Physics Beyond the Standard Model

- Supersymmetry
- Dynamical Symmetry Breaking - Technicolor
- Grand Unified Theories: the SU(5) GUT
- Unification energy and weak mixing angle
- Supersymmetric SU(5)
- Proton Decay
- Neutrino mass: Dirac and Majorana neutrinos
- Neutrino Oscillations
- Magnetic Monopoles
- Superstrings

Reference: Donald H. Perkins, Introduction to High Energy Physics, Fourth Edition

The Standard Model

- $SU(3)_C \times SU(2) \times U(1)_Y$ = Standard Model
- no serious conflict with data
- shortcomings:
  - can we further unify electroweak and strong interactions?
    - Grand Unified Theory (GUT)
  - hierarchy problem
    - quantum effects are important at the Planck scale of 10^{19} GeV
    - new particles at the Planck scale would lead to divergences in the Higgs mass through virtual loops, unless something is done to cancel them
      - Supersymmetric models are designed to do this
  - left-handed (only) neutrinos means massless neutrinos
    - but neutrinos appear to have mass (oscillations)
  - gravity left out
    - Supergravity??

Supersymmetry

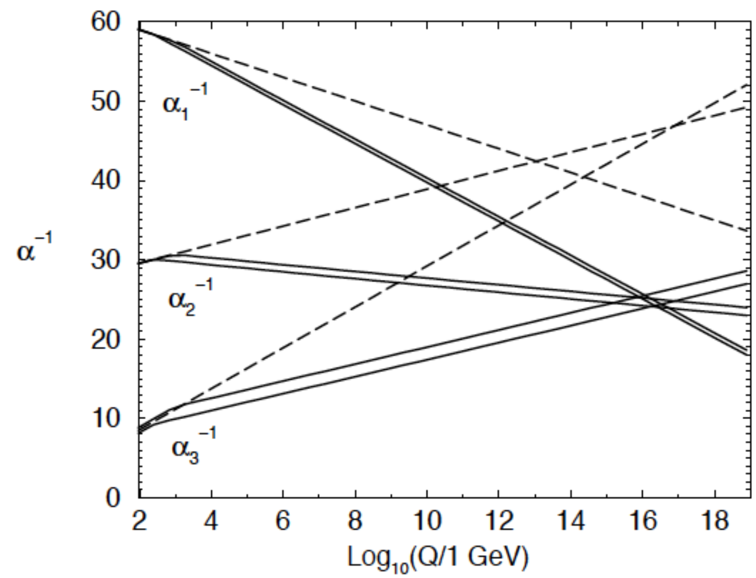
- Supersymmetry could provide cancellations in the divergent amplitudes - solving the hierarchy problem
- Generalized space-time symmetry -> Fermion-boson symmetry
  - every fermion has a superpartner: a boson
  - every boson has a superpartner: a fermion
- Broken symmetry
  - Mass (superpartners) >> Mass (original particles)
- However, radiative corrections from virtual boson and fermion loops are of opposite sign $\Rightarrow$ cancel
  - for this to work, superpartner masses need to satisfy relation

$$|M_F^2 - M_B^2| < 1 \text{ TeV}^2$$

- Associated production often assumed
  - R parity
- Lightest Supersymmetric Particle (LSP)
  - stable
  - Neutralino?

Motivations for Supersymmetry

- Supersymmetry could provide cancellations in the divergent amplitudes - solving the hierarchy problem
- Analogous muon magnetic moment
- Unification of gauge couplings
- Dark matter candidate (LSP)
- Possible additional sources of CP violation could explain baryogenesis



Supersymmetry

- Minimal Supersymmetric Standard Model (MSSM)
  - Two-Higgs-doublet extension to SM + supersymmetric partners

Field Content of the MSSM					
Super-Multiplets	Boson Fields	Fermionic Partners	SU(3)	SU(2)	U(1)
gluon/gluino	g	$\widetilde{g}$	8	1	0
gauge/	$W^{\pm}, W^0$	$\widetilde{W}^{\pm}, \widetilde{W}^0$	1	3	0
gaugino	B	$\widetilde{B}$	1	1	0
slepton/	$(\widetilde{\nu}, \widetilde{e}^-)_L$	$(\nu, e^-)_L$	1	2	-1
lepton	$\widetilde{e}^-_R$	e^-_R	1	1	-2
squark/	$(\widetilde{u}_L, \widetilde{d}_L)$	$(u, d)_L$	3	2	1/3
quark	$\widetilde{u}_R$	u_R	3	1	4/3
	$\widetilde{d}_R$	d_R	3	1	$-2/3$
Higgs/	(H^0_d, H^-_d)	$(\widetilde{H}^0_d, \widetilde{H}^-_d)$	1	2	-1
higgsino	(H^+_u, H^0_u)	$(\widetilde{H}^+_u, \widetilde{H}^0_u)$	1	2	1

Supersymmetry

- Minimal Supersymmetric Standard Model (MSSM)

Particle	Spin	Sparticle	Spin
quark Q	$\frac{1}{2}$	squark $\tilde{Q}$	0
lepton l	$\frac{1}{2}$	slepton $\tilde{l}$	0
photon γ	1	photino $\tilde{\gamma}$	$\frac{1}{2}$
gluon G	1	gluino $\tilde{G}$	$\frac{1}{2}$
$W^{\pm}$	1	wino $\tilde{W}^{\pm}$	$\frac{1}{2}$
Z^0	1	zino $\tilde{Z}^0$	$\frac{1}{2}$

HIGGS PARTICLES

Two scalar (CP even) neutral particles: h^0 H^0

One pseudoscalar (CP odd) neutral A^0

Two charged scalars H^+ H^-

- Two Higgs doublets 5 physical Higgs particles (3 fields are "eaten" by W/Z)
  - 4 higgsinos ($\tilde{H}^0_{1,2}$ $\tilde{H}^{\pm}$)
  - mix with four gauginos (photino, winos, zino) to form
    - 4 charginos $\chi^{\pm}_{1,2}$
    - 4 neutralinos $\chi^0_{1,2,3,4}$

R-parity

- MSSM introduces multiplicative R-parity invariance

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

  SM particles then have R positive

  SUSY partners have R negative
- SUSY particle produced in pairs
- LSP is absolutely stable
  - Dark matter candidate
  - Must be electrically uncharged and color neutral

MSSM Parameters

SUSY conserving

- Gauge couplings: g_s, g, g'
- Higgsino mass parameter: μ
- Higgs-fermion Yukawa coupling constants:

$$\lambda_u, \ \lambda_d, \ \lambda_e$$

SUSY breaking

- Gaugino Majorana masses: M_1, $M_{2,}$ M_3
- Scalar squared mass for squarks and sleptons (5)
  - Corresponds to superpartners of $(u,d)_L$ $u_L{}^c$ $d_L{}^c$ $(\nu, e)_L$ $e_L{}^c$
- Higgs-squark-squark and Higgs-slepton-slepton trilinear interaction terms (3) or $\lambda_i A_i$'s (yield v_d and v_u – or v_1 and v_2)
- Scalar squared-mass parameters
  - $m_1{}^2$ $m_2{}^2$ $m_{12}{}^2$

Additional terms run the number of independent parameters to 124

MSSM Parameters

124 independent parameters

- 18 are SM parameters
- 1 Higgs sector (equiv. to Higgs mass)
- 105 new parameters

Parameters can be constrained by known phenomenology

- Conservation of separate lepton numbers: L_e, L_μ, L_τ
- Absence of flavor-changing neutral currents (FCNC)
- Constraints on CP violation

In order to reduce parameters and accommodate these constraints, a number of theoretical frameworks are proposed

Gaugino Mass Unification and constrained MSSM

Motived by Grand Unification, set gaugino mass together at a high mass scale

$$M_1(M_X) = M_2(M_X) = M_3(M_X) = m_{1/2}$$

Then, at the EW scale:

$M_3 = (g_s^2/g^2)M_2 \simeq 3.5\ M_2$ $\quad$ $M_1 = (5g'^2/3g^2)M_2 \simeq 0.5\ M_2$

And the masses and mixings of the charginos and neutralinos are dependent only on

μ and $\tan\beta$

Gaugino Mass Unification and constrained MSSM

mSUGRA (minimal supergravity) takes this a step further:

$$M^2_{\tilde{Q}}(M_X) = M^2_{\tilde{U}}(M_X) = M^2_{\tilde{D}}(M_X) = m_0^2 \mathbf{1}\,,$$

$$M^2_{\tilde{L}}(M_X) = M^2_{\tilde{E}}(M_X) = m_0^2 \mathbf{1}\,,$$

$$m_1^2(M_X) = m_2^2(M_X) = m_0^2\,,$$

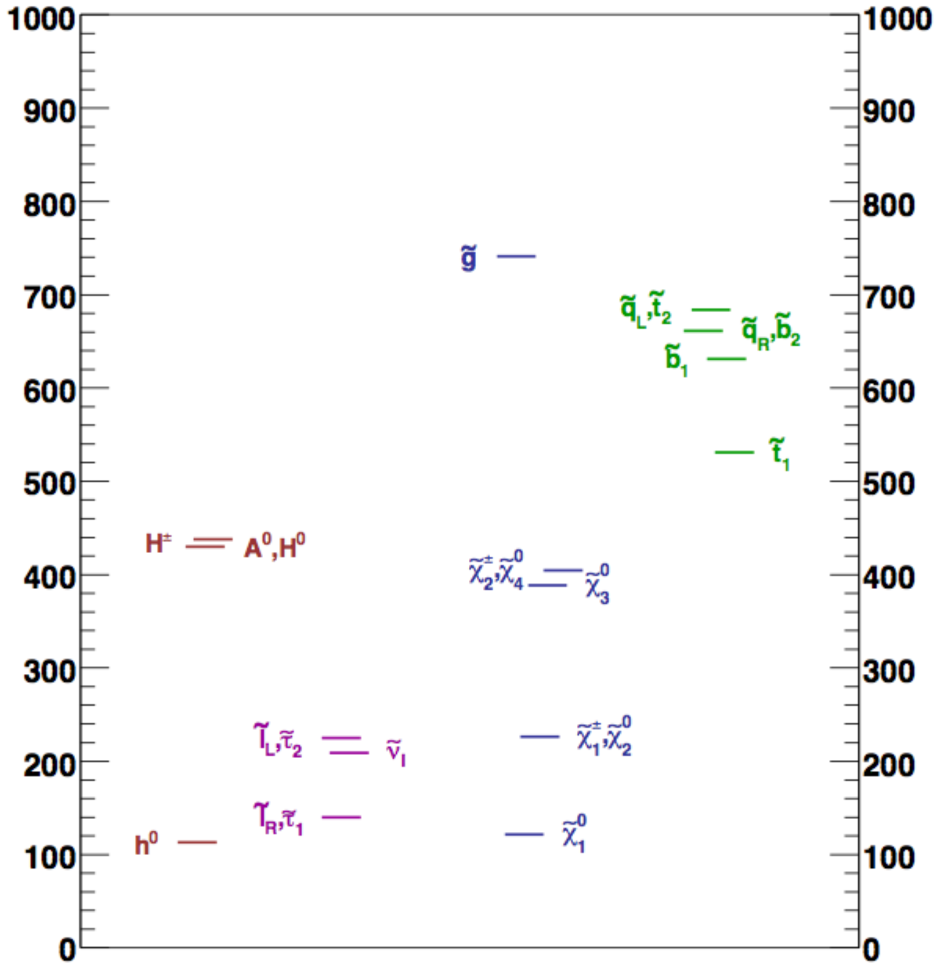
$$A_U(M_X) = A_D(M_X) = A_E(M_X) = A_0 \mathbf{1}\,,$$

Constrained MSSM

- Five parameters:

  m_0, A_0, $m_{1/2}$, $\tan\beta$, $\mathrm{sgn}(\mu_0)$

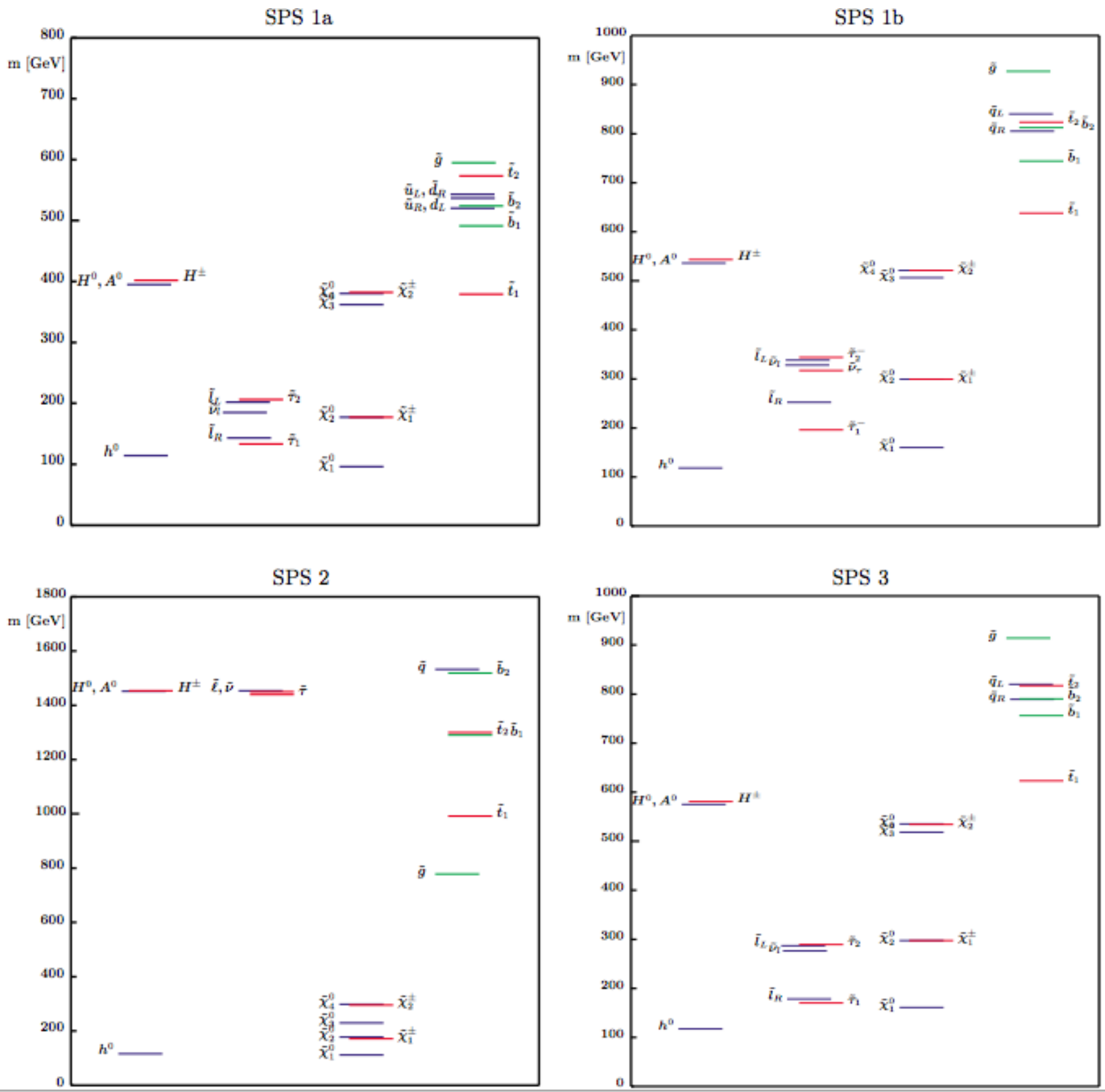
Best-fit CMSSM Spectrum



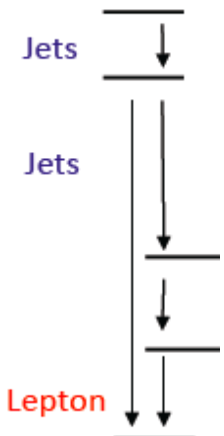
The spectrum at the best-fit CMSSM point, assuming LSP is the lightest neutralino

J. Ellis, "The Physics Prospects for CLIC," arXiv:0811.1366

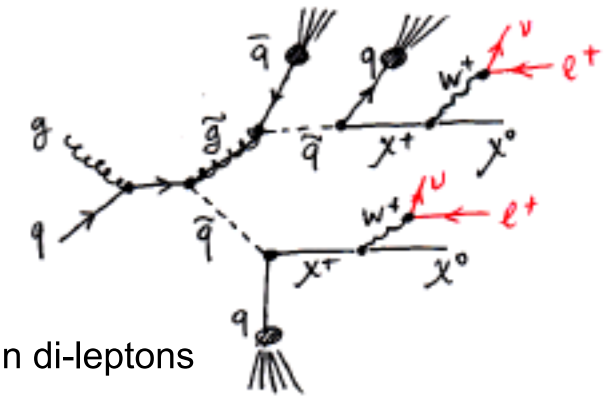
Example candidate spectra



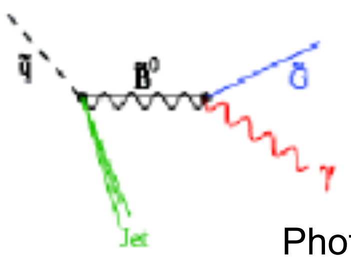
Search Strategies



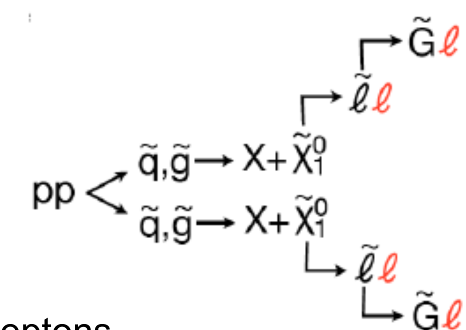
Jets and missing E_T



Same sign di-leptons



Photons

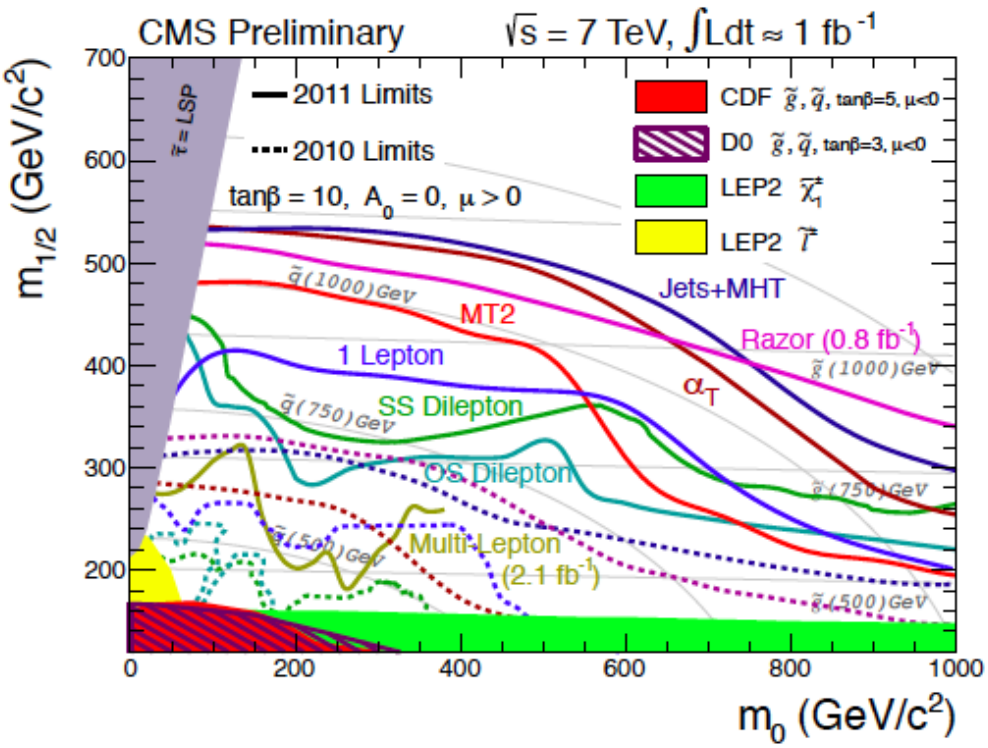


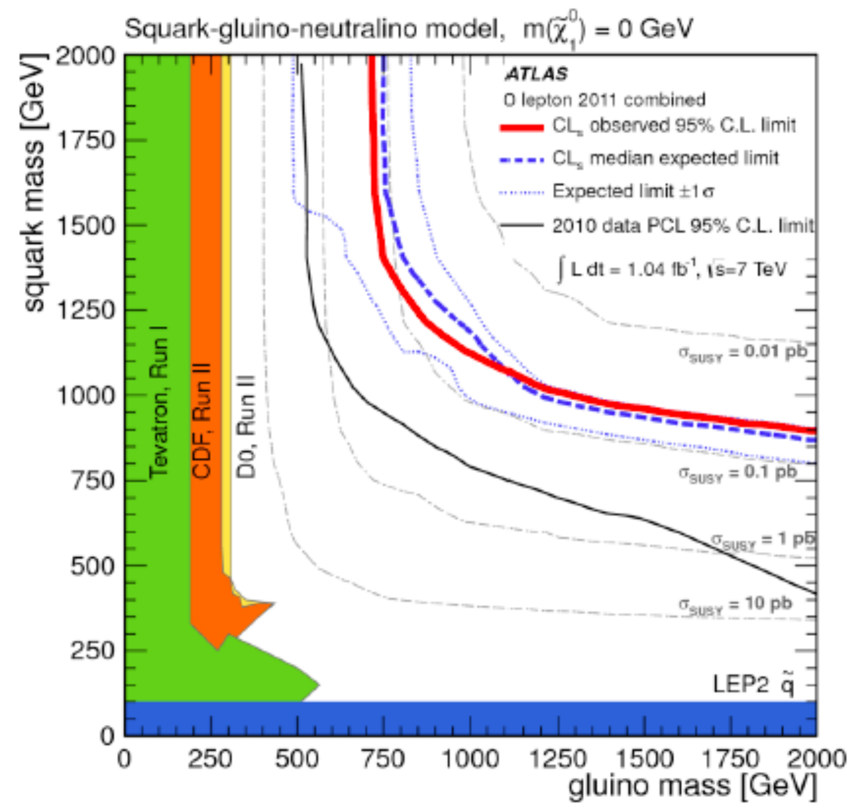
Multi-leptons

S. Lowette, 2012; S. Thomas, 2012

LHC Limits

ATLAS, arXiv:1109:6572





https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

S. Kraml, Moriond EM 2012

Supersymmetric Higgs

$$\mathcal{L} = |D_\mu \phi_1|^2 + |D_\mu \phi_1|^2 - V(\phi_1, \phi_2) \ ,$$

$$V = -\begin{pmatrix} \phi_1^\dagger & \phi_2^\dagger \end{pmatrix} M^2 \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} + \cdots \ ,$$

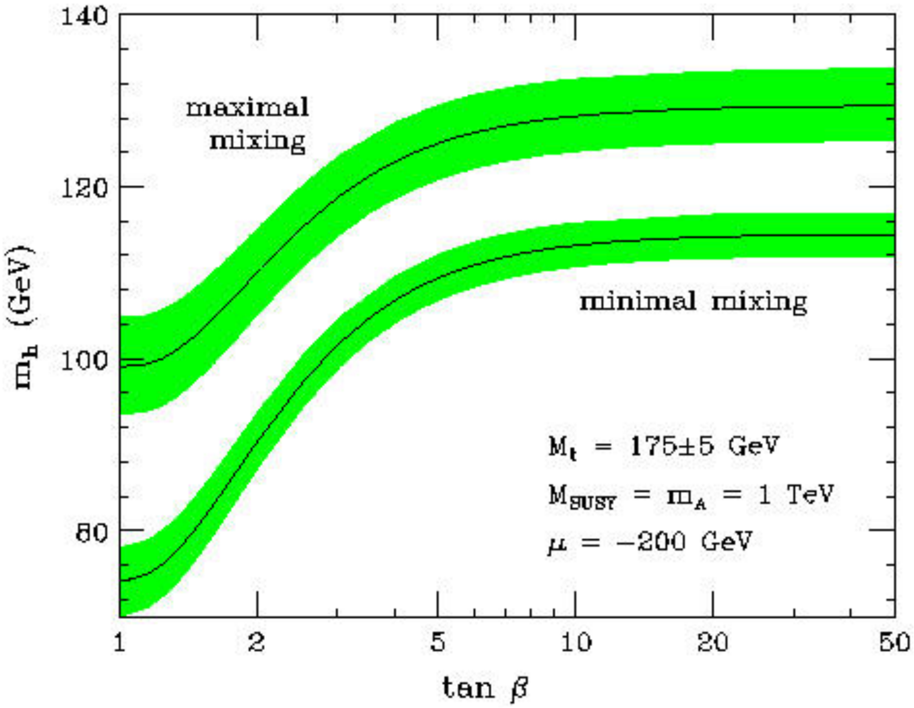
$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_1 \end{pmatrix} \ , \qquad \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}} v_2 \end{pmatrix} \ .$$

$$\tan \beta = \frac{v_2}{v_1} \ .$$

$$v_1^2 + v_2^2 = v^2 = (246 \text{ GeV})^2 \ .$$

Supersymmetry

- Masses and couplings of the particles described by five parameters in the cMSSM framework:
  - m_0, A_0, $m_{1/2}$, tan β, sgn(μ_0)
  - mixing angle: $\tan\beta = v_2/v_1$
    - v_1 and v_2 are vacuum expectation values of the Higgs fields H_1 and H_2



MSSM Higgs boson couplings

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h^0	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to 1$	$\sin(\beta-\alpha) \to 1$
H^0	$\sin\alpha/\sin\beta \to 1/\tan\beta$	$\cos\alpha/\cos\beta \to \tan\beta$	$\cos(\beta-\alpha) \to 0$
A^0	$1/\tan\beta$	$\tan\beta$	0

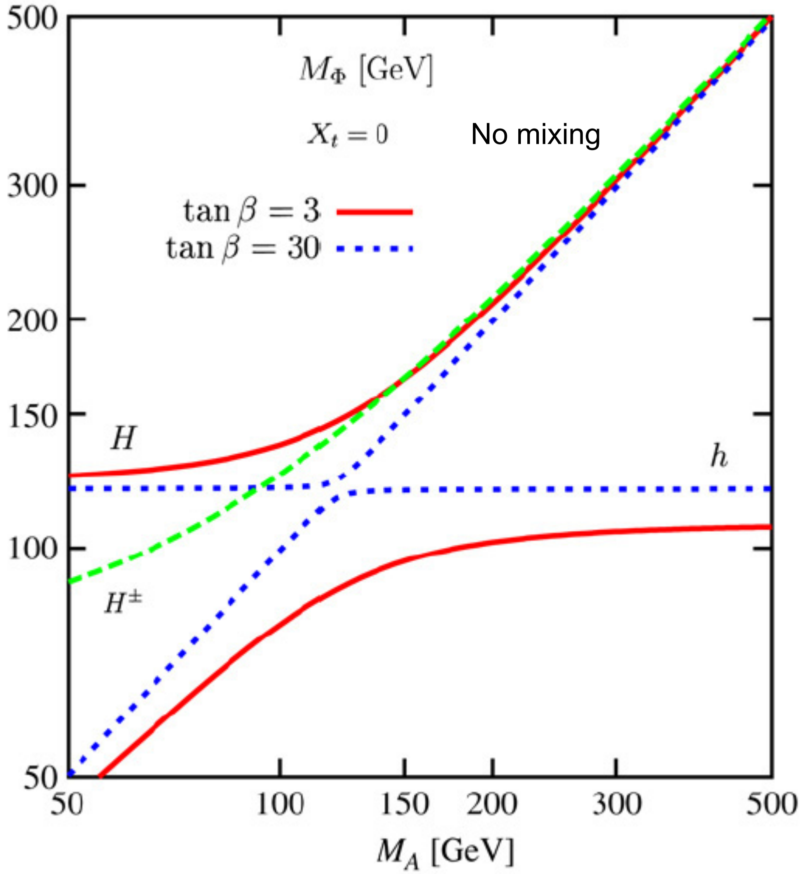
Table 2.1.2: *MSSM neutral Higgs boson couplings to fermions and gauge bosons normalized to the SM Higgs couplings, and their limit for $M_A \gg M_Z$ [decoupling regime].*

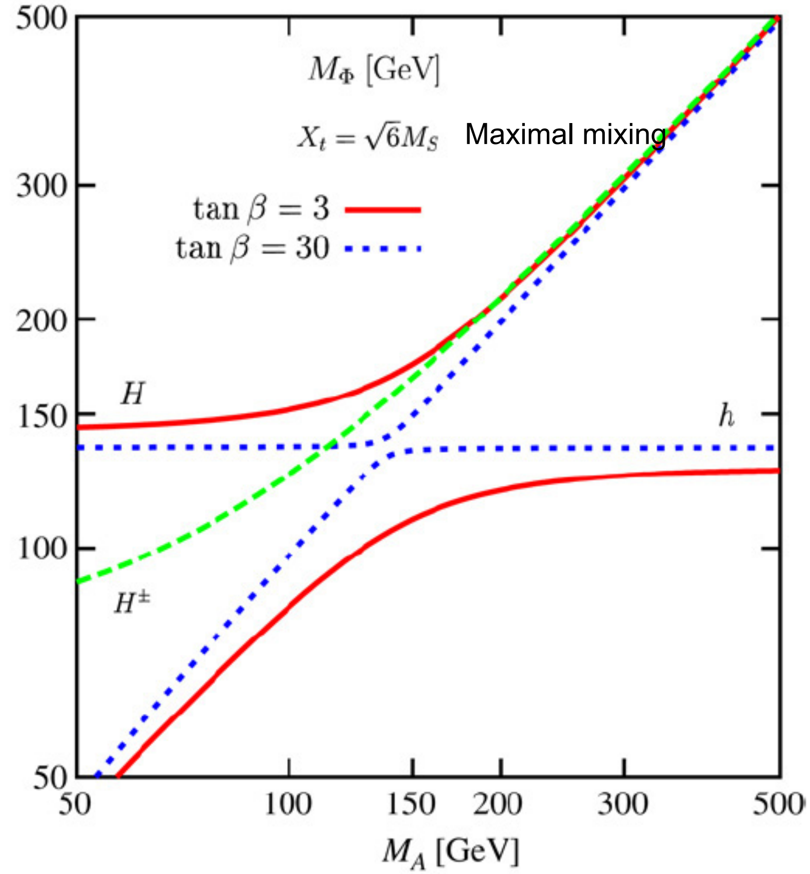
α Is the mixing angle in the neutral CP-even sector

From TESLA TDR

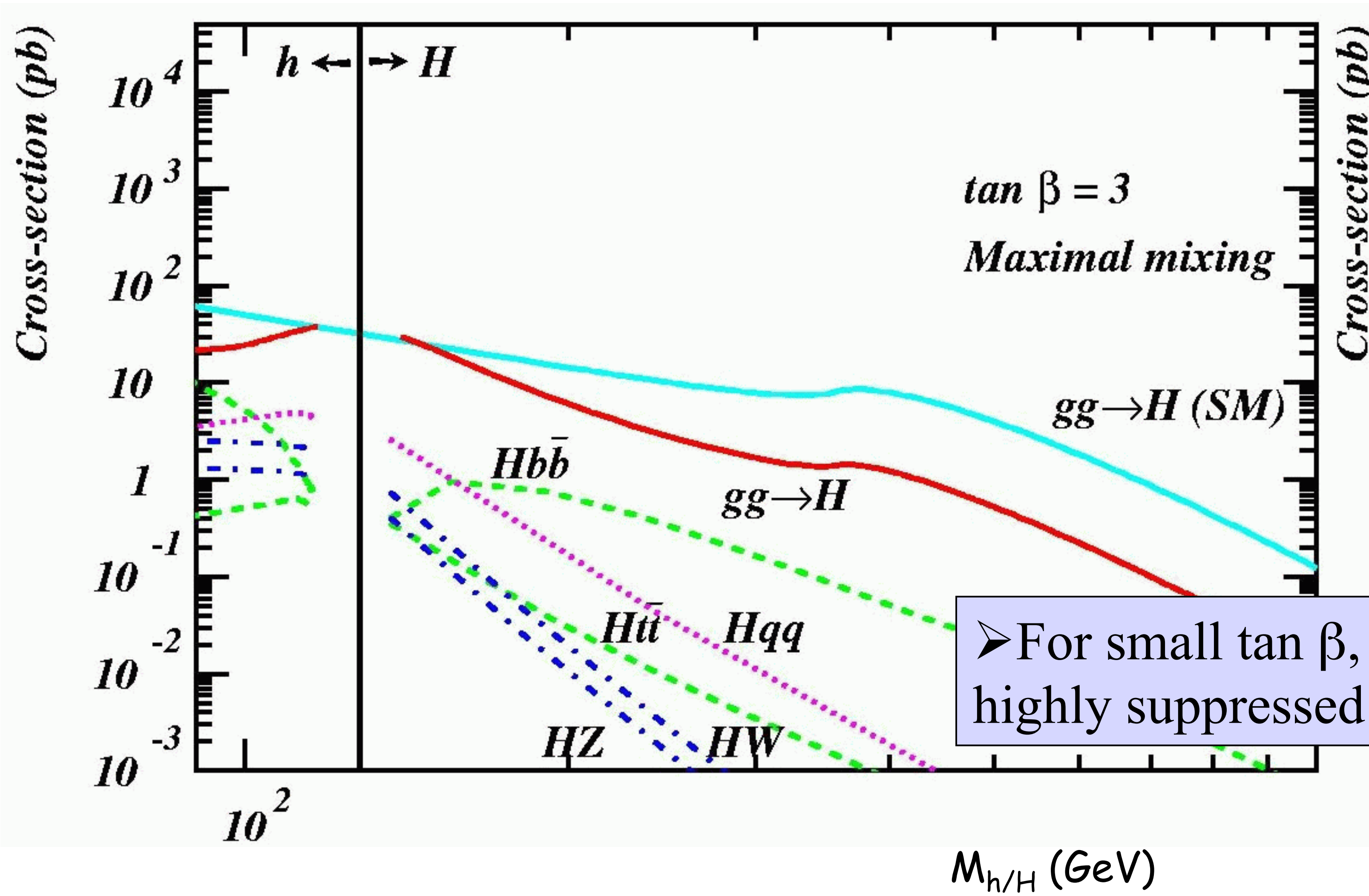
Supersymmetry

A. Djouadi / Physics Reports 459 (2008) 1–241



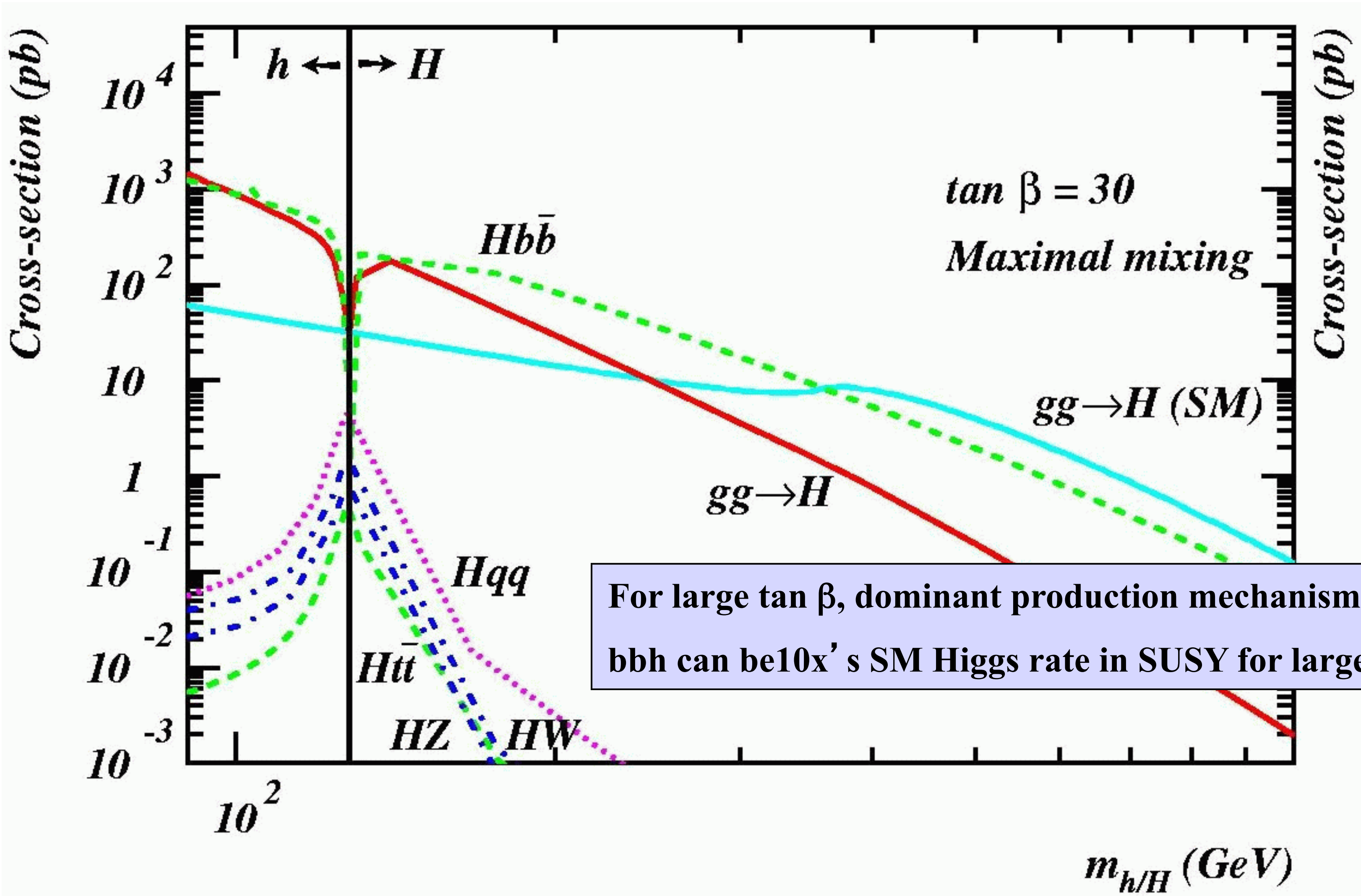


Hadron Collider Cross sections -SUSY



- For small tan β, σ(bbh) highly suppressed

Hadron Collider Cross sections -SUSY



For large tan β, dominant production mechanism is with b's

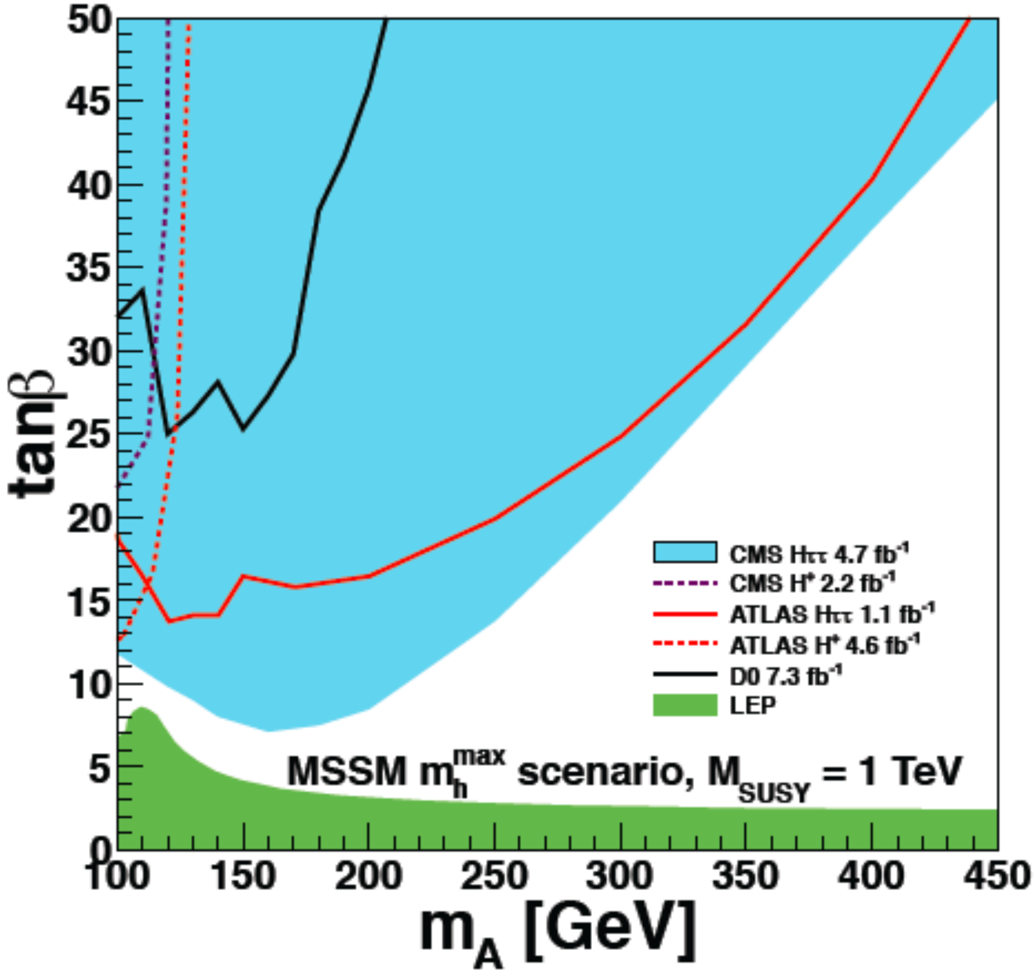
bbh can be10x's SM Higgs rate in SUSY for large tan β

MSSM Higgs Limits

arXiv:1202.4083

ATLAS CONF 2012-11

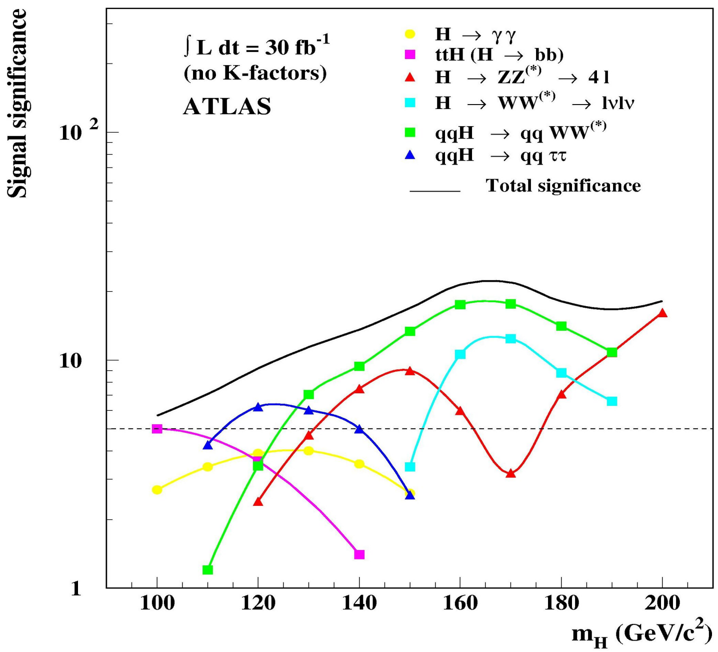
CMS PAS HIG-11-019

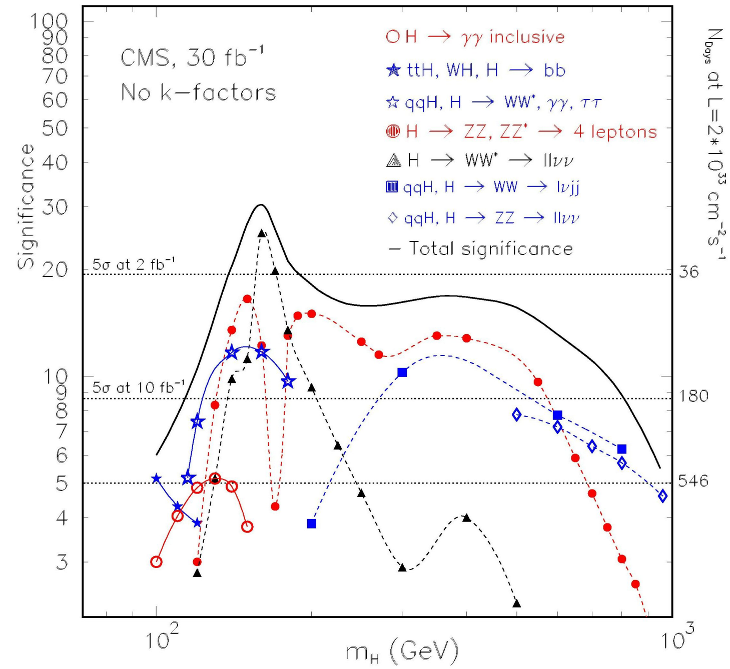


Mar-6-12

Sridhara Dasu

If there is a light SM Higgs, we'll find it at the LHC





Dawson, Aspen, 2004

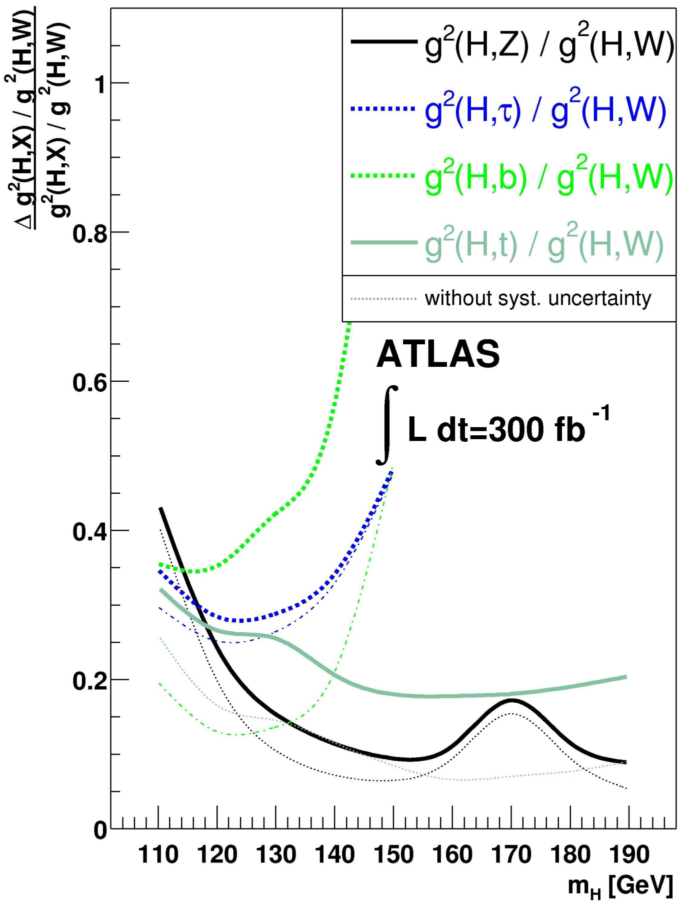
No holes in M_h coverage

Discovery happens early!
(plots are 30 fb^{-1})

If we find a "Higgs-like" object, what then?

- We need to:
  - Measure Higgs couplings to fermions & gauge bosons
  - Measure Higgs spin/parity
  - Reconstruct Higgs potential
- Many models have other signatures:
  - New gauge bosons (little Higgs)
  - Other new resonances (Extra D)
  - Scalar triplets (little Higgs, NMSSM)
  - Colored scalars (MSSM)
  - etc

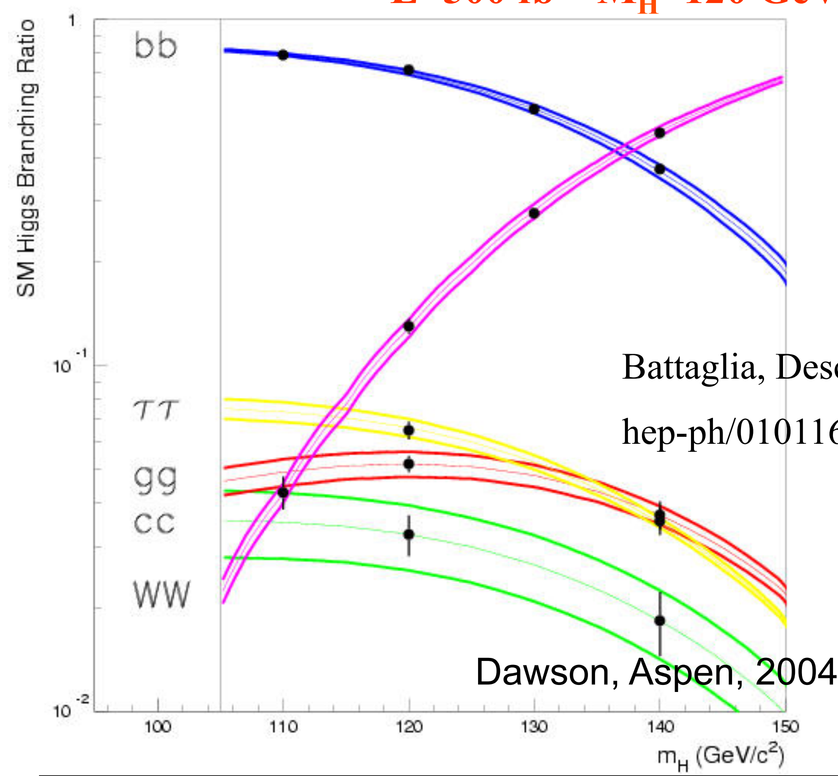
Absolute measurements of Higgs couplings



Duhrssen, ATL-PHYS-2003-030

e^+e^- LC at $\sqrt{s}$=350 GeV

L=500 fb^{-1}, M_H=120 GeV

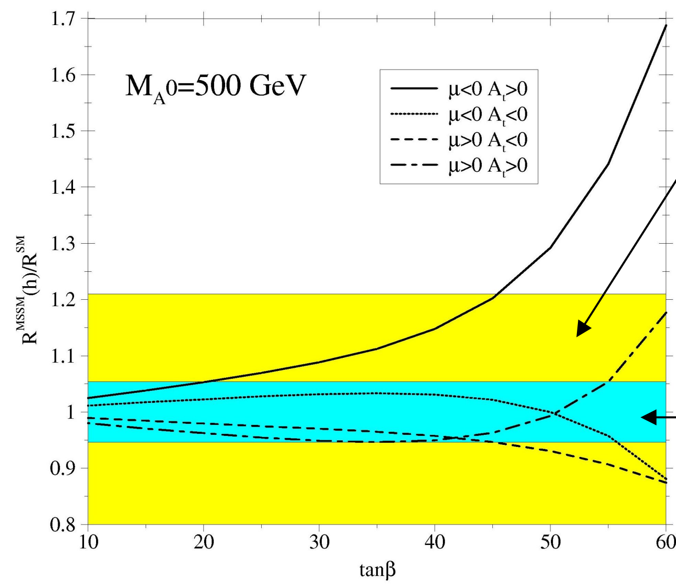


LC can measure g_{ZZh} to few% through $\sigma(e^+e^- \rightarrow Zh)$

How well do we need Higgs couplings?

- MSSM example:

$$R = \frac{BR(h \to b\bar{b})}{BR(h \to \tau^+\tau^-)}$$

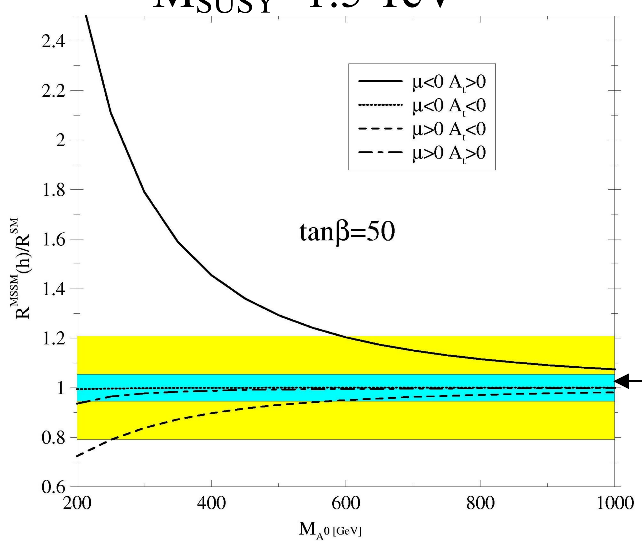


21% deviation from SM

5.4% deviation from SM

Dawson, Aspen, 2004

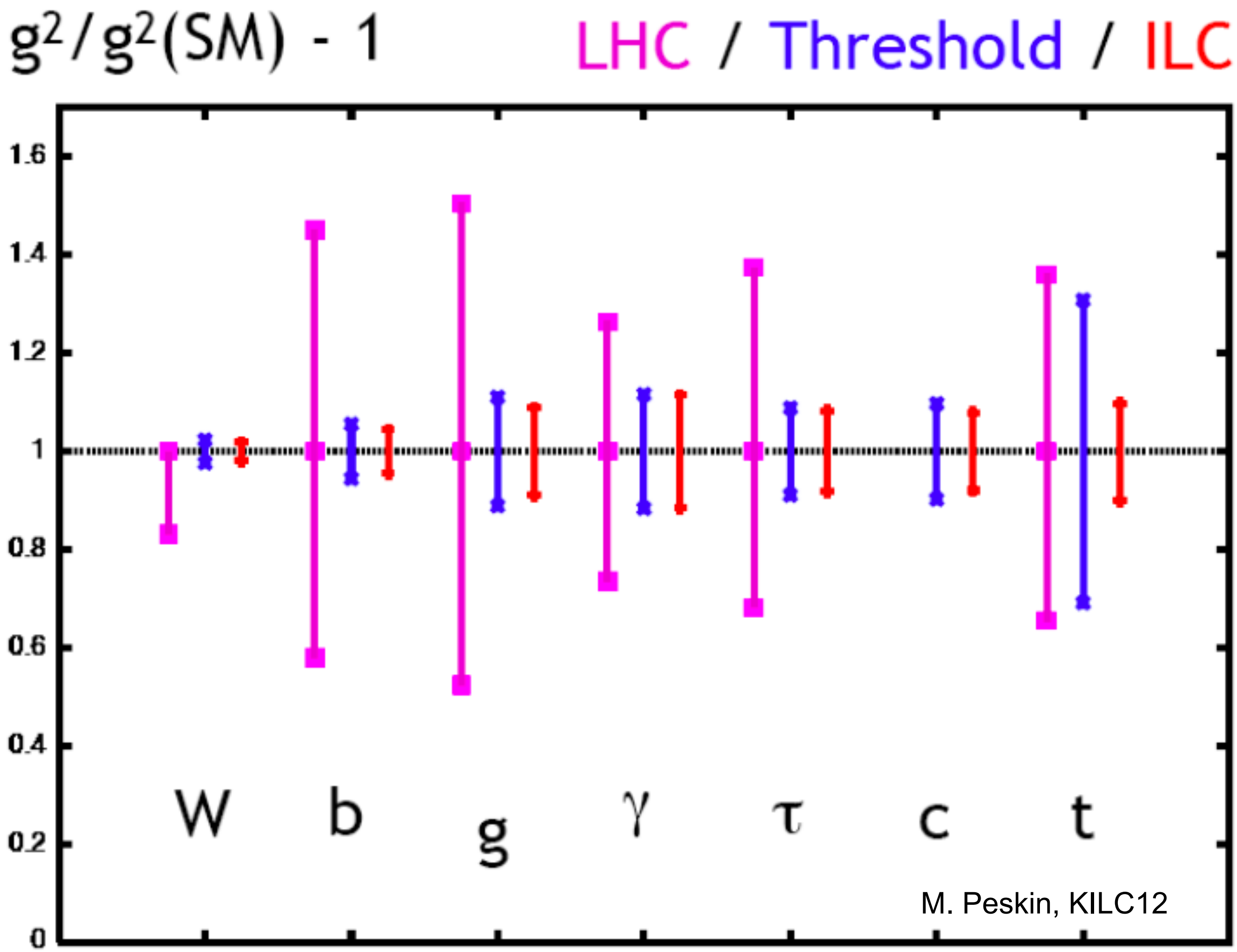
M_{SUSY}=1.5 TeV



Note rapid approach to decoupling limit

Guasch, Hollik, Penaranda, hep-ph/0307012

LHC & LC



$g^2/g^2(SM) - 1$
LHC / Threshold / ILC
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
W
b
g
γ
τ
c
t
M. Peskin, KILC12

SUSY - Summary

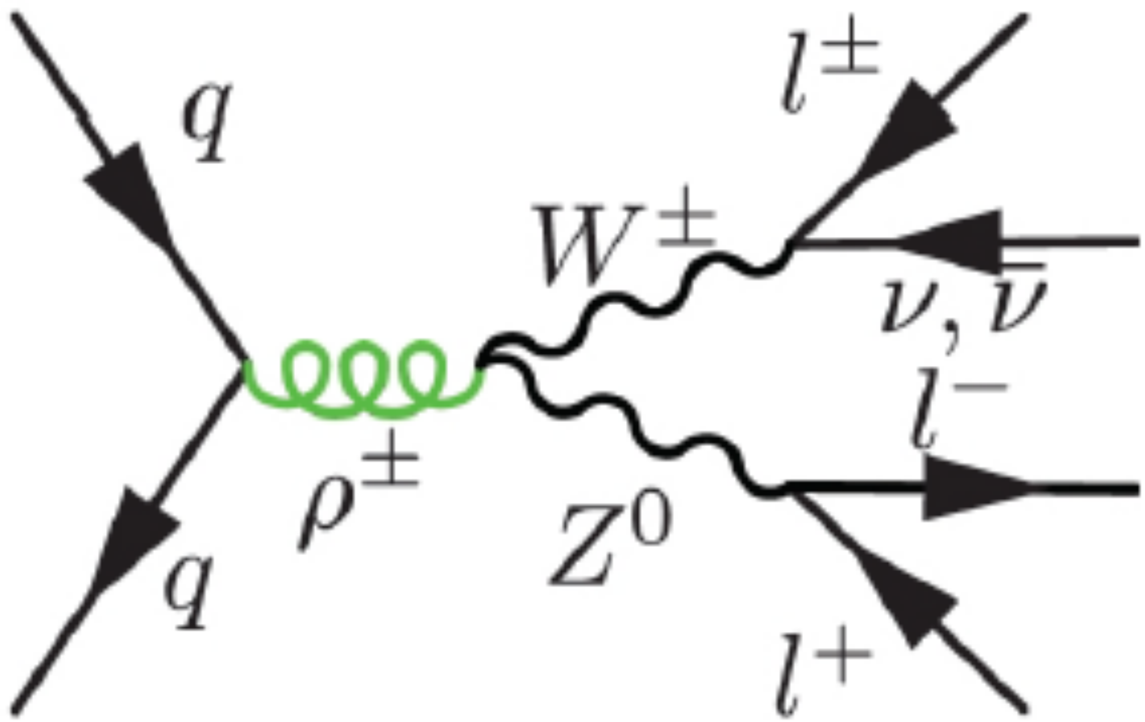
- Supersymmetry is motivated to solve a number of questions of particle physics
- It is expected to appear, if it exits, below a TeV, based on solving the hierarchy problem
- The parameter space is large, making its exploration challenging to experiments
- The LHC has constrained the possibilities already, dampening the prospects for the simpler realizations

Dynamical Symmetry Breaking

New strong interaction

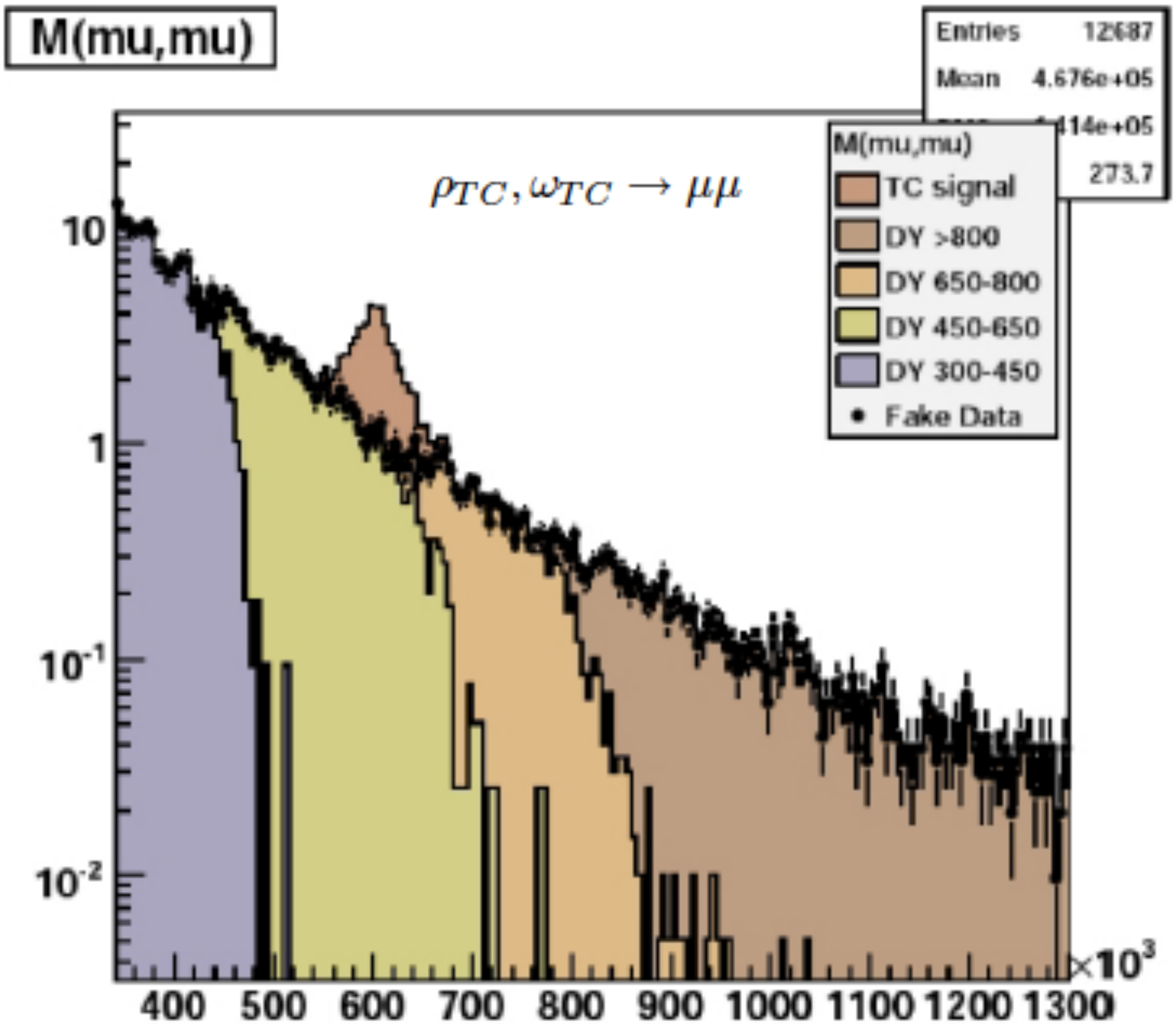
- Electroweak symmetry may be broken by fermion condensates bound by a new strong interaction.
- A simplest version is called technicolor
  - a new force which looks like QCD but at a larger energy scale
  - technifermions appear carrying both electroweak charges and technicharges
- Alternative versions, such as top condensation or topcolor, introduce electroweak breaking condensates involving top quarks

Dynamical Symmetry Breaking



V. Bansal

Dynamical Symmetry Breaking



J. Love and J. Butler

Dynamical Symmetry Breaking

Table 1: Summary of the mass limits. Symbols are defined in the text.

Process	Excluded mass range	Decay channels	Ref.
$p\bar{p} \to \rho_T \to W\pi_T$	$170 < m_{\rho_T} < 215$ GeV and $80 < m_{\pi_T} < 115$ GeV for $M_V = 500$ GeV	$\rho_T \to W\pi_T$ $\pi_T^0 \to b\bar{b}$ $\pi_T^\pm \to b\bar{c}$	[19]
$p\bar{p} \to \omega_T \to \gamma\pi_T$	$140 < m_{\omega_T} < 290$ GeV for $m_{\pi_T} \approx m_{\omega_T}/3$ and $M_T = 100$ GeV	$\omega_T \to \gamma\pi_T$ $\pi_T^0 \to b\bar{b}$ $\pi_T^\pm \to b\bar{c}$	[20
$p\bar{p} \to \omega_T/\rho_T$	$m_{\omega_T} = m_{\rho_T} < 203$ GeV for $m_{\omega_T} < m_{\pi_T} + m_W$ or $M_T > 200$ GeV	$\omega_T/\rho_T \to \ell^+\ell^-$	[21
	$m_{\omega_T} = m_{\rho_T} < 280$ GeV for $m_{\omega_T} < m_{\pi_T} + m_W$ or $M_T > 500$ GeV	$\omega_T/\rho_T \to \ell^+\ell^-$	[22
$e^+e^- \to \omega_T/\rho_T$	$90 < m_{\rho_T} < 206.7$ GeV $m_{\pi_T} < 79.8$ GeV	$\rho_T \to WW$, $W\pi_T$, $\pi_T\pi_T$, $\gamma\pi_T$, hadrons	[23
$p\bar{p} \to \rho_{T8}$	$260 < m_{\rho_{T8}} < 480$ GeV	$\rho_{T8} \to q\bar{q},\ gg$	[25]
$p\bar{p} \to \rho_{T8}$ $\to \pi_{LQ}\pi_{LQ}$	$m_{\rho_{T8}} < 510$ GeV $m_{\rho_{T8}} < 600$ GeV $m_{\rho_{T8}} < 465$ GeV	$\pi_{LQ} \to c\nu$ $\pi_{LQ} \to b\nu$ $\pi_{LQ} \to \tau q$	[28] [28] [27]
$p\bar{p} \to g_t$	$0.3 < m_{g_t} < 0.6$ TeV for $0.3m_{g_t} < \Gamma < 0.7m_{g_t}$	$g_t \to b\bar{b}$	[35]
$p\bar{p} \to Z'$	$m_{Z'} < 480$ GeV for $\Gamma = 0.012m_{Z'}$ $m_{Z'} < 780$ GeV for $\Gamma = 0.04m_{Z'}$	$Z' \to t\bar{t}$	[36]

Process	Excluded mass range	Decay channels	Ref.
$p\bar{p} \to \rho_{T8}$	$260 < m_{\rho_{T8}} < 480$ GeV	$\rho_{T8} \to q\bar{q},\ gg$	[25]
$p\bar{p} \to \rho_{T8}$ $\to \pi_{LQ}\pi_{LQ}$	$m_{\rho_{T8}} < 510$ GeV $m_{\rho_{T8}} < 600$ GeV $m_{\rho_{T8}} < 465$ GeV	$\pi_{LQ} \to c\nu$ $\pi_{LQ} \to b\nu$ $\pi_{LQ} \to \tau q$	[28] [28] [27]

Particle Data Group

Dynamical Symmetry Breaking

- A Challenge for Technicolor has been its large effect on electroweak radiative corrections.
  - The S-parameter is not compatible with EW precision data
  - Possible solution is to assume the TC gauge dynamics is different from QCD, with a slowly evolving (or walking) gauge coupling

Walking Technicolor

Grand Unified Theories: the SU(5) GUT

- Can we unify weak, EM and strong forces into one theory?
  - $SU(3)_C \times SU(2) \times U(1)_Y$
  - All are gauge theories, motivating unification
- Considering the "running" of the coupling constants
  - U(1) coupling g' increases with energy (remember α increases with E)
  - the non-Abelian couplings decrease
    - SU(2) g
    - SU(3) g_s
  - do these couplings extrapolate to a common value at high energy?
    - Assuming no new physics between EW scale and Planck scale
    - Or is more physics needed?

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

Grand Unified Theories: the SU(5) GUT

- Early, simple model was SU(5) of Georgi and Glashow in 1974
  - quarks and leptons brought together into multiplets
  - leptons and quarks interact through heavy bosons, the Y and X
    - Q = -1/3 Q = -2/3
    - 12 new gauge bosons

      N^2-1 = 24

      U(1) – 1

      SU(2) – 3

      SU(3) – 8

      12 more (X, Y)

- Fermion multiplets

		I_3	$Q/\lvert e\rvert$
W	ν_e	$+\frac{1}{2}$	0
W, X	e^-	$-\frac{1}{2}$	-1
X	$\bar{d}_R$	0	$+\frac{1}{3}$
G	$\bar{d}_B$	0	$+\frac{1}{3}$
G	$\bar{d}_G$	0	$+\frac{1}{3}$

Grand Unified Theories: the SU(5) GUT

$$
\left[\begin{array}{ccccc|cccccccccc}
0 & W & X_r & X_g & X_b & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\overline{W} & 0 & Y_r & Y_g & Y_b & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\overline{X}_r & \overline{Y}_r & 0 & g_{r\bar{g}} & g_{r\bar{b}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\overline{X}_g & \overline{Y}_g & \bar{g}_{r\bar{g}} & 0 & g_{g\bar{b}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\overline{X}_b & \overline{Y}_b & \bar{g}_{r\bar{b}} & \bar{g}_{g\bar{b}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hline
0 & 0 & 0 & 0 & 0 & 0 & Y_r & Y_g & Y_b & X_r & X_g & X_b & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & \overline{Y}_r & 0 & g_{r\bar{g}} & g_{r\bar{b}} & W & 0 & 0 & 0 & X_b & X_g \\
0 & 0 & 0 & 0 & 0 & \overline{Y}_g & \bar{g}_{r\bar{g}} & 0 & g_{g\bar{b}} & 0 & W & 0 & X_b & 0 & X_r \\
0 & 0 & 0 & 0 & 0 & \overline{Y}_b & \bar{g}_{r\bar{b}} & \bar{g}_{g\bar{b}} & 0 & 0 & 0 & W & X_g & X_r & 0 \\
0 & 0 & 0 & 0 & 0 & \overline{X}_r & \overline{W} & 0 & 0 & 0 & g_{r\bar{g}} & g_{r\bar{b}} & 0 & Y_b & Y_g \\
0 & 0 & 0 & 0 & 0 & \overline{X}_g & 0 & \overline{W} & 0 & \bar{g}_{r\bar{g}} & 0 & g_{g\bar{b}} & Y_b & 0 & Y_r \\
0 & 0 & 0 & 0 & 0 & \overline{X}_b & 0 & 0 & \overline{W} & \bar{g}_{r\bar{b}} & \bar{g}_{g\bar{b}} & 0 & Y_g & Y_r & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & \overline{X}_b & \overline{X}_g & 0 & \overline{Y}_b & \overline{Y}_g & 0 & g_{r\bar{g}} & g_{r\bar{b}} \\
0 & 0 & 0 & 0 & 0 & 0 & \overline{X}_b & 0 & \overline{X}_r & \overline{Y}_b & 0 & \overline{Y}_r & \bar{g}_{r\bar{g}} & 0 & g_{g\bar{b}} \\
0 & 0 & 0 & 0 & 0 & 0 & \overline{X}_g & \overline{X}_r & 0 & \overline{Y}_g & \overline{Y}_r & 0 & \bar{g}_{r\bar{b}} & \bar{g}_{g\bar{b}} & 0
\end{array}\right]
\left[\begin{array}{c}
\nu_e \\ e \\ \bar{d}_r \\ \bar{d}_g \\ \bar{d}_b \\
\hline
\bar{e} \\ d_r \\ d_g \\ d_b \\ u_r \\ u_g \\ u_b \\ \bar{u}_r \\ \bar{u}_g \\ \bar{u}_b
\end{array}\right]
$$

Grand Unified Theories: the SU(5) GUT

- SU(5) has the following attractive features:
  - fractionally charge quarks are natural since $\Sigma_i Q_i = 0$ in multiplet
- Equality of proton and electron charge explained
- Charge conservation automatic
- Similarity of lepton and quark weak doublet patterns explained

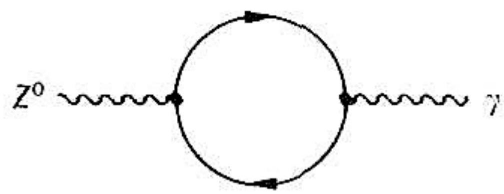
$$\psi_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \psi_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$\psi_R = (e^-)_R \qquad \psi_R = (u)_R$$

$$\psi_R = (d)_R$$

Unification energy and weak mixing angle

- Since the Z and the photon are orthogonal, the following diagram must vanish



- $\Sigma_f Q_f (I_3^f - Q_f \sin^2 \theta_W) = 0$
  $\Sigma_f Q_f I_3^f - \Sigma_f Q_f^2 \sin^2 \theta_W = 0$
  $\sin^2 \theta_W = (\Sigma_f Q_f I_3^f) / (\Sigma_f Q_f^2) = 3/8$

		I_3	$Q/\lvert e \rvert$	IQ	Q^2
W	ν_e	$+\frac{1}{2}$	0	0	0
W, X	e^-	$-\frac{1}{2}$	-1	1/2	1
X	$\bar{d}_R$	0	$+\frac{1}{3}$	0	1/9
G	$\bar{d}_B$	0	$+\frac{1}{3}$	0	1/9
G	$\bar{d}_G$	0	$+\frac{1}{3}$	0	1/9
				1/2	4/3

since $e = g \sin \theta_W \Rightarrow \sin^2 \theta_W = e^2/g^2 = 3/8$ at unification

$$e^2 = g^2 \sin^2 \theta_W = \frac{3g^2}{8}$$

Unification energy and weak mixing angle

- The couplings of U(1), SU(2), and SU(3) are
  - $\alpha_1 = 8\,\alpha_{em}/3 = 8\,(e^2/4\pi)/3$
  - $\alpha_2 = g^2/4\pi$
  - $\alpha_3 = g_s^2/2\pi$
- Unification at $E = M_X$:

$$\alpha_1(M_X) = \alpha_2(M_X) = \alpha_3(M_X) = \alpha_{\rm GUT}$$

$$\alpha(q^2) = \frac{\alpha(\mu^2)}{1 + R\alpha(\mu^2)\ln(q^2/\mu^2)}$$

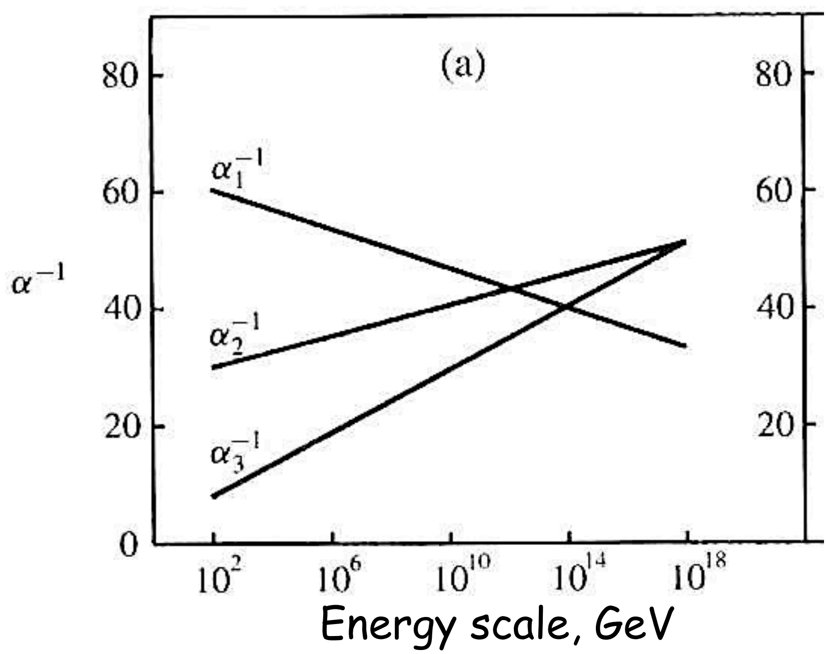
$$R = -\beta_0 = \frac{11n_b - 4n_f}{12\pi}$$

$n_b = 0$ [U(1)] 2 [SU(2)] 3 [SU(3)]
$n_f = 3$

Unification energy and weak mixing angle

$$\alpha(q^2) = \frac{\alpha(\mu^2)}{1 + R\alpha(\mu^2)\ln(q^2/\mu^2)}$$

$$R = -\beta_0 = \frac{11n_b - 4n_f}{12\pi}$$



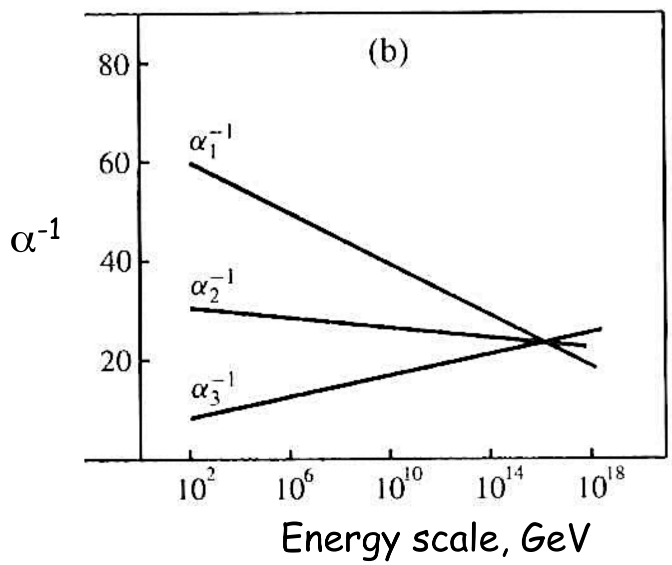
Unification fails

Supersymmetric SU(5)

- Supersymmetry introduces new elementary fermions and bosons, so the slopes of the couplina constants change

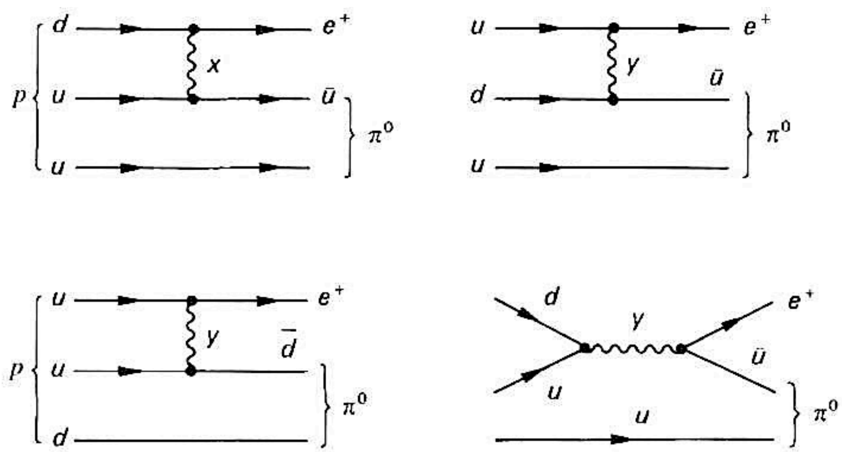
$$R_{\mathrm{SUSY}} = \frac{9n_b - 6n_f}{12\pi}$$

- there is also an energy scale where this evolution takes over, E_{SUSY}
- For E_{SUSY} = 1 TeV, unification appears at $E_{GUT} = 3 \times 10^{16}$ GeV with $\alpha_{GUT} = 1/24$



Proton Decay

- Grand Unification implies quarks can transform to leptons



Note, B and L are not conserved, but B-L is conserved

$$\tau_p = \frac{A M_X^4}{\alpha_{\mathrm{GUT}}^2 M_p^5}$$

- Consider non-SUSY unification: $M_X = 3 \times 10^{14}$GeV, $\alpha_{GUT} = 1/43$, A=1

$$\tau_p \simeq 10^{30\pm1}\ \mathrm{yr}$$

Nucleon Decay Experiments

- Prediction motivated proton decay searches

$$\tau_p \simeq 10^{30\pm1}\ \mathrm{yr}$$

- Table is list as of 2001
  from E. Kearns

tracking detector:

	Fiducial Mass	
NUSEX (1982)	130 t	Fe/streamer
KGF (1980)	140 t	Fe/prop. tube
Frejus (1984)	700 t	Fe/flash chamber
Soudan (1981)	770 t	Fe/drift tube

water Cherenkov:

Kamiokande (1983) 1040 t
- 2700 mwe,
- 1000 50-cm pmts, 20% photocathode coverage
- outer veto, solar neutrinos

IMB (1982) 3300 t
- 1580 mwe,
- 2048 20-cm PMTs, low photocathode coverage
- augmented by wls plates,
- pre-SK: largest, best proton decay limits

Super-K (1996) 22500 t
- more on this detector shortly

Proton Decay

- No proton decay events have been seen, despite very sensitive experiments, like SuperK
  - Today, for $p \rightarrow e^+ + \pi^0$, τ_P / BR > 8 x 10^{33} years

Proton Decay

p DECAY MODES	Partial mean life (10^{30} years)	Confidence level	p (MeV/c)
	Antilepton + meson		
$N \to e^+ \pi$	> 158 (n), > 8200 (p)	90%	459
$N \to \mu^+ \pi$	> 100 (n), > 6600 (p)	90%	453
$N \to \nu \pi$	> 112 (n), > 25 (p)	90%	459
$p \to e^+ \eta$	> 313	90%	309
$p \to \mu^+ \eta$	> 126	90%	297
$n \to \nu \eta$	> 158	90%	310
$N \to e^+ \rho$	> 217 (n), > 75 (p)	90%	149
$N \to \mu^+ \rho$	> 228 (n), > 110 (p)	90%	113
$N \to \nu \rho$	> 19 (n), > 162 (p)	90%	149
$p \to e^+ \omega$	> 107	90%	143
$p \to \mu^+ \omega$	> 117	90%	105
$n \to \nu \omega$	> 108	90%	144
$N \to e^+ K$	> 17 (n), > 150 (p)	90%	339
$p \to e^+ K^0_S$	> 120	90%	337
$p \to e^+ K^0_L$	> 51	90%	337
$N \to \mu^+ K$	> 26 (n), > 120 (p)	90%	329

Proton Decay

Lepton + meson

$n \rightarrow e^- \pi^+$	> 65	90%	459
$n \rightarrow \mu^- \pi^+$	> 49	90%	453
$n \rightarrow e^- \rho^+$	> 62	90%	150
$n \rightarrow \mu^- \rho^+$	> 7	90%	114
$n \rightarrow e^- K^+$	> 32	90%	340
$n \rightarrow \mu^- K^+$	> 57	90%	330

Lepton + mesons

$p \rightarrow e^- \pi^+ \pi^+$	> 30	90%	448
$n \rightarrow e^- \pi^+ \pi^0$	> 29	90%	449
$p \rightarrow \mu^- \pi^+ \pi^+$	> 17	90%	425
$n \rightarrow \mu^- \pi^+ \pi^0$	> 34	90%	427
$p \rightarrow e^- \pi^+ K^+$	> 75	90%	320
$p \rightarrow \mu^- \pi^+ K^+$	> 245	90%	279

Antilepton + photon(s)

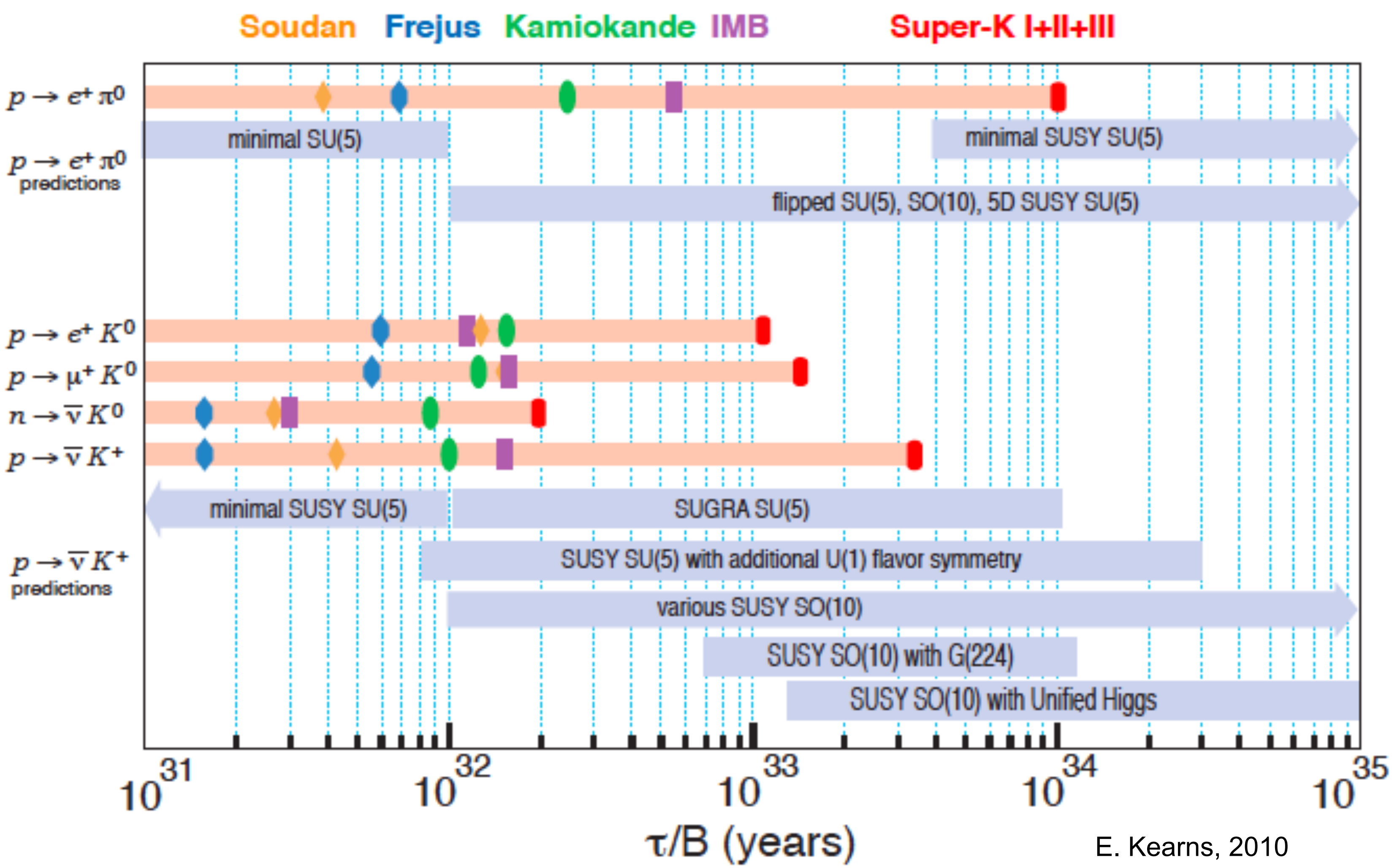
$p \rightarrow e^+ \gamma$	> 670	90%	469
$p \rightarrow \mu^+ \gamma$	> 478	90%	463
[illegible]	[illegible]	[illegible]	[illegible]

Model	Ref.	Modes	τ_N (years)
Minimal $SU(5)$	Georgi, Glashow [2]	$p \to e^+\pi^0$	$10^{30} - 10^{31}$
Minimal SUSY $SU(5)$	Dimopoulos, Georgi [11], Sakai [12] Lifetime Calculations: Hisano, Murayama, Yanagida [13]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$	$10^{28} - 10^{32}$
SUGRA $SU(5)$	Nath, Arnowitt [14, 15]	$p \to \bar{\nu}K^+$	$10^{32} - 10^{34}$
SUSY $SO(10)$ with anomalous flavor $U(1)$	Shafi, Tavartkiladze [16]	$p \to \bar{\nu}K^+$ $n \to \bar{\nu}K^0$ $p \to \mu^+K^0$	$10^{32} - 10^{35}$
SUSY $SO(10)$ MSSM (std. $d=5$)	Lucas, Raby [17], Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$
		$n \to \bar{\nu}K^0$	$10^{32} - 10^{33}$
SUSY $SO(10)$ ESSM (std. $d=5$)	Pati [18]	$p \to \bar{\nu}K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d=5$)	Babu, Pati, Wilczek [19, 20, 21], Pati [18]	$p \to \bar{\nu}K^+$	$\lesssim 2 \cdot 10^{34}$
		$p \to \mu^+K^0$	$B \sim (1-50)\%$
SUSY $SU(5)$ or $SO(10)$ MSSM ($d=6$)	Pati [18]	$p \to e^+\pi^0$	$\sim 10^{34.9\pm1}$
Flipped $SU(5)$ in CMSSM	Ellis, Nanopoulos and Wlaker[22]	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{36}$
Split $SU(5)$ SUSY	Arkani-Hamed, *et. al.* [23]	$p \to e^+\pi^0$	$10^{35} - 10^{37}$
$SU(5)$ in 5 dimensions	Hebecker, March-Russell[24]	$p \to \mu^+K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$
$SU(5)$ in 5 dimensions option II	Alciati *et.al.*[25]	$p \to \bar{\nu}K^+$	$10^{36} - 10^{39}$
GUT-like models from Type IIA string with D6-branes	Klebanov, Witten[26]	$p \to e^+\pi^0$	$\sim 10^{36}$

TABLE I: Summary of the expected nucleon lifetime in different theoretical models.

R. Svoboda, 2010

Nucleon Decay



Neutrino mass: Dirac and Majorano neutrinos

- In the Standard Model, neutrinos are assumed to be massless and interact only in left-handed helicity state (antineutrinos righthanded)
- Indeed, neutrinos are very light
  - but they should have mass to explain neutrino oscillations
  - so RH neutrinos exist

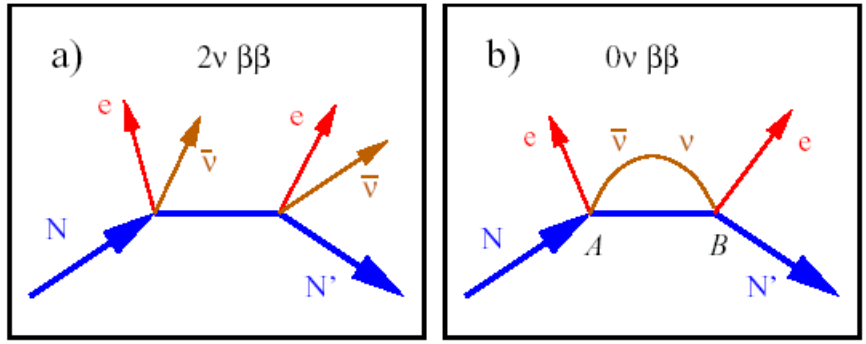
- Neutrinos as Dirac particles
  - spin 1/2 particles with one of the two spin state missing

- Majorana
  - alternative treatment
  - neutrino is its own antiparticle
  - one spin 1/2 particle with two substates: ν_L and ν_R

Neutrinoless Double β-decay

- If the neutrino is a Majorana particle, then neutrinoless double β-decay is possible:

$$2n \to 2p + 2e^-$$



- Double β-decay

$$2n \to 2p + 2e^- + 2\bar{\nu}_{eR}$$

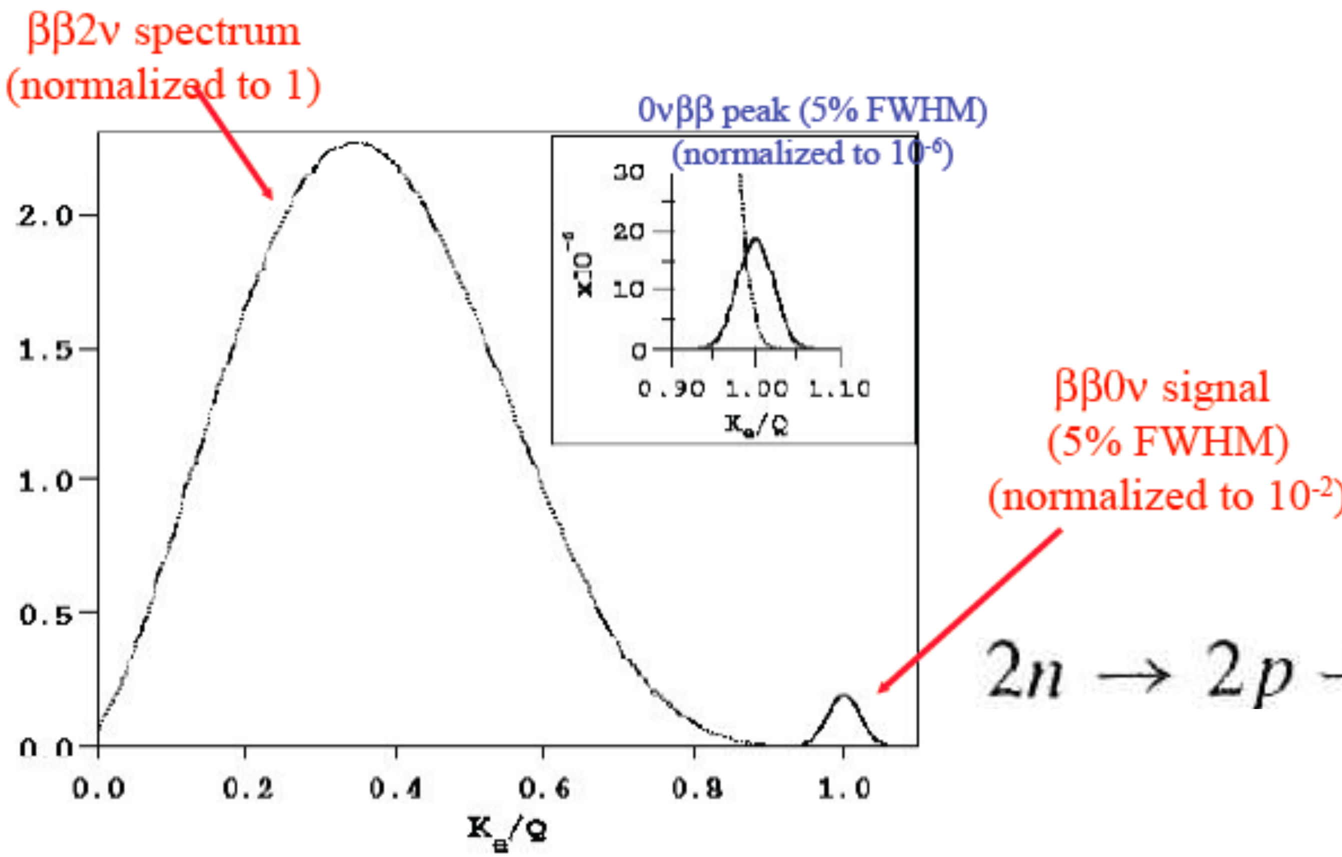
is observed, for example in ^{82}Se → ^{82}Kr, with a mean lifetime of 10^{20} years

- If the neutrino is its own antiparticle, the neutrino produced in the 1st decay, can be absorbed in the 2nd decay, resulting in neutrinoless double β-decay

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

$$\bar{\nu}_{eR} \; (\equiv \nu_{eR}) + n \to p + e^-$$

Neutrinoless Double β-decay



$$2n \rightarrow 2p + 2e^-$$

$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_{eR}$$

Neutrinoless Double β-decay

- Neutrinoless double β-decay requires Majorana neutrinos, but it also requires the neutrinos to have mass
  - If the neutrino is massless, the first process will produce purely RH antineutrinos and the absorption of the neutrino can only occur if it is LH (left-handed)
  - However, if the neutrino has mass, the produced neutrino will have a small component of the LH helicity
- Recall from V-A theory, the suppression of the "wrong" helicity is

$$1 - {}^{v}/_{c} = m_\nu^2 / 2E_\nu$$

- Decay rate then goes as

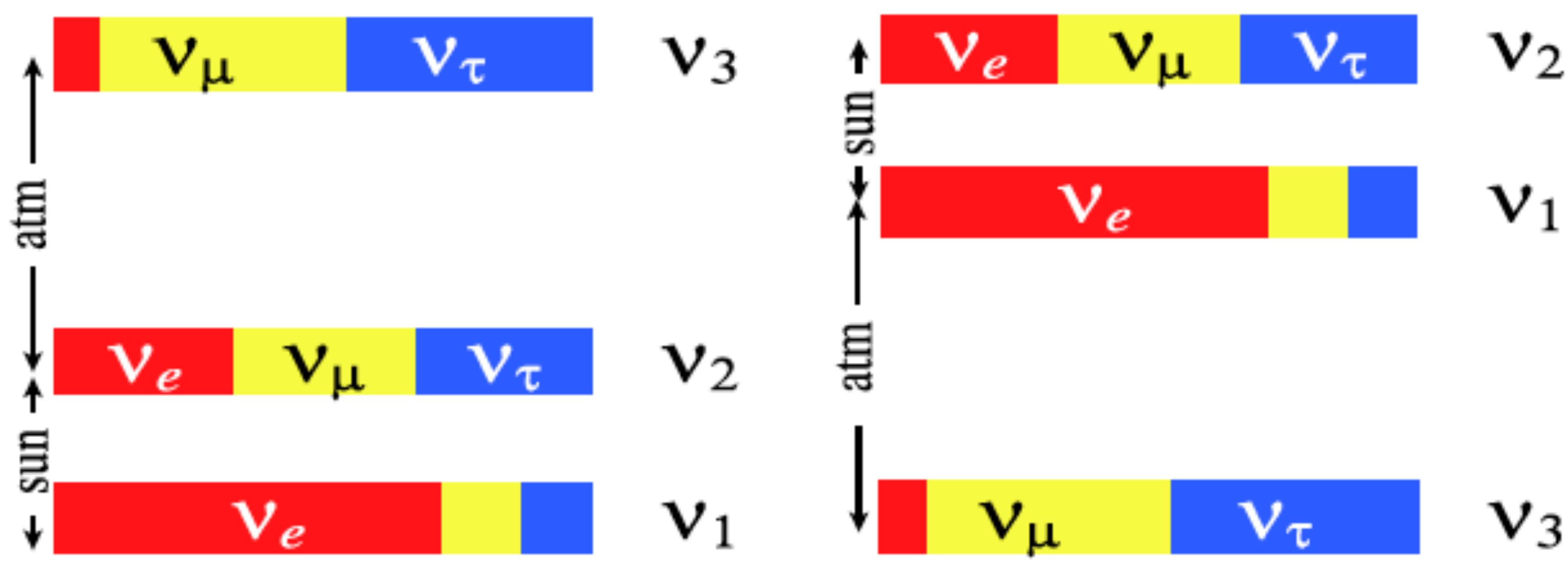
$$\Gamma = G\, |M|^2\, |m_{\beta\beta}|^2$$

where the effective mass, $m_{\beta\beta}$, is

$$m_{\beta\beta} = \sum m_i\, U^2_{ei}$$

Neutrinoless Double β-decay

NEUTRINO MASS SPECTRUM

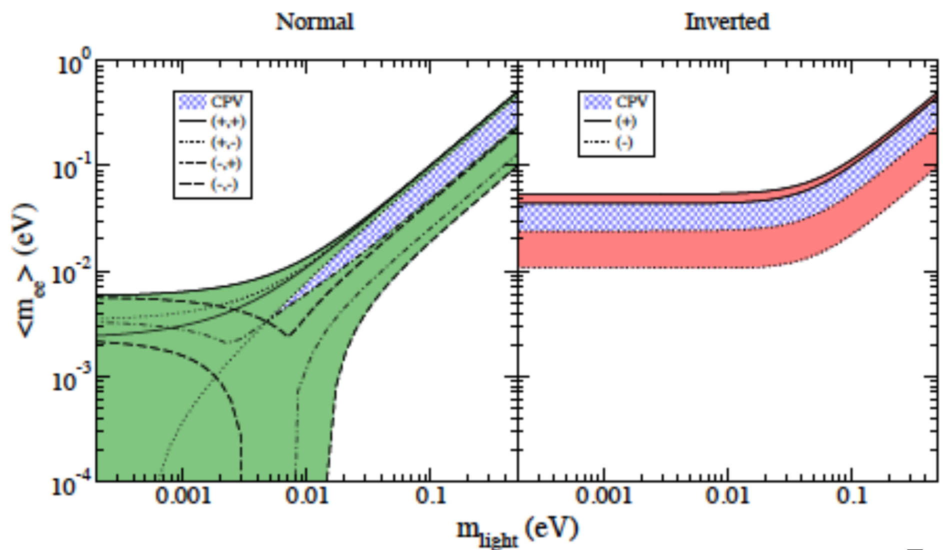


NORMAL HIERARCHY

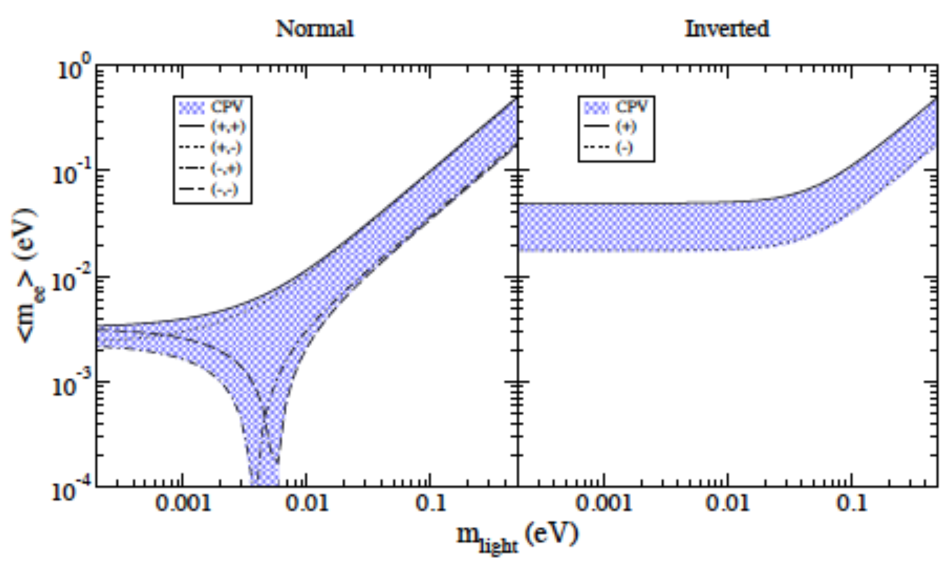
INVERTED HIERARCHY

From W. Rodejohann, arxiv: 1106.1334v3

Neutrinoless Double β-decay



From W. Rodejohann, arxiv: 1106.1334v3



Neutrinoless Double β-decay

Only mass differences can be extracted from the neutrino mixing experiments

Neutrinoless double beta-decay could reveal the mass

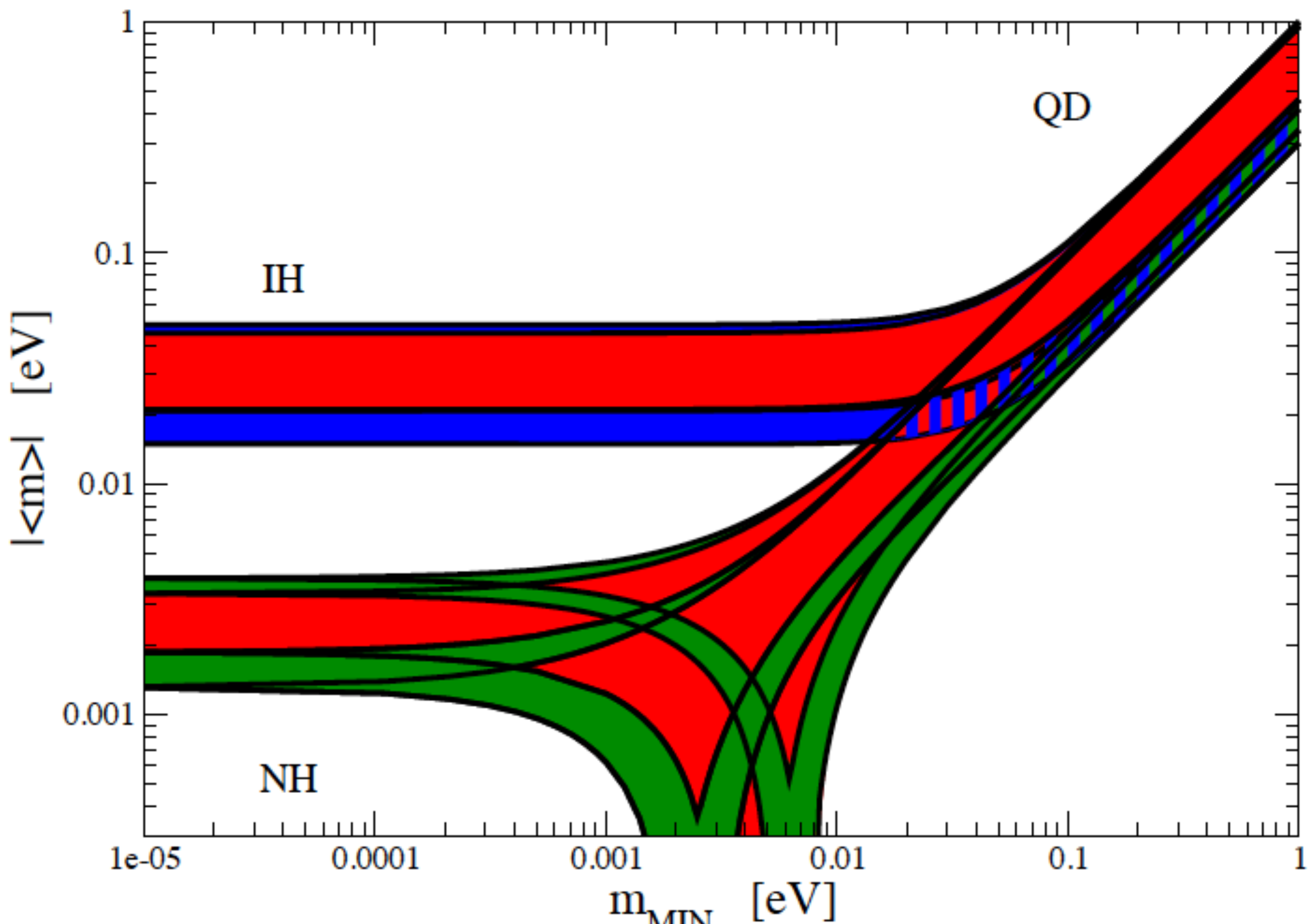


Figure 13.11: The effective Majorana mass $|<m>|$ (including a 2σ uncertainty)

Neutrinoless Double β-decay

- Example of an experiment that has been done:
  - Heidelberg-Moscow Experiment (arxiv 0103062)
  - Large 11 kg of germanium crystals containing 86% ^{76}Ge

$$\tau(0\nu) > 1.9 \times 10^{25} \text{ years } (^{76}Ge \rightarrow {}^{76}Se + 2e^-)$$

$$\Rightarrow m_\nu(0\nu\beta\beta) < 0.53 \text{ eV}$$

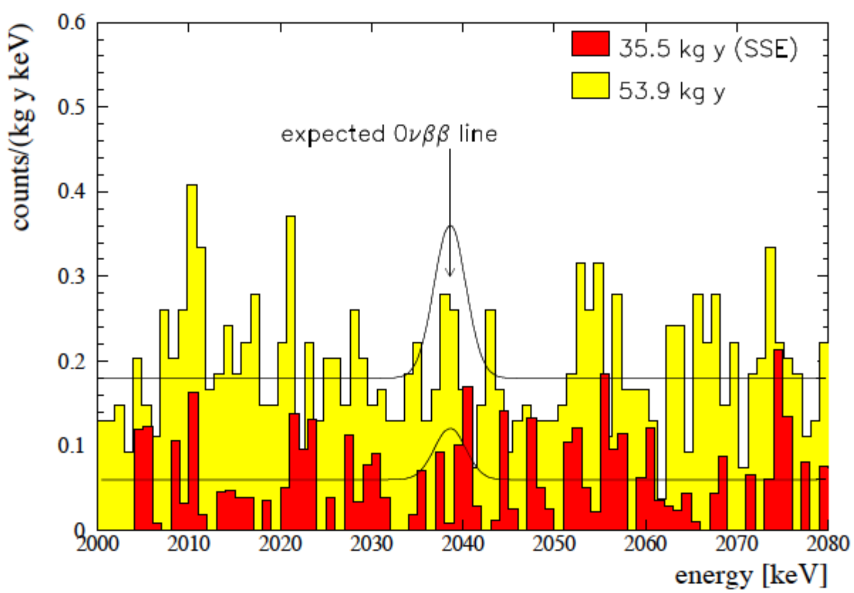


Fig. 4. Sum spectrum of all five detectors with 53.9 kg y and SSE spectrum with

Neutrinoless Double β-decay

- Experimental limits

Table 2. Experimental limits at 90% C.L. on the most interesting isotopes for $0\nu\beta\beta$. Using the nuclear matrix element ranges from Table 5 we also give the maximal and minimal limits on $\langle m_{ee} \rangle$.

Isotope	$T_{1/2}^{0\nu}$ [yrs]	Experiment	$\langle m_{ee} \rangle_{\rm min}^{\rm lim}$ [eV]	$\langle m_{ee} \rangle_{\rm max}^{\rm lim}$ [eV]
^{48}Ca	5.8×10^{22}	CANDLES[18]	3.55	9.91
^{76}Ge	1.9×10^{25}	HDM[19]	0.21	0.53
	1.6×10^{25}	IGEX[20]	0.25	0.63
^{82}Se	3.2×10^{23}	NEMO-3[21]	0.85	2.08
^{96}Zr	9.2×10^{21}	NEMO-3[22]	3.97	14.39
^{100}Mo	1.0×10^{24}	NEMO-3[21]	0.31	0.79
^{116}Cd	1.7×10^{23}	SOLOTVINO[23]	1.22	2.30
^{130}Te	2.8×10^{24}	CUORICINO[24]	0.27	0.57
^{136}Xe	5.0×10^{23}	DAMA[25]	0.83	2.04
^{150}Nd	1.8×10^{22}	NEMO-3[26]	2.35	5.08

Note: The limits on $T_{1/2}^{0\nu}$ from NEMO-3 measurements assume the standard light neutrino mechanism.

http://arxiv.org/pdf/1106.1334.pdf

Neutrinoless Double β-decay

- EXO
  - An Advanced Enriched Xenon Double Beta Decay Observatory
  - Project to bring sensitivity on $M(\nu_e)$ ~ 10 meV
  - Uses isotopically enriched ^{136}Xe
  - Capture and identify resulting ^{136}Ba (optically)
  - Goal 1-10 tons of Xenon

Some important isotopic phase space factors

Isotope	G [10^{-14} yrs^{-1}]	Q [keV]	nat. abund. [%]
^{48}Ca	6.35	4273.7	0.187
^{76}Ge	0.623	2039.1	7.8
^{82}Se	2.70	2995.5	9.2
^{96}Zr	5.63	3347.7	2.8
^{100}Mo	4.36	3035.0	9.6
^{110}Pd	1.40	2004.0	11.8
^{116}Cd	4.62	2809.1	7.6
^{124}Sn	2.55	2287.7	5.6
^{130}Te	4.09	2530.3	34.5
^{136}Xe	4.31	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

http://arxiv.org/pdf/1106.1334.pdf

Neutrinoless Double β-decay

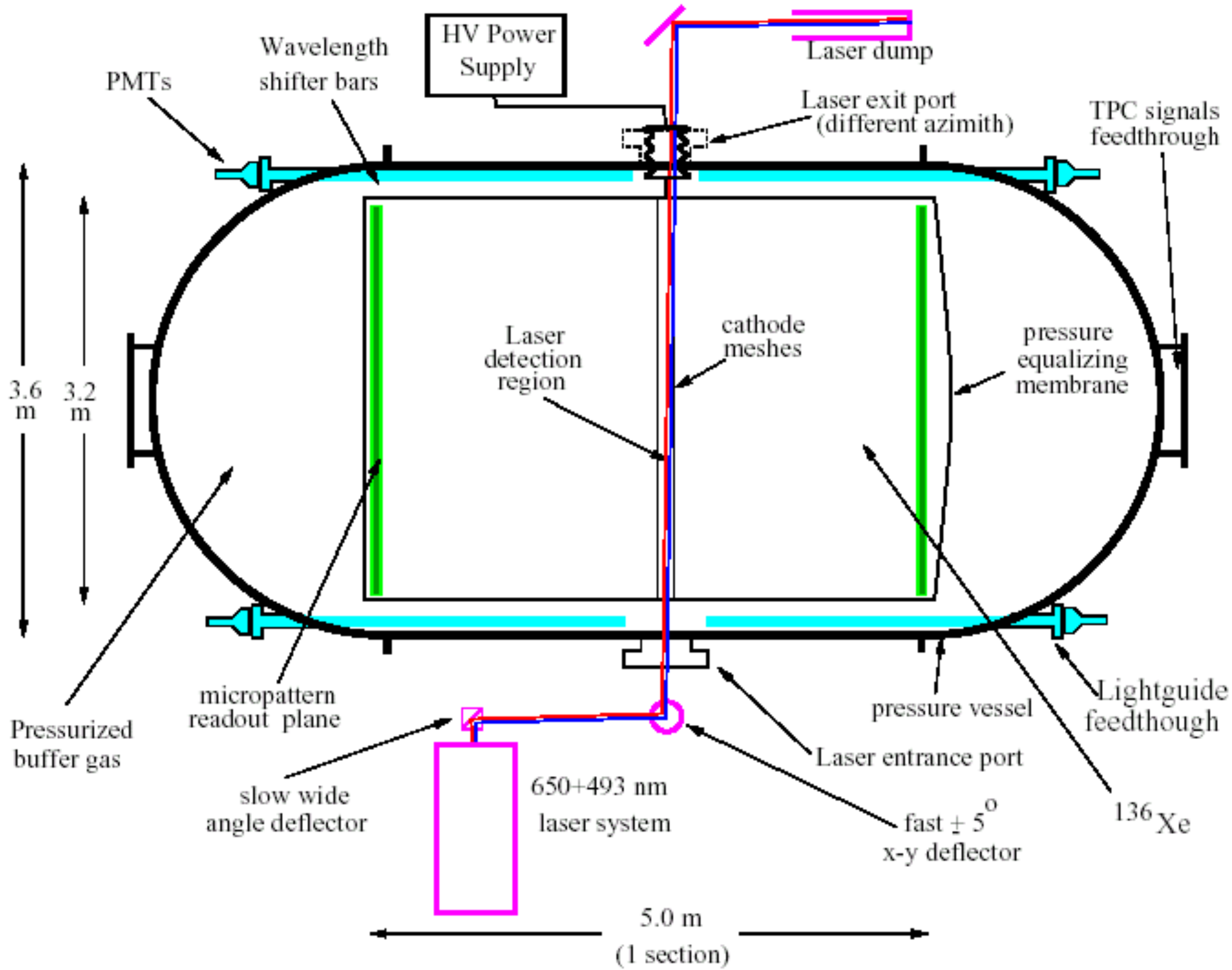
EXO (Enriched Xenon Observatory)

^{136}Xe is an ideal isotope for this purpose since:

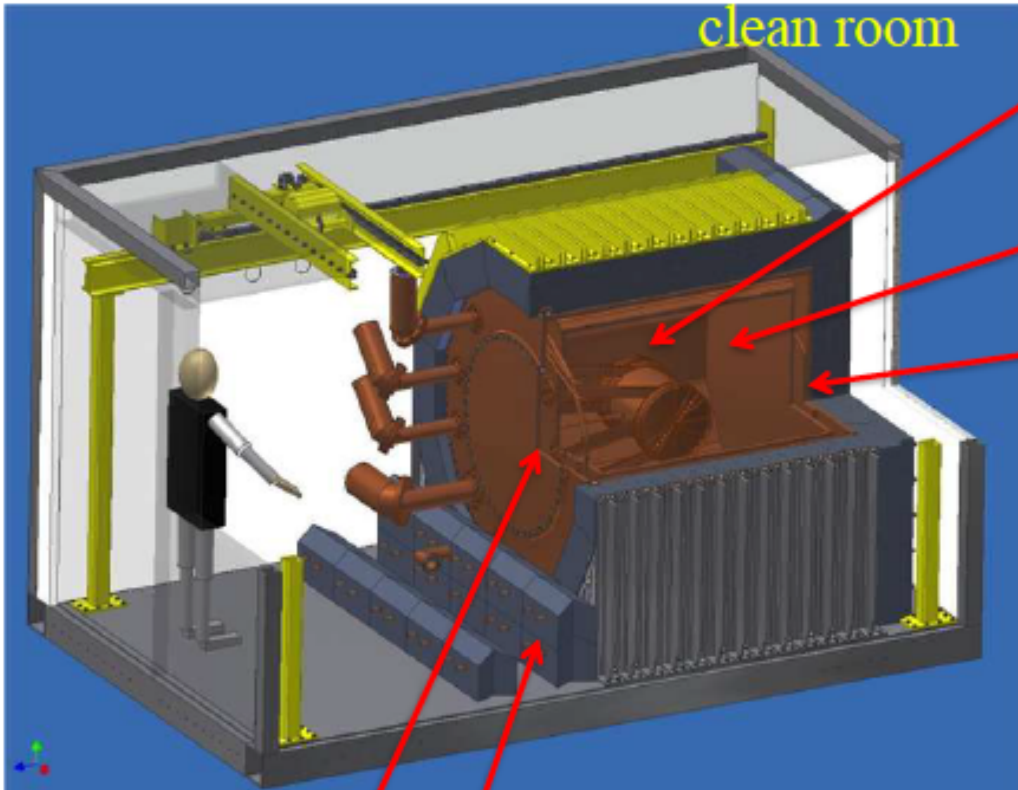
- it is one of the easiest isotopes to enrich;
- like argon, which is the mainstay of proportional chambers, it represents a good ionization detecting medium;
- it exhibits substantial scintillation that can be used to complement the ionization detection;
- most importantly its $\beta\beta$ decay produces a final state nucleus of ^{136}Ba that can be identified in its atomic form with powerful new techniques of high resolution optical spectroscopy;
- it has not long-lived isotopes that can be activated;
- being chemically inert it can be easily purified with different techniques involving molecular sieves, hot metal getters and electric discharges;
- being a gas at STP it can be easily transferred, so that new purification techniques or even drastically different detector designs can be easily implemented.

Neutrinoless Double β-decay

- EXO
  - 10 atm gas TPC
  - or liquid detector



The EXO-200 Detector



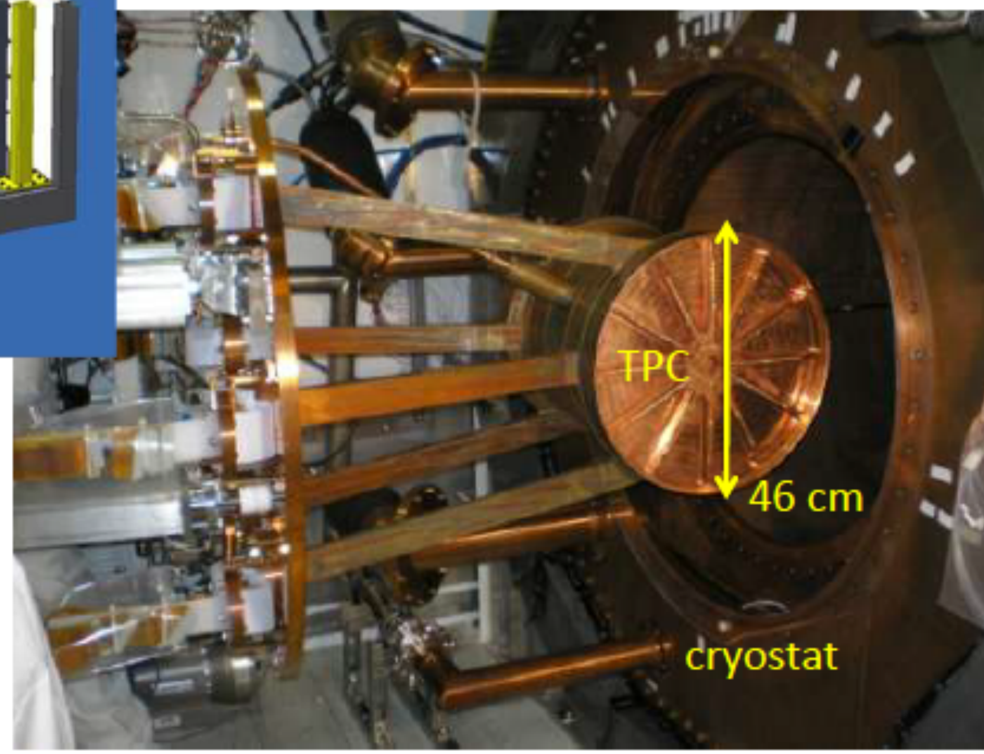
Xe Vessel

HFE (Heat transfer fluid)

Vacuum insulation

Copper cryostat

25cm enclosure of
low-activity lead



Neutrinoless Double β-decay

- Projects

Table 4. Sensitivity at 90% C.L. of the seven most developed projects for about three (phase II of GERDA and MAJORANA, KamLAND, SNO+) five (EXO, SuperNEMO and CUORE) and ten (full-scale GERDA plus MAJORANA) years of measurements. Taken from[11].

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T^{0\nu}_{1/2}$ [yrs]	Status	Start of data-taking
GERDA	^{76}Ge	18	3×10^{25}	running	$\sim$ 2011
		40	2×10^{26}	in progress	$\sim$ 2012
		1000	6×10^{27}	R&D	$\sim$ 2015
CUORE	^{130}Te	200	$6.5 \times 10^{26*}$	in progress	$\sim$ 2013
			$2.1 \times 10^{26**}$		
MAJORANA	^{76}Ge	30-60	$(1-2) \times 10^{26}$	in progress	$\sim$ 2013
		1000	6×10^{27}	R&D	$\sim$ 2015
EXO	^{136}Xe	200	6.4×10^{25}	in progress	$\sim$ 2011
		1000	8×10^{26}	R&D	$\sim$ 2015
SuperNEMO	^{82}Se	100-200	$(1-2) \times 10^{26}$	R&D	$\sim$ 2013-2015
KamLAND-Zen	^{136}Xe	400	4×10^{26}	in progress	$\sim$ 2011
		1000	10^{27}	R&D	$\sim$ 2013-2015
SNO+	^{150}Nd	56	4.5×10^{24}	in progress	$\sim$ 2012
		500	3×10^{25}	R&D	$\sim$ 2015

Note: * For a background of 10^{-3}/keV/kg/yr; ** for a background of 10^{-2}/keV/kg/yr.

http://arxiv.org/pdf/1106.1334.pdf

Magnetic Monopoles

- Dirac proposed in 1931 that magnetic monopoles might exist with magnetic charge

$$g = n\left(\frac{4\pi\hbar c}{2e}\right)$$

- Dirac inspected Maxwell's equations

$$\nabla \bullet \vec{E} = 4\pi\rho$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \bullet \vec{B} = 0$$

$$\nabla \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c} j$$

Magnetic Monopoles

- Maxwell's equations

$$\nabla \bullet \vec{E} = 4\pi\rho$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\nabla \bullet \vec{B} = 0$$

$$\nabla \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c} j$$

- Symmetry can be restored by adding magnetic monopoles

$$\nabla \bullet \vec{E} = 4\pi\rho$$

$$\nabla \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t} \quad \left(-\frac{4\pi}{c} j_m\right)$$

$$\nabla \bullet \vec{B} = 0 \quad (+4\pi\rho_m)$$

$$\nabla \times \vec{B} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c} j$$

Magnetic monopole terms

Magnetic Monopoles

- Dirac showed that the existence of magnetic monoples would lead at the quantum level to a condition:

$$qg/4\pi = 1/2\ n \qquad \text{where n is an integer}$$

- Dirac thought this might explain the quantization of charge
- In GUT, electric charge is one of the generators of the symmetry, requiring all particles to have a multiple of a fundamental unit of charge
- Monopoles of charge $g = n\left(\frac{4\pi\hbar c}{2e}\right)$ and mass $M_{GUT}/\alpha \sim 10^{17}$ GeV are expected in GUTs

Magnetic Monopoles

- So monopoles appear needed by fundamental considerations
- However, their existence is a threat to the early universe
  - Their expected large mass could have led to a closed universe
  - and a short lifetime
  - Inflation solves this problem

- GUTS + standard cosmology leads to *glut* of monopoles
  - for a monopole mass ~ 10^{16} GeV

$$\rho_M \geq 5 \times 10^{-18}\, gm / cm^3$$

  - taking Hubble constant ~ $(10^{10}\text{ yr})^{-1}$

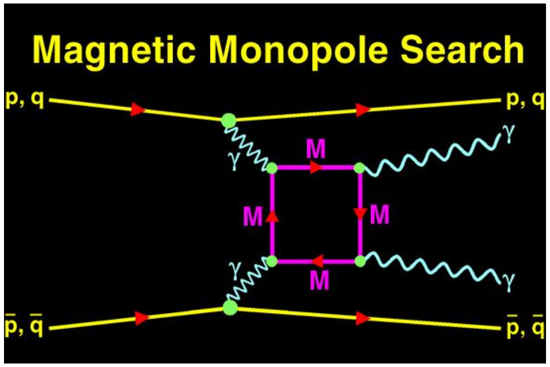
$$\rho_c = \frac{3H^2}{8\pi G} \approx 8 \times 10^{-29}\, gm / cm^3$$

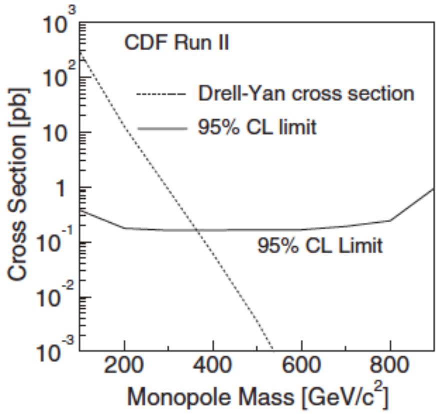
$$\Omega \equiv \rho / \rho_c \geq 3 \times 10^{11} \quad \text{and} \quad t_0 \leq 30{,}000\, yrs$$

Magnetic Monopoles

- Searches for magnetic monopoles
  - Magnetic monopoles will change the flux in a loop (superconducting) when it passes through the loop
  - Magnetic monopoles will ionize or excite atoms when they pass through detectors through the magnetic interaction with atomic electrons
  - Collider (Fermilab)

A. Abulencia et al., PRL 96, 201801, 2006.





- Constraints on what its mass must be if it does exist:
  > 360 GeV

Magnetic Monopoles

- Searches for magnetic monopoles
  - Magnetic monopoles will change the flux in a loop (superconducting) when it passes through the loop
  - Phys. Rev. Lett. 48, 1378–1381 (1982)
- First Results from a Superconductive Detector for Moving Magnetic Monopoles

Blas Cabrera

Physics Department, Stanford University, Stanford, California 94305

- Received 5 April 1982

- A velocity- and mass-independent search for moving magnetic monopoles is being performed by continuously monitoring the current in a 20-cm^2-area superconducting loop. A single candidate event, consistent with one Dirac unit of magnetic charge, has been detected during five runs totaling 151 days. These data set an upper limit of 6.1×10^{-10} cm^{-2} sec^{-1} sr^{-1} for magnetically charged particles moving through the earth's surface.

Magnetic Monopoles

- Particle Data Group Summary:

Magnetic Monopole Searches

Isolated supermassive monopole candidate events have not been confirmed. The most sensitive experiments obtain negative results.

Best cosmic-ray supermassive monopole flux limit:

$< 1.0 \times 10^{-15}\ \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$ for $1.1 \times 10^{-4} < \beta < 0.1$

- Parker bound of 10^{-15} $\mathrm{cm}^{-2}\mathrm{sec}^{-1}\mathrm{sr}^{-1}$
- destroys galactic magnetic field of few microgauss

Magnetic Monopoles

Monopole Production Cross Section — Accelerator Searches

X-SECT (cm^2)	*MASS* (GeV)	*CHG* (g)	*ENERGY* (GeV)	*BEAM*	*DOCUMENT ID*		*TECN*
<5E−38	45–102	1	206	e^+e^-	[1] ABBIENDI	08	OPAL
<0.2E−36	200–700	1	1960	$p\bar{p}$	[2] ABULENCIA	06K	CNTR
< 2.E−36		1	300	e^+p	[3,4] AKTAS	05A	INDU
< 0.2 E−36		2	300	e^+p	[3,4] AKTAS	05A	INDU
< 0.09E−36		3	300	e^+p	[3,4] AKTAS	05A	INDU
< 0.05E−36		≥ 6	300	e^+p	[3,4] AKTAS	05A	INDU
< 2.E−36		1	300	e^+p	[3,5] AKTAS	05A	INDU
< 0.2E−36		2	300	e^+p	[3,5] AKTAS	05A	INDU
< 0.07E−36		3	300	e^+p	[3,5] AKTAS	05A	INDU
< 0.06E−36		≥ 6	300	e^+p	[3,5] AKTAS	05A	INDU
< 0.6E−36	>265	1	1800	$p\bar{p}$	[6] KALBFLEISCH	04	INDU
< 0.2E−36	>355	2	1800	$p\bar{p}$	[6] KALBFLEISCH	04	INDU
< 0.07E−36	>410	3	1800	$p\bar{p}$	[6] KALBFLEISCH	04	INDU
< 0.2E−36	>375	6	1800	$p\bar{p}$	[6] KALBFLEISCH	04	INDU
< 0.7E−36	>295	1	1800	$p\bar{p}$	[7,8] KALBFLEISCH	00	INDU
< 7.8E−36	>260	2	1800	$p\bar{p}$	[7,8] KALBFLEISCH	00	INDU
< 2.3E−36	>325	3	1800	$p\bar{p}$	[7,9] KALBFLEISCH	00	INDU
< 0.11E−36	>420	6	1800	$p\bar{p}$	[7,9] KALBFLEISCH	00	INDU

Magnetic Monopoles

Monopole Production — Other Accelerator Searches

MASS (GeV)	*CHG* (g)	*SPIN*	*ENERGY* (GeV)	*BEAM*	*DOCUMENT ID*		*TECN*
> 610	≥ 1	0	1800	$p\overline{p}$	[14] ABBOTT	98K	D0
> 870	≥ 1	1/2	1800	$p\overline{p}$	[14] ABBOTT	98K	D0
>1580	≥ 1	1	1800	$p\overline{p}$	[14] ABBOTT	98K	D0
> 510			88–94	e^+e^-	[15] ACCIARRI	95C	L3

Magnetic Monopoles

Monopole Flux — Cosmic Ray Searches

"Caty" in the charge column indicates a search for monopole-catalyzed nucleon decay.

FLUX ($cm^{-2}sr^{-1}s^{-1}$)	*MASS* (GeV)	*CHG* (*g*)	*COMMENTS* ($\beta = v/c$)	*EVTS*	*DOCUMENT ID*		*TECN*
$<1.3E-15$	$1E4<M<5E13$	1	$\beta > 0.05$	0	[16] BALESTRA	08	PLAS
$<0.65E-15$	$>5E13$	1	$\beta > 0.05$	0	[16] BALESTRA	08	PLAS
$<1E-18$		1	$\gamma > 1$ E8	0	[17] HOGAN	08	RICE
$<1.4E-16$		1	$1.1E-4 < \beta < 1$	0	[18] AMBROSIO	02B	MCRO
$<3E-16$		Caty	$1.1E-4 < \beta < 5E-3$	0	[19] AMBROSIO	02C	MCRO
$<1.5E-15$		1	$5E-3 < \beta < 0.99$	0	[20] AMBROSIO	02D	MCRO
$<1E-15$		1	1.1×10^{-4}–0.1	0	[21] AMBROSIO	97	MCRO
$<5.6E-15$		1	(0.18–3.0)E−3	0	[22] AHLEN	94	MCRO
$<2.7E-15$		Caty	$\beta \sim 1 \times 10^{-3}$	0	[23] BECKER-SZ...	94	IMB
$<8.7E-15$		1	$>2.E-3$	0	THRON	92	SOUD
$<4.4E-12$		1	all β	0	GARDNER	91	INDU
$<7.2E-13$		1	all β	0	HUBER	91	INDU
$<3.7E-15$	$>E12$	1	β=1.E−4	0	[24] ORITO	91	PLAS
$<3.2E-16$	$>E10$	1	$\beta > 0.05$	0	[24] ORITO	91	PLAS
$<3.2E-16$	$>E10$–E12	2, 3		0	[24] ORITO	91	PLAS
$<3.8E-13$		1	all β	0	BERMON	90	INDU
$<5.E-16$		Caty	$\beta < 1.E-3$	0	[23] BEZRUKOV	90	CHER
$<1.8E-14$		1	$\beta > 1.1E-4$	0	[25] BUCKLAND	90	HEPT

Magnetic Monopoles

Monopole Flux — Astrophysics

FLUX $(cm^{-2}sr^{-1}s^{-1})$	MASS (GeV)	CHG (g)	COMMENTS ($\beta = v/c$)	EVTS	DOCUMENT ID		TECN
<1.3E−20			faint white dwarf		[32] FREESE	99	ASTR
<1.E−16	E17	1	galactic field	0	[33] ADAMS	93	COSM
<1.E−23			Jovian planets		[32] ARAFUNE	85	ASTR
<1.E−16	E15		solar trapping	0	BRACCI	85B	ASTR
<1.E−18		1		0	[32] HARVEY	84	COSM
<3.E−23			neutron stars		KOLB	84	ASTR
<7.E−22			pulsars	0	[32] FREESE	83B	ASTR
<1.E−18	<E18	1	intergalactic field	0	[32] REPHAELI	83	COSM
<1.E−23			neutron stars	0	[32] DIMOPOUL...	82	COSM
<5.E−22			neutron stars	0	[32] KOLB	82	COSM
<5.E−15	>E21		galactic halo		SALPETER	82	COSM
<1.E−12	E19	1	β=3.E−3	0	[34] TURNER	82	COSM
<1.E−16		1	galactic field	0	PARKER	70	COSM

[32] Catalysis of nucleon decay.

[33] ADAMS 93 limit based on "survival and growth of a small galactic seed field" is 10^{-16} $(m/10^{17}$ GeV$)$ $cm^{-2}\,s^{-1}\,sr^{-1}$. Above 10^{17} GeV, limit 10^{-16} $(10^{17}$ GeV$/m)$ $cm^{-2}\,s^{-1}\,sr^{-1}$ (from requirement that monopole density does not overclose the universe) is more stringent.

[34] Re-evaluates PARKER 70 limit for GUT monopoles.

Magnetic Monopoles

Monopole Density — Matter Searches

DENSITY	*CHG (g)*	*MATERIAL*	*EVTS*	*DOCUMENT ID*		*TECN*
<6.9E−6/gram	>1/3	Meteorites and other	0	JEON	95	INDU
<2.E−7/gram	>0.6	Fe ore	0	[35] EBISU	87	INDU
<4.6E−6/gram	> 0.5	deep schist	0	KOVALIK	86	INDU
<1.6E−6/gram	> 0.5	manganese nodules	0	[36] KOVALIK	86	INDU
<1.3E−6/gram	> 0.5	seawater	0	KOVALIK	86	INDU
>1.E+14/gram	>1/3	iron aerosols	>1	MIKHAILOV	83	SPEC
<6.E−4/gram		air, seawater	0	CARRIGAN	76	CNTR
<5.E−1/gram	>0.04	11 materials	0	CABRERA	75	INDU
<2.E−4/gram	>0.05	moon rock	0	ROSS	73	INDU
<6.E−7/gram	<140	seawater	0	KOLM	71	CNTR
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Magnetic Monopoles

Monopole Density — Astrophysics

DENSITY	CHG (g)	MATERIAL	EVTS	DOCUMENT ID		TECN
<1.E−9/gram	1	sun, catalysis	0	[37] ARAFUNE	83	COSM
<6.E−33/nucl	1	moon wake	0	SCHATTEN	83	ELEC
<2.E−28/nucl		earth heat	0	CARRIGAN	80	COSM
<2.E−4/prot		42cm absorption	0	BRODERICK	79	COSM
$<2.E-13/m^3$		moon wake	0	SCHATTEN	70	ELEC

[37] Catalysis of nucleon decay.

Neutrino Oscillations

We discussed neutrino oscillations earlier

Experiments:

Reactor

disappearance of electron neutrino
since muon cannot be produced by MeV neutrinos

Accelerator

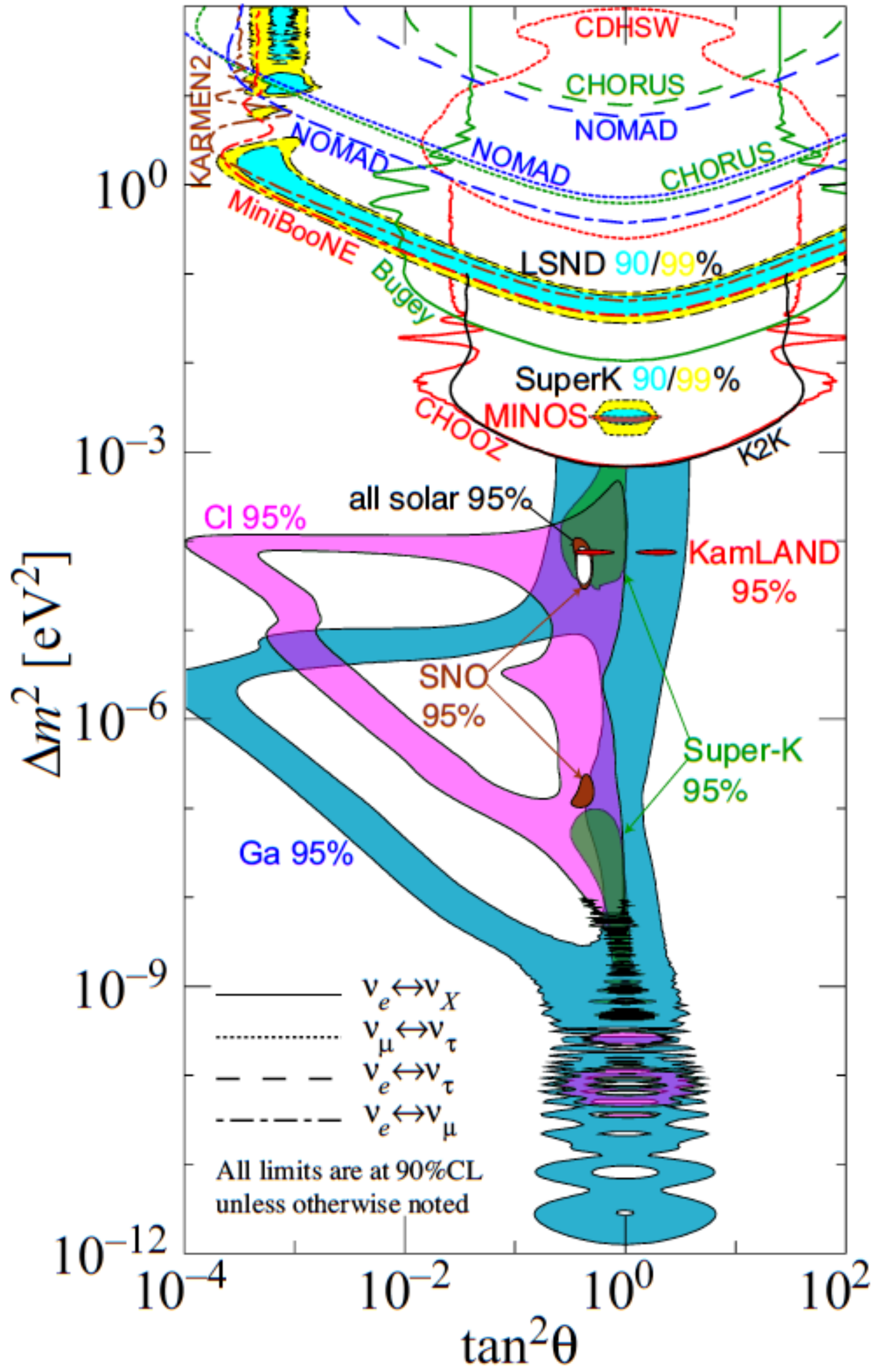
appearance of electron neutrino,
from muon neutrino beam

Solar

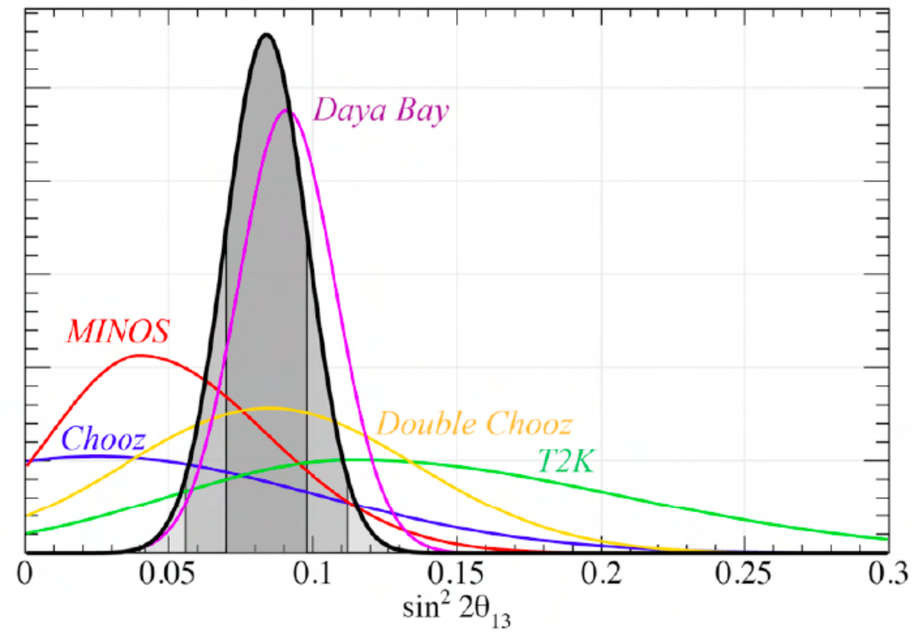
disappearance of electron neutrino

Atmospheric

electron and muon produced in atmosphere by cosmic rays



Neutrino Oscillations



Ideogram of recent θ_{13} results for normal hierarchy, $\delta_{CP}=0$, and maximal θ_{23}

$$|\Delta m^2_{21}| \cong 7.6 \times 10^{-5}\ \text{eV}^2\,,$$
$$|\Delta m^2_{31}| \cong 2.4 \times 10^{-3}\ \text{eV}^2\,,$$
$$|\Delta m^2_{21}|/|\Delta m^2_{31}| \cong 0.032\,.$$

Neutrino Oscillations

- The conclusions of the neutrino oscillation observations is that the neutrinos have small masses, with flavor differences of much less than 1 eV
- A question arises regarding the very large difference in the masses of the fundamental fermions, ranging from the mass of the top quark at 175 GeV, down to the neutrino masses of ~10^{-12} GeV

- One possibility from GUTs (seesaw mechanism) is that the SM LH neutrinos mix with very massive (10^{17} GeV) RH Majorana neutrino states

$$m_\nu \sim m_L^2 / M_{\text{GUT}}$$

where m_L is the typical charged lepton or quark mass

Superstrings

"Millennium Madness"

Physics Problems for the Next Millennium

- In 1900 the world-renowned mathematician David Hilbert presented twenty-three problems at the International Congress of Mathematicians in Paris. These problems have inspired mathematicians throughout the last century. Indeed, Hilbert's address has had a profound impact on the direction of mathematics, reaching far beyond the original twenty-three problems themselves.

- As a piece of millennial madness, all participants of the Strings 2000 Conference were invited to help formulate the ten most important unsolved problems in fundamental physics. Each participant was allowed to submit one candidate problem for consideration. To qualify, the problem must not only have been important but also well-defined and stated in a clear way.

- The best 10 problems were selected at the end of the conference by a selection panel consisting of: Michael Duff (University of Michigan), David Gross (Institute for Theoretical Physics, Santa Barbara), Edward Witten (Caltech & Institute for Advanced Studies)

Superstrings

The 10 questions with comments prepared by Professor Andrew Whitaker, QUB, Belfast

1. Are all the (measurable) dimensionless parameters that characterize the physical universe calculable in principle or are some merely determined by historical or quantum mechanical accident and uncalculable?

- The current theory of the basic building-blocks of the universe has to assume their masses, lifetimes and so on. Should there be a more fundamental theory that predicts them?

2. How can quantum gravity help explain the origin of the universe?

- There is as yet no theory of quantum gravity; this is perhaps the major blemish on today's theoretical physics. When this theory is produced, will it, as Hawking suggests, explain the existence of the universe without the necessity of assuming a Big Bang?

3. What is the lifetime of the proton and how do we understand it?

- We have never detected the decay of a proton and so think of it as stable, but many of today's speculative theories predict that it will decay, though with an extremely long lifetime. Experiments with enormous numbers of protons are checking this; will the theories be proved correct?

4. Is Nature supersymmetric, and if so, how is supersymmetry broken?

Theories of supersymmetry suggest that all the various forces of nature – electromagnetic, nuclear and even gravitation – may in principle be identical, and claim that this would be seen in experiments at high enough energies. Are they correct? If so, why is the symmetry lost at low energies?

Superstrings

5. Why does the universe appear to have one time and three space dimensions?

- Many of today's speculative theories argue that there are in principle many more dimensions than four (three space and one time) but that several of these dimensions are 'rolled up' so that we don't experience them. Are these theories correct? If so, what causes the 'rolling up'?

6. Why does the cosmological constant have the value that it has, is it zero and is it really constant?

- The cosmological constant appears in Einstein's theory of gravitation, but its value has to be selected. If it is zero, it predicts the expansion of the universe following from the Big Bang. Einstein's original work was performed before the Big Bang was known, and he chose the cosmological constant to be non-zero, so as to prevent the expansion. He later called this his 'biggest mistake'. But is the constant actually precisely zero, or even constant at all?

7. What are the fundamental degrees of freedom of M-theory (the theory whose low-energy limit is eleven-dimensional supergravity and which subsumes the five consistent superstring theories) and does the theory describe Nature?

- Modern string theories, which are hugely popular, describe the basic building-blocks of nature not as particles but as short strings. This avoids some difficulties of previous theories, but do string theories actually tell us anything about nature? If so, what?

(Comments on the 10 questions by Professor Andrew Whitaker, QUB, Belfast)

Superstrings

8. What is the resolution of the black hole information paradox?

- When a particle in a quantum-mechanically pure state disappears into a black hole, its state changes to a thermal one; it now has a particular temperature. This constitutes a fundamental violation of the laws of quantum theory. How does it occur?

9. What physics explains the enormous disparity between the gravitational scale and the typical mass scale of the elementary particles?

- Mass and energy are linked by Einstein's equation . But typical gravitational energies are immensely lower than the values of for typical elementary particles. Why?

10. Can we quantitatively understand quark and gluon confinement in Quantum Chromodynamics and the existence of a mass gap?

- We believe that the proton consists of three quarks, but that it is impossible to extract a free quark. The theory of quantum chromodynamics suggest that this is because, as the distance between two quarks increases, the force of attraction between them increases, rather than decreasing as for gravitation or electrostatics. But can this theory be made rigorous? Can it explain the masses of the various types of quark?

(Comments on the 10 questions by Professor Andrew Whitaker, QUB, Belfast)

Superstrings

- Unify all fundamental interactions including gravity
- Point-like interactions result in divergences
- Divergences are cured by replacing point particles by strings
- These strings are expected to have lengths of order of the Planck scale:

$$l_P = \frac{\hbar}{M_P c} = 1.6 \times 10^{-35}\ \mathrm{m}$$

where the Planck mass is

$$M_P = \sqrt{\hbar c / G_N} = 1.2 \times 10^{19}\ \mathrm{GeV}$$

- Elementary particles are different modes of oscillation of the loop of the string

Superstrings

1985- it seemed clear that there are five different superstring theories, each requiring <u>ten dimensions</u> (nine space and one time),

The five theories,
- type I,
- type IIA,
- type IIB,
- E8 X E8 heterotic (HE, for short),
- SO(32) heterotic (HO, for short).

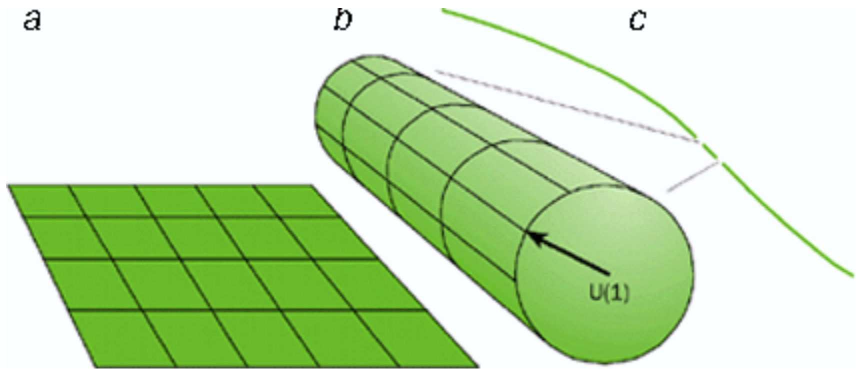
The type II theories have two supersymmetries in the ten-dimensional sense, while the other three have just one.

The type I theory is based on unoriented open and closed strings, whereas the other four are based on oriented closed strings

The IIA theory is special in that it is non-chiral (i.e., it is parity conserving), whereas the other four are chiral (parity violating)

Superstrings

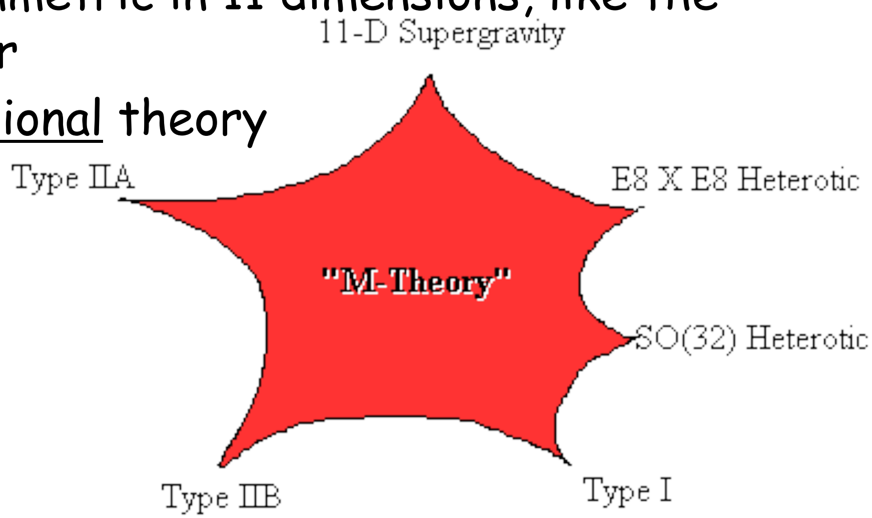
- The ten dimensions of string theory include the usual four dimensions plus others than are curled up, perhaps to dimension of the Planck scale, but some might be large.



- Gravity is unified with other forces, supersymmetric particles are predicted, and divergences cancel.

Superstrings

- M Theory
  - 1994 revolution (E. Witten)
  - The five string theories are shown to be different approximations of the same theory
  - This unique theory is supersymmetric in 11 dimensions, like the 11-D supergravity of past favor
  - There is one, unique, <u>11 dimensional</u> theory



- Three radical ideas
  - Supersymmetry
  - Extra space-time dimensions
  - Extended objects

Large Extra Dimensions

- Some of the extra dimensions could be quite large
- The experimental limits on the size of extra dimensions are not very restrictive
  - to what distance has the r^{-2} force law been measured?
  - extra dimensions could be as large as 0.1 mm, for example
  - experimental work is underway now to look for such large extra dimensions (see measurements later in this lecture)

Large Extra Dimensions

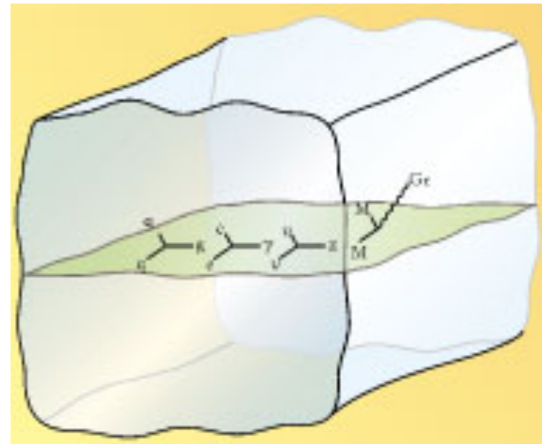
(see "Large Extra Dimensions: A New Arena for Particle Physics", Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

An exciting new idea explains the hierarchy problem

- In addition to the three infinite spatial dimensions we know about, it is assumed there are n new spatial dimensions of finite extent R.
- The space spanned by the new dimensions is called "the bulk."
- The particles of the standard model
  - quarks, leptons, and gauge bosons

  all live in our familiar realm of three spatial dimensions, which forms a hypersurface, or "3-brane" within the bulk.
- The propagation of electroweak and strong forces is then confined to the 3-brane.

Large Extra Dimensions



- Gravity is different:
  - Gravitons propagate in the full (3 + n)-dimensional space

- Addressing the hierarchy problem:
  - At distances less than R, gravity spreads in all the 3 + n spatial dimensions, and therefore the gravitational force falls like $r^{-(2+n)}$ with increasing separation r.
  - Thus gravity's strength, relative to the electric force, is rapidly diluted with increasing separation--and just as rapidly augmented with increasing proximity.
  - Of course, when r exceeds R, the gravitational force reverts to its normal r^{-2} falloff, there being no longer any extra-dimensional space in which to spread out.

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Large Extra Dimensions

- In superstring theory, we see extra dimensions not much larger than the 10^{-33} cm Planck length.
- Suppose the n extra dimensions are much larger--perhaps even macroscopic.
  - At large distances (r > R) $F \sim 1/(M_{pl}\, r)^2$
  - But at short distances (r < R) $F \sim 1/(M_* r)^{2+n}$
    - where M_* is the true energy scale of gravity in 3 + n dimensions.
- Match the expressions at r=R
  - $(M_{pl}\, R)^2 = (M_* R)^{2+n}$
  - $M_{Pl}^2 = M_*^{2+n} R^n$

If we now assume that $M_* \approx M_{ew} \approx 1$ TeV
we find that $R \approx 2 \times 10^{(32/n)-17}$ cm.

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Large Extra Dimensions

- If there were only one extra dimension ($n = 1$), its size R would have to be of order 10^{10} km to account for the weakness of gravity.
  - An extra dimension that large would long ago have made itself obvious in the dynamics of the Solar System.
- But two equal extra dimensions would be on the order of a millimeter in length.
  - Very exciting is the $n = 2$ case of two millimeter-sized dimensions, which is the subject of active search by several tabletop Cavendish-type experiments, checking Newtonian gravity at short range.
- As the number of the new dimensions increases, their size gets smaller.
  - For six equal extra dimensions, the size is only about 10 fermi.

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

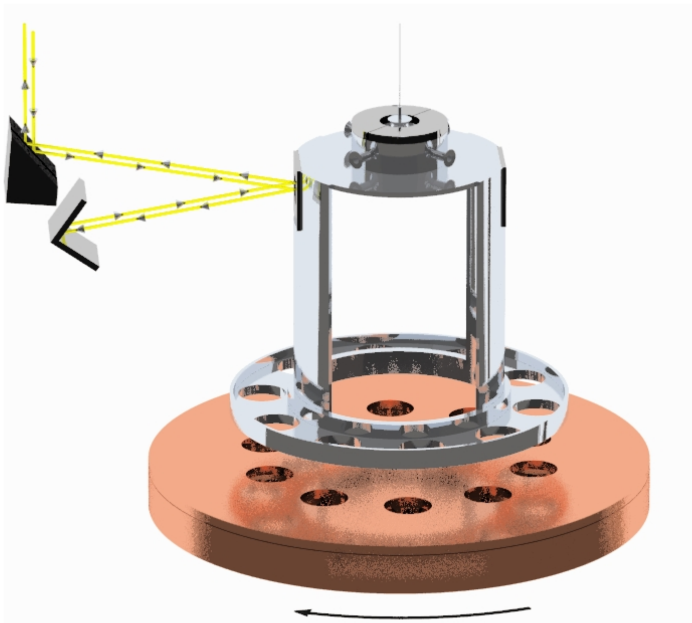
Large Extra Dimensions

$$R \approx 2 \times 10^{(32/n)-17} \text{ cm}$$

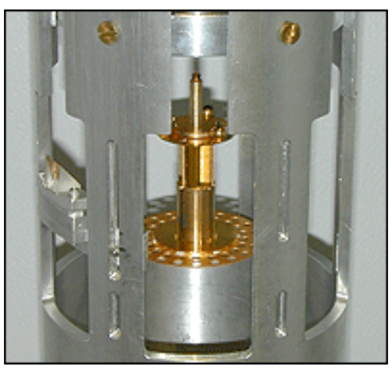
n	R
1	2×10^{10} km
2	2 mm
3	9.3 nm
4	2×10^{4} fm
5	500 fm
6	43 fm

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Experimental Test for Large Extra Dimensions



Eot-Wash hep-ex/0202008

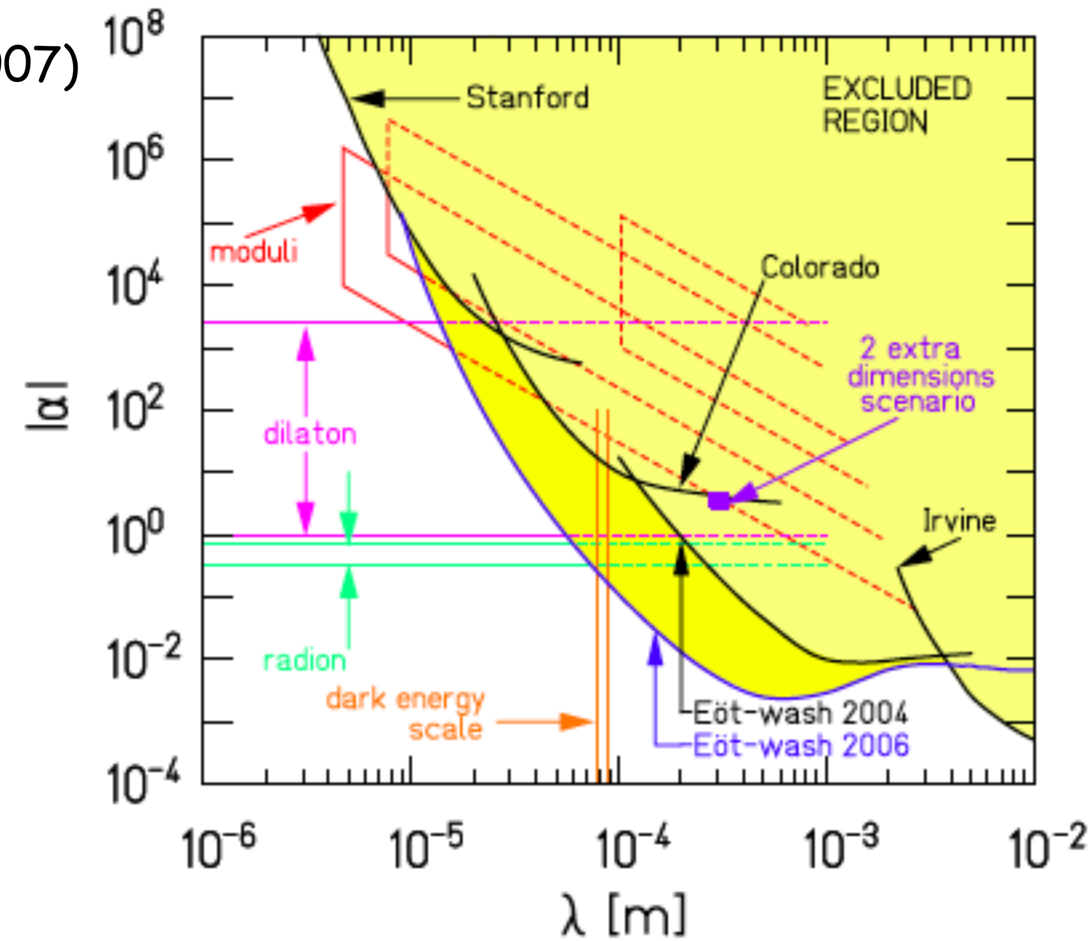


- Pendulum - ring with 10 holes bored into it
- rotating attractor situated just below the ring consists of 2 disks
- upper disk has 10 holes identical to those in the ring.
- As the attractor rotates, the gravitational force causes the ring to twist back and forth 10 times for every revolution of the attractor
- lower, and thicker, attractor disk also has 10 holes bored into it, but these larger holes are rotated by 18 degrees compared to those in the upper disk, so that they lie halfway between the holes in the upper disk.
- If the inverse-square law is correct, the lower holes produce a twist on the ring that just cancels the twist induced by the upper disk
- However, if gravity becomes stronger at short distances as the theory suggests, the twist induced by the lower disk, which is farther from the ring, will be too small to cancel the twist from the upper disk and we will see a clear twist signal that varies 10 times for every revolution of the attractor.

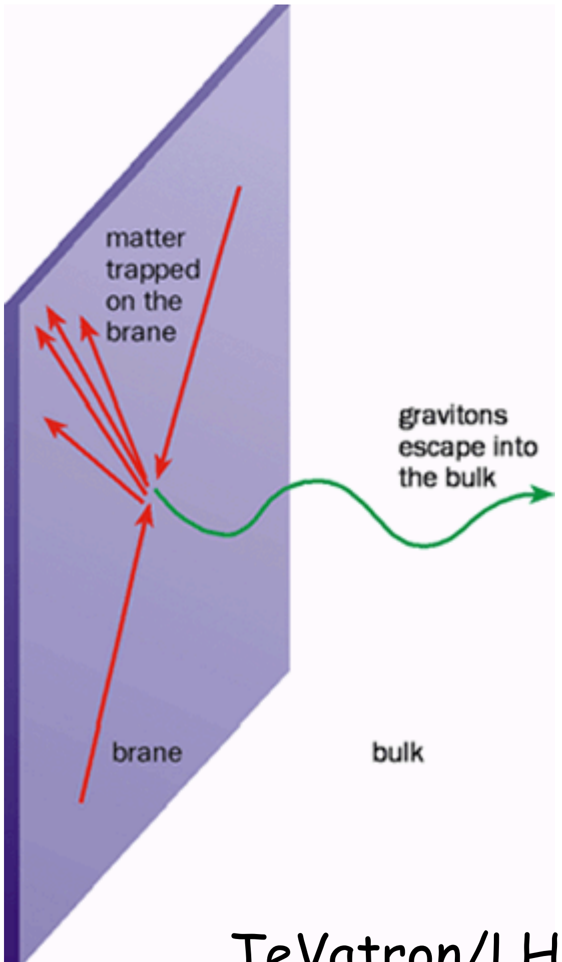
Experimental Test for Large Extra Dimensions

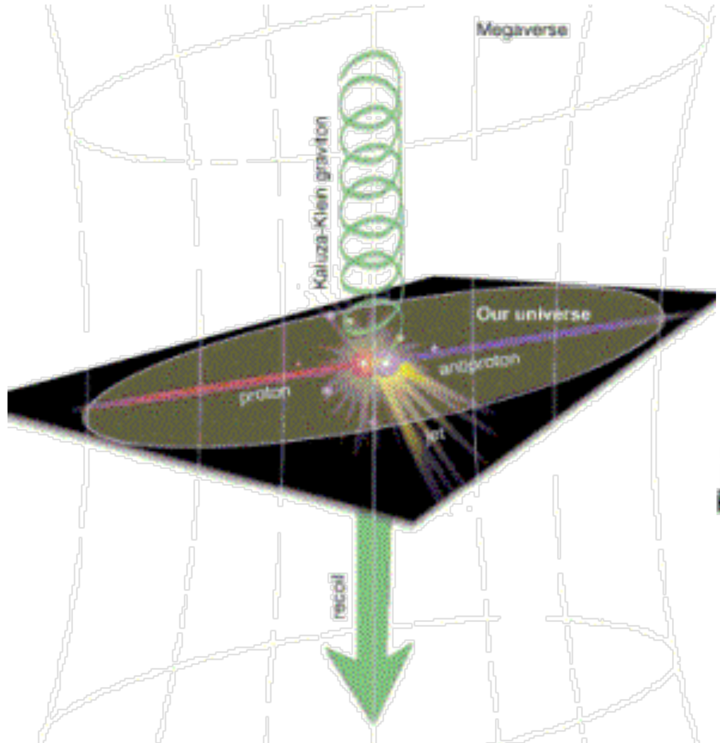
- Limits on inverse square law
- Phys. Rev. Lett 98, 021101 (2007)
  - D.J. Kapner et al.

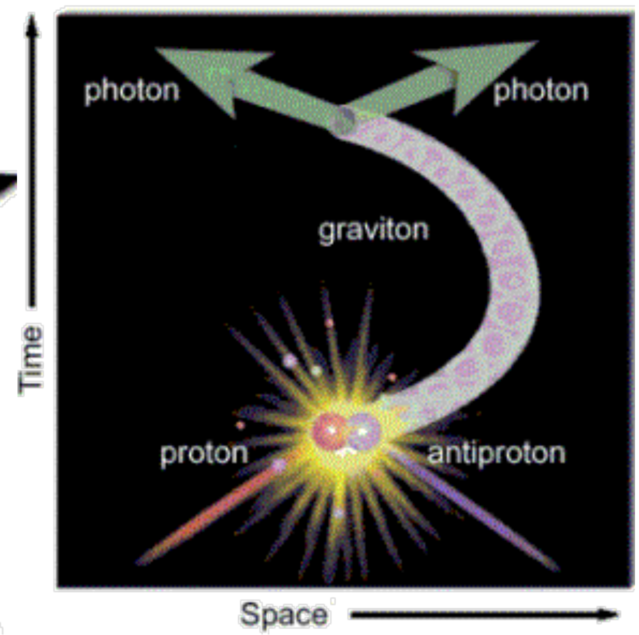
$$V(r) = -G\frac{m_1 m_2}{r}(1 + \alpha e^{-r/\lambda})$$



Extra Dimensions at Colliders

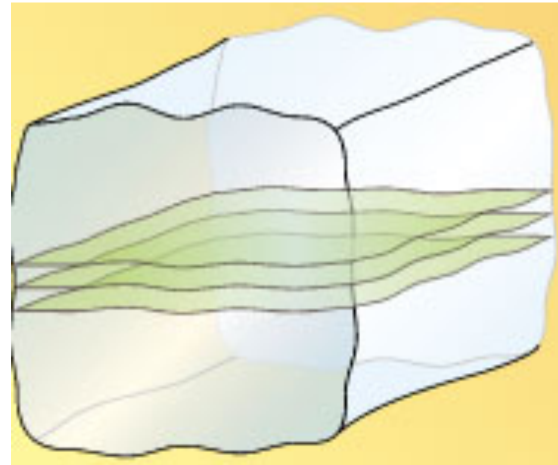






TeVatron/LHC limits are now about 1 TeV for the higher dimensional Planck scale

Interactions Between Branes



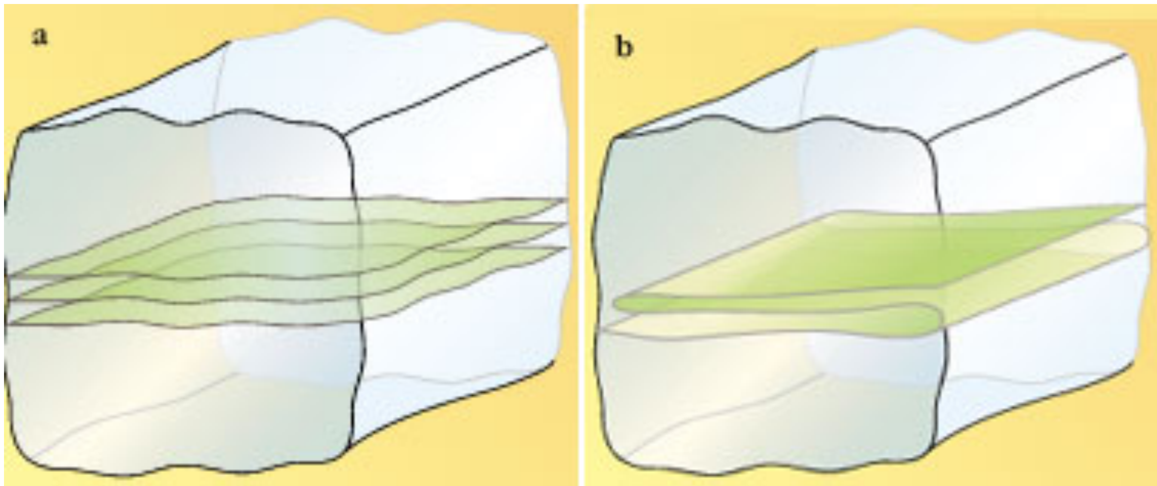
- Perhaps our brane is not alone in the bulk, but there are others as well
- The physics on those other branes
  - the particles that inhabit them, and their forces and symmetries

  may be different from ours.
- Nevertheless, their presence would influence physics on our brane.
  - That's because branes are sources for bulk fields, much as charges are sources for the electric field. The values of these bulk fields at the location of our brane may determine the parameters of our standard model
    - for example, the electron mass,
    - the Cabbibo angle,
    - and the electroweak-mixing angle.
  - Conversely, these parameters probe the location of those other branes in the bulk.

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Interactions Between Branes

- It might even be that 3-brane regions separated from us by short distances across the bulk are not really separate branes with fundamental parameters different from ours.
- They could conceivably be separate folds of our own 3-brane.
- It might be that the astrophysical and cosmological anomalies we attribute to "dark matter" are actually weak manifestations, across short intervals of the bulk, of ordinary matter in adjacent folds of our 3-brane.



(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Theoretical Issues

- What stabilizes the size of the extra dimensions?
- If quantum gravity really gets strong near a TeV, why don't virtual black holes give rise to nearly instantaneous proton decay?
- What does this framework do to the predicted supersymmetric unification of the electroweak and strong coupling strengths near M_{Pl}

(see Large Extra Dimensions: A New Arena for Particle Physics, Nima Arkani-Hamed, Savas Dimopoulos, and Georgi Dvali, Physics Today, February, 2002)

Proton Decay and Virtual Black Holes

- Consider proton decay in 4 dimensions where $M_{pl} \sim 10^{19}$ GeV
  - Virtual black holes will emerge in the vacuum
  - These virtual black holes live one Planck time ~ 5 x 10^{-44} sec
  - When two quarks fall into the black hole at the same time, $q + q \rightarrow \bar{q} + l$ processes can occur
  - Prob that 2 quarks are within one Planck length (10^{-33} cm) within the proton is $(m_p/M_{Pl})^3 \sim 10^{-57}$. This is a probability per proton crossing time ~ 10^{-31} yr.
  - An additional factor of m_p/M_{Pl} accounts for the requirement that a vitual black hole be present when the two quarks are near each other.
  - So $\tau_P \sim m_p^{-1} (M_{Pl}/m_p)^4 \sim 10^{45}$ yr, long compared to the expected proton lifetime -> this is okay
  - WHAT ABOUT THE CASE FOR EXTRA DIMENSIONS?

Proton Decay and Virtual Black Holes

- Consider proton decay in 4 + n dimensions where M_{pl}~1 TeV
  - Two effects change the rate from the SM
    - The Planck mass is smaller, leading to more virtual BHs
    - The extra dimensions affect the rate if the fermions are allowed to propagate through d additional dimensions from the standard 3
  - Now $\tau_P \sim m_p^{-1} (M_*/m_p)^{4+d}$
    - if d = 0 and $M_* \sim 1$ TeV, $\tau_P \sim 10^{-19}$ yr -> far too short
    - if d = 7 and $M_* \sim 1$ TeV, $\tau_P \sim 100$ yr -> still too short
  - We know $\tau_P > 10^{33}$ yr
    - Therefore $M_* > 10^{64/(4+d)}$ GeV
    - For d = 7, $M_* > 700$ TeV

hep-ph/0009154