

Electroweak Theory at Multi-TeV Collider

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Peking University

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)
Theory 1973 10 years
 - ▶ Top-quark discovery (1995)
Existence: $b\bar{b}$ FB asymmetry (1977) 18 years
 - ▶ Higgs-like scalar discovery (2012)
Theory 1964 48 years

History is not just a thing of the past!

July 4th, 2012

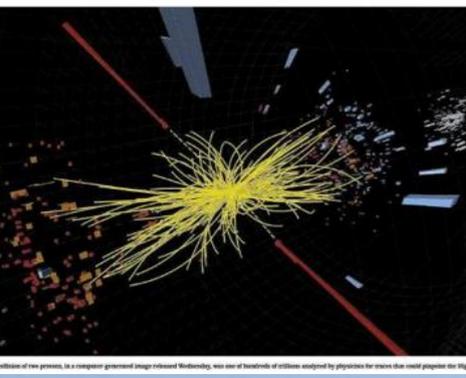


July 4th 2012

The discovery of a new particle

Discovery upends world of physics

Discovery upends world of physics. CERN reports finding particle that could solve mysteries large and small.



The Economist. In praise of charter schools. Britain's banking scandal spreads. Volkswagen overtakes the rest. A power struggle at the Vatican. When Lanesome George met Nora.

新素粒子検出 年内に結論か. 日米欧2チーム. Finding the Higgs boson.

新素粒子検出 年内に結論か. 日米欧2チーム.

Milhares de moradores de bairros sociais em risco de perderem RSI. A mudança está a passar despercebida, mas deve afectar milhares de beneficiários de RSI que vivem em habitação social agora, morar numa casa comunitária é uma forma de rendimento Portugal, 12.

Science: la matière dévoilée. Le boson de Higgs, particule manquante pour expliquer l'Univers, vient d'être découvert. Les physiciens du CERN de Genève ont prouvé son existence à 99,9999%.

IMPÔTS: CE QUI VA CHANGER. 7,2 milliards de plus dès 2012. Réforme fiscale à l'automne.

В ТЕАТРЫ БУДУТ ПУСКАТЬ ПО МОБИЛЬНЫМ ТЕЛЕФОНАМ. ДВОИМ ПОУЛИТ СЕРВЕИ ГАРРИ НА СЕРП. ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ. «КРЕМЛЕВСКИЕ» САМОЛЕТЫ ПРИШЛОСЬ МЕНЯТЬ НА ПЕРЕПРАВЕ. МЕТРО СПУСКАЮТ НА ВОДУ.

ALGEMEEN DAGBLAD. Zieke Kaj en zijn moeder toch samen in de VS. EINDELIJK GELIJK NA 48 JAAR.

Frankfurter Allgemeine. Masse macht's. Große Mehrheit im Europaparlament gegen Ato.

ALGÉRIE L'INDÉPENDANCE. Une fête sans panache. La souffrance, mais pas de haine.

La Hallada la partícula clave para a comprensión del universo. Scientists claim to have discovered 'God particle'.

CHINADAILY. DANGEROUS MOVE. Freeing captured animals may lead to disasters.

THE TIMES OF INDIA. UNDER FIRE FROM OPPN. ADJUSTING DIESEL BETTER THAN TAXING CARS, SAYS MONTEK 15. BLADE RUNNER PI STORIS SET FOR OLYMPIC HISTORY.

Big bang moment: Scientists may have found 'God particle'. Adarsh scam: Finally, CBI charges sheets 13.

THE HINDU. RARE CHOLA INSCRIPTIONS. MAY HAVE BEEN POISONED. SUBBARAO ON MFIS. RAHANE RETURNS. Elusive particle found, looks like Higgs boson. CERN physicists hail evidence of game-changing discovery of subatomic particle.

CORRIERE DELLA SERA. Rinvio a oggi il voto sui nuovi consiglieri. Nomine Rai bloccate. Scontro Fini-Schifani. La particella che può svelare i segreti dell'universo.

gazeta. Ukraińcy biją się o język Rosyjski. Czasikę Higgsa fizycy najpierw wymyślili, potem szukali 40 lat.

আনন্দবাজার পত্রিকা. বিজ্ঞানের 'ঈশ্বর' দর্শন. সত্যেন্দ্রনাথকে বিন্দ্র প্রণাম.

The New York Times. Oil Backed Up, Iranians Put It On Idled Ships. Romney Now Says Health Mandate by Obama is a Tax. Physicists Find Elusive Particle Seen as Key to Universe.

The Gazette. EL PAIS. A solas con la prueba del VIH. De Villota pierde el ojo derecho. Pistorius estará en los Juegos.

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Theory 1973

10 years

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Theory 1967

48 years

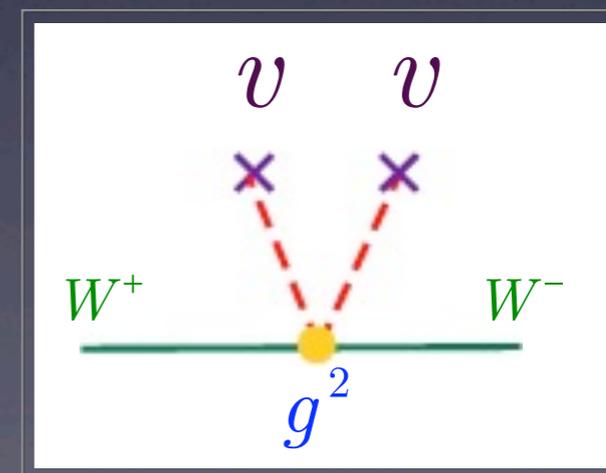
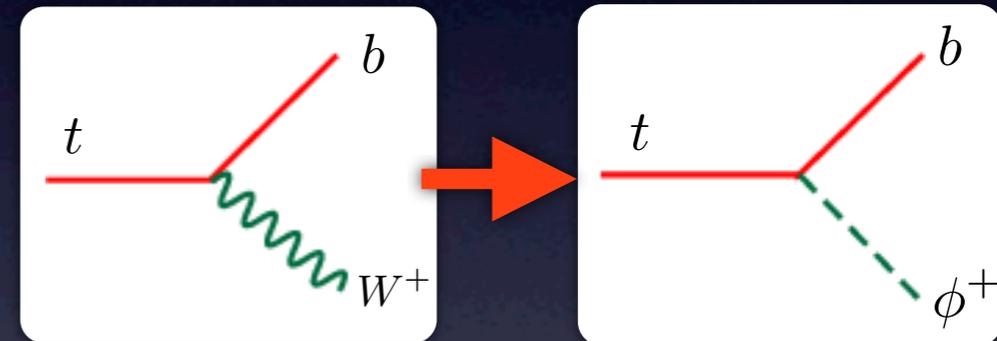
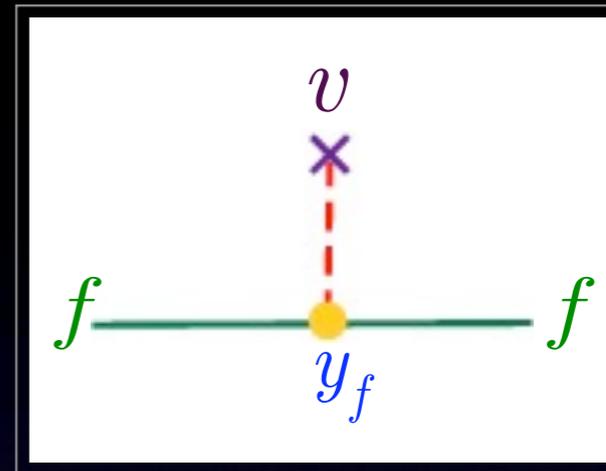
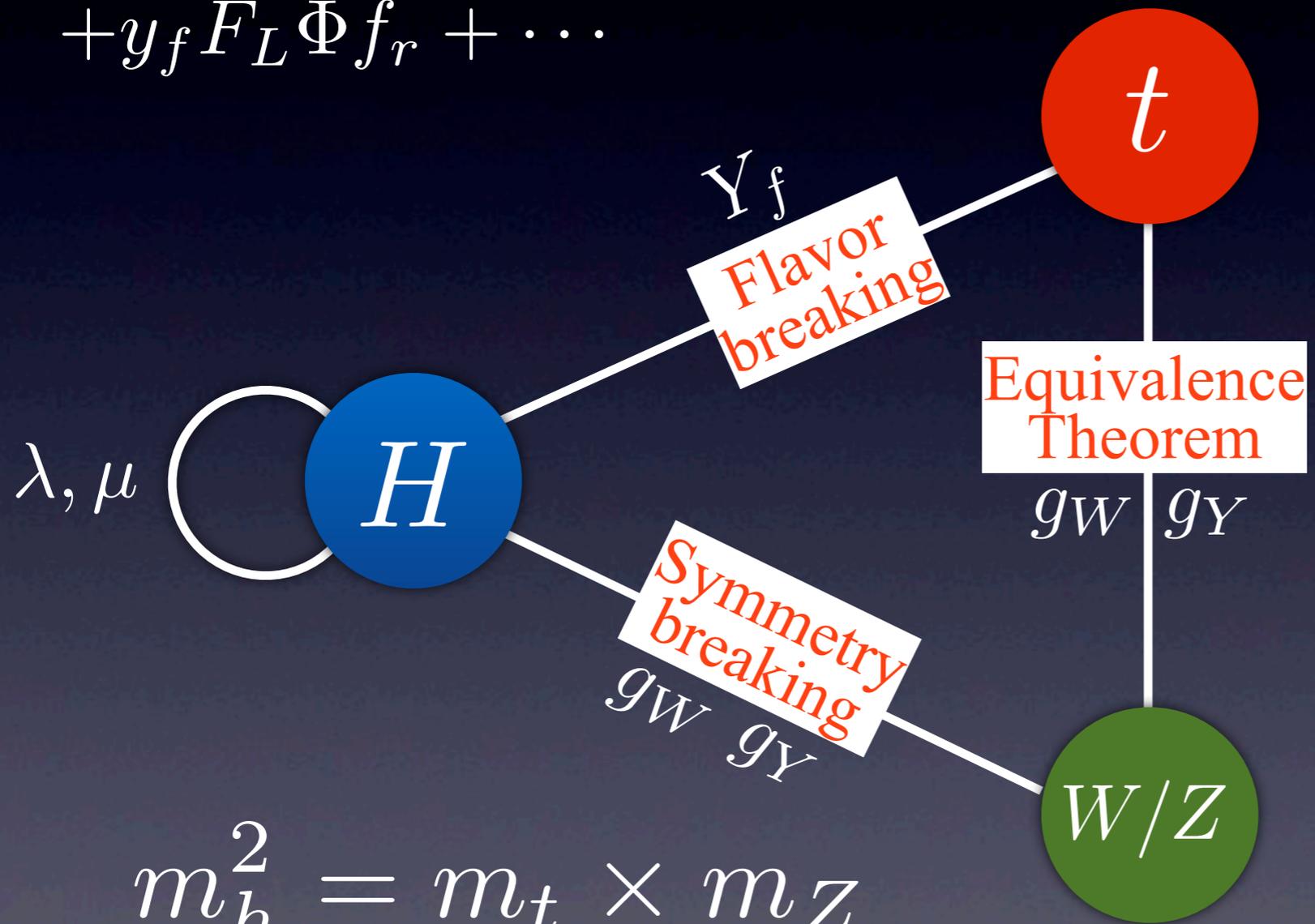
- ▶ New Physics beyond the SM
Extra dim (KK, 1921)
SUSY (1966)

?years

Electroweak triangle

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

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



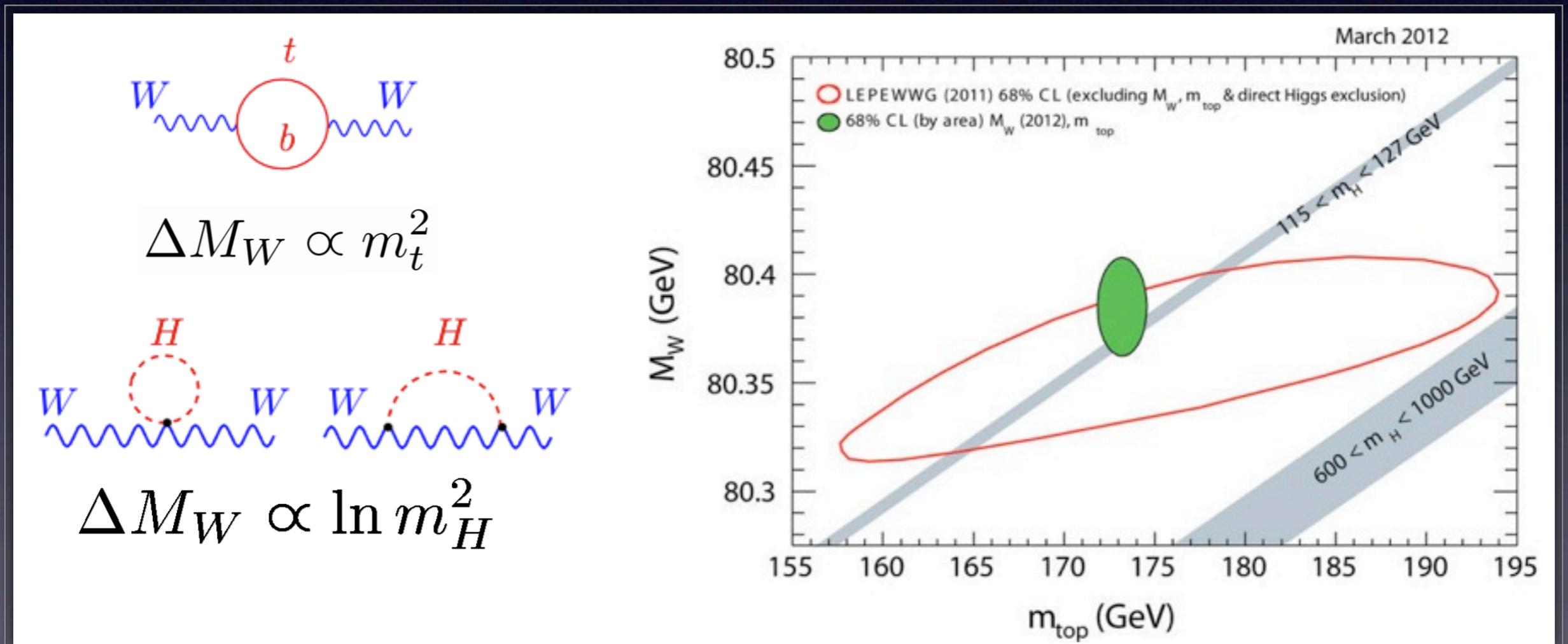
$$m_h^2 = m_t \times m_Z$$

Error ~ 0.001 !!!

W -boson, Top-quark and Higgs boson

- Highly correlated at the quantum level

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



Outline

- LEP

Precision machine

- Tevatron

Precision machine + discovery machine

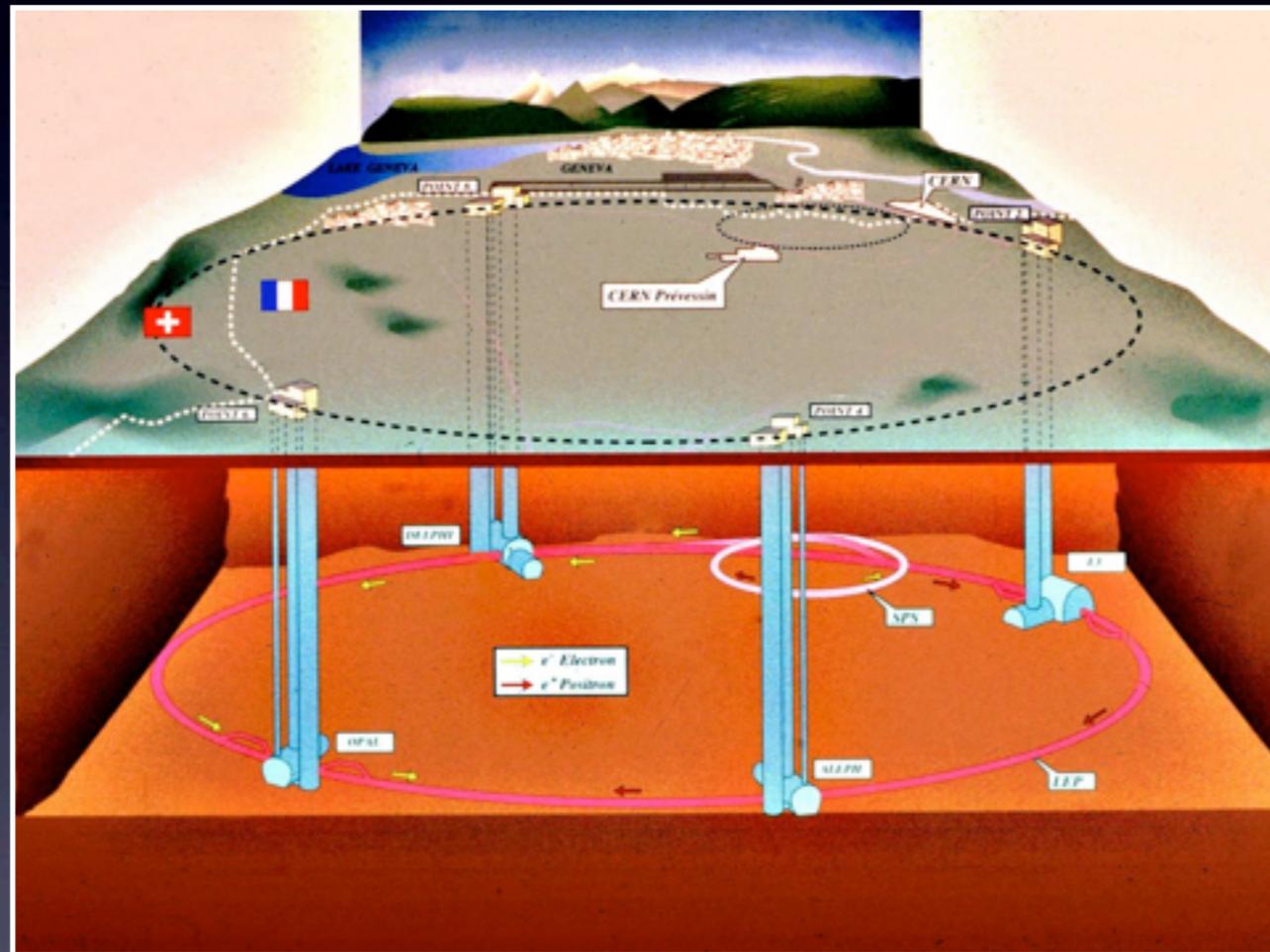
- LHC

Discovery machine + Precision machine

Higgs boson and others

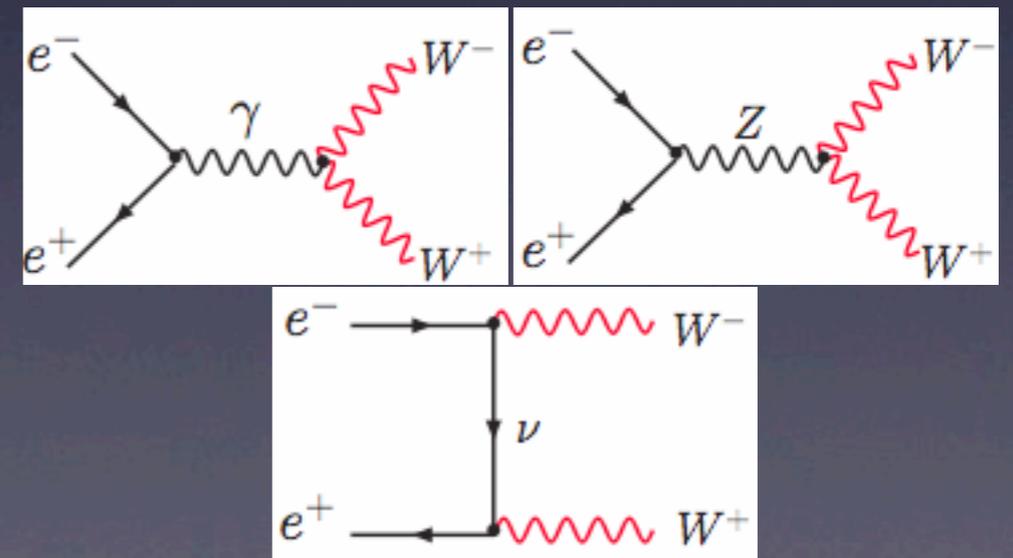
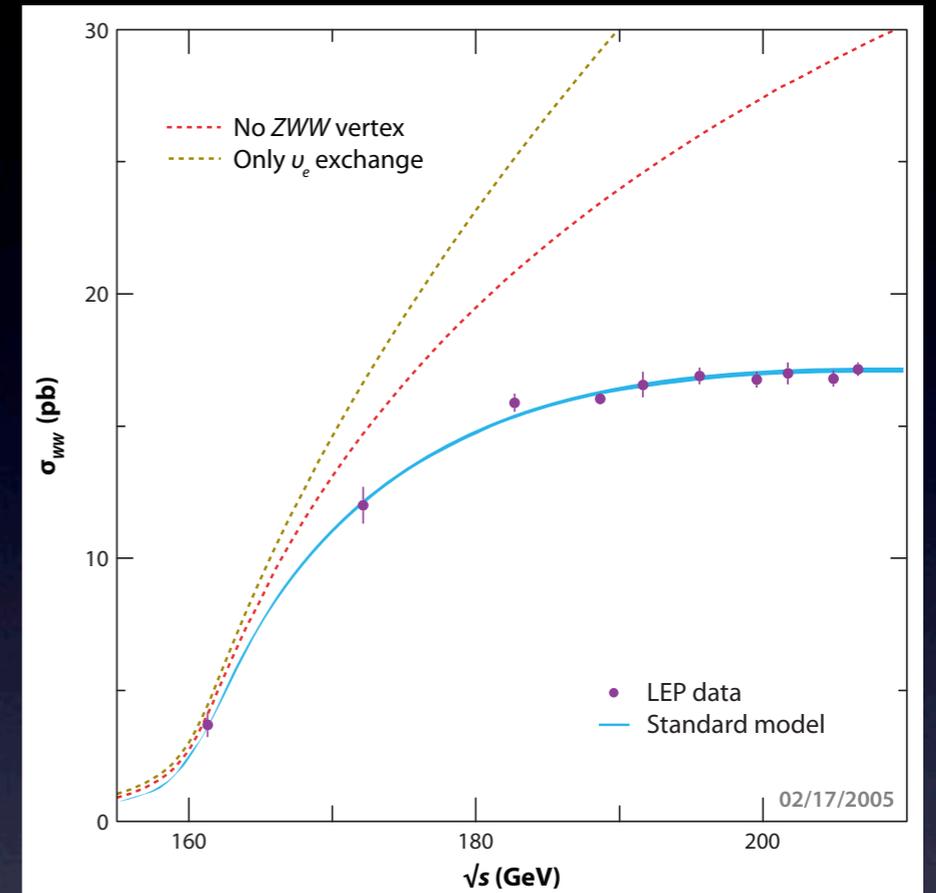
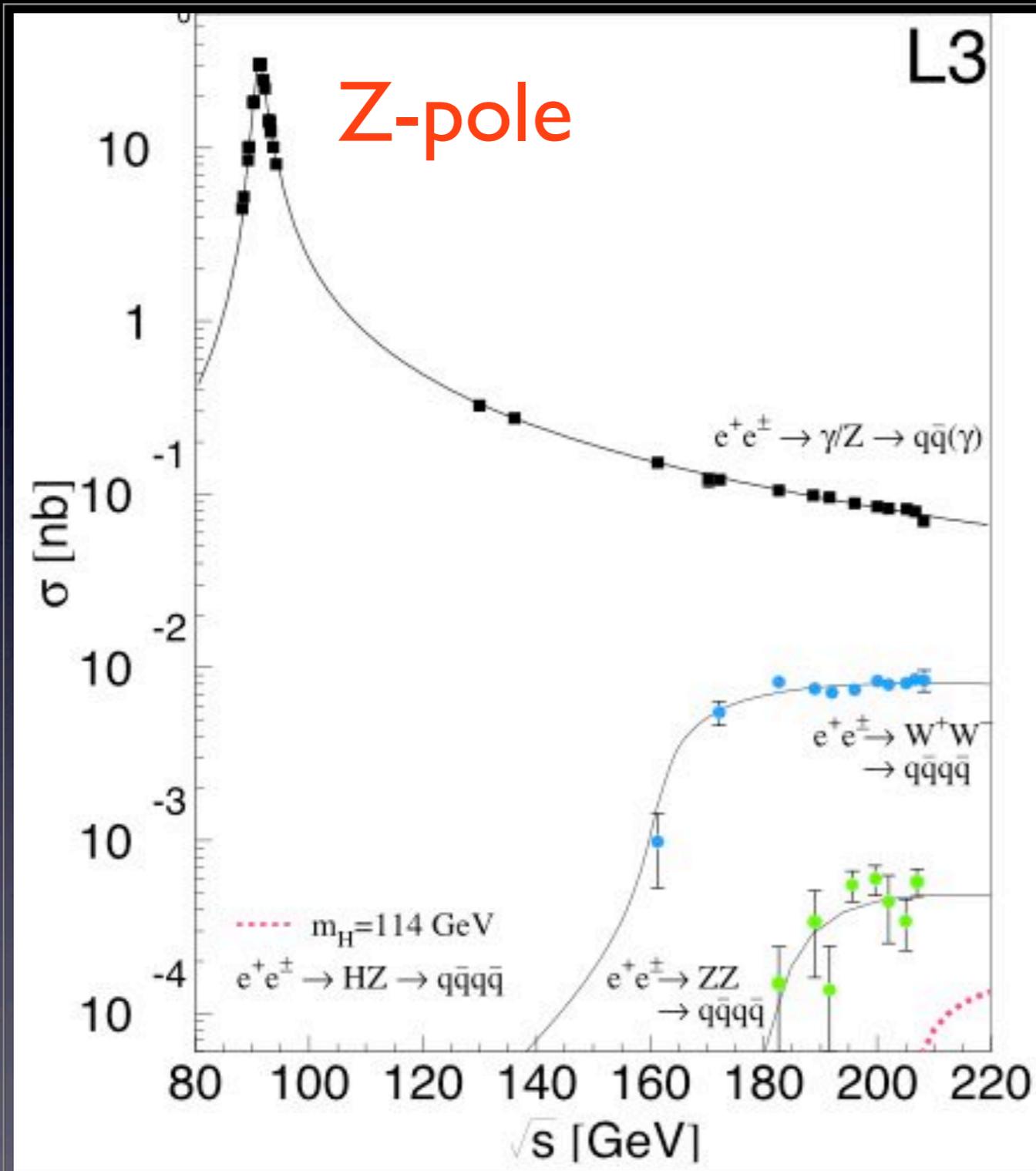
- SLHC, VLHC, Higgs Factory, ILC, ...

Large Electron-Positron Collider (1989-2001)



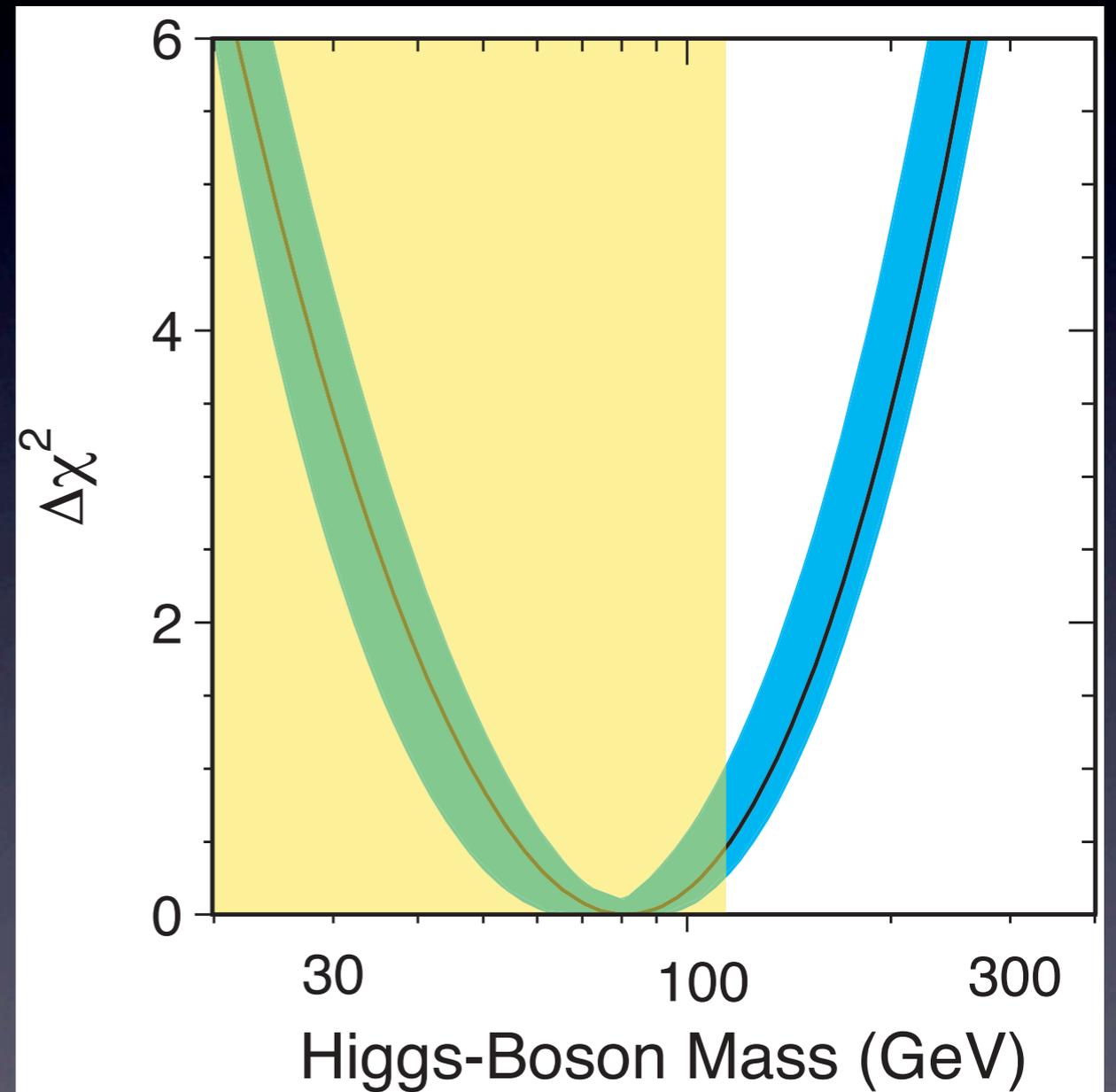
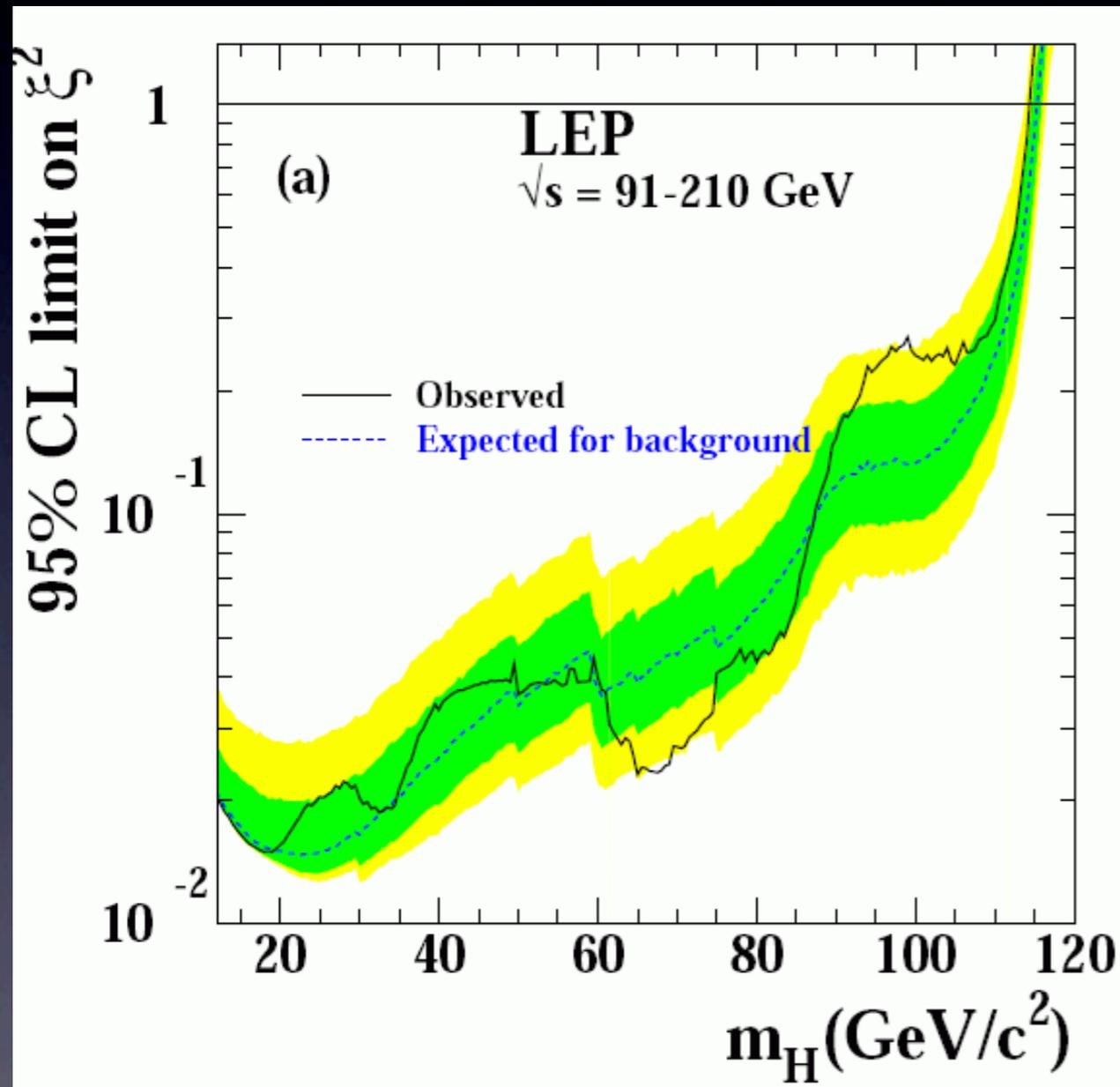
A Precision machine of EW interaction

Electroweak theory tests at tree level



Higgs searches at LEP

- No evidence for Higgs $m_h > 114$ GeV



Tevatron

(1983-2011)



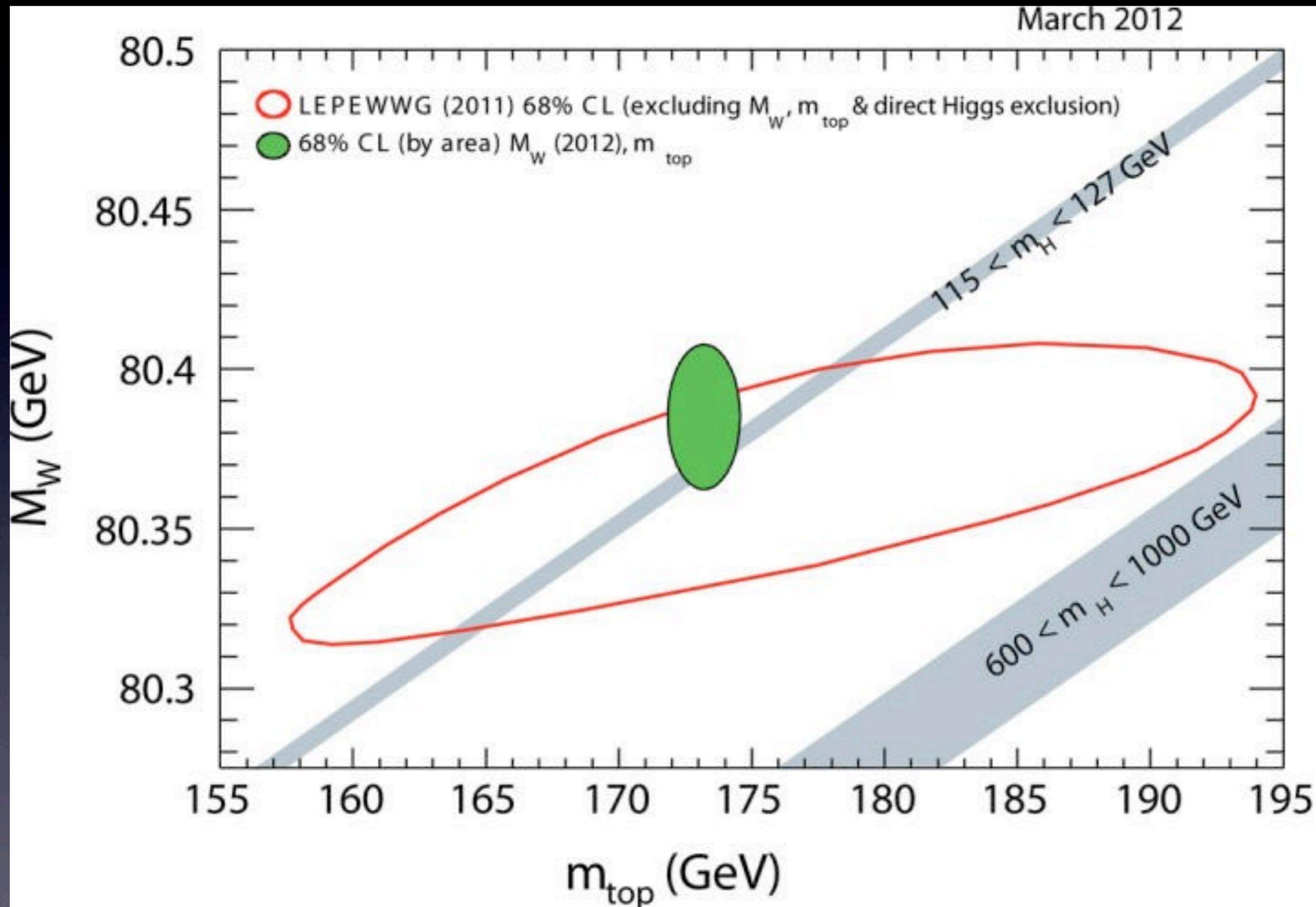
A precision machine built to test QCD

A precision machine of EW

A discovery machine of Top-quark

Precision measurements of W -boson

March 2012



Top discovery: EW theory tests at Loop level

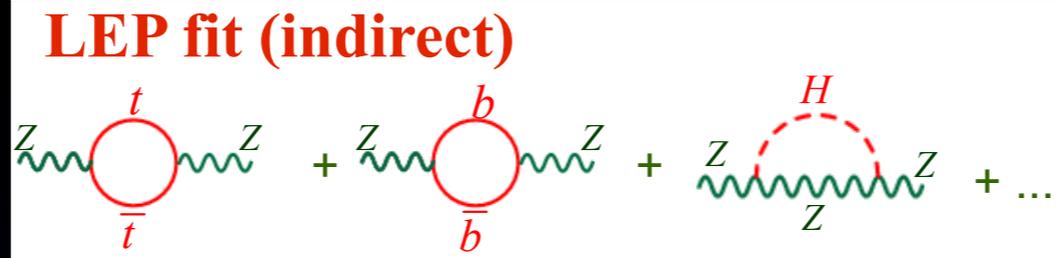
Bardeen, Hill, Lindner
Top-condensation (1989)
 $m_t > 218\text{GeV}$

Ibanez, Ross
SUGRA-GUT (1983)
 $30 < m_t < 150\text{GeV}$

Pendleton, Ross
GUT (1980)
 $m_t = 130\text{GeV}$

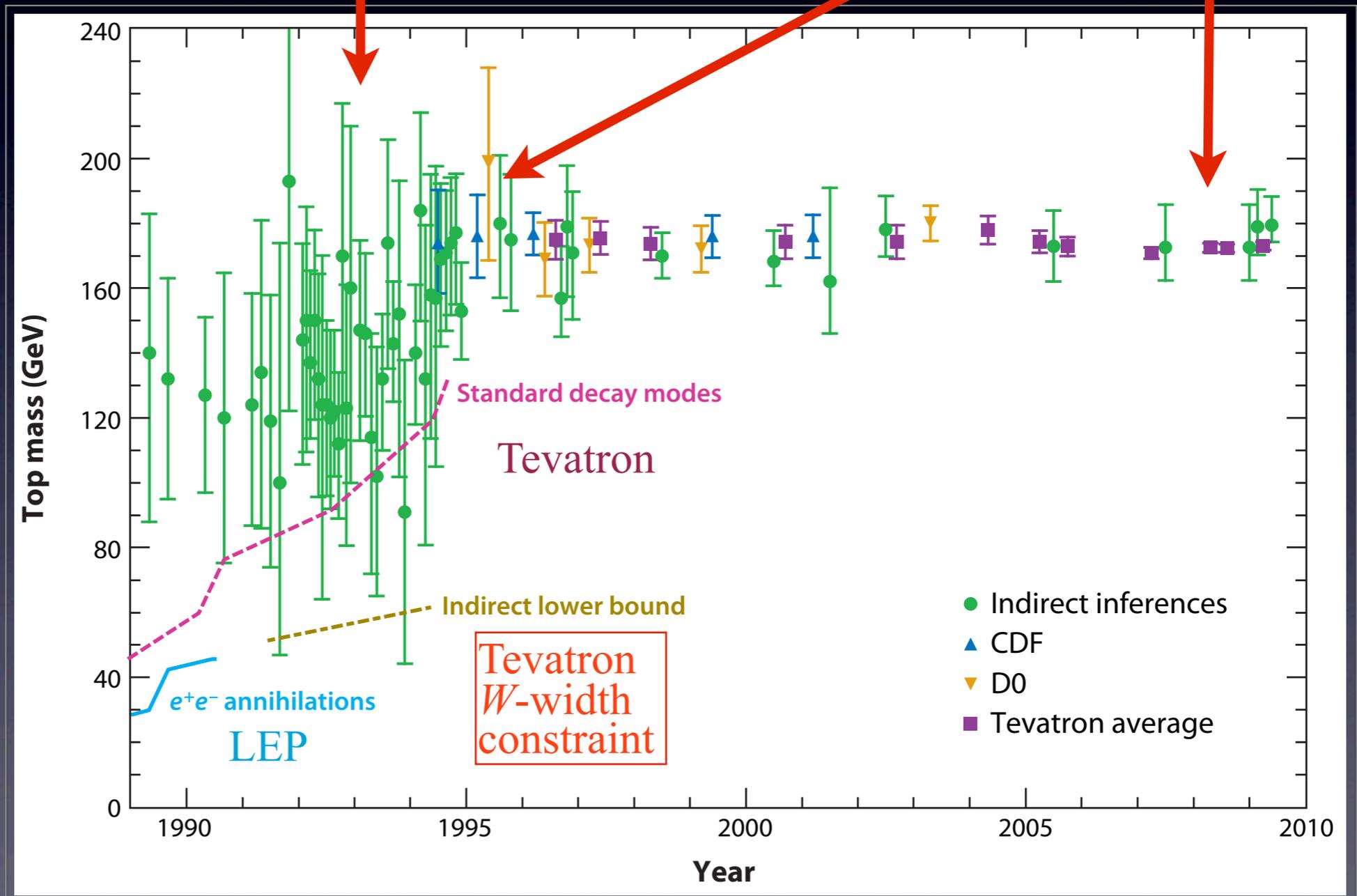
Glashow (1980)
 $m_{tt} > 38\text{GeV}$

Tristan
1983



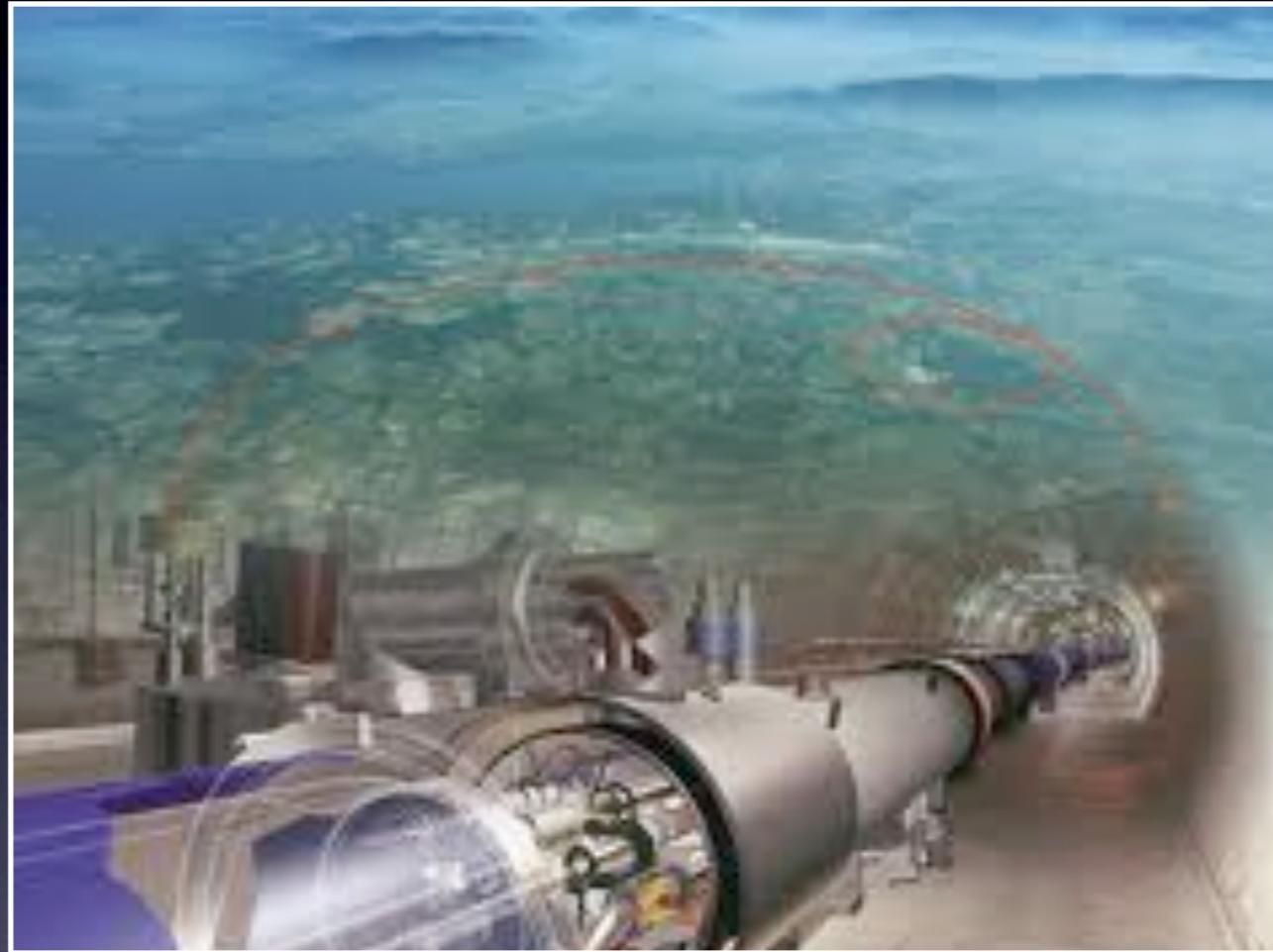
**Tevatron
(1995)
Discovery**

**Tevatron
Precision**



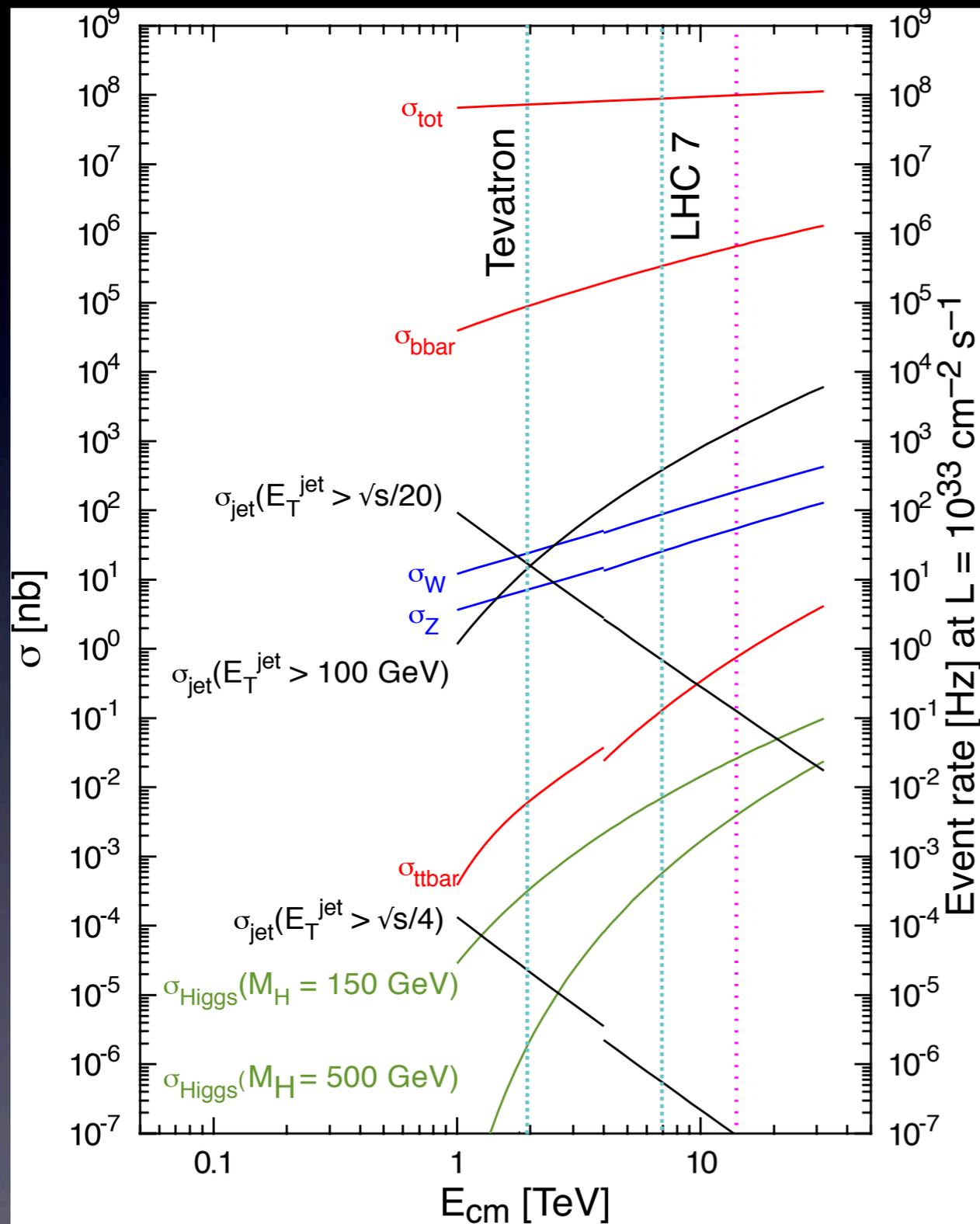
Large Hadron Collider

(2007-?)



A discovery machine of EW interaction
A top-quark factory

LHC: perfect for SM and NP



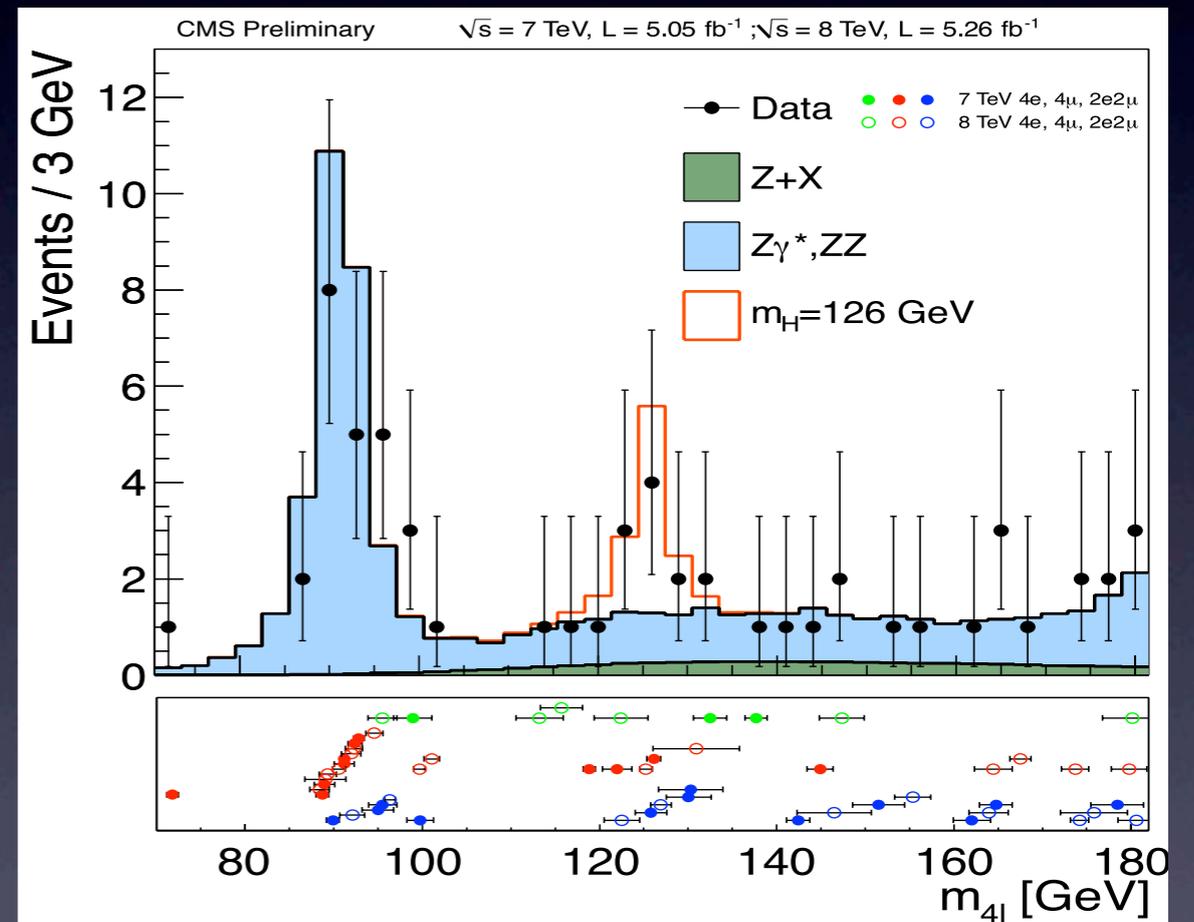
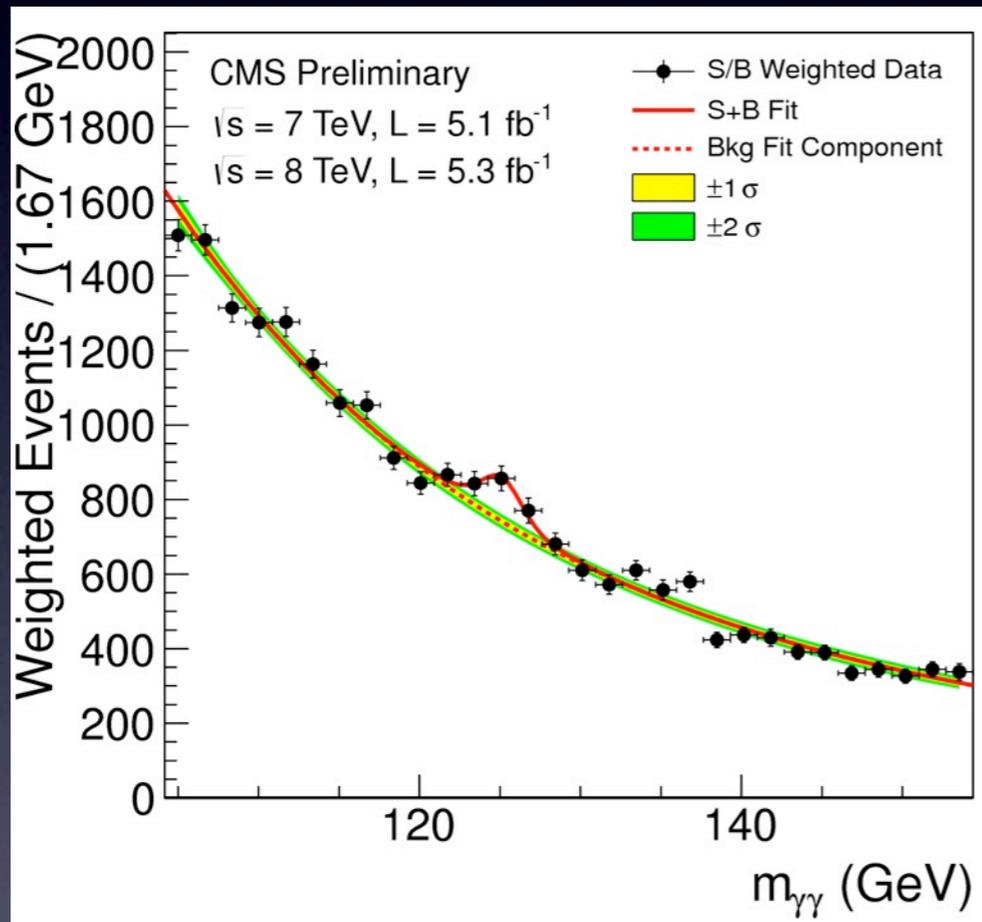
Rate at 8TeV LHC

with $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$

 Inelastic p-p reactions:	$10^8 / s$
 bottom quark pairs:	$5 \times 10^5 / s$
 top quark pairs:	$1 / s$
 $W \rightarrow \ell\nu$:	$15 / s$
 $Z \rightarrow \ell\ell$:	$1.5 / s$
 Higgs boson (150GeV):	$0.02 / s$
 Gluino, Squarks (1TeV):	$0.003 / s$

A new boson found $\sim 125\text{GeV}$

- 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

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

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

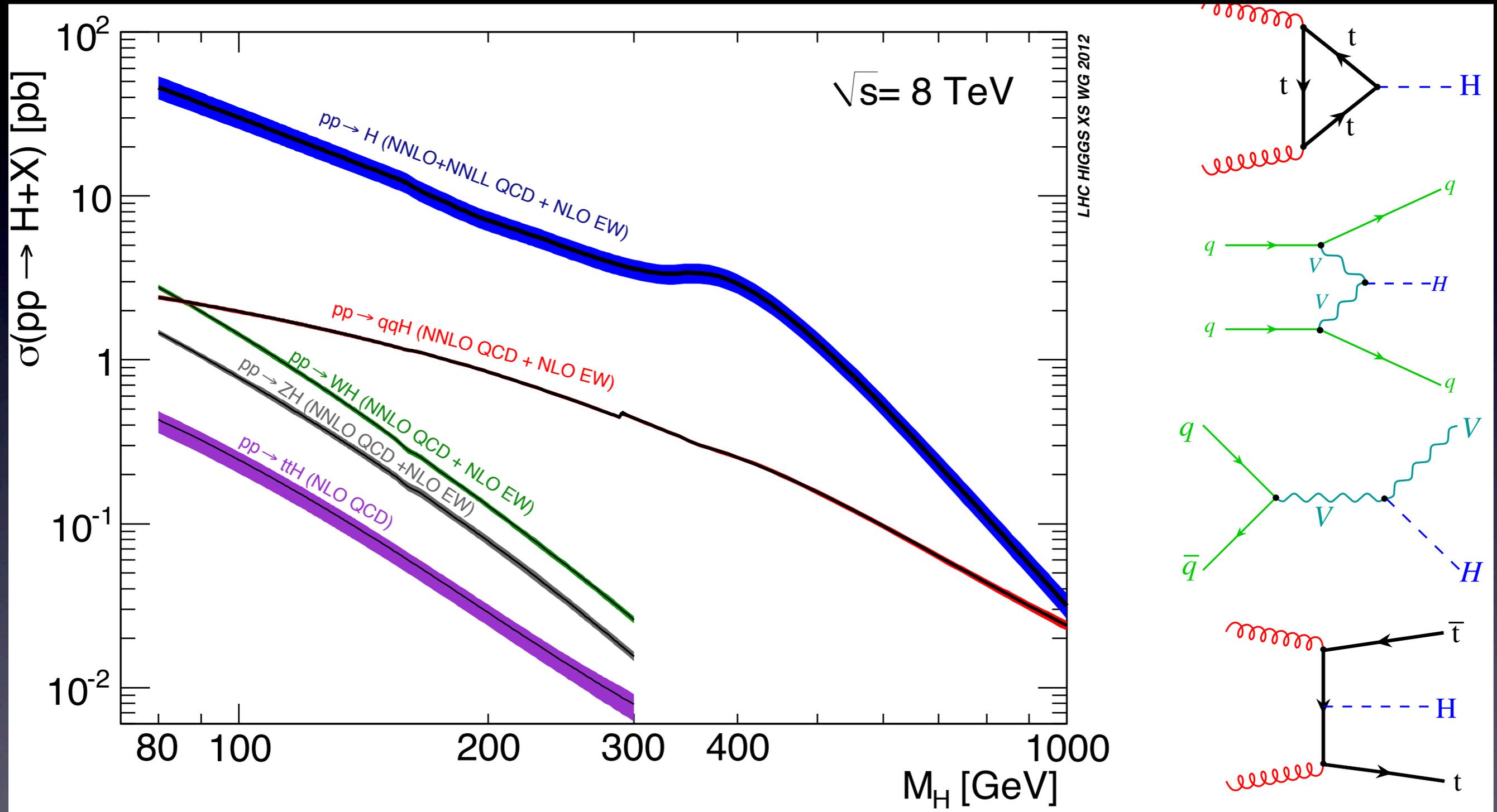
The ground state determined was tested with good accuracy
(thanks to Tevatron)

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

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

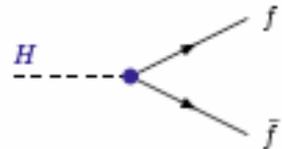
$$\lambda_{(\text{tree})} = \frac{1}{2} m_h^2 / v^2 \sim 0.13$$

Higgs boson production

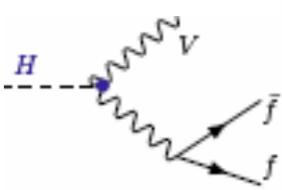


Higgs boson decay

bb dominant
 $m_H < 120$ GeV

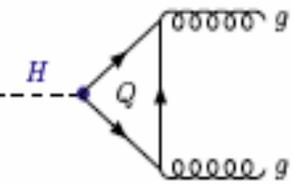


WW dominant
 $m_H > 130$ GeV

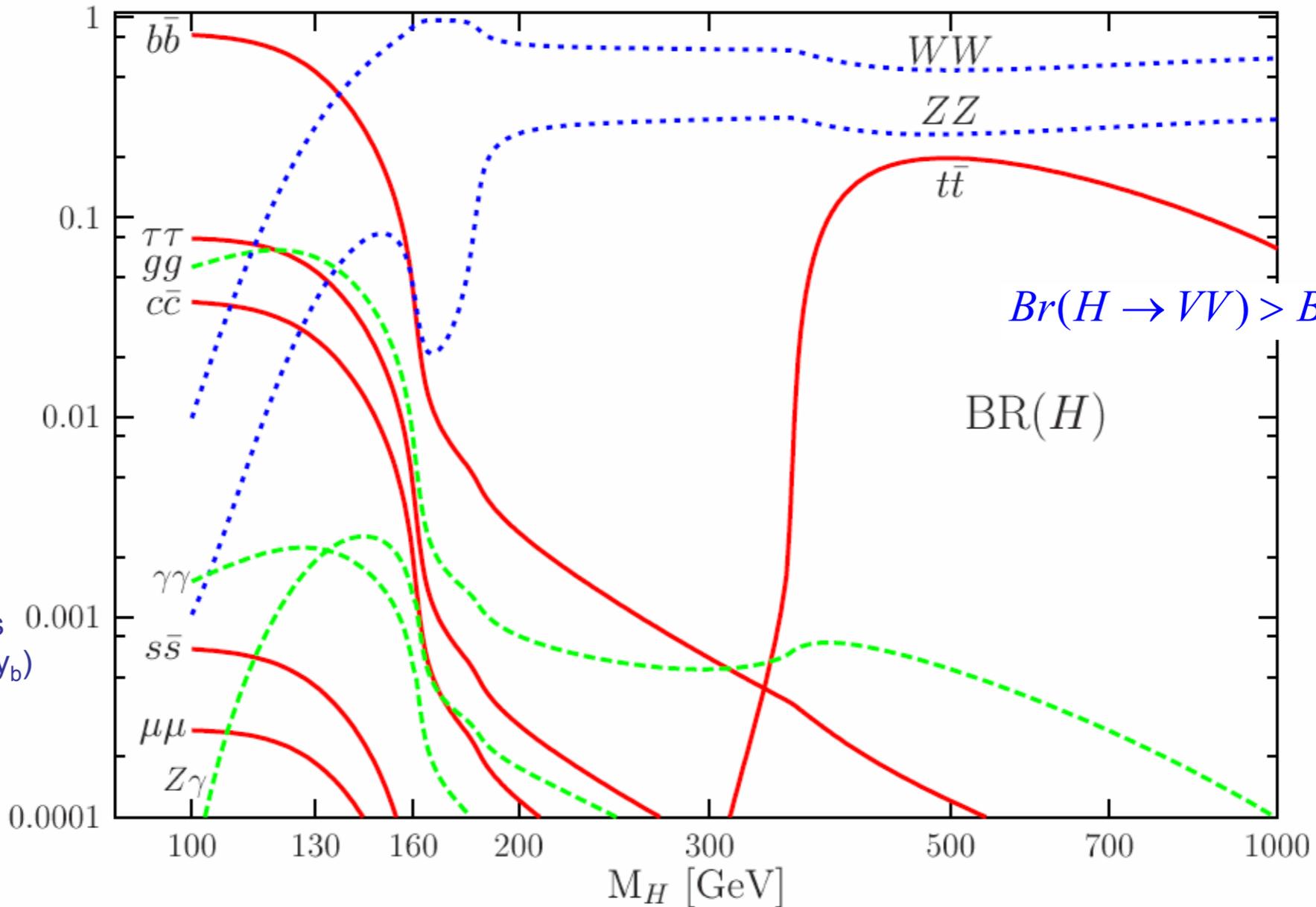
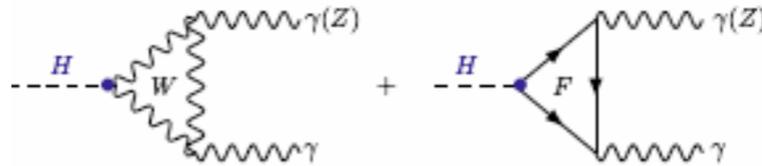


(gauge coupling is much larger than y_b)

gg large
 $m_H < 130$ GeV



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

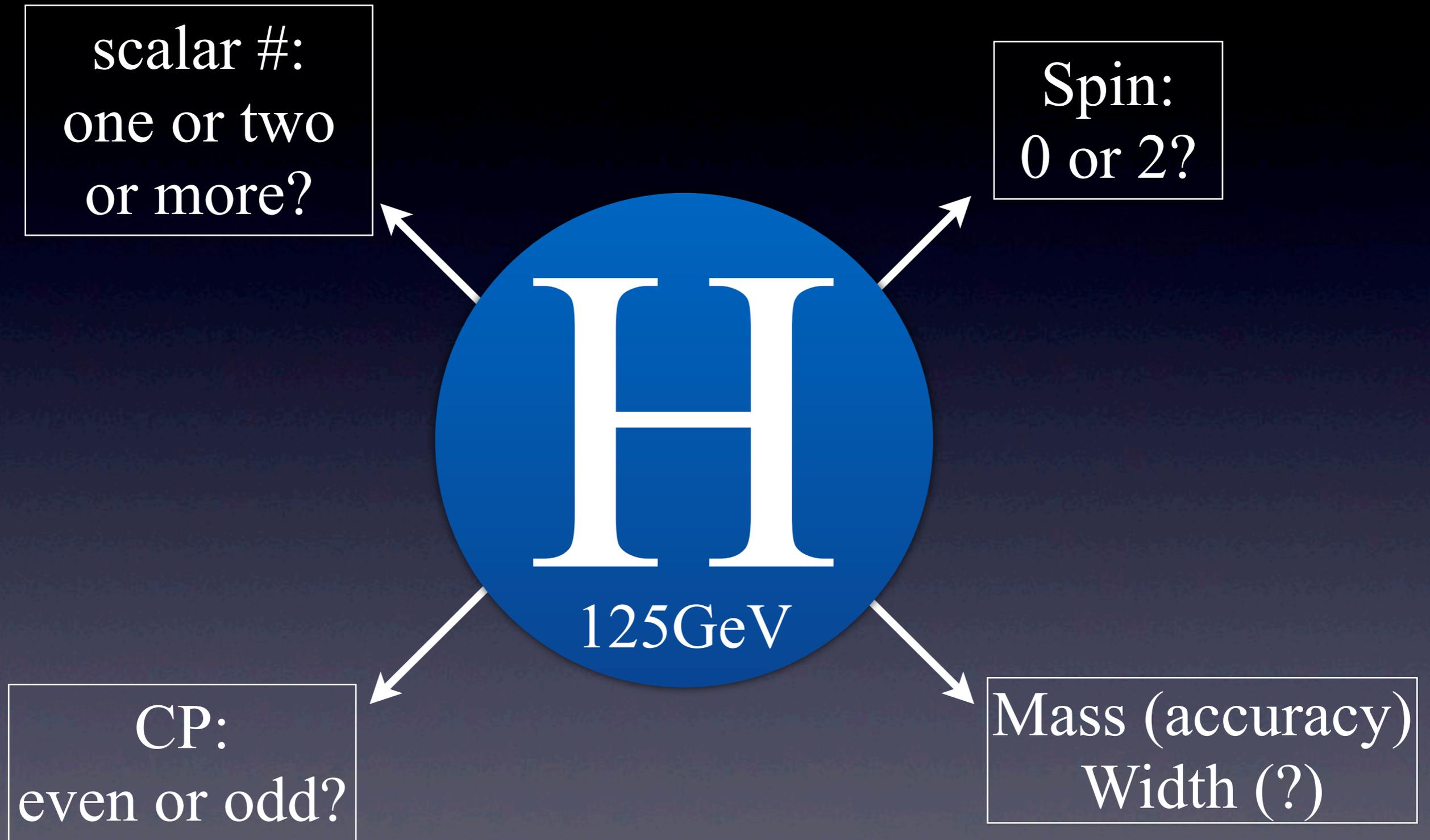


$$\frac{\Gamma(h \rightarrow WW)}{\Gamma(h \rightarrow ZZ)} \sim 2$$

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

BR(H)

Questions of the top priority



1. What can we learn
from 125GeV?

(半个贰百五)

Theoretical problems

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

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

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

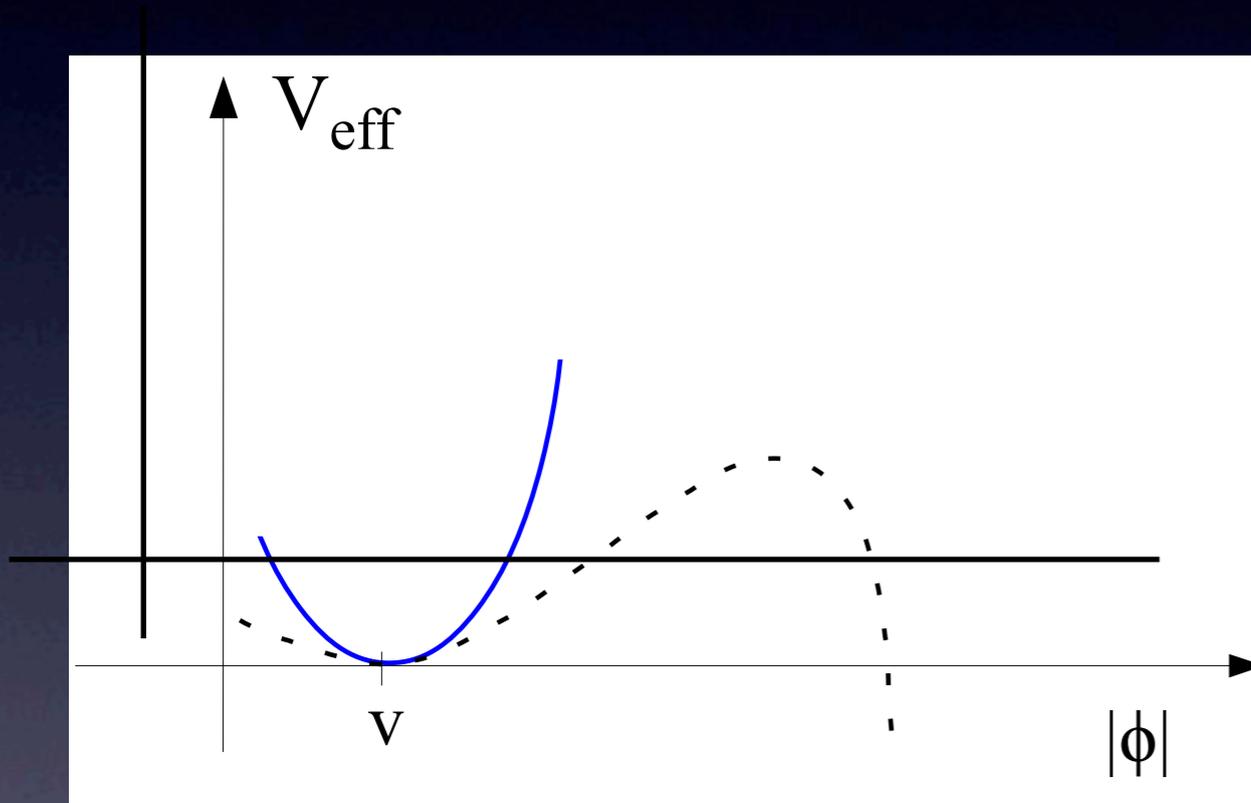
- Due to quantum correction, the Higgs self coupling as well as the masses depend on considered energy

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

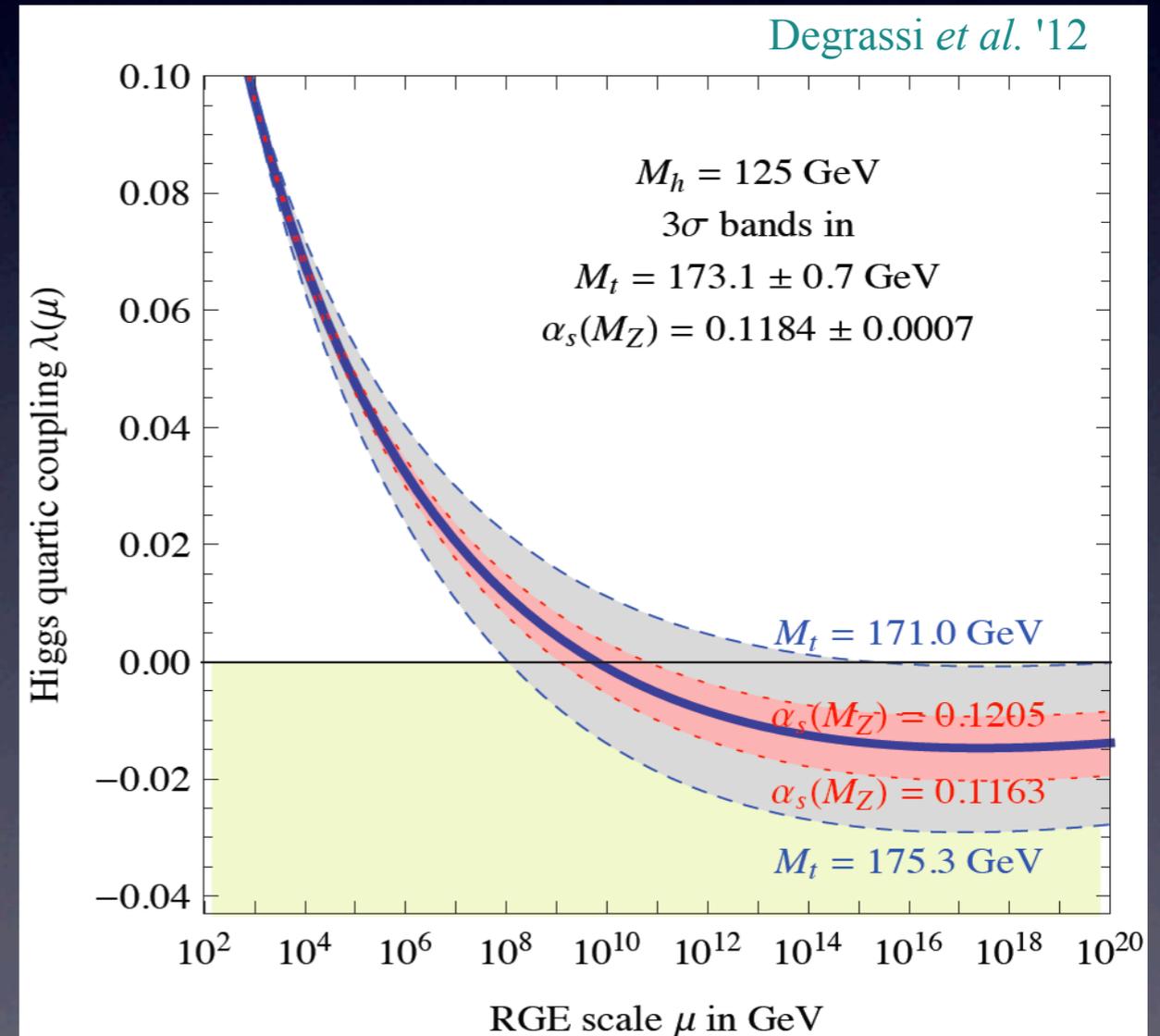
$\lambda(|\phi|) < 0 \quad \longrightarrow \quad V(|\phi|) < V(v) \quad \text{Vacuum unstable}$

Vacuum stability bound at NNLO

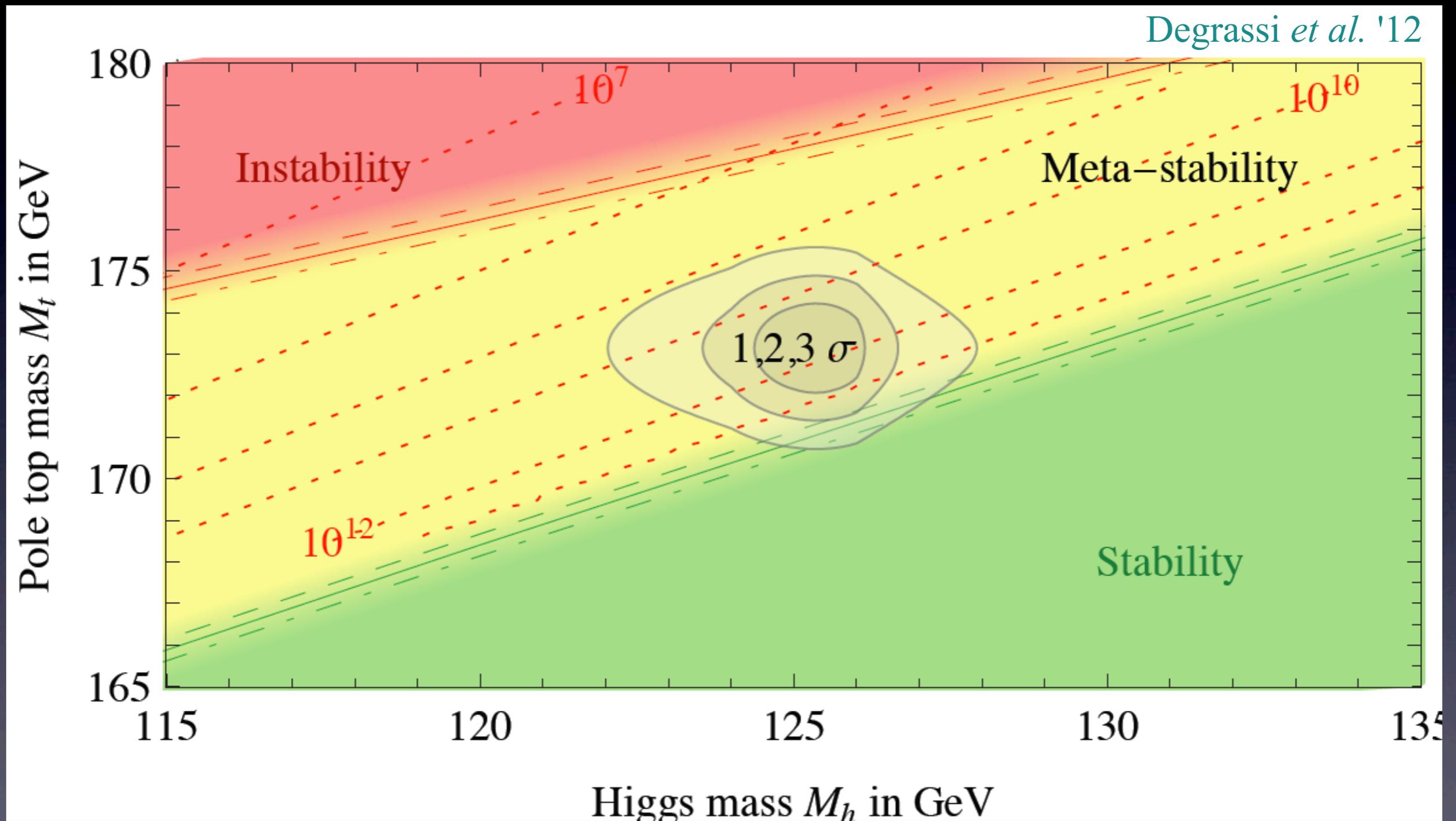
$$M_h \text{ [GeV]} > 129.4 + 2.0 \left(\frac{M_t \text{ [GeV]} - 173.1}{1.0} \right) - 0.5 \left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}}$$



Might we live in a metastable vacuum?



Top quark and 125 GeV Higgs boson



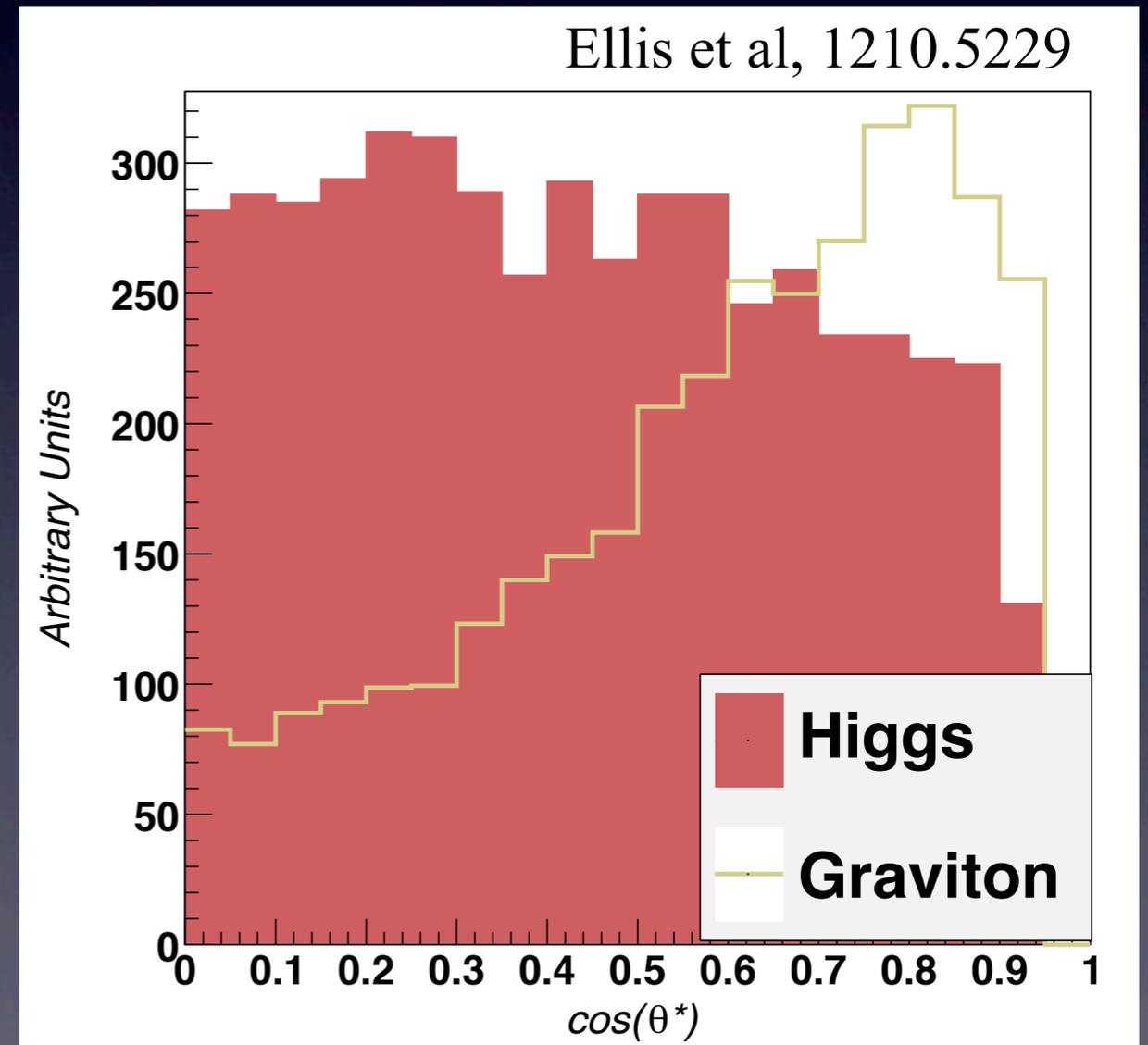
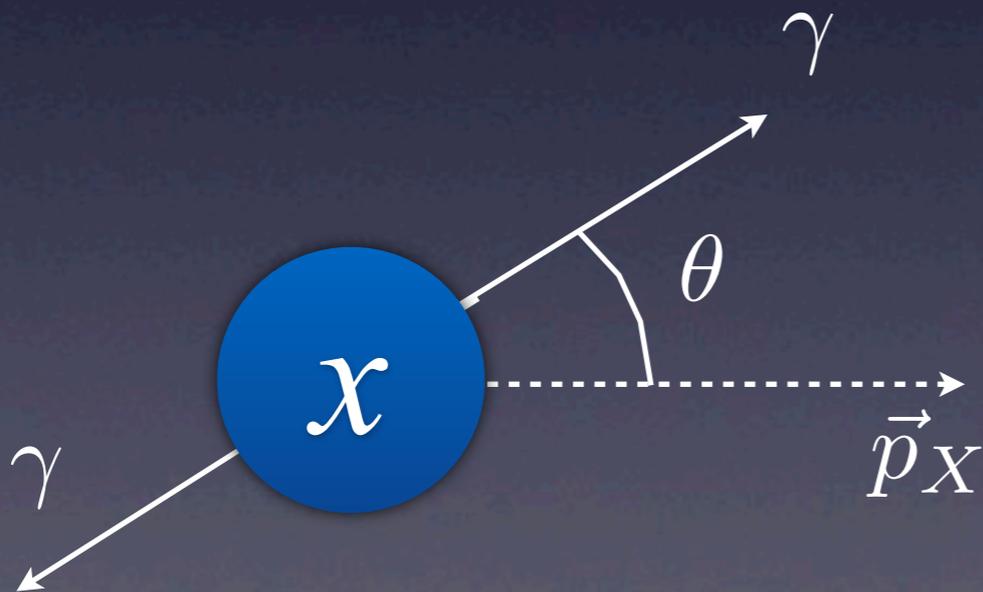
2. What about spin?

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

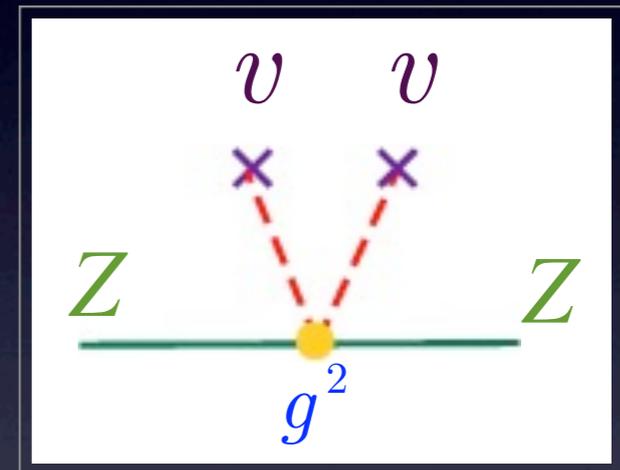


3. CP Property

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

$$(D\phi)^2 \rightarrow \left(1 + \frac{h}{v}\right)^2 m_V^2 V_\mu V^\mu$$
$$g_{hVV} = -2i \frac{m_V^2}{v} g_{\mu\nu}$$



- 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)

- $ZZ \rightarrow 4\ell$ 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 :

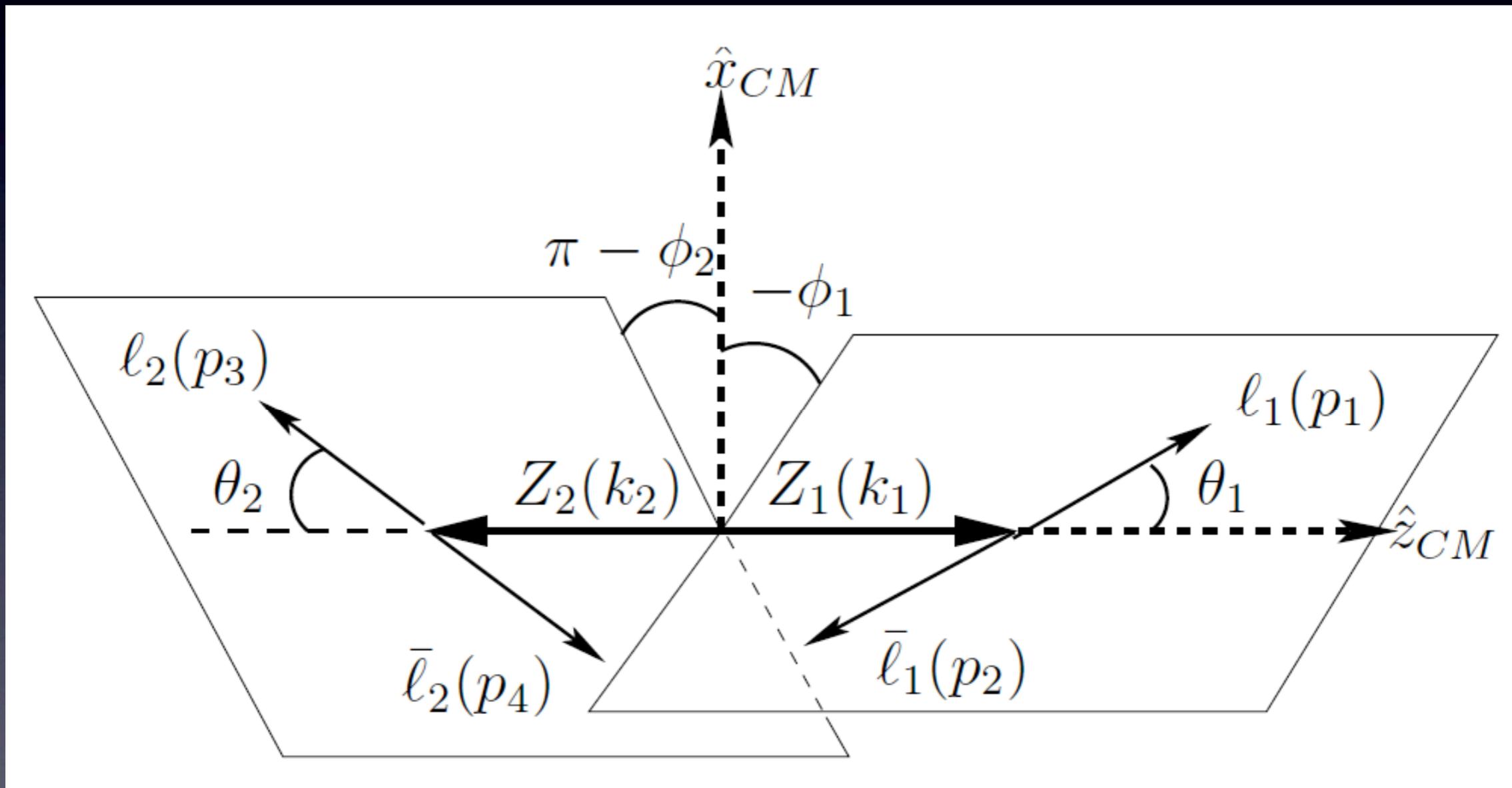
$$\mathcal{L}_{eff} = \frac{1}{2} m_S S \left(c_1 Z^\nu Z_\nu + \frac{1}{2} \frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4} \frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

the other two terms are higgs imposters!!

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

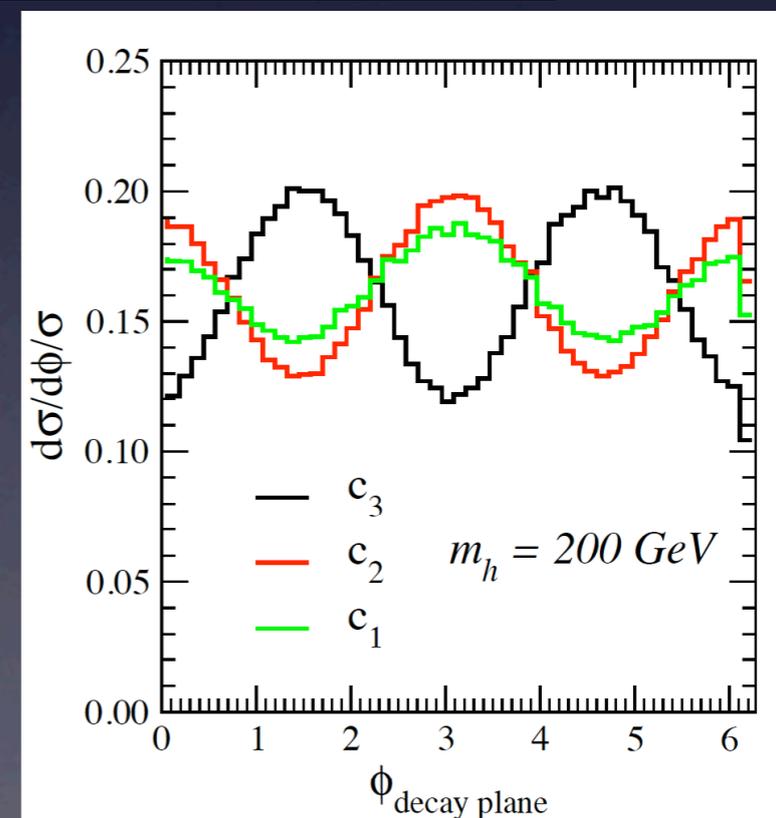
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$$\frac{d\Gamma}{\Gamma d\phi} = \frac{1}{N} \left\{ \frac{8}{9} \cos(2\phi + 2\delta) + \frac{\pi^2}{2} \frac{M_L}{M_T} \left(\frac{g_R^2 - g_L^2}{g_R^2 + g_L^2} \right)^2 \cos(\phi + \delta) + \frac{16}{9} \left(\frac{M_L^2}{M_T^2} + 2 \right) \right\}$$

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

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

$$\text{Br}(H \rightarrow WW^*) = 23\% \quad \star$$

$$\text{Br}(H \rightarrow ZZ^*) = 2.9\% \quad \star$$

$$\text{Br}(H \rightarrow bb) = 56\% \quad \star$$

$$\text{Br}(H \rightarrow cc) = 2.8\%$$

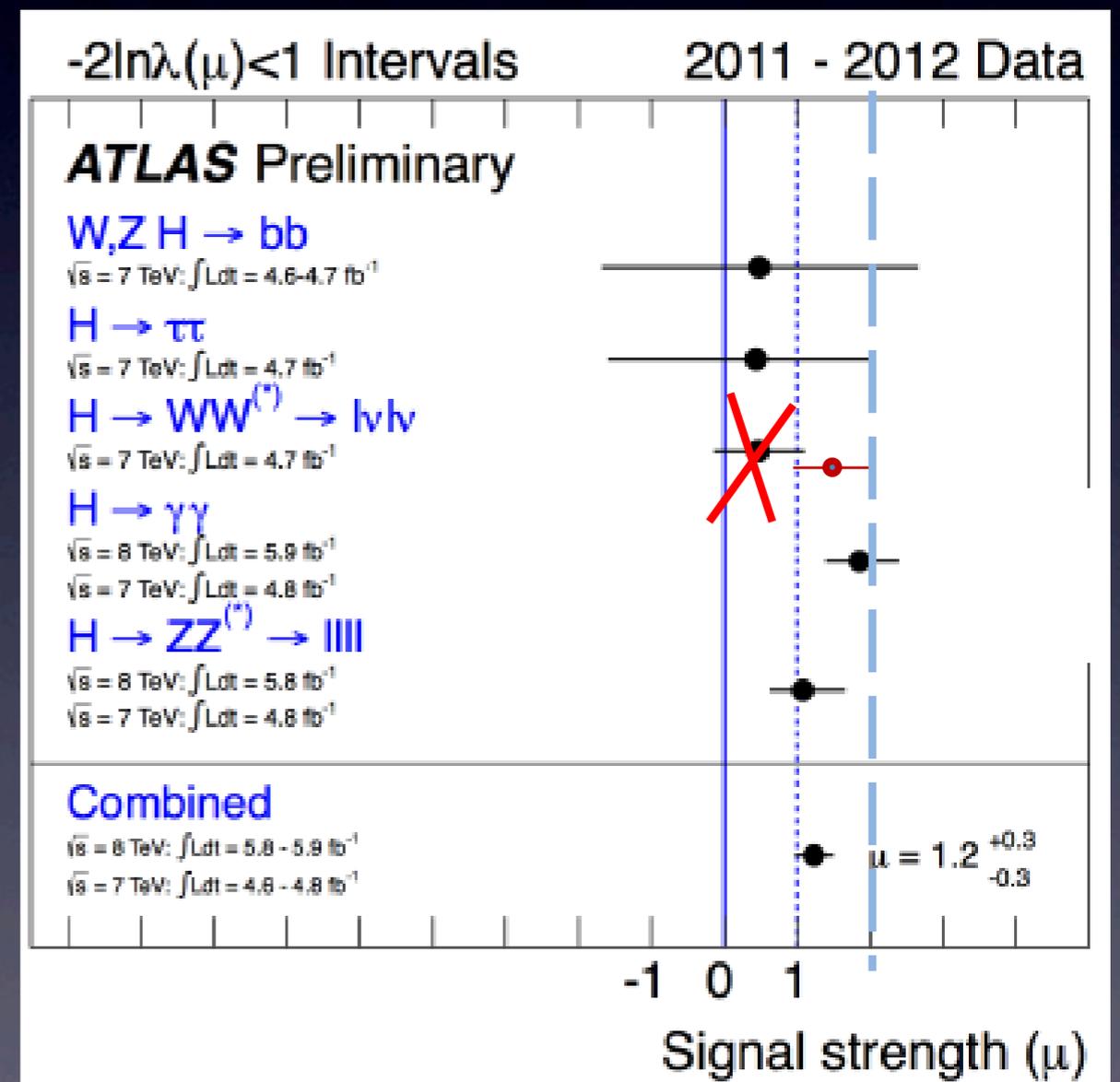
$$\text{Br}(H \rightarrow \tau\tau) = 6.2\% \quad \star$$

$$\text{Br}(H \rightarrow \mu\mu) = 0.021\%$$

$$\text{Br}(H \rightarrow gg) = 8.5\% \quad \star$$

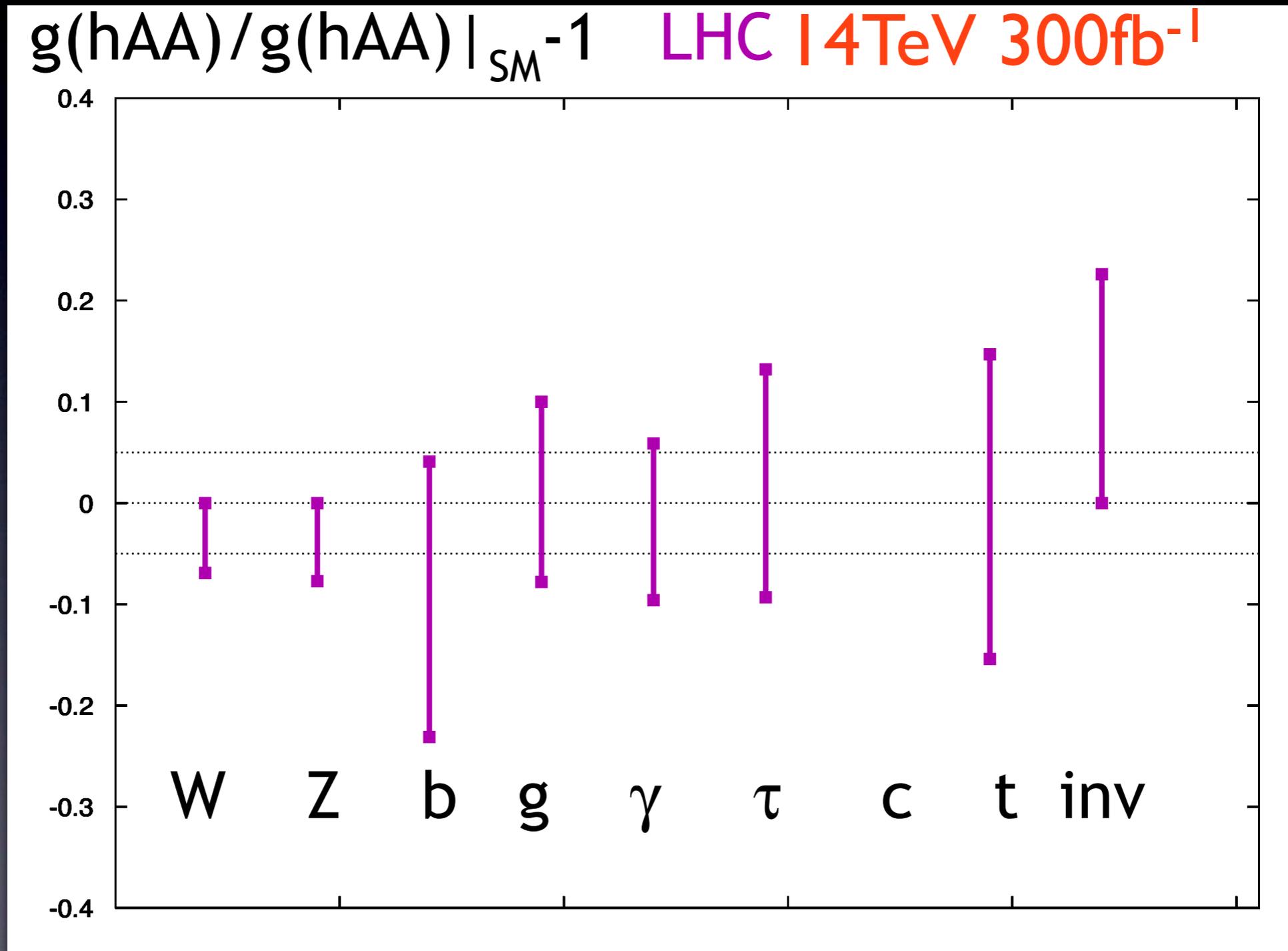
$$\text{Br}(H \rightarrow \gamma\gamma) = 0.23\% \quad \star$$

$$\text{Br}(H \rightarrow \gamma Z) = 0.16\% \quad \star$$



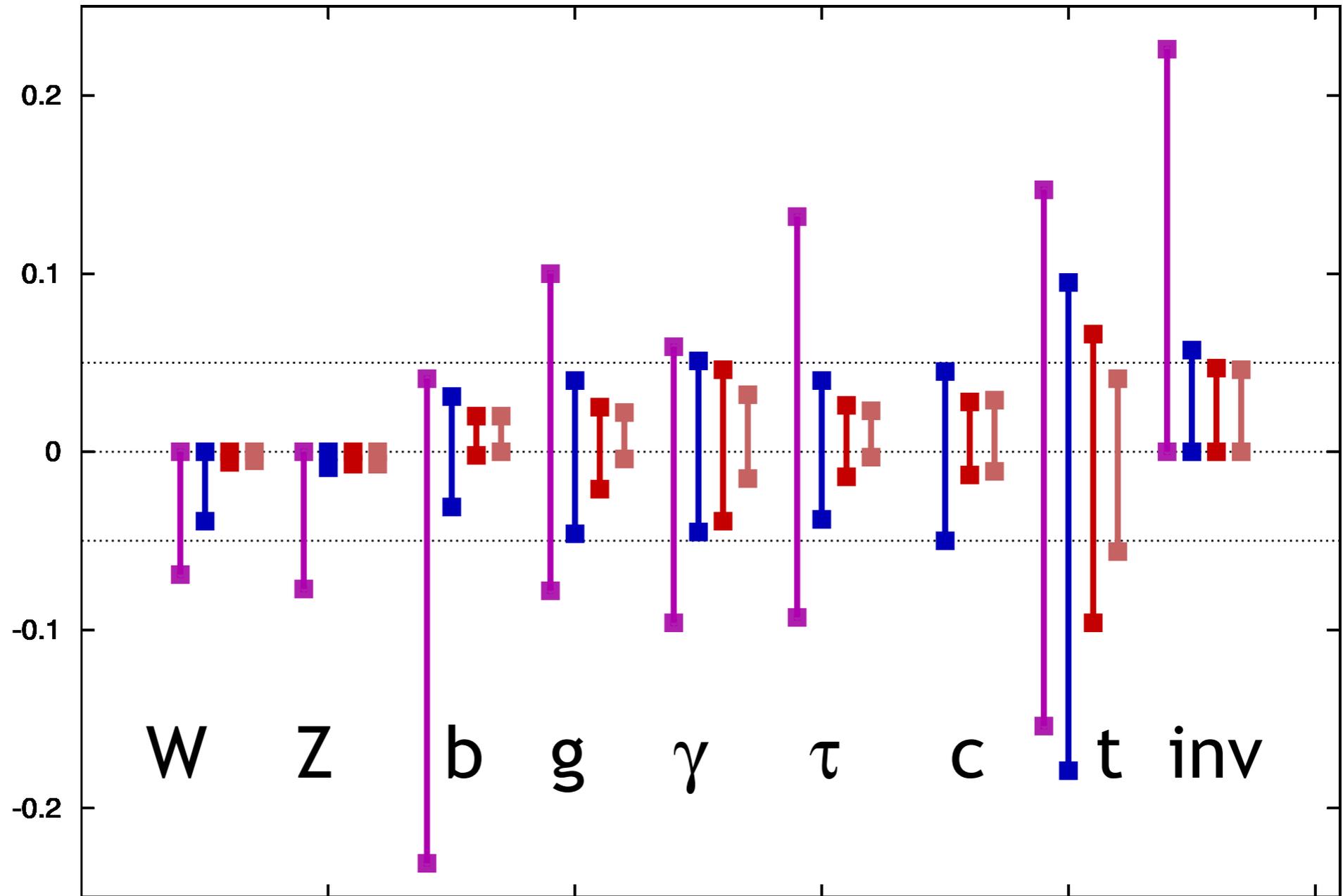
Higgs boson couplings

Peskin, 1208.5152



Higgs boson couplings at LC

$g(hAA)/g(hAA)|_{SM}^{-1}$ LHC/ILC1/ILC/ILCTeV



LHC:
14TeV
300fb⁻¹

ILC1:
250GeV
250fb⁻¹

ILC:
500GeV
500fb⁻¹

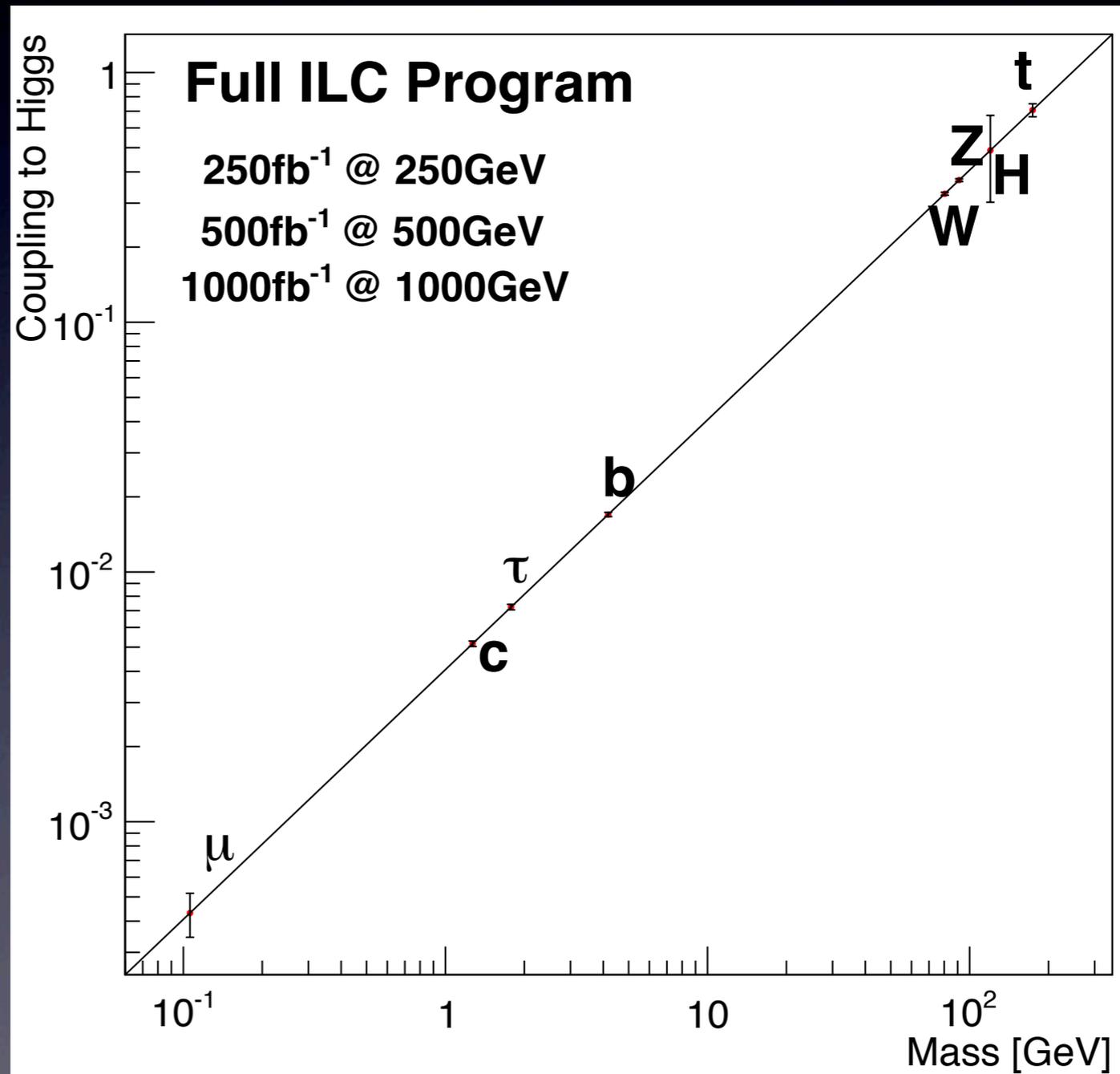
ILC TeV:
1000GeV
1000fb⁻¹

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



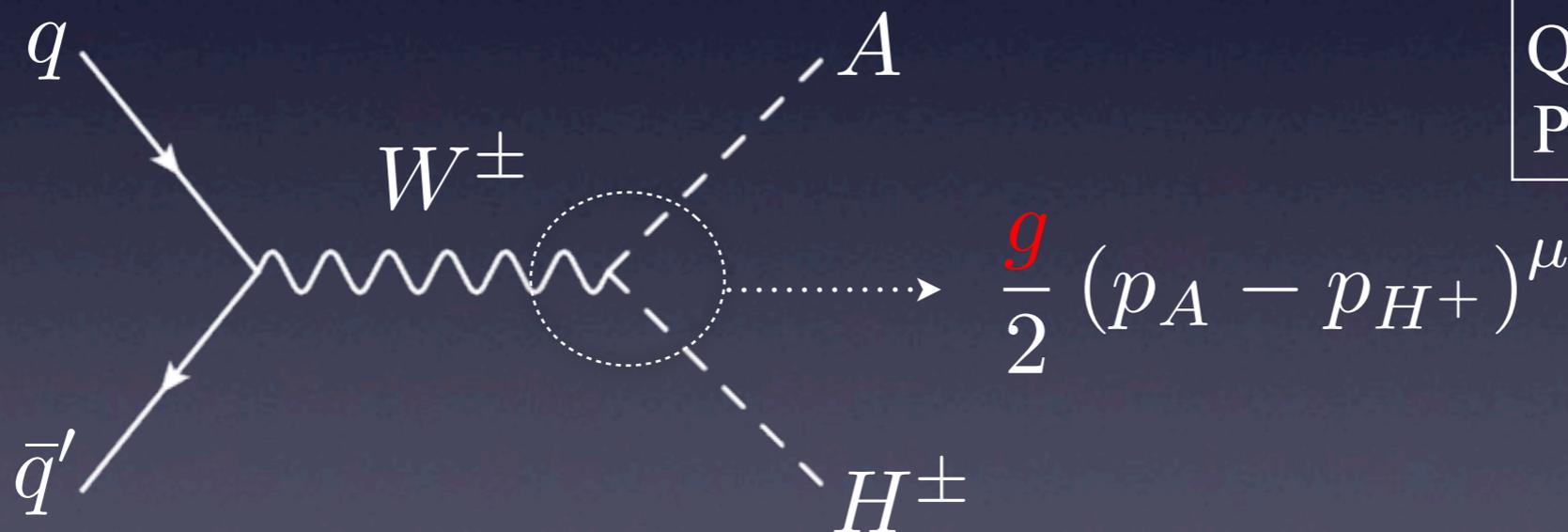
5. Only one scalar?

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 $pp \rightarrow W^\pm \rightarrow AH^\pm$



QHC, Kanemura, Yuan
PRD69 (2004) 075008

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

σ_{prod} depends only
on g and m_A

Light Higgs scenario

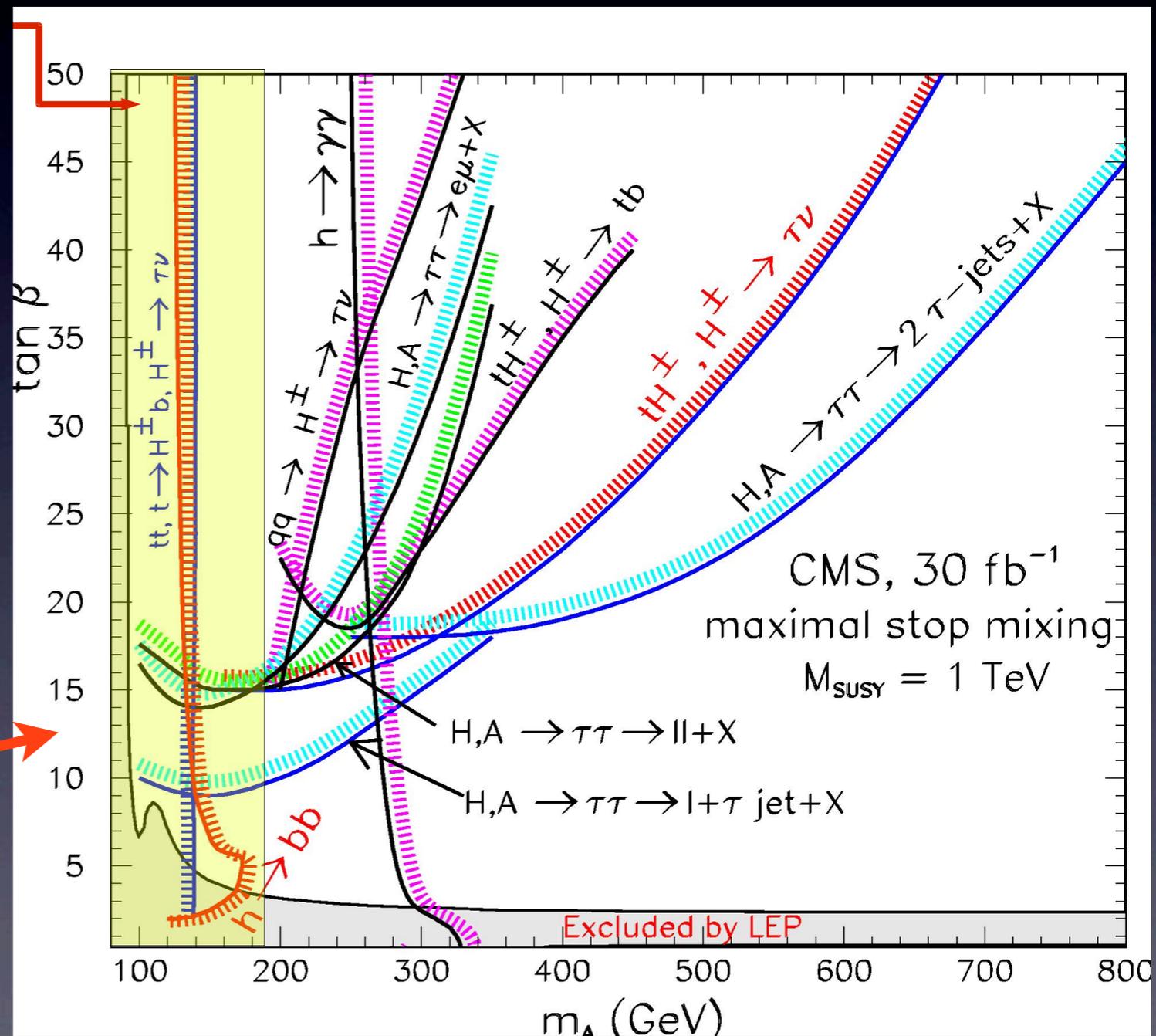
Belyaev, QHC, Nomura, Tobe, Yuan,
PRL100 (2008) 061801

- 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)
 $m_t > 218\text{GeV}$

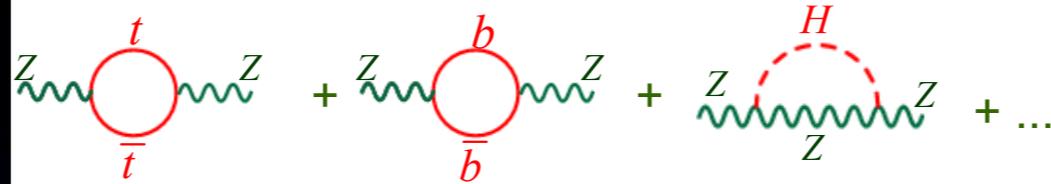
Pendleton, Ross
GUT (1980)
 $m_t = 130\text{GeV}$

Ibanez, Ross
SUGRA-GUT (1983)
 $30 < m_t < 150\text{GeV}$

Glashow (1980)
 $m_{tt} > 38\text{GeV}$

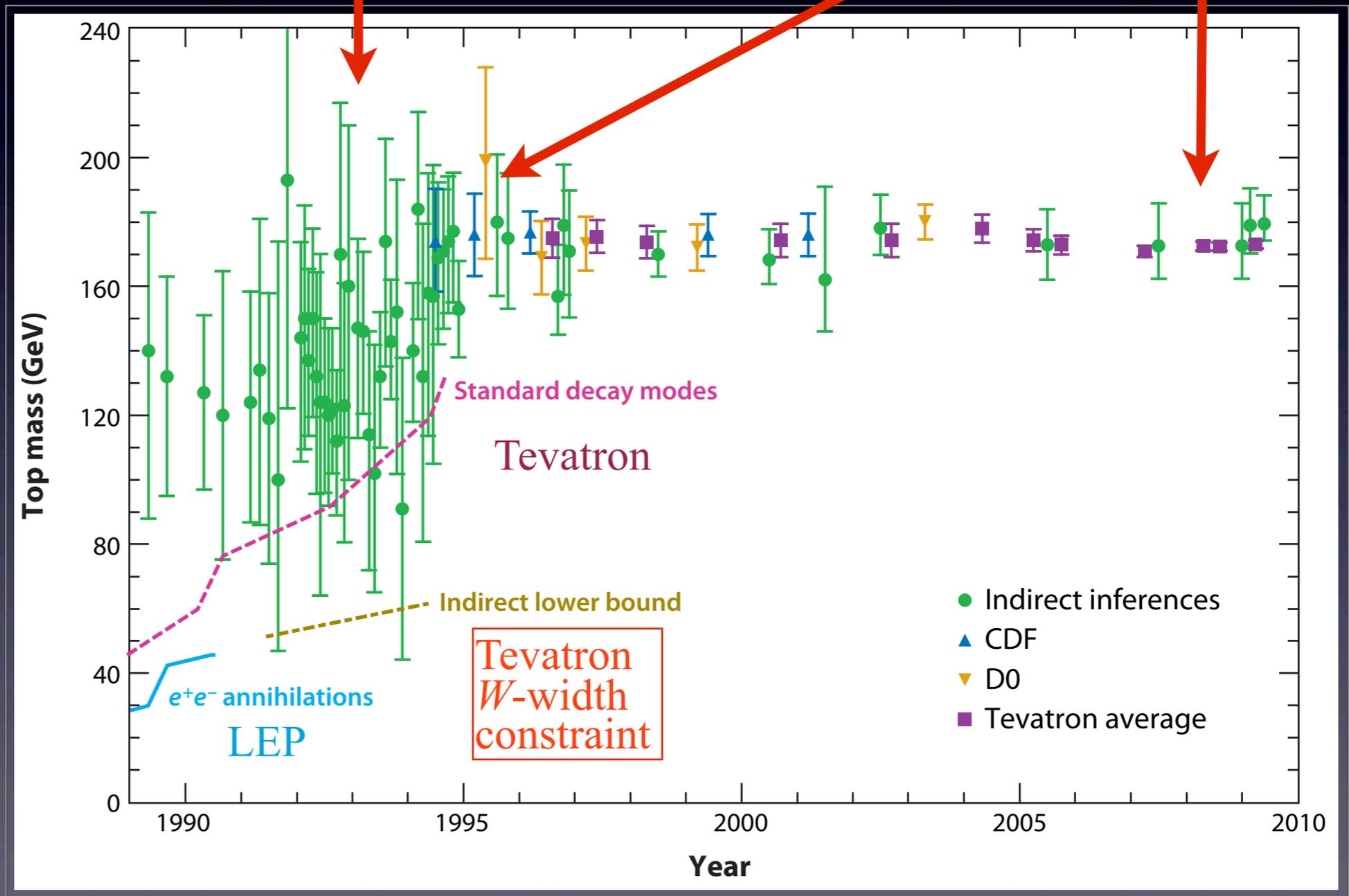
Tristan
1983

LEP fit (indirect)



**Tevatron
(1995)
Discovery**

**Tevatron
Precision**



Experiments versus Theories

- Physics is associated with many scales

WEAK

TeV

GUT

PLANCK

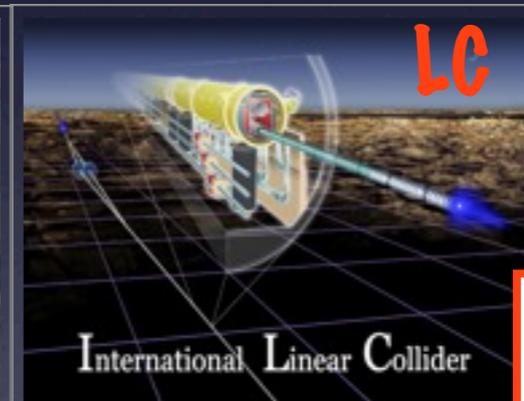
Hierarchy

EWSB
Dark Matter

SUSY

Unification,
Neutrino See-Saw

Quantum
Gravity



Higgs
Factory

THANK
YOU!