The Standard Model

OUTLINE

Electroweak Unification

- Chiral fermion states
- Electroweak reactions: $e^+e^- \to f\,\bar{f}$
- PETRA and LEP1 data

Higgs Field

- Spontaneous symmetry breaking
- LEP2 and LHC

Weak Mixing in the Quark Sector

- CKM matrix
- CP violation in the B^0 system

Weak Mixing in the Neutrino Sector

- SNO
- Neutrino masses and Oscillations

Conclusion

Elementary Particles

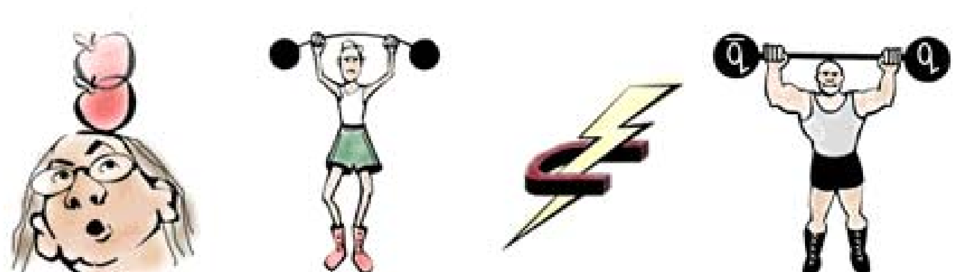
Fermions			Bosons
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$...	Spin = 0, 1, 2...	Mesons ($q\bar{q}$)

Leptons

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

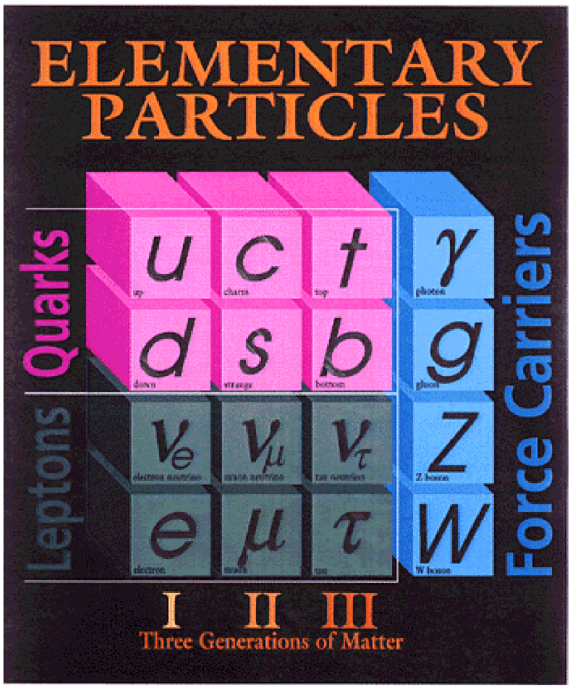
Quarks

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



	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Standard Model



The SM provides a general description of the physics physics currently accessible with modern particle accelerators. The minimal SM postulates that matter is composed of fundamental spin-$\frac{1}{2}$ **quarks** and spin-$\frac{1}{2}$ **leptons** interacting via spin one **gauge bosons**.

Electroweak Lagrangian:

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}(\text{weak CC}) + \mathcal{L}(\text{weak NC}) + \mathcal{L}(\text{em NC}) \\
\mathcal{L}(\text{weak CC}) &= \frac{g}{\sqrt{2}} \left(J_\mu^- \, W^{\mu +} + J_\mu^+ \, W^{\mu -} \right) \\
\mathcal{L}(\text{weak NC}) &= \frac{g}{\cos\theta_W} \left(J_\mu^3 - \sin^2\theta_W \, J_\mu^{\text{em}} \right) Z^\mu \\
\mathcal{L}(\text{em NC}) &= e \, J_\mu^{\text{em}} A^\mu
\end{aligned}$$

QCD: The gluon couples to the color charge of the quark. The strong potential for short interquark distances ($r \lesssim R_{\text{hadron}} \simeq 1/\Lambda_{\text{QCD}} \simeq 1$ fm) is:

$$V_{\text{QCD}} \simeq -\frac{4\,\alpha_s}{3\,r},$$

where α_s is the strong coupling constants between quarks and gluons. At large distances ($r > 1$ fm), a confining term must be added to confine quarks inside hadrons.

Chiral Fermion States

Unification of the E&M and weak interactions: the former has a purely vectorial coupling [γ_μ] while the latter as a $V - A$ character [$\gamma_\mu(1-\gamma_5)$]. Let's absorb the $(1-\gamma_5)$ in the definition of the spinors:

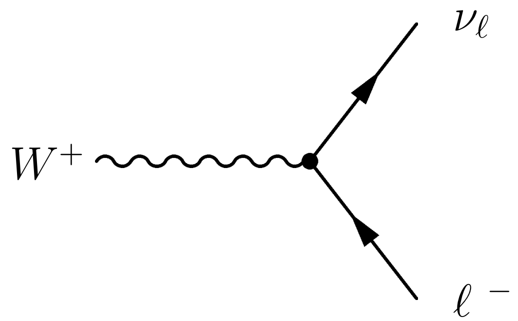
$$u_L(p) = \frac{(1-\gamma_5)}{2}u(p) \quad \text{and} \quad v_R(p) = \frac{(1-\gamma_5)}{2}v(p)$$

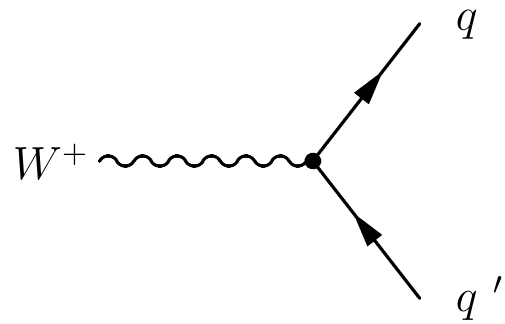
$$u_R(p) = \frac{(1+\gamma_5)}{2}u(p) \quad \text{and} \quad v_L(p) = \frac{(1+\gamma_5)}{2}v(p)$$

Here L =left-handed and R =right-handed. Thus:

$$j_\mu^- = \bar{\nu}\gamma_\mu\frac{(1-\gamma_5)}{2}\ell \quad \text{and} \quad j_\mu^- = \bar{q}\gamma_\mu\frac{(1-\gamma_5)}{2}q'$$

$$j_\mu^- = \bar{\nu}_L\,\gamma_\mu\,\ell_L \quad \text{and} \quad j_\mu^- = \bar{q}_L\,\gamma_\mu\,q'_L$$





Pure vectorial weak vertex

Conseqences:

$$u = \frac{(1-\gamma_5)}{2}u + \frac{(1+\gamma_5)}{2}u = u_L + u_R$$

and

$$\bar{u} = \bar{u}\frac{(1+\gamma_5)}{2} + \bar{u}\frac{(1-\gamma_5)}{2} = \bar{u}_L + \bar{u}_R$$

Plus,

$$\bar{u}_L\gamma_\mu u_R = \bar{u}_R\gamma_\mu u_L = 0$$

Thus the electromagntic current can be written as:

$$j_\mu^{em} = -\bar{e}\gamma_\mu e = -\bar{e}_L\gamma_\mu e_L - \bar{e}_R\gamma_\mu e_R$$

Define: $j_\mu^\pm = \bar{\chi}_L\gamma_\mu\sigma^\pm\chi_L$ with $\sigma^\pm = \frac{1}{2}(\sigma^1 \pm i\sigma^2)$:

$$\vec{j}_\mu = \frac{1}{2}\bar{\chi}_L\gamma_\mu\,\vec{\sigma}\,\chi_L \quad \text{and} \quad J_\mu^Y = 2j_\mu^{em} - 2j_\mu^3$$

with

$$\chi_L$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

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

$SU(2)_L \otimes U(1)_Y$

Unified electro-weak vertex:

$$-i\left[g_w\,\vec{j}_\mu\cdot\vec{W}^\mu + \frac{g'}{2}J_\mu^Y B^\mu\right]$$

with $W_\mu^\pm \equiv \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2)$

$$\vec{j}_\mu\cdot\vec{W}^\mu = j_\mu^1 W^{\mu\,1} + j_\mu^2 W^{\mu\,2} + j_\mu^3 W^{\mu\,3}$$

$$\vec{j}_\mu\cdot\vec{W}^\mu = \frac{1}{\sqrt{2}}j_\mu^+ W^{\mu\,+} + \frac{1}{\sqrt{2}}j_\mu^- W^{\mu\,-} + j_\mu^3 W^{\mu\,3}$$

such that

$$-\frac{ig_w}{\sqrt{2}}j_\mu^\pm = -\frac{ig_w}{2\sqrt{2}}[\bar{u}\gamma_\mu(1-\gamma_5)u]W^{\mu\pm}$$

The neutral underlying $SU(2)_L \otimes U(1)_Y$ allow the W^3 and the B to mix to the physical states called photon and the Z:

$$A_\mu = B_\mu \cos\theta_w + W_\mu^3 \sin\theta_w$$

$$Z_\mu = -B_\mu \sin\theta_w + W_\mu^3 \cos\theta_w$$

and with $g_w \sin\theta_w = g' \cos\theta_w = g_e$ then

$$-i\left[g_w\,j_\mu^3\cdot W^{\mu 3} + \frac{g'}{2}J_\mu^Y B^\mu\right]$$

$$= -ig_e j_\mu^{em} A^\mu - ig_z(j_\mu^3 - \sin^2\theta_w j_\mu^{em})Z^\mu$$

Weak Neutral Current

Knowing that $j_\mu^{em} = j_\mu^3 + \frac{1}{2} j_\mu^Y$ and $g_Z = \frac{g_e}{\sin\theta_w \cos\theta_w}$.

$$-ig_z\,(j_\mu^3 - \sin^2\theta_w j_\mu^{em}) Z^\mu \qquad [Z^0 \text{ weak current}]$$

where within a particle doublet:

$$j_\mu^{em} = \sum_{i=1}^{2} Q_i(\bar{u}_{iL}\gamma_\mu u_{iL} + \bar{u}_{iR}\gamma_\mu u_{iR})$$

Then the $Z^0 \to f\,\bar{f}$ vertex factor depends on the particular quark and lepton (*i.e.* f) involved:

$$\frac{-ig_Z}{2}\gamma^\mu(c_V^f - c_A^f\gamma_5) \qquad [Z^0 \text{ vertex factor}]$$

with

f	c_V	c_A
ν_ℓ	$\frac{1}{2}$	$\frac{1}{2}$
ℓ	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$
q	$\frac{1}{2} - \frac{4}{3}\sin^2\theta$	$\frac{1}{2}$
q'	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

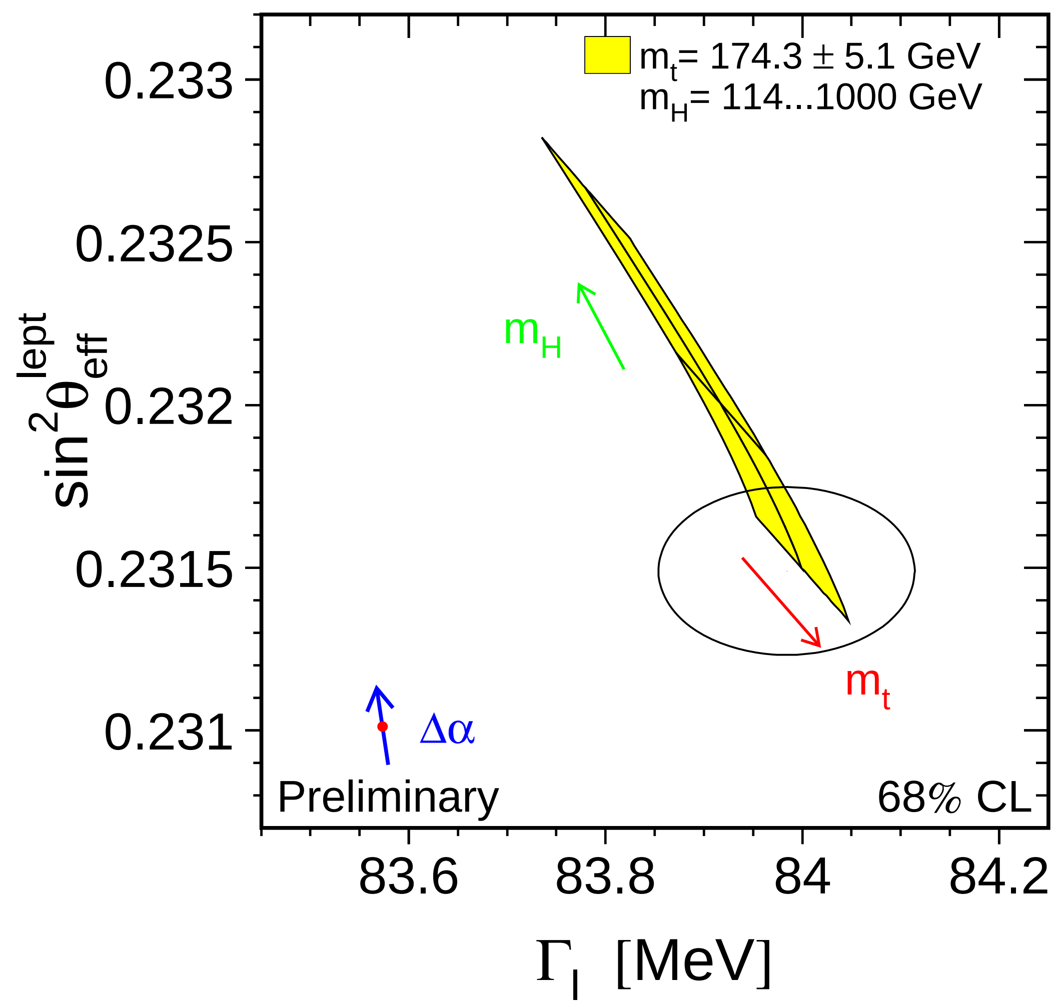
Weinberg Angle

Reaction like the *pure* neutral reaction $\nu_\mu + e^- \to \nu_e + \mu^-$ were used to make the first measurement in 1973 of c_V^ℓ and c_A^ℓ and thus:

$$\sin^2\theta_w = 0.22 \pm 0.03$$

At SLC/LEP Z^0 bosons were produced copiously and it allowed a very precise determination of the properties Z. Using all experimental data:

$$\sin^2\theta_w = 0.23147 \pm 0.00016$$



PETRA: Data at $\sqrt{s} = 34\,\text{GeV}$

In real the reaction has a contribution from the γ and the Z: $\mathcal{M} = \mathcal{M}_\gamma + \mathcal{M}_Z$.

$$|\mathcal{M}|^2 = |\mathcal{M}_\gamma|^2 + |\mathcal{M}_Z|^2 + 2Re(\mathcal{M}_\gamma, \mathcal{M}_Z)$$

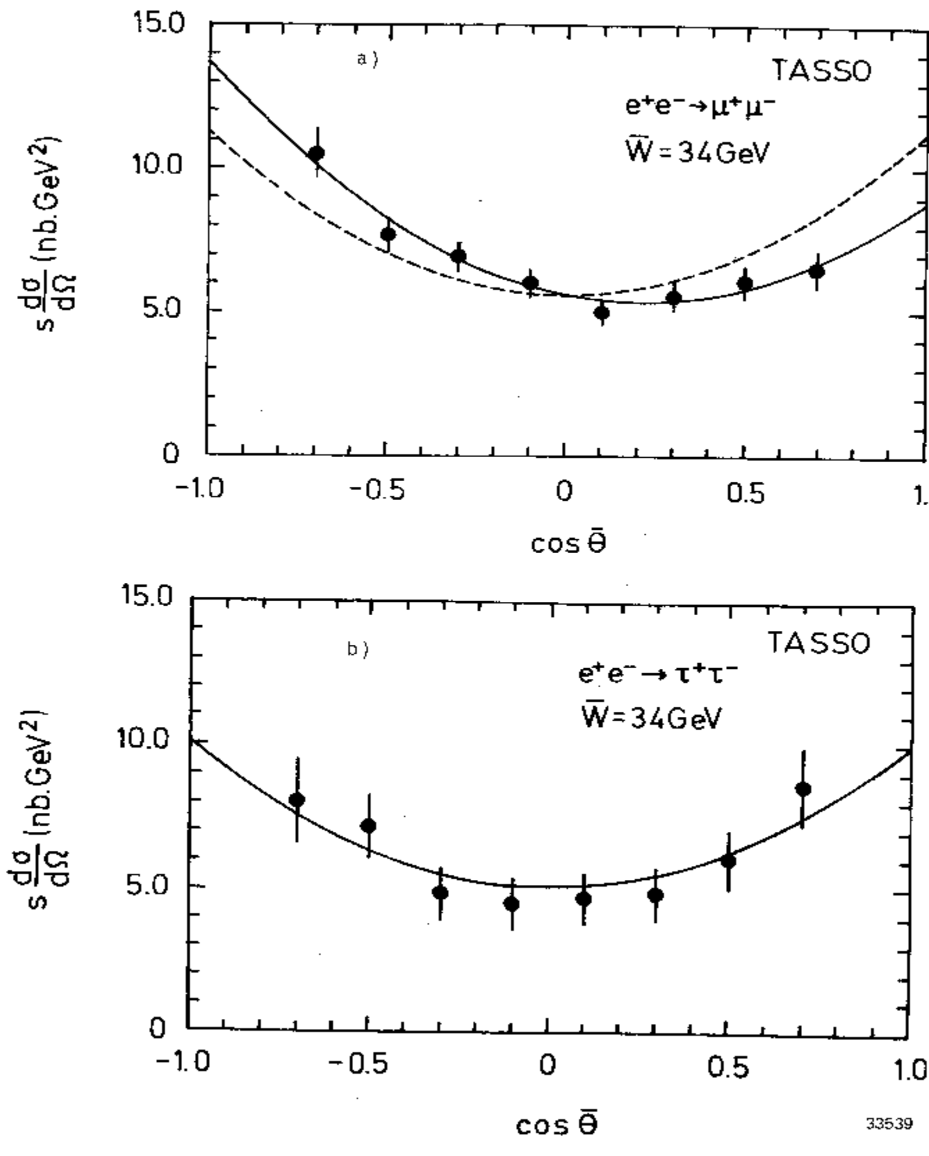
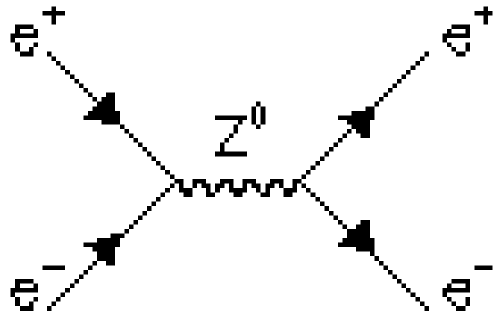
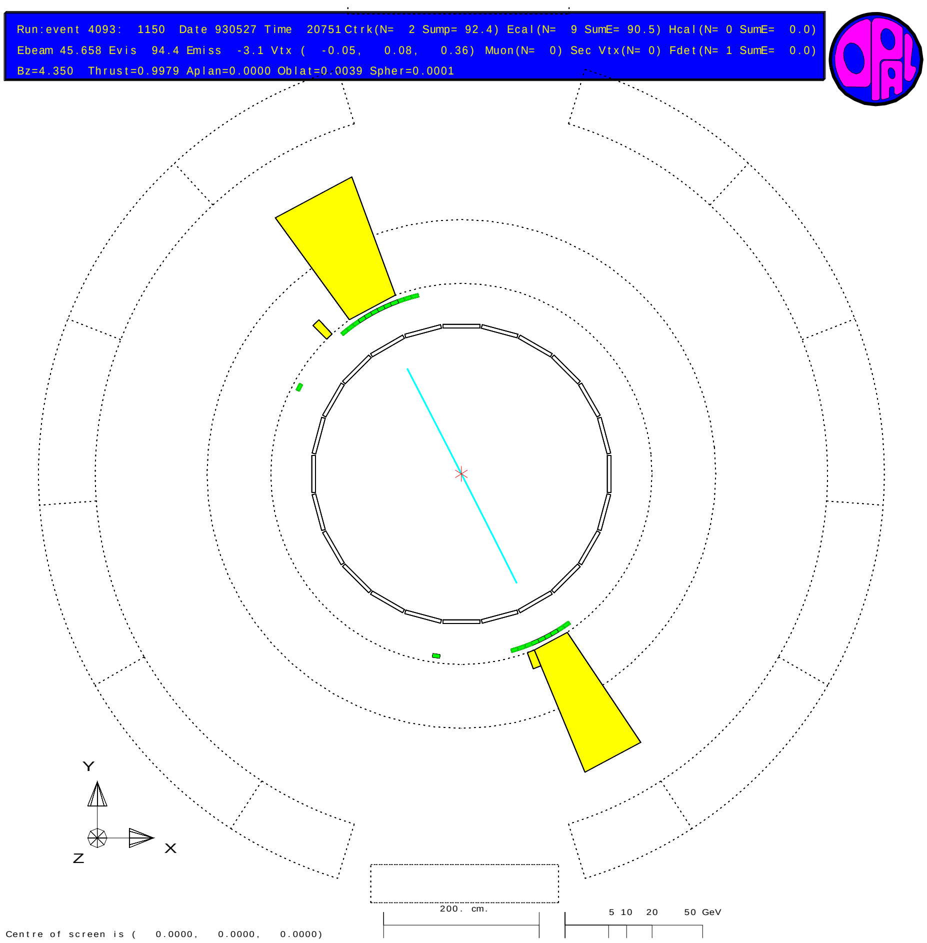


Fig. 3

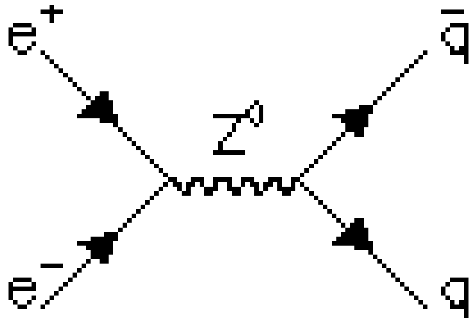
Leptonic Events at LEP1



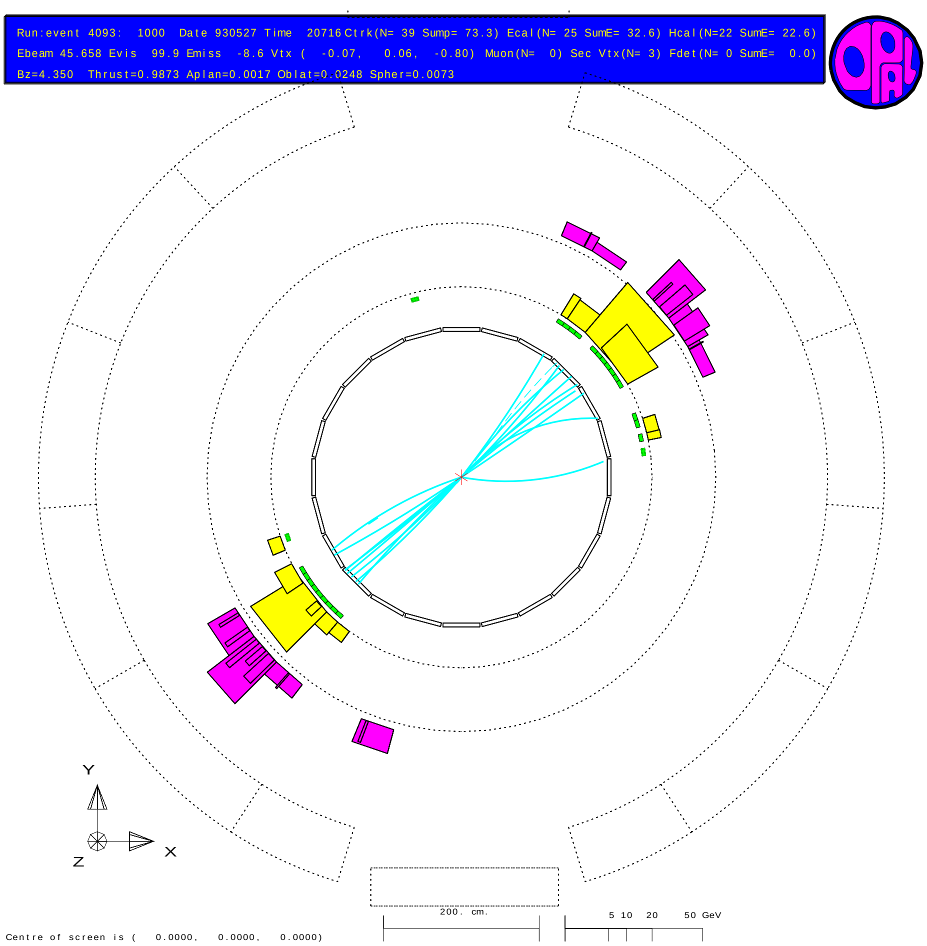
$$E_{\text{CM}} \simeq 91 GeV$$



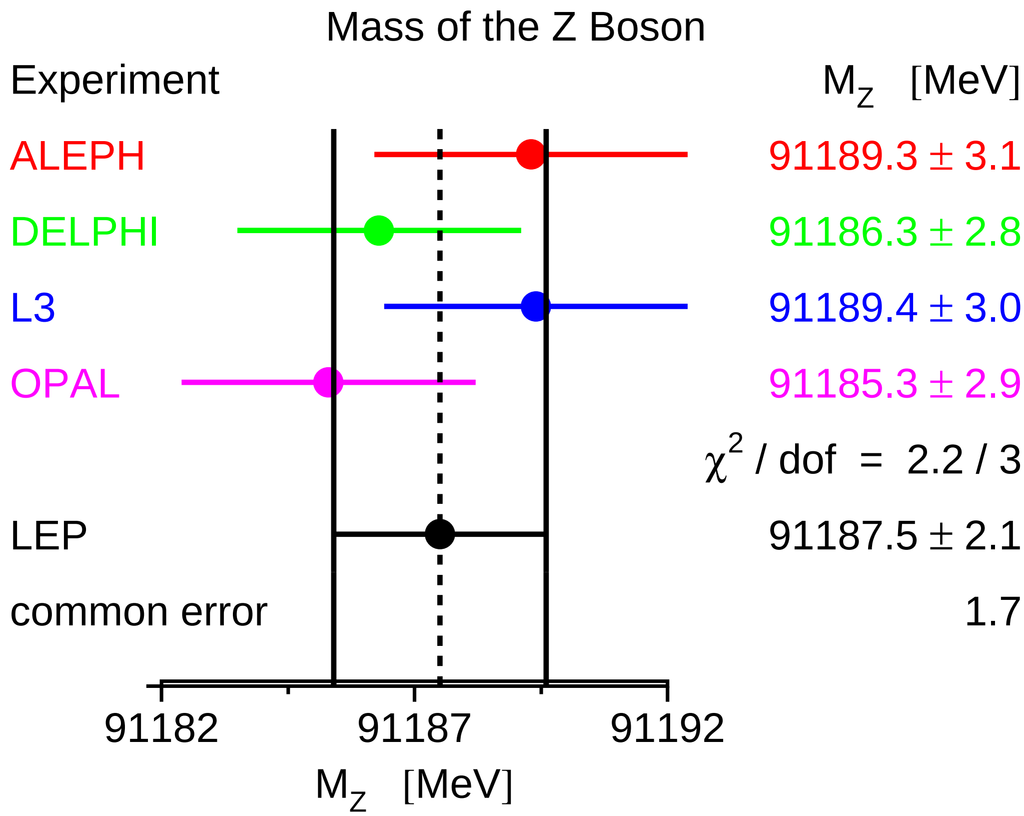
Hadronic Events at LEP1



$$E_{\mathrm{CM}} \simeq 91 GeV$$



Mass & Width of the Z Boson



Total Width (final LEP average June 2001)

$$\Gamma_Z \equiv \Gamma(Z \to X) = 2.4952 \pm 0.0023 \text{ GeV}$$

Hadronic Width

$$\Gamma(Z \to q\overline{q}) = 1.7442 \pm 0.0020 \text{ GeV}$$

Leptonic Width

$$\Gamma(Z \to \ell^+\ell^-) = 0.083991 \pm 0.000087 \text{ GeV}$$

Such that

$$\Gamma_Z = \Gamma(Z \to q\overline{q}) + 3\,\Gamma(Z \to \ell^+\ell^-) + \text{invisible}$$

Number of Neutrino Types

Invisible Width (calculated)

$$\Gamma(Z \to \nu_\ell \bar{\nu}_\ell) = 0.1666 \text{ GeV}$$

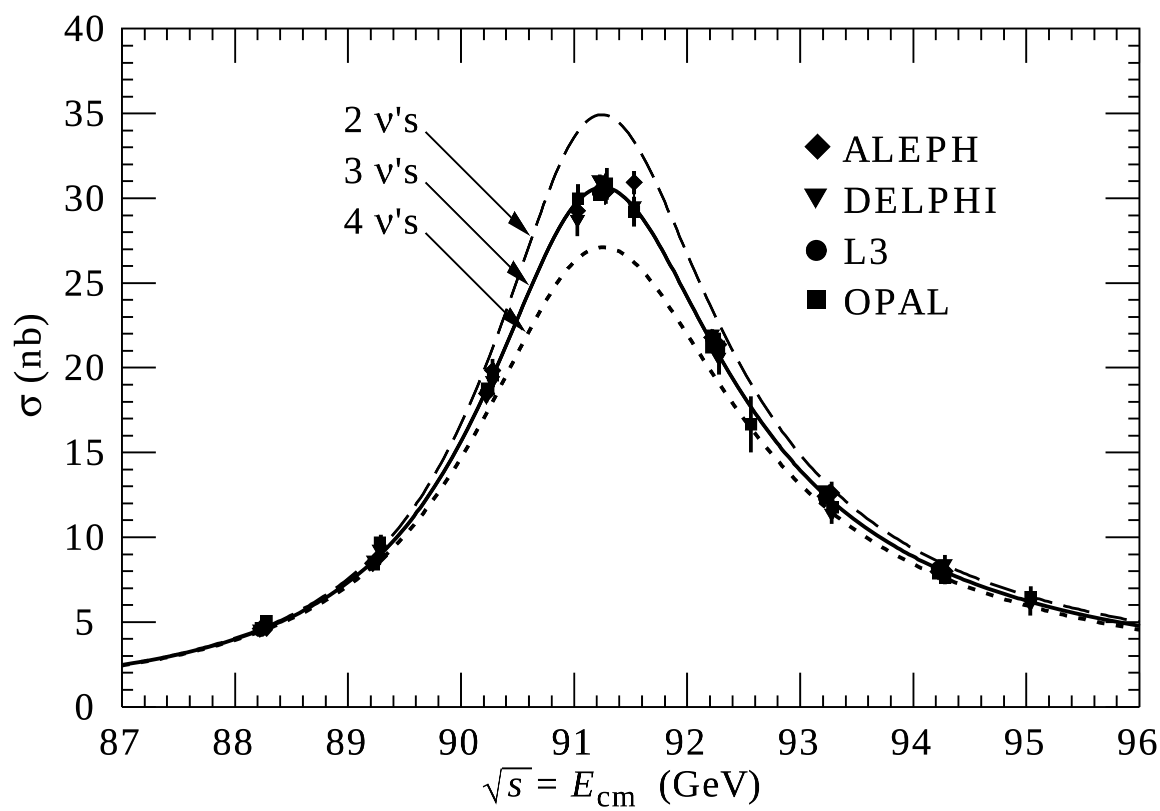
Thus

$$\Gamma_Z = \Gamma_{q\bar{q}} + 3\,\Gamma_{\ell\bar{\ell}} + N_\nu\,\Gamma_{\nu\bar{\nu}}$$

Implies

$$N_\nu = 2.9841 \pm 0.0083$$

Consistent $N_\nu = 3$!!!



Higgs Field

Physicists have theorized the existence of the so-called Higgs field, which in theory interacts with other particles to give them **mass**. The Higgs field requires a particle, the Higgs boson. The Higgs boson has not been observed, but physicists are looking for it with great enthusiasm.

Limit on the SM Higgs mass with data collected at LEP2 $\sqrt{s} = 161 - 210$ GeV:

$m_H > 113.5$ GeV (95% CL)

Spontaneous symmetry breaking:

The form of the Lagrangian that couples the Higgs field and the quarks is constrained by $SU(2)_L$ gauge invariance:

$$\mathcal{L} = \sum_{j,k} [Y_{jk} (\bar{u}^j_L, \bar{d}^j_L) \begin{pmatrix} \phi^0 \\ -\phi^+ \end{pmatrix}^* u^k_R + Y'_{jk} (\bar{u}^j_L, \bar{d}^j_L) \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} d^k_R]$$

where j and k run over quarks generations, L and R denotes left- and right-handed component, and Y_{jk} and Y'_{jk} are the Yukawa couplings. The complex Higgs doublet undergoes spontaneous symmetry breaking:

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

where v is the Higgs vacuum expectation and $H(x)$ is the Higgs field corresponding to the Higgs boson.

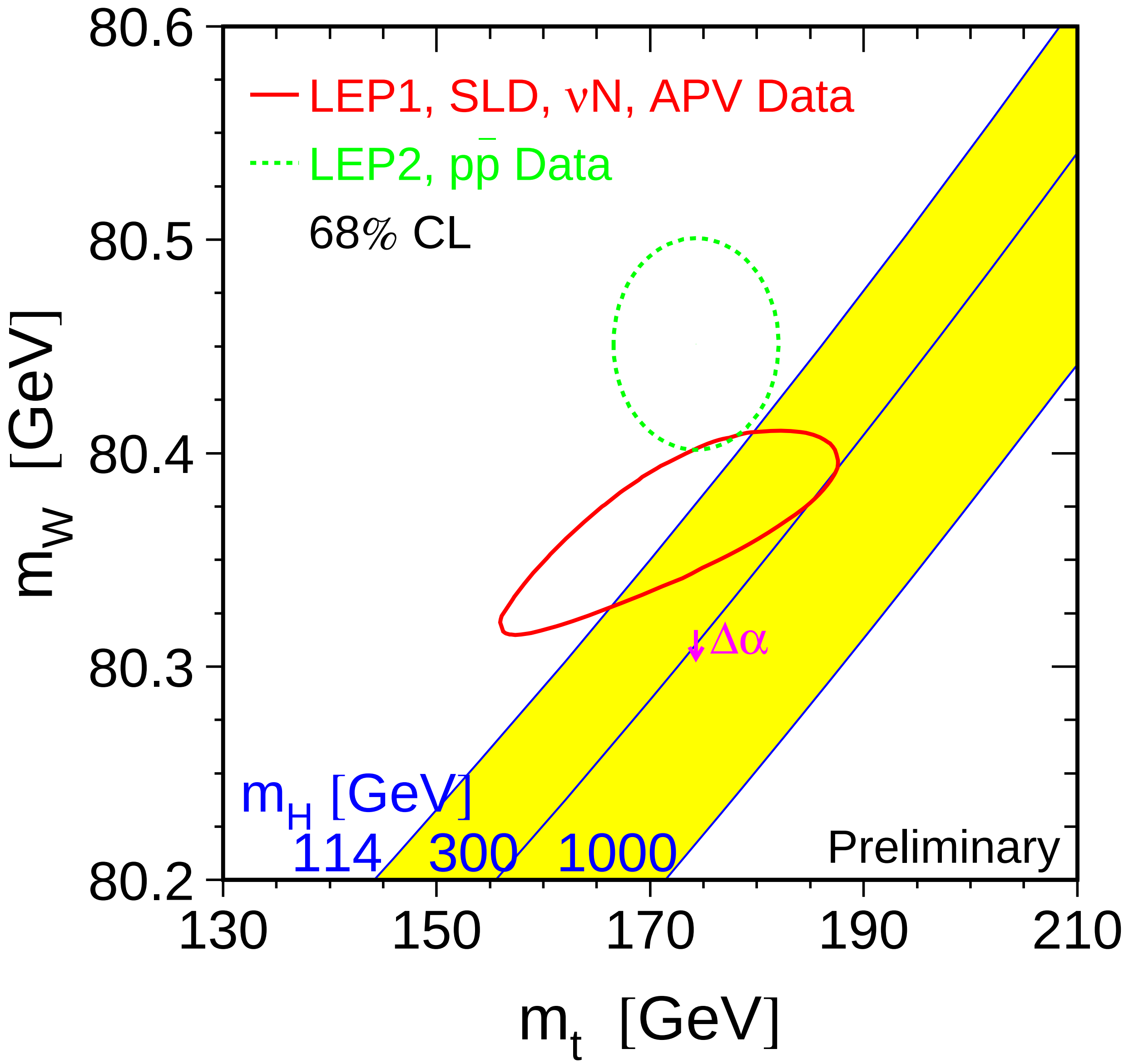
$$\mathcal{L} = \sum_{j,k} [Y_{jk} \bar{u}^j_L u^k_R + Y'_{jk} \bar{d}^j_L d^k_R] \frac{1}{\sqrt{2}} [v + H(x)]$$

The term proportional to v generate the quark mass $m_{jk} \equiv \frac{-v}{\sqrt{2}} Y_{jk}$ and $m'_{jk} \equiv \frac{-v}{\sqrt{2}} Y'_{jk}$.

Higgs Mass

Present limit on the Higgs Mass from direct and indirect measurements of $\mathrm{m}_{\mathrm{top}}$ and M_{W}:

$m_H < 188$ GeV (95% CL)

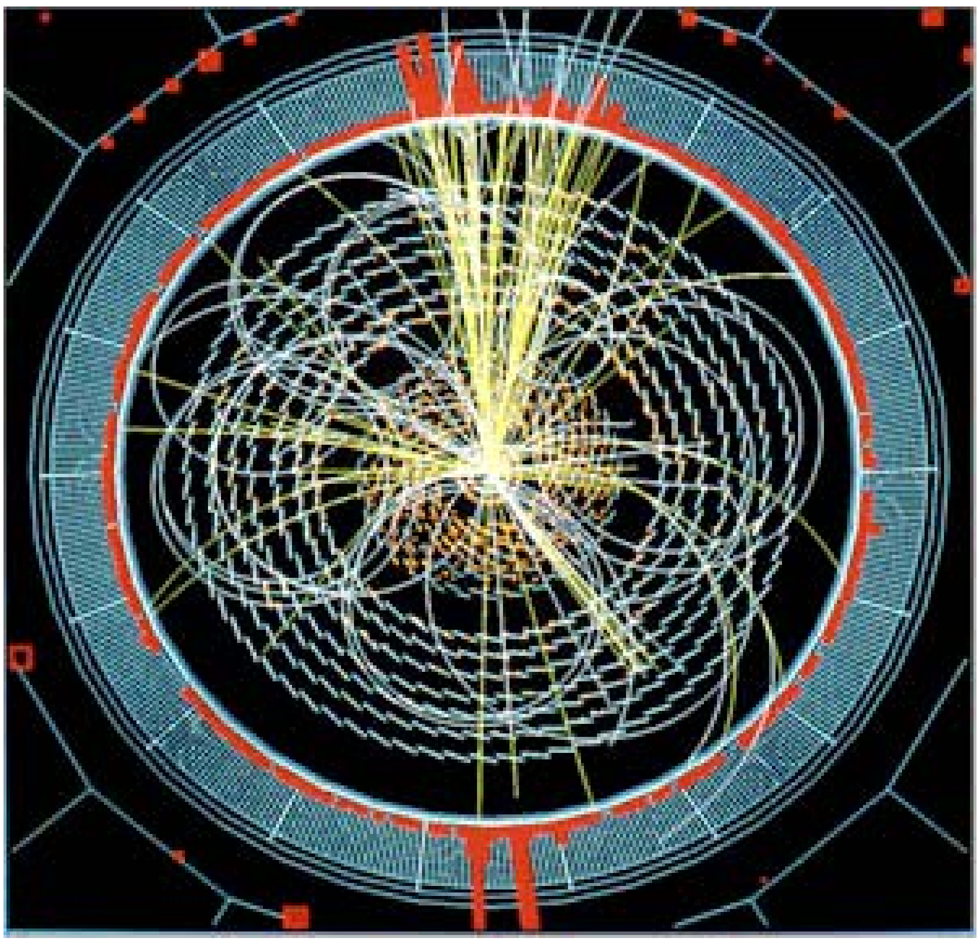


Standard Model parameter relations confirmed at quantum level that small Higgs masses are preferred.

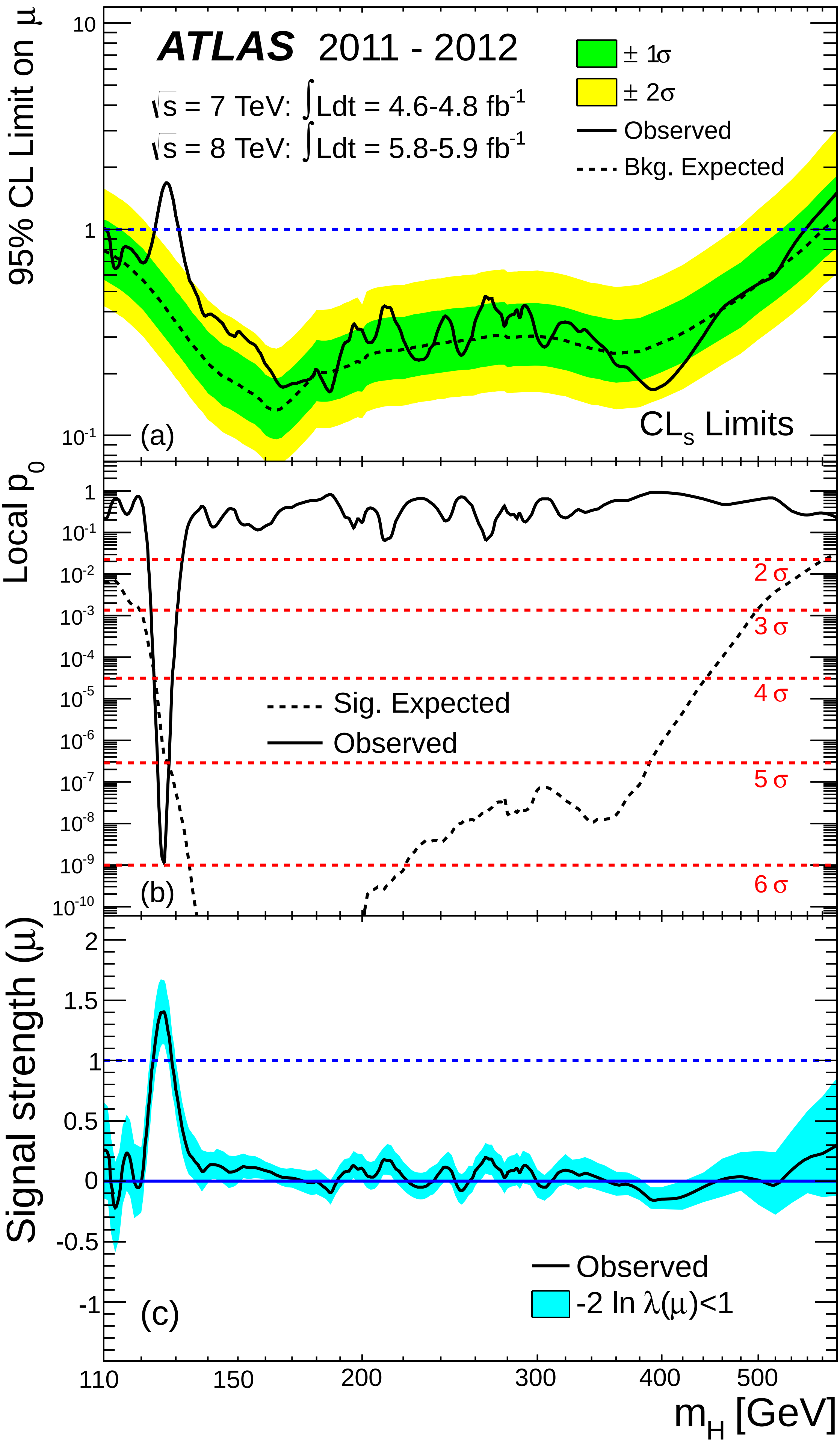
LHC: Large Hadron Collider

The LHC, in construction at CERN, is a proton-proton collider with $\sqrt{s} = 14\,\text{TeV}$. The SPS collider which discovered the $W - Z$ bosons had $\sqrt{s} = 0.45\,\text{TeV}$ and the Tevatron collider at FermiLab has $\sqrt{s} = 1.8\,\text{TeV}$.

Higgs events at the LHC



LHC will take data in 2007 !!!

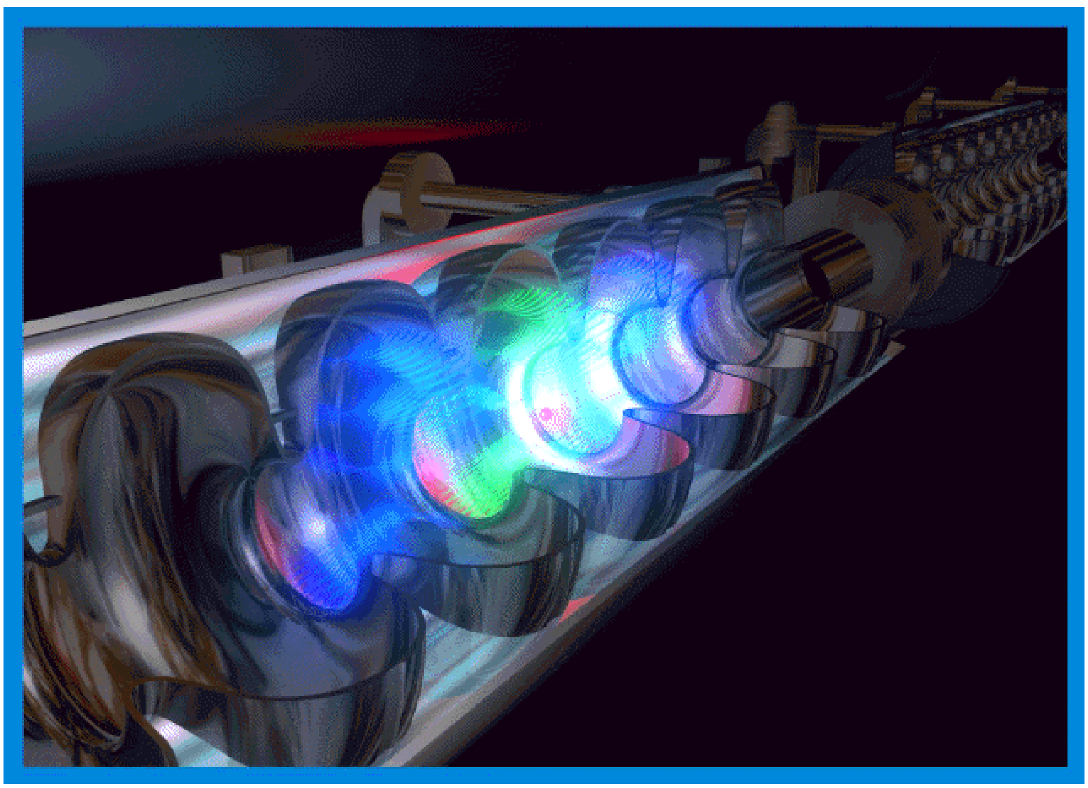


ATLAS 2011 - 2012
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
± 1σ
± 2σ
Observed
Bkg. Expected
CLs Limits
95% CL Limit on μ
(a)
Local p0
Sig. Expected
Observed
2 σ
3 σ
4 σ
5 σ
6 σ
(b)
Signal strength (μ)
Observed
-2 ln λ(μ)<1
(c)
mH [GeV]
110
150
200
300
400
500

NLC: Next linear Collider

The Next Linear Collider (NLC) is proposed as the future generation of accelerator to probe matter. The design of the NLC is a 0.5 TeV e^+e^- collider to investigate the properties of the $W-Z$ bosons, the top quark, and their couplings; and search for super-symmetric particles (SUSY).

Superconducting Acceleration Cavity



CKM Matrix

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \qquad \text{[CKM Matrix]}$$

such that

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

The CKM matrix can be decomposed as:

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}\beta \\ 0 & 1 & 0 \\ -s_{13}\gamma & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, and i, j denote the quark generations. The middle matrix has incorporate the complex phase δ such that $\beta = e^{-i\delta}$ and $\gamma = e^{i\delta}$ to describe a rotation between quarks that are two generations apart. Multiplying these matrices:

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Wolfenstein Parameterization

Based on hierarchical we can expand in powers of the Cabibbo angle $\lambda = s_{12} = 0.22$, with $s_{23} = A\lambda^2$ and $s_{13}e^{-i\delta} = A\lambda^3(\rho - i\eta)$:

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Complex phase allow CP violation in the framework of Standard Model for a 3×3 CKM matrix

Or be neglecting the CP phase and the small $b \to u$ and $t \to d$ transitions:

$$V \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & 0 \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ 0 & -A\lambda^2 & 1 \end{pmatrix}$$

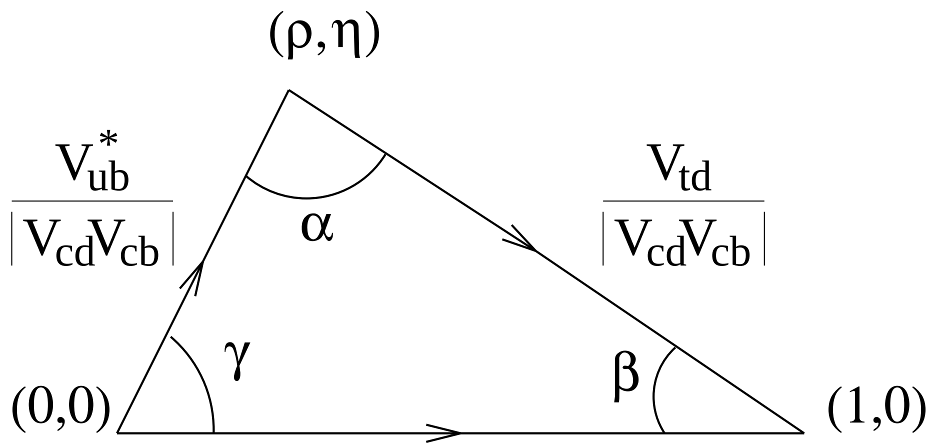
By neglecting the s_{23} we have the simple Cabbibo description $\theta_C \equiv \lambda$:

$$V \sim \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & 0 \\ -\lambda & 1-\frac{1}{2}\lambda^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \simeq \begin{pmatrix} \cos\theta_C & \sin\theta_C & 0 \\ -\sin\theta_C & \cos\theta_C & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

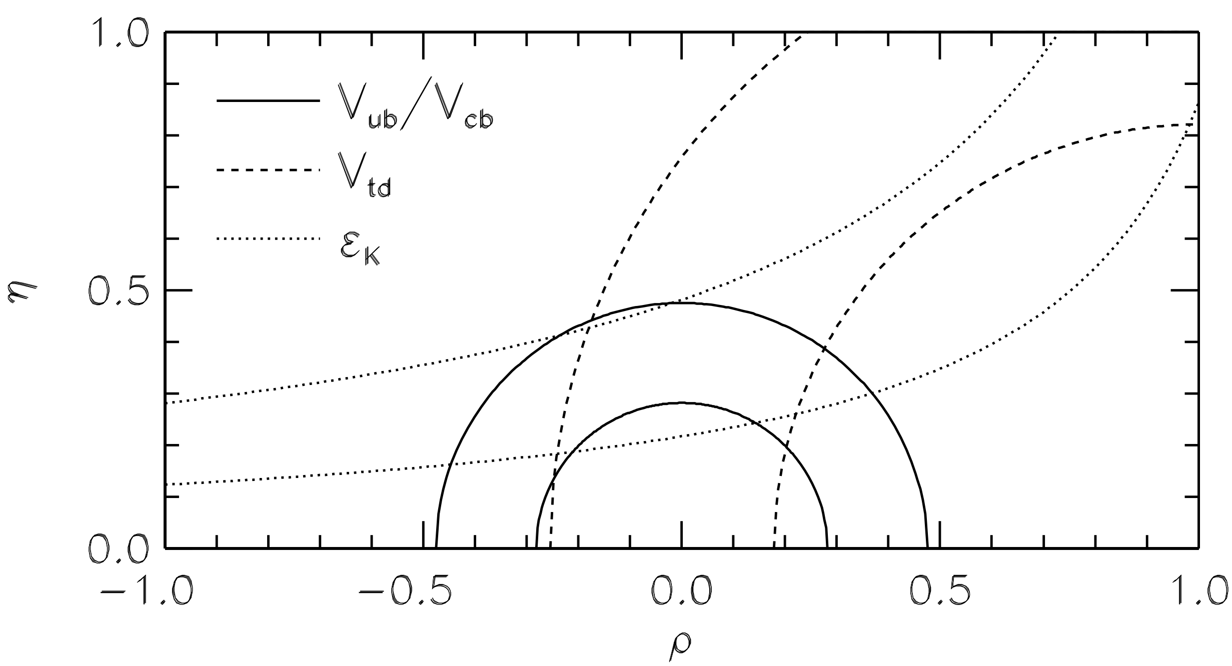
Unitary Triangle

To describe CP violation we use the $\rho - \eta$ plane with the condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$



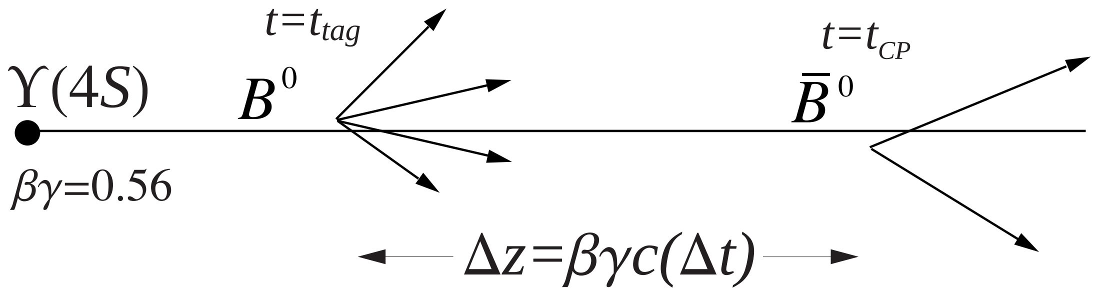
1. $|V_{\rm ub}|/\ |V_{\rm cb}|$
2. CP violation in Kaon System
3. $B^0 - \bar{B}^0$ Mixing

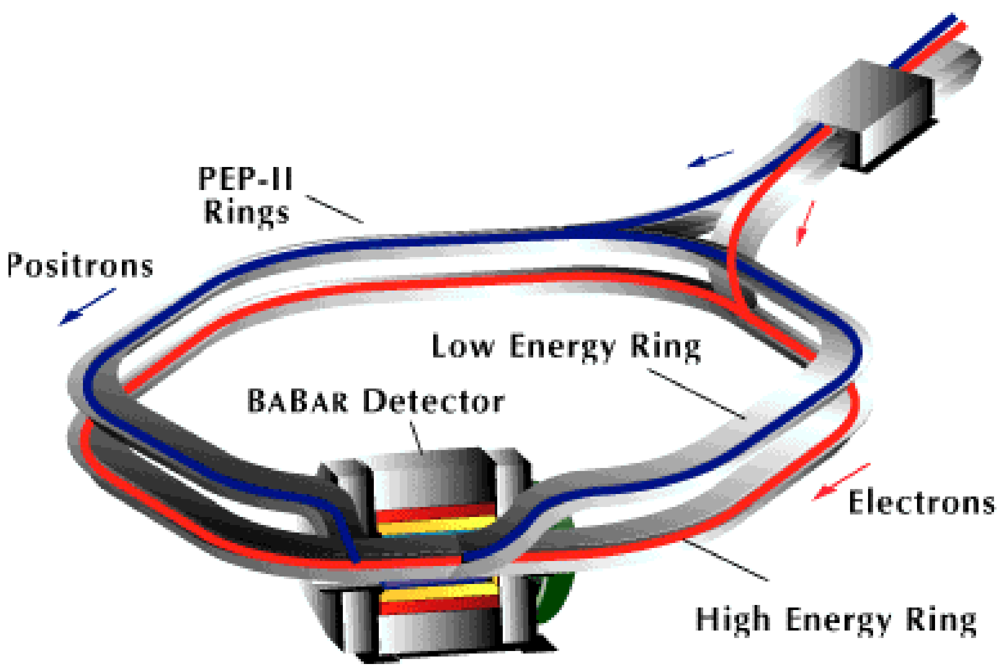


B Factories

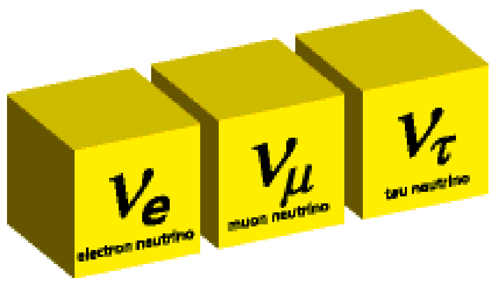
Time evolution of the B^0 system since the integration over time gives simply the mass difference and NOT the CP phase: Asymmetric B-factories [BaBar & Belle] operating at the $\Upsilon(4S)$ with luminosity $\sim 10^{34} cm^{-2} s^{-1}$ (PETRA in the 1980's had $\mathcal{L} \sim 10^{31} cm^{-2} s^{-1}$!!!).

Measure the angles of the unitary triangle

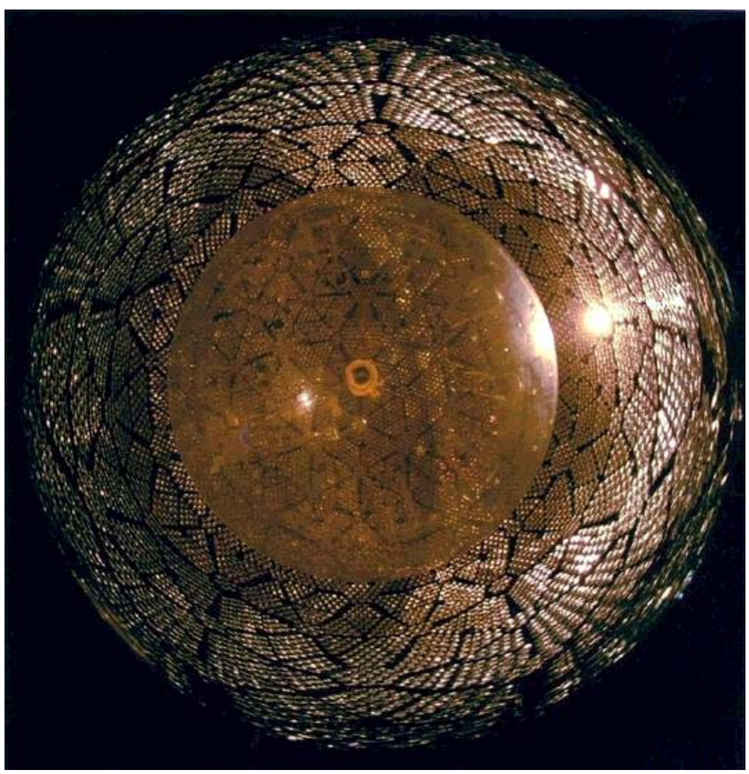




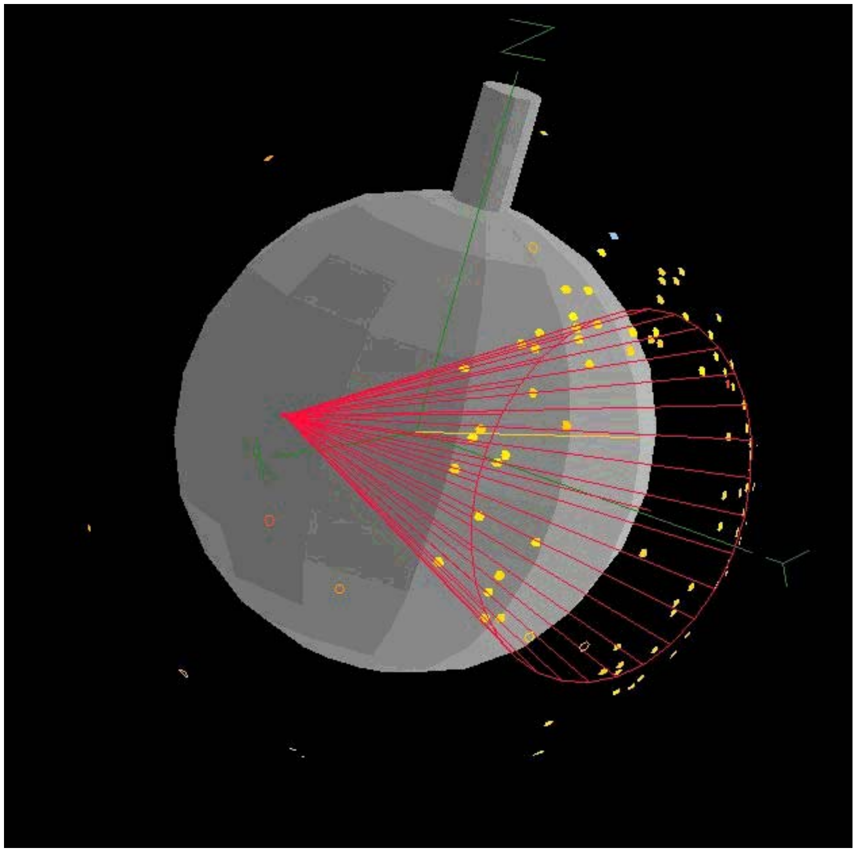
Sudbury Neutrino Observatory



Construction Phase



Solar Neutrino Event



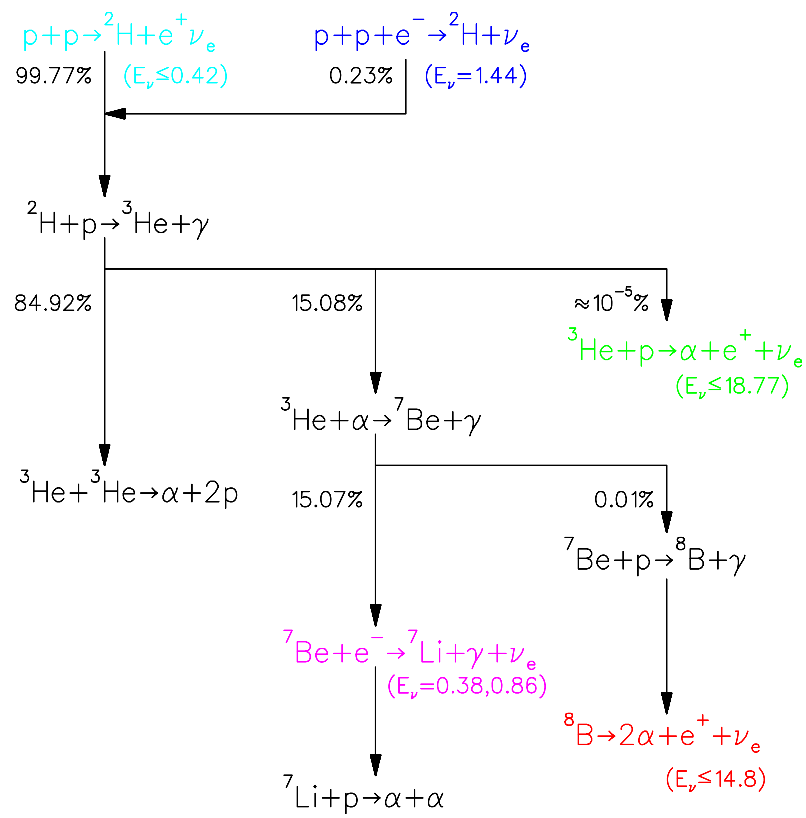
Cherenkov Light

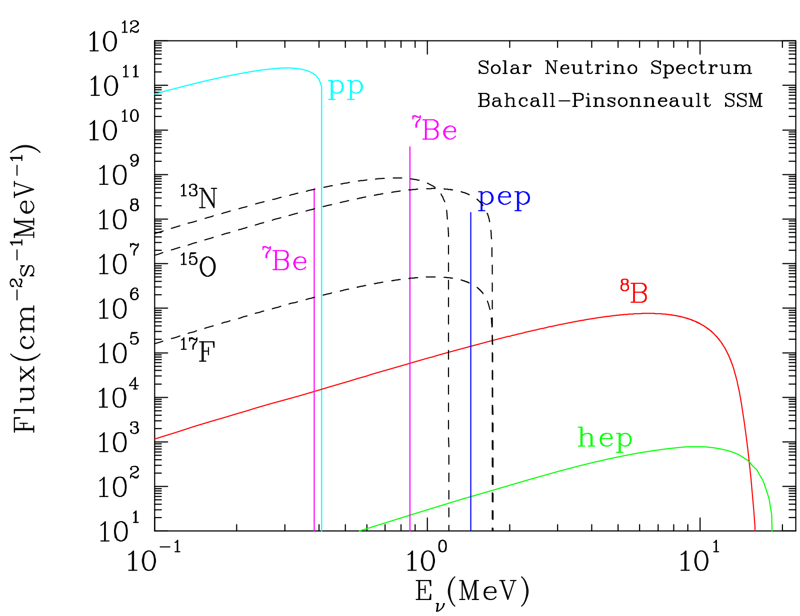
When a particle travels through a medium such that its velocity v is greater than the velocity of light in the medium c/n, radiation is emitted. The radiation is confined to a **cone** around the direction of the incident particle.

SNO = Heavy Water Cherenkov Detector

Neutrinos from the Sun

Solar Fusion Chain
and
Neutrino Flux

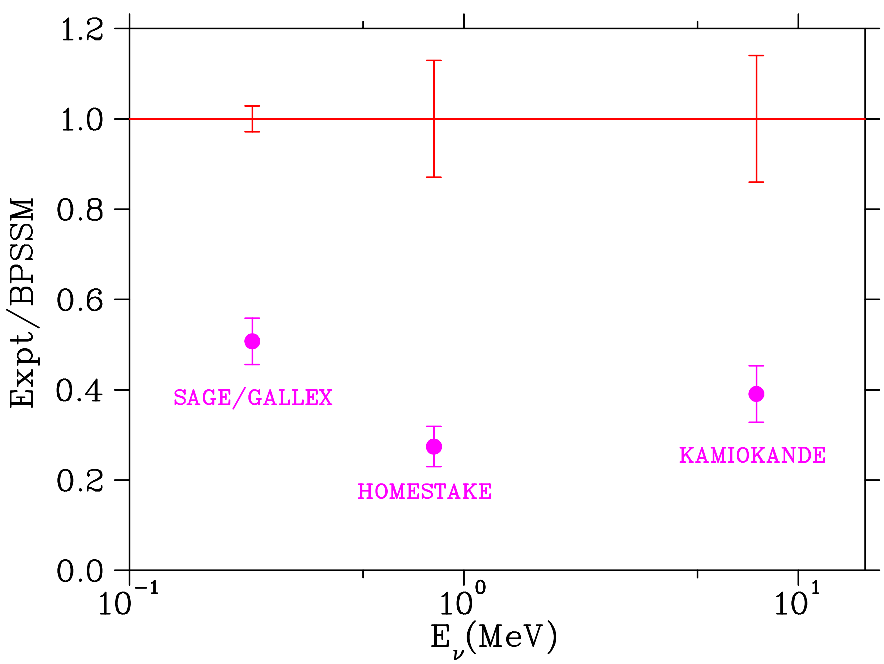




The Solar Neutrino Problem

	BP SSM	Expt	Expt/BPSSM
Homestake	$9.3^{+1.2}_{-1.4}$	$2.55 \pm 0.14 \pm 0.14$	0.273 ± 0.021
	a)	a)	
Kamiokande		$2.80 \pm 0.19 \pm 0.33$	0.423 ± 0.058
Super-Kamiokande	$6.62^{+0.93}_{-1.12}$	$2.51^{+0.14}_{-0.13} \pm 0.18$	0.379 ± 0.029
Combined		2.586 ± 0.195	0.391 ± 0.029
	b)	b)	
SAGE		$69 \pm 10^{+5}_{-7}$	0.504 ± 0.089
GALLEX	137^{+8}_{-7}	$69.7^{+3.9}_{-4.5}$	0.509 ± 0.059
Combined		69.5 ± 6.7	0.507 ± 0.049
	a)	a)	

Units a) SNU (10^{-36}/s/tgt atom)
b) $10^6/cm^2/s$



From Hata and Langacker, preprint 1997.

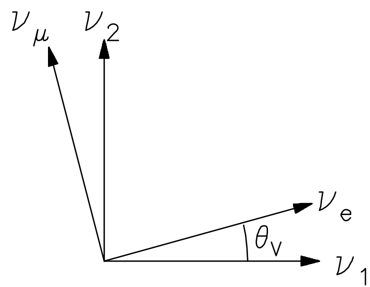
Neutrino Oscillations

For simplicity consider only two neutrino flavours, ν_e, ν_μ

- Suppose the flavour eigenstates, $|\nu_e\rangle, |\nu_\mu\rangle$ are not the mass eigenstates, $|\nu_1\rangle, |\nu_2\rangle$ Then the flavour eigenstates can be represented as a superposition of the mass eigenstates,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

where θ is the mixing angle between the mass states.



The time evolution of the flavour states becomes,

$$\begin{aligned} |\nu_e\rangle_t &= \cos\theta e^{-iE_1 t}|\nu_1\rangle + \sin\theta e^{-iE_2 t}|\nu_2\rangle \\ |\nu_\mu\rangle_t &= -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle \end{aligned}$$

Writing the time evolution in terms of the mass matrix gives,

$$i\frac{d}{dt}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{2}\begin{pmatrix} -\frac{\Delta m^2}{2E}\cos 2\theta & \frac{\Delta m^2}{2E}\sin^2\theta \\ \frac{\Delta m^2}{2E}\sin^2\theta & \frac{\Delta m^2}{2E}\cos 2\theta \end{pmatrix}\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

where E is the energy of the electron neutrino in MeV and

$$\Delta m^2 \equiv |m_2^2 - m_1^2|$$

- The survival probability of an electron neutrino after travelling a distance, L, is

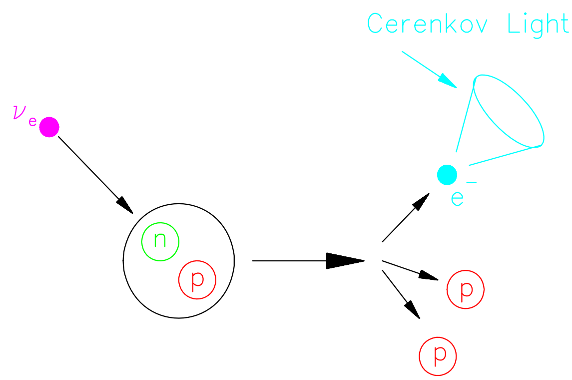
$$P_e = 1 - \sin^2 2\theta \sin^2\left[\pm\frac{1.27\Delta m^2 L}{E}\right]$$

- Furthermore, you can get an enhancement of flavour conversion in the sun due to the *Mikheyev Smirnov Wofenstein (MSW) Effect*

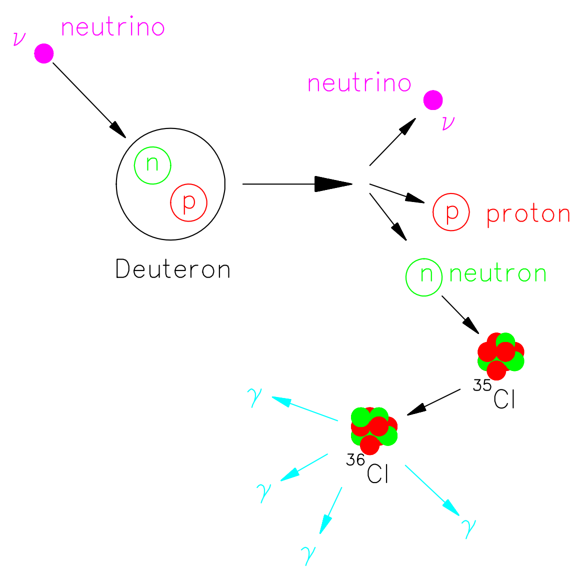
Deuterium Reactions

Detecting Neutrinos with Deuterium

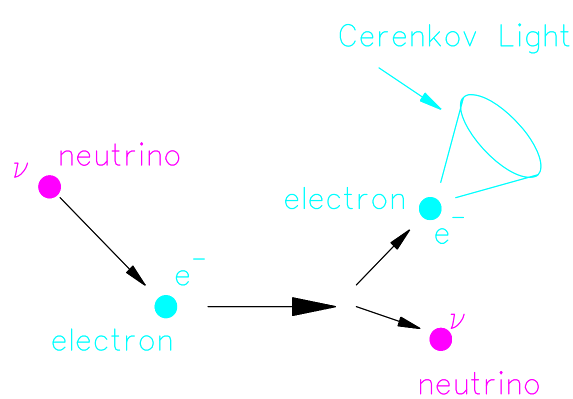
Charged Current



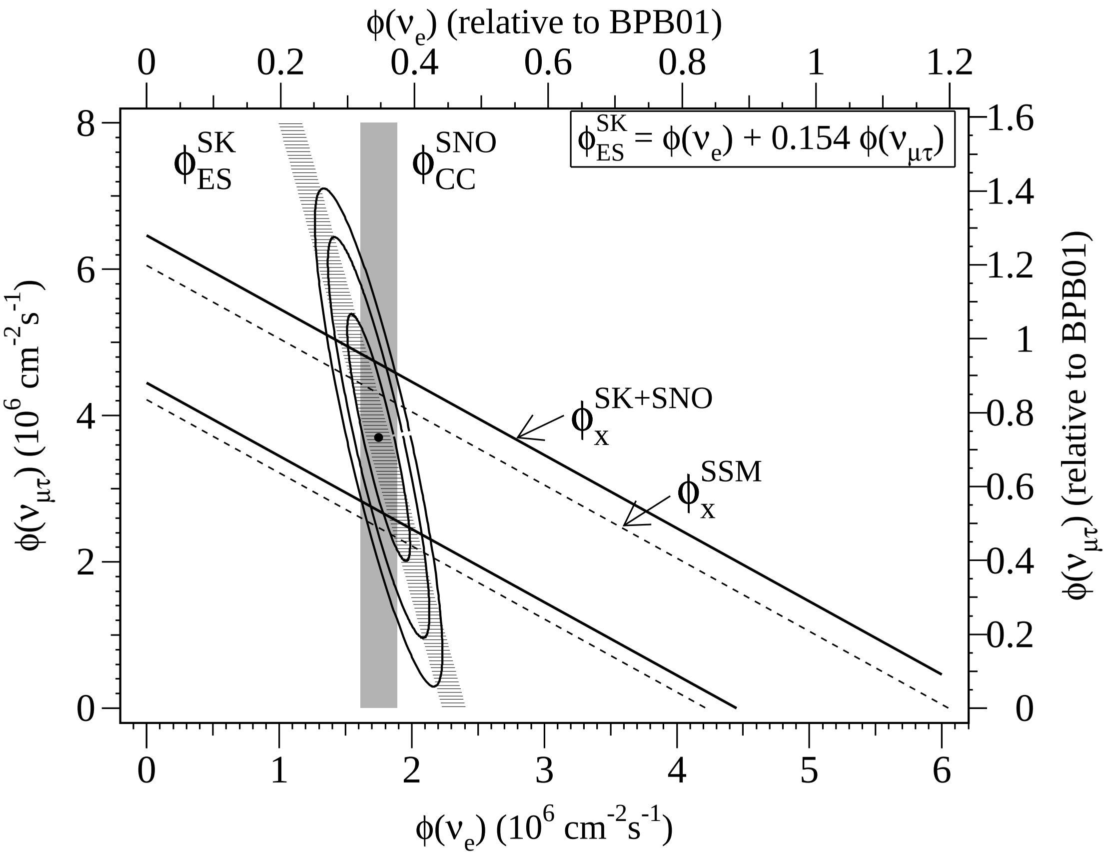
Neutral Current



Electron Scattering



SNO: First Results



Φ^{SNO}_{CC}: Sensitive to ν_e only!

Φ^{SK}_{ES}: Sensitive to ν_e, ν_μ, and ν_τ

Here $\Phi^{\text{SK}}_{ES} = \Phi(\nu_e) + 0.154\Phi(\nu_{\mu\tau})$

$\Phi(\nu_{\mu\tau}) \neq 0$ at the 3.3 standard deviation.

$\longrightarrow$ First evidence of solar neutrino oscillation !!!

Next: measure CC/NC will provide an unambiguous statement on whether neutrinos oscillate on their way to the earth from the core of the sun.

Summary

The open questions of particle physics:

- Weak flavor mixing in the quark and neutrino sectors.
- Search of the Higgs boson and new physics beyond the SM.

Elementary Particles 75-462 & 562:

- **Constituents of matter**
- **Fundamental forces**
- **Conservation Laws**
- **Invariance Principles and Symmetries**
- **Relativistic Kinematics**
- **Quark Model**
- **QED and QCD**
- **Feynman Rules**
- **Electroweak interactions**
- **Open questions!**

URL: http://www.physics.carleton.ca/∼alainb/