Top Secret

The "Truth" Story

C.-P. Yuan

Michigan State University

- Introduction
- Mass of Top Quark, prior to its discovery
- Top & Electroweak Symmetry Breaking
- Properties of Top
- Discriminate Models of Electroweak Symmetry Breaking
- Conclusion

Top Story

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People have long asked,

" What is the world made of? "
and
" What holds it together? "

Elementary Particle Physics
or
High Energy Physics

Studying Fundamental Interactions (Forces) in Nature

Leptons

- Don't feel the strong force
- Integer or Zero charge
- Flavours:

e^-	"electron" (0.511 MeV)	(1897)	In atoms
μ^-	"Muon" (206 m_e)	(1937)	First seen in Cosmic Ray
τ^-	"Tau" (17 m_μ)	(1975)	Seen at SLAC (Stanford Linear Accelerator Center)
ν_e	"electron neutrino" Pauli's explanation of Beta Decay (1930)	(1956)	
ν_μ	"Muon neutrino"	(1962)	
ν_τ	"Tau neutrino"	(2000)	

Mass

$$\nu_e < 3\ \text{eV}$$

$$\nu_\mu < 0.19\ \text{MeV}$$

$$\nu_\tau < 18.2\ \text{MeV}$$

Quarks

- Feel the strong force
- Fractionally charged

$$Q = \begin{Bmatrix} 2/3 \\ -1/3 \end{Bmatrix} \times \text{ Proton charge}$$

- Constituents of neutron and proton
  (udd) (uud)

$\begin{pmatrix} u \\ d \end{pmatrix}$ "up" "down"

- First Evidence:

Stanford Linear Accelerator Center
(Giant Electron Microscope)

- Flavors:

u	"up"		
d	"down"		
s	"strange"		
c	"charmed"	(1974)	
b	"bottom"	(1977)	"Beauty"
t	"top"	(1995)	"Truth"

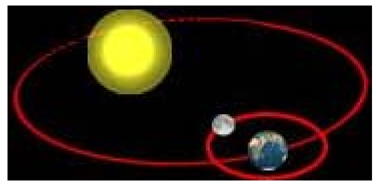
@ Fermilab
(Tevatron)

Interactions

Four forces in Nature

1 Gravity

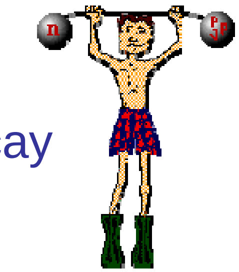
Newton



2 Electromagnetism

Faraday

3 Weak Interaction



Beta (radioactive) decay

Sun is shining

Time scales: $10^{-12} \sim 10^{3}$ sec

4 Strong Interaction

Hold nuclei together

Time scales: 10^{-23} sec

The Standard Model of Particle Physics

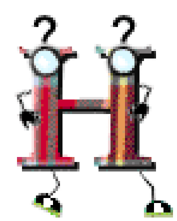
- Gauge Symmetry (Gravity is not included)

$$\underbrace{SU(3)_{\text{Color}}}_{\text{QCD}} \otimes \underbrace{SU(2)_{\text{Left}} \otimes U(1)_{\text{Hyper charge}}}_{\text{WEAK} \oplus \text{QED}}$$

(Strong Interaction)

(Unification of
Weak and Electromagnetic)

Spontaneously Broken
(Higgs Mechanism)



$$U(1)_{\text{E.M.}}$$

QED
(Electromagnetic Interaction)

The Standard Model of Particle Physics

- Matter fields (make up all visible matter in the universe)
  - Fermions (Spin 1/2)

Lepton

(No Strong Interaction)

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

$$e^-_R \quad \mu^-_R \quad \tau^-_R$$

Quarks

(q)

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

$$u_R \; u_R \; u_R \quad c_R \; c_R \; c_R \quad t_R \; t_R \; t_R$$

$$d_R \; d_R \; d_R \quad s_R \; s_R \; s_R \quad b_R \; b_R \; b_R$$

3 families

  - Scalar (Spin 0)

Higgs Boson (Not yet found!)

(From Higgs Mechanism —— Spontaneous Symmetry Breaking)

The Standard Model of Particle Physics

❖ Interactions (mediated by interchanging Gauge Bosons, spin-1 force carrier)

1) Electromagnetic Interaction (QED)

Photon (massless)

2) Strong Interaction (QCD)

Gluon (massless) (1979)

3) Weak Interaction

W^+, W^- and Z Gauge Bosons (1983)

(massive $M_W = 80.42 \text{ GeV}$ $M_Z = 91.187 \text{ GeV}$ $1 \text{ GeV} = 10^9 \text{ eV}$)

In SM, the Mass of W-boson, either $W^\pm$ or Z , arises from the Higgs Mechanism

(Without it, Gauge Bosons have to be massless from gauge principle.)

Higgs Mechanism in the SM

Two outstanding mysteries in the Electroweak theory :

- The cause of Electroweak Symmetry Breaking

  (M_W = 80 GeV, M_Z = 91 GeV)

- The origin of Flavor Symmetry Breaking

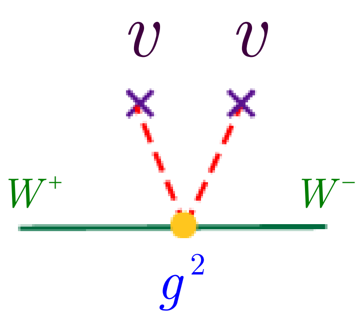
  (Quarks and Leptons have diverse masses.)

Both Symmetry Breaking are accommodated by including a fundamental weak doublet of scalar (Higgs) boson:

$$\Phi = \begin{pmatrix} \frac{v + H + i\,\phi^0}{\sqrt{2}} \\ i\,\phi^- \end{pmatrix}$$

- To generate M_W and M_Z

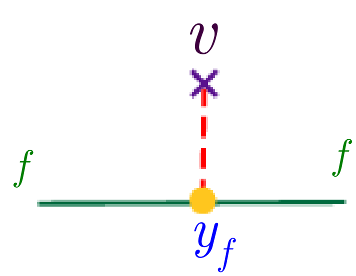
$$L_\Phi = \left(D_\mu \Phi\right)^+ \left(D^\mu \Phi\right) - \lambda\left(\Phi^+\Phi - \frac{v^2}{2}\right)^2$$



$$M_W = \frac{1}{2} g v$$

- To generate m_f

$$y_f \bar{F}_L \Phi f_R + \cdots$$



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

How does SM predict … ?

- In Quantum Mechanics

  Schrodinger Equation:

$$i\frac{\partial \Psi}{\partial t} = H\Psi$$

1. Figure out what H is.
2. Insert H in S.E.
3. Calculate Predictions

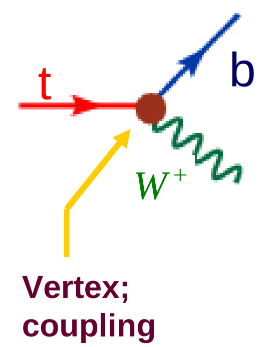
- In Relativistic Quantum Field Theory

  SM gives the Interaction Lagrangian $\mathcal{L}$

$\mathcal{L}$

⇓

Feynman Rules
Feynman Diagrams }



⇓

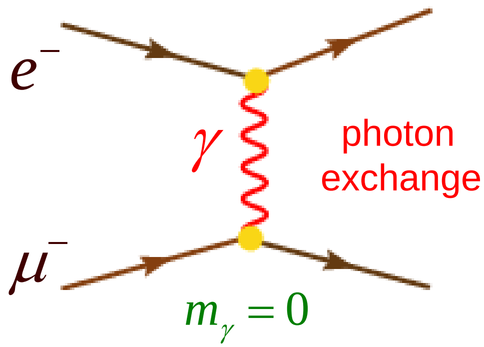
S-Matrix Elements

⇓

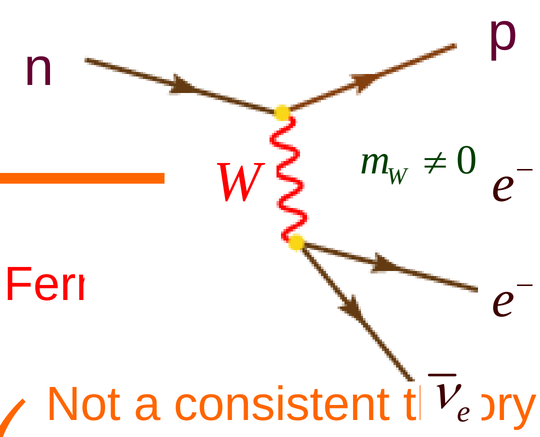
Predictions

Electro-weak Unification

Electromagnetic Interaction:



Weak Interaction: (Beta Decay)



Ferı

(Not a consistent t ory.
Violate Unitarity condition
sions.)

Allows: Self-consistent calculations at high energy and to higher orders of perturbative theory

Prices to pay:

1) $W^\pm$ must exist 1983
2) Simplest version requires also massive Z^0 1983

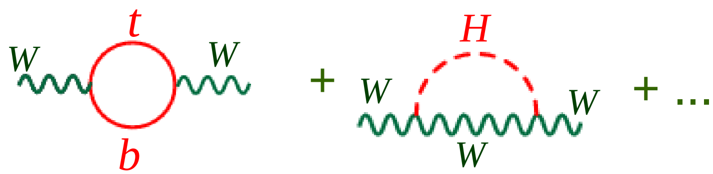
New weak charge preserving interactions 1973

⟹ $SU(2) \times U(1)$

Some Examples of Loop Corrections

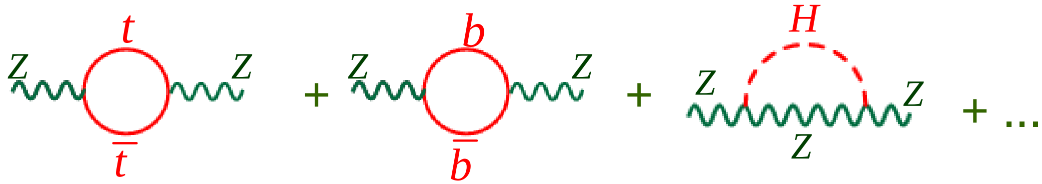
(Radiative corrections)

1) $m_W \sim$

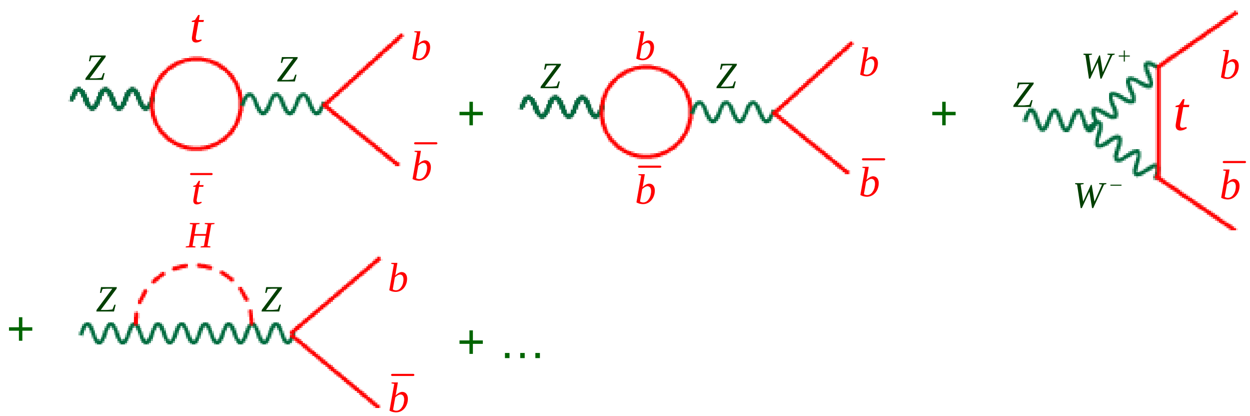


Sum over Intermediate states

$m_Z \sim$

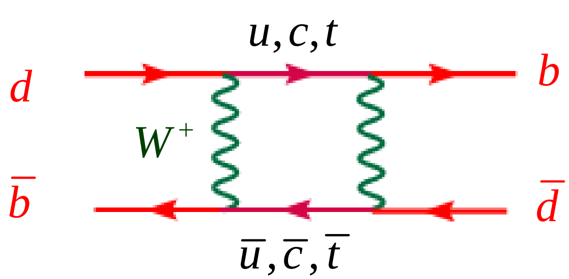


2) $\Gamma_{Z \to b\bar{b}} \sim$



3) $B_d - \bar{B}_d$ mixing

B^0



$\bar{B}^0$

Free Parameters in Standard Model

$SU(3)_{\text{color}} \times SU(2)_{\text{Left}} \times U(1)_{\text{Hypercharge}}$

g_3, g_2, g_1
λ, μ

$$\left\{ \begin{array}{l} \alpha_S, \alpha_{\text{em}}, \theta_{\text{Weak mixing}} \\ V \text{ (vacuum expectation value)} \\ m_H \text{ (Higgs Boson mass)} \end{array} \right\}$$

This set can be traded by
$\alpha_S, \alpha_{\text{em}}, G_F, m_Z, m_H$

(3) Lepton masses

(e, μ, τ) m_ν's=0

(6) Quark masses

(u, d, s, c, b, t)

Mixing of quark weak eigenstates and mass eigenstates → 3 angles and 1 phase (CP violation)

(1) Strong CP phase

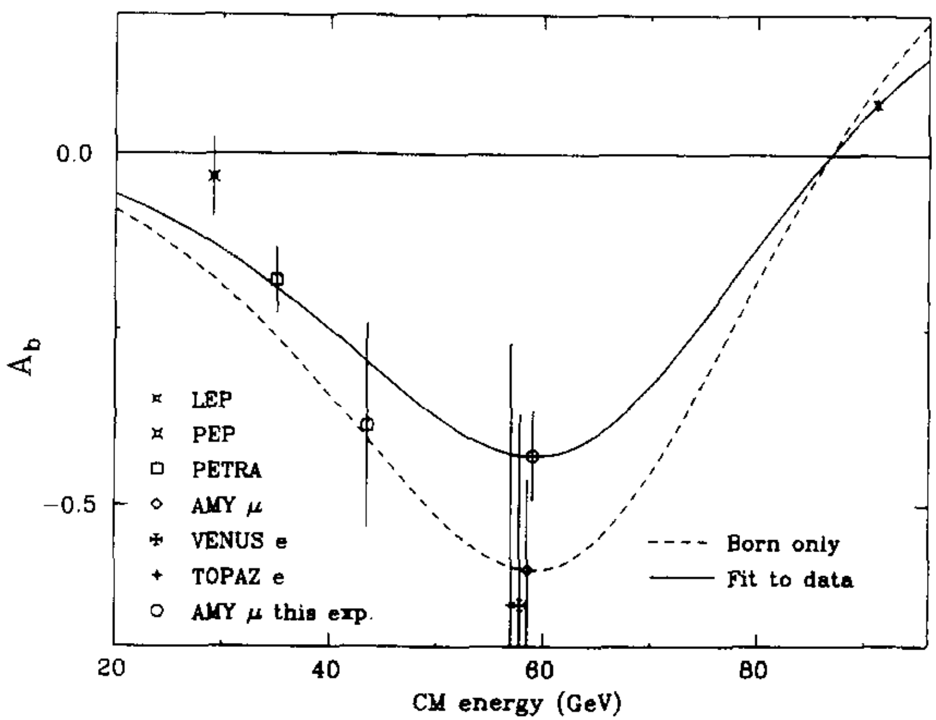
→ Total of 19 free parameters.
So far, all experimental data agree with the prediction of SM.

To include neutrino masses (suggested by Neutrino Oscillation data) in the SM

- For Dirac Neutrinos
  → Add 3 masses and 3 mixing angles with 1 CP violation phase
- For Majorana Neutrinos
  → Add 3 masses and 3 mixing angles with 3 CP violation phase

Top Exists

(induced from data before 1990)



Forward-Backward Asymmetry of bottom quark (A_b) in

$$e^+e^- \to b\bar{b}$$

confirmed weak isospin of *b*

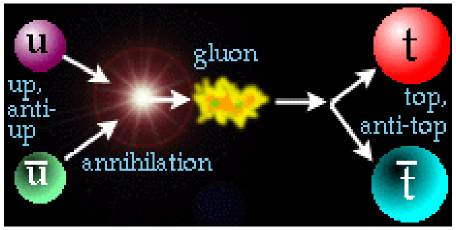
$$T_3 = -\frac{1}{2}$$

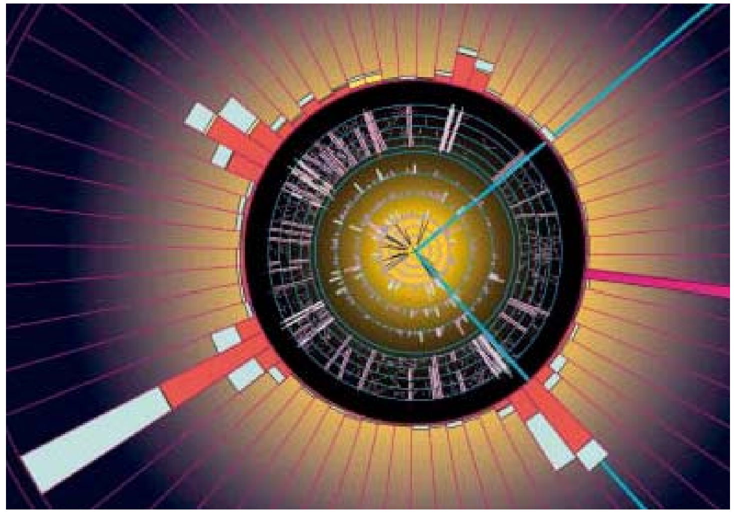
⇨ $T_3 = \frac{1}{2}$ state must exist,

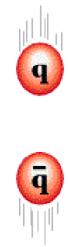
which is called

TOP.

March 2, 1995







We had champaign
at the MSU High Energy physics
conference room to celebrate the
discovery of the Top Quark at FNAL
Tevatron by CDF & D0 groups.

Recently,

$$m_t = 170.9 \pm 1.8 \text{ GeV}$$

Chronology of Top Hunting

Where is the Top Quark?

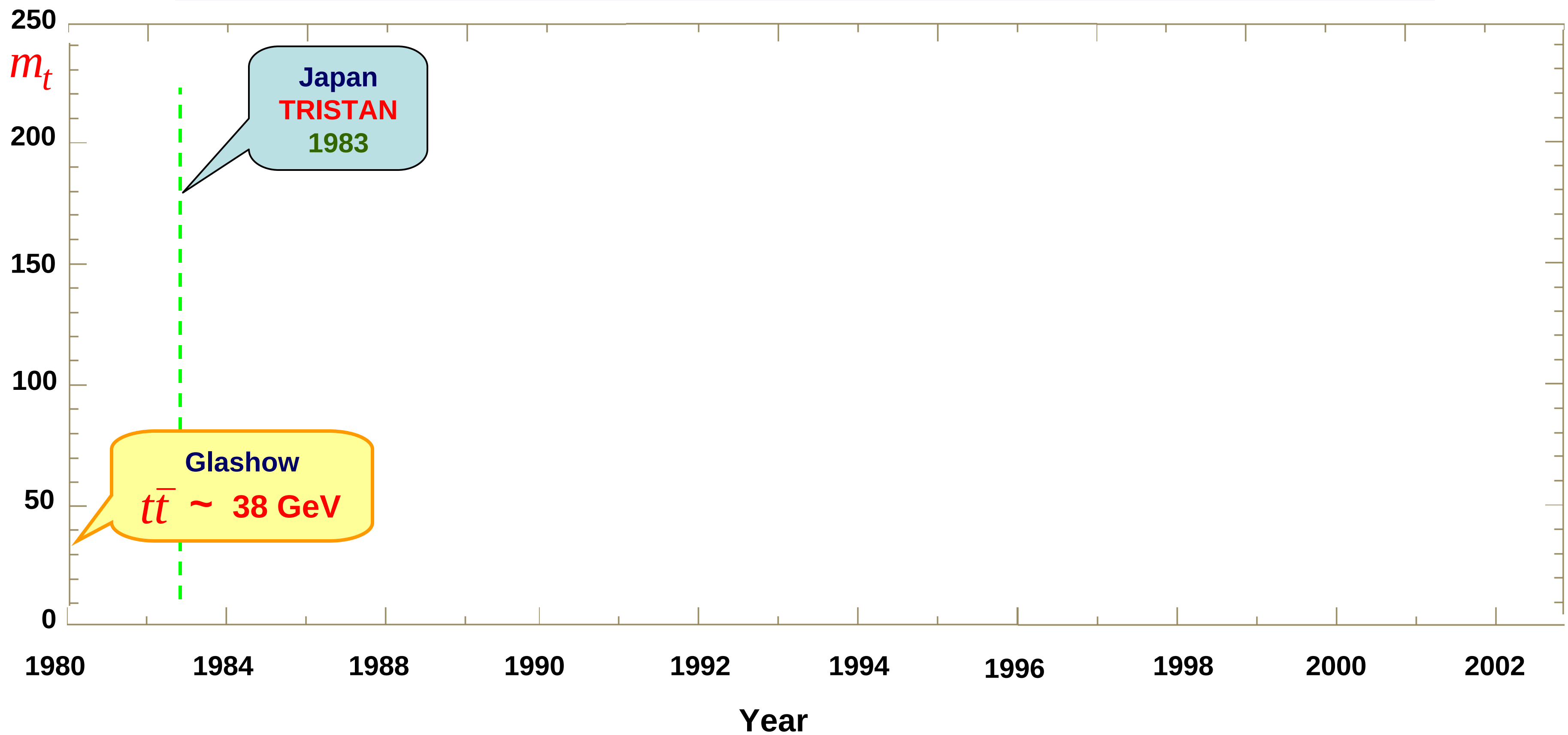
1980

Sheldon L. Glashow[(a)]

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 17 October 1980)

Arguments are presented suggesting that the top-quark analog of the J/ψ should lie at 38 ± 2 GeV. Should there exist a fourth $Q=\frac{2}{3}$ quark h, the first $\bar{h}h$ state must be heavier than 300 GeV.



Chronology of Top Hunting

MASS AND MIXING ANGLE PREDICTIONS FROM INFRA-RED FIXED POINTS

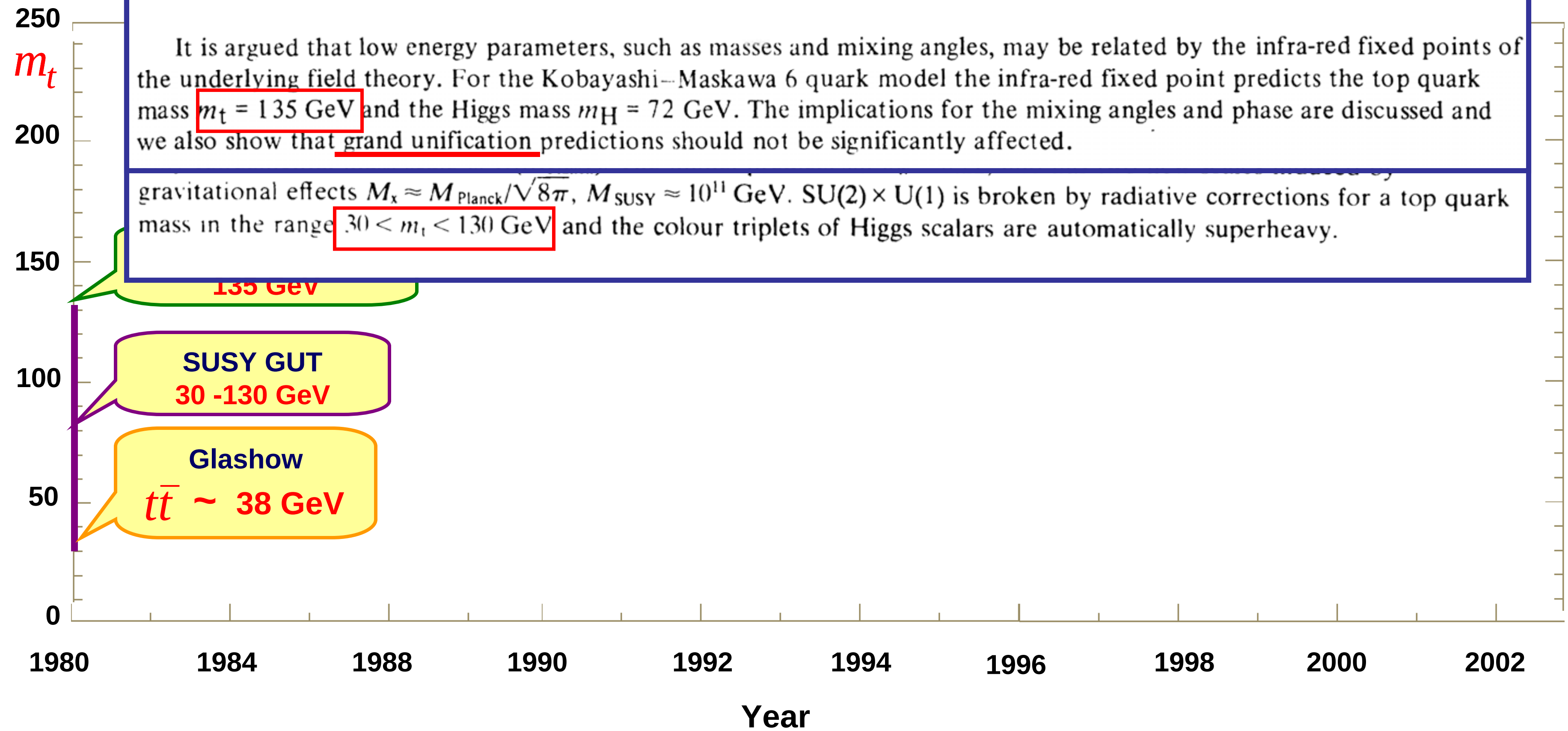
1980

B. PENDLETON and G.G. ROSS
Theoretical Physics Department, Oxford OX1 3NP, UK

Received 15 July 1980
Revised manuscript received 3 November 1980

It is argued that low energy parameters, such as masses and mixing angles, may be related by the infra-red fixed points of the underlying field theory. For the Kobayashi–Maskawa 6 quark model the infra-red fixed point predicts the top quark mass m_t = 135 GeV and the Higgs mass m_H = 72 GeV. The implications for the mixing angles and phase are discussed and we also show that grand unification predictions should not be significantly affected.

gravitational effects $M_x \approx M_{Planck}/\sqrt{8\pi}$, $M_{SUSY} \approx 10^{11}$ GeV. SU(2) × U(1) is broken by radiative corrections for a top quark mass in the range $30 < m_t < 130$ GeV and the colour triplets of Higgs scalars are automatically superheavy.



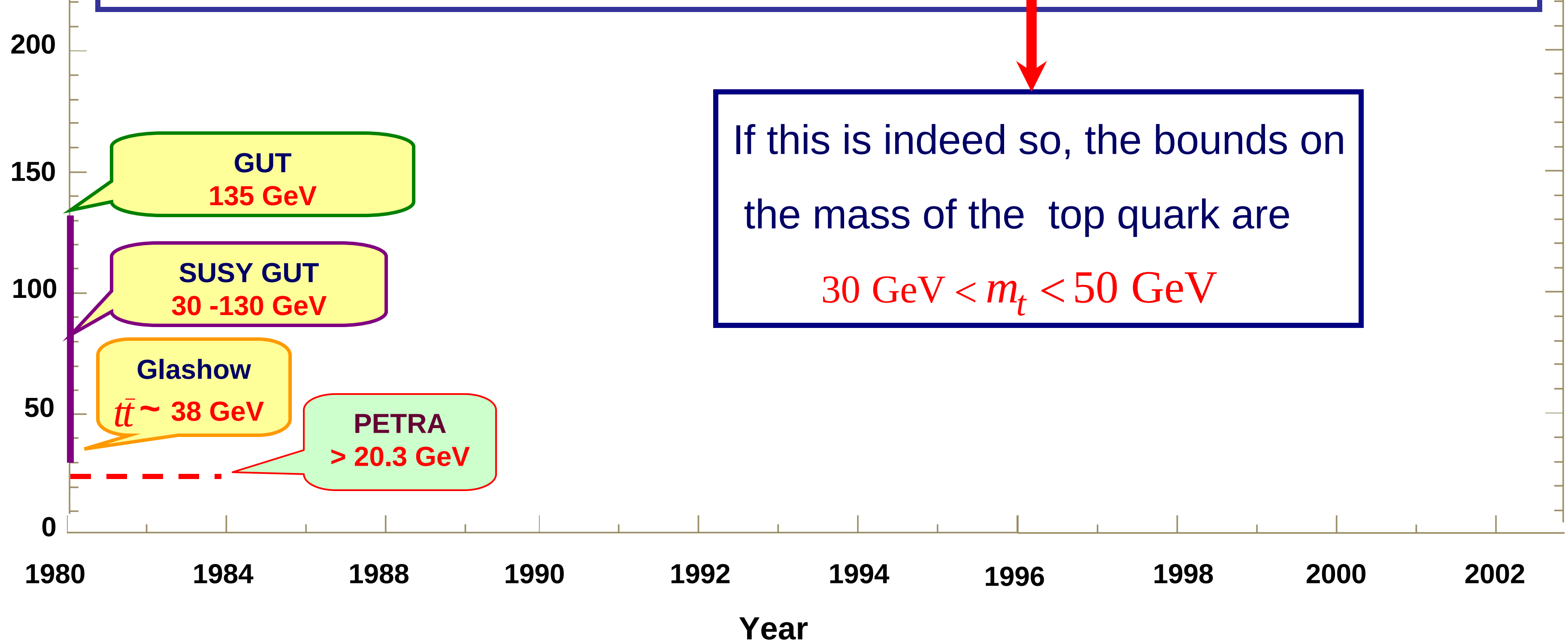
Chronology of Top Hunting

ASSOCIATED PRODUCTION OF AN ISOLATED, LARGE-TRANSVERSE-MOMENTUM LEPTON (ELECTRON OR MUON), AND TWO JETS AT THE CERN $p\bar{p}$ COLLIDER

1984

UA1 Collaboration, CERN, Geneva, Switzerland

A clear signal is observed for the production of an isolated large-transverse-momentum lepton in association with two or three centrally produced jets. The two-jet events cluster around the $W^{\pm}$ mass, indicating a novel decay of the Intermediate Vector Boson. The rate and features of these events are not consistent with expectations of known quark decays (charm, bottom). They are, however, in agreement with the process $W \to t\bar{b}$ followed by $t \to b\ell\nu$, where t is the sixth quark (top) of the weak Cabibbo current. If this is indeed so, the bounds on the mass of the top quark are $30\ \mathrm{GeV}/c^2 < m_t < 50\ \mathrm{GeV}/c^2$.

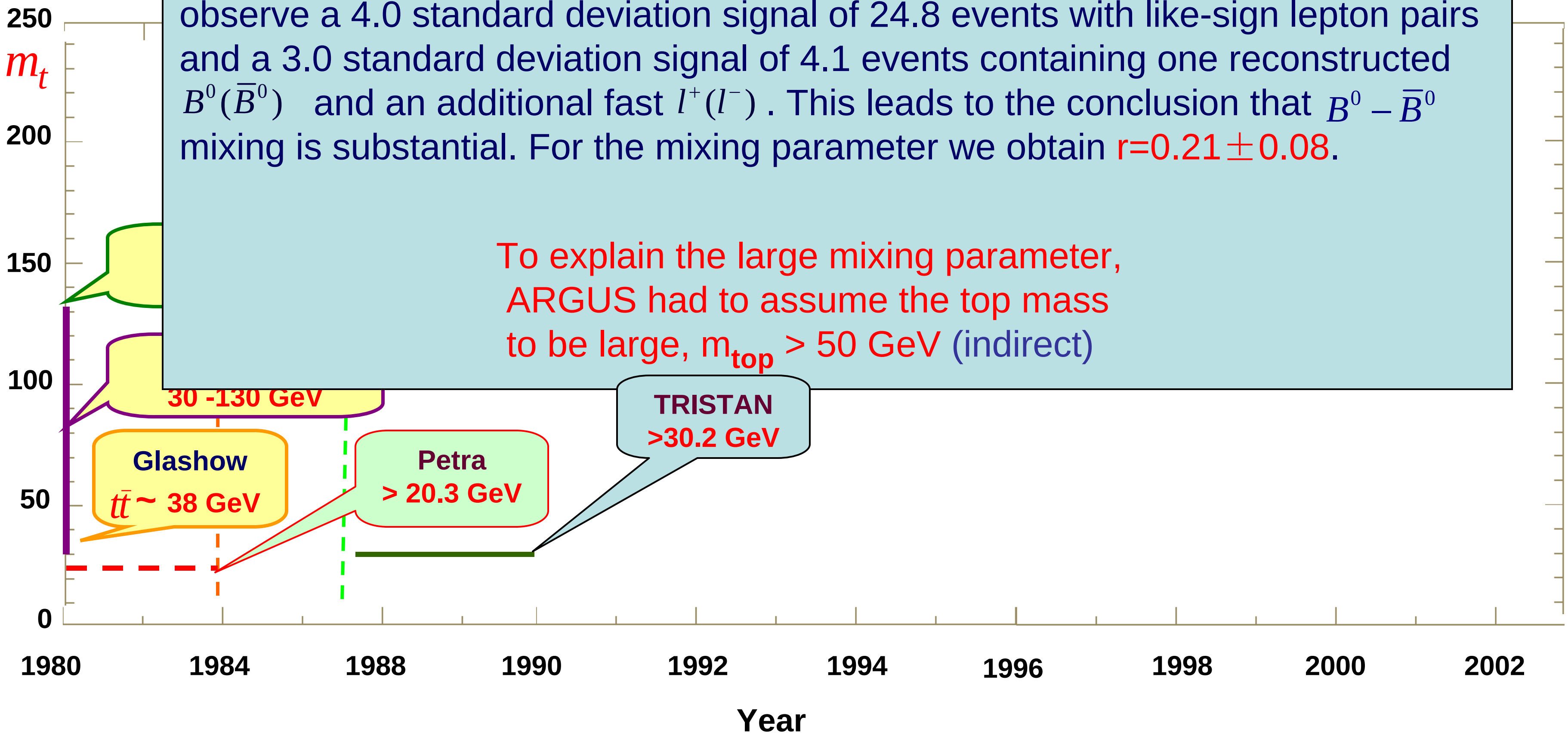


Chronology of Top Hunting

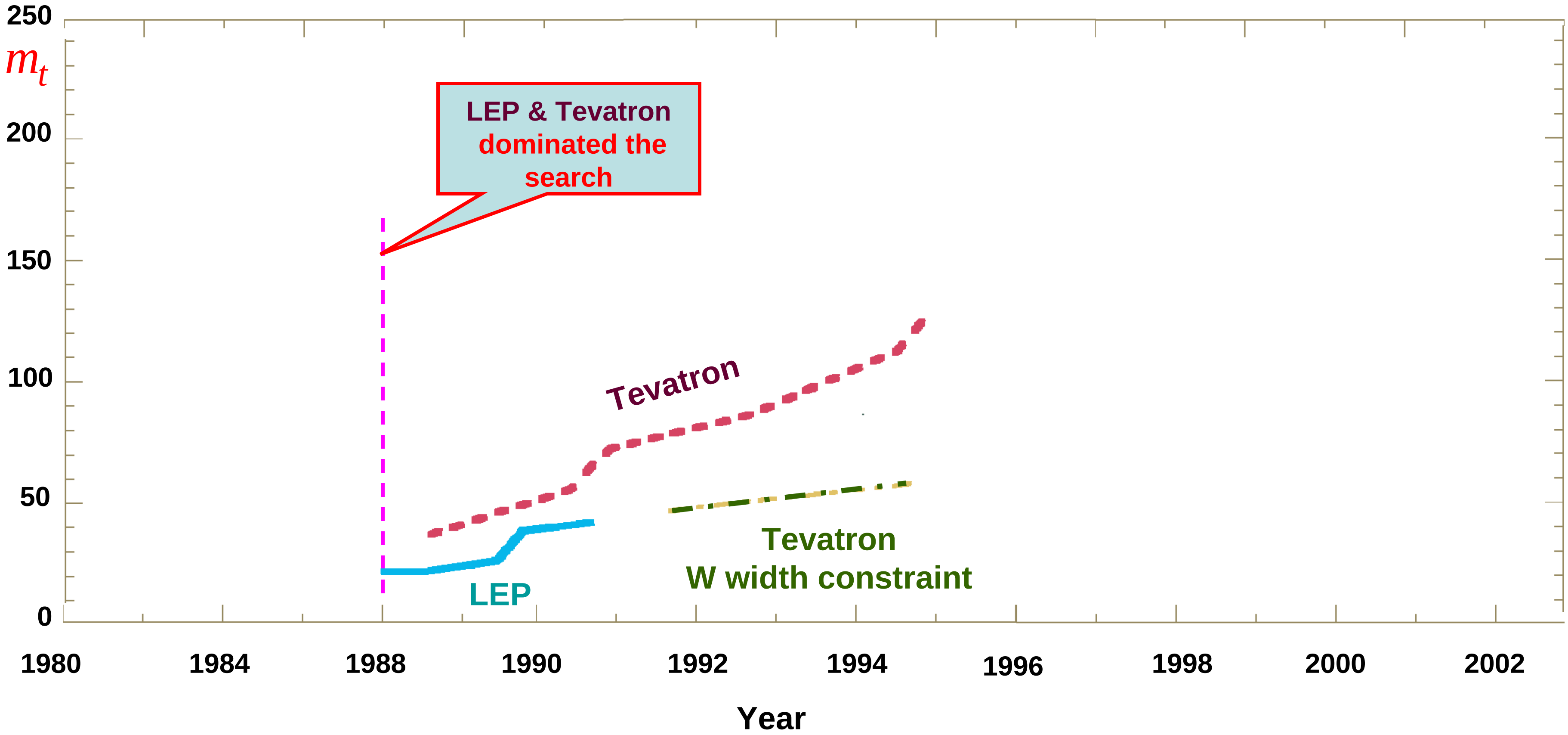
Observation of $B^0-\overline{B}^0$ mixing
ARGUS Collaboration
Received 9 April 1987

Using the ARGUS detector at the DORIS II storage ring we have searched in three different ways for $B^0-\overline{B}^0$ mixing in Υ(4S) decays. One explicitly mixed event, a decay $\Upsilon\to B^0\overline{B}^0$, has been completely reconstructed. Furthermore, we observe a 4.0 standard deviation signal of 24.8 events with like-sign lepton pairs and a 3.0 standard deviation signal of 4.1 events containing one reconstructed $B^0(\overline{B}^0)$ and an additional fast $l^+(l^-)$. This leads to the conclusion that $B^0-\overline{B}^0$ mixing is substantial. For the mixing parameter we obtain r=0.21$\pm$0.08.

To explain the large mixing parameter,
ARGUS had to assume the top mass
to be large, m_{top} > 50 GeV (indirect)



Chronology of Top Hunting

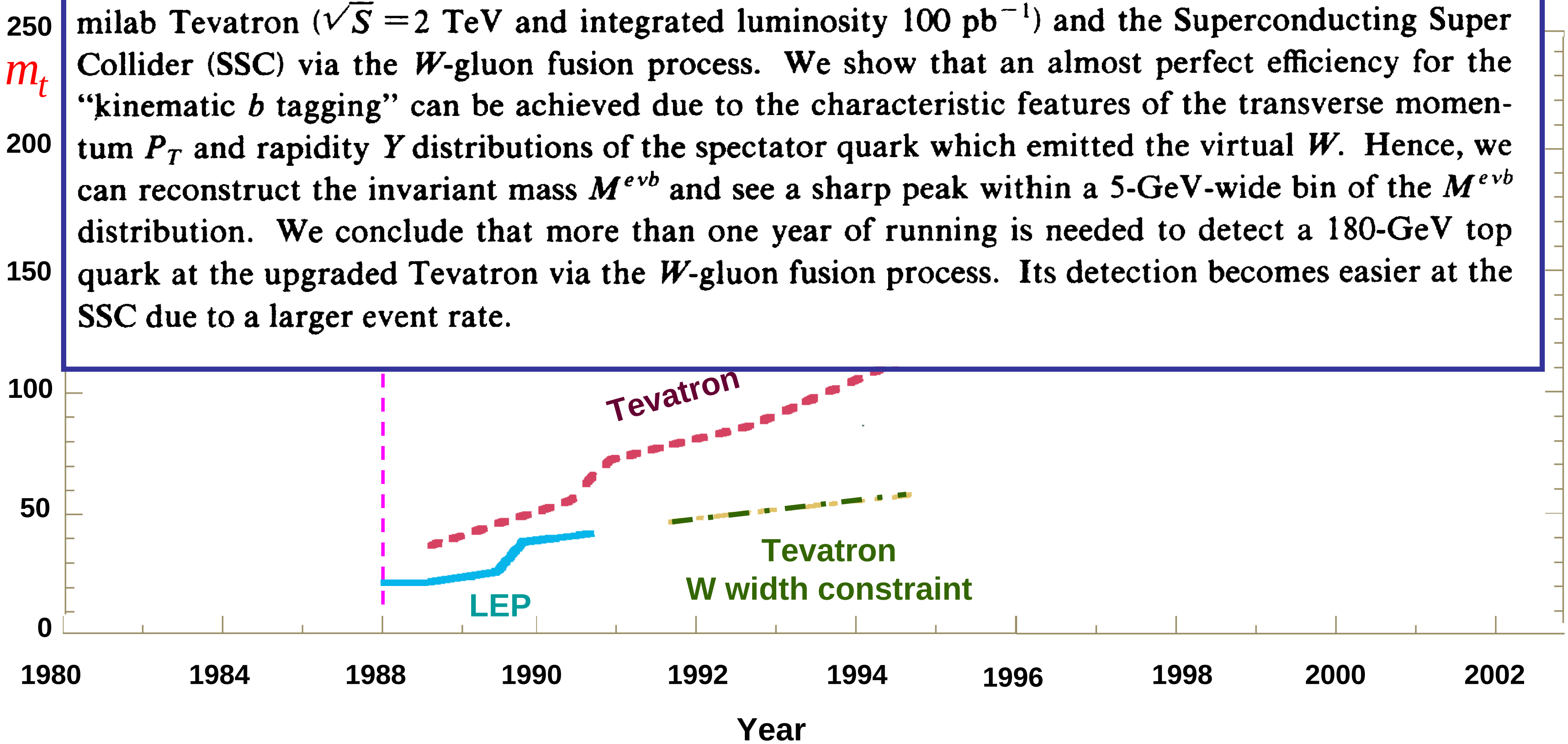


Chronology of Top Hunting

New method to detect a heavy top quark at the Fermilab Tevatron

C.-P. Yuan
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 15 May 1989)

We present a new method to detect a heavy top quark with mass $\sim$180 GeV at the upgraded Fermilab Tevatron ($\sqrt{S}=2$ TeV and integrated luminosity 100 pb^{-1}) and the Superconducting Super Collider (SSC) via the W-gluon fusion process. We show that an almost perfect efficiency for the "kinematic b tagging" can be achieved due to the characteristic features of the transverse momentum P_T and rapidity Y distributions of the spectator quark which emitted the virtual W. Hence, we can reconstruct the invariant mass $M^{e\nu b}$ and see a sharp peak within a 5-GeV-wide bin of the $M^{e\nu b}$ distribution. We conclude that more than one year of running is needed to detect a 180-GeV top quark at the upgraded Tevatron via the W-gluon fusion process. Its detection becomes easier at the SSC due to a larger event rate.



Chronology of Top Hunting

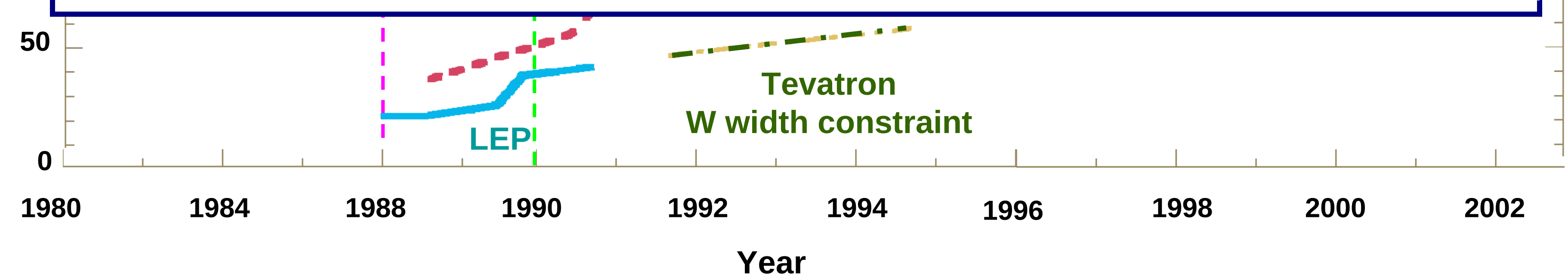
Minimal dynamical symmetry breaking of the standard model

William A. Bardeen, Christopher T. Hill, and Manfred Lindner
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510

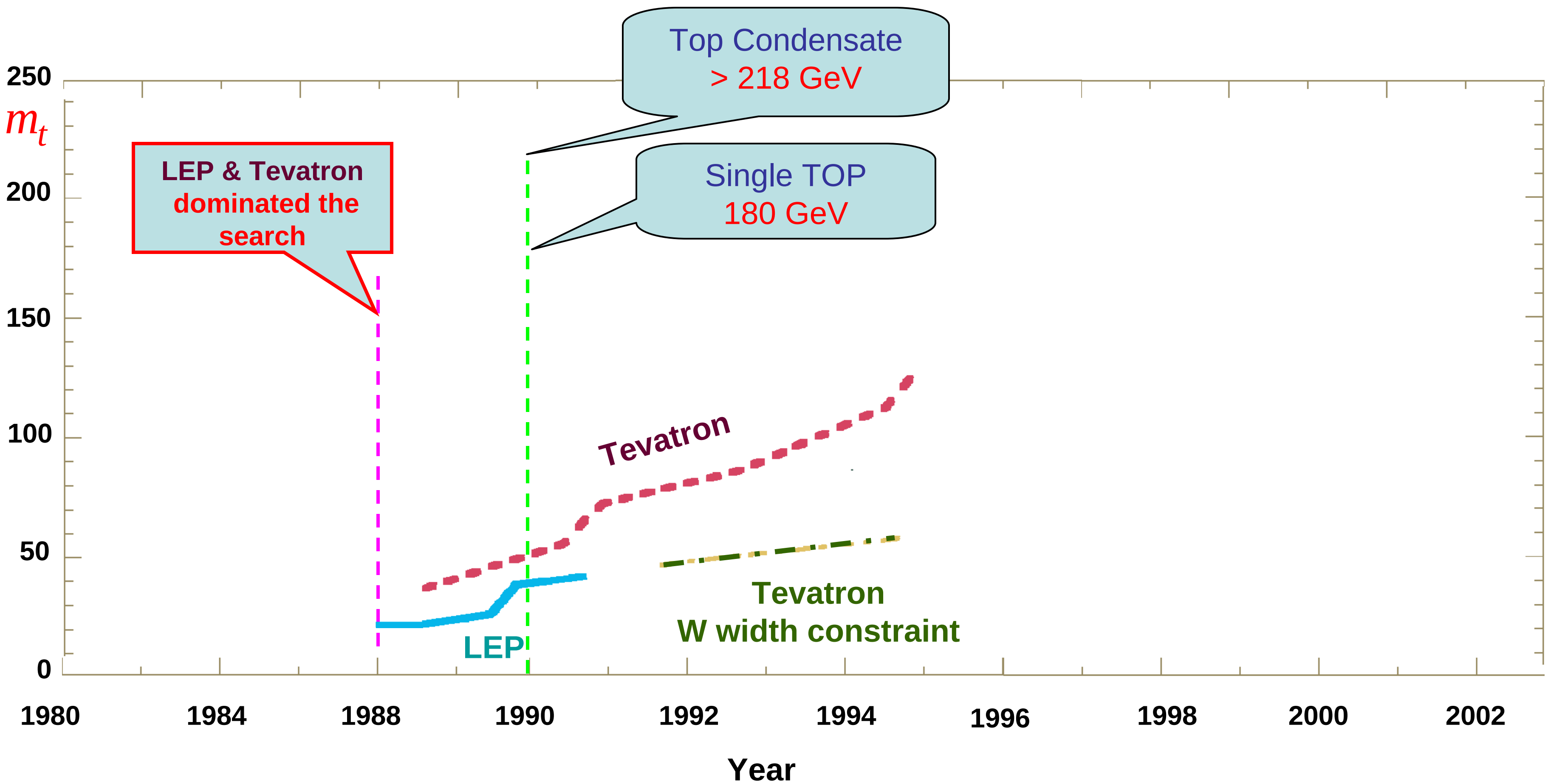
(Received 21 July 1989; revised manuscript received 2 November 1989)

We formulate the dynamical symmetry breaking of the standard model by a top-quark condensate in analogy with BCS theory. The low-energy effective Lagrangian is the usual standard model with supplemental relationships connecting masses of the top quark, W boson, and Higgs boson which now appears as a $\bar{t}\,t$ bound state. Precise predictions for m_t and m_H are obtained by abstracting the compositeness condition for the Higgs boson to boundary conditions on the renormalization-group equations for the full standard model at high energy.

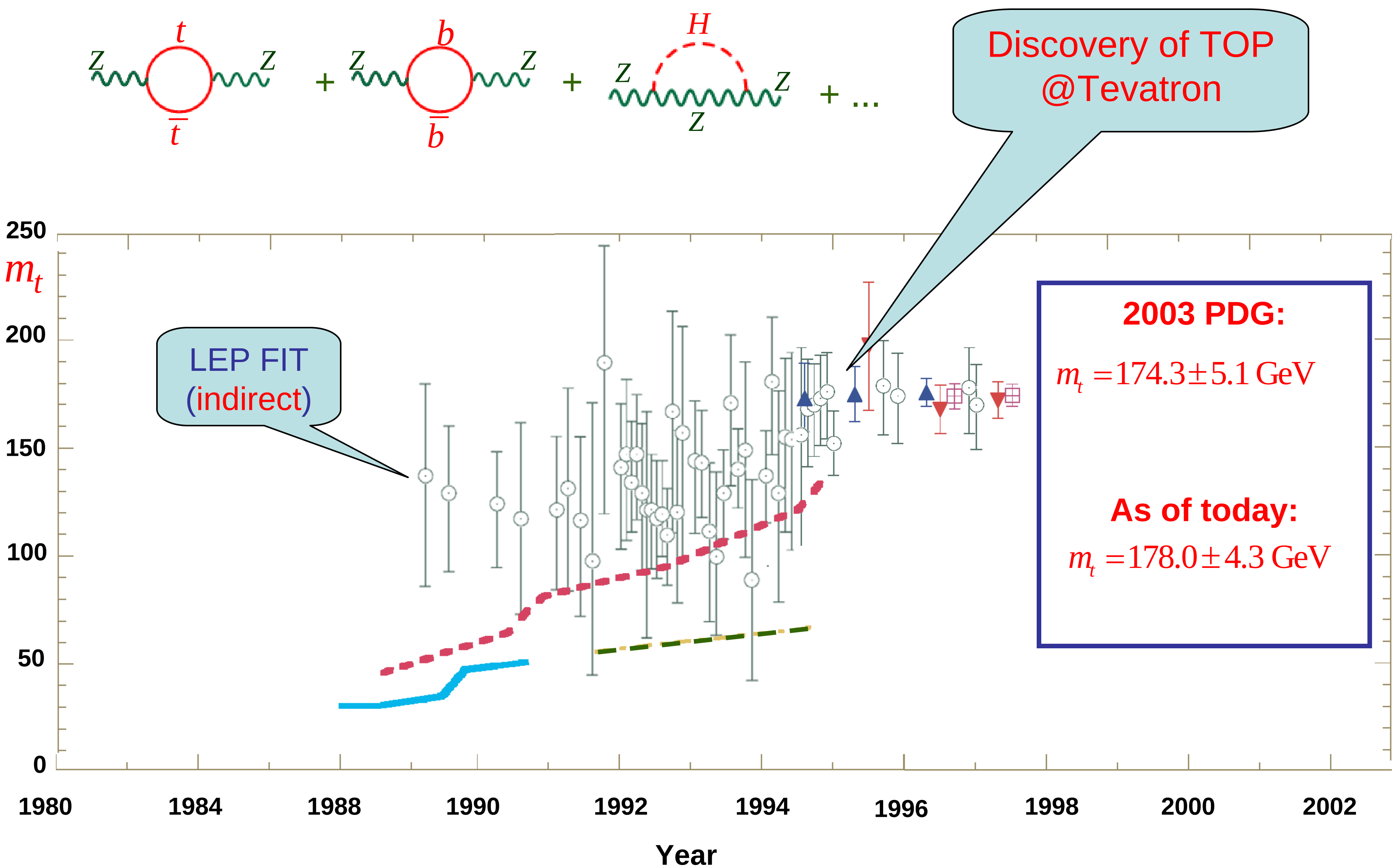
Λ (GeV)	10^{19}	10^{17}	10^{15}	10^{13}	10^{11}	10^{10}	10^{9}	10^{8}	10^{7}	10^{6}	10^{5}	10^{4}
m_t^{phys} (GeV)	218	223	229	237	248	255	264	277	293	318	360	455
Pert.	± 2	± 3	± 3	± 3	± 5	± 6	± 7	± 9	± 12	± 16	± 25	± 45
m_H^{phys} (GeV)	239	246	256	268	285	296	310	329	354	391	455	605
Pert.	± 3	± 3	± 4	± 5	± 8	± 9	± 11	± 15	± 21	± 32	± 56	± 142



Chronology of Top Hunting

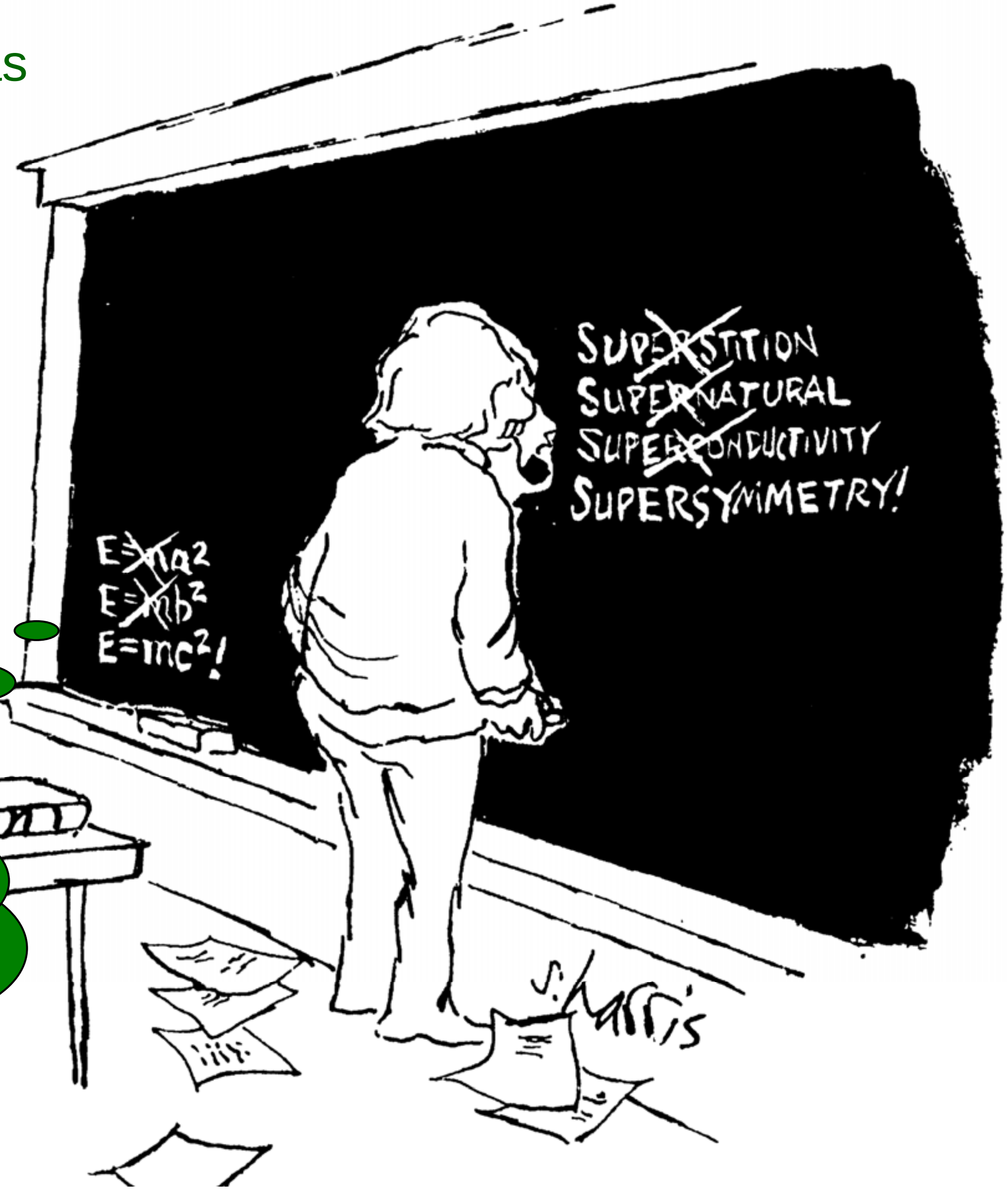


Chronology of Top Hunting



Lessons we learned from the History on the discovery of Top Quark

- Only Experimental Data has the final say about Mother Nature.
- The interaction between Experimentalists and Theorists is essential for the advance of science.



Theorists should not give up any probable idea.

What motivated my 1990 single-top paper

(with $m_t = 180$ GeV)

Spontaneous Electroweak Symmetry Breaking

↓

Massive W-Boson

↓

Existence of logitudinal W-boson W_L

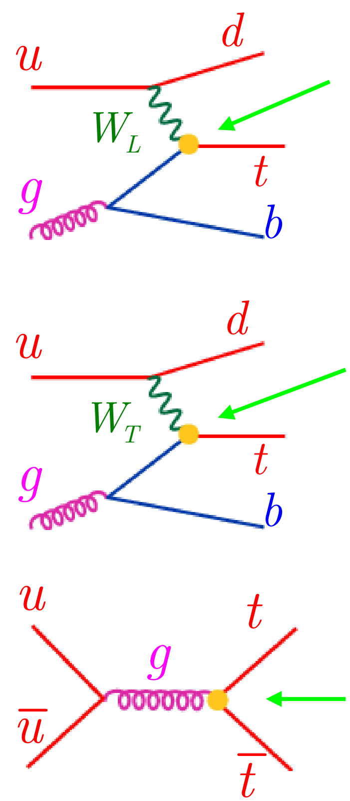
↓

Study interaction of $W_L W_L \to W_L W_L$ in the TeV region

Goldstone Boson Equivalence theorem

W_L can also interact strongly with top quark if

$$m_t \simeq \frac{v}{\sqrt{2}} \approx 175 \text{ GeV}$$



$$g^2_{\text{eff}} \simeq \left(\frac{\sqrt{2}m_t}{v}\right)^2 \simeq 1$$

$$g^2_{\text{weak}} \simeq \frac{1}{2.5}$$

$$(g_S)^2 \simeq 1$$

What motivated my 1990 single-top paper

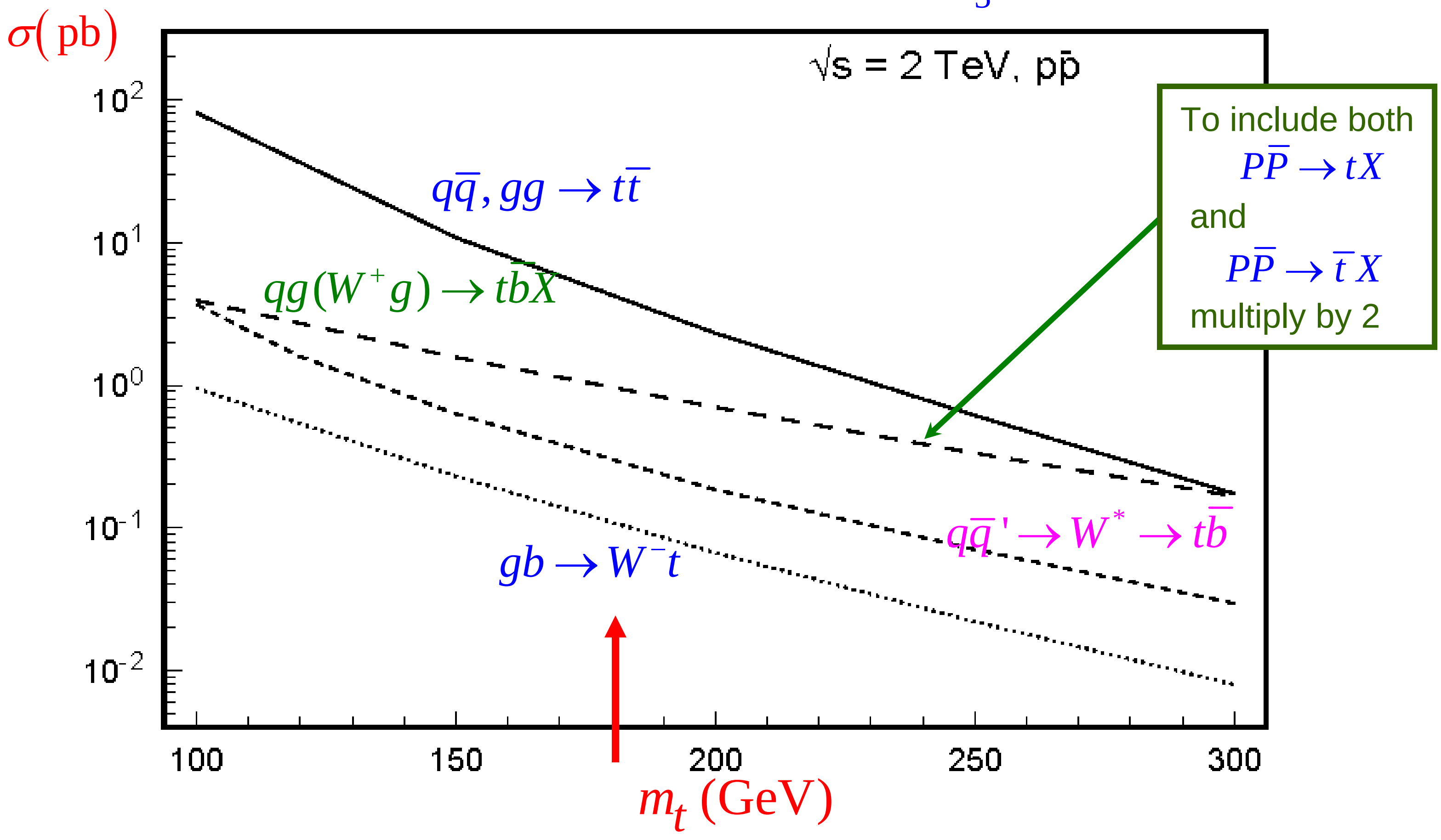
(with $m_t = 180$ GeV)

For $m_t = 180$ GeV,

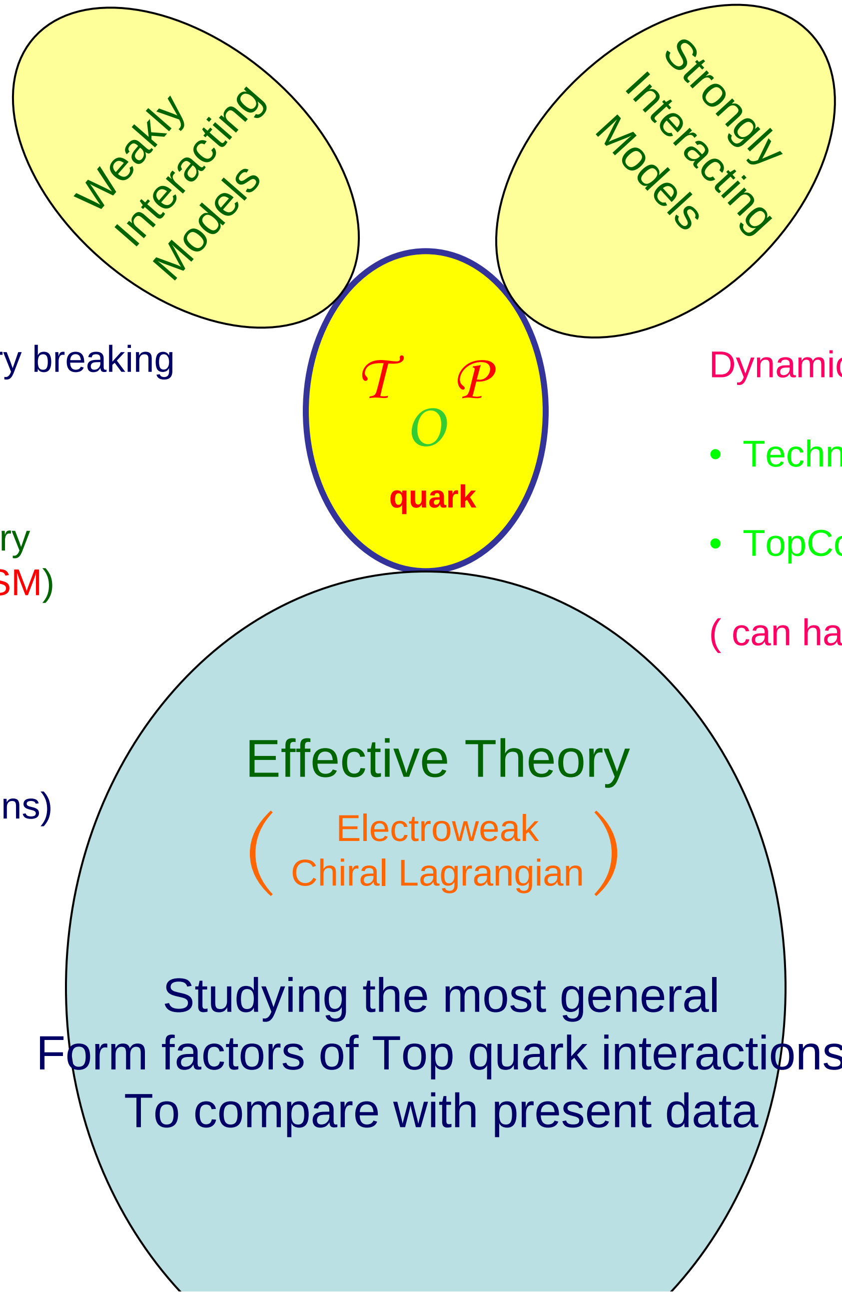
$$\sigma\left(Wg \to t\bar{b}, \bar{t}b\right) \sim \frac{1}{3}\sigma\left(t\bar{t}\right)$$

$$\sigma\left(\mathrm{W}^* \to t\bar{b}, \bar{t}b\right) \sim \frac{1}{3}\sigma\left(Wg \to t\bar{b}, \bar{t}b\right)$$

$$\sigma\left(\mathrm{Wt}\right) \sim \frac{1}{3}\sigma\left(\mathrm{W}^* \to t\bar{b}\right)$$



Ideas of Symmetry Breaking (in 4-dim)



Spontaneously symmetry breaking

- Supersymmetry
- Minimal supersymmetry Standard Model (MSSM) with Radiative EWSB and soft SUSY-breaking

(Elementary Higgs bosons)

$h, H, H^{\pm}, A$

Top-down approach

Dynamical Symmetry Breaking

- Technicolor
- TopColor / Condensate / Seesaw Models

(can have composite Higgs bosons)

$H \equiv < t\bar{t} >$

Bottom-up approach

Top quark Decay $(m_t > m_W)$

- If the *SU(2)* structure $\begin{pmatrix} t \\ b \end{pmatrix}_L$ of the Standard Model holds,

  then $t \to bW^+$ always occurs at tree level in any model.

➡ $\mathrm{Br}\left(t \to bW\right) \sim 1$

- For a Standard Model t, the decay width $t \to bW^+$

$$\Gamma_t \sim 1.6 \text{ GeV} \left(\frac{m_t}{180}\right)^3$$

Lifetime

$$\tau_{\text{decay}} = \frac{1}{\Gamma_t} \sim 4.4 \times 10^{-25} \left(\frac{m_t}{180}\right)^3 \text{ sec}$$

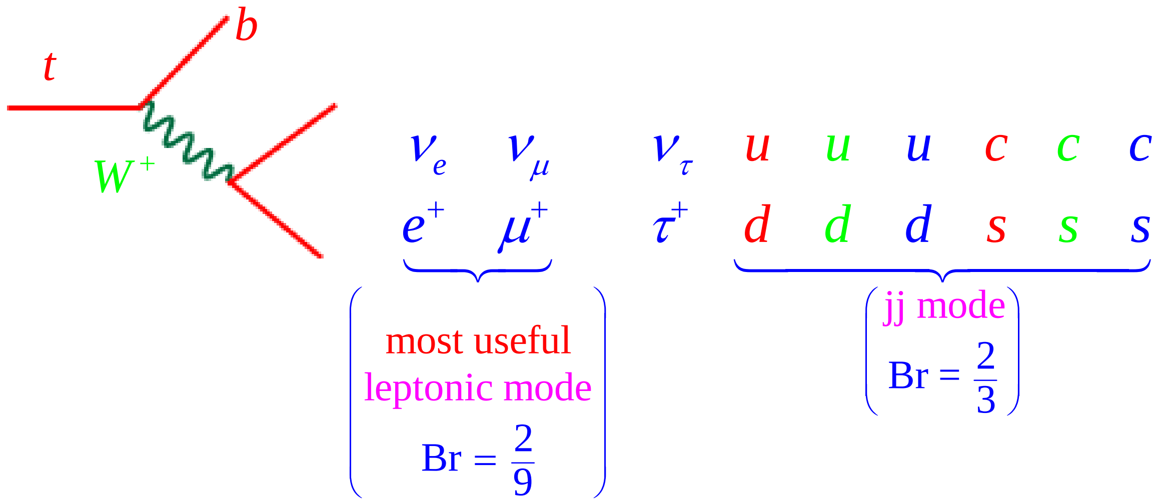
➡ t decays before it feels non-perturbative strong interaction.

$$\left(\frac{1}{\Lambda_{\text{QCD}}} \sim \frac{1}{0.2 \text{ GeV}} \sim 3.3 \times 10^{-24} \text{ sec}\right)$$

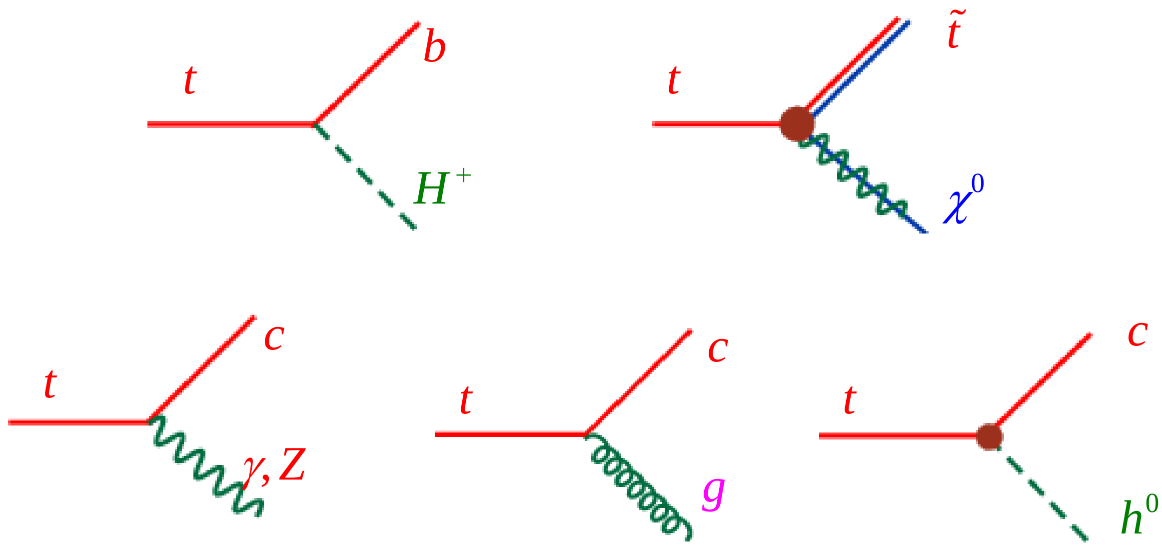
Studying Property of Bare quark.

Decay Branching Ratio of Top quark

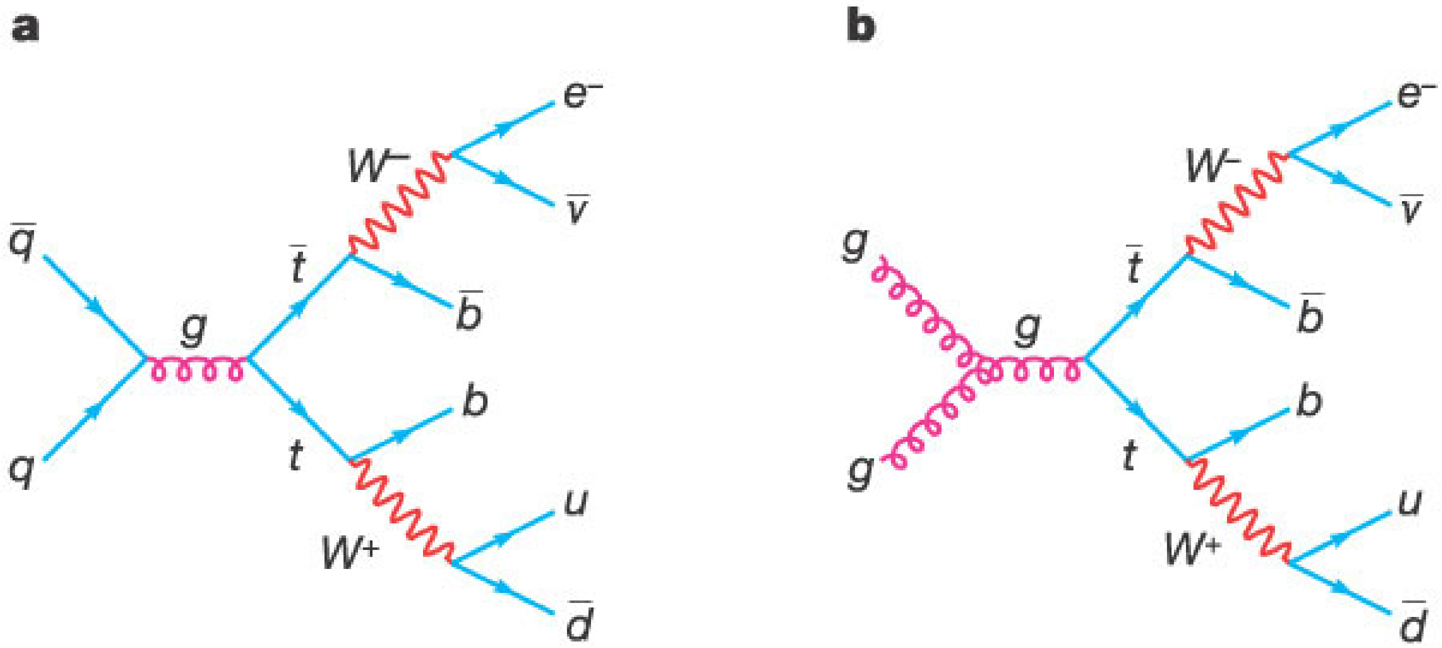
- In the SM:



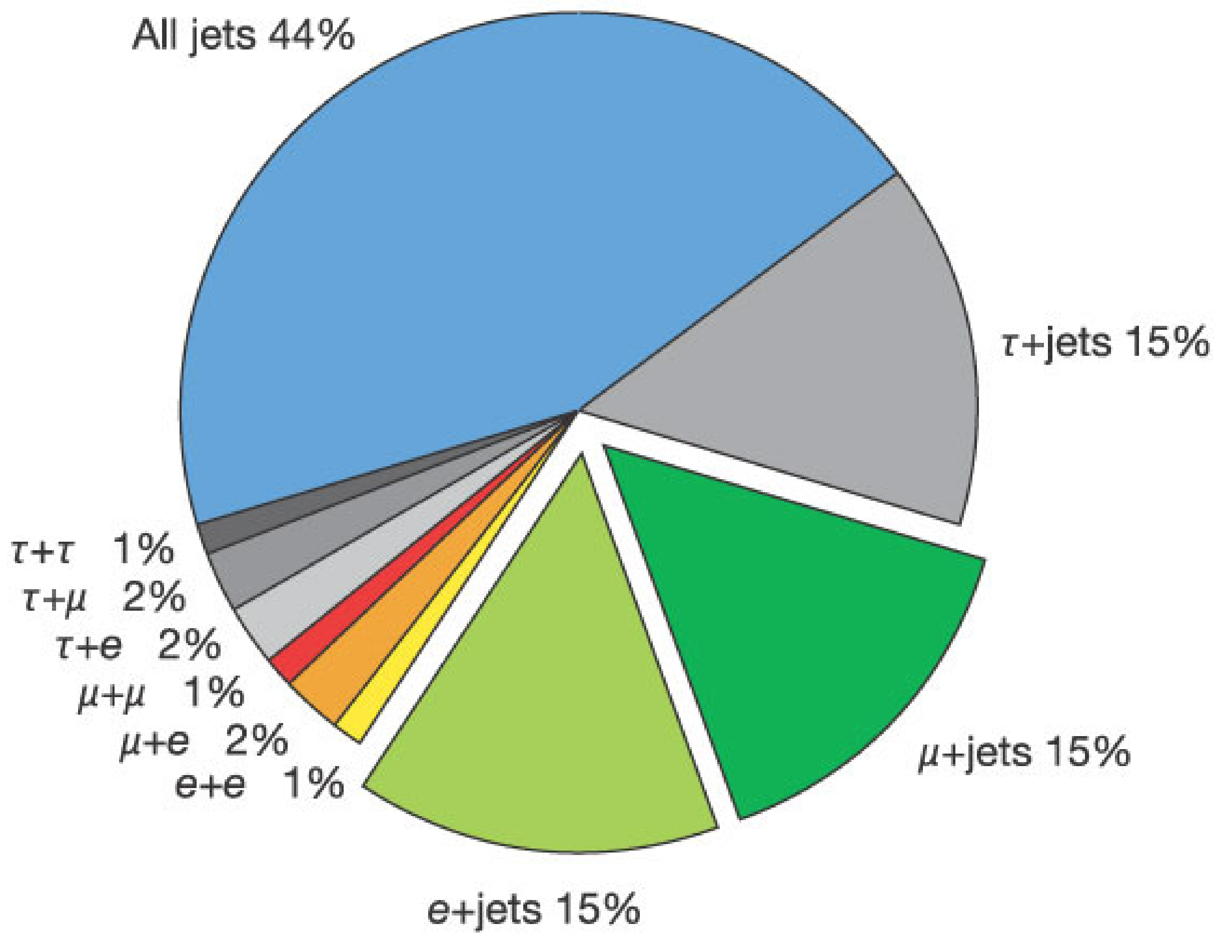
- New Physics:



$t\bar{t}$ Pair Production



Br in $t\bar{t}$ decay modes

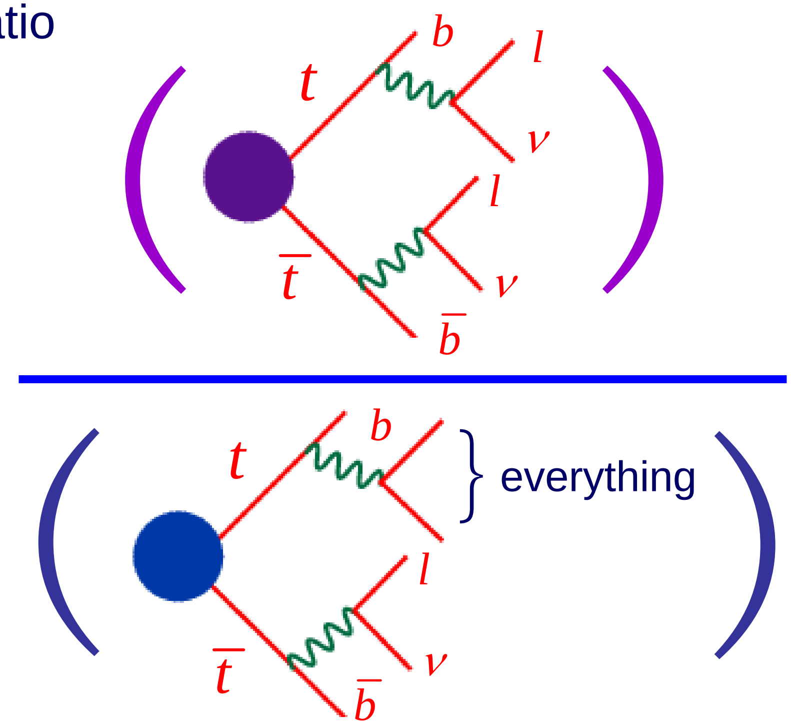


How to measure Branching Ratio (BR) ?

$t \to b W^+$, $W^+ \to l^+ \nu$

This can be done by measuring the ratio

$$R_l \equiv \frac{Br\left(t\bar{t} \to ll + X\right)}{Br\left(t\bar{t} \to l + X\right)} =$$



If $t \to b H^+$, $H^+ \to j\ j$, then

R_l differs from R_l^{SM}.

What if ... ?

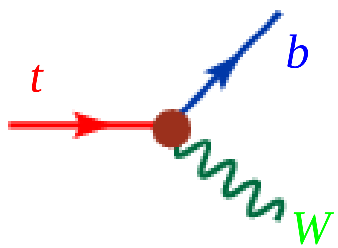
It is however possible that new physics

might not change the $\mathrm{Br}\left(t \to bW\right)$,

(e.g. no additional new light fields with mass less than m_t)

but will strongly modify the width of $\Gamma\left(t \to bW\right)$,

due to the interaction



is strongly modified.

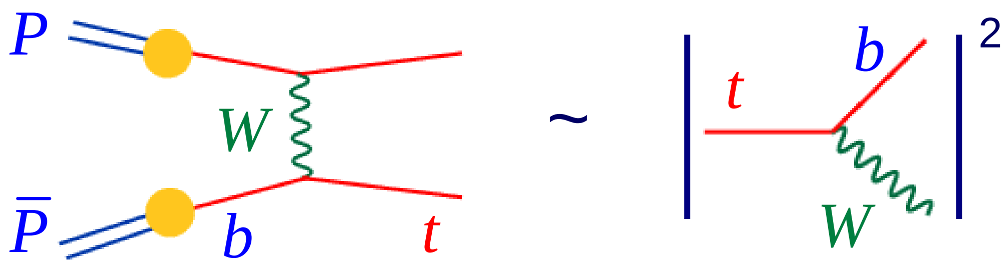
Hence, the lifetime of top quark is different from SM's prediction.

➡ Need to study the interaction of t–b-W .

$P\overline{P} \to t\,X$ and $P\overline{P} \to \overline{t}\,X$

(single top production)

Since



Measuring σ_t

assume SM → CKM element V_{tb}

in general → $\Gamma(t \to bW)$

Combine with $\mathrm{Br}(t \to bW)$

$$\Gamma_{\mathrm{tot}} = \frac{\Gamma(t \to bW)}{\mathrm{Br}(t \to bW)}$$

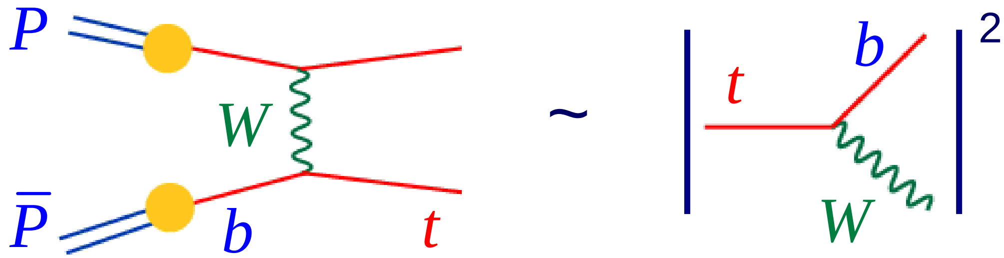
Lifetime of Top

$$\tau_{\mathrm{top}} = \frac{1}{\Gamma_{\mathrm{tot}}}$$

$P\bar{P} \to t\,X$ and $P\bar{P} \to \bar{t}\,X$

(single top production)

Since



The asymmetry in the production rate

$$A_t^{\mathrm{CPX}} = \frac{\sigma(p\bar{p} \to t) - \sigma(p\bar{p} \to \bar{t})}{\sigma(p\bar{p} \to t) + \sigma(p\bar{p} \to \bar{t})}$$

can be used to measure CP-violation.

$\mathrm{C}:\ P \leftrightarrow \bar{P}$

$\mathrm{P}:\ \vec{x} \leftrightarrow -\vec{x}$

This observable is unique for $p\bar{p}$ collider.
(Tevatron)

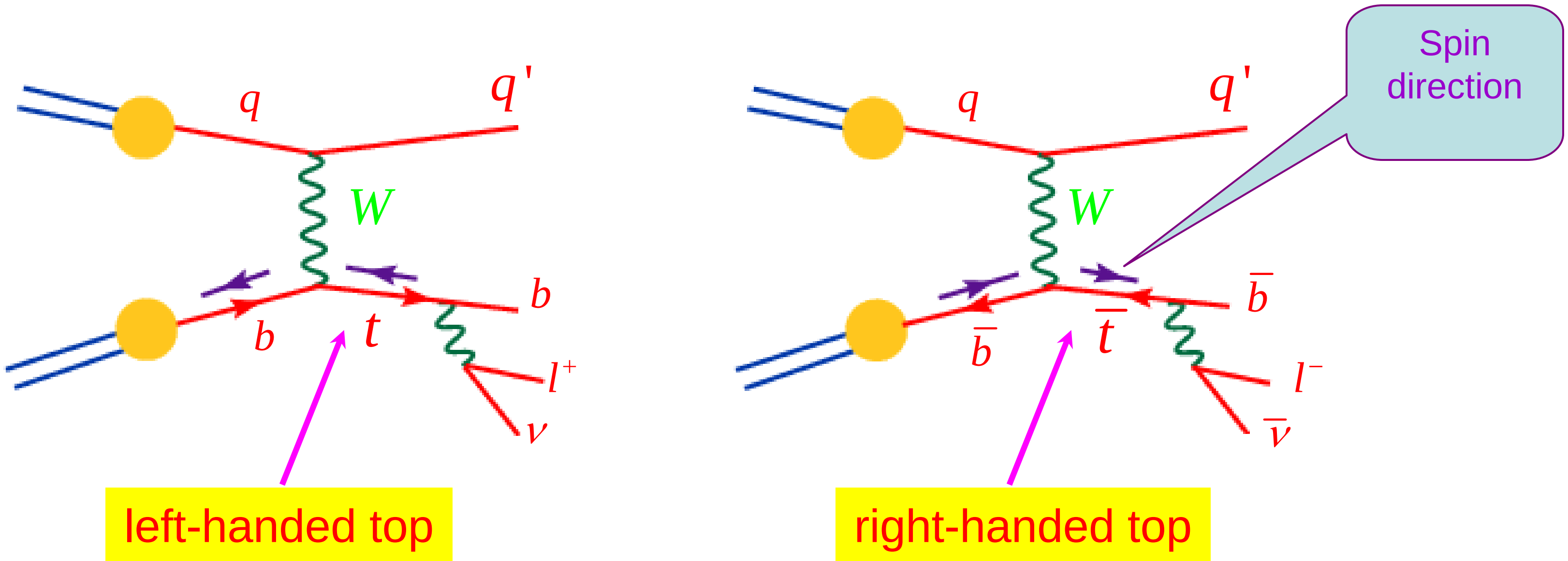
For 2 fb^{-1},

$$\delta A_t^{\mathrm{CPX}} \sim 20\%$$

A SM t ($\bar{t}$) is purely

left-handed (right-handed) polarized

in the single-top process.

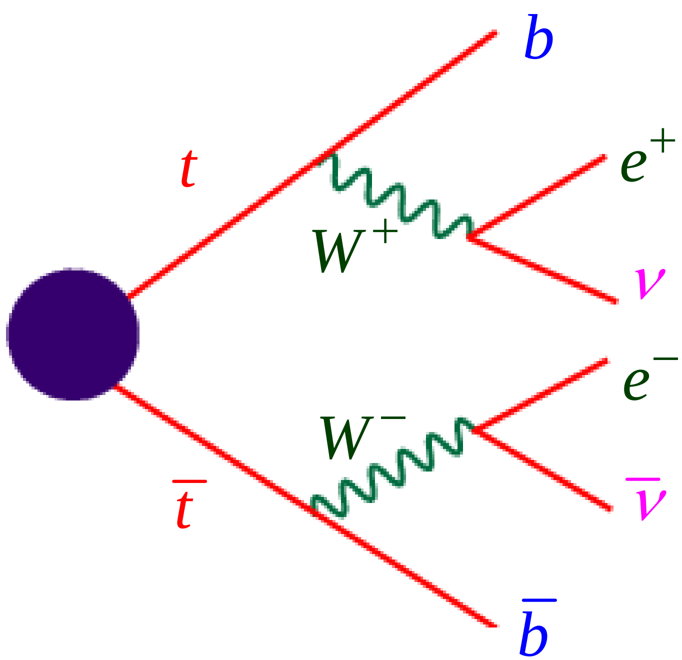


Measuring both

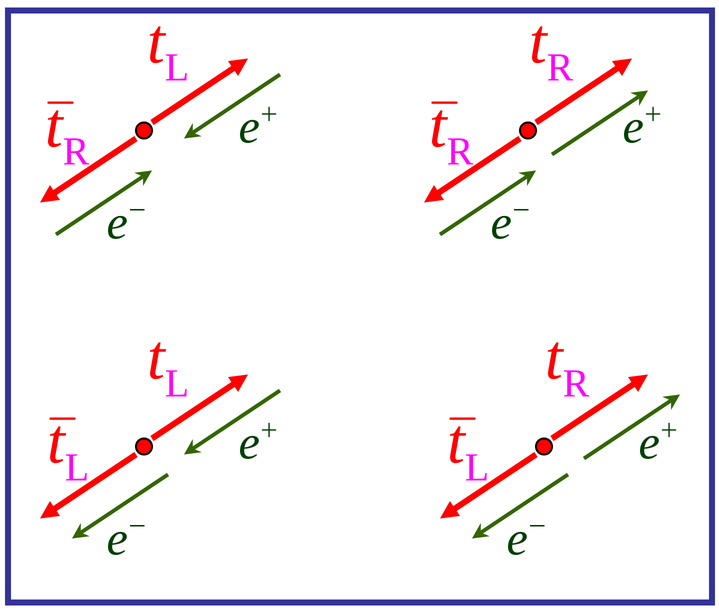
$$\left\langle \vec{\sigma}_t \bullet \vec{p}_b \times \vec{p}_{l^+} \right\rangle \text{ and } \left\langle \vec{\sigma}_{\bar{t}} \bullet \vec{p}_{\bar{b}} \times \vec{p}_{l^-} \right\rangle$$

➡ Probe CP-violation at the LHC

Spin correlation in $t\bar{t}$ events



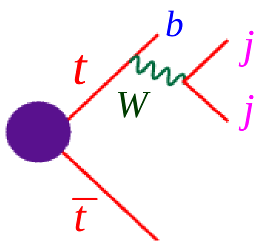
In the $t\bar{t}$ center-of-mass frame

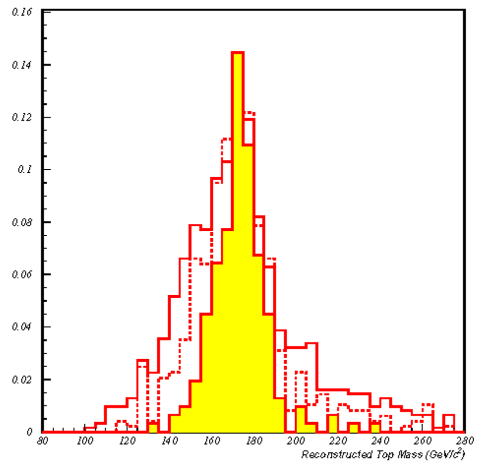


If $\sigma\left(t_L\bar{t}_L\right) \neq \sigma\left(t_R\bar{t}_R\right)$, then CP is violated.

Need better measurement of m_t

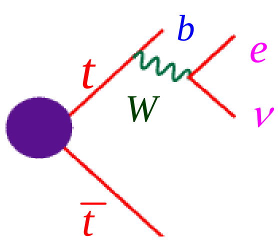
- From the invariant mass of ($b\,j\,j$)

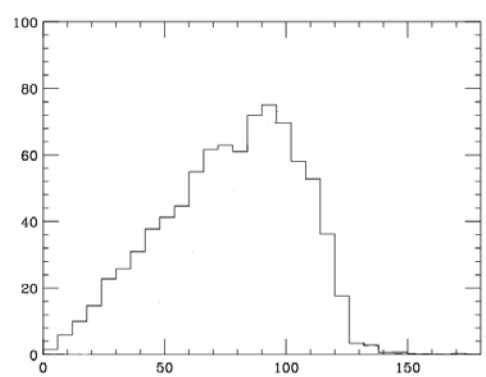




m_{bjj}

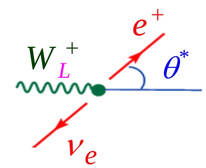
- From the invariant mass of ($b\,e$)



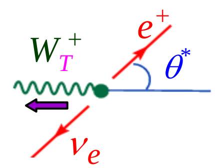


m_{be}

- From the polarization of W



$\sim \sin^2\theta^*$

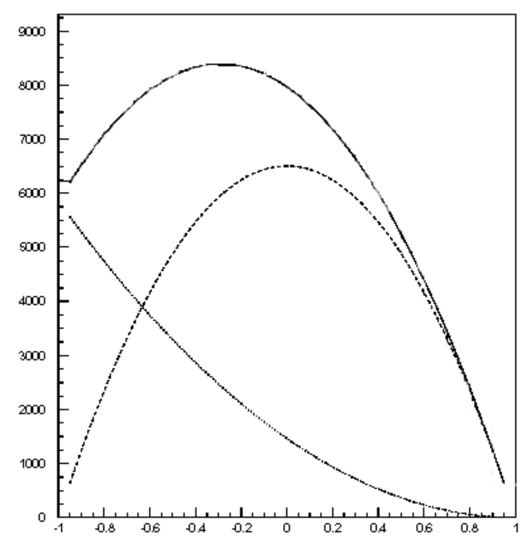


$\sim \left(1-\cos\theta^*\right)^2$

$$F(\cos\theta^*) \sim (1-f_{\rm Long})\left(\frac{1-\cos\theta^*}{2}\right)^2 + f_{\rm Long}\left(\frac{\sin\theta^*}{\sqrt{2}}\right)^2$$

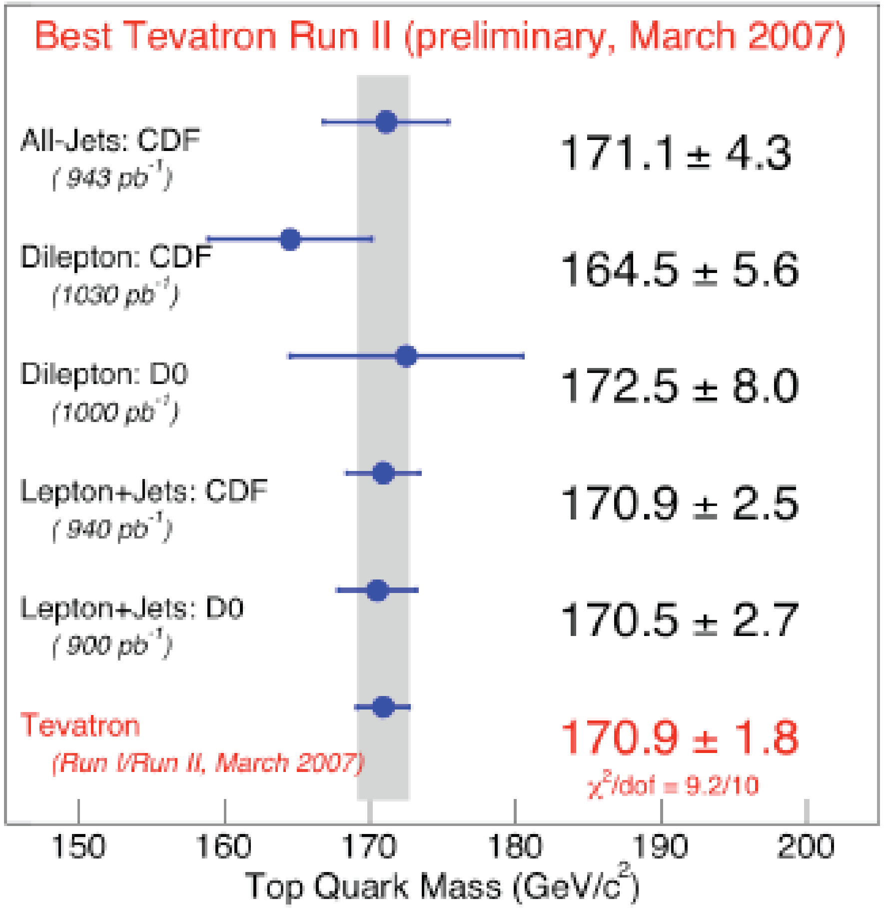
$$f_{\rm long} = \frac{\Gamma(t\to bW_L)}{\Gamma(t\to bW_L)+\Gamma(t\to bW_T)} = \frac{m_t^2}{2m_W^2+m_t^2}$$

$$\cos\theta^* = \frac{2m_{be}^2}{m_t^2-m_W^2}-1$$



$\cos\theta^*$

Top Quark Mass

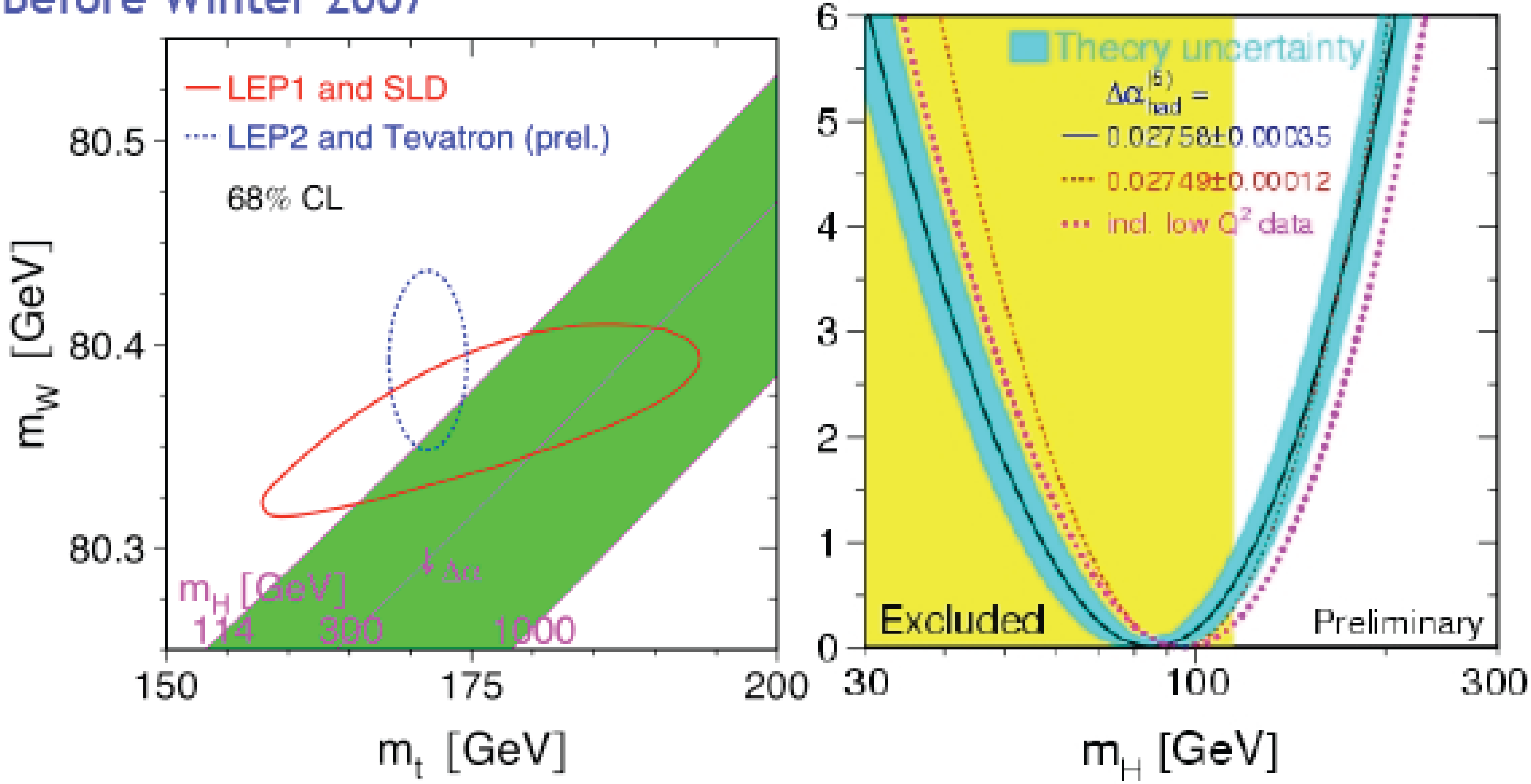


New Tevatron average (3 weeks ago): Top mass now measured to 1.8 GeV

http://tevewwg.fnal.gov/top

Impact on Higgs Mass

Before Winter 2007



Predicted Higgs mass from W loop corrections (LEP EWWG):

$m_H=85^{+39}_{-28}$ GeV (<166 GeV at 95% CL)

direct search from LEP II: m_H>114.4 GeV

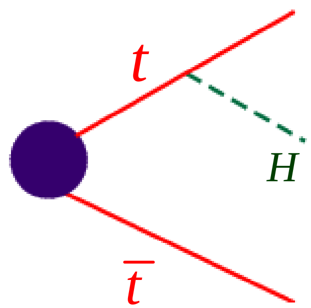
http://lepewwg.web.cern.ch/LEPEWWG/

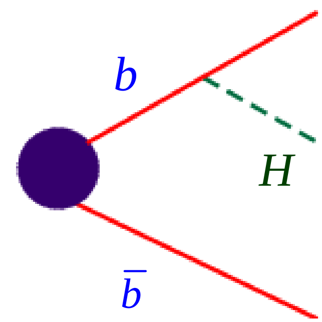
Impact on Higgs Mass

- Summer 2006 SM Higgs fit: (LEP EWWG)
  - $M_H = 85^{+39}_{-28}$ GeV
  - $M_H < 166$ GeV (95% CL)
  - $M_H < 199$ GeV (95% CL) Including LEPII direct exclusion
- Updated preliminary SM Higgs fit: (With new CDF W Mass)
  - $M_H = 80^{+36}_{-26}$ GeV (M. Grünewald, private communication)
  - $M_H < 153$ GeV (95% CL)
  - $M_H < 189$ GeV (95% CL) Including LEPII direct exclusion
- Updated preliminary SM Higgs fit: (With new Tevatron top mass)
  - $M_H = 76^{+33}_{-24}$ GeV
  - $M_H < 144$ GeV (95% CL)
  - $M_H < 182$ GeV (95% CL) Including LEPII direct exclusion

Discriminating Models of Electroweak Symmetry Breaking

Testing the interaction of Top, Bottom and Higgs Boson





SM: $y_t^{SM} = \frac{m_t}{\sqrt{2}v} = 1$ $\quad y_b^{SM} = \frac{m_b}{\sqrt{2}v} = \frac{1}{40}$

MSSM: $(\tan\beta = 40)$ $\quad y_t = y_t^{SM} \cdot \cot\beta = \frac{1}{40}$ $\quad y_b = y_b^{SM} \cdot \tan\beta = 1$

TopColor: $H \equiv < t\bar{t} >$ $\quad y_t = 1$ $\quad y_b = 1$

If Higgs boson exists

Discovering the Higgs boson and studying its interaction is essential to probe the electroweak symmetry breaking and the flavor symmetry breaking

Otherwise,

Studying interaction among longitudinal W and Z bosons in the TeV region and interaction of longitudinal W (Z) boson and heavy fermions (top and bottom)

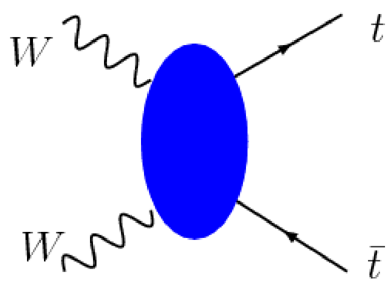
Higgsless Model

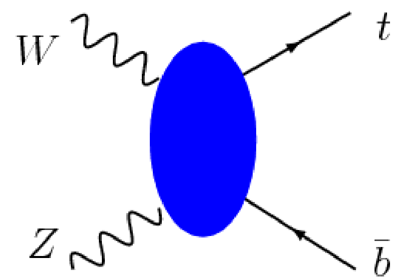
(Extra-dimension Models)

- No elementary or composite Higgs boson to regulate unitarity violation in the TeV region for

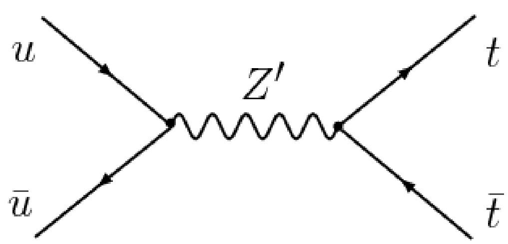
  W W, ZZ $\rightarrow$ W W, Z Z and W Z $\rightarrow$ W Z

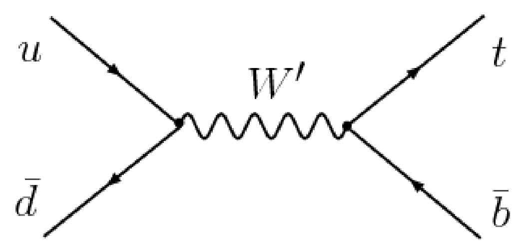
- Need to study W W, Z Z $\rightarrow$ t t , W Z $\rightarrow$ t b scatterings in the TeV region





- Look for W' and Z', to delay unitarity breakdown





Summary

We need experimental Data
to advance our knowledge.

Fermilab Tevatron

⇓

CERN LHC (Large Hadron Collider)

⇓

ILC (International Linear Collider)

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