Electroweak Theory at Multi-TeV Collider

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Colloquium @ IHEP, Nov. 29, 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

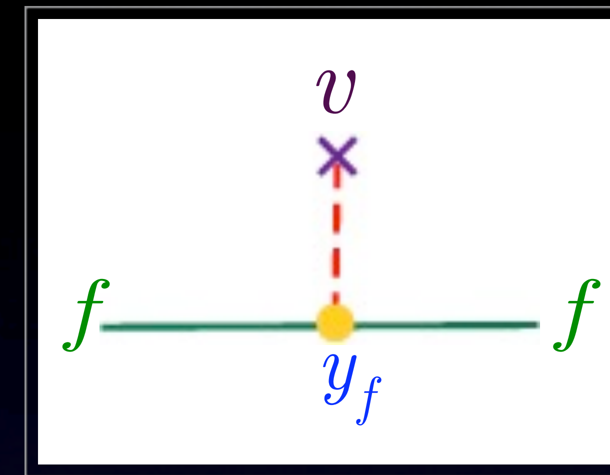
- History of particle hunting
  - W and Z boson discovery (1983)
    Theory 1973 — 10 years
  - Top-quark discovery (1995)
    Existence: $b\bar{b}$ FB asymmetry (1977) — 18 years
  - Higgs-like scalar discovery (2012)
    Theory 1967 — 48 years
  - New Physics beyond the SM
    Extra dim (KK, 1921)
    SUSY (1966)

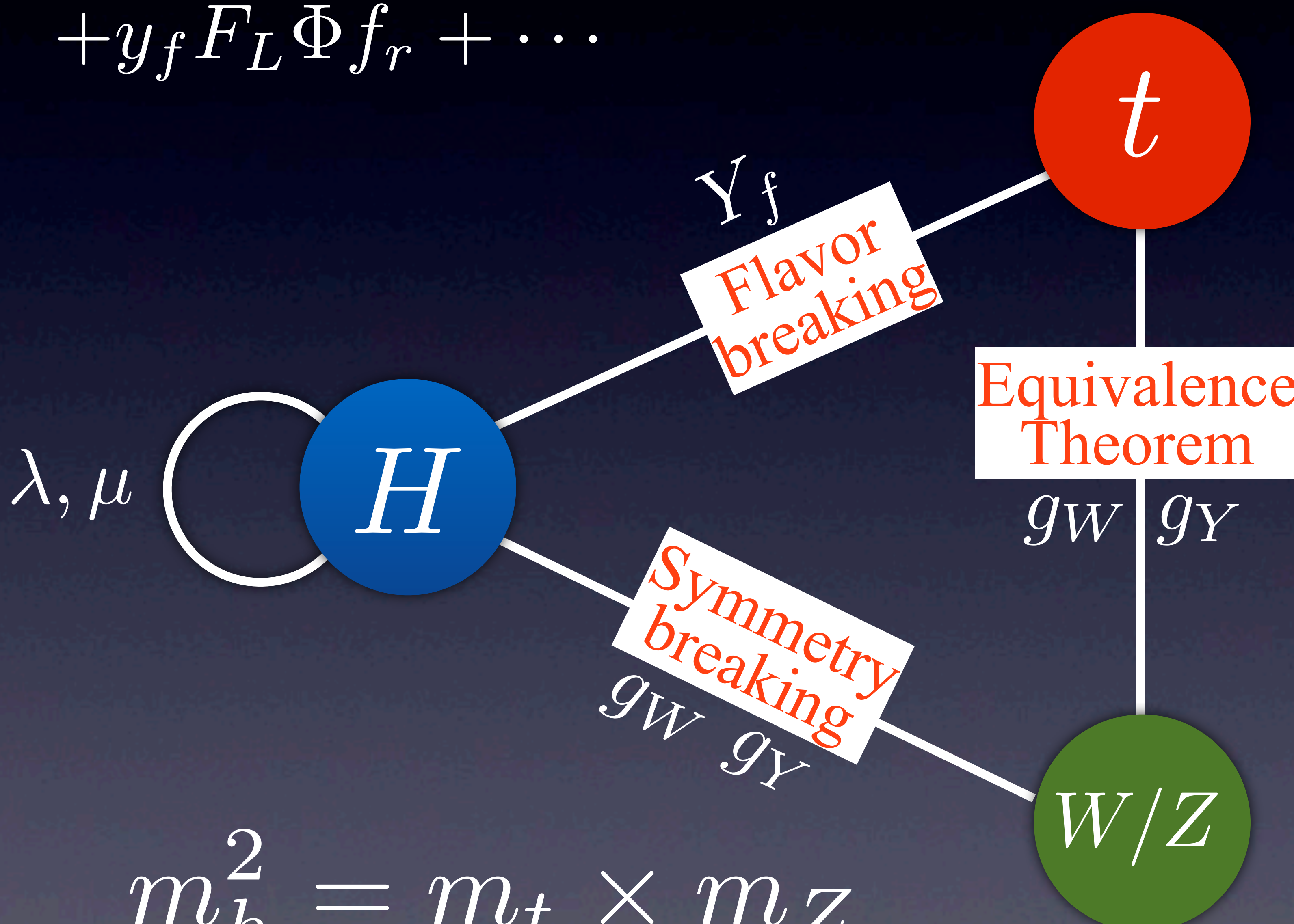
?years

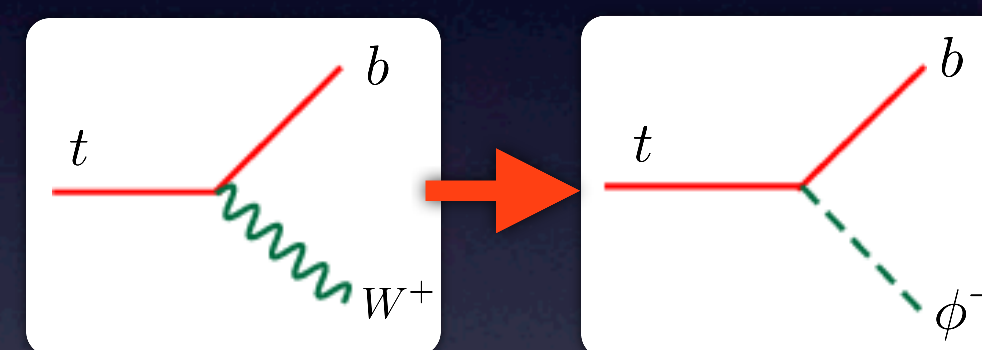
Electroweak triangle

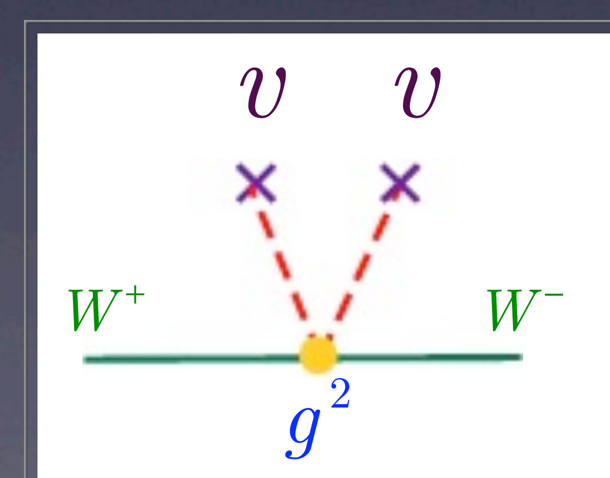
$$\mathcal{L} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \mu^2 \Phi^\dagger \Phi + \lambda \left(\Phi^\dagger \Phi\right)^2$$

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









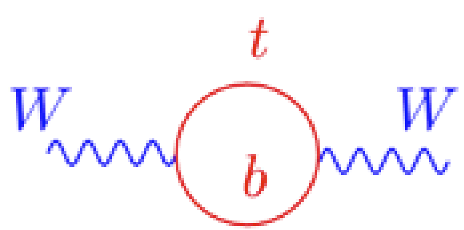
$$m_h^2 = m_t \times m_Z$$

Error ~ 0.001 !!!

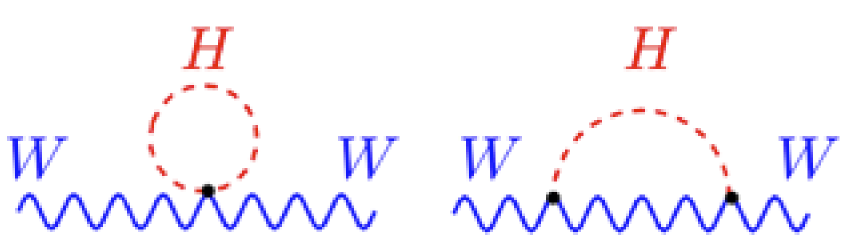
W-boson, Top-quark and Higgs boson

- Highly correlated at the quantum level

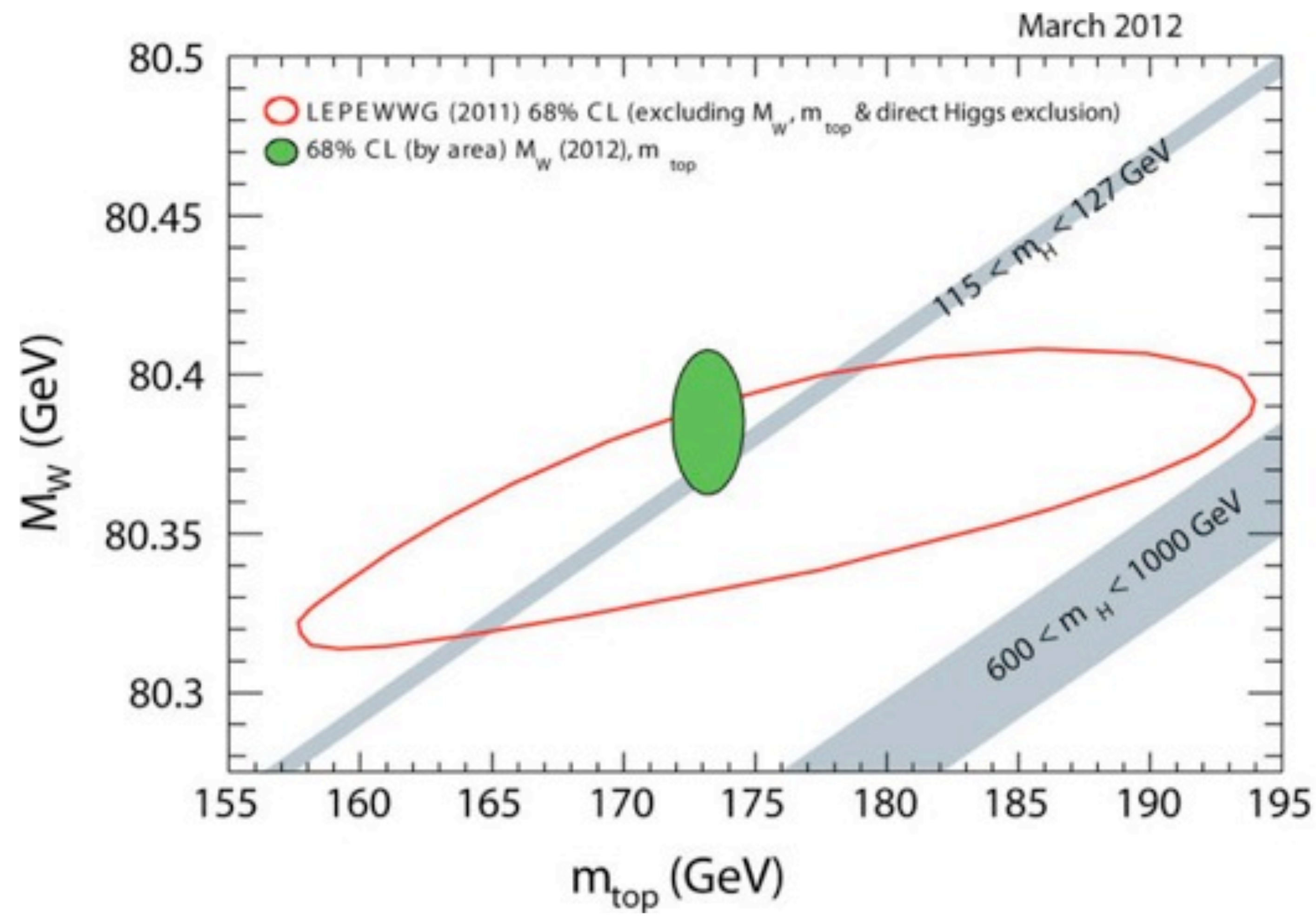
$$M_W = 80.3827 - 0.0579 \ln\left(\frac{M_H}{100\ \text{GeV}}\right) - 0.008 \ln^2\left(\frac{M_H}{100\ \text{GeV}}\right)$$
$$+0.543\left(\left(\frac{m_t}{175\ \text{GeV}}\right)^2 - 1\right) - 0.517\left(\frac{\Delta\alpha_{had}^{(5)}(M_Z)}{0.0280} - 1\right) - 0.085\left(\frac{\alpha_s(M_Z)}{0.118}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



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



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



Outline

- LEP

  Precision machine

- Tevatron

  Precision machine + discovery machine

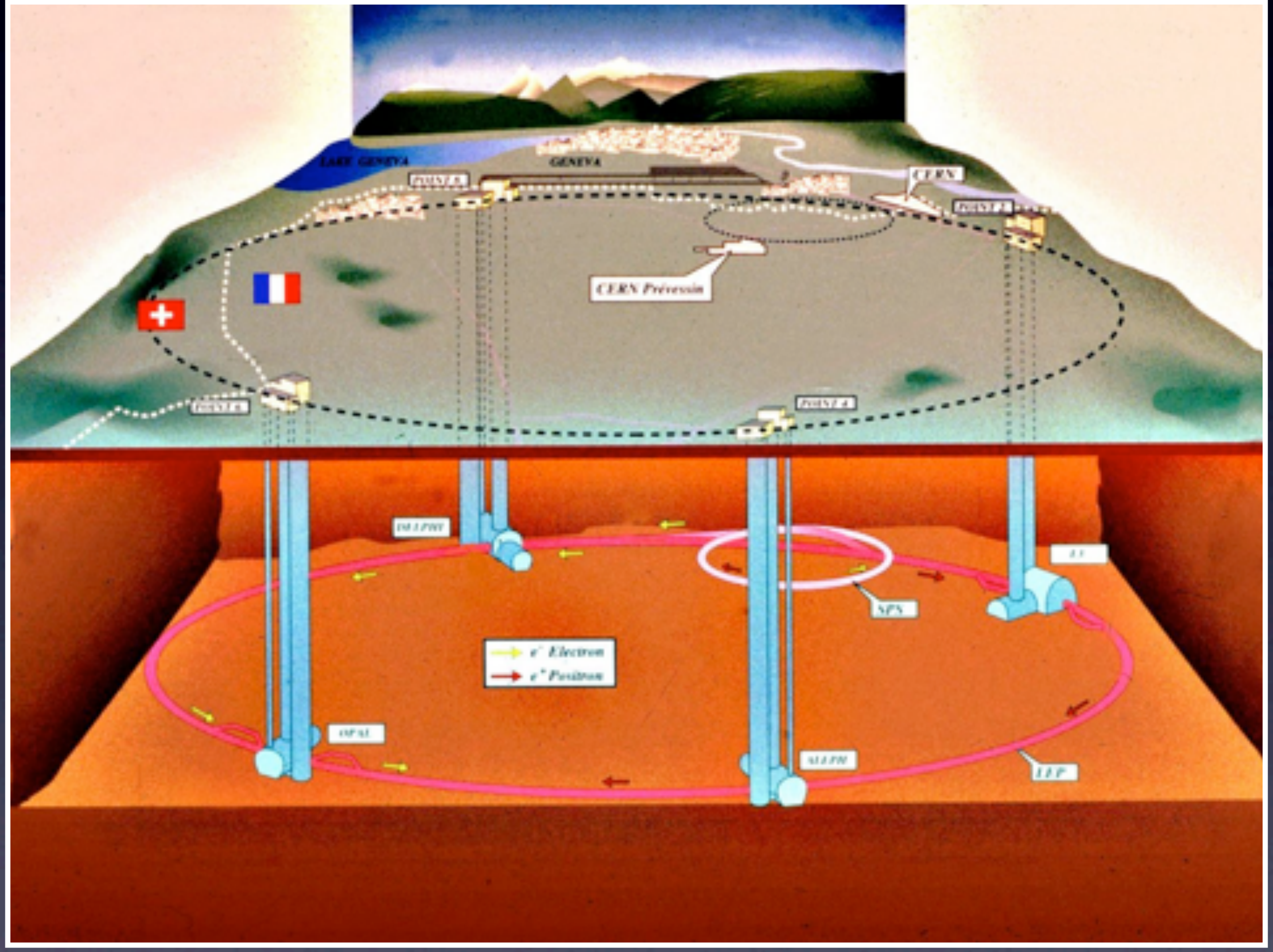
- LHC

  Discovery machine + Precision machine

  Higgs boson and others

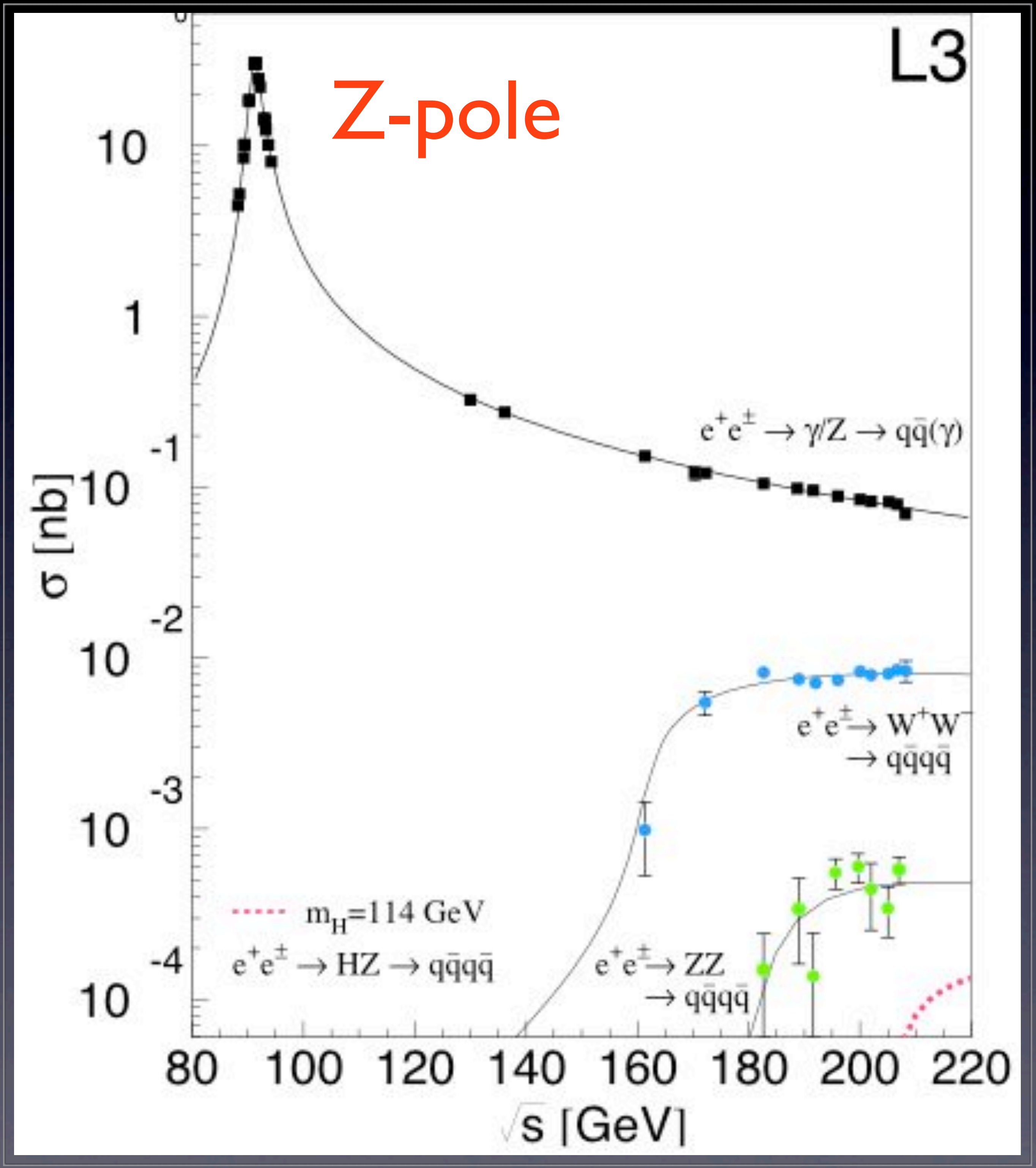
- SLHC, VLHC, Higgs Factory, ILC, ...

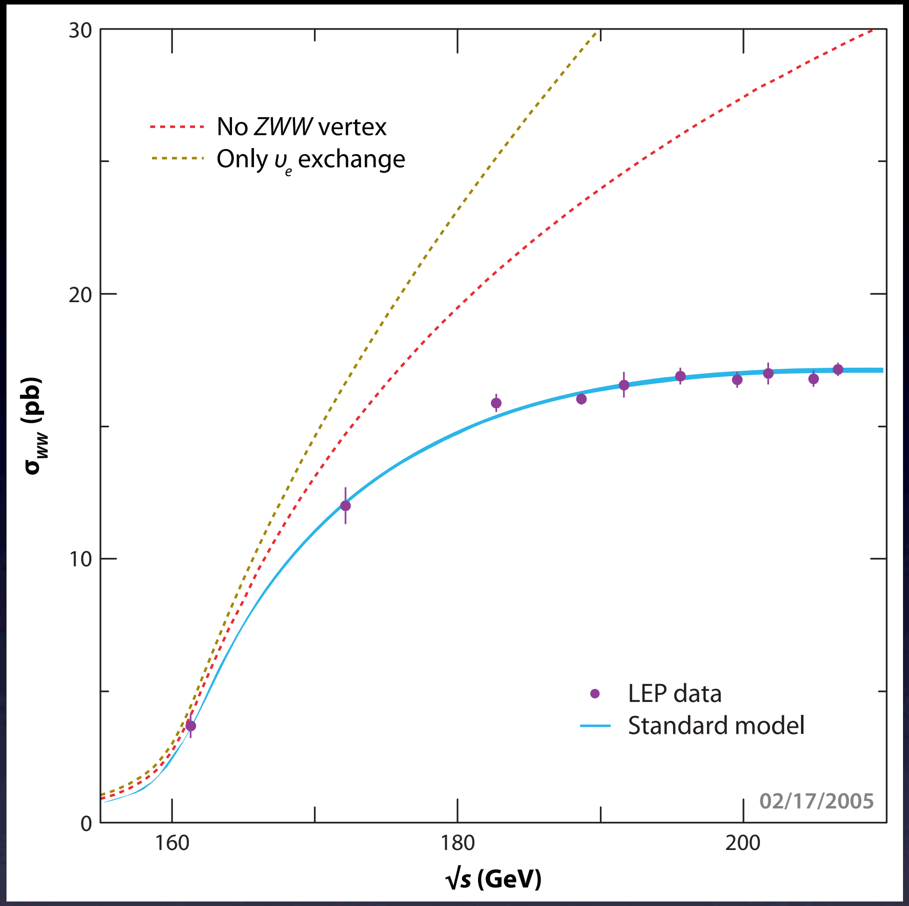
Large Electron-Positron Collider (1989-2001)

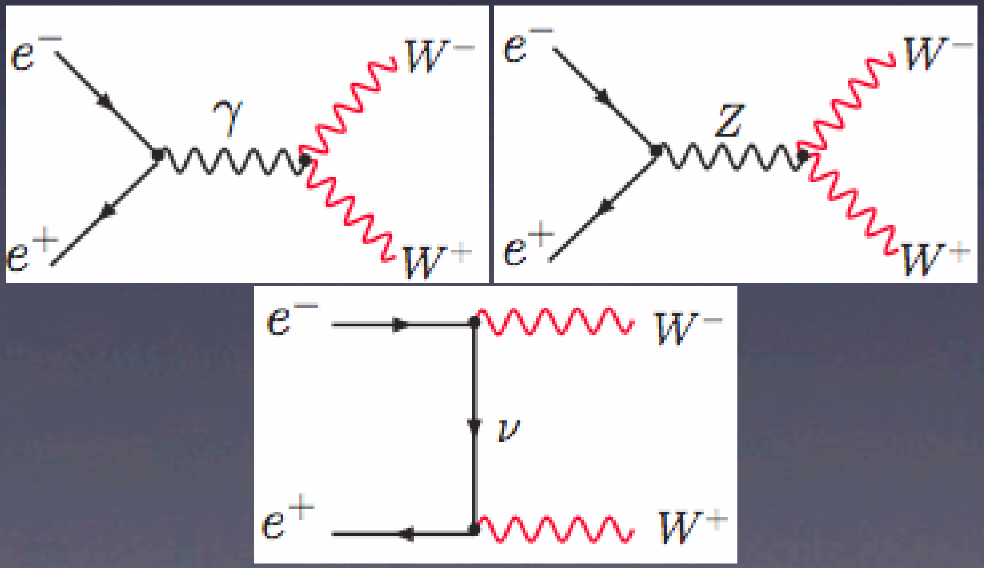


A Precision machine of EW interaction

Electroweak theory tests at tree level

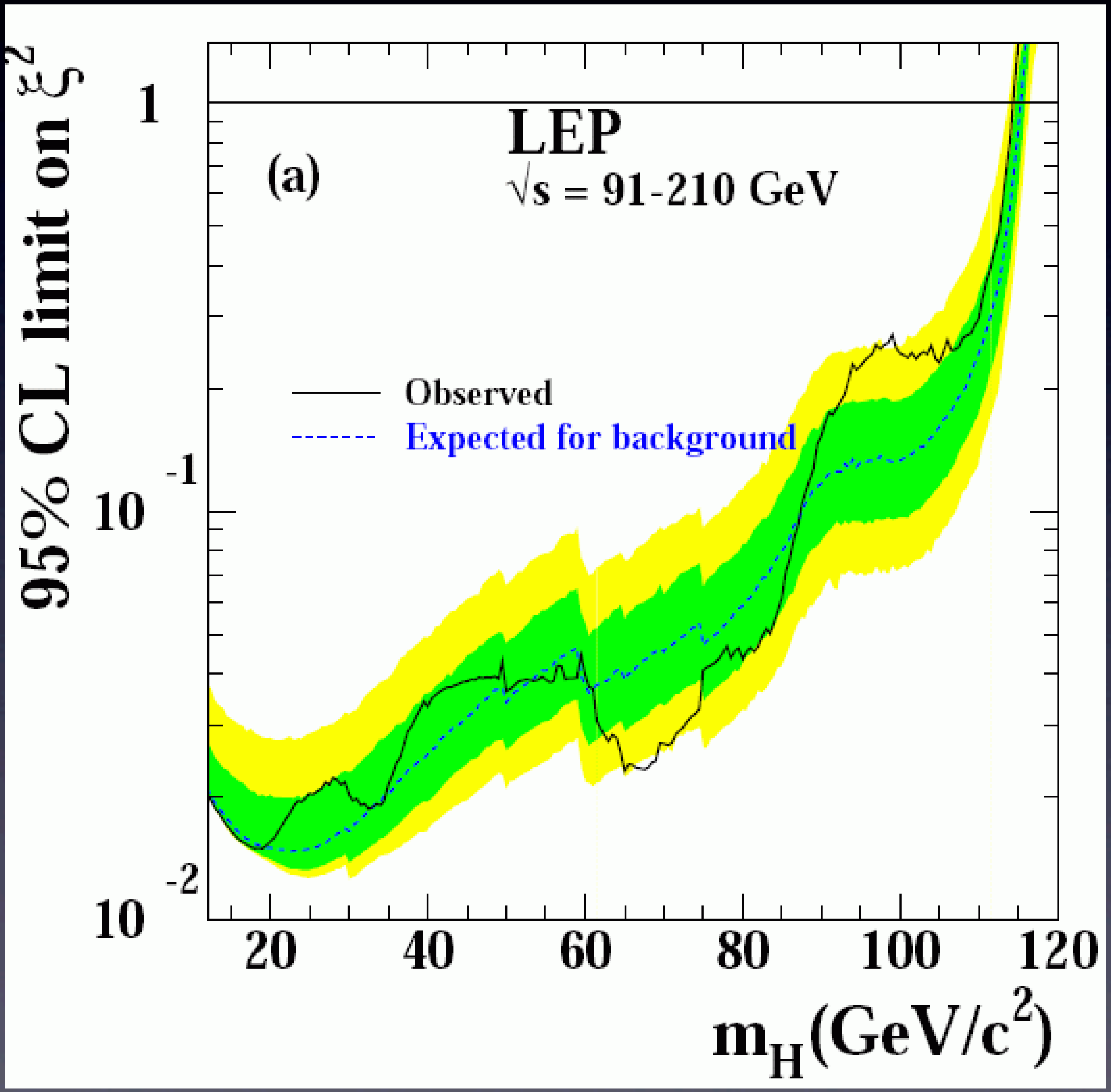


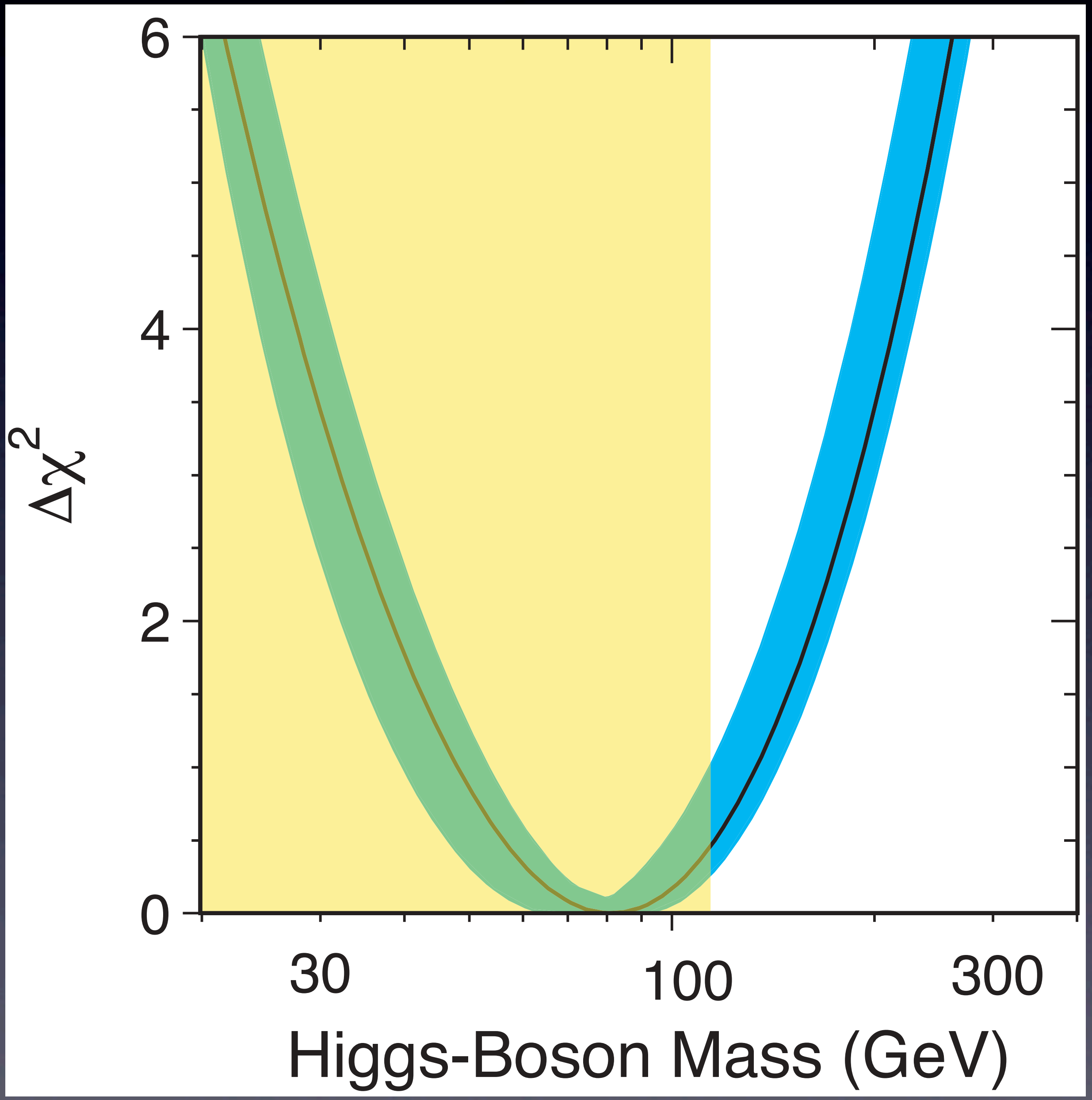




Higgs searches at LEP

- No evidence for Higgs $m_h > 114$ GeV

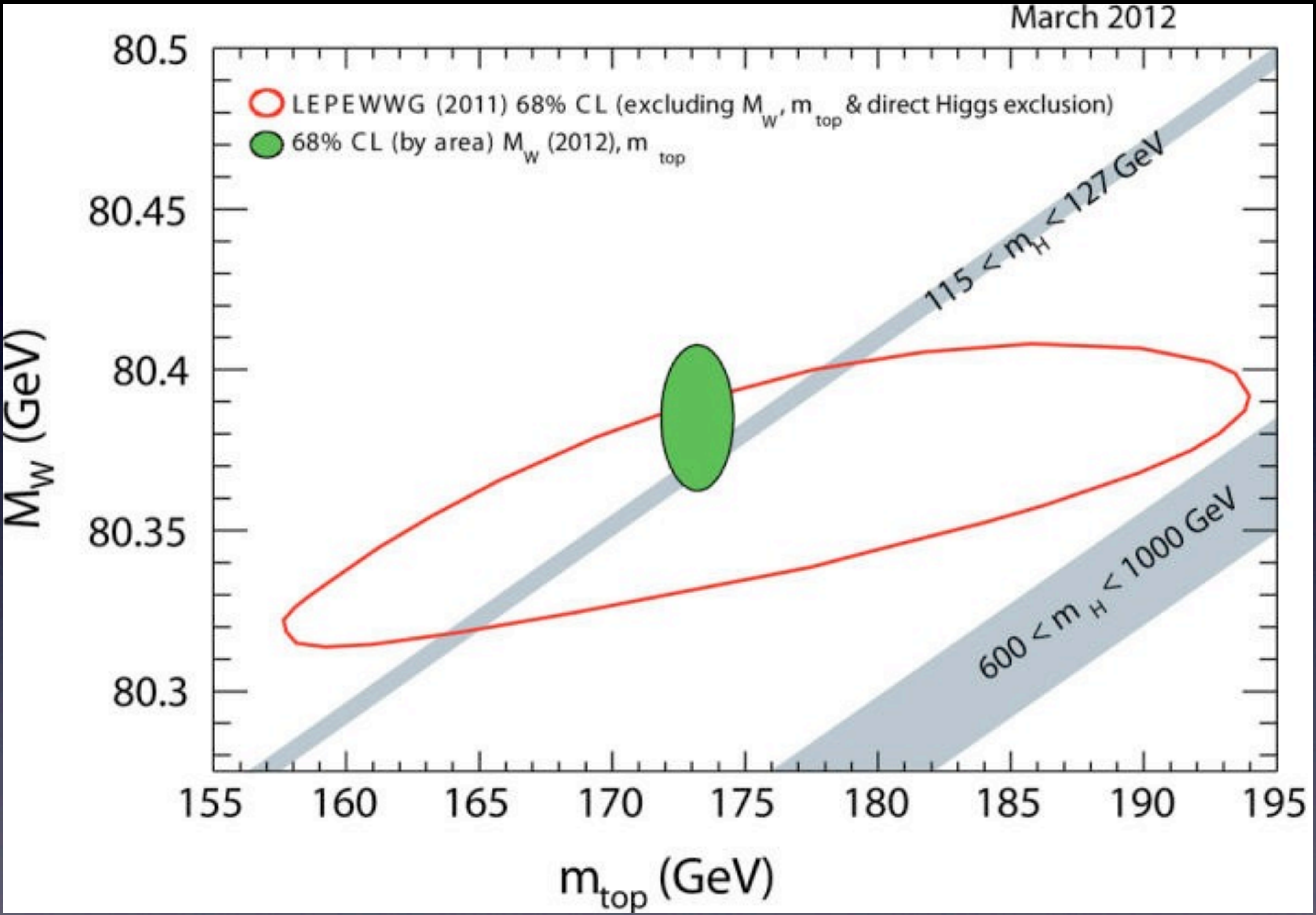




Tevatron
(1983-2011)

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

Precision measurements of *W*-boson



Top discovery: EW theory tests at Loop level

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

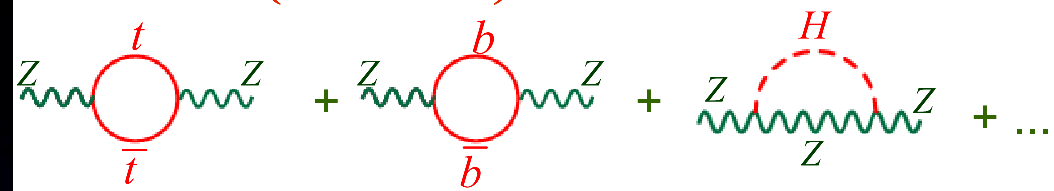
Ibanez, Ross
SUGRA-GUT (1983)
30<m_t<150GeV

Pendleton, Ross
GUT (1980)
m_t=130GeV

Glashow (1980)
m_{tt}>38GeV

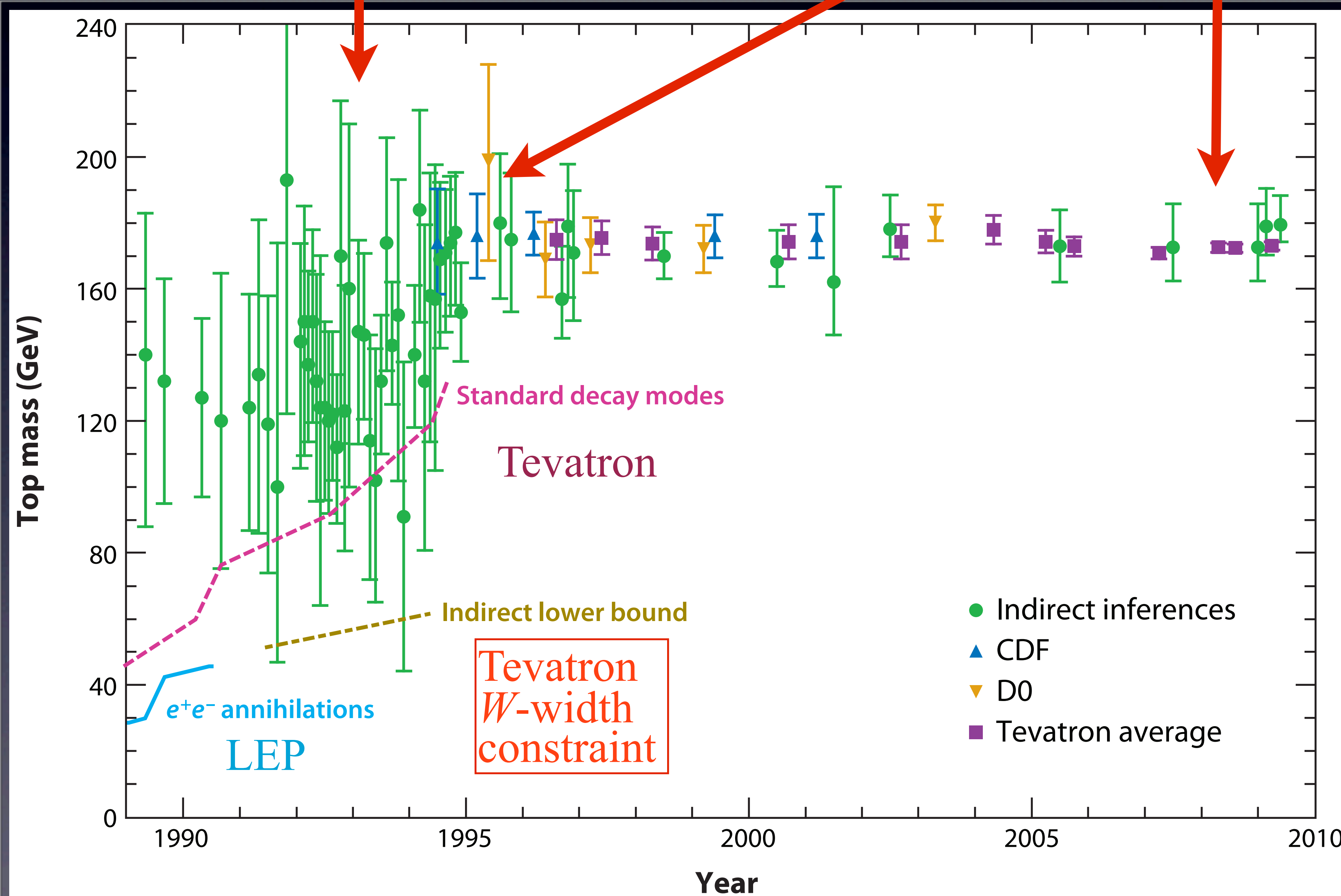
Tristan
1983

LEP fit (indirect)

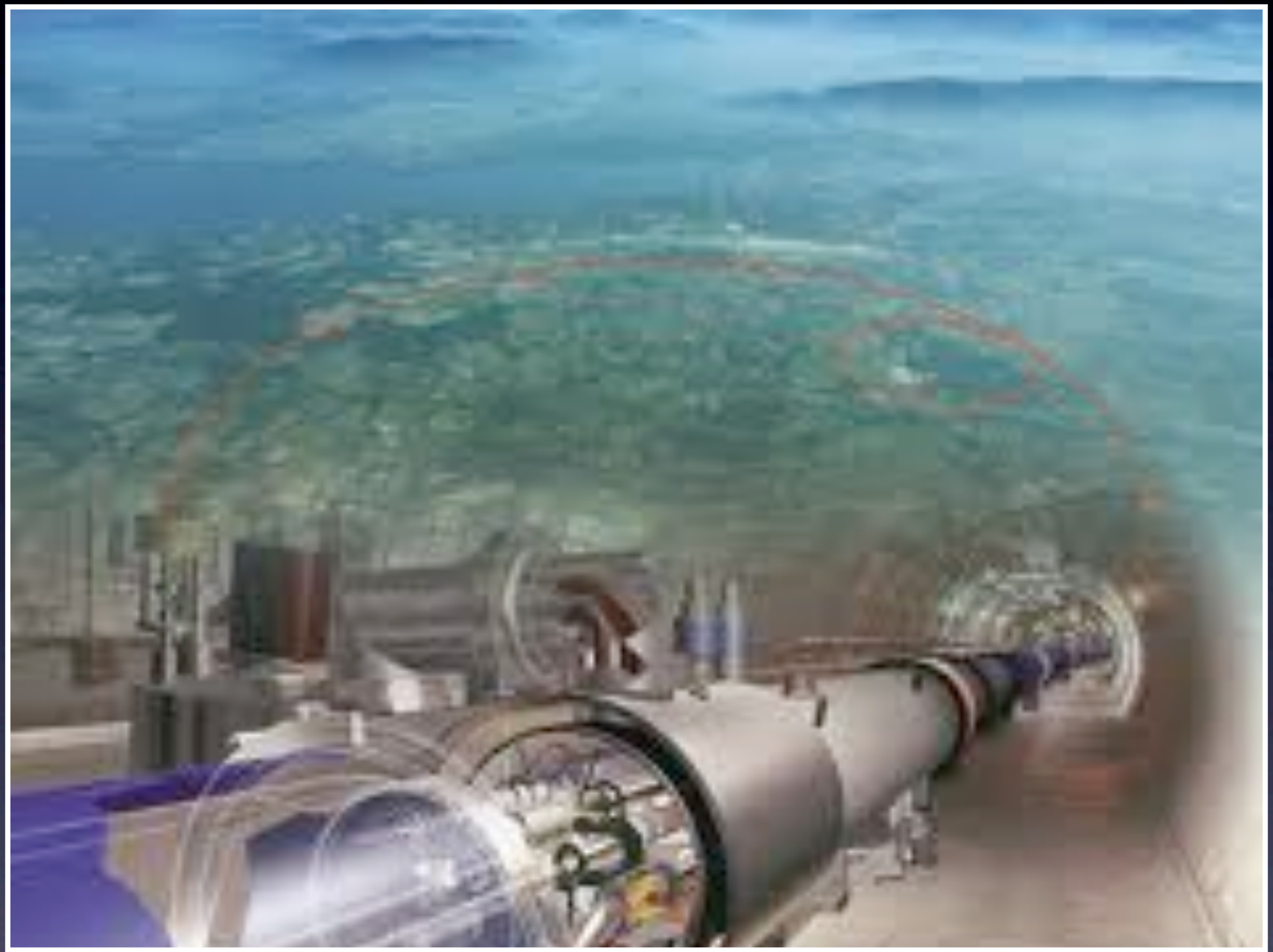


Tevatron
(1995)
Discovery

Tevatron
Precision

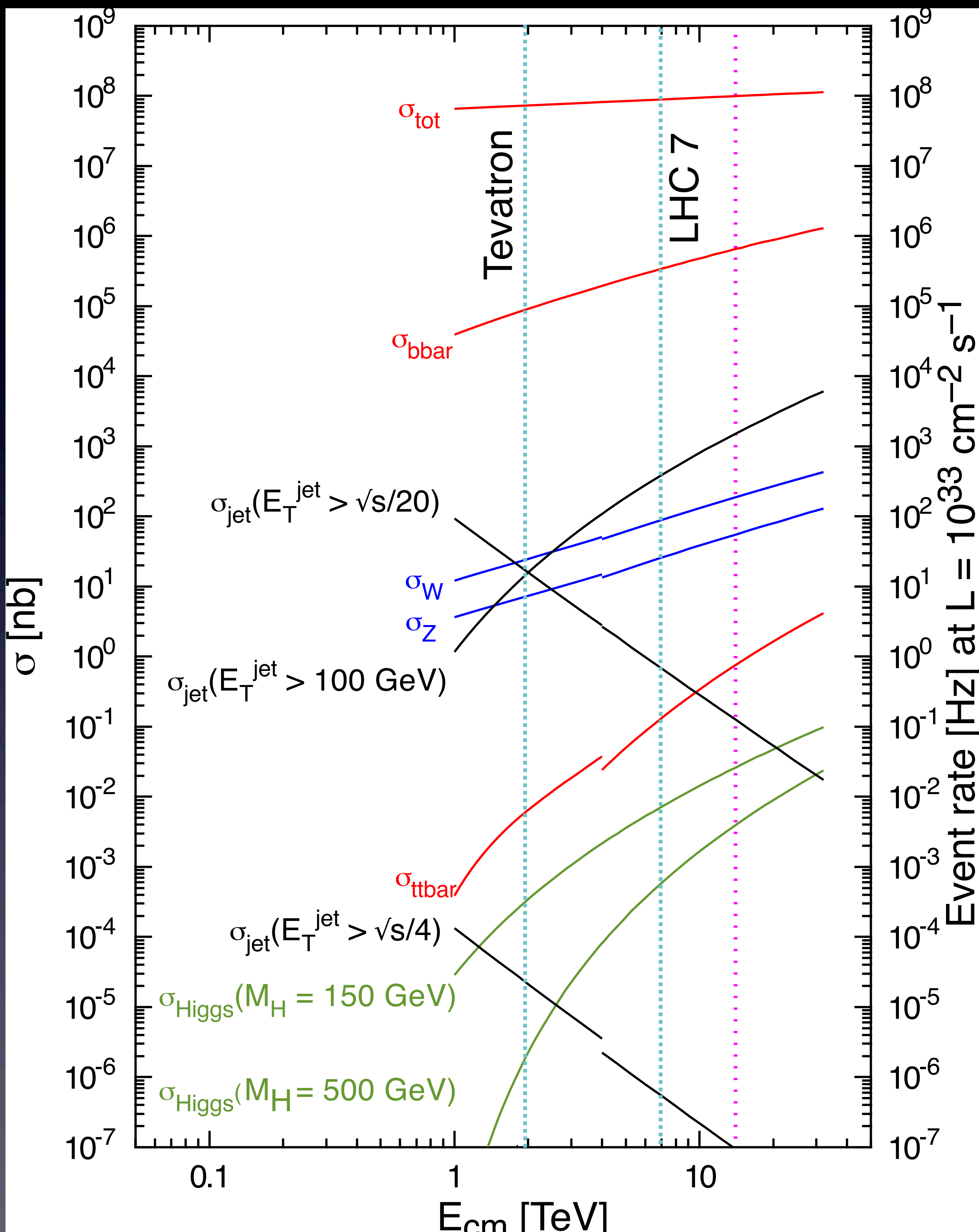


Large Hadron Collider
(2007-?)



A discovery machine of EW interaction
A top-quark factory

LHC: perfect for SM and NP

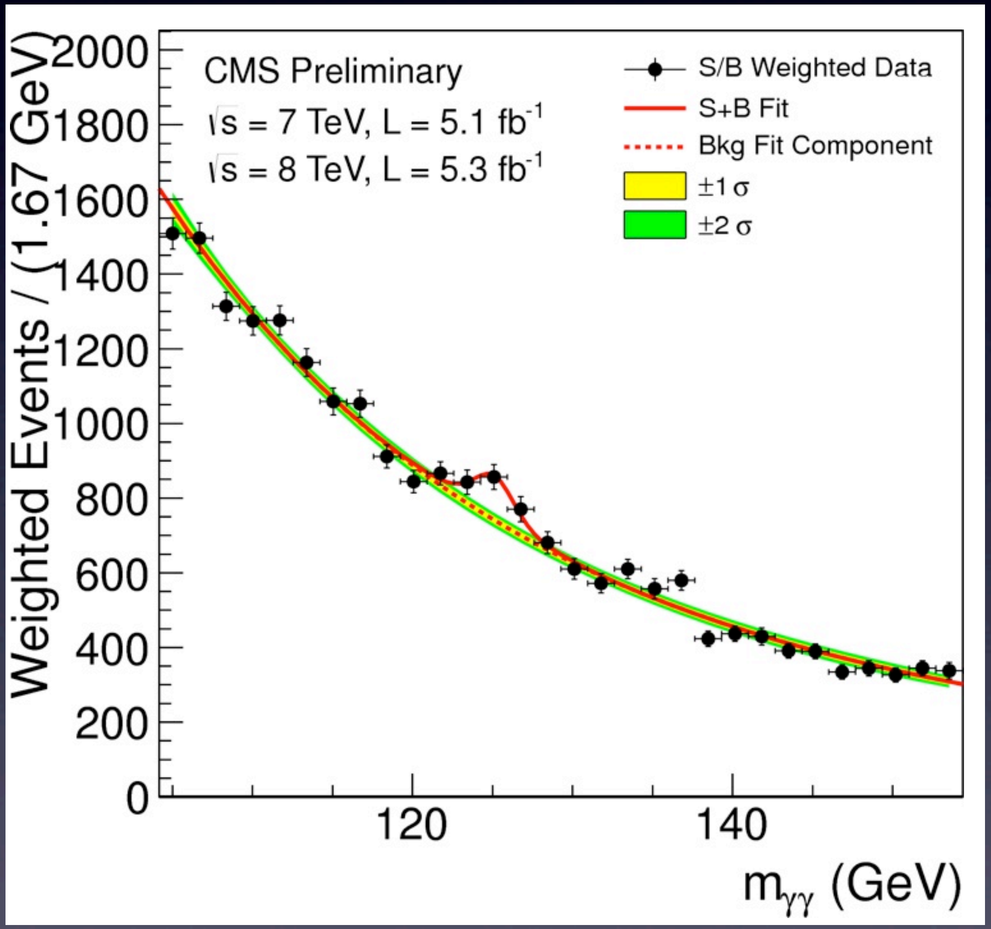


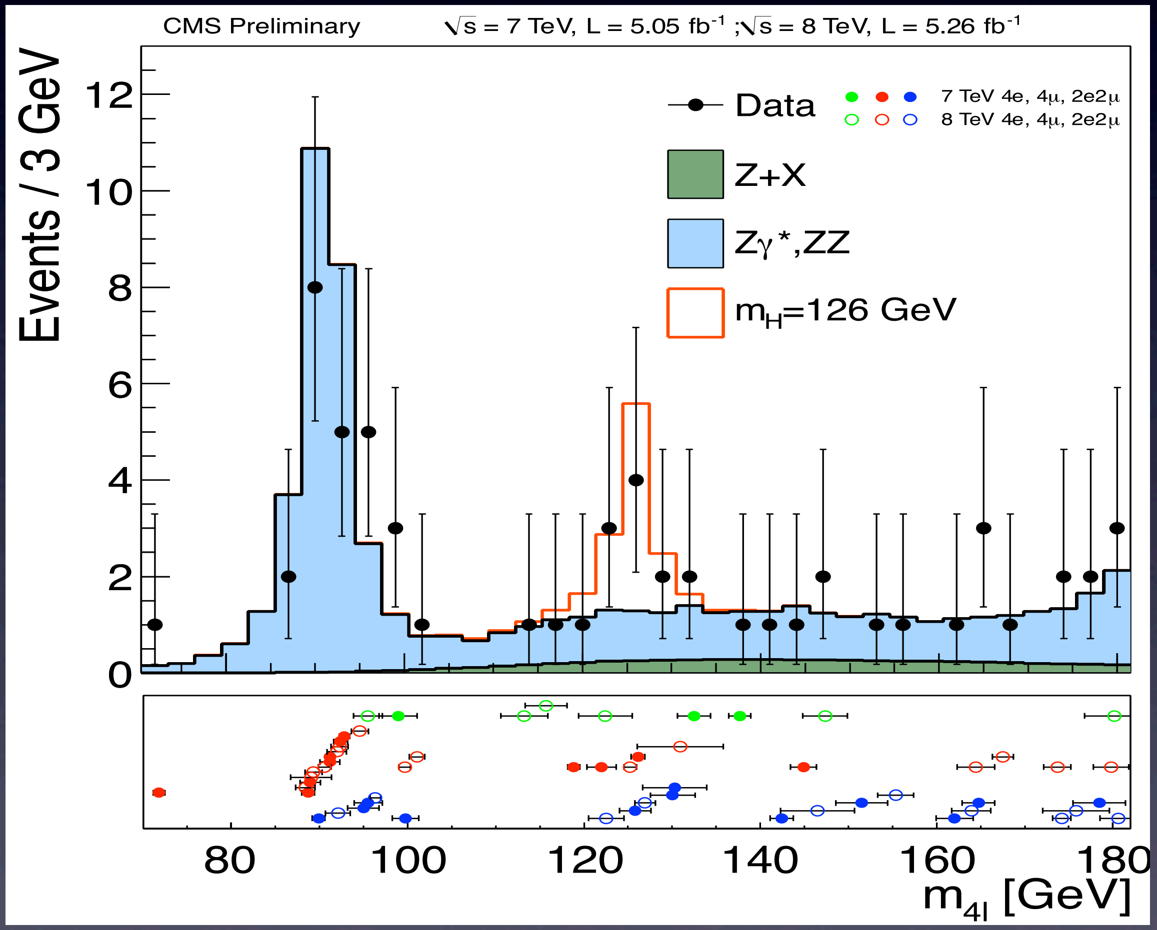
Rate at 8TeV LHC with $\mathcal{L} = 10^{33}\mathrm{cm}^{-2}s^{-1}$

- **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 (150GeV):** $0.02/s$
- **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

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

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

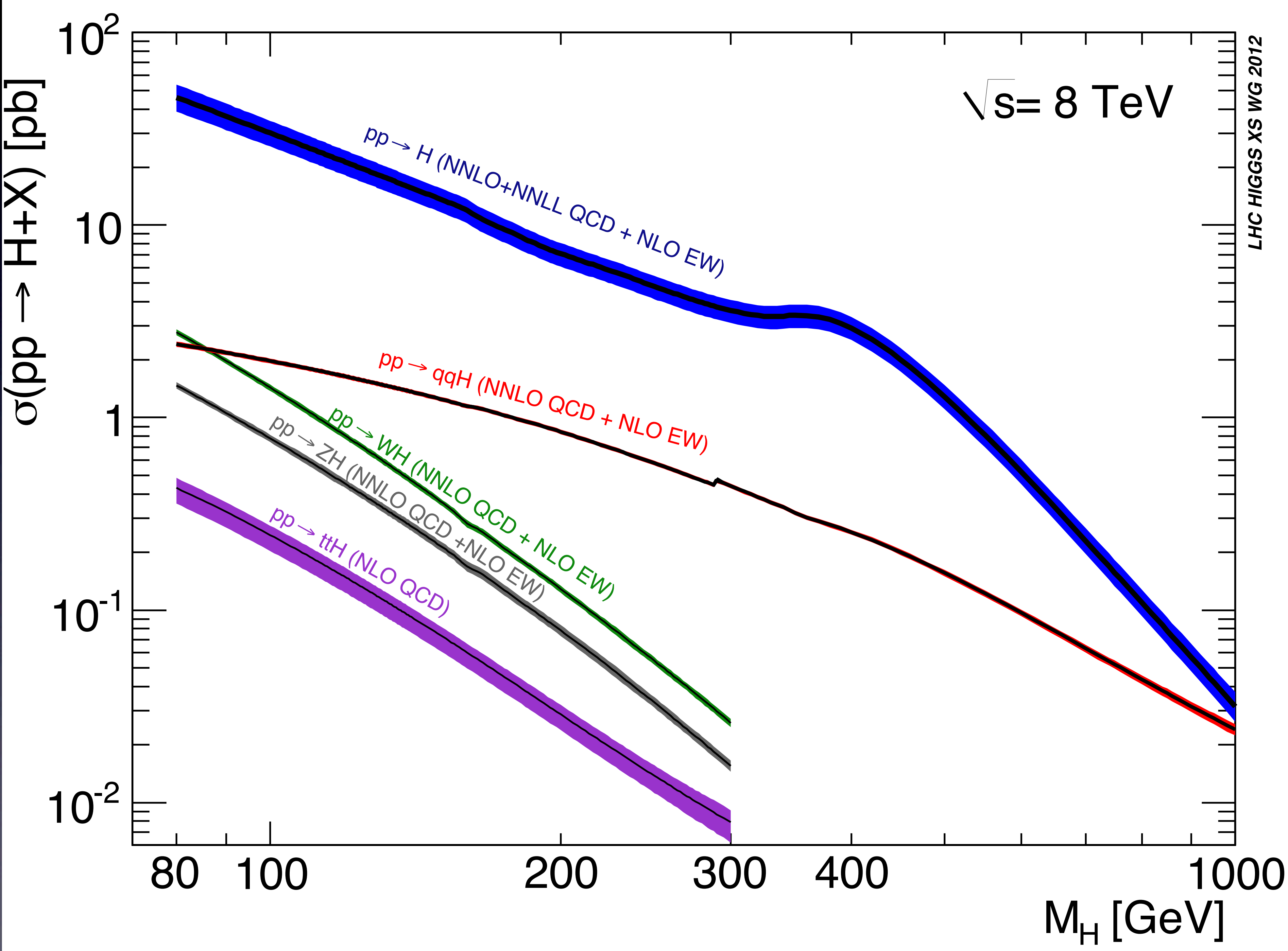
The ground state determined was tested with good accuracy (thanks to Tevatron)

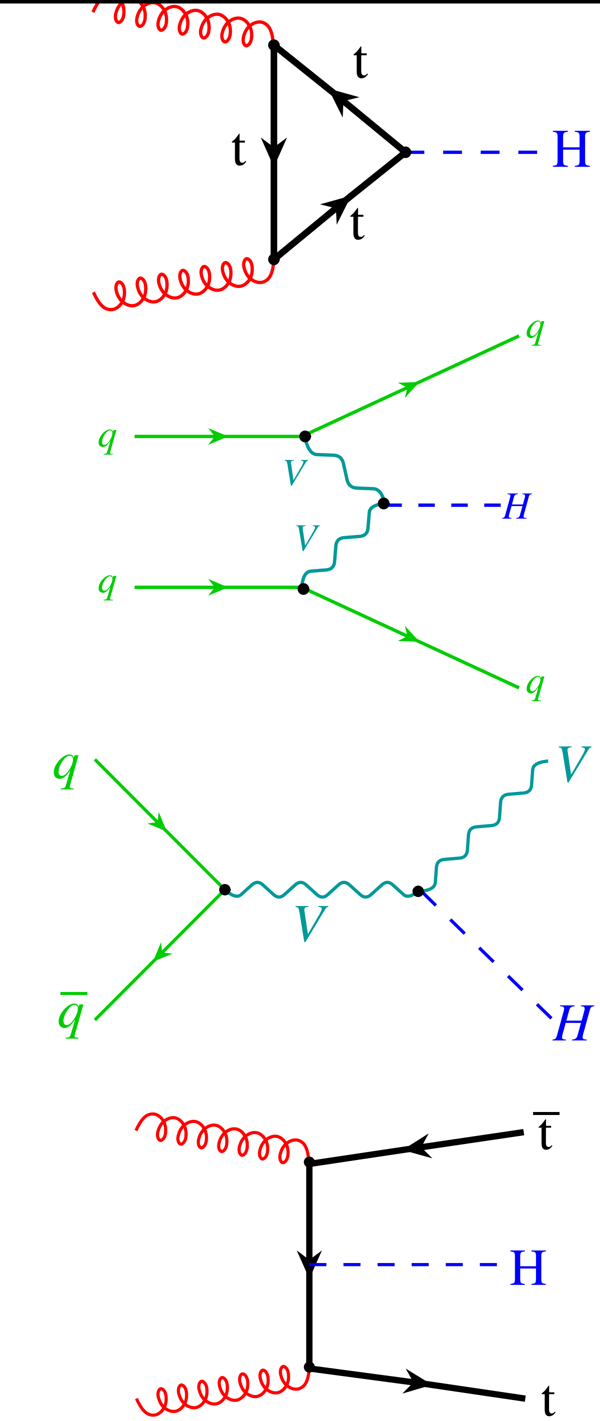
$$v = \langle \phi^+\phi \rangle^{1/2} \sim 246\ \text{GeV} \quad [\ m_W = \tfrac{1}{2}\, g\, v\ ]$$

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

$$\lambda_{(\text{tree})} = \tfrac{1}{2}\, m_h^{\ 2} / v^2 \sim 0.13$$

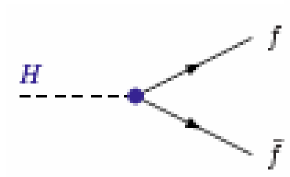
Higgs boson production



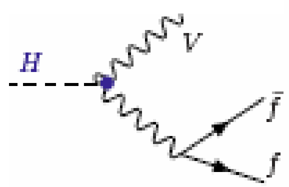


Higgs boson decay

bb dominant
m_H< 120 GeV

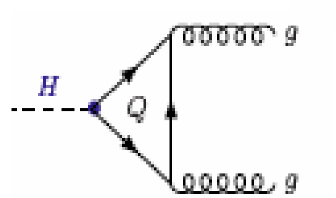


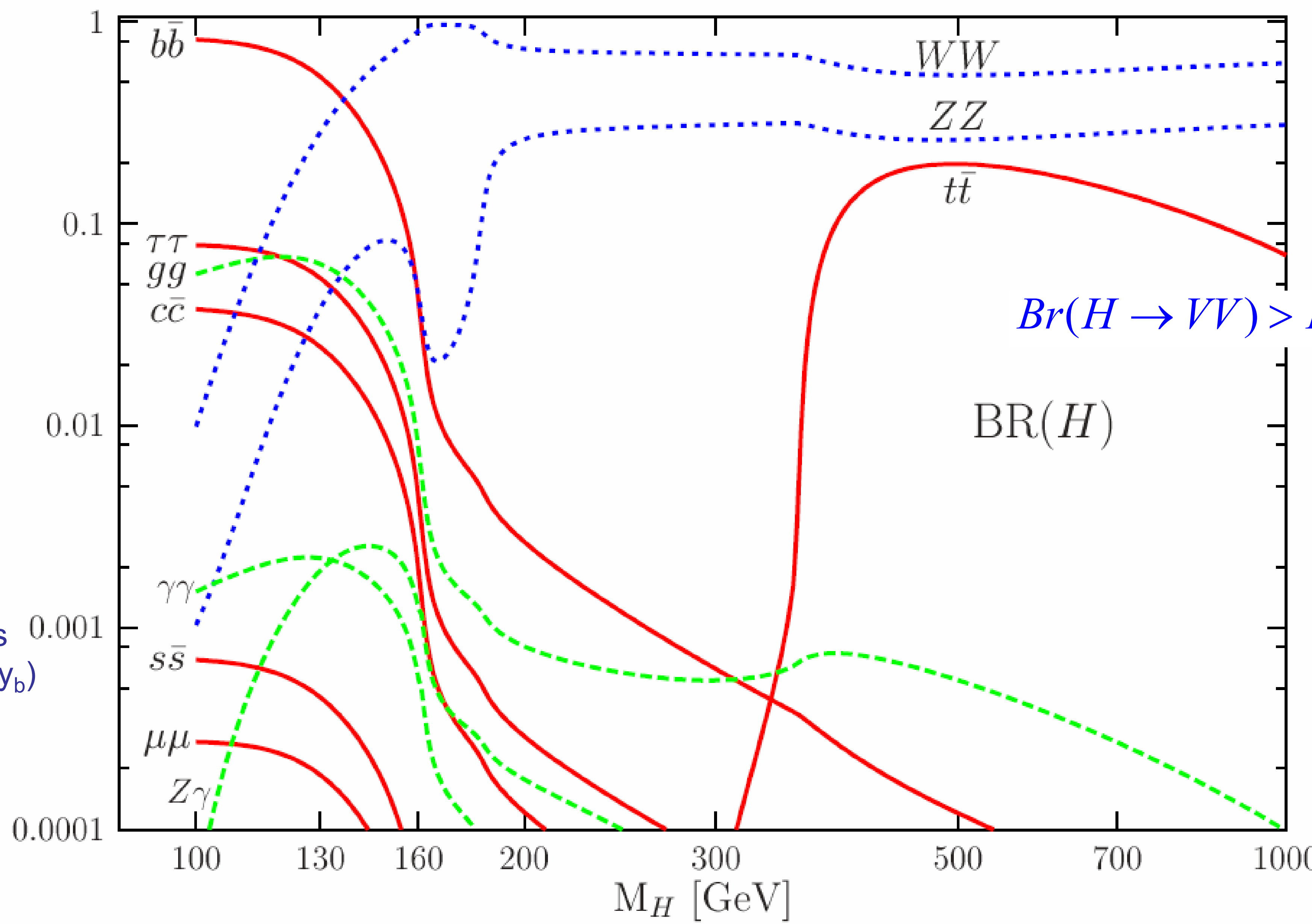
WW dominant
m_H> 130 GeV



(gauge coupling is much larger than y_b)

gg large
m_H<130 GeV

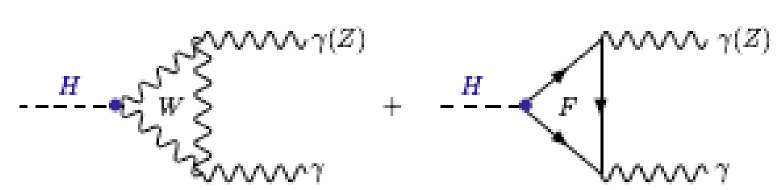




$$\frac{\Gamma(h\to WW)}{\Gamma(h\to ZZ)}\sim 2$$

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

γγ reaches maximal
m_H~130 GeV
(Important at LHC)



Questions of the top priority

scalar #:
one or two
or more?

Spin:
0 or 2?

CP:
even or odd?

Mass (accuracy)
Width (?)

1. What can we learn from 125GeV?

（半个贰百五）

Theoretical problems

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

vacuum instability

possible internal inconsistency 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

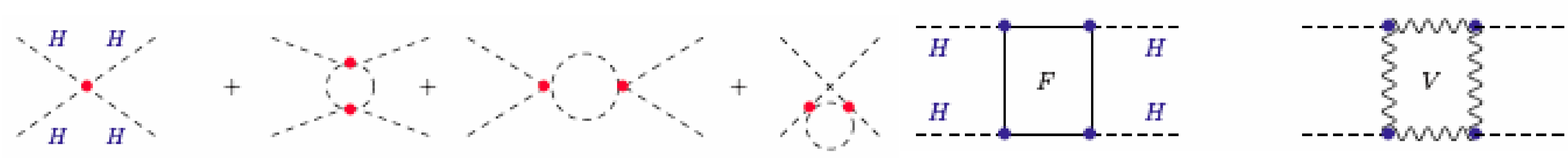
(unexplained span over 5 orders of magnitude and strongly hierarchical structure of the Yukawa coupl.)

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



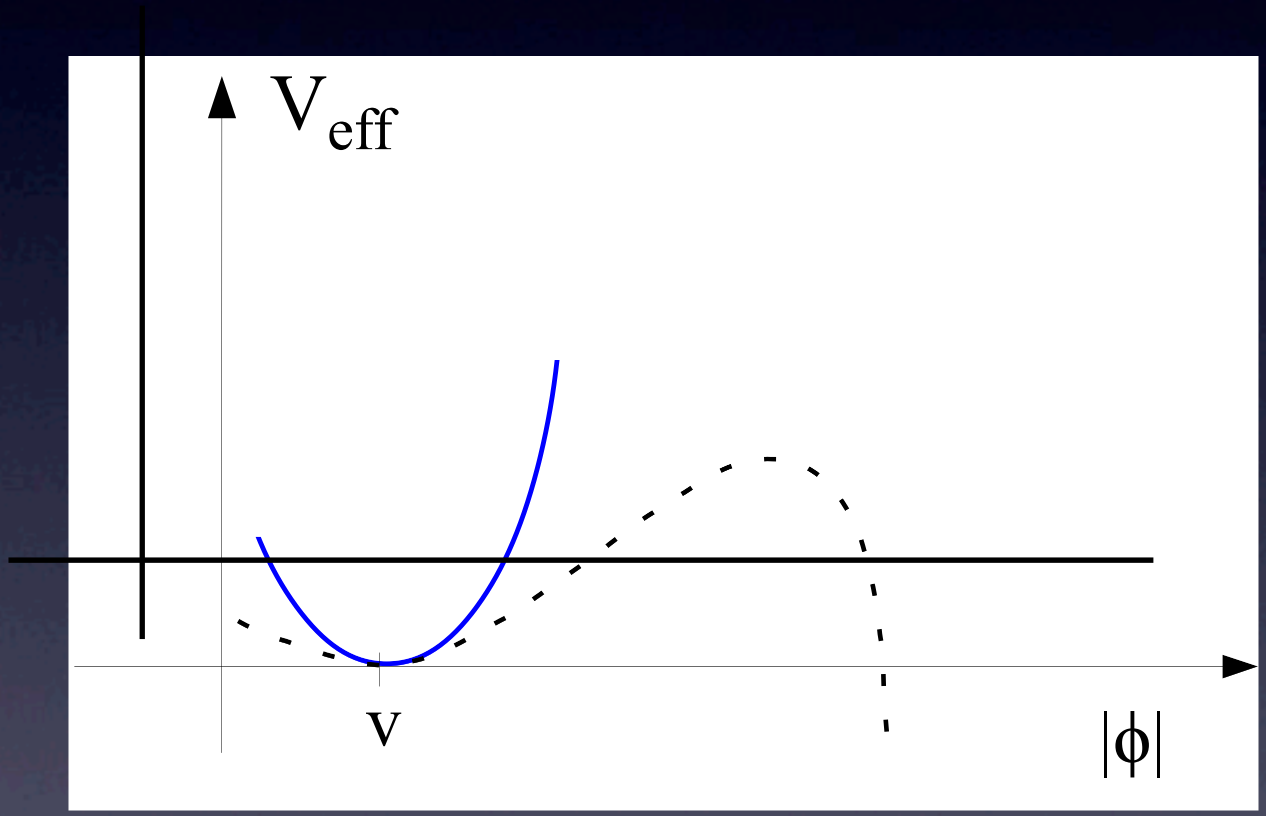
$$\frac{d\lambda}{d\ln Q^2} \simeq \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

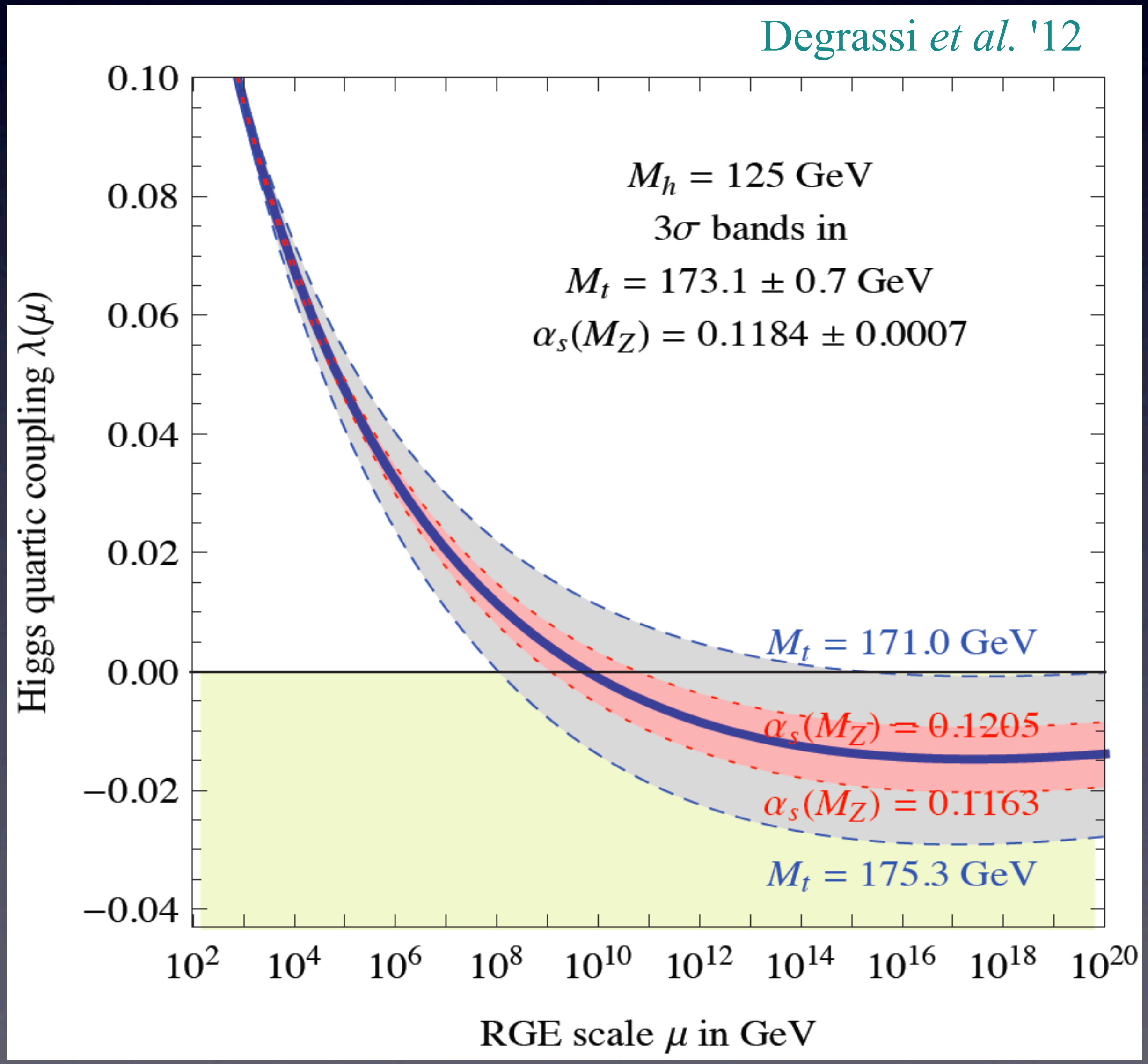
$$\lambda(|\phi|) < 0 \;\longrightarrow\; V(|\phi|) < V(v)$$

Vacuum unstable

Vacuum stability bound at NNLO

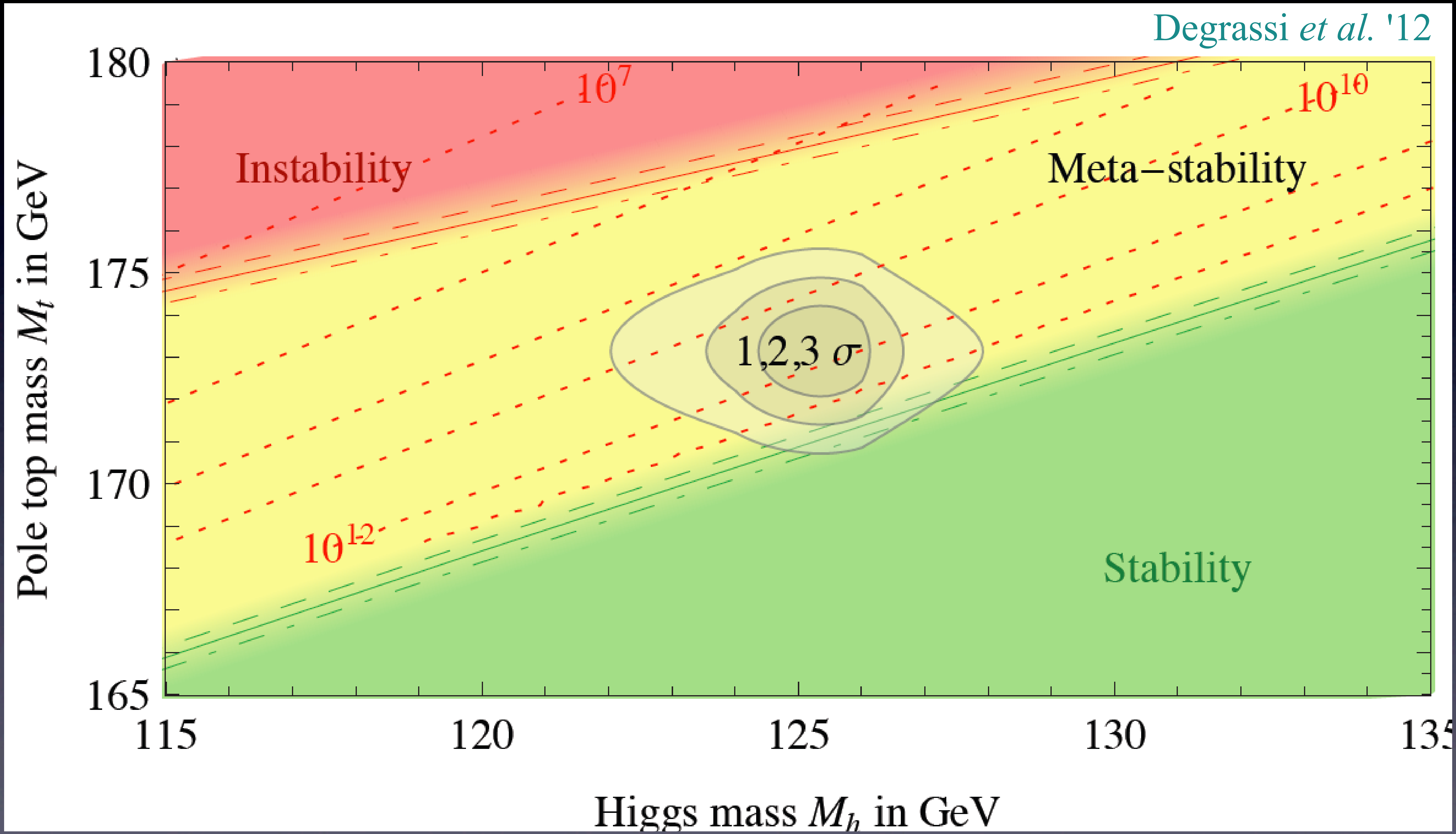
$$M_h\ [\mathrm{GeV}] > 129.4 + 2.0\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{1.0}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}$$





Might we live in a metastable vacuum?

Top quark and 125GeV Higgs boson



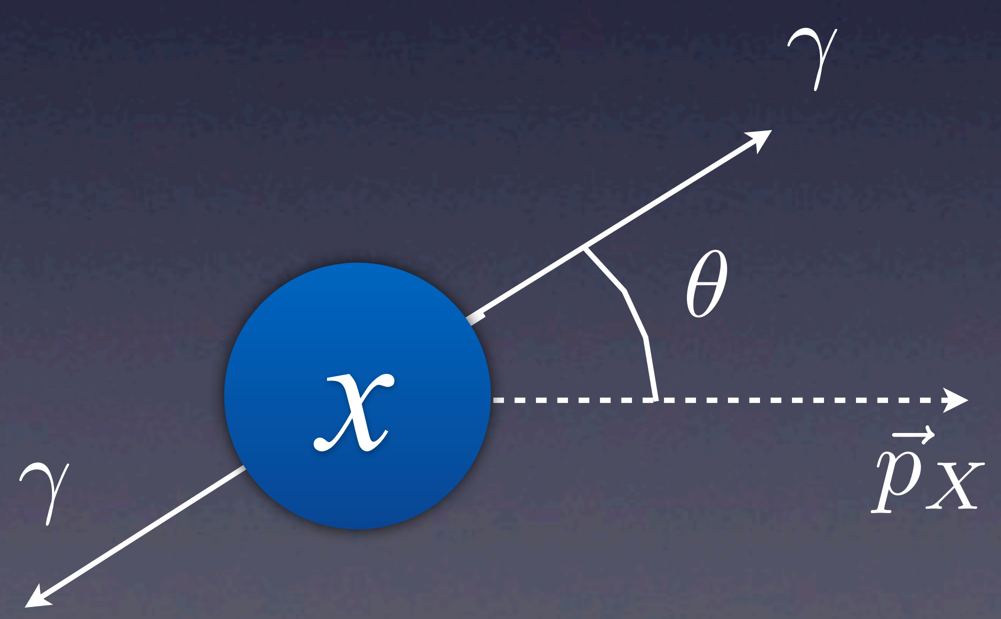
2. What about spin?

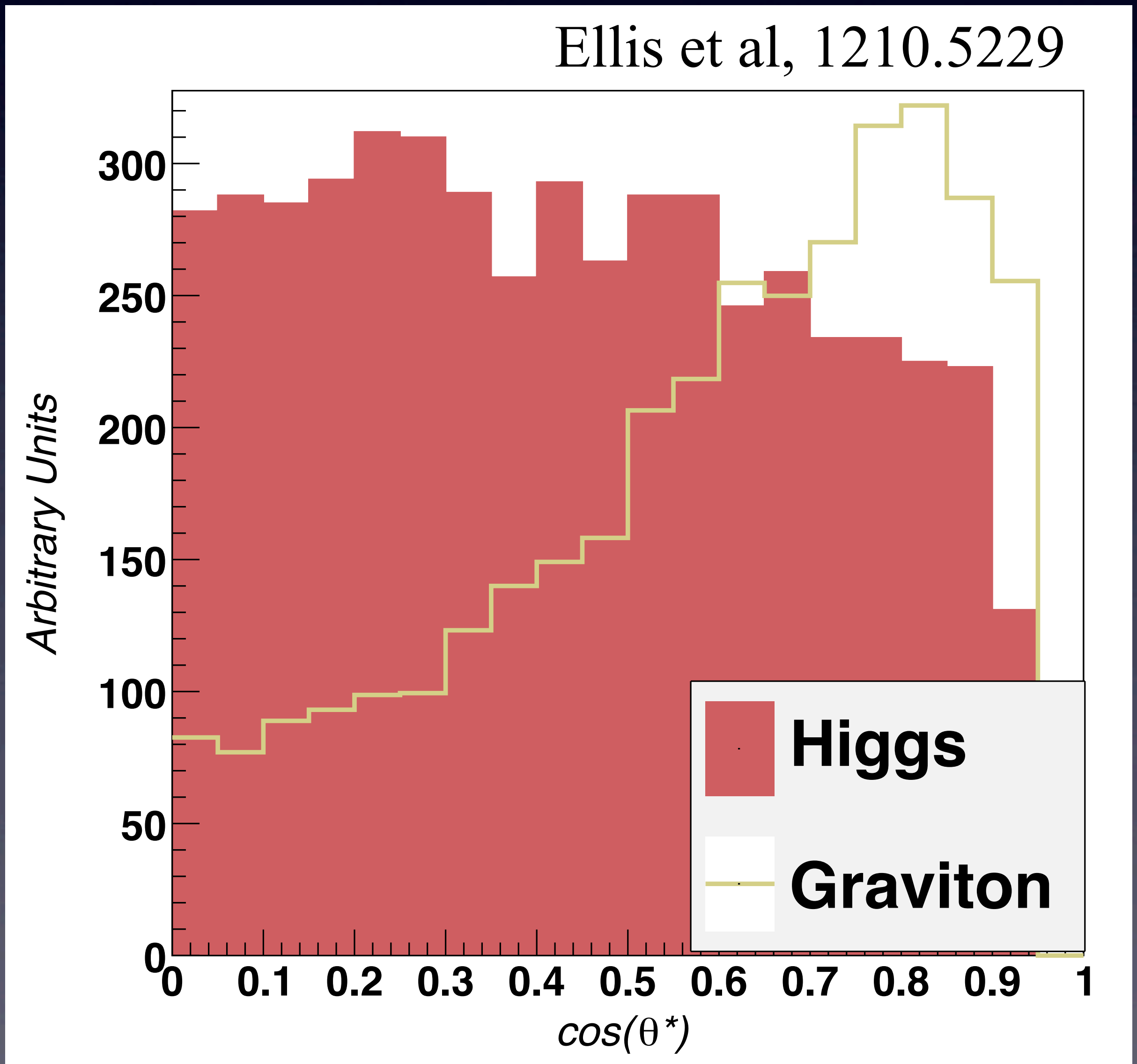
Spin-0 or Spin-2

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





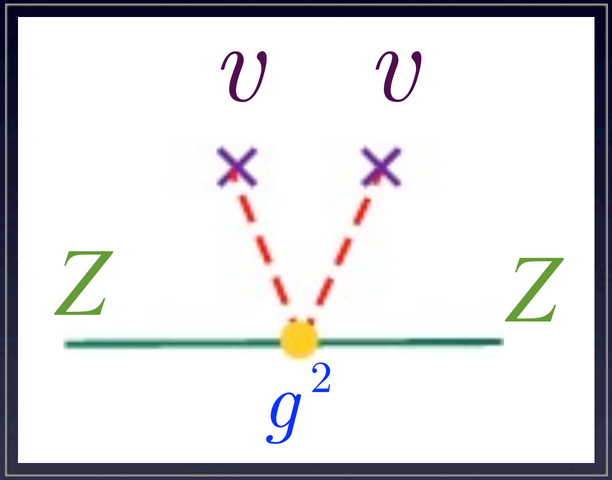
3. CP Property

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:

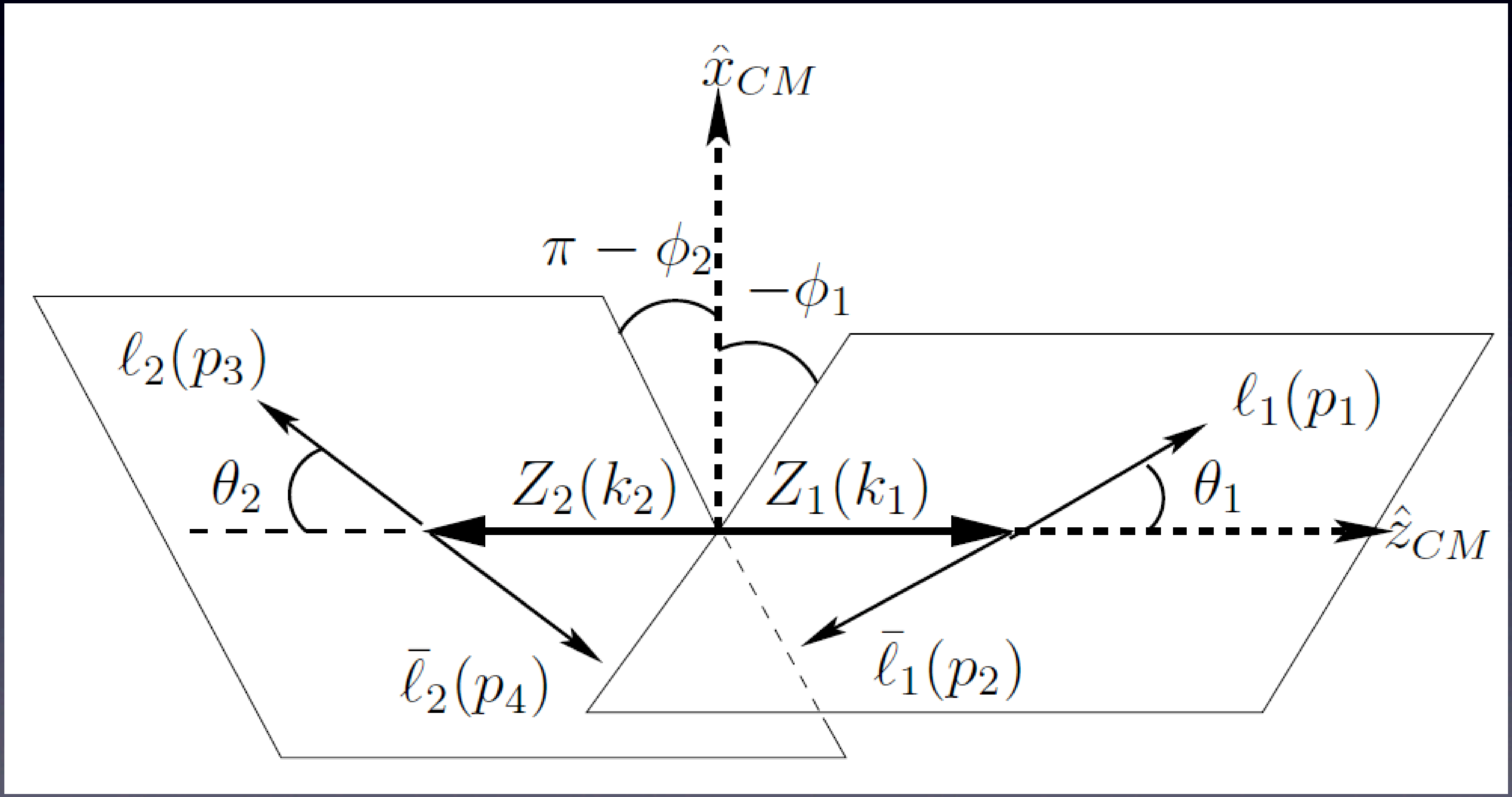
the other two terms are higgs imposters!!

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

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

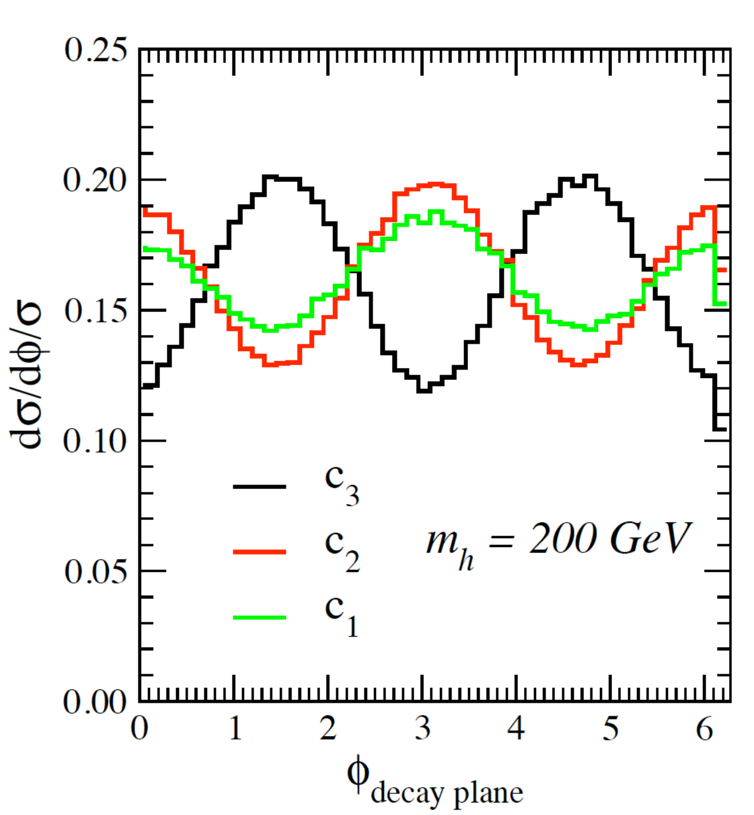
$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^\nu Z_\nu + \frac{1}{2}\frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4}\frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

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

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

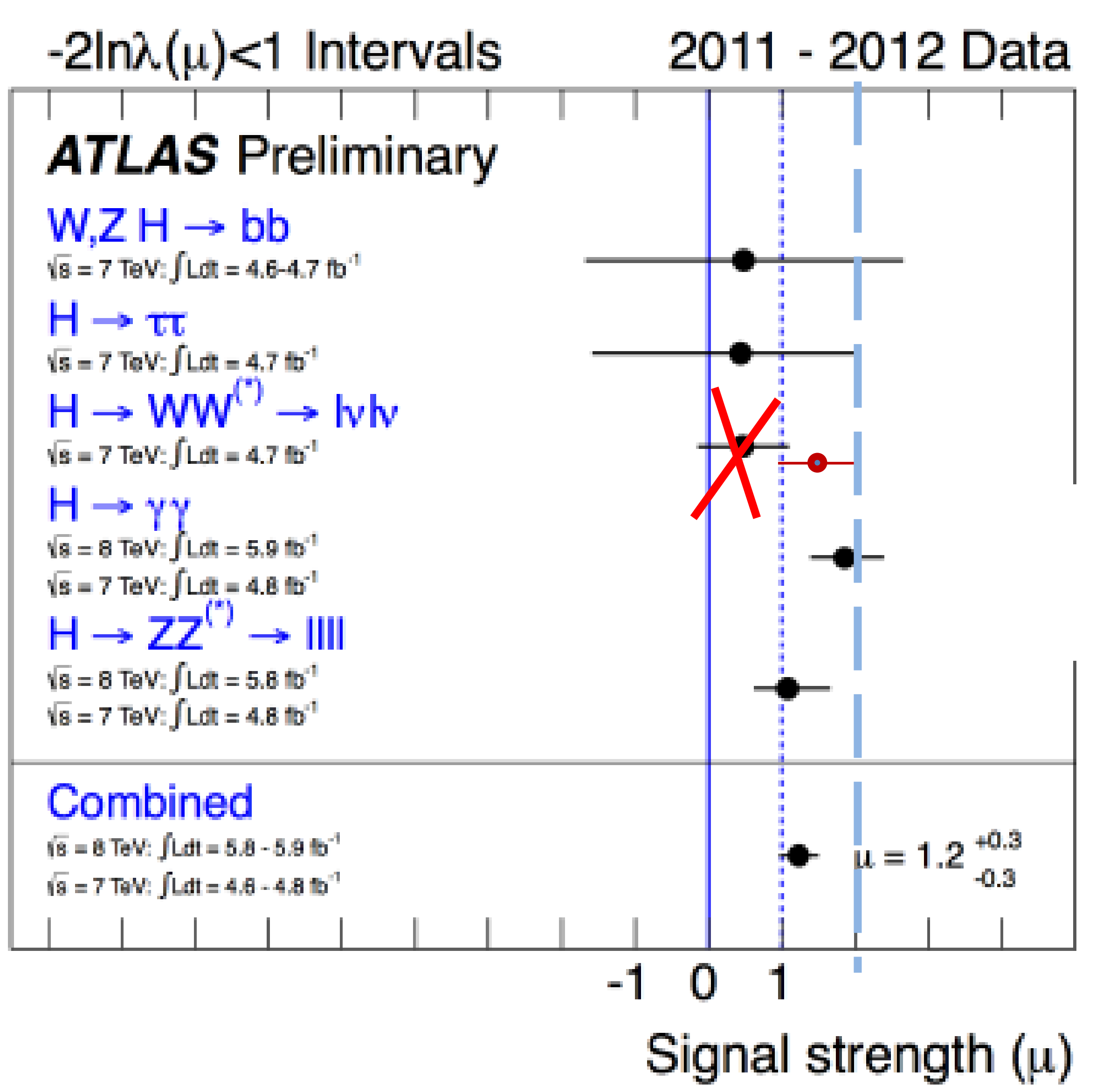
- New set of reference SM parameters

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

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

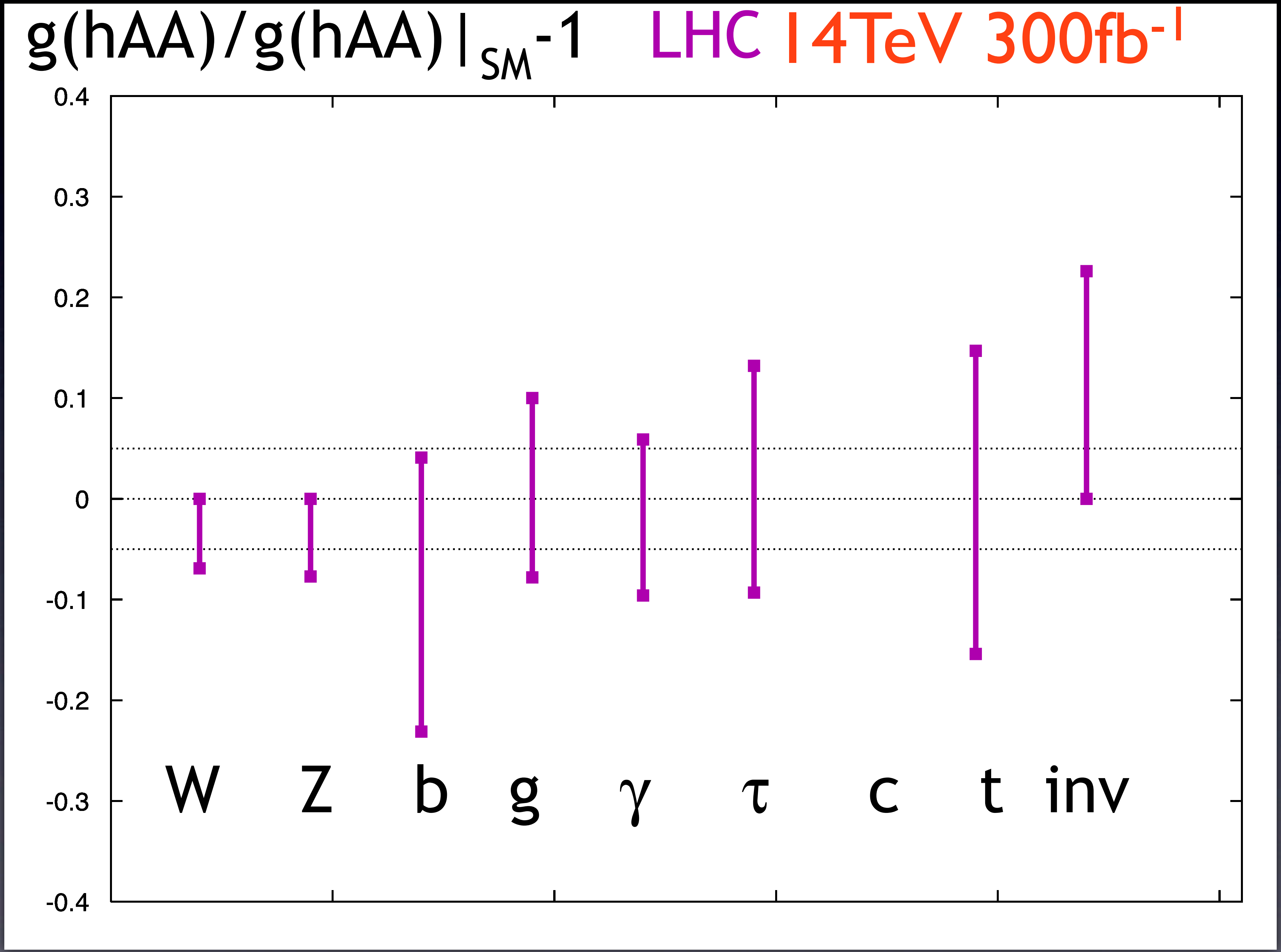
$\mathrm{Br}(H \to bb) = 56\%$ ★
$\mathrm{Br}(H \to cc) = 2.8\%$
$\mathrm{Br}(H \to \tau\tau) = 6.2\%$ ★
$\mathrm{Br}(H \to \mu\mu) = 0.021\%$

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



Higgs boson couplings

Peskin, 1208.5152



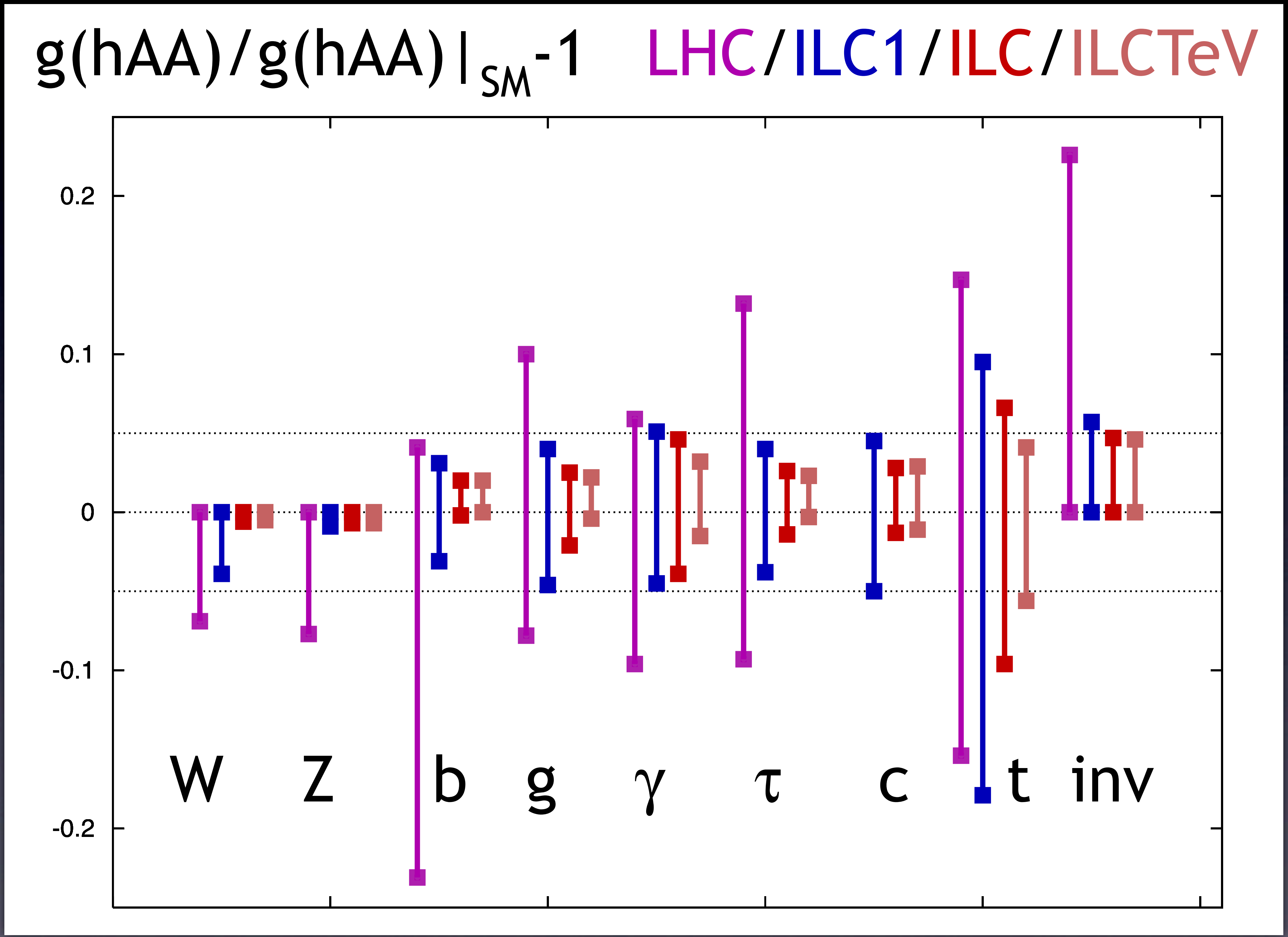
Higgs boson couplings at LC

LHC:
14TeV
300fb^{-1}

ILC1:
250GeV
250fb^{-1}

ILC:
500GeV
500fb^{-1}

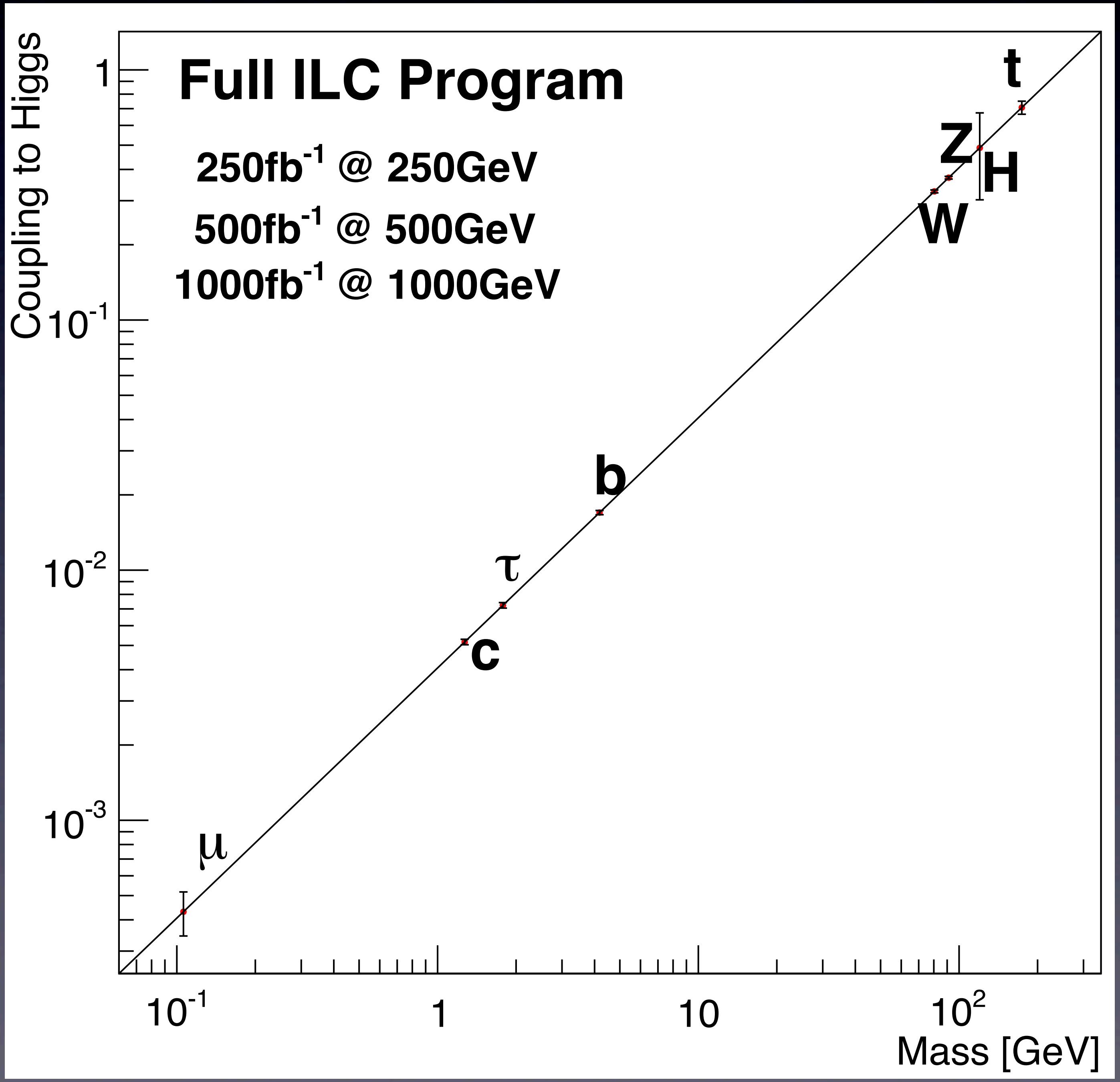
ILC TeV:
1000GeV
1000fb^{-1}



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

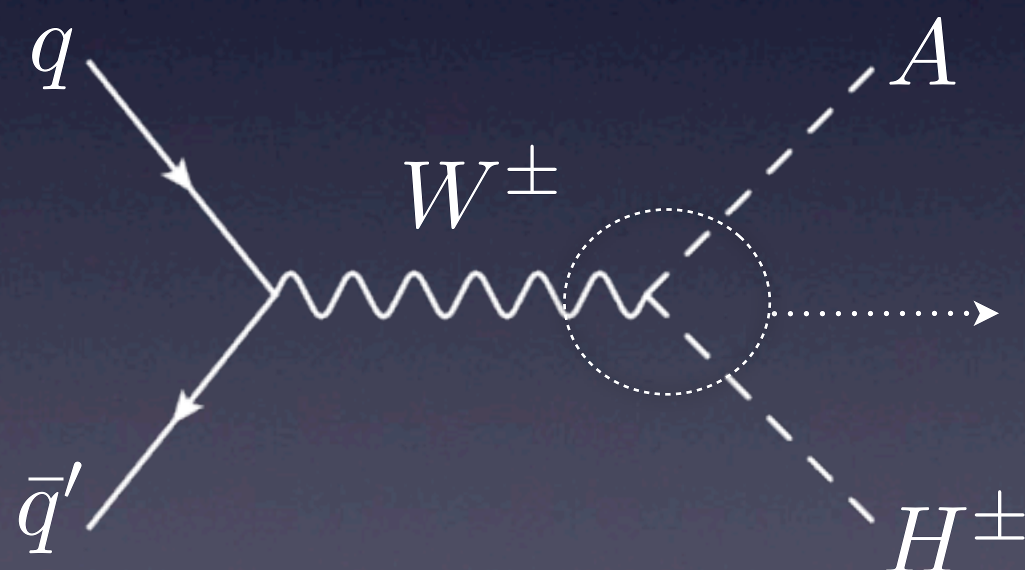
5. Only one scalar?

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 $pp \to W^{\pm} \to AH^{\pm}$



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

QHC, Kanemura, Yuan
PRD69 (2004) 075008

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

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

Light Higgs scenario

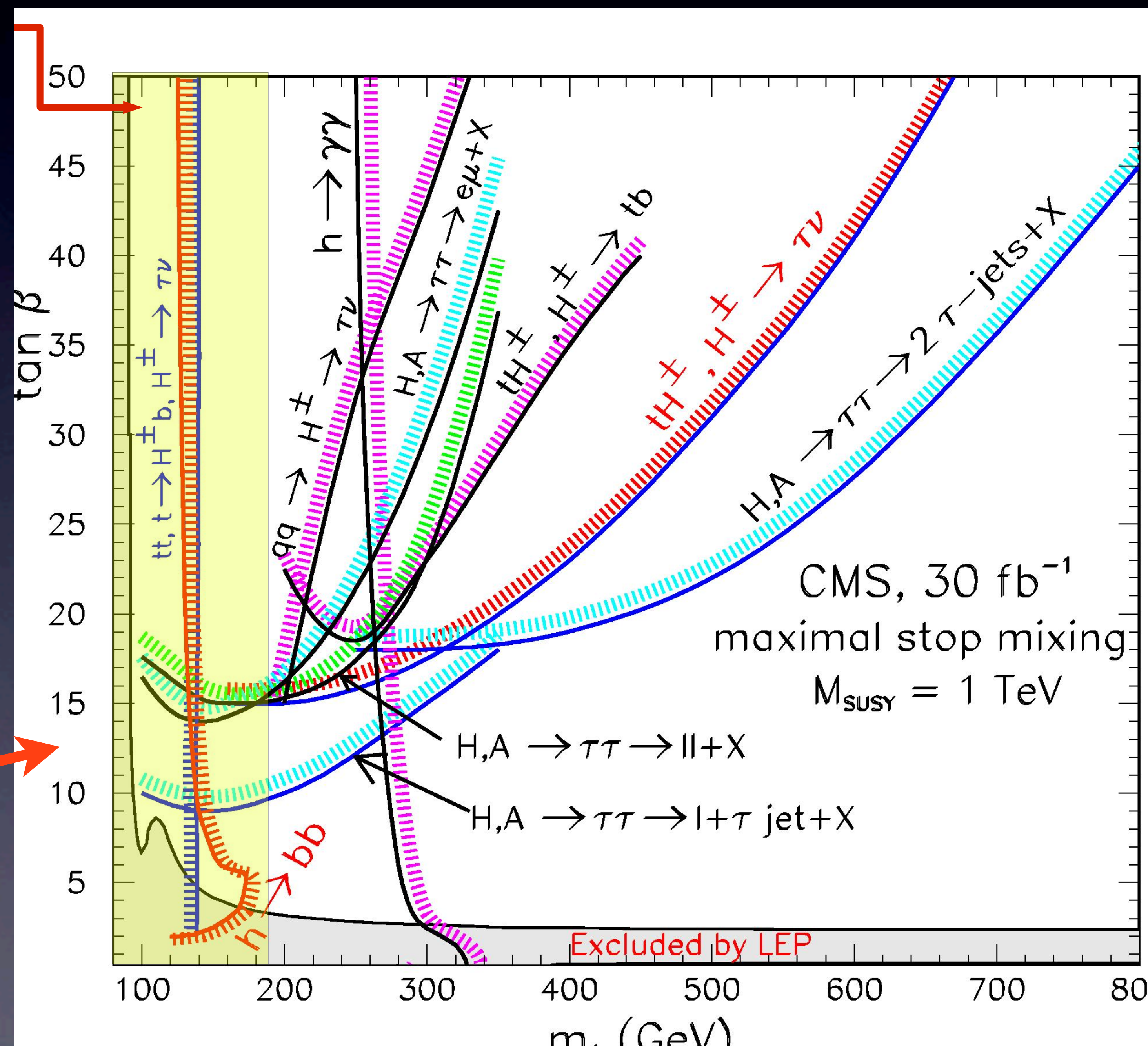
Belyaev, QHC, Nomura, Tobe, Yuan,
PRL100 (2008) 061801

- 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?
- ....

What we learned from top discovery

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

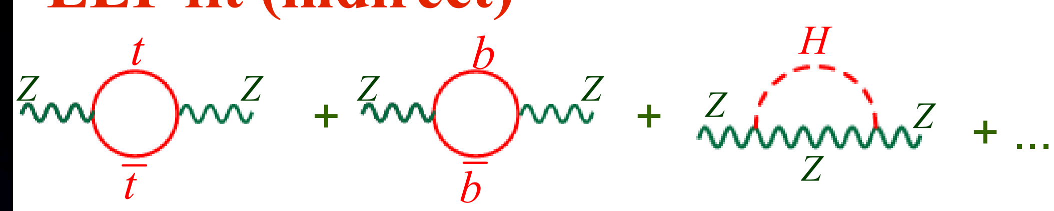
Pendleton, Ross
GUT (1980)
m_t=130GeV

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

Glashow (1980)
m_{tt}>38GeV

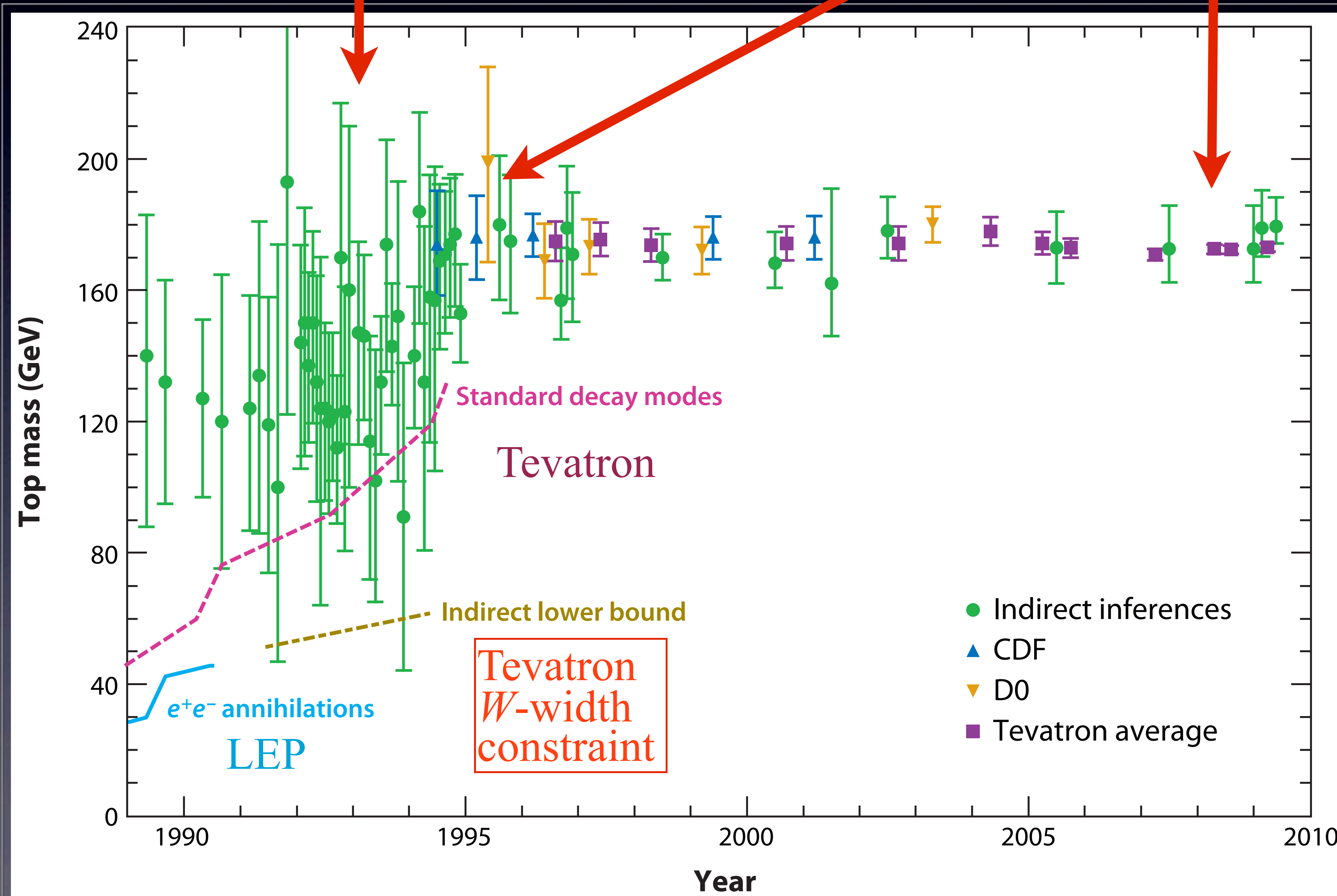
Tristan
1983

LEP fit (indirect)



Tevatron (1995) Discovery

Tevatron Precision



Experiments versus Theories

- Physics is associated with many scales

EWSB
Dark Matter

SUSY

Unification,
Neutrino See-Saw

Quantum
Gravity

Higgs Factory

THANK YOU!