Particle Physics Beyond the Standard Model

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HCP Summer School 2007

Overview

- Why there must be physics beyond the Standard Model
- Why it should be at 1 TeV
- Why it *should not* be at 1 TeV
- Status of the Standard Model

Why BSM?

- Hypercharge
- Gravity
- Neutrinos
- Unifying principles?

Neutrinos

Neutrino mass not possible in SM renormalizable Lagrangian.

Requires new particles (e.g., right-handed neutrinos) or new physics at the scale M:

$$0.1\ \mathrm{eV} \sim m_\nu = \frac{\ell H \ell H}{M} \to M \sim 10^{14}\ \mathrm{GeV}$$

(solar system)

Gravity

Including gravity in the Standard Model allows for graviton-graviton scattering which has a big unitarity problem at high energies.

$$\sigma \sim \frac{E^n}{M_{pl}^{n+2}} \qquad M_{pl} \simeq 10^{19}\ \mathrm{GeV}$$

(galactic core)

Hypercharge

Running the hypercharge coupling up to high energies makes it blow up - Landau pole

$$\frac{1}{g'^2(M_Z)} = \frac{1}{g'^2(\Lambda)} + \frac{b_Y}{8\pi^2}\log\frac{\Lambda}{M_Z} \qquad b_Y = \frac{41}{6}$$

$$\Lambda = M_Z\, e^{8\pi^2/g'^2 b_Y} \sim 10^{41}\ \mathrm{GeV}$$

(10^{14} H^{-1})

Unifying Principles?

The SU(5) symmetry group perfectly embeds all SM matter in complete representations.

$$\overline{5}: \quad \begin{pmatrix} \overline{d} \\ \overline{d} \\ \overline{d} \\ e \\ \nu \end{pmatrix}_L \qquad 10: \quad \begin{pmatrix} 0 & \overline{u} & \overline{u} & u & d \\ & 0 & \overline{u} & u & d \\ & & 0 & u & d \\ & & & 0 & \overline{e} \\ & & & & 0 \end{pmatrix}_L$$

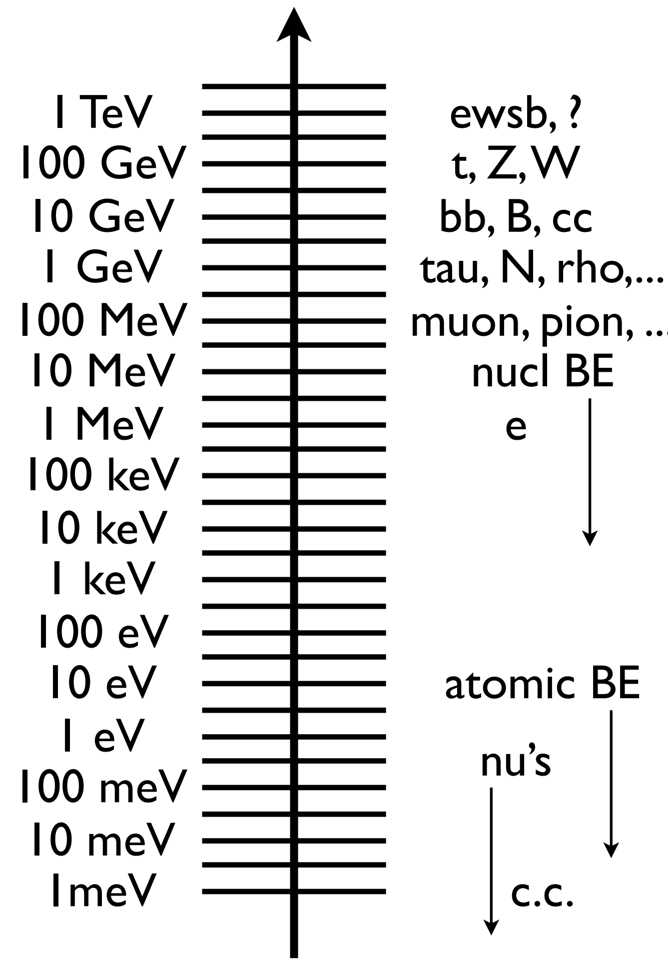
(Super)string theory is a theory of quantized strings which naturally contains a spin-2 massless mode.

Why BSM at 1 TeV?

- Naturalness / The Hierarchy Problem
- Dark Matter
- Why Not?

Why Not?

If you look at energy scales...
why should there be a desert?



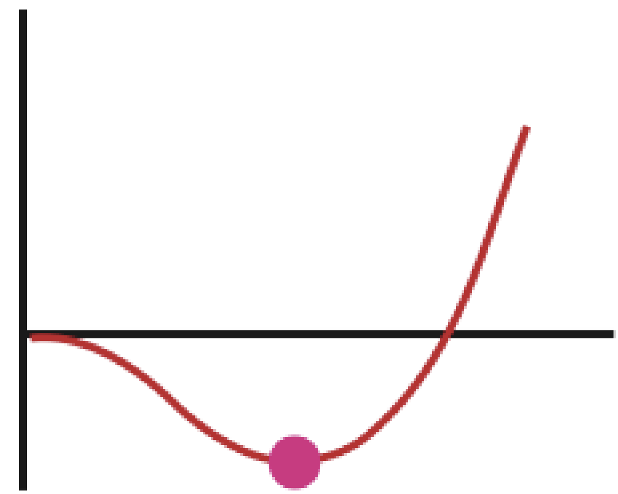
Natural EWSB

The electroweak scale depends on the Higgs mass parameter:

$$V(H) = m^2|H|^2 + \lambda|H|^4$$

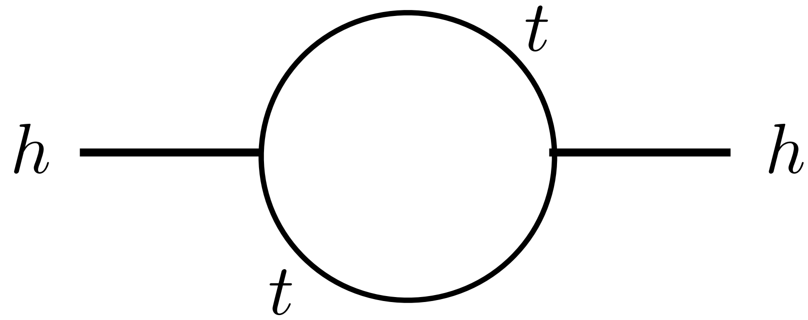
$$m^2 < 0$$

$$\langle H \rangle \equiv v \sim \sqrt{\frac{-m^2}{\lambda}}$$

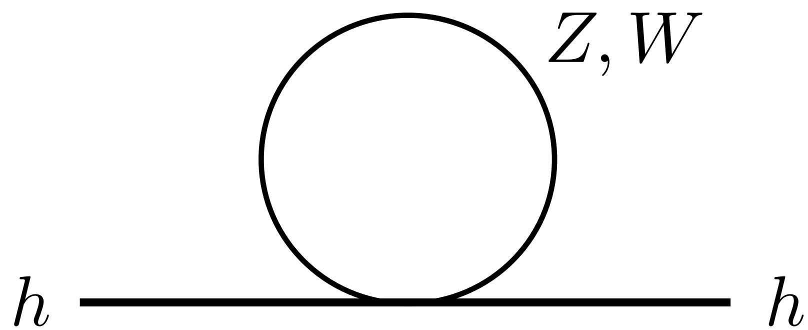


Quantum corrections to m^2 correct the vev

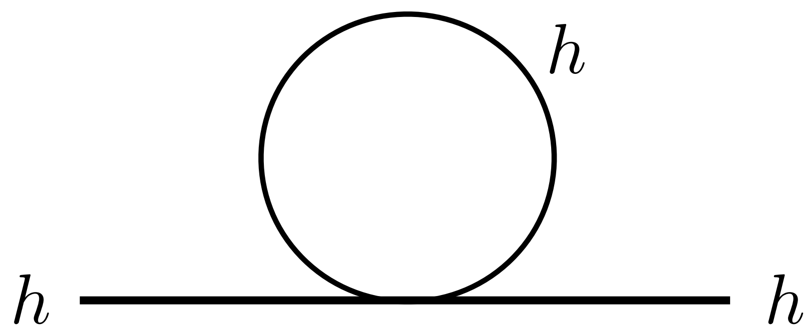
Model Independent: Weak Coupling



$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$

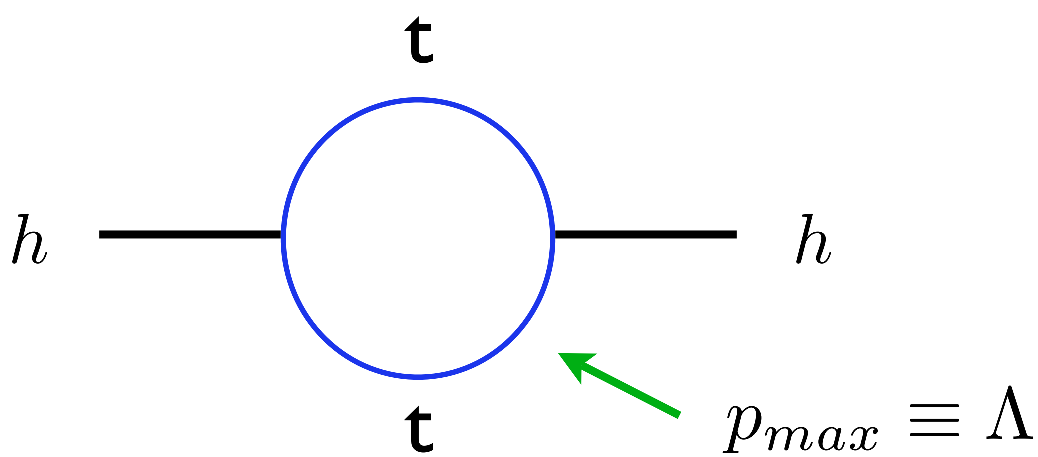


$$\delta m_h^2 \sim \frac{9}{64\pi^2}g^2\Lambda^2$$



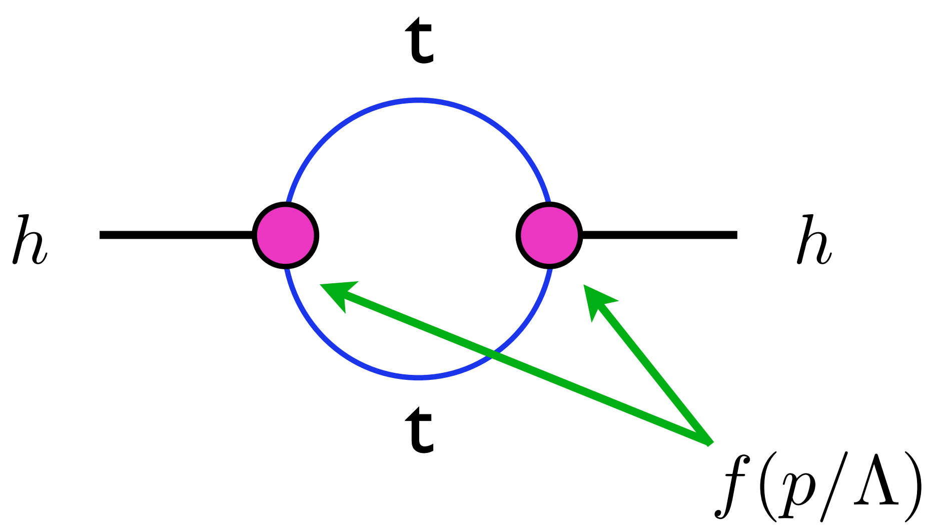
$$\delta m_h^2 \sim \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

Regulating the Theory



Whatever makes this finite
becomes important at energies
of order Λ

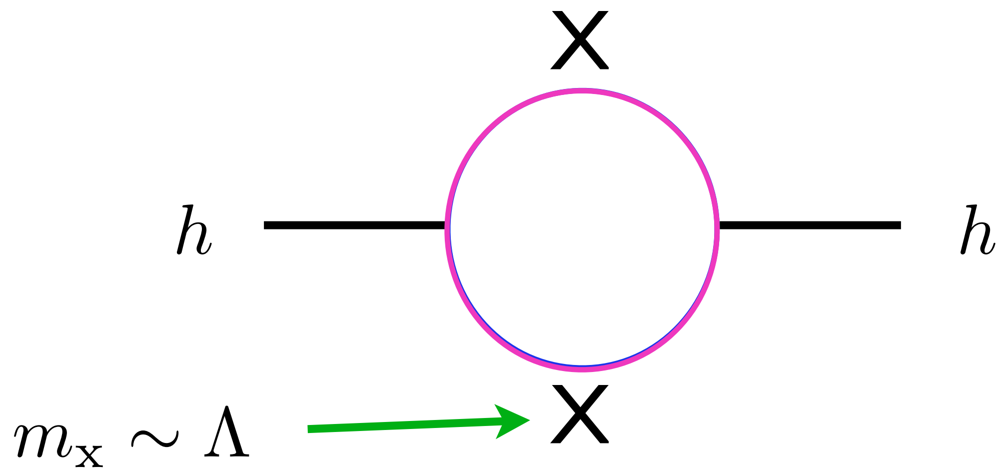
Regulating the Theory



Whatever makes this finite becomes important at energies of order Λ

Momentum-dependent couplings (compositeness)

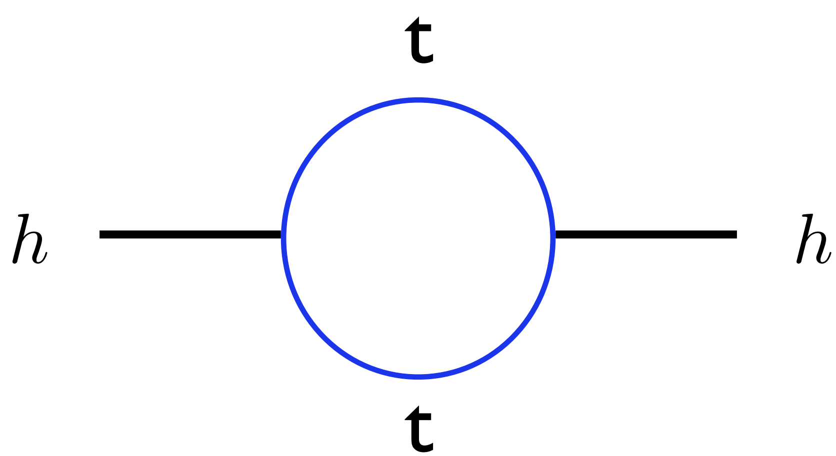
Regulating the Theory



Whatever makes this finite becomes important at energies of order Λ

New particles in the loop

Regulating the Theory

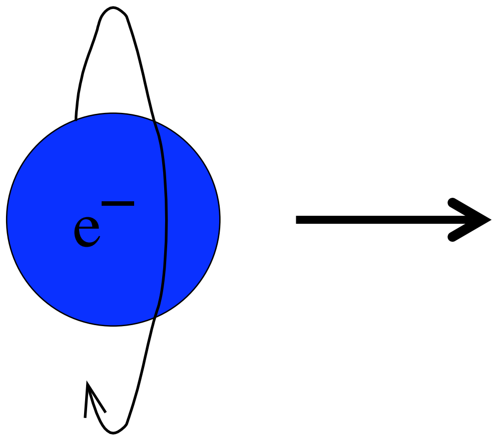


Whatever makes this finite becomes important at energies of order Λ

From the top loop,

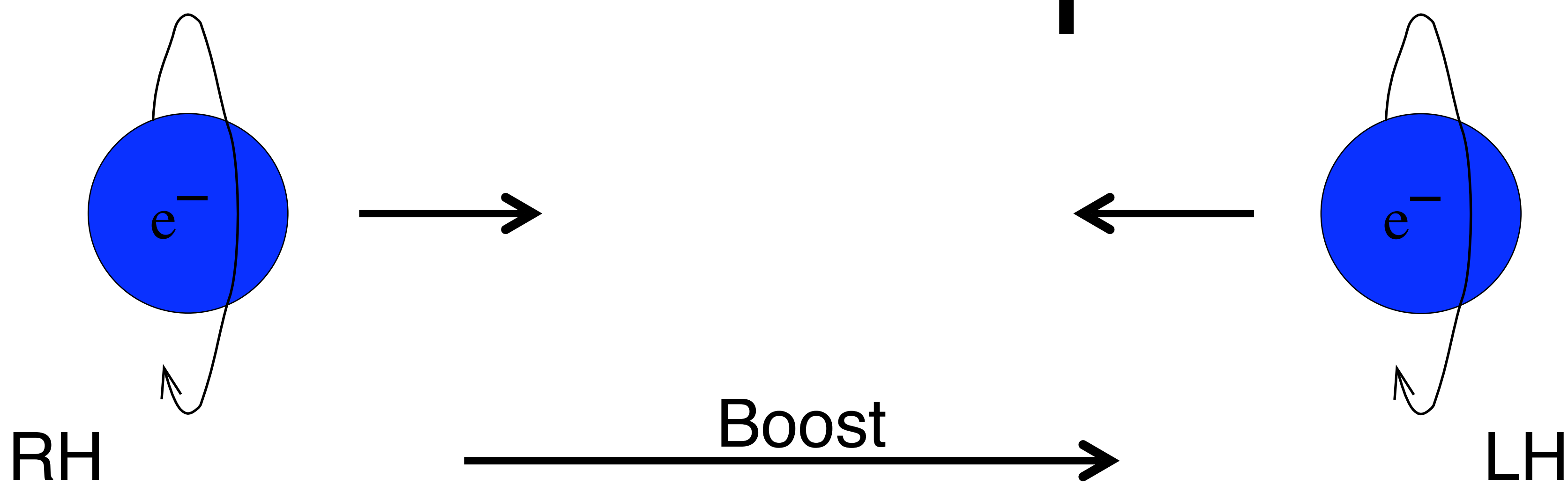
$\delta m_h \sim (1/5)\Lambda$, and so the cutoff is $\Lambda \sim 1\ \mathrm{TeV}$

Non-zero spin

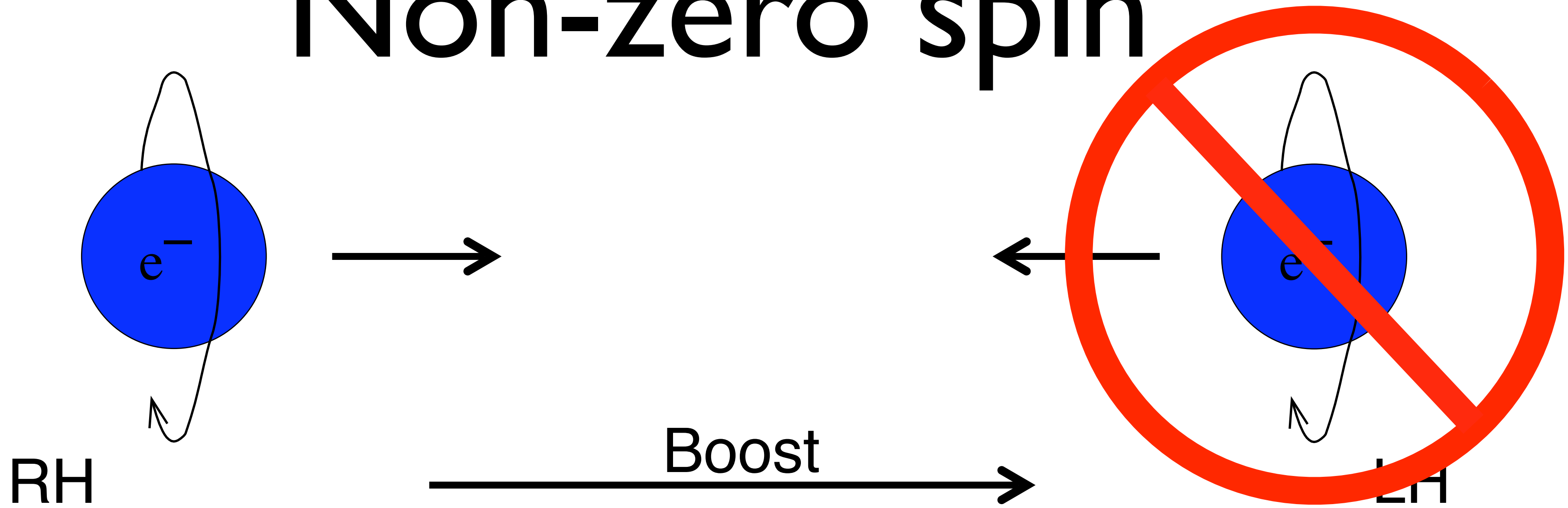


RH

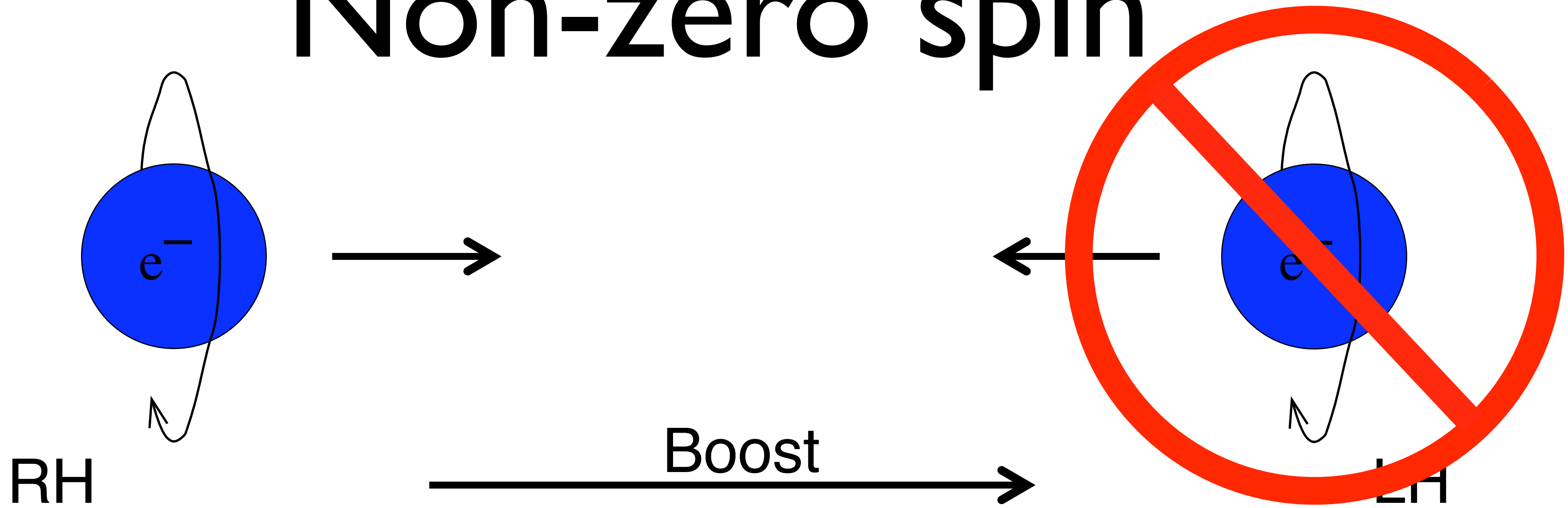
Non-zero spin

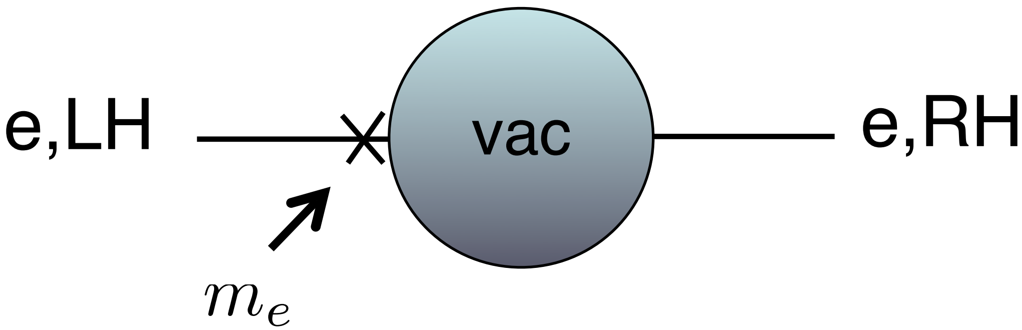


Non-zero spin



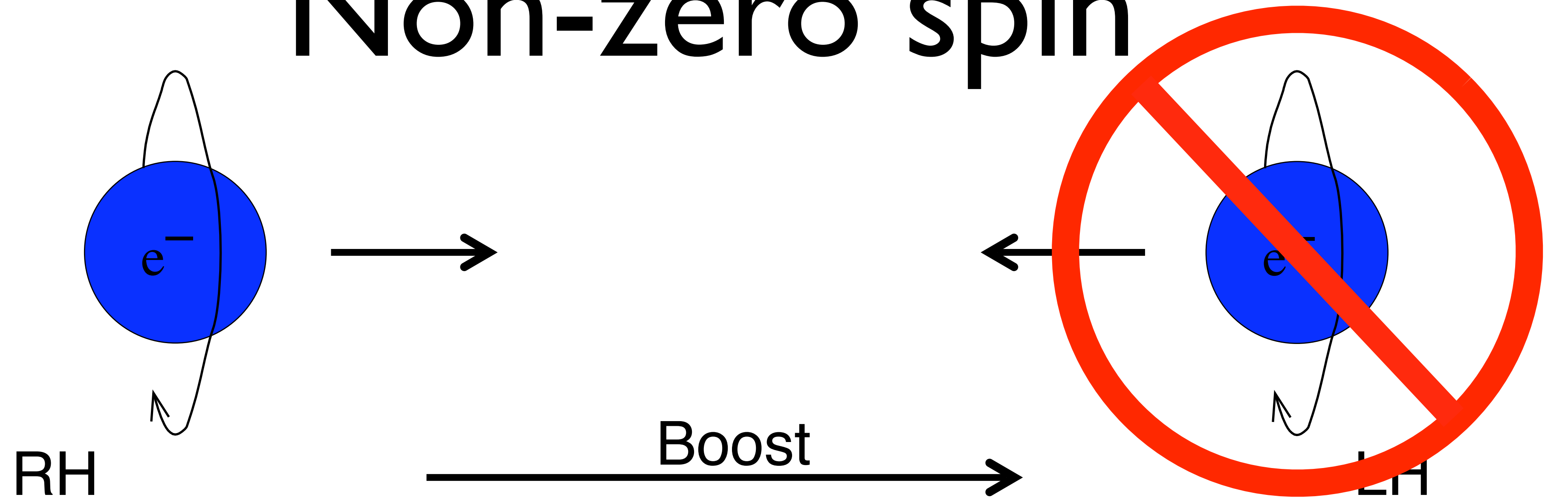
Non-zero spin

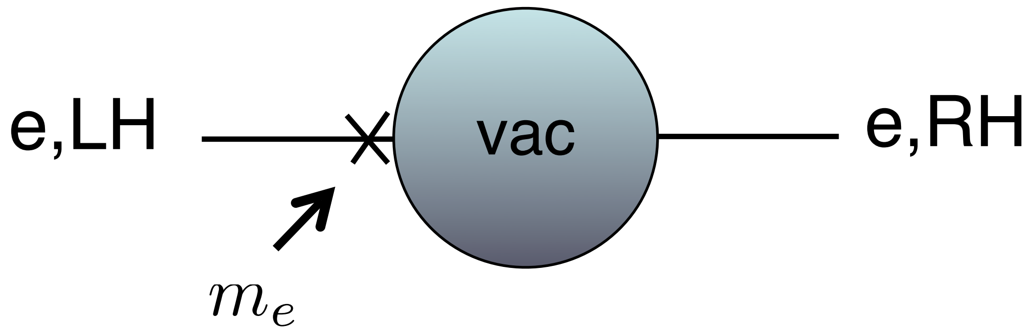




$$\delta m_e \sim \epsilon\, m_e \ln \Lambda$$

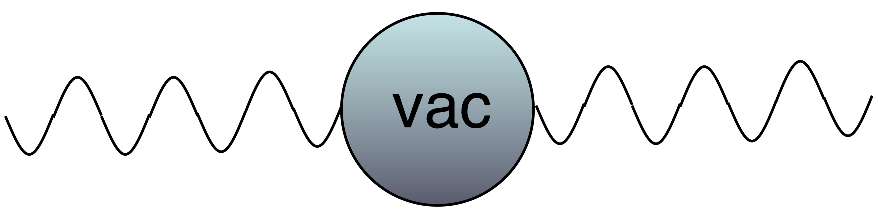
Non-zero spin





$$\delta m_e \sim \epsilon\, m_e \ln \Lambda$$

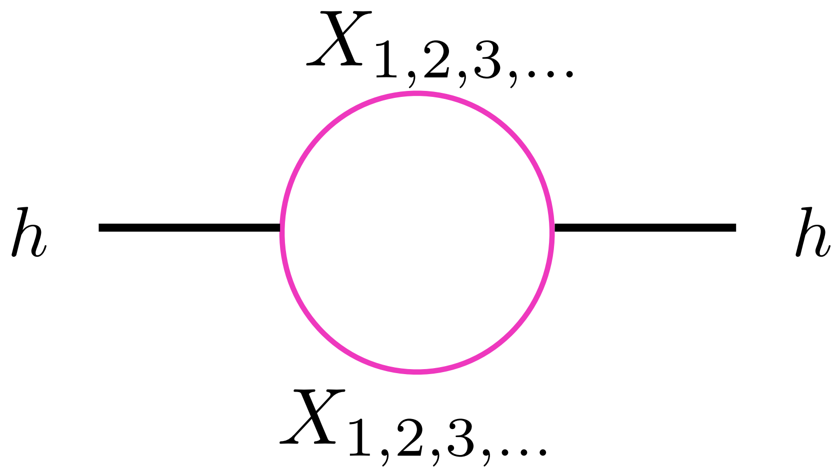
Photon:



Remains massless:

2 polarizations vs. 3

Fine-tuned EWSB



$$m_{X_i} = \Lambda >> 1 \text{ TeV}$$

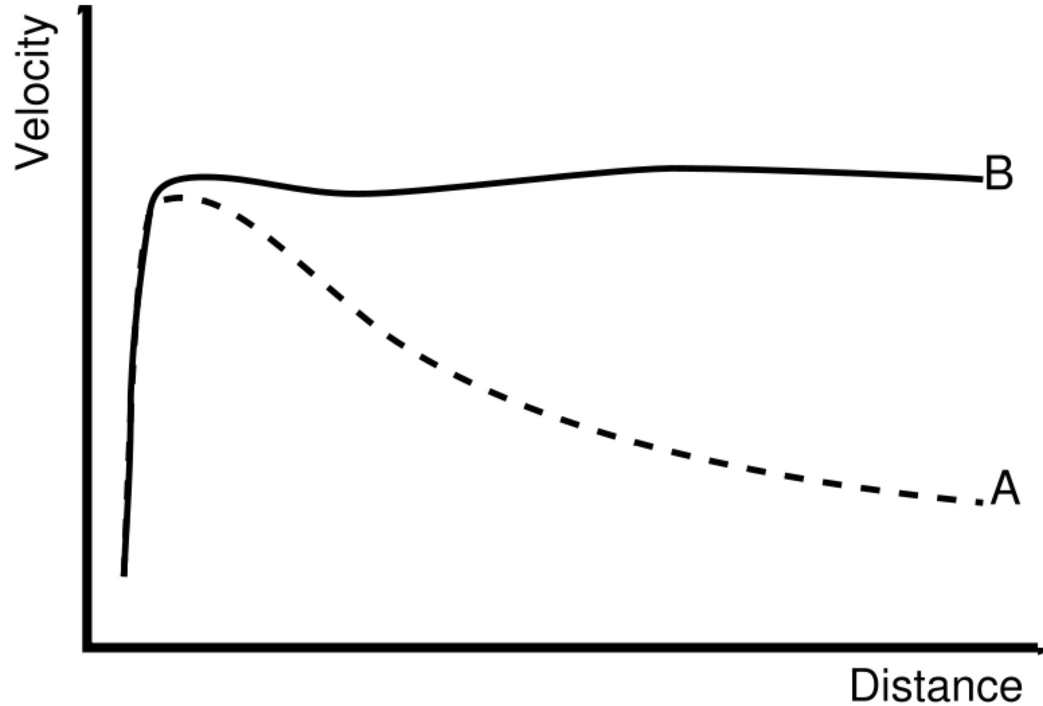
$$\# \frac{\lambda_1^2}{16\pi^2} m_{X_1}^2 + \# \frac{\lambda_2^2}{16\pi^2} m_{X_2}^2 + \# \frac{\lambda_3^2}{16\pi^2} m_{X_3}^2 + \cdots \ll \Lambda^2$$

The Hierarchy Problem

Historical - hierarchy between the GUT
scale and the weak scale

Either God hates particle physicists,
or we are very unlucky (proportional to the inverse tuning)
or perhaps a new view of the physical Universe is
necessary (anthropics)

Dark Matter



$$\rho \sim \frac{1}{r^2}$$

$$\Omega_{DM} \sim 0.1$$

Dark Matter

(1) Assume new heavy particle in thermal equilibrium:

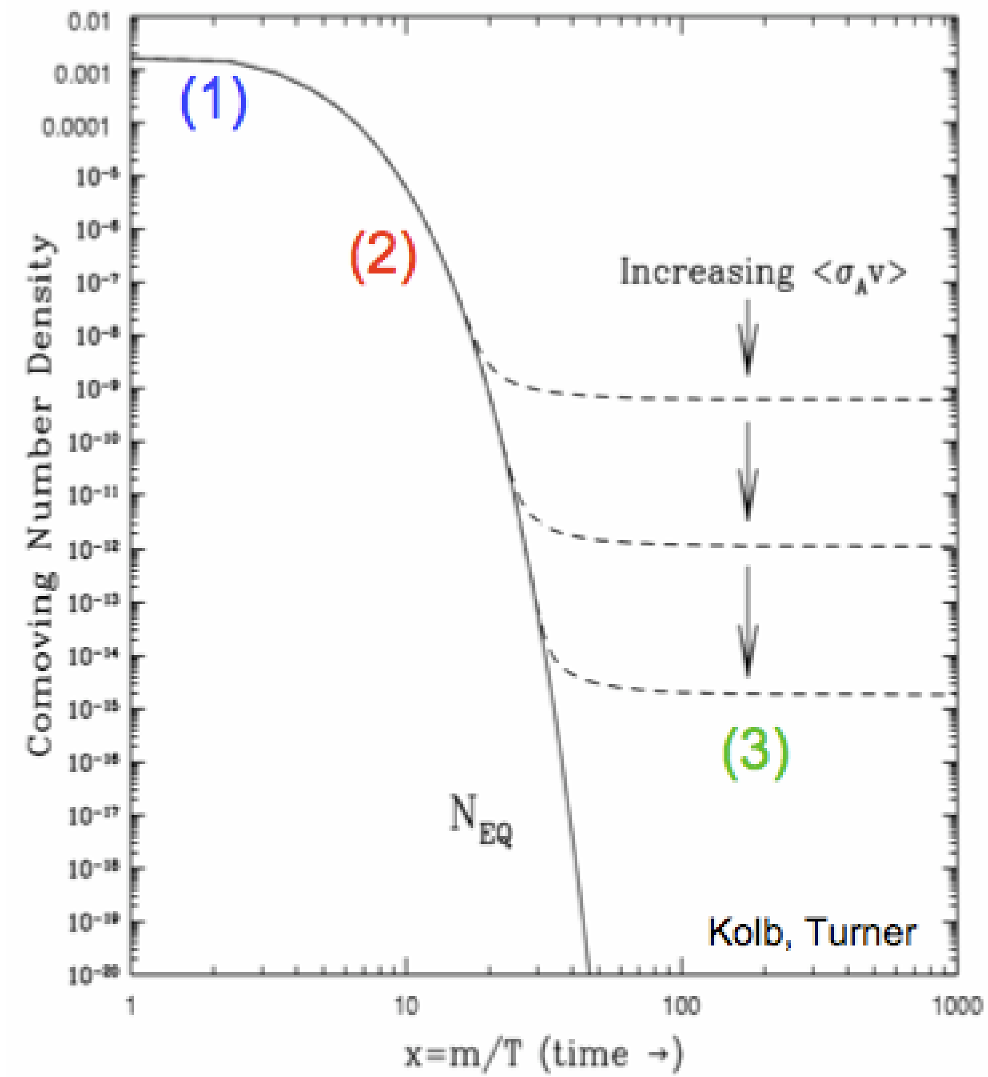
$$\chi\chi \leftrightarrow f\bar{f}$$

(2) The Universe cools:

$$\chi\chi \rightarrow f\bar{f} \qquad \chi\chi \not\leftarrow f\bar{f}$$

(3) Chi freezes out

$$\chi\chi \not\leftrightarrow f\bar{f}$$



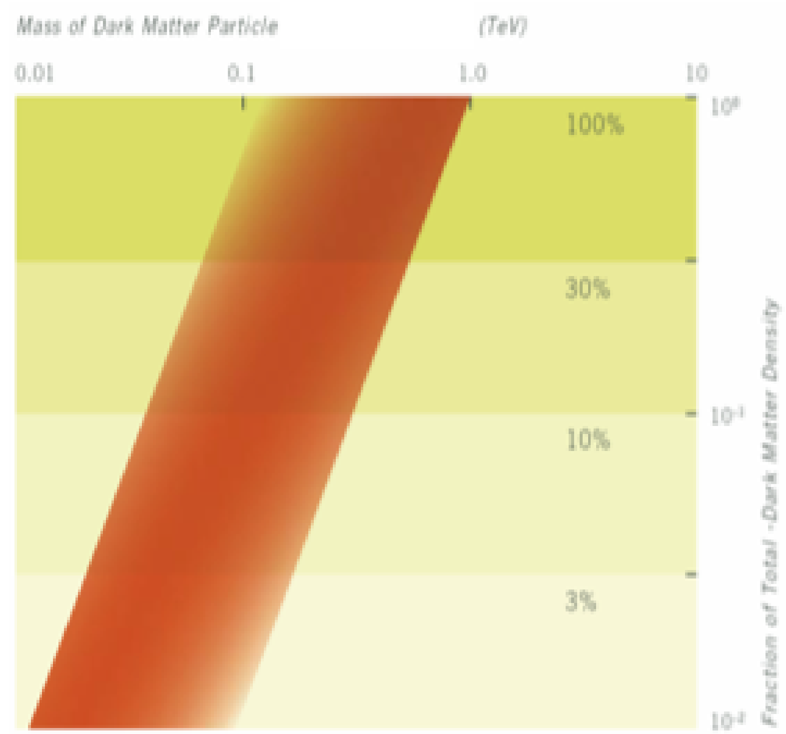
The Weak Connection

- Amount of DM left inversely proportional to annihilation cross section:

$$\Omega_{DM} \sim \frac{1}{\langle \sigma_A v \rangle}$$

- Constant of proportionality? take:

$$\sigma_A = \frac{k\alpha^2}{m_\chi^2} \rightarrow \Omega_{DM} \sim m^2$$



HEPAP LHC/ILC Subpanel (2006)
[band width from k = 0.5 – 2, S and P wave]

- Coincidence (?!):

$$m_\chi \sim 0.1 - 1\ \mathrm{TeV} \rightarrow \Omega_{DM} \sim 0.1$$

Arguments Against BSM at 1 TeV

- Electroweak Precision
- Flavor Changing Neutral Currents
- CP Violation
- Baryon and Lepton Number Violation

SM Operator Analysis

All dimension 4 operators involving fermions allowed by gauge symmetry:

$$\mathcal{L}_f = \bar{\psi}_a i \not{D} \psi_a + y^u_{ij} H^\dagger q_i u^c_j + y^d_{ij} H q_i d^c_j + y^\ell_{ij} H \ell_i e^c_j$$

Baryon number and Lepton number automatically conserved (and B-L quantum mechanically)!

Proton stability explained by "accidental" symmetries.

Dimension 5 Operator

$$m_\nu \sim Z_\nu \frac{\ell H \ell H}{\Lambda} \to \frac{\Lambda}{Z_\nu} \sim 10^{14}\ \mathrm{GeV}$$

Could violate Lepton number at high energies

Dimension 6 Operators

proton decay can occur via:

$$Z_{q\ell} \frac{qqq\ell}{\Lambda} \rightarrow \frac{\Lambda}{Z_{q\ell}} > few \times 10^{14}$$

$$\tau_p > 10^{32} y$$

New physics at a TeV better not violate B and L

Coupling to W and Z

$$Z_\mu \overline{u}_L \gamma^\mu u_L \rightarrow Z_\mu \overline{u}_L \gamma^\mu (V_{uL}^\dagger V_{uL}) u_L$$

$$\hookrightarrow \quad = 1$$

$$W_\mu^+ \overline{u}_L \gamma^\mu d_L \rightarrow W_\mu^+ \overline{u}_L \gamma^\mu (V_{uL}^\dagger V_{dL}) d_L$$

$$\hookrightarrow \quad = V_{CKM}$$

Flavor changing at tree-level is only in “charged currents”

Only phase left (perturbatively) is the CKM phase

Dimension 6 - Flavor

$$\mathcal{L}_{\Delta F=2} = \frac{z_{sd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu s_L)^2 + \frac{z_{cu}}{\Lambda_{\rm NP}^2}(\overline{c_L}\gamma_\mu u_L)^2 + \frac{z_{bd}}{\Lambda_{\rm NP}^2}(\overline{d_L}\gamma_\mu b_L)^2 + \frac{z_{bs}}{\Lambda_{\rm NP}^2}(\overline{s_L}\gamma_\mu b_L)^2$$

$$\Lambda_{\rm NP} \gtrsim \begin{cases} \sqrt{\mathcal{I}m(z_{sd})}\ 2\times 10^4\ TeV & \epsilon_K \\ \sqrt{z_{sd}}\ 1\times 10^3\ TeV & \Delta m_K \\ \sqrt{z_{cu}}\ 8\times 10^2\ TeV & \Delta m_D \\ \sqrt{z_{bd}}\ 5\times 10^2\ TeV & \Delta m_B \\ \sqrt{z_{bs}}\ 2\times 10^2\ TeV & \Delta m_{B_s} \end{cases}$$

Y. Nir lectures

New physics at a TeV better have a special flavor structure.

Dimension 6 - LEP II and APV

SCALE LIMITS for Contact Interactions: $\Lambda(eeqq)$

Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see each reference.

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>23.3	**>12.5**	95	[32] CHEUNG	01B	RVUE	$(eeuu)$
>11.1	**>26.4**	95	[32] CHEUNG	01B	RVUE	$(eedd)$
> 5.6	**>4.9**	95	[33] BARATE	00I	ALEP	$(eebb)$
> 1.0	**>2.1**	95	[34] ABREU	99A	DLPH	$(eecc)$

SCALE LIMITS for Contact Interactions: $\Lambda(\ell\ell\ell\ell)$

Lepton universality assumed. Limits are for $\Lambda^{\pm}_{LL}$ only. For other cases, see reference.

Λ^{+}_{LL}(TeV)	Λ^{-}_{LL}(TeV)	CL%	DOCUMENT ID		TECN	COMMENT
>9.1	>8.2	95	ABDALLAH	06C	DLPH	E_{cm}= 130–207 GeV
>7.7	**>9.5**	95	[25] ABBIENDI	04G	OPAL	E_{cm}= 130–207 GeV

New Physics Constraints

TeV-scale physics better have some very special features

SM Status and Hints

- Electroweak Precision and the Higgs mass
- g-2
- Tevatron searches

Precision Tests

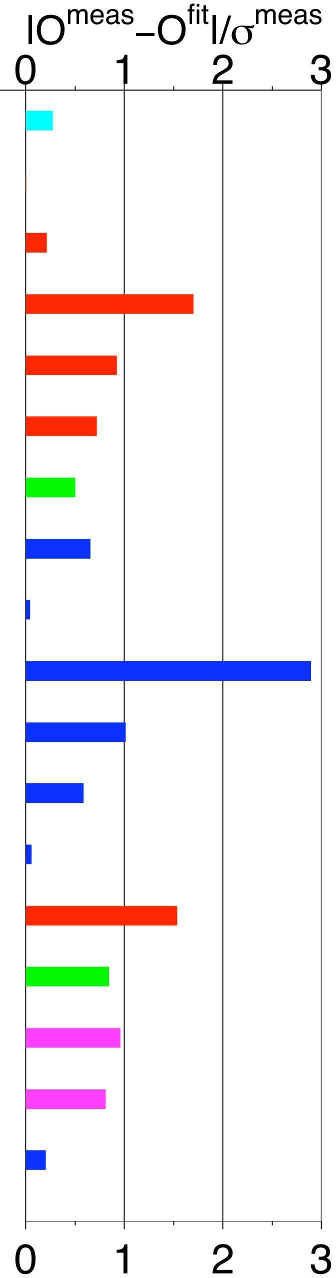
Precision measurements agree well

biggest discrepancy

$$\chi^2/\text{d.o.f.}=16.8/14$$

continuing updates

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^0 [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	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	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

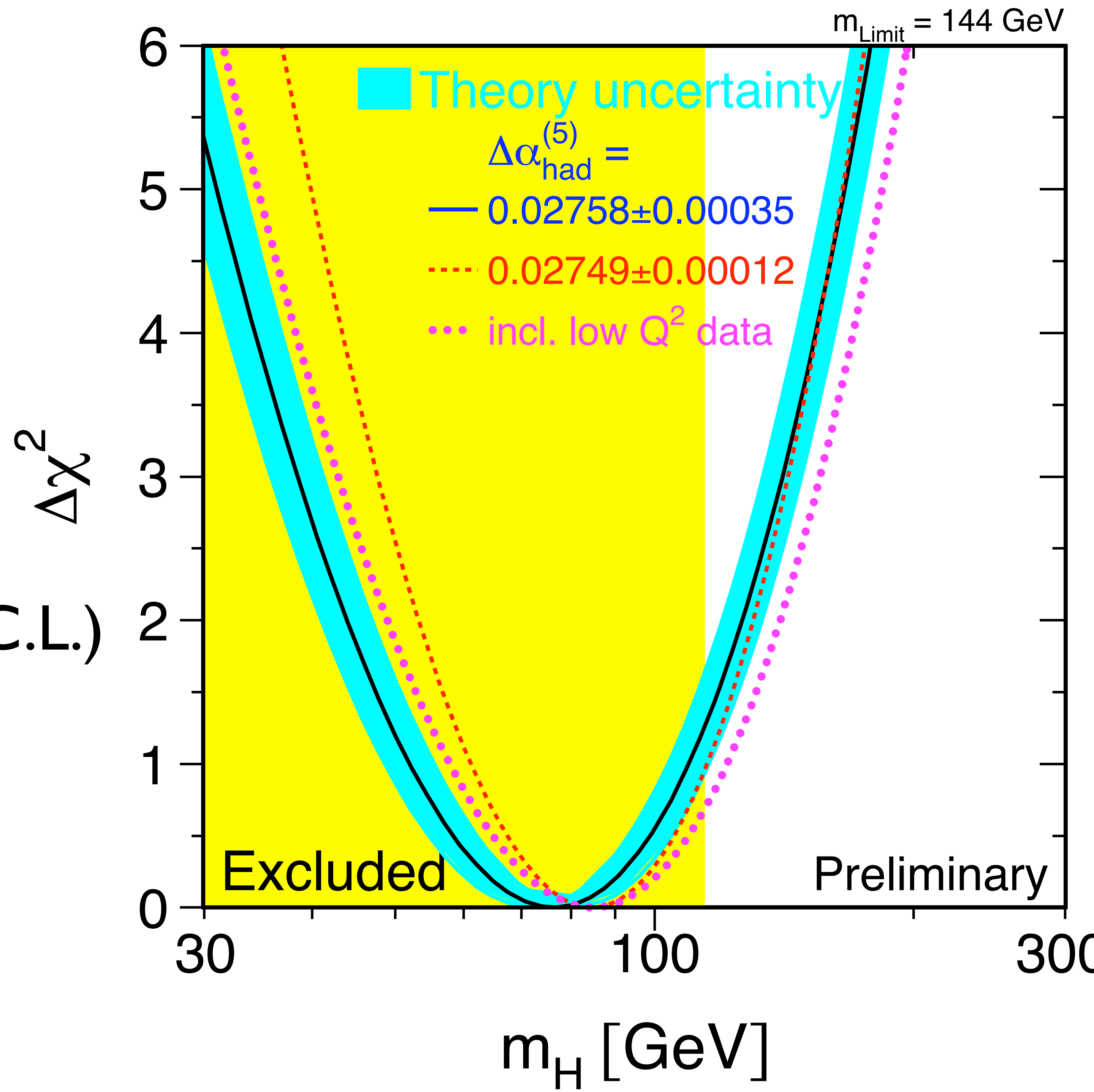


Higgs mass fit

76 $^{+33}_{-24}$ GeV

< 144 GeV (95% C.L.)

LEP II Bound:
> 114.4 GeV

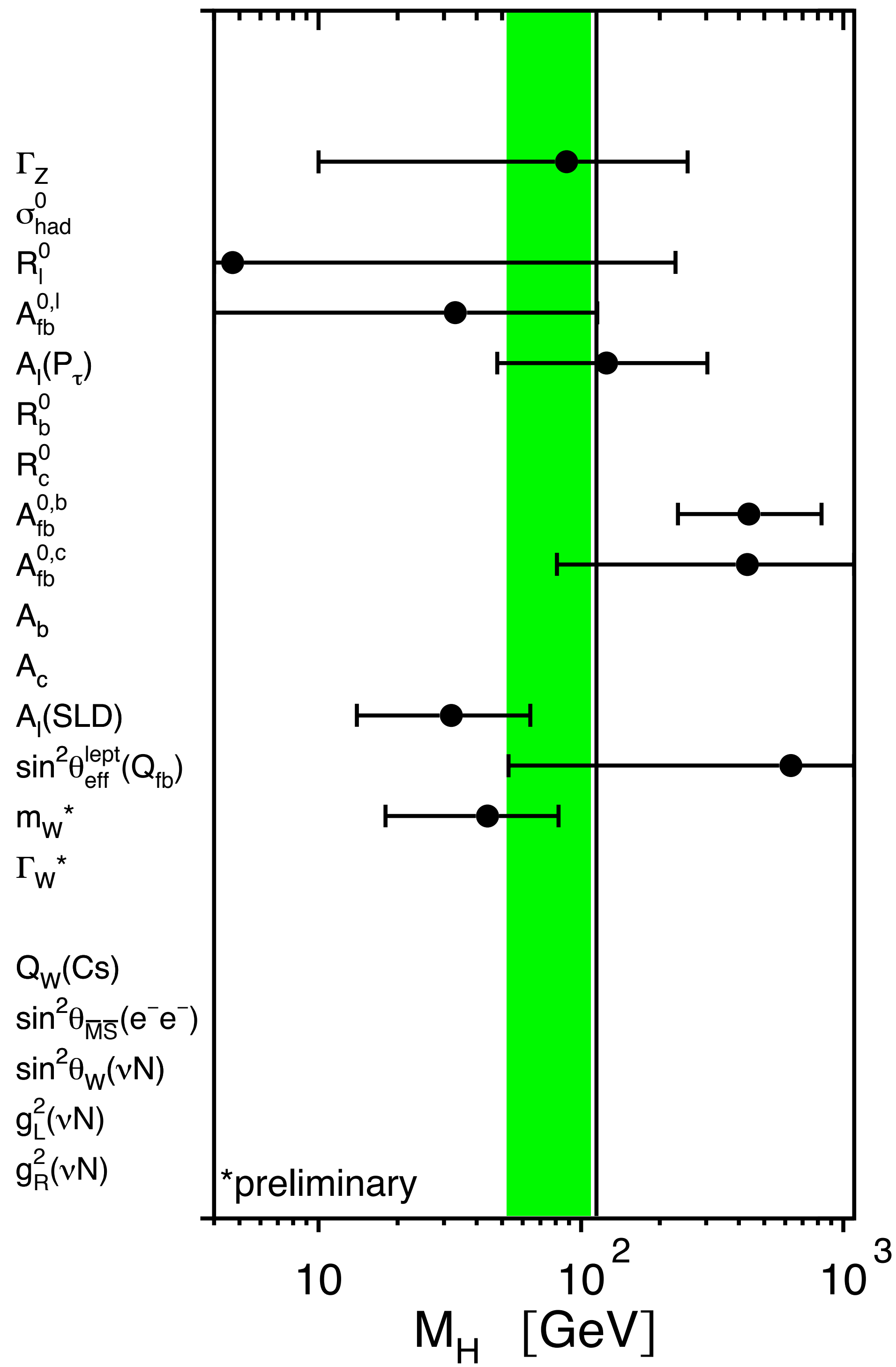


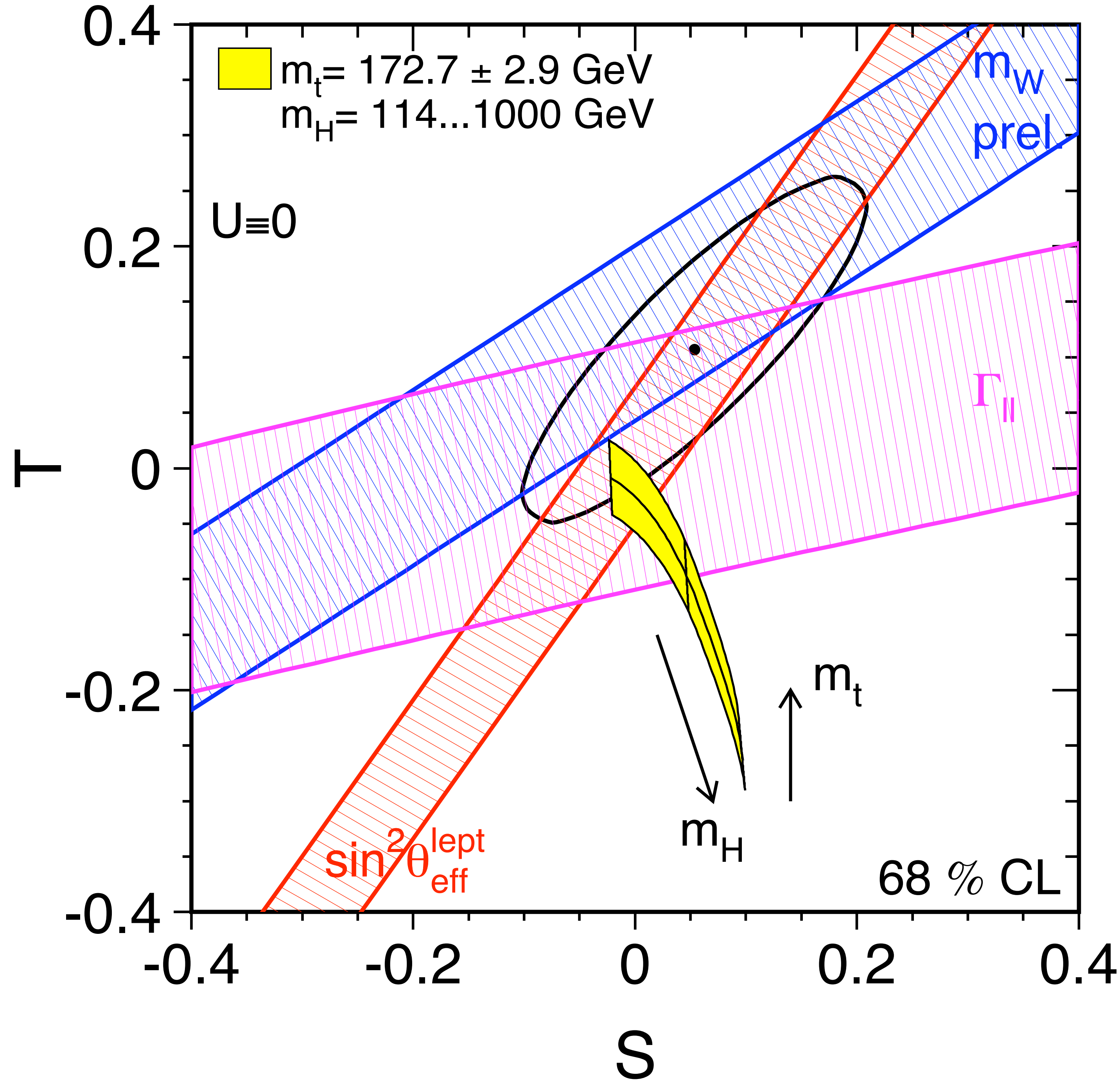
Sensitivity to m_h

Discrepancy in observables sensitive to the Higgs mass

$\chi^2/\text{dof}=11/4$

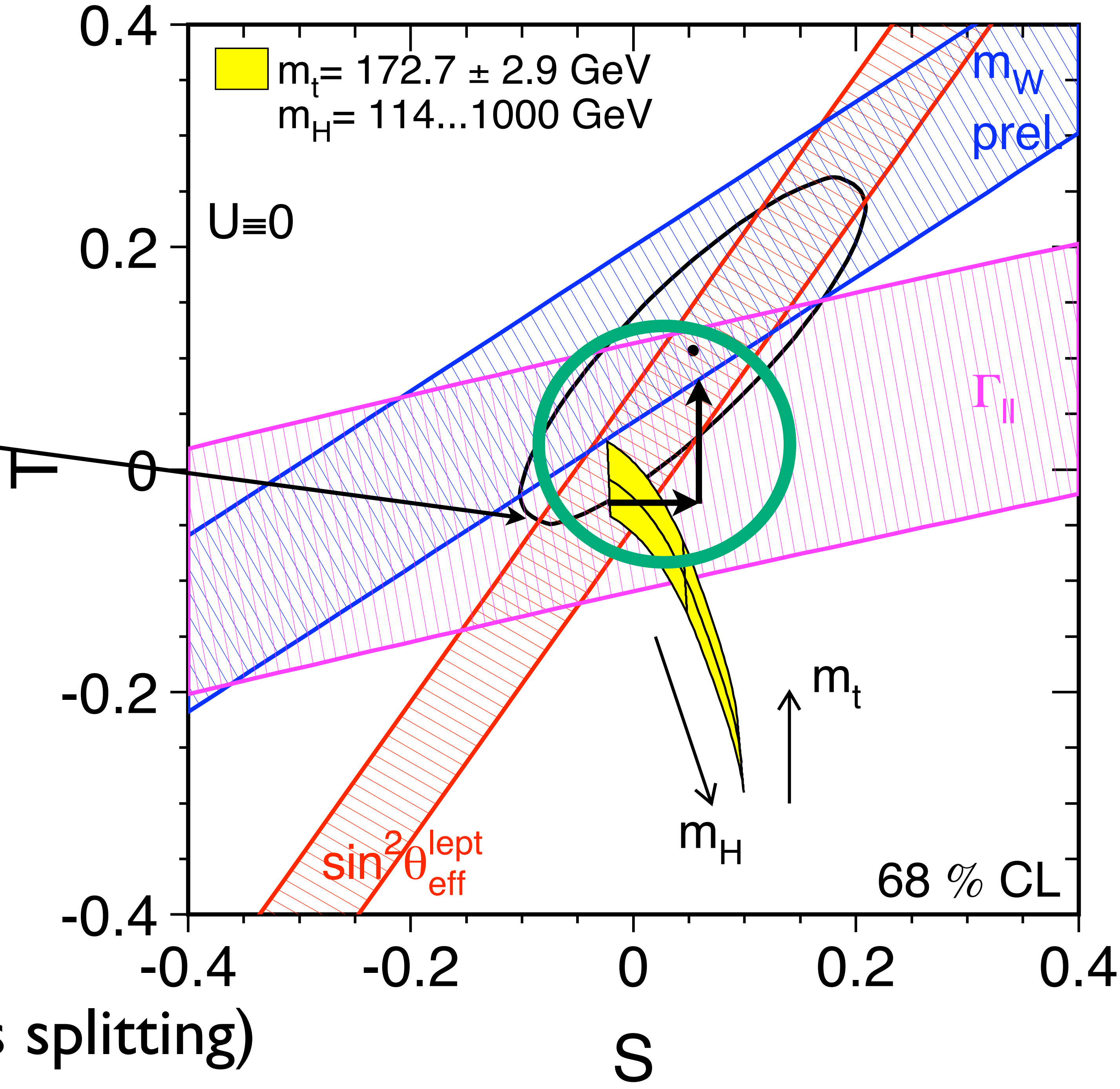
Gambino, '04





mt= 172.7 ± 2.9 GeV
mH= 114...1000 GeV
U≡0
mW
prel.
Γll
mt
mH
sin2θeff lept
68 % CL
T
S
0.4
0.2
0
-0.2
-0.4
-0.4
-0.2
0
0.2
0.4

New Physics?



additions to S,T

new heavy (from Higgs):

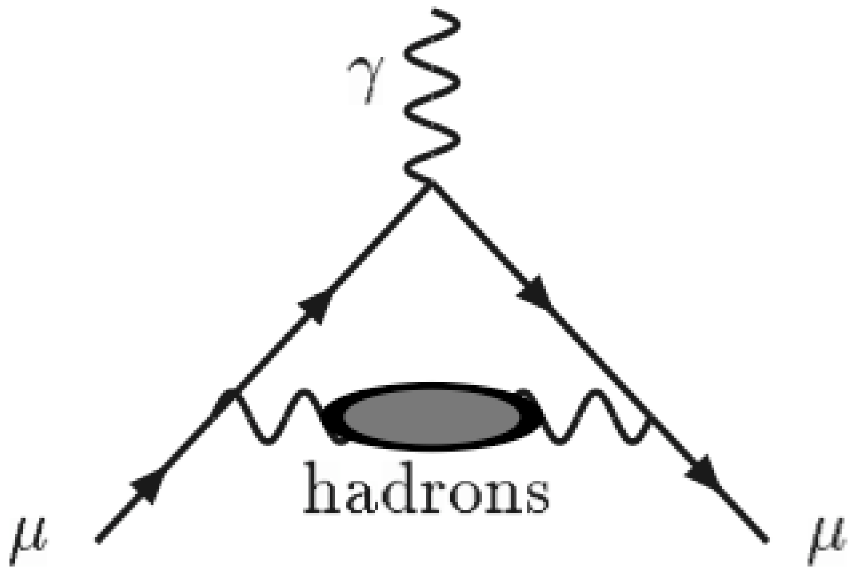
$\ell, e^c, \nu^c, \bar{\ell}, \bar{e}^c, \bar{\nu}^c$

$$\Delta S = \frac{1}{3\pi} \sim 0.1$$

$\Delta T > 0$ (mass splitting)

Muon g-2

$$a_\mu(\text{w.a.}) = 11659203(8) \times 10^{-10}$$



$11\,658\,470.35(28) \times 10^{-10}$ (QED)

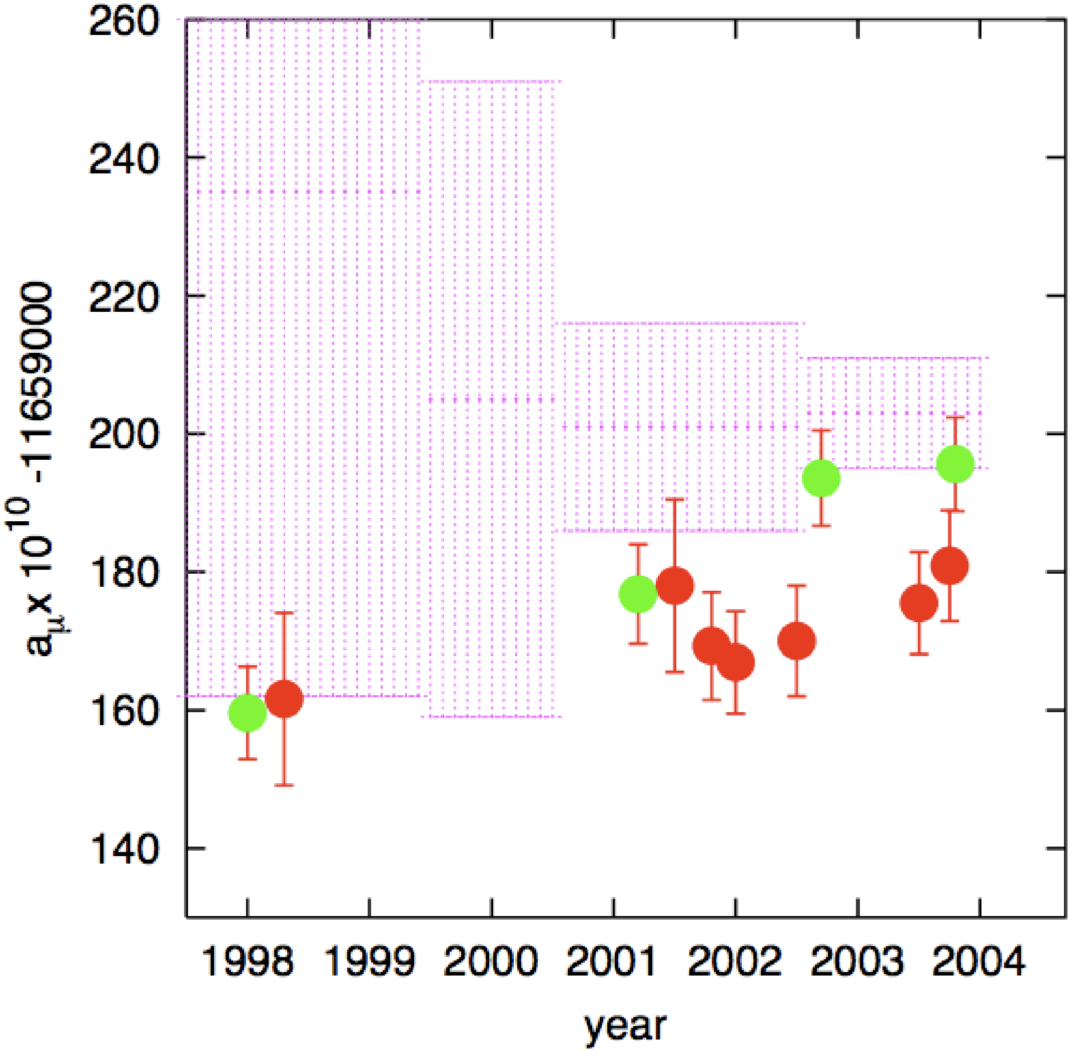
$+694(7) \times 10^{-10}$ (had, Leading Order)

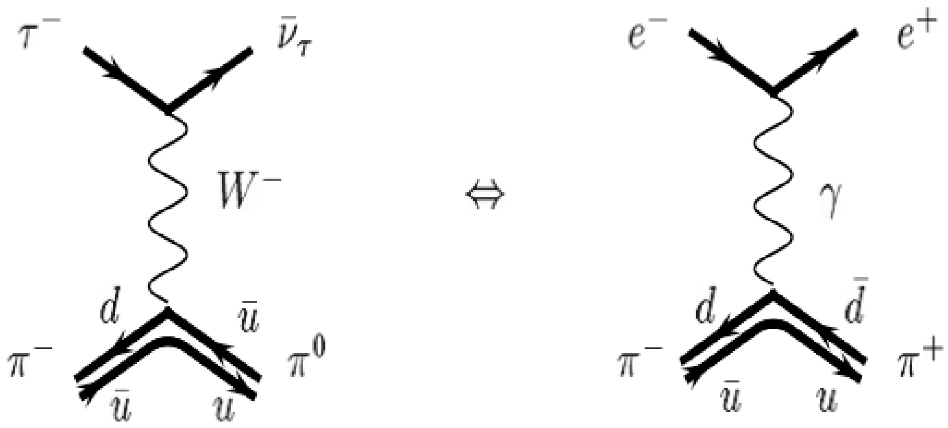
$-10.0(6) \times 10^{-10}$ (had, Higher Order)

$+8(4) \times 10^{-10}$ (had, Light by Light)

$+15.4(2) \times 10^{-10}$ (EW)

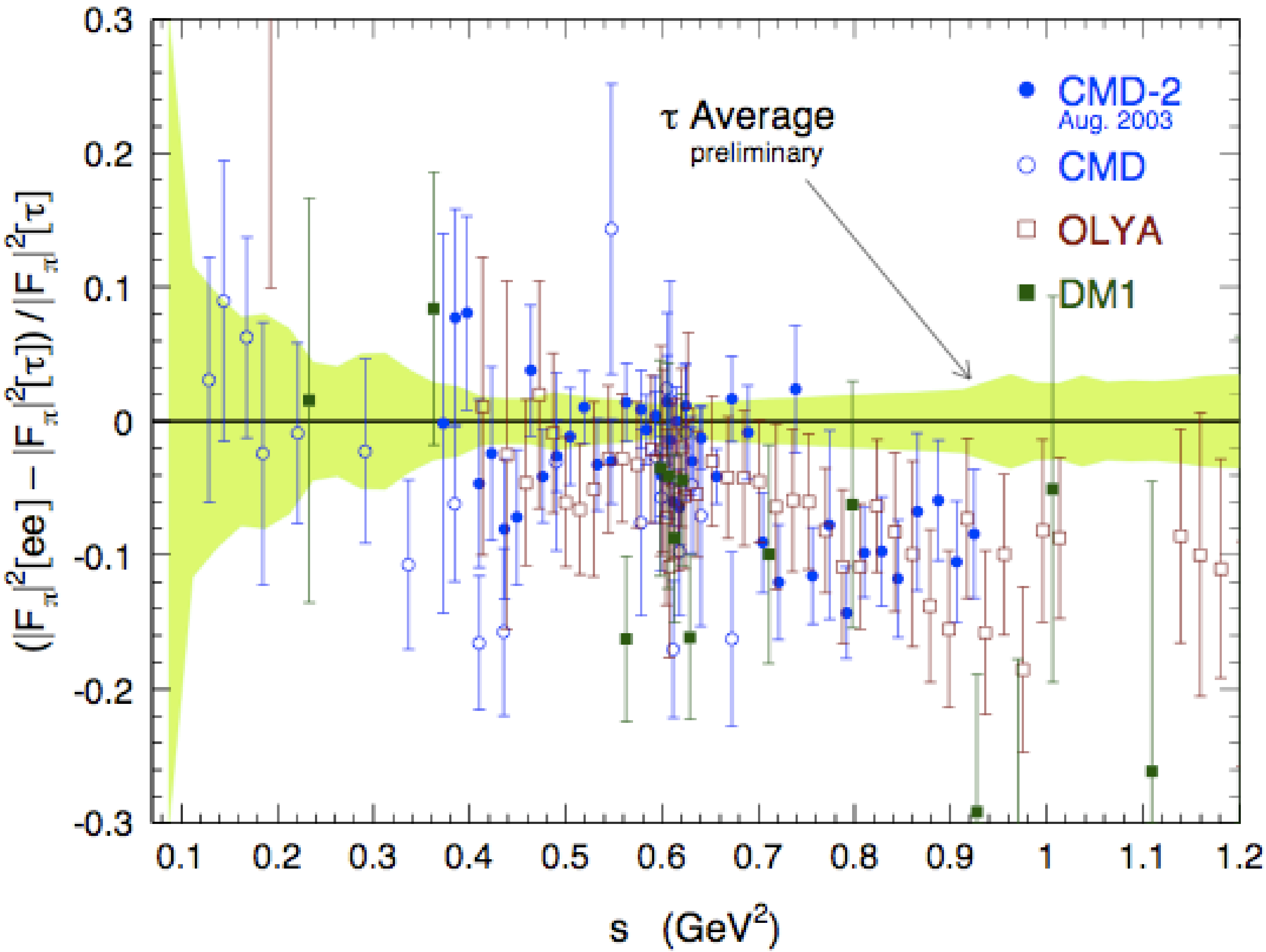
Muon g-2





Straight e+ e- vs. taus

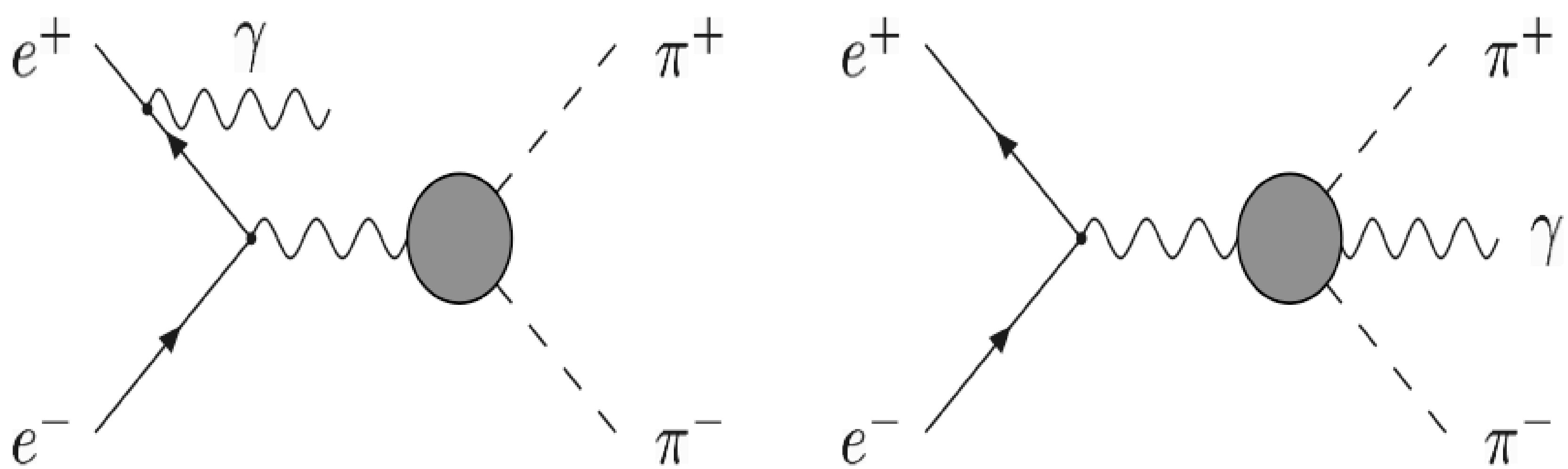
Muon g-2



τ Average
preliminary
CMD-2
Aug. 2003
CMD
OLYA
DM1
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
s (GeV²)
(|Fπ|²[ee] − |Fπ|²[τ]) / |Fπ|²[τ]

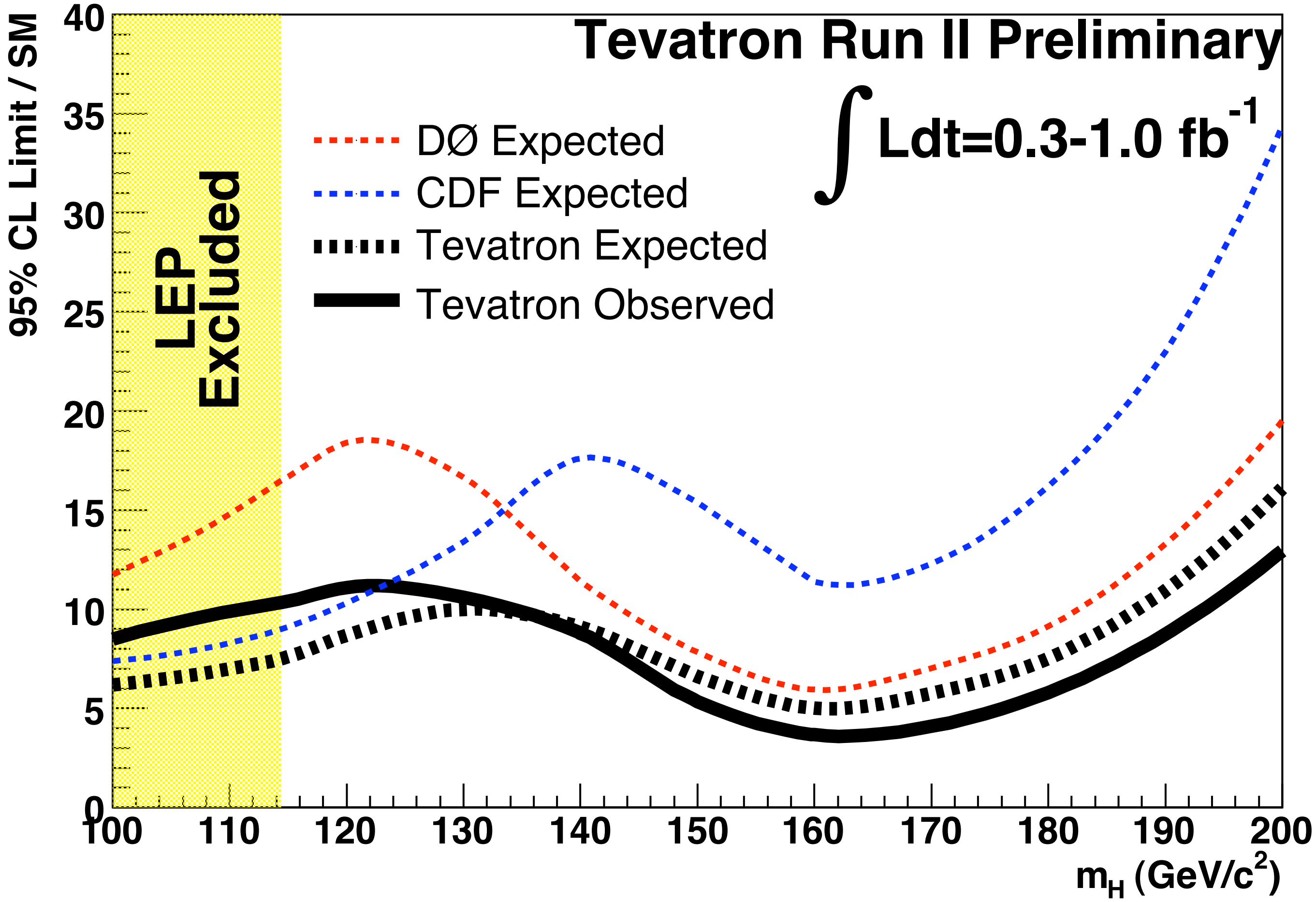
Muon g-2

Babar (and in principle Belle) can do it via radiative return:

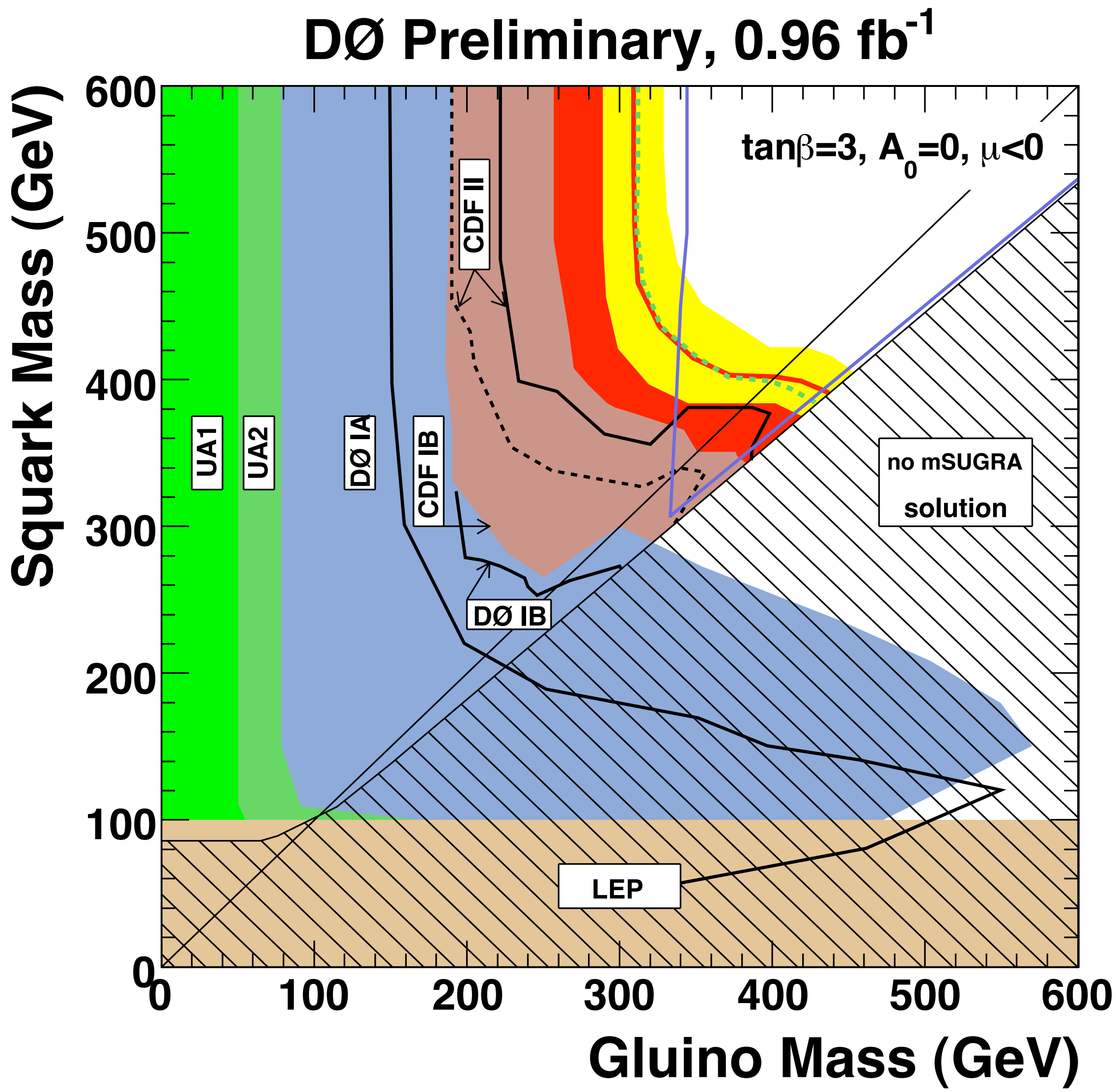


Tevatron Searches

SM Higgs is tough



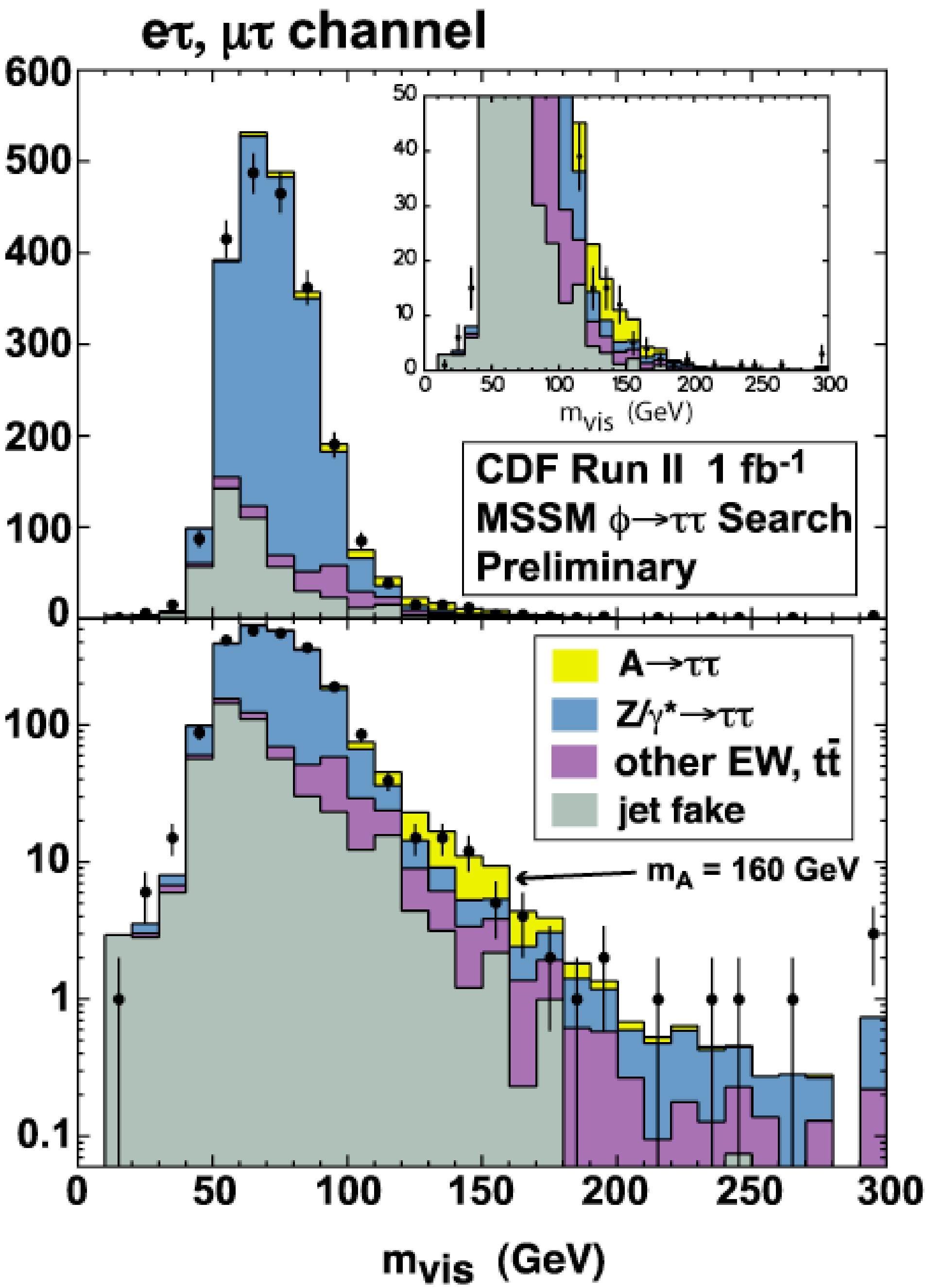
Tevatron - New Particles

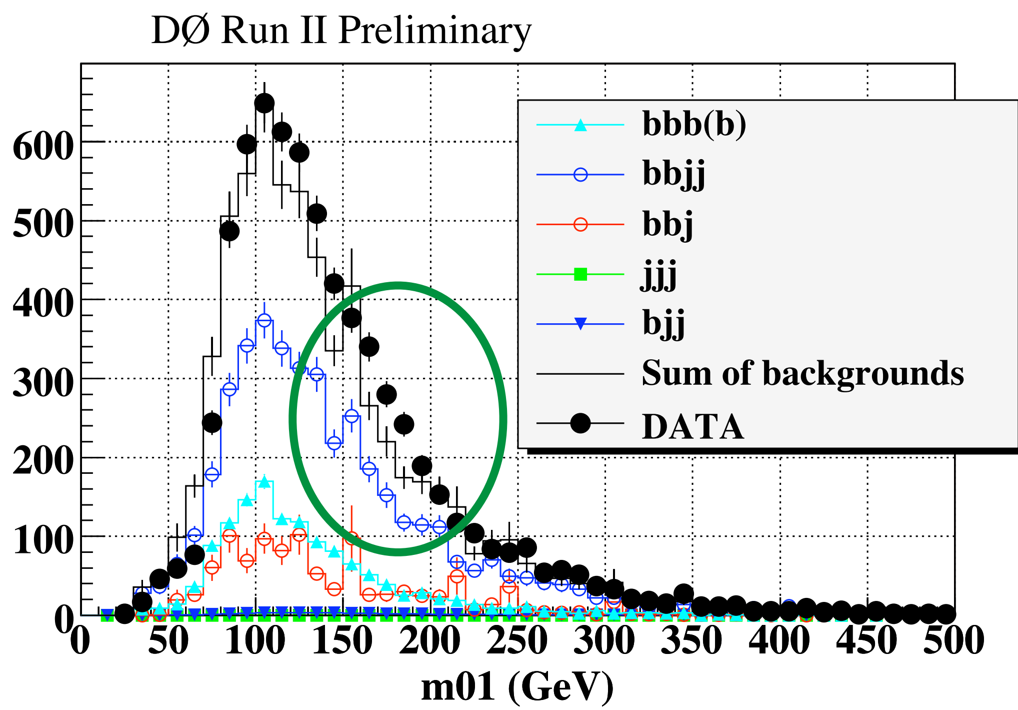


Significant bounds on squarks and gluinos

Tevatron non-SM Higgs

CDF



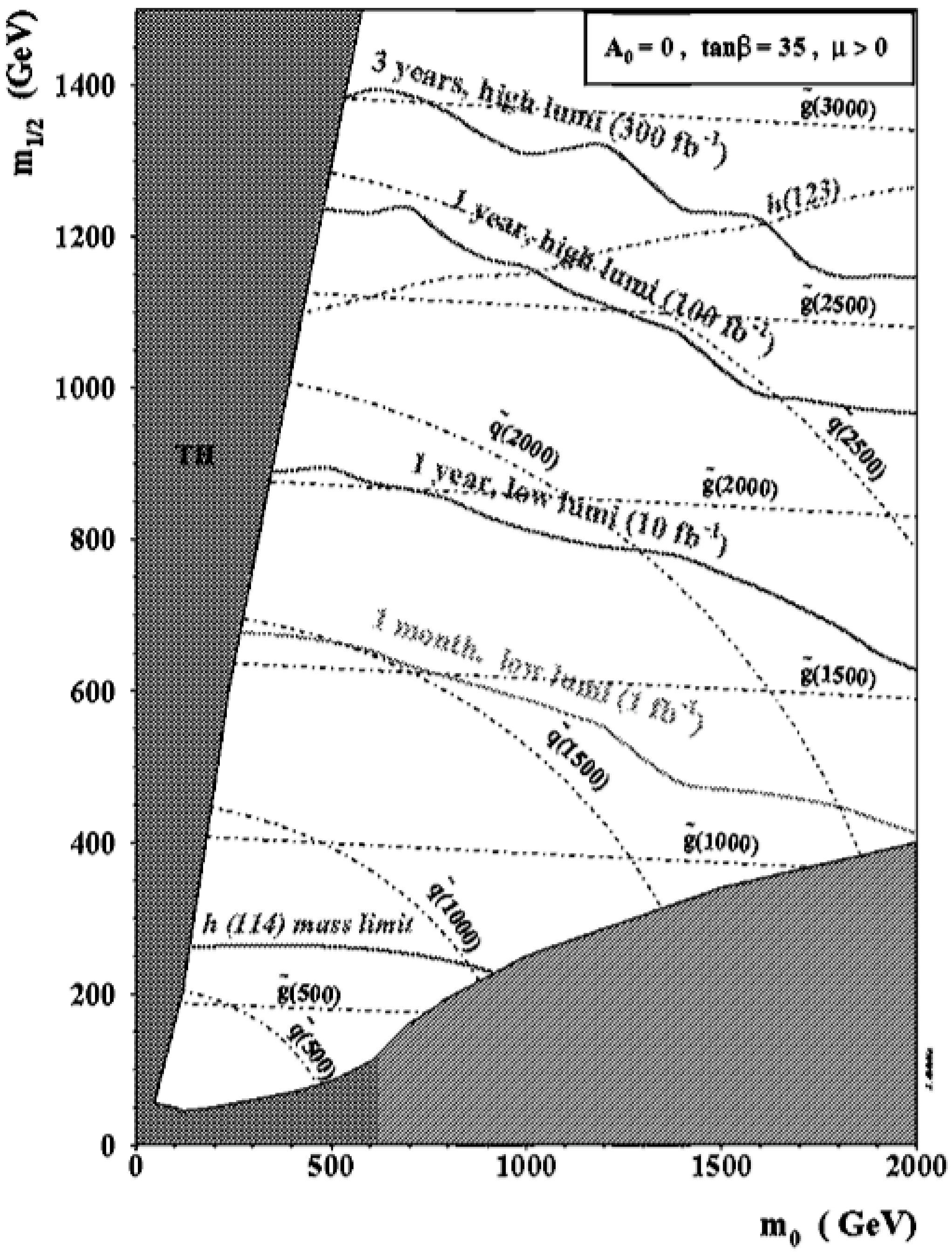


Motivated New Physics

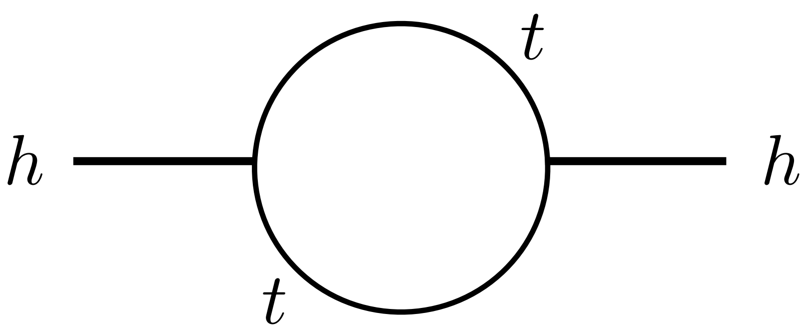
- Natural Electroweak Scale
- Consistent with precision data
- Dark Matter Candidate
- Non-standard Higgs phenomenology

Natural EW Scale

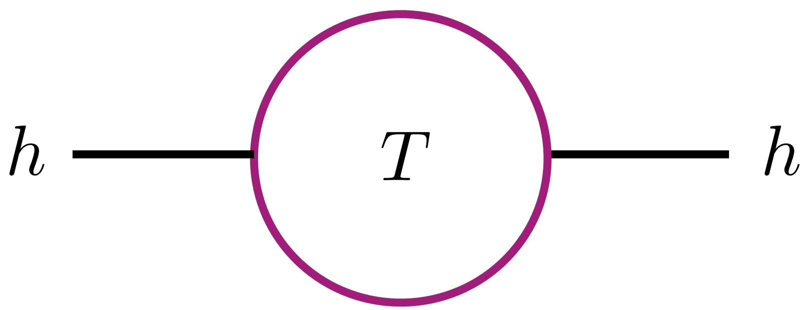
New colored particles at low enough energies to expect a large cross section at hadron colliders - top loop



Model Independent: Weak Coupling



$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2 \Lambda^2$$



$$\delta m_{h(t)} + \delta m_{h(T)} \sim \frac{3}{8\pi^2}\lambda_T^2 M_T^2$$

$$M_T \sim 5 m_h$$

(about 8x and 12x for gauge and Higgs)

EW Precision

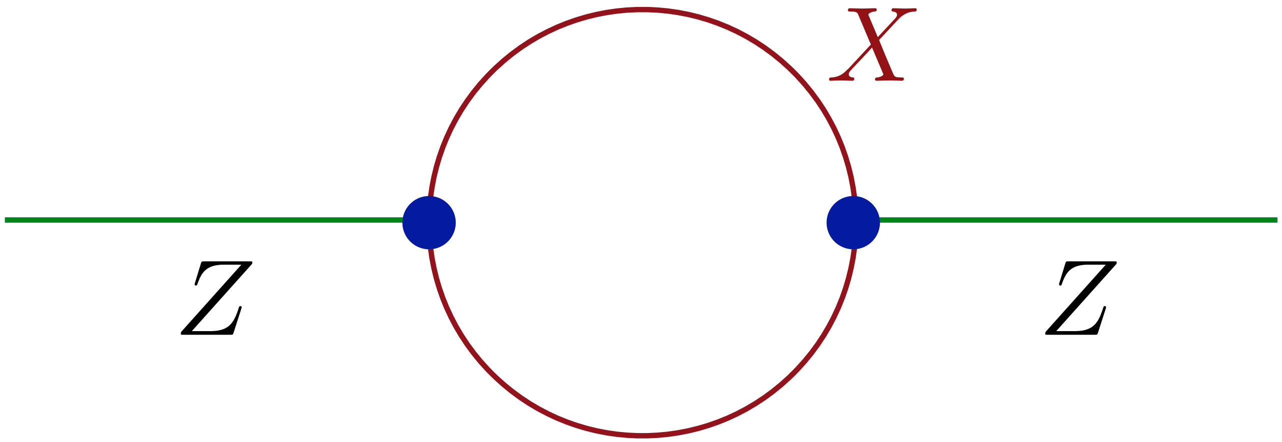
Single couplings can be avoided if new particles are "odd" under a new parity symmetry (and SM particles are "even").

Few Per Mil Corrections...

$$\delta M_Z^2 \sim \delta (M_Z^0)^2 \left(1 + \frac{M_Z^2}{M_{Z'}^2}\right)$$

$M_{Z'} > 1 - 2$ TeV

Few Per Mil Corrections...



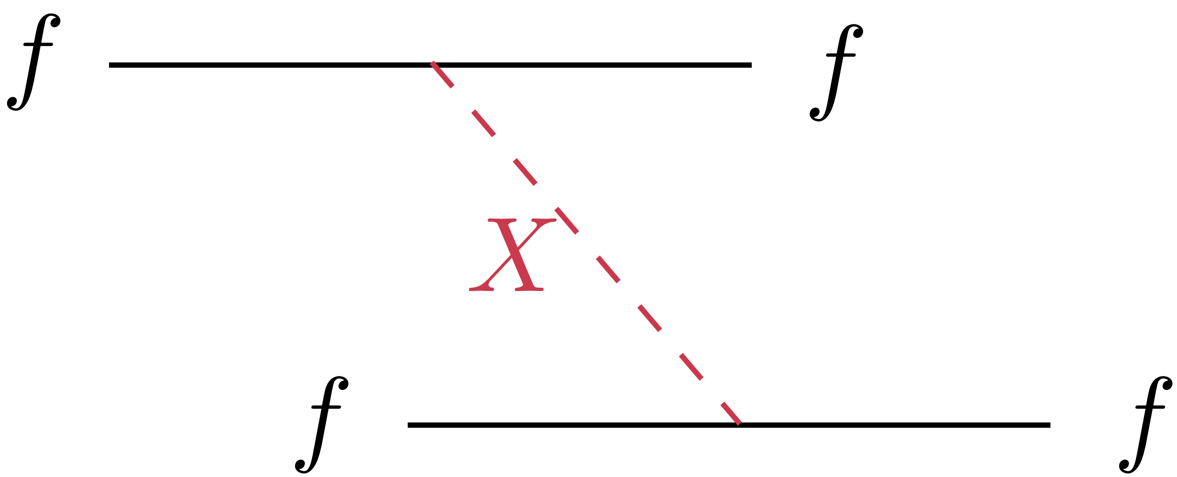
$$\delta M_Z^2 \sim \delta(M_Z^0)^2 \left(1 + \frac{g^2}{16\pi^2}\frac{M_Z^n}{M_X^n}\right)$$

M_X > 100 GeV

Requiring new gauge bosons to be parity odd avoids tree-level mixing

Scalar field exchange

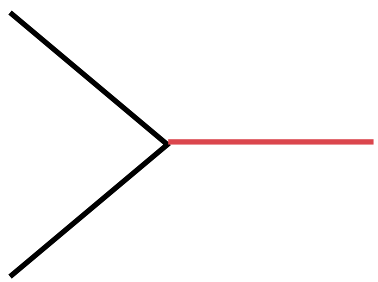
Can mediate flavor-changing neutral currents, or even proton decay.



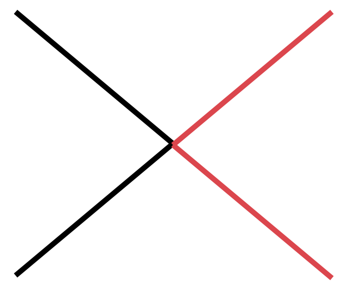
Eliminating single field couplings again can avoid these problems.

New Parity and DM

Dark matter needs a neutral, weakly coupled stable particle



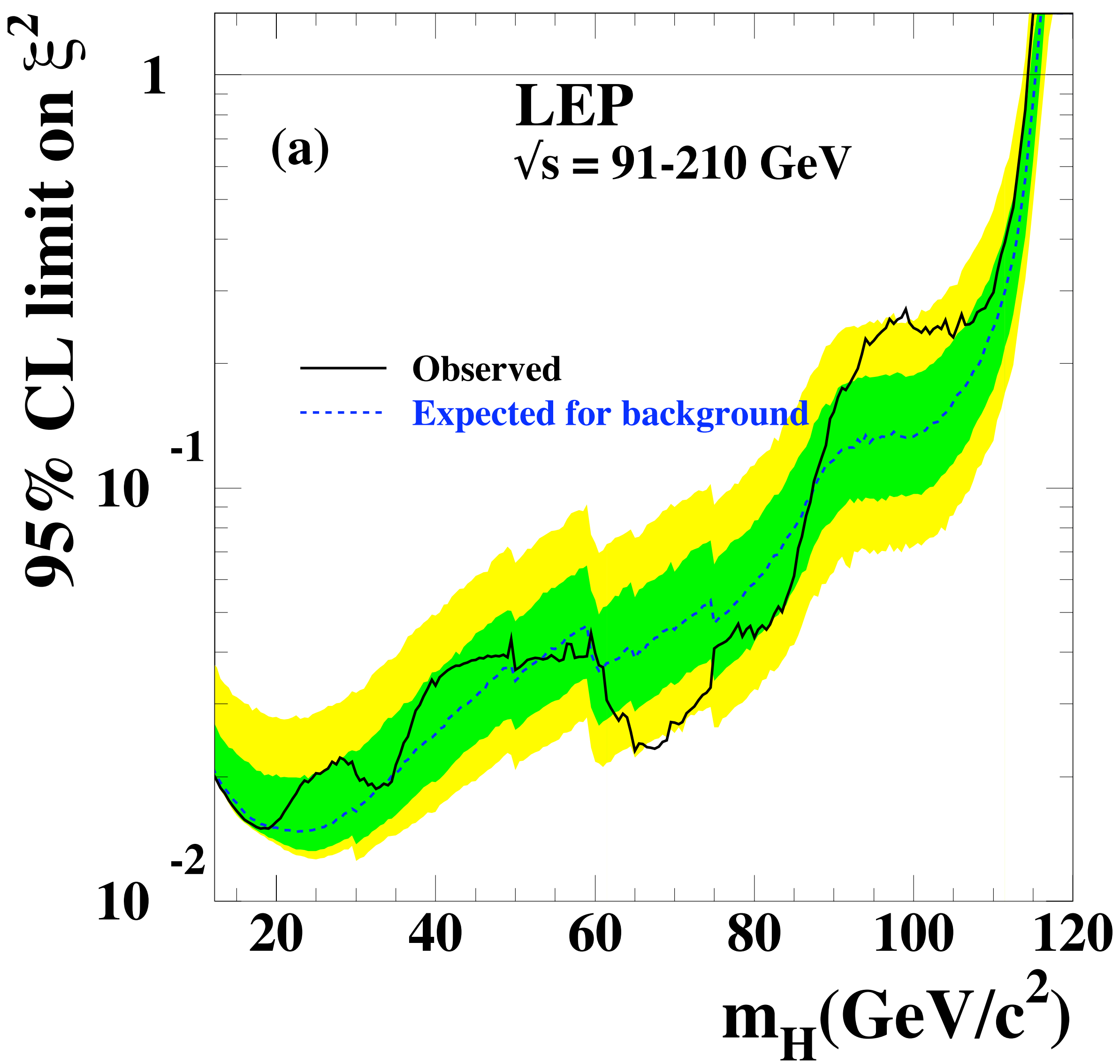
FORBIDDEN



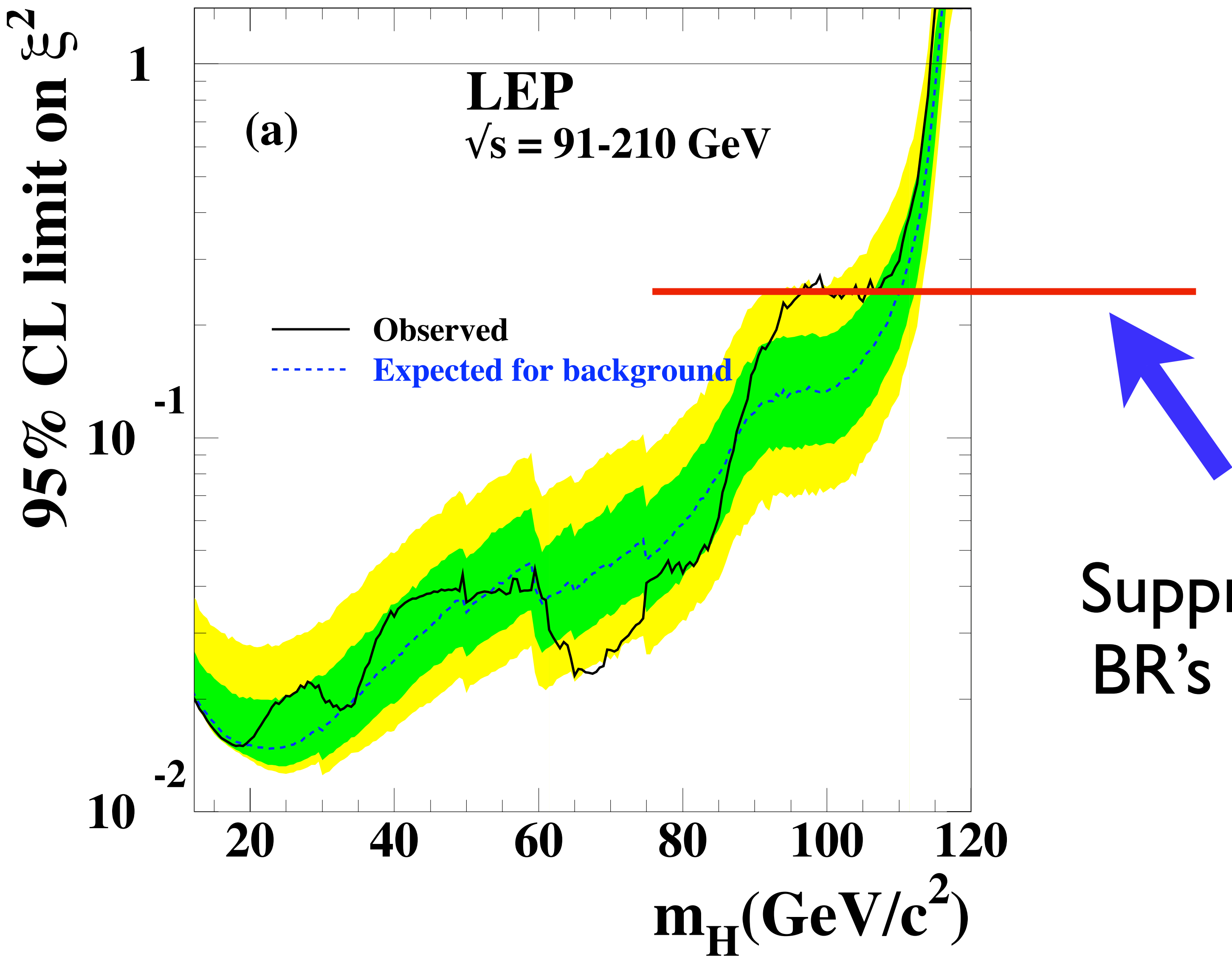
ALLOWED

Lightest Parity Odd Particle (LPOP) will not decay!

Non-Standard Higgs?



Non-Standard Higgs?

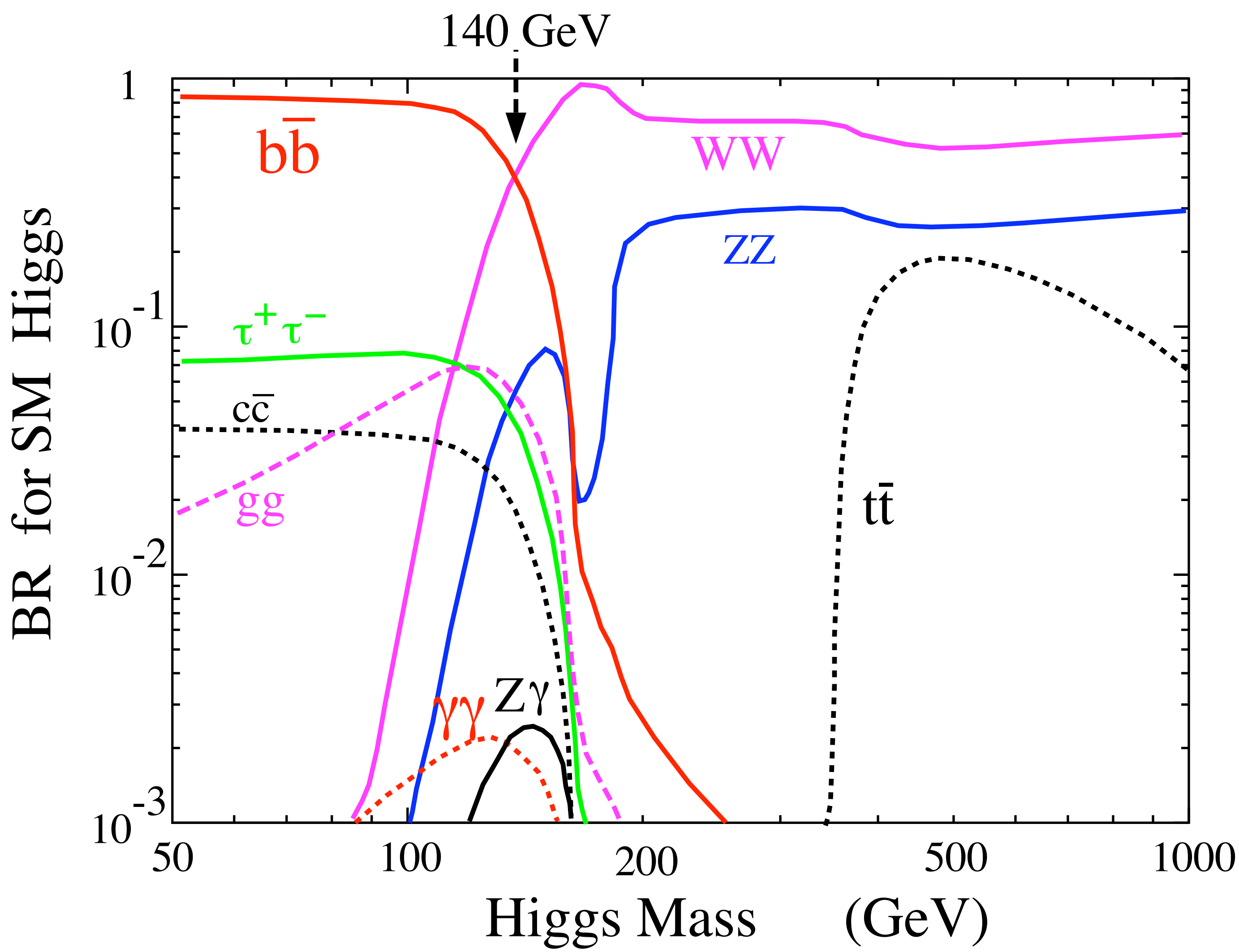


Suppress SM BR's to 20%

Small Higgs Width

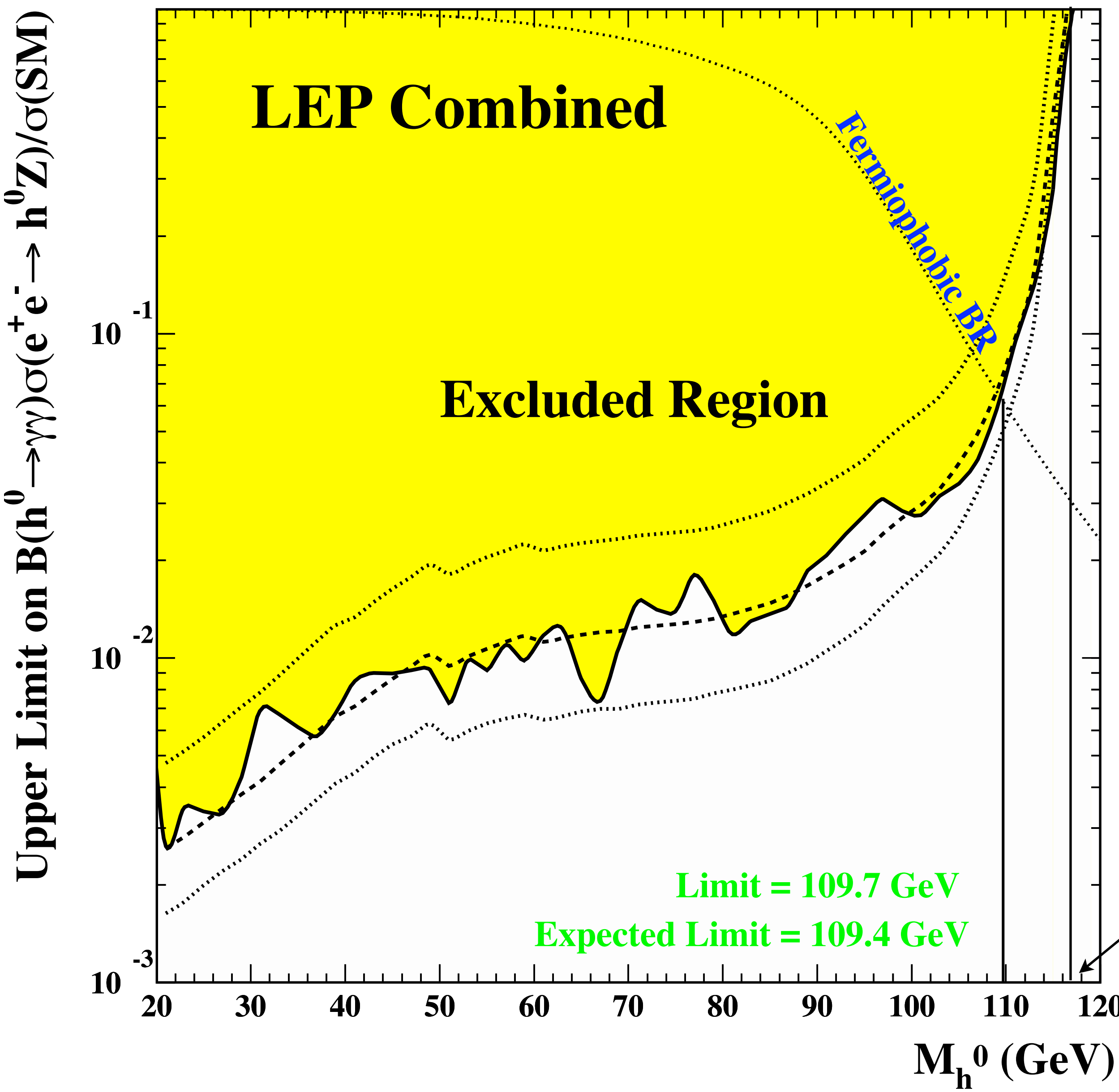
very
sensitive to
new
particles

Small Higgs Width



very sensitive to new particles

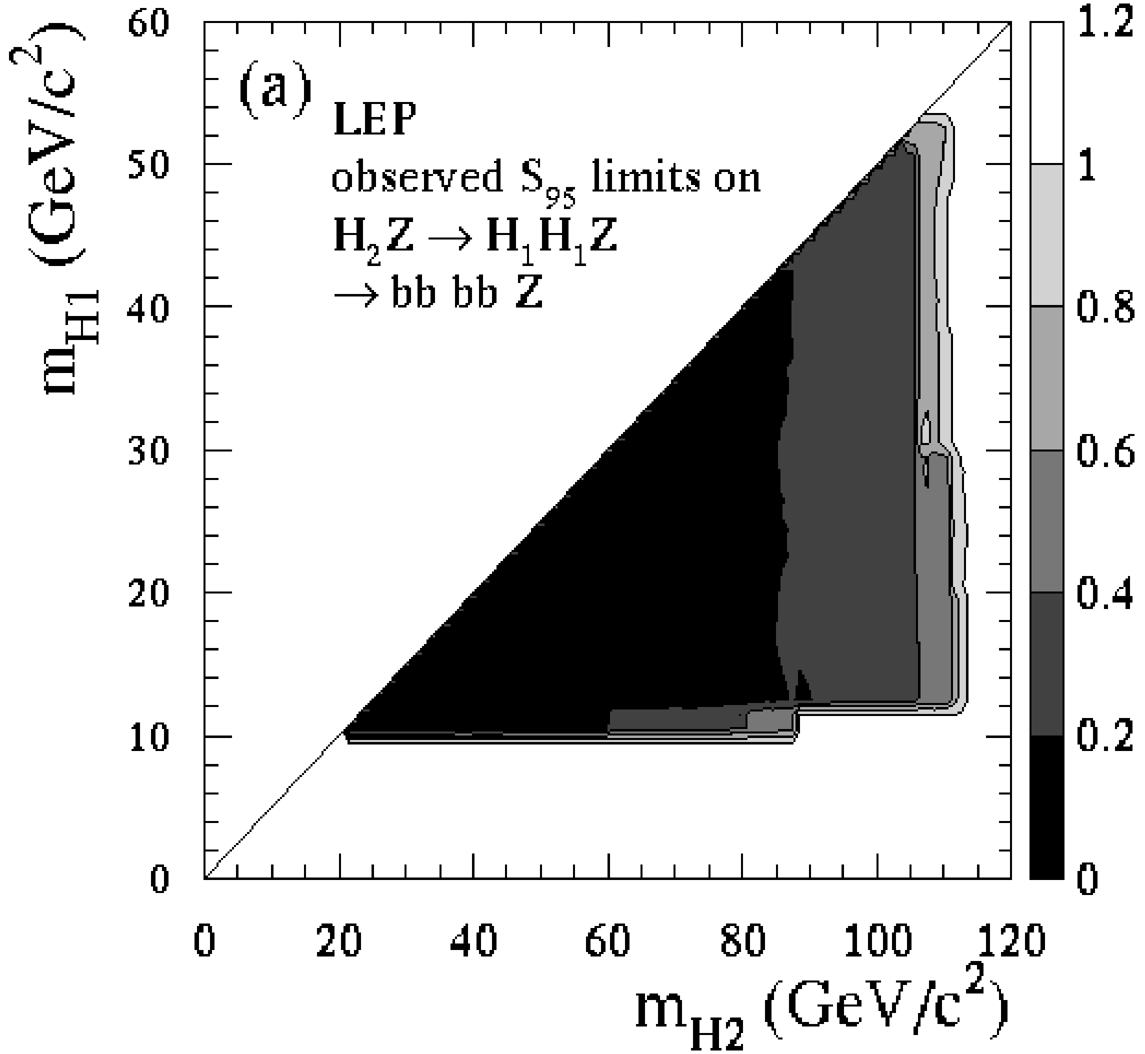
Fermionphobic



Exclusively
2 photons

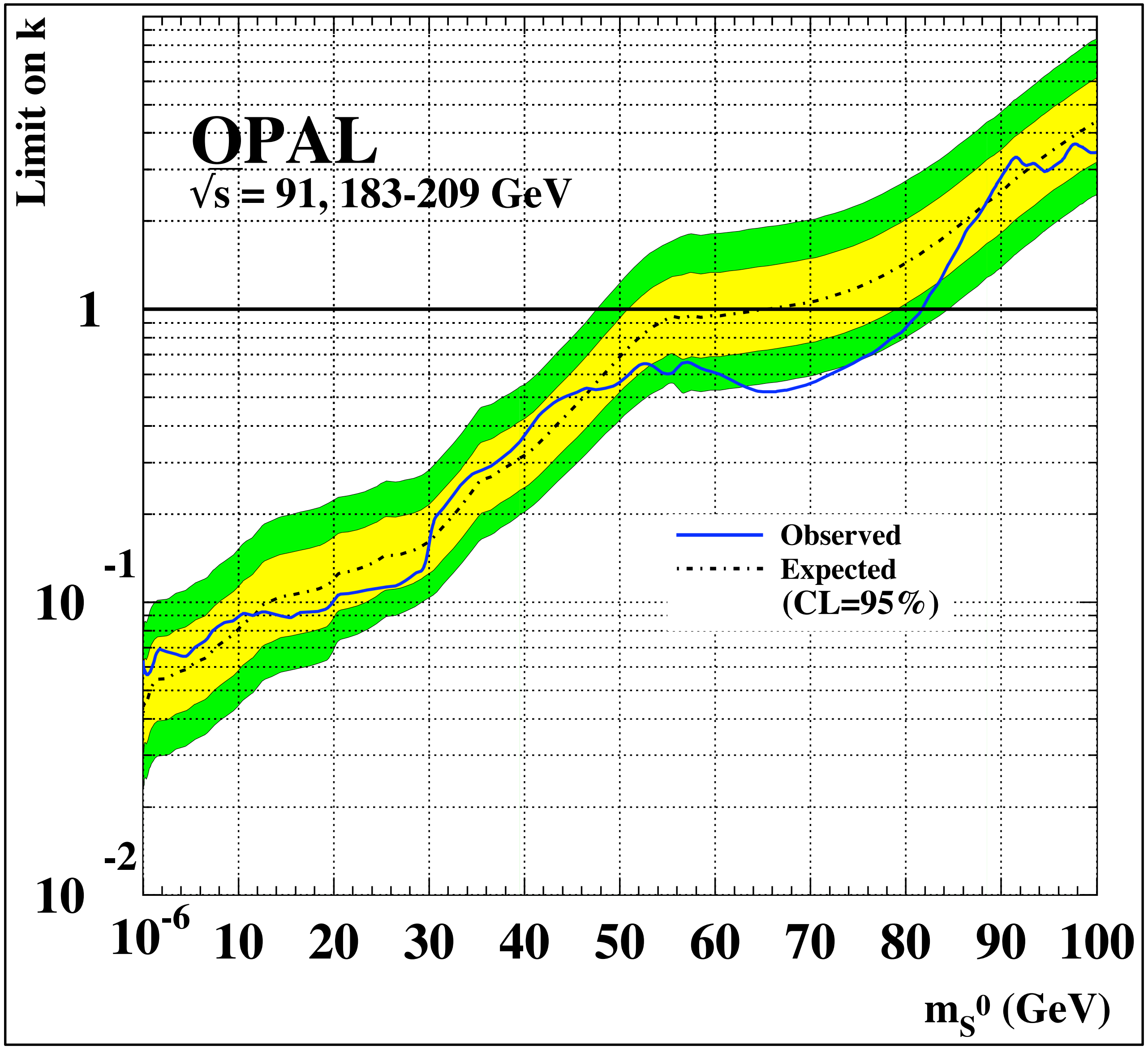
117 GeV

H to 4b



(a)
LEP
observed S_{95} limits on
$H_2Z \rightarrow H_1H_1Z$
$\rightarrow$ bb bb Z
m_{H1} (GeV/c^2)
m_{H2} (GeV/c^2)
0
10
20
30
40
50
60
0
20
40
60
80
100
120
0
0.2
0.4
0.6
0.8
1
1.2

Model Independent



New Higgs decays?

$$h \to a^0 a^0 \to b\bar{b}b\bar{b} \qquad m_h > 110 \text{ GeV}$$

$$h \to a^0 a^0 \to \tau\bar{\tau}\tau\bar{\tau} \qquad m_h > 86 \text{ GeV}$$

$$h \to a^0 a^0 \to gggg \qquad m_h > 86 - 100 \text{ GeV?}$$

$$h \to a^0 a^0 \to 6\pi^0 \qquad m_h > 117 \text{ GeV}$$

$$h \to a^0 a^0 \to 4\gamma \qquad m_h > 117 \text{ GeV}$$

$$h \to ss \to a^0 a^0 a^0 a^0$$

$$\to b\bar{b}b\bar{b}b\bar{b}b\bar{b} \qquad m_h > 82 \text{ GeV???}$$

Tomorrow

Supersymmetry, standard and not