Electroweak Theory at Multi-TeV Collider
(Collider Physics)

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Peking University

Lecture of Frontier of Theoretical Physics
@ UCAS, July 3, 2012

Lamb's Nobel Lecture

WILLIS E. LAMB, JR.

Fine structure of the hydrogen atom

Nobel Lecture, December 12, 1955

When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called « elementary particles »: the electron and the proton. A deluge of other « elementary » particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. I have heard it said that « the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine ».

Tears of Joy

- History of particle hunting
  - W and Z boson discovery (1983) — 10 years
    Theory 1973
  - Top-quark discovery (1995) — 18 years
    Existence: $b\bar{b}$ FB asymmetry (1977)
  - Higgs-like scalar discovery (2012) — 48 years
    Theory 1964

History is not just a thing of the past!

July 4th , 2012

July 4th 2012
The discovery of a new particle

From J. Ellis's talk at 7th workshop of TeV scale physics at Tsinghua University, 11-11-2012

Tears of Joy

- History of particle hunting
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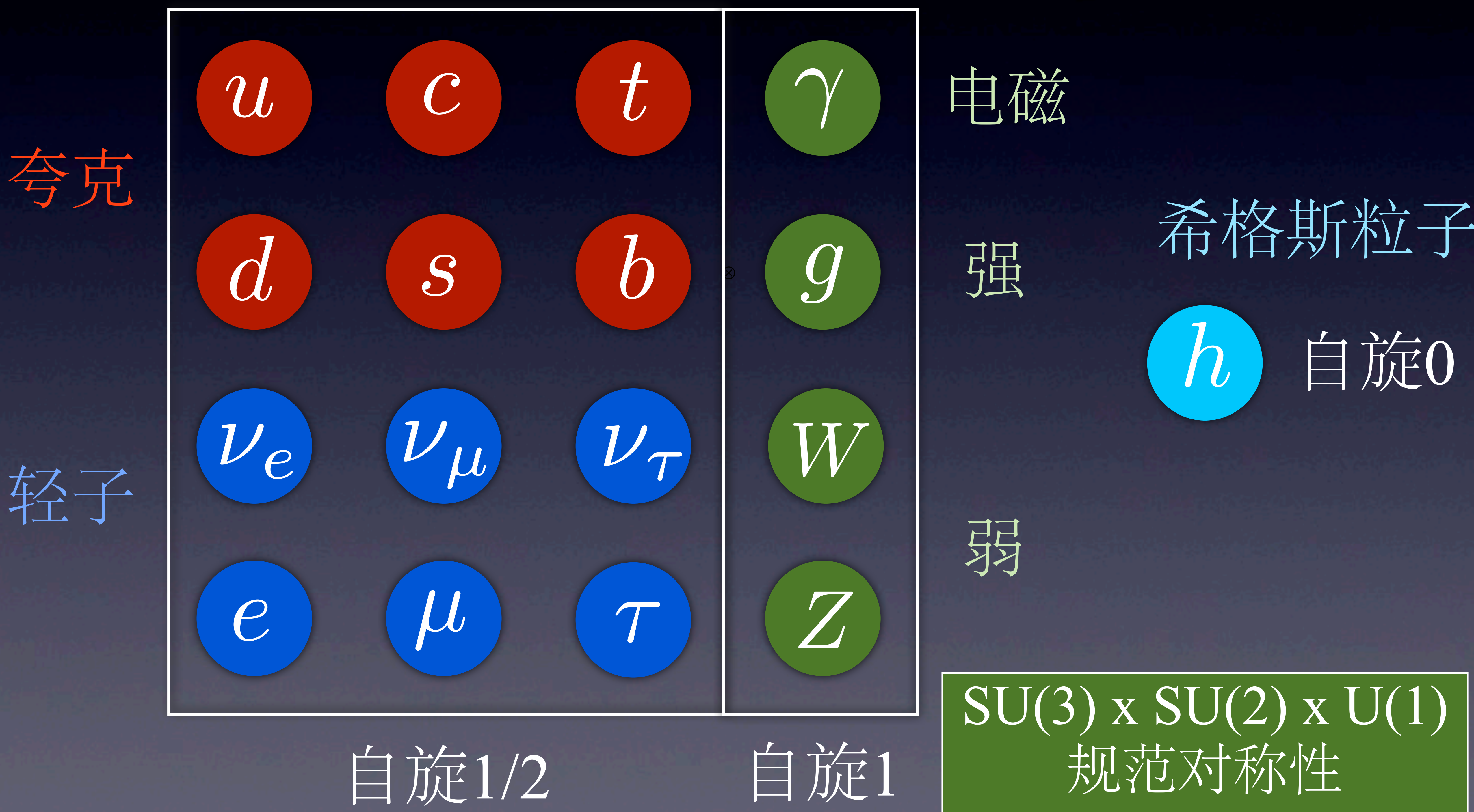
    Theory 1973
    10 years
  - Top-quark discovery (1995)
    Existence: $b\bar{b}$ FB asymmetry (1977)
    18 years
  - Higgs-like scalar discovery (2012)
    Theory 1967
    48 years
  - New Physics beyond the SM
    Extra dim (KK, 1921)
    SUSY (1966)
    ?years

粒子物理的标准模型

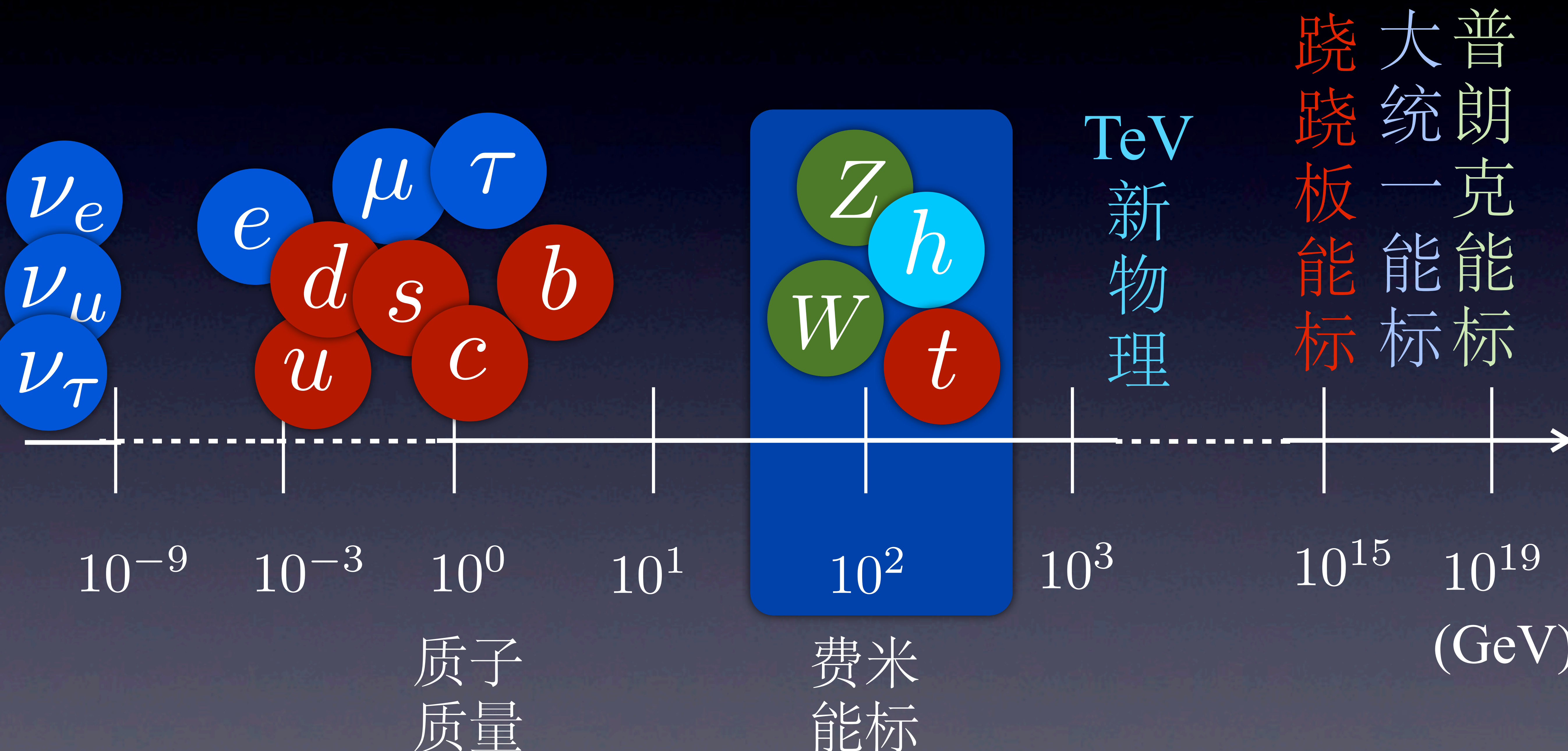
已知基本粒子谱



标准模型的两大疑难

<u>电弱对称性破缺起源</u> 和 <u>味对称性破缺起源</u>

（W 和 Z 质量）　　　（费米子质量）

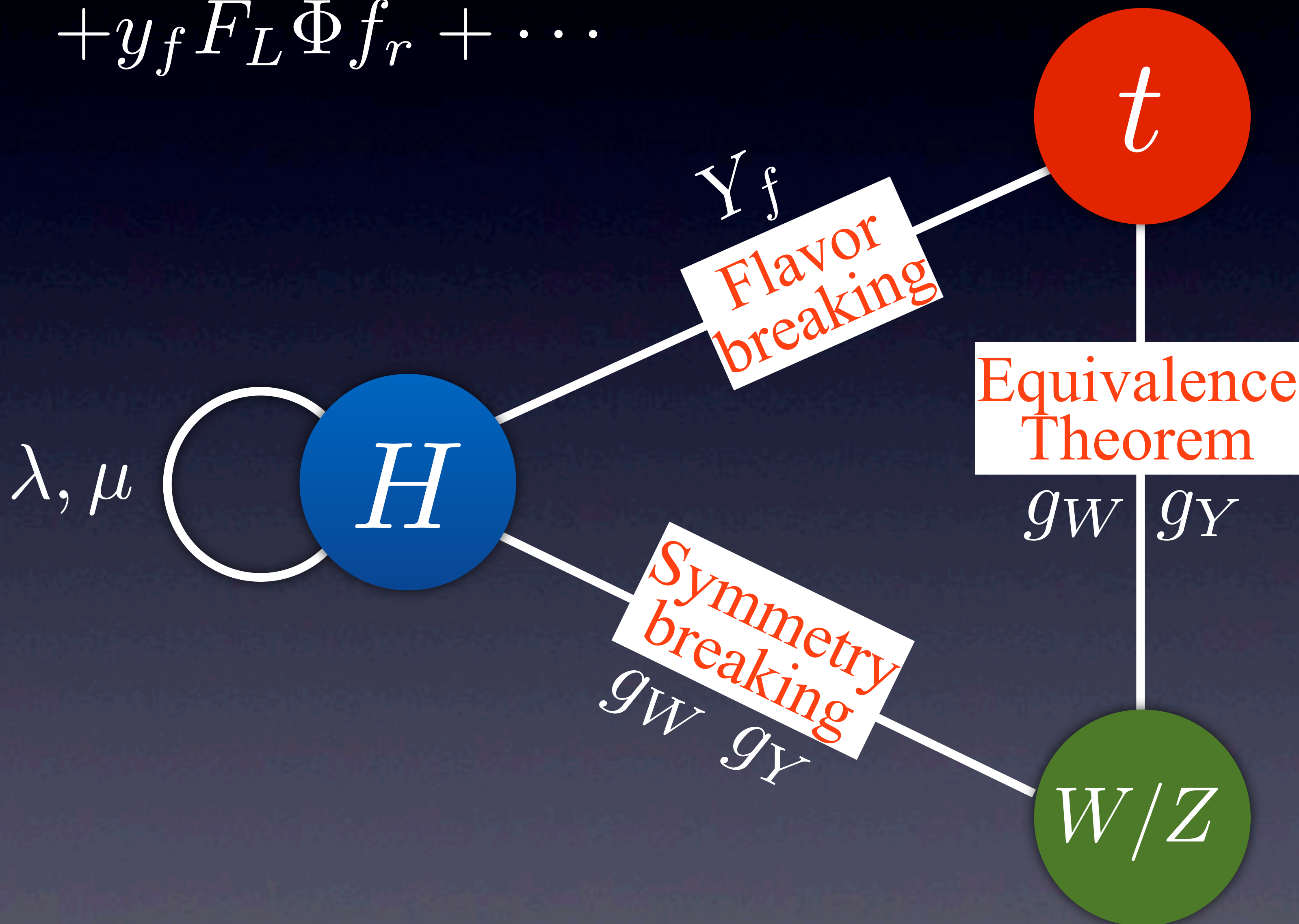


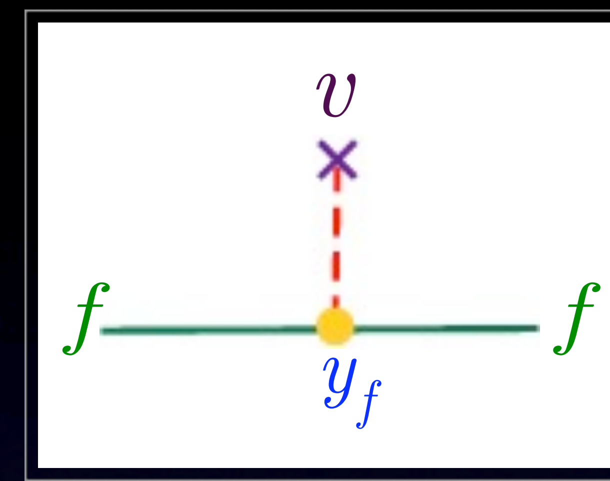
$\mathrm{GeV} = 10^9 \mathrm{eV}$

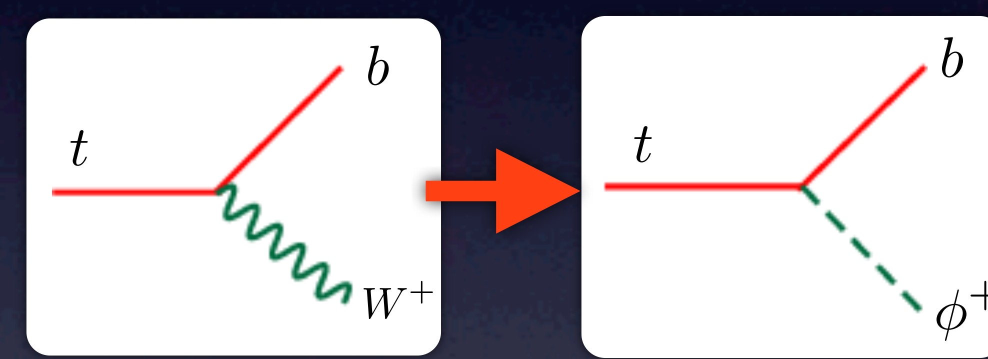
Electroweak triangle

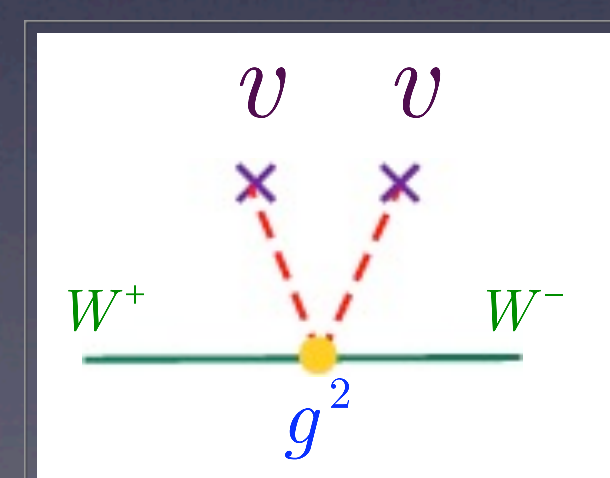
$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

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





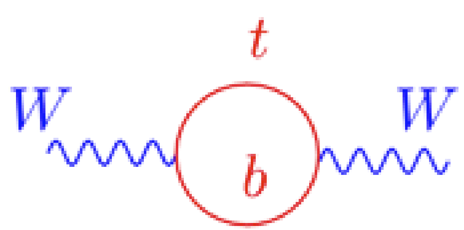




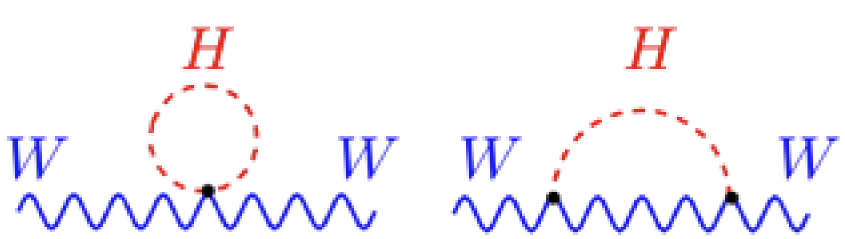
W-boson, Top-quark and Higgs boson

- Highly correlated at the quantum level

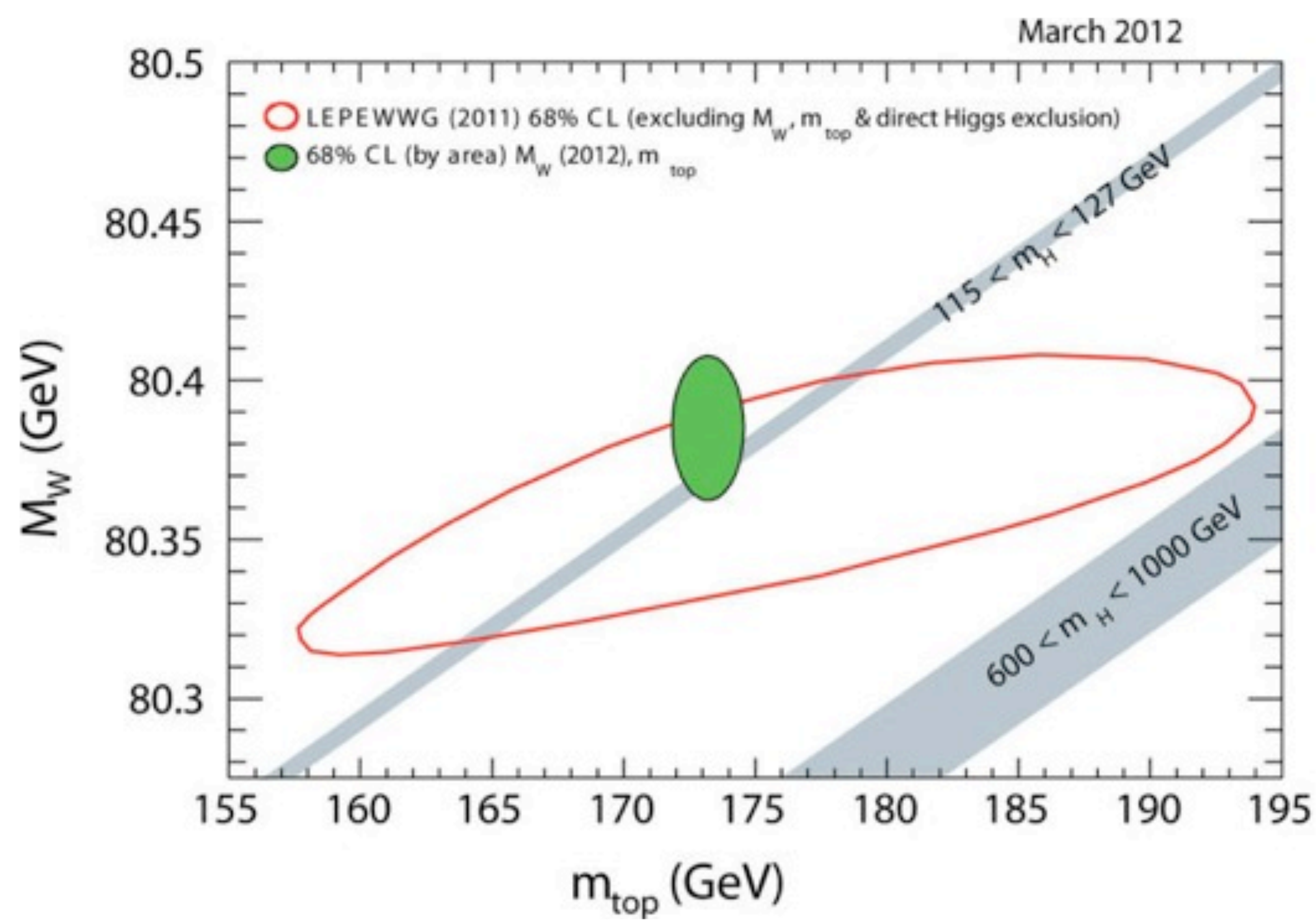
$$M_W = 80.3827 - 0.0579 \ln\left(\frac{M_H}{100\ \mathrm{GeV}}\right) - 0.008 \ln^2\left(\frac{M_H}{100\ \mathrm{GeV}}\right)$$
$$+0.543\left(\left(\frac{m_t}{175\ \mathrm{GeV}}\right)^2 - 1\right) - 0.517\left(\frac{\Delta\alpha_{had}^{(5)}(M_Z)}{0.0280} - 1\right) - 0.085\left(\frac{\alpha_s(M_Z)}{0.118} - 1\right)$$



$$\Delta M_W \propto m_t^2$$



$$\Delta M_W \propto \ln m_H^2$$



Outline

- LEP

  Precision machine

- Tevatron

  Precision machine + discovery machine

- LHC

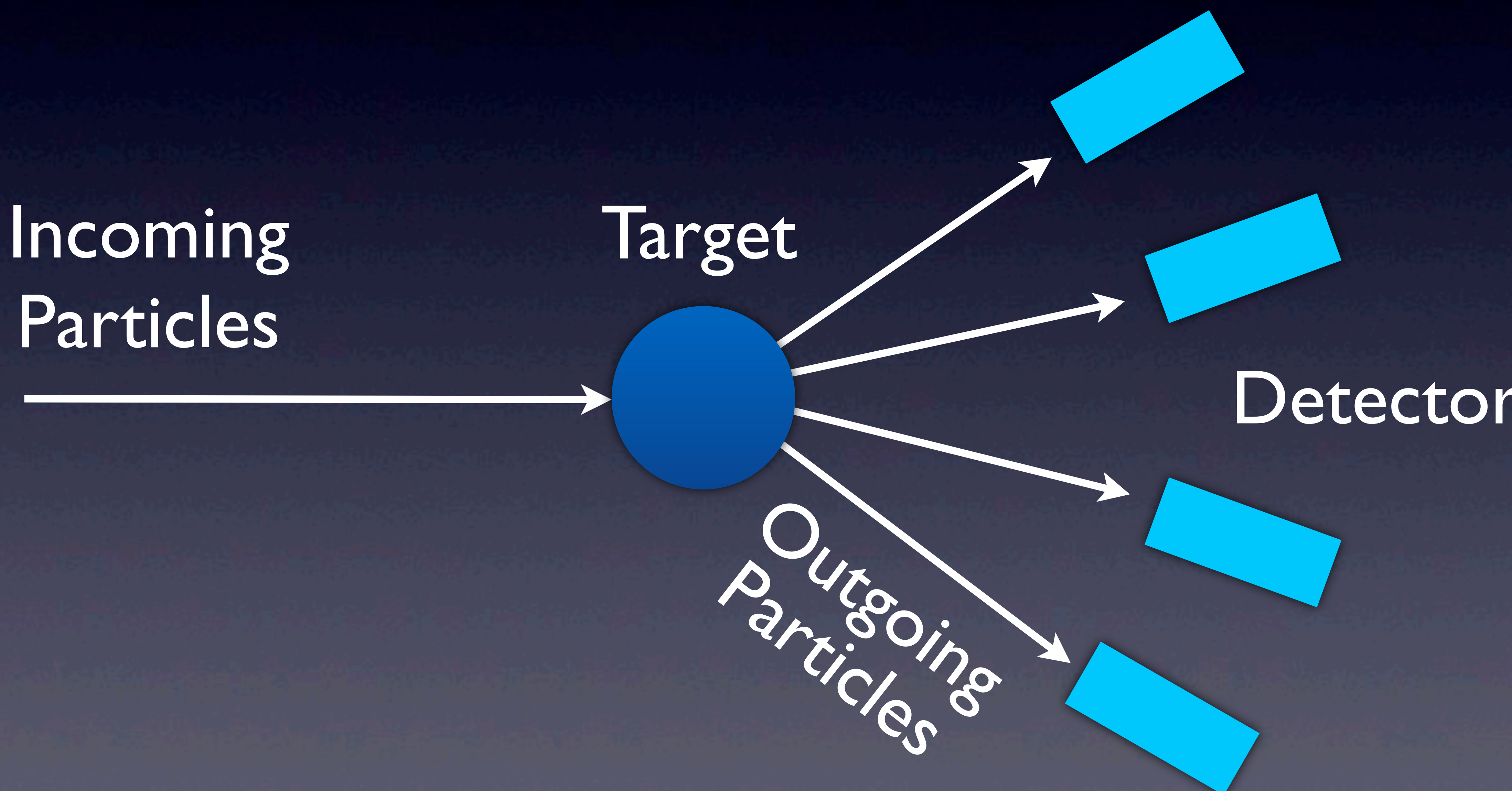
  Discovery machine + Precision machine

  Higgs boson and others

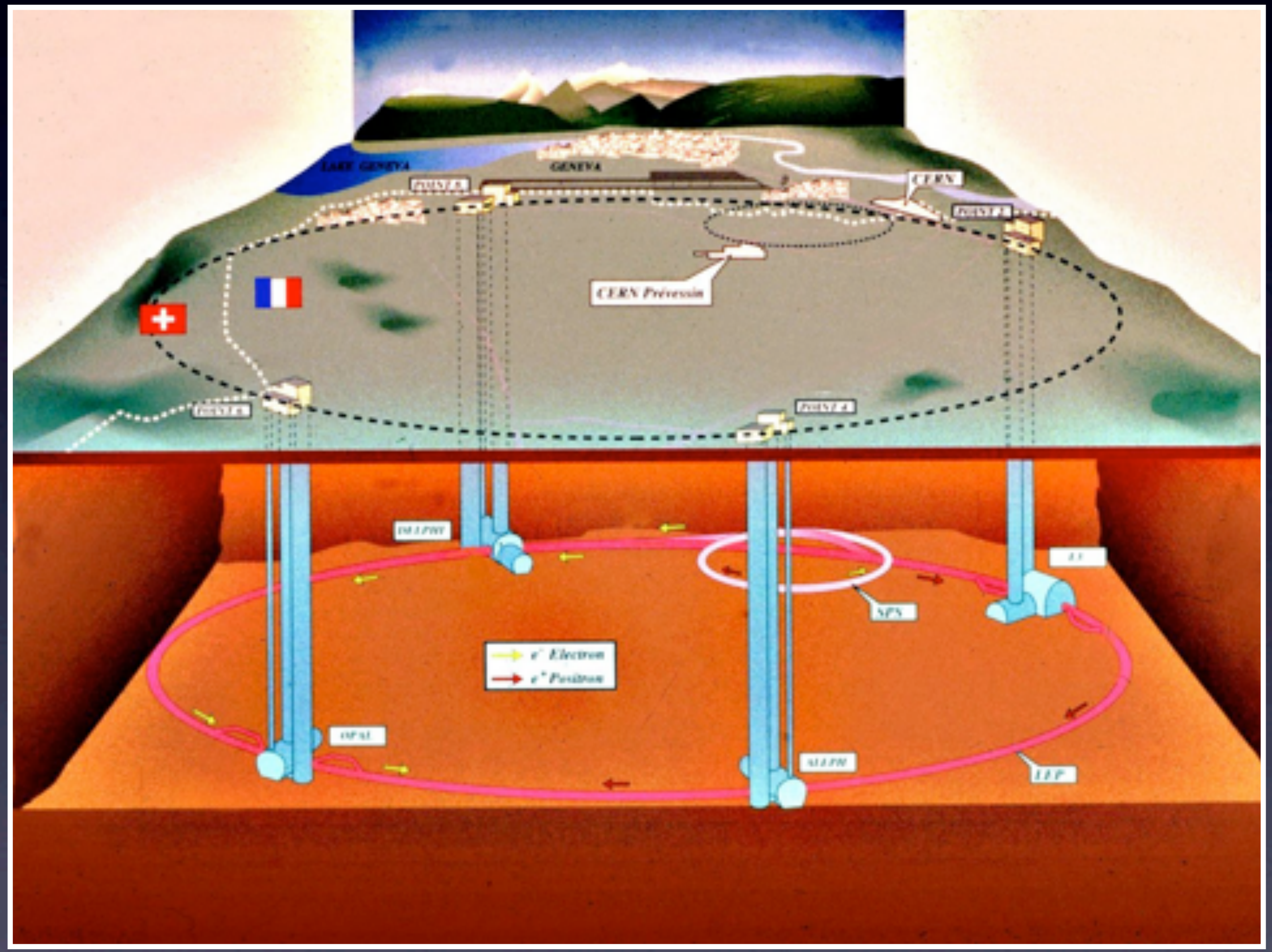
- SLHC, VLHC, Higgs Factory, ILC, ...

Rutherford scattering

1909-1911 : The begin of the collider experiments

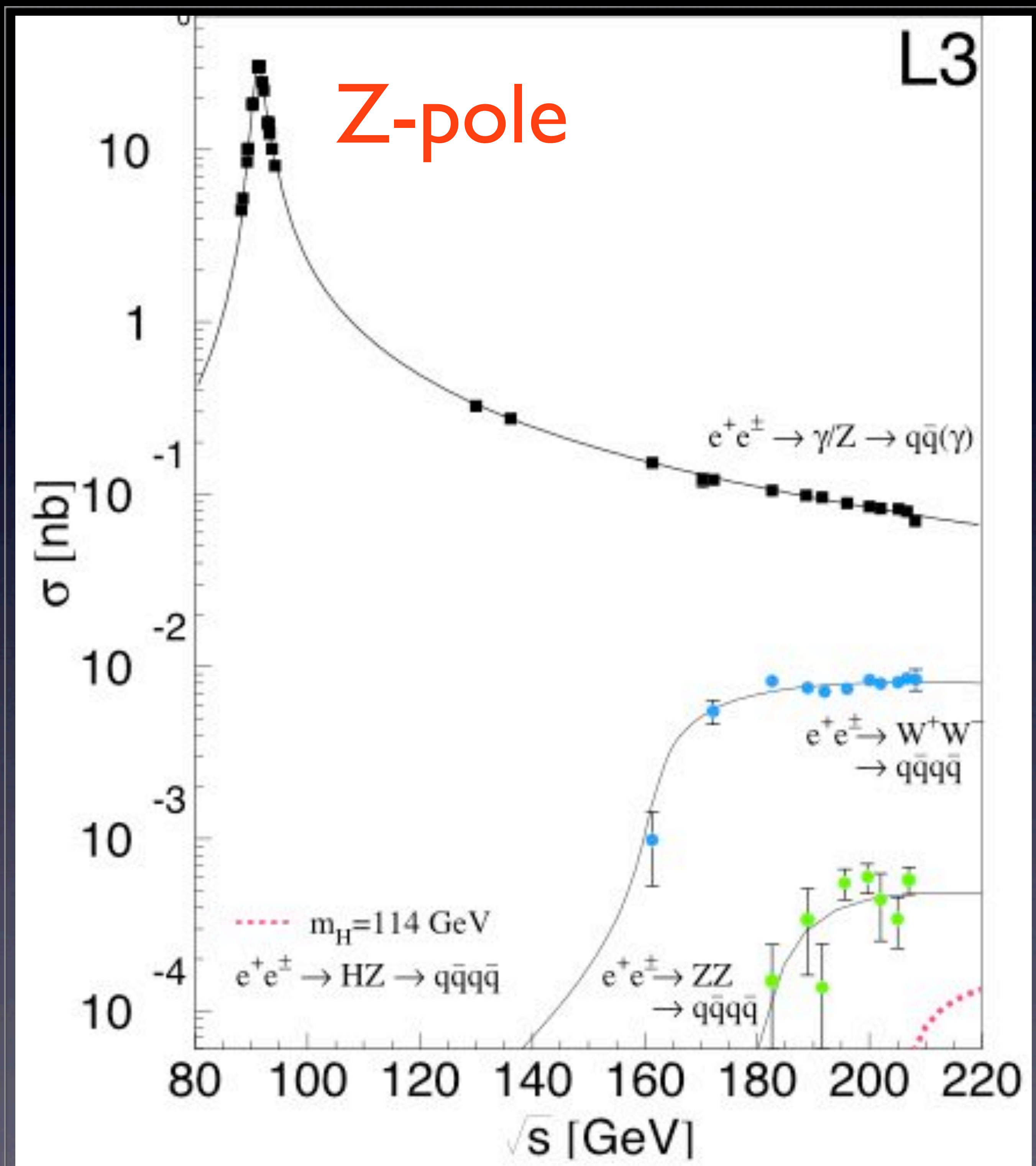


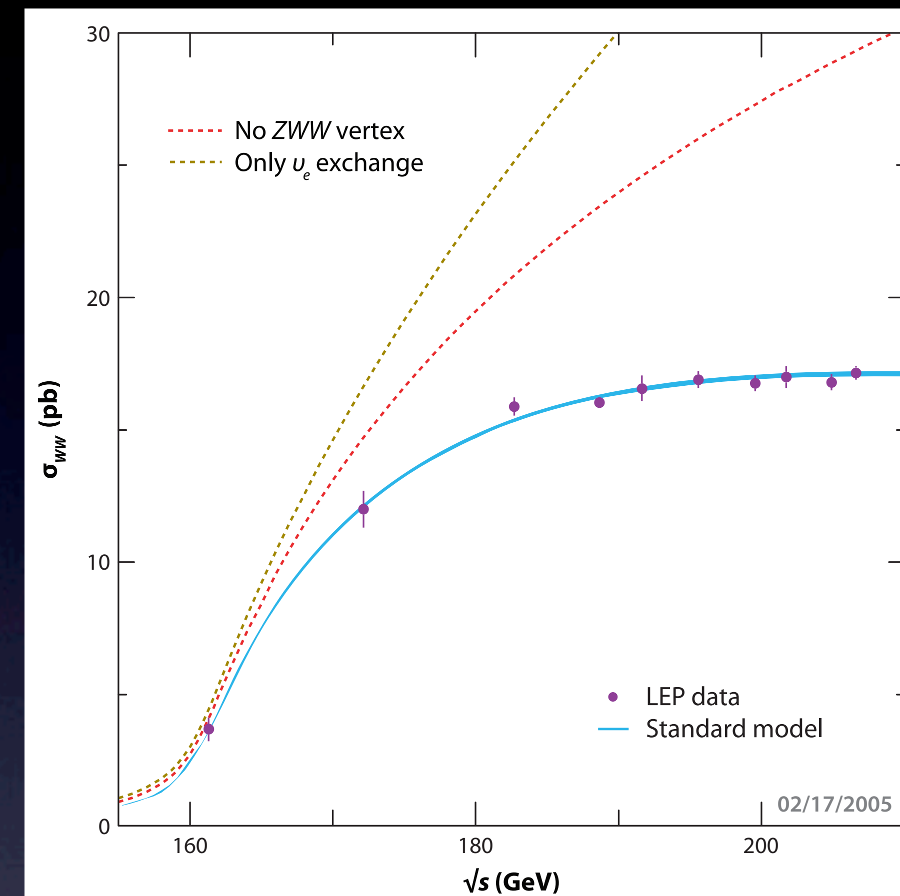
Large Electron-Positron Collider (1989-2001)

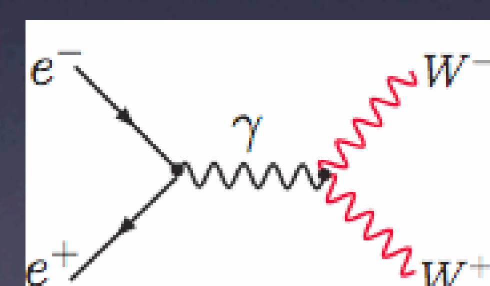


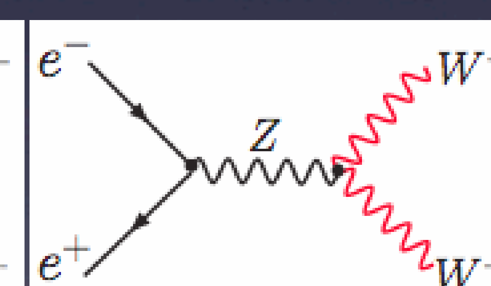
A Precision machine of EW interaction

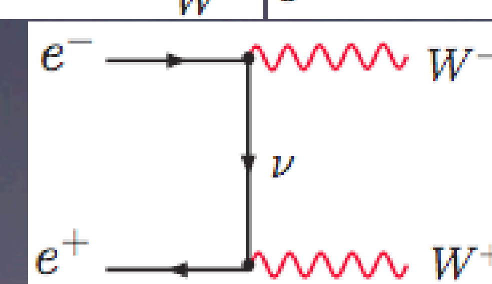
Electroweak theory tests at tree level





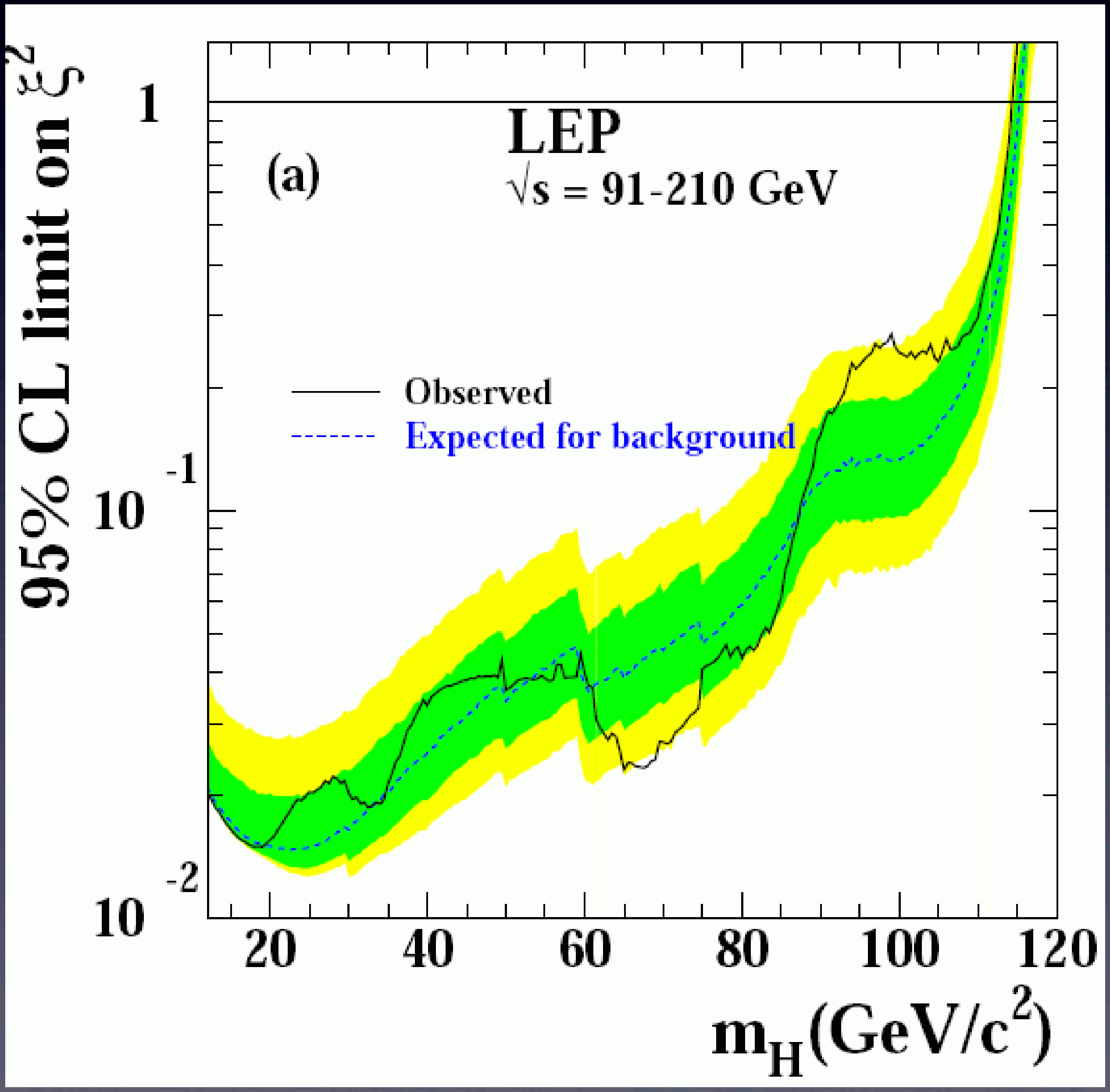


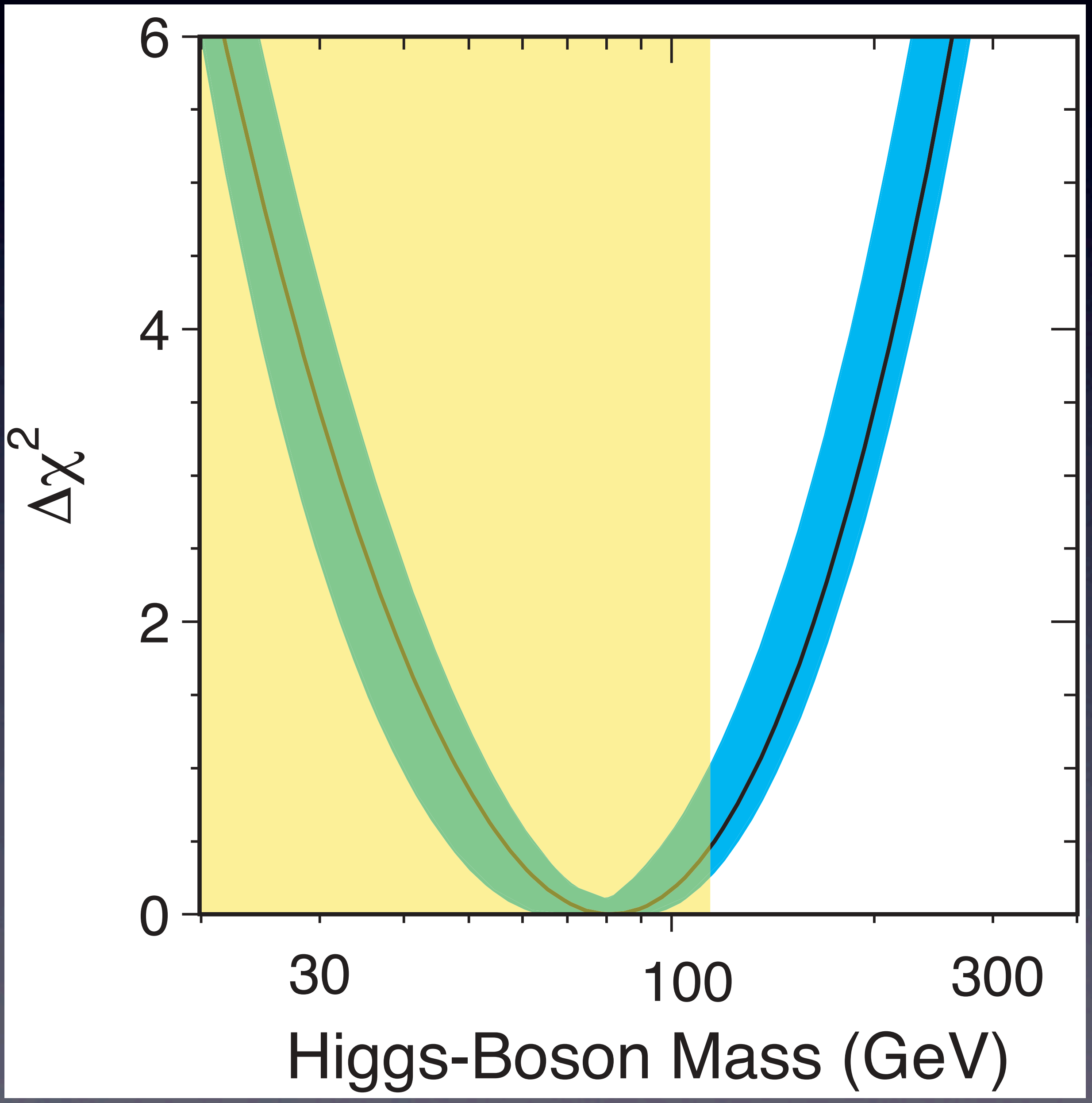




Higgs searches at LEP

- No evidence for Higgs $m_h > 114 \text{ GeV}$

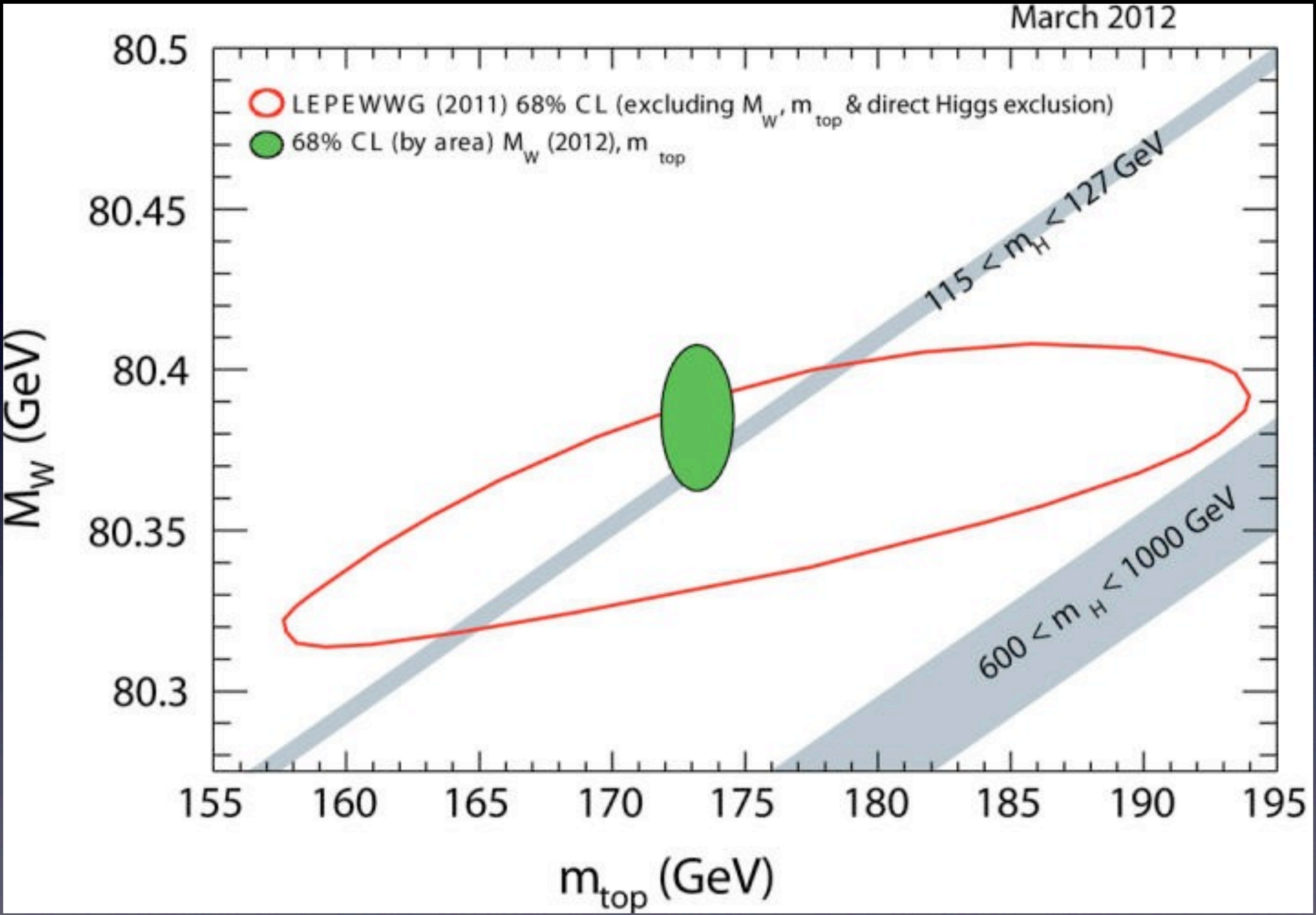




Tevatron
(1983-2011)

A precision machine built to test QCD
A precision machine of EW
A discovery machine of Top-quark

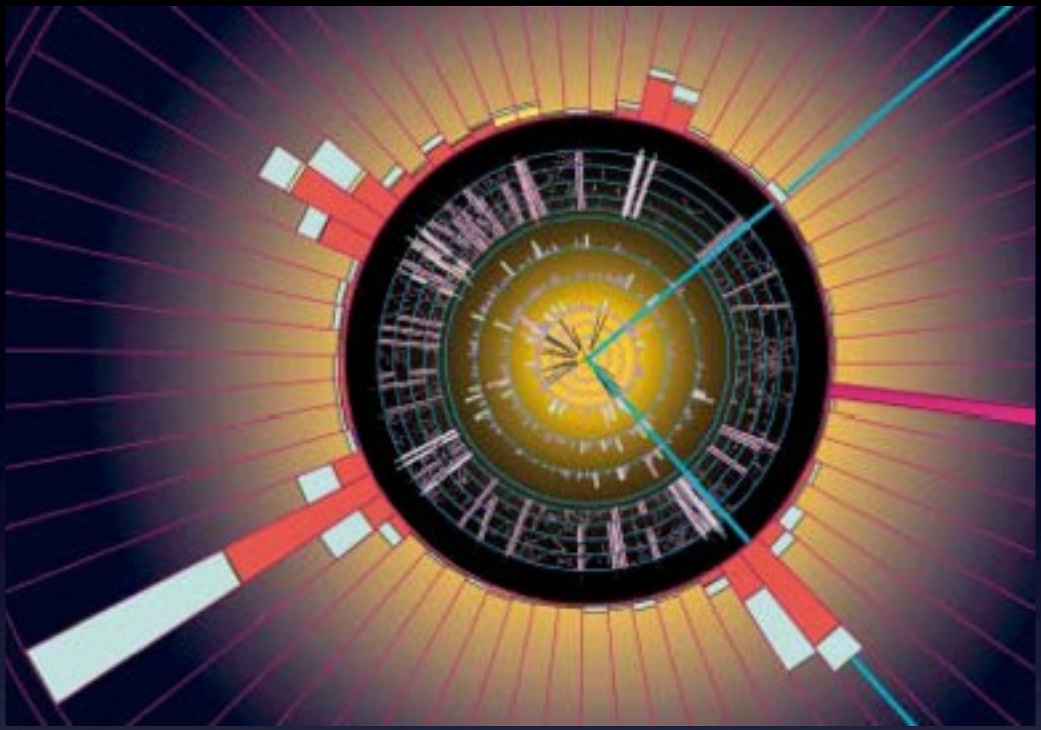
Triumph of *W*-boson Precision



Top Quark Discovery

Such a Long Journey

March 2, 1995



High energy physicists had
Champaign
to celebrate the discovery of
the Top Quark at FNAL Tevatron by D0 & CDF groups.

Recently,

$$m_t = (173.1 \pm 1.0)\text{GeV}$$

Top Exists
(induced from data)

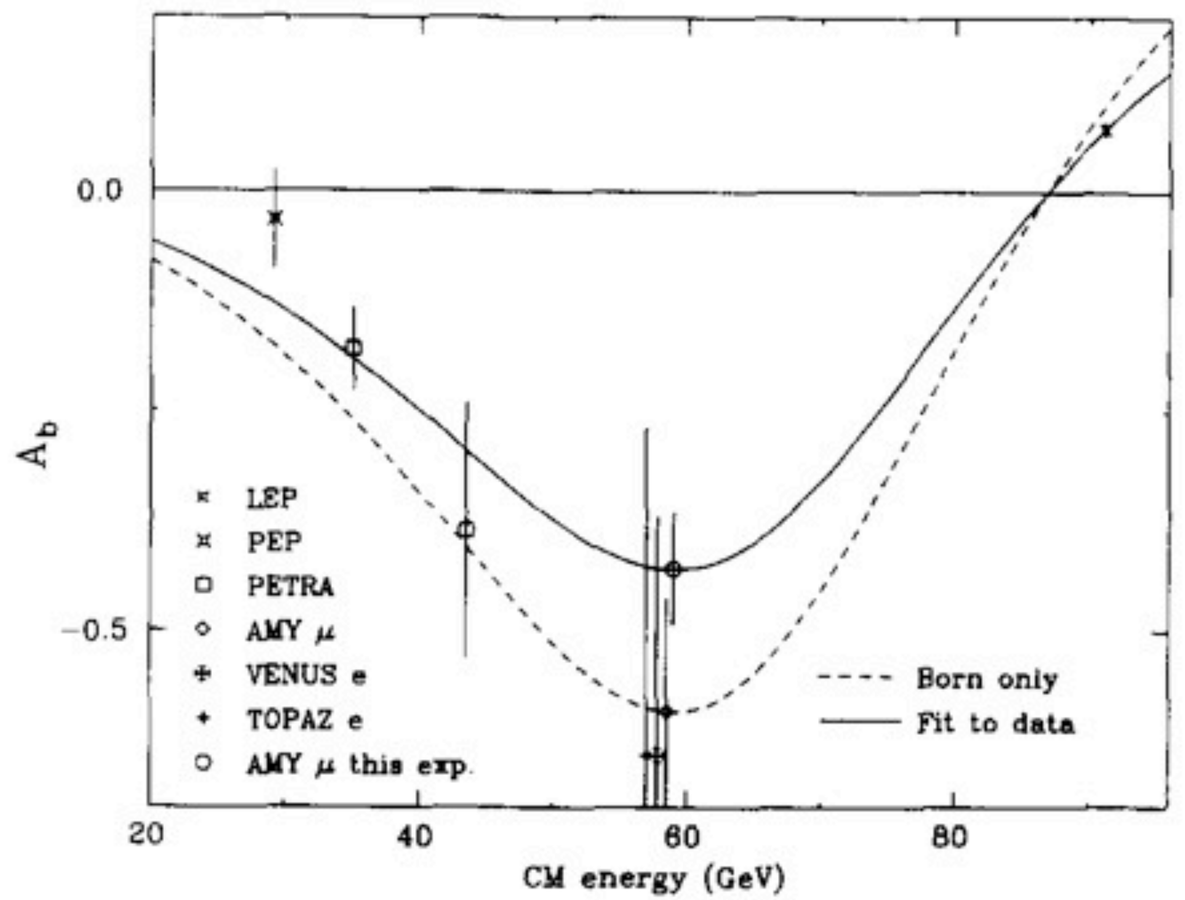


Fig. 5. The present measurement of the asymmetry A_b together with other experiments. The statistical and systematic errors are added in quadrature. The two curves are the Born term prediction without mixing (broken line) and the fit to the data (solid line) with mixing parameter χ. See the text.

Forward-Backward Asymmetry of bottom quark (A_b) in

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

confirmed weak isospin of b

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

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

which is called

TOP.

But it was such a long journey to find the TOP

Chronology of Top Hunting

Where is the Top Quark?

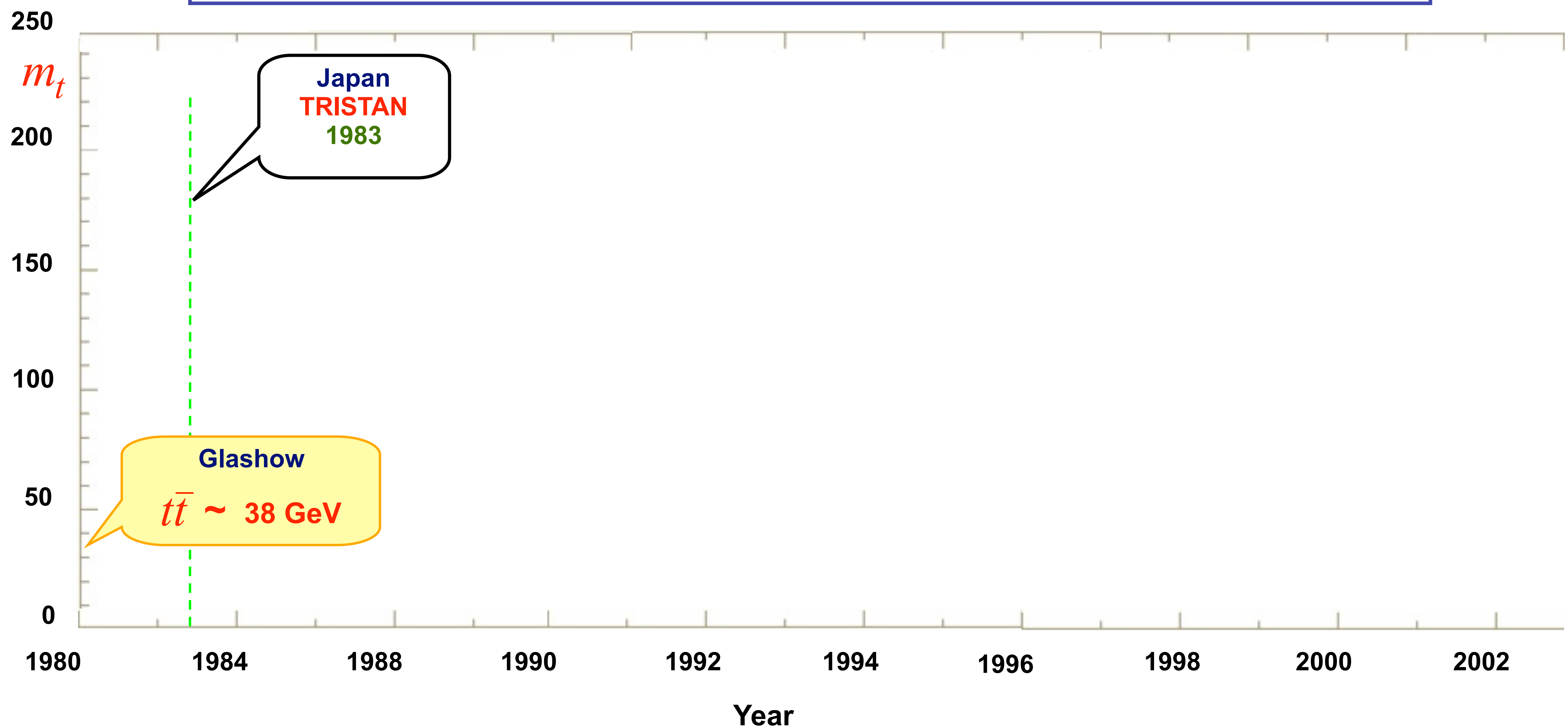
1980

Sheldon L. Glashow[a]

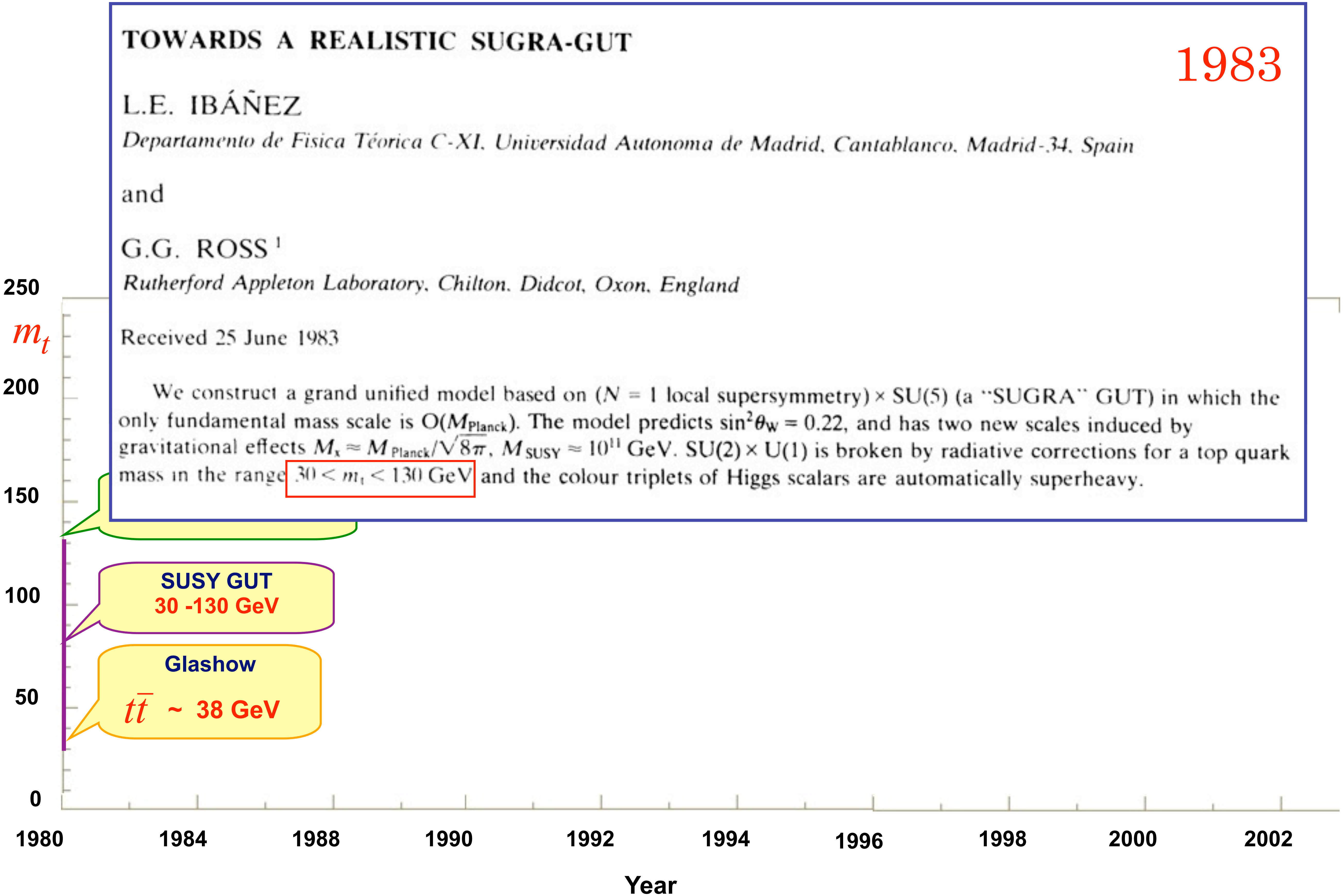
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(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



TOWARDS A REALISTIC SUGRA-GUT

L.E. IBÁÑEZ
Departamento de Fisica Téorica C-XI, Universidad Autonoma de Madrid, Cantablanco, Madrid-34, Spain

and

G.G. ROSS [1]
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, England

Received 25 June 1983

We construct a grand unified model based on ($N = 1$ local supersymmetry) × SU(5) (a "SUGRA" GUT) in which the only fundamental mass scale is $O(M_{Planck})$. The model predicts $\sin^2\theta_W = 0.22$, and has two new scales induced by 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.

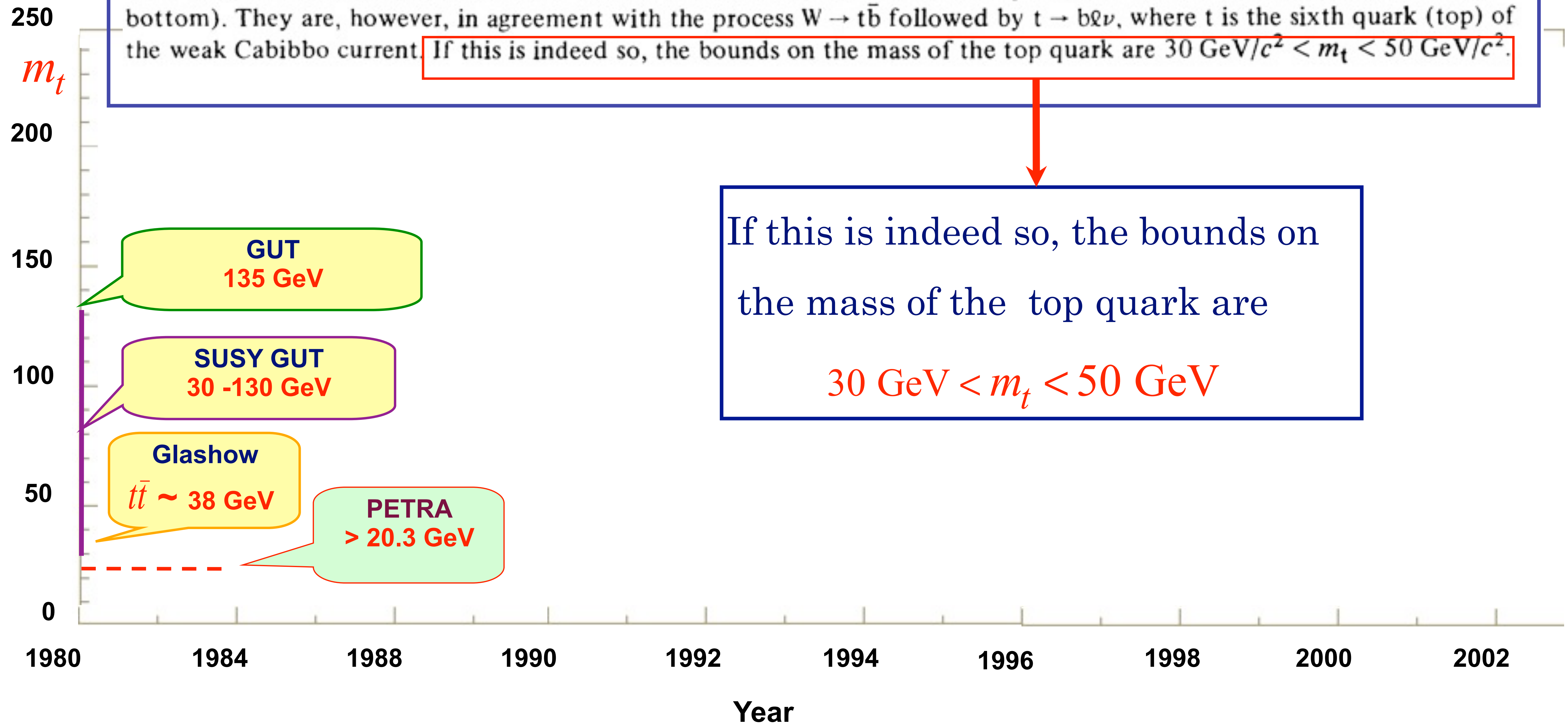
Chronology of Top Hunting

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 $30\ \mathrm{GeV}/c^2 < m_t < 50\ \mathrm{GeV}/c^2$.



If this is indeed so, the bounds on the mass of the top quark are

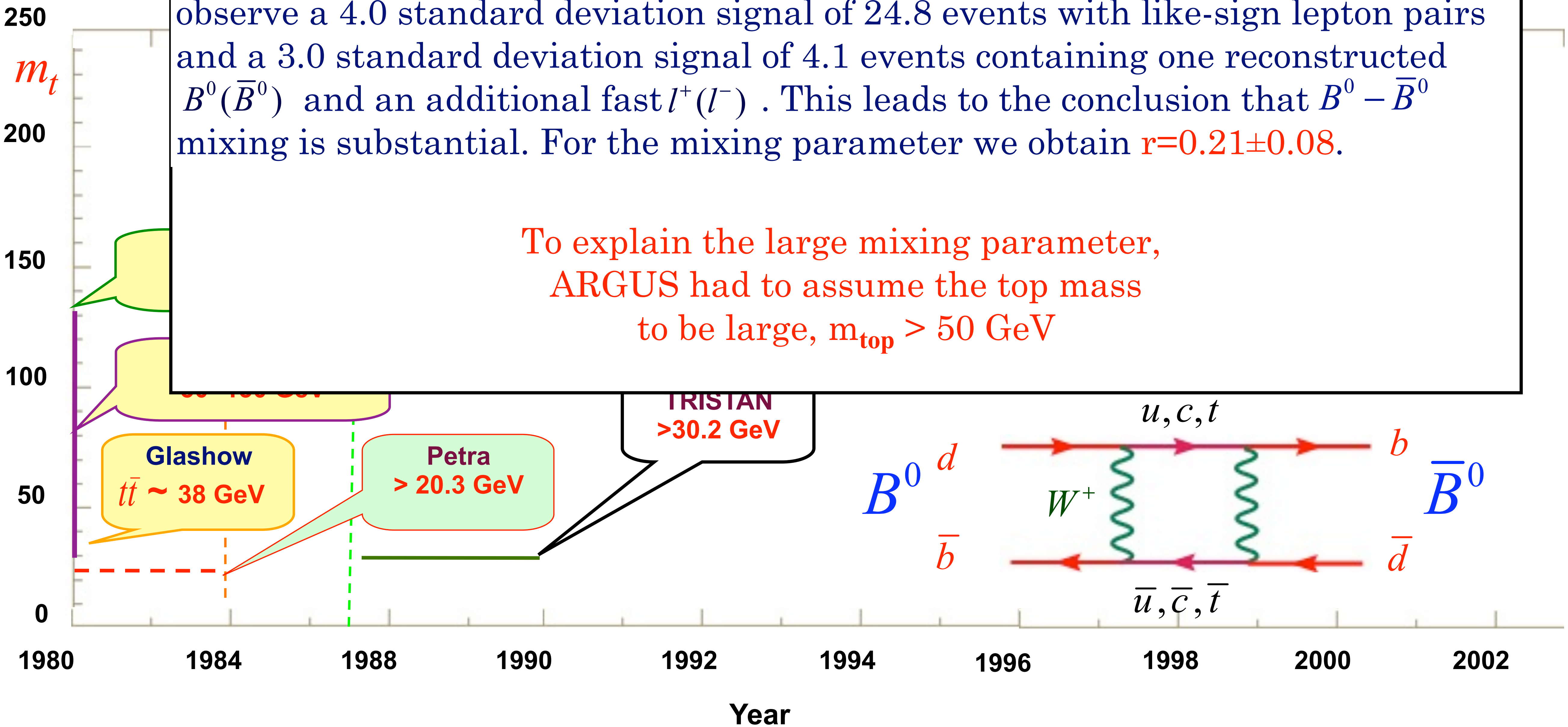
$$30\ \mathrm{GeV} < m_t < 50\ \mathrm{GeV}$$

Chronology of Top Hunting

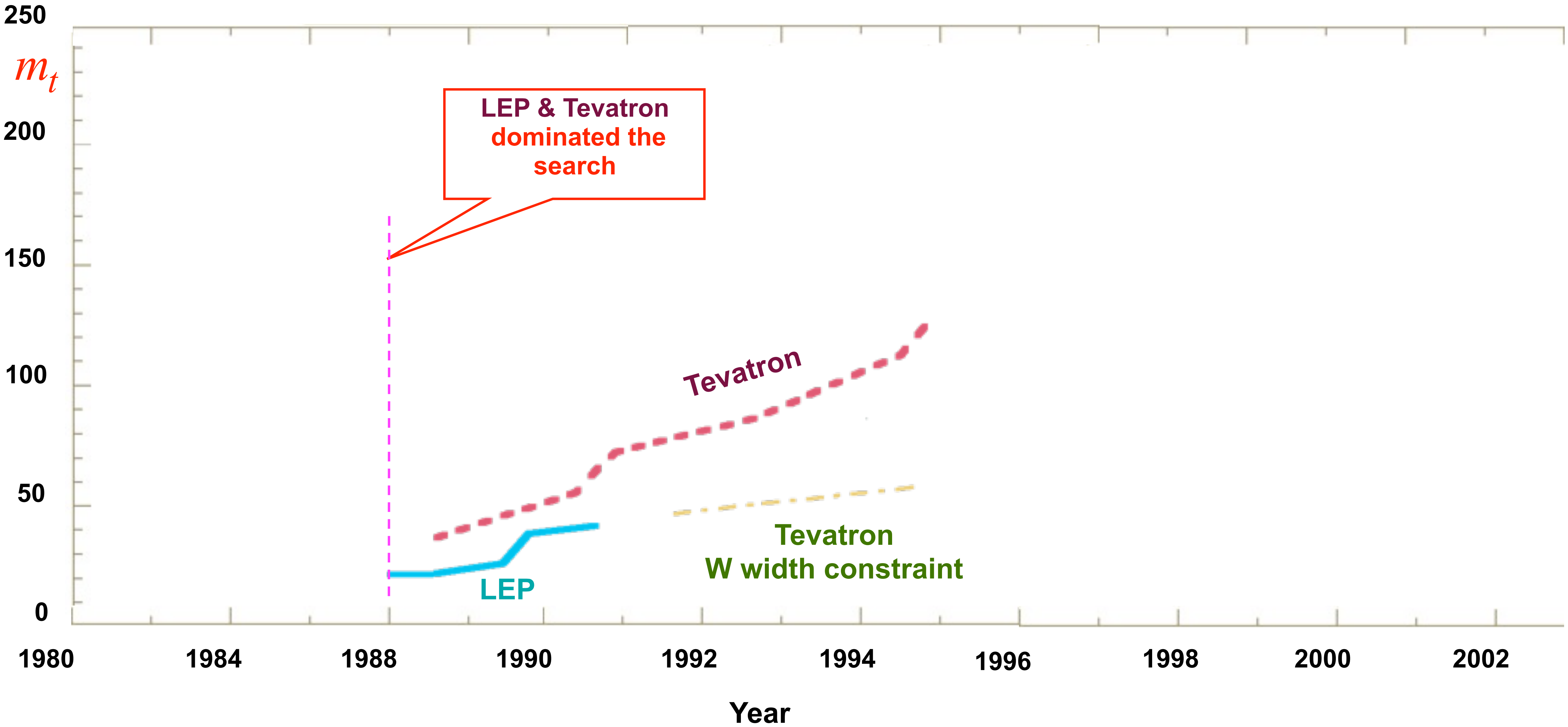
Observation of $B^0 - \overline{B}^0$ mixing
ARGUS Collaboration
Received 9 April 1987

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 $\Upsilon(4S)$ 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±0.08.

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



Chronology of Top Hunting

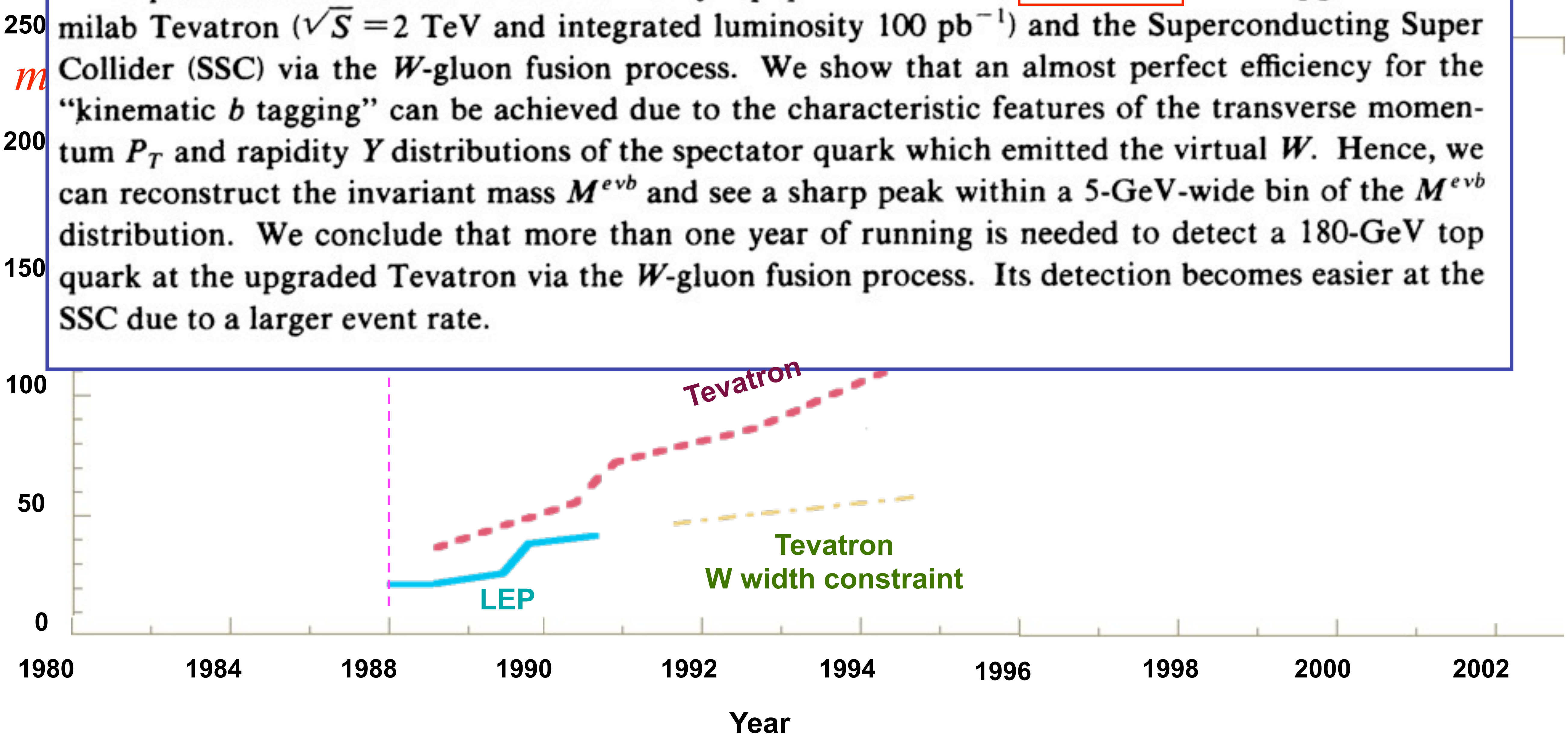


Chronology of Top Hunting

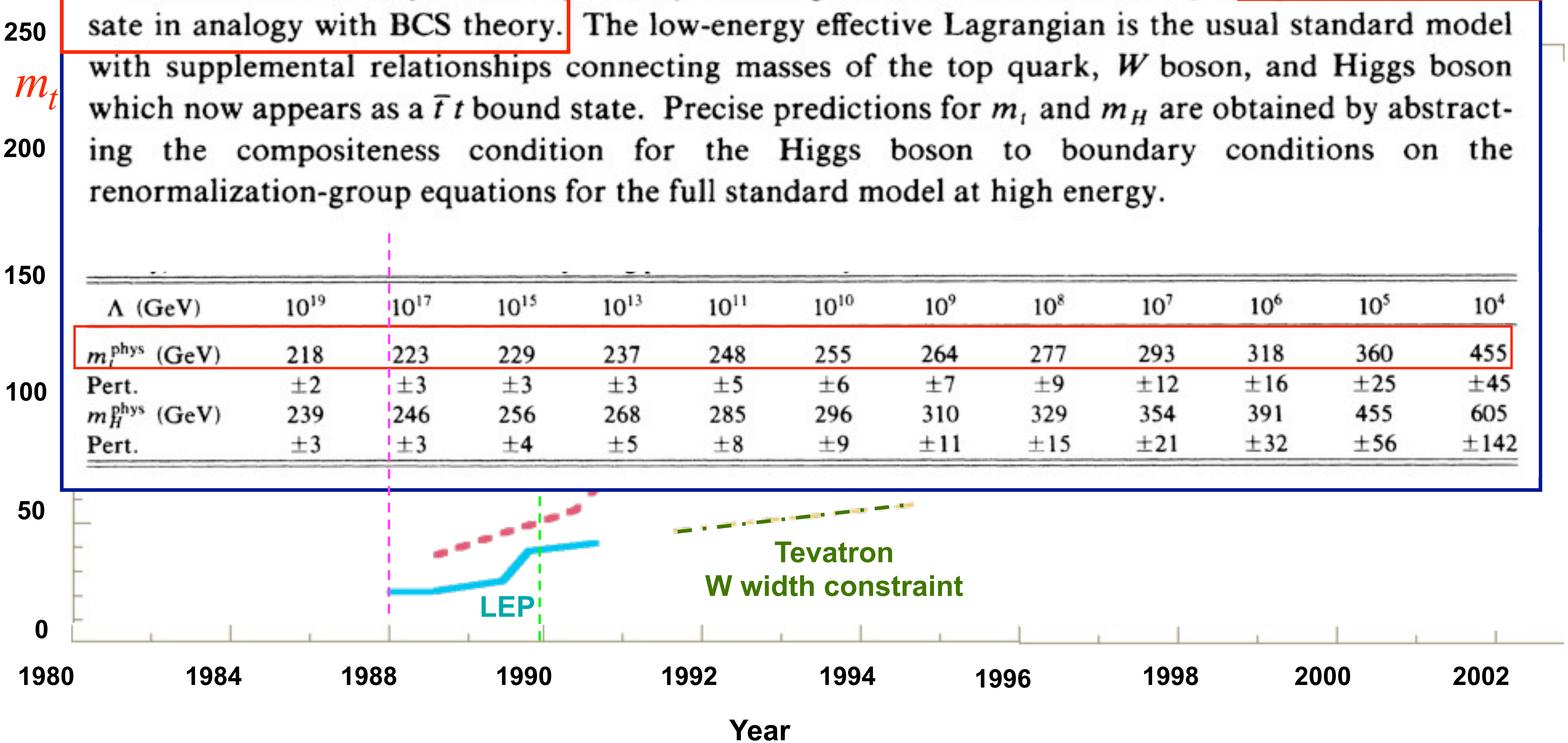
New method to detect a heavy top quark at the Fermilab Tevatron

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 ~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^{evb} and see a sharp peak within a 5-GeV-wide bin of the M^{evb} 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



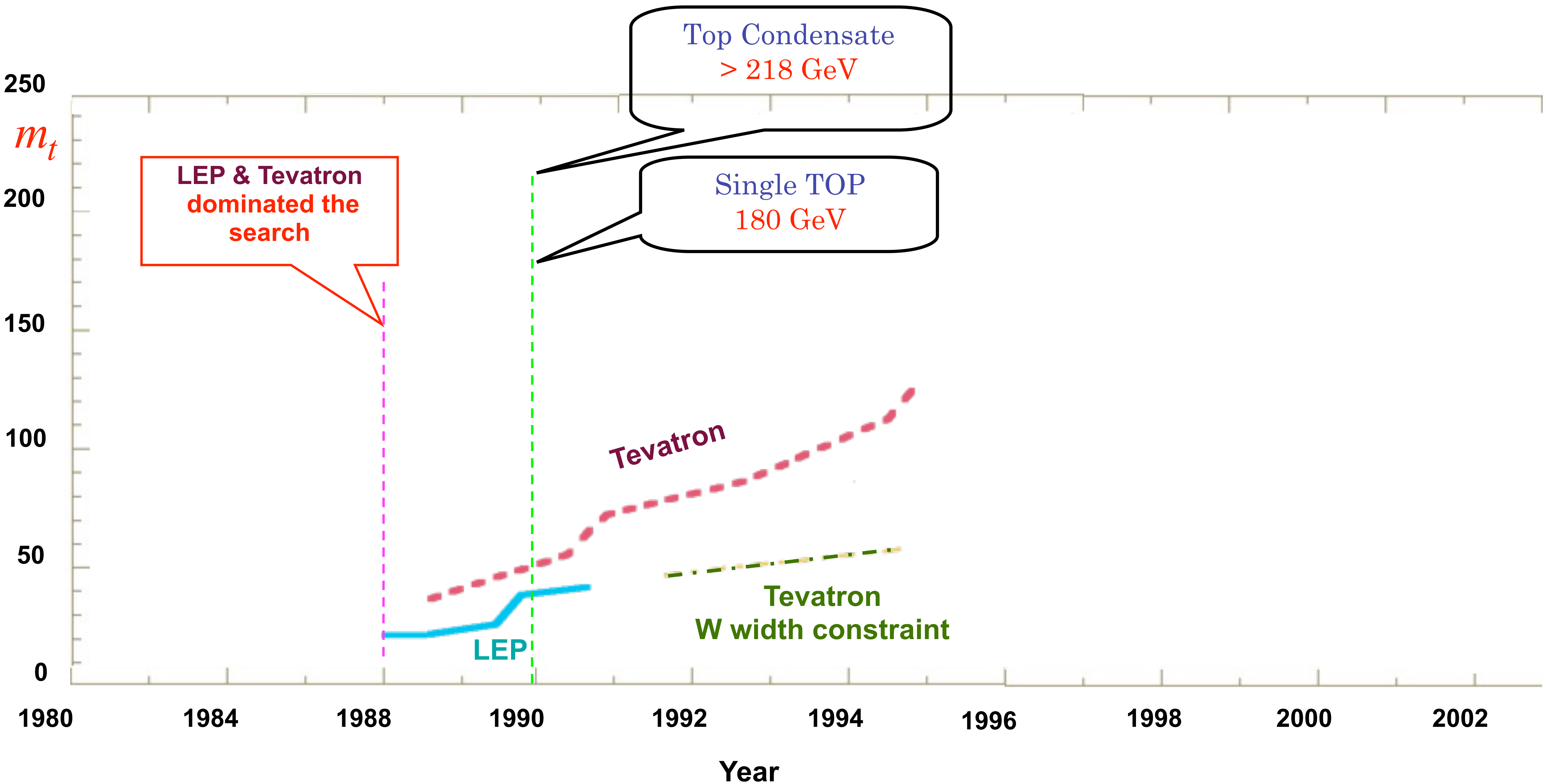
Minimal dynamical symmetry breaking of the standard model

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)

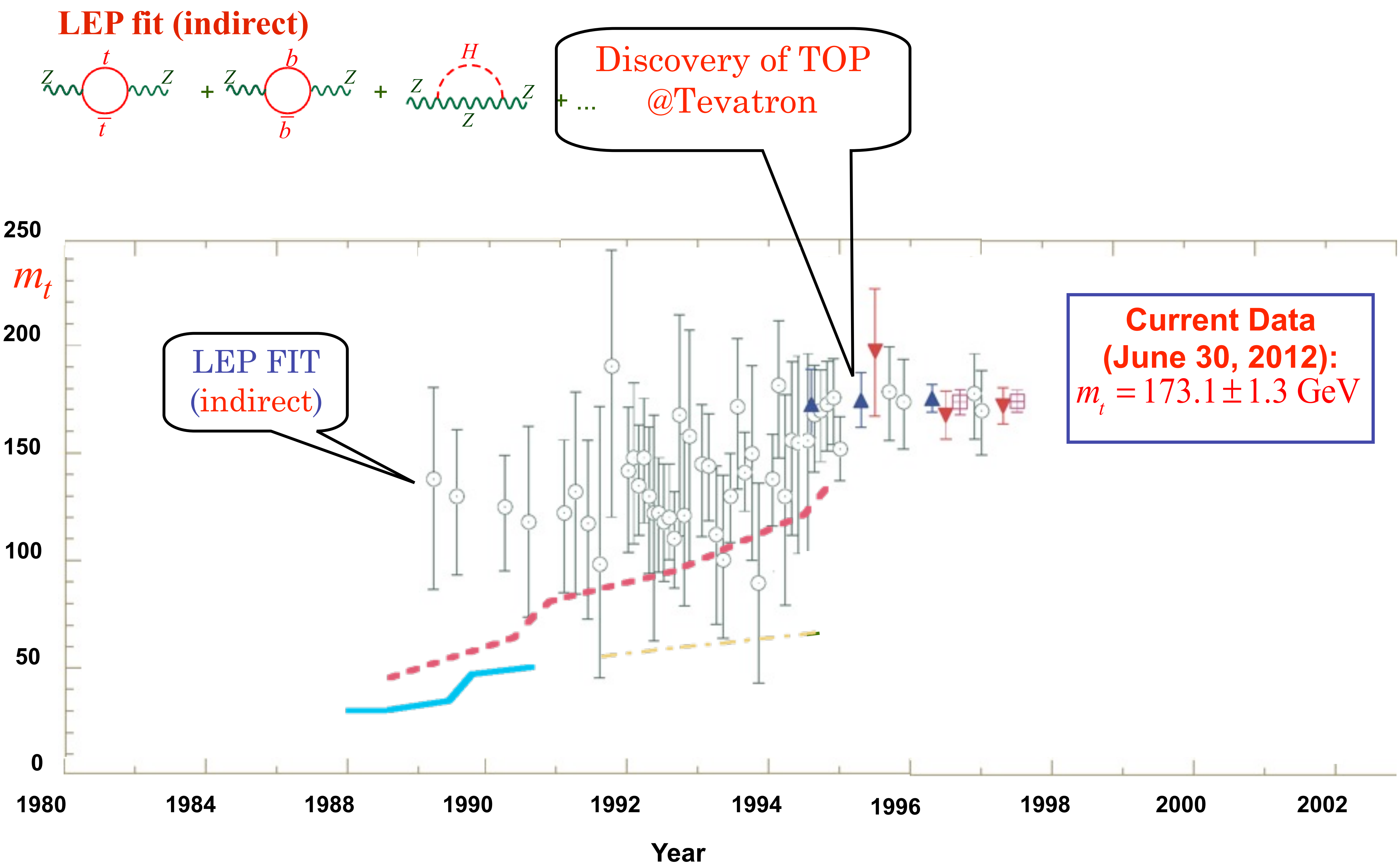
We formulate the dynamical symmetry breaking of the standard model by a top-quark condensate in analogy with BCS theory. The low-energy effective Lagrangian is the usual standard model with supplemental relationships connecting masses of the top quark, W boson, and Higgs boson which now appears as a $\bar{t}t$ 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



Top discovery: EW theory tests at Loop level

Bardeen, Hill, Lindner
Top-condensation (1989)
m_t >218GeV

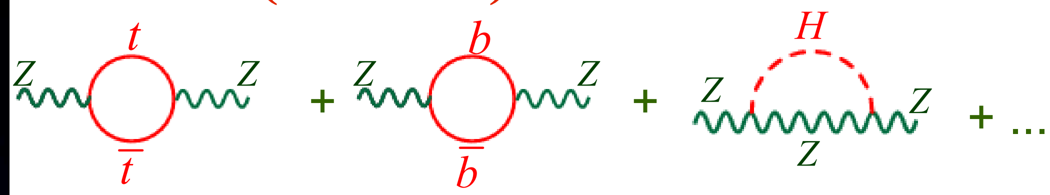
Ibanez, Ross
SUGRA-GUT (1983)
30<m_t<150GeV

Pendleton, Ross
GUT (1980)
m_t=130GeV

Glashow (1980)
m_{tt}>38GeV

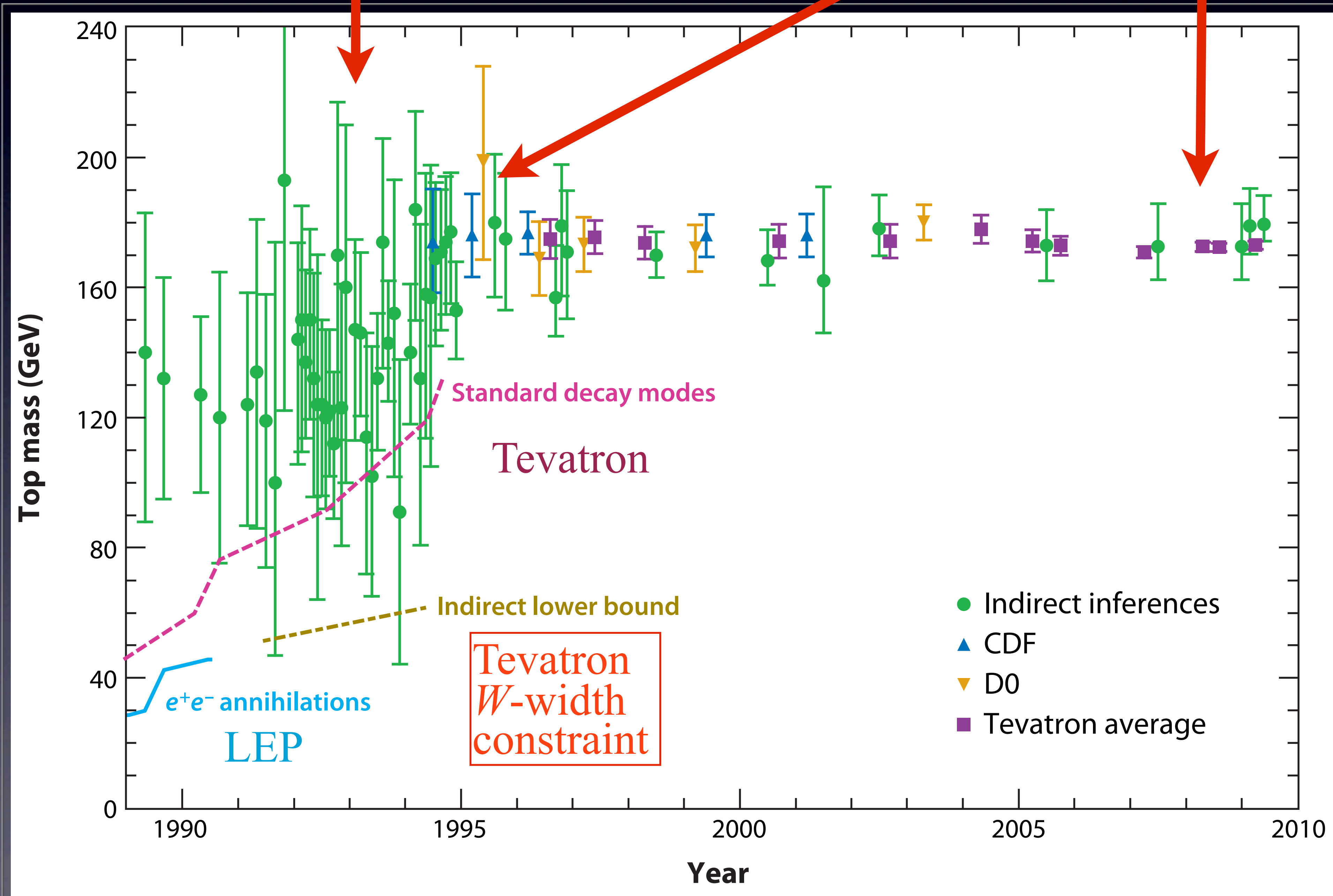
Tristan
1983

LEP fit (indirect)

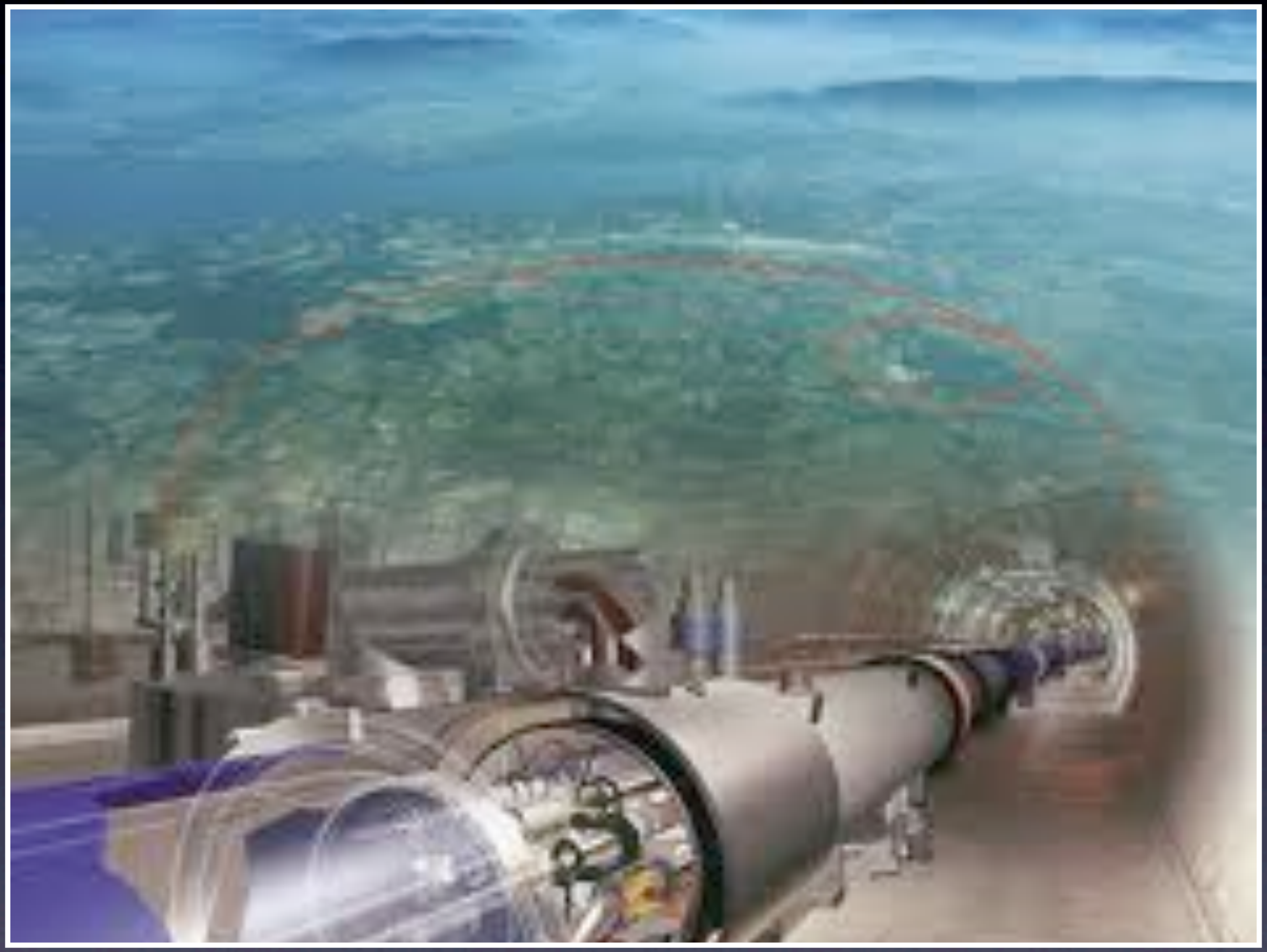


Tevatron (1995) Discovery

Tevatron Precision

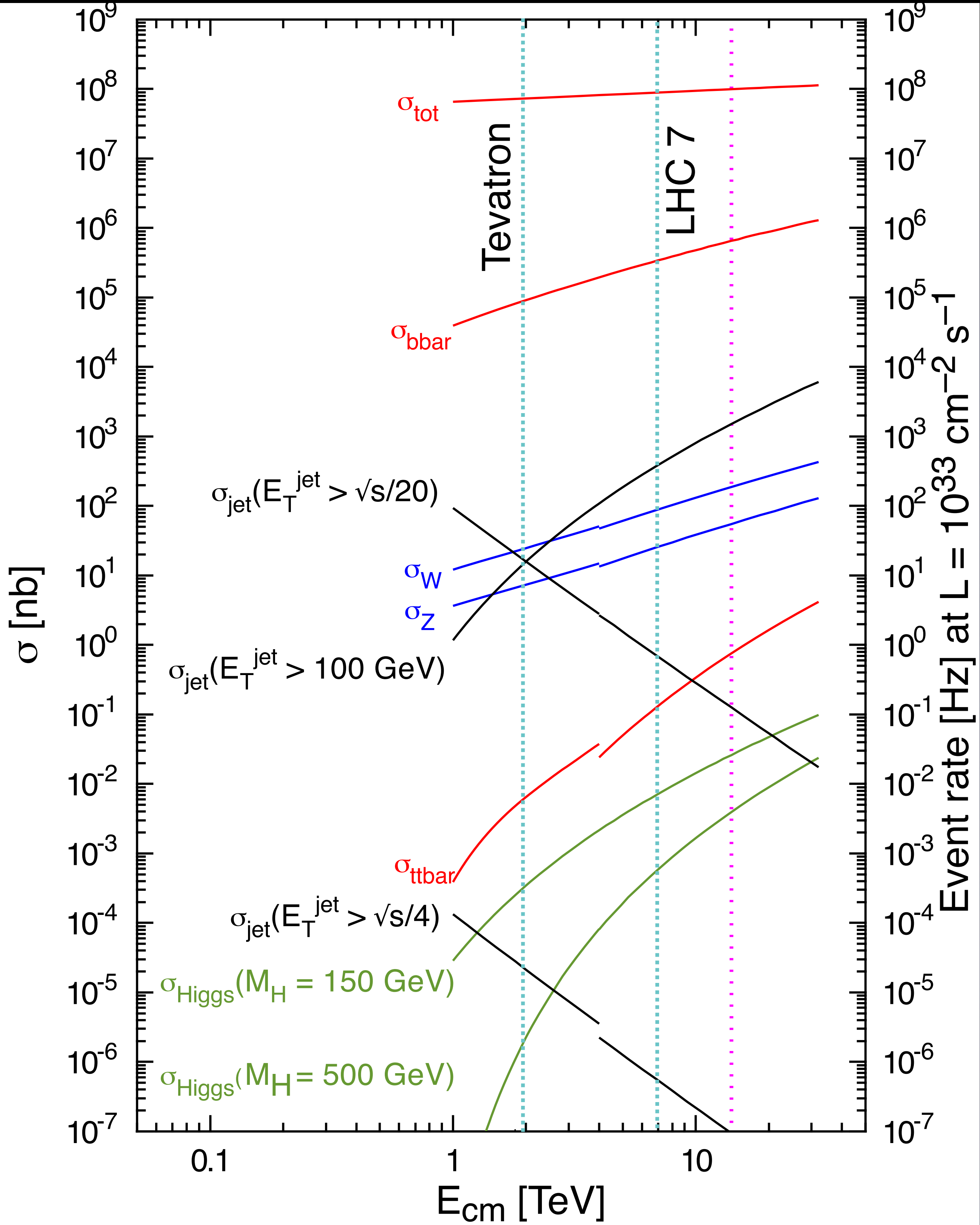


Large Hadron Collider
(2007-?)



A discovery machine of EW interaction
A top-quark factory

LHC: perfect for SM and NP

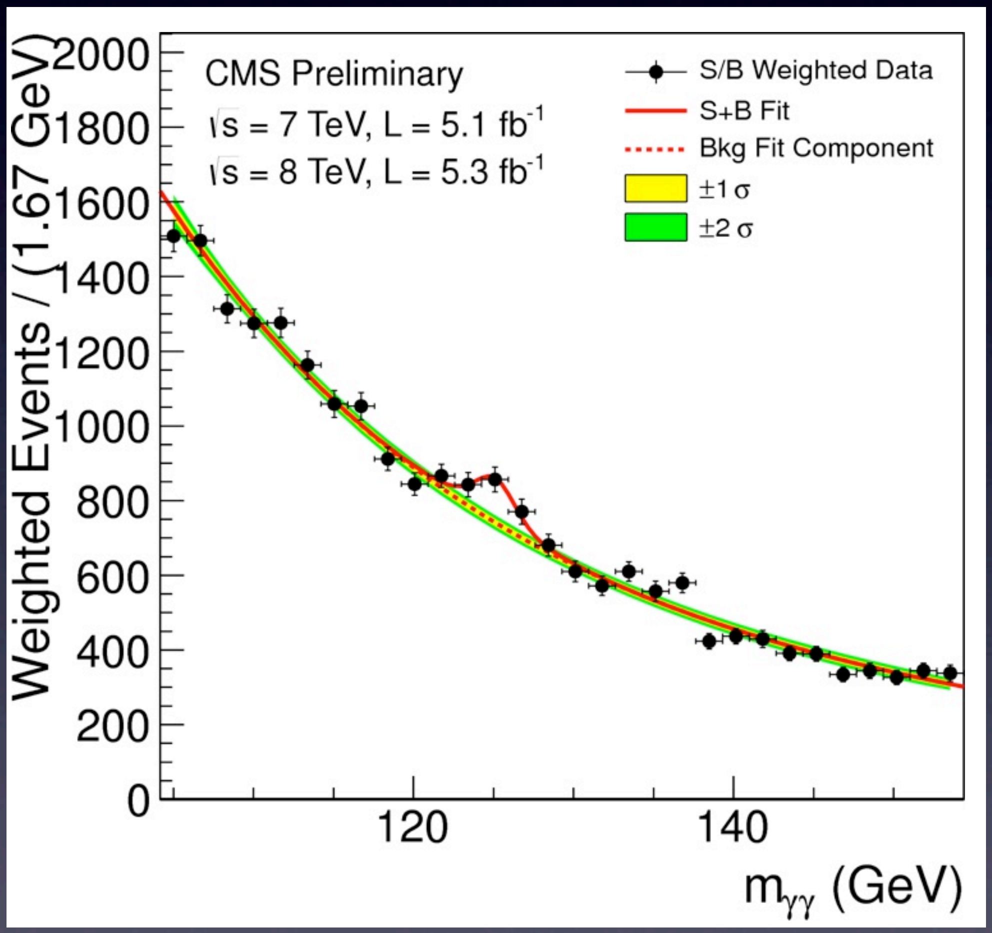


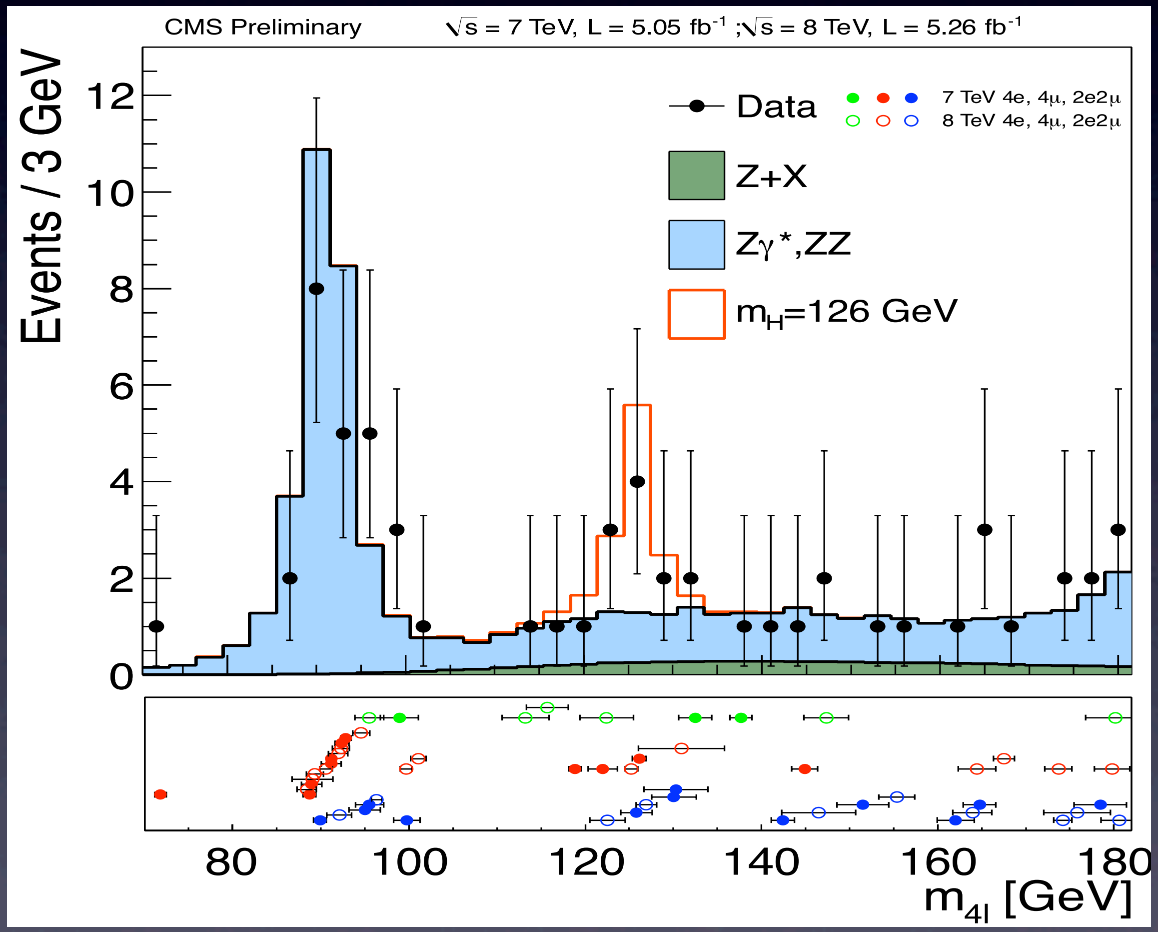
Rate at 8TeV LHC
with $\mathcal{L} = 10^{33} \mathrm{cm}^{-2} s^{-1}$

- ★ Inelastic p-p reactions: $10^8/s$
- ★ bottom quark pairs: $5 \times 10^5/s$
- ★ top quark pairs: $1/s$
- ★ $W \to \ell\nu$: $15/s$
- ★ $Z \to \ell\ell$: $1.5/s$
- ★ Higgs boson $0.02/s$
- ★ Gluino, Squarks : (1TeV) $0.003/s$

A new boson found ~125GeV

- The evidence is strong that the new particle decays to $\gamma\gamma$ and ZZ with rates roughly consistent with those predicted for the SM Higgs boson.





The observed decay modes indicate that the new particle is a boson.

Higgs mechanism in the SM

- Higgs mechanism: the most economical and simple choice to achieve the spontaneous symmetry breaking

$$\mathscr{L}_{\text{higgs}}(\phi, A_a, \psi_i) = D\phi^+ D\phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda(\phi^+\phi)^2 + Y^{ij}\, \psi_L{}^i\, \psi_R{}^j\, \phi$$

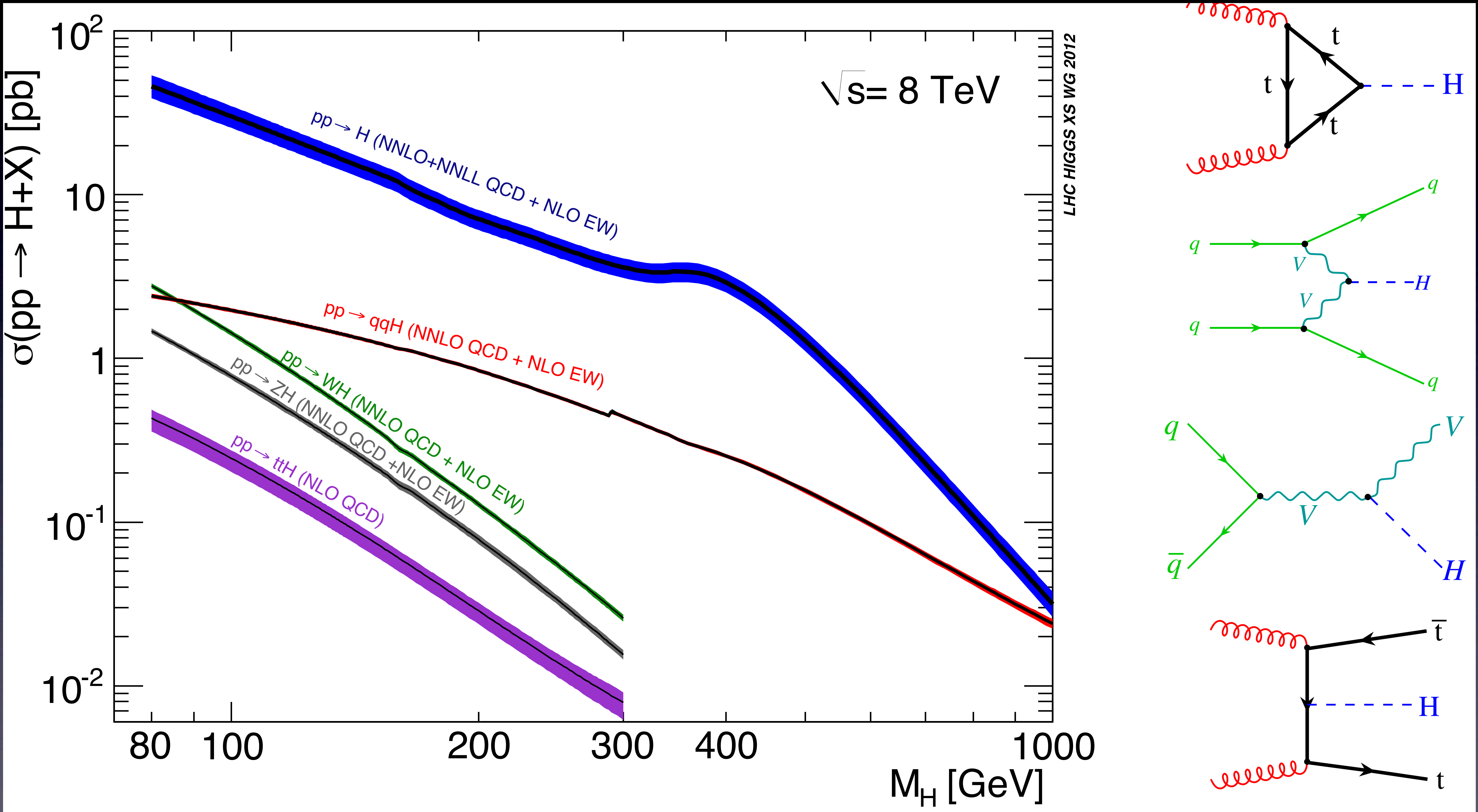
The ground state determined was tested with good accuracy (thanks to Tevatron)

$$v = \langle \phi^+\phi \rangle^{1/2} \sim 246 \text{ GeV} \quad [\, m_W = ½\, g\, v \,]$$

On July 4th, the 4th d.o.f. of the Higgs field is observed.

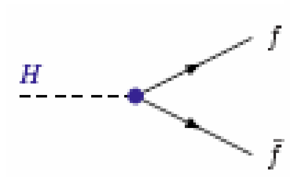
$$\lambda_{(\text{tree})} = ½\, m_h{}^2 / v^2 \sim 0.13$$

Higgs boson production

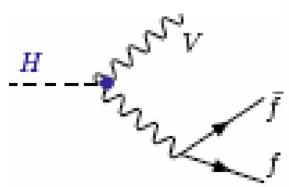


Higgs boson decay

bb dominant
m_H< 120 GeV

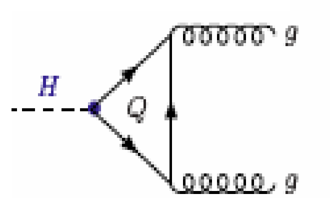


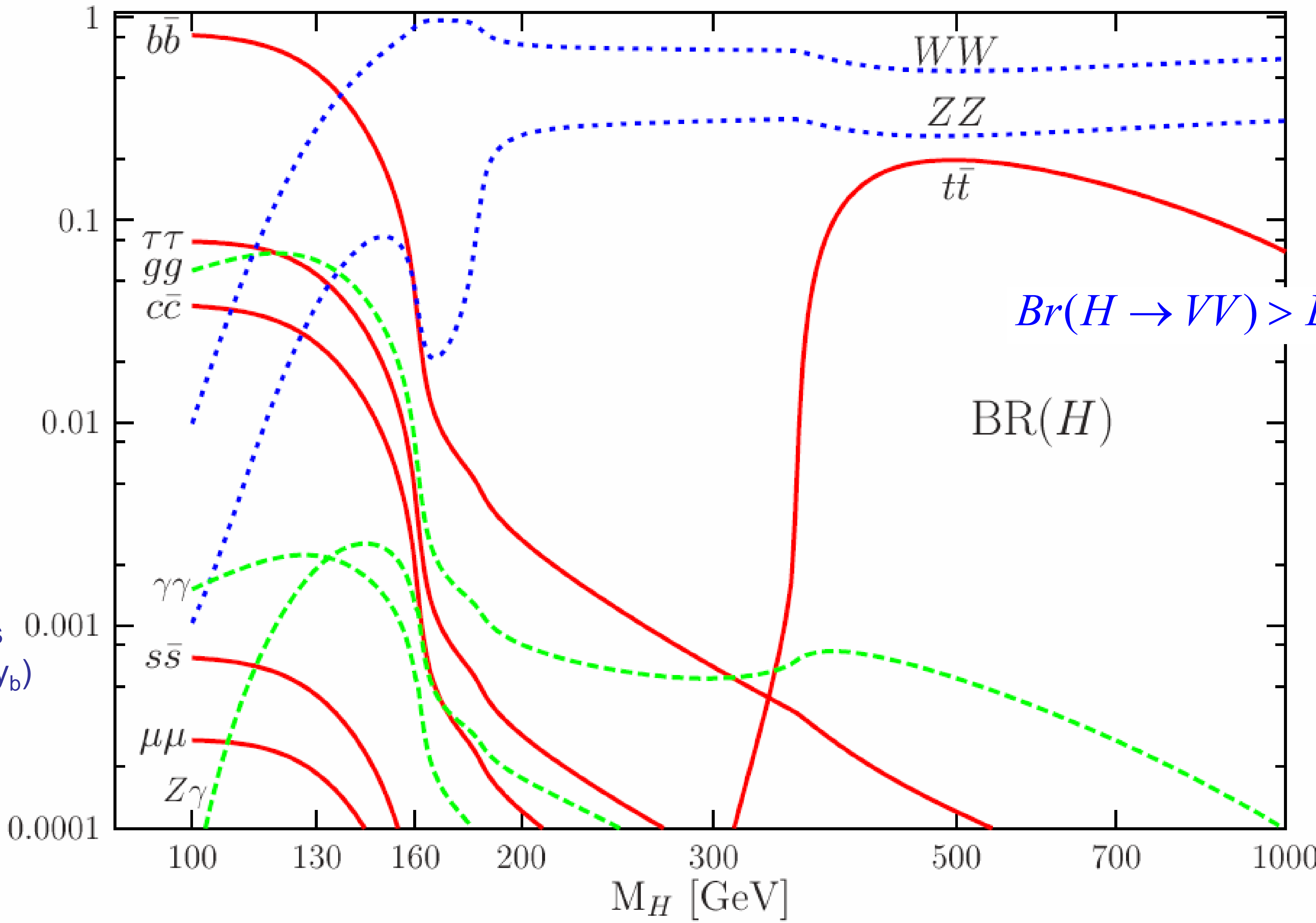
WW dominant
m_H> 130 GeV



(gauge coupling is much larger than y_b)

gg large
m_H<130 GeV

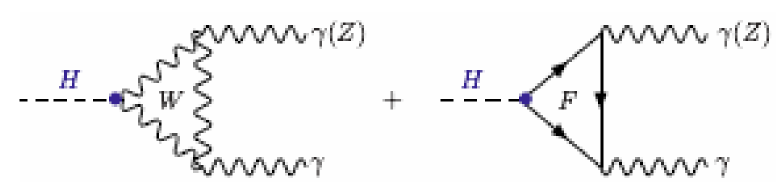




$$\frac{\Gamma(h \to WW)}{\Gamma(h \to ZZ)} \sim 2$$

$$Br(H \to VV) > Br(H \to tt)$$

$\gamma\gamma$ reaches maximal
m_H~130 GeV
(Important at LHC)



Questions of the top priority

scalar #:
one or two
or more?

Spin:
0 or 2?

H
125GeV

CP:
even or odd?

Mass (accuracy)
Width (?)

1. What can we learn from 125GeV?

Theoretical problems

$$V(\phi) = -\mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\ i} \psi_R^{\ j} \phi$$

vacuum instability

possible <u>internal inconsistency</u> of the model ($\lambda < 0$) at large energies

[*key dependence on* m_h]

Quadratic sensitivity to the cut-off

$$\Delta\mu^2 \sim \Delta m_h^{\ 2} \sim \Lambda^2$$

(indication of *new physics* close to the electroweak scale ?)

SM flavour problem

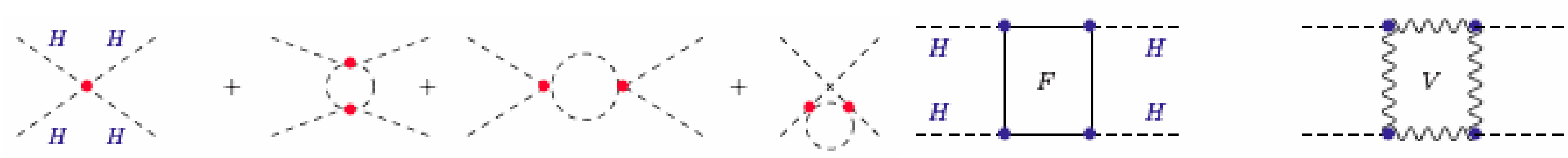
(unexplained span over 5 orders of magnitude and strongly hierarchical structure of the Yukawa coupl.)

Vacuum stability

- At large field values the shape of the Higgs potential is determined by the RGE evolution of the Higgs self coupling

$$V_{\text{eff}}(|\phi| \gg v) \approx \lambda(|\phi|)\,|\phi|^4 + \mathcal{O}(v^2\,|\phi|^2)$$

- Due to quantum correction, the Higgs self coupling as well as the masses depend on considered energy



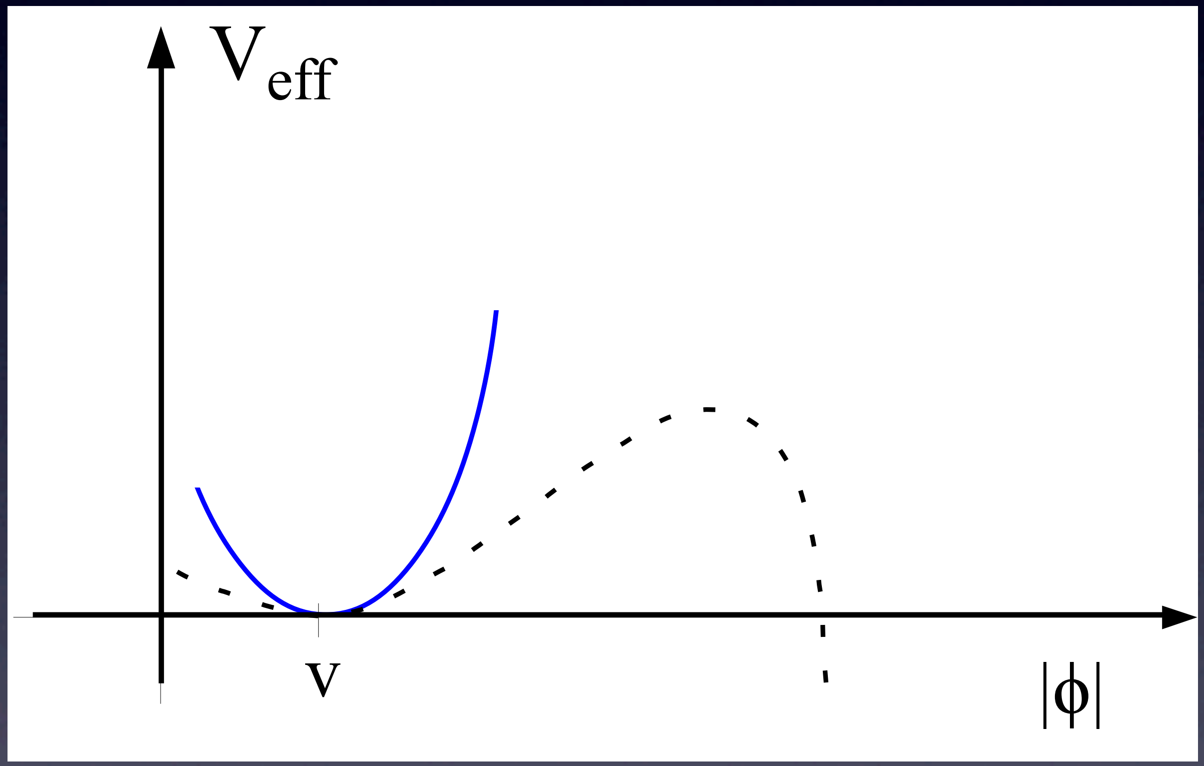
$$\frac{d\lambda}{d\ln Q^2} \simeq \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

$$\lambda(|\phi|) < 0 \;\Longrightarrow\; V(|\phi|) < V(v)$$

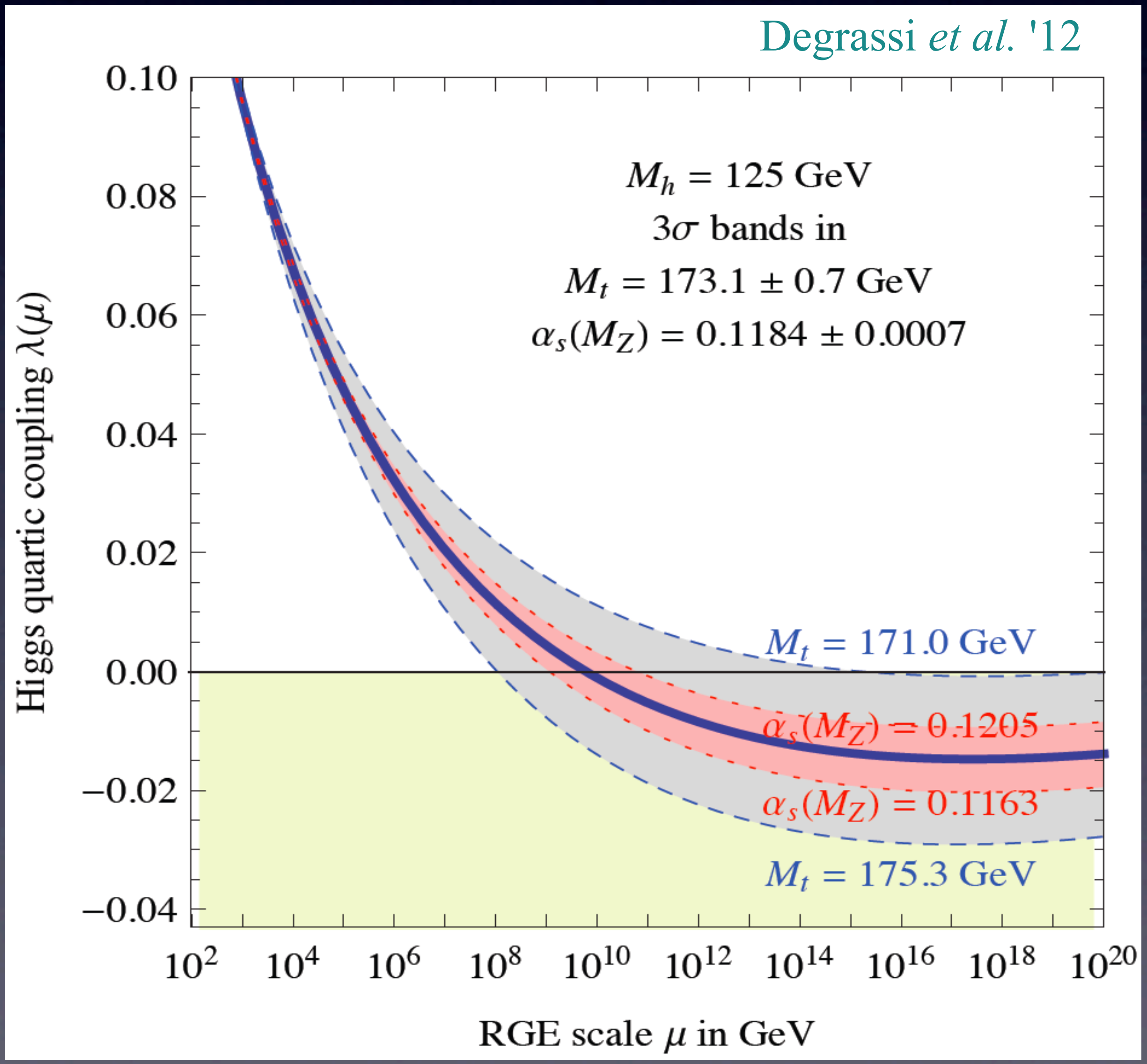
Vacuum unstable

Vacuum stability bound at NNLO

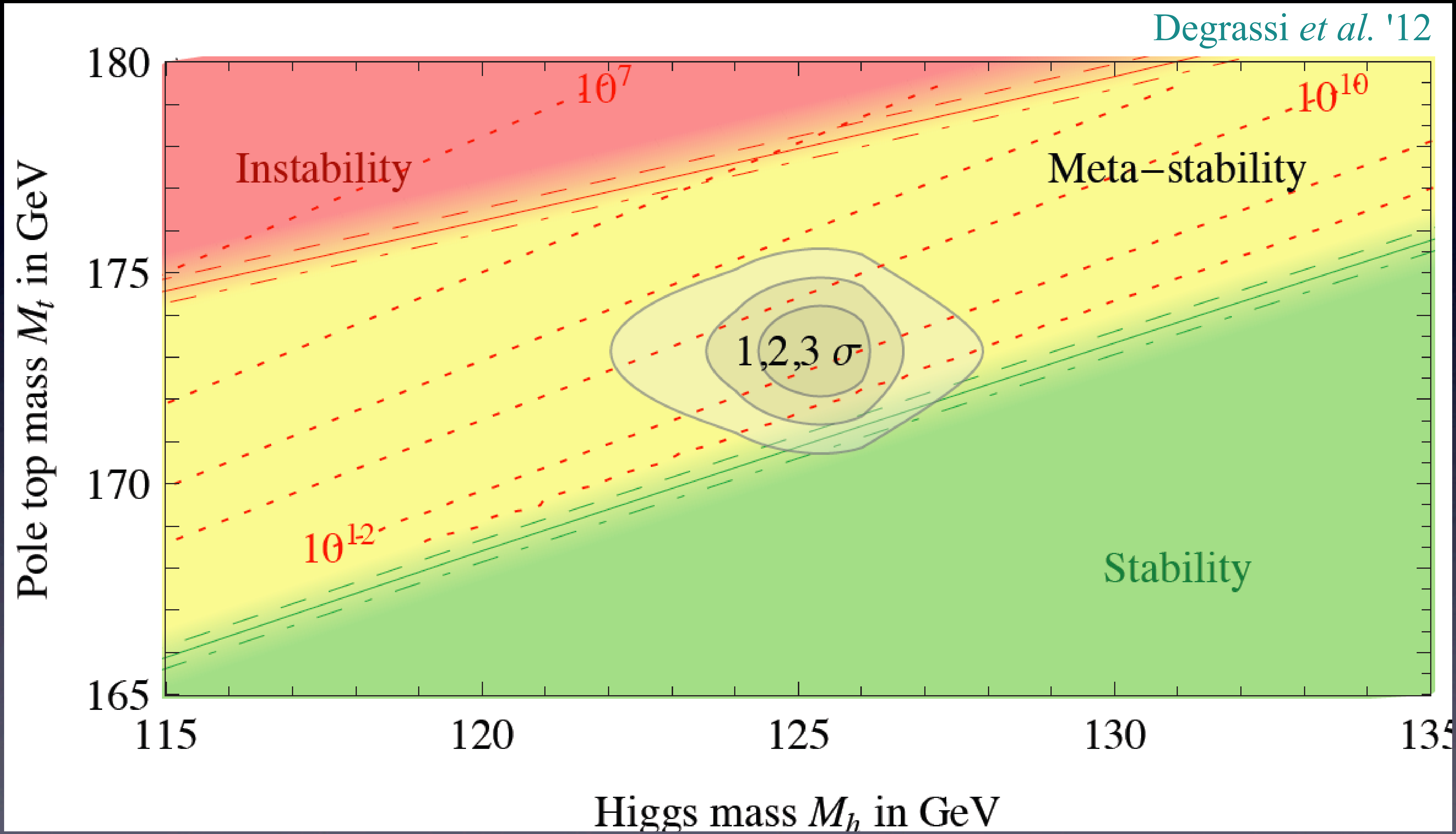
$$M_h\ [\mathrm{GeV}] > 129.4 + 2.0\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{1.0}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$



Might we live in a metastable vacuum?



Top quark and 125GeV Higgs boson



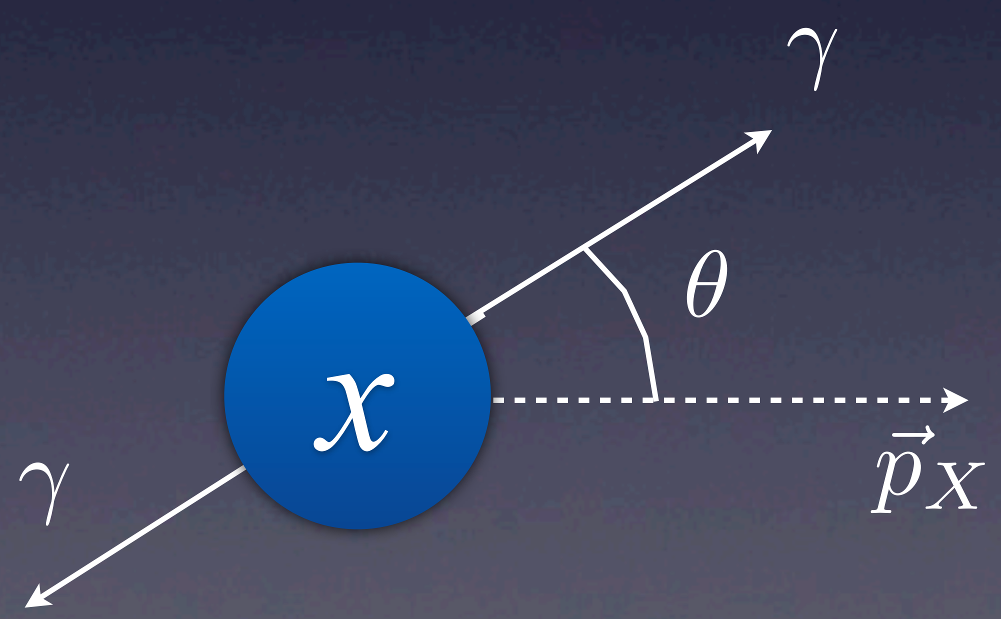
2. What about spin?

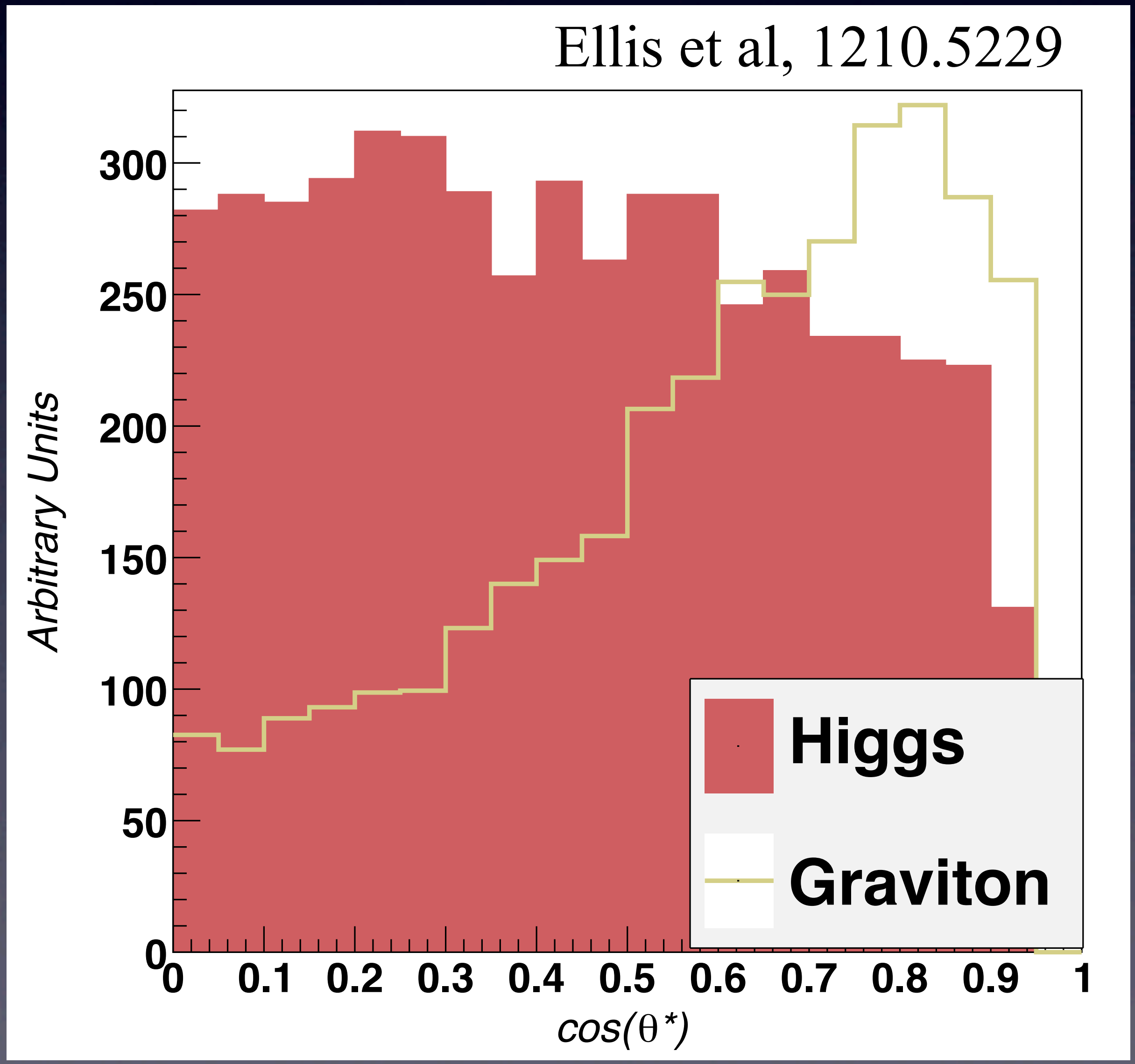
Spin-0 or Spin-2

- It is very likely to be spin-0, but we have to check it.

Spin-2: $$\frac{d\sigma}{d\cos\theta} \sim \frac{1}{4} + \frac{3}{2}\cos^2\theta + \frac{1}{4}\cos^4\theta$$

Spin-0: $$\frac{d\sigma}{d\cos\theta} \sim 1$$





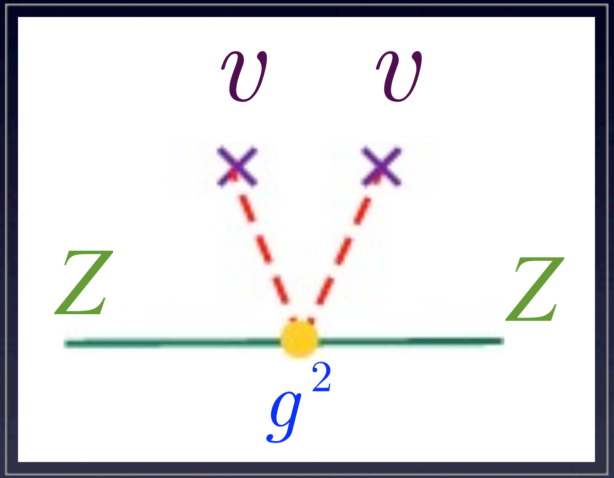
3. CP Property

CP-even or CP-odd

- It is very likely to be CP-even, but we also need check it.
- In the SM the couplings of the Higgs boson to pair of Ws and Zs are fixed by gauge structure

$$(D\phi)^2 \to (1+\frac{h}{v})^2 m_V^2 V_\mu V^\mu$$

$$g_{hVV} = -2i\frac{m_V^2}{v} g_{\mu\nu}$$



- A field without vacuum expectation value can couple to Ws and Zs through dimension-5 operators. In a weak-coupling theory the operators come from loops.

$$\frac{A}{M} h F_{\mu\nu} F^{\mu\nu} + \frac{B}{M} h \epsilon_{\mu\nu\rho\sigma} F^{\mu\nu} F^{\rho\sigma}$$

Spin and coupling structure of Higgs (imposters)

- $ZZ \to 4\ell$ final state is unique because full kinematics distributions can be reconstructed.

QHC, Jackson, Keung, Low, Shu,
PRD81 (2010) 015010, 0911.3398

- A general analysis of a scalar decaying into ZZ:

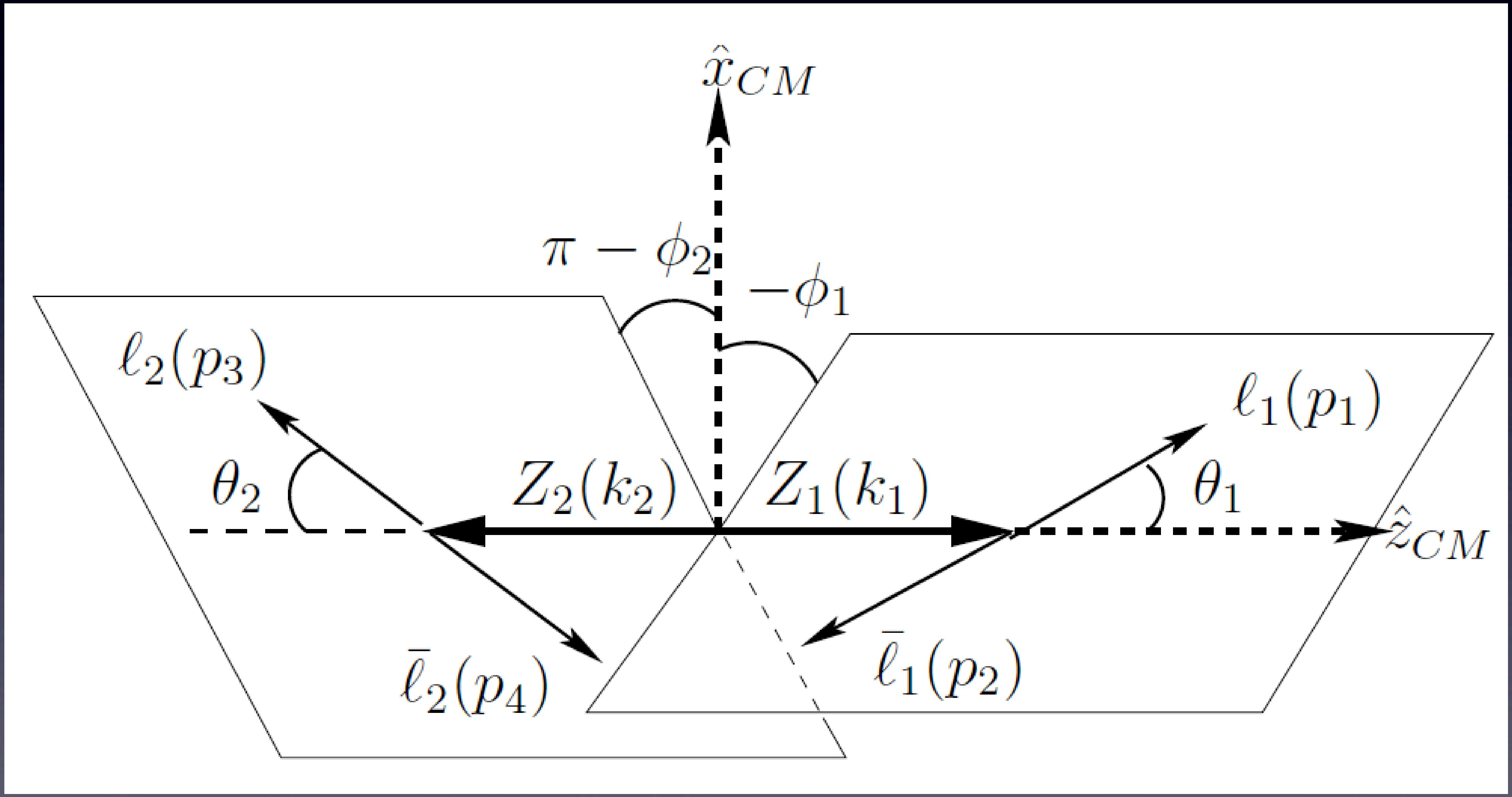
the other two terms are higgs imposters!!

$$\mathcal{L}_{eff} = \frac{1}{2} m_S S \left(c_1 Z^\nu Z_\nu + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

higgs mechanism predicts only this term!

Decay plane correlation

- One particular angle is very useful: the azimuthal angle between the decay plane



Decay plane correlation

$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^\nu Z_\nu + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

$$\frac{d\Gamma}{\Gamma d\phi} = \frac{1}{N} \left\{ \frac{8}{9} \cos(2\phi + 2\delta) + \frac{\pi^2}{2} \frac{M_L}{M_T} \left(\frac{g_R^2 - g_L^2}{g_R^2 + g_L^2} \right)^2 \cos(\phi + \delta) + \frac{16}{9} \left(\frac{M_L^2}{M_T^2} + 2 \right) \right\}$$

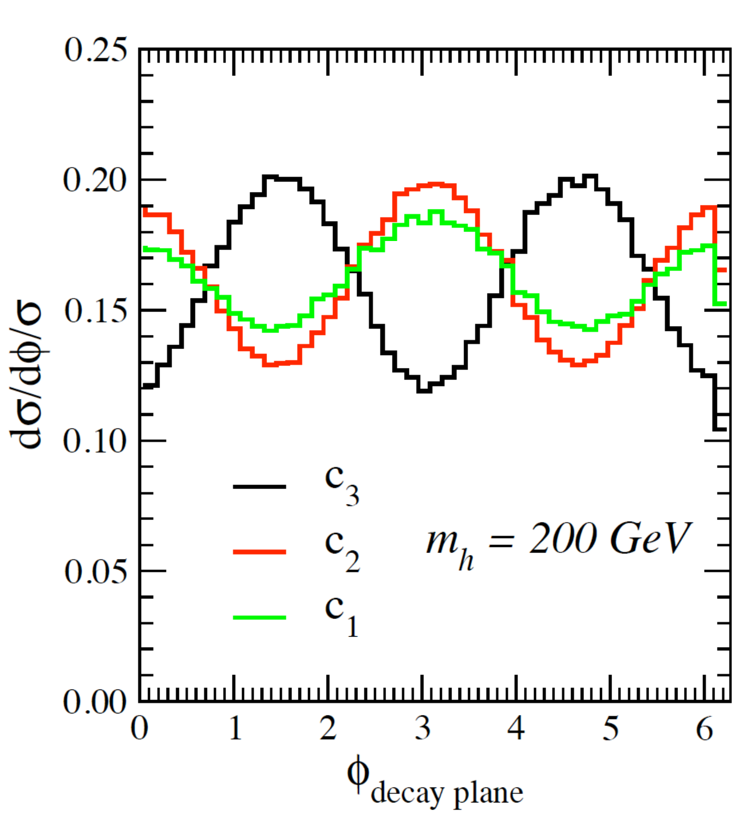
Negligible (~0.06) in the SM!

$\delta = 0$ for vanishing c_3

(CP-even scalar!)

$\delta = \pi/2$ for vanishing c_1 and c_2

(CP-odd scalar!)



4. Is it just the SM Higgs?

Higgs boson couplings

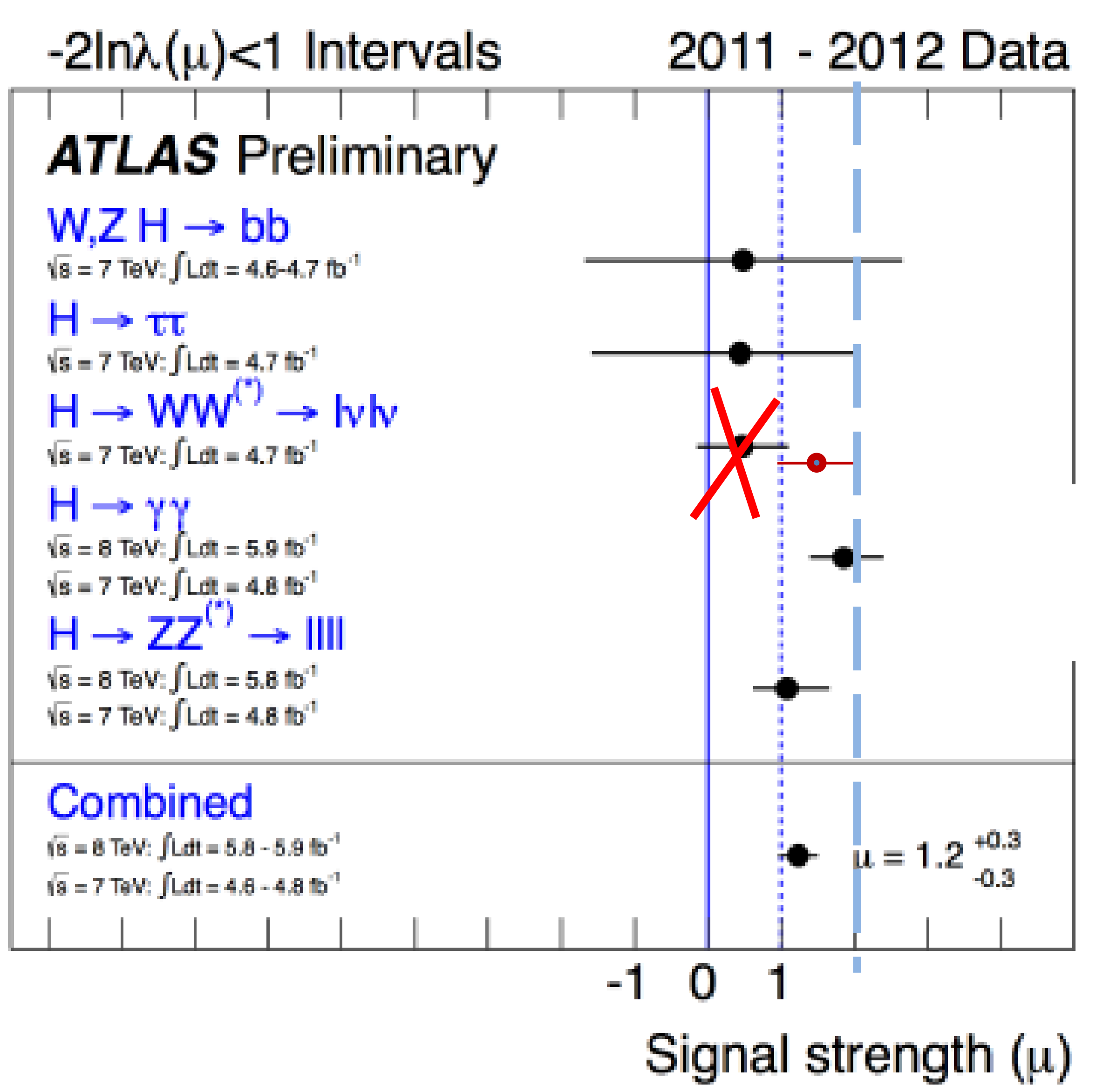
- New set of reference SM parameters

$m_H \sim 126$ GeV $\quad \Gamma_H = 4.2$ MeV $\quad \lambda = (m_H/v)^2/2 = 0.131$

$Br(H \to WW^*) = 23\%$ ★
$Br(H \to ZZ^*) = 2.9\%$ ★

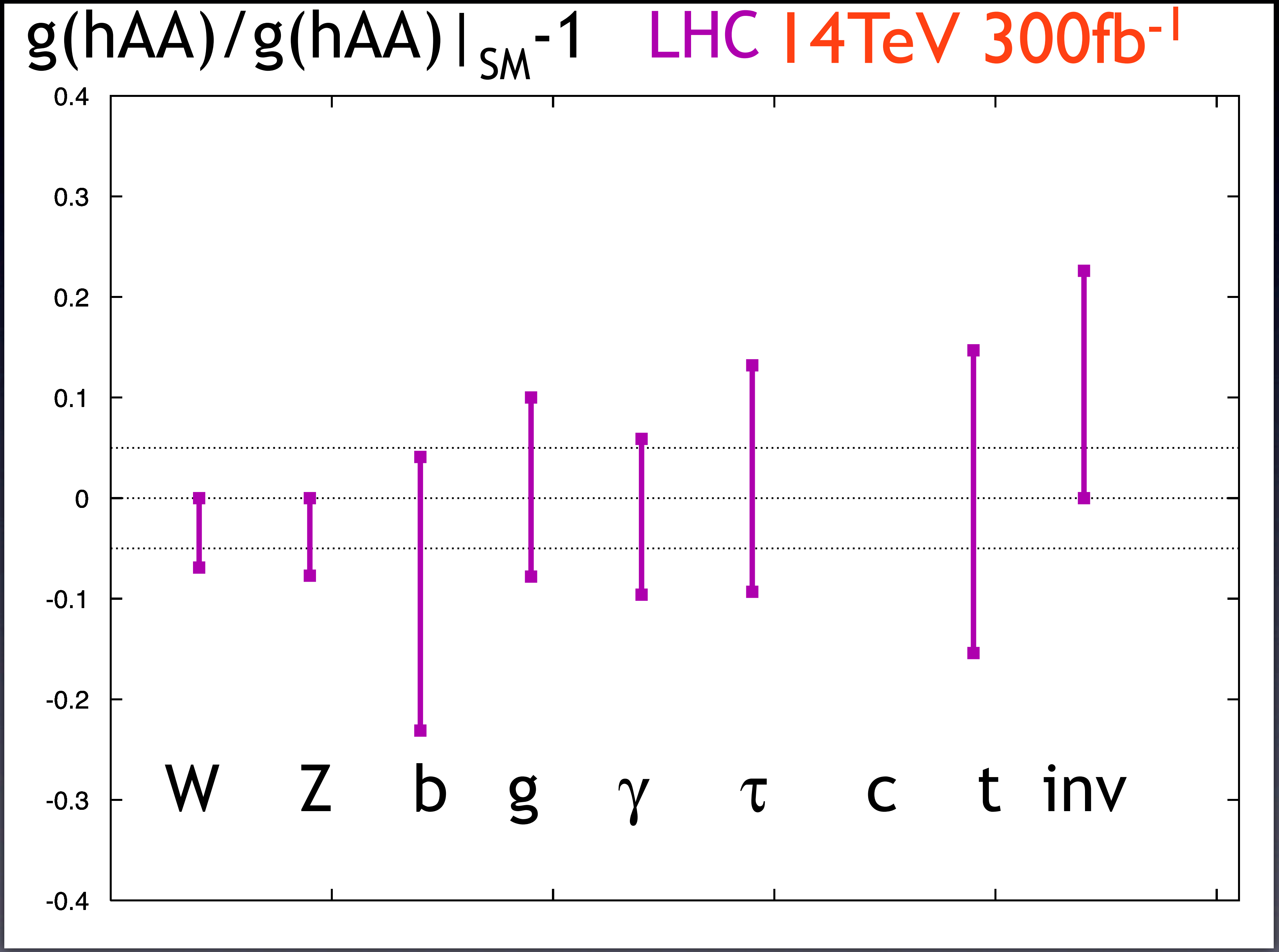
$Br(H \to bb) = 56\%$ ★
$Br(H \to cc) = 2.8\%$
$Br(H \to \tau\tau) = 6.2\%$ ★
$Br(H \to \mu\mu) = 0.021\%$

$Br(H \to gg) = 8.5\%$ ★
$Br(H \to \gamma\gamma) = 0.23\%$ ★
$Br(H \to \gamma Z) = 0.16\%$ ★



Higgs boson couplings

Peskin, 1208.5152



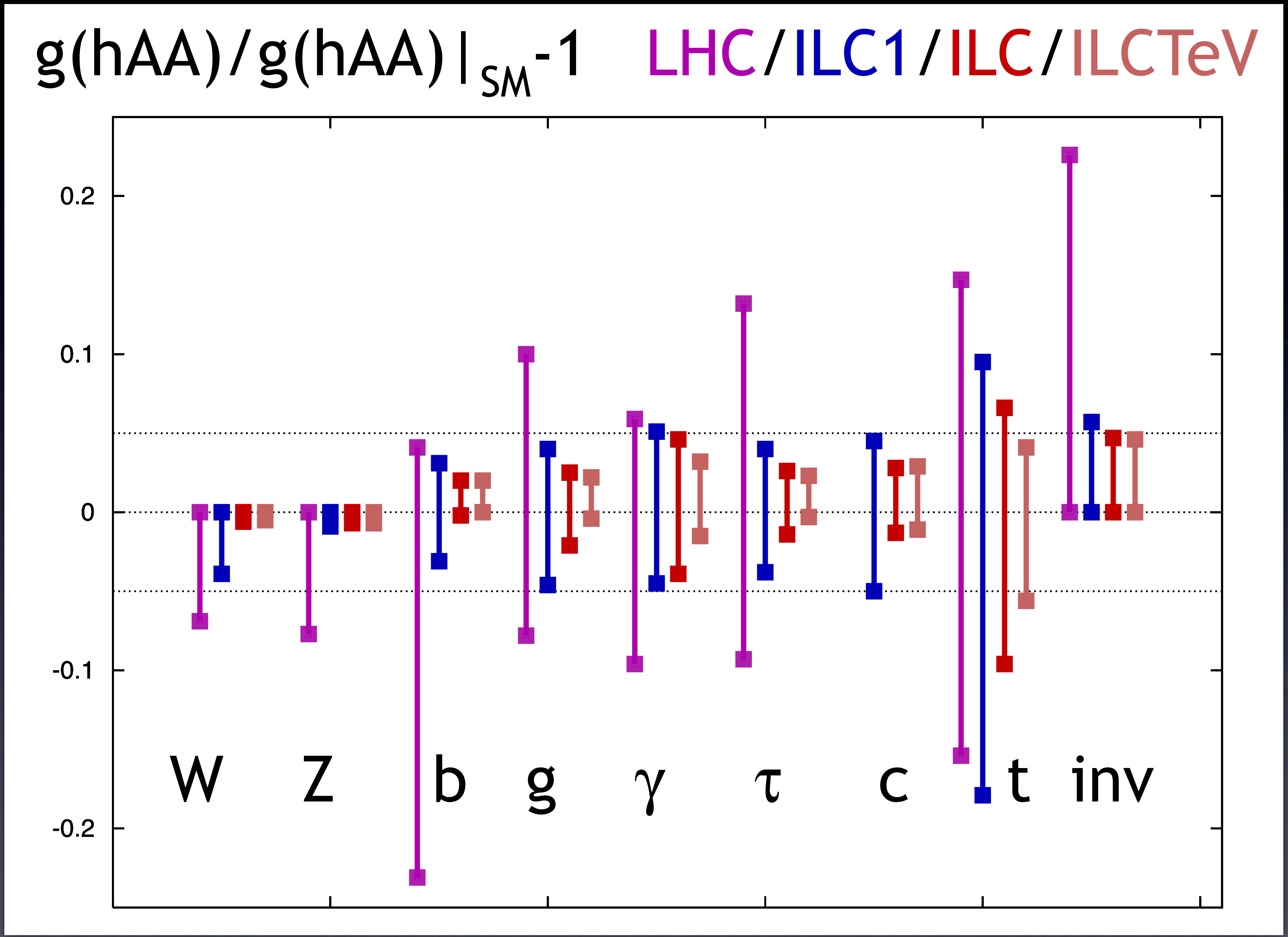
Higgs boson couplings at LC

LHC:
14TeV
$300 fb^{-1}$

ILC1:
250GeV
$250 fb^{-1}$

ILC:
500GeV
$500 fb^{-1}$

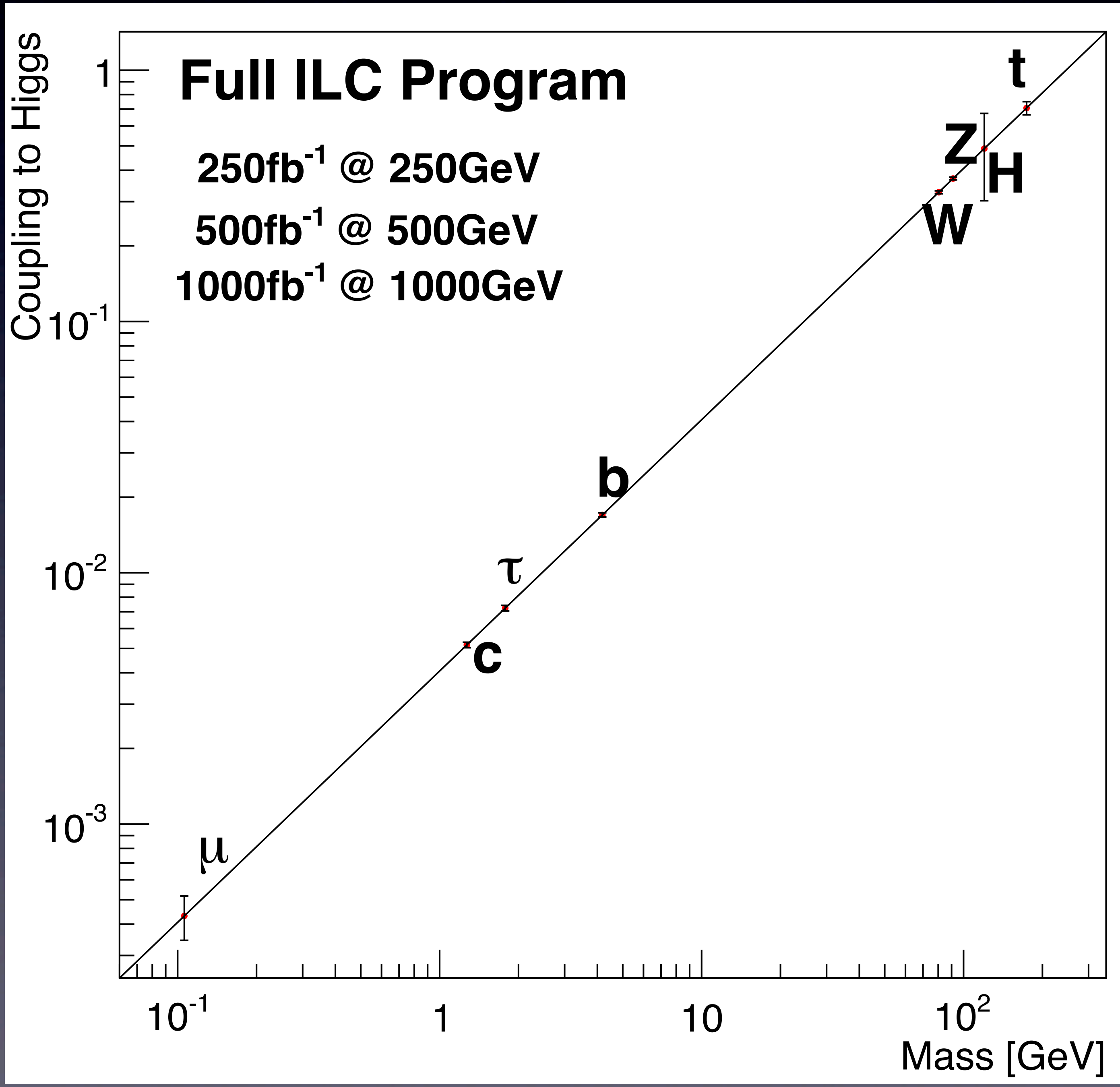
ILC TeV:
1000GeV
$1000 fb^{-1}$



Higgs boson couplings at LC

- If the simple scalar Higgs model is correct, the Higgs couplings to each particle is proportional to its mass.

We can test this hypothesis to high accuracy.



2002
ACFA
LC study

5. Only one scalar?

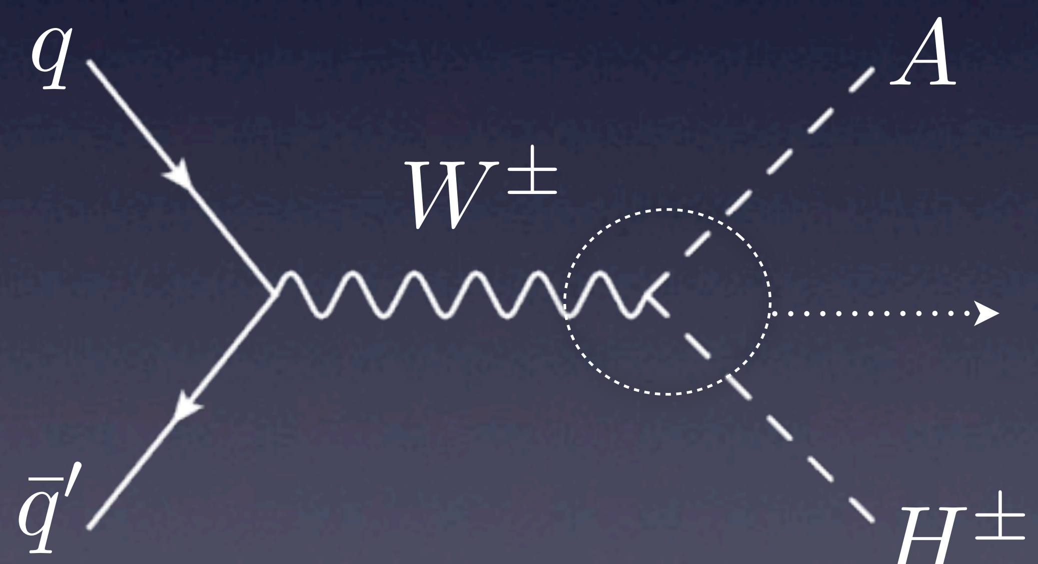
Charged Higgs boson

- In the MSSM: 5 physical Higgs fields

2 CP-even Higgs boson	h and H
1 CP-odd Higgs boson	A
2 Charged Higgs boson	$H^{\pm}$

- A very promising channel $pp \to W^{\pm} \to AH^{\pm}$

QHC, Kanemura, Yuan
PRD69 (2004) 075008



$$\frac{g}{2}\left(p_A - p_{H^+}\right)^{\mu}$$

$$m_{H^+}^2 = m_A^2 + m_W^2$$

→ $\sigma_{\rm prod}$ depends only on g and m_A

Light Higgs scenario

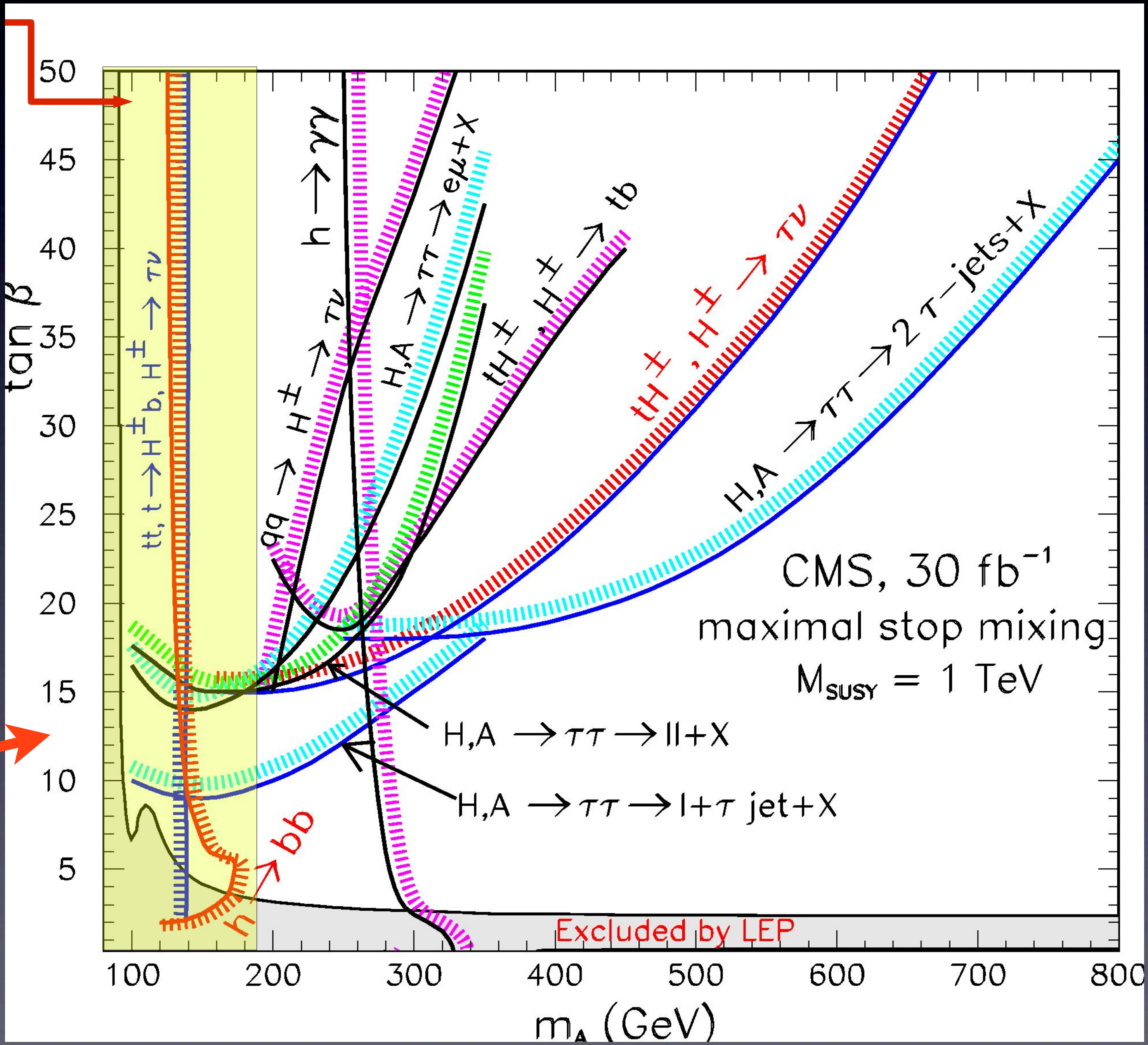
Belyaev, QHC, Nomura, Tobe, Yuan,
PRL100 (2008) 061801

- No-decoupling regime

$$m_A \sim m_H < m_h$$

(recently rediscovered by many groups)

Entire Yellow shaded region can be covered by $AH^\pm$ production



Direct searches of New Physics

New Physics Models

Supersymmetry

MSSM, NMSSM,
nMSSM, uMSSM
R-violating

Extra Dimension

Flat (ADD, UED)

Warped (RS1)

Little Higgs

Simple Little Higgs

Little Higgs

Little Higgs with T-parity

Higgsless

Technicolor

Top quark condensate

Three-site

New Physics Models

Dark Matter

R-parity conserved SUSY
(MSSM, NMSSM, nMSSM)

Little Higgs with T-parity

Universal Extra Dim
(KK parity)

RS with KK parity

~~Dark Matter~~

R-violation SUSY

Little Higgs Model

Top quark condensate

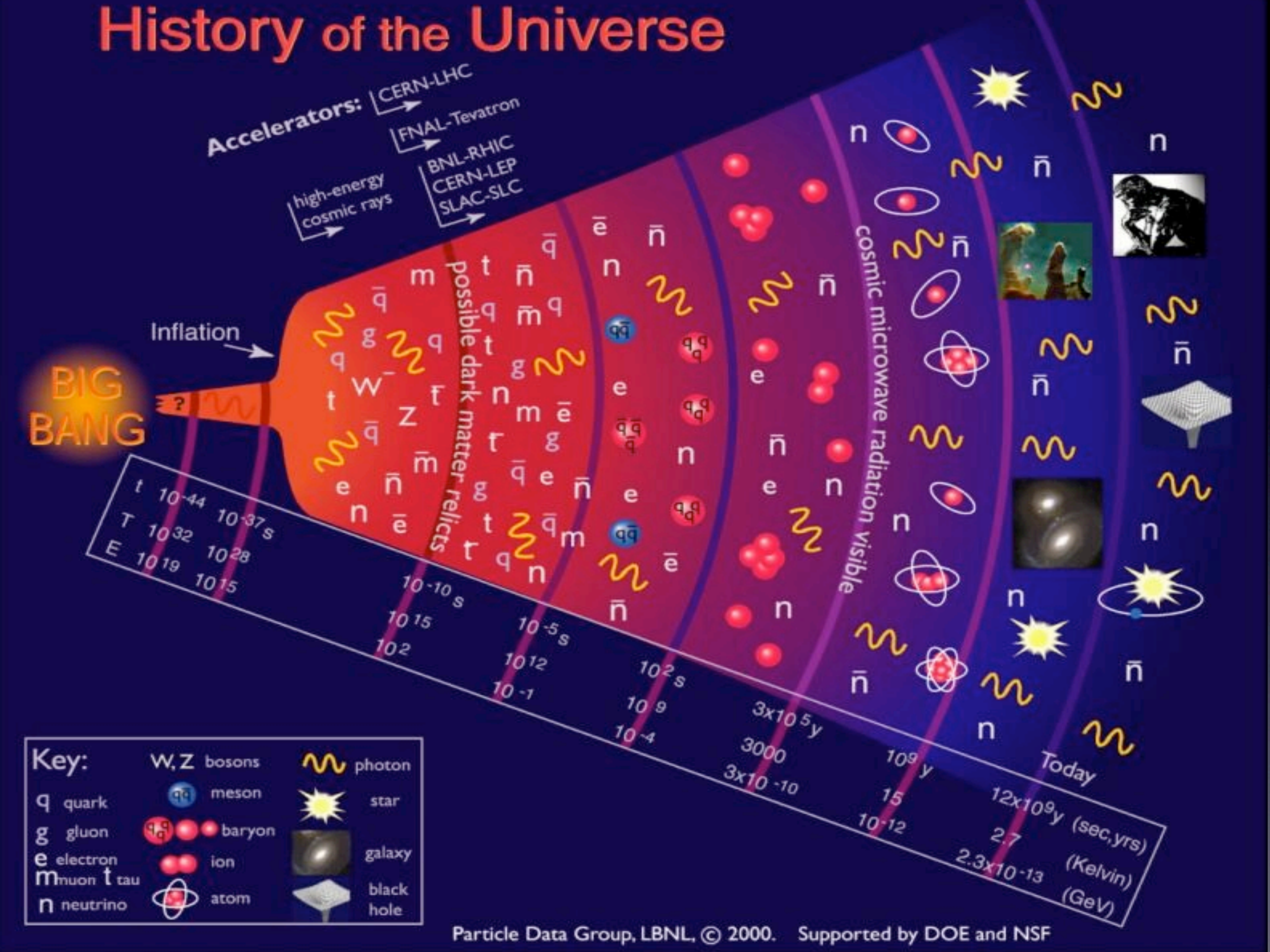
Technicolor

ADD, RS1

Conclusion

Questions raised by Quigg

- What is the agent of EWSB? Higgs? One or more?
- Is the Higgs elementary or composite? Self-interaction?
- Does the Higgs give mass to fermions, or only to weak bosons? Quark mass and mixing angle? Yukawa hierarchy?
- What stabilizes the Higgs mass below 1 TeV?
- What will be the next symmetry? Extra heavy gauge bosons? Grand unification?
- Are there 4th generation? Or new exotic (vector-like) fermions?
- Strong CP problem?
- What are dark matters? Might DM have a flavor structure? Or is DM really related to fundamental particle?
- ....


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

What we learned from top discovery

Bardeen, Hill, Lindner
Top-condensation (1989)
m_t >218GeV

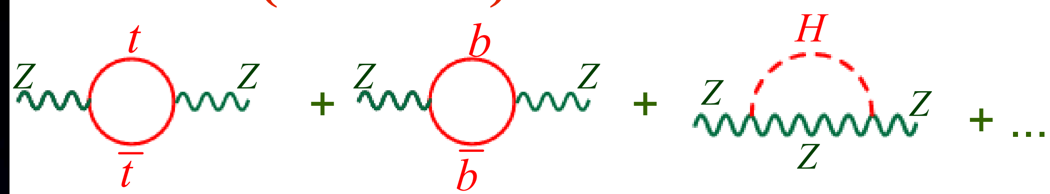
Pendleton, Ross
GUT (1980)
m_t=130GeV

Ibanez, Ross
SUGRA-GUT (1983)
30<m_t<150GeV

Glashow (1980)
m_{tt}>38GeV

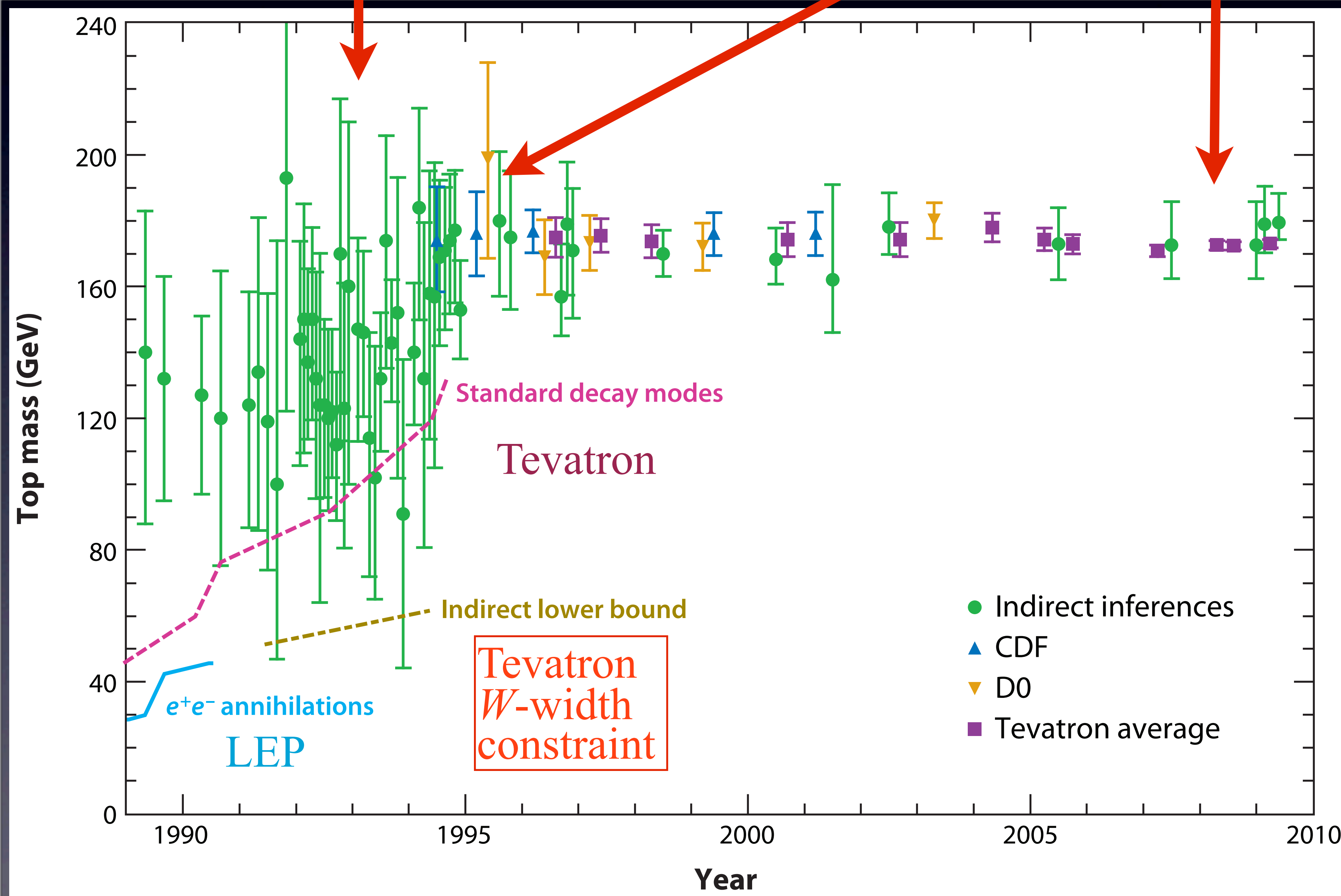
Tristan
1983

LEP fit (indirect)



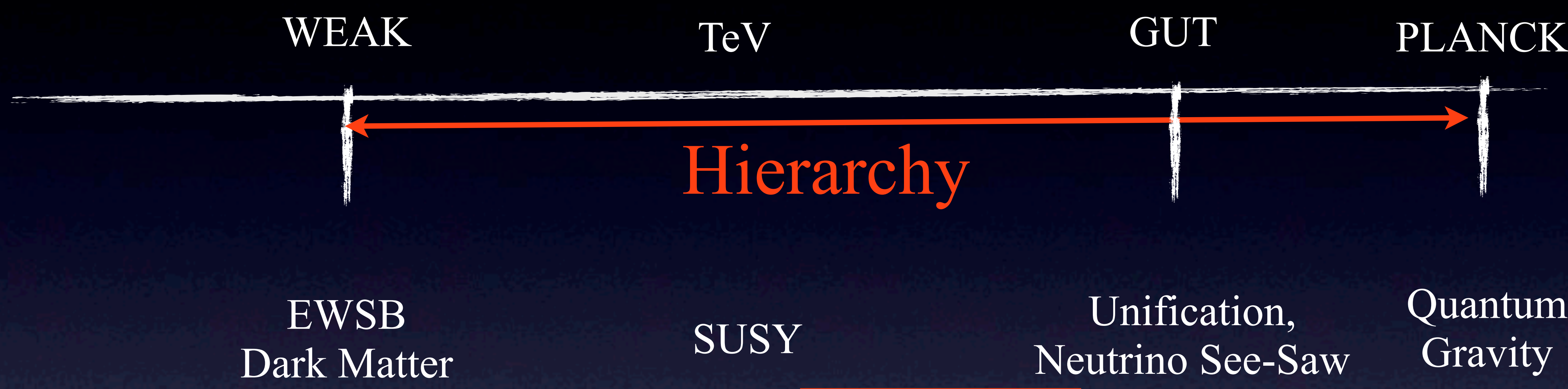
Tevatron
(1995)
Discovery

Tevatron
Precision



Experiments versus Theories

- Physics is associated with many scales



Higgs Factory

THANK YOU!