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The Road Ahead

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It's been a rough road for the hadron-collider community:

- Death of SSC (1993)
- Delay in Tevatron, LHC schedules
- Slow turn-on of Run II luminosity
- Big discoveries in other areas (ν, cosmology)

⋮

But we've also had many successes, and there are good reasons for optimism

CERN $Sp\bar{p}S$ - designed to discover W, Z

W, Z discovered 1983

Nobel Prize (Rubia + van der Meer) 1984

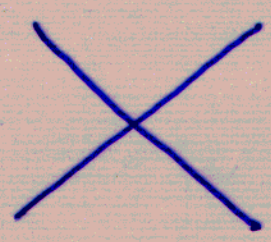
Tevatron - designed to mass-produce W, Z

$M_W = 80.454 \pm 0.059$ GeV (0.07%)

Run IIa ≈ 0.030 GeV expected

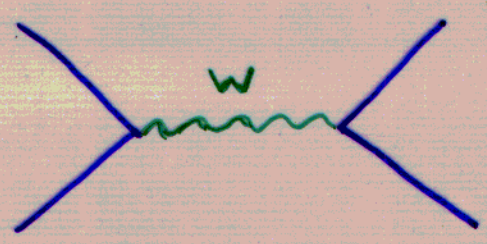
We delivered what we promised

Discovered the "weak scale" $\equiv M_W$



Fermi theory

$E < M_W$



$SU(2) \times U(1)_Y$ theory

$E > M_W$

We delivered more than what we promised

Top quark - most dramatic discovery at the Tevatron (thus far)

1977 b quark discovered

~1980 $m_t > 15$ GeV

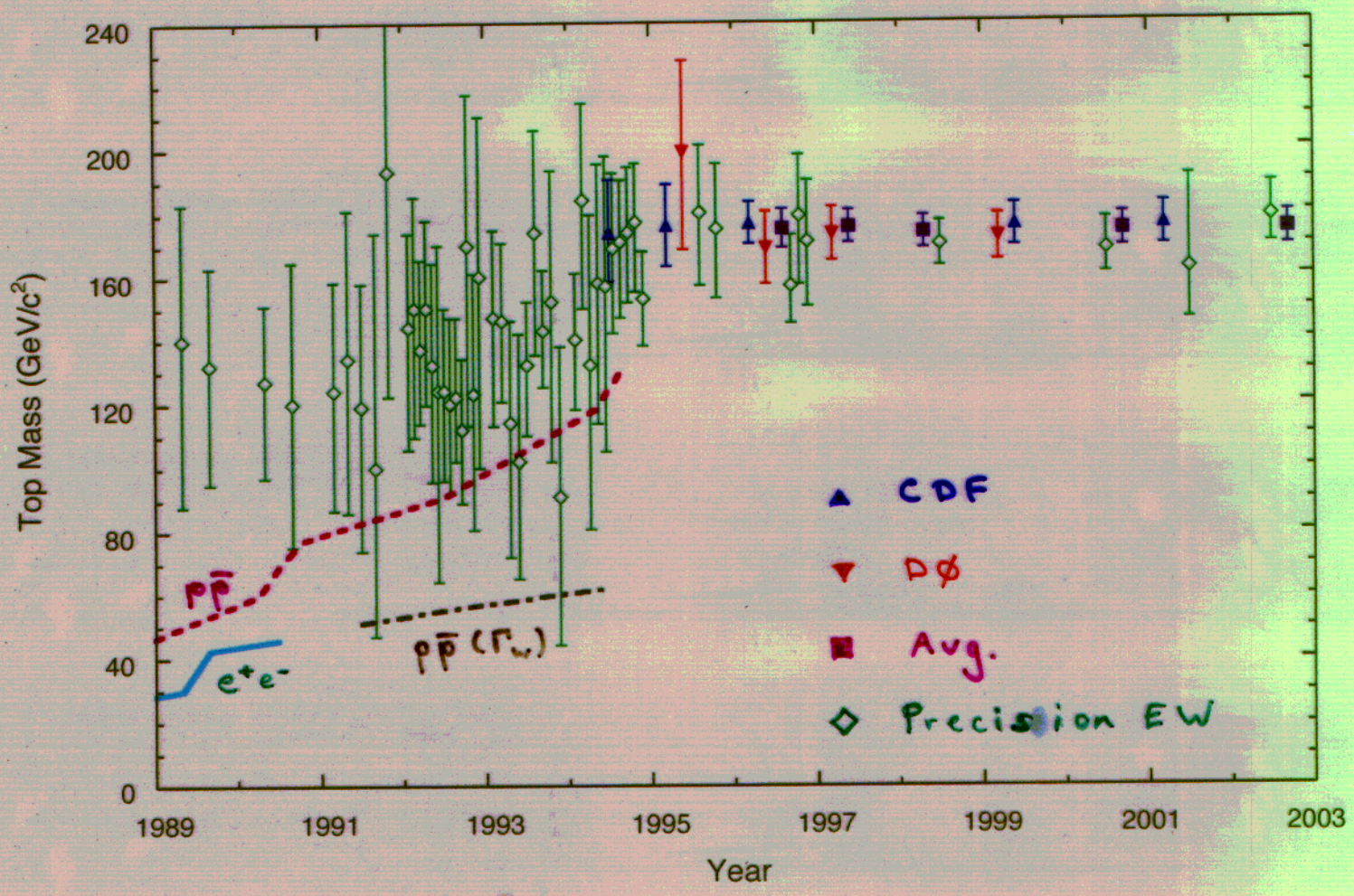
1984 $m_t \approx 40$ GeV ? (UA1)

1987 $m_t < 200$ GeV (precision EW)

1989 LEP, SLC

1995 t quark discovered

$m_t \approx 175$ GeV


240
200
160
120
80
40
0
Top Mass (GeV/c²)
1989
1991
1993
1995
1997
1999
2001
2003
Year
pp̄
e⁺e⁻
pp̄ (Γw)
CDF
DØ
Avg.
Precision EW

Quigg

- Top quark was <u>not</u> a central motivation for $Sp\bar{p}S$ or Tevatron
- We anticipated the existence of top ...
- ... and we used precision EW data to narrow its mass range ...
- ... but <u>the large top mass was a real surprise</u>

We developed new techniques

SVX b tagging

1983 b lifetime measured

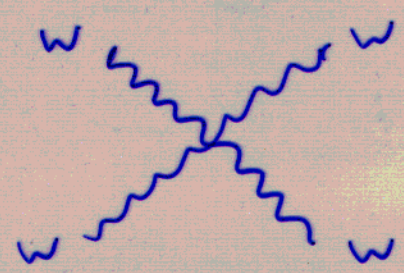
1988 $\epsilon_b \sim$ small

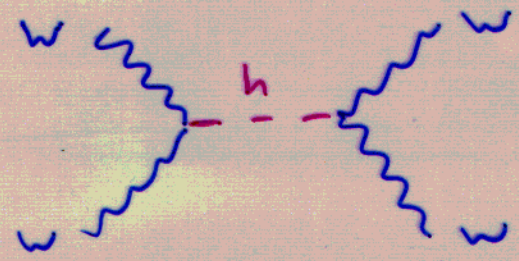
1995 $\epsilon_b \approx 50\%$

Main motivation for LHC:

Discover the physics of electroweak symmetry breaking

Example: Standard Model



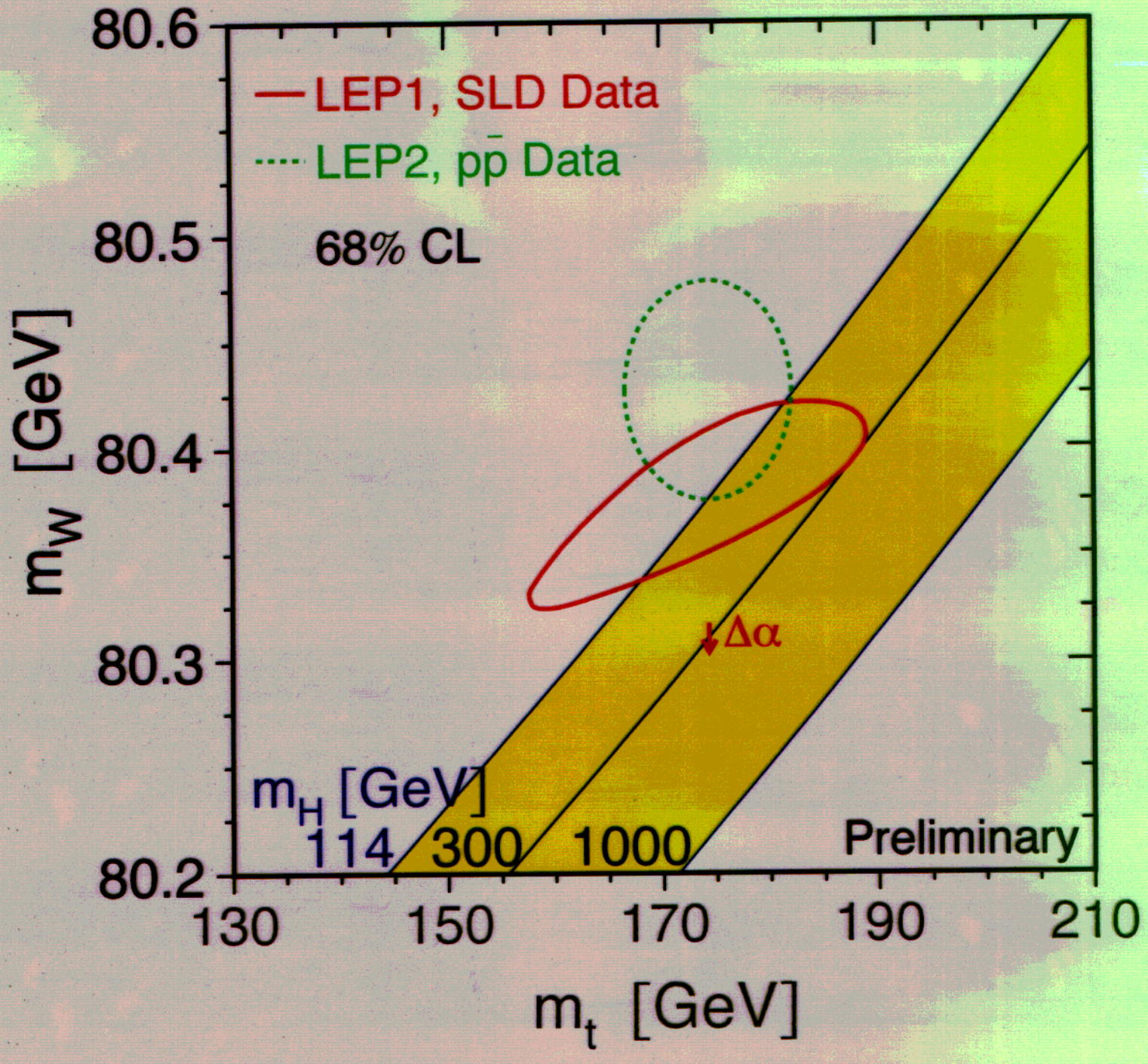


$SU(2) \times U(1)_Y$ theory — Standard Model

$E < m_h$ — $E > m_h$

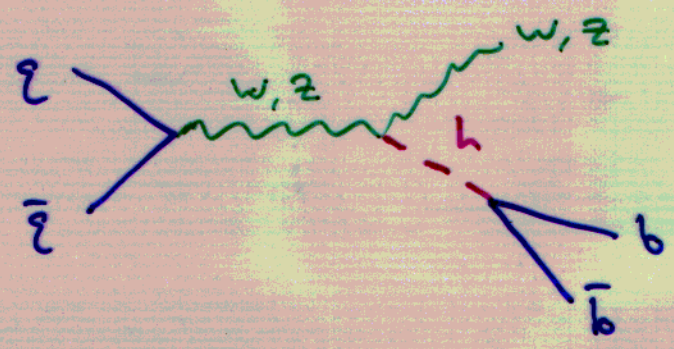
Non-linear realization — Linear realization

m_h is "scale of electroweak symmetry breaki


LEP1, SLD Data
LEP2, $p\bar{p}$ Data
68% CL
$\Delta\alpha$
m_H [GeV]
114
300
1000
Preliminary
80.6
80.5
80.4
80.3
80.2
m_W [GeV]
130
150
170
190
210
m_t [GeV]

LEP EWWG

Light Higgs might be accessible at Tevatron



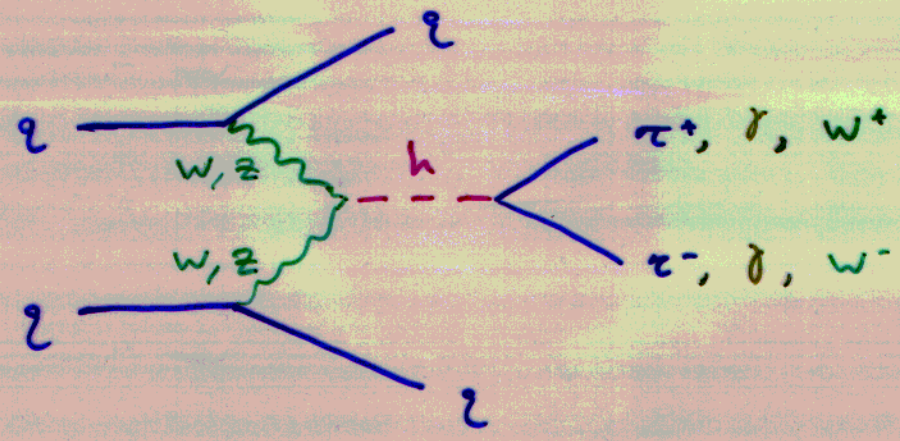
- Higgs was not a motivation for Tevatron
- b tagging essential
- Requires a lot of integrated luminosity...

... but recall

1996	TeV 2000 study	$\Delta m_t = 13$ GeV	(70 pb⁻
1998	CDF, DØ	$\Delta m_t = 5.1$ GeV	(100 pb

"Data make you smarter" Amidei + Broc

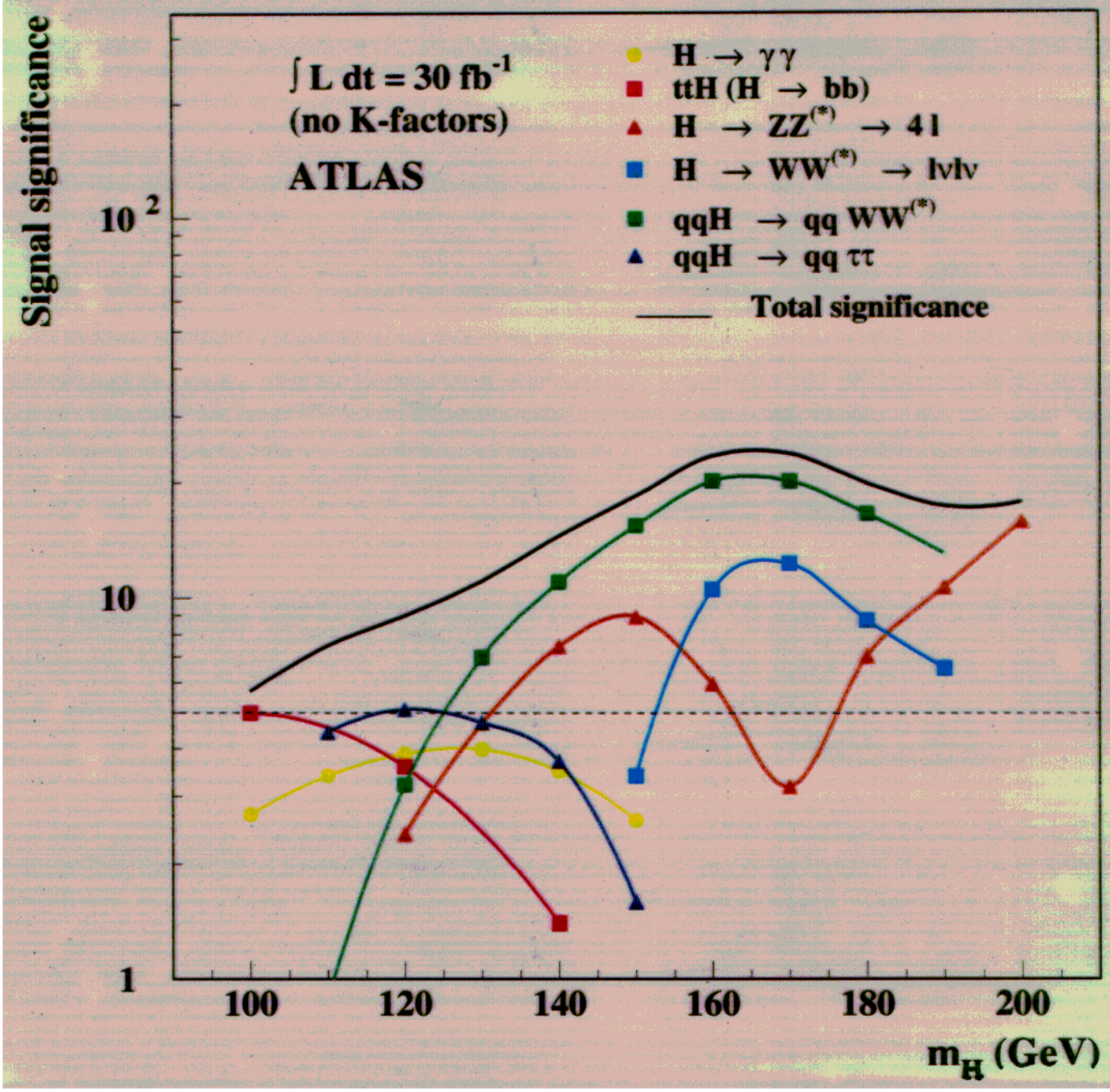
Vector-boson fusion as a source of light Higgs

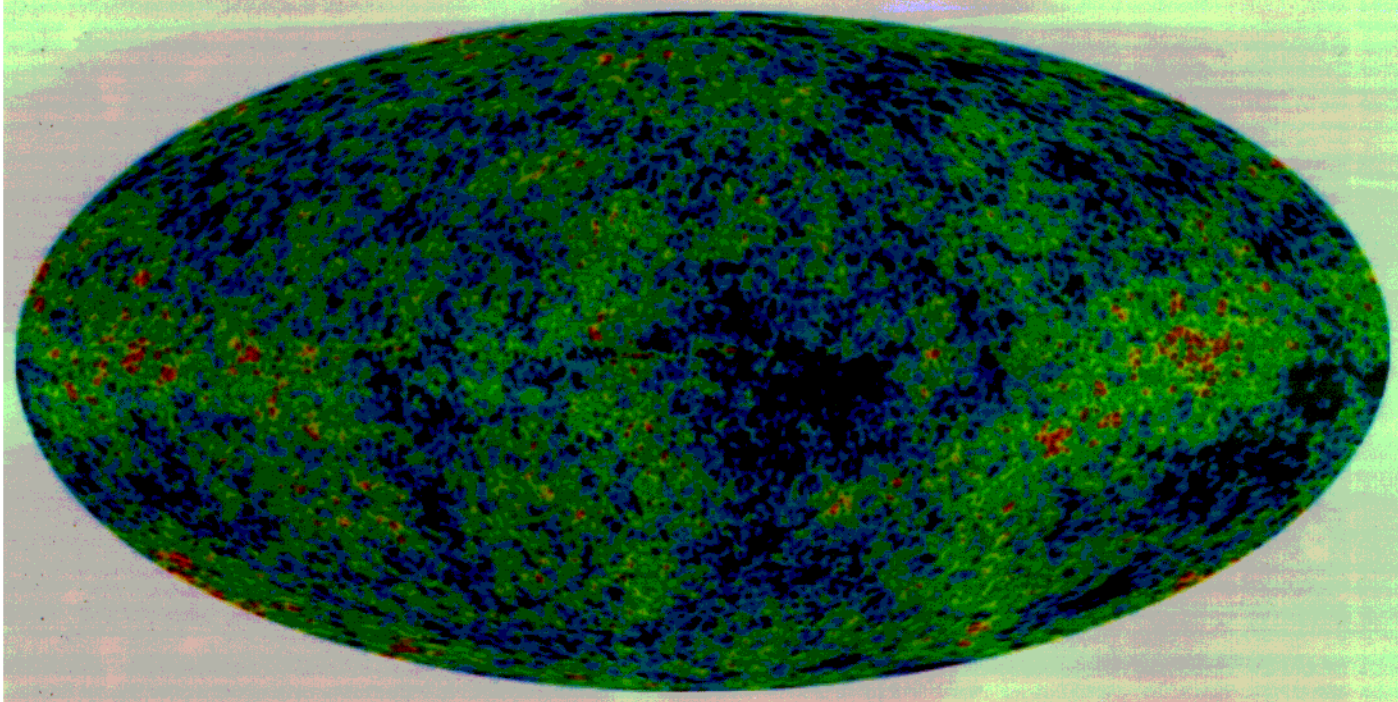


Rainwater
+ Zeppenfeld

"Studies make you smarter"

K. Jacobs


∫ L dt = 30 fb^{-1}
(no K-factors)
ATLAS
H → γγ
ttH (H → bb)
H → ZZ$^{(*)}$ → 4l
H → WW$^{(*)}$ → lνlν
qqH → qq WW$^{(*)}$
qqH → qq ττ
Total significance
Signal significance
10^2
10
1
100
120
140
160
180
200
m_H (GeV)



$$\Omega_{TOT} = \Omega_B + \Omega_{DM} + \Omega_\Lambda = 1.02 \pm 0.02$$

$$\Omega_B = 0.044 \pm 0.004$$

$$\Omega_{DM} = 0.22 \pm 0.04$$

$$\Omega_\Lambda = 0.73 \pm 0.04$$

$\Omega_{TOT} = 1$ and other features are consistent with inflation

Dark matter - Could we find it at the LHC?

- Was not a motivation for LHC
- Potentially more exciting than physics of electroweak symmetry breaking
- SUSY candidate -

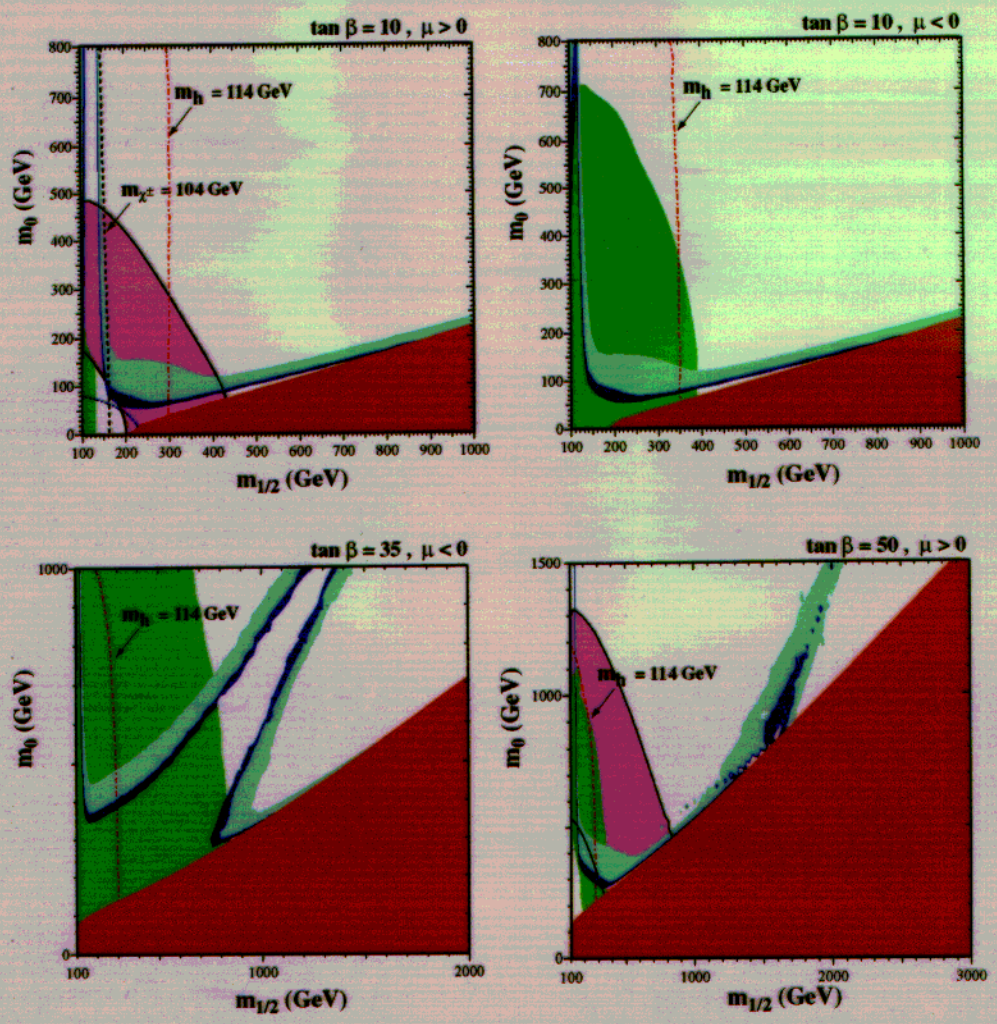
  "neutralino" = Higgsino + Zino + Photino

  But SUSY generically produces too much dark matter

Dark energy

- Why isn't it huge? ($\Lambda \sim M_p^2$)
- Why isn't it zero?

Neither dark matter nor energy were anticipate



χ-τ̃ annihil

χχ → h → ...

Figure 1: *The* $(m_{1/2}, m_0)$ *planes for (a)* $\tan\beta = 10, \mu > 0$, *(b)* $\tan\beta = 10, \mu < 0$, *(c)* $\tan\beta = 35, \mu < 0$, *and (d)* $\tan\beta = 50, \mu > 0$. *In each panel, the region allowed by the older cosmological constraint* $0.1 \leq \Omega_\chi h^2 \leq 0.3$ *has medium shading, and the region allowed by the newer cosmological constraint* $0.094 \leq \Omega_\chi h^2 \leq 0.129$ *has very dark shading. The disallowed region where* $m_{\tilde{\tau}_1} < m_\chi$ *has dark (red) shading. The regions excluded by* $b \to s\gamma$ *have medium (green) shading, and those in panels (a,d) that are favoured by* $g_\mu - 2$ *at the 2-*σ *level have medium (pink) shading. A dot-dashed line in panel (a) delineates the LEP constraint on the* $\tilde{e}$ *mass and the contours* $m_{\chi^\pm} = 104$ *GeV* ($m_h = 114$ *GeV) are shown as near-vertical black dashed (red dot-dashed) lines in panel (a) (each panel).*

Ellis, Olive,
Santoso, Spano

Neutrino mass

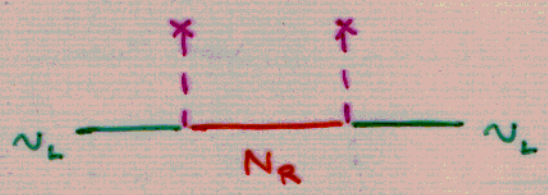
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{matrix} u_R \\ d_R \end{matrix}$$

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \begin{matrix} N_R \\ e_R \end{matrix}$$ ← has $SU(2) \times U(1)_Y$ allowed mass

Electron mass:

$$m_e \sim y v$$

Neutrino mass:



$$m_\nu \sim y^2 \frac{v^2}{M_R}$$

$$M_R \approx 10^{15}\ \text{GeV} \Rightarrow m_\nu \sim 10^{-5} - 10^{2}\ \text{eV}$$

Langacker
Phys. Rep. 19[illegible]

We anticipated neutrino masses ...

... but not the large mixing angles

$\theta_{12} \approx 30°$ $\quad \theta_{23} \approx 45°$

Grand Unification

$SU(5) \to SU(3)_c \times SU(2)_L \times U(1)_Y$

- Fails in SM
- Succeeds in MSSM due to two Higgs doublets and their superpartners
- Also succeeds in SM w/ six Higgs doublets, but $M_U \approx 10^{14}$ GeV $\to$ p decay
- N_R suggests SO(10):

$SU(5)$: $\bar{5} + 10 + 1$ ← N_R

$SO(10)$: 16

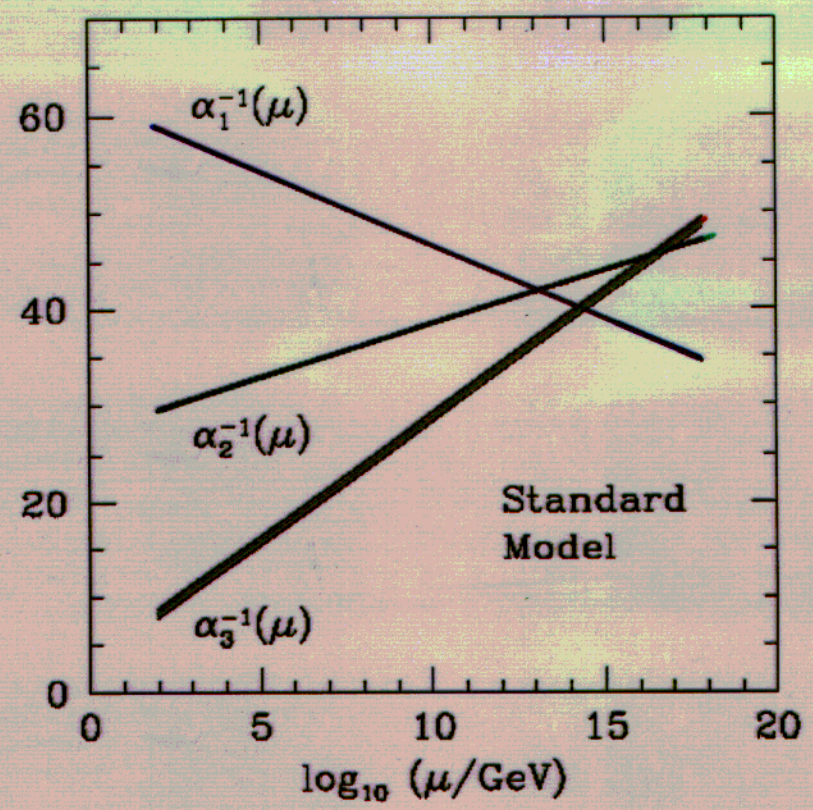
$SO(10) \to SU(5) \to SU(3)_c \times SU(2)_L \times U(1)_Y$

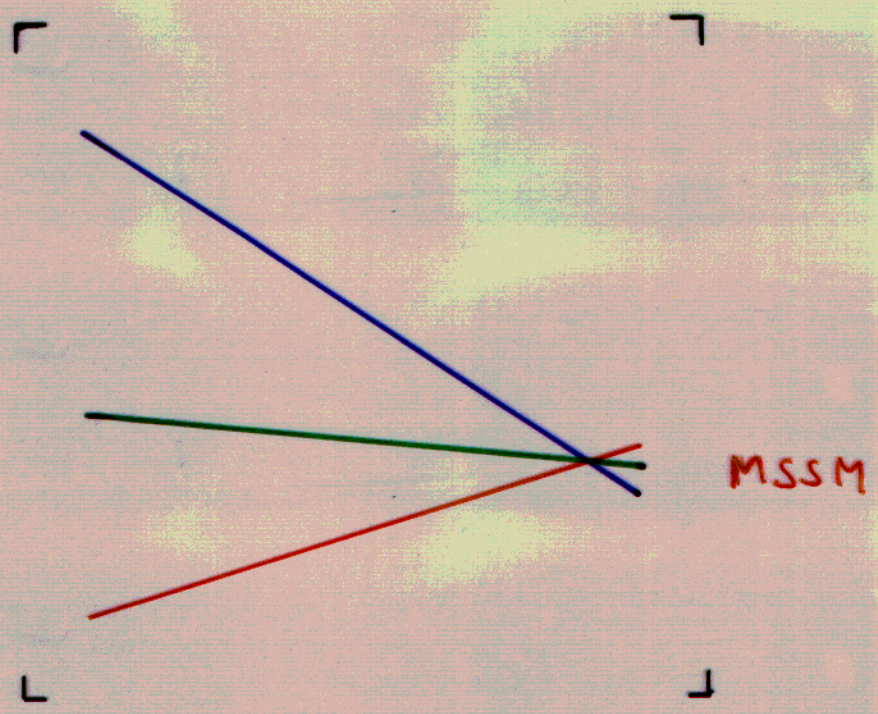
Other (non-SUSY) possibilities also open; e.g.

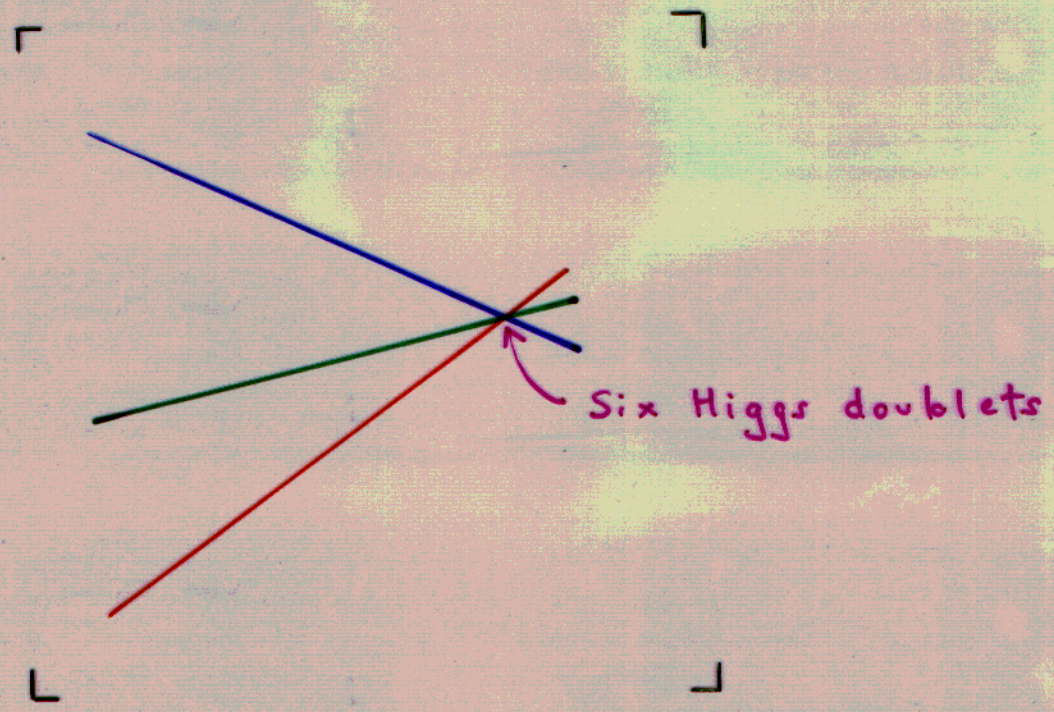
$SO(10) \to SU(4)_c \times SU(2)_L \times SU(2)_R \to SM$

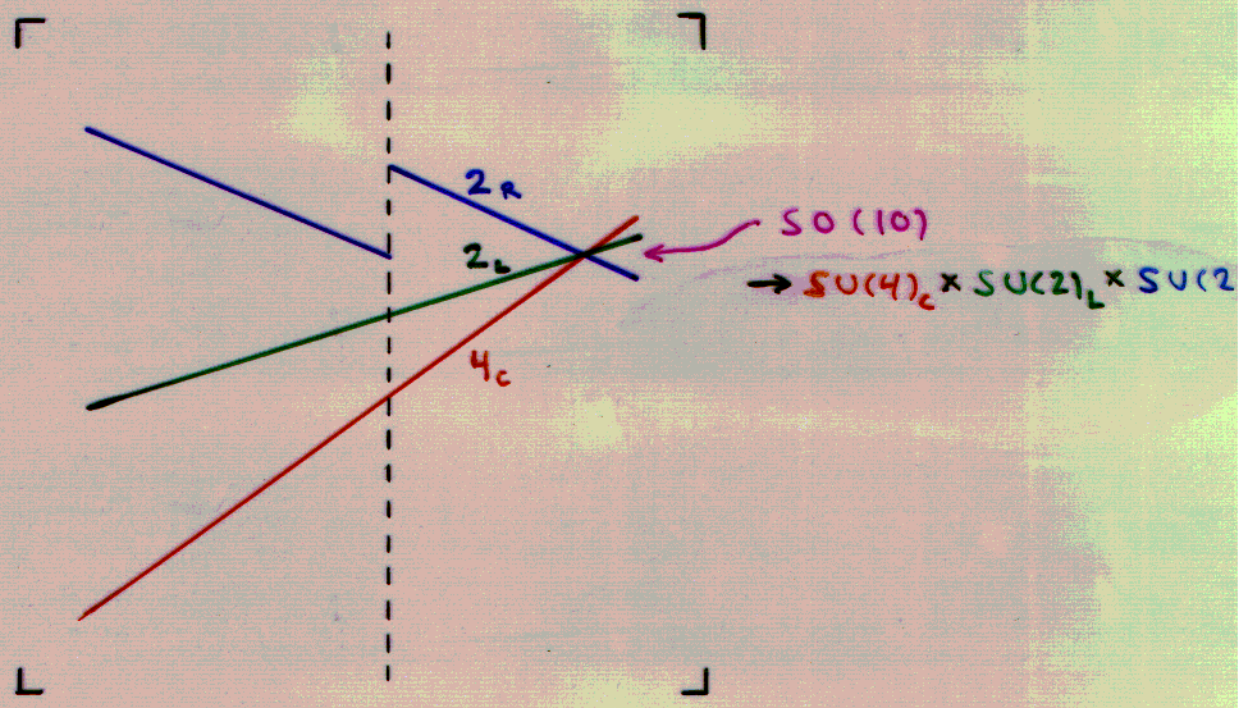
but requires intermediate scale

– lose <u>prediction</u> of $\sin^2\theta_W$


$\alpha_1^{-1}(\mu)$
$\alpha_2^{-1}(\mu)$
$\alpha_3^{-1}(\mu)$
Standard Model
60
40
20
0
0
5
10
15
20
$\log_{10}(\mu/\mathrm{GeV})$

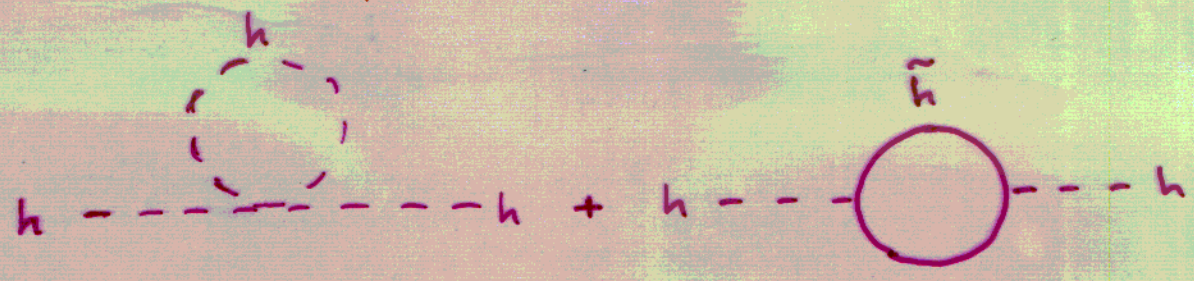

MSSM


Six Higgs doublets


2_R
2_L
4_c
SO(10)
→ $SU(4)_c \times SU(2)_L \times SU(2$

SUSY also stabalizes (but does not explain)

the hierarchy $m_h \ll M_U$ if $M_{SUSY} \lesssim 1$ TeV...



but leaves behind mystery $\Lambda \ll M_{SUSY}^2$

<u>SUSY SU(5) is still attractive, but it's</u>

<u>unlikely we have anticipated the details</u>

<u>LHC will decide</u>

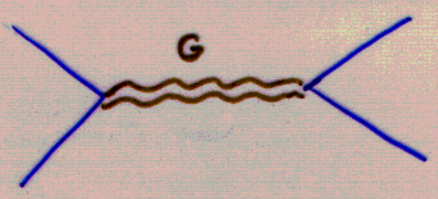
Why the Higgs boson is so important

- We have no experience with fundamental scalar fields ϕ, nor with $\langle \phi \rangle \neq 0$.

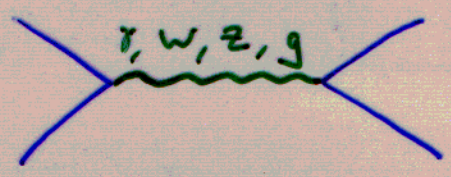
  QCD: $\langle q\bar{q} \rangle \neq 0$

  EW: $\langle T\bar{T} \rangle \neq 0$ Technicolor

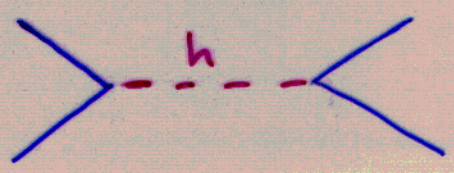
- Higgs boson is a new force of nature



$s=2$



$s=1$



$s=0$

- Higgs is responsible for CKM mixing and $\not{CP}$

$$\mathcal{L}_{Yukawa} = \Gamma_u^{ij}\, \bar{Q}_L^i \epsilon \phi^* u_R^j + \Gamma_d^{ij}\, \bar{Q}_L^i \phi\, d_R^j$$

$\mathbb{C}$, non-diagonal

and similarly for MNS mixing

Why curious pattern of masses and mixing?

- Why is $\Lambda \ll \langle \phi \rangle^2$?

Why is $\Lambda \neq 0$? "Quintessence"?

- What drives inflation? "Inflaton"?

- Grand unification relies on Higgs field(s)

- What is the dark matter?

Neutralino = Higgsino + Zino + Photino

Axions

Higgs is central to SM

<u>and</u>

to physics beyond the SM