The Higgs Boson
and
Physics Beyond the Standard Model

Marc Sher

College of William and Mary

HUGS Summer School, June 10-11, 2010

Outline

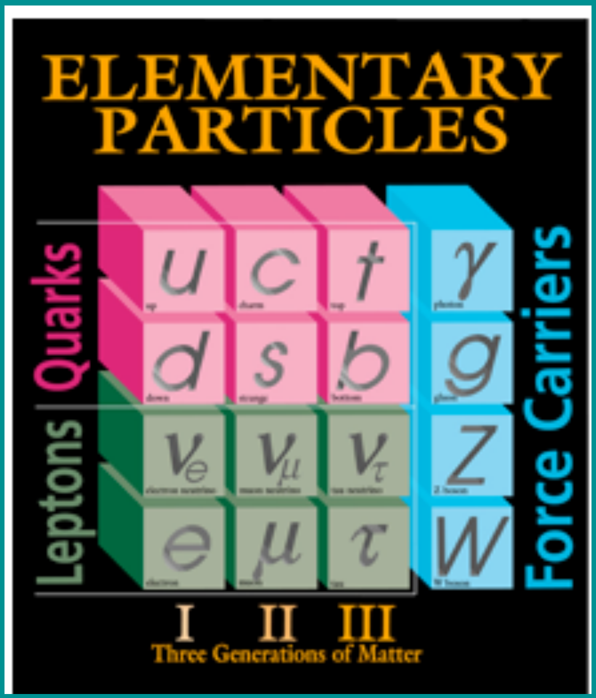
1. Introduction to the Higgs mechanism in the SM, theoretical bounds on the Higgs mass.
2. Experimental signatures, electroweak precision tests, timeline for the Tevatron and LHC.   Problems with the SM.
3. Supersymmetry
4. Dynamical symmetry breaking (technicolor), extra dimensions.
5. Axions, Z-primes; low energy tests of SM

The Standard Model

Group: $\underbrace{SU(3)}_{\text{QCD}} \times \underbrace{SU(2) \times U(1)}_{\text{Electroweak}}$

Gauge bosons:

- SU(3): G_μ^i, $i=1\ldots8$
- SU(2): W_μ^i, $i=1,2,3$
- U(1): B_μ



$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad u_R, \quad d_R, \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad e_R$$

$$\psi_{L,R} = \frac{1 \mp \gamma_5}{2}$$

Masses

- The photon and gluon are massless.
- The W mass is 80.400 +/- 0.025 GeV, the Z mass is 91.1875 +/- 0.002 GeV.
- The top quark mass is 173.1 +/- 1.3 GeV, the other quarks and the leptons are much lighter.
- Neutrino masses are small but nonzero.
- If the SU(2) symmetry of the Standard Model is unbroken, then the W, Z and all of the quarks and leptons would be massless.

Why massless?

Consider QED. The Lagrangian is $\mathcal{L}_A = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$

where $F^{\mu\nu} = (\partial^\mu A^\nu - \partial^\nu A^\mu)$

This is invariant under $eA^\mu \longrightarrow eA^\mu + \partial^\mu \alpha(x)$

A mass term would be of the form $m^2 A^\mu A_\mu$ which clearly violates gauge invariance.

A fermion mass term is of the form $m\, \bar{\Psi}_L \Psi_R$ + h.c.

Since this multiplies a doublet by a singlet, it is also not gauge invariant.

So the gauge symmetry must be broken.

How does one break the symmetry?

- Could just add the mass terms. That breaks the symmetry. Resulting theory turns out to be non-renormalizable.
- Instead, break it “spontaneously”. The Lagrangian is invariant, but the ground state (solution of eq. of motion) is not. Similar to a ferromagnet and rotational symmetry. This turns out (not trivial to show) to be completely renormalizable.

Abelian Higgs model -- U(1) symmetry

Add a complex scalar field to the QED Lagrangian:

$\mathcal{L} = \mathcal{L}_{QED} + (D^\mu\Phi)^*(D_\mu\Phi) - V(\Phi)$

where

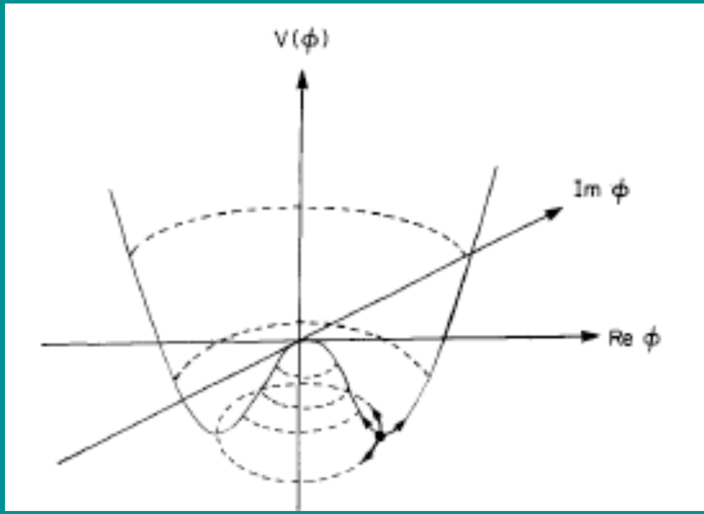
$D_\mu = \partial_\mu + ig A_\mu$ and $V(\Phi) = \mu^2 \Phi^*\Phi + \lambda (\Phi^*\Phi)^2$

We assume $\lambda > 0$. This is gauge invariant under

$\Phi(x) \to e^{i\alpha(x)} \Phi$, $gA^\mu \to gA^\mu + \partial^\mu\alpha(x)$.

If $\mu^2 > 0$, then this is just adding a scalar field with mass μ and a self-interaction. But if $\mu^2 < 0$ .....

If $\mu^2 < 0$, then we can plot V as a function of Re(Φ) and Im(Φ):



The minimum of the potential is at $\Phi^*\Phi = -\mu^2/2\lambda$

When a minimum is selected (conventionally so the minimum is on the real axis), the rotational symmetry is broken. Note that the Lagrangian is symmetric under $\Phi \dashrightarrow e^{i\alpha}\,\Phi$, but the solution picks out a specific direction, just like a ferromagnet.

To find masses, one expands around the ground state.

Write $\Phi(x) = \dfrac{v}{\sqrt{2}} + \dfrac{\phi_1 + i\phi_2}{\sqrt{2}}$ where $v^2 = \mu^2/\lambda$

Plug this into the Lagrangian, and one gets:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}g^2v^2A^\mu A_\mu}_{\text{massive vector field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_1)^2 + \mu^2\phi_1^2}_{\text{massive scalar field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_2)^2 + gvA_\mu\partial^\mu\phi_2}_{\text{Goldstone boson}} + \ldots$$

Looks like a massive vector and a massive scalar, but there is a weird mixing term. Better is to write $\phi(x) = \frac{e^{i\frac{\chi(x)}{v}}}{\sqrt{2}}(v + H(x))$

Then, by performing a U(1) rotation on $\phi(x)$, with $\alpha(x)=\chi(x)/v$, one gets

$$\mathcal{L} = \mathcal{L}_A + \frac{g^2v^2}{2}A^\mu A_\mu + \frac{1}{2}\left(\partial^\mu H\partial_\mu H + 2\mu^2H^2\right) + \ldots$$

Massive vector, massive scalar, no other fields!!

So the phase of the complex scalar field is “eaten” by the vector field.

Before: massless vector (2 d.o.f.) and complex scalar (2 d.o.f)

After: massive vector (3 d.o.f) and massive scalar (1 d.o.f.)

The massive scalar is the Higgs field. Its mass-squared is $-2\mu^2 = 2\lambda v^2$.

The mass of the vector field is g v.   In the Standard Model, the W mass is known, g is known, so v is known (246 GeV).   But the mass of the Higgs is still undetermined.

The Higgs in the Standard Model

We introduce a complex scalar doublet $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

The Lagrangian is $\mathcal{L}_\phi = (D^\mu \phi)^\dagger D_\mu \phi - \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2$

where $D_\mu \phi = (\partial_\mu - igA^a_\mu \tau^a - ig' Y_\phi B_\mu),$

With $\mu^2 < 0$, the minimum is at $\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

Shifting to expand around the minimum, as before, the W gets a mass of gv/2, the Z gets a mass of $(g^2+g'^2)^{1/2}$ v/2, and the photon stays massless.

Start with 4 massless vectors (8 d.o.f) and a complex scalar doublet (4 d.o.f)

End with 3 massive vectors (9 d.o.f), a massless vector (2 d.o.f) and a massive Higgs (1 d.o.f)

Again, v is known from M_W and g, and is 246.225 GeV. Alas, the Higgs mass depends on λ and is undetermined.

We can also give mass to the fermions.

$$\mathcal{L}_{Yukawa} = -\Gamma_u^{ij}\bar{Q}_L^i \phi^c u_R^j - \Gamma_d^{ij}\bar{Q}_L^i \phi d_R^j - \Gamma_e^{ij}\bar{L}_L^i \phi l_R^j + h.c.$$

When we expand about the vacuum, the Yukawa terms give

$$m_f = \Gamma_f \frac{v}{\sqrt{2}}$$

So the interaction of the Higgs with fermions are flavor-diagonal and proportional to the fermion mass.

Catch-22 of particle physics: The Higgs interacts more strongly with heavy particles. Accelerators are made of light particles

So, we know precisely what the interaction is between the Higgs and a particle of mass M. The only unknown is the mass of the Higgs.

Can we say anything?

Upper limits to the Higgs mass

Unitarity bound:

Any scattering amplitude can be expanded in partial waves:

$$\mathcal{A} = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

From this, one can get the cross section:

$$\sigma = \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1) |a_l|^2 .$$

Using the optical theorem in quantum mechanics:

$$\sigma = \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1) |a_l|^2 = \frac{1}{s} \mathrm{Im}\left[\mathcal{A}(\theta=0)\right]$$

Combining these two gives:

$$|a_l|^2 = \mathrm{Re}(a_l)^2 + \mathrm{Im}(a_l)^2 = \mathrm{Im}(a_l) \quad \longrightarrow \quad |\mathrm{Re}(a_l)| \leq \frac{1}{2} .$$

This is true for all processes. Suppose there is no Higgs. Then one can consider the cross section for $W^+W^- \to W^+W^-$ and expand in partial waves. One gets that $a_0 = s/(32\pi v^2)$, and thus unitarity breaks down for $s > (1.8\ \text{TeV})^2$. Other channels give a breakdown for $s > (1.2\ \text{TeV})^2$. Thus there must be a Higgs or something else at the TeV scale.

With a Higgs, one finds that the mass must be less than 710 GeV to avoid unitarity breakdown.

Other bounds on the Higgs mass

The Higgs mass is proportional to λ, which is arbitrary. But like all couplings, λ runs with energy scale. Its renormalization group eqn:

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$

where y_t is the top Yukawa coupling. Note, if λ starts out very large, then it blows up (due to the first term) at some high energy scale. But if it starts out too small, it goes negative (due to the last term) at some high energy scale.

If one requires that the Standard Model be valid up to 10^{19} GeV, then M_{higgs} is between 130 and 200 GeV.

If one requires only that it be valid up to 10 TeV, then M_{higgs} is between 70 and 450 GeV.

We will shortly see that precision electroweak experiments force M_{higgs} to be between 114 and 150 GeV

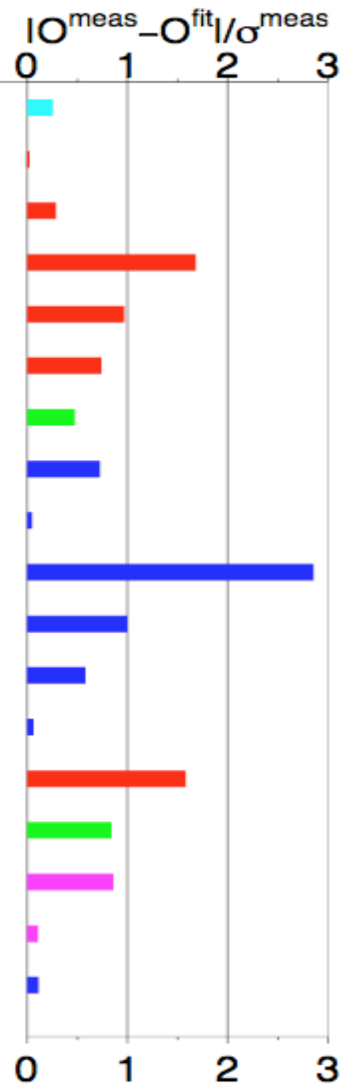
Indirect Evidence for the Higgs

The Higgs will appear in many processes at one-loop. The top quark will as well. Thus high precision experiments at low energies will be sensitive to their masses. The sensitivity to the top quark mass is quadratic, but the sensitivity to the Higgs mass, alas, is logarithmic.

Input parameters: $1/\alpha = 137.03599968$, $M_Z = 91.1876$ GeV, $G_\mu = .0000116637$ GeV^{-2}

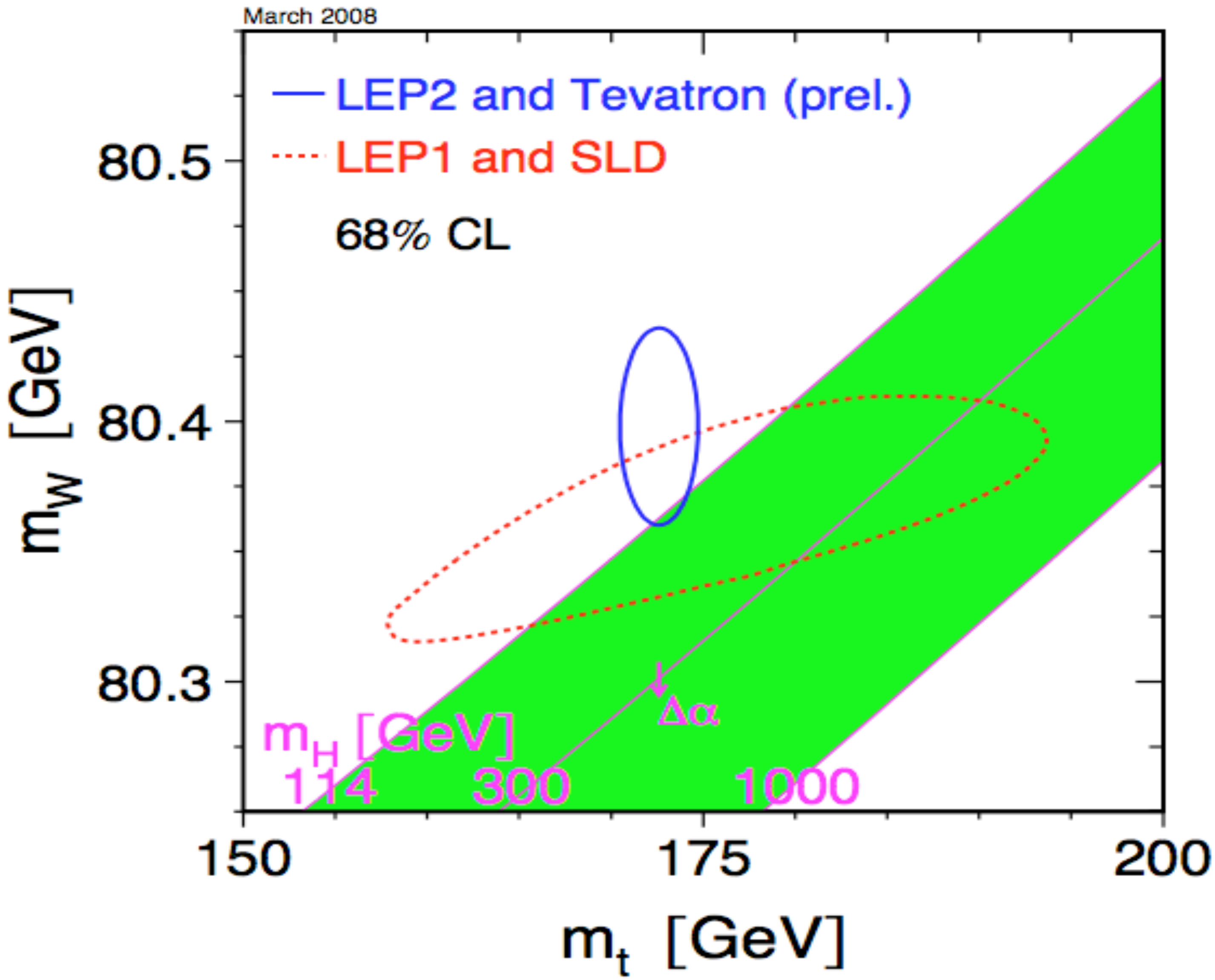
Output: M_W, Γ_W, Γ_Z, forward-backward asymmetries (A_{fb}) in b,c,lepton production, total production cross sections, R, for b,c, leptons, $\sin^2\theta_W$ measurements, total hadronic cross sections, etc. These are all measured very precisely.

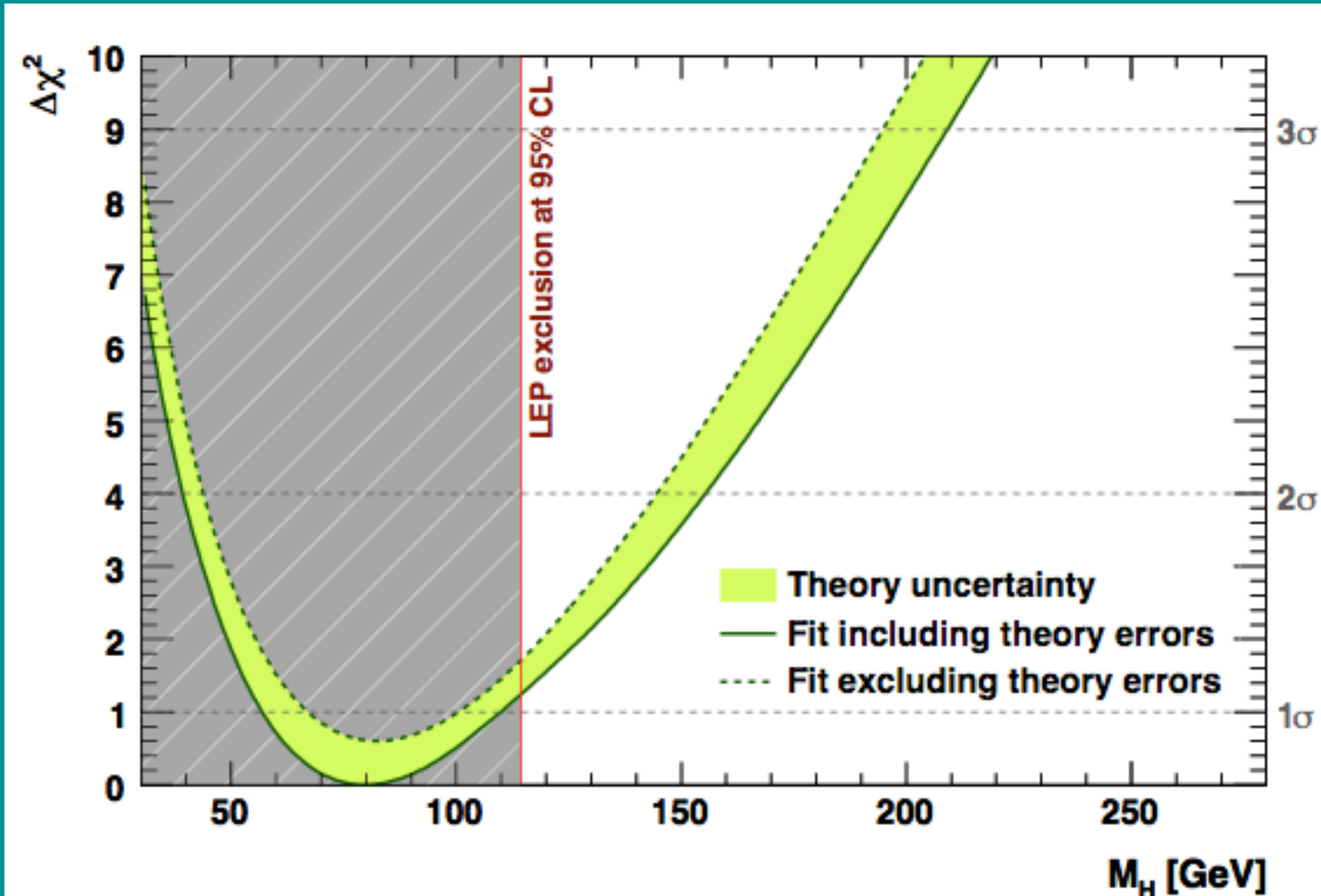
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.377
Γ_W [GeV]	2.097 ± 0.048	2.092
m_t [GeV]	172.6 ± 1.4	172.8



March 2008

LEP has determined that M_H > 114 GeV





$\Delta\chi^2$
10
9
8
7
6
5
4
3
2
1
0
50
100
150
200
250
M_H [GeV]
LEP exclusion at 95% CL
3σ
2σ
1σ
Theory uncertainty
Fit including theory errors
Fit excluding theory errors

Experimental Detection

e^+e^- colliders (LEP)---current bounds

hadron colliders (Tevatron, LHC)

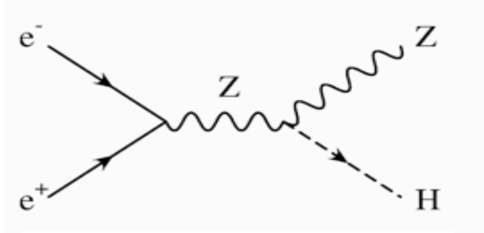
timeline for the next few years

LEP (1989-2002)

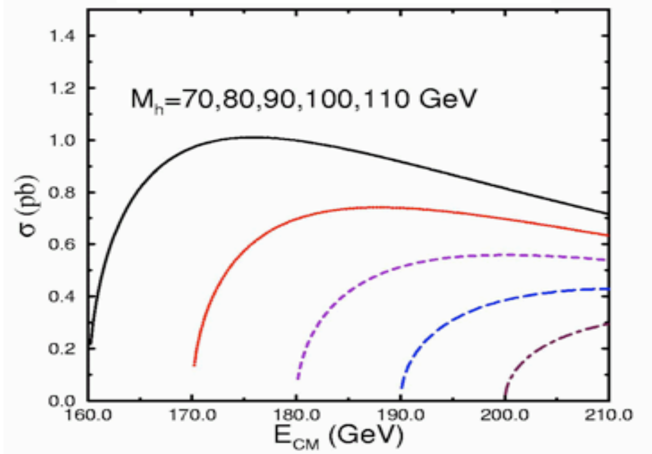
- Spent many years on the Z-pole, then increased c.o.m. energy to 200 GeV for several years.
- Not enough energy to make top pairs, so must rely on couplings to W and Z.
- There is no Z-H-H vertex.
- So must rely on Z-Z-H vertex to produce Higgs. Will not have energy to produce a Higgs heavy enough to decay to WW or ZZ, so Higgs decays to b quarks or tau leptons.

Higgs Searches at LEP2

- LEP2 searched for $e^+e^- \rightarrow ZH$
- Rate turns on rapidly after threshold, peaks just above threshold, $\sigma \sim \beta^3/s$
- Measure recoil mass of Higgs; ***result independent of Higgs decay pattern***
  - $P_{e-} = \sqrt{s}/2(1,0,0,1)$
  - $P_{e+} = \sqrt{s}/2(1,0,0,-1)$
  - $P_Z = (E_Z, \vec{p}_Z)$
- Momentum conservation:
  - $(P_{e-} + P_{e+} - P_Z)^2 = P_h^2 = M_H^2$
  - $s - 2\sqrt{s}\,E_Z + M_Z^2 = M_H^2$



$$e^+e^- \rightarrow ZH$$



LEP2 : $M_H > 114.1$ GeV

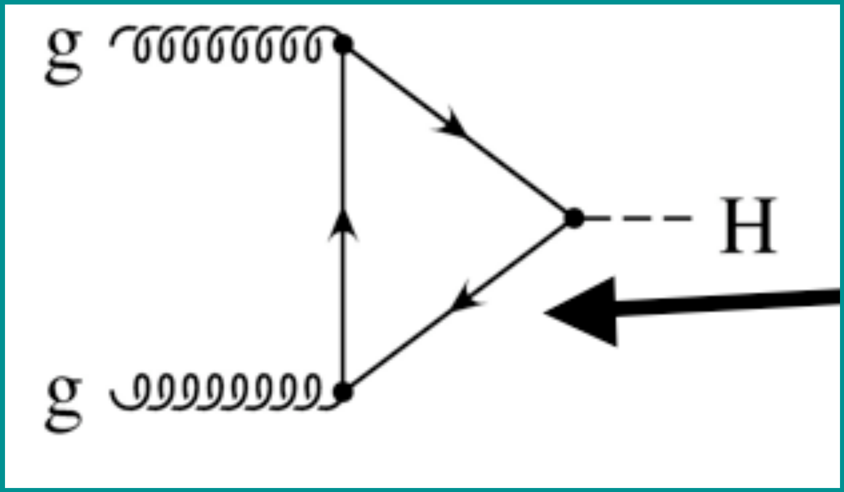
Higgs Production at Hadron Colliders

- Many possible production mechanisms, importance depends on:
  - Size of production cross section
  - Size of branching ratios to observable channels
  - Size of background
  - Most importantly -- Higgs mass

Need to see more than one channel to verify that it is really a Higgs boson.

Largest production process

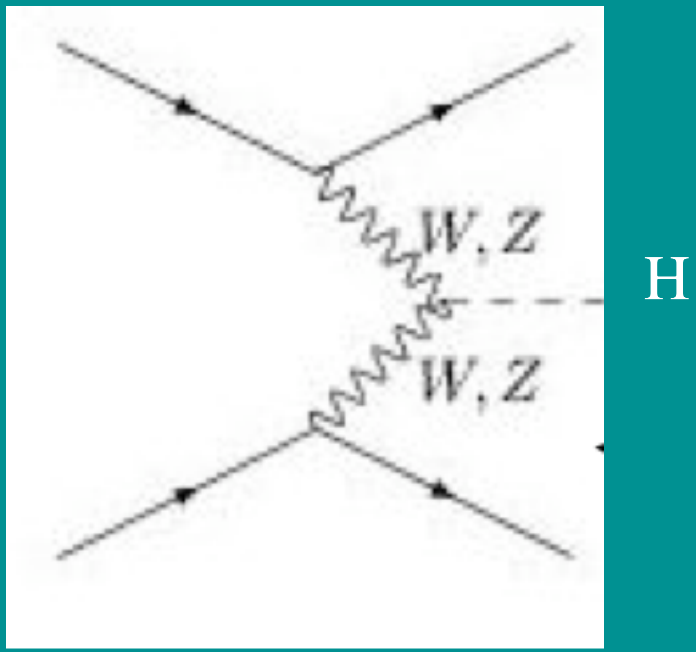
Gluon fusion - largest rate at both the Tevatron and the LHC.   Depends on the top quark Yukawa coupling.



Top quark loop

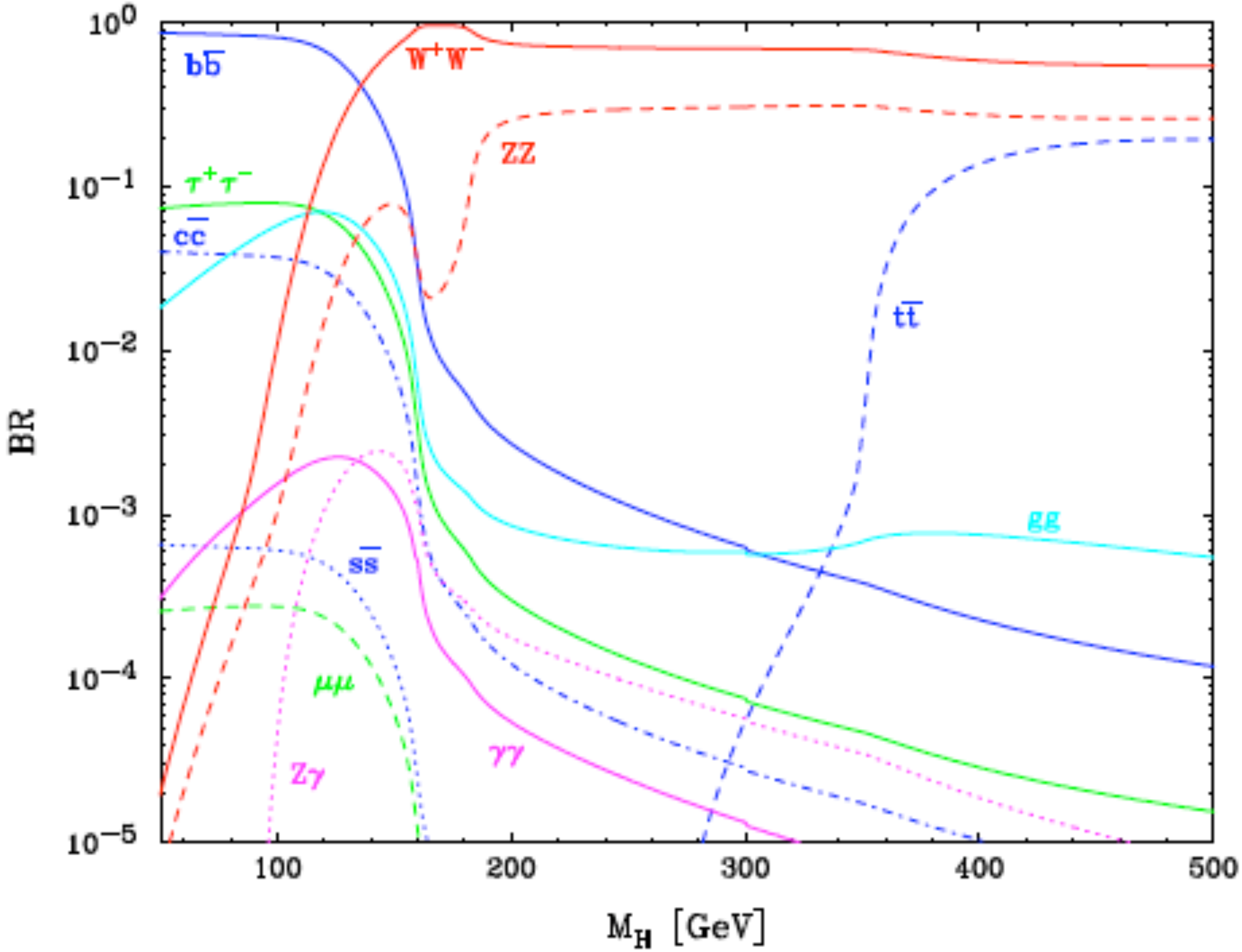
Next most important production process

Vector boson fusion.



W/Z Strahlung

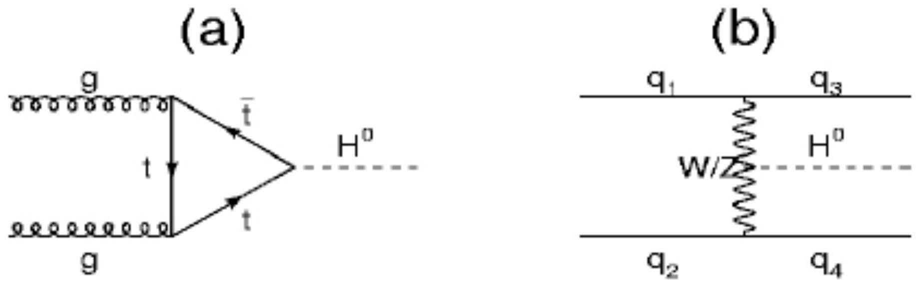
Same as for LEP   q-qbar --> Z --> Z + H, or q-qbar --> W --> W + H.   Only important at the Tevatron (many more antiquarks).   Very, very clean theoretically, pdf's well-understood, NNLO corrections calculated.

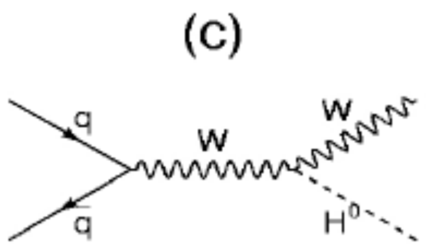


Higgs Decays

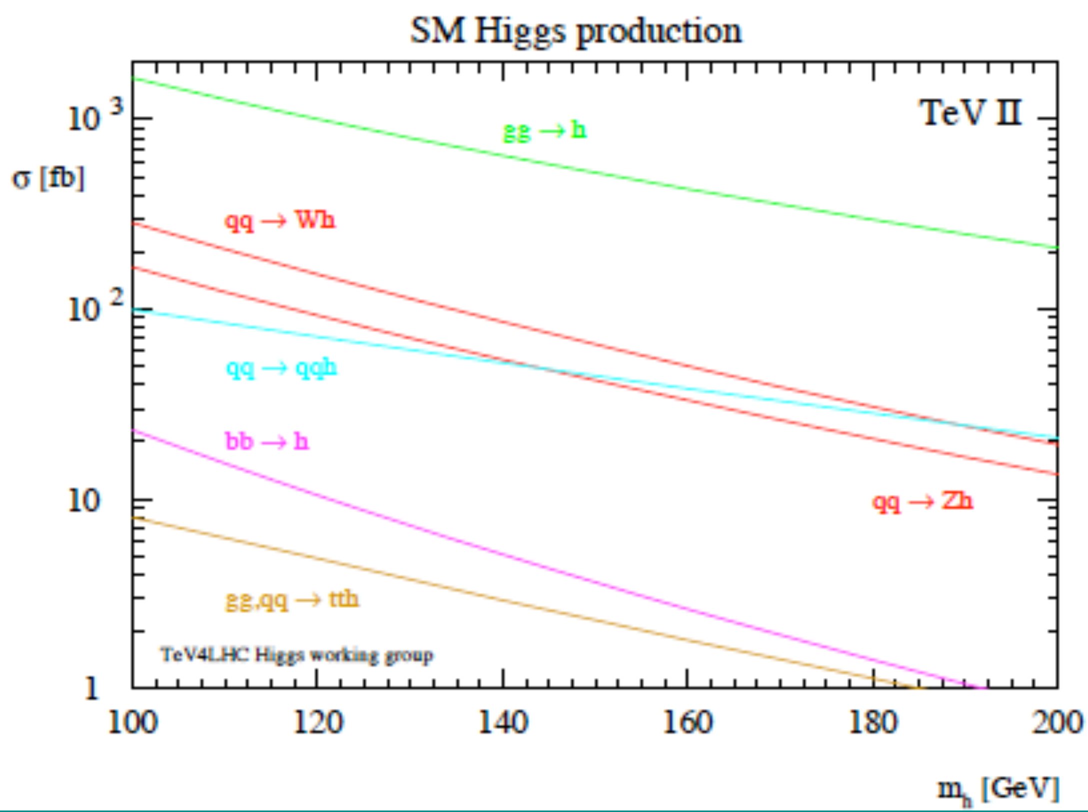
Higgs at the Tevatron

- proton-antiprotons at 2 TeV. Currently have analyzed 6 fb^{-1}, expect to have 12 fb^{-1} by the end of 2011.
- Note: A fb^{-1} is a measure of the luminosity times the time. With a 1 fb cross section, 6 fb^{-1} integrated luminosity yields 6 events.





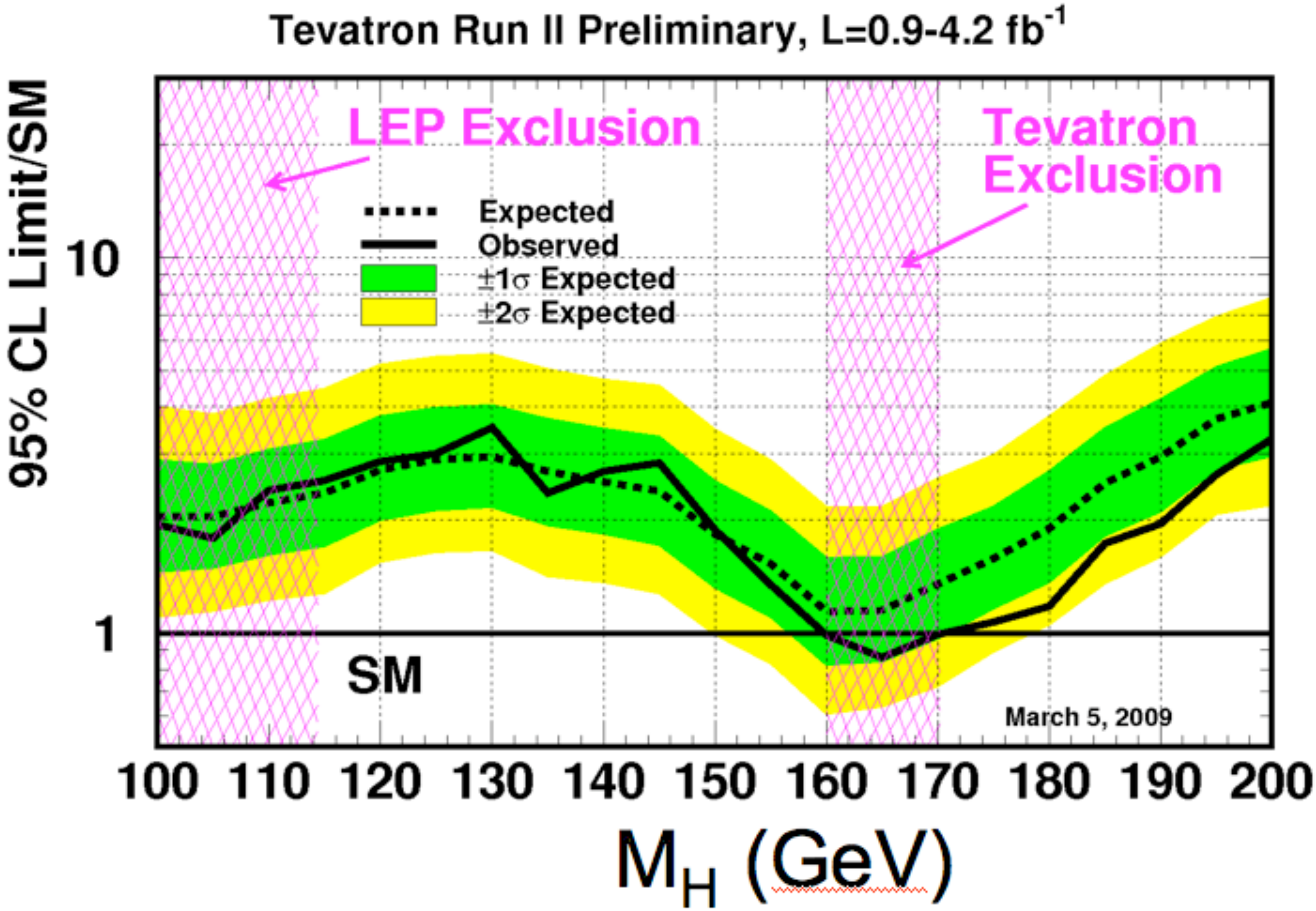
Note--total rate for b-bbar production is 10^9 times p-pbar --> H --> b-bbar. Thus, the WH and ZH modes are much more promising than gluon fusion.



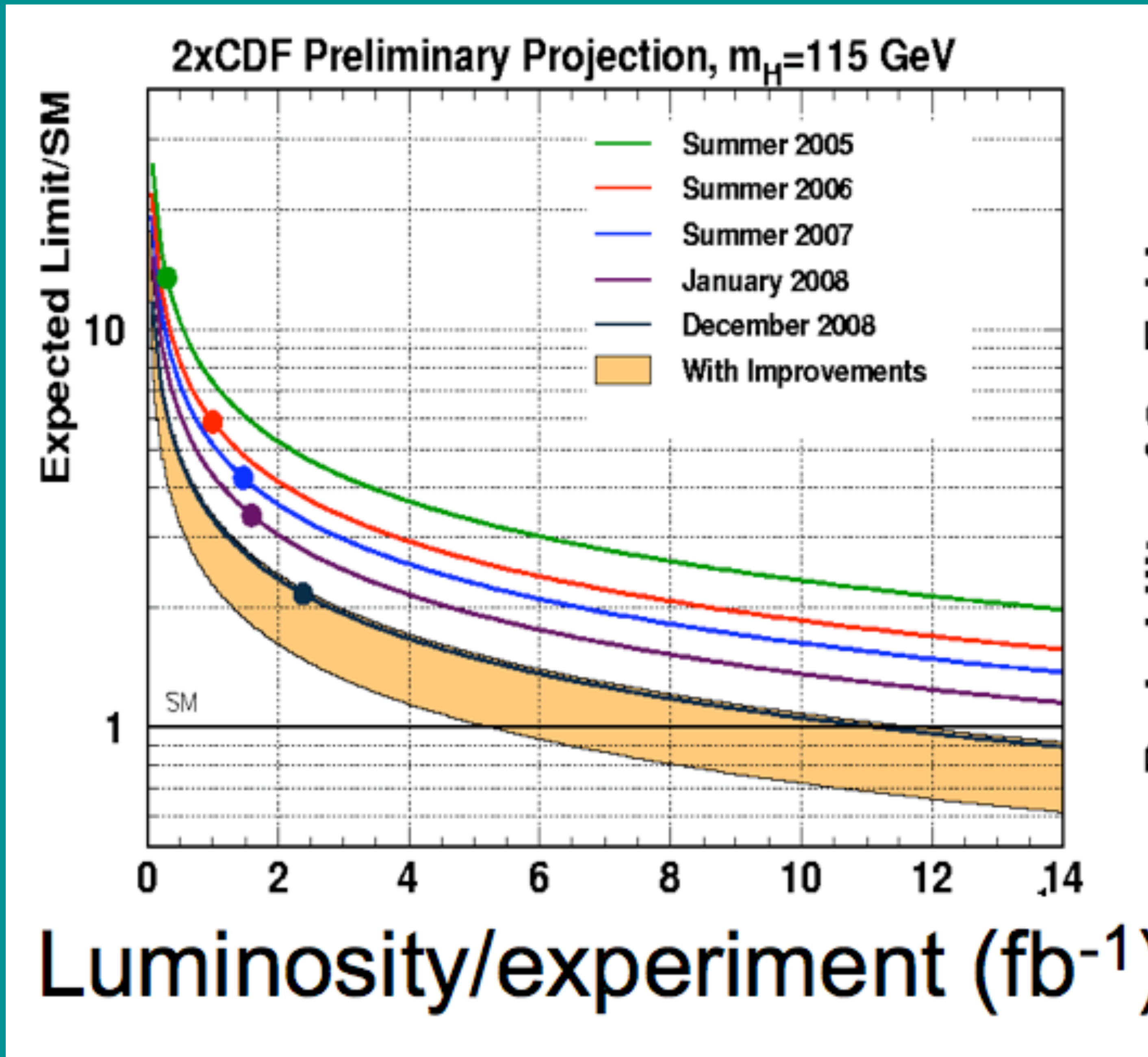
For M_H < 140, the H --> b-bbar dominates, so WH, ZH is needed.

For M_H > 140, H --> W^+W^- dominates, so gluon fusion is better (get dileptons)

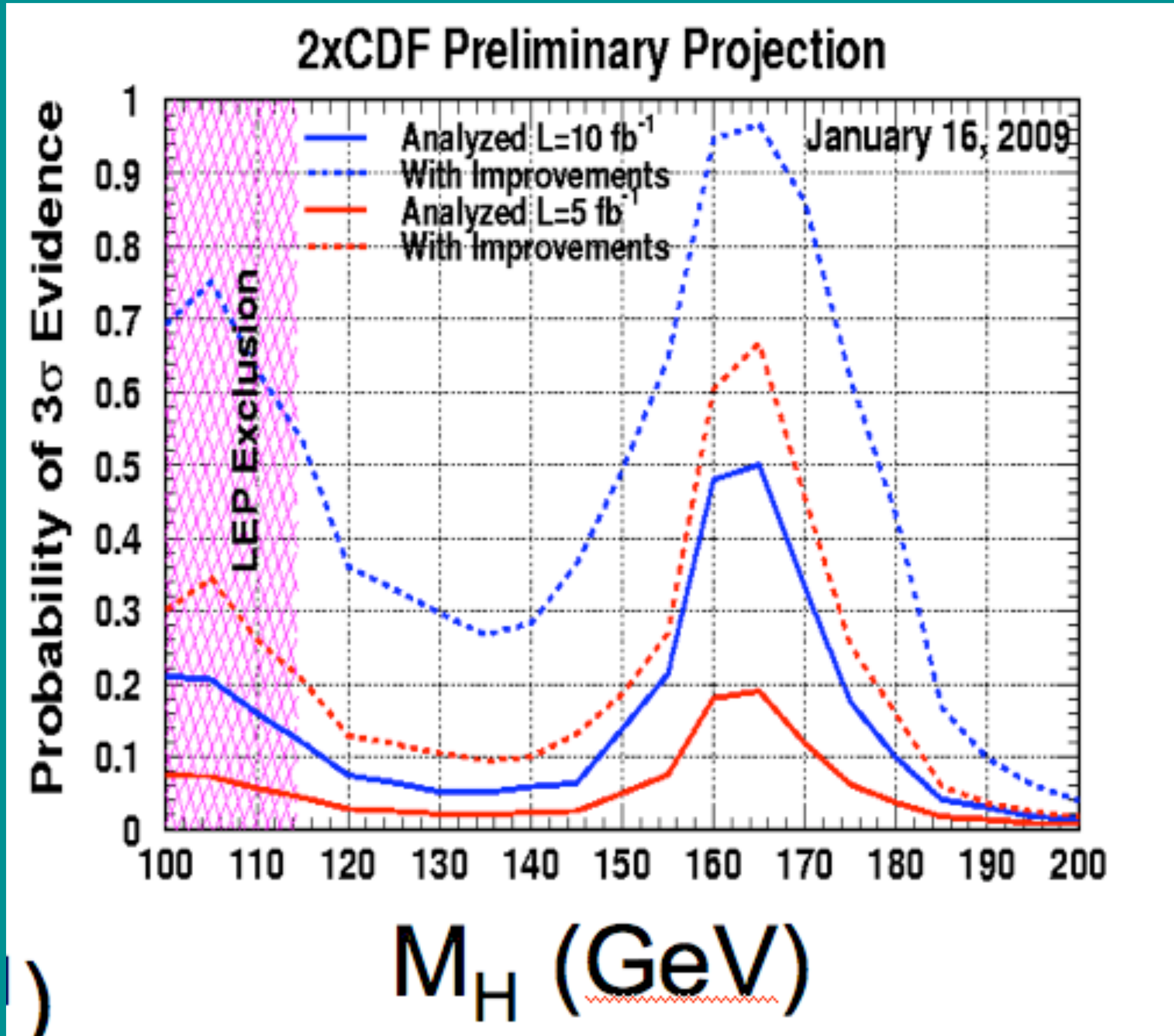
In practice, all modes are looked for.



Tevatron Run II Preliminary, L=0.9-4.2 fb-1
95% CL Limit/SM
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
10
1
SM
March 5, 2009
100 110 120 130 140 150 160 170 180 190 200
M_H (GeV)



2xCDF Preliminary Projection, m_H=115 GeV
Expected Limit/SM
10
1
SM
Summer 2005
Summer 2006
Summer 2007
January 2008
December 2008
With Improvements
0
2
4
6
8
10
12
14
Luminosity/experiment (fb-1)


2xCDF Preliminary Projection
January 16, 2009
Analyzed L=10 fb-1
With Improvements
Analyzed L=5 fb-1
With Improvements
LEP Exclusion
Probability of 3σ Evidence
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
100
110
120
130
140
150
160
170
180
190
200
M_H (GeV)

Bottom line: Tevatron

If there is no Higgs below 180 GeV, the Tevatron will exclude almost the whole region at 95% by the end of 2011, with a small window possible around 130 GeV.

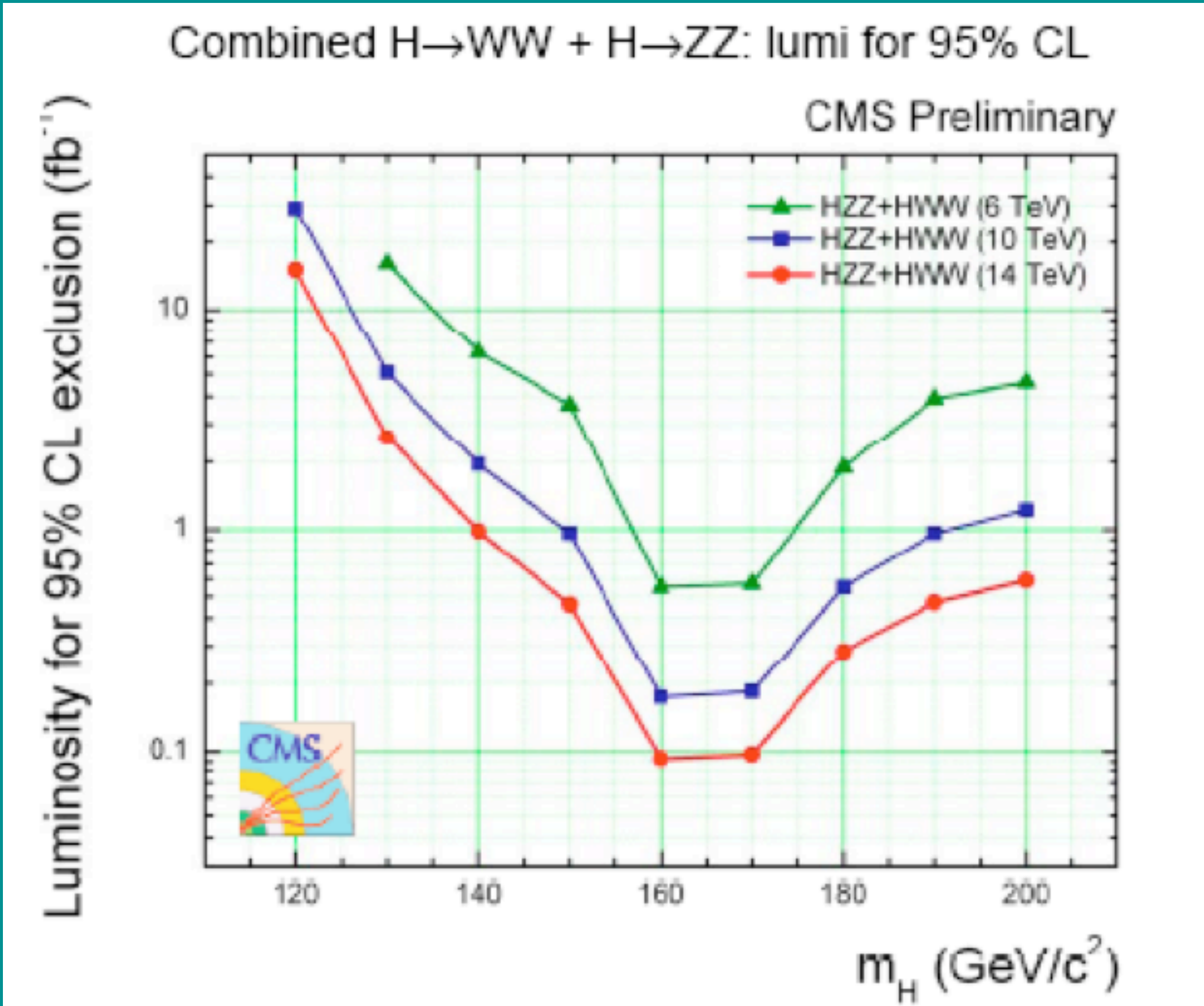
If there is a Higgs below 180 GeV, the Tevatron has a good chance of getting 3 sigma evidence, unless it is in the 120-140 GeV region, in which case there is a chance, but not above 50%.

There is no chance of a 5 sigma discovery for any mass range, alas.

The Higgs at the LHC

- The H --> b-bbar decay has huge QCD backgrounds (as does H --> gluons), and so, in the low mass region (below 130 GeV or so), one must look for rare decays: H --> $\gamma\gamma$, which has a BR below 10^{-3}. There will be a very small peak above the continuum background. Probably need 20 fb^{-1} at least. That will take until 2014-2015.

However, above 130 GeV, the signal for H --> ZZ --> 4 leptons is “gold-plated”. Fairly straightforward discovery with a few fb^{-1}. This will occur by the end of 2013.


Combined H→WW + H→ZZ: lumi for 95% CL
CMS Preliminary
HZZ+HWW (6 TeV)
HZZ+HWW (10 TeV)
HZZ+HWW (14 TeV)
Luminosity for 95% CL exclusion (fb-1)
10
1
0.1
120
140
160
180
200
mH (GeV/c2)
CMS

Summary for the LHC

Discovery:

Need ~20 fb^{-1} to probe M_H=115 GeV (2015, with luck)

10 fb^{-1} gives 5σ discovery for 127< M_H< 440 GeV (2014)

3.3 fb^{-1} gives 5σ discovery for 136< M_H 190 GeV (2013)

Problems with the Standard Model

- Many unanswered questions
  - Why is there such a wide range of fermion masses?
  - Why are the fermion mixing angles so strange?
  - Why the specific representations of fermions?
  - Why the specific coupling constant values?
  - -- etc.

Most of these questions deal with why parameters have certain values.

But the most serious problem is the so-called "hierarchy problem".

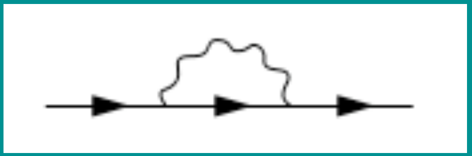
The hierarchy problem

We know that at high energies, the Standard Model must break down. At energies of 10^{19} GeV, a particle's Compton wavelength is smaller than its Schwarzschild radius, so quantum gravity is crucial.

Also, almost all Grand Unified Theories (which unite the strong, weak and EM interactions) have scales fairly close to 10^{19} GeV.

So there will certainly be new physics at a very high energy scale.

Consider the electron self-energy in QED



This gives a contribution of $(3\alpha m/2\pi) \log (\Lambda/m)$ to the electron mass, where Λ is the cutoff of the integral. This is not directly observable, but if there is new physics at a scale of 10^{19} GeV, this contribution is there. Fortunately, logs are never large, and this is only a fraction of the observed electron mass. Note that the correction to the mass is proportional to the electron mass, so if the electron mass is zero, it stays zero. This is due to a symmetry, chiral symmetry.

However, for scalars, the correction is quadratic. One typically gets ΔM^2 is proportional to $\alpha \Lambda^2$. No symmetry says that the shift is proportional to the mass.

So, if Λ is about 10^{19} GeV, then the shift in the mass^2 is $O(10^{36})$ GeV^2. In order for the total Higgs mass to be of the order of the electroweak scale, one must fine-tune the mass by 34 orders of magnitude.

Even if one does that, two loop effects will require fine-tuning of 32 orders of magnitude, etc.

Thus, we do not understand how the weak scale can be so many orders of magnitude smaller than the GUT/Planck scale. It requires ridiculous fine-tuning.

Solutions

- Make the Higgs composite, composed of new particles held together by a new interaction -- this is “technicolor”.
- Include a new symmetry that keeps the scalar light -- this is “supersymmetry”.
- Add an additional dimension with a warped geometry, which can naturally give the hierarchy -- called Randall-Sundrum, or warped geometry.
- just say “that’s the way it is”, rely on religious explanations -- called the “anthropic principle”.

Other problems:

Baryogenesis

Fact: The baryon number of the universe ((the density of baryons - the density of antibaryons)/(density of photons)) is 10^{-9}

How can such an asymmetry arise?

Andrei Sakharov gave 3 conditions that must be met:

1. There must be baryon number violation (or no asymmetry can be generated)
2. There must be CP violation (or else whatever you do will generate antibaryons)
3. The universe must go out of thermal equilibrium (or else whatever you make will be unmade).

Major discovery in the 80’s: the Standard Model does all three.

1. There are nonperturbative effects (called sphalerons) that generate a small baryon number violation. It is suppressed by a factor of $\exp(-4\pi/\alpha)$, thus negligible. But at high temp, the suppression goes away. Typically, sphalerons can change a lepton asymmetry into a baryon asymmetry, and neutrino physics can easily violate lepton number. So baryon number violation exists.
2. Also, the standard model violates CP, through the CKM matrix.
3. Also, the standard model goes through a phase transition at temperatures around the weak scale---out of equilibrium.

Alas, CP violation in the standard model is small. Calculations (difficult!) show that a sufficient baryon asymmetry can only be generated if the Higgs mass is below 40 GeV.

It isn't.

Need new physics of some kind.

Supersymmetry

Supersymmetry (SUSY) was not invented to solve the hierarchy problem. It was invented because it is an interesting new type of symmetry and is the only symmetry known which connects bosons and fermions.

It was realized shortly thereafter that local supersymmetry automatically contains general relativity, and thus might lead to a quantum theory of gravity.

Only later was it realized that it also solves the hierarchy problem.

Supersymmetry relates fermions to bosons. Thus a supersymmetric transformation, Q, must give

$$F = Q\,B$$

Note that since bosonic fields have dimensions of mass, and fermionic fields have dimensions of mass$^{3/2}$, the operator Q must have dimensions of mass$^{1/2}$ and must have spin 1/2.

What would two SUSY transformations do? It must take a boson into a boson, but Q^2 B must have units of (mass)B. The only possible object with units of mass is the four-momentum, so two SUSY transformations gives a translation. In a sense, a supersymmetric transformation is the square root of a translation.

Supersymmetry is defined via the relation:

$$\{Q_\alpha, \bar{Q}_\beta\} = -2\,(\gamma^\mu)_{\alpha\beta}\, P_\mu$$

Since two SUSY transformations give a translation, it is not unreasonable to suppose that local supersymmetry will give general covariance, which automatically leads to general relativity. In fact, local supersymmetry is called “supergravity” and does contain GR. More details are beyond the scope of these lectures.

In SUSY, every state must come with a supersymmetric partner. All spin 1/2 particles must have a spin zero partner; all spin 0 or 1 particles must have a spin 1/2 partner. If SUSY were unbroken, particles would have the same mass as their partners. Since we don’t observe a massless spin 1/2 partner of the photon, or a spin 0 particle with the mass of the electron, SUSY must be broken.

New particles:

Spin 0: squarks and sleptons (including the selectron, sneutrino, smuon, stau, stop…)

Spin 1/2: Higgsinos, gluino, photino, wino, zino

Solves hierarchy problem: In loops, every time a particle appears in a loop, one can have another diagram with the partners in the loop. Since bosonic and fermionic loops have a sign difference, these will cancel. One effectively replaces the Λ in the expression for ΔM^2 with M_{SUSY}, the scale at which SUSY is broken. This is typically 1 TeV, and so the hierarchy problem is solved.

This cancellation is one of the most remarkable features of SUSY. One can prove that “all mass and coupling constant renormalizations in a supersymmetric theory are given entirely by wavefunction renormalization, to all orders in perturbation theory”. Since wavefunction renormalizations are often an overall multiplicative factor, the mass shift will vanish to all orders in perturbation theory.

It was this theorem that gave hope to the idea that local supersymmetry (supergravity) would be a finite theory of quantum gravity.

Isn't it a bit of a stretch to solve a fine-tuning problem by doubling the particle spectrum?

It's worked in the past. Consider the self-energy of the electron in Classical E&M. The energy of a charged sphere is

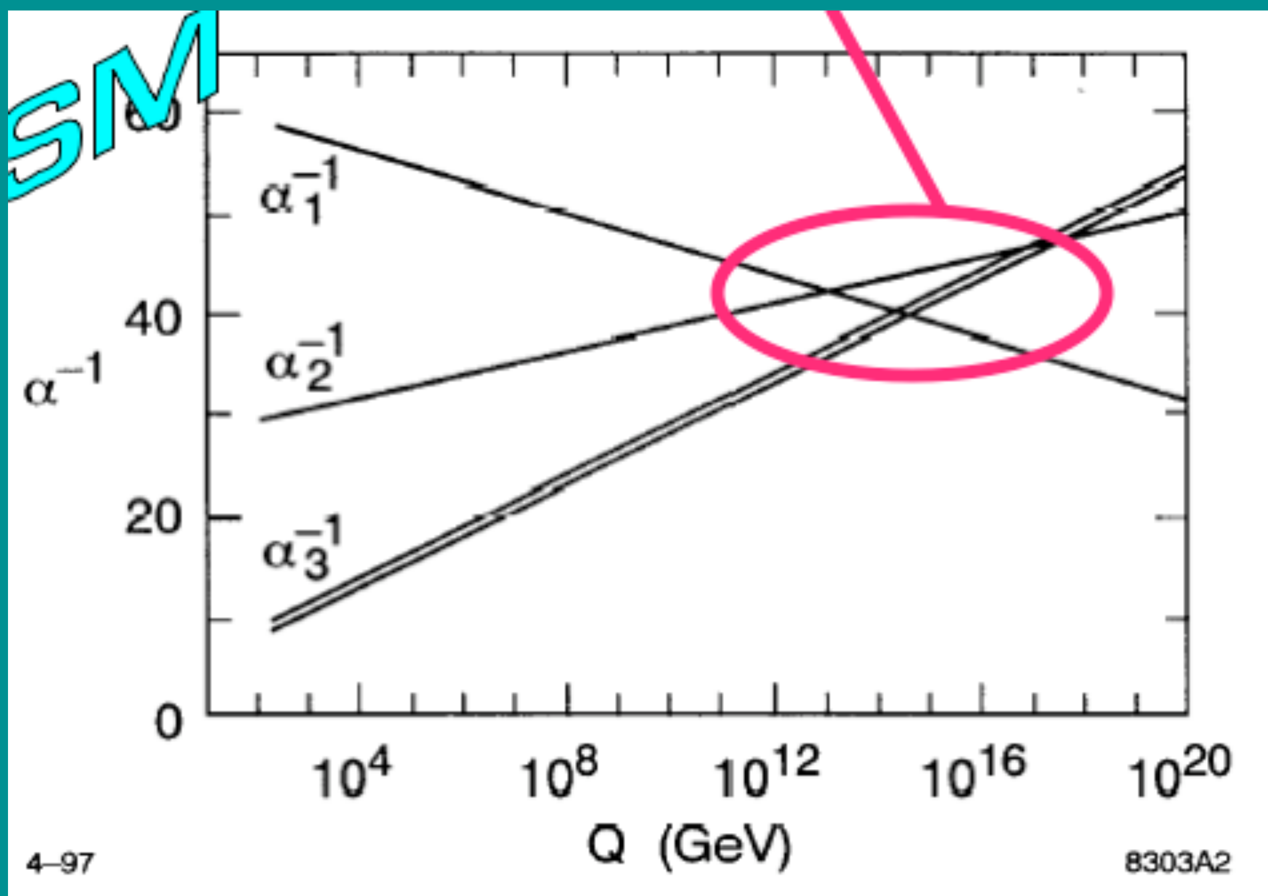
$\Delta E = (3/5)(e^2/4\pi\varepsilon_o r)$, where r is the size of the sphere. The electron is known to be pointlike down to a scale of 10^{-18} cm, so $r < 10^{-18}$ cm, which gives $\Delta E > 100\ m_e c^2$.

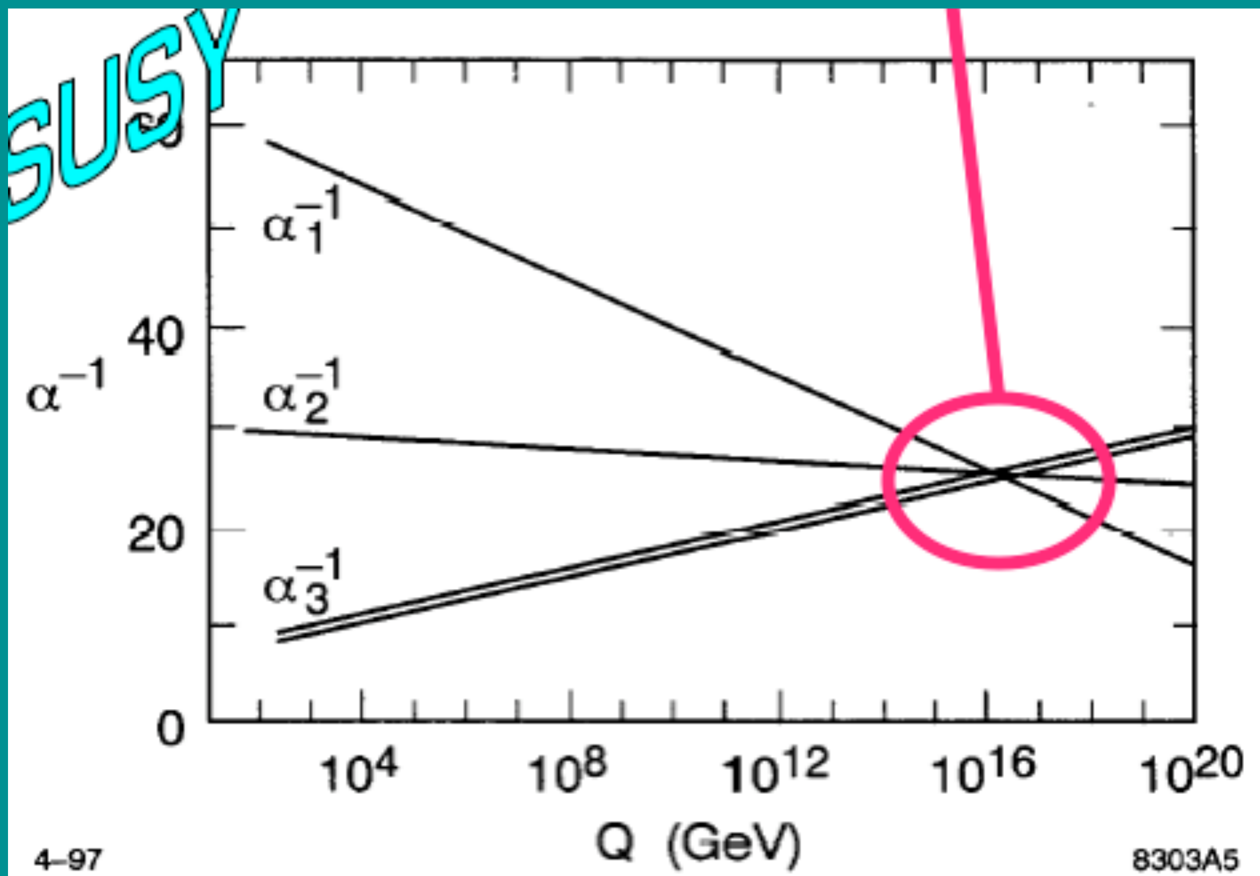
Thus, a fine-tuning is needed for the electron mass. What is the solution?

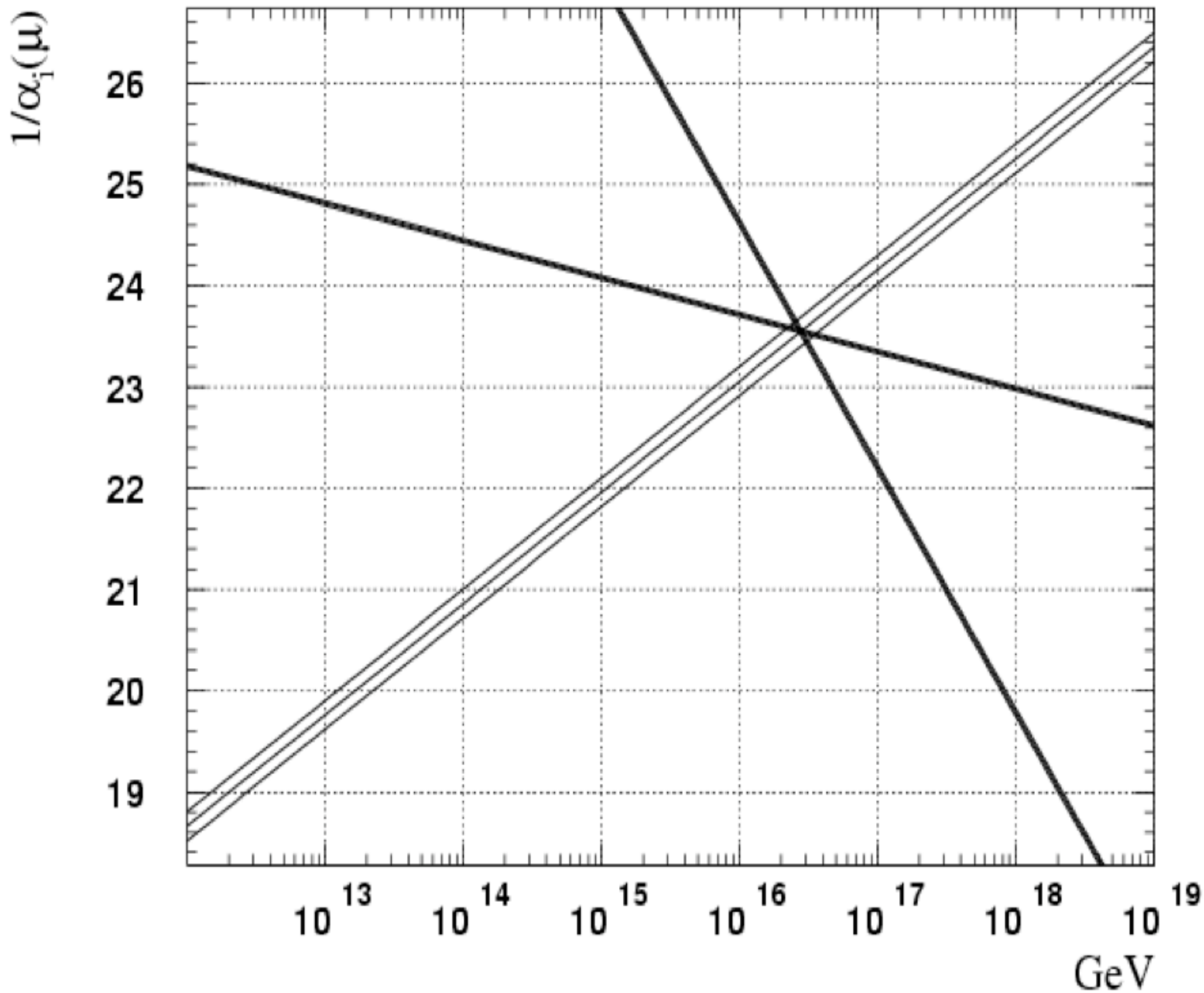
ANTIMATTER! The E-field around the electron can fluctuate into electrons and positrons, and one can't distinguish between the new electron and the original, so the effective size is spread out. The "linear divergence" turns into a logarithmic divergence, solving the fine-tuning.

So: doubling the particle spectrum solves a fine-tuning problem.

Another motivation for SUSY




SUSY
α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
40
20
0
10^4
10^8
10^{12}
10^{16}
10^{20}
Q (GeV)
4–97
8303A5


$1/\alpha_i(\mu)$
26
25
24
23
22
21
20
19
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
GeV

Breaking SUSY

If you multiply the defining relation of SUSY by γ_o and take a trace, one gets $H = (1/4)Q_\alpha Q^\alpha$. Since the Q's annihilate the vacuum, one concludes that a supersymmetric vacuum has zero energy (first theory to specify the zero of energy). Also, a non-supersymmetric ground state has positive energy.

This is very different that breaking a gauge symmetry. There, the vacuum value of a scalar is nonzero. Here, the value of the vacuum energy is the key. If it is nonzero, SUSY is broken, independent of the vacuum value of a scalar.

Facts about global susy (stated without proof). One can introduce a “superpotential”, W, which is at most CUBIC in the fields and depends on fields and not their conjugates. If scalar fields are ϕ and their fermionic partners are ψ, then the Yukawa terms are

$$(\partial^2 W / \partial \phi_i \partial \phi_j) \psi^i \psi^j$$

and there are two contributions to the scalar potential:

F-terms: $V_F = \Sigma \left| \partial W / \partial \phi \right|^2$

D-terms: $V_D = (1/2) \Sigma_a \left| \Sigma_I (g_a \phi^*_I T^a \phi_I) \right|^2$

If either of these two contributions is nonzero in the vacuum, then SUSY is broken

For example: $V_F = \Sigma \,|\, \partial W / \partial \phi|^2$

Suppose there are fields A,X,Y and a superpotential is $W = g\,A\,Y + h\,X\,(A^2 - M^2)$

Then $V = g^2|A|^2 + h^2|A^2-M^2|^2 + |gY+2hAX|^2$

This can never be zero, so SUSY is broken.

This might work, but alas, one can prove that if SUSY at the electroweak scale is spontaneously broken, there will have to be a charged scalar lighter than the electron. There isn't.

Instead, SUSY is broken explicitly. If you add DIMENSIONFUL terms to the Lagrangian, the cancellations of SUSY are not affected. So just add mass terms for all of the squarks, sleptons, gauginos….

This is extremely ugly, and people didn't like it for a while. But then it was discovered that these mass terms automatically arise in the low-energy limit of spontaneously broken supergravity models. They also arise from the low-energy limit of superstring theory.

The Minimal Supersymmetric Standard Model (MSSM)

Since the superpotential contains fields, and not their conjugates, one must have two Higgs doublets to give mass to all of the fermions, H_1 and H_2. Two complex doublets --> 8 fields, three get eaten, five remain, a charged scalar, a pseudoscalar and two scalars. There is thus a charged Higgsino and two neutral Higgsinos.

The superpotential involving Higgs is simple:

$W = \mu\, H_1\, H_2$ + standard Yukawa couplings.

Fermions and sfermions

quarks and squarks

leptons and sleptons

gauge bosons and gauginos

W boson and wino

gluon and gluino

B boson and bino

Higgs bosons and higgsinos

particle	sparticle	$SU(3)_c$	$SU(2)_w$	$U(1)_Y$
$\begin{pmatrix} u \\ d \end{pmatrix}_i$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_i$	3	2	$\frac{1}{6}$
u_i^c	$\tilde{u}_i^c$	$\bar{3}$	1	$-\frac{2}{3}$
d_i^c	$\tilde{d}_i^c$	$\bar{3}$	1	$\frac{1}{3}$
$\begin{pmatrix} \nu \\ e \end{pmatrix}_i$	$\begin{pmatrix} \tilde{\nu} \\ \tilde{e} \end{pmatrix}_i$	1	2	$-\frac{1}{2}$
e_i^c	$\tilde{e}_i^c$	1	1	1
W	$\tilde{W}$	1	3	0
g	$\tilde{g}$	8	1	0
B	$\tilde{B}$	1	1	0
$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}$	1	2	$\frac{1}{2}$
$\begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$	$\begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}$	1	2	$-\frac{1}{2}$

Neutralinos!

In the MSSM, it is assumed that there is an R-parity, which is -1 for SUSY partners and +1 for “regular” fields. This is needed to avoid rapid proton decay.

Thus SUSY particles are always made in pairs, and the lightest is stable (the leading dark matter candidate).

In general, the masses are all arbitrary, however, some reasonable assumptions reduce the parameter-space.

The fact that there are very strong constraints on FCNC and atomic parity violation in nuclei implies that the masses of the five lightest squarks are the same (this automatically occurs in supergravity models, anyway).

It is also assumed that gaugino masses (gluino, wino, bino) are identical at a high scale (true in all GUTs), and thus scale like the couplings.

Finally, there is a parameter called the “A” parameter that involves couplings of squarks to higgsinos.

Total: 5 free parameters. (Squark/slepton mass, gaugino mass, A, the ratio of vacuum values ($\tan\beta$) and μ. All masses, couplings, etc. follow from these. Many, many analyses of this parameter space. It can be messy--the mass matrix for the wino, bino and two Higgsinos is a 4x4 matrix, for example.

- Neutralinos are an excellent dark matter candidate!
- The lightest one may be a stable WIMP with $\Omega_\chi h^2 \approx \Omega_{DM} h^2$

$$(\tilde{W}^3, \tilde{B}, \tilde{H}_1^0, \tilde{H}_2^0) \begin{pmatrix} M_2 & 0 & \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_2 v_2}{\sqrt{2}} \\ 0 & M_1 & \frac{g_1 v_1}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} \\ \frac{-g_2 v_1}{\sqrt{2}} & \frac{g_1 v_1}{\sqrt{2}} & 0 & -\mu \\ \frac{g_2 v_2}{\sqrt{2}} & \frac{-g_1 v_2}{\sqrt{2}} & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{W}^3 \\ \tilde{B} \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix}$$

$$\chi = \alpha \tilde{B} + \beta \tilde{W}^3 + \gamma \tilde{H}_1 + \delta \tilde{H}_2$$

Note: Properties of neutralino LSP will depend on its composition!

Recall that: F-terms: $V_F = \Sigma \left| \partial W / \partial \phi \right|^2$

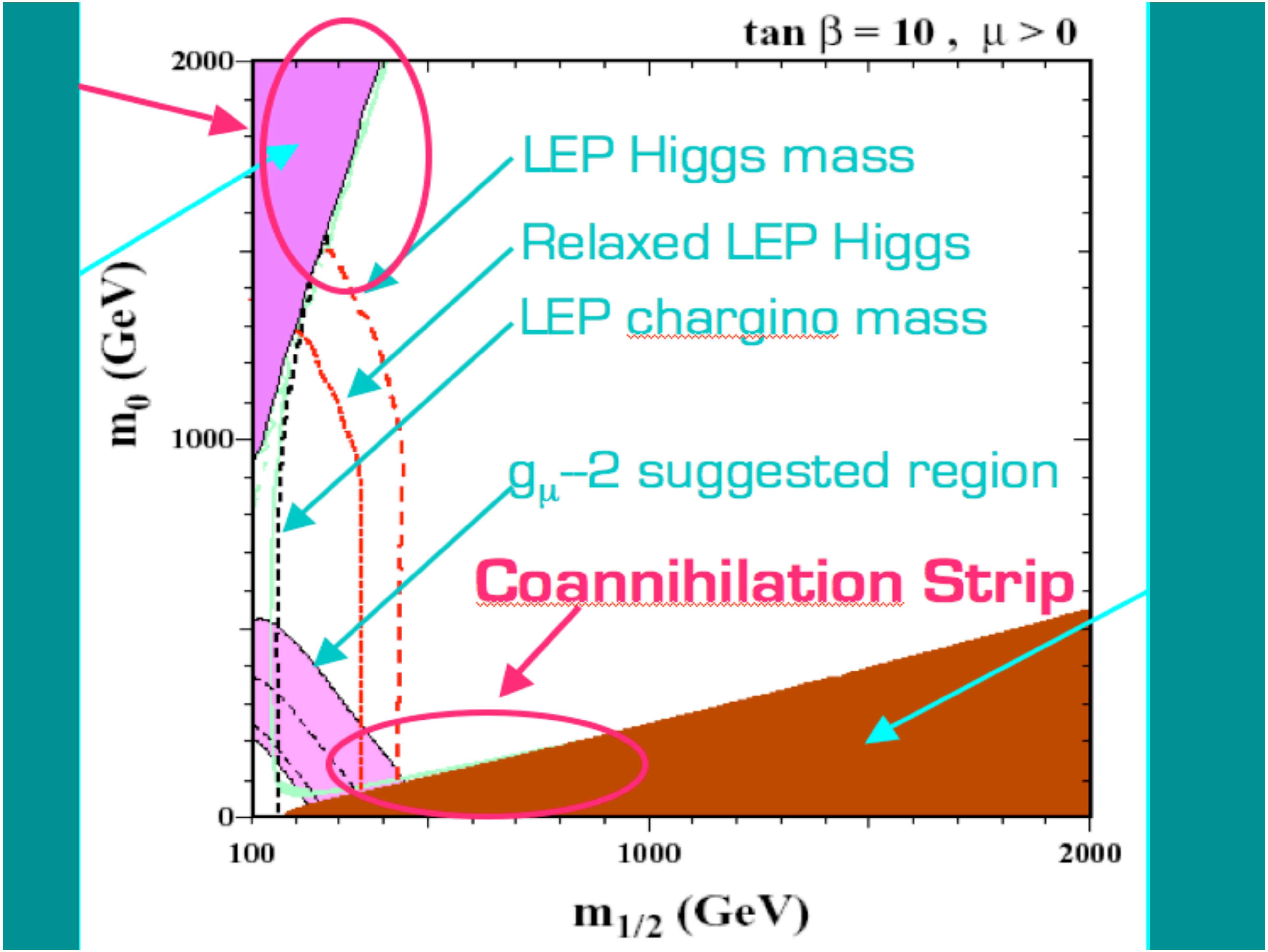
The superpotential has no terms involving three Higgs fields, since three doublets don't make a singlet. So its derivative has no quadratic terms, and the square has no quartic terms. So the quartic terms in the potential are COMPLETELY determined by gauge couplings.

To leading order, one finds that the lightest Higgs boson must be lighter than the Z. One-loop corrections (due to heavy top/stop loops) raise this bound to 130 GeV.

If a Higgs is not found below about 130 GeV, the MSSM is dead. Most extensions can raise this to about 140-150, but not much more.

Most papers contain plots of the squark/slepton mass parameter (m_o) vs. the gaugino mass parameter ($m_{1/2}$) for various value of A (which turns out to matter very little), $\tan\beta$ and the sign of μ.

Typical plot:



tan β = 10 , μ > 0
LEP Higgs mass
Relaxed LEP Higgs
LEP chargino mass
g_μ–2 suggested region
Coannihilation Strip
2000
1000
0
100
1000
2000
m_0 (GeV)
$m_{1/2}$ (GeV)

Experimental Searches

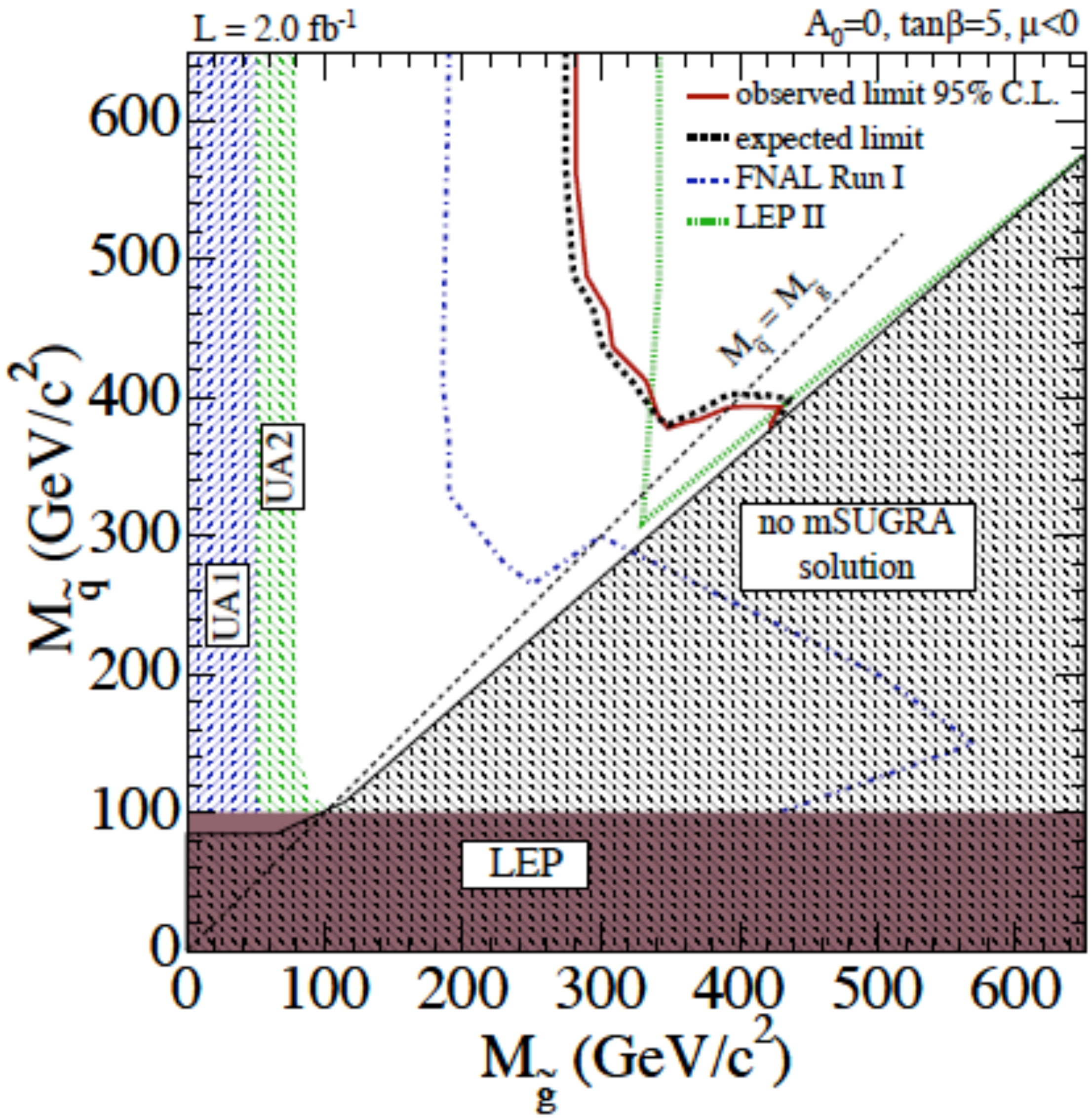
Key signature (assuming R-parity) is that the LSP will leave the detector. Get missing energy. For example, at an e^+e^- collider, one could have

$$e^+e^- \to \gamma, Z \to \tilde{L}^+\tilde{L}^- \to L^+L^- + \mathrm{LSP} + \mathrm{LSP}$$

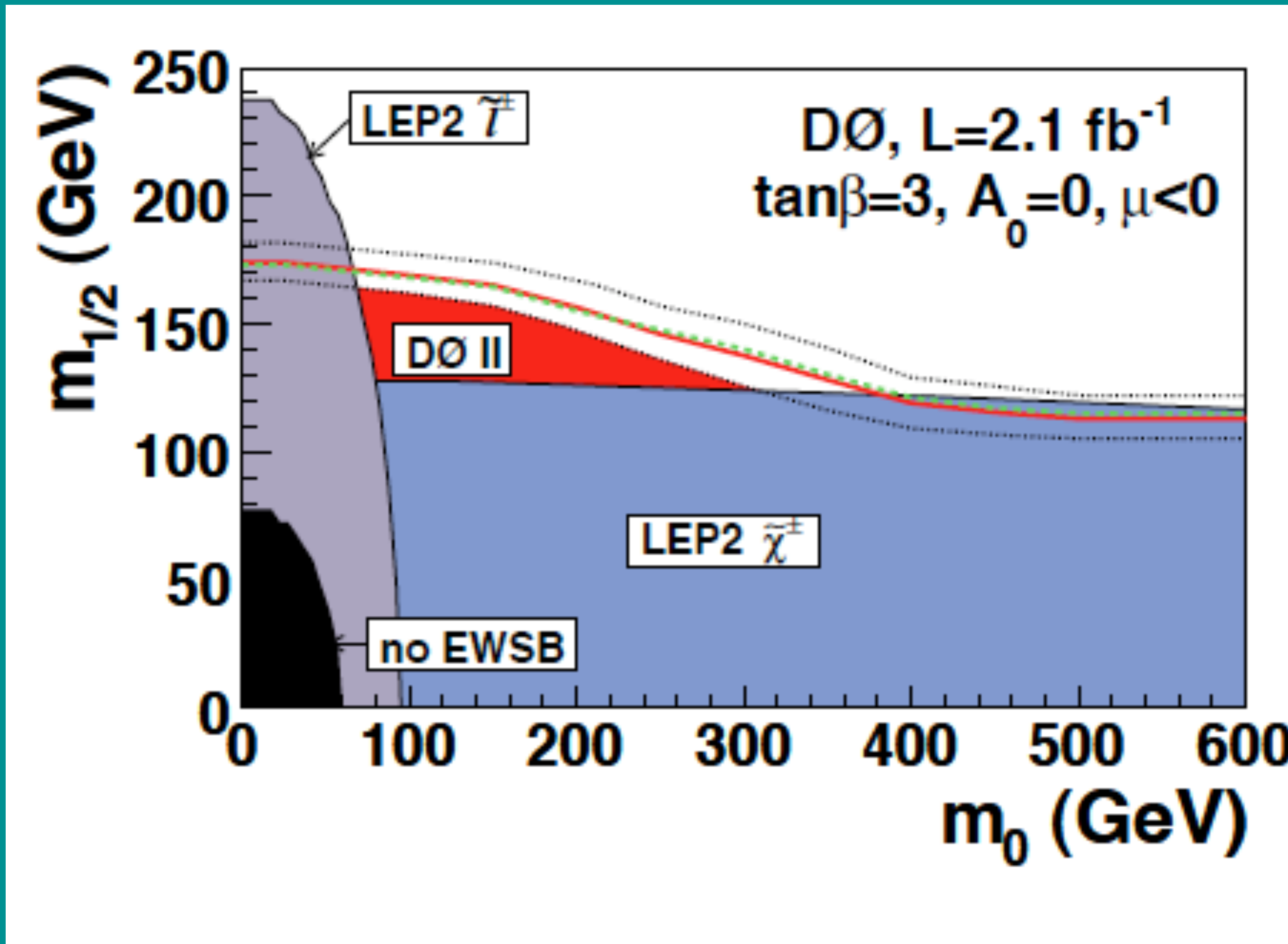
leading to a lepton pair plus missing energy. Same for squarks. Missing energy is the key to most SUSY searches, but there can be very, very long chains of decays. Analysis is very complicated.

- $\tilde{q}\tilde{\bar{q}} \longrightarrow q\tilde{N}_1^0\bar{q}\tilde{N}_1^0 \longrightarrow$ 2 jets + Missing energy
- $\tilde{q}\tilde{\bar{q}} \longrightarrow q\tilde{N}_2^0\bar{q}\tilde{N}_1^0 \longrightarrow q\tilde{N}_1^0\ell\bar{\ell}\bar{q}\tilde{N}_1^0 \longrightarrow$ 2 jets + 2 leptons + Missing energy

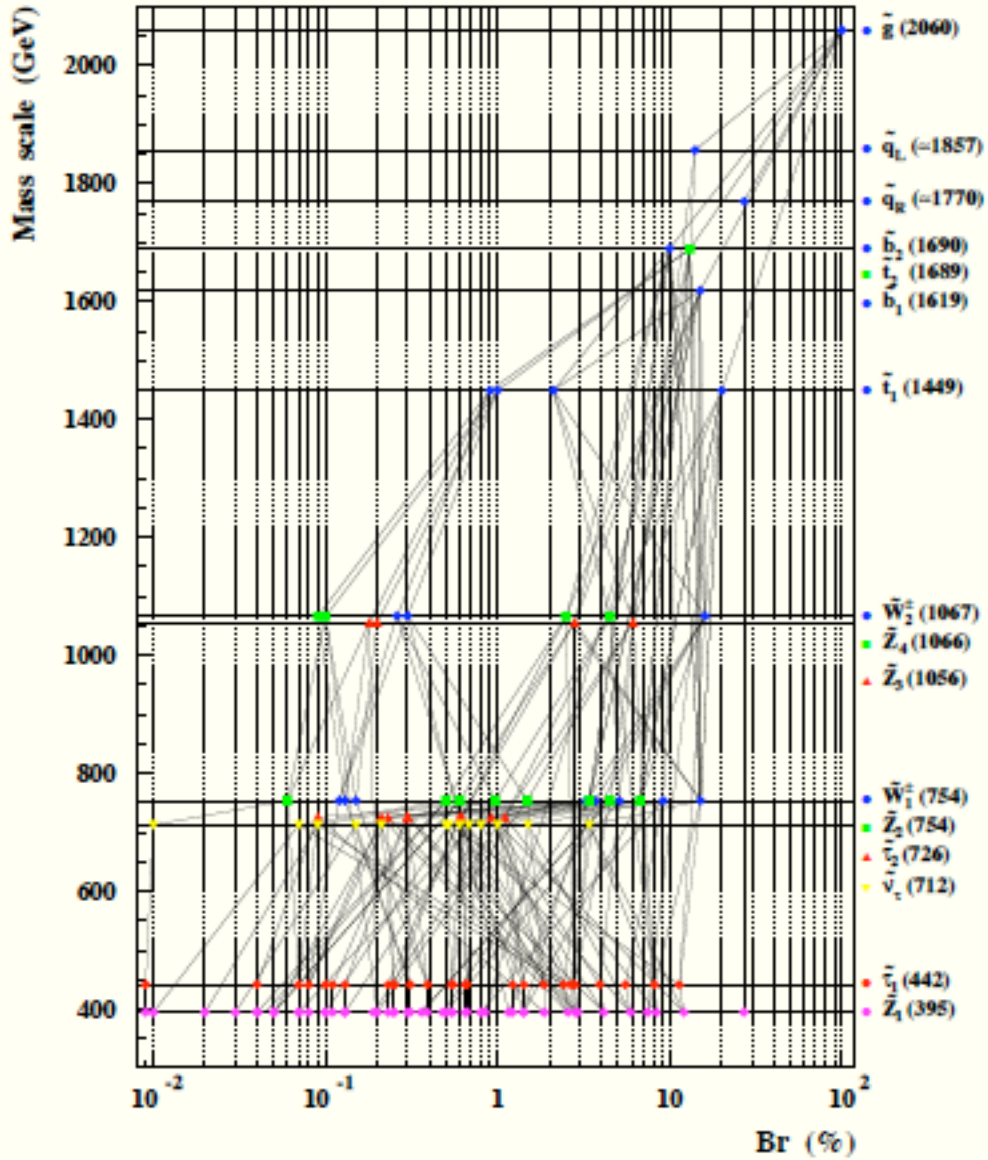
- $\tilde{g}\tilde{g} \rightarrow (\bar{q}\tilde{q})(\bar{q}\tilde{q}) \rightarrow (q\bar{q}\tilde{C}_1^+)(q\bar{q}\tilde{C}_1^+) \rightarrow (q\bar{q}W^+)(q\bar{q}W^+) \rightarrow$ 4 jets+ $\ell^+\ell^+$ + Missing energy



L = 2.0 fb^{-1}
A_0=0, tanβ=5, μ<0
observed limit 95% C.L.
expected limit
FNAL Run I
LEP II
UA1
UA2
$M_{\tilde{q}} = M_{\tilde{g}}$
no mSUGRA solution
LEP
$M_{\tilde{q}}$ (GeV/c^2)
$M_{\tilde{g}}$ (GeV/c^2)
0
100
200
300
400
500
600

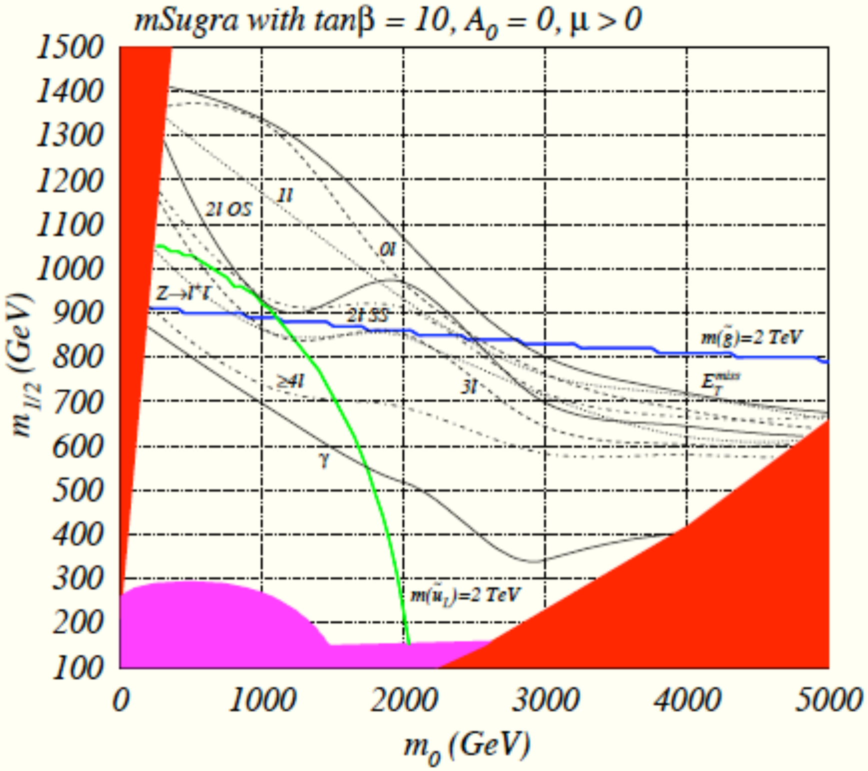


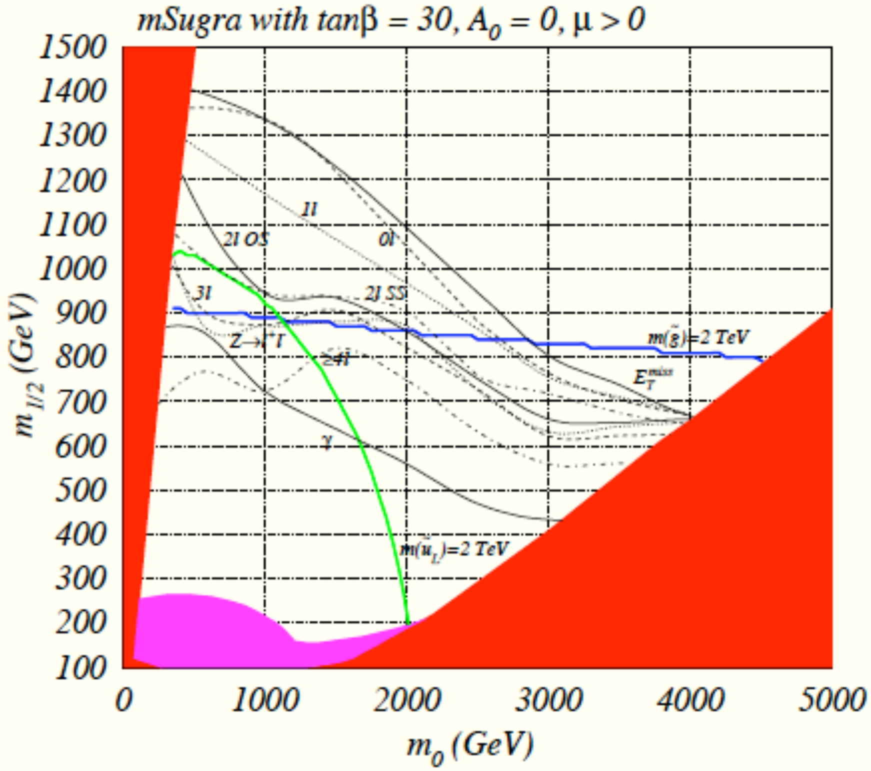
$m_{1/2}$ (GeV)
250
200
150
100
50
0
0
100
200
300
400
500
600
m_0 (GeV)
LEP2 $\tilde{l}^{\pm}$
DØ, L=2.1 fb^{-1}
tanβ=3, A_0=0, μ<0
DØ II
LEP2 $\tilde{\chi}^{\pm}$
no EWSB



$\tilde{Z}_1$ qq	(27.0 %)	$\tilde{Z}_1$ τνWWWbb	(4.1 %)
$\tilde{Z}_1$ τνWbb	(12.1 %)	$\tilde{Z}_1$ ττbb	(2.9 %)
$\tilde{Z}_1$ ττWWbb	(8.4 %)	$\tilde{Z}_1$ ττqq	(2.9 %)
$\tilde{Z}_1$ WWbb	(7.4 %)	$\tilde{Z}_1$ τνZWbb	(2.8 %)
$\tilde{Z}_1$ τνqq	(5.9 %)	$\tilde{Z}_1$ τνhWbb	(2.6 %)

Sparticle reach of LHC for 100^{-1} fb





SUSY summary

- Completely solves the hierarchy problem.
- Gives unification of couplings to very high accuracy.
- Provides an automatic dark matter candidate.
- Is a necessary ingredient in string theory.
- Leads to extraordinary signatures, mostly involving missing energy events.
- Can be ruled out---there must be a light Higgs, below 130 GeV in the simplest model, below 150 GeV in more complicated models.

Alternative solutions to the gauge hierarchy problem

- Technicolor
- Warped Extra Dimensions

- Will also discuss extra Z bosons (not relevant for hierarchy problem).

Technicolor

- Invented in the late 70's
- Gets rid of elementary scalars.

Basic idea: the "higgs" is a bound state of elementary "technifermions", bound together by a new force, called technicolor.

Suppose there is no Higgs boson. Would the W and Z be completely massless?

Surprising answer: No. The reason is QCD. We know that massless QCD has (two quarks) an $SU(2)_L \times SU(2)_R$ chiral symmetry.

When the interaction becomes strong, the quarks condense, so $\langle \bar{q}_L q_R \rangle$ acquires a nonzero value in the ground state. The breaking of the chiral symmetry down to a diagonal SU(2) (isospin), results in three Goldstone bosons, aka pions. Pion masses arise because the quark masses aren't exactly zero.

But $\langle \bar{q}_L q_R \rangle$ also breaks the electroweak symmetry because the left-handed quarks are doublets and the right-handed quarks are singlets. Thus, the W and Z get small masses.

Straightforward to show that $M_W = M_z \cos\theta_W = (3/4)^{1/2} g\, f_\pi$ Numerically, this is 50 MeV. Too small, although the Z to W mass ratio is ok.

So, suppose there is a new force with new quarks, which is just like QCD but with a scale that is 1600 times bigger. Then a similar condensation will give the right W and Z masses.

Choose a new group SU(N_{TC}) whose coupling becomes strong at Λ_{TC} = hundreds of GeV. Let techniquarks be left-handed doublets (under isospin) and right-handed singlets. When α_{TC} becomes strong, the techniquarks chiral symmetry is broken, Goldstone bosons appear which become the longitudinal components of the W and Z. Masses all work out fine. No hierarchy problem, no "elementary scalar" problem, no vacuum stability constraints, easy to explain the scale by asymptotic freedom.

Alas, also no fermion masses.

In the standard model, fermions get mass from a Yukawa term, $\bar{\psi}\,\psi\,\phi$. In technicolor, there is no Higgs, so the masses must arise from a $\bar{\psi}\,\psi\,\bar{\Psi}\,\Psi$ term, with the latter two fields being techniquarks.

But this term doesn't arise just from the technicolor group, so one must introduce a new interaction, ETC (extended technicolor), which connect regular quarks to techniquarks.

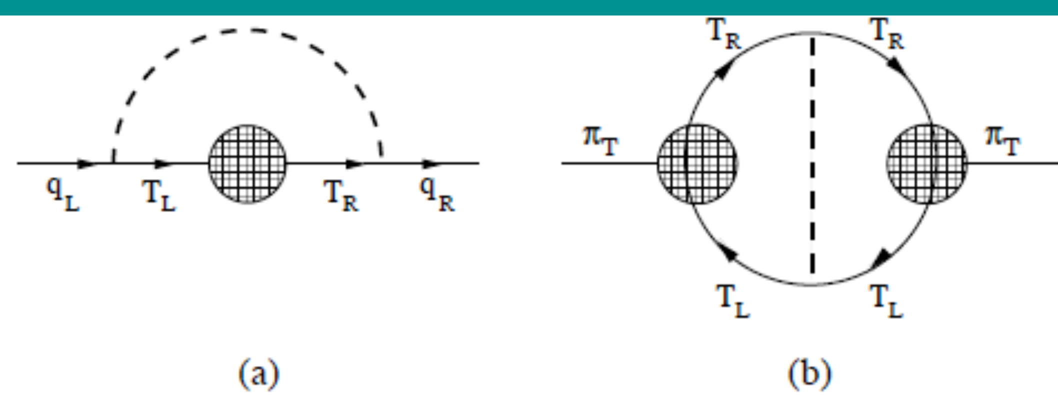


Figure 1: *Graphs for ETC generation of masses for (a) quarks and leptons and (b) technipions. The dashed line is a massive ETC gauge boson. Higher–order technicolor gluon exchanges are not indicated; from Ref. [15].*

This works, and gives mass to fermions which is of the order of $(g_{ETC}/M_{ETC})^2 <\Psi_L \Psi_R>_{ETC}$

Many papers about the phenomenology of these models. One expects many new states at LHC energies. The most interesting developments (theoretically) have been due to the realization that the dynamics of Technicolor do NOT have to be identical to a scaled up QCD. The group doesn't have to be SU(N). Thus there is a lot of new strong interaction physics to be explored.

Unfortunately, there are a few serious problems with Technicolor models, and these are severe enough that MOST physicists have given up on it.

Problems with Technicolor

1. Flavor changing Neutral Currents.
$$\mathcal{H}'_{|\Delta S|=2} = \frac{g^2_{ETC} V^2_{ds}}{M^2_{ETC}} \, \bar{d}\,\Gamma^\mu s \, \bar{d}\,\Gamma'_\mu s + \mathrm{h.c.}$$
   This gives K-Kbar mixing at too big a rate, unless M_{ETC} is very large. But then the quark and lepton masses are 10-1000 times too small.
2. Precision electroweak measurements. Can be characterized by a parameter S, experimental value is -0.07 +/- 0.11. In Technicolor, it is 0.25 times $N_{TC}/3$.
3. The quark masses scale as $1/M_{ETC}$, and for the top mass to be as big as observed, M_{ETC} must be very low, close to the TC scale. This is inconsistent with other fermion masses.

Solutions

- Stop assuming that TC is just scaled-up QCD. It turns out that if one has the gauge coupling, α_{TC}, running VERY slowly, then one gets a different dynamics if it remains strong up to the ETC scale. This is called “walking technicolor”. This can solve the FCNC and S-parameter problems. With new dynamics “topcolor” for the top quark, the top mass can be explained as well.
- Many feel that there are too many epicycles, but nonetheless, this is still a possible alternative (which has much more interesting strong interaction dynamics) to the Higgs mechanism.

Extra Dimensions

Basic idea: Suppose there is an extra dimension of space, x_5, but it is curled up, with a small radius R. Then any function must be periodic in x_5. Thus it can be Fourier-expanded. The zero mode is independent of x_5, the higher modes have wavelengths R/n, or energies n/R. If R is smaller than an inverse TeV, we would not have seen them.

These higher modes are called KK modes (for Kaluza and Klein).

Several versions:

1. If standard model particles are confined to our 4 dimensions, then only gravity propagates in the extra dimension(s). From Gauss' Law, the gravitational force in n extra dimensions scales like $1/r^{n+2}$. As one increases the energy scale, the interaction then grows like E^{n+2}. Becomes strong MUCH more quickly, and the Planck scale can be much, much lower. "Solves" hierarchy problem. Need at least 2 extra dimensions, and then the size is microns or smaller. Hard to test. Also don't explain the size of the extra dimension.

2. Universal extra dimensions. Everything propagates in the extra dimensions, so they must be smaller than a few inverse TeV. Turns out that models require KK states to be produced in pairs. This means that the lightest is stable (LKP) and is a dark matter candidate. However, these models don’t say anything about the hierarchy problem and are inconsistent with many grand unified theories.

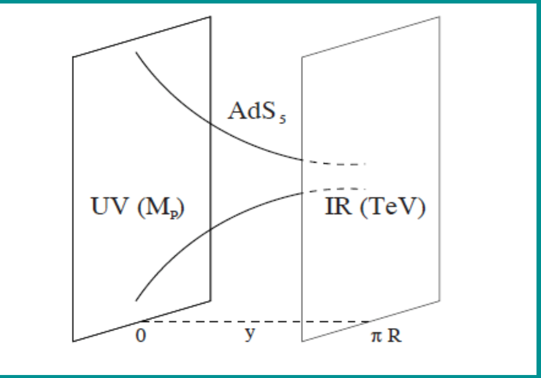
3. There are Higgsless models, in which the extra dimension is compactified on an "orbifold" (semicircle-- S_1/Z_2), so there are two 4-branes separated by a fifth dimension. One can arrange to break the symmetry by boundary conditions on the orbifold without a Higgs. These models tend to have severe problems with precision electroweak tests.
4. The most exciting and recent development concerns "warped extra dimensions", which completely solve the gauge hierarchy problem AND the fermion hierarchy problem

Warped Extra Dimensions

Setup: Compactify the fifth dimension on S_1/Z_2 (a semicircle) so the size is πR and there are two 4-branes. Assume that at any point in the 5D space, the 4D metric is flat and Lorentz-invariant. Further, require the 5D space to have a bulk cosmological constant (constant vacuum energy). There is only one metric that gives this (called AdS_5):

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}\, dx^\mu dx^\nu - dy^2$$

The factor $e^{-2k|y|}$ is called the "warp factor".



If one assumes that the Higgs is "stuck" on the TeV brane, then the hierarchy problem is solved. Here's how:

$S = \int d^5x \ (-\det(g))^{1/2} (\mathcal{L}_5 + [g^{\mu\nu} D_\mu H \, D_\nu H - V(H)] \, \delta(y-\pi R))$

where $V(H) = \lambda[(H^* H - v^2)^2]$

The determinant of the metric is $-e^{-8ky}$ and $g_{\mu\nu} = \eta_{\mu\nu} e^{-2ky}$

so the Higgs part becomes

$S_{higgs} = \int d^4x \, e^{-4\pi kR} [e^{+2\pi kR} \eta^{\mu\nu} D_\mu H \, D_\nu H - V(H)]$

Now, normalizing the fields so the coefficient of the kinetic term is unity, one gets

$S_{higgs} = \int d^4x \, [\eta^{\mu\nu} D_\mu H \, D_\nu H - \lambda \, (H^* H - v^2 e^{-2\pi kR})^2]$

So the effective v is $v \, e^{-\pi kR}$

k and R (in Planck units) are both O(1). Suppose kR = 12, then v is 10^{-16} times the Planck scale, and

THE HIERARCHY PROBLEM IS SOLVED.

Suppose fermions propagate in the 5th dimension. There is a single parameter for each fermion (5D Dirac mass). Solving equations of motion gives the 5D wavefunctions. If they overlap a lot with the TeV brane, they have a big Yukawa coupling. If they overlap a little, they have a small Yukawa coupling.

A small shift in the mass parameter makes a huge shift in the overlap, due to the exponential factor in $g_{\mu\nu}$

For example, a field with a mass parameter 0.7 will have a mass of 175 GeV, and a field with a mass parameter of 0.3 will have a mass of 0.0005 GeV.

FERMION MASS HIERARCHY PROBLEM IS SOLVED

- Problems?
- To avoid problems with precision EW tests, need to have the KK gauge bosons heavier than 3 TeV (not good news for LHC)
- But need to have an $SU(2)_R$ symmetry in the 5D space, and need to be very careful in placing the b and t quarks in the 5D space--somewhat unnatural.
- KK fermions can be below 1 TeV.
- There is no dark matter candidate.

Axions

In QED, the Lagrangian is $(-1/4)F^{\mu\nu}F_{\mu\nu}$. This is gauge invariant. But there is another gauge invariant term one can write down: $(-1/4)\varepsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}$.

The first is $E^2 + B^2$, the second is $E\cdot B$. Why don't we include this term? It turns out that it can be written as a total divergence. So, when integrating over the volume to get the action, it changes into a surface integrals (Stokes thm.) and since the fields vanish at infinity, this term makes no contribution.

But in QCD, there are solutions of the vacuum field equations that do NOT vanish at infinity, and thus this term can't be dropped. These solutions are called instantons.

For these solutions, when you integrate $(1/16\pi^2)\varepsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}$ over all space, you get an integer, n. Summing over all vacuum configurations gives the complete vacuum state $|\theta\rangle = \Sigma\, e^{in\theta}\,|n\rangle$.

The parameter θ is measurable and gives a new parameter of QCD. The Lagrangian term is then $(\theta/64\pi^2)\,\varepsilon^{\mu\nu\alpha\beta}G_{\mu\nu}G_{\alpha\beta}$, where G is the gluon field.

What does this new term do?

It violates CP !! This leads to a nonzero electric dipole moment for the neutron.

One note: The weak interactions violate CP as well, and can also give a contribution. The actual coefficient is not θ, but $\bar{\theta} = \theta$ + arg(det(M)), where M is the quark mass matrix. From here on, I will refer to θ, but will really mean θ + arg(det(M))

The current limit on the EDM of the neutron is around 10^{-24} e-cm, and that corresponds to $\theta < 10^{-11}$

STRONG CP PROBLEM: Why is θ so small? Especially given that it is composed of two terms which should both be O(1).

- Solution 1: Assume CP is a symmetry of the Lagrangian, and break this symmetry spontaneously. If one can do so while ensuring that the det(M) is real, problem is solved. These solutions are possible, but quite contrived.
- Solution 2: If there is a massless quark, then θ can be rotated away into the phase of the quark field. But lattice calculations have made it clear that the up and down quarks are not massless.
- Solution 3: The axion.

The axion

- In 1975, Peccei and Quinn noted that if one expands the Higgs sector, one can impose a new U(1) axial symmetry on the Lagrangian. This symmetry allows one to redefine the phases of the quark fields, and the θ parameter can be rotated away.
- E.g. In the SM, the Yukawa term ($\psi\ \psi\ \phi$) has a symmetry ψ --> exp(i $\alpha\gamma_{5)},\ \phi$ $-$$-$> exp($-2\alpha$). This is just part of the usual chiral symmetry. But if there are two Higgs doublets, one coupling to up-quarks and one to down quarks, then there can be independent rotations for each. One combination is the usual chiral symmetry, the other is new. The freedom to rotate the fermion phases allows one to set the θ parameter to zero. This works…..but

- Shortly thereafter, Weinberg and Wilczek noted that Goldstone's theorem says that when a global symmetry is spontaneously broken, there must be a massless pseudoscalar particle. In this case, it gets a small mass due to non-perturbative effects (roughly Λ^2/F_{PQ}, where F_{PQ} is the scale at which the symmetry is broken). This particle was called the axion.
- It was quickly realized that if F_{PQ} was of the electroweak scale, the axion would have been seen in K -->πa, so models where F_{PQ} is much larger were developed.
- It seems contrived, but in the past 20 years it has been realized that broken global symmetries are a ubiquitous feature of string theories and GUT models, and many models automatically have axions.
- Let us now look at its properties.

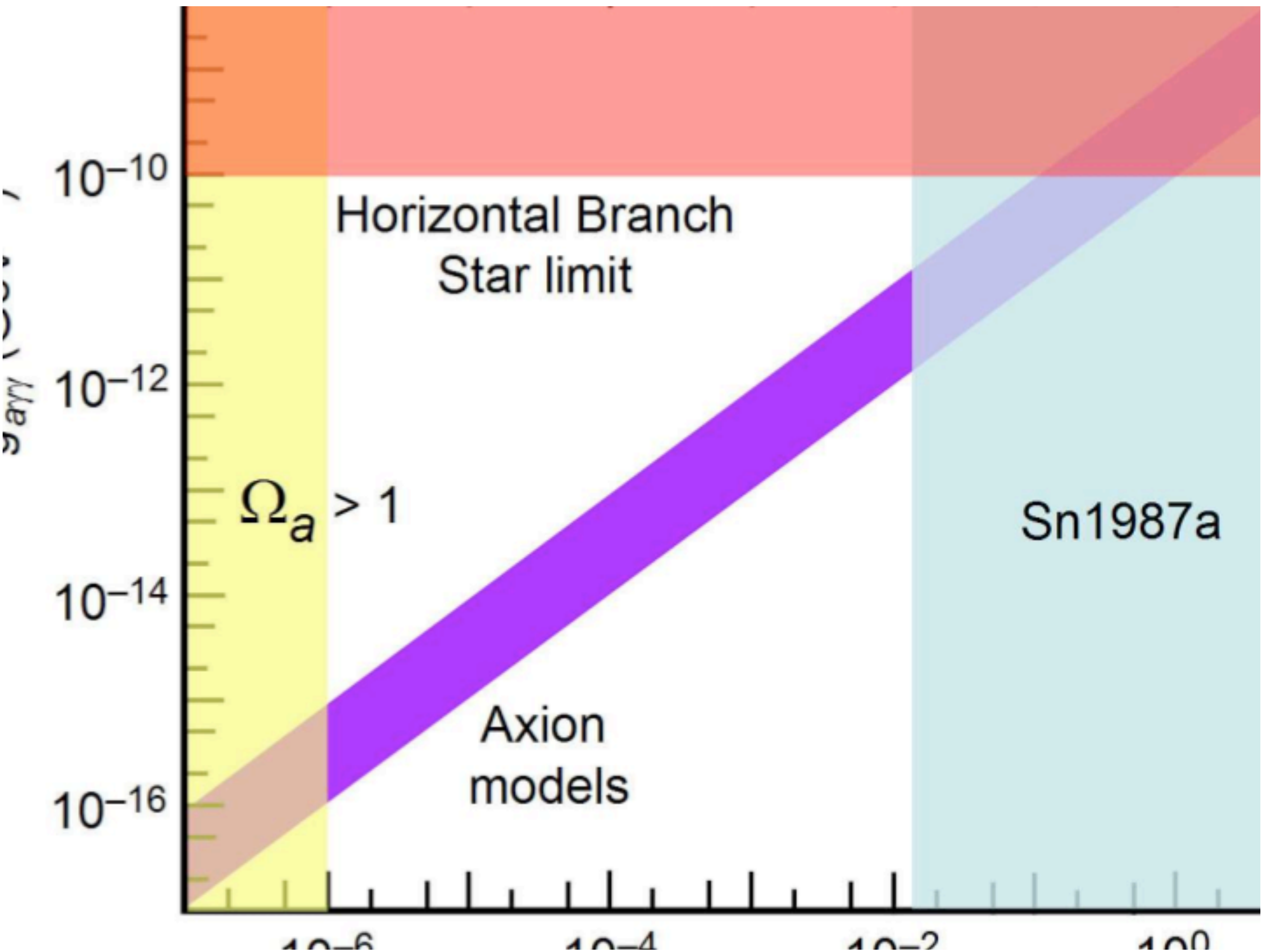
Axion mass and couplings

- There is a fairly weak model dependence. Roughly, the mass is 0.06 eV (10^8 GeV/F_{PQ}).
- The coupling to fermions is of the form $\partial_\mu a \, f \, \gamma^\mu \gamma_5 \, f$, with a coefficient of roughly m_f / F_{PQ}. In some models, the charges are such that the coupling to the electron is smaller by a factor of α.
- The coupling to photons is of the form a E·B, with a coefficient of α / F_{PQ}.

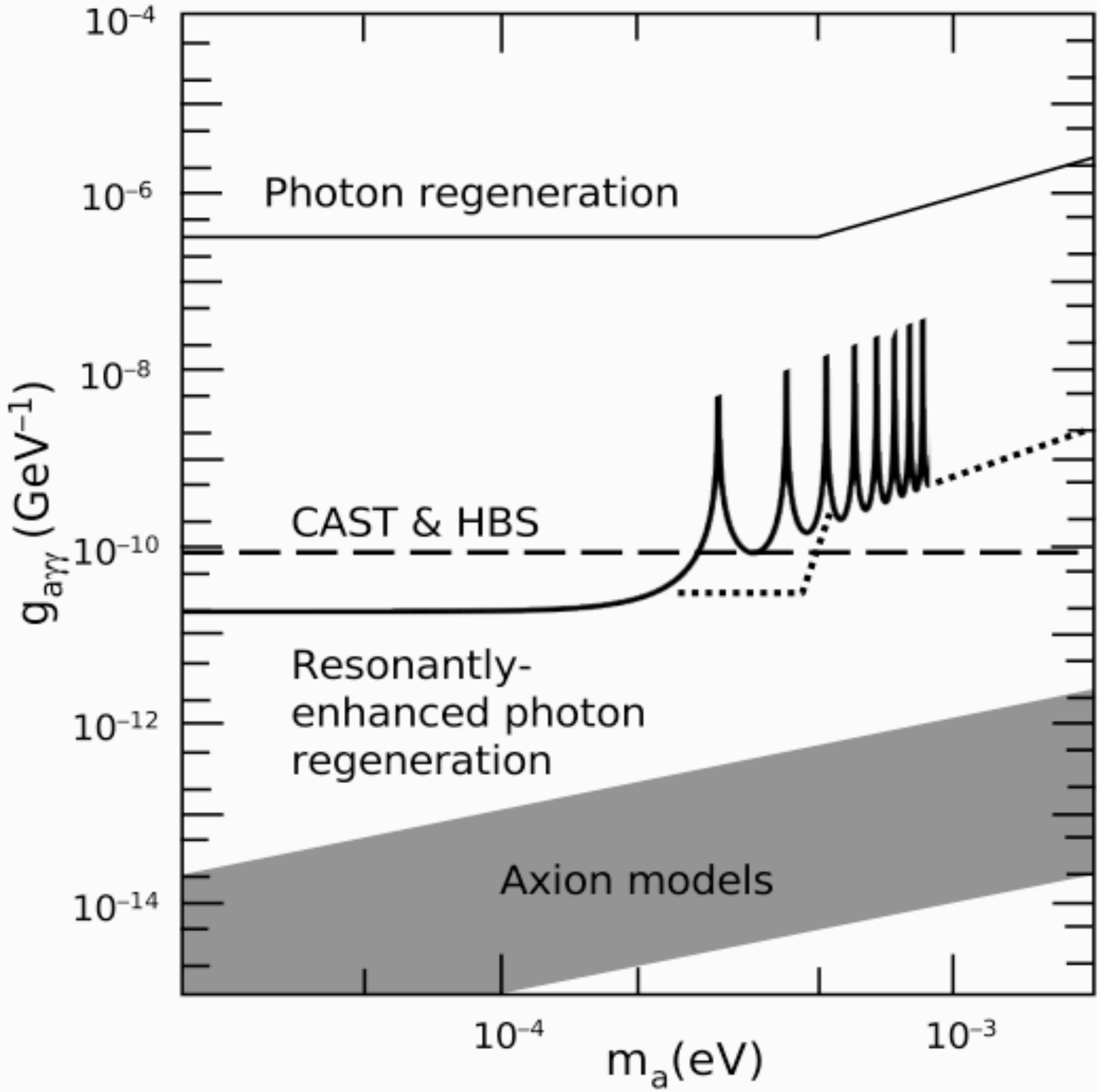
- What are current bounds?

- Stars have plenty of electrons and protons, and the axion is so light and weakly interacting that they can remove energy from the star, cooling it too much. This gives an upper bound on the coupling which gives an upper bound on the axion mass of 0.1 eV (roughly a lower bound on F_{PQ} of 10^8 GeV).
- SN 1987a had a core collapse that lasted 10 seconds. Axions would have made that go faster, so one gets a lower bound on F_{PQ} of 10^9 GeV.
- The cosmology of axions is very involved. It turns out that the current density of axions increases by a higher power of F_{PQ} than 1, so the energy density today in axions INCREASES as F_{PQ} increases, or as the mass decreases. This gives an UPPER bound on F_{PQ} of $10^{11\text{-}12}$ GeV. If that bound is saturated, axions are the dark matter. Note that this bound is midway between the weak and Planck scales.

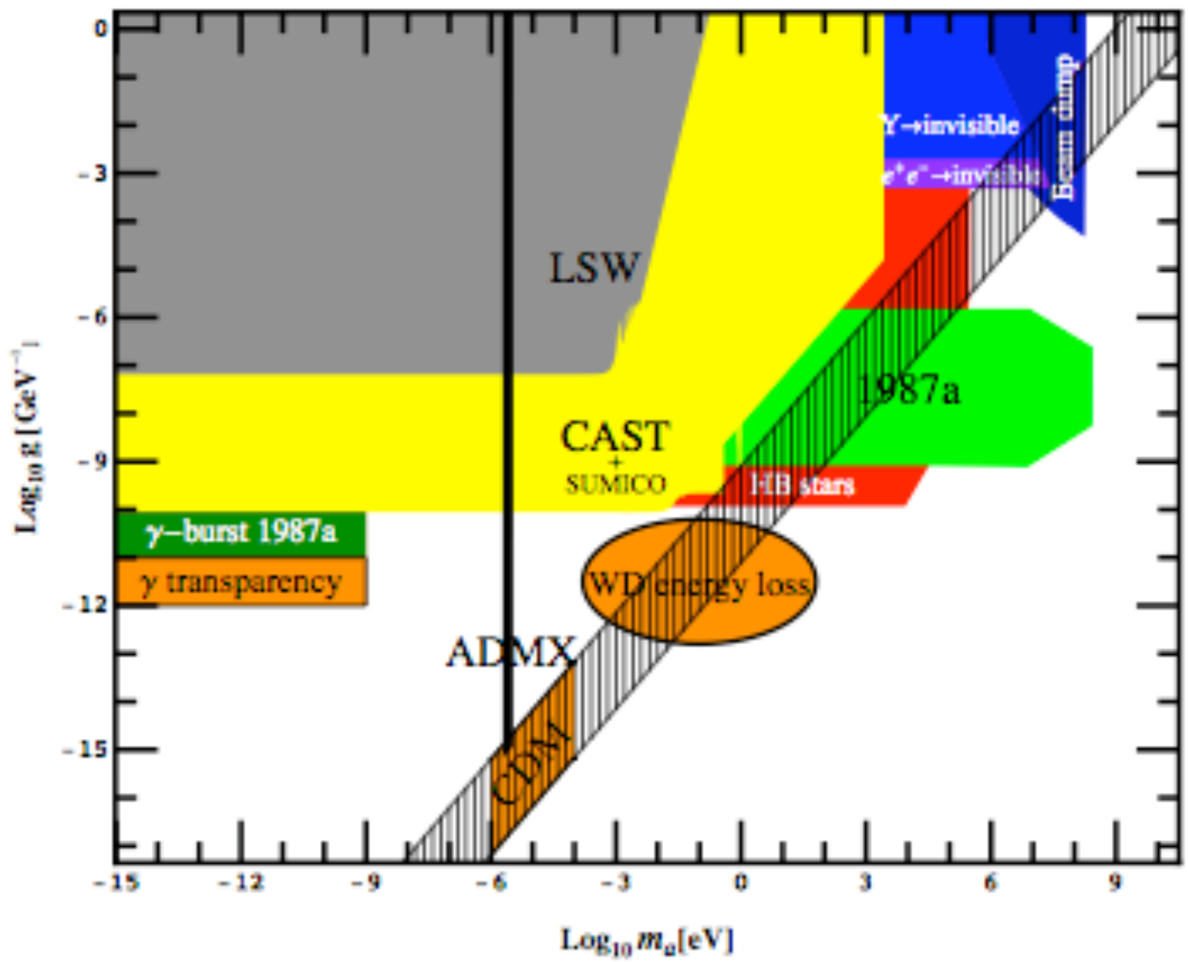
- Searches in the laboratory. Most use the E·B coupling of the axion. If one has a strong magnetic field, an axion entering the field can convert to a photon. The energy of the photon is the same as the axion mass, and a resonant cavity can amplify the signal. Experimenters have looked at axions from the Sun (corresponding to F_{PQ} of 10^9 GeV), there are resonant cavity experiments. Recently, experiments made axions in a high intensity E-field (with a B field present), send them through a wall and look for photons on the other side. No success yet. But it is tough. The Q-value of the axion signal is 10^6, so one must be right on resonance to detect them, and there are orders of magnitude to cover.



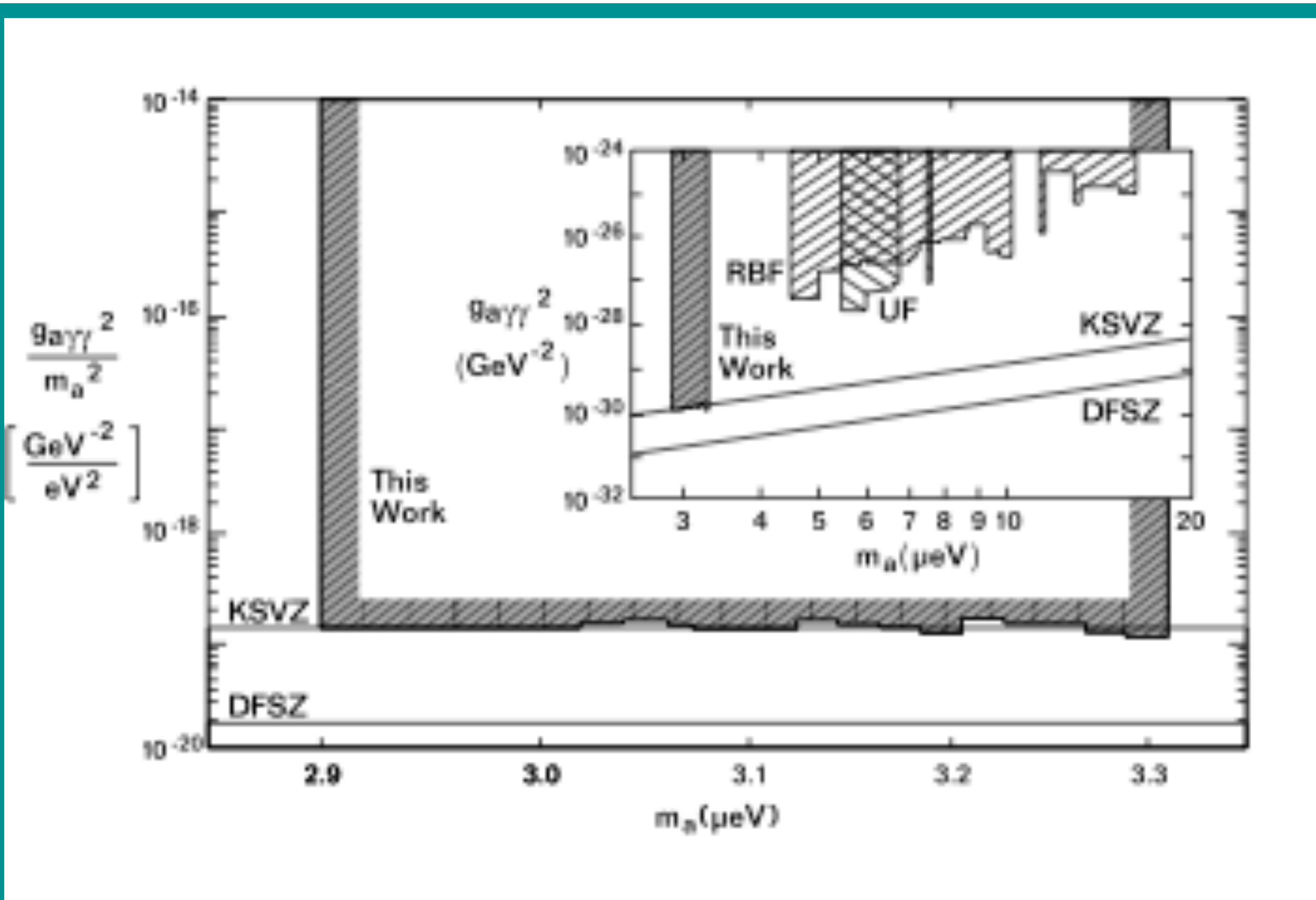
10^{-10}
10^{-12}
10^{-14}
10^{-16}
Horizontal Branch
Star limit
$\Omega_a > 1$
Sn1987a
Axion
models



10^{-4}
10^{-6}
Photon regeneration
10^{-8}
CAST & HBS
10^{-10}
$g_{a\gamma\gamma}$ (GeV^{-1})
Resonantly-
enhanced photon
regeneration
10^{-12}
Axion models
10^{-14}
10^{-4}
10^{-3}
m_a(eV)



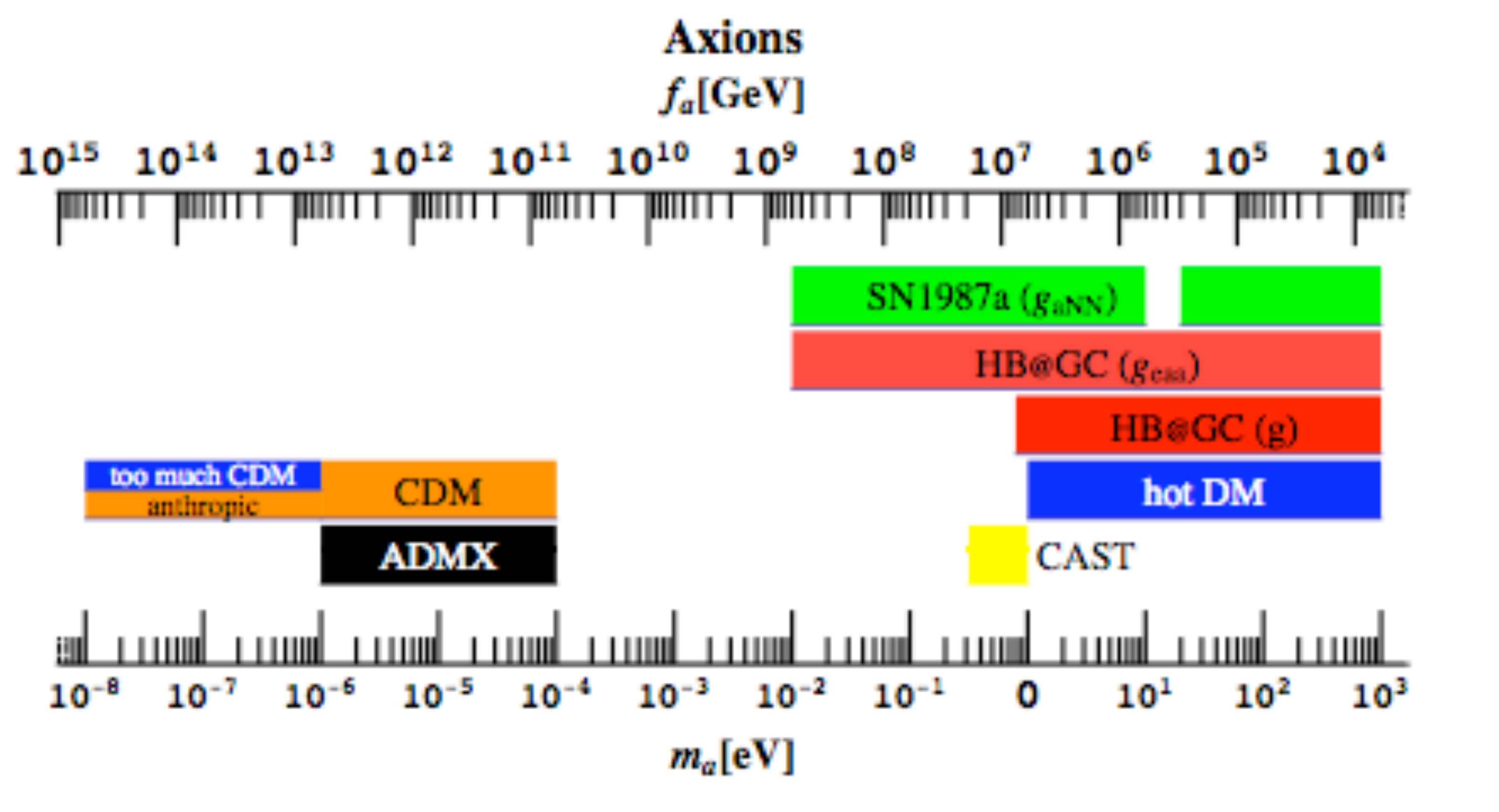
LSW
CAST
+
SUMICO
γ−burst 1987a
γ transparency
ADMX
CDM
WD energy loss
HB stars
1987a
Υ→invisible
e⁺e⁻→invisible
Beam dump
0
-3
-6
-9
-12
-15
-15
-12
-9
-6
-3
0
3
6
9
Log10 g [GeV⁻¹]
Log10 ma[eV]



Typical Power in Microwave Cavity :

10^{-26} Watts

Finally, experiments in the lab are barely reaching the Interesting region. Photon regeneration experiments will not for the foreseeable future.



Axions
f_a[GeV]
10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4}
SN1987a (g_{aNN})
HB@GC (g_{eea})
HB@GC (g)
too much CDM
anthropic
CDM
hot DM
ADMX
CAST
10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 0 10^{1} 10^{2} 10^{3}
m_a[eV]

Z-primes

- Many, many models have extra Z’s.
- GUTs with neutrino masses (SO(10) or E6) all contain one or two extra Z’s, with very specific quantum numbers.
- Extra dimension models have extra Z’s.
- Almost all extensions of the MSSM contain extra Z’s.

A general analysis of extra Z's is very complicated. In principle, the quantum numbers of the fermions under the extra U(1) are completely arbitrary. But the most popular models do specify these quantum numbers.

Two issues which don't directly involve fermions:

1. The gauge boson mass matrix involving the Z and the Z´ will be a 2x2 matrix, with M_Z^2 and $M_{Z'}^2$ on the diagonal and Δ^2 on the off-diagonal. These depend on coupling constants and vacuum values. In the limit that the Z´ mass is much heavier, one gets the smallest eigenvalue: $M_1^2 = M_Z^2 - \Delta^4/M_{Z'}^2$. The mixing angle is then $\Delta^2/M_{Z'}^2$. We measure M_1, of course, so the effect is to change the value of the weak mixing angle, $\sin^2\theta_W$. This can't change by more than .001 or so (and even less if fermion interactions are specified).

2. In general, one can have kinetic mixing:

$$(-1/4)[\, F^1_{\mu\nu} F^{1\mu\nu} + F^2_{\mu\nu} F^{2\mu\nu} + \chi F^1_{\mu\nu} F^{2\mu\nu}]$$

When dealing with Z and Z', this extra term has only a second order effect on M_1 and θ, and can be neglected. However, it does affect interactions of the Z'. One can, in general, have mixing with the photon, and this happens in hidden sector models. This can result in microcharged particles.

To bound extra Z's, we need to examine precision electroweak measurements.

To examine a particular model, one must look at fermion assignments. Most popular are:

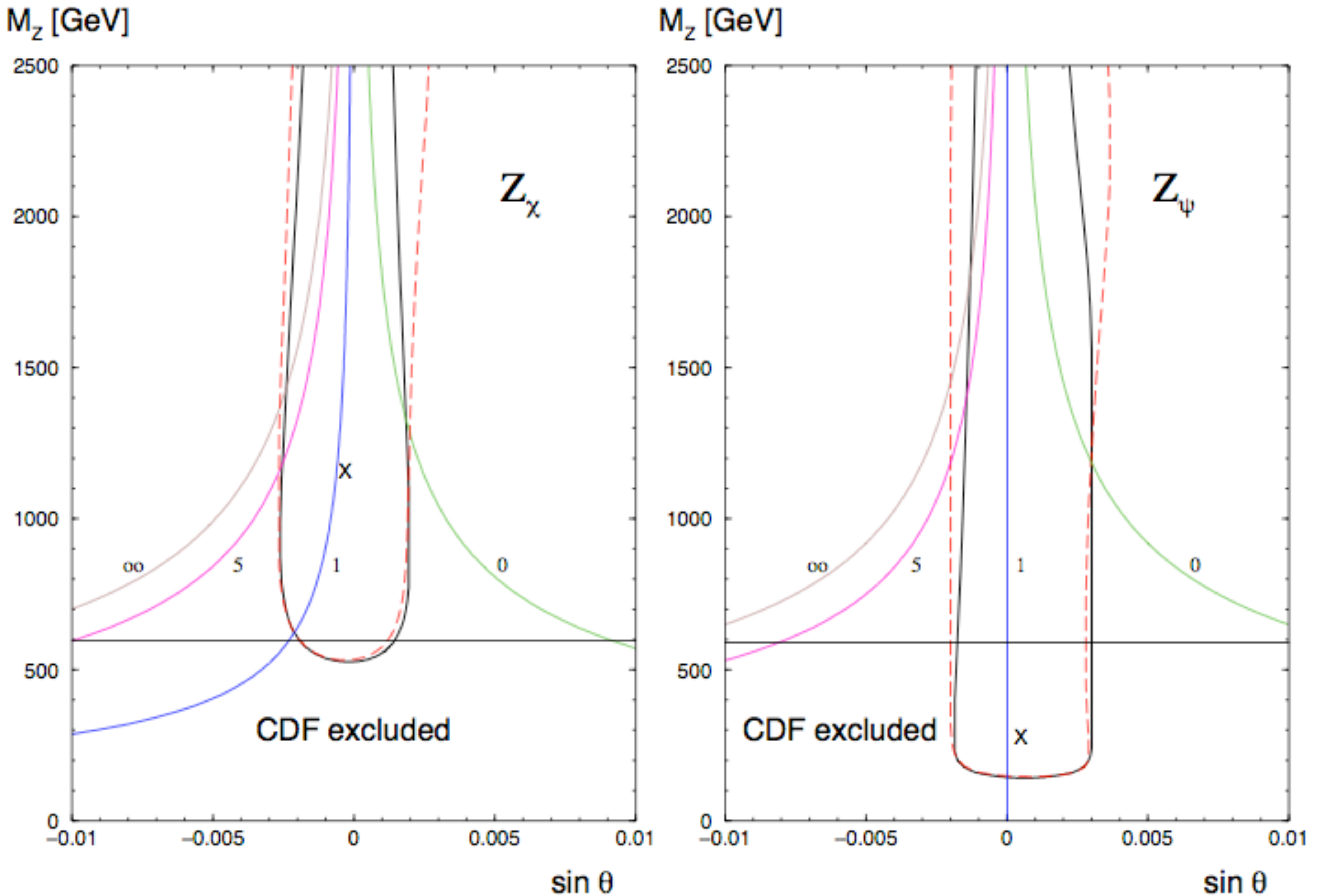
1. Same quantum numbers as the SM U(1). This occurs in extra dimension models.
2. Left-right models, in which $Q = T^3_L + T^3_R + U_{B-L}$. These arise from SO(10) models or models which descend from $SU(2)_L \times SU(2)_R \times U(1)$.
3. The E6 grand unified model has two extra Z's, and the fermion quantum numbers are specified. If it breaks into a single extra U(1), different combinations depend on how it breaks. There are four specific versions that arise--quantum numbers are known for each.

Typical bounds

There are two main parameters, the Z´ mass and the mixing angle, θ. The mixing angle can be best measured by high precision experiments on the Z-pole. The specific experiments and a typical result are on the next slides.

Quantity		Group(s)	Value	Standard Model	pull
M_Z	[GeV]	LEP	91.1867 ± 0.0021	91.1865 ± 0.0021	0.1
Γ_Z	[GeV]	LEP	2.4939 ± 0.0024	2.4957 ± 0.0017	-0.8
$\Gamma(\text{had})$	[GeV]	LEP	1.7423 ± 0.0023	1.7424 ± 0.0016	—
$\Gamma(\text{inv})$	[MeV]	LEP	500.1 ± 1.9	501.6 ± 0.2	—
$\Gamma(\ell^+\ell^-)$	[MeV]	LEP	83.90 ± 0.10	83.98 ± 0.03	—
σ_{had}	[nb]	LEP	41.491 ± 0.058	41.473 ± 0.015	0.3
R_e		LEP	20.783 ± 0.052	20.748 ± 0.019	0.7
R_μ		LEP	20.789 ± 0.034	20.749 ± 0.019	1.2
R_τ		LEP	20.764 ± 0.045	20.794 ± 0.019	-0.7
$A_{FB}(e)$		LEP	0.0153 ± 0.0025	0.0161 ± 0.0003	-0.3
$A_{FB}(\mu)$		LEP	0.0164 ± 0.0013		0.2
$A_{FB}(\tau)$		LEP	0.0183 ± 0.0017		1.3
R_b		LEP + SLD	0.21656 ± 0.00074	0.2158 ± 0.0002	1.0
R_c		LEP + SLD	0.1735 ± 0.0044	0.1723 ± 0.0001	0.3
$R_{s,d}/R_{(d+u+s)}$		OPAL	0.371 ± 0.023	0.3592 ± 0.0001	0.5
$A_{FB}(b)$		LEP	0.0990 ± 0.0021	0.1028 ± 0.0010	-1.8
$A_{FB}(c)$		LEP	0.0709 ± 0.0044	0.0734 ± 0.0008	-0.6
$A_{FB}(s)$		DELPHI + OPAL	0.101 ± 0.015	0.1029 ± 0.0010	-0.1
A_b		SLD	0.867 ± 0.035	0.9347 ± 0.0001	-1.9
A_c		SLD	0.647 ± 0.040	0.6676 ± 0.0006	-0.5
A_s		SLD	0.82 ± 0.12	0.9356 ± 0.0001	-1.0
A_{LR} (hadrons)		SLD	0.1510 ± 0.0025	0.1466 ± 0.0015	1.8
A_{LR} (leptons)		SLD	0.1504 ± 0.0072		0.5
A_μ		SLD	0.120 ± 0.019		-1.4
A_τ		SLD	0.142 ± 0.019		-0.2
$A_e(Q_{LR})$		SLD	0.162 ± 0.043		0.4
$A_\tau(\mathcal{P}_\tau)$		LEP	0.1431 ± 0.0045		-0.8
$A_e(\mathcal{P}_\tau)$		LEP	0.1479 ± 0.0051		0.3
$\bar{s}_\ell^2(Q_{FB})$		LEP	0.2321 ± 0.0010	0.2316 ± 0.0002	0.5

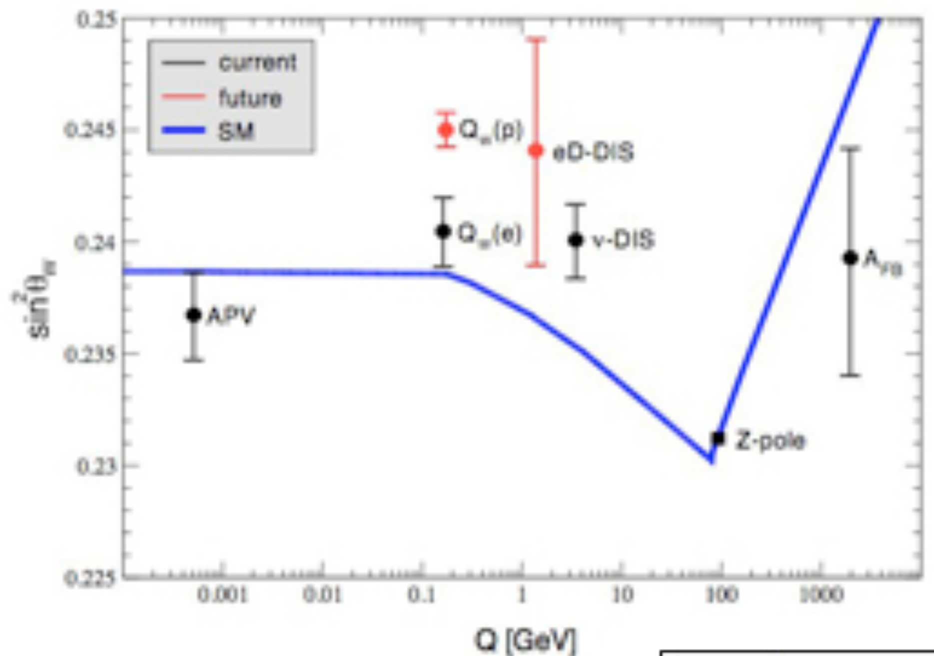
Quantity	Group(s)	Value	Standard Model	pull
m_t [GeV]	Tevatron	173.8 ± 5.0	171.4 ± 4.8	0.5
M_W [GeV]	Tevatron + UA2	80.404 ± 0.087	80.362 ± 0.023	0.5
M_W [GeV]	LEP	80.37 ± 0.09		0.1
R^-	NuTeV	$0.2277 \pm 0.0021 \pm 0.0007$	0.2297 ± 0.0003	-0.9
R^ν	CCFR	$0.5820 \pm 0.0027 \pm 0.0031$	0.5827 ± 0.0005	-0.2
R^ν	CDHS	$0.3096 \pm 0.0033 \pm 0.0028$	0.3089 ± 0.0003	0.2
R^ν	CHARM	$0.3021 \pm 0.0031 \pm 0.0026$		-1.7
$R^{\bar\nu}$	CDHS	$0.384 \pm 0.016 \pm 0.007$	0.3859 ± 0.0003	-0.1
$R^{\bar\nu}$	CHARM	$0.403 \pm 0.014 \pm 0.007$		1.1
$R^{\bar\nu}$	CDHS 1979	$0.365 \pm 0.015 \pm 0.007$	0.3813 ± 0.0003	-1.0
$g_V^{\nu e}$	CHARM II	-0.035 ± 0.017	-0.0395 ± 0.0004	—
$g_V^{\nu e}$	all	-0.041 ± 0.015		-0.1
$g_A^{\nu e}$	CHARM II	-0.503 ± 0.017	-0.5063 ± 0.0002	—
$g_A^{\nu e}$	all	-0.507 ± 0.014		-0.1
$Q_W(\mathrm{Cs})$	Boulder	$-72.41 \pm 0.25 \pm 0.80$	-73.10 ± 0.04	0.8
$Q_W(\mathrm{Tl})$	Oxford + Seattle	$-114.8 \pm 1.2 \pm 3.4$	-116.7 ± 0.1	0.5

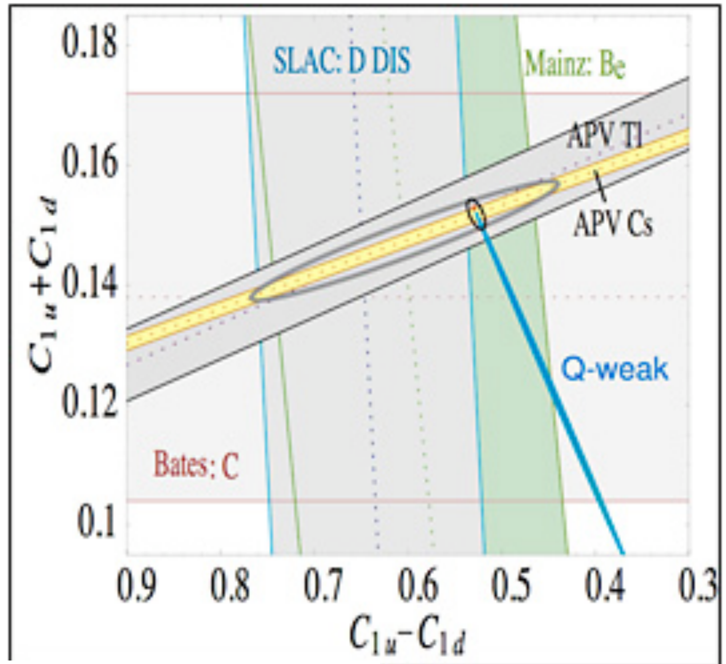


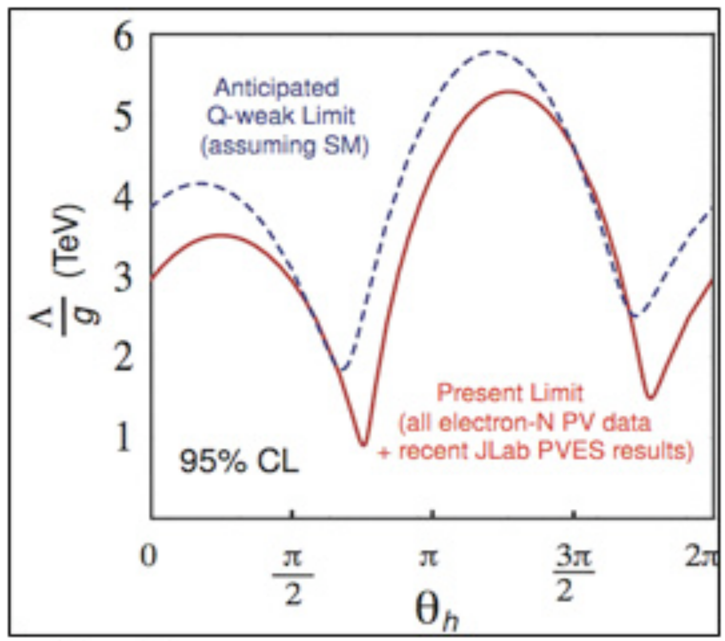
M_Z [GeV]
2500
2000
1500
1000
500
0
−0.01
−0.005
0
0.005
0.01
sin θ
Z_χ
oo
5
1
0
x
CDF excluded
M_Z [GeV]
2500
2000
1500
1000
500
0
−0.01
−0.005
0
0.005
0.01
sin θ
Z_ψ
oo
5
1
0
x
CDF excluded

		Z_χ	Z_ψ	Z_η	Z_{LR}	Z_{SM}	$Z_{\rm string}$	SM
ρ_0 free		551(591)	151(162)	379(433)	570(609)	822(924)	582(618)	
	$\sin\theta$	-0.0006	$+0.0004$	-0.0010	$+0.0002$	-0.0015	-0.0002	
	$\sin\theta_{\rm min}$	-0.0022	-0.0015	-0.0058	-0.0010	-0.0040	-0.0011	
	$\sin\theta_{\rm max}$	$+0.0020$	$+0.0021$	$+0.0019$	$+0.0022$	$+0.0008$	$+0.0008$	
	ρ_0	0.9993	0.9974	0.9979	0.9995	0.9982	0.9996	0.9996
	$\rho_0^{\rm min}$	0.9931	0.9923	0.9931	0.9917	0.9933	0.9986	0.9985
	$\rho_0^{\rm max}$	1.0010	1.0017	1.0017	1.0013	1.0018	1.0011	1.0017
	$\chi^2_{\rm min}$	27.62	27.52	27.34	27.71	26.83	27.34	28.37

The next major improvements will come with Q_{weak} at Jlab, which will improve some of these up closer to the TeV scale. And then the LHC will, by 2014-2015, push the bounds up to the 2-3 TeV scale.


current
future
SM
$Q_w(p)$
eD-DIS
$Q_w(e)$
ν-DIS
APV
A_{FB}
Z-pole
$\sin^2\theta_W$
Q [GeV]


SLAC: D DIS
Mainz: Be
APV Tl
APV Cs
Q-weak
Bates: C
$C_{1u}+C_{1d}$
$C_{1u}-C_{1d}$


Anticipated
Q-weak Limit
(assuming SM)
Present Limit
(all electron-N PV data
+ recent JLab PVES results)
95% CL
$\frac{\Lambda}{g}$ (TeV)
θ_h

DARK PHOTONS

- In 2007, the PAMELA experiment detected an unusually large excess of positrons coming from the galactic center and the excess seemed to increase between 10 and 100 GeV. That is consistent with dark matter in the galaxy annihilating to e^+e^- pairs, and is inconsistent with what is expected from high-energy cosmic ray interactions. There had been hints from earlier experiments, but this was more definitive.
- A possible excess was also observed last year by FERMI.
- However, there was no excess in antiprotons.

- So theorists began thinking about dark matter candidates which would decay into leptons, but not quarks.
- If there is a light particle (scalar or vector) that has a mass below a GeV, it will decay leptonically. The WIMP (SUSY?) will then annihilate into a pair of these particles.
- The most natural (and superstring-based) of these particles are “Dark Photons”.
- A dark photon is the gauge boson of a new U(1), under which all standard model particles are neutral.

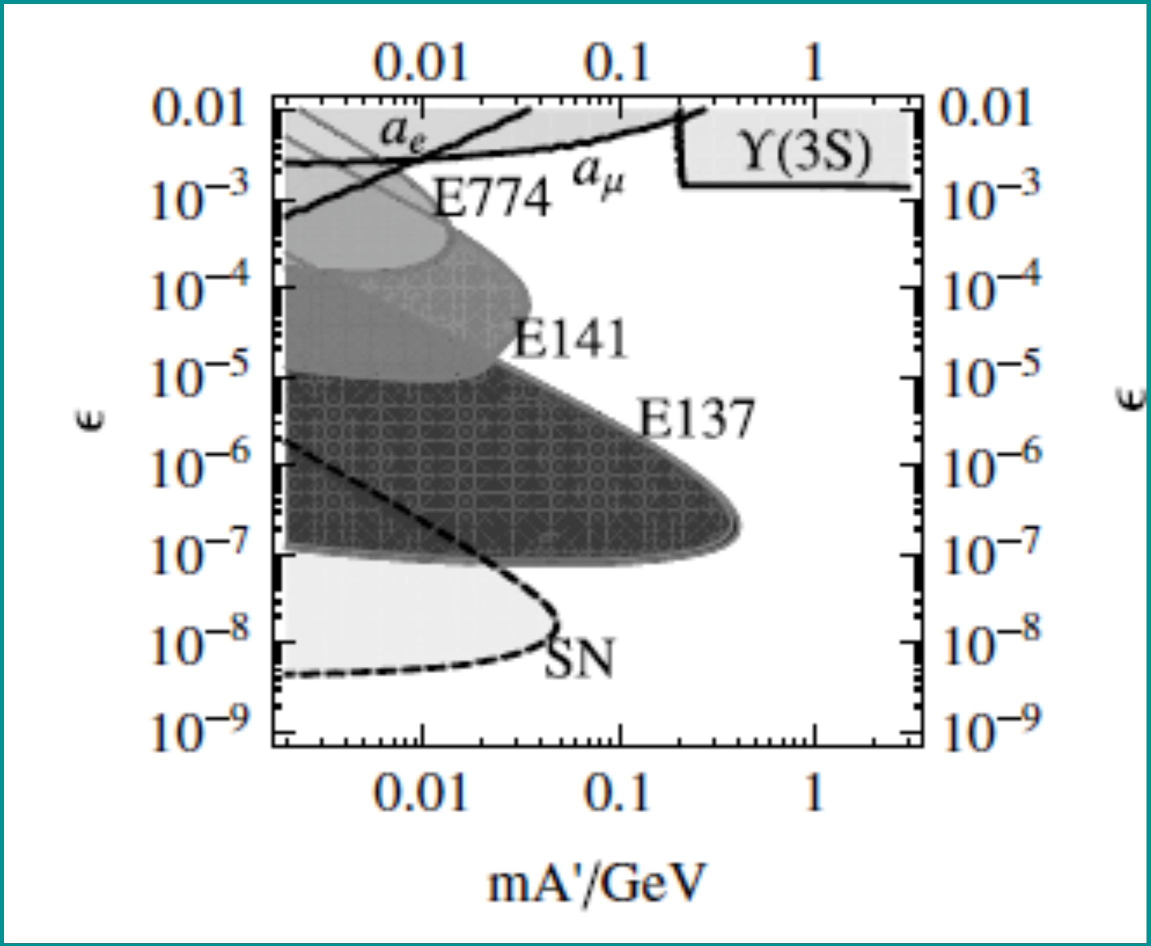
- The dark photon will mix with the photon:

$$(-1/4)[\, F_{\mu\nu} F^{\mu\nu} + F'_{\mu\nu} F'^{\mu\nu} + \varepsilon F_{\mu\nu} F'^{\mu\nu}]$$

and thus standard model particles will have a weak coupling to the dark photon, proportional to ε .

Where does it come from? The most popular superstring theory is based on a group E8 x E8. One of the E8's breaks into the SM, and the other is the hidden sector (responsible for SUSY breaking). Typically, the hidden sector will have U(1)'s. They will mix due to loops, and typically $10^{-8} < \varepsilon < 10^{-2}$. In addition, the U(1) is broken naturally giving a mass of the order of $\varepsilon^{1/2}$ times the weak scale, which is in the MeV-GeV region.

Current bounds:



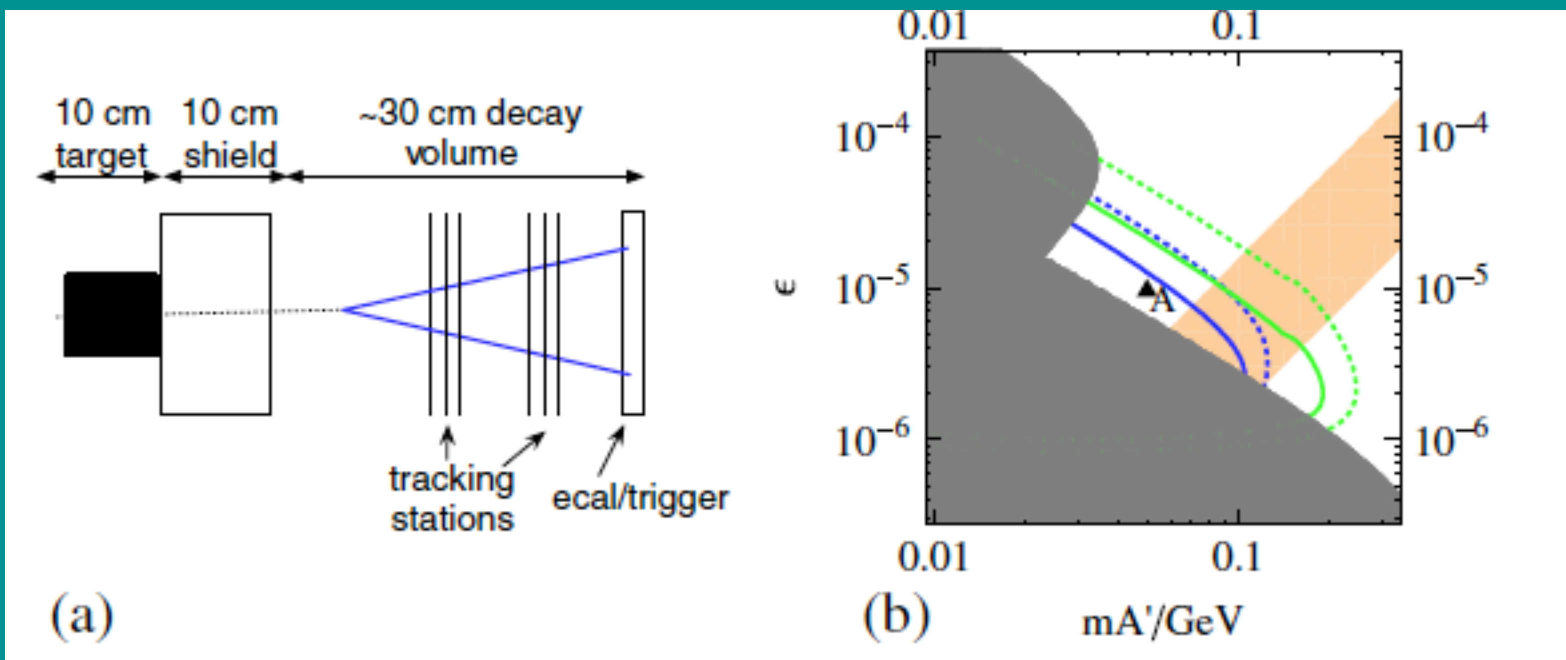
σ = 100 pb $(\varepsilon/10^{-4})^2$ (100 MeV/m_A)^2 for e+N

γct = 1 mm $(10^{-4}/\varepsilon)^2$ (100 MeV/m_A)

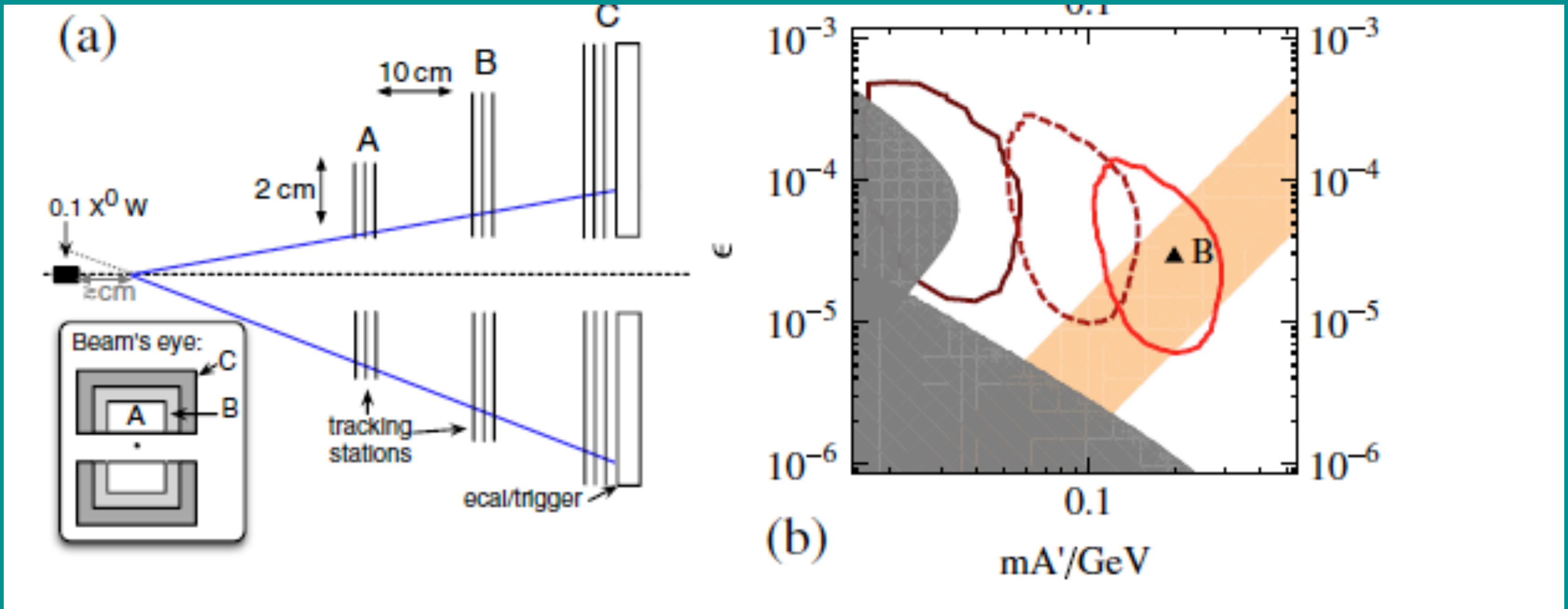
Proposed Experiments (Bjorken- 2009)

- 200 MeV electron beam on a 10 cm tungsten target.

Decay length of A’ is 5 cm. Need continuous beam.

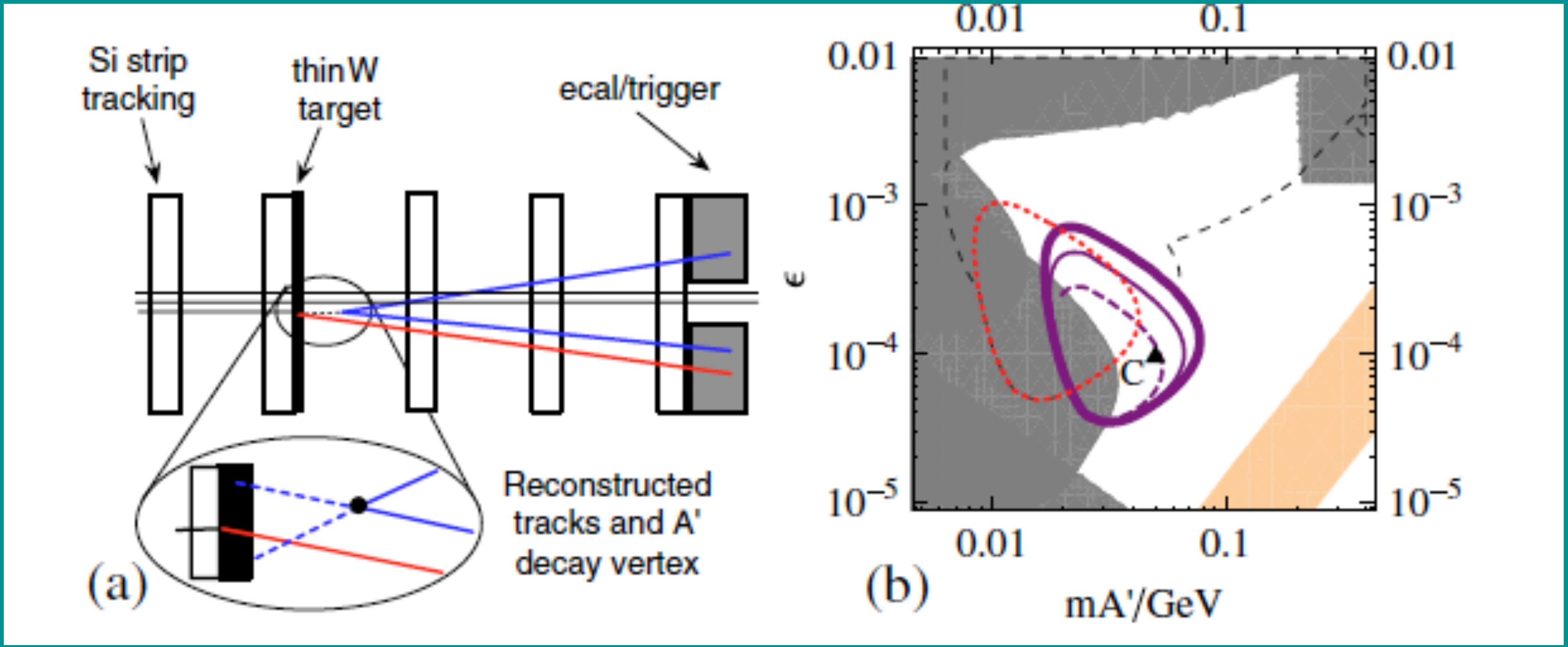


- 6 GeV beam with current of 100 nA, and a two-arm spectrometer. Decay length of 1 cm.

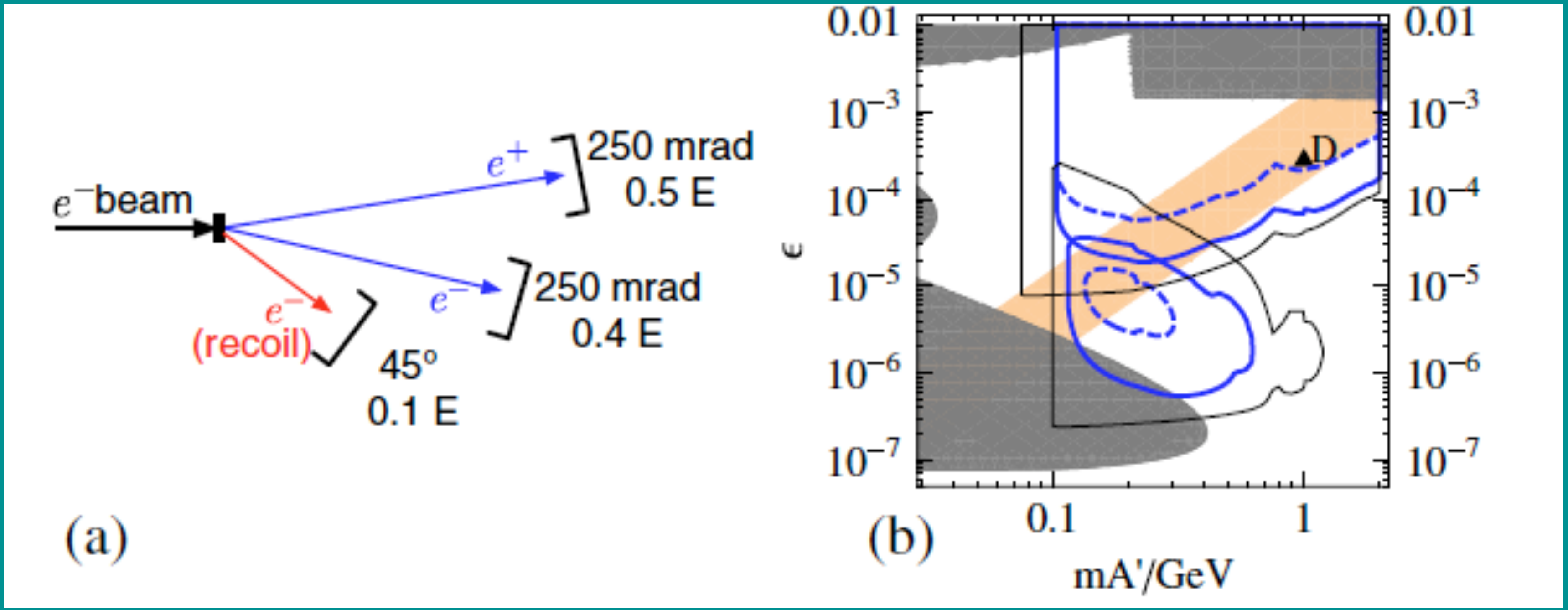


Three regions correspond to different geometries and currents

- Beam energy of 1 GeV, silicon strip layers.



- 4 GeV beam, high resolution spectrometer. Bjorken says that both Hall A and Hall B look especially appropriate for this



Many different scenarios here, but it covers the biggest region of parameter space.

Summary