Lecture 5

Experimental particle physics

Units

Typical units used in this course.

Energy: 1 eV= 1.602×10^{-19} J :

1 keV = 10^{3} eV (ionisation energy) 1 MeV= 10^{6} eV (nuclear binding energy) ,

1 GeV= 10^{9} eV (accelerator energy)

Distance 1 fm = 10^{-15} m (size of a proton)

Momentum units : eV/c Mass units : eV/c^{2}

Conversion

Convert from MKS-SI units :

Eg Momentum $5\times10^{-23}\ \text{kgms}^{-1} = X\ \text{eV}/c = X\ \frac{1.602\times10^{-19}\,\text{J}}{3\times10^{8}\,\text{ms}^{-1}} = X\ \times 0.534\ \times10^{-27}\ \text{kgms}^{-1}$

$$\Rightarrow\ X = \frac{5\times10^{-23}}{0.534\ \times10^{-27}} = 9.36\times10^{4}\ \text{eV}/c = 93.6\ \text{keV}/c$$

Convert to MKS-SI units :

Eg mass $= 1.2\ \frac{\text{GeV}}{c^{2}} = 1.2\times\ \frac{10^{9}\times1.602\times10^{-19}\ \text{J}}{\left(3\times10^{8}\right)^{2}\ \text{m}^{2}\text{s}^{-2}} = 2.136\times10^{-27}\ \text{kg}$

Natural units

You may encounter natural units in some texts.

Convention $c = 1, \quad \hbar = 1$

Eg $E = \hbar\omega \rightarrow E = \omega \quad , \quad E^2 = (pc)^2 + (mc^2)^2 \rightarrow E^2 = p^2 + m^2$

Counter intuitive eg frequency in units of GeV.

Conversion table:

Quantity	Natural units	SI
Energy	1 GeV	1.602×10^{-10}J
Mass	1 GeV	1.78×10^{-27}kg
Momentum	1 GeV	5.34×10^{-19}kgms^{-1}
Time	1 GeV^{-1}	6.58×10^{-25}s
Frequency	1 GeV	1.52×10^{24}s^{-1}
Distance	1 GeV^{-1}	1.97×10^{-16}m

- Hadron decays and conservation laws
- Neutrino oscillations
- The LHC and the Higgs discovery
- Problems and possible solutions of the Standard Model

Particles in nature

PARTICLE DATA

(Mass in MeV/c^2; Lifetime in Seconds; Charge in Units of Proton Charge.)

QUARKS (Spin $\frac{1}{2}$)

	Flavor	Charge	Mass (speculative): Bare	Effective: In baryons	Effective: In mesons
First generation	d	$-\frac{1}{3}$	7.5	363	310
	u	$+\frac{2}{3}$	4.2		
Second generation	s	$-\frac{1}{3}$	150	538	483
	c	$+\frac{2}{3}$	1100	1500	
Third generation	b	$-\frac{1}{3}$	4200	4700	
	t	$+\frac{2}{3}$	175000		

LEPTONS (Spin $\frac{1}{2}$)

	Lepton	Charge	Mass	Lifetime	Principal decays
First generation	e	−1	0.511003	∞	—
	ν_e	0	small	∞	—
Second generation	μ	−1	105.659	2.197×10^{-6}	$e\nu_\mu\bar{\nu}_e$
	ν_μ	0	small	∞	—
Third generation	τ	−1	1784	3.3×10^{-13}	$\mu\nu_\tau\bar{\nu}_\mu$, $e\nu_\tau\bar{\nu}_e$, $\rho\nu_\tau$
	ν_τ	0	small	∞	—

MEDIATORS (Spin 1)

Mediator	Charge	Mass	Lifetime	Force
gluon	0	0	∞	strong
photon (γ)	0	0	∞	electromagnetic } electroweak
$W^\pm$	±1	81,800	unknown	(charged) weak } electroweak
Z^0	0	92,600	unknown	(neutral) weak } electroweak

BARYONS (Spin $\frac{1}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
N p	uud	+1	938.280	∞	—
N n	udd	0	939.573	900	$pe\bar{\nu}_e$
Λ	uds	0	1115.6	2.63×10^{-10}	$p\pi^-$, $n\pi^0$
Σ^+	uus	+1	1189.4	0.80×10^{-10}	$p\pi^0$, $n\pi^+$
Σ^0	uds	0	1192.5	6×10^{-20}	$\Lambda\gamma$
Σ^-	dds	−1	1197.3	1.48×10^{-10}	$n\pi^-$
Ξ^0	uss	0	1314.9	2.90×10^{-10}	$\Lambda\pi^0$
Ξ^-	dss	−1	1321.3	1.64×10^{-10}	$\Lambda\pi^-$
Λ_c^+	udc	+1	2281	2×10^{-13}	not established

BARYONS (Spin $\frac{3}{2}$)

Baryon	Quark content	Charge	Mass	Lifetime	Principal decays
Δ	uuu, uud, udd, ddd	+2, +1, 0, −1	1232	0.6×10^{-23}	$N\pi$
Σ^*	uus, uds, dds	+1, 0, −1	1385	2×10^{-23}	$\Lambda\pi$, $\Sigma\pi$
Ξ^*	uss, dss	0, −1	1533	7×10^{-23}	$\Xi\pi$
Ω^-	sss	−1	1672	0.82×10^{-10}	ΛK^-, $\Xi^0\pi^-$, $\Xi^-\pi^0$

PSEUDOSCALAR MESONS (Spin 0)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
$\pi^\pm$	$u\bar{d}$, $d\bar{u}$	+1, −1	139.569	2.60×10^{-8}	$\mu\nu_\mu$
π^0	$(u\bar{u} - d\bar{d})/\sqrt{2}$	0	134.964	8.7×10^{-17}	$\gamma\gamma$
$K^\pm$	$u\bar{s}$, $s\bar{u}$	+1, −1	493.67	1.24×10^{-8}	$\mu\nu_\mu$, $\pi^\pm\pi^0$, $\pi^\pm\pi^\pm\pi^\mp$
K^0, $\bar{K}^0$	$d\bar{s}$, $s\bar{d}$	0, 0	497.72	K_S^0 0.892×10^{-10}; K_L^0 5.18×10^{-8}	$\pi^+\pi^-$, $\pi^0\pi^0$; $\pi e\nu_e$, $\pi\mu\nu_\mu$, $\pi\pi\pi$
η	$(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$	0	548.8	7×10^{-19}	$\gamma\gamma$, $\pi^0\pi^0\pi^0$, $\pi^+\pi^-\pi^0$
η'	$(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$	0	957.6	3×10^{-21}	$\eta\pi\pi$, $\rho^0\gamma$
$D^\pm$	$c\bar{d}$, $d\bar{c}$	+1, −1	1869	9×10^{-13}	$K\pi\pi$
D^0, $\bar{D}^0$	$c\bar{u}$, $u\bar{c}$	0, 0	1865	4×10^{-13}	$K\pi\pi$
$F^\pm$ (now $D_s^\pm$)	$c\bar{s}$, $s\bar{c}$	+1, −1	1971	3×10^{-13}	not established
$B^\pm$	$u\bar{b}$, $b\bar{u}$	+1, −1	5271	14×10^{-13}	$D + ?$
B^0, $\bar{B}^0$	$d\bar{b}$, $b\bar{d}$	0, 0	5275		
η_c	$c\bar{c}$	0	2981	6×10^{-23}	$KK\pi$, $\eta\pi\pi$, $\eta'\pi\pi$

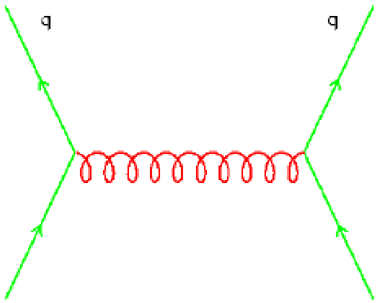
VECTOR MESONS (Spin 1)

Meson	Quark content	Charge	Mass	Lifetime	Principal decays
ρ	$u\bar{d}$, $d\bar{u}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$	+1, −1, 0	770	0.4×10^{-23}	$\pi\pi$
K^*	$u\bar{s}$, $s\bar{u}$, $d\bar{s}$, $s\bar{d}$	+1, −1, 0, 0	892	1×10^{-23}	$K\pi$
ω	$(u\bar{u} + d\bar{d})/\sqrt{2}$	0	783	7×10^{-23}	$\pi^+\pi^-\pi^0$, $\pi^0\gamma$
ϕ	$s\bar{s}$	0	1020	20×10^{-23}	K^+K^-, $K^0\bar{K}^0$
J/ψ	$c\bar{c}$	0	3097	1×10^{-20}	e^+e^-, $\mu^+\mu^-$, 5π, 7π
D^*	$c\bar{d}$, $d\bar{c}$, $c\bar{u}$, $u\bar{c}$	+1, −1, 0, 0	2010	$>1 \times 10^{-22}$	$D\pi$, $D\gamma$
Υ	$b\bar{b}$	0	9460	2×10^{-20}	$\tau^+\tau^-$, $\mu^+\mu^-$, e^+e^-

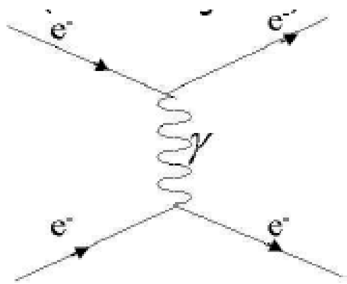
More information available from the Review of Particle Physics:
http://www-pdg.lbl.gov/

The fundamental forces

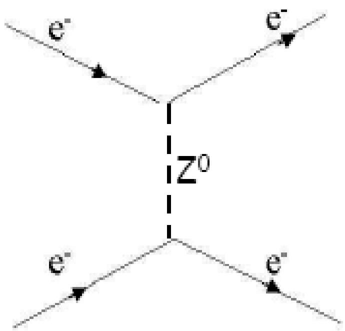
Different exchange particles mediate the forces:

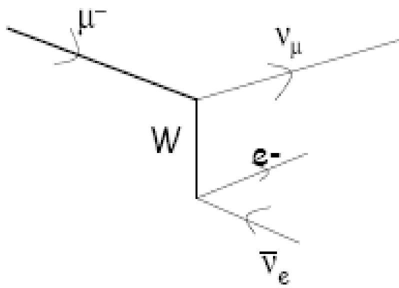


strong



electromagnetic





weak

Interaction	Relative strength	Range	Exchange	Mass (GeV)	Charge	Spin
Strong	*1*	Short (~ fm)	Gluon	*0*	*0*	*1*
Electromagnetic	*1/137*	Long ($1/r^2$)	Photon	*0*	*0*	*1*
Weak	10^{-9}	Short (~ 10^{-3} fm)	$W^+ W^-, Z$	*80.4,80.4, 91.2*	*+e,-e,0*	*1*
Gravitational	10^{-38}	Long ($1/r^2$)	Graviton ?	*0*	*0*	*2*

No quantum field theory yet for gravity

Decays

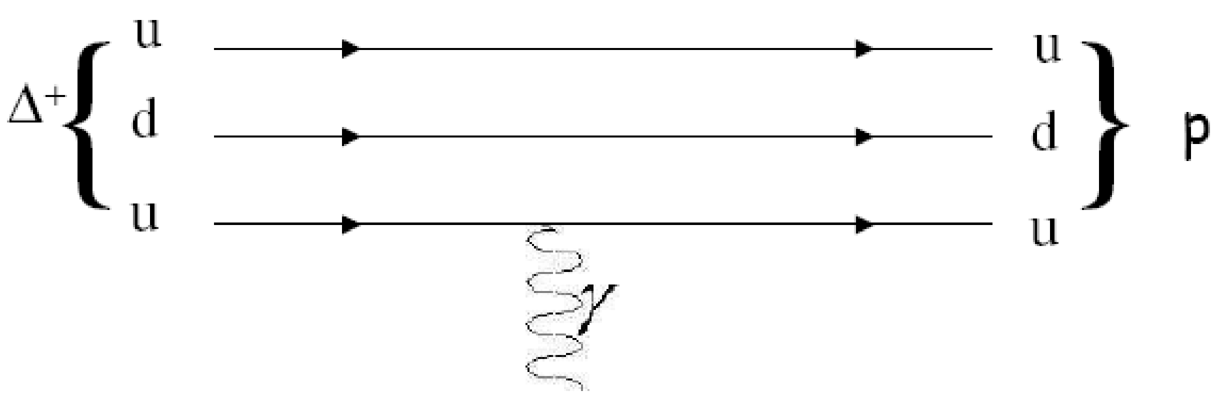
Impossible to quote a set of simple rules for lifetimes which are correct in all cases.

There are some general observations which can be made.

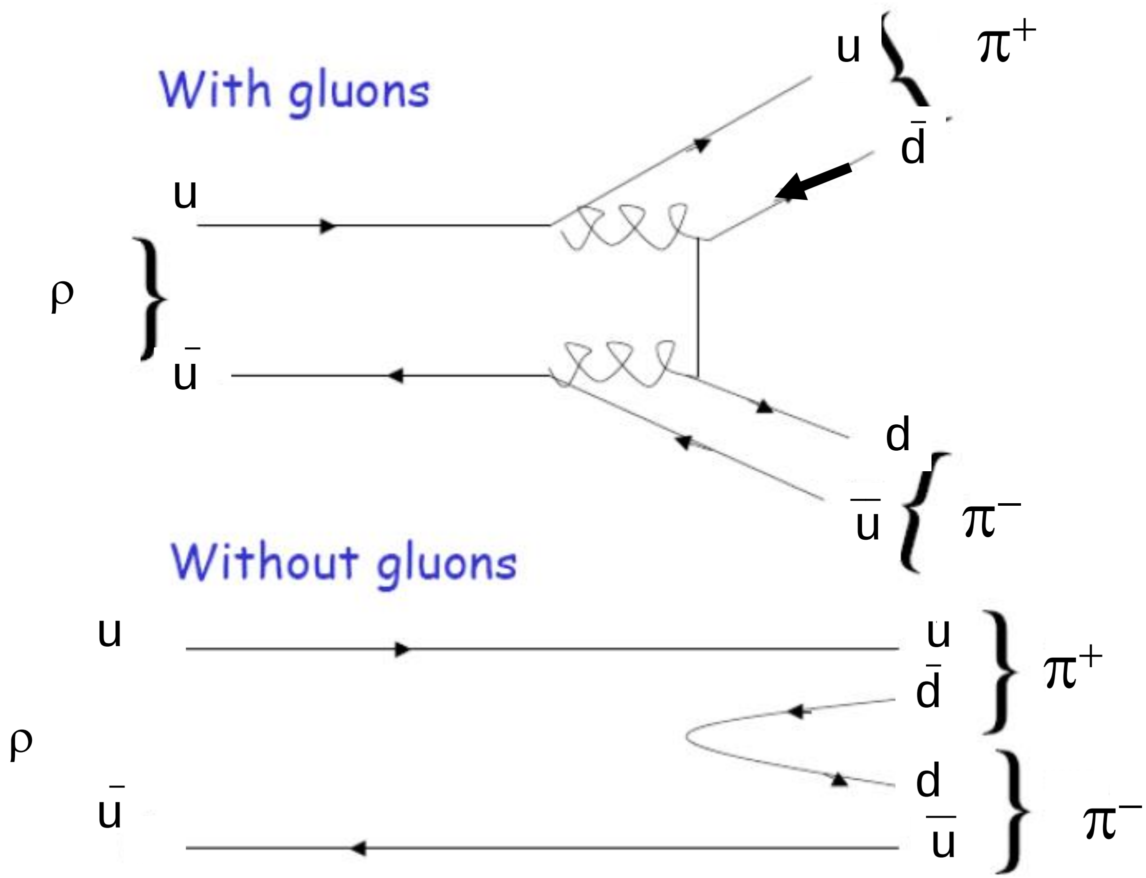
Lifetimes: strong $\left(10^{-22}-10^{-24}s\right)$, weak $\left(10^{-7}-10^{-13}s\right)$, electromagnetic $\left(10^{-16}-10^{-21}s\right)$

These are approximate and there are exceptions.

Electromagnetic decays

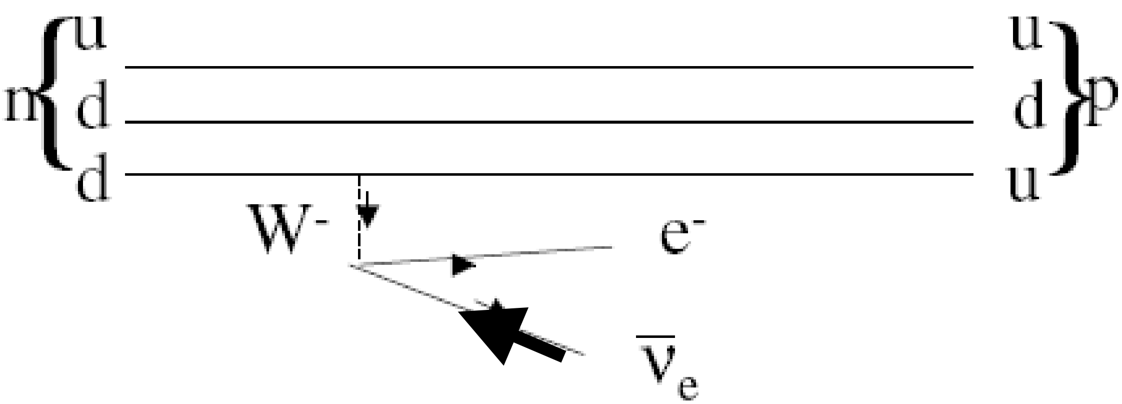


Strong decay



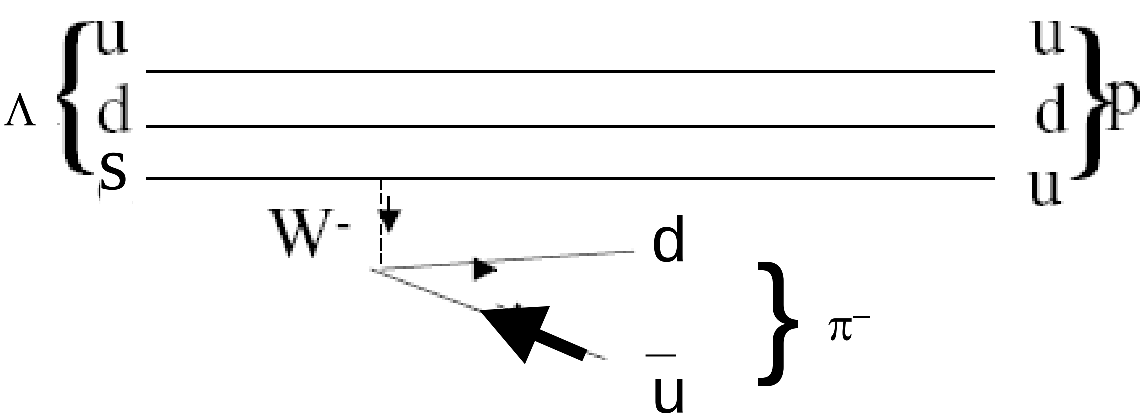
$$\rho \rightarrow \pi^{+} + \pi^{-}$$

Weak decays



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

$$\Delta S = 0$$



$$\Lambda \to p + \pi^{-}$$

$$|\Delta S| = 1!$$

Strangeness is violated.

Strangeness (and the other flavour quantum numbers, C, B) are not conserved in weak decays.

Conserved quantities

Quantity	Strong	Weak	Electromagnetic
Energy	✓	✓	✓
Linear momentum	✓	✓	✓
Angular momentum	✓	✓	✓
Baryon number	✓	✓	✓
Lepton number	✓	✓	✓
Flavour (S,C,$\bar{B}$)	✓	-	✓
Charges (em, strong and weak forces)	✓	✓	✓

Easy after you've seen lots of questions + solutions !

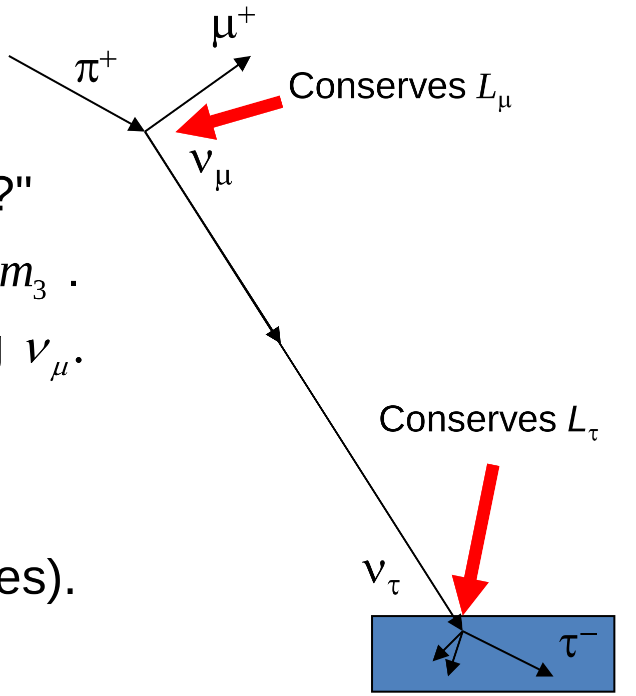
Neutrino oscillations

Hypothesis: ν_e, ν_μ, ν_τ are eigenstates of flavour (lepton number) but not "mass eigenstates".

$$\nu_e = A\nu_1 + B\nu_2 + C\nu_3 \; ; \; \nu_\mu = D\nu_1 + E\nu_2 + F\nu_3 \; ; \; \nu_\tau = G\nu_1 + H\nu_2 + I\nu_3$$

ν_1, ν_2, ν_3 are mass eigenstates with definite energy: $\nu_i(t) = \nu_i(0) e^{-\frac{iE_i t}{\hbar}}$

$E_i = \sqrt{p_i^2 c^2 + m_i^2 c^4}$; $A, B, C, D....$ are coefficients to be measured.



Remarks:

(1) It is nonsense to ask "what is the mass of, eg ν_e ?"

Any measurement would return a value of m_1 , m_2 or m_3 .

(2) The weak force produces a flavour eigenstate, eg ν_μ.

If m_1 , m_2 and m_3 have different masses, this allows interference effects as the particle moves and the conversion of neutrino species, eg $\nu_\mu \leftrightarrow \nu_\tau$ (next slides).

Lepton number is violated:

flavour produced $\neq$ flavour measured

Whole process violates: L_μ, L_τ

Neutrino oscillations

Simplicity: two neutrino flavour eigenstates, ν_α and ν_β eg ν_e and ν_μ.

Mass eigenstates ν_i, ν_j are mixtures of ν_α and ν_β

$$\nu_i = \nu_i(0)e^{-\frac{iE_i t}{\hbar}} = -\sin\theta\,\nu_\alpha + \cos\theta\,\nu_\beta \text{ and } \nu_j = \nu_j(0)e^{-\frac{iE_j t}{\hbar}} = \cos\theta\,\nu_\alpha + \sin\theta\,\nu_\beta$$

$$\nu_\alpha = -\sin\theta\nu_i + \cos\theta\,\nu_j \text{ and } \nu_\beta = \cos\theta\,\nu_i + \sin\theta\,\nu_j$$

θ is a mixing angle - must be measured.

Particle starts off as a ν_α at $t = 0$.

$$\Rightarrow \nu_i(0) = -\sin\theta \times 1 + \cos\theta \times 0 = -\sin\theta \;;\; \nu_j(0) = \cos\theta$$

$$\Rightarrow \nu_i(t) = -\sin\theta\, e^{-\frac{iE_i t}{\hbar}} \quad \nu_j(t) = \cos\theta\, e^{-\frac{iE_j t}{\hbar}}$$

$$\nu_\beta(t) = \cos\theta\,\nu_i(t) + \sin\theta\,\nu_j(t) = \sin\theta\,\cos\theta\left(-e^{-\frac{iE_i t}{\hbar}} + e^{-\frac{iE_j t}{\hbar}}\right)$$

Neutrino oscillations

$$\nu_\beta(t) = \cos\theta\,\nu_i(t) + \sin\theta\,\nu_j(t) = \sin\theta\ \cos\theta\left(-e^{\frac{iE_it}{\hbar}} + e^{-\frac{iE_jt}{\hbar}}\right)$$

$$\Rightarrow \left|\nu_\beta(t)\right|^2 = (\sin\theta\ \cos\theta\ )^2\left(-e^{-\frac{iE_it}{\hbar}} + e^{-\frac{iE_jt}{\hbar}}\right)\left(-e^{\frac{iE_it}{\hbar}} + e^{-\frac{iE_jt}{\hbar}}\right) = \frac{\sin^2 2\theta}{4}\left(1 - e^{\frac{i(E_j-E_i)t}{\hbar}} - e^{\frac{-i(E_j-E_i)t}{\hbar}} + 1\right)$$

$$\Rightarrow \left|\nu_\beta(t)\right|^2 = \sin^2 2\theta\ \sin^2\left[\frac{(E_j - E_i)t}{2\hbar}\right]$$

$\Rightarrow$ Probability of $\nu_\alpha \to \nu_\beta$: $P_{\nu_\alpha\to\nu_\beta} = \left[\sin 2\theta\ \sin\frac{(E_j-E_i)t}{2\hbar}\right]^2$

Can rewrite in terms of mass states m_j, m_i :

$$P_{\nu_\alpha\to\nu_\beta} = \left\{\sin(2\theta\ )\sin\left\{\frac{(m_j^2 - m_i^2)c^4}{4E\hbar}\frac{L}{c}\right\}\right\}^2 = \left\{\sin(2\theta\ )\sin\left\{\frac{L}{L_0}\right\}\right\}^2$$

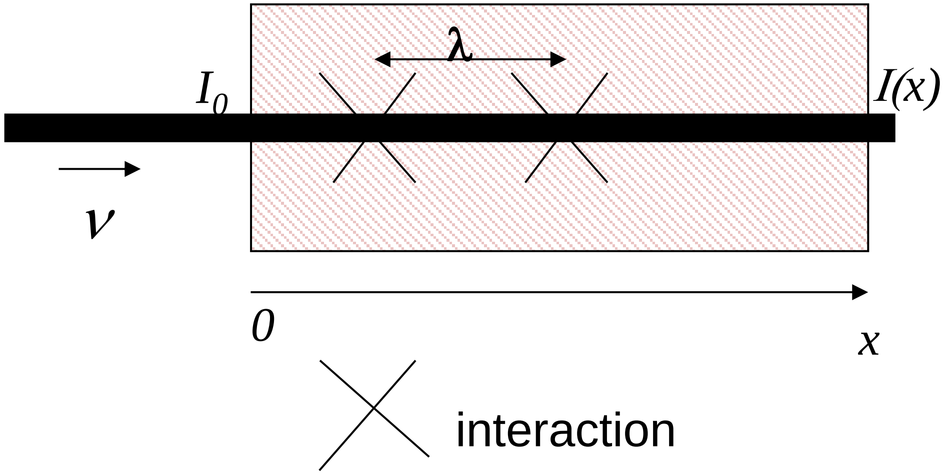
If neutrino travels a distance $L \approx ct$,Oscillation length $L_0 = \dfrac{4E\hbar c}{(m_j^2 - m_i^2)c^4}$

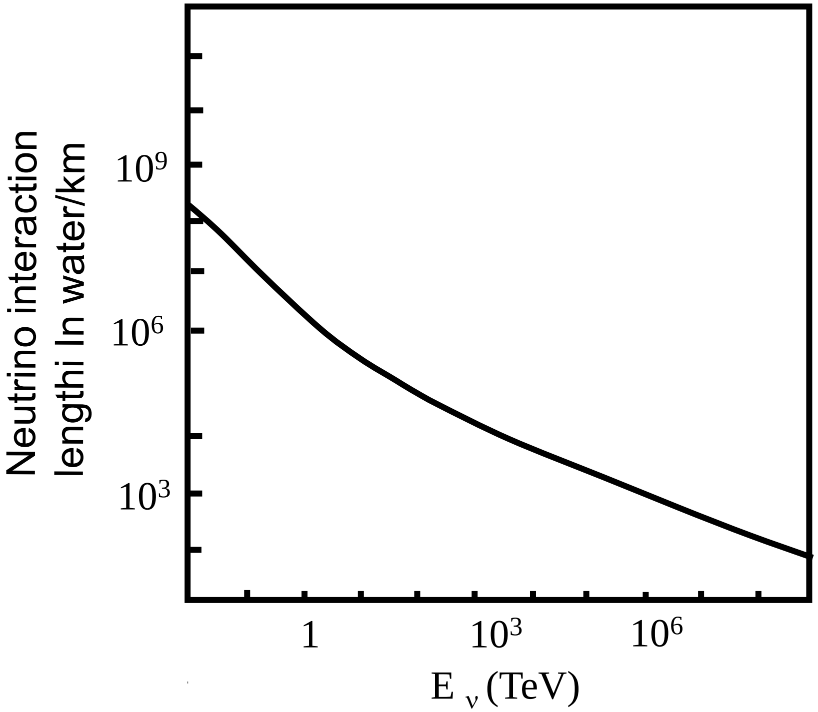
Neutrino oscillations if there is a mass difference $\Delta m^2 = m_j^2 - m_i^2 \neq 0$ and a non-zero mixing angle $\theta\ \neq 0$.

Neutrino Interactions in Matter

Beam of neutrinos entering and propagating through matter:

$\lambda =$ interaction length $\equiv$ mean distance between interactions (also called mean free path)

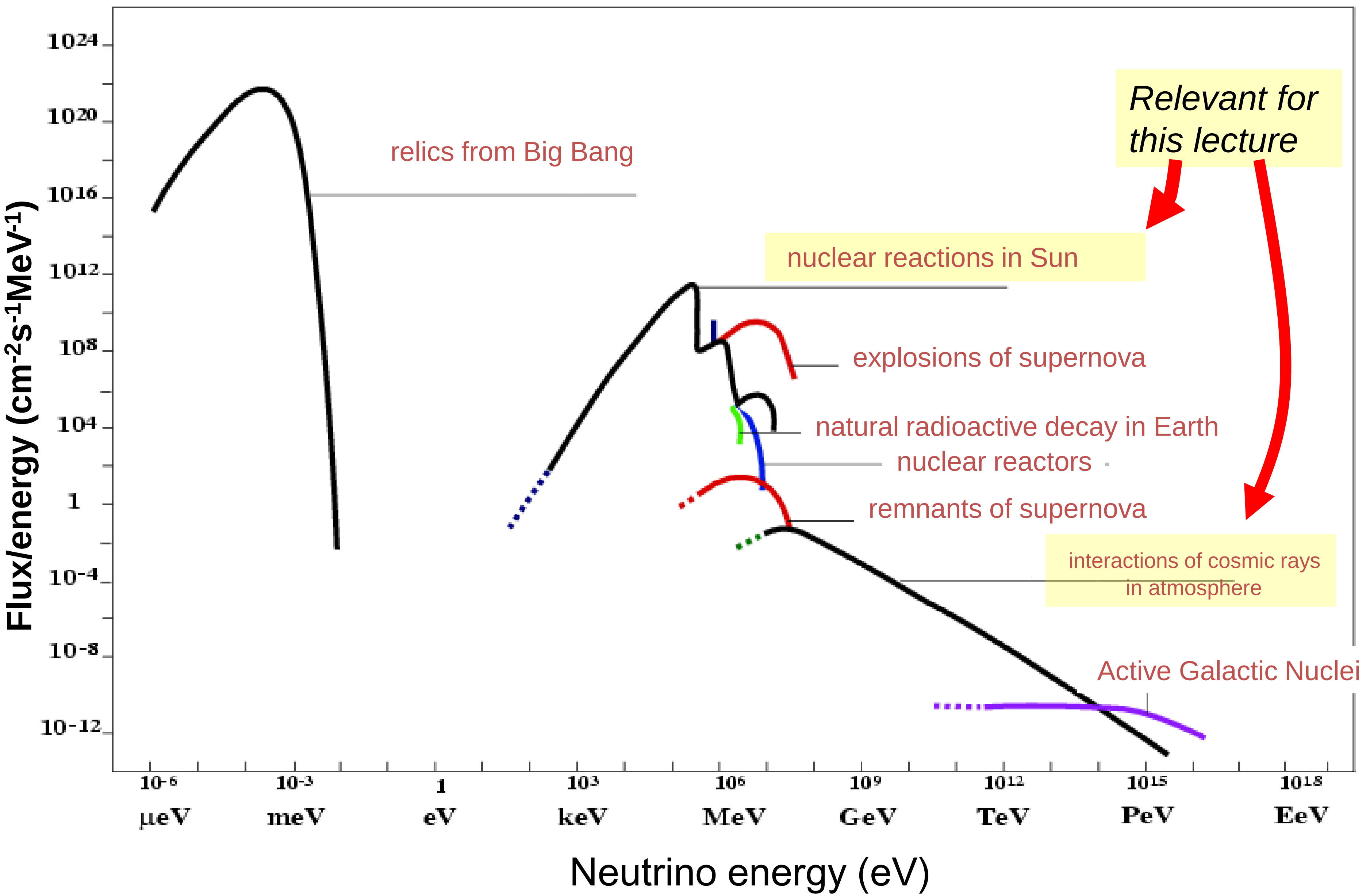




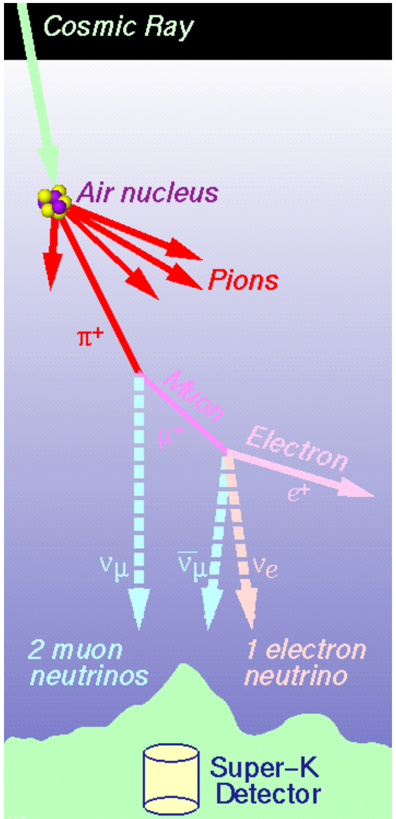
Probability of interaction ~ 10^{-5} / km water at 100 TeV energy

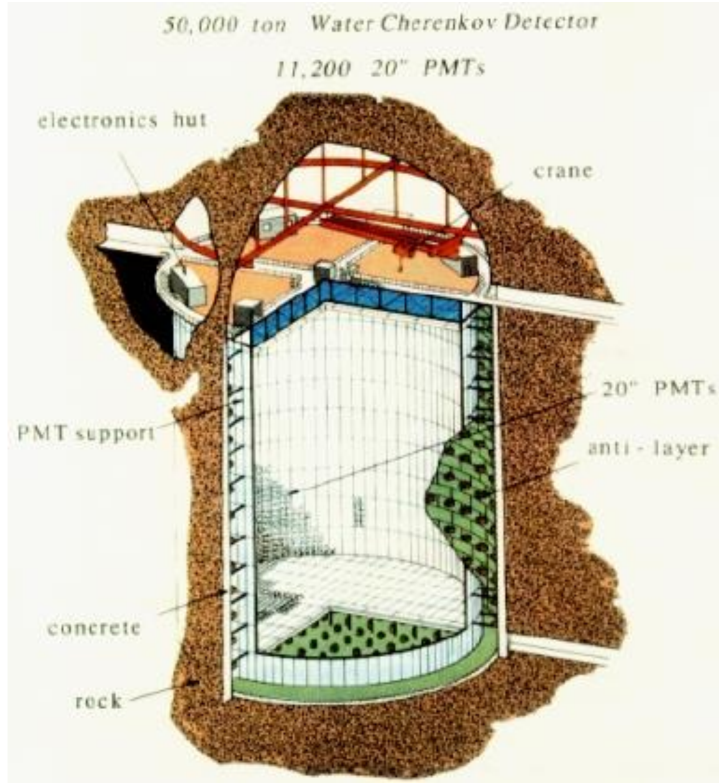
100 billion neutrinos pass through your thumbnail each second but only 1-2 will interact in your body during your lifetime.

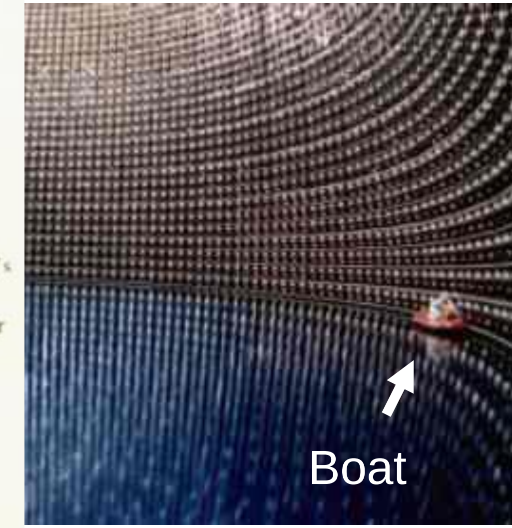
Neutrinos arriving at Earth – not for the exam



Atmospheric neutrinos and Super Kamiokande







Cosmic rays interact in atmosphere

to produce pions π^+, π^- :

$\pi^- \to \mu^- + \bar{\nu}_\mu, \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

(2 muon neutrinos, 1 electron neutrino)

Neutrinos enter Super-K detector.

Underground in Japanese Alps.

Neutrinos measured in Super-Ks water Cerenkov detector.

Eg $\bar{\nu}_e + p \to e^+ + X, \nu_\mu + p \to \mu^- + X, \ \bar{\nu}_\mu + p \to \mu^+ + X$ ($X \equiv$ anything)

electrons and muons distinguished by Cerenkov light - measured in photomultipliers. Energy and direction measured.

Expt: 50,000 tons of water, 1200 photomultipliers

Super-K: ν_μ oscillations

Expect $R = \dfrac{\text{flux of muon-neutrinos}}{\text{flux of electron-neutrinos}} \approx 2$

Observed $R \approx 1.3$

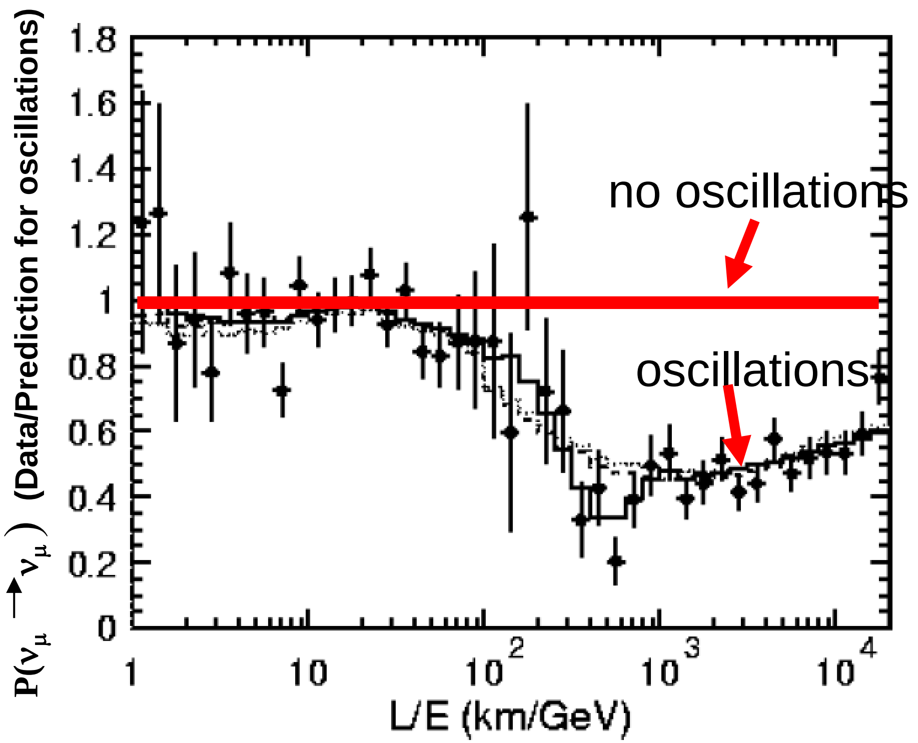
Additional observations

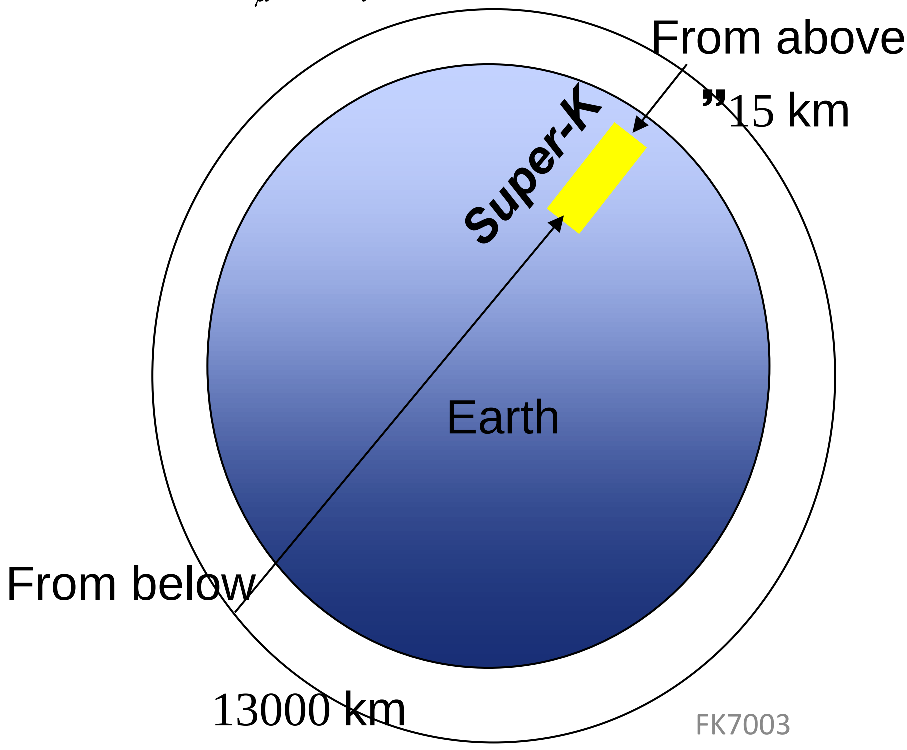
Flux of electron-neutrinos from below=Flux of electron-neutrinos from above

$\Rightarrow$ electron neutrinos haven't oscillated.

Flux of muon-neutrinos from below< Flux of muon-neutrinos from above

$\Rightarrow$ muon neutrinos have oscillated to tau neutrinos: $\nu_\mu \rightarrow \nu_\tau$





Atmospheric neutrino results

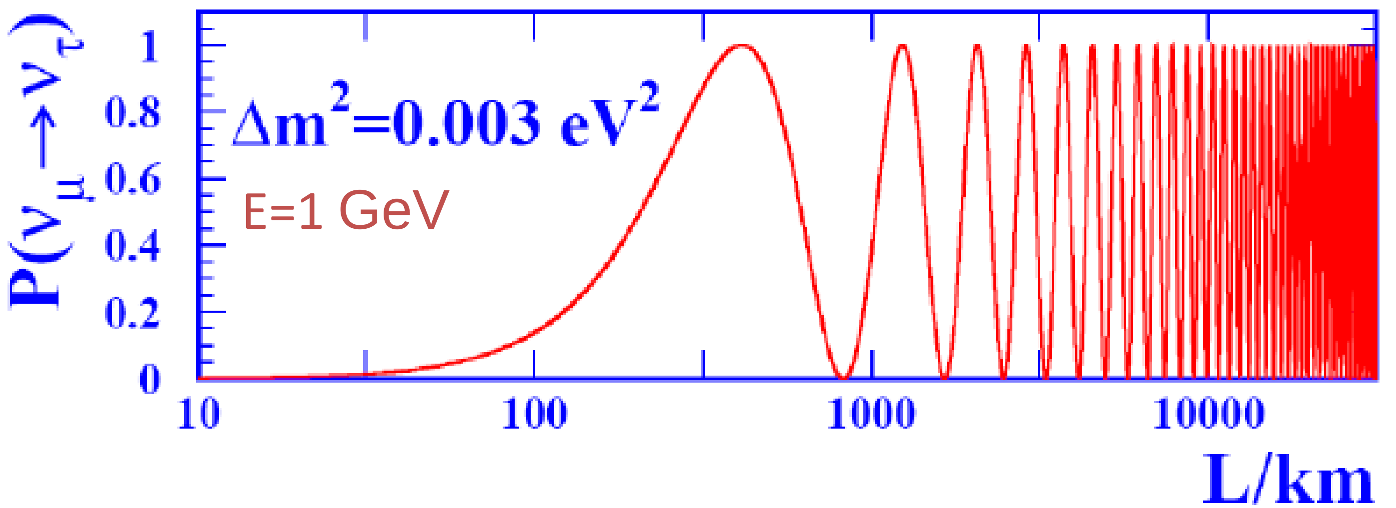
Evidence for muon neutrino turning into a tau neutrinos.

Super-K data + constraints from other experiments:

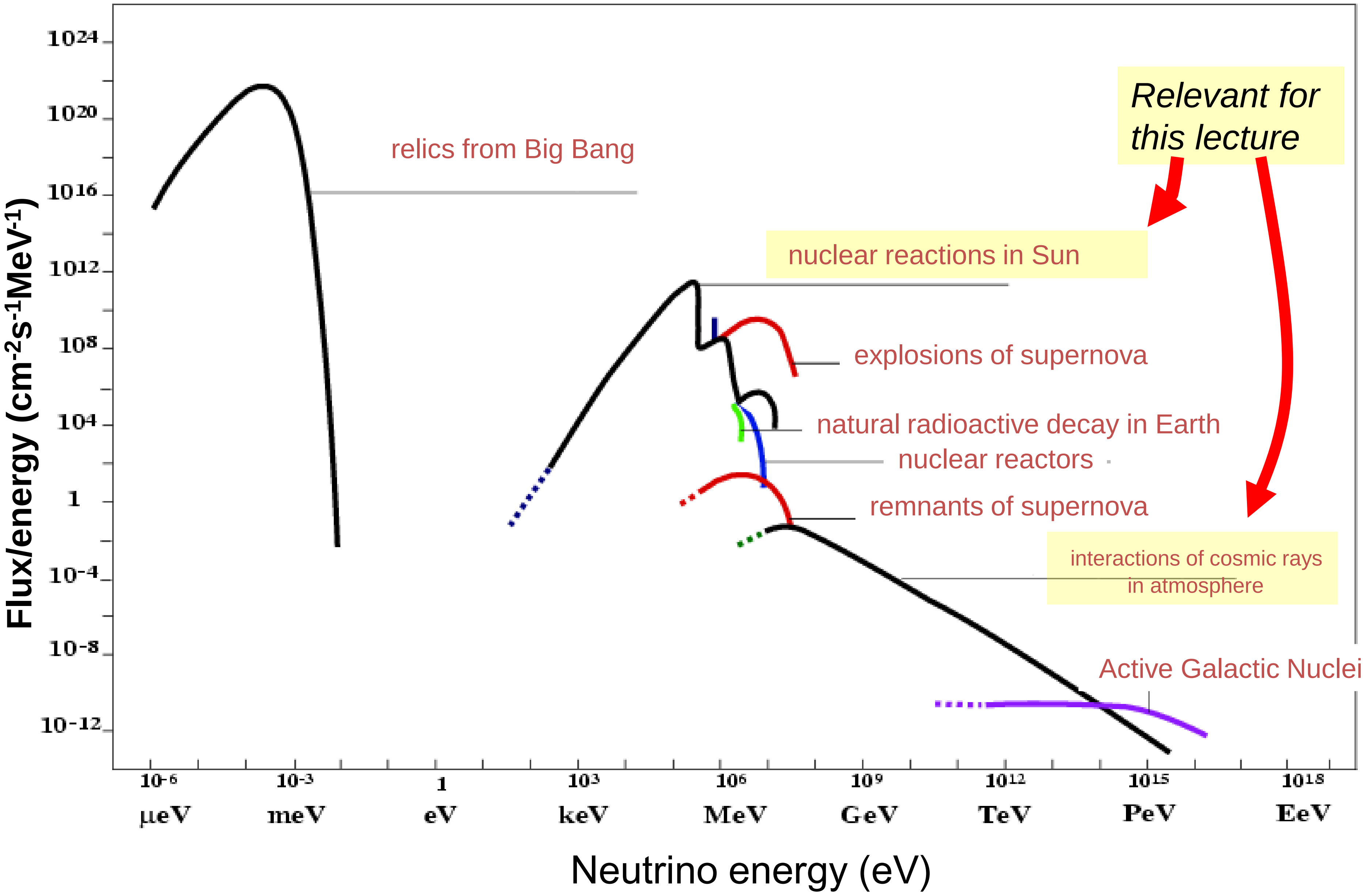
$\nu_\mu = -\sin\theta_{atm}\nu_i + \cos\theta_{atm}\nu_j$ and $\nu_\tau = \cos\theta_{atm}\nu_i + \sin\theta_{atm}\nu_j$

$\theta_{atm} \approx 45^o$ $\Delta m^2_{atm} \approx 3\times10^{-3}\,\text{eV}^2/c^4$

Note: approximate with two flavour and two mass state neutrinos.



Neutrinos arriving at Earth – not for the exam



Solar neutrino problem

Ray Davis et al. 1968

Vat of 600 tons chlorine (cleaning fluid) in Homestead gold mine in South Dakota.

Depth reduces background from cosmic rays

Looked for $\nu_e + {}^{37}\text{Cl} \rightarrow {}^{37}\text{Ar} + e^-$

Collected 33 argon atoms.

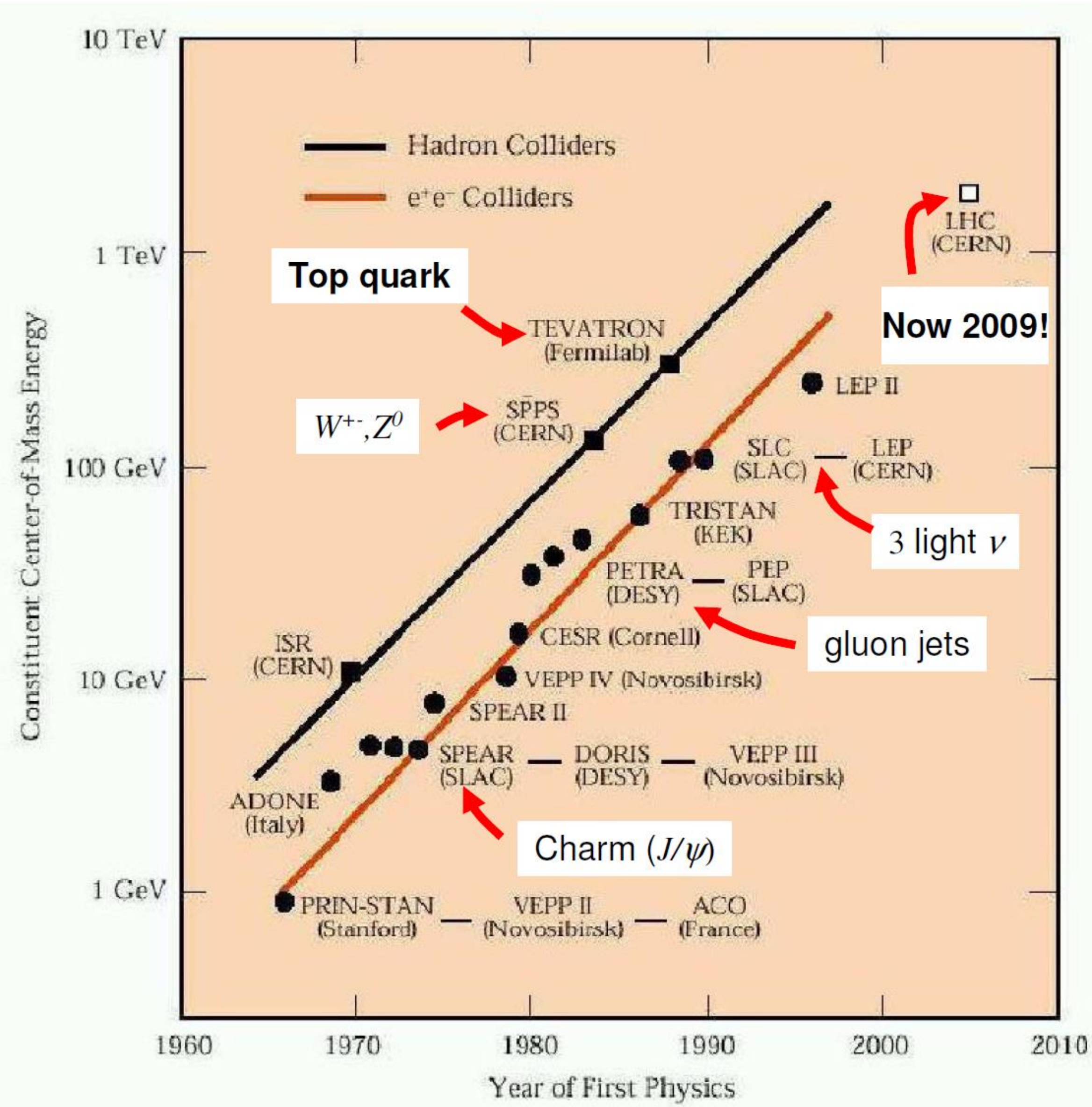
(flushed out with He and their radioactive decays counted)

Prediction of standard solar model $\approx$ 100.

$\Rightarrow$ Solar neutrino problem: 1/3 of expected rate of solar neutrinos

First evidence of neutrino oscilltions.

History of accelerators in particle physics



Traditionally collide hadron-hadron (eg pp, $p\overline{p}$...) and electron-positron. + ep (HERA)

Colliders are successful tools for discovering fundamental particles and measuring their properties.

The Higgs boson

Was the missing particle in the Standard Model. Explains mass generation of the fundamental particles.

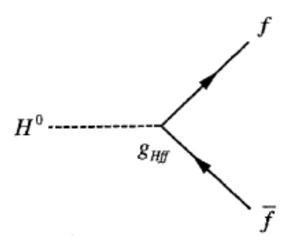
The Higgs mechanism is a way of explaining why, in an apparently unified electroweak theory, the W^{+-} and Z^0 are heavy and the γ is massless.

Some consequences:

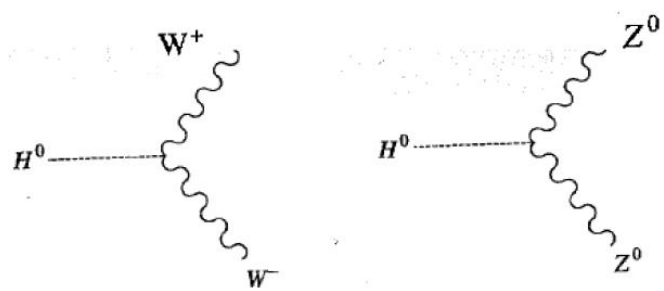
A spin-0 massive boson, the Higgs particle H^0, is required.

A Higgs field pervades space: particles interacting with the field acquire mass.

A fermion with mass m_f couples to the Higgs boson with strength g_{Hff}.

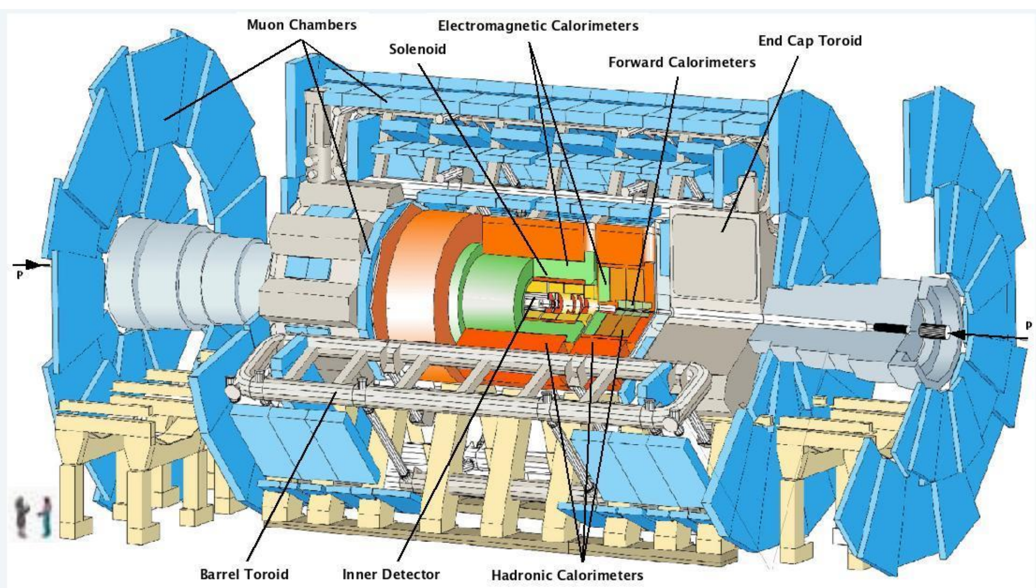


A gauge boson (W, Z) couples:



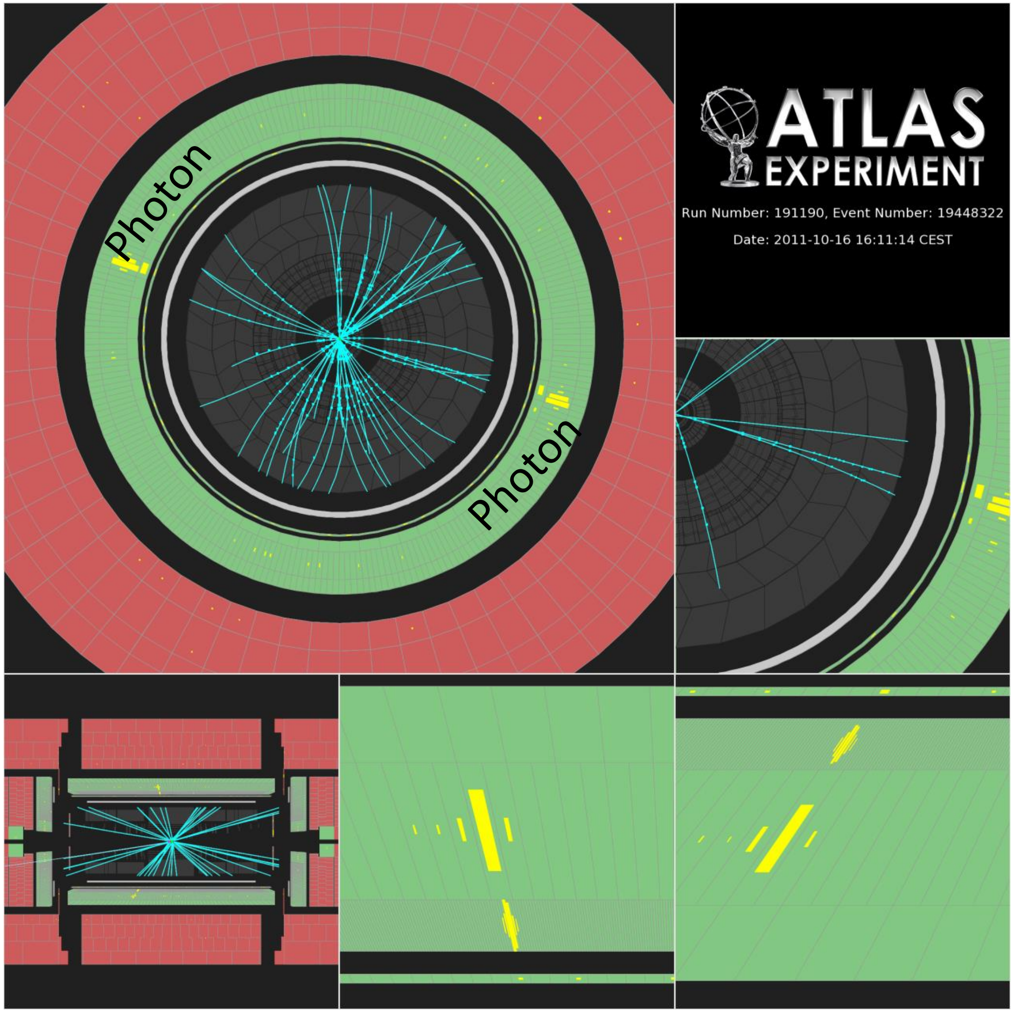
The Large Hadron Collider

27km ring
Collides protons :
13 TeV c.o.m. energy



ATLAS detector.
Measures particles produced after a pp collision.

Looking for $H \to \gamma\gamma$ at the LHC



Measure mass of a photon pair after a pp collision:

$$\left(P_{\gamma 1} + P_{\gamma 2}\right)^2 = m_{pair}^2 c^2$$

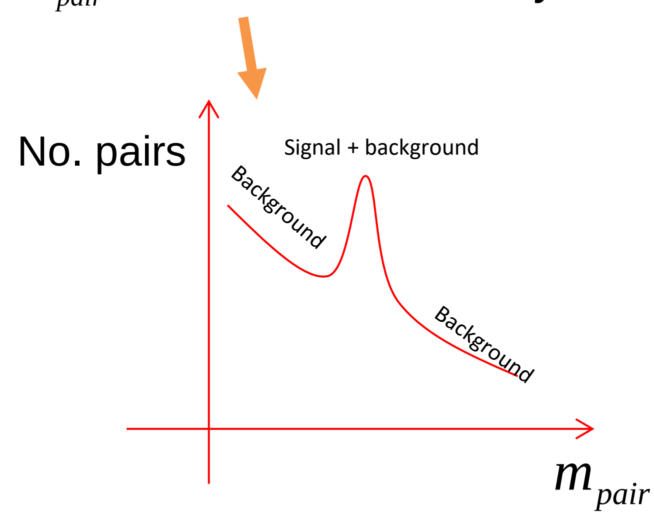
If a pair come from a Higgs (signal)

$\Rightarrow \; m_{pair} = m_H$

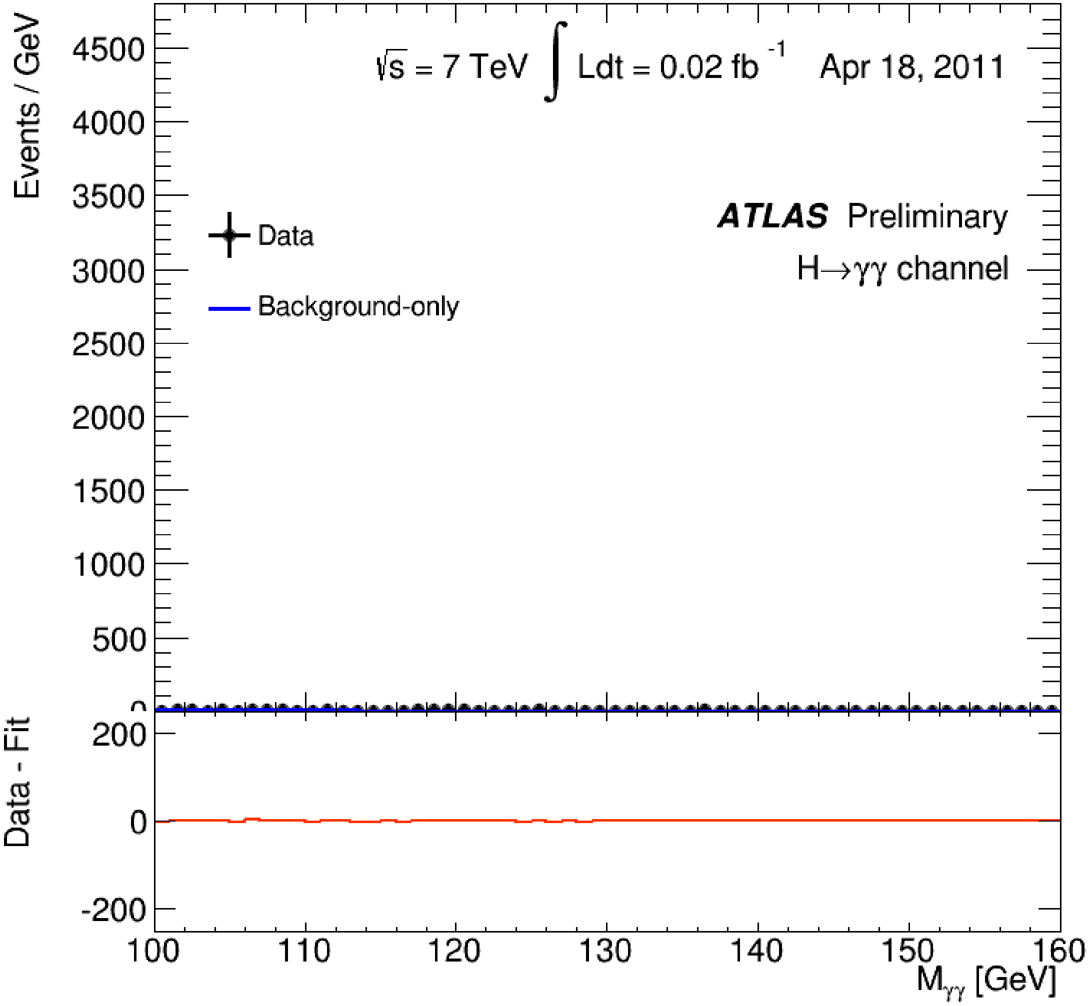
If they come from different processes (background)

$\Rightarrow \; m_{pair} \to$ many possible values

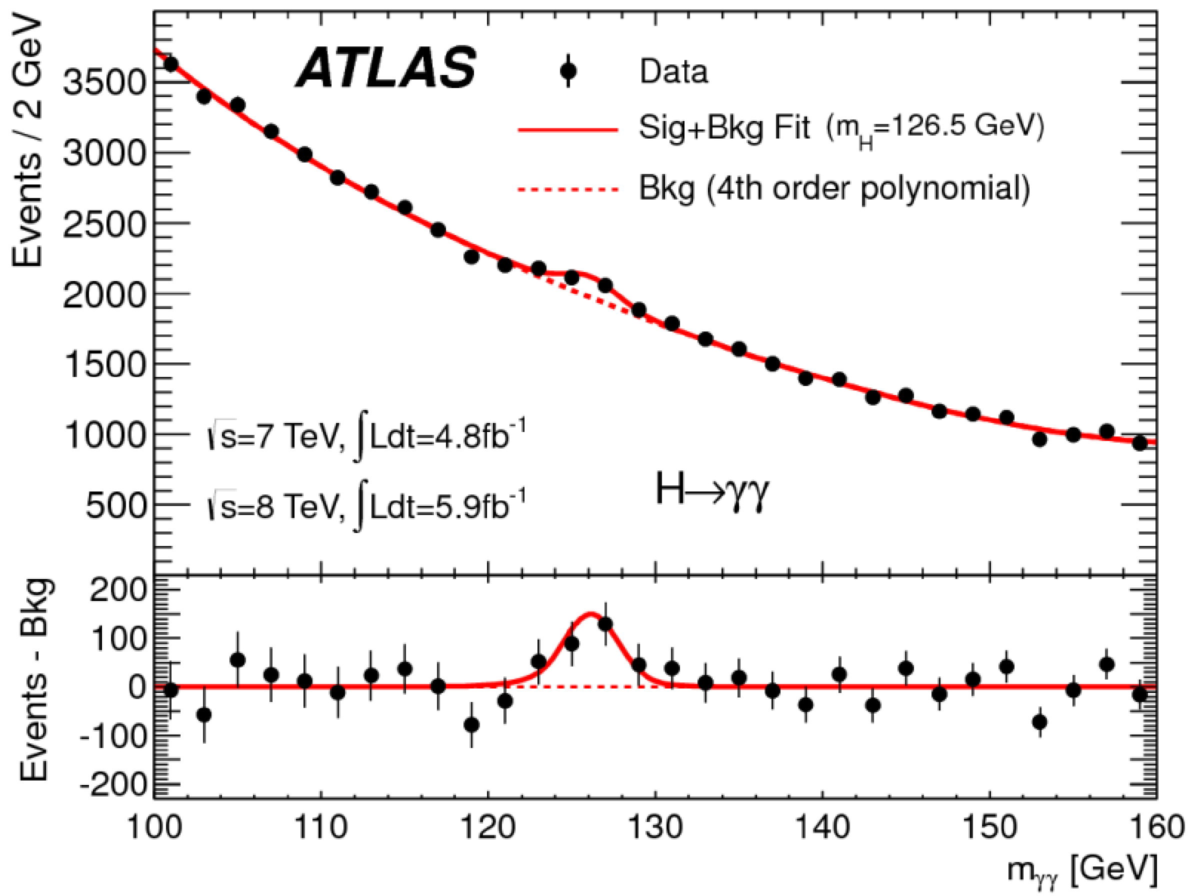
Plot m_{pair} distribution for many collisions:



Waiting for the Higgs



Observation of a Higgs → photons



Higgs found at 125 GeV/c^2 mass !

So who came up with the Higgs theory ?

- Higgs was first to predict the boson
- The symmetry breaking theory is often attributed to
  - Higgs (Nobel 2013)
  - Englert (Nobel 2013)
  - Brout (deceased)
- No consensus.

published almost simultaneously by three independent groups in 1964: by Robert Brout and François Englert, by Peter Higgs;[4] and by Gerald Guralnik, C. R. Hagen, and Tom Kibble.[5][6][7] The Higgs mechanism is therefore also called the **Brout–Englert–Higgs mechanism** or **Englert–Brout–Higgs–Guralnik–Hagen–Kibble mechanism**,[8] **Anderson–Higgs mechanism**,[9] **Anderson–Higgs-Kibble mechanism**,[10] **Higgs–Kibble mechanism** by Abdus Salam[11] and **ABEGHHK'tH mechanism** [for Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble and 't Hooft] by Peter Higgs.[11]

A discovery of a new field pervading all of space

The electromagnetic field couples to electric charge

The strong field couples to colour charge

The weak field couples to weak charge.

Higgs field couples to mass !

Problems of the Standard Model

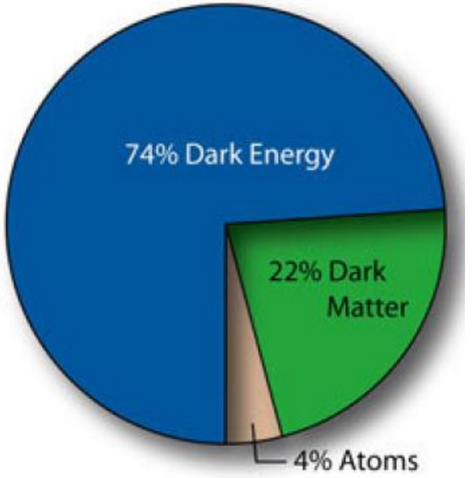
Some open areas in particle physics about which the Standard Model has nothing to say.

(i) Forces: unification and gravity

Is there hope for a theory which unifies all of the fundamental forces or at least the strong, em and weak forces ?

Why is gravity weak until the Planck mass (the hierarchy problem) ?

(ii) Cosmology: Dark matter.



22% of universe's energy budget is "dark matter".

Promising candidate: WIMPs - electrically neutral and weakly interacting massive particles

(mass $1 \leftrightarrow 10$ TeV $\Rightarrow$ LHC !)

(iii) Matter-antimatter asymmetry

(iv) Smallness of neutrino masses.

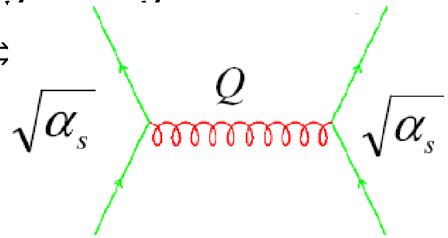
+ many more!

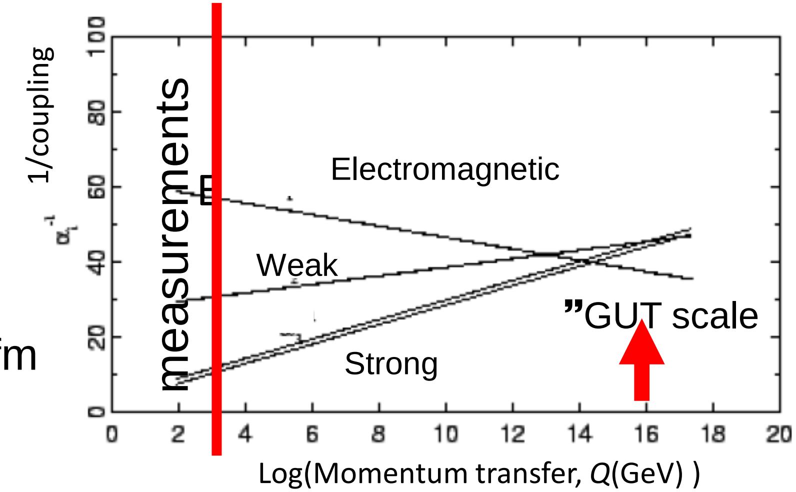
Grand unified scale

The coupling constants vary with momentum transfer (or distance)

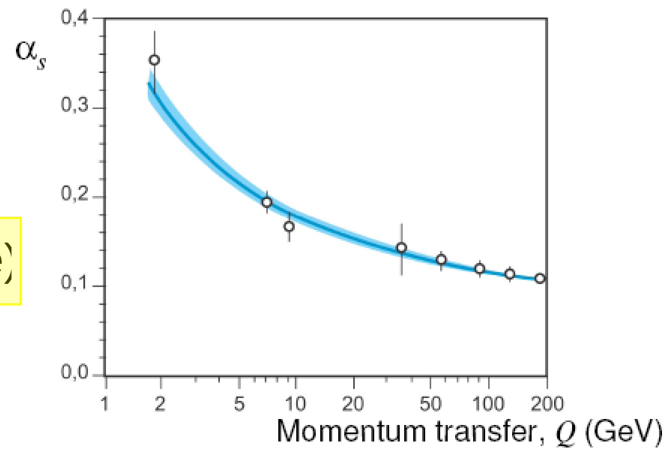
Eg strong force becomes weak at short distances (<1fm

$\Rightarrow$





Couplings appear to unify for $Q \sim 10^{16}$ GeV (grand unified scale)



Grand Unified Theories

Unify strong, electromagnetic and weak forces within a grand unified theory (GUT) with new physics appearing at the GUT scale $\sim 10^{16}$ GeV

Simplest model: SU(5) (Georgi-Glashow).

Introduce new heavy exchange bosons X and Y: mass $\sim 10^{16}$ GeV.

Prediction of proton decay.

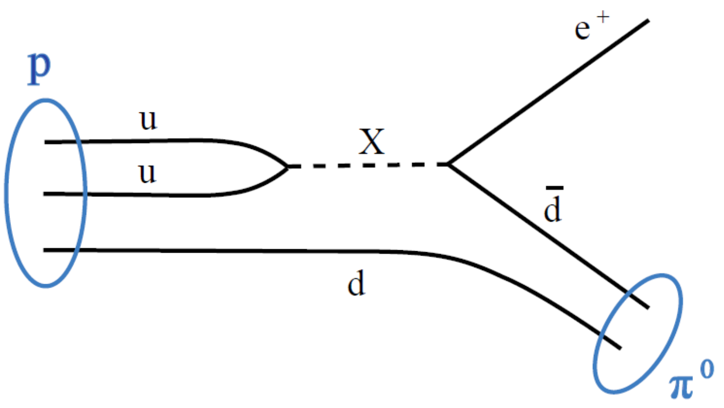
Violation of lepton and baryon number.

Eg $p \to \pi^0 + e^+$

Predictions for lifetime $\tau \sim 10^{30}$ years.

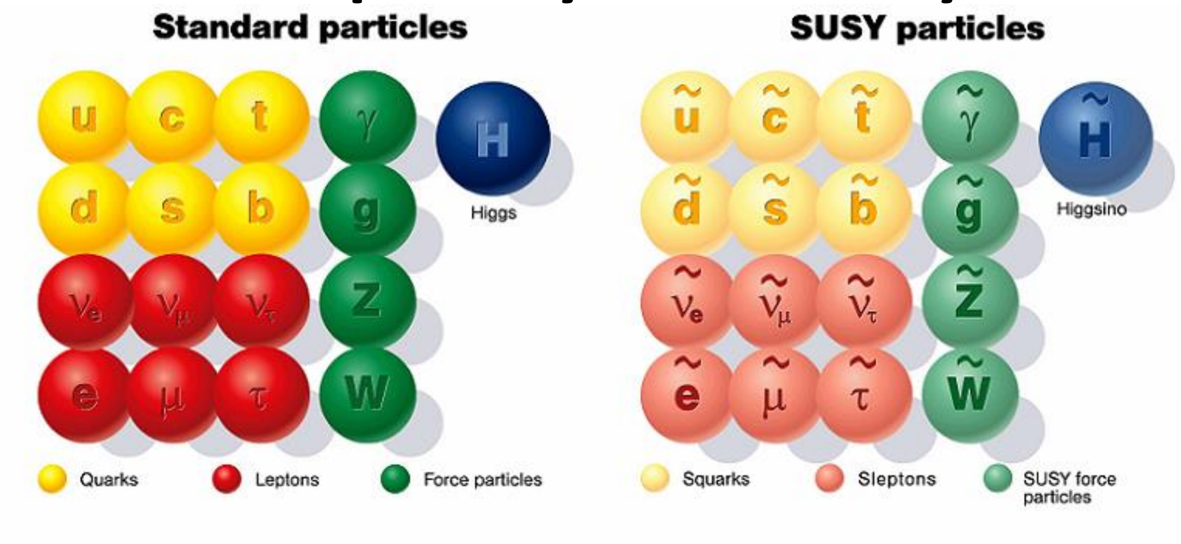
Current limits (SuperK) $\tau >\sim 10^{33}$ years.

Other GUTS predict $\tau > 10^{33}$ years.



GUTs also predict heavy magnetic monopoles $m \sim 10^{16}$ GeV and explain charge quantisation.

Supersymmetry



Every Standard Model has a supersymmetry partner.

Symmetry between bosons and fermion

Quarks (fermions) $\leftrightarrow$ Squarks (bosons) ; W, Z, γ, g (bosons) $\leftrightarrow$ $\tilde{W}, \tilde{Z}, \tilde{\gamma}, \tilde{g}$ (fermions)

Symmetry is broken otherwise SM and SUSY particles (sparticleS) would have the same mass.

SM and SUSY particles have different R-parity. Conservation of R-parity stops SUSY sparticles decaying to SM particles.

R=$(-1)^{3(B-L)+2S}$ $=+1$ SM particles (15.07)

$=-1$ SUSY partner particles.

B=baryon number, L=lepton number, S=Spin quantum number.

Supersymmetry

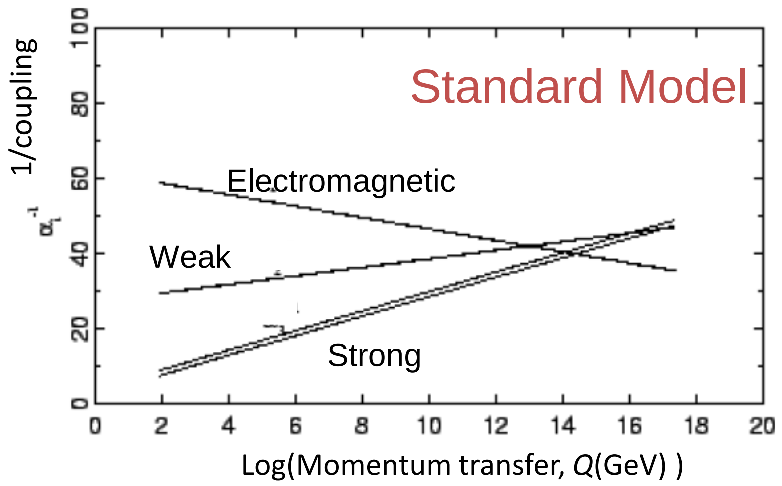
Many reasons for looking for SUSY, amongs them...

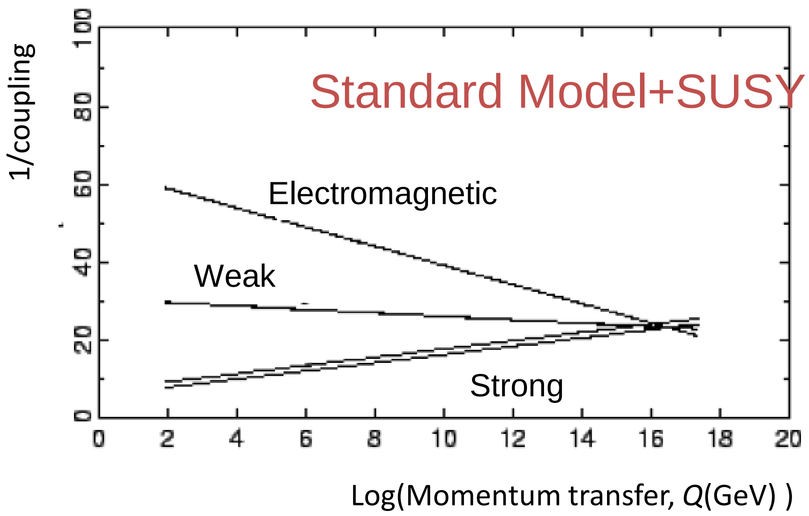
(1) It predicts a dark matter candidate: i.e. a WIMP with mass $\sim$ TeV.

Neutralino: $\tilde{\chi}^0$ a mixed state of SUSY partners of the Higgs, Z and γ.

(2) Unification of the couplings is more exact if SUSY sparticles exist.

Can develop SUSY grand unified theories (GUTs) which unify the electromagnetic, weak and strong forces.





(3) Solves the hierarchy problem (beyond this course)

Summary

- Hadron decays for different forces
- Neutrino oscillations show neutrino mass
- Accelerators used as probes of the structure of matter and to produce heavy particles.
- Many problems with the Standard Model and many proposed solutions.
- The Standard Model remains unbroken.

Good luck with the rest of the course !!