

# 12. Beyond the Standard Model

## Particle and Nuclear Physics

Prof. Tina Potter



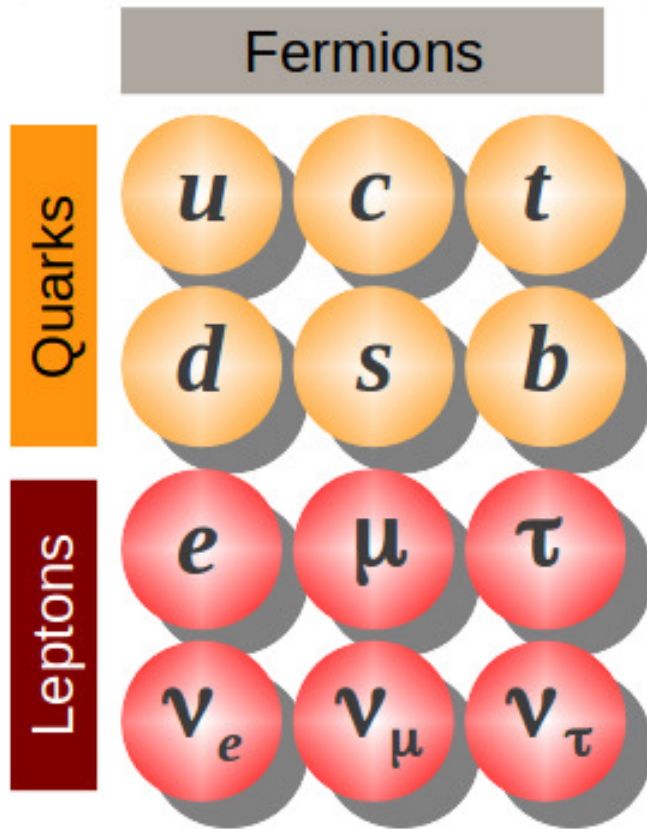
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# In this section...

- Summary of the Standard Model
- Problems with the Standard Model
- Neutrino oscillations
- Supersymmetry

# The Standard Model (2012)

Matter: point-like spin  $\frac{1}{2}$  Dirac fermions

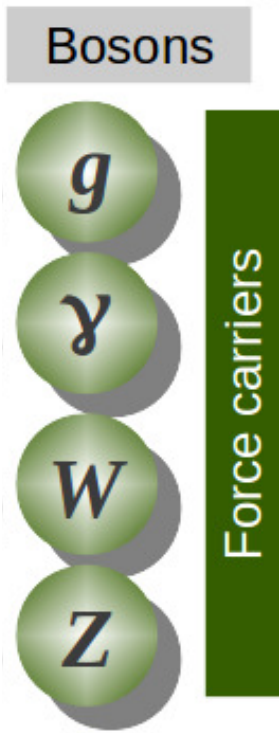


+ antiparticles

	Fermion		Charge [e]	Mass
1 <sup>st</sup> gen.	Electron	$e^-$	-1	0.511 MeV
	Electron neutrino	$\nu_e$	0	$\sim 0$
	Down quark	$d$	-1/3	4.8 MeV
	Up quark	$u$	+2/3	2.3 MeV
2 <sup>nd</sup> gen.	Muon	$\mu^-$	-1	106 MeV
	Muon neutrino	$\nu_\mu$	0	$\sim 0$
	Strange quark	$s$	-1/3	95 MeV
	Charm quark	$c$	+2/3	1.3 GeV
3 <sup>rd</sup> gen.	Tau	$\tau^-$	-1	1.78 GeV
	Tau neutrino	$\nu_\tau$	0	$\sim 0$
	Bottom quark	$b$	-1/3	4.7 GeV
	Top quark	$t$	+2/3	173 GeV

# The Standard Model (2012)

## Forces: mediated by spin 1 bosons



Force	Particle	Mass
Electromagnetic	Photon $\gamma$	0
Strong	8 gluons $g$	0
Weak (CC)	$W^\pm$	80.4 GeV
Weak (NC)	$Z$	91.2 GeV

- The Standard Model also predicts the existence of a spin-0 **Higgs boson** which gives all particles their masses via its interactions. Evidence from LHC confirms this, with  $m_H \sim 125$  GeV.
- The Standard Model successfully describes **all** existing particle physics data, with the exception of one
  - $\Rightarrow$  **Neutrino Oscillations**  $\Rightarrow$  **Neutrinos have mass**

In the SM, neutrinos are treated as massless; right-handed states do not exist  $\Rightarrow$  indication of physics **Beyond the Standard Model**

# Problems with the Standard Model

The Standard Model successfully describes **all** existing particle physics data (though question marks over the neutrino sector).

**But:** many (too many?) input parameters:

- Quark and lepton masses
- Quark charge
- Couplings  $\alpha_{\text{EM}}$ ,  $\sin^2 \theta_W$ ,  $\alpha_s$
- Quark (+ neutrino) generation mixing –  $V_{\text{CKM}}$

23 free parameters in SM

- 9 fermion masses ( $e, \mu, \tau, u, d, s, c, b, t$ )
- 4 CKM: 3 mixing angles + CPV phase
- 4 PMNS: 3 mixing angles + CPV phase
- 3 gauge couplings: U(1), SU(2), SU(3)
- 3 other: QCD vacuum angle (strong CPV), Higgs VEV, Higgs mass

**and:** many unanswered questions:

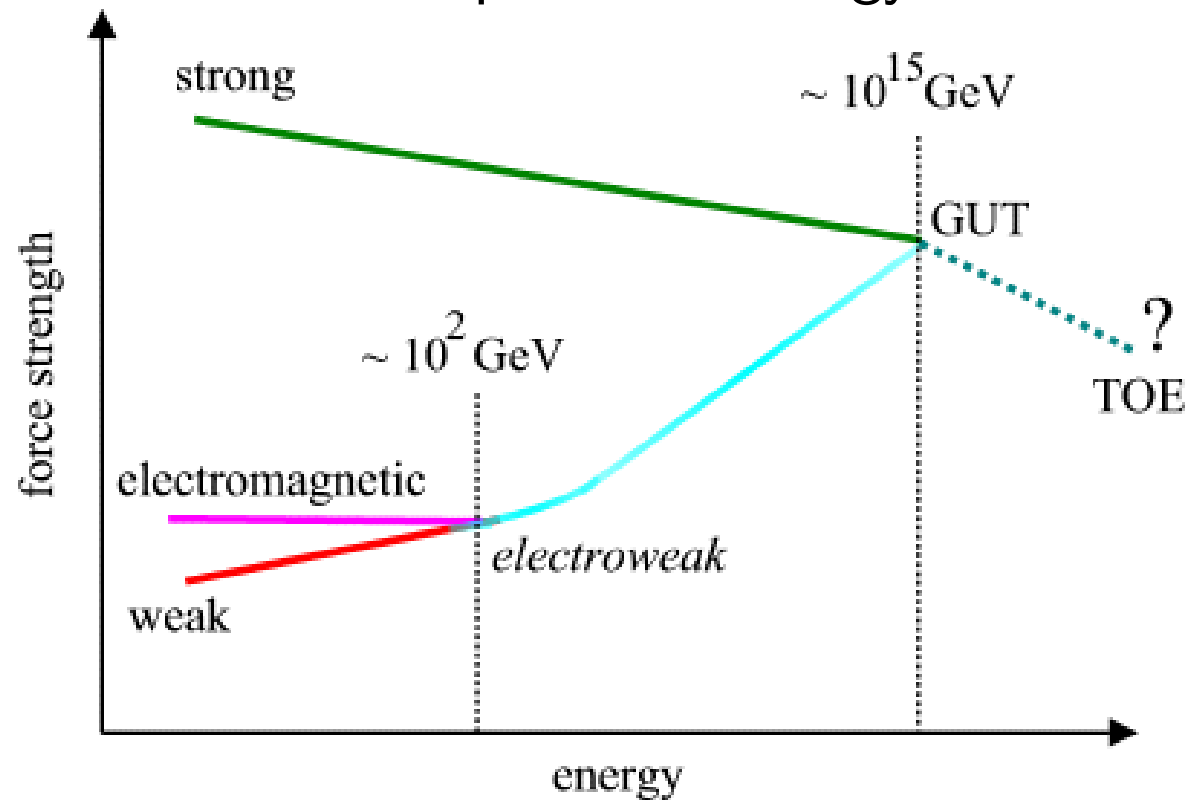
- Why so many free parameters?
- Why only three generations of quarks and leptons?
- Where does mass come from? (Higgs boson probably OK)
- Why is the neutrino mass so small and the top quark mass so large?
- Why are the charges of the  $p$  and  $e$  identical?
- What is responsible for the observed matter-antimatter asymmetry?
- How can we include gravity?

etc

# Beyond the Standard Model – further unification??

Grand Unification Theories (GUTs) aim to unite the strong interaction with the electroweak interaction. Underpins many ideas about physics beyond the Standard Model.

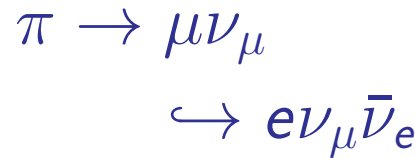
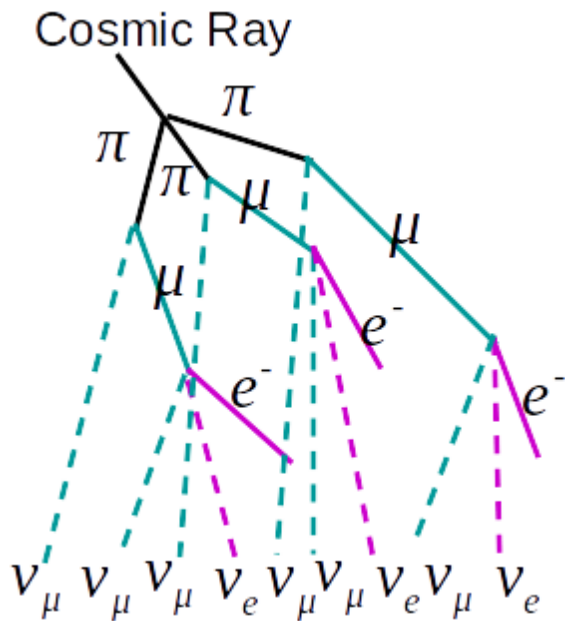
The strength of the interactions depends on energy:



- Suggests unification of all forces at  $\sim 10^{15}$  GeV?
- Strength of Gravity only significant at the Planck Mass  $\sim 10^{19}$  GeV

# Neutrino Oscillations

In 1998 the Super-Kamiokande experiment announced convincing evidence for **neutrino oscillations** implying that neutrinos have mass.

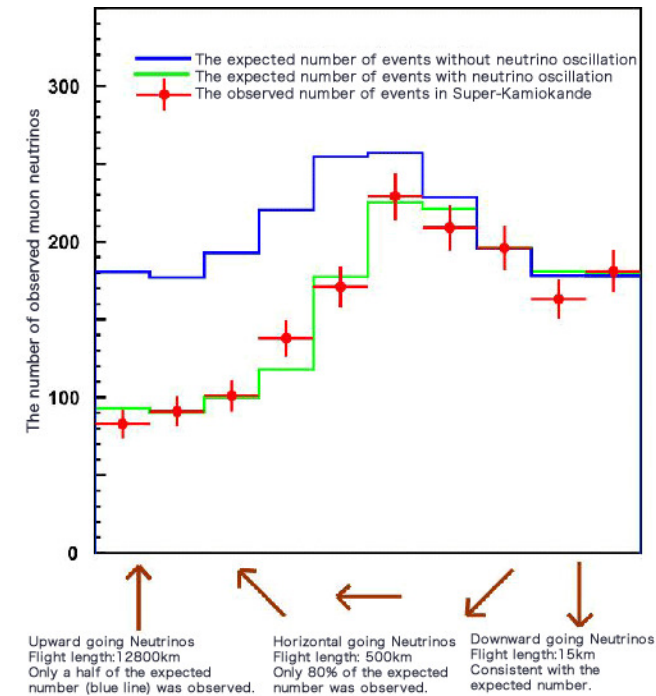


Expect

$$\frac{N(\nu_\mu)}{N(\nu_e)} \sim 2$$

Super-Kamiokande results indicate a deficit of  $\nu_\mu$  from the upwards direction. Upward neutrinos created further away from the detector.

- Interpreted as  $\nu_\mu \rightarrow \nu_\tau$  **oscillations**
- Implies neutrino **mixing** and neutrinos have **mass**



# Detecting Neutrinos

Neutrinos are detected by observing the lepton produced in **charged current** interactions with nuclei. e.g.  $\nu_e + N \rightarrow e^- + X$        $\bar{\nu}_\mu + N \rightarrow \mu^+ + X$

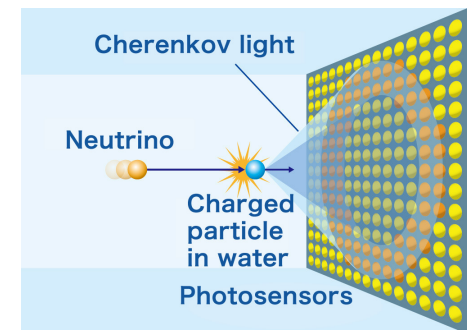
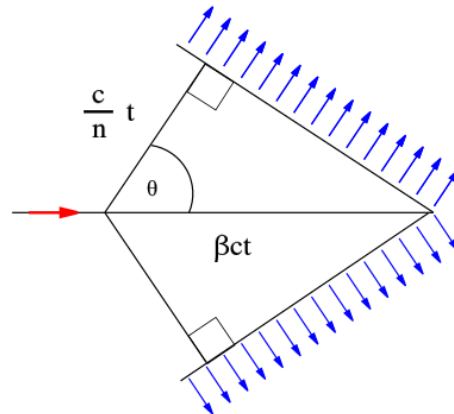
## Size Matters:

- Neutrino cross-sections on nucleons are tiny;  $\sim 10^{-42} (E_\nu / \text{GeV}) \text{m}^2$
- Neutrino mean free path in water  $\sim$  light-years.
- Require very large mass, cheap and simple detectors.
- Water Čerenkov detection

## Čerenkov radiation

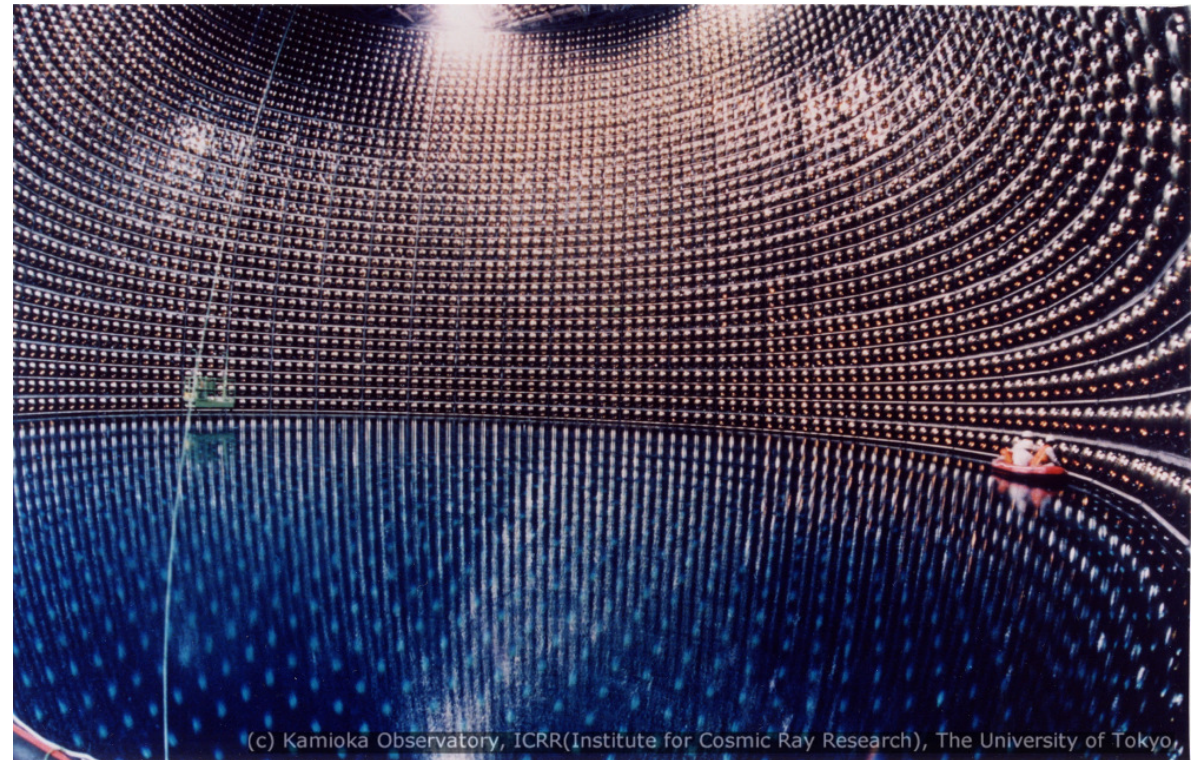
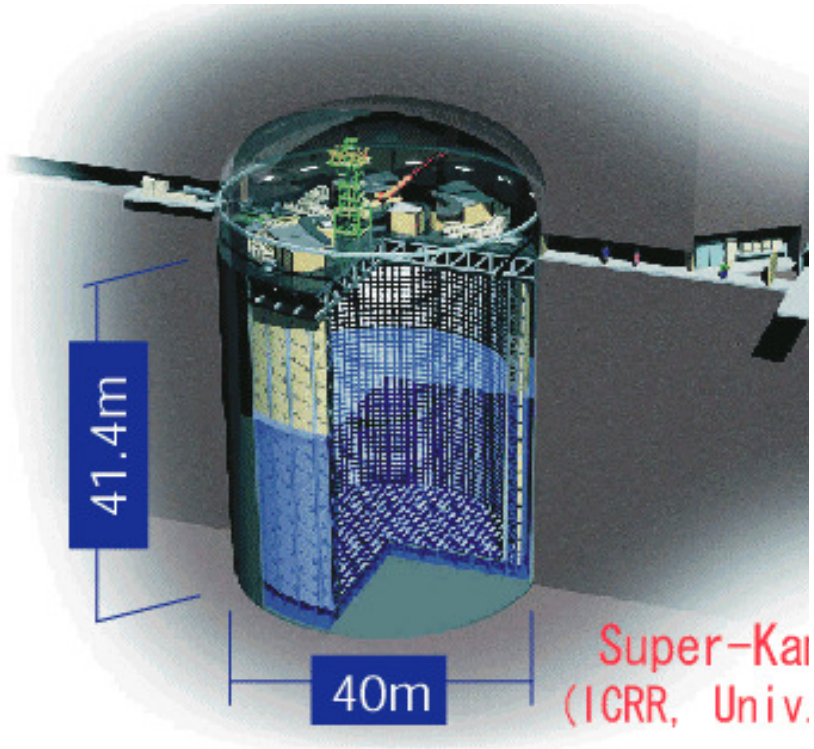
- Light is emitted when a charged particle traverses a dielectric medium
- A coherent wavefront forms when the velocity of a charged particle exceeds  $c/n$  ( $n =$  refractive index)
- Čerenkov radiation is emitted in a cone i.e. at fixed angle with respect to the particle.

$$\cos \theta_C = \frac{c}{nv} = \frac{1}{n\beta}$$



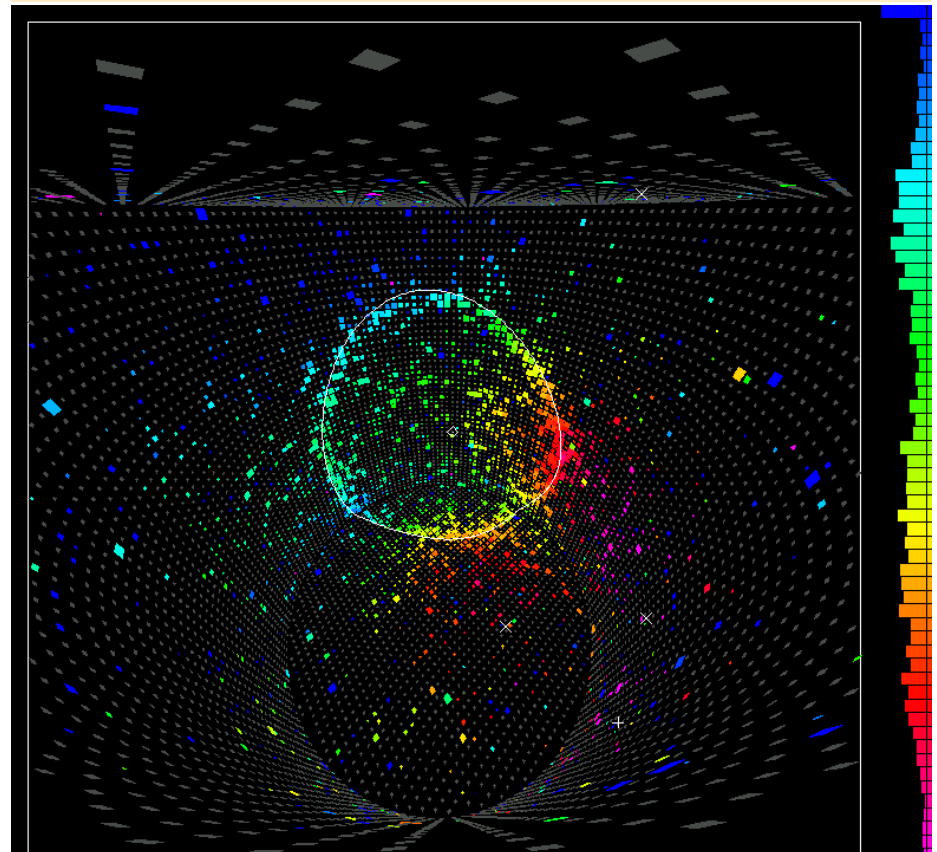
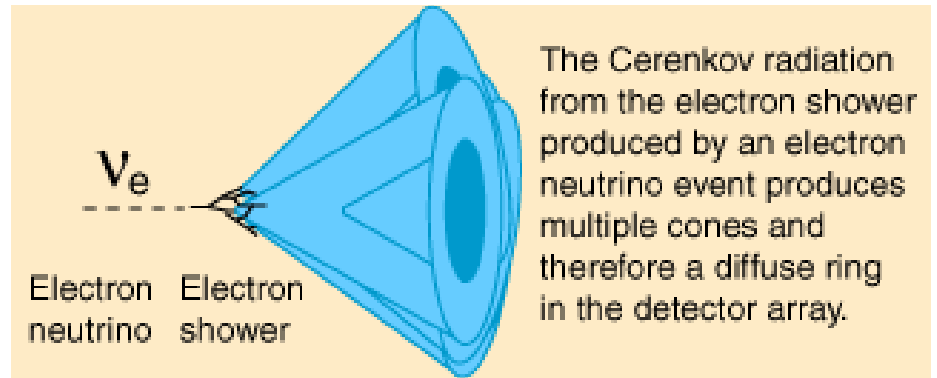
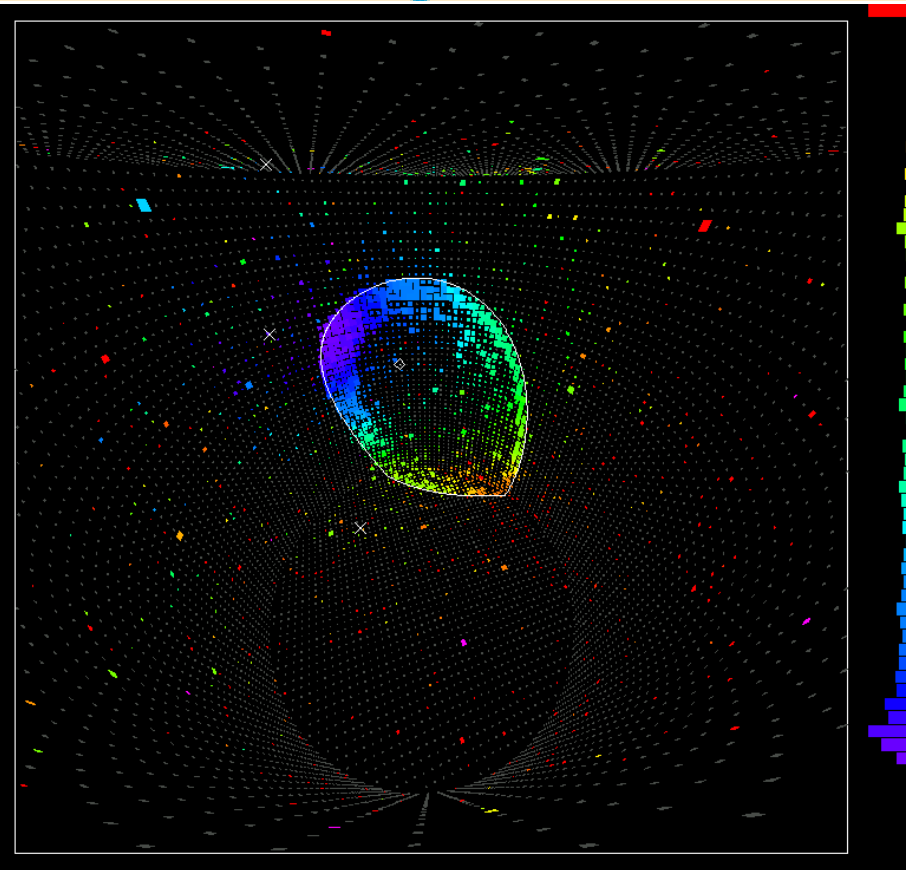
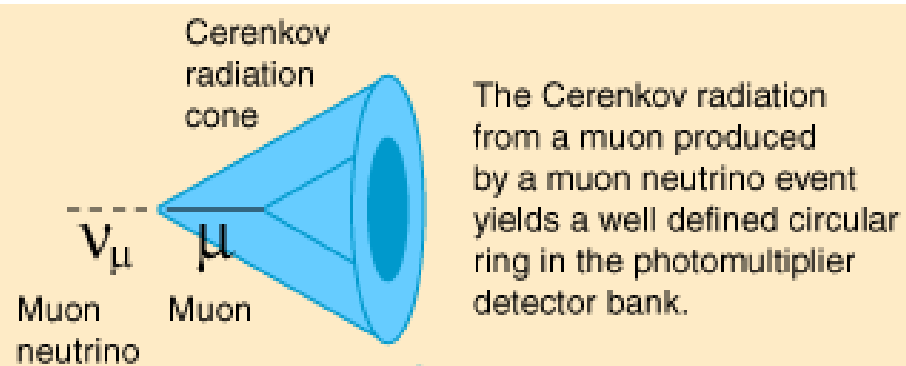
# Super-Kamiokande

Super-Kamiokande is a Water Čerenkov detector sited in Kamioka, Japan

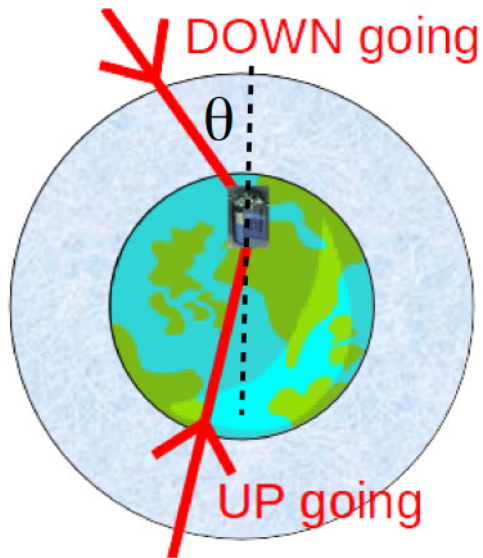


50,000 tons of water

Surrounded by  $11,146 \times 50$  cm diameter, photo-multiplier tubes



# Super-Kamiokande $\nu$ deficit



## Expect

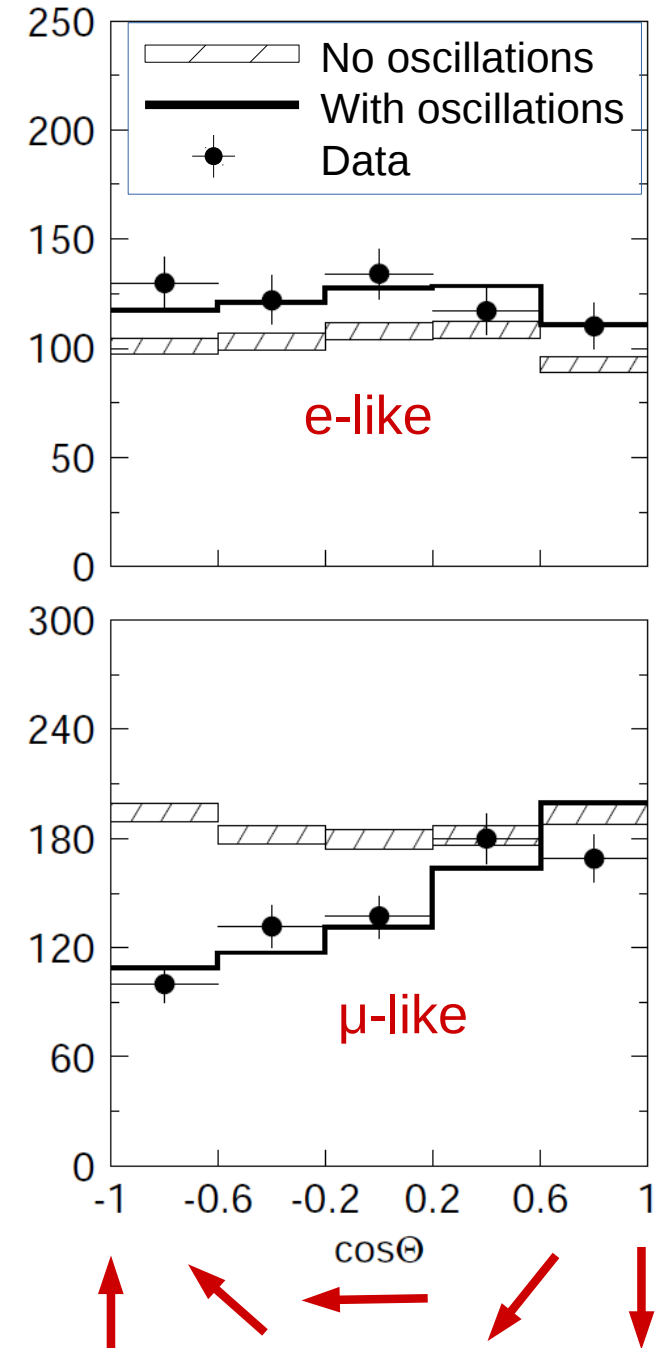
- Isotropic (flat) distributions in  $\cos \theta$
- $N(\nu_\mu) \sim 2N(\nu_e)$

## Observe

- Deficit of  $\nu_\mu$  from **below**
- Whereas  $\nu_e$  look as expected

## Interpretation

- $\nu_\mu \rightarrow \nu_\tau$  **oscillations**
- $\Rightarrow$  neutrinos have **mass**



# Neutrino Mixing

The quark states which take part in the **weak** interaction ( $d'$ ,  $s'$ ) are related to the flavour (mass) states ( $d$ ,  $s$ )

Weak Eigenstates  $\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$  Mass Eigenstates  
Cabibbo angle  $\theta_C \sim 13^\circ$

Suppose the same thing happens for neutrinos. Consider only the first two generations for simplicity.

Weak Eigenstates  $\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$  Mass Eigenstates  
= flavour eigenstates Mixing angle  $\theta$

e.g. in  $\pi^+$  decay produce  $\mu^+$  and  $\nu_\mu$  i.e. the neutrino state that couples to the weak interaction.

The  $\nu_\mu$  corresponds to a linear combination of the states with definite mass,  $\nu_1$  and  $\nu_2$  or expressing the mass eigenstates in terms of the weak eigenstates

$$\nu_e = +\nu_1 \cos \theta + \nu_2 \sin \theta$$

$$\nu_\mu = -\nu_1 \sin \theta + \nu_2 \cos \theta$$

$$\nu_1 = +\nu_e \cos \theta - \nu_\mu \sin \theta$$

$$\nu_2 = +\nu_e \sin \theta + \nu_\mu \cos \theta$$

# Neutrino Mixing

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Suppose a muon neutrino with momentum  $\vec{p}$  is produced in a **weak** decay, e.g.  
 $\pi^+ \rightarrow \mu^+ \nu_\mu$

At  $t = 0$ , the wavefunction

$$\psi(\vec{p}, t = 0) = \nu_\mu(\vec{p}) = \nu_2(\vec{p}) \cos \theta - \nu_1(\vec{p}) \sin \theta$$

The time evolution of  $\nu_1$  and  $\nu_2$  will be different if they have different masses

$$\nu_1(\vec{p}, t) = \nu_1(\vec{p}) e^{-iE_1 t} ; \quad \nu_2(\vec{p}, t) = \nu_2(\vec{p}) e^{-iE_2 t}$$

After time  $t$ , state will in general be a mixture of  $\nu_e$  and  $\nu_\mu$

$$\begin{aligned} \psi(\vec{p}, t) &= \nu_2(\vec{p}) e^{-iE_2 t} \cos \theta - \nu_1(\vec{p}) e^{-iE_1 t} \sin \theta \\ &= [\nu_e(\vec{p}) \sin \theta + \nu_\mu(\vec{p}) \cos \theta] e^{-iE_2 t} \cos \theta - [\nu_e(\vec{p}) \cos \theta - \nu_\mu(\vec{p}) \sin \theta] e^{-iE_1 t} \sin \theta \\ &= \nu_\mu(\vec{p}) [\cos^2 \theta e^{-iE_2 t} + \sin^2 \theta e^{-iE_1 t}] + \nu_e(\vec{p}) [\sin \theta \cos \theta (e^{-iE_2 t} - e^{-iE_1 t})] \\ &= c_\mu \nu_\mu(\vec{p}) + c_e \nu_e(\vec{p}) \end{aligned}$$

# Neutrino Mixing

Probability of oscillating into  $\nu_e$

$$\begin{aligned} P(\nu_e) &= |c_e|^2 = \left| \sin \theta \cos \theta (e^{-iE_2 t} - e^{-iE_1 t}) \right|^2 \\ &= \frac{1}{4} \sin^2 2\theta (e^{-iE_2 t} - e^{-iE_1 t}) (e^{iE_2 t} - e^{iE_1 t}) \\ &= \frac{1}{4} \sin^2 2\theta \left( 2 - e^{i(E_2 - E_1)t} - e^{-i(E_2 - E_1)t} \right) \\ &= \sin^2 2\theta \sin^2 \left[ \frac{(E_2 - E_1)t}{2} \right] \end{aligned}$$

But

$$E = \sqrt{\vec{p}^2 + m^2} = \vec{p} \sqrt{1 + \frac{m^2}{\vec{p}^2}} \sim \vec{p} + \frac{m^2}{2\vec{p}}$$

for  $m \ll E$

$$1 + x \sim (1 + x/2)^2$$

when  $x$  is small, can ignore  $x^2$  term

$$\Rightarrow E_2(\vec{p}) - E_1(\vec{p}) \sim \frac{m_2^2 - m_1^2}{2\vec{p}} \sim \frac{m_2^2 - m_1^2}{2E}$$

$$\Rightarrow P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 \left[ \frac{(m_2^2 - m_1^2)t}{4E} \right]$$

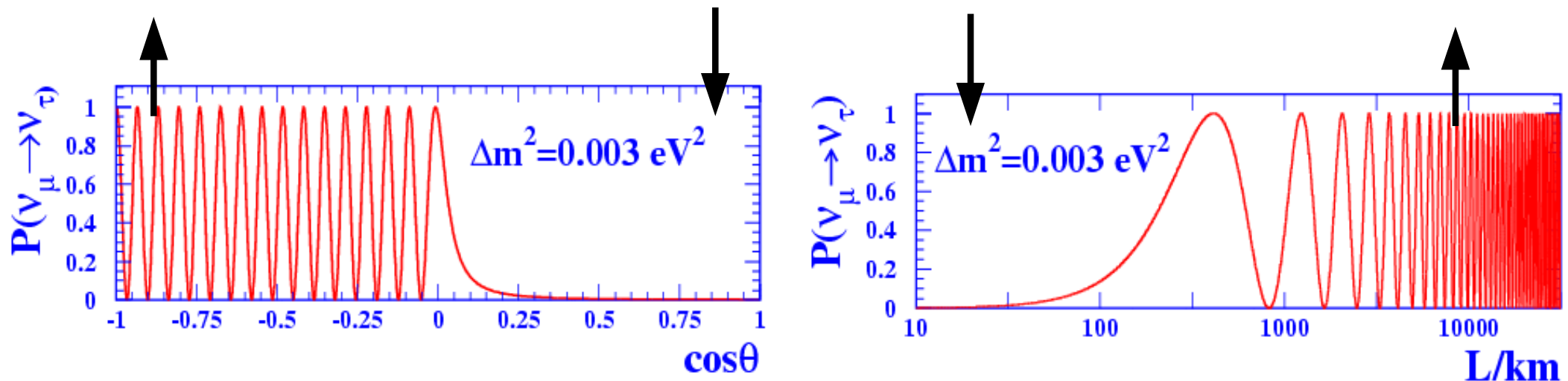
# Neutrino Mixing

For  $\nu_\mu \rightarrow \nu_\tau$  
$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \left[ \frac{(m_3^2 - m_2^2)t}{4E} \right] = \sin^2 2\theta \sin^2 \left[ \frac{1.27 \Delta m^2 L}{E_\nu} \right]$$

where  $L$  is the distance travelled in km,  
 $\Delta m^2 = m_3^2 - m_2^2$  is the mass difference in  $(\text{eV})^2$   
 and  $E_\nu$  is the neutrino energy in GeV.

## Interpretation of Super-Kamiokande Results

For  $E(\nu_\mu) = 1$  GeV (typical of atmospheric neutrinos)



Results are consistent with  $\nu_\mu \rightarrow \nu_\tau$  oscillations:

$$|m_3^2 - m_2^2| \sim 2.5 \times 10^{-3} \text{ eV}^2; \quad \sin^2 2\theta \sim 1$$

# Neutrino Mixing – Comments

- Neutrinos almost certainly have mass
  - Neutrino oscillation only **sensitive to mass differences**
  - More evidence for neutrino oscillations
    - **Solar neutrinos** (SNO experiment)
    - **Reactor neutrinos** (KamLand)
- suggest  $|m_2^2 - m_1^2| \sim 8 \times 10^{-5} \text{ eV}^2$ .
- More recent experiments use neutrino beams from accelerators or reactors; observe energy spectrum of neutrinos at a distant detector.
  - At fixed  $L$ , observation of the values of  $E_\nu$  at which minima/maxima are seen determines  $\Delta m^2$ , while depth of minima determine  $\sin^2 2\theta$ .
  - Note all these experiments only tell us about mass **differences**.
  - Best constraint on absolute mass comes from the end point in Tritium  $\beta$ -decay,  $m(\nu_e) < 2 \text{ eV}$ .

# Three-flavour oscillations

This whole framework can be generalised...

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

where

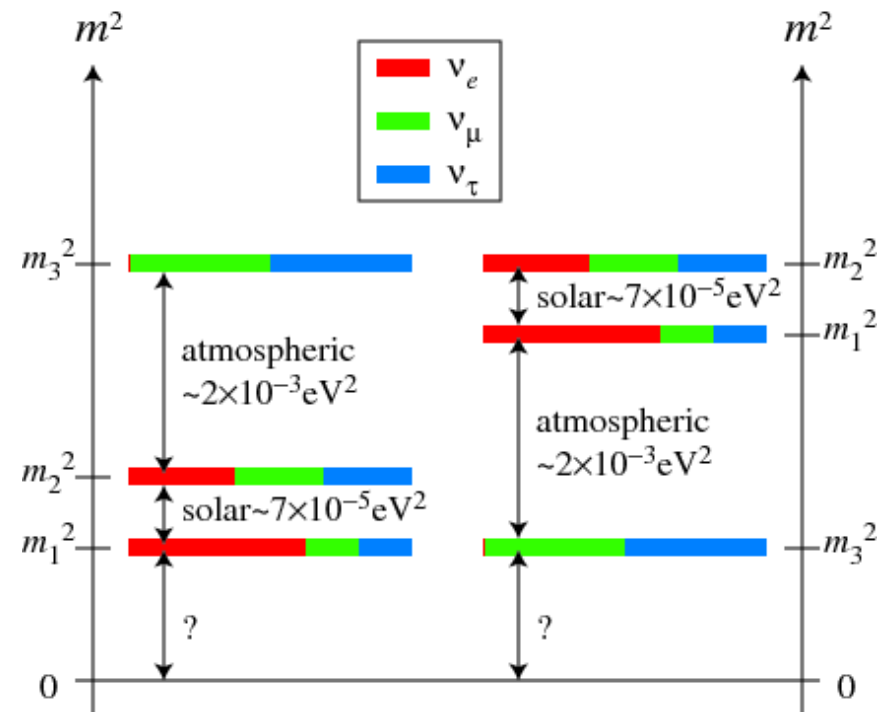
$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{23}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

defining  $\cos \theta_{12} = c_{12}$  etc.

This is an active field!

Current status...

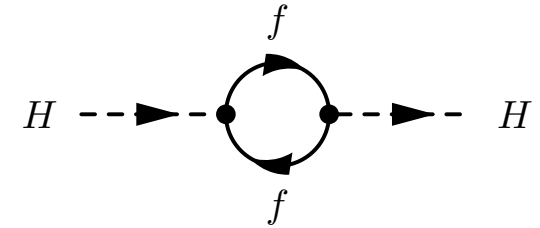
- $\sin^2 \theta_{12} = 0.304 \pm 0.014$
- $\sin^2 \theta_{23} = 0.51 \pm 0.06$
- $\sin^2 \theta_{13} = 0.0219 \pm 0.0012$



# Supersymmetry (SUSY)

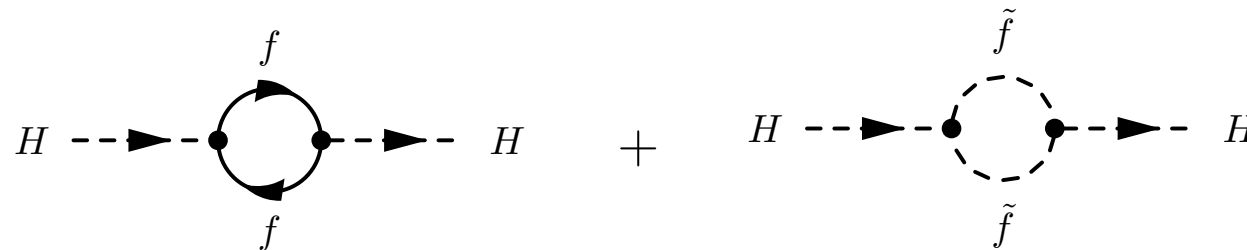
A significant problem is to explain why the Higgs boson is so light.

- The effect of loop corrections on the Higgs mass should be to drag it up to the highest energy scale in the problem (i.e. unification, or Planck mass).



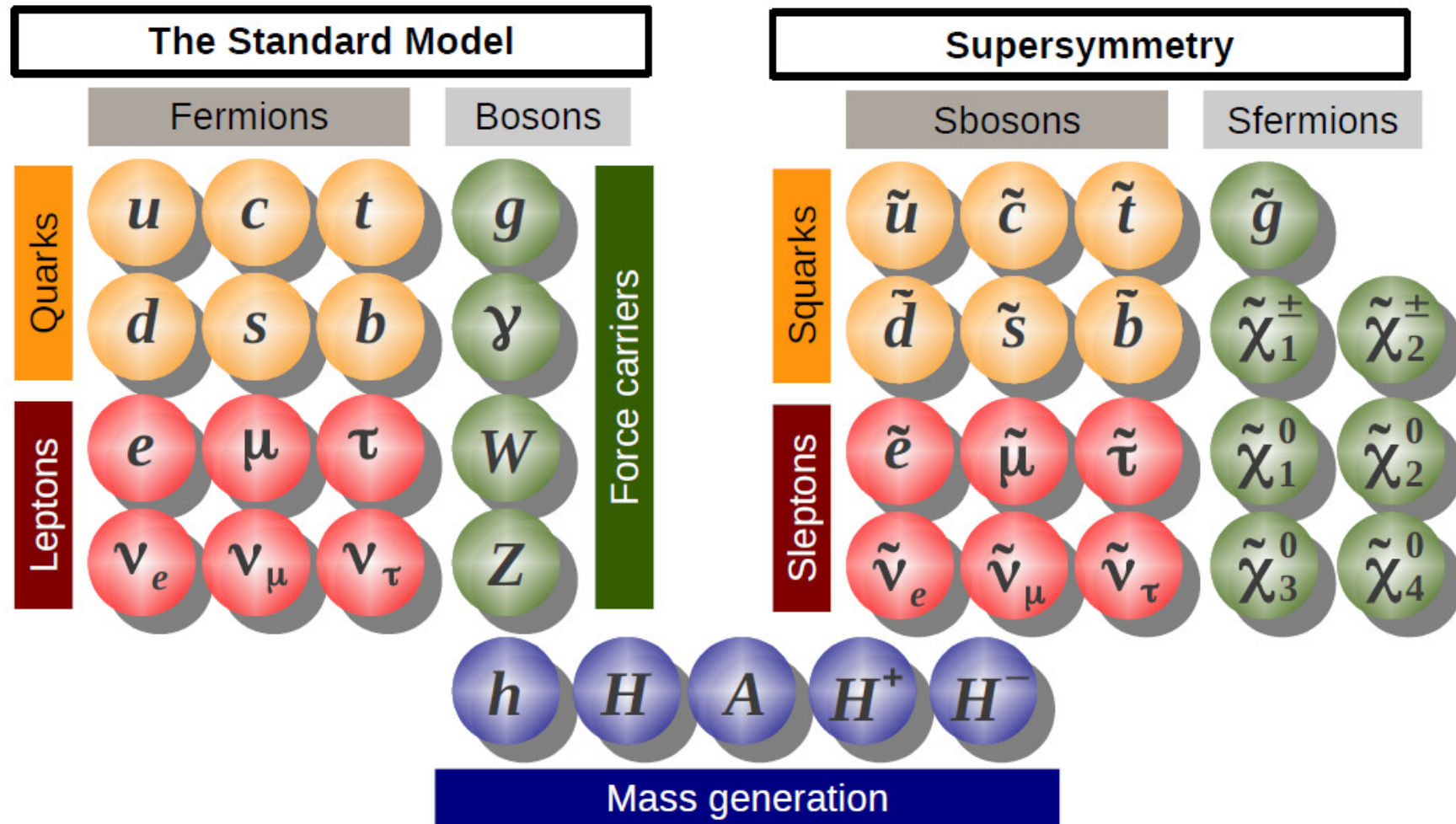
- One attractive solution is to introduce a new space-time symmetry, “supersymmetry” which links fermions and bosons (the only way to extend the Poincaré symmetry of special relativity and respect quantum field theory.)

- Each fermion has a boson partner, and vice versa, with the same couplings. Boson and fermion loops contribute with opposite sign, giving a natural cancellation in their effect on the Higgs mass.



- Must be a broken symmetry, because we clearly don't see bosons and fermions of the same mass.
- However, this doubles the particle content of the model, without any direct evidence (yet), and introduces lots of new unknown parameters.

# The Supersymmetric Standard Model



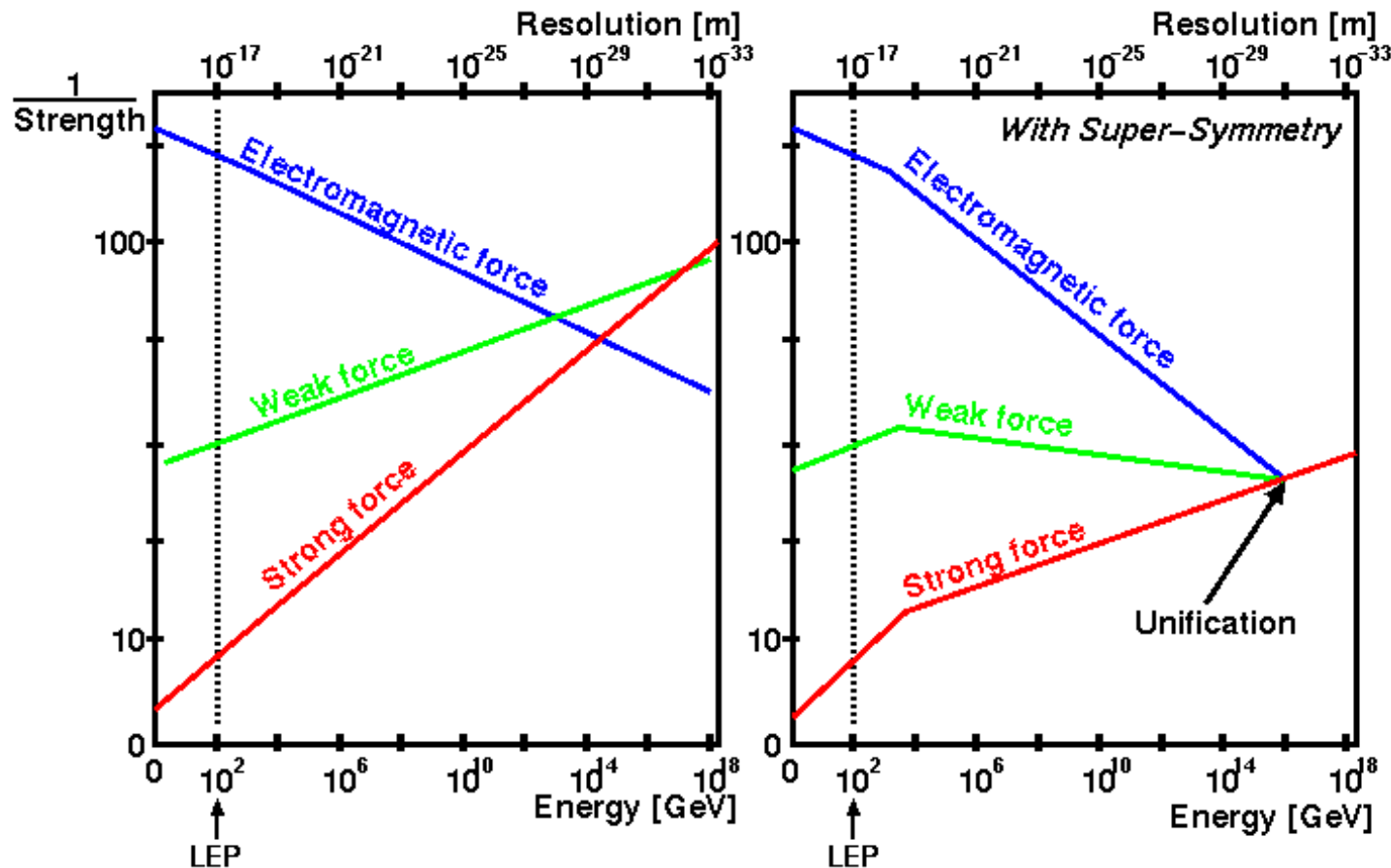
$$\text{SM} : W^\pm, W^0, B \xrightarrow{\text{mixing}} W^\pm, Z, \gamma$$

$$\text{SUSY} : \tilde{H}_u^0, \tilde{H}_d^0, \tilde{W}^0, \tilde{B}^0 \xrightarrow{\text{mixing}} \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

$$\tilde{H}_u^+, \tilde{H}_d^-, \tilde{W}^+, \tilde{W}^- \xrightarrow{\text{mixing}} \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$$

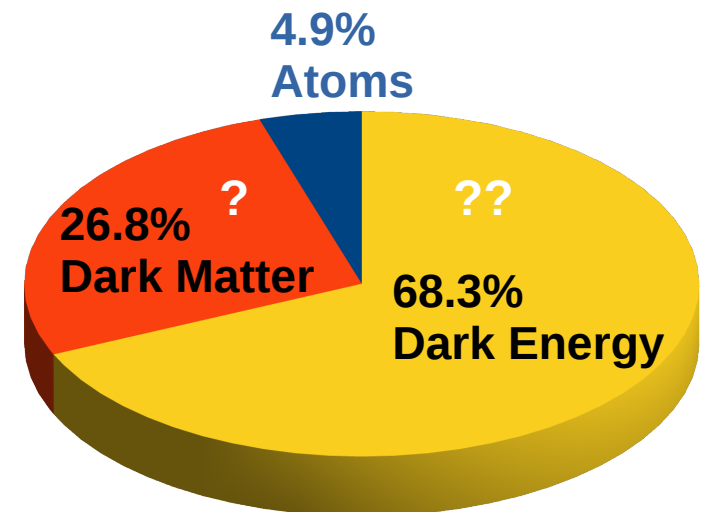
# SUSY and Unification

- In the Standard Model, the interaction strengths are not quite unified at very high energy.
- Add **SUSY**, the running of the couplings is modified, because sparticle loops contribute as well as particle loops.
- Details depend on the version of SUSY, but in general unification much improved.



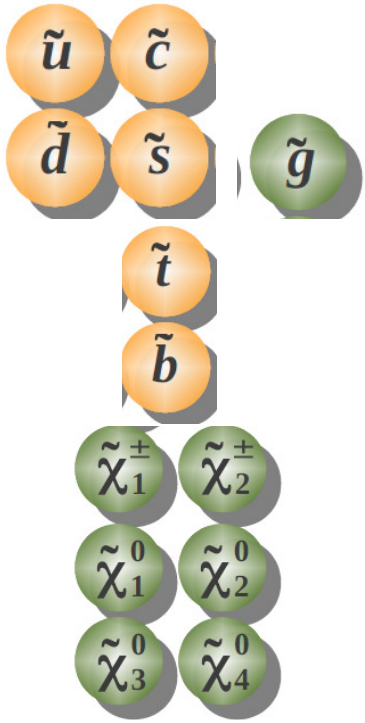
# SUSY and cosmology

- SUSY, or any unified theory, tends to have potential problems with explaining the non-observation of proton decay.
- For this reason, many versions of SUSY introduce a conserved quantity “ $R$ -parity”, which means that sparticles have to be produced in pairs.
- A consequence is that the lightest sparticle would have to be **stable**. In many scenarios this would be a “neutralino”  $\tilde{\chi}_1^0$  (a mixture of neutral “gauginos” and “Higgsinos”).
- Cosmologists tell us that  $\sim 25\%$  of the mass in the universe is in the form of “**dark matter**”, which interacts gravitationally, but otherwise only weakly.
- The lightest sparticle could be a candidate for the “WIMPs” (Weakly Interacting Massive Particles) which could comprise dark matter.
- So there are several different reasons why SUSY is attractive.



# However, no sign of supersymmetry yet...

On general grounds, some sparticles ought to be seen at energies around 1 TeV or lower. So LHC ought to be able to see them, especially squarks+gluinos (high  $\sigma$  @LHC).



ATLAS SUSY Searches\* - 95% CL Lower Limits  
June 2021

ATLAS Preliminary  
 $\sqrt{s} = 13$  TeV

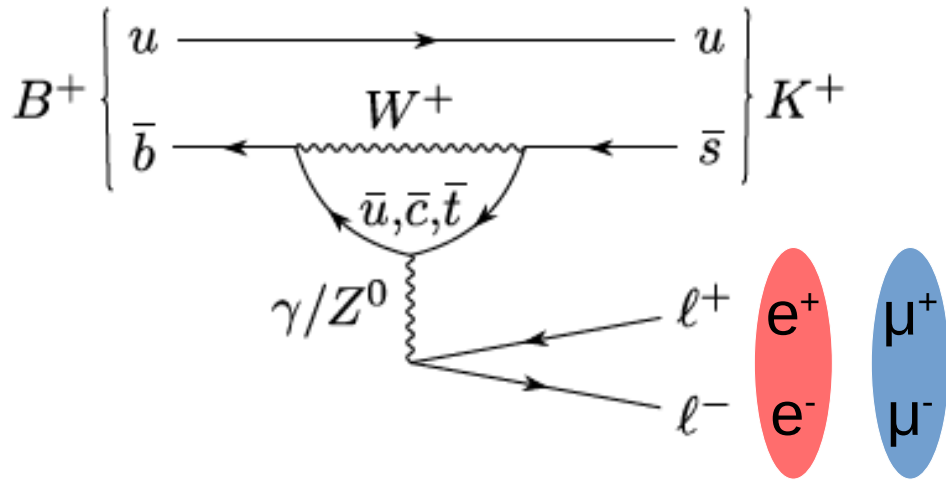
Model	Signature	$\int \mathcal{L} dt$ [fb $^{-1}$ ]	Mass limit	Reference						
Inclusive Searches	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 $e, \mu$ mono-jet	2-6 jets 1-3 jets	$E_T^{miss}$ 139 36.1	$\tilde{q}$ [1x, 8x Degen.] $\tilde{q}$ [8x Degen.]	1.0 0.9	1.85	$m(\tilde{\chi}_1^0) < 400$ GeV $m(\tilde{q})-m(\tilde{\chi}_1^0)=5$ GeV	2010.14293 2102.10874	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 $e, \mu$	2-6 jets	$E_T^{miss}$ 139	$\tilde{g}$ $\tilde{g}$	2.3 Forbidden	1.15-1.95	$m(\tilde{\chi}_1^0)=0$ GeV $m(\tilde{\chi}_1^0) < 1000$ GeV	2010.14293 2010.14293	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 $e, \mu$	2-6 jets	$E_T^{miss}$ 139	$\tilde{g}$	2.2		$m(\tilde{g})-m(\tilde{\chi}_1^0)=50$ GeV	2101.01629	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	$ee, \mu\mu$	2 jets	$E_T^{miss}$ 36.1	$\tilde{g}$	1.2		$m(\tilde{\chi}_1^0) < 600$ GeV	1805.11381	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	0 $e, \mu$	7-11 jets	$E_T^{miss}$ 139	$\tilde{g}$	1.15	1.97	$m(\tilde{\chi}_1^0) < 600$ GeV	2008.06032	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}WZ\tilde{\chi}_1^0$	SS $e, \mu$	6 jets	$E_T^{miss}$ 139	$\tilde{g}$	1.15	1.97	$m(\tilde{g})-m(\tilde{\chi}_1^0)=200$ GeV	1909.08457	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0-1 $e, \mu$ SS $e, \mu$	3 $b$ 6 jets	$E_T^{miss}$ 79.8 139	$\tilde{g}$ $\tilde{g}$	1.25	2.25	$m(\tilde{\chi}_1^0) < 200$ GeV $m(\tilde{g})-m(\tilde{\chi}_1^0)=300$ GeV	ATLAS-CONF-2018-041 1909.08457	
	$\tilde{b}_1\tilde{b}_1$	0 $e, \mu$	2 $b$	$E_T^{miss}$ 139	$\tilde{b}_1$ $\tilde{b}_1$	1.255 0.68		$m(\tilde{\chi}_1^0) < 400$ GeV 10 GeV $< \Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 20$ GeV	2101.12527 2101.12527	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0 \rightarrow bh\tilde{\chi}_1^0$	0 $e, \mu$ 2 $\tau$	6 $b$ 2 $b$	$E_T^{miss}$ 139 139	$\tilde{b}_1$ $\tilde{b}_1$	Forbidden	0.23-1.35	$\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=100$ GeV $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)=130$ GeV, $m(\tilde{\chi}_1^0)=0$ GeV	1908.03122 ATLAS-CONF-2020-031	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0-1 $e, \mu$	$\geq 1$ jet	$E_T^{miss}$ 139	$\tilde{t}_1$	1.25		$m(\tilde{\chi}_1^0)=1$ GeV	2004.14060,2012.03799	
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	1 $e, \mu$	3 jets/1 $b$	$E_T^{miss}$ 139	$\tilde{t}_1$	Forbidden	0.65	$m(\tilde{\chi}_1^0)=500$ GeV	2012.03799		
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tau b\nu, \tilde{t}_1 \rightarrow \tau\tilde{G}$	1-2 $\tau$	2 jets/1 $b$	$E_T^{miss}$ 139	$\tilde{t}_1$	Forbidden	1.4	$m(\tilde{\tau}_1)=800$ GeV	ATLAS-CONF-2021-008		
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 / \tilde{c}\tilde{c}, \tilde{c} \rightarrow \tau\tilde{\chi}_1^0$	0 $e, \mu$ 0 $e, \mu$	2 $c$ mono-jet	$E_T^{miss}$ 36.1 139	$\tilde{t}_1$ $\tilde{t}_1$	0.55	0.85	$m(\tilde{\chi}_1^0)=0$ GeV $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=5$ GeV	1805.01649 2102.10874		
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h\tilde{\chi}_1^0$	1-2 $e, \mu$	1-4 $b$	$E_T^{miss}$ 139	$\tilde{t}_1$	0.067-1.18		$m(\tilde{\chi}_2^0)=500$ GeV	2006.05880		
$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 + Z$	3 $e, \mu$	1 $b$	$E_T^{miss}$ 139	$\tilde{t}_1$	Forbidden	0.86	$m(\tilde{\chi}_1^0)=360$ GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^0)=40$ GeV	2006.05880		
EIV direct	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via WZ	Multiple $l$ /jets $ee, \mu\mu$	$\geq 1$ jet	$E_T^{miss}$ 139 139	$\tilde{\chi}_1^+ / \tilde{\chi}_2^0$ $\tilde{\chi}_1^+ / \tilde{\chi}_2^0$	0.205	0.96	$m(\tilde{\chi}_1^0)=0$ , wino-bino $m(\tilde{\chi}_1^+)-m(\tilde{\chi}_1^0)=5$ GeV, wino-bino	2106.01676, ATLAS-CONF-2021-022 1911.12606	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^+$ via WW	2 $e, \mu$		$E_T^{miss}$ 139	$\tilde{\chi}_1^+$	0.42		$m(\tilde{\chi}_1^0)=0$ , wino-bino	1908.08215	
	$\tilde{\chi}_1^+ \tilde{\chi}_2^0$ via Wb	Multiple $l$ /jets		$E_T^{miss}$ 139	$\tilde{\chi}_1^+ / \tilde{\chi}_2^0$	Forbidden	1.06	$m(\tilde{\chi}_1^0)=70$ GeV, wino-bino	2004.10894, ATLAS-CONF-2021-022	
	$\tilde{\chi}_1^+ \tilde{\chi}_1^+$ via $\tilde{\ell}_L/\tilde{\nu}$	2 $e, \mu$		$E_T^{miss}$ 139	$\tilde{\chi}_1^+$	1.0		$m(\tilde{\ell}, \tilde{\nu})=0.5m(\tilde{\chi}_1^+)+m(\tilde{\ell}_L^0)$	1908.08215	
	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	2 $\tau$		$E_T^{miss}$ 139	$\tilde{\tau}$	0.16-0.3	0.12-0.39	$m(\tilde{\tau}_1^0)=0$	1911.06660	
	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$ $ee, \mu\mu$	0 jets $\geq 1$ jet	$E_T^{miss}$ 139 139	$\tilde{\ell}$ $\tilde{\ell}$	0.256	0.7	$m(\tilde{\chi}_1^0)=0$ $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=10$ GeV	1908.08215 1911.12606	
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 $e, \mu$ 4 $e, \mu$ 0 $e, \mu$	$\geq 3$ $b$ 0 jets $\geq 2$ large jets	$E_T^{miss}$ 36.1 139 139	$\tilde{H}$ $\tilde{H}$ $\tilde{H}$	0.13-0.23	0.29-0.88	$BR(\tilde{\chi}_1^0 \rightarrow h\tilde{G})=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	1806.04030 2103.11684 ATLAS-CONF-2021-022	
	Long-lived particles	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^+$ prod., long-lived $\tilde{\chi}_1^+$	Disapp. trk	1 jet	$E_T^{miss}$ 139	$\tilde{\chi}_1^+$ $\tilde{\chi}_1^+$	0.21	0.66	Pure Wino Pure higgsino	ATLAS-CONF-2021-015 ATLAS-CONF-2021-015
		Stable $\tilde{g}$ R-hadron	Multiple		36.1	$\tilde{g}$	2.0			1902.01636,1808.04095
		Metastable $\tilde{g}$ R-hadron, $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	Multiple		36.1	$\tilde{g}$	[ $\tau(\tilde{g})=10$ ns, 0.2 ns]	2.05 2.4	$m(\tilde{\chi}_1^0)=100$ GeV	1710.04901,1808.04095
RPV	$\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_1^0, \tilde{\chi}_1^+ \rightarrow Z\ell + \ell\ell\ell$	3 $e, \mu$		$E_T^{miss}$ 139	$\tilde{\chi}_1^+ / \tilde{\chi}_1^0$	[BR(Z $\tau$ )=1, BR(Z $e$ )=1]	0.625	1.05	Pure Wino	2011.10543
	$\tilde{\chi}_1^+ \tilde{\chi}_1^+ / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\nu\nu$	4 $e, \mu$	0 jets	$E_T^{miss}$ 139	$\tilde{\chi}_1^+ / \tilde{\chi}_2^0$	[ $a_{33} \neq 0, a_{132} \neq 0$ ]	0.95	1.55	$m(\tilde{\chi}_1^0)=200$ GeV	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q\tilde{q}q$	Multiple	4-5 large jets	36.1	$\tilde{g}$	[ $m(\tilde{\chi}_1^0)=200$ GeV, 1100 GeV]	1.3	1.9	Large $\mathcal{J}_{112}^0$	1804.03568
	$\tilde{u}, \tilde{t} \rightarrow t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow tbs$	Multiple		36.1	$\tilde{u}$	[ $\mathcal{K}_{231}^0=2e-4, 1e-2$ ]	0.55	1.05	$m(\tilde{\chi}_1^0)=200$ GeV, bino-like	ATLAS-CONF-2018-003
	$\tilde{u}, \tilde{t} \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow bbs$	Multiple	$\geq 4$ $b$	139	$\tilde{u}$	Forbidden	0.95	$m(\tilde{\chi}_1^0)=500$ GeV	2010.01015	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow bs$	2 $e, \mu$	2 jets + 2 $b$	36.7	$\tilde{t}_1$	[ $qq, bs$ ]	0.42	0.61		1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 $e, \mu$ 1 $\mu$	2 $b$ DV	36.1 136	$\tilde{t}_1$ $\tilde{t}_1$	[ $1e-10 < \mathcal{K}_{231}^0 < 1e-8, 3e-10 < \mathcal{K}_{232}^0 < 3e-9$ ]	1.0	0.4-1.45	$BR(\tilde{t}_1 \rightarrow b\ell/hp) > 20\%$ $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%, \cos\theta_{\mu} = 1$	1710.05544 2003.11956
	$\tilde{\chi}_1^+ \tilde{\chi}_2^0 / \tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^+ \rightarrow bbs$	1-2 $e, \mu$	$\geq 6$ jets	139	$\tilde{\chi}_1^0$	0.2-0.32		Pure higgsino	ATLAS-CONF-2021-007	

\*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models of supersymmetry.

# Signs of anything else?

(non-examinable)

## LHCb Flavour Anomalies



Lepton universality in SM predicts  $R = \frac{\mu\mu}{ee} = 1$

Test using rare decays of  $B$  mesons

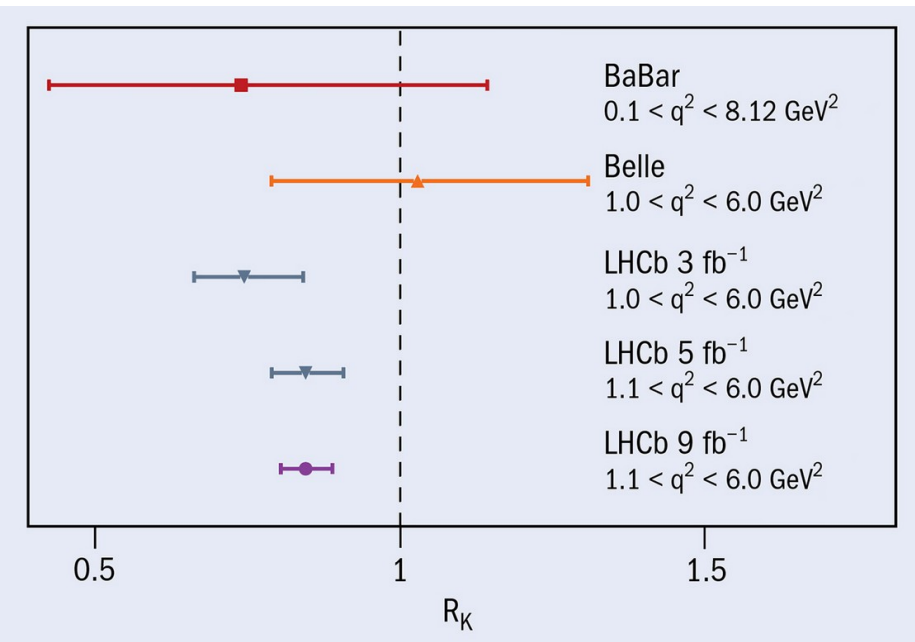
- easy to see deviations from small values
- precise theory predictions

$$R_K = 0.85 \pm 0.04(\text{stat.}) \pm 0.01(\text{syst.})$$

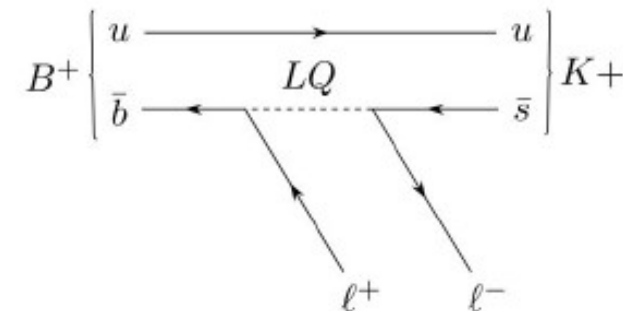
3 standard deviations from prediction.  
Evidence of something new!

*5 std.dev is gold standard for discovery.*

Similar effects seen in several rare decay modes.



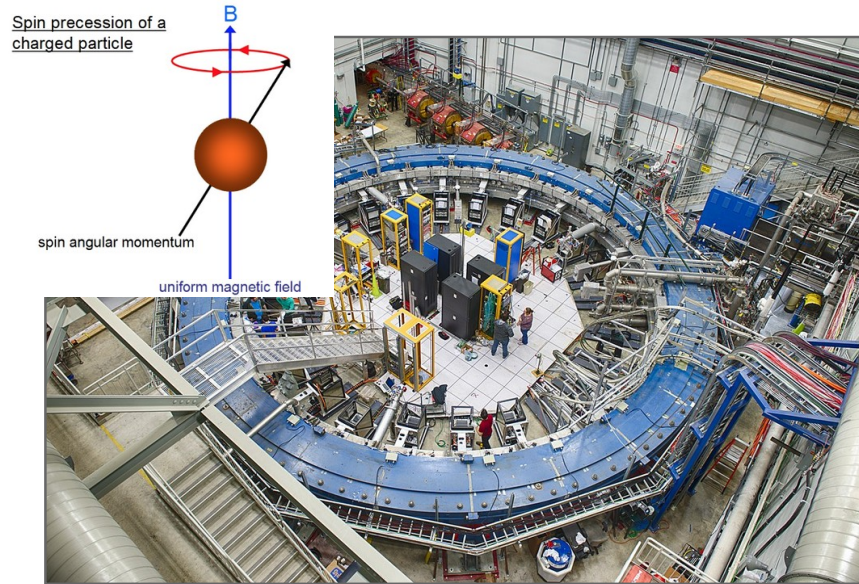
This might be the first glimpse of new particles affecting decay rates, e.g. Leptoquarks



# Signs of anything else?

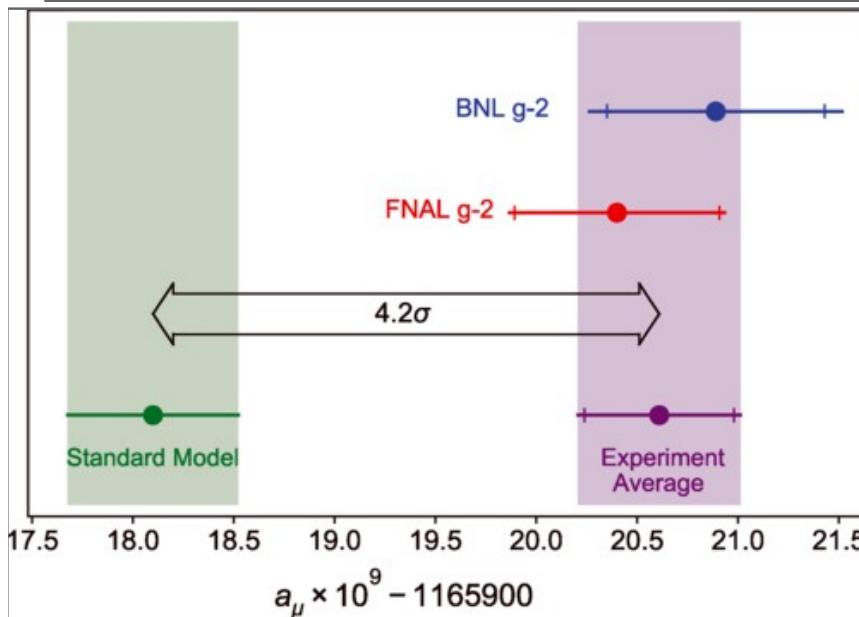
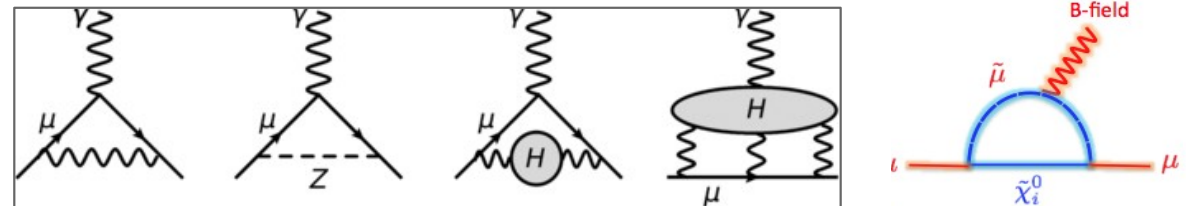
(non-examinable)

## Muon g-2 Anomaly



Measure muon spin precession in magnetic field. Precision test of QED – precession frequency depends on how much it interacts with the magnetic field.

All known particles contribute to the muon's magnetic moment. Measure this very precisely and look for deviations.



20 year anomaly has been confirmed with a new measurement at Fermilab – measured muon magnetic moment to 0.46 ppm.

4.2 standard deviations from prediction.

Evidence of something new! Perhaps smuons?

# Follow the results from LHC yourself!

To date (2024) LHC has taken only  $\sim 5\%$  of its planned total dataset.  
Stay tuned!!

<http://atlas.ch>

<http://cms.web.cern.ch>

<http://lhcb-public.web.cern.ch/lhcb-public/>

# Summary

- Over the past 50 years our understanding of the fundamental particles and forces of nature has changed beyond recognition.
- The Standard Model of particle physics is an enormous success. It has been tested to very high precision and can model **almost all** experimental observations so far.
- The Higgs “hole” is now becoming closed, though some other aspects of the SM are not quite yet under as much experimental “control” as one might wish for (the neutrino sector, the CKM matrix, etc).
- Good reasons to expect that the next few years will bring many more (un)expected surprises (more Higgs or gauge bosons, SUSY?).

Problem Sheet: q.29-30

Up next...

Section 13: Nuclear Physics, Basic Nuclear Properties