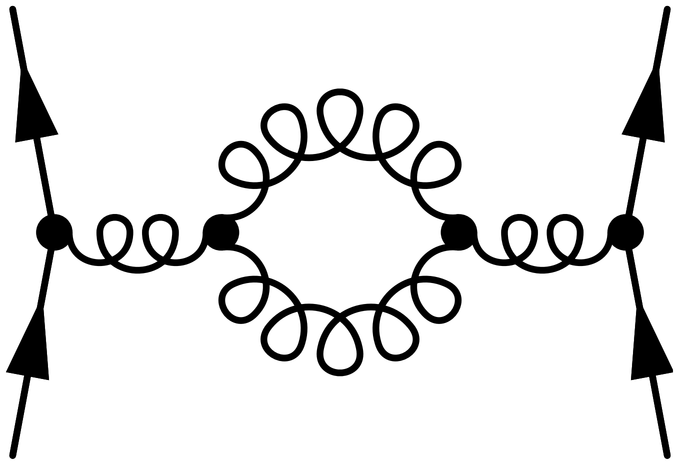
arXiv: 1909.09193

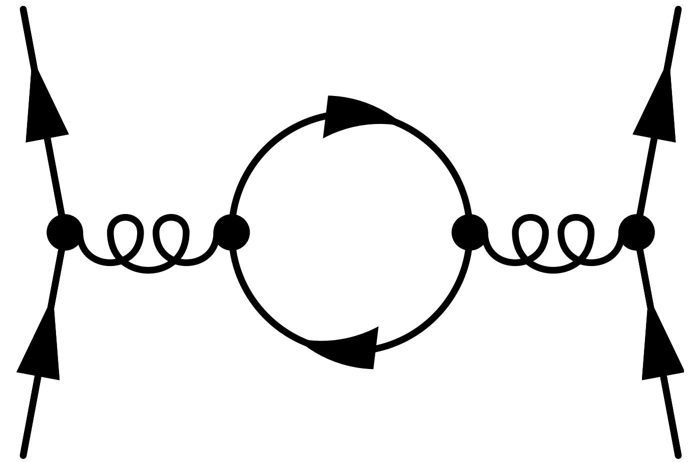
Measurement of strong coupling from V cross sections



1912.04387

Vacuum polarization in QCD





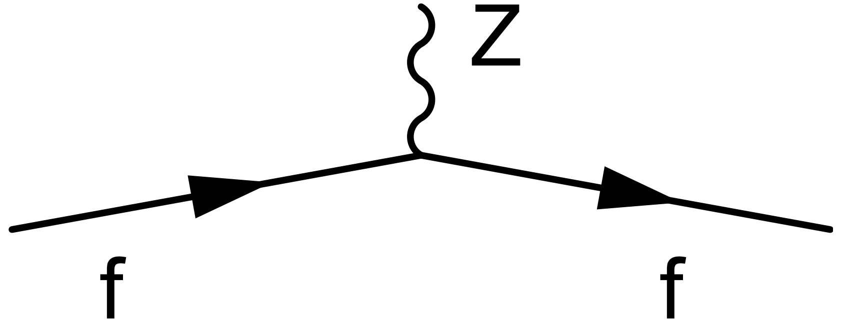
Effects from quark polarization and gluon polarization give opposite effects!

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

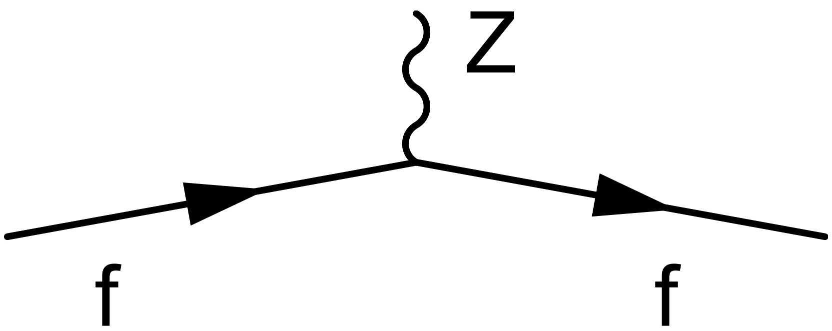
f=6,n=3 →a<0→asymptotic freedom (upper limit on no more than 17 generations of quarks)

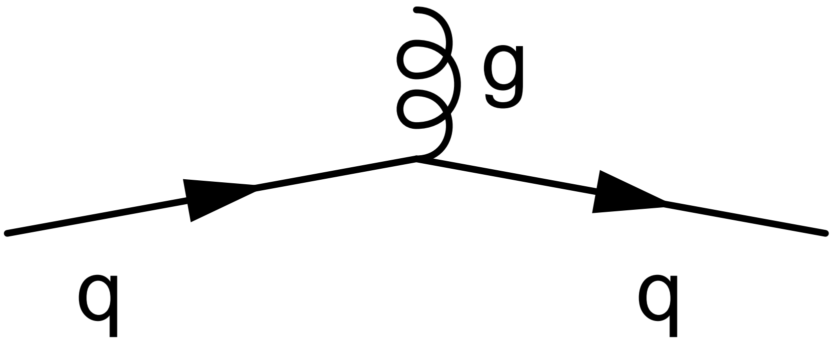
On to the weak interactions (start with neutral)

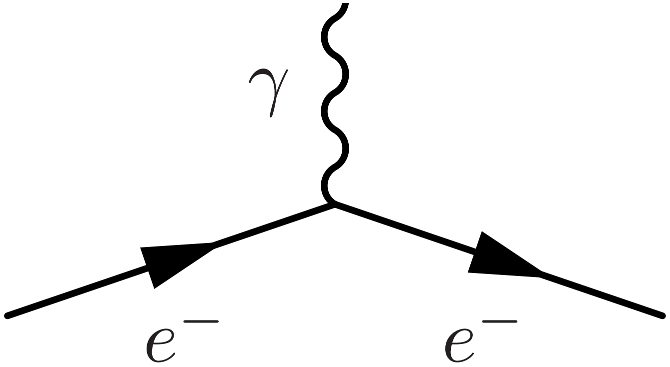
where f here
is any fermion (Z boson couples to all quarks,
charged leptons and neutral leptons)



Aside to be careful of



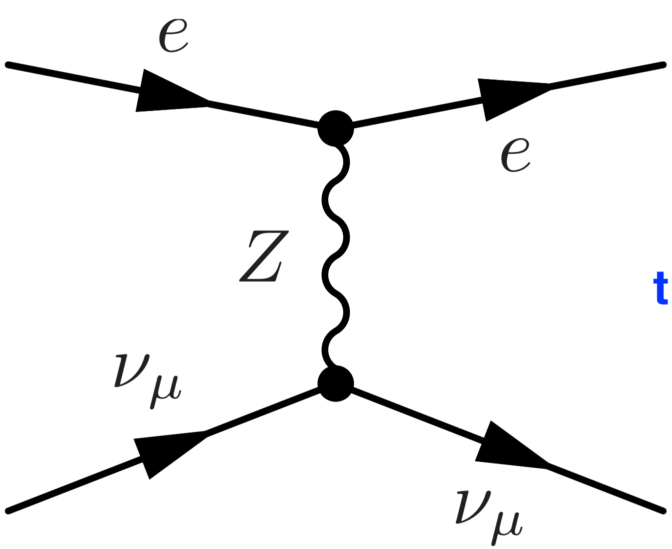




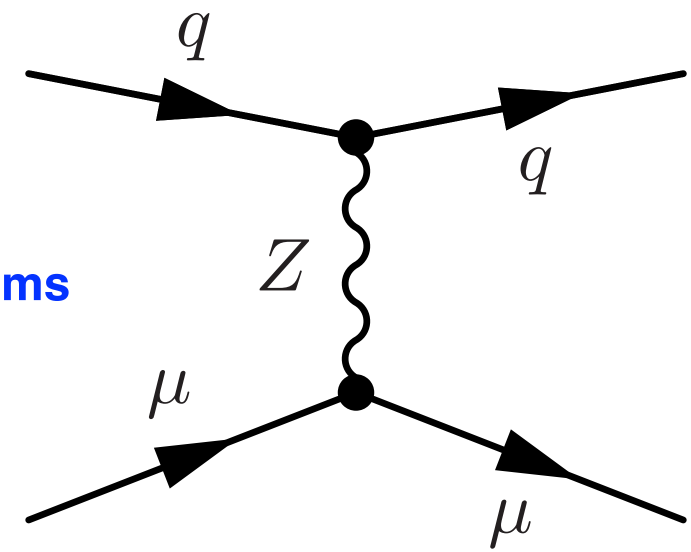
Griffiths uses a jagged straight line for EW bosons, but I will not. Just be careful, regardless of your choice!

What processes can the Z boson mediate?

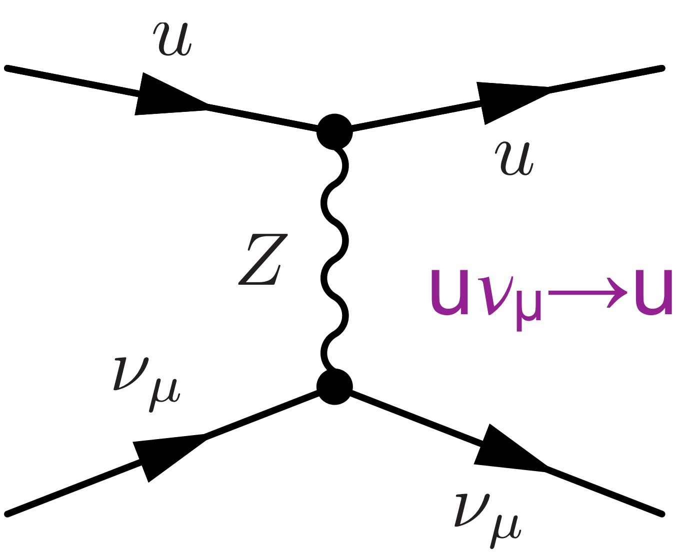
$e^-\nu_e \longrightarrow e^-\nu_e$



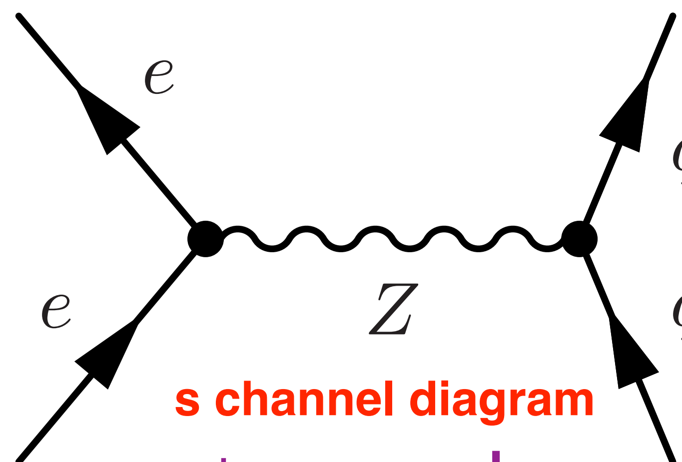
$\mu^-q \longrightarrow \mu^-q$



t channel diagrams



$u\nu_\mu \longrightarrow u\nu_\mu$

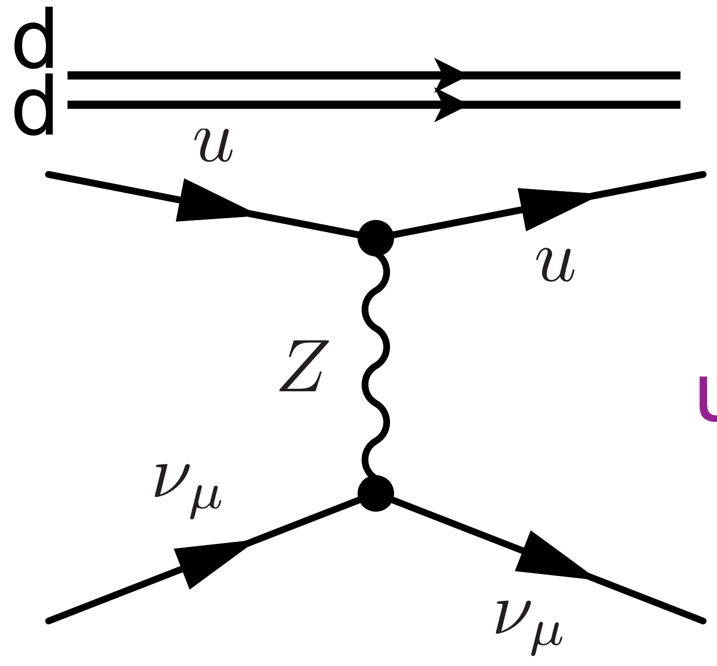


s channel diagram

$e^+e^- \longrightarrow$ qqbar

Of course…

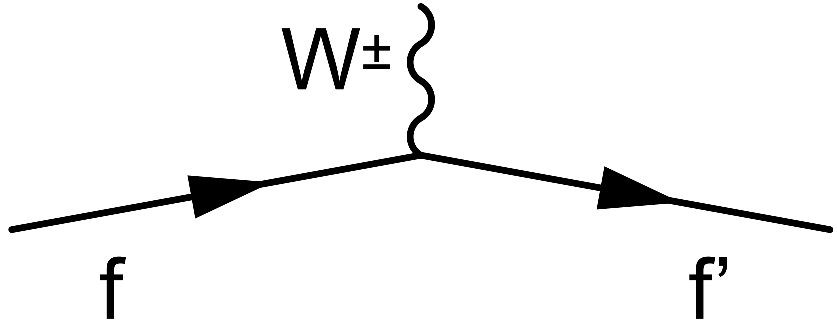
We of course don't scatter the bare quarks, but quarks inside hadrons (here inside a neutron)



$u\nu_\mu \longrightarrow u\nu_\mu$

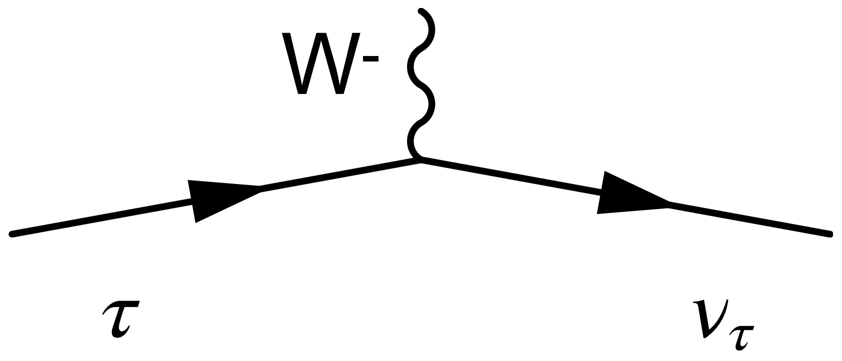
Charged weak interactions

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



Charged weak interactions

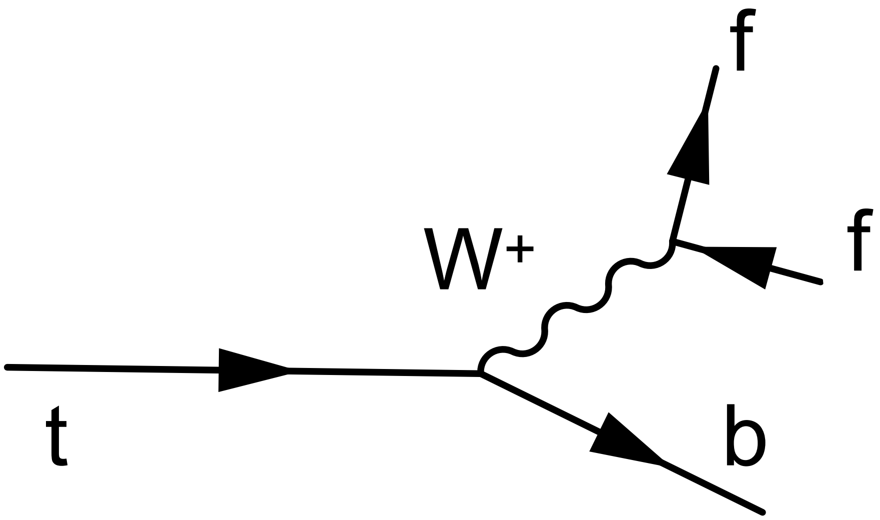
Remember that W bosons are the only ones involved in change of flavor or type of matter. Example, a tau converts into a tau neutrino and a W boson:



Charged weak interactions

Top quarks decay nearly ~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

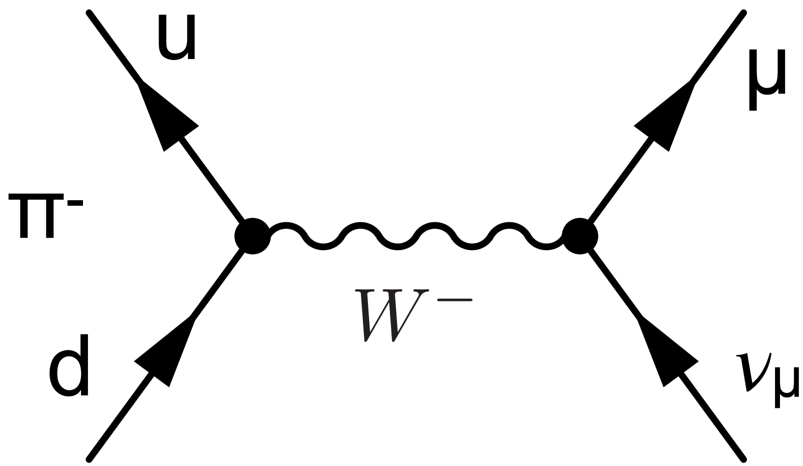
Check lepton flavor numbers and EM charge!



Charged weak interactions

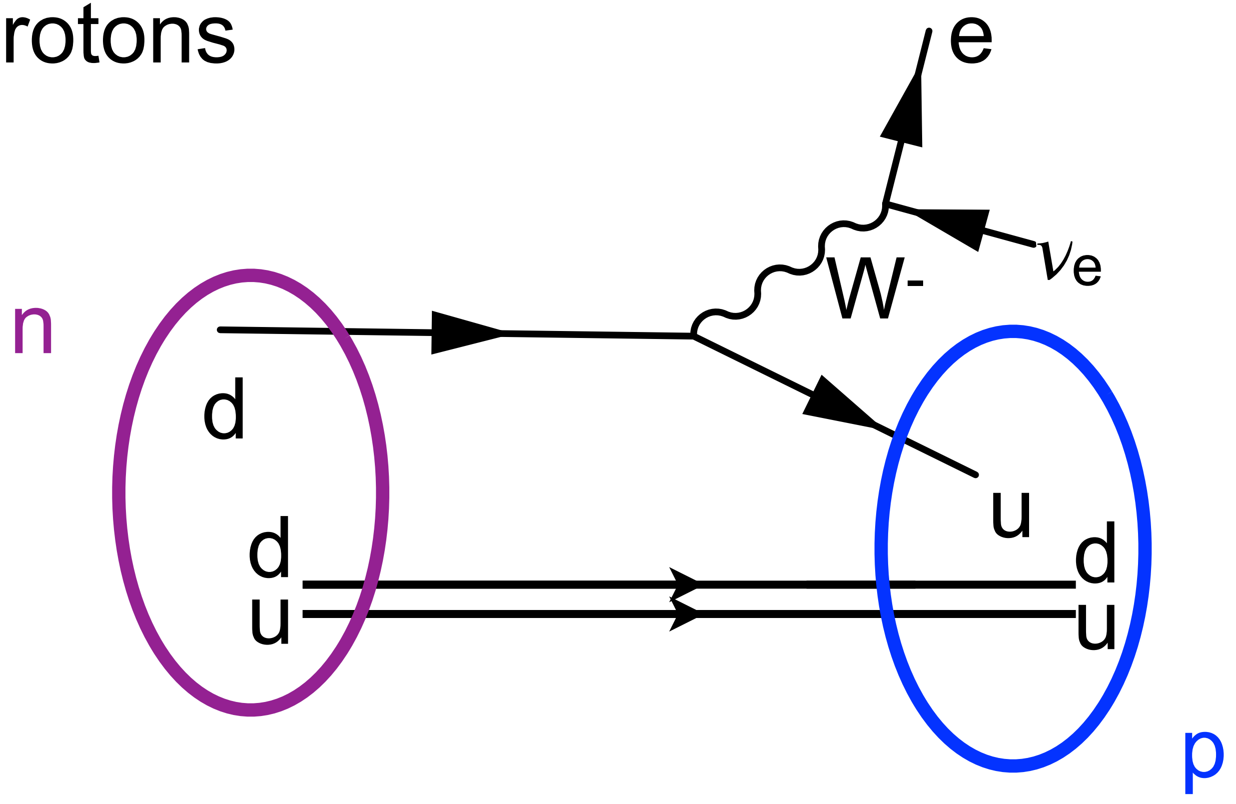
This is how a charged pion can decay to a muon (and an anti-muon neutrino). Could have guessed W boson involvement, because it involves a change of flavor (here charged pion decay is much slower than neutral pion decay)

Check lepton flavor numbers and EM charge!



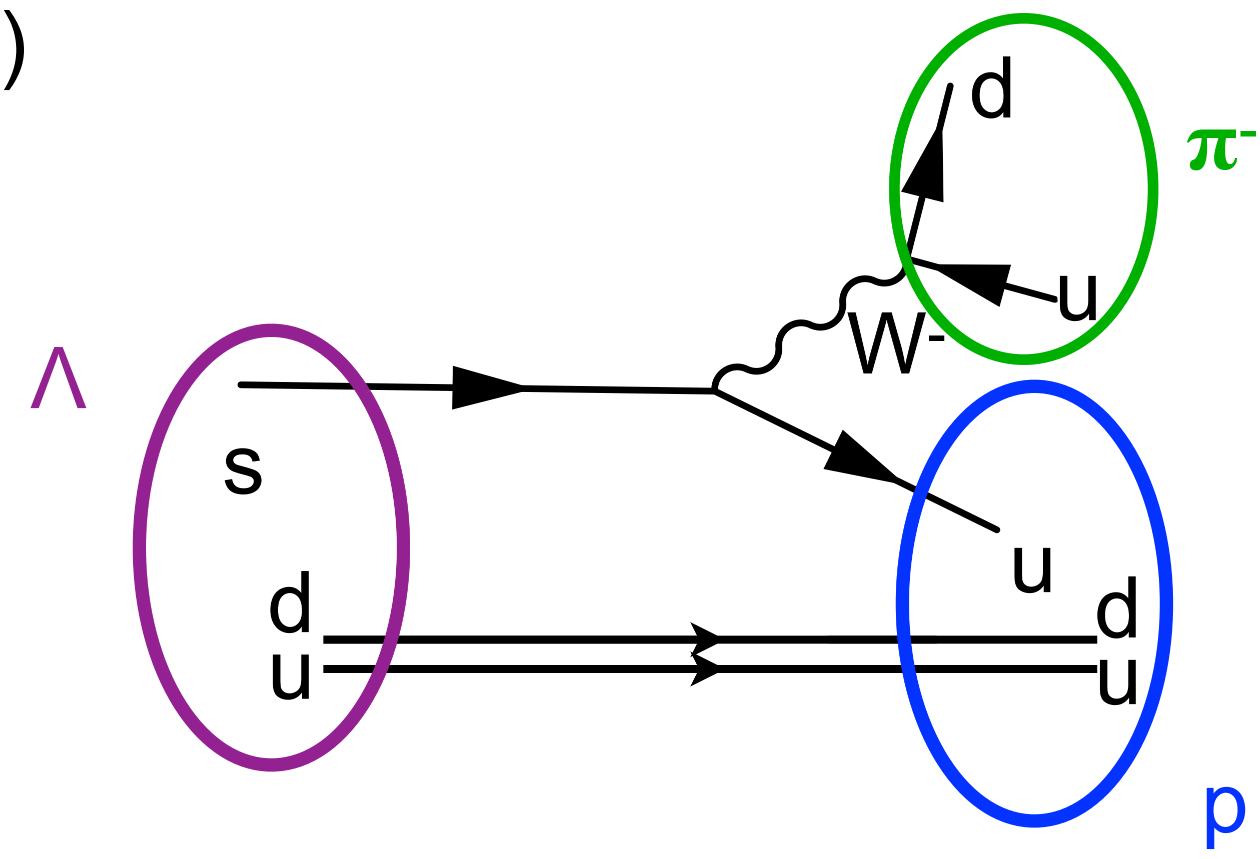
What processes can the W boson mediate?

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



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)

$\Lambda \rightarrow p\pi^-$



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

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

What weak force couples to

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

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

The Kobayashi-Maskawa matrix

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

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

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

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

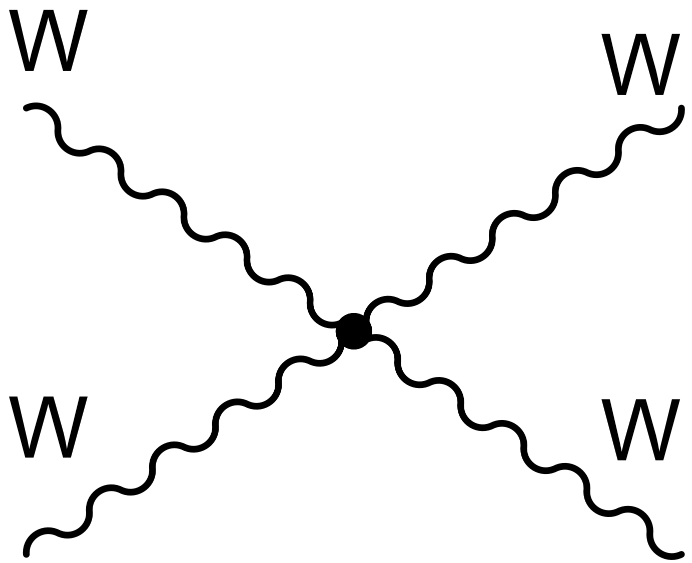
2017 PDG

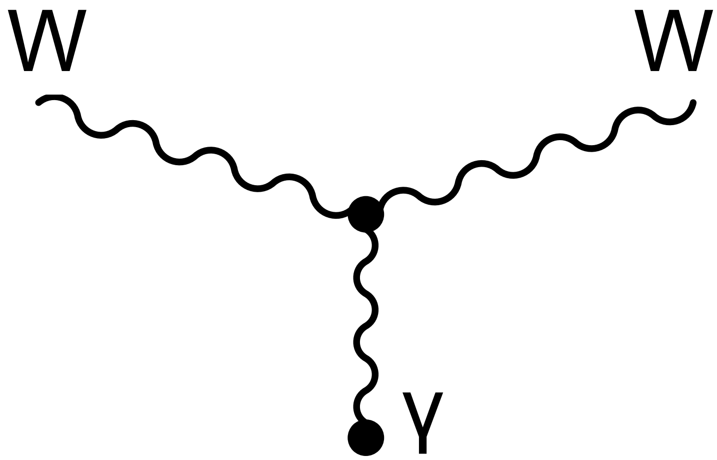
Off-diagonal numbers are small, which has implications for which decays happen more/less frequently. The matrix has to be unitary. Note that I've cheated a bit, because there are phases in the matrix that I have ignored so far

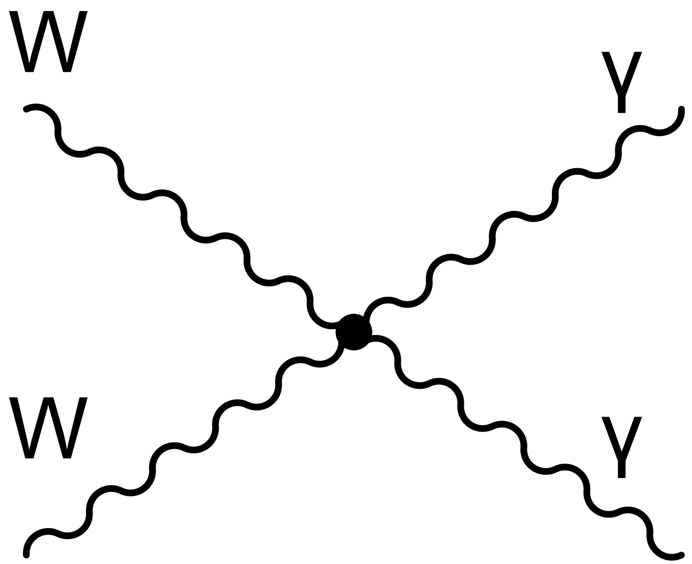
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 0.97434 & 0.22506 & 0.00357 \\ 0.22492 & 0.97351 & 0.0411 \\ 0.00875 & 0.0403 & 0.99915 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

2017 PDG

Boson couplings in weak theory

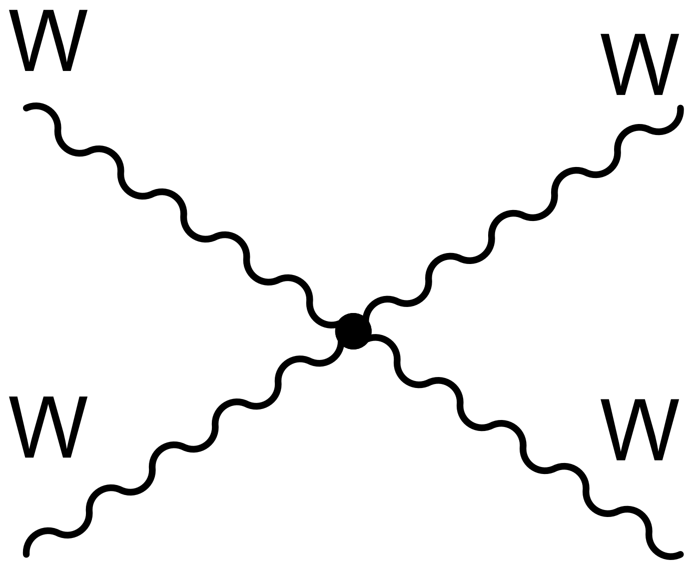


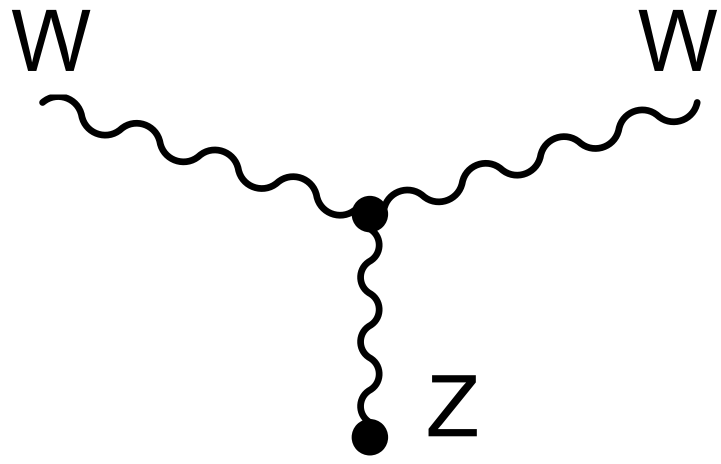


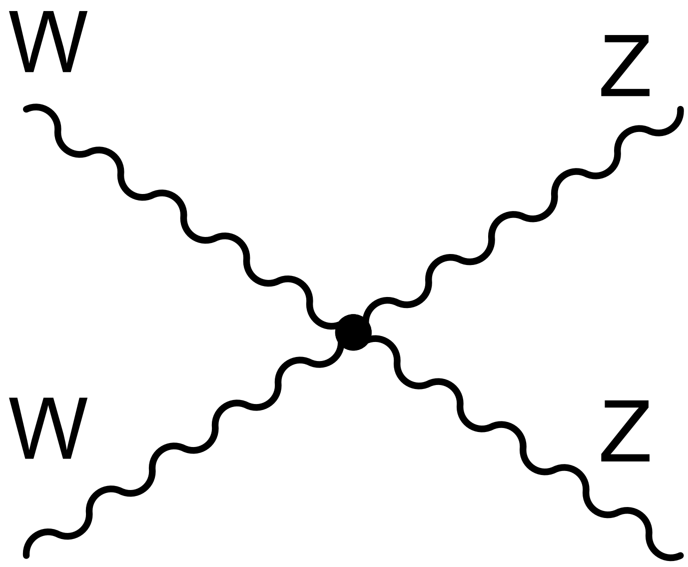


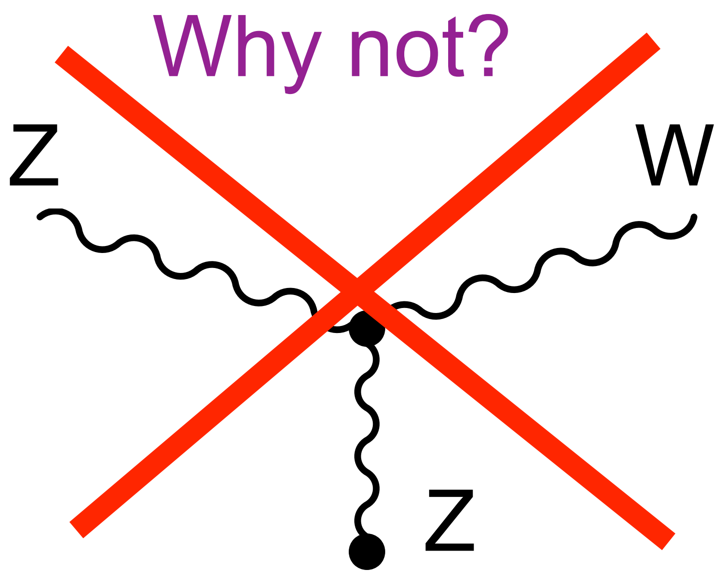
In general, can always replace a photon by a Z boson in a diagram. What about the reverse?

Boson couplings in weak theory









Here's a good set of questions for you

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?

Why can't this decay occur?

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

Hint, look at the energy in the rest frame

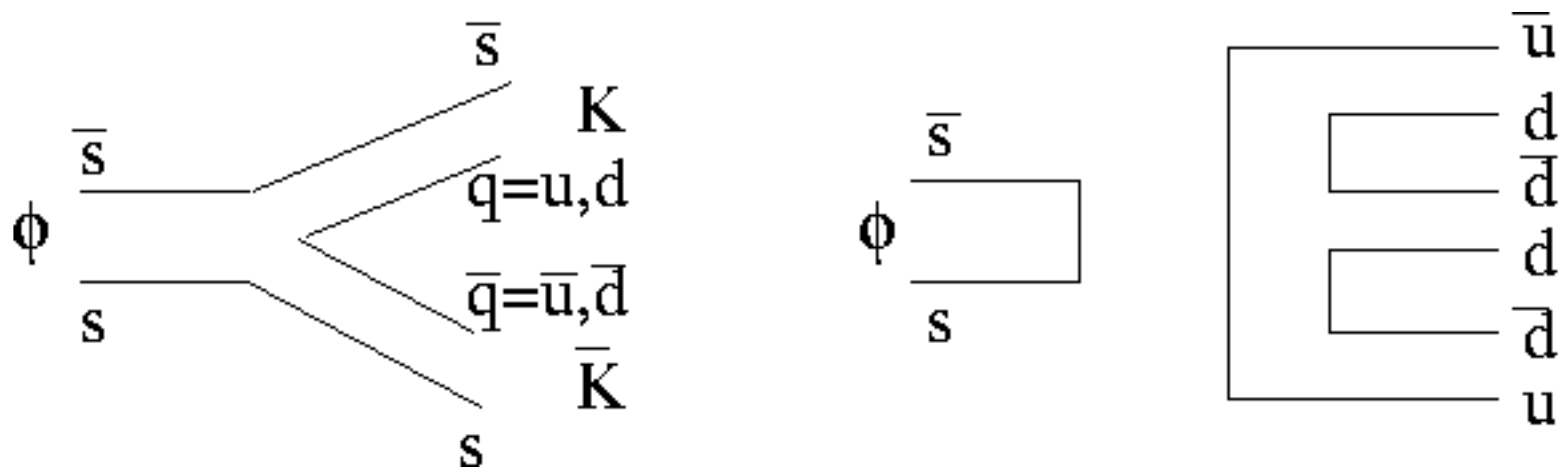
Beyond conservation of energy

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)

OZI rule

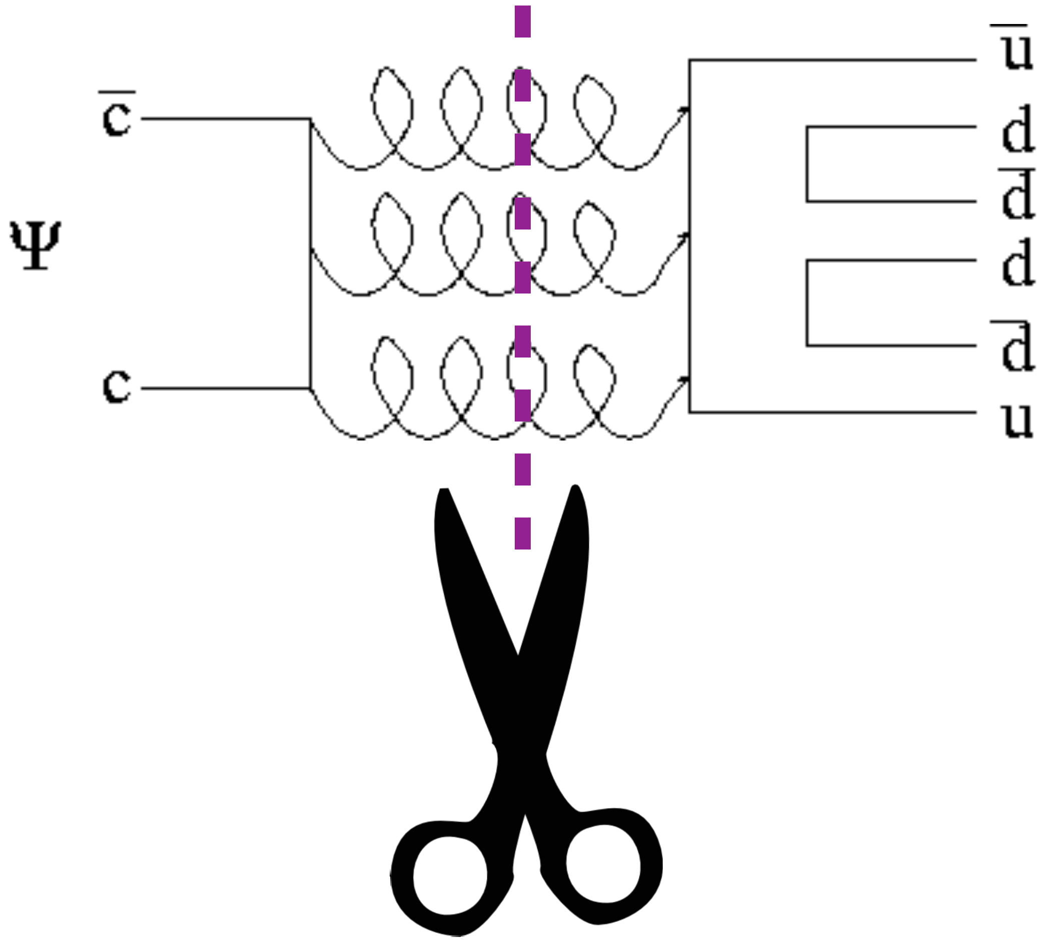
https://www.ippp.dur.ac.uk/~krauss/Lectures/QuarksLeptons/QCD/Quarkonium_0.html



The phi decays much more commonly to K Kbar, despite a phase space preference for decays to three pions. Why? The OZI rule…

OZI rule

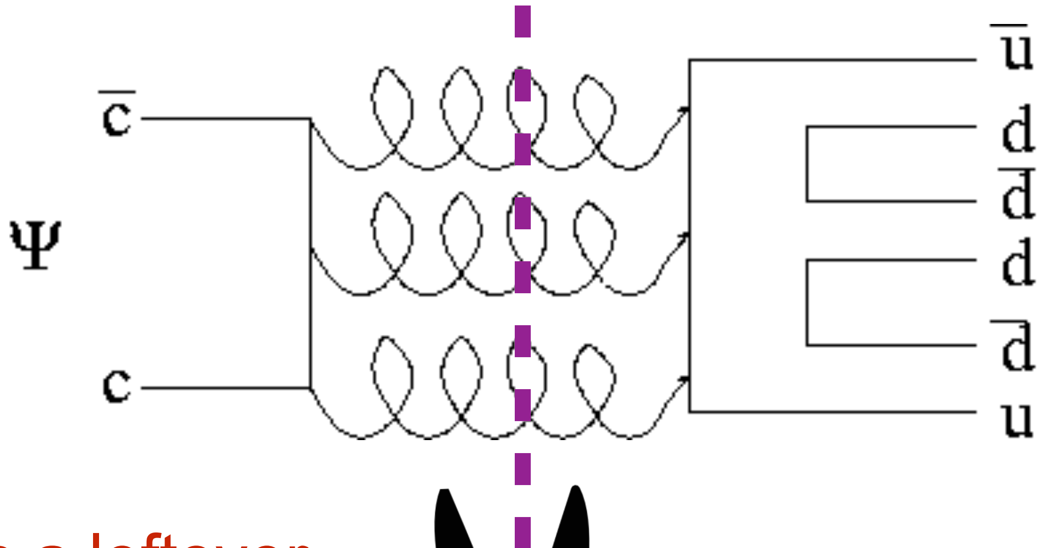
http://www.ippp.dur.ac.uk/~krauss/Lectures/QuarksLeptons/QCD/Equations/jpsidecay.gif



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

OZI rule

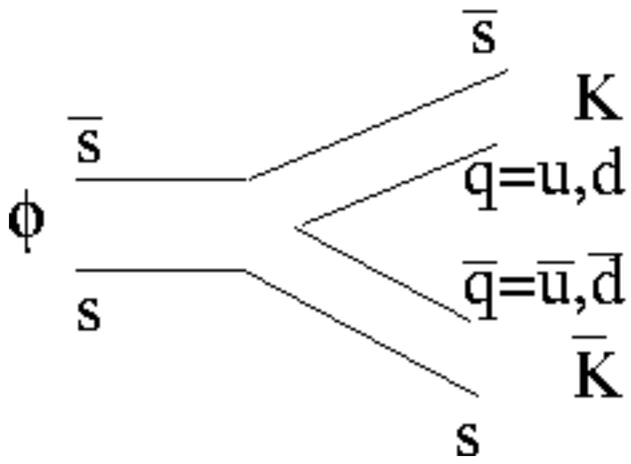
http://www.ippp.dur.ac.uk/~krauss/Lectures/QuarksLeptons/QCD/Equations/jpsidecay.gif

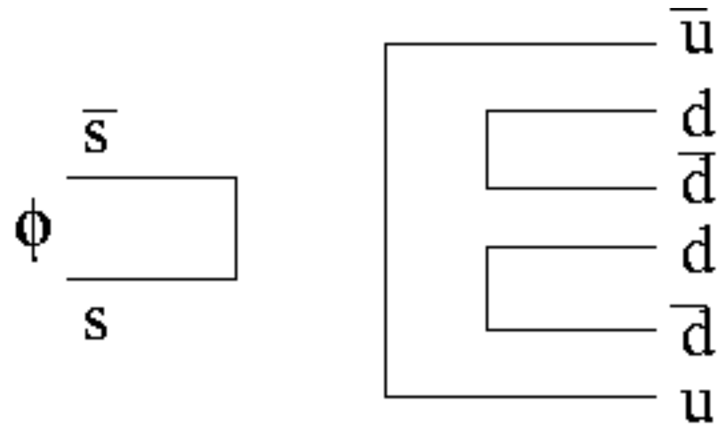


If there was a leftover quark, it could carry some of the initial energy in its rest mass. There isn't one here!

If we can make that cut, it means all the energy of the quarks is temporarily in the form of gluons. But QCD couplings decrease at high energy, so there is less probability of this happening

OZI rule





Explained by the OZI rule, let's go over this

$\phi(1020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(48.9 ± 0.5) %	S=1.1
Γ_2	$K^0_L K^0_S$	(34.2 ± 0.4) %	S=1.1
Γ_3	$\rho\pi + \pi^+\pi^-\pi^0$	(15.32 ± 0.32) %	S=1.1
Γ_4	$\rho\pi$		
Γ_5	$\pi^+\pi^-\pi^0$		

https://pdg.lbl.gov/2012/listings/rpp2012-list-phi-1020.pdf

Decays

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 nucleii), electrons and neutrinos

Lifetimes

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

μ: 2.2×10^{-6} s

π^+: 2.6×10^{-8} s

π^0: 8.3×10^{-17} s

τ: 2.9×10^{-13} s

n (free): 880 s

top quark: 4×10^{-25} s

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

Why so different?

Typical decay times

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

EM decays: 10-16 s (π^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

Phase space

Phase space

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

Time for some homework

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