Section X
The Standard Model and Beyond

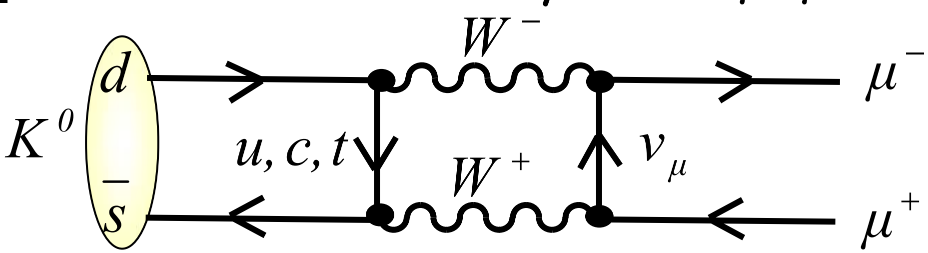
The Top Quark

The Standard Model predicts the existence of the TOP quark

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{matrix} +2/3\,e \\ -1/3\,e \end{matrix}$$

which is required to explain a number of observations.

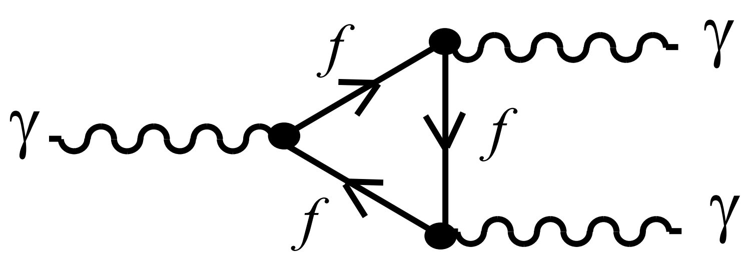
<u>Example:</u> Absence of the decay $K^0 \to \mu^+\mu^-$



$$B\left(K^0 \to \mu^+\mu^-\right) < 10^{-9}$$

The top quark cancels the contributions from the u, c quarks.

<u>Example:</u> Electromagnetic anomalies



This diagram leads to infinities in the theory unless

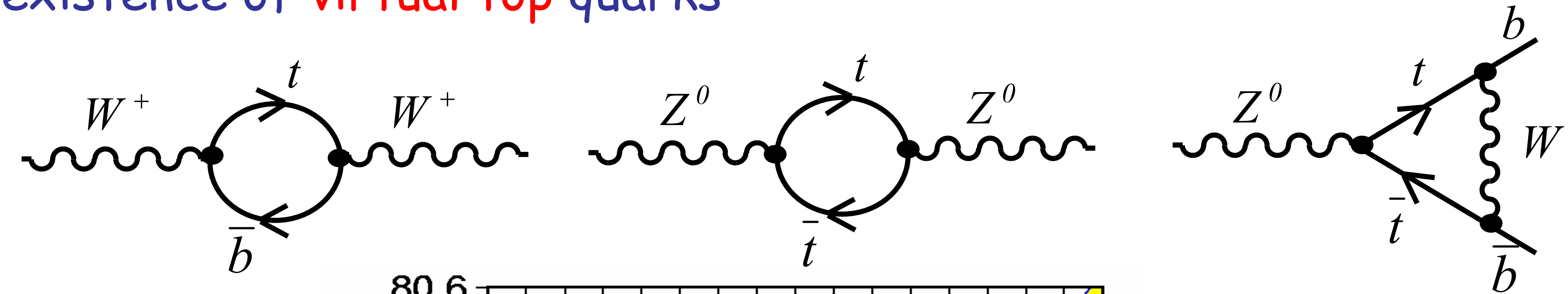
$$\sum_f Q_f = 0$$

where the sum is over all fermions (and colours)

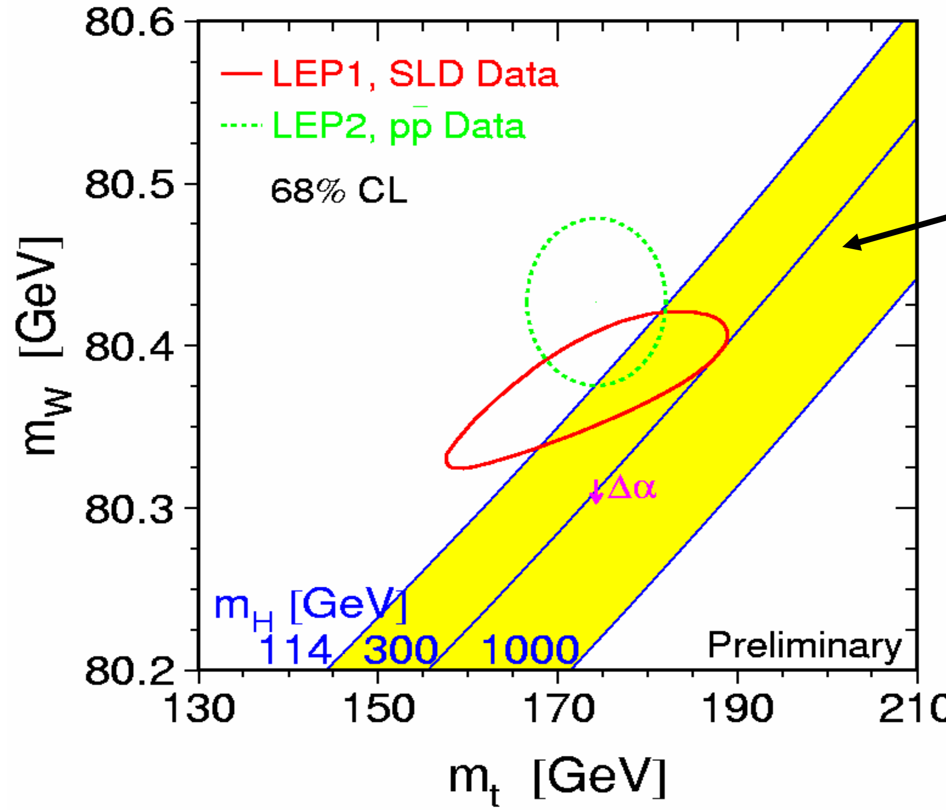
$$\sum_f Q_f = \left[3\times(-1)\right] + \left[3\times 3\times \tfrac{2}{3}\right] + \left[3\times 3\times\left(-\tfrac{1}{3}\right)\right] = 0$$

At LEP, m_t too heavy for $Z^0 \to t\bar{t}$ or $W \to t\bar{b}$

However, measurements of M_Z, M_W, Γ_Z and Γ_W are sensitive to the existence of virtual top quarks



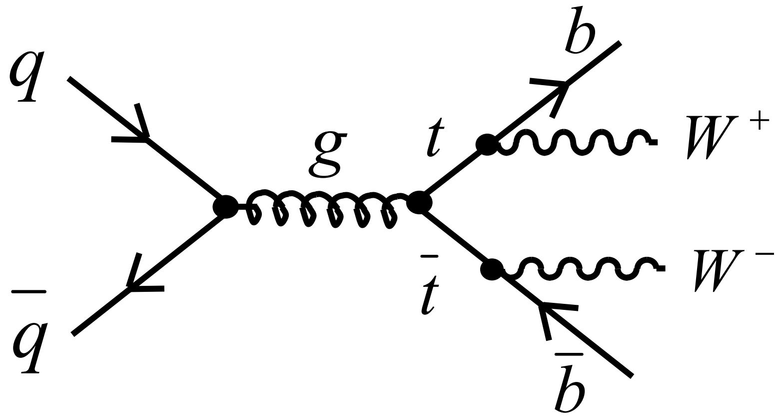
Example:



Standard Model prediction

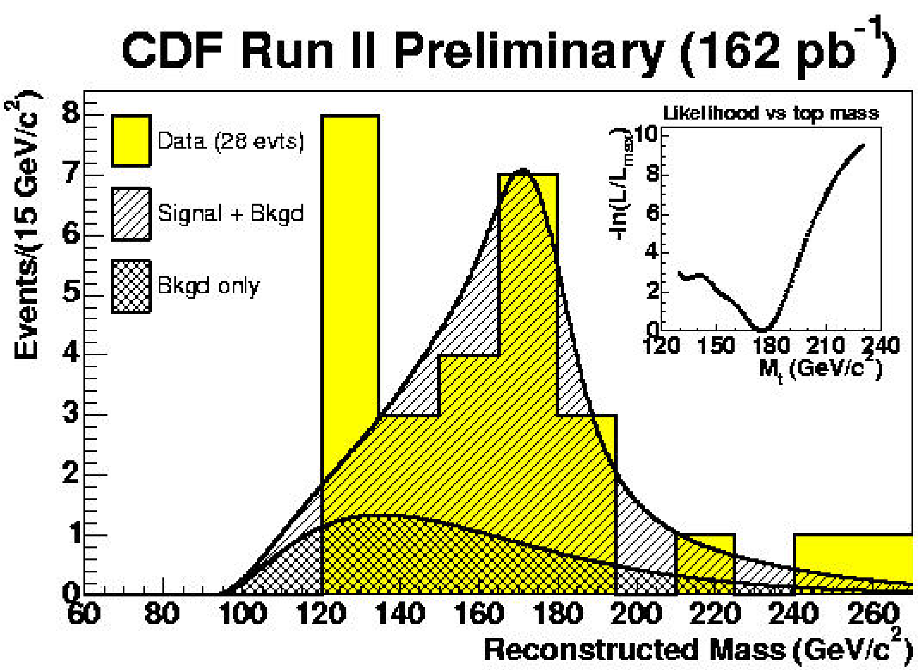
Also depends on the Higgs mass

The top quark was discovered in 1994 by the CDF experiment at the worlds highest energy $p\bar{p}$ collider ($\sqrt{s} = 1.8\,\text{TeV}$), the Tevatron at Fermilab, US.



Final state $W^+W^-b\bar{b}$

Mass reconstructed in a similar manner to M_W at LEP, i.e. measure jet/lepton energies/momenta.



$$m_{top} = (178 \pm 4.3)\,\text{GeV}$$

Most recent result 2005

The Standard Model c. 2006

<u>MATTER:</u> Point-like spin ½ Dirac fermions.

	Fermion		Charge/e	Mass
1st Generation	Electron	e^-	-1	0.511 MeV
	Electron neutrino	ν_e	0	0?
	Down quark	d	-1/3	0.35 GeV
	Up quark	u	+2/3	0.35 GeV
2nd Generation	Muon	μ^-	-1	0.106 GeV
	Muon neutrino	ν_μ	0	0?
	Strange quark	s	-1/3	0.5 GeV
	Charm quark	c	+2/3	1.5 GeV
3rd Generation	Tau	τ	-1	1.8 GeV
	Tau neutrino	ν_τ	0	0?
	Bottom quark	b	-1/3	4.5 GeV
	Top quark	t	+2/3	178 GeV

and

ANTI-PARTICLES

FORCES: Mediated by spin 1 bosons

Force	Particle(s)	Mass
Electromagnetic	Photon	0
Strong	8 Gluons	0
Weak (CC)	$W^{\pm}$	80.4 GeV
Weak (NC)	Z^0	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.

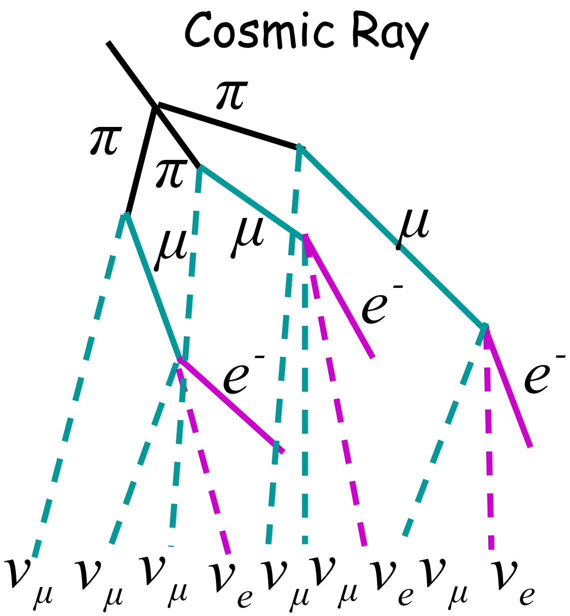
- The Standard Model successfully describes ALL existing particle physics data, with the exception of one

$\Rightarrow$ Neutrino Oscillations $\Rightarrow$ Neutrinos have mass

First indication of physics BEYOND THE STANDARD MODEL

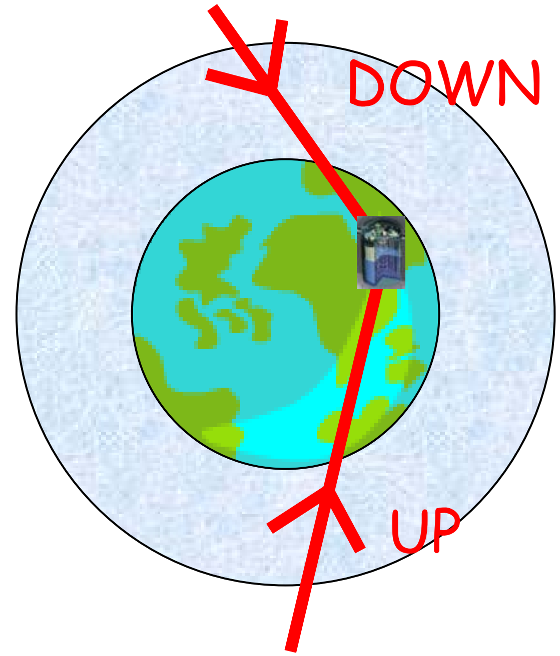
Atmospheric Neutrino Oscillations

In 1998 the Super-Kamiokande experiment announced convincing evidence for NEUTRINO OSCILLATIONS implying that neutrinos have mass.



$$\pi \to \mu\, \nu_\mu$$
$$\mu \to e\, \nu_\mu\, \bar{\nu}_e$$

$$\text{Expect} \quad \frac{N_{\nu_\mu}}{N_{\nu_e}} \approx 2$$



Super-Kamiokande results indicate a deficit of ν_μ from the upwards direction.

- Interpreted as $\nu_\mu \to \nu_\tau$ 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. $\nu_e + N \rightarrow e^- + X$ $\qquad \bar{\nu}_\mu + N \rightarrow \mu^+ + X$

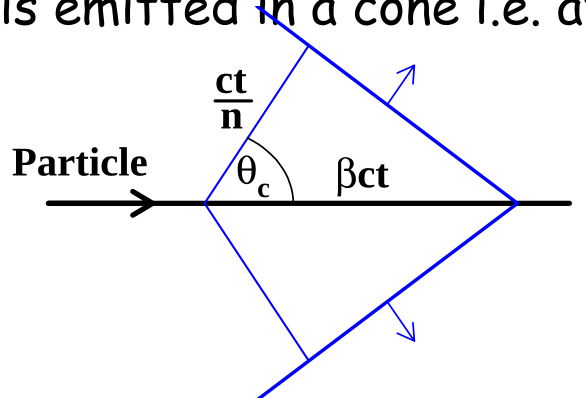
<u>Size Matters:</u>

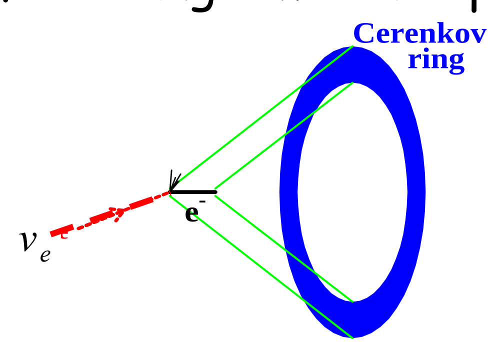
- Neutrino mean free path in water ~ light-years.
- Require very large mass, cheap and simple detectors
- Water Cherenkov detection

<u>Cherenkov radiation</u>

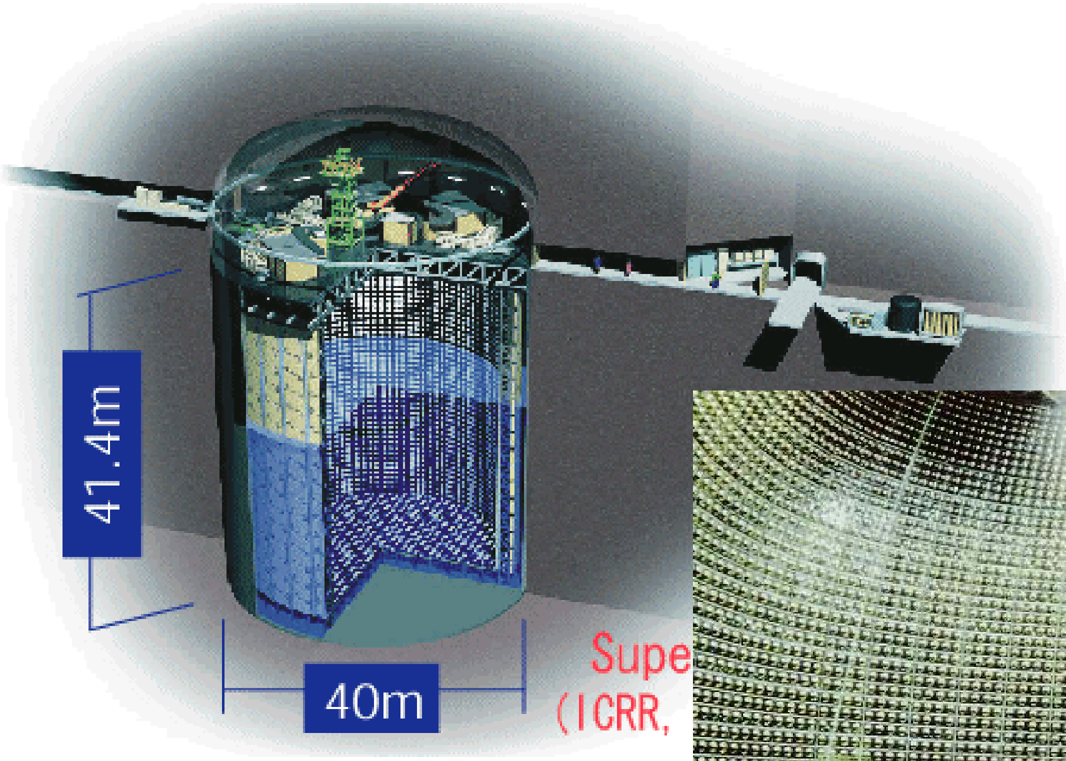
- Light is emitted when a charged particle traverses a dielectric medium
- A coherent wavefront forms when the velocity of a charged particle exceeds c/n (n = refractive index)
- Cherenkov radiation is emitted in a cone i.e. at fixed angle with respect to the particle.

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

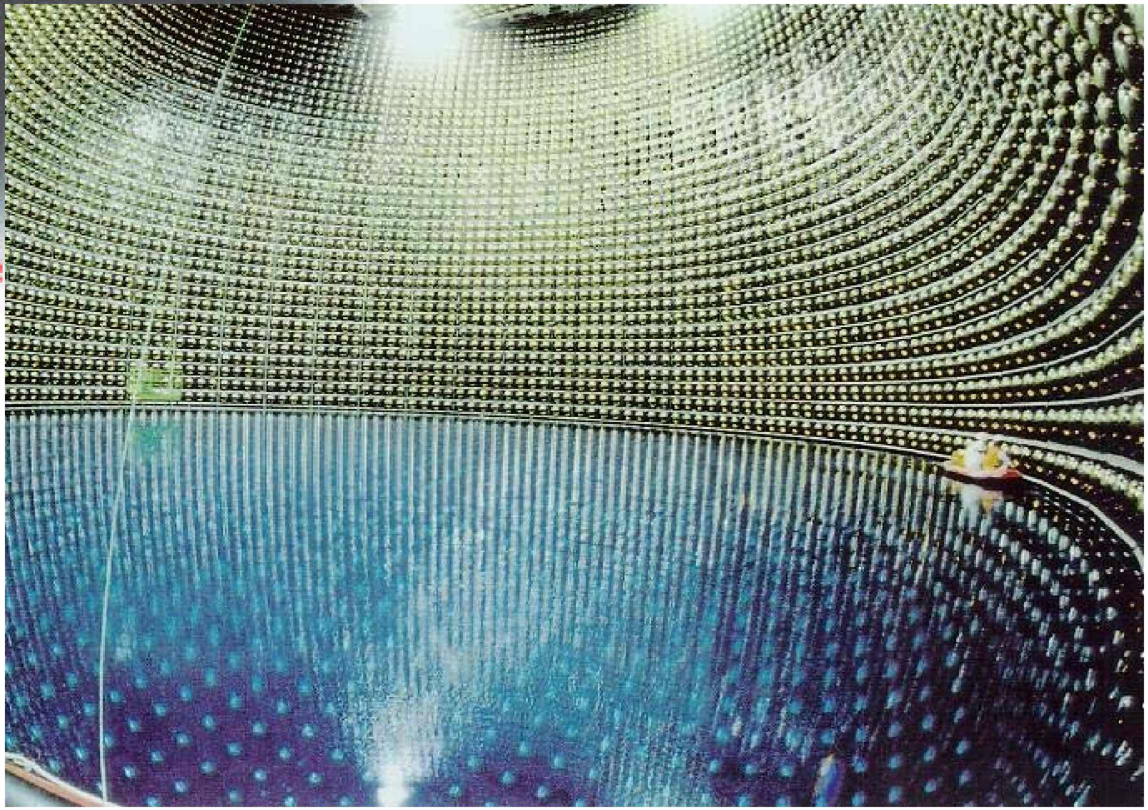




Super-Kamiokande



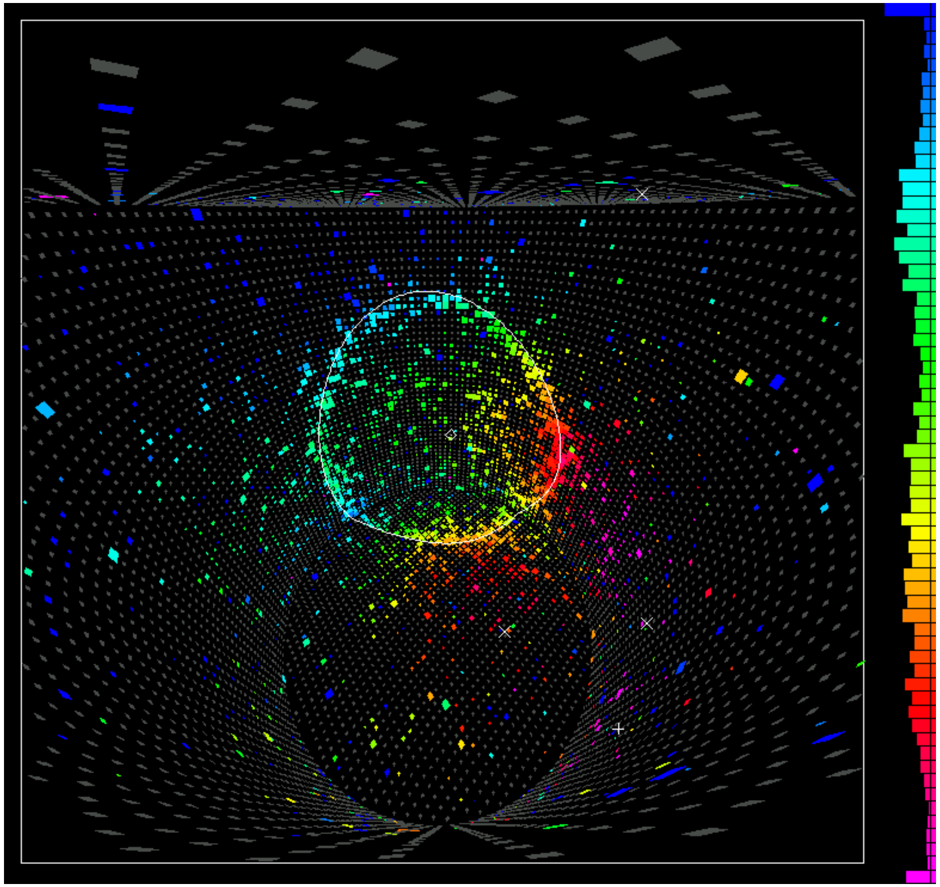
Super-Kamiokande is a water Cherenkov detector sited in Kamioka, Japan



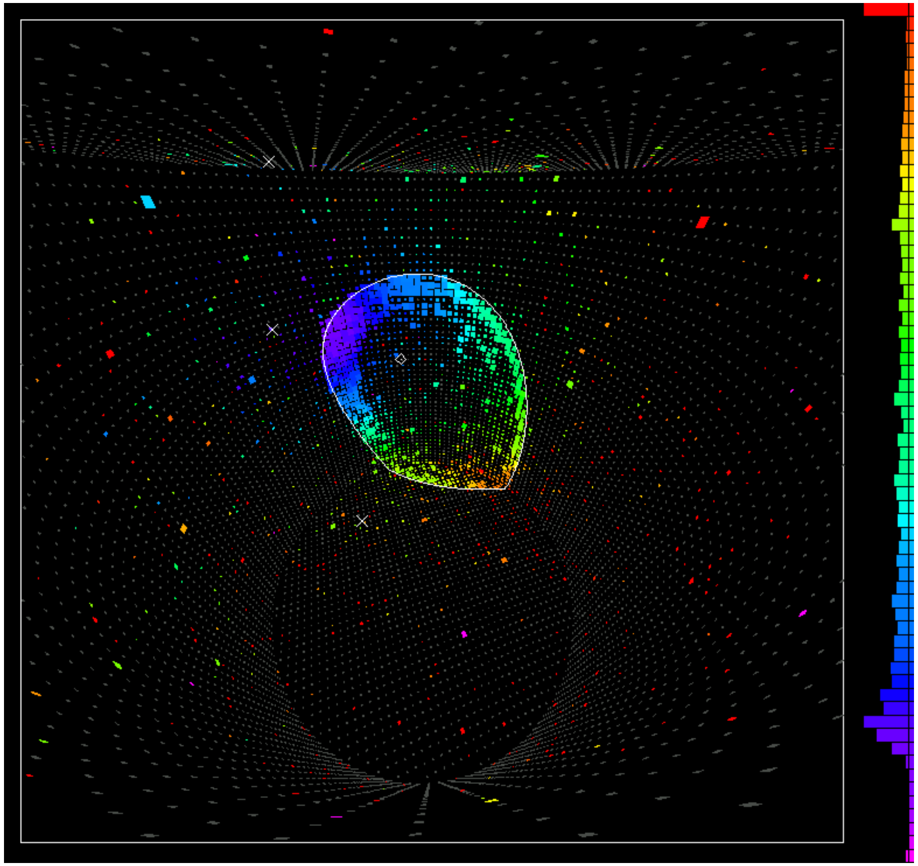
- 50,000 tons of water
- Surrounded by 11,146, 50 cm diameter, photo-multiplier tubes

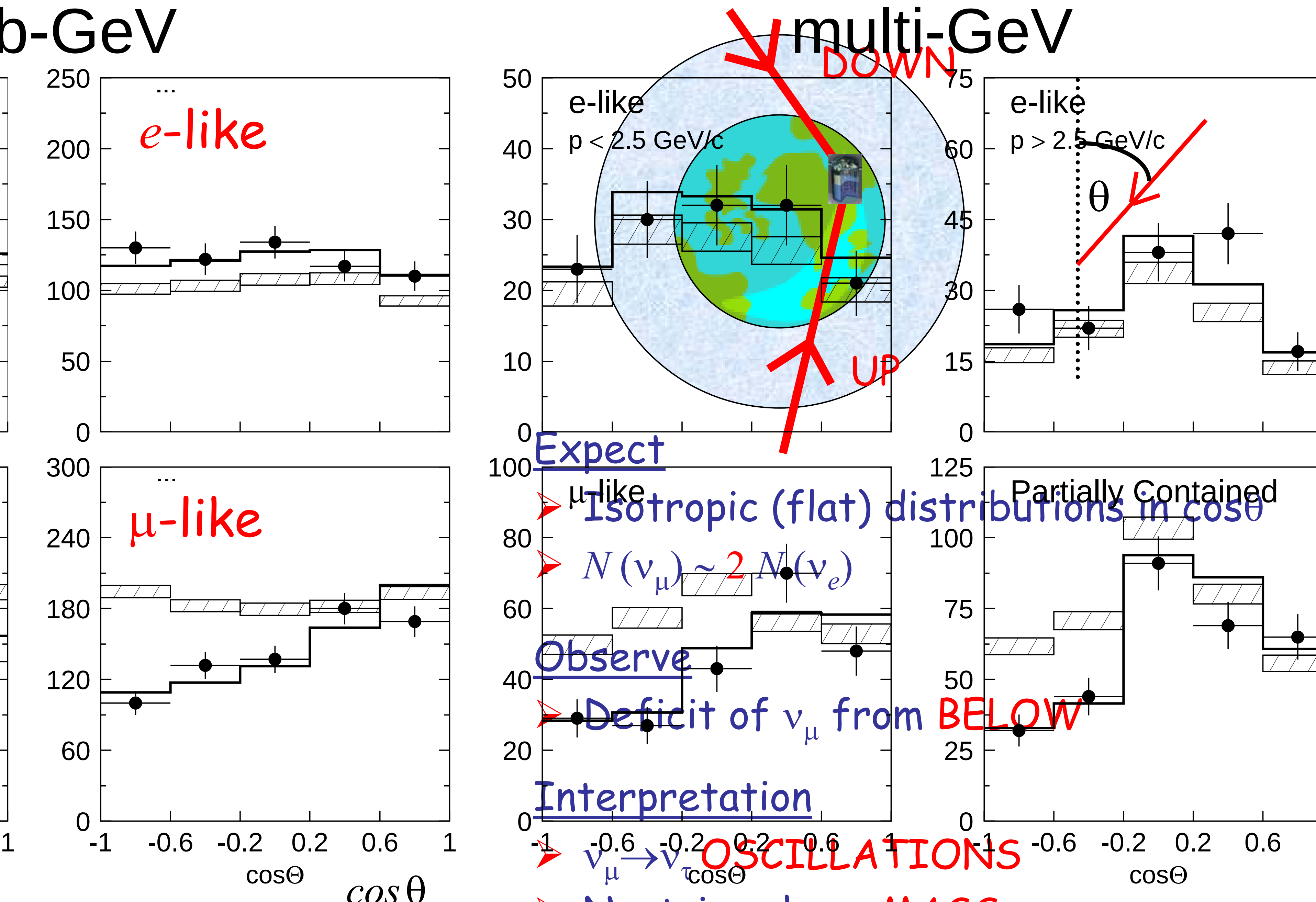
Example of events:

$$\nu_e + N \rightarrow e^- + X$$



$$\nu_\mu + N \rightarrow \mu^- + X$$





Expect

- Isotropic (flat) distributions in cosθ
- $N(\nu_\mu) \sim 2\, N(\nu_e)$

Observe

- Deficit of ν_μ from BELOW

Interpretation

- $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS
- 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
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\vartheta_C & \sin\vartheta_C \\ -\sin\vartheta_C & \cos\vartheta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$
Mass Eigenstates

ϑ_C = Cabibbo angle

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

Weak Eigenstates
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$
Mass Eigenstates

ϑ = Mixing angle

- e.g. in π^+ decay produce μ^+ and ν_μ i.e. the state that couples to the weak interaction. The ν_μ corresponds to a linear combination of the states with definite mass, ν_1 and ν_2

$$\nu_e = +\cos\vartheta\, \nu_1 + \sin\vartheta\, \nu_2$$
$$\nu_\mu = -\sin\vartheta\, \nu_1 + \cos\vartheta\, \nu_2$$

or expressing the mass eigenstates in terms of the weak eigenstates

$$\nu_1 = +\cos\vartheta\, \nu_e - \sin\vartheta\, \nu_\mu$$

$$\nu_2 = +\sin\vartheta\, \nu_e + \cos\vartheta\, \nu_\mu$$

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

At $t = 0$, the wavefunction

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

The time dependent parts of the wavefunction are given by

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

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

After time t,

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

Probability of oscillating into ν_e

$$P(\nu_e) = |c_e|^2 = \left[\sin\vartheta\cos\vartheta\left(e^{-iE_2 t} - e^{-iE_1 t}\right)\right]^2$$

$$= \frac{1}{4}\sin^2 2\vartheta\left(e^{-iE_2 t} - e^{-iE_1 t}\right)\left(e^{iE_2 t} - e^{iE_1 t}\right)$$

$$= \frac{1}{4}\sin^2 2\vartheta\left(2 - e^{i(E_2-E_1)t} - e^{-i(E_2-E_1)t}\right)$$

$$= \sin^2 2\vartheta \sin^2\left[\frac{(E_2 - E_1)t}{2}\right]$$

But $E = \left(p^2 + m^2\right)^{1/2} = p\left(1 + \frac{m^2}{p^2}\right)^{1/2} \approx p + \frac{m^2}{2p}$ for m << E

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

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

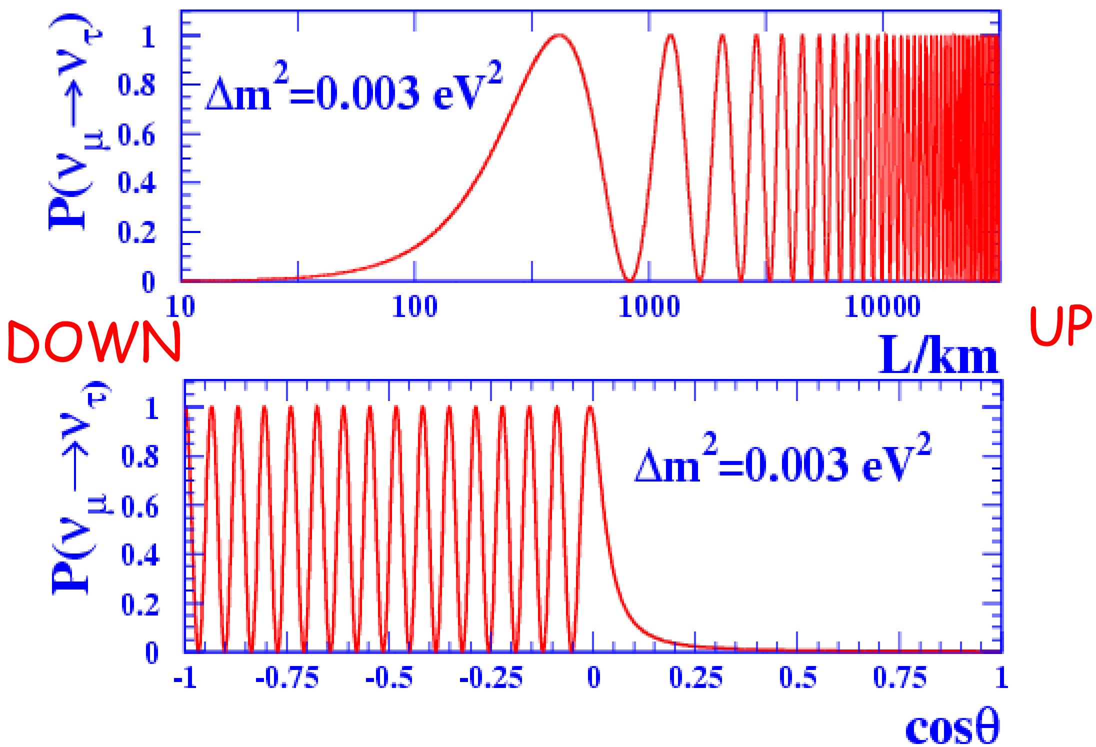
Equivalent expression for $\nu_\mu \to \nu_\tau$

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\vartheta \sin^2\left[\frac{1.27\left(m_3^2 - m_2^2\right)L}{E_\nu}\right]$$

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

Interpretation of Super-Kamiokande Results

For $E_{\nu_\mu} = 1\,\mathrm{GeV}$ (typical of atmospheric neutrinos)



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

$$\left|m_3^2 - m_2^2\right| \sim 2.5\times10^{-3}\ \text{eV}^2$$
$$\sin^2 2\theta \approx 1$$

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)

See nuclear physics

suggest $\left|m_2^2 - m_1^2\right| \approx 10^{-5}\ \text{eV}^2$

- IF mass states $\nu_3 > \nu_2 > \nu_1$, then

$$m_{\nu_3} \sim \sqrt{2.5\times10^{-3}}\ \text{eV} \sim 0.05\ \text{eV}$$
$$m_{\nu_2} \sim \sqrt{10^{-5}}\ \text{eV} \sim 0.003\ \text{eV}$$

Problems with the Standard Model

The Standard Model successfully describes ALL existing particle physics data (with the exception of neutrino oscillations).

BUT: many input parameters: Quark and lepton masses
Quark charges
Couplings $\alpha_{em}, sin^2\vartheta_W, \alpha_s$
Quark generation mixing

AND: many unanswered questions:

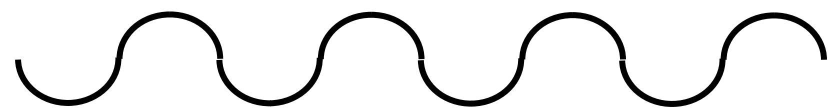
- Why so many free parameters ?
- Why only 3 generations of quarks and leptons ?
- Where does mass come from ? (Higgs boson?)
- Why is the neutrino mass so small and the top quark mass so large ?
- Why are the charges of the p and e identical ?
- What is responsible for the observed matter-antimatter asymmetry ?
- How can we include gravity ?

etc

The Higgs Mechanism

The Higgs mechanism introduces a NEW (Higgs) field into the vacuum which interacts with particles that propagate through it.

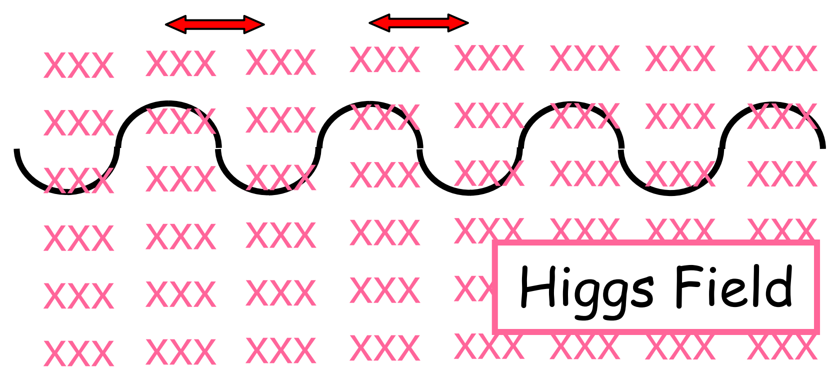
Classical Vacuum



Massless particle

Boundary conditions at $\pm\infty$

Higgs Vacuum

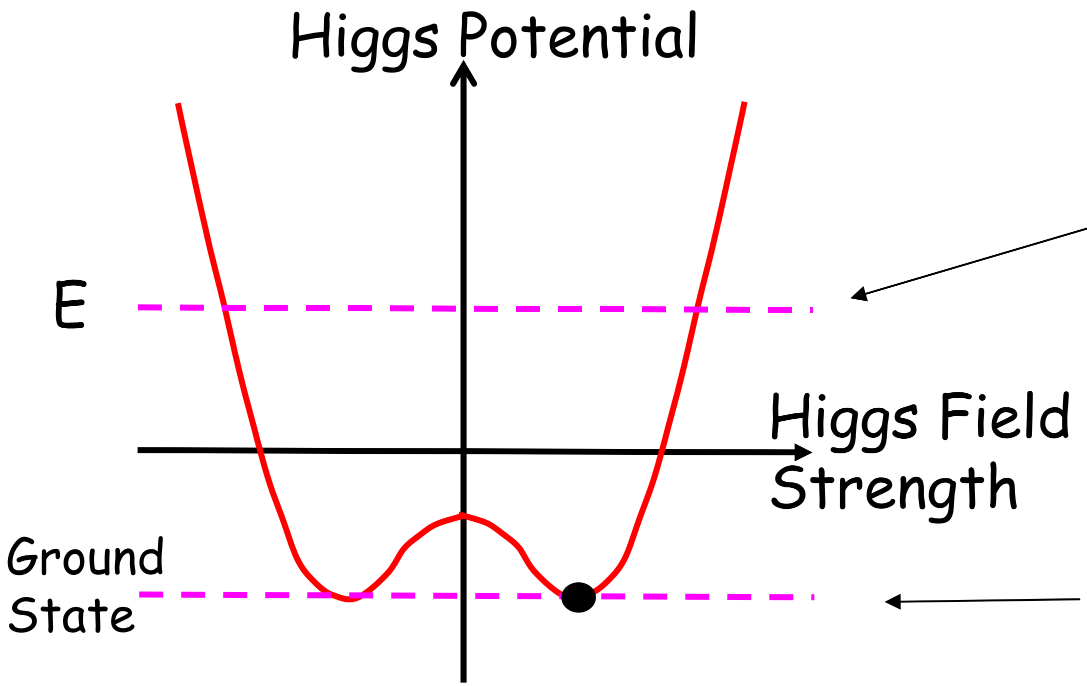


Particle induces currents in the Higgs field which modifies the form of the particle wavefunction and hence its propagation. Particle appears to have MASS due to interaction.

Local boundary conditions.

The combined massless particle + Higgs system behaves identically to a MASSIVE particle in a classical vacuum.

The Higgs Potential



At HIGH temp, average Higgs field in vacuum is zero. Massless particles.

At LOW temp, Higgs field is non-zero everywhere. Particles acquire MASS.

Consequences

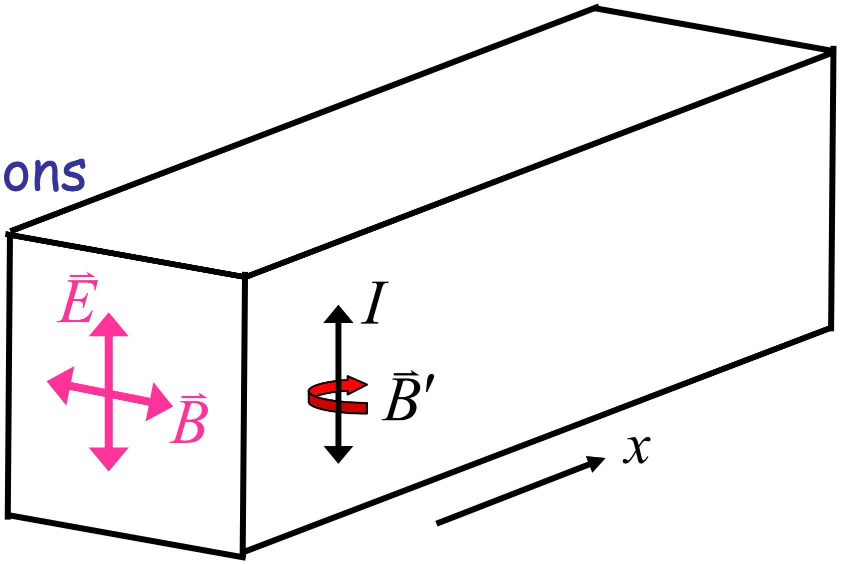
- Particles travelling through the Higgs field acquire MASS via their interactions with it.
- The quantum associated with the Higgs field is a neutral spin 0 boson $\Rightarrow$ HIGGS BOSON
- For the theory to be calculable, requires the Higgs boson to be discovered with an energy scale ≤ 1 TeV

ANALOGY: Photon in a waveguide.

- Consider a plane polarized photon in vacuum. Boundary conditions at ∞. The wavefunction has the form

$$\psi \sim e^{i(\omega t - kx)}$$

- When the photon enters a waveguide, need to satisfy local boundary conditions



- $\vec{E}$ sets up current I in walls and I induces a $\vec{B}$ field which oscillates along direction of motion.

- The form of the photon wavefunction becomes

$$\psi \sim e^{-k'x}$$

and the photon no longer propagates beyond $\sim 1/k'$

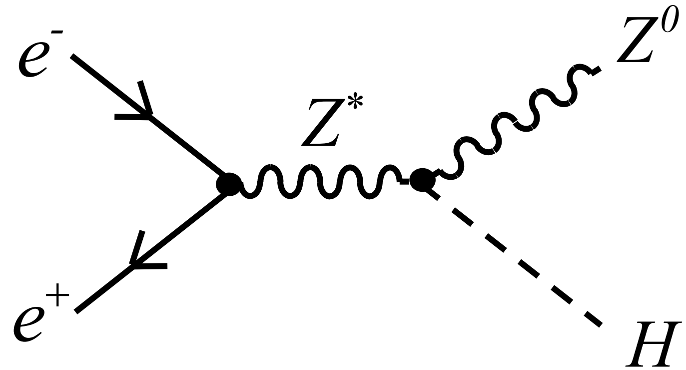
- For a massive virtual particle, range $\sim 1/m$

$\Rightarrow$ Photon behaves like a MASSIVE particle

Higgs at LEP

Higgs Production at LEP

IF $M_H < \sqrt{s} - M_Z$



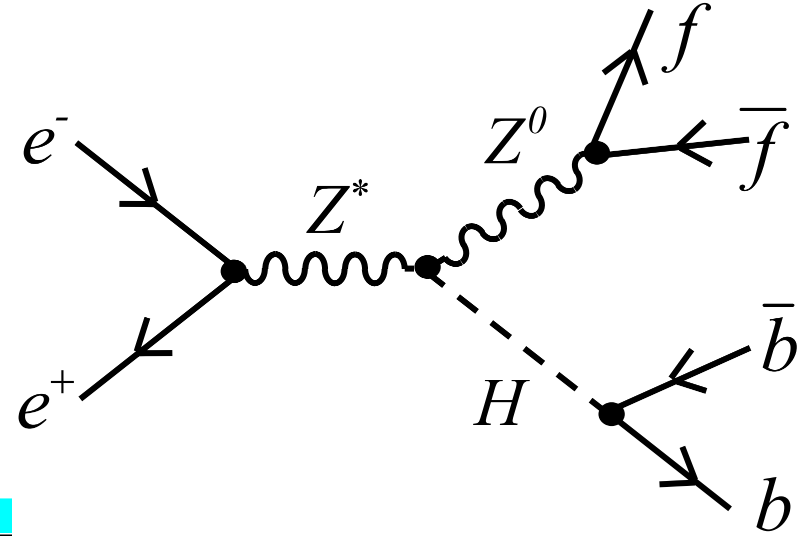
In 2000, LEP operated with $\sqrt{s} \approx 207\ \mathrm{GeV}$, therefore had the potential to discover Higgs boson IF $M_H < 116\ \mathrm{GeV}$

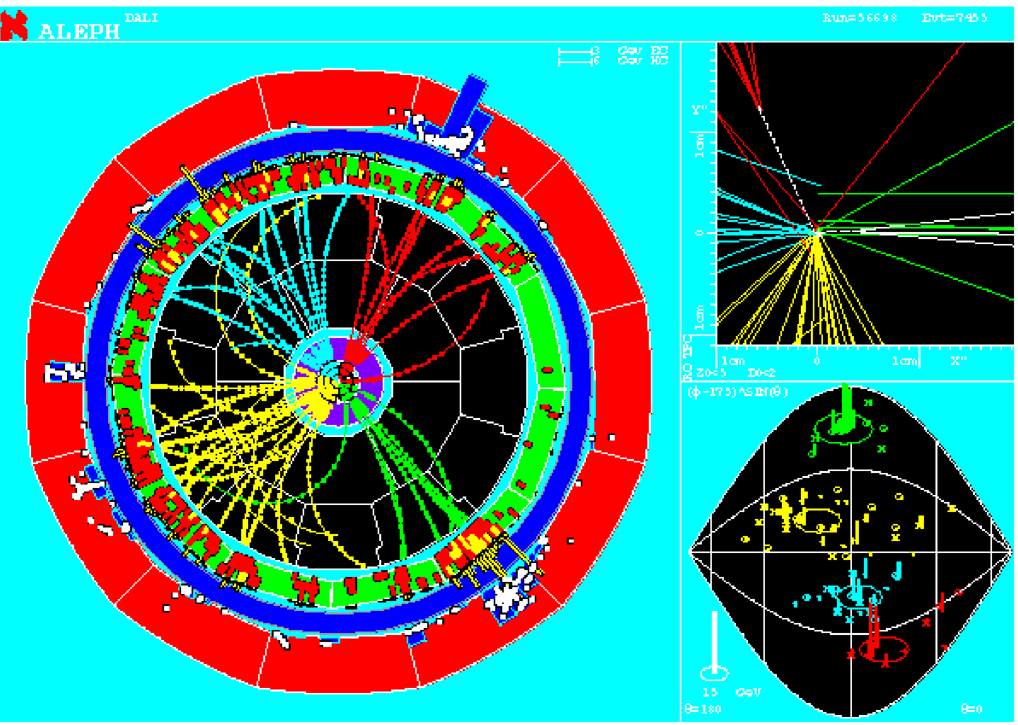
Higgs Decay

- The Higgs boson couples to mass
- Hence, partial widths proportional to m^2 of particle involved
- The Higgs boson decays preferentially to the most massive particle kinematically allowed
- For $M_H < 116\ \mathrm{GeV}$ this is the b quark

At LEP search for

$$e^+e^- \rightarrow H^0 Z^0 \rightarrow b\bar{b}\, f\bar{f}$$





4 possible $e^+e^- \rightarrow H^0 Z^0$ events observed in the final year of LEP operation, consistent with

$$M_H = 115 \text{ GeV}$$

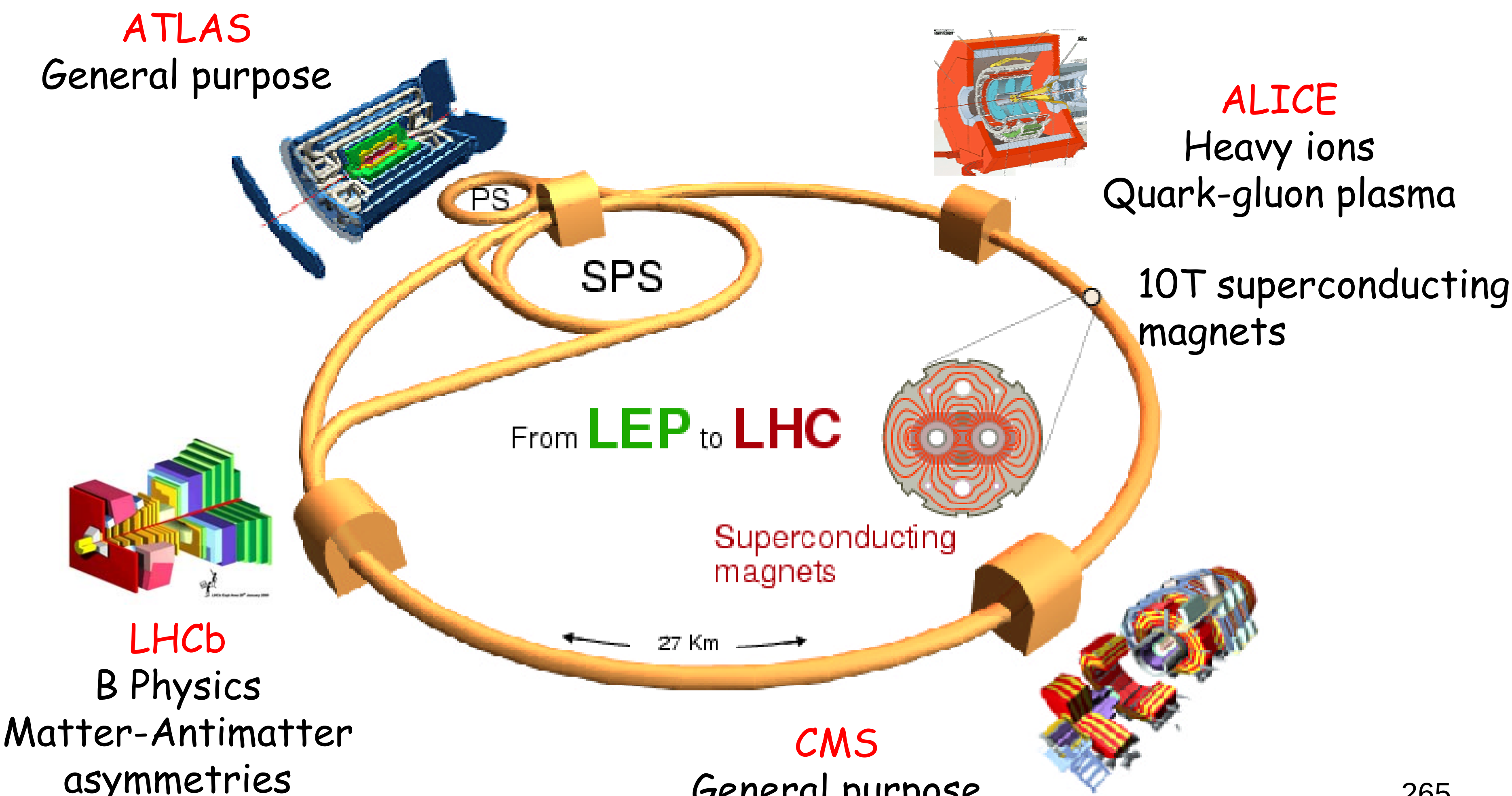
The evidence is tantalizing
BUT FAR FROM conclusive

$\Rightarrow$ LARGE HADRON COLLDER (2007)

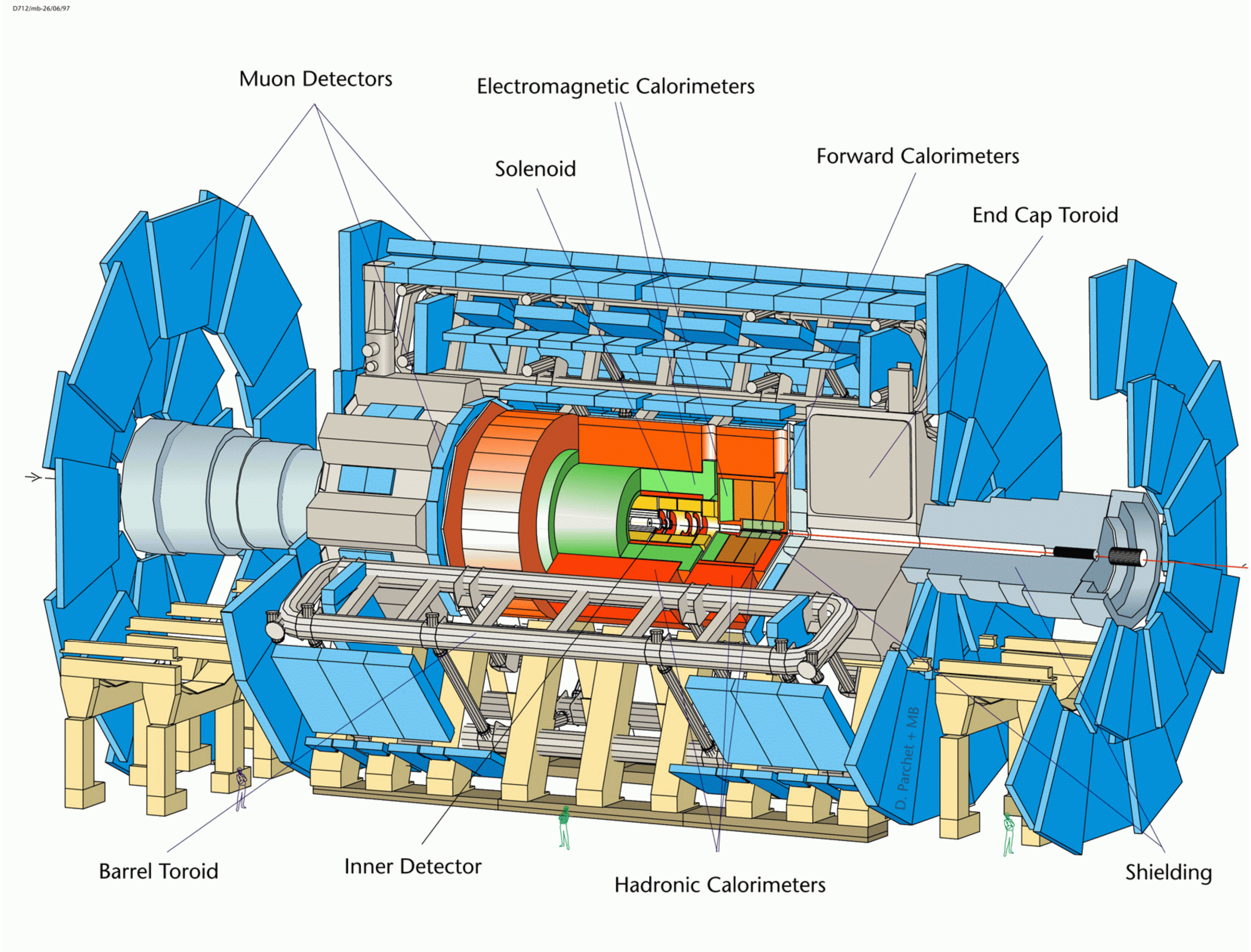
The Large Hadron Collider

The LHC is a new proton-proton collider being constructed in the LEP tunnel at CERN.

$$7\ \text{TeV} + 7\ \text{TeV}: \quad \sqrt{s} = 14\ \text{TeV}$$



ATLAS



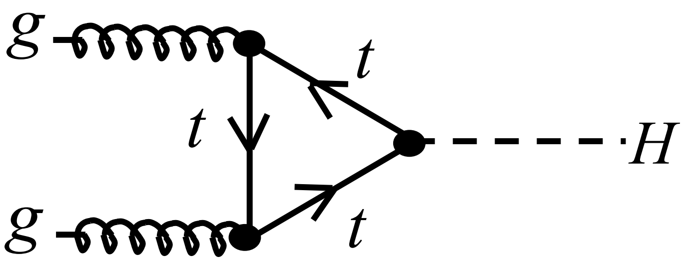
D712/mb-26/06/97
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
D. Parchet + MB

Higgs at LHC

Higgs Production at the LHC

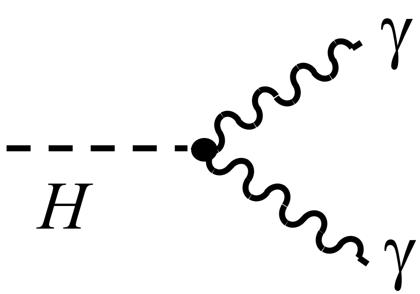
The dominant Higgs production mechanism at the LHC is

"gluon fusion"

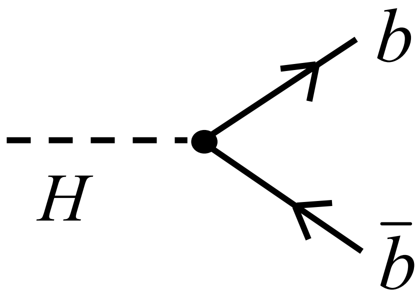


Higgs Decay at the LHC

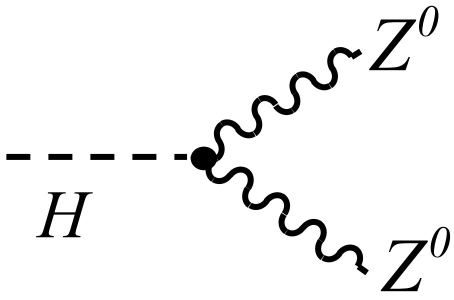
Depending on the mass of the Higgs boson, it will decay in different ways



Low Mass

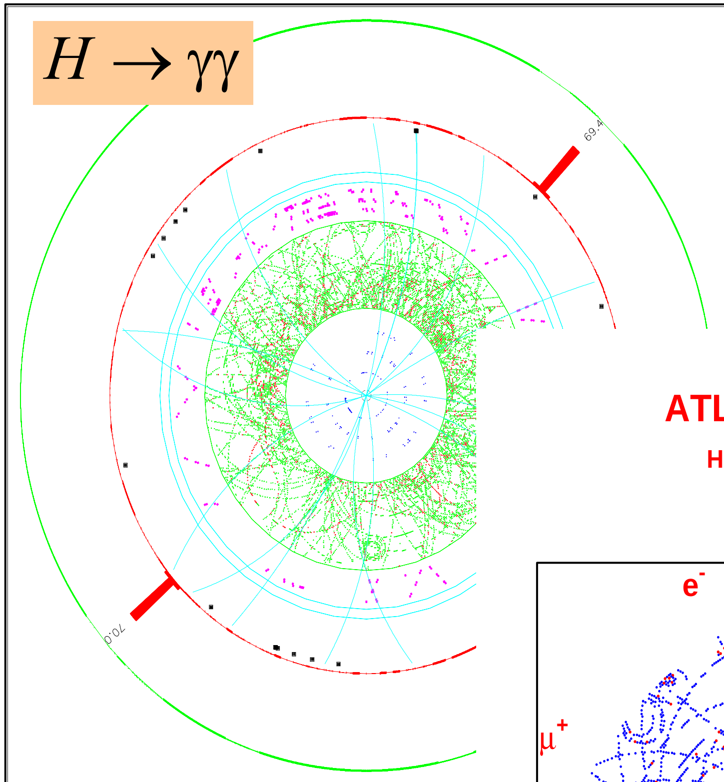


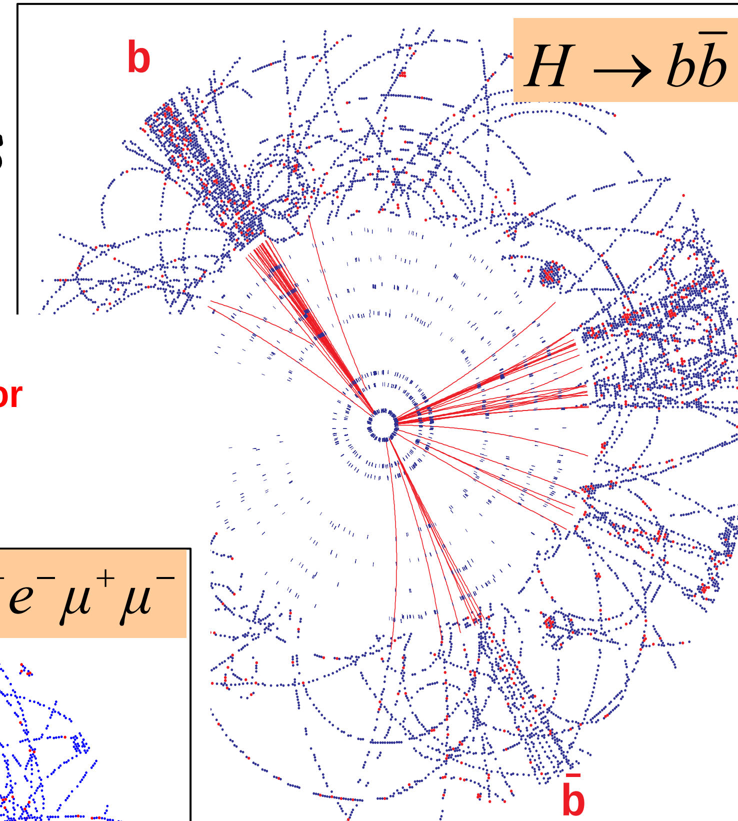
Medium mass



High mass

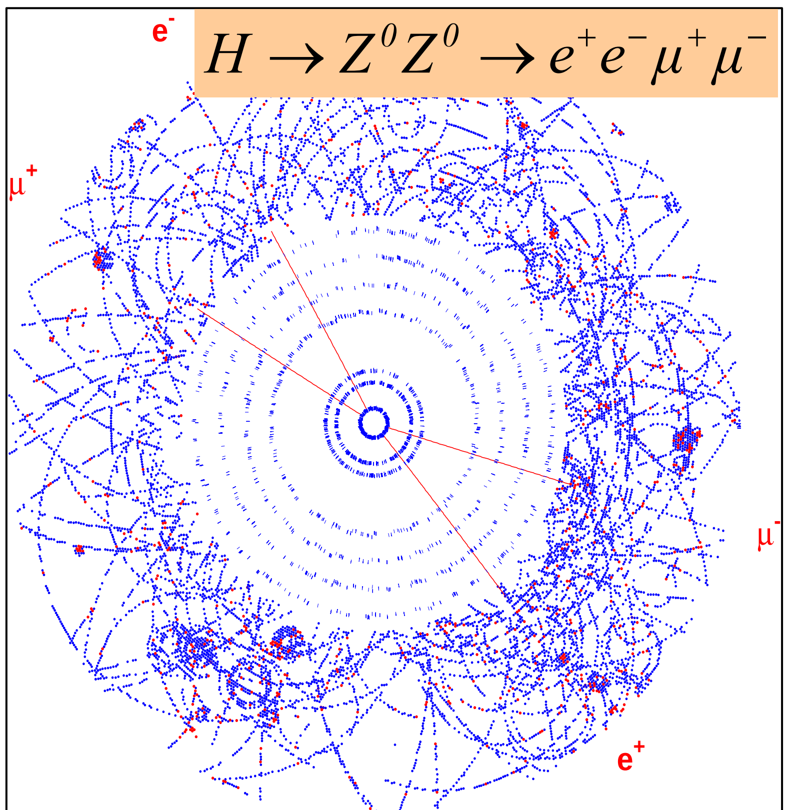
ATLAS Higgs Events





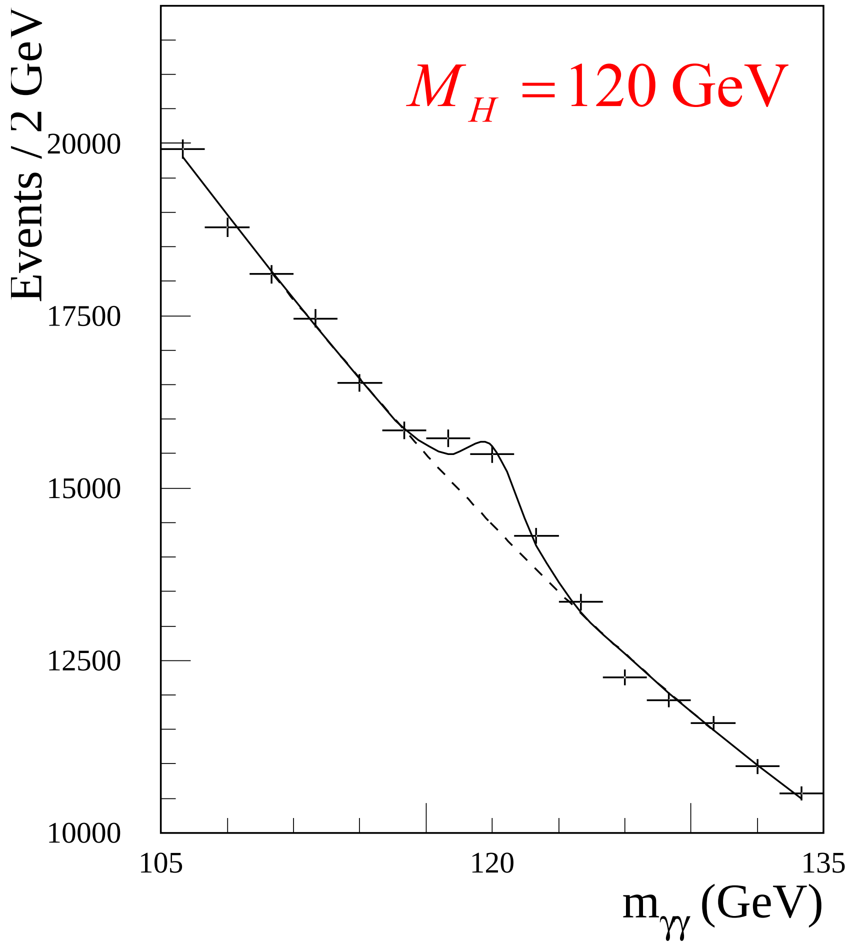
ATLAS Barrel Inner Detector

$H \to ZZ^* \to \mu^+\mu^- e^+ e^-$ (m_H = 130 GeV)

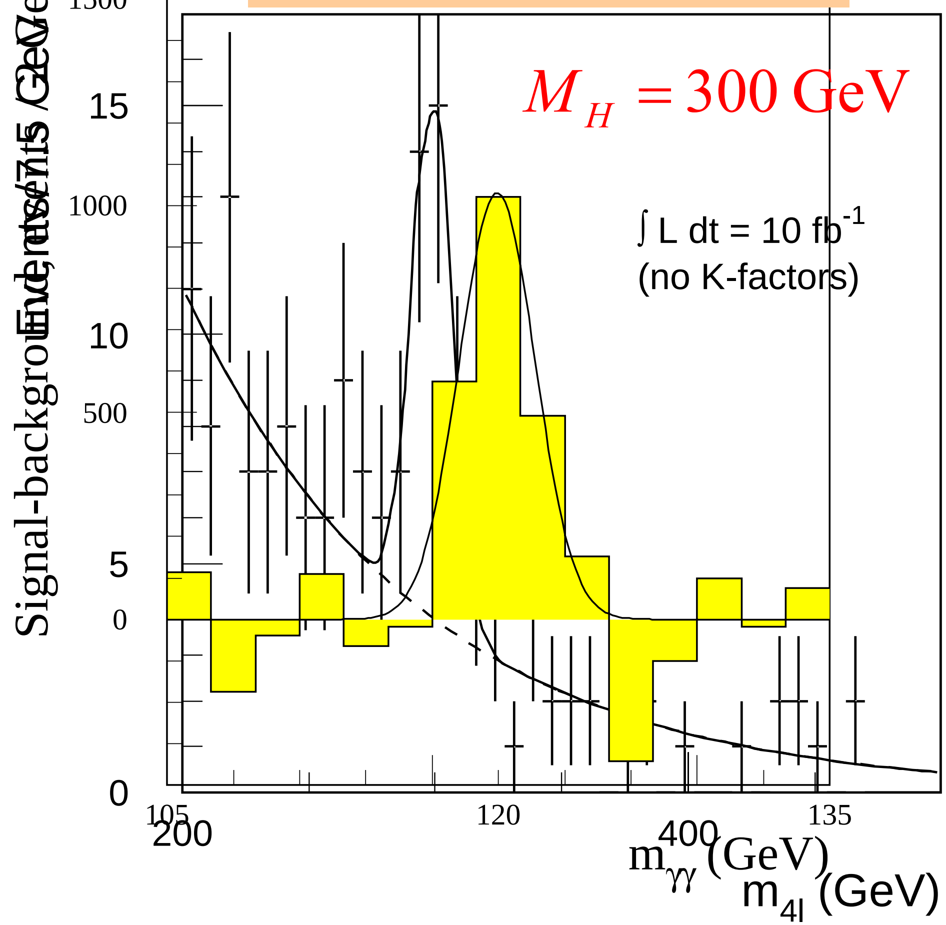


Future Higgs signals in ATLAS ? (by Graduate student currently in 2006 Part II course?)

$H \to \gamma\gamma$



$H \to Z^0 Z^0 \to e^+ e^- \mu^+ \mu^-$

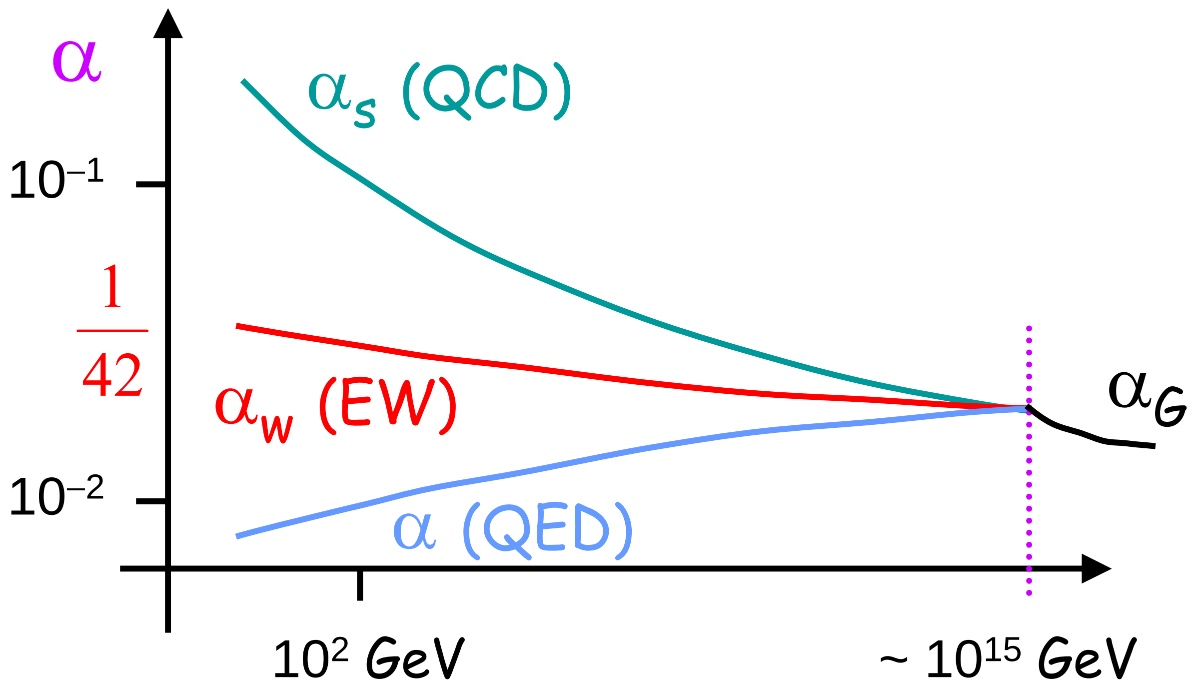


- ➢ LHC CAN discover the Higgs boson up to a mass of ~ 1 TeV.
- ➢ LHC MAY also discover PHYSICS BEYOND THE STANDARD MODEL

Beyond the Standard Model

Grand Unification Theories (GUTs) aim to unite the strong interaction with the electroweak interaction.

The strength of the interactions depends on energy:



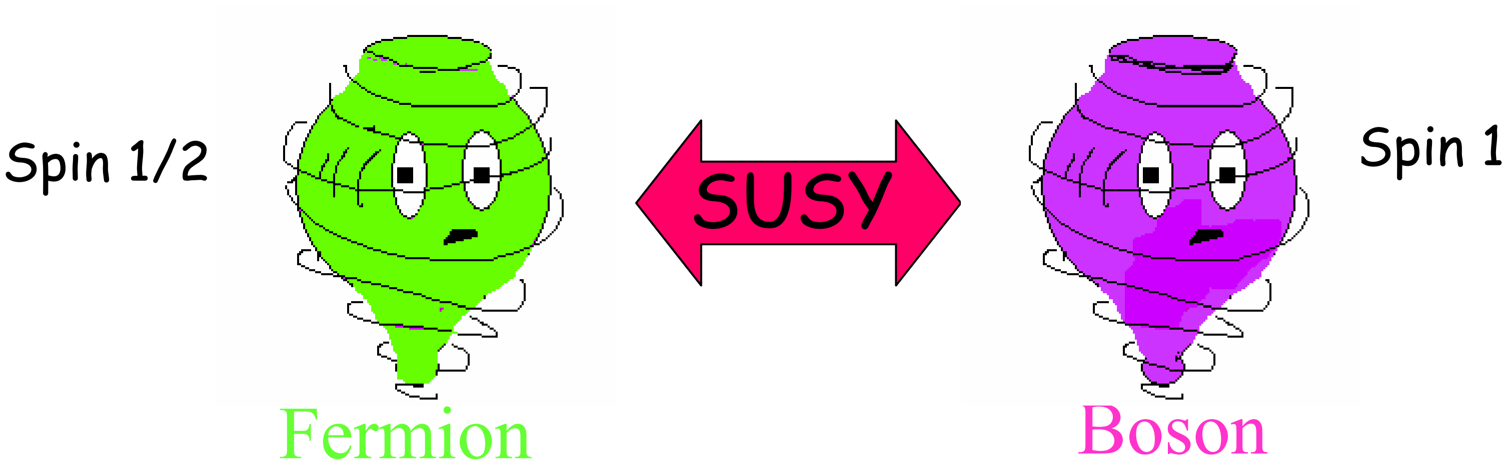
- Unification of all forces at ~10^{15} GeV.
- Strength of Gravity only significant at the Planck Mass ~10^{19} GeV

Supersymmetry (SUSY)

Supersymmetry (SUSY) is a Grand Unified Theory that links fermions and bosons

$\Rightarrow$ SUPERFAMILY

It predicts that every known particle has a SUPERSYMMETRIC partner which is identical except for its SPIN



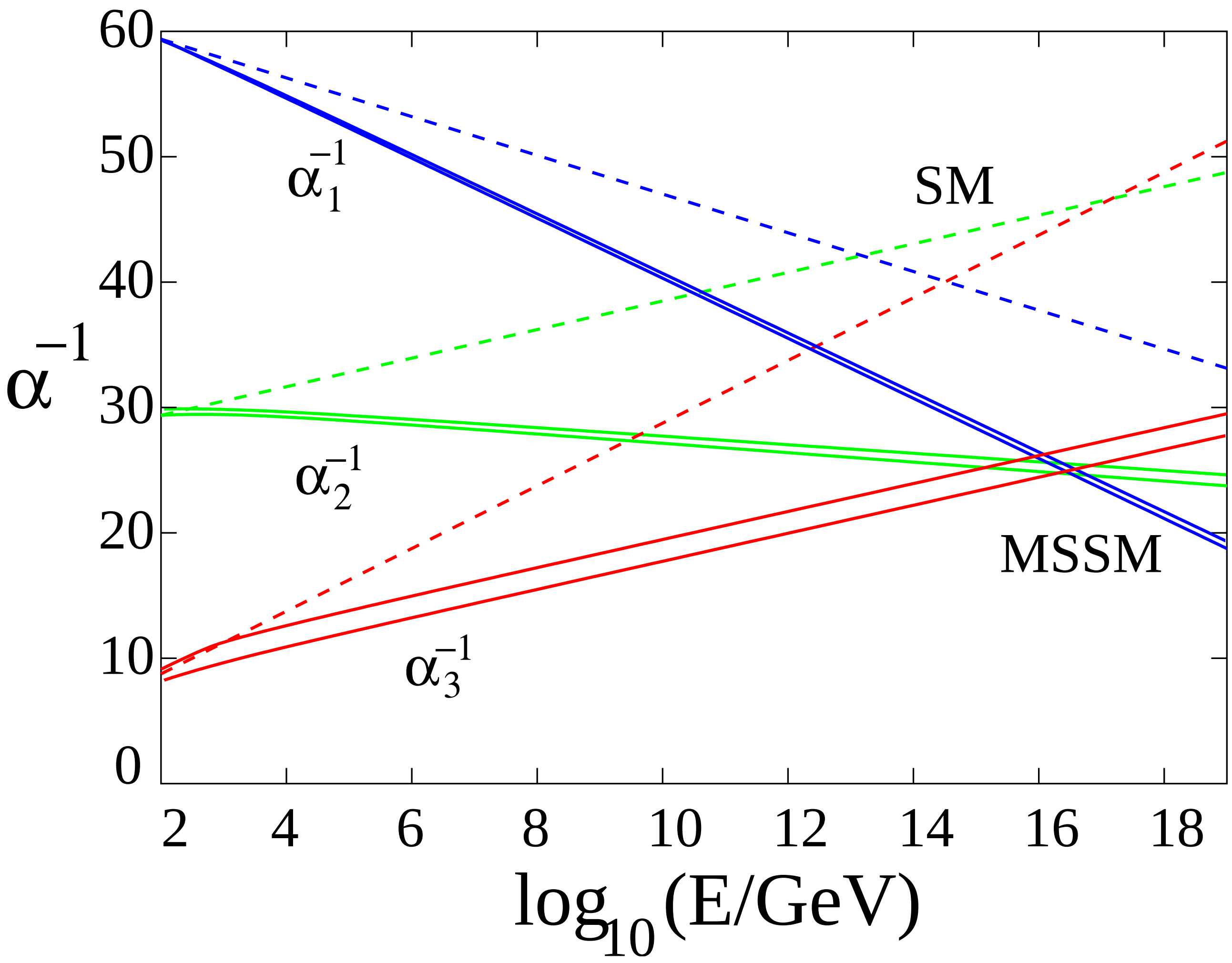
- Linked to Gravity through a theory called SUPERGRAVITY
- Mass of Sparticles not predicted, but MUST be < 1 TeV

The Supersymmetric Standard Model

	SPIN 0	SPIN 1/2	SPIN 1
MATTER	SQUARKS $\tilde{u}, \tilde{d}, \tilde{s}, \tilde{c}, \tilde{b}, \tilde{t}$ SLEPTONS $\tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau$	QUARKS u, d, s, c, b, t LEPTONS $e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$	
FORCES		GAUGINOS $\tilde{\gamma}, \tilde{W}, \tilde{Z}, \tilde{g}$	GAUGE BOSONS γ, W, Z, g
MASS	HIGGS BOSONS h^0, H^0, A^0, $H^\pm$	HIGGSINOS $\tilde{H}$	

➢ In the Standard Model, the interaction strengths are not quite unified at very high energy.

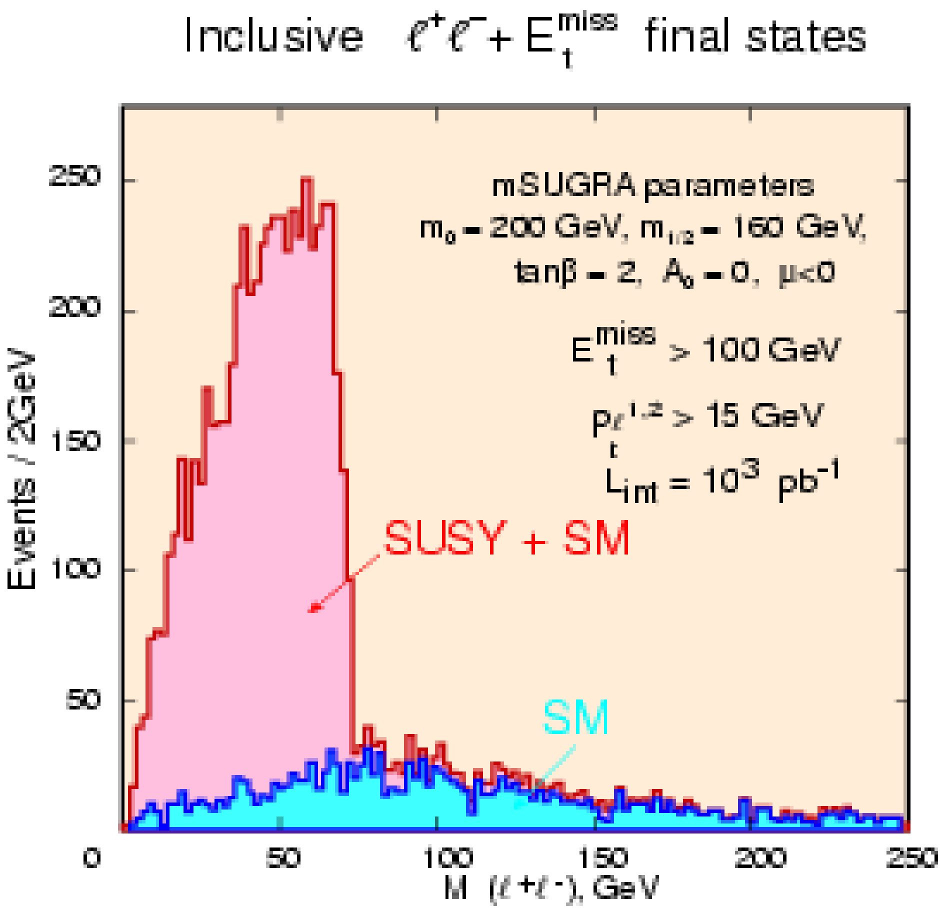
➢ Add SUSY: unification much improved.

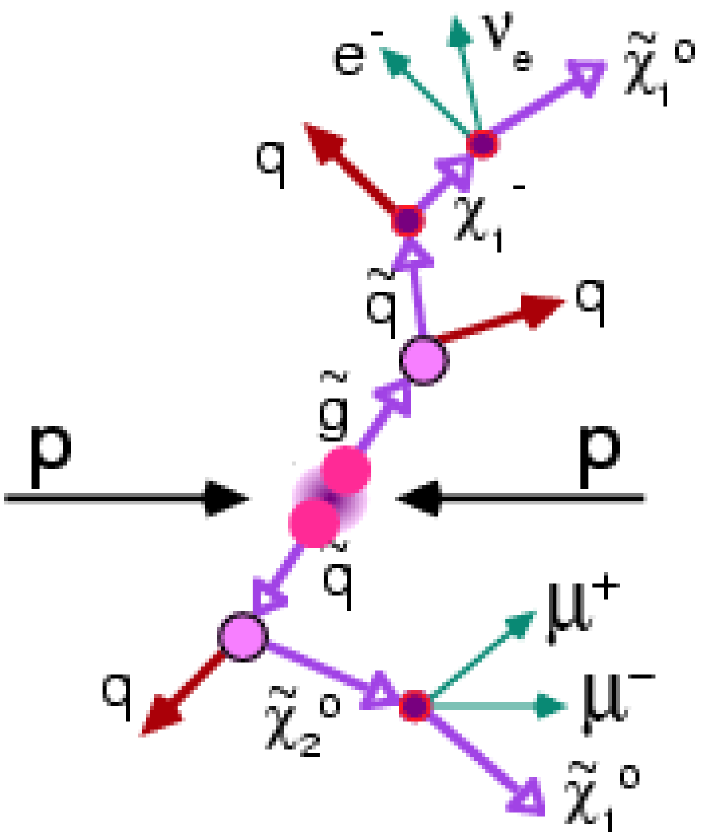


SUSY at LHC

The LHC will search for SUSY sparticles with masses < 1 TeV.

e.g. SUSY events will have "missing energy" plus $\ell^+\ell^-$





Summary

At this point my story about particle physics ends……

- Over the past 30 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 describes ALL experimental observations.

- However, we are beginning to get hints that physics beyond the Standard Model is at work (e.g. neutrino oscillations).

- We expect that the next few years will bring many more (un)expected surprises (Higgs boson, SUSY, etc).

Simulation of a
"Mini Black-Hole"
at the LHC