Higgsology: Theory and Practice

Tao Han (PITT PACC)
PITTsburgh Particle physics,
Astrophysics and Cosmology Center

Sangam@HRI
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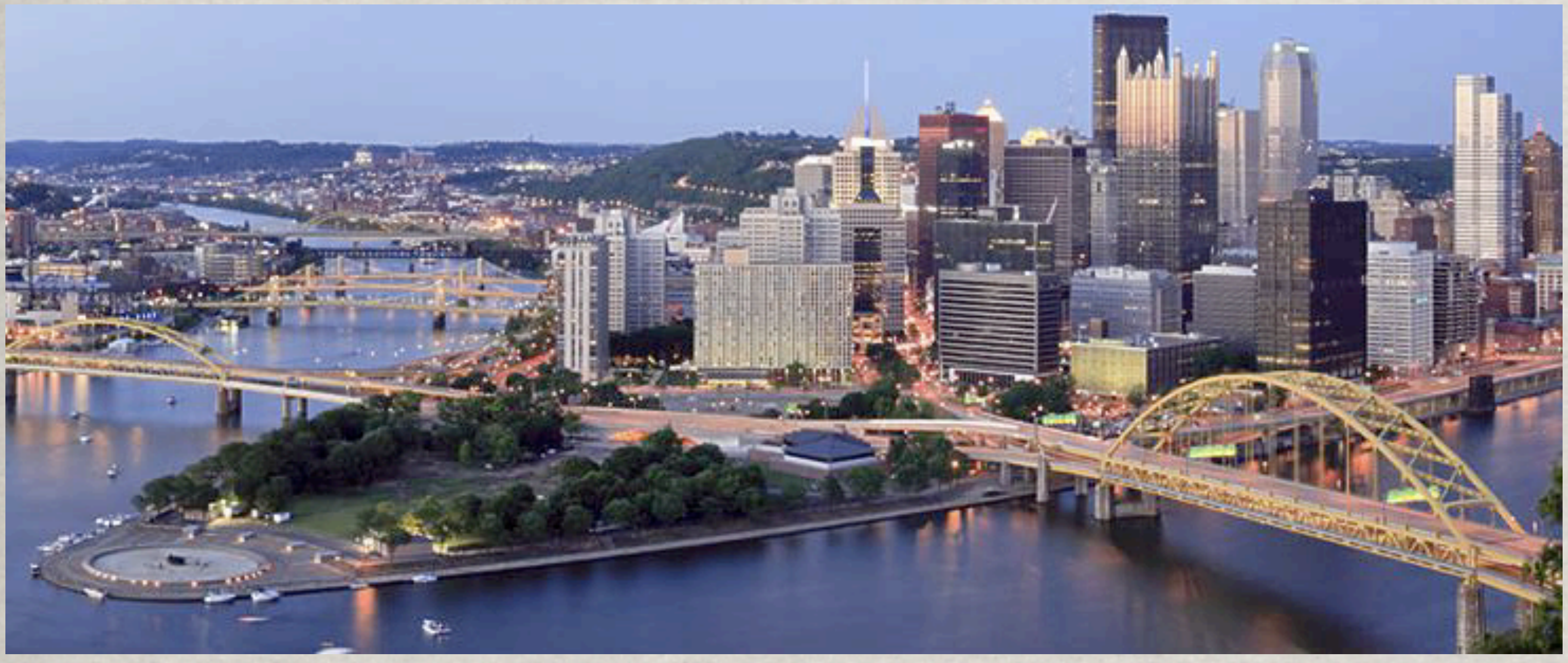
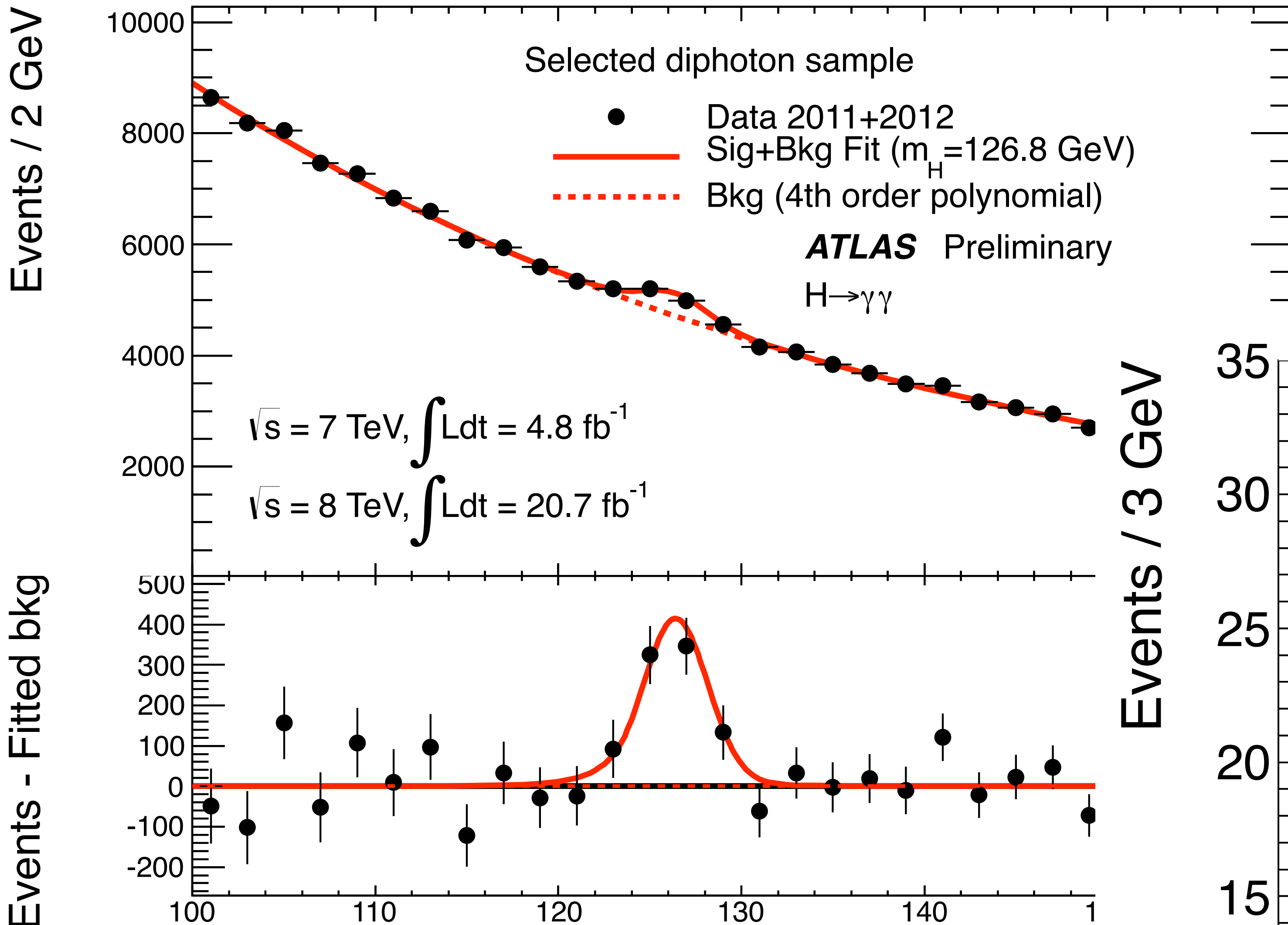
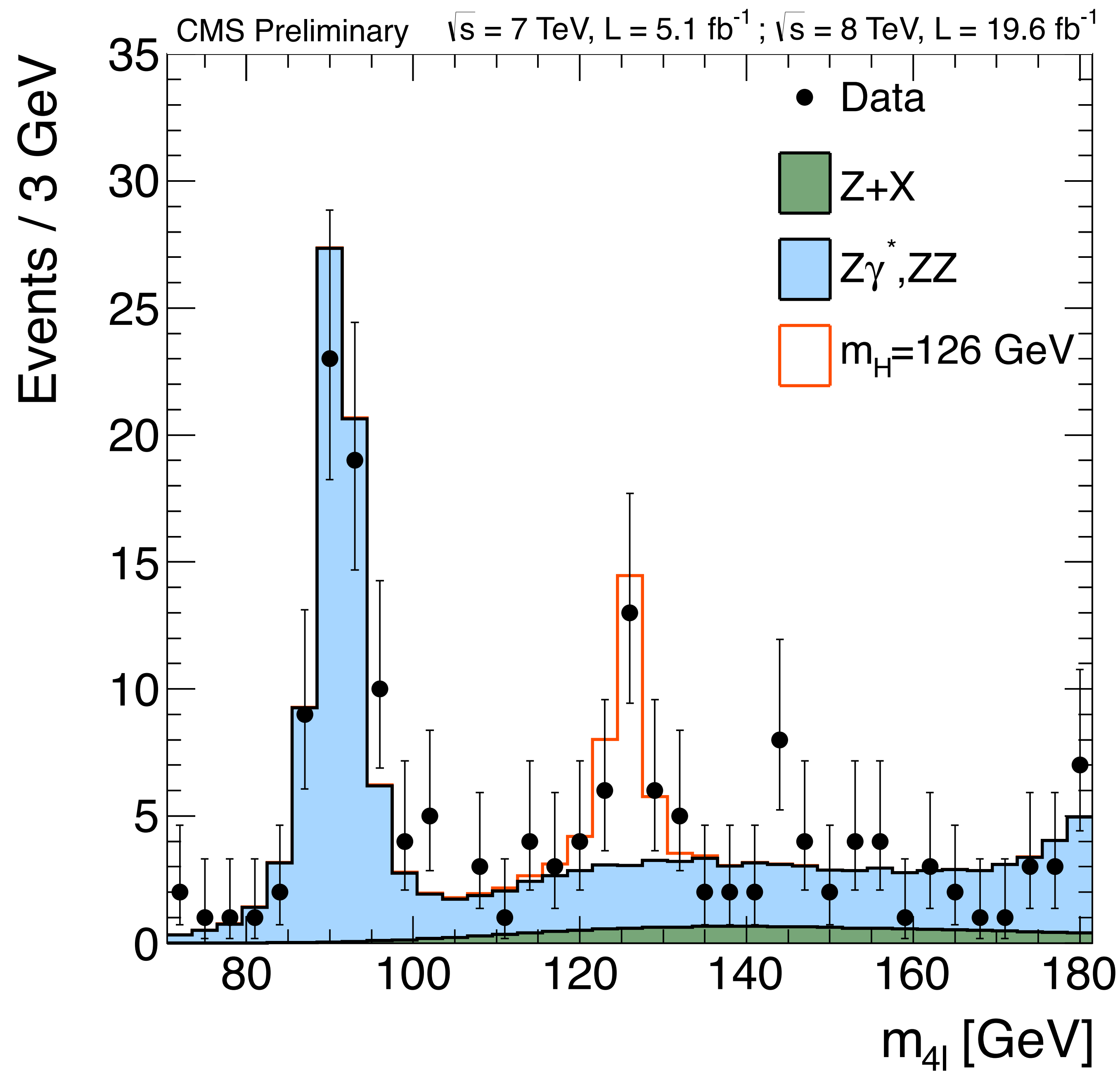


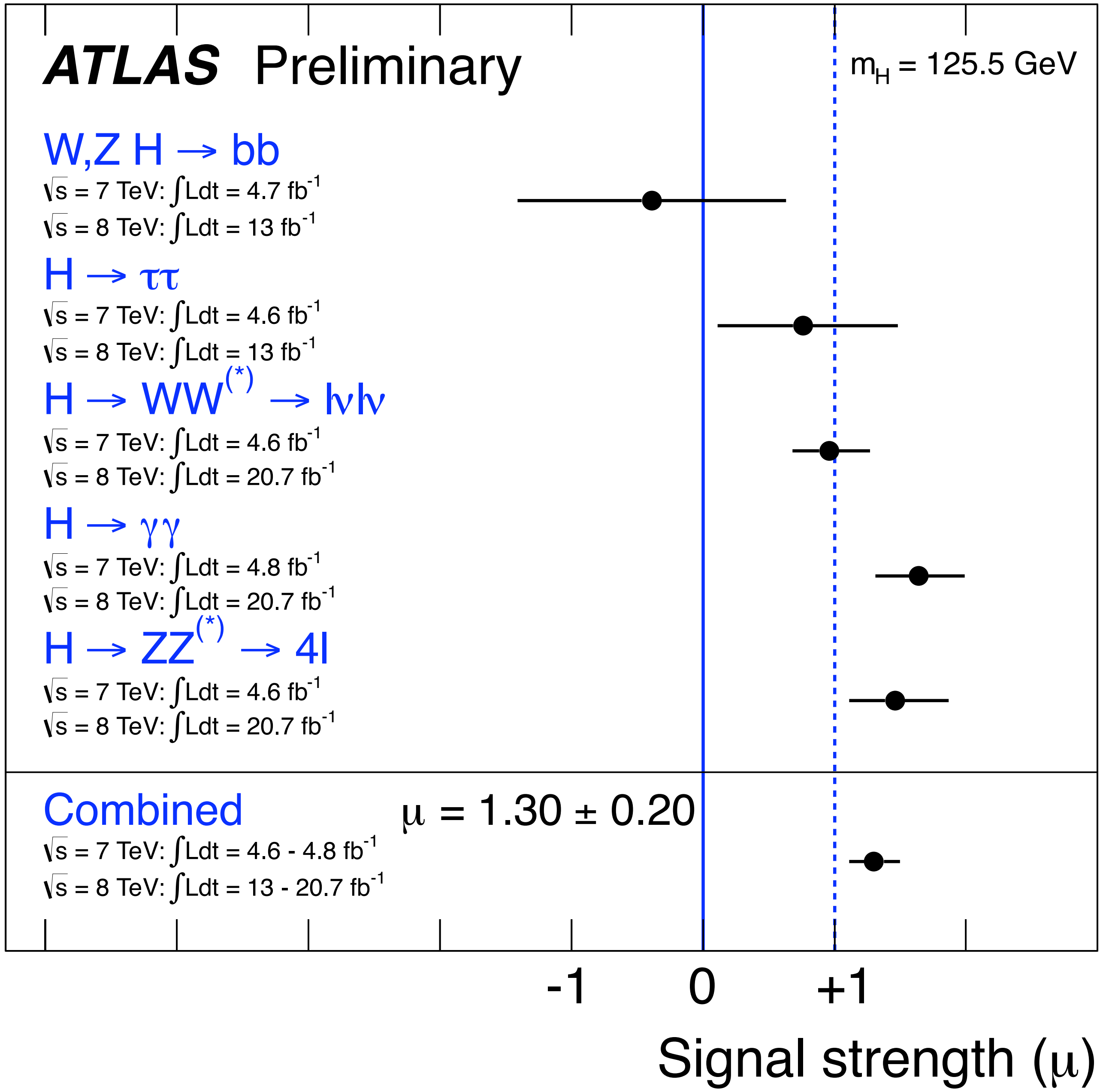
Pheno 2013: May 6-8

It is one of the most exciting times:





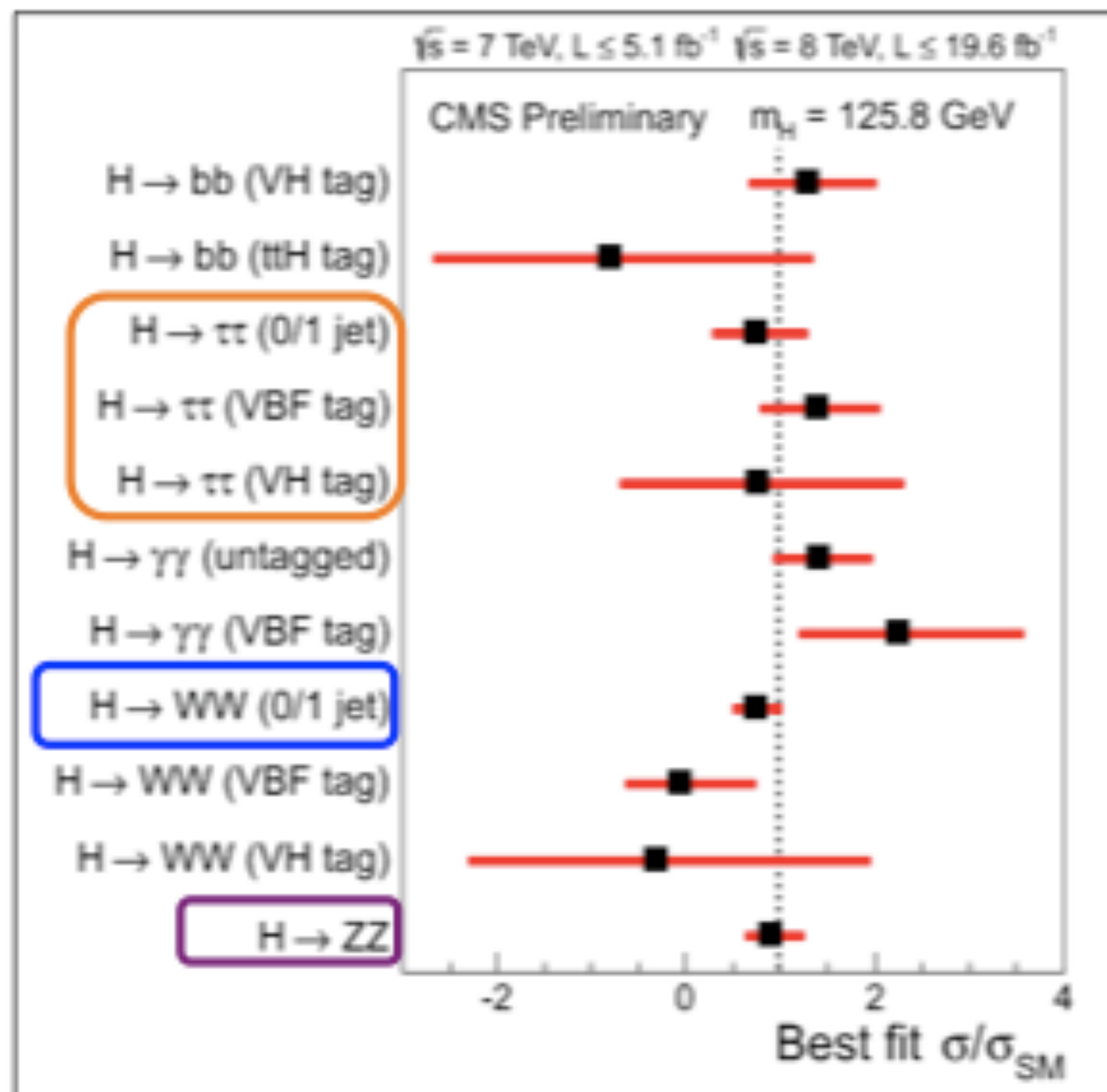
Tao Han



the observed boson: 125.8 ± 0.6 GeV

$$m_H = 125.5 \pm 0.2\ (\mathrm{stat})\ ^{+0.5}_{-0.6}\ (\mathrm{sys})\ \mathrm{GeV}$$

$$\mu = 1.43 \pm 0.16\ (\mathrm{stat}) \pm 0.14\ (\mathrm{sys})$$



Mosaic of the CMS and ATLAS detectors (as in 2007), part of the Large Hadron Collider at CERN. In 2012, research teams used these detectors to fingerprint decay products from the long-sought Higgs boson and determine its mass, successfully testing a key prediction of the standard model of particle physics.

Photos: Maximilien Brice and Claudia Marcelloni/CERN

Fabiola Gianotti, ALTAS spokesperson
Runner-up of 2012 Person of the year

This discovery opens up a new era in HEP!

In these Lectures, I wish to convey to you:

- This is truly an "LHC Revolution", ever since the "November Revolution" in 1974 for the J/ψ discovery!
- It strongly argues for new physics beyond the Standard Model (BSM).

Outline

Lecture I: Higgs Sector in the SM

A. The Higgs Mechanism

1. A historic count
2. The spontaneous symmetry breaking
3. The Goldstone Theorem
4. The Higgs mechanism

B. The Higgs Boson Interactions

1. The Standard Model
2. The Higgs boson interactions

Lecture II: Higgs Physics at Colliders

A. Higgs Boson Decay

1. Decay to fermions
2. Decay WW, ZZ
3. Decay through loops

B. Higgs Boson Production at the LHC

1. The leading channels
2. The search strategies
3. Signal characteristics

C. Higgs Boson Production at e^+e^- colliders

D. Higgs Boson Production at a muon collider

Lecture III: Higgs and Beyond

-- Motive for Physics Beyond SM

A. A Weakly Coupled Scalar?

1. The Higgs mechanism ≠ Higgs boson!
2. Why not a heavier, broader Higgs?

B. SM Higgs Sector at Higher Energies

1. Triviality bound
2. Vacuum stability
3. Naturalness

C. New Physics associated with the Higgs

1. Supersymmetry
2. Extended Higgs sector
3. Composite Higgs
4. Coupling deviations from SM

Lect I. Higgs Sector in the SM

A. The Higgs Mechanism

1. A historical Count:

(a). Deep Root in QED

Maxwell Equations ➔

Lorentz invariance, U(1) Gauge Invariance

Although the electromagnetic fields in **E**(x,t), **B**(x,t) seem adequate for all practical purposes, the introduction of co-variant vector potential $A_\mu(x,t)$ is viewed as revolutionary!‡

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

1). Lorentz/Local Gauge invariance manifest.

2). Classically, geometrical interpretation: fiber bundles…

3). Quantum-mechanically, wave function for the EM field.

‡ Still with dispute: physical? redundancy?

Dirac's relativistic theory:
Lorentz/Local gauge invariant

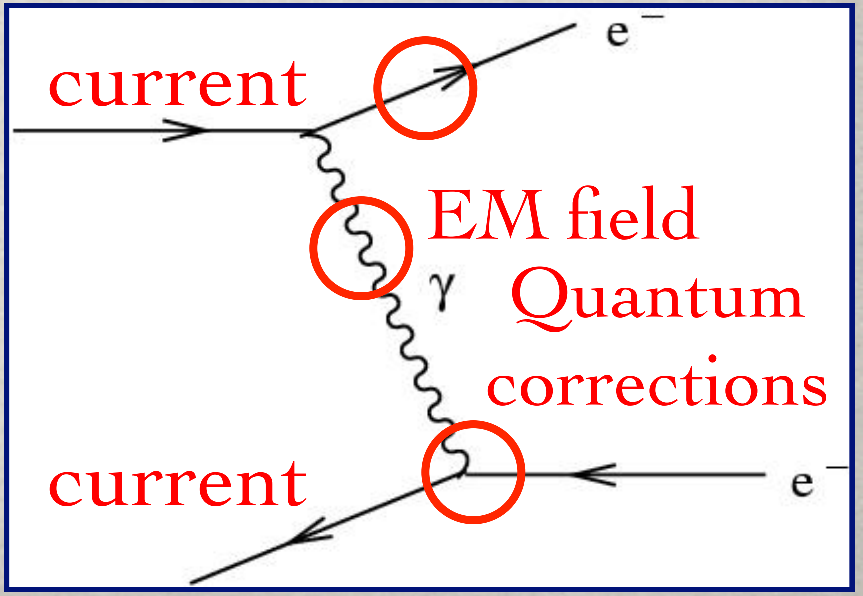
➔ antiparticle e^+

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m_e)\psi$$

$$D_\mu = \partial_\mu + ieA_\mu$$

Feynman/Schwinger/Tomonaga
➔ Renormalization

* The perturbation theory, thus Feynman diagram approach, the most successful aspect.
* QED becomes the most accurate theory in science.



Warmup Exercise 1:

For charge scalar field $\phi^{\pm}$, construct the locally $U(1)_{em}$ gauge invariant Lagranian and derive the Feynman rules for its EM interactions.

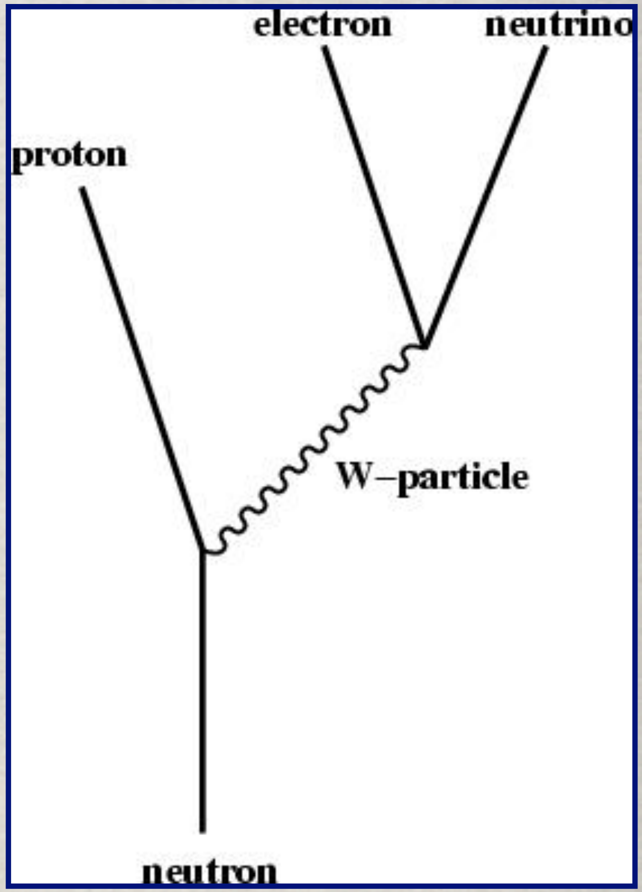
Sketch a calculation for the differential and total cross section for the process:

$$e^{+} e^{-} \rightarrow \phi^{+} \phi^{-}$$

(b). Build up the Weak Interactions

beta decay n → p^+ e^- ν → Charged current interaction: $W^{\pm}$

ν N → ν N → Neutral current interaction: Z^0



$$-\mathcal{L}^{cc}_{eff} = \frac{G_F}{\sqrt{2}} J^{\mu}_{W} J^{\dagger}_{W\mu}, \qquad -\mathcal{L}^{NC}_{eff} = \frac{G_F}{\sqrt{2}} J^{\mu}_{Z} J_{Z\mu}.$$

$$J^{(\pm)}_{\lambda} = \sum_i \bar{\psi}_i \tau_{\pm} \gamma_{\lambda} (1 - \gamma_5) \psi_i,$$

Fermi was inspired by the EM curren-current interactions to construct the weak interaction.

(parity violation → V-A interactions)

The fact $G_F = (300\ \text{GeV})^{-2}$ implies that:

1. A new mass scale to show up at O(100 GeV).
2. Partial-wave Unitarity requires new physics below $E < 300$ GeV

Exercise 2:

Assume that the $\nu\, e \rightarrow \nu\, e$ scattering amplitude to be

$$M = G_F\, E_{cm}^2$$

estimate the unitarity bound on the c.m. energy.

Partial wave expansion:

$$a_{I\ell}(s) \;=\; \frac{1}{64\pi}\int_{-1}^{1} d\cos\theta\;\, P_\ell(\cos\theta)\;\, \mathcal{M}^I(s,t)$$

Partial wave unitarity:

$$Im\,(a_{I\ell}) = |a_{I\ell}|^2 < 1, \quad Re\,(a_{I\ell}) < \frac{1}{2}$$

(c). Idea of Unification:

Within a frame work of relativistic, quantum, gauge field theory

PARTIAL-SYMMETRIES OF WEAK INTERACTIONS

SHELDON L. GLASHOW †

Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

Received 9 September 1960

Abstract: Weak and electromagnetic interactions of the leptons are examined under the hypothesis that the weak interactions are mediated by vector bosons. With only an isotopic triplet of leptons coupled to a triplet of vector bosons (two charged decay-intermediaries and the photon) the theory possesses no partial-symmetries. Such symmetries may be established if additional vector bosons or additional leptons are introduced. Since the latter possibility yields a theory disagreeing with experiment, the simplest partially-symmetric model reproducing the observed electromagnetic and weak interactions of leptons requires the existence of at least four vector-boson fields (including the photon). Corresponding partially-conserved quantities suggest leptonic analogues to the conserved quantities associated with strong interactions: strangeness and isobaric spin.

The birth of the Standard Model:

VOLUME 19, NUMBER 21 PHYSICAL REVIEW LETTERS 20 NOVEMBER 1967

[11] In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.

[12] M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282

bra is slightly larger than that (0.23%) obtained from the ρ-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma(\eta\to\pi^+\pi^-\gamma)/$ ...) calculated in Refs. 12 and 14.

. M. Brown and P. Singer, Phys. Rev. Letters 8, (1962).

A MODEL OF LEPTONS*

Steven Weinberg†

Physics Department,
ambridge, Massachusetts
1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences

on a right-handed singlet

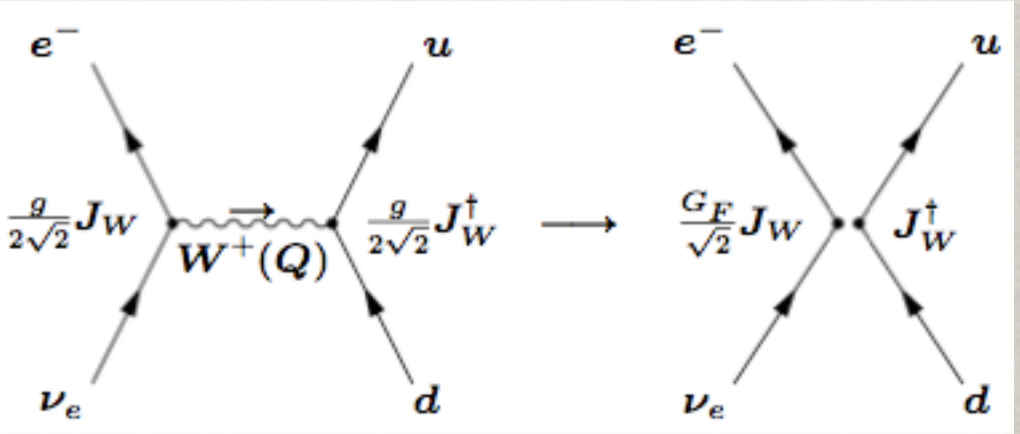
$$R=[\tfrac{1}{2}(1-\gamma_5)]e.$$

The EW Unifcation I: Couplings

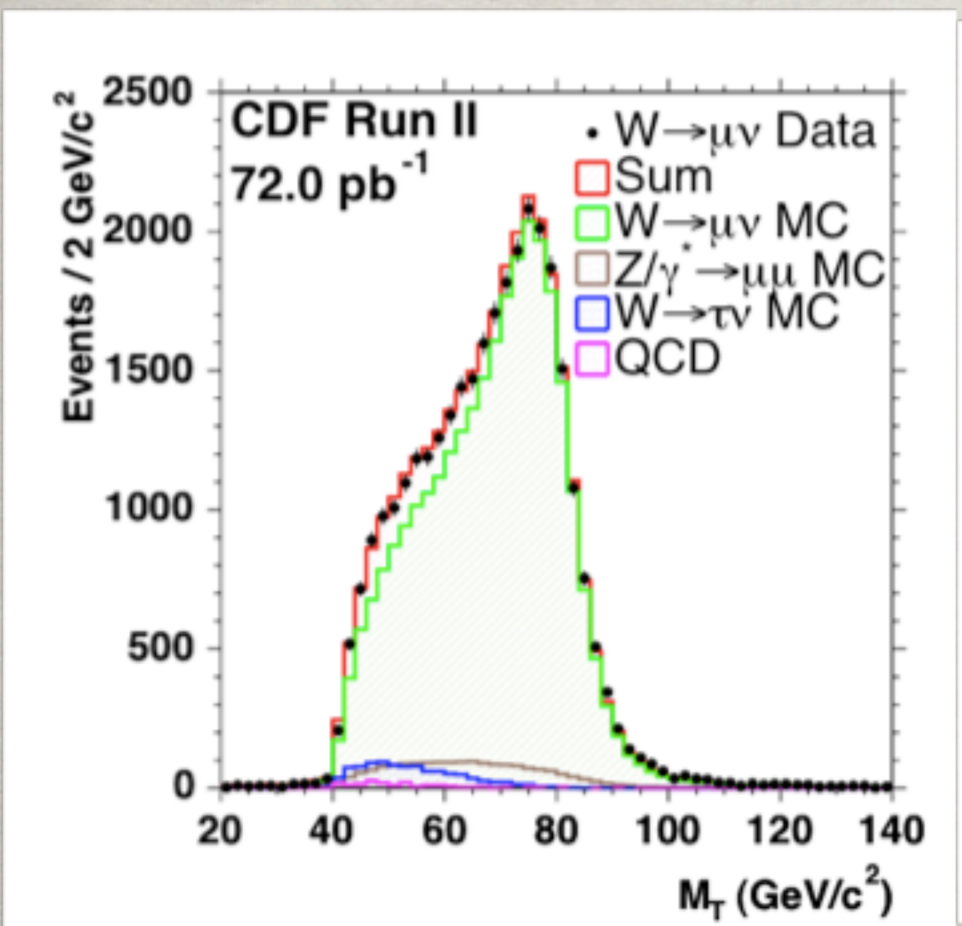
$SU(2)_L \otimes U(1)_Y$ interactions.

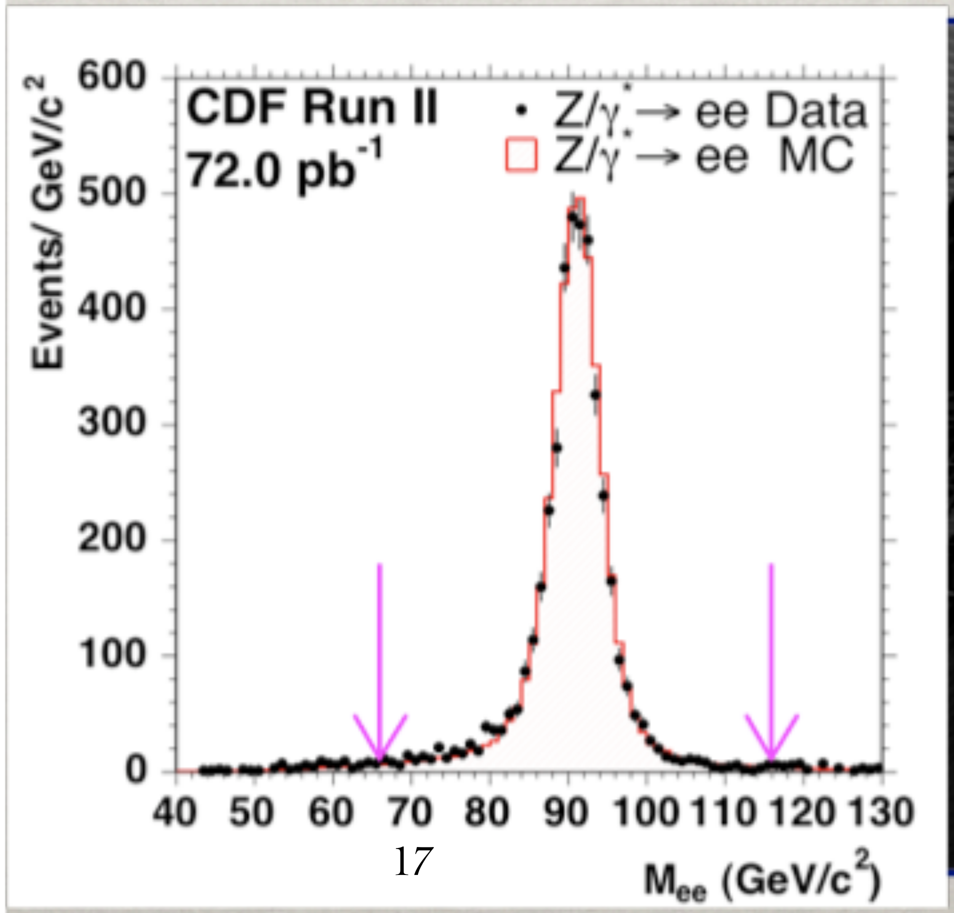
$e = g \sin\theta_W$ coupling unification

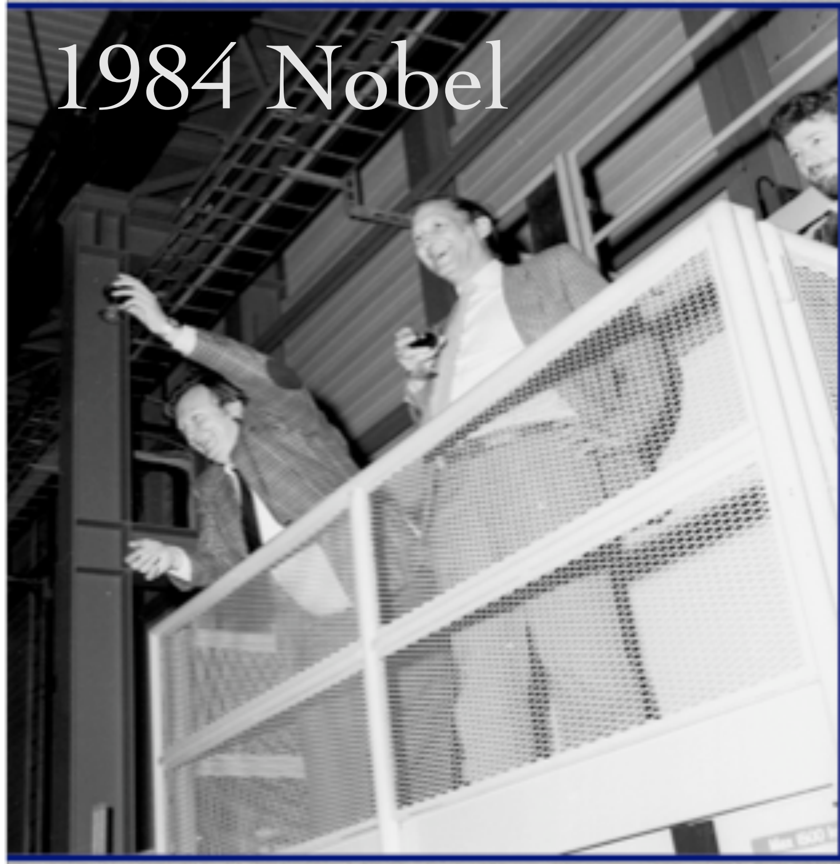
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$ short – range scale.



The EW scale is fully open up:







The EW Unifcation II: Particle representation

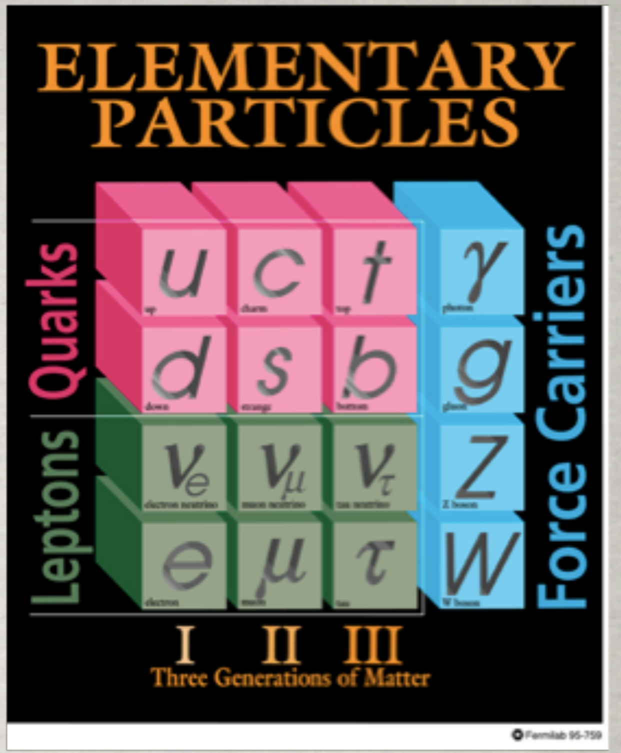
- Simple structure and particle contents:

Leptons:

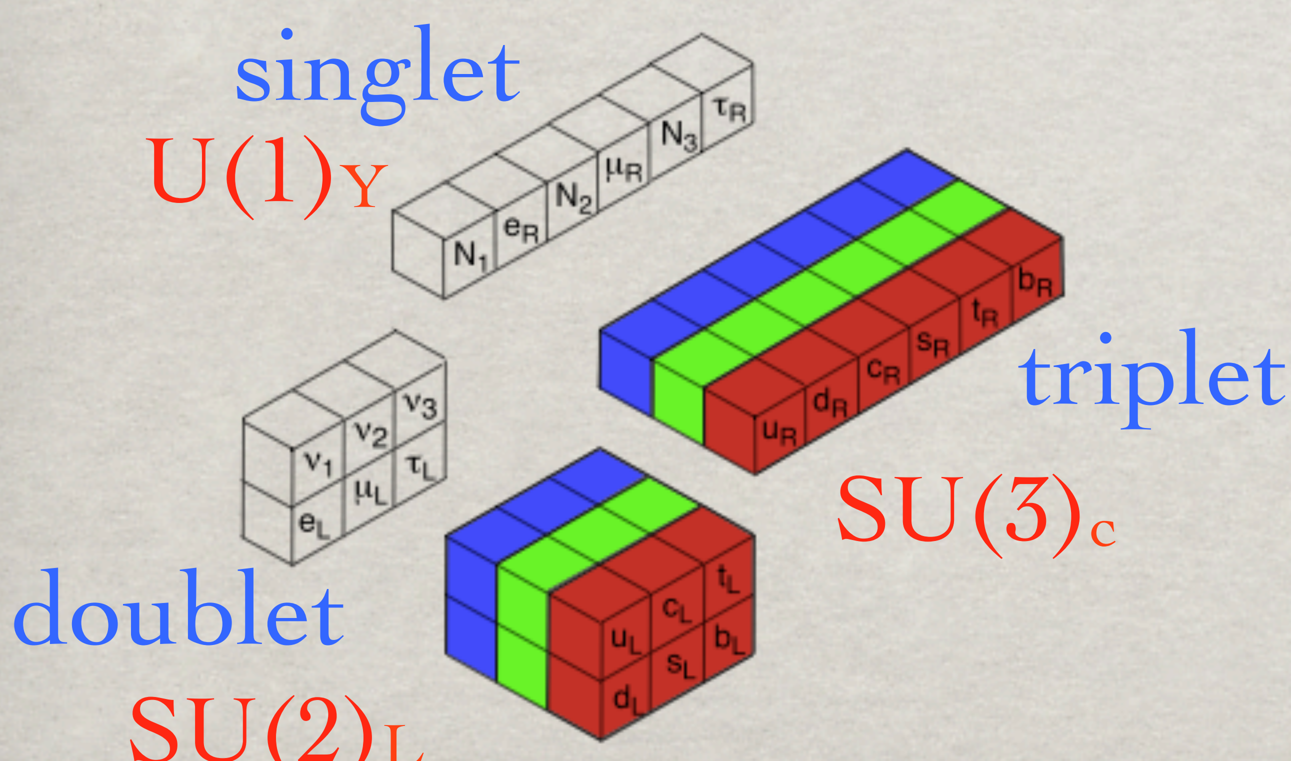
$$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L, \quad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L, \quad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L, \quad e_R, \ \mu_R, \ \tau_R, \quad (\nu'_R s\ ?)$$

Quarks:

$$\begin{pmatrix}u\\ d\end{pmatrix}_L, \quad \begin{pmatrix}c\\ s\end{pmatrix}_L, \quad \begin{pmatrix}t\\ b\end{pmatrix}_L, \quad u_R, \ d_R, \ c_R, \ s_R, \ t_R, \ b_R$$



(1979 Nobel)



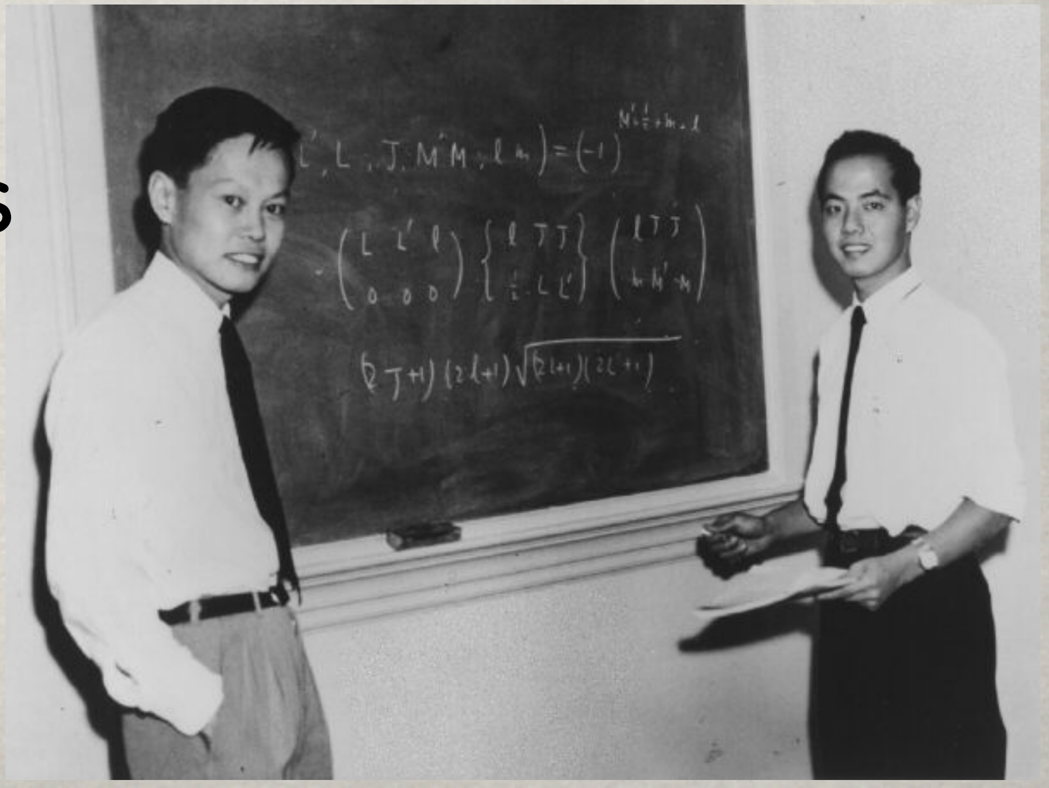
BUT, The local gauge symmetry prevents gauge bosons from acquiring masses!

$$\frac{1}{2}M_A^2 A_\mu A^\mu \rightarrow \frac{1}{2}M_A^2 (A_\mu - \frac{1}{e}\partial_\mu \alpha)(A^\mu - \frac{1}{e}\partial^\mu \alpha) \neq \frac{1}{2}M_A^2 A_\mu A^\mu$$

Worse, chiral fermion masses also forbidden by gauge symmetry!

$$-m_e \bar{e} e = -m_e \bar{e}\Big(\frac{1}{2}(1-\gamma_5) + \frac{1}{2}(1+\gamma_5)\Big)e = -m_e(\bar{e}_R e_L + \bar{e}_L e_R)$$

``The Left- and right-chiral electrons carry different Weak charges''
(1957 Noble Prize)



Pauli's Criticism:

An Anecdote by Yang: SU(2) gauge symmetry

Wolfgang Pauli (1900-1958) was spending the year in Princeton, and was deeply interested in symmetries and interactions.... Soon after my seminar began, when I had written on the blackboard,

Wolfgang Pauli and C. N. Yang

$(\partial_\mu - i\epsilon \mathbf{B}_\mu)\psi$

Pauli asked, "What is the mass of this field $\mathbf{B}_\mu$?" I said we did not know. Then I resumed my presentation but soon Pauli asked the same question again. I said something to the effect that it was a very complicated problem, we had worked on it and had come to no definite conclusions. I still remember his repartee: "That is not sufficient excuse". I was so taken aback that I decided, after a few moments' hesitation, to sit down. There was general embarrassment. Finally Oppenheimer, who was chairman of the seminar, said "We should let Frank proceed". I then resumed and Pauli did not ask any more questions during the seminar.

2. The Spontaneous Symmetry Breaking -- Nature May Not be THAT Symmetric:

"The Lagrangian of the system may display an symmetry, but the ground state does not respect the same symmetry."

Known Example: Ferromagnetism

Domains Before Magnetization

Domains After Magnetization

Above a critical temperature, the system is symmetric, magnetic dipoles randomly oriented. Below a critical temperature, the ground state is a completely ordered configuration in which all dipoles are ordered in some arbitrary direction,

SO(3) → SO(2)

Known Example: QCD condensation

Consider the two-flavor massless QCD:

$$-\frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} - \sum_{u,d}(\bar{q}_L\gamma^\mu D_\mu q_L + \bar{q}_R\gamma^\mu D_\mu q_R)$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \rightarrow \left(U_L\,\gamma_L + U_R\,\gamma_R\right)\begin{pmatrix} u \\ d \end{pmatrix} \Rightarrow SU(2)_L \otimes SU(2)_R$$

QCD below Λ_{QCD} becomes strong and forms condensate: $\langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \sim v^3$

$$SU(2)_L \otimes SU(2)_R \Rightarrow SU(2)_V, \text{thus } U_L = U_R.$$

Chiral symmetry breaking to iso-spin.

The concept of SSB: profound, common.

Y. Nambu was the first one to have formulated the spontaneous symmetry breaking in a relativistic quantum field theory (1960).

He is the one to propose the understanding of the nucleon mass by dynamical chiral symmetry breaking: The Nambu-Jona-Lasinio Model.

2008 Nobel Prize in physics: "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

Be aware of the difference between the dynamical mass for baryons (you and me) and that of elementary particles by the Higgs mechanism.

Exercise 3:

Find (or make up) other examples for spontaneous symmetry breaking.

Also, think about the relations between the fundamental theoretical formalisms (Newton's Law; Maxwell Equations; Einstein Equation; Lagrangians...) and specific states for a given system (initial and boundary conditions of a system).

3. The Goldstone Theorem -- A show stopper or helper?

"If a continuous symmetry of the system is spontaneously broken, then there will appear a massless degree of freedom, called the Nambu-Goldstone boson."

Symmetry: $[Q, H] = QH - HQ = 0$

Vacuum state: $H |0\rangle = E_{min} |0\rangle$ But: $Q |0\rangle \neq 0 = |0'\rangle$

$$(QH - HQ)|0\rangle = 0 = (E_{min} - H)|0'\rangle,$$

thus: $H |0'\rangle = E_{min} |0'\rangle$

There is a new, non-symmetric state $|0'\rangle$,
that has a degenerate energy with vacuum $|0\rangle$,
thus massless: the Nambu-Goldstone boson.

The Goldstone Theorem (continued)

Broken Symmetries*

JEFFREY GOLDSTONE
Trinity College, Cambridge University, Cambridge, England

AND

ABDUS SALAM AND STEVEN WEINBERG†
Imperial College of Science and Technology, London, England

(Received March 16, 1962)

Some proofs are presented of Goldstone's conjecture, that if there is continuous symmetry transformation under which the Lagrangian is invariant, then either the vacuum state is also invariant under the transformation, or there must exist spinless particles of zero mass.

Properties of the Nambu-Goldstone boson:
1. Massless, gapless in spectrum
3. Decouple at low energies:

$\langle G| Q |0\rangle \neq 0$, $\langle G(p)| j^\mu(x)|0\rangle \sim e^{-ipx} p^\mu v$

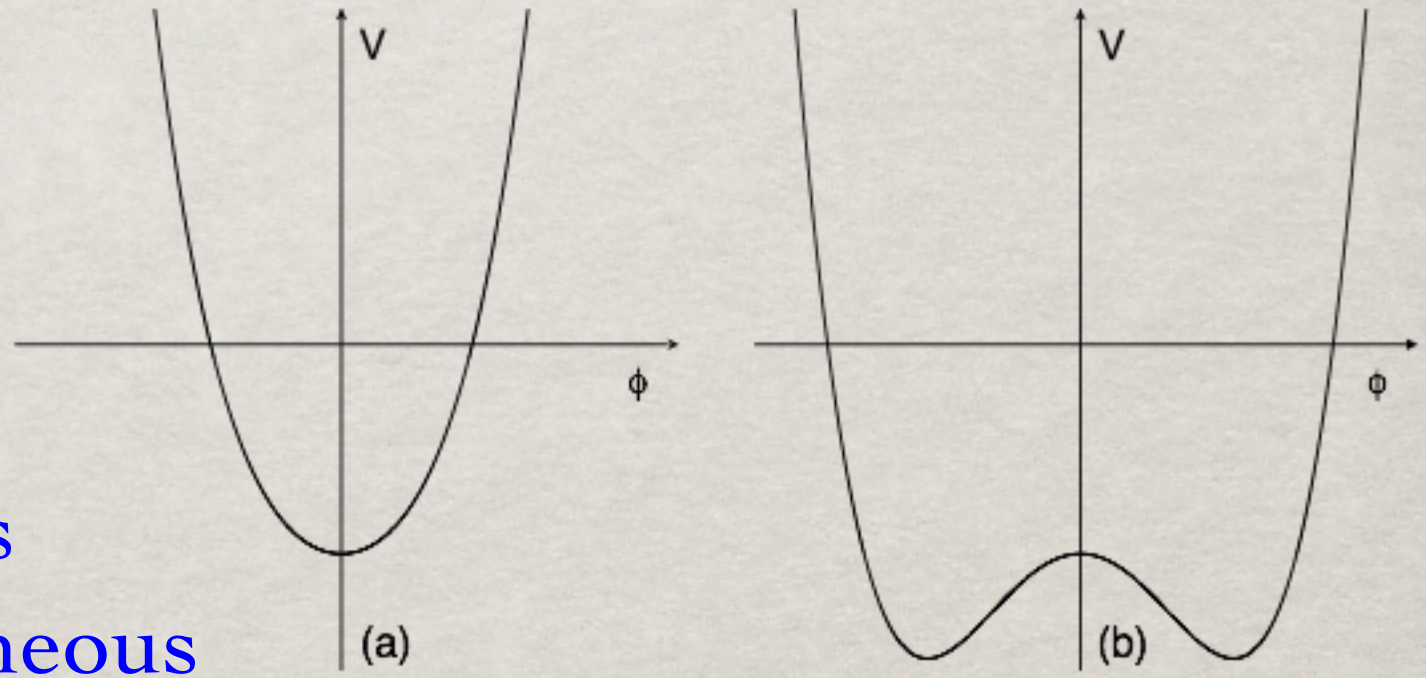
A illustrative (Goldstone's original) Model:

(a). Background complex scalar field Φ:

$$\mathcal{L} = \partial^\mu \phi^* \partial_\mu \phi - V(\phi^* \phi) \qquad V = \frac{\lambda}{4}\left(\phi^*\phi - \frac{\mu^2}{\lambda}\right)^2$$

Invariant under a U(1) global transformation:

$$\phi \to e^{i\alpha}\ \phi$$



For $\mu^2 > 0$, the vacuum is shifted, and thus spontaneous symmetry breaking.

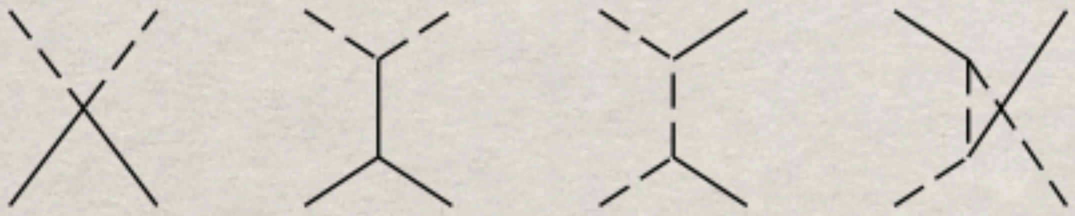
$$v = \langle 0|\phi|0\rangle = \mu/\sqrt{\lambda}.$$

Particle spectrum:[§]

Shift: $R = \sqrt{2} Re(\phi - v), \quad I = \sqrt{2}\ Im\phi,$

Then:
$$\mathcal{L} = \frac{1}{2}\partial^\mu R \partial_\mu R - \frac{\lambda v^2}{2} R^2 - \frac{\lambda\mu}{2\sqrt{2}} R^3 - \frac{\lambda}{16} R^4$$
$$+ \frac{1}{2}\partial^\mu I \partial_\mu I - \frac{\lambda\mu}{2\sqrt{2}} R I^2 - \frac{\lambda}{16}(R^2 I^2 + I^4)$$

* R is a massive scalar: $M_R = \sqrt{\lambda}\, v$.
* I is massless, interacting.
* Though not transparent, it can be verified:[§]



$$\mathcal{M}(RI \to RI)|_{p\to 0} \to 0!$$

I does decouple at low energies!

Exercise 4: Show this result by an explicit calculation.

[§] C. Burgges, hep-ph/9812468

(b). Field Φ Re-definition:

[+] C. Burgges, hep-ph/9812468

Weinberg's 1st Law of Theoretical Physics[+]:

"You can use whatever variables you like. But if you used the wrong one, you'd be sorry."

Define:

$$\phi(x) = \chi(x)\, e^{i\theta(x)},$$

$$\mathcal{L} = -\partial_\mu \chi \partial^\mu \chi - \chi^2 \partial_\mu \theta \partial^\mu \theta - V(\chi^2).$$

(this is like from the rectangular *form* to the *polar form*.)

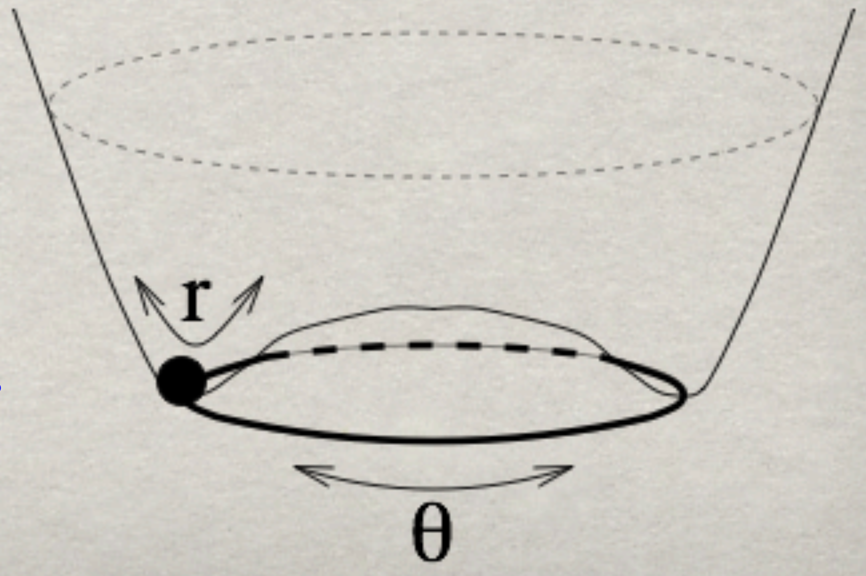
We then see that:

* the θ field is only derivatively coupled, and thus decoupled at low energies
* the θ field respects an inhomogeneous transformation

$$\theta \rightarrow \theta + \alpha, \quad \phi = v e^{i\theta(x)}$$

a phase rotation from the vacuum:

* the $\chi(x)$ is massive radial excitation.



Known example: Chiral symmetry breaking

$$-\frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} - \sum_{u,d}(\bar{q}_L\gamma^\mu D_\mu q_L + \bar{q}_R\gamma^\mu D_\mu q_R)$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \to \left(U_L\,\gamma_L + U_R\,\gamma_R\right)\begin{pmatrix} u \\ d \end{pmatrix} \Rightarrow SU(2)_L \otimes SU(2)_R$$

QCD breaks the chiral symmetry dynamically:

$$SU(2)_L \otimes SU(2)_R \Rightarrow SU(2)_V, \text{thus } U_L = U_R.$$

(3+3) - 3 = 3 Goldstone bosons: π^+, π^-, π^0

In the non-linear formulation of the Chiral Lagrangian for the Goldstone bosons:

$$\phi = \frac{v}{\sqrt{2}}\exp(i\vec{\tau}\cdot\vec{\pi}/v) \equiv \frac{v}{\sqrt{2}}U, \quad \mathcal{L} = \frac{v^2}{4}Tr(\partial^\mu U \partial_\mu U)$$

necessarily derivative coupling.

The pion-pion scattering:

$$\pi_i + \pi_j \to \pi_k + \pi_\ell \quad (i, j, k, \ell = 1, 2, 3)$$

$$A(s,t,u) = \frac{s}{v^2}.$$

in accordance with the Low Energy theorem.

Chiral perturbation theory agrees well with the pion-pion scattering data,¶ supporting the Goldstone nature.

Exercise 5: Linearize the Chiral Lagrangian for ππ interaction and calculate one scattering amplitude.¶

¶ J. Donoghue et al., Dynamics of the SM.

"Pseudo-Nambu-Goldstone Bosons"

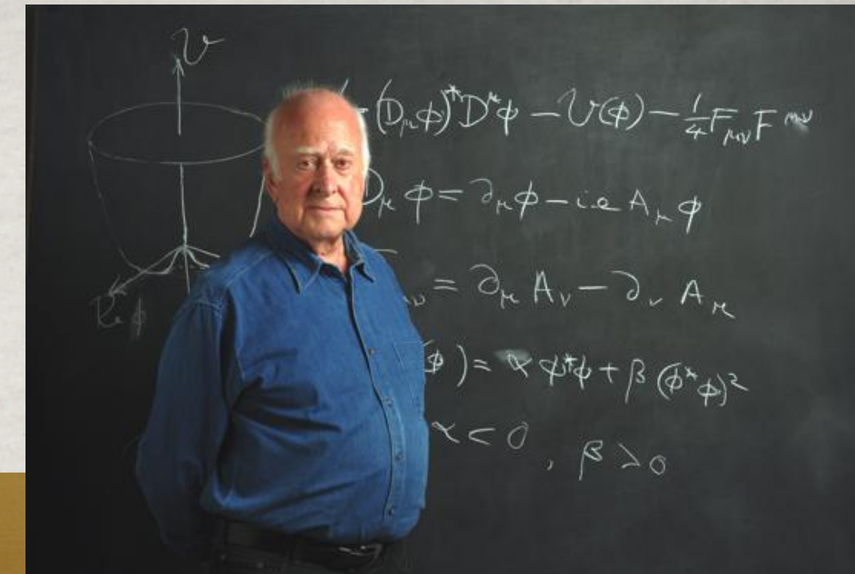
When a continuous symmetry is broken both explicitly AND spontaneously, and if the effect of the explicit breaking is much smaller than the SSB, then the Goldstone are massive, governed by the explicit breaking, thus called:
"Pseudo-Nambu-Goldstone bosons".

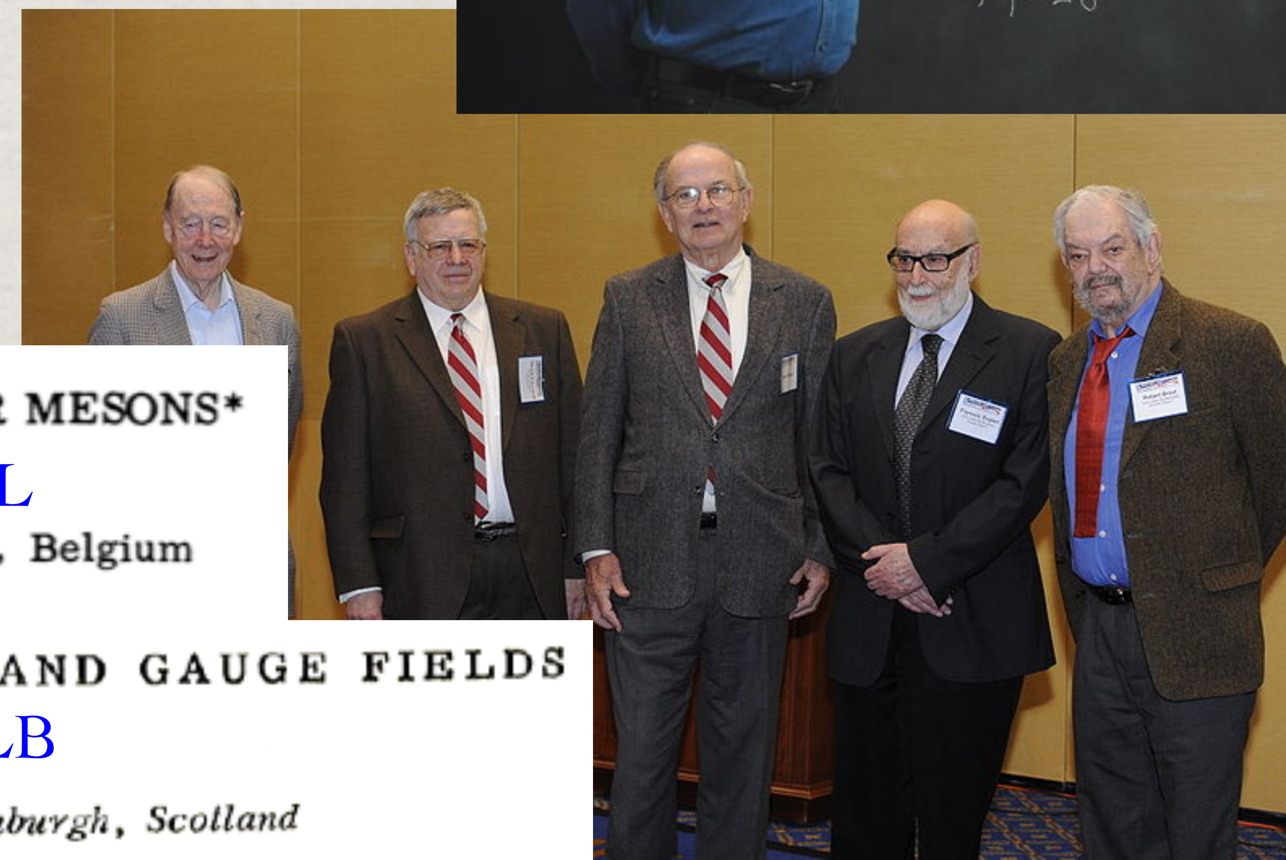
The pions are NOT massless, due to explicit symmetry breaking. They are "Pseudo-Nambu-Goldstone bosons".

Except the photon, no massless boson (a long-range force carrier) has been seen in particle physics!

4. The Magic in 1964: The “Higgs Mechanism”

“If a LOCAL gauge symmetry is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode.”





BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964) PRL

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964 PLB

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964) PRL

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964) PRL

A illustrative (original) Model:¶

$$\mathscr{L} = |\mathscr{D}^\mu \phi|^2 - \mu^2 |\phi|^2 - |\lambda| (\phi^* \phi)^2 - \tfrac{1}{4} F_{\mu\nu} F^{\mu\nu},$$

where

$$\phi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$

is a complex scalar field[4] and as usual

$$\mathscr{D}_\mu \equiv \partial_\mu + iqA_\mu$$

and

$$F_{\mu\nu} \equiv \partial_\nu A_\mu - \partial_\mu A_\nu.$$

The Lagrangian (5.3.1) is invariant under U(1) rotations

$$\phi \to \phi' = e^{i\theta} \phi$$

and under the local gauge transformations

$$\phi(x) \to \phi'(x) = e^{iq\alpha(x)} \phi(x),$$
$$A_\mu(x) \to A'_\mu(x) = A_\mu(x) - \partial_\mu \alpha(x).$$

¶ C. Quigg, Gauge Theories of the Strong ...

A illustrative (original) Model:¶

After the EWSB, parameterized in terms of

$$\langle \phi \rangle_0 = v/\sqrt{2}, \qquad \phi = e^{i\zeta/v}(v+\eta)/\sqrt{2} \approx (v+\eta+i\zeta)/\sqrt{2}.$$

Then the Lagrangian appropriate for the study of small oscillations is

$$\mathcal{L}_{\text{so}} = \tfrac{1}{2}[(\partial_\mu \eta)(\partial^\mu \eta) + 2\mu^2\eta^2] + \tfrac{1}{2}[(\partial_\mu \zeta)(\partial^\mu \zeta)] - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + qvA_\mu(\partial^\mu \zeta) + \frac{q^2v^2}{2}A_\mu A^\mu + \cdots$$

The gauge field acquires a mass, mixes with the Goldstone boson.

Upon diagonalization: $$\frac{q^2v^2}{2}\left(A_\mu + \frac{1}{qv}\partial_\mu \zeta\right)\left(A^\mu + \frac{1}{qv}\partial^\mu \zeta\right),$$

a form that pleads for the gauge transformation

$$A_\mu \to A'_\mu = A_\mu + \frac{1}{qv}\partial^\mu \zeta,$$

which corresponds to the phase rotation on the scalar field

$$\phi \to \phi' = e^{-i\zeta(x)/v}\phi(x) = (v+\eta)/\sqrt{2}.$$

the resultant Lagrangian is then:

$$\mathcal{L}_{so} = \frac{1}{2}[(\partial_\mu \eta)(\partial^\mu \eta) + 2\mu^2\eta^2] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{q^2v^2}{2}A'_\mu A'^\mu$$

- an η-field, with $(\text{mass})^2 = -2\mu^2 > 0$; the Higgs boson!
- a massive vector field A'_μ, with mass $= qv$
- no ζ-field.

- By virtue of a gauge choice - the unitary gauge, the ζ-field disappears in the spectrum: a massless photon "swallowed" the massless NG boson!

Degrees of freedom count:

Before EWSB:	After:
2 (scalar)+2 (gauge pol.);	1 (scalar)+3 (gauge pol.)

- Two problems provide cure for each other!

massless gauge boson + massless NG boson

→ massive gauge boson + no NG boson

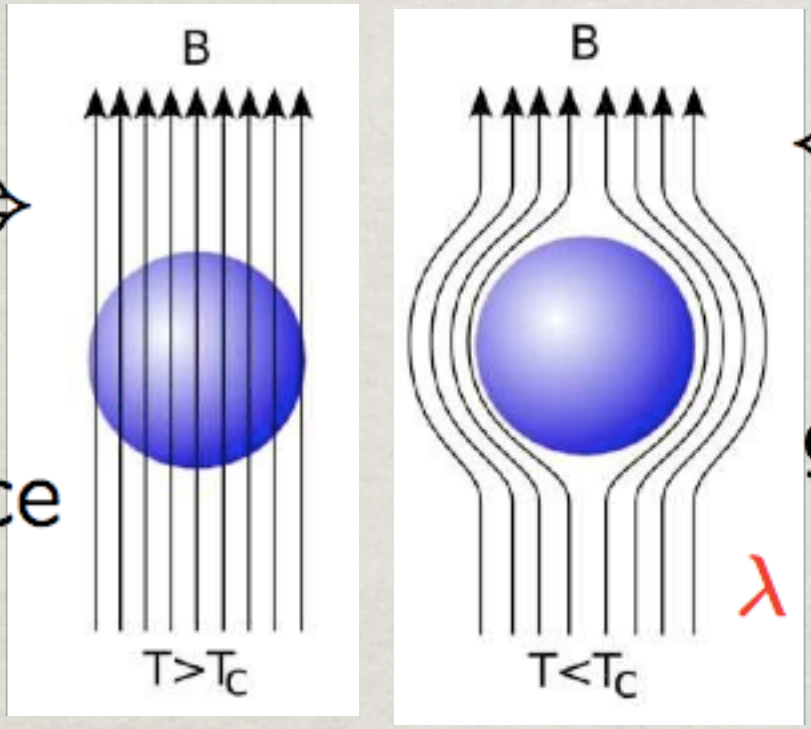
This is truly remarkable!

Known example: Superconductivity

Normal phase⇒

$E^2 = p^2c^2$

Long-range force



⇐Superconducting phase

$E^2 = p^2c^2 + m^2c^4$

gap leads to $\sim exp(-r/\lambda)$

$\lambda \sim m^{-1}$ penetration depth

In "conventional" electro-magnetic superconductivity:

$m_\gamma \sim m_e/1000$, $T_c^{em} \sim \mathcal{O}(\text{few } K)$. BCS theory.

In "electro-weak superconductivity":

$m_w \sim G_F^{-\frac{1}{2}} \sim 100$ GeV, $T_c^w \sim 10^{15} K!$

True understanding was the work of many hands, most notably:[†]

- 1960: Nambu formulated spontaneous symmetry breaking for chiral fermions to dynamically generate the nucleon mass (Nambu-Jona-Lasinio model)
- 1961,1962: Goldstone theorem challenged the implementation of spontaneous symmetry breaking for gauge symmetry: No experimental observation for a massless Goldstone boson.
- 1963: Anderson conjectured a non-relativistic version of a massive Goldstone mode, the "plasmon" in superconductor.
- 1964: Englert+Brout; Higgs; Guralnik+Hagen+Kibble showed the U(1) photon mass generation mechanism, evading the Goldstone theorem in locally gauge invariant theory.[§]

† Univ. of Edinburgh, Peter Higgs and the Higgs Boson.

§ Sidney Coleman:

(in 1989) that they "had been looking forward to tearing apart this idiot who thought he could get around the Goldstone theorem".

"Evading the Goldstone Theorem" continues †

- 1964: Higgs (PRL) first commented on the spin-zero boson, in the revised version (upon Nambu's request to compare with the other's works)¶

¶ Peter Higgs: My Life as a Boson.

- 1966: Higgs (PRD) laid out the scalar scattering/decay in an Abelian U(1) model.‡

¶

> It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8] It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields.[9]

‡

PHYSICAL REVIEW VOLUME 145, NUMBER 4 27 MAY 1966

Spontaneous Symmetry Breakdown without Massless Bosons*

PETER W. HIGGS†
Department of Physics, University of North Carolina, Chapel Hill, North Carolina
(Received 27 December 1965)

- 1967: Weinberg (PRL) laid out the fermion mass generation, formulated the $SU(2)_L \times U(1)_Y$ SM.

† Univ. of Edinburgh, Peter Higgs and the Higgs Boson.

As for the name …

1972: Ben Lee (Rochester Conf. at FNAL) named “Higgs boson” and the “Higgs mechanism”.[§]

§ Peter Higgs: My Life as a Boson.

Font Size:

The New York Review of Books

The Crisis of Big Science

MAY 10, 2012

Steven Weinberg

As to my responsibility for the name “Higgs boson,” because of a mistake in reading the dates on these three earlier papers, I thought that the earliest was the one by Higgs, so in my 1967 paper I cited Higgs first, and have done so since then. Other physicists apparently have followed my lead. But as Close points out, the earliest paper of the three I cited was actually the one by Robert Brout and François Englert. In extenuation of my mistake, I should note that Higgs and Brout and Englert did their work independently and at about the same time, as also did the third group (Gerald Guralnik, C.R. Hagen, and Tom Kibble). But the name “Higgs boson” seems to have stuck. ↩

Recollection:

The Symmetry

QED (1950's)

↓

Yang-Mills Theory [Yang, Mills,1954]

↓

EW unification theory [Glashow,1960]

The Breaking

Spontaneous symmetry breaking in particle physics [Nambu, 1960;Goldstone,1962]

↓

Prediction of the existence of massive Higgs boson [Higgs, 1964]

↓

Higgs mechanism + EW unification theory [Weinberg, 1967; Salam,1968]

B. Higgs Boson Interactions

1. The SM Lagrangian: $\mathcal{L}_{SU(2)\times U(1)} = \mathcal{L}_{gauge} + \mathcal{L}_{\phi} + \mathcal{L}_{f} + \mathcal{L}_{Yuk}.$

The gauge part is **Pure gauge sector:**

$$\mathcal{L}_{gauge} = -\frac{1}{4}W^{i}_{\mu\nu}W^{\mu\nu i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu},$$

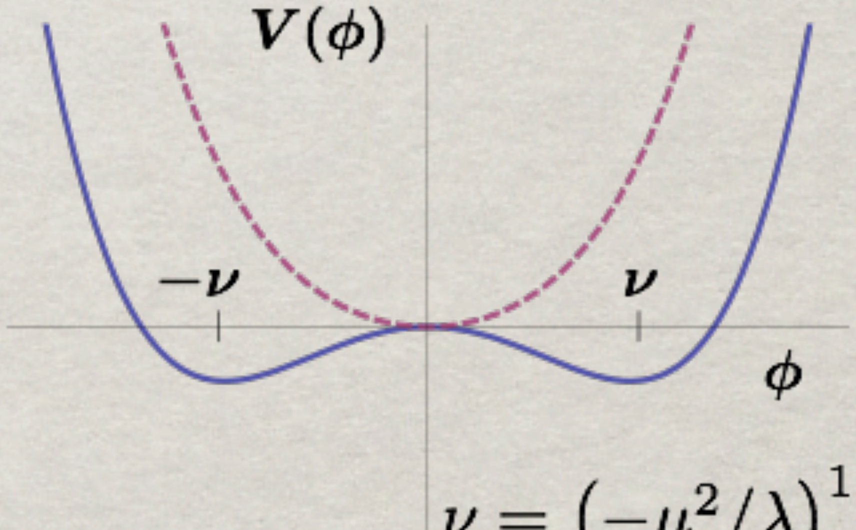
The scalar part of the Lagrangian is

The Higgs: $\mathcal{L}_{\phi} = (D^{\mu}\phi)^{\dagger}D_{\mu}\phi - V(\phi)$ $\quad D_{\mu}\phi = \left(\partial_{\mu} + ig\frac{\tau^{i}}{2}W^{i}_{\mu} + \frac{ig'}{2}B_{\mu}\right)\phi,$

$$V(\phi) = +\mu^{2}\phi^{\dagger}\phi + \lambda(\phi^{\dagger}\phi)^{2}.$$

$$\phi = \frac{1}{\sqrt{2}}e^{i\sum \xi^{i}L^{i}}\begin{pmatrix}0\\ \nu + H\end{pmatrix}$$

$$\phi \to \phi' = e^{-i\sum \xi^{i}L^{i}}\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ \nu + H\end{pmatrix}$$



$$\nu = (-\mu^{2}/\lambda)^{1/2}$$

$$\mathcal{L}_{\phi} = (D^{\mu}\phi)^{\dagger}D_{\mu}\phi - V(\phi)$$

$$= M_{W}^{2}W^{\mu +}W^{-}_{\mu}\left(1 + \frac{H}{\nu}\right)^{2} + \frac{1}{2}M_{Z}^{2}Z^{\mu}Z_{\mu}\left(1 + \frac{H}{\nu}\right)^{2}$$

$$M_{H}^{2} = -2\mu^{2} = 2\lambda v^{2}$$

$$+ \frac{1}{2}(\partial_{\mu}H)^{2} - V(\phi). \qquad V(\phi) = -\frac{\mu^{4}}{4\lambda} - \mu^{2}H^{2} + \lambda\nu H^{3} + \frac{\lambda}{4}H^{4}.$$

The Fermions:§

$$\mathcal{L}_f = \sum_{m=1}^{F} \left(\bar{q}^0_{mL} i \not{D} q^0_{mL} + \bar{l}^0_{mL} i \not{D} l^0_{mL} + \bar{u}^0_{mR} i \not{D} u^0_{mR} + \bar{d}^0_{mR} i \not{D} d^0_{mR} + \bar{e}^0_{mR} i \not{D} e^0_{mR} + \bar{\nu}^0_{mR} i \not{D} \nu^0_{mR} \right)$$

$$D_\mu q^0_{mL} = \left(\partial_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu + \frac{ig'}{6} B_\mu \right) q^0_{mL}$$

$$D_\mu l^0_{mL} = \left(\partial_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu - \frac{ig'}{2} B_\mu \right) l^0_{mL}$$

$$D_\mu u^0_{mR} = \left(\partial_\mu + \frac{2ig'}{3} B_\mu \right) u^0_{mR}$$

$$D_\mu d^0_{mR} = \left(\partial_\mu - \frac{ig'}{3} B_\mu \right) d^0_{mR}$$

$$D_\mu e^0_{mR} = \left(\partial_\mu - ig' B_\mu \right) e^0_{mR}$$

$$D_\mu \nu^0_{mR} = \partial_\mu \nu^0_{mR},$$

Gauge invariant, massless.

However, a fermion mass must flip chirality:

$$m_f(\bar{f}_L f_R + \bar{f}_R f_L)$$

and thus not SM gauge invariant!

Need something like a doublet:

$$y_f(\bar{f}_1, f_2)_L \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}_L f_R$$

that's the Higgs doublet!

§ P. Langacker: TASI Lectures 2007.

The gauge invariant Yukawa interactions:

$$\mathcal{L}_{Yuk} = -\sum_{m,n=1}^{F} \left[\Gamma^u_{mn} \bar{q}^{\,0}_{mL} \tilde{\phi} u^0_{nR} + \Gamma^d_{mn} \bar{q}^{\,0}_{mL} \phi d^0_{nR} + \Gamma^e_{mn} \bar{l}^{\,0}_{mn} \phi e^0_{nR} + \Gamma^\nu_{mn} \bar{l}^{\,0}_{mL} \tilde{\phi} \nu^0_{nR} \right] + h.c.,$$

After the EWSB,

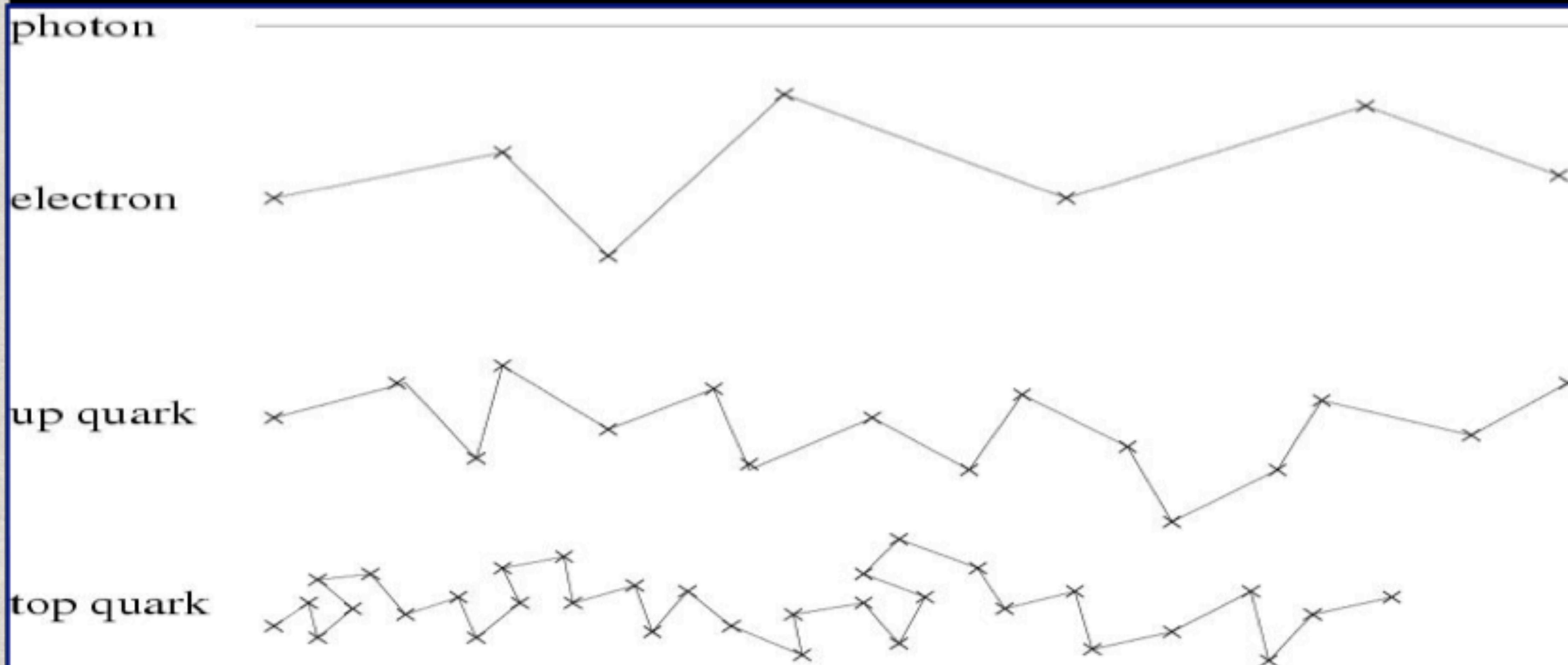
$$-\mathcal{L}_{Yuk} \to \sum_{m,n=1}^{F} \bar{u}^0_{mL} \Gamma^u_{mn} \left(\frac{\nu + H}{\sqrt{2}} \right) u^0_{mR} + (d, e, \nu) \text{ terms}$$

$$= \bar{u}^0_L \left(M^u + h^u H \right) u^0_R + (d, e, \nu) \text{ terms } + h.c.,$$

$$-\mathcal{L}_{Yuk} = \sum_i m_i \bar{\psi}_i \psi_i \left(1 + \frac{g}{2M_W} H \right) = \sum_i m_i \bar{\psi}_i \psi_i \left(1 + \frac{H}{\nu} \right)$$

2. Higgs Boson Couplings:

Masses determined by interactions with vacuum:



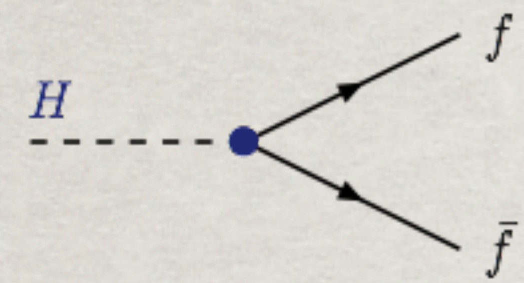
$$M_{W,Z} = \frac{1}{2} g_V v, \quad m_f = \frac{g_f}{\sqrt{2}} v, \quad v^{-2} = \sqrt{2}\, G_F.$$

Thus, where ever is mass, there will be H!

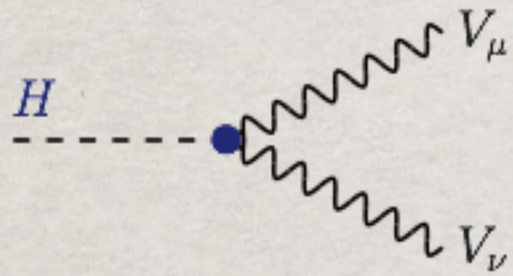
The Low-Energy-theorem:

$$m_i \to m_i \left(1 + \frac{H}{v}\right) \text{ for } p_H < v.$$

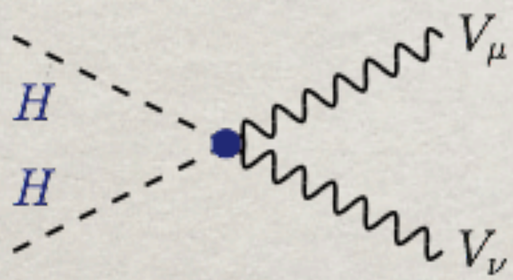
Feynman rules:



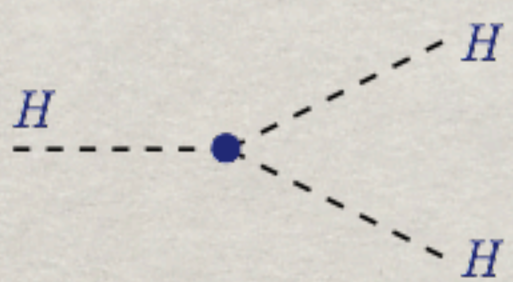
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f \qquad \times (i)$$



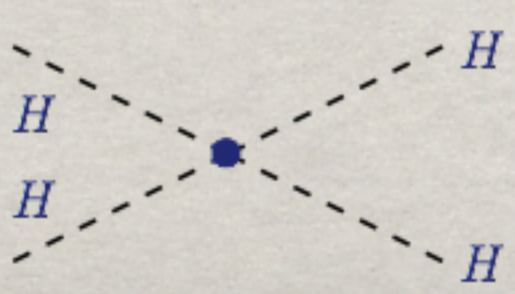
$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2 \qquad \times (-ig_{\mu\nu})$$



$$g_{HHVV} = 2M_V^2/v^2 = 2\sqrt{2}G_\mu M_V^2 \qquad \times (-ig_{\mu\nu})$$



$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2} M_H^2 \qquad \times (i)$$



$$g_{HHHH} = 3M_H^2/v^2 = 3\sqrt{2}G_\mu M_H^2 \qquad \times (i)$$

Exercise 6: Verify the above Feynman rules by invoking the low-energy theorem:

$$m_i \to m_i(1+\frac{H}{v}) \quad \text{for} \quad p_H < v.$$

Goldstone-boson Equivalence Theorem:

At high energies $E \gg M_W$, the longitudinally polarized gauge bosons behave like the corresponding Goldstone bosons. (They remember their origin!)

Caution: Very often, we say at high energies, $M_W \to 0$.
Rigorously speaking, we mean: g, $M_W \to 0$, but $M_W/g \to v/2$.

Exercise 7: Verify the Goldstone-boson Equivalence Theorem by examining the HWW vertex.
Hint: Use $\epsilon_L^\mu \to p_H^\mu/M_W$. It should give you HHH vertex.

Lecture II: Higgs Physics at Colliders

A. Higgs Boson Decay

1. Decay to fermions
2. Decay WW, ZZ
3. Decay through loops

B. Higgs Boson Production at the LHC

1. The leading channels
2. The search strategies
3. Signal characteristics

C. Higgs Boson Production at e^+e^- colliders

D. Higgs Boson Production at a muon collider

Pre-requisite formulae:

For a $2 \to n$ scattering process:

$$\sigma(ab \to 1+2+...n) = \frac{1}{2s} \overline{\sum} |\mathcal{M}|^2 \; dPS_n,$$

$$dPS_n \equiv (2\pi)^4 \; \delta^4 \left(P - \sum_{i=1}^{n} p_i \right) \Pi_{i=1}^{n} \frac{1}{(2\pi)^3} \frac{d^3\vec{p}_i}{2E_i},$$

$$s = (p_a + p_b)^2 \equiv P^2 = \left(\sum_{i=1}^{n} p_i \right)^2,$$

where $\overline{\sum} |\mathcal{M}|^2$: dynamics (dimension $4 - 2n$);

dPS_n: kinematics (Lorentz invariant, dimension $2n - 4$.)

For a $1 \to n$ decay process, the partial width in the rest frame:

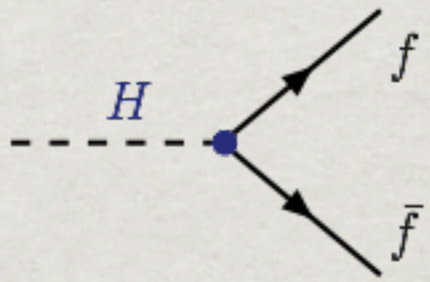
$$\Gamma(a \to 1+2+...n) = \frac{1}{2M_a} \overline{\sum} |\mathcal{M}|^2 \; dPS_n.$$

$$\tau = \Gamma_{tot}^{-1} = (\sum_f \Gamma_f)^{-1}.$$

A. Higgs Boson Decay§

$$\Gamma = g^2 \, \frac{dPS_2}{2m} \, \sum |M|^2 \propto \frac{g^2}{4\pi} \, m \, \beta^{2\ell+1}$$

1. Decay to fermions:



$$\Gamma_{\rm Born}(A \to f\bar{f}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H \, m_f^2 \, \beta_f$$

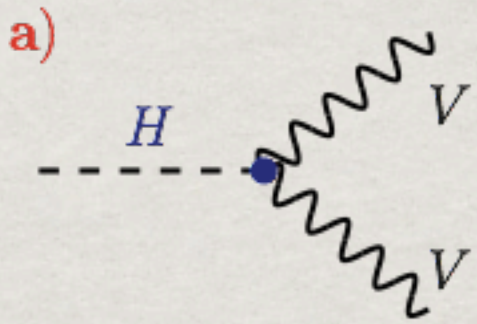
The largest higher-order effect is the quark running mass:

$$\begin{aligned} \bar{m}_Q(\mu)_{LO} &= \bar{m}_Q(m_Q)\left(\frac{\alpha_s(\mu)}{\alpha_s(m_Q)}\right)^{\frac{2b_0}{\gamma_0}} \\ &= \bar{m}_Q(m_Q)\left(1 - \frac{\alpha_s(\mu)}{4\pi}\ln\left(\frac{\mu^2}{m_Q^2}\right) + \cdots\right) \end{aligned}$$

§ L. Reina, TASI lectures, 2011.

A. Higgs Boson Decay§

2. Decay to WW,ZZ:



$$\Gamma(H \to VV) = \frac{G_\mu M_H^3}{16\sqrt{2}\pi}\, \delta_V \sqrt{1-4x}\,(1-4x+12x^2)\ , \quad x = \frac{M_V^2}{M_H^2}$$

$$\Gamma = g^2\ \frac{dPS_2}{2m}\ \sum |M|^2 \propto \frac{g^2}{4\pi}\ m\ \beta^{2\ell+1}$$

The unusual M^3 dependence is due to the V_L: M_H/M_V.

Exercise 8:

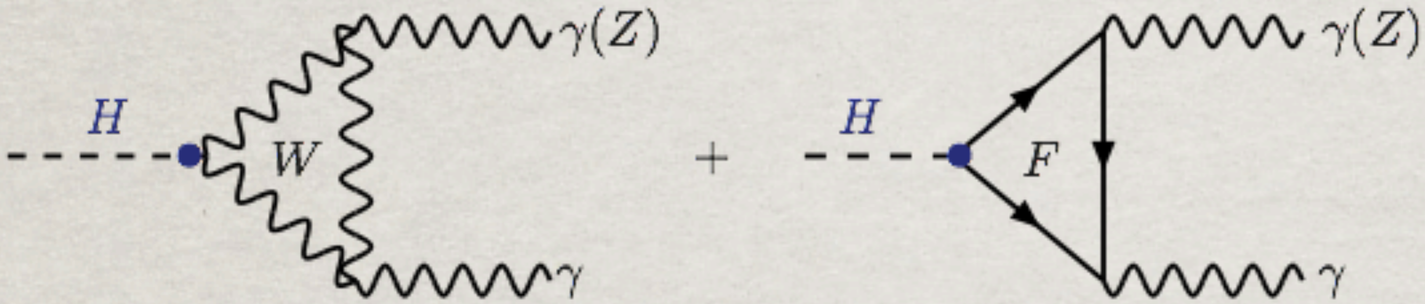
Calculate the Higgs decay to polarized pairs V_TV_T, V_LV_T, and V_LV_L.

§ L. Reina, TASI lectures, 2011.

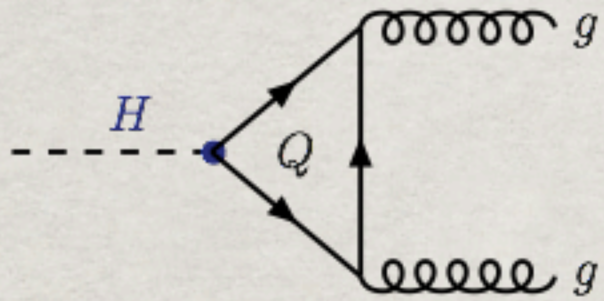
A. Higgs Boson Decay§

3. Decay through loops:

a)



b)



Sensitive to new charged (Q,L), colored (Q) heavy states in loops.

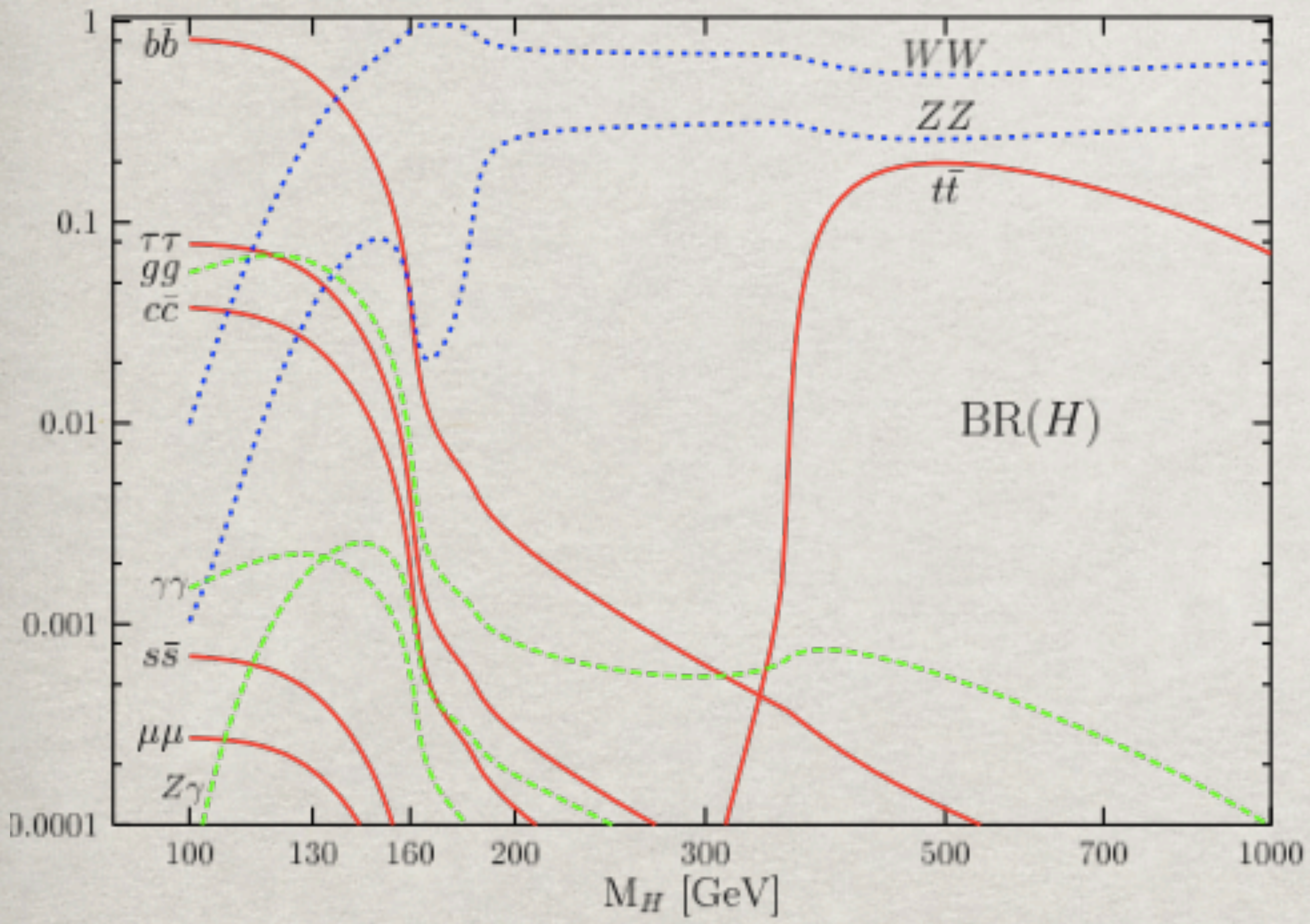
$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c^f Q_f^2 A_f^H(\tau_f) + A_W^H(\tau_W) \right|^2$$

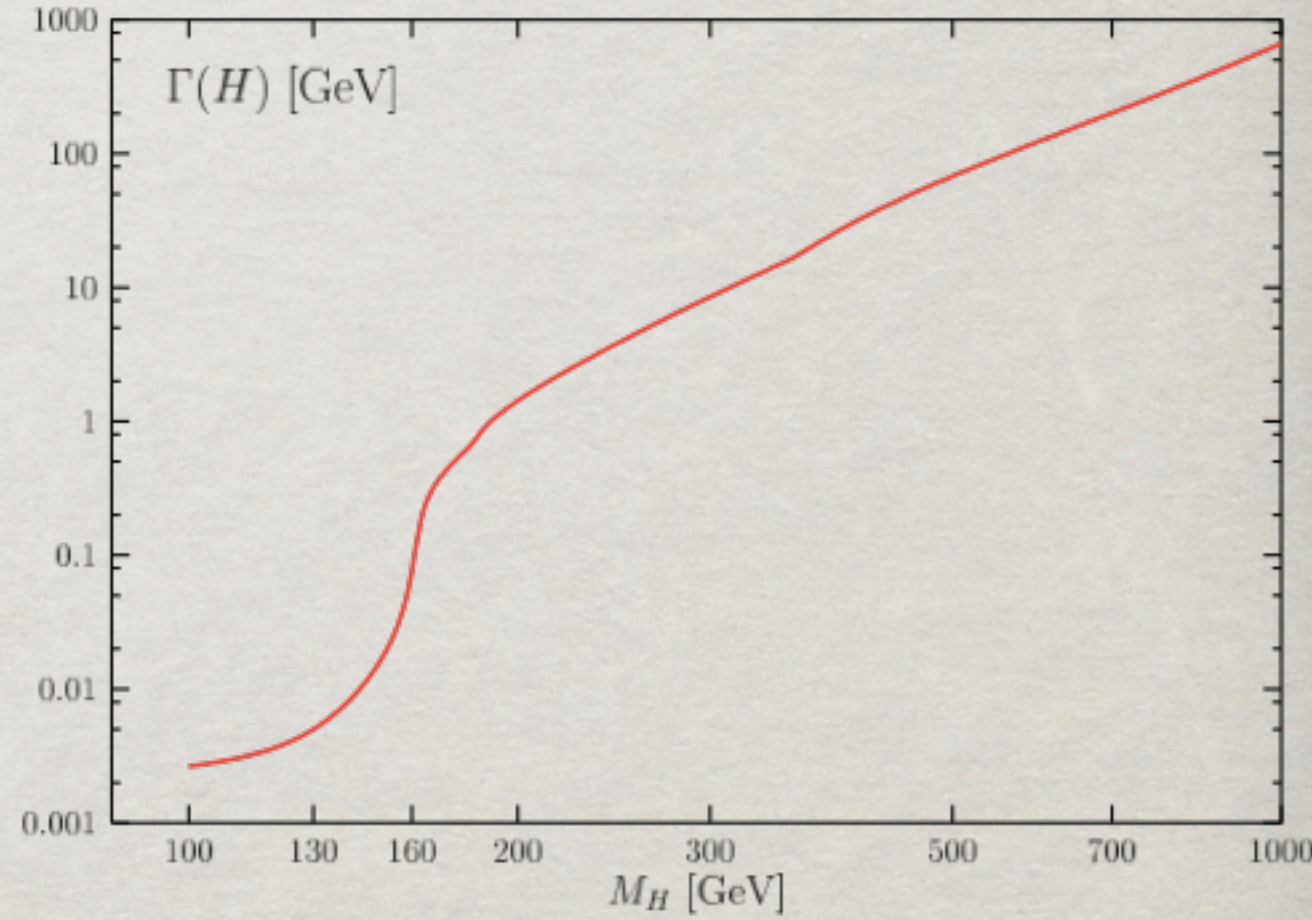
$$\Gamma(H \to \gamma Z) = \frac{G_F^2 M_W^2 \alpha M_H^3}{64\pi^4} \left(1 - \frac{M_Z^2}{M_H^2}\right)^3 \left| \sum_f A_f^H(\tau_f, \lambda_f) + A_W^H(\tau_W, \lambda_W) \right|^2$$

$$\Gamma(H \to gg) = \frac{G_F \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_q A_q^H(\tau_q) \right|^2$$

§ L. Reina, TASI lectures, 2011.

As the results for a SM Higgs:
The branching fractions and total width





For m_H = 125 GeV, Γ(total) ≈ 4 MeV

BR(bb) ≈ 60%

BR(ττ) ≈ 8%

BR(WW) ≈ 21%

BR(ZZ) ≈ 2%

BR(gg) ≈ 9%

BR(γγ) ≈ 0.22%

Particle production in hadronic collisions:

The luminosity:

$$\mathcal{L} \propto f n_1 n_2 / a,$$

(a some beam transverse profile) in units of #particles/cm^2/s

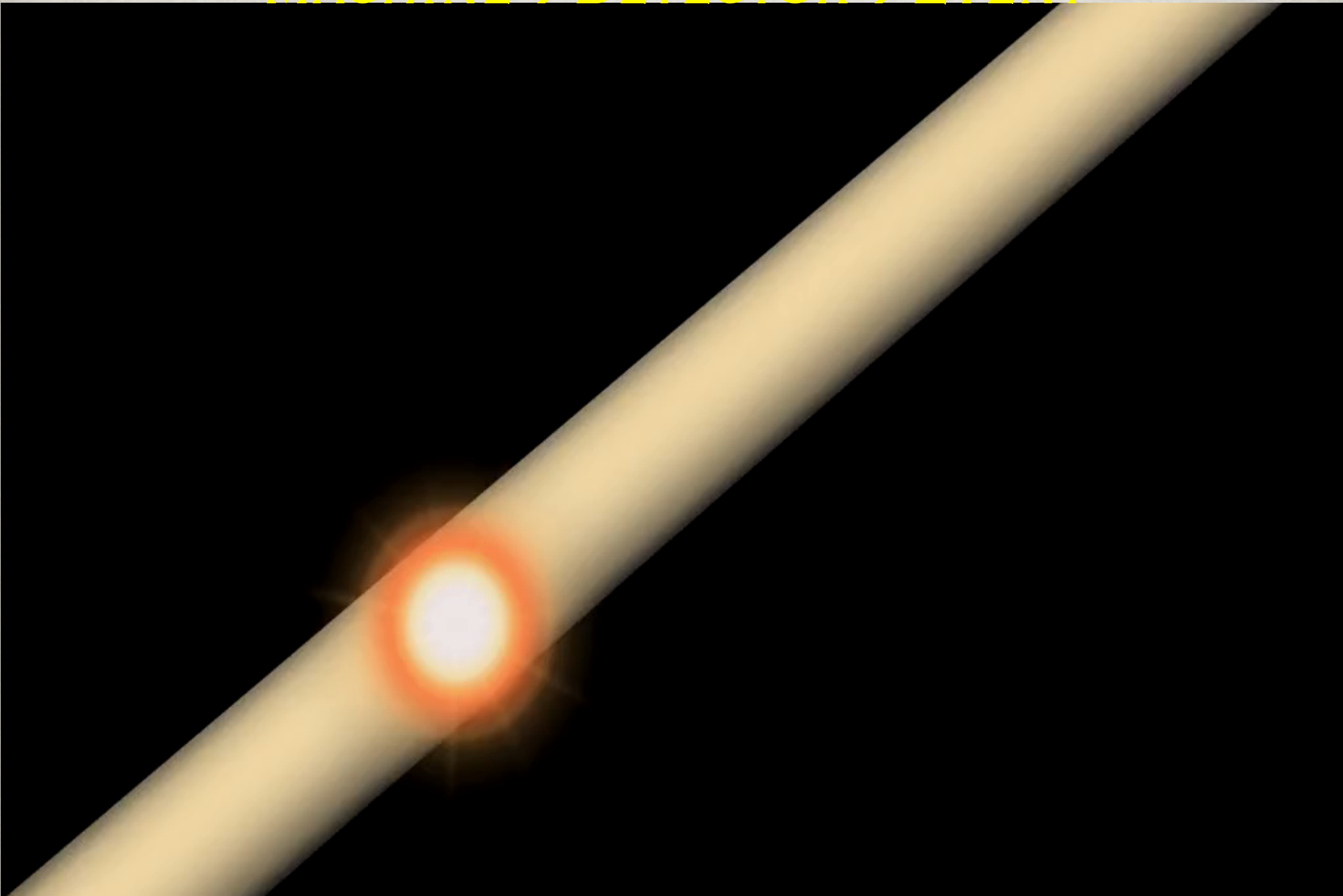
$\Rightarrow 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 1\ \mathrm{nb}^{-1}\ \mathrm{s}^{-1} \approx 10\ \ \mathrm{fb}^{-1}/\mathrm{year}.$

Current and future high-energy colliders:

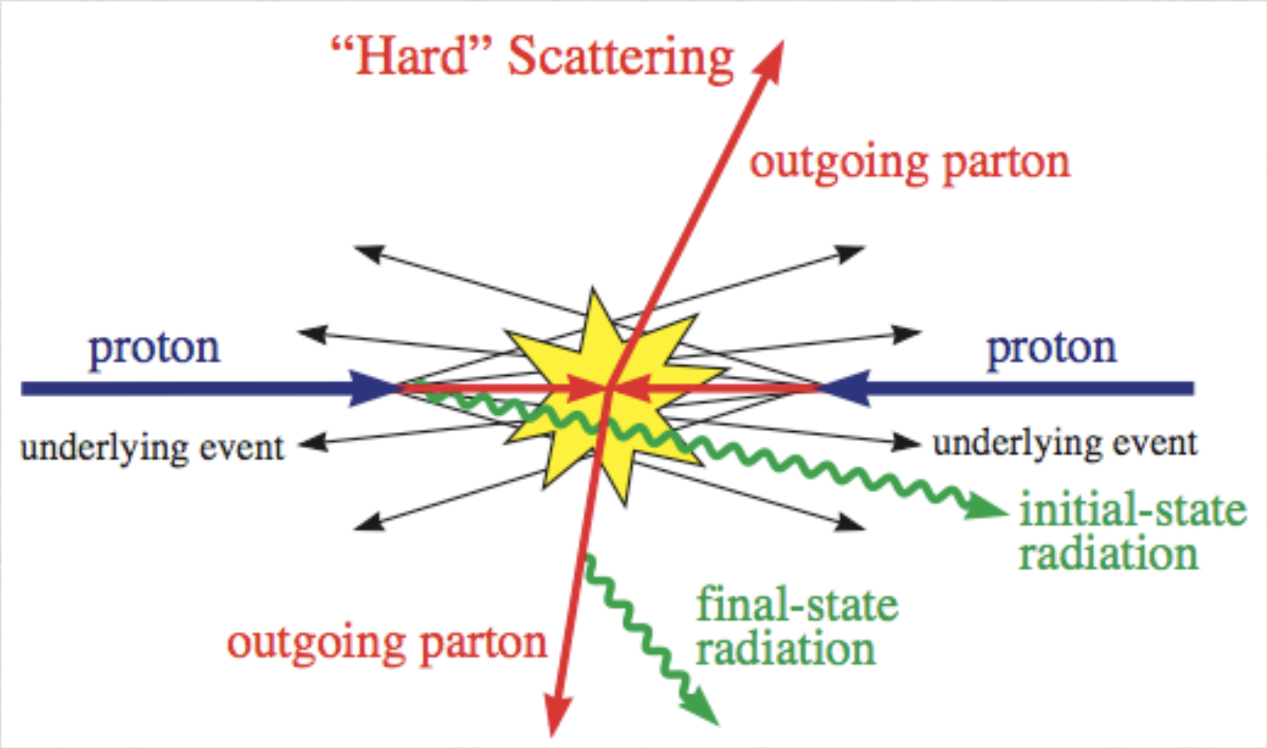
Hadron Colliders	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (cm^{-2}s^{-1})	$\delta E/E$	f (MHz)	#/bunch (10^{10})	L (km)
Tevatron	1.96	2.1×10^{32}	9×10^{-5}	2.5	p: 27, $\bar{p}$: 7.5	6.28
LHC	(7) 14	(10^{32}) 10^{34}	0.01%	40	10.5	26.66

e^+e^- Colliders	$\sqrt{s}$ (TeV)	$\mathcal{L}$ (cm^{-2}s^{-1})	$\delta E/E$	f (MHz)	polar.	L (km)
ILC	0.5–1	2.5×10^{34}	0.1%	3	80, 60%	14 – 33
CLIC	3–5	$\sim 10^{35}$	0.35%	1500	80, 60%	33 – 53

Trapping The Higgs :
Machine→Detector→Event



Particle production in hadronic collisions:



In high energy collisions involving a hadron, the total cross sections can be factorized into two factors:

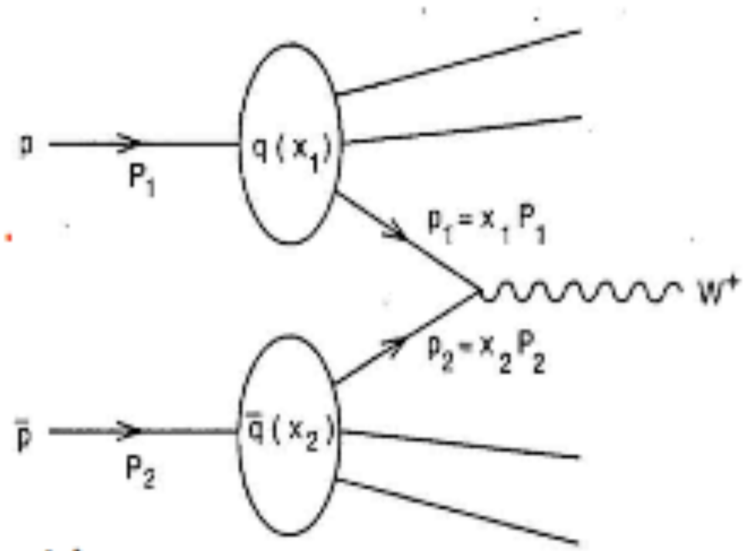
(1). hard subprocess of parton scattering with a large scale $\mu^2 \gg \Lambda^2_{QCD}$;

(2). "parton distribution functions" (hadronic structure with $Q^2 < \mu^2$.)

Observable cross sections at hadron level:

$$\sigma_{pp}(S) = \int dx_1 dx_2 P_1(x_1, Q^2) P_2(x_2, Q^2)\ \hat{\sigma}_{parton}(s).$$

$$= \sum_{ij} \int d\tau \frac{dL_{ij}}{d\tau}\ \sigma_{ij}(s), \quad \tau = s/S$$

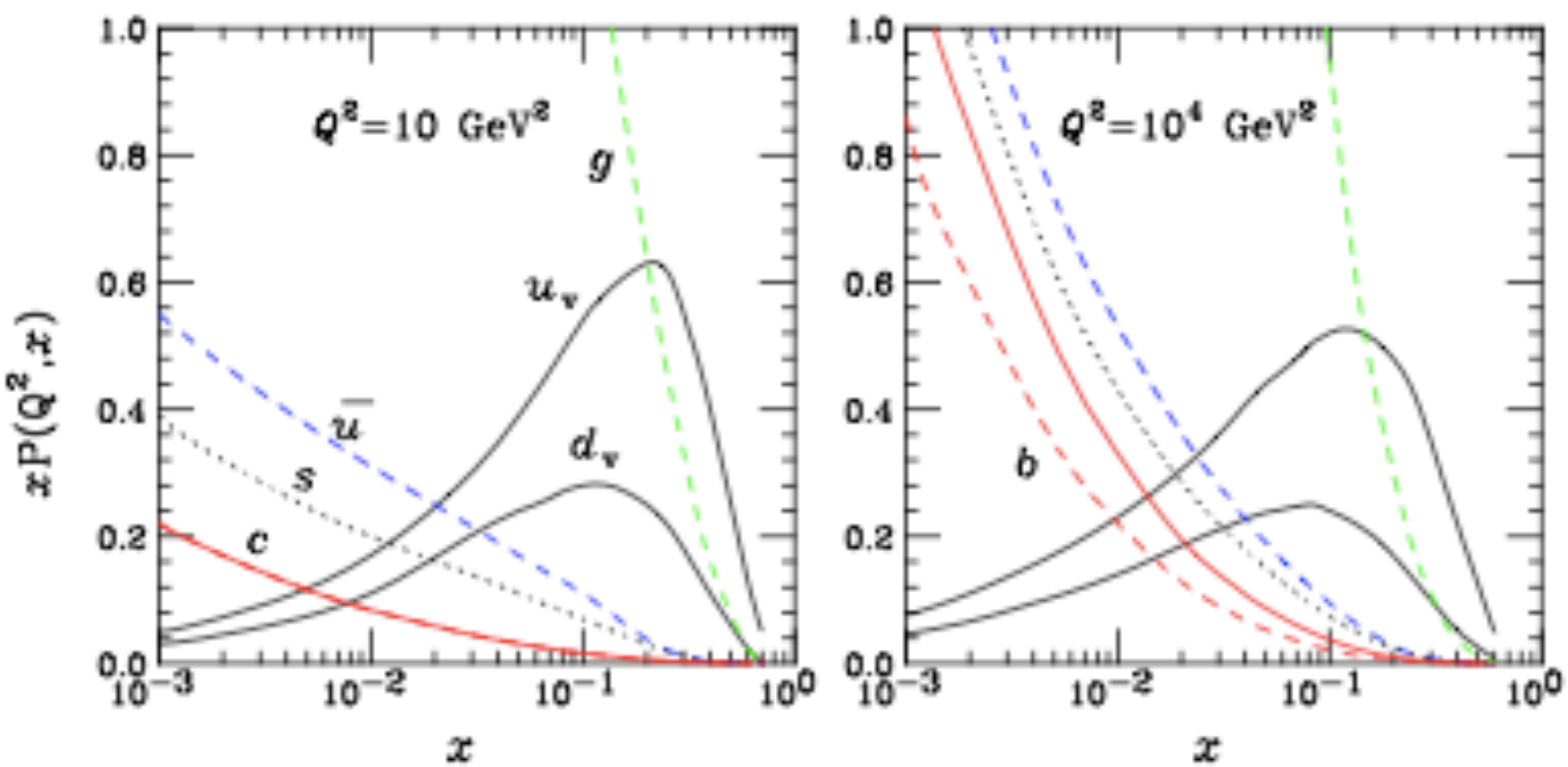


† $\hat{\sigma}_{parton}(s)$ is theoretically calculated by perturbation theory (in the SM or models beyond the SM).

† $\hat{\sigma}_{parton}(s)$ is theoretically calculated by perturbation theory (in the SM or models beyond the SM).

Ultra violet (UV) divergence (beyond leading order) is renormalized;
Infra-red (IR) divergence is cancelled by soft gluon emissions;
Co-linear divergence (massless) is factorized into PDF
– The essence of "factorization theorem".

Typical quark/gluon parton distribution functions $P(x, Q^2)$:

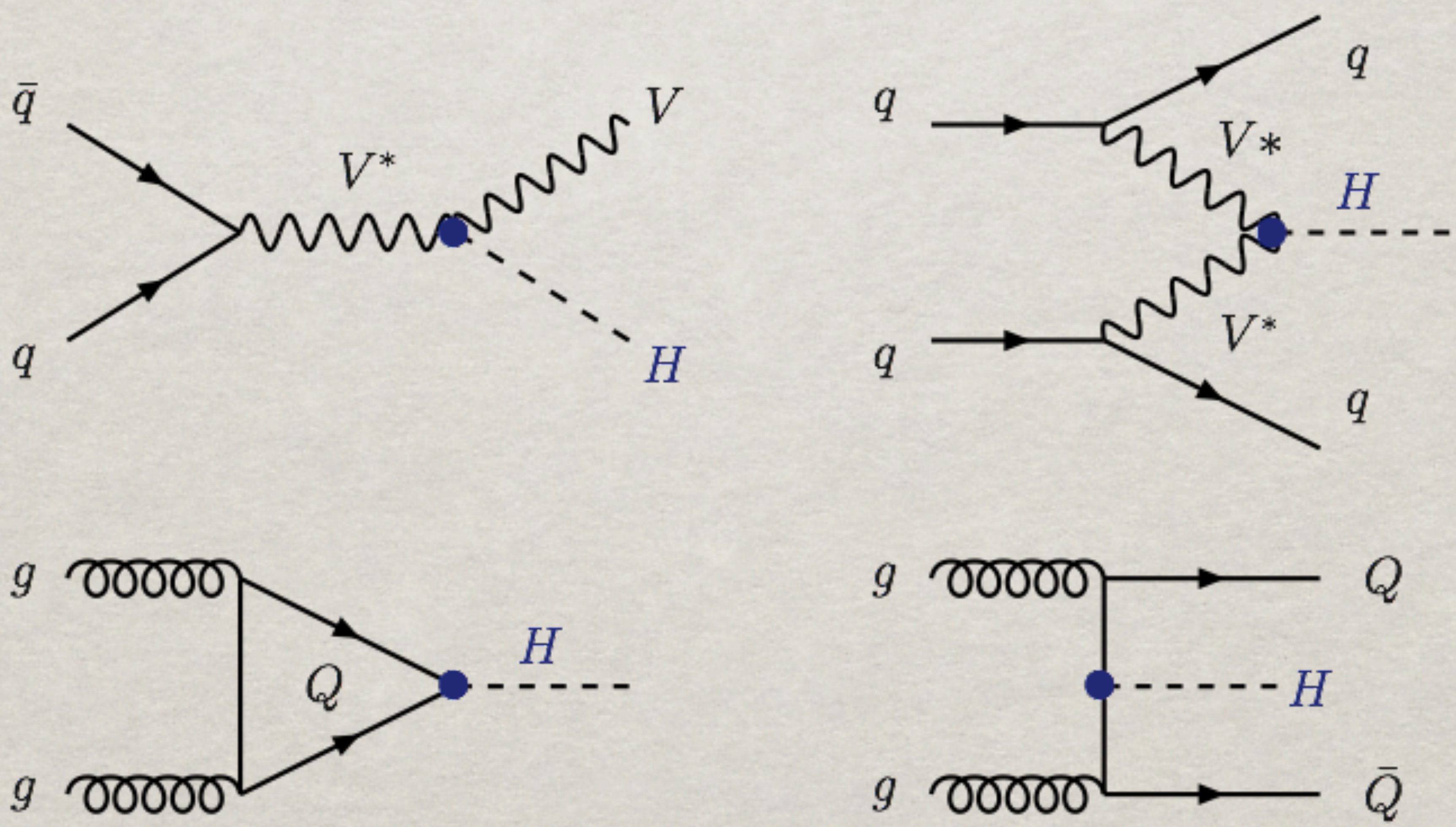


B. Higgs Boson Production at LHC

1. The leading channels:

Recall that the Higgs couples preferably to heavier particles.

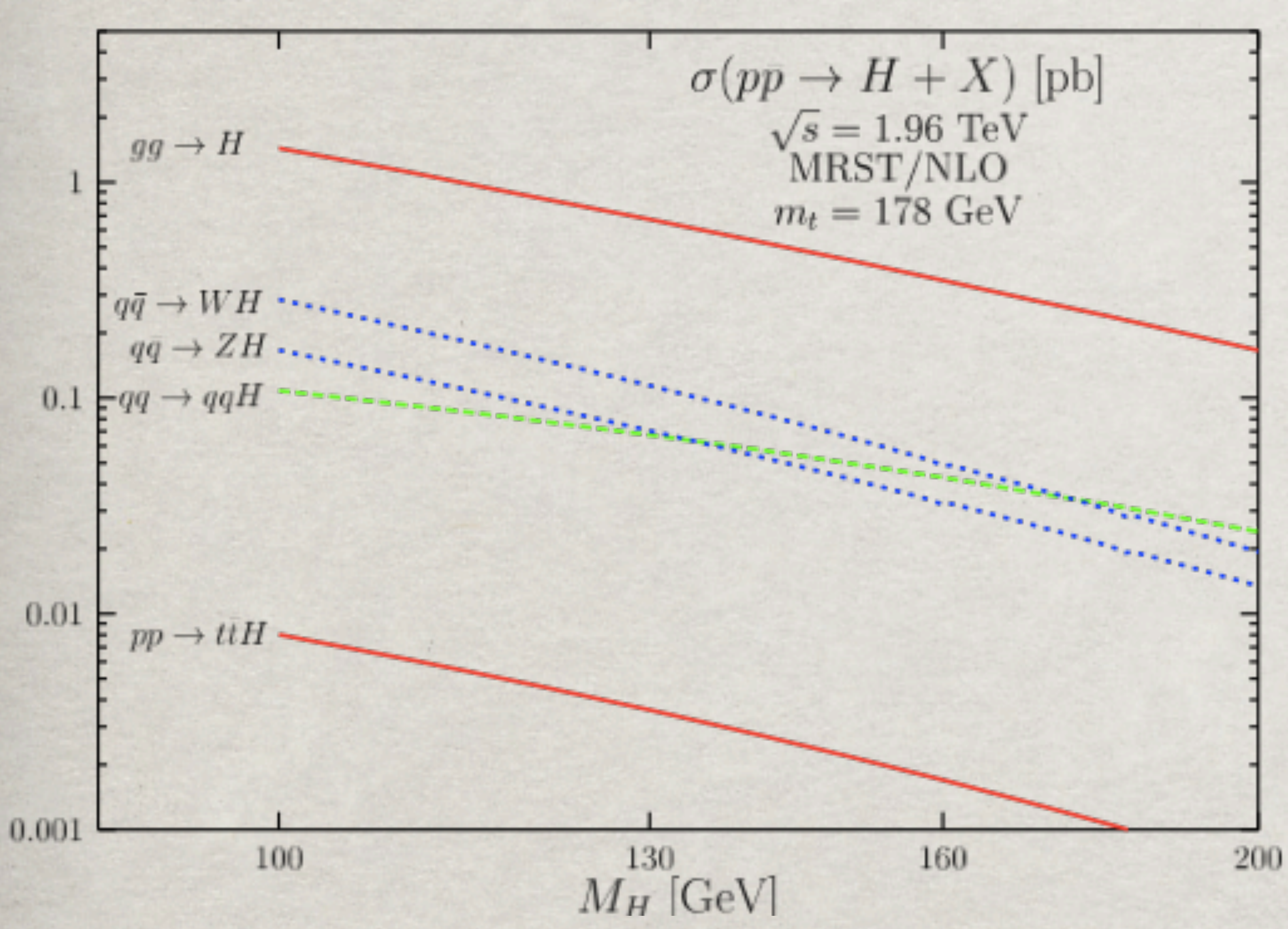
$$
\begin{aligned}
\text{associated production with } W/Z: &\quad q\bar{q} \longrightarrow V + H \\
\text{vector boson fusion}: &\quad qq \longrightarrow V^*V^* \longrightarrow qq + H \\
\text{gluon} - \text{gluon fusion}: &\quad gg \longrightarrow H \\
\text{associated production with heavy quarks}: &\quad gg, q\bar{q} \longrightarrow Q\bar{Q} + H
\end{aligned}
$$

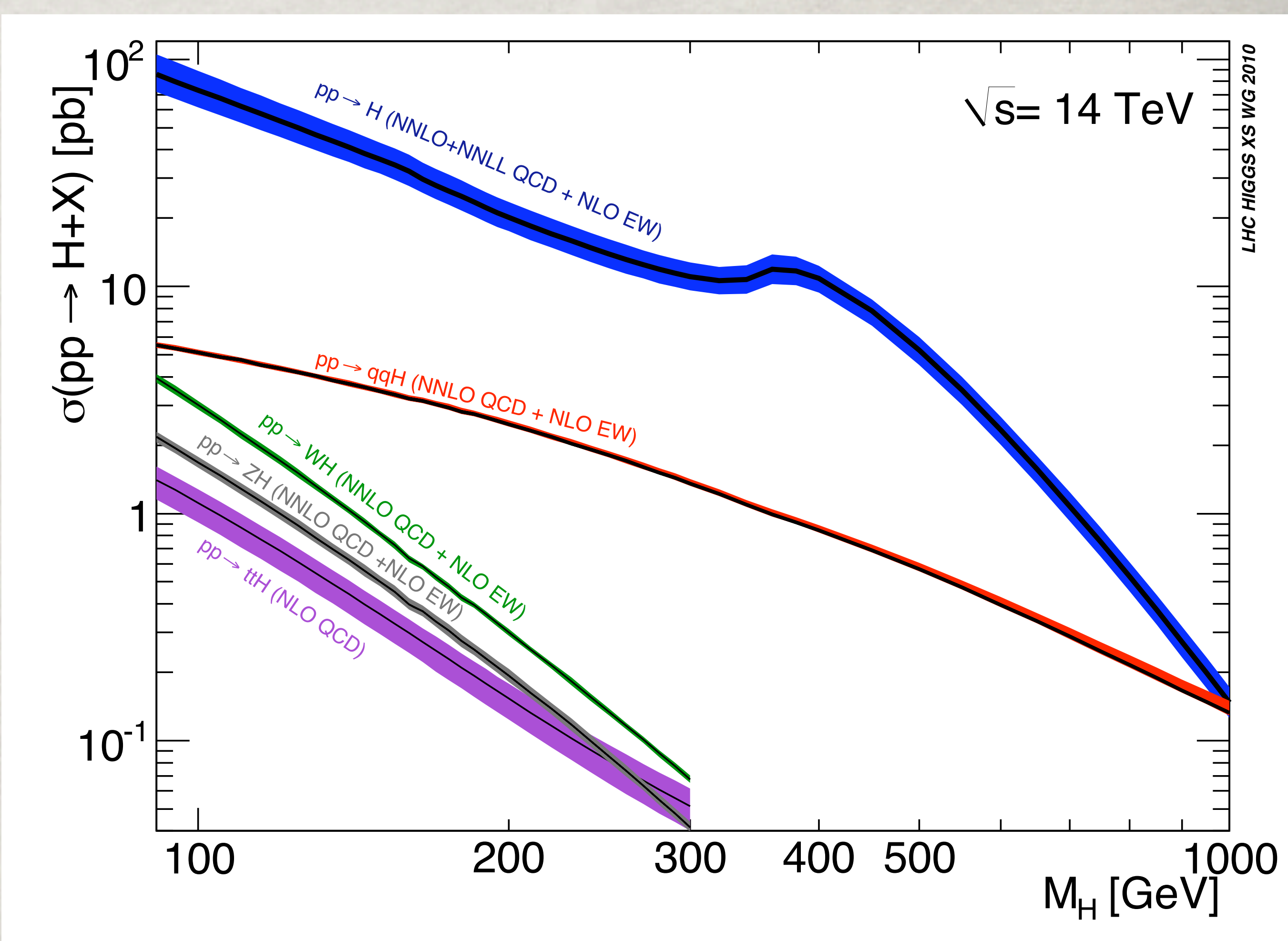


Calculation history and references compiled by Laura Reina

process	$\sigma_{NLO,NNLO}$ by
$gg \to H$	S.Dawson, NPB 359 (1991), A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser *et al.*, JHEP 0212 (2002); V.Ravindran *et al.*, NPB 634 (2002) D. de Florian *et al.*, PRL 82 (1999) R.Harlander, W.Kilgore, PRL 88 (2002) (NNLO) C.Anastasiou, K.Melnikov, NPB 646 (2002) (NNLO) V.Ravindran *et al.*, NPB 665 (2003) (NNLO) S.Catani *et al.* JHEP 0307 (2003) (NNLL), G.Bozzi *et al.*, PLB 564 (2003), NPB 737 (2006) (NNLL) C.Anastasiou, R.Boughezal, F.Petriello, JHEP (2008) (QCD+EW)
$q\bar{q} \to (W,Z)H$	T.Han, S.Willenbrock, PLB 273 (1991) M.L.Ciccolini, S.Dittmaier, and M.Krämer (2003) (EW) O.Brien, A.Djouadi, R.Harlander, PLB 579 (2004) (NNLO)
$q\bar{q} \to q\bar{q}H$	T.Han, G.Valencia, S.Willenbrock, PRL 69 (1992) T.Figy, C.Oleari, D.Zeppenfeld, PRD 68 (2003) M.L.Ciccolini, A.Denner,S.Dittmaier (2008) (QCD+EW) P.Bolzoni, F.Maltoni, S.O.Moch, and M.Zaro (2010) (NNLO)
$q\bar{q}, gg \to t\bar{t}H$	W.Beenakker *et al.*, PRL 87 (2001), NPB 653 (2003) S.Dawson *et al.*, PRL 87 (2001), PRD 65 (2002), PRD 67,68 (2003)
$q\bar{q}, gg \to b\bar{b}H$	S.Dittmaier, M.Krämer, M.Spira, PRD 70 (2004) S.Dawson *et al.*, PRD 69 (2004), PRL 94 (2005)
$gb(\bar{b}) \to b(\bar{b})H$	J.Campbell *et al.*, PRD 67 (2003)
$b\bar{b} \to H$	D.A.Dicus *et al.* PRD 59 (1999); C.Balasz *et al.*, PRD 60 (1999). R.Harlander, W.Kilgore, PRD 68 (2003) (NNLO)

Production cross sections at hadron colliders:

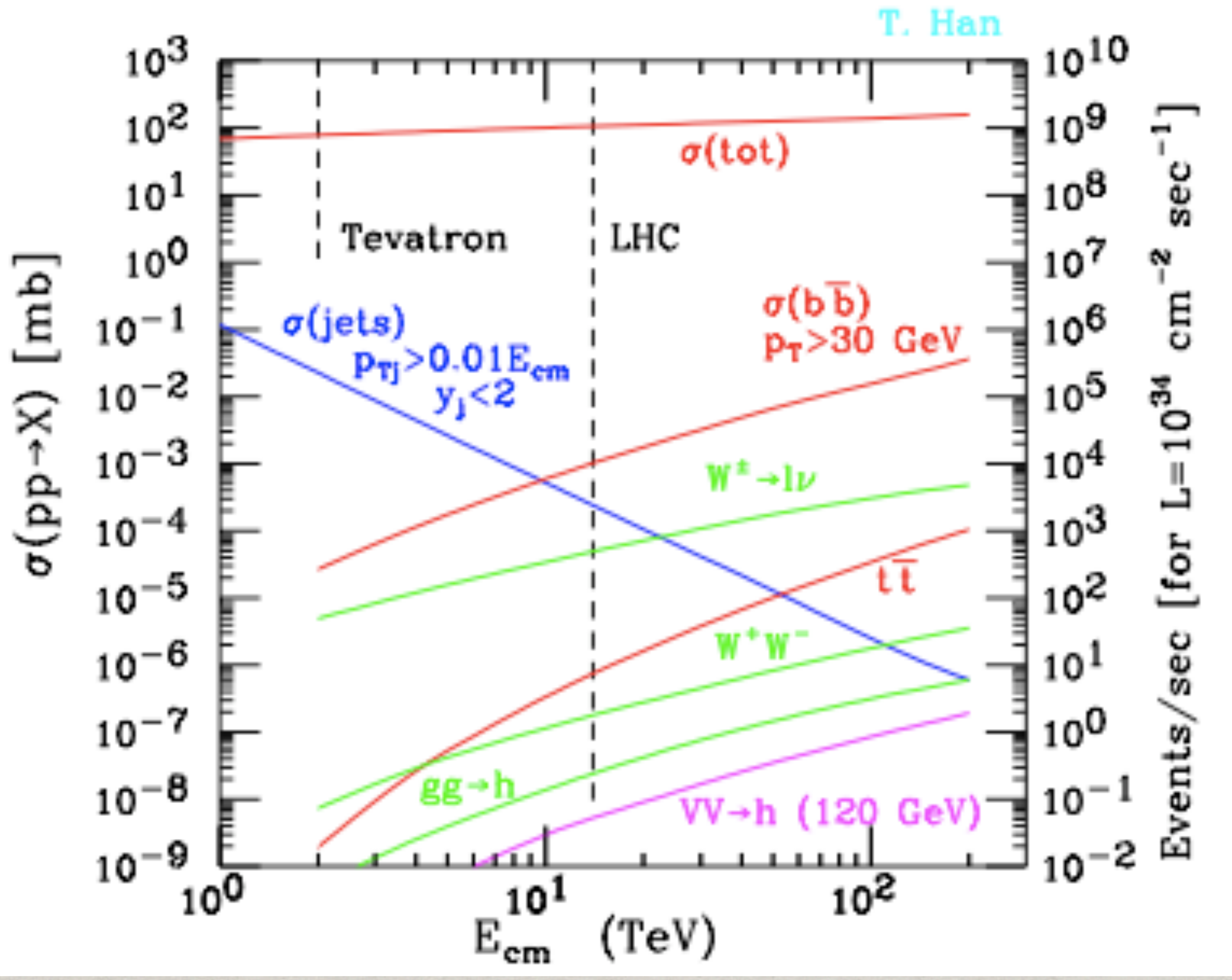




Exercise 9: List three leading processes for SM Higgs pair production and comment on their relative sizes.

§ L. Reina, TASI lectures, 2011.
A. Djouadi, hep-ph/0503172.

Total rates in hadronic collisions:



2. Signal Search Strategy:

Searching for the Higgs boson at the LHC is highly non-trivial!

In theory:

- assume a mass parameter;
- predict the production cross section;
- specify a (good) final state in H decay;
- identify the SM backgrounds;
- calculate the observability by S/√B or alike

In experiments:

- specify a (good) final state from H decay;
- compare with the SM backgrounds;
- assume a mass parameter and compare with theory;
- estimate the sensitivity (μ signal strength, p-value)

Salute to theorists/experimentalists:

We Made It!

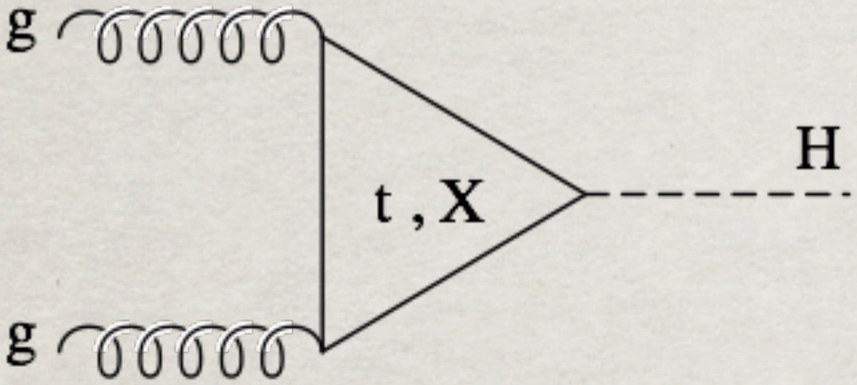
We want to know more (experimentally):

- Is there more than one Higgs boson?
- Does this H decay to other things unexpected?
- Couplings as accurate as possible:
  - to verify the SM prediction: Spin, parity …
  - to seek for hints for new physics.

Still a lot of hard, but fun work to do!

3. Signal Characteristics:

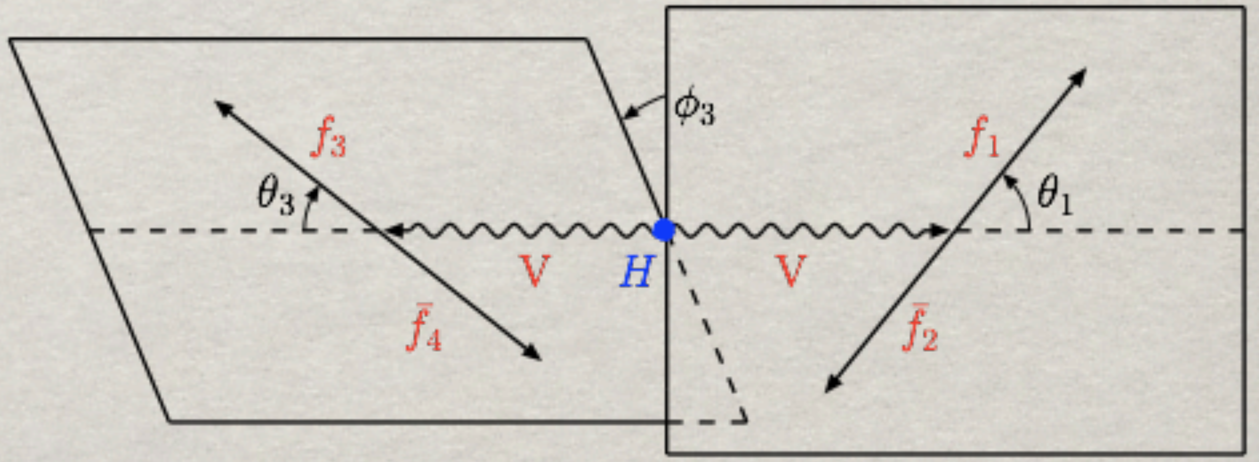
(a). Gluon fusion: The leading production channel



σ(125 GeV@ 8 TeV) ≈ 20 pb
σ(125 GeV@14 TeV) ≈ 40 pb

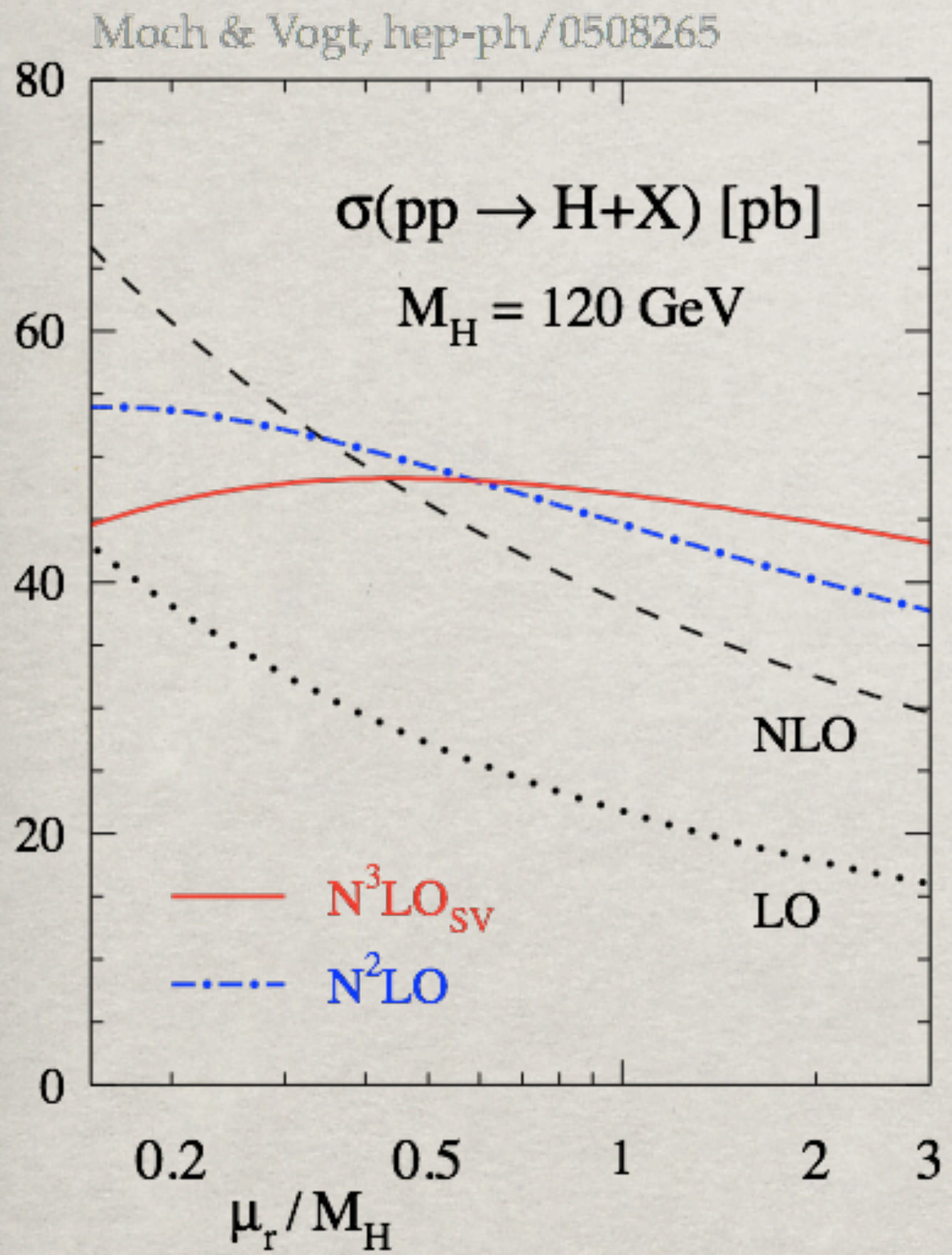
- Need clean decay modes: γγ, WW, ZZ
- Effects from radiative corrections very large!§
- Sensitive to new colored particles in the loop:

gg → H sensitive to new colored states: Q
H → γγ sensitive to new charged states: Q, L
H → ZZ → 4 leptons
best to study the Higgs
CP properties:



§ L. Reina, TASI lectures, 2011.

QCD corrections to $gg \to H$

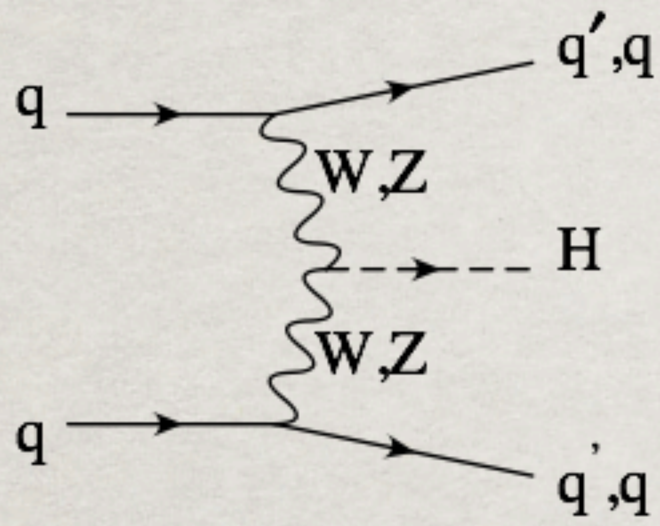


- Large QCD corrections: K-factor of about 2
- Stabilization of scale dependence needs N^3LO or at least NNLO corrections
- Cross section estimate for $m_H = 126$ GeV at 8 TeV from LHC XS WG, determined at NNLL QCD and NLO EW

$$\sigma(gg \to H) = 19.22\,\text{pb} \pm 14.7\%$$

- Error is linear combination of $\approx 7.5\%$ scale uncertainty and $\approx 7.2\%$ from gluon pdf and α_s error
- Additional uncertainty from use of effective hgg vertex (heavy top approximation) is estimated to be below 2%

(b). The Vector Boson Fusion:



$\sigma(14\ \text{TeV}) \approx 4$ pb

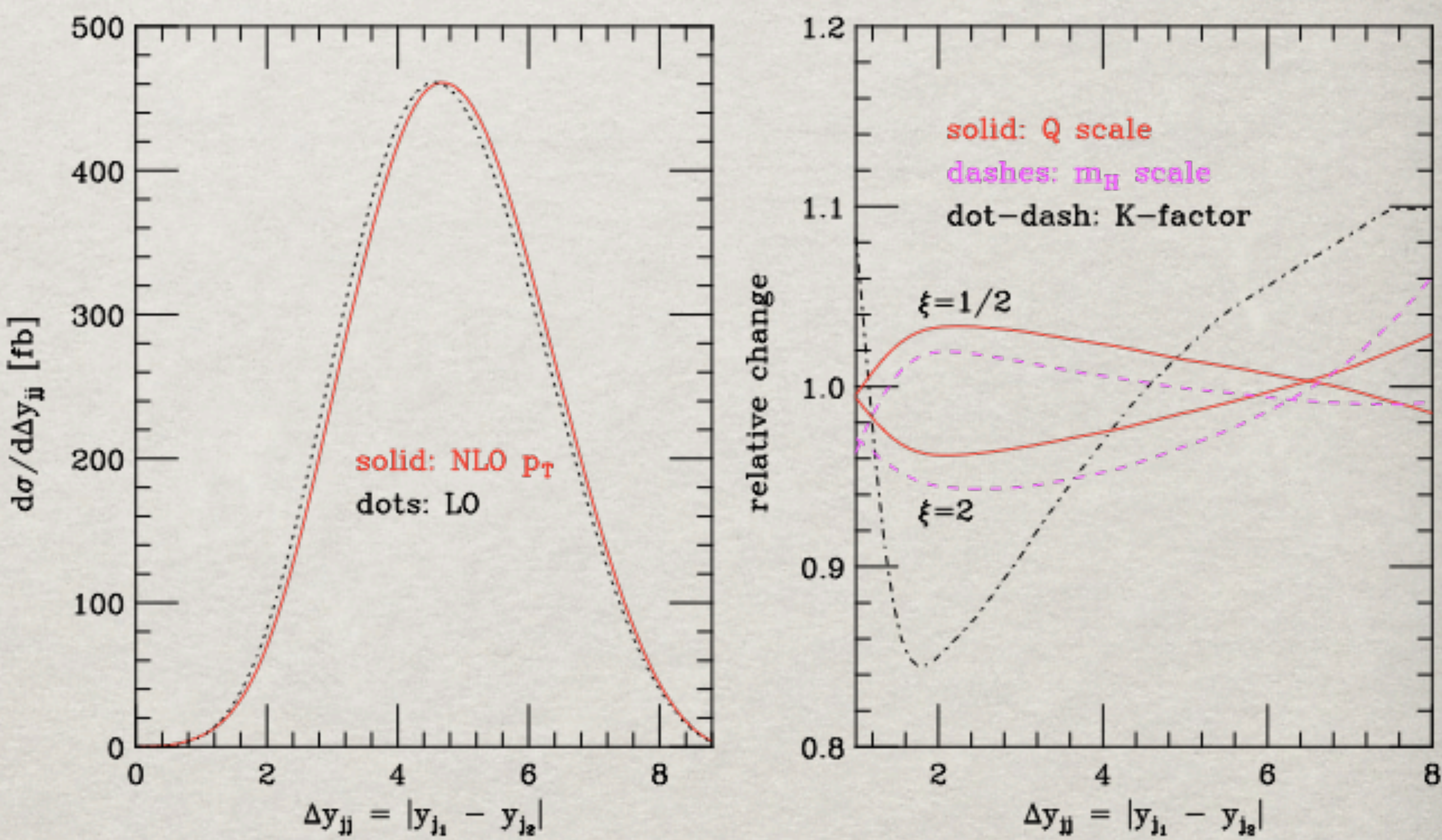
- Need clean decay modes: ττ, WW, ZZ, γγ
- Effects from radiative corrections very small!
  -> color singlet exchange, low jet activities.
- Sensitive to HWW, HZZ couplings
- Good for H → ττ, γγ
- A bit lower rate, but unique kinematics

NLO corrections to VBF

- Small QCD corrections of order 10%
- Tiny scale dependence of NLO result
  - $\pm 5\%$ for distributions
  - $< 1\%$ for σ_{total}
- pdf error is below 3% since pdf's are dominated by valence quarks
- $\approx -5\%$ EW corrections included

  Ciccolini, Denner, Dittmaier, 0710.4749

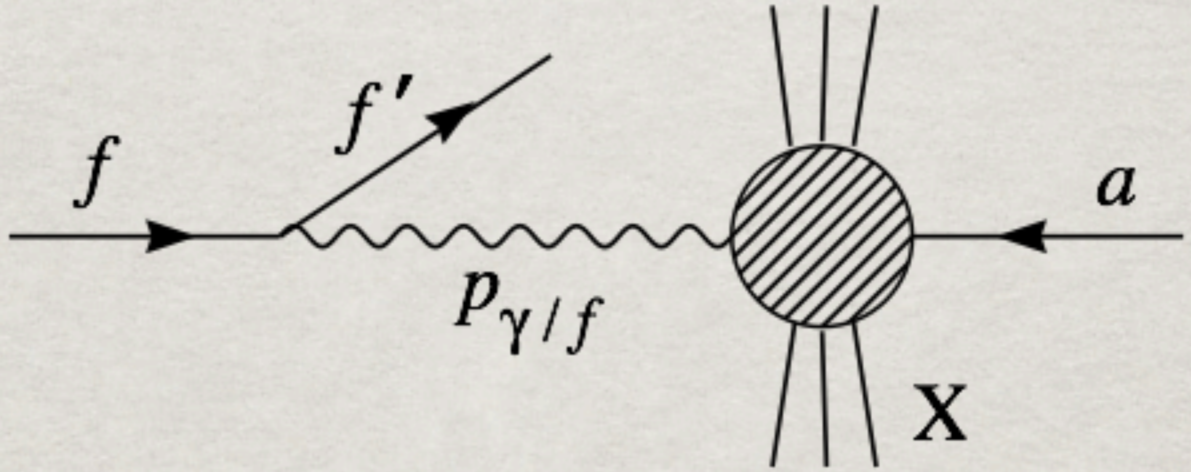
  Figy, Palmer, Weiglein arXiv:1012.4789
- Very small cross section error of about 3% for $m_H = 126$ GeV



$m_H = 120$ GeV, typical VBF cuts

Basic feature: V radiation off a quark

The familiar Weizsäcker-Williams approximation



$$\sigma(fa \to f'X) \approx \int dx\, dp_T^2\, P_{\gamma/f}(x, p_T^2)\, \sigma(\gamma a \to X),$$

$$P_{\gamma/e}(x, p_T^2) = \frac{\alpha}{2\pi}\frac{1+(1-x)^2}{x}\left(\frac{1}{p_T^2}\right)\Big|_{m_e}^{E}.$$

Exercise 10: Qualitative feature for V radiation off a quark

- Generalize to massive gauge bosons:

$$P^T_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{8\pi^2}\,\frac{1+(1-x)^2}{x}\,\frac{p_T^2}{(p_T^2+(1-x)M_V^2)^2},$$
$$P^L_{V/f}(x,p_T^2) = \frac{g_V^2+g_A^2}{4\pi^2}\,\frac{1-x}{x}\,\frac{(1-x)M_V^2}{(p_T^2+(1-x)M_V^2)^2}.$$

Special kinematics for massive gauge boson fusion processes:

For the accompanying jets,

At low-p_{jT},

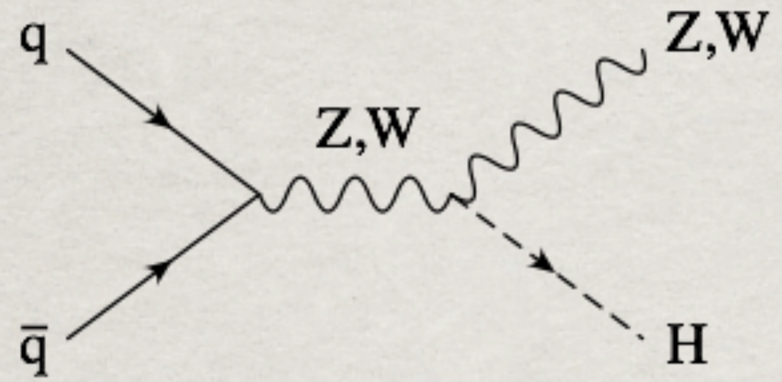
$$\left.\begin{aligned} &p_{jT}^2 \approx (1-x)M_V^2 \\ &E_j \sim (1-x)E_q \end{aligned}\right\} \textit{forward jet tagging}$$

At high-p_{jT},

$$\left.\begin{aligned} &\frac{d\sigma(V_T)}{dp_{jT}^2} \propto 1/p_{jT}^2 \\ &\frac{d\sigma(V_L)}{dp_{jT}^2} \propto 1/p_{jT}^4 \end{aligned}\right\} \textit{central jet vetoing}$$

has become important tools for Higgs searches, single-top signal etc.

(c). VH Associate production:

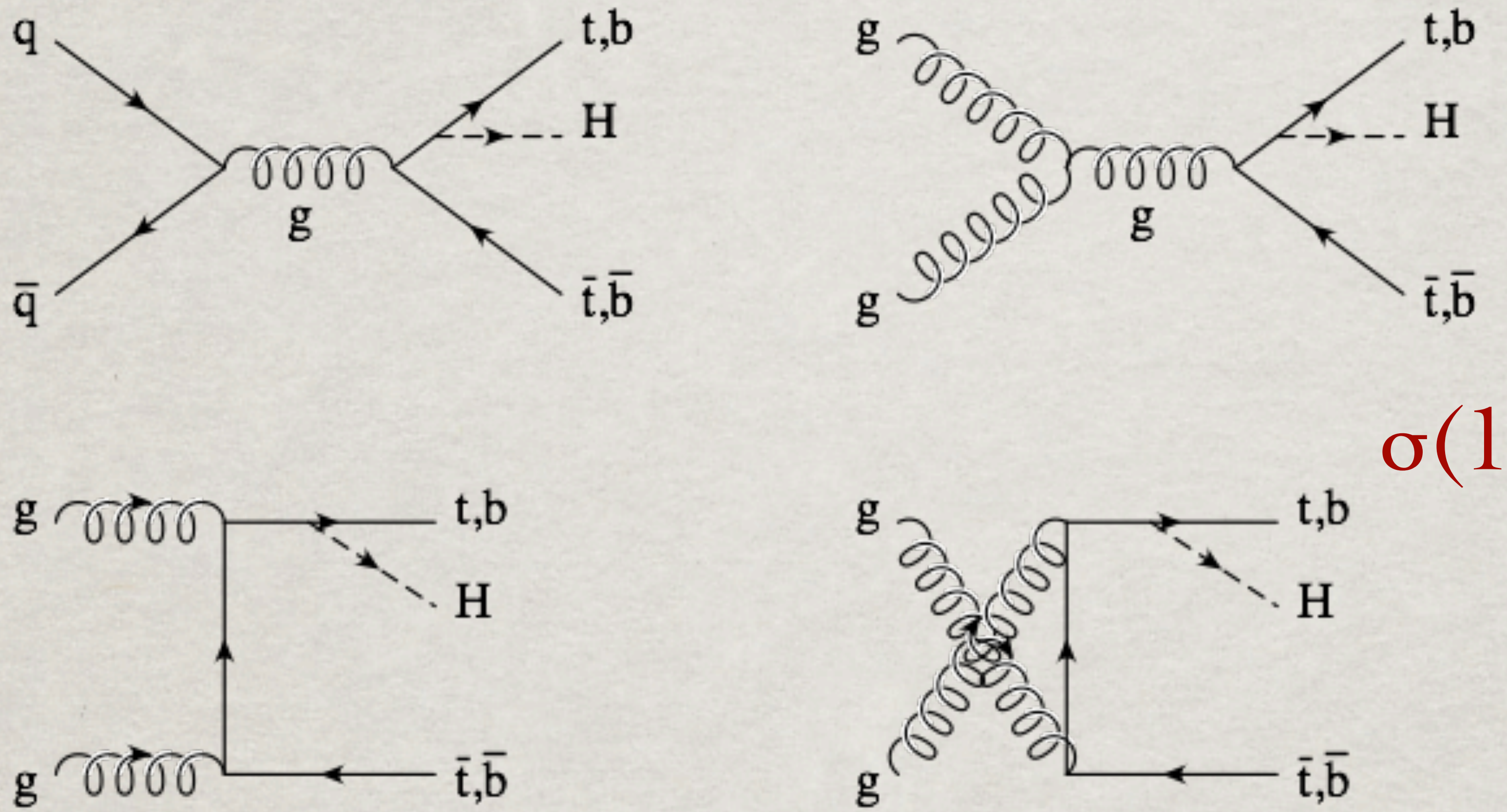


$\sigma(14\ \text{TeV}) \approx 2.2$ pb

- W/Z leptonic decays serve as good trigger.
- Effects from radiative corrections very modest.
- Sensitive to HWW, HZZ couplings
- Do not need clean decay modes: chance for b bbar !

  Boosted Higgs helps for the signal ID!

(d). Top quark pair associate production:



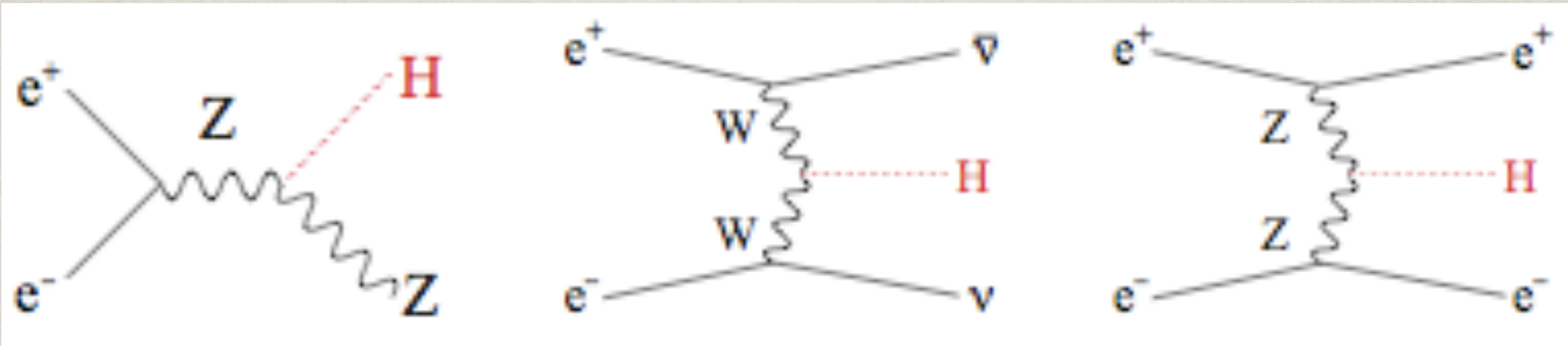
σ(14 TeV) ≈ 0.6 pb

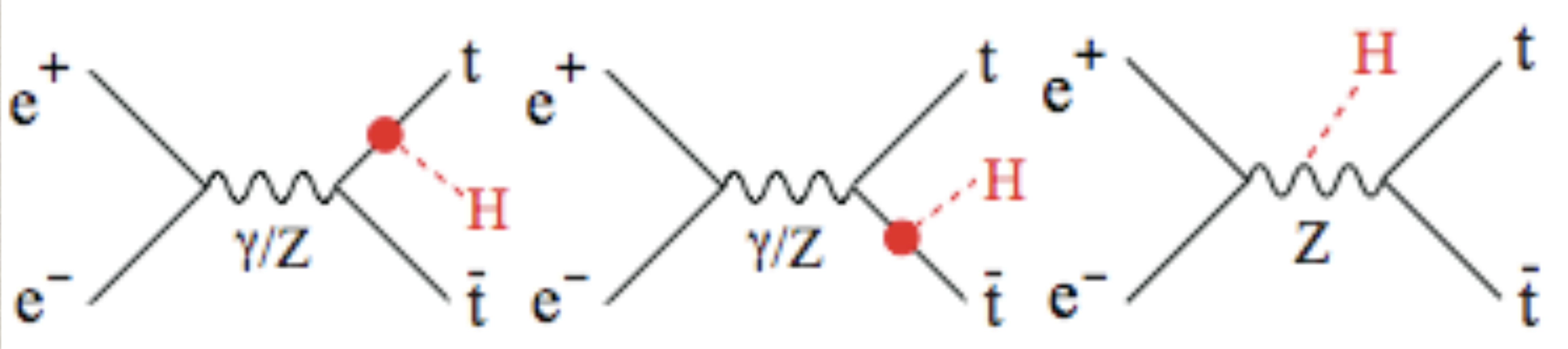
- Top leptonic decays serve as good trigger.
- Effects from radiative corrections can be large.
- Directly sensitive to Htt coupling
- Do not need clean decay modes: chance for b bbar !
- Combinatorics of the 4 b's are difficult to handle...

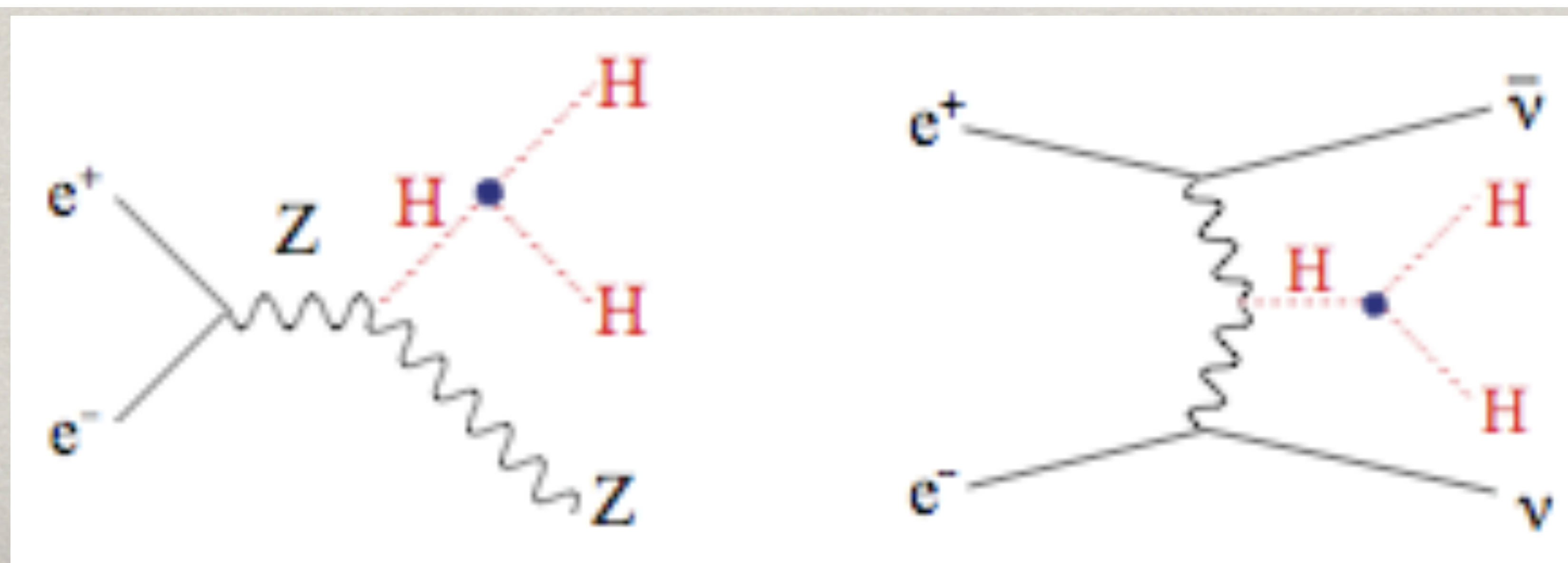
C. Higgs Boson Production at e^+e^- Colliders

1. The leading channels:

Recall that the Higgs couples preferably to heavier particles.







The idea of a Higgs Factory:

Two Candidate Sites

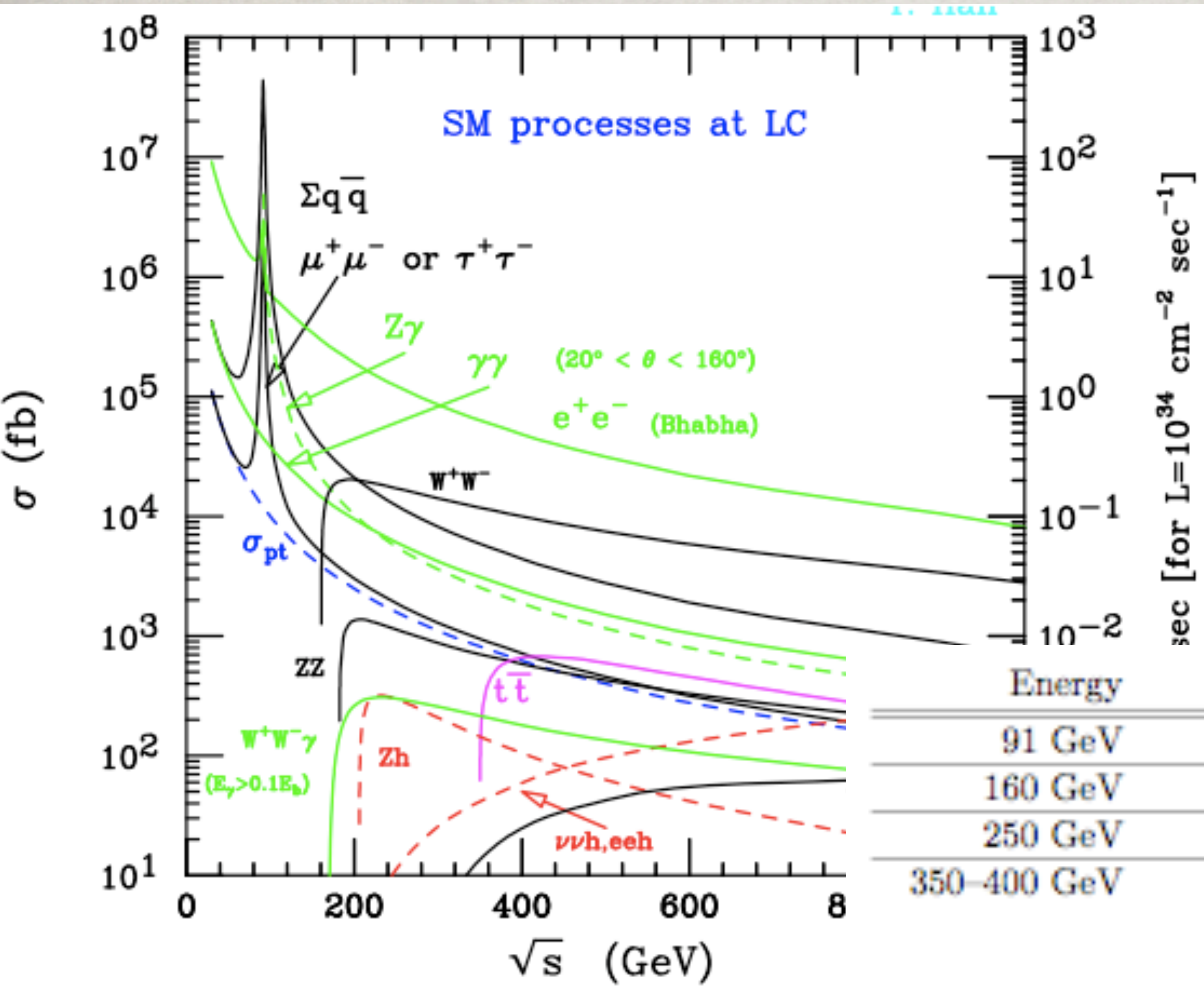
- Kyushu
  - Sefuri mountains
- Tohoku
  - Kitakami mountains

In order to focus the de
one of them will be cho

1. Geology and other techni
2. Infrastructure and econon
3. Political aspects

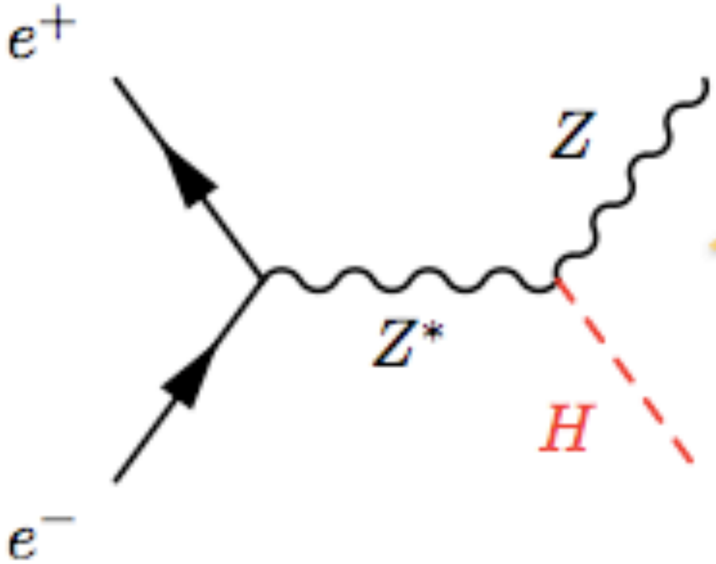
- Staging
  - A Higgs factory with a CM energy of ~250 GeV to start
  - Upgraded in stages to ~500 GeV (ILC baseline)
  - Technical expandability to ~1 TeV to be secured
- Guideline for cost sharing
  - The host country to cover 50% of the expenses (construction) of the overall project of the 500 GeV machine.
  - The actual contribution, however, should be left to negotiations among the governments.

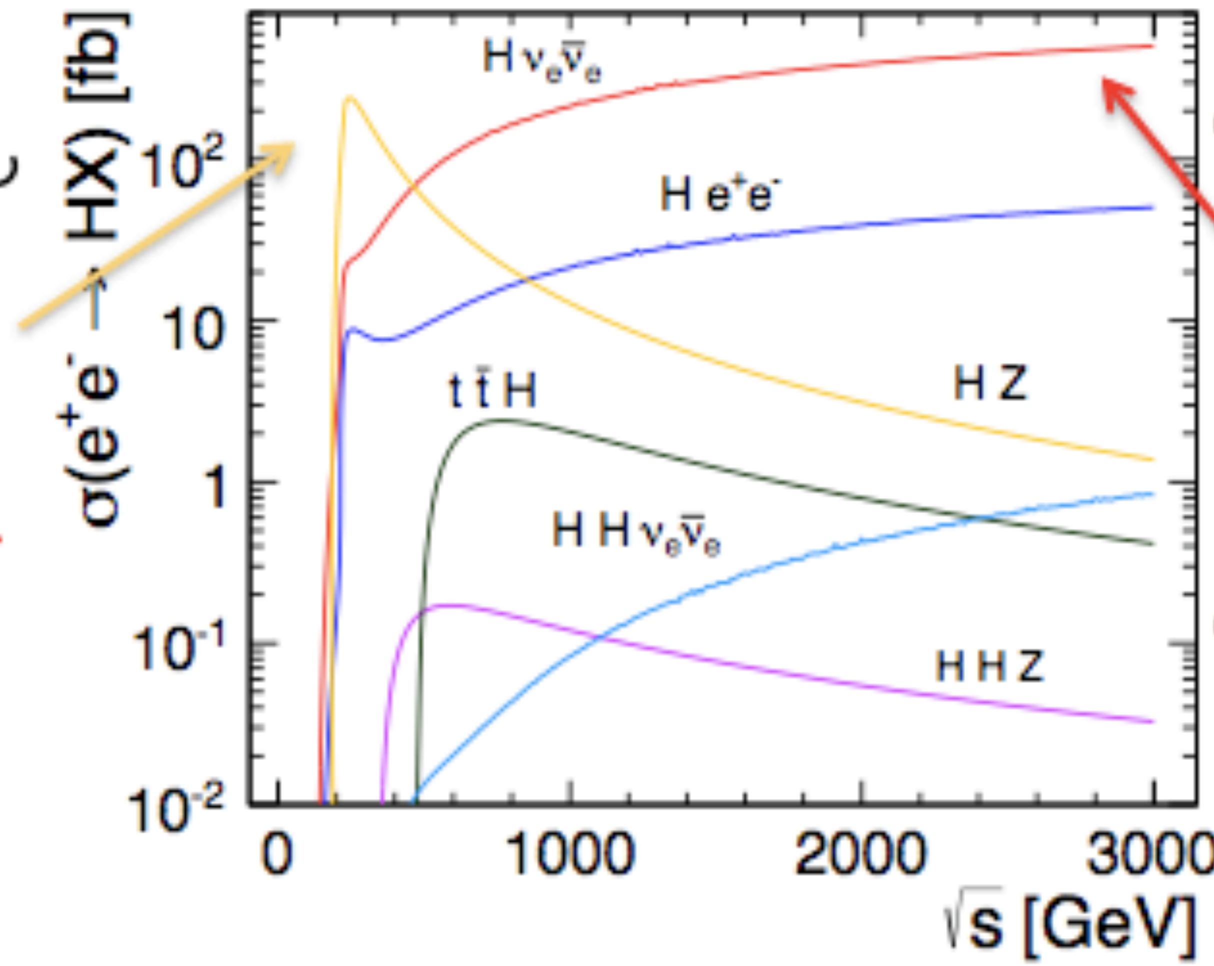
Total rates in e⁺e⁻ collisions:

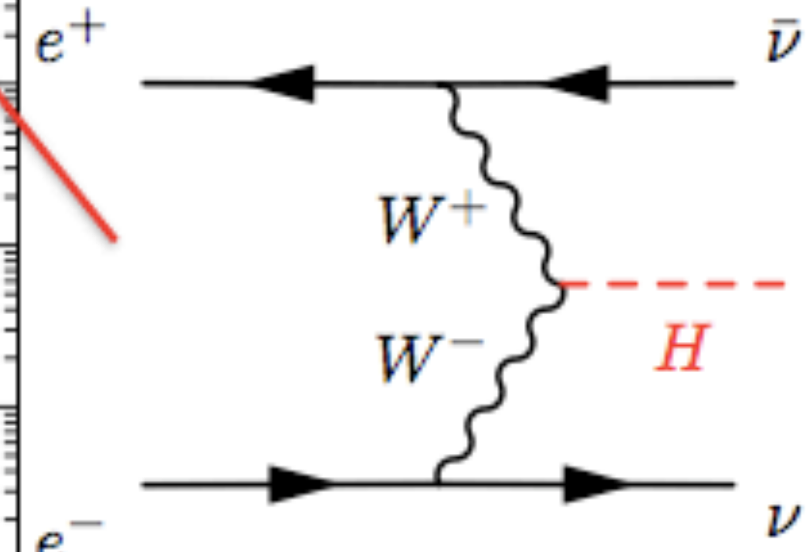


Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$	precision Higgs couplings
350–400 GeV	$e^+e^- \to t\bar{t}$	top quark mass and couplings
	$e^+e^- \to WW$	precision W couplings
	$e^+e^- \to \nu\bar{\nu}h$	precision Higgs couplings
500 GeV	$e^+e^- \to f\bar{f}$	precision search for Z'
	$e^+e^- \to t\bar{t}h$	Higgs coupling to top
	$e^+e^- \to Zhh$	Higgs self-coupling
	$e^+e^- \to \tilde{\chi}\tilde{\chi}$	search for supersymmetry
	$e^+e^- \to AH, H^+H^-$	search for extended Higgs states
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}hh$	Higgs self-coupling
	$e^+e^- \to \nu\bar{\nu}VV$	composite Higgs sector
	$e^+e^- \to \nu\bar{\nu}t\bar{t}$	composite Higgs and top
	$e^+e^- \to \tilde{t}\tilde{t}^*$	search for supersymmetry

2. Higgs production:







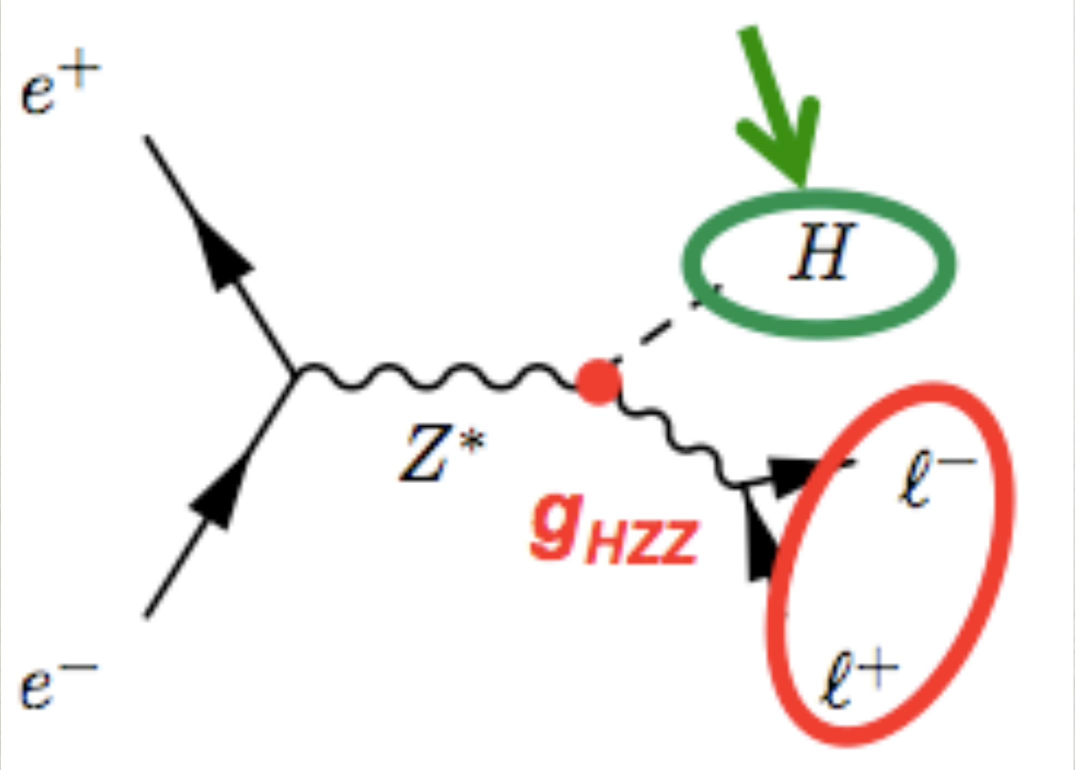
	250 GeV	350 GeV	500 GeV	1 TeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \rightarrow ZH)$	240 fb	129 fb	57 fb	13 fb	6 fb	1 fb
$\sigma(e^+e^- \rightarrow \nu\nu H)$	8 fb	30 fb	75 fb	210 fb	309 fb	484 fb
Int. Luminosity	250 fb^{-1}	350 fb^{-1}	500 fb^{-1}	1 ab^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	60,000	45,500	28,500	13,000	7,500	2,000
# vvH events	2,000	10,500	37,500	210,000	460,000	970,000

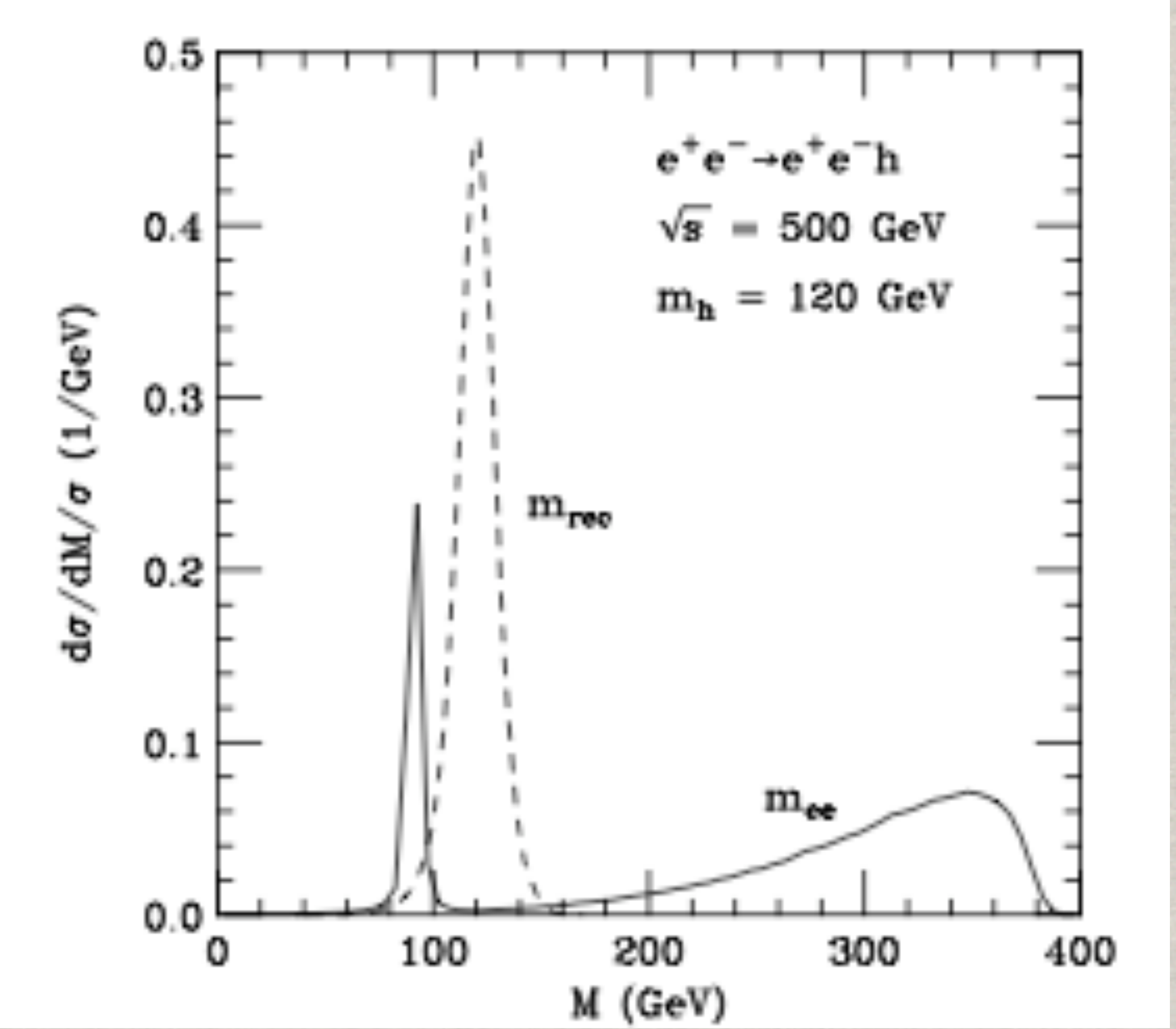
3. Recoil mass technique:

$$e^-(p_1)\, e^+(p_2) \to f(q_1)\, \bar{f}(q_2)\, h(q_3).$$

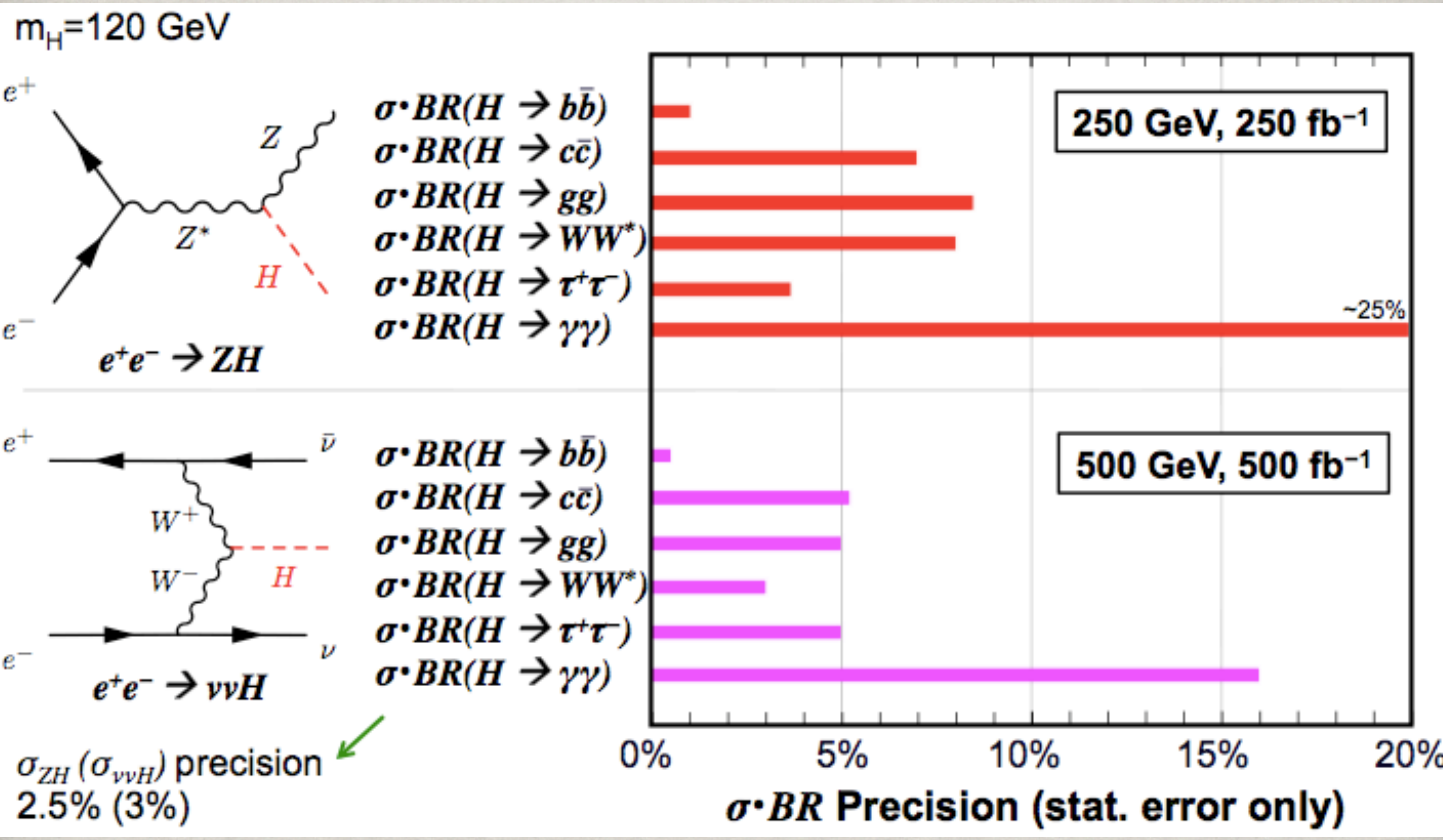
The Higgs boson signal may be best identified by examining the recoil mass variable

$$m_{rec}^2 = (p_1 + p_2 - q_1 - q_2)^2 = s + m_{f\bar{f}}^2 - 2\sqrt{s}(E_f + E_{\bar{f}}),$$





Branching accuracy



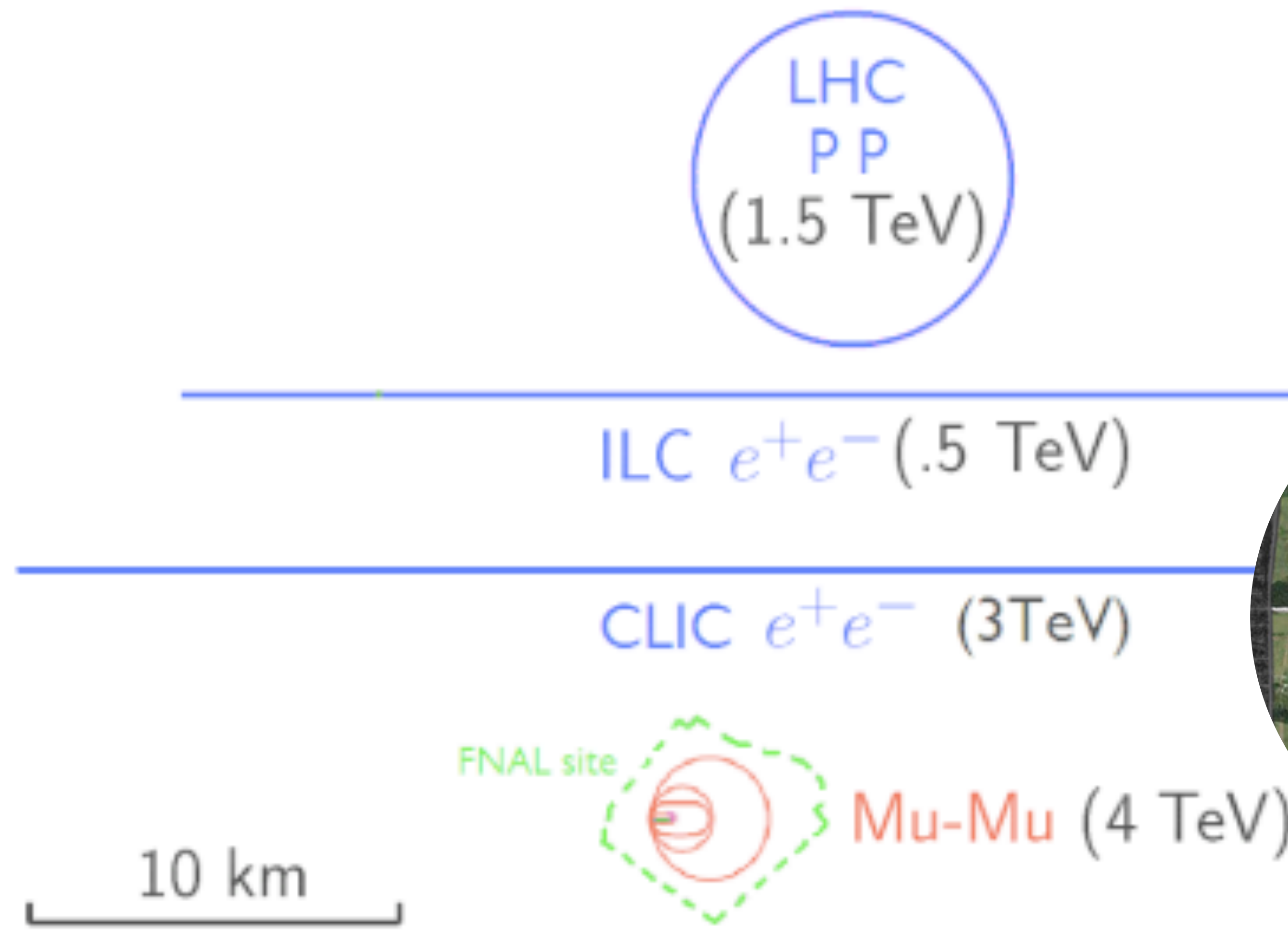
D. Higgs Boson Production at a muon Collider

Advantages of a Muon Collider

(1). Less radiative energy loss

$$\Delta E \sim \gamma^4 = (\frac{E}{m_\mu})^4$$

which allows a higher energy and much smaller machine:*



and a better beam-energy resolution: $\delta p/p \sim 0.1\% - 0.003\%$.

(2). Some natural beam-polarization via $\pi^- \to \mu^- \bar{\nu}$.

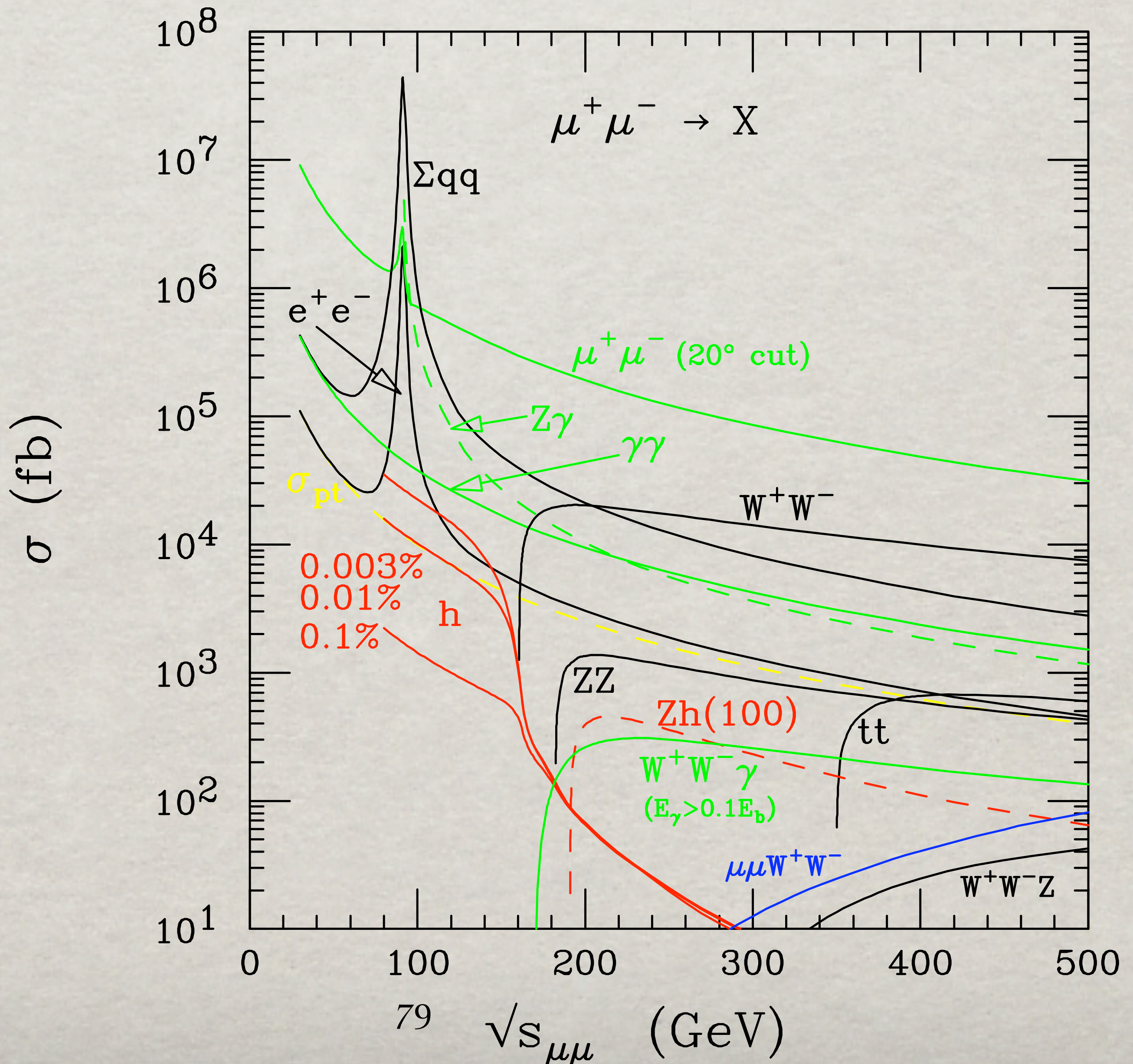
Challenges for a Muon Collider

"Never play with an unstable thing!"

(1). Luminosity: Beam cooling on transverse momentum

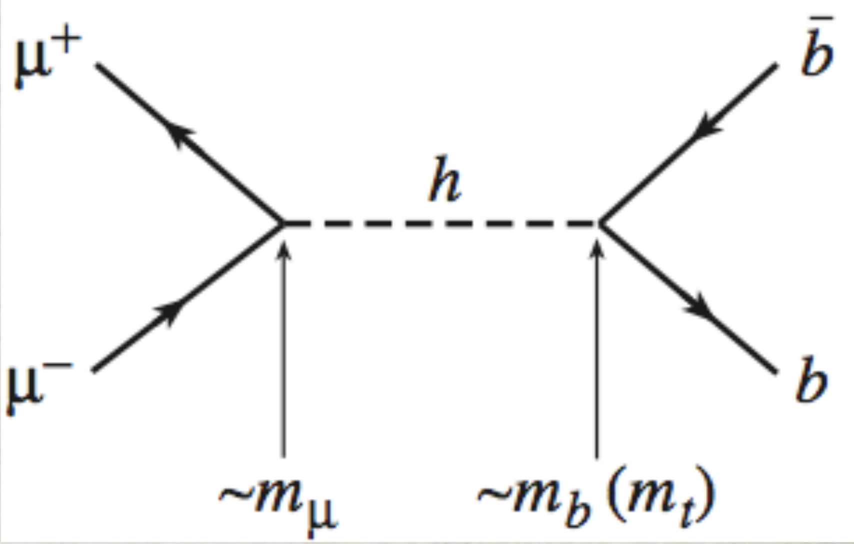
(2). Detector backgrounds: Muon decay and re-scattering

(3). Neutrino hazard: When E_{cm} reaching Multi-TeV.



Muon Collider as a Higgs Factory

Resonant Production:



$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$

At the peak with a perfect energy resolution:

$$\begin{aligned}\sigma_{peak}(\mu^+\mu^- \to h) &= \frac{4\pi}{m_h^2} BR(h \to \mu^+\mu^-)\\ &\approx 41 \text{ pb at } m_h = 125 \text{ GeV}.\end{aligned}$$

About 40,000 events produced per fb^{-1}

SM Higgs is (very) narrow:

At m_h=126 GeV, Γ_h = 4.2 MeV

Must convolute with energy profile:

$$\frac{dL(\sqrt{\hat{s}})}{d\sqrt{\hat{s}}} = \frac{1}{\sqrt{2\pi}\Delta}\exp[\frac{-(\sqrt{\hat{s}}-\sqrt{s})^2}{2\Delta^2}],$$

$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h\to\mu^+\mu^-)\mathrm{Br}(h\to X)}{(\hat{s}-m_h^2)^2+\Gamma_h^2 m_h^2}.$$

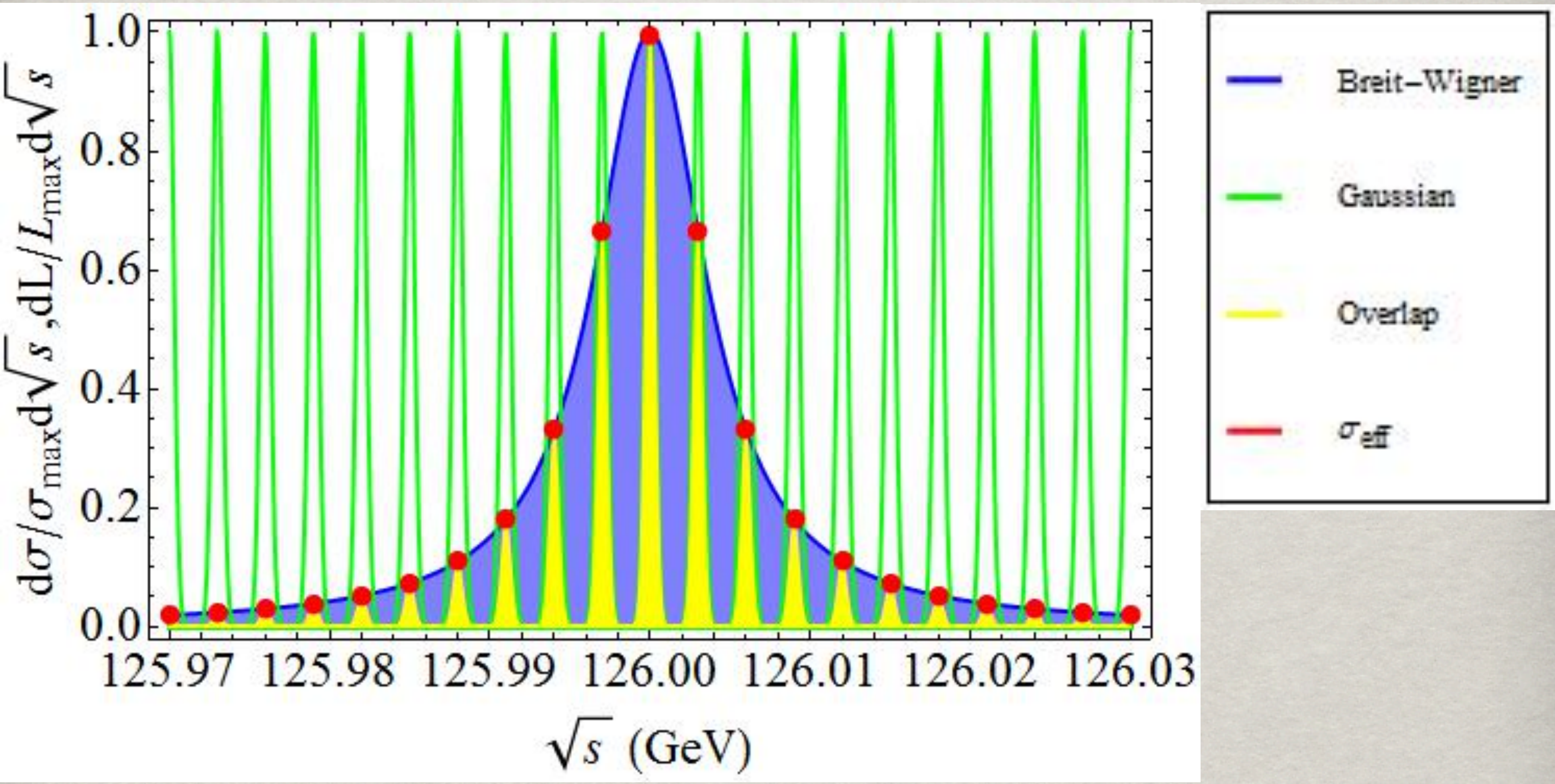
$$\sigma_{\rm eff}(s) = \int d\sqrt{\hat{s}}\,\frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\sigma(\mu^+\mu^- \to h \to X)$$

$$\propto \begin{cases} \Gamma_h^2 B/[(s-m_h^2)^2+\Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B\exp[\frac{-(m_h-\sqrt{s})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$

Extreme (good) Case:

Energy Spread much smaller than the physical width:

($\Delta = 0.3$ MeV, $\Gamma_h \approx 4.2$ MeV)

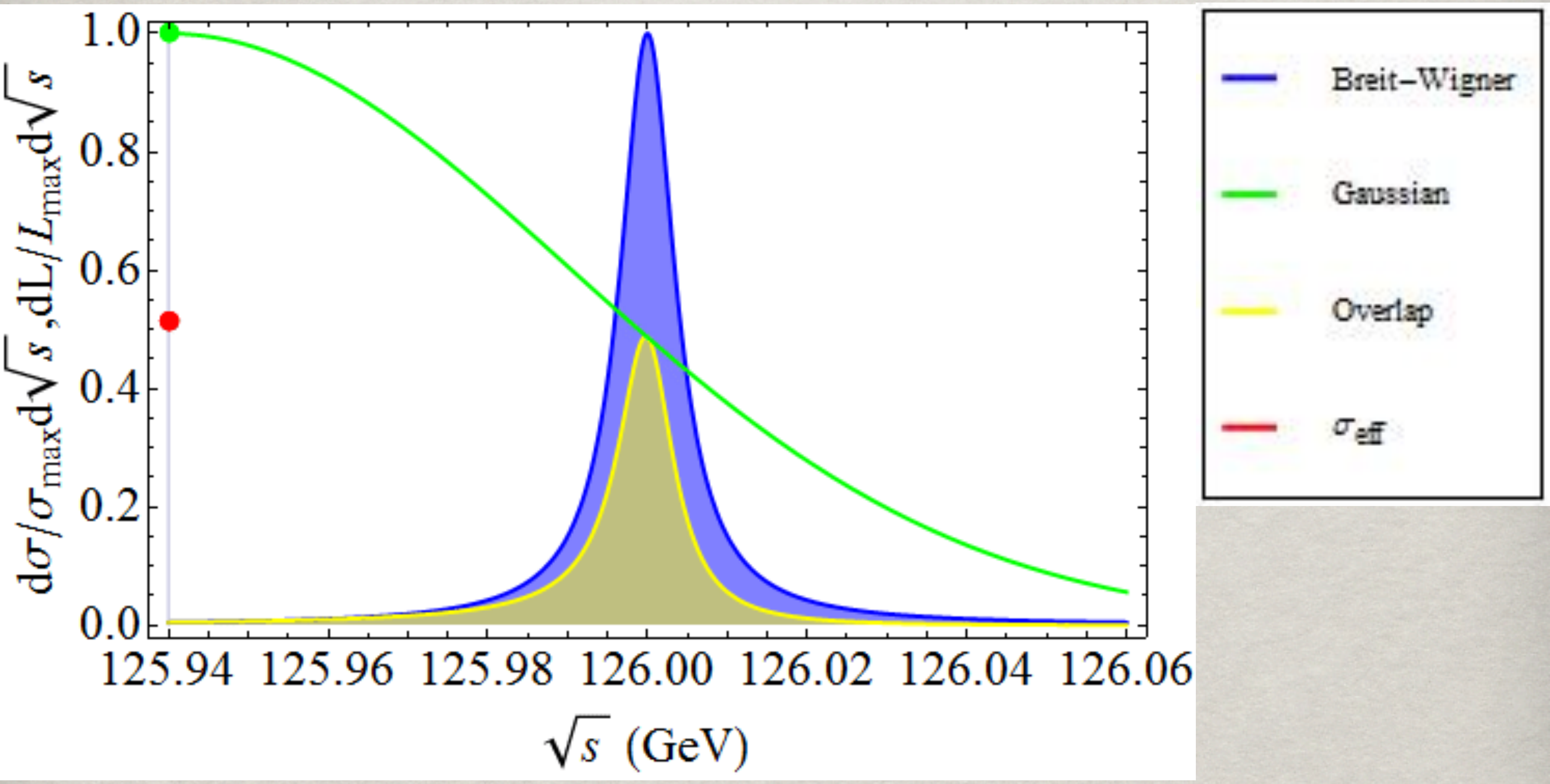


Recall: Z line shape with $\Gamma_Z \approx 2.5$ GeV

Extreme (bad) Case:

Energy Spread much larger than the physical width:

($\Delta = 50$ MeV, $\Gamma_h \approx 4.2$ MeV)

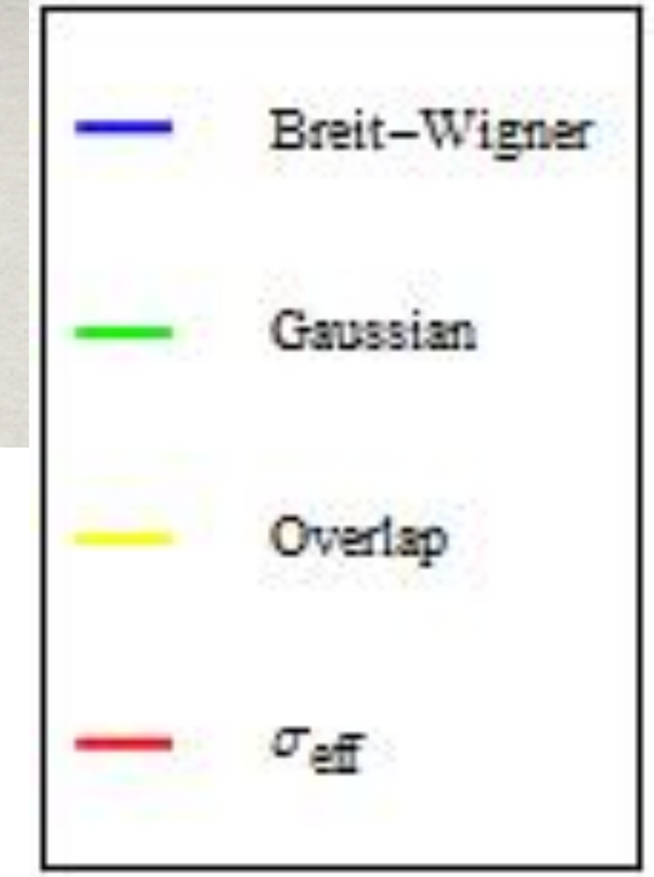


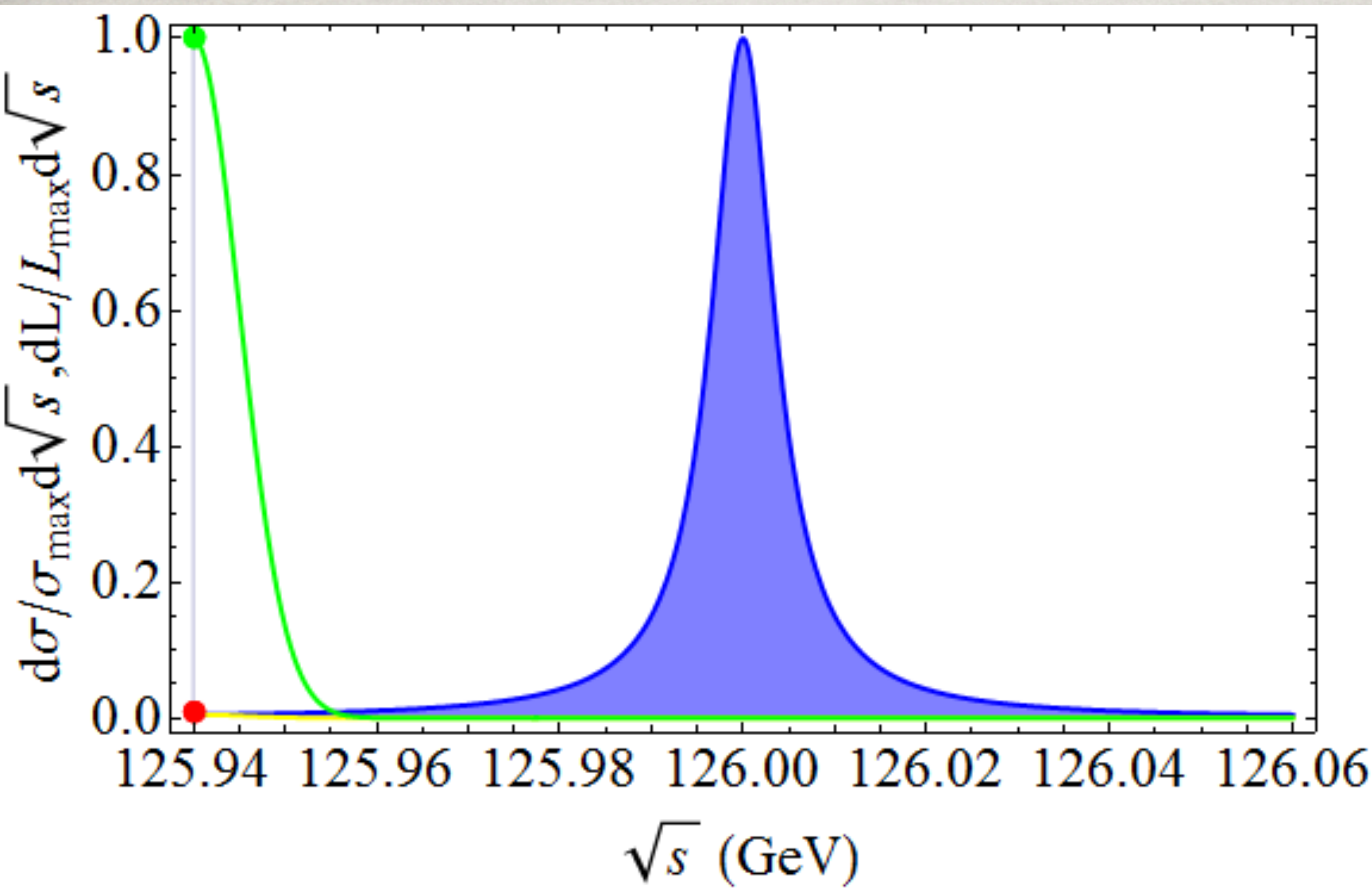
Recall: J/ψ scan $\Gamma \approx 93$ keV

“Normal” (ideal) case:

Energy Spread comparable:

(Δ = 5 MeV, $\Gamma_h \approx 4.2$ MeV)

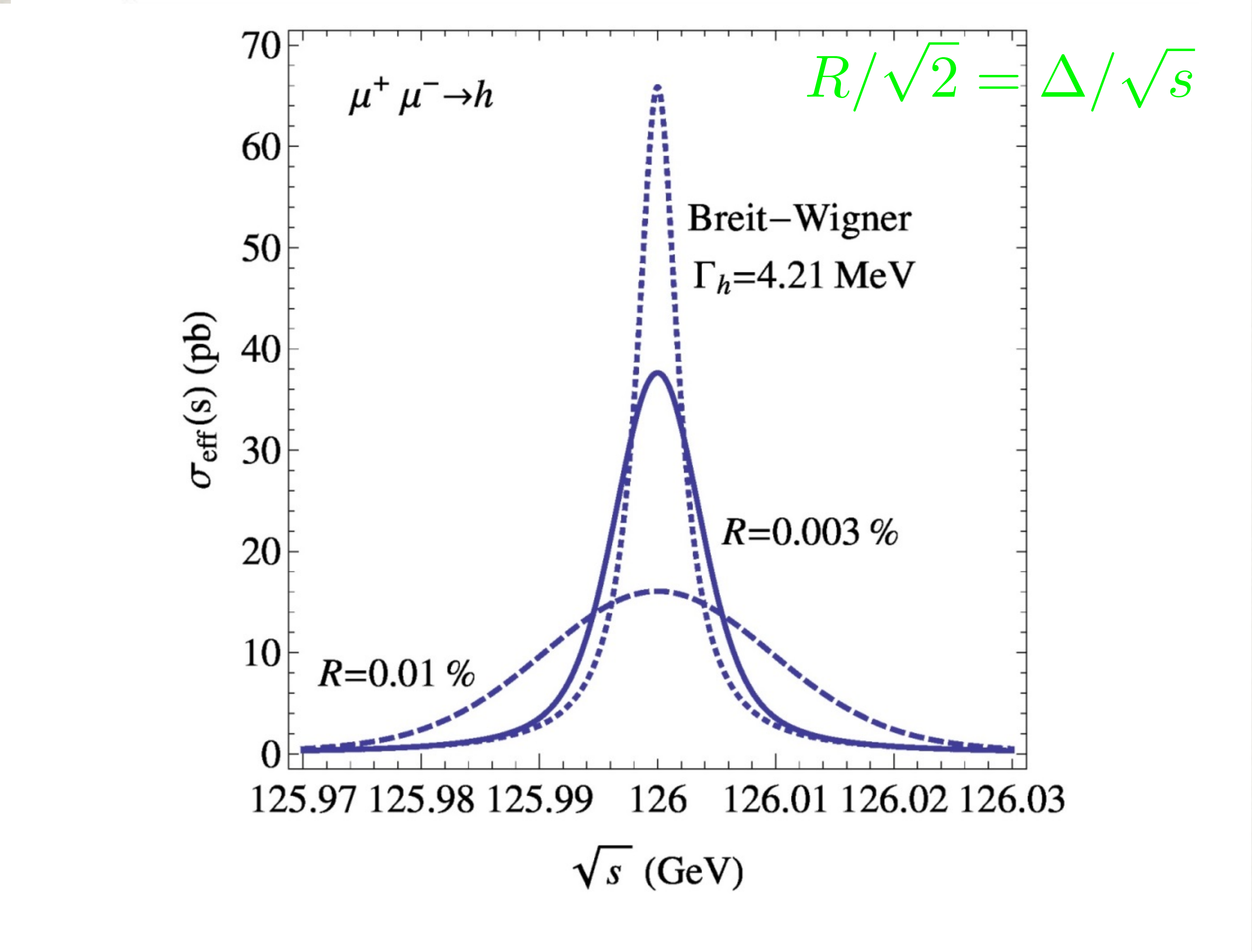




An optimal fitting would reveal Γ_h

Realistic studies:

- TH and Z. Liu, arXiv: 1210.7803.



$R/\sqrt{2} = \Delta/\sqrt{s}$

$$\text{Case A}: \quad R = 0.01\% \; (\Delta = 8.9\,\text{MeV}), \;\; L = 0.5\ \text{fb}^{-1},$$

$$\text{Case B}: \quad R = 0.003\% \; (\Delta = 2.7\,\text{MeV}), \;\; L = 1\ \text{fb}^{-1}.$$

Leading signals and background rates

The SM Higgs

R (%)	$\mu^+\mu^- \to h$ $\sigma_{\rm eff}$ (pb)	$h \to b\bar{b}$		$h \to WW^*$	
		σ_{Sig}	σ_{Bkg}	σ_{Sig}	σ_{Bkg}
0.01	16	7.6	15	3.7	0.051
0.003	38	18		5.5	

With a cone angle cut: $10^o < \theta < 170^o$

Lecture III: Higgs and Beyond

-- Motive for Physics Beyond SM

A. A Weakly Coupled Scalar?

1. The Higgs mechanism ≠ Higgs boson!
2. A heavier, broader Higgs?

B. SM Higgs Sector at Higher Energies

1. Triviality bound
2. Vacuum stability
3. Naturalness

C. New Physics associated with the Higgs

1. Supersymmetry
2. Extended Higgs sector
3. Composite Higgs
4. Coupling deviations from SM

A. A Weakly Coupled Light Higgs?

1. The Higgs Mechanism DOES NOT require a Higgs boson!

"If a LOCAL gauge symmetry is spontaneously broken, then the gauge boson acquires a mass by absorbing the Goldstone mode."

The Non-Linear realization:

$$\Phi = \frac{1}{\sqrt{2}}(v+H)U\,, \qquad U = \exp[i\pi^a\tau^a/v]$$

$\mathcal{G}_{\rm SM} = SU(2)_L \otimes U(1)_Y$, as

$$U \to U' = g_L U g_Y^\dagger\,, \qquad H \to H' = H\,,$$

$$g_L = \exp[-i\theta_L^a\tau^a/2]\,, \qquad g_Y = \exp[-i\theta_Y\tau^3/2]\,.$$

Then leave out the singlet H, the SM gauge symmetry spontaneously broken:

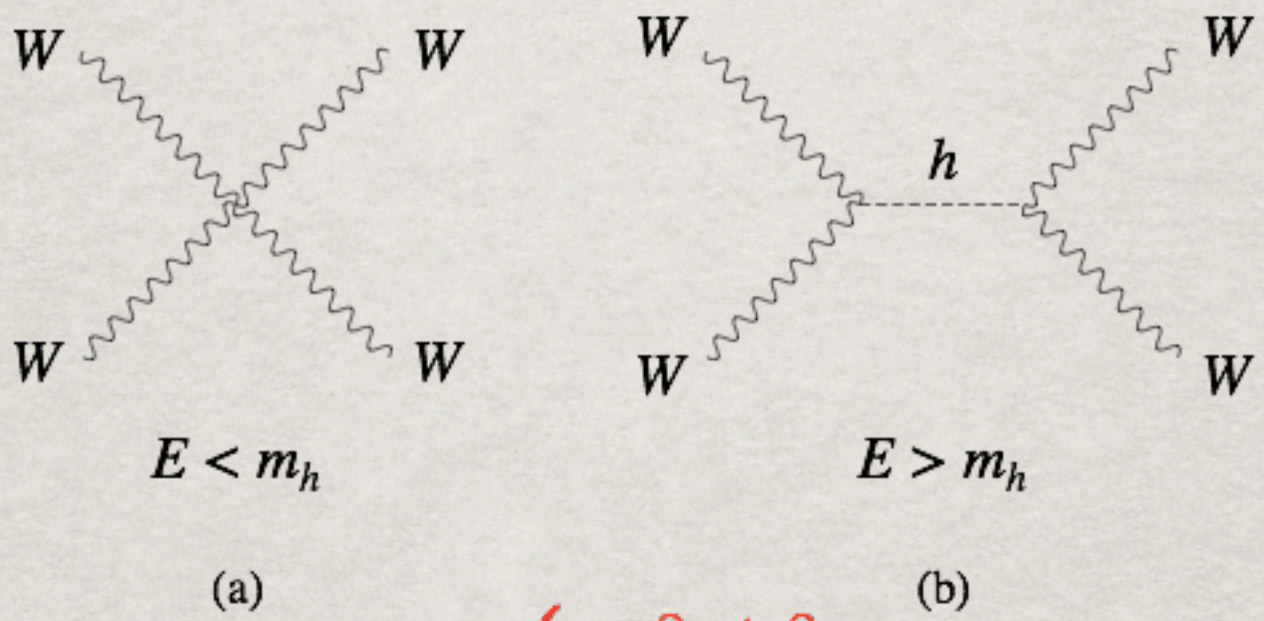
$$D_\mu U = \partial_\mu U + igW_\mu^a\frac{\tau^a}{2}U - ig'UB_\mu\frac{\tau^3}{2}$$

$$\mathcal{L} = \frac{1}{2}Tr(D_\mu\Phi^\dagger D^\mu\Phi) \Rightarrow \frac{v^2}{4}Tr(D_\mu U^\dagger D^\mu U) \longrightarrow \frac{v^2}{4}(\sum_i g^2W_i^2 + g'^2B^2)$$

(fermion masses can be accommodated similarly)

Higgs boson could be absent, but:

Consider the massive gauge boson scattering:



$$\mathcal{M}(W_L W_L \to W_L W_L) \sim \begin{cases} E_{cm}^2/v^2 & \text{no light Higgs,} \\ m_h^2/v^2 & \text{with a SM Higgs.} \end{cases}$$

Partial-wave unitarity demands

$$a_0 = \frac{1}{16\pi} \frac{m_h^2 \text{ or } E_{cm}^2}{v^2} \lesssim 1$$
$$\Rightarrow \quad m_h \text{ or } E_{cm} \lesssim \mathcal{O}(1\ \text{TeV}).$$

Exercise 11: Verify this unitarity bound by an explicit partial wave analysis.

2. Natural dynamics prefers a heavier, broad Higgs boson!

In low-energy QCD, a generic dynamical mass is

$m \sim 4\pi f_\pi \sim 1$ GeV:

$m(f_0) \sim 0.4$ -1.2 GeV, $\Gamma \sim 0.6$ - 1.0 GeV !

$m(\rho^{\pm,0}) \sim 0.77$ GeV, $\Gamma \sim 0.15$ GeV.

Lessons from QCD and other strong dynamical models (Technicolor-like, composite, dilaton...) argue the dynamical mass to be of the order

$4\pi v \approx 2$ TeV!

And typically strong interacting: Γ(total) $\geq$ 20%M !

--- except the pseudo Goldstone bosons.

Personal Statement I:

The fact that we do have observed
a rather light, weakly coupled boson:

m_h = 125-126 GeV, $\Gamma < 1$ GeV,

is truly revolutionary!

We have just discovered a “fifth (weak) force”:

$\lambda \approx 1/8$!

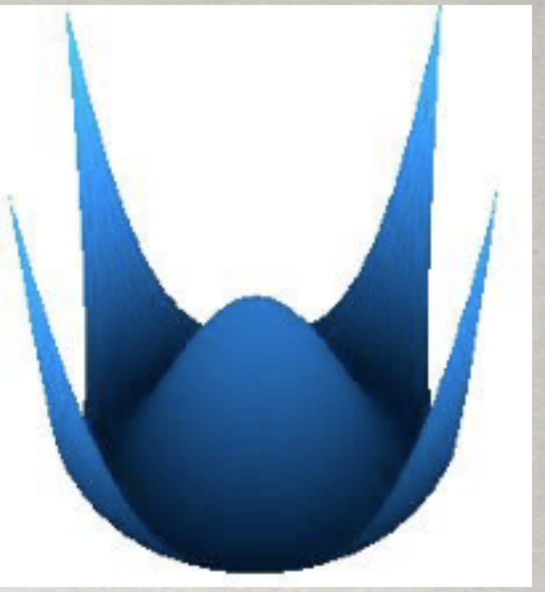
Hopes for uncovering a deeper theory:

- λ determined by other couplings like in SUSY?

where $\lambda = (g_1^2 + g_2^2)/8$

- or dynamically generated by a new strong force?

B. SM Higgs Sector at Higher Energies



Recall the SM Higgs sector: $V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$

$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V = \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

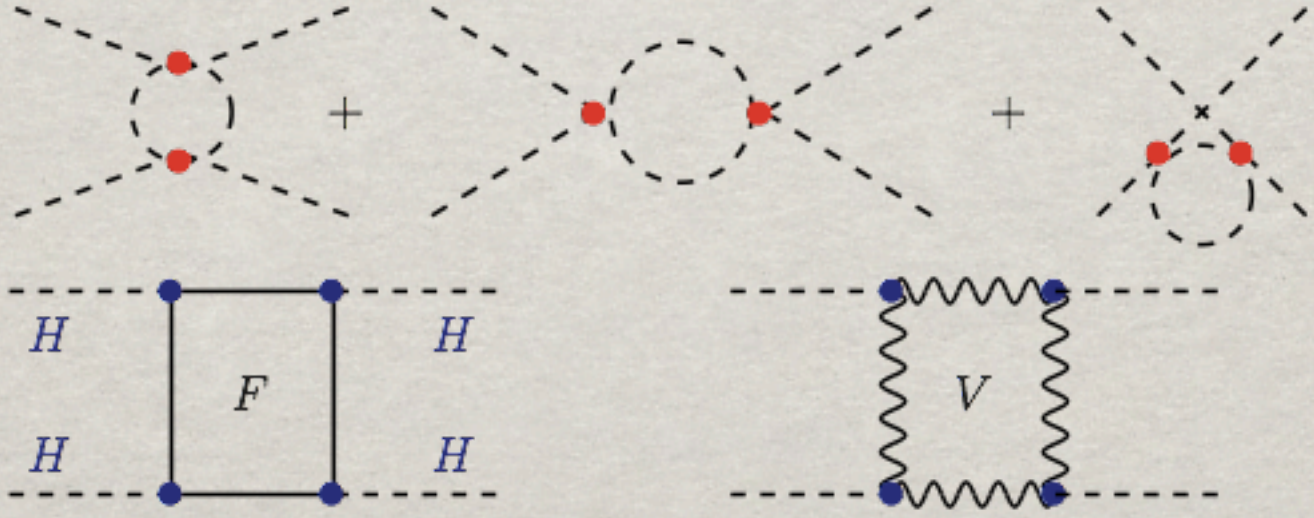
$$M_H^2 = 2\lambda v^2 = -2\mu^2$$

Crucial conditions: $\mu^2(Q^2) < 0, \quad \lambda(Q^2) > 0$

Renormalization Group Equation Evolution at NLO:

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$

$$t = \ln(Q^2/Q_0^2)$$



1. Triviality bound

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$

$$M_H^2 = 2\lambda v^2 = -2\mu^2$$

How large MH (λ) can be dragged up?

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 \qquad \lambda(Q) = \frac{\lambda(Q_0)}{1 - \frac{3}{4\pi^2}\lambda(Q_0)\ln\left(\frac{Q^2}{Q_0^2}\right)}$$

There is a (famous) Landau Pole!
(present in all but non-Abelian gauge theories)

1. If SM valid to infinite energy, then $\lambda(Q_0) = 0$, a non-interacting trivial theory!
2. Since M_H is non-zero, then the theory has a cutoff:

$$M_H^2 < \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$

For M_H = 125 GeV, the cutoff is too far to be relevant.

2. Vacuum stability bound

For small λ, the To-Yukawa dominates:

$$32\pi^2 \frac{d\lambda}{dt} = -24 y_t^4 \qquad \lambda(\Lambda) = \lambda(v) - \frac{3}{4\pi^2} y_t^4 \log\left(\frac{\Lambda^2}{v^2}\right)$$

To have a stable vacuum,

$$\lambda(\Lambda) > 0 \quad \longrightarrow \quad M_H^2 > \frac{3v^2}{2\pi^2} y_t^4 \log\left(\frac{\Lambda^2}{v^2}\right)$$

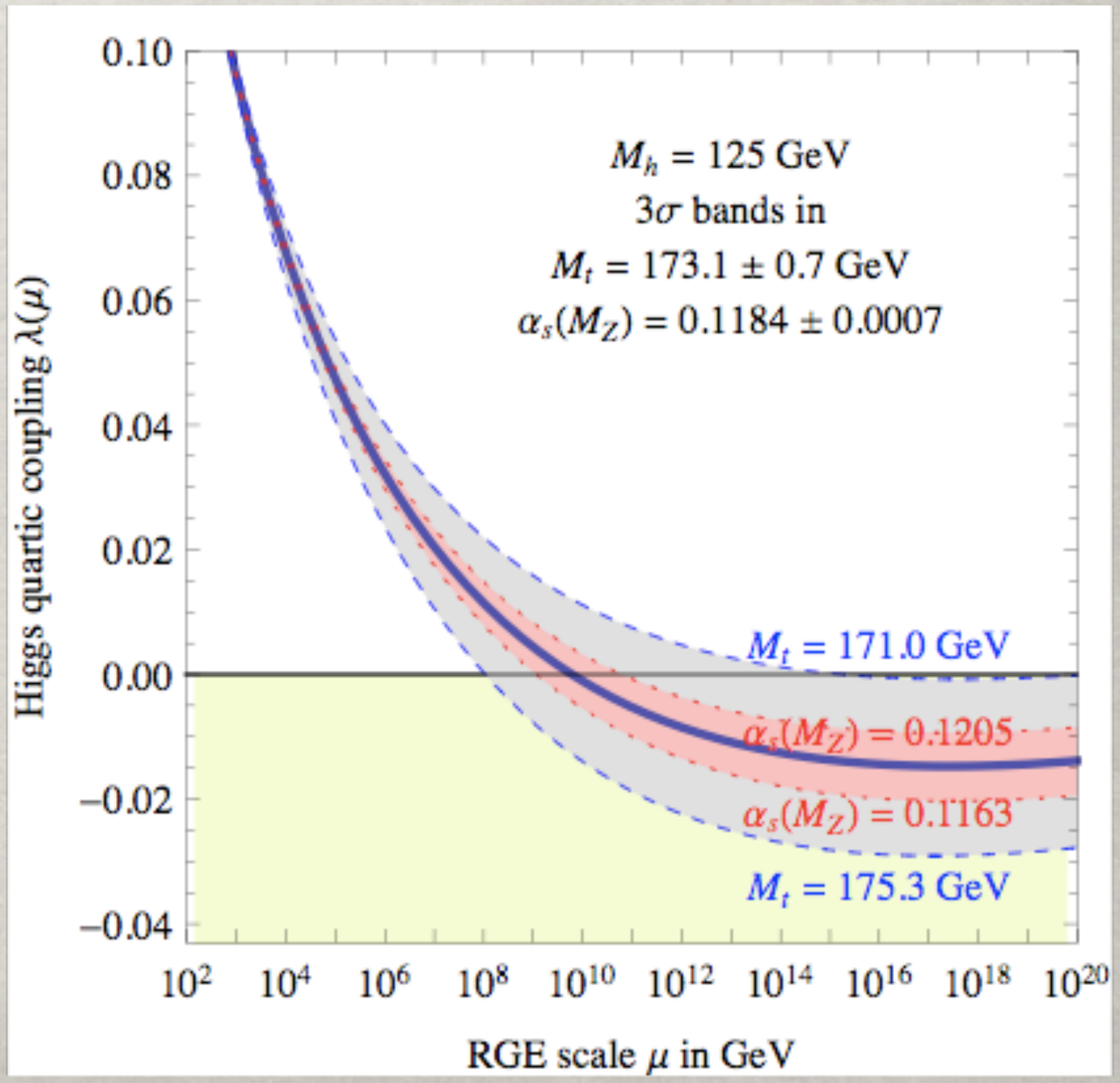
$$\Lambda_C \sim 10^3 \text{ GeV} \quad \Rightarrow \quad M_H \gtrsim 70 \text{ GeV}$$

$$\Lambda_C \sim 10^{16} \text{ GeV} \quad \Rightarrow \quad M_H \gtrsim 130 \text{ GeV}$$

Much renewed interest, updates:[$]

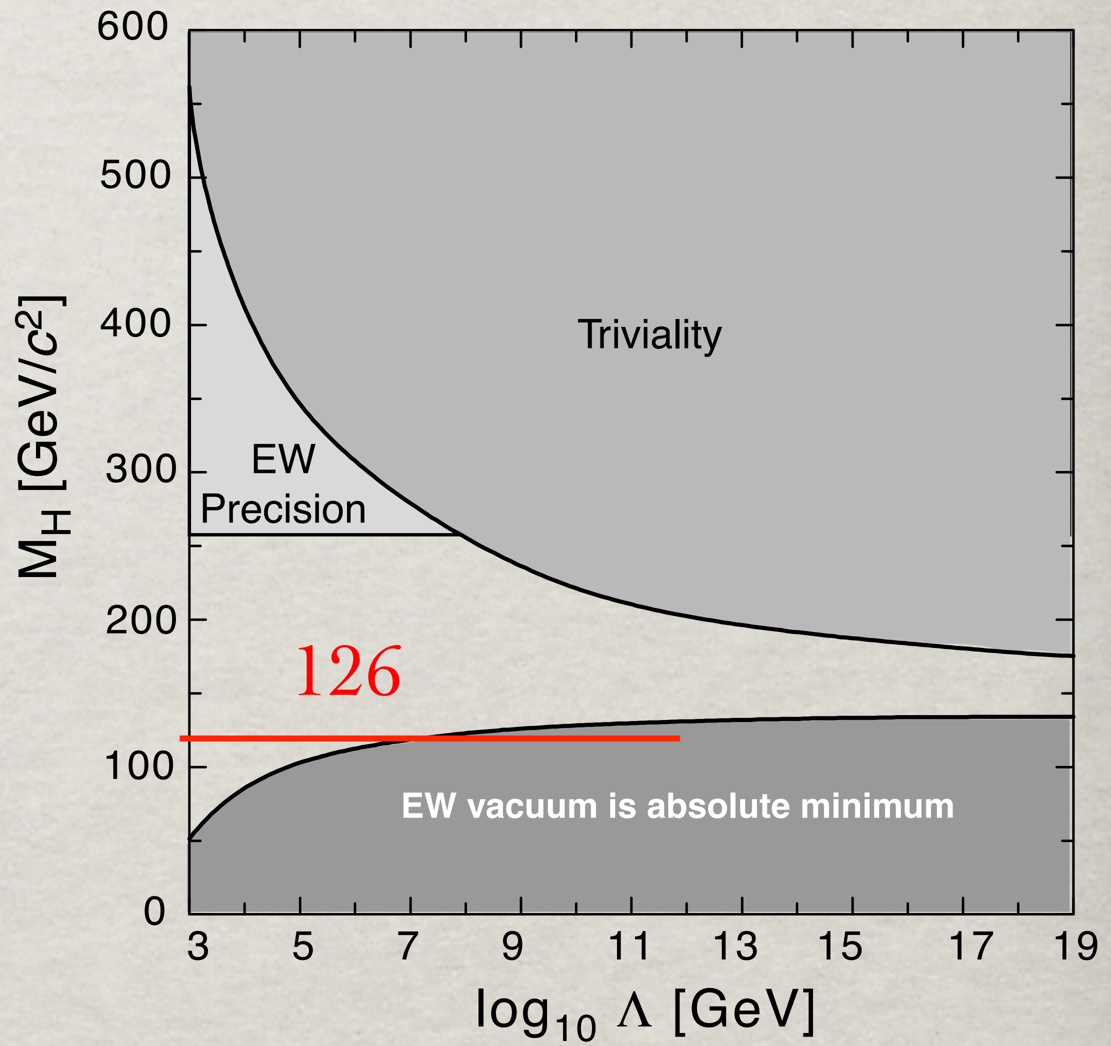
$ G. Degrassi et al., arXiv:1205.6497.

For M_H = 125 GeV,
then $\Lambda(m_t{=}175) < 10^7$ GeV.



Personal Statement II:

Based on the vacuum stability argument, something Beyond the Standard Model should exist above the EW scale!

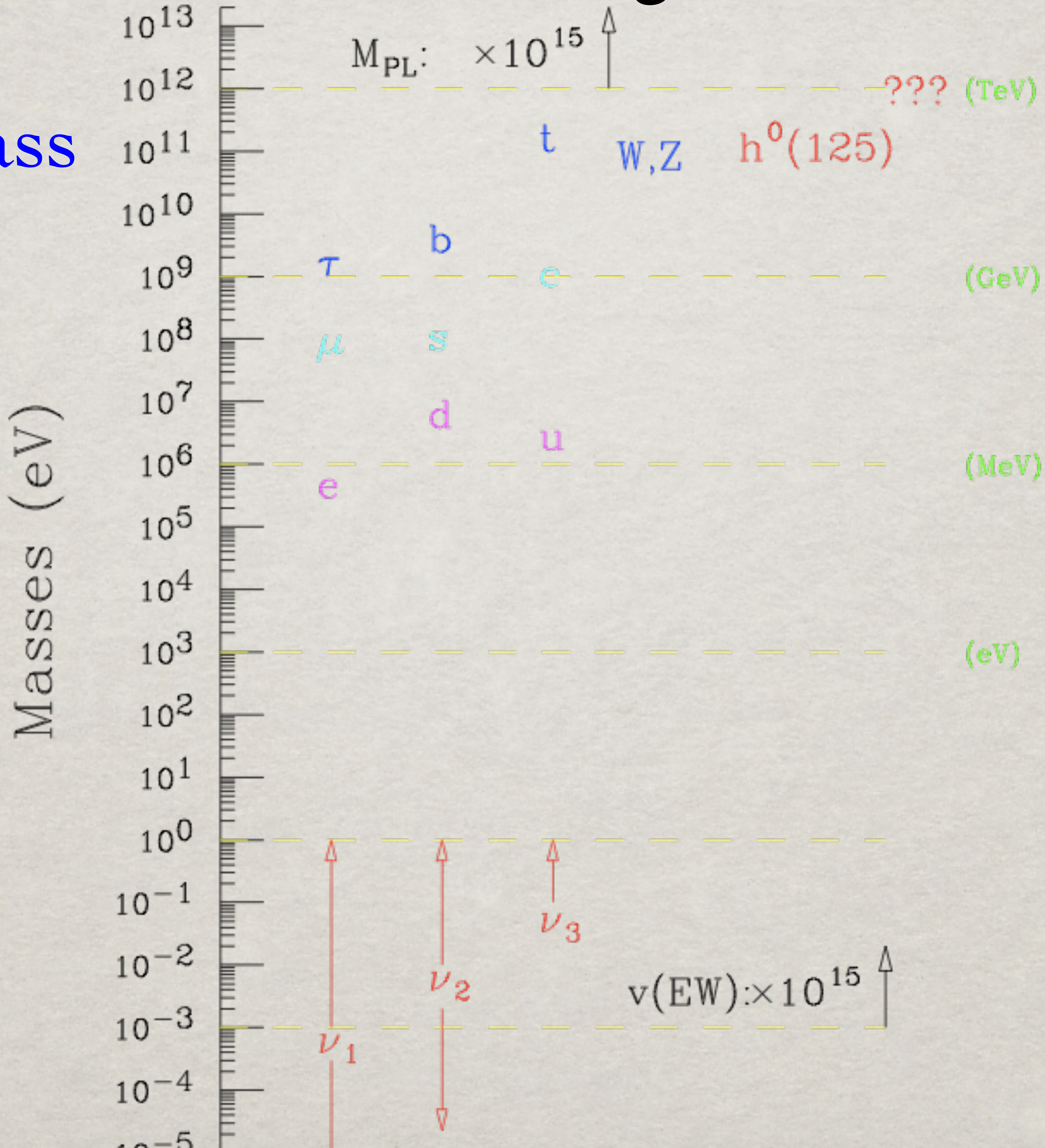


However,

1. the scale maybe too high for LHC physics;
2. a quasi-stable universe would evade a relevant scale.

3. "Naturalness" argument:

Particle mass hierarchy:



Since all the masses are generated like $\sim g\, v$,
the natural scale should be just v.

Thus, except M_W, M_Z, M_H, $m_t \sim g\, v$,
all others are unnatural: (to some extent)
$m_b \sim 5$ GeV, $m_e \sim 0.5$ MeV, $m_\nu < 0.2$ eV ...

But, they are "technically natural":

For a given mass, if the quantum corrections are merely logarithmically dependent upon the high energy scale, then the mass parameter is said technically natural.

t'Hooft statement for "technical naturalness":

If a parameter is turned off (set to 0), the system results in an enlarged symmetry, then this parameter must be technically natural.

$$m_e \sim m^0_e\, [1 + 3\alpha/4\pi\, \ln(\Lambda/m_e)]$$

If m^0_e is turned off, the system possesses a chiral symmetry.

Dynamical scale generation is natural!

Recall in QCD: coupling runs logarithmically between vastly separated scales:

$$\alpha_s(\Lambda^2) \approx \frac{1}{\ln \frac{\Lambda^2}{\Lambda_{QCD}^2}} \quad e.g. \quad (\frac{\Lambda}{\Lambda_{QCD}})^2 \approx (\frac{E_{LHC}}{\Lambda_{QCD}})^2 \approx 10^8.$$

Dynamical scale can be generated by "dimensional transmutation":

$$\Lambda_{TC} \approx \Lambda \ \exp(-\frac{1}{2\alpha_{TC}}) \approx 4\pi v.$$

However, this picture (Technicolor and variations) doesn't work (well) in EW:

* It is strong interaction, not seen in EW physics.
* Fermion masses/mixing a real killer.
* No fundamental scalar (at least not a light one).

"It is interesting to note that there are no weakly coupled scalar particles in nature; scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry." -- Ken Wilson, 1970

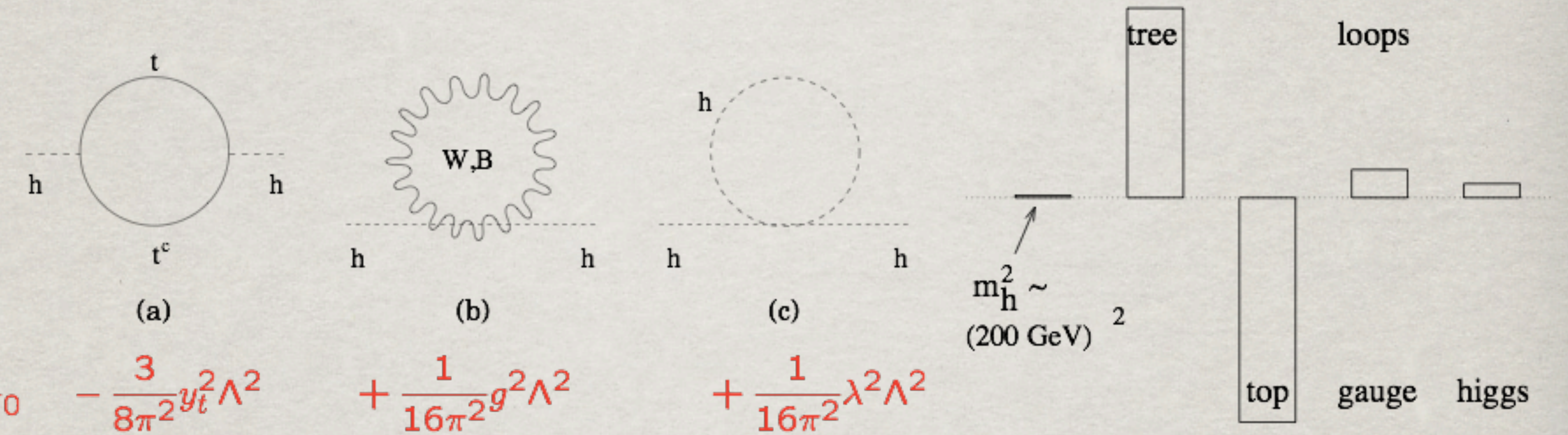
No symmetry to protect M_H in the SM,
→ it is unstable against quantum corrections.

Amazing !

Unnatural: Fine-tuned to

0.05 mm/0.5 cm ~ 10^{-2}

A light SM-like Higgs unnatural!



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t^2 \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

If $\Lambda^2 \gg m_H^2$, then unnaturally large cancellations must occur.

$$(200\ \text{GeV})^2 = m_{H0}^2 + \left[-(2\ \text{TeV})^2 + (700\ \text{GeV})^2 + (500\ \text{GeV})^2\right] \left(\frac{\Lambda_{t,W,H}}{10\ \text{TeV}}\right)^2$$

If believing $\Lambda \to M_{PL}$, then the cancellation IS ... !!! ???

"Naturalness requirement": less than 90% cancellation on m_H^2

$$\Lambda_t \lesssim 3\ \text{TeV} \quad \Lambda_W \lesssim 9\ \text{TeV} \quad \Lambda_H \lesssim 12\ \text{TeV}$$

Cancellation Mechanisms ?

- Super-symmetry (SUSY) (symmetry between *opposite* spin & statistics)

  Natural cancellations:
  $\tilde{t}$ versus t
  $\tilde{W}$ versus W
  $\tilde{H}$ versus H
  H_d versus H_u,

$$\Delta m_H^2 \sim (M_{SUSY}^2 - M_{SM}^2)\, \frac{\lambda_f^2}{16\pi^2} \ln\left(\frac{\Lambda}{M_{SUSY}}\right).$$

Weak scale SUSY is natural if $M_{SUSY} \sim \mathcal{O}(1 \text{ TeV})$.

- The Little Higgs idea – Strongly interacting dynamics:
  An alternative way to keep H light (naturally).
  Again, predicting new states:

$$W^\pm, Z, B \leftrightarrow W_H^\pm, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

(cancellation among same spin states!)

A light Higgs implies new physics near 1 TeV!

Personal Statement III:

A light Higgs is unnatural.

"Naturalness" argument strongly indicates the existence of TeV scale new physics.

If you give up this belief, you are subscribing the "anthropic principle".✤

✤ A physicist talking about the anthropic principle runs the same risk as a cleric talking about pornography: no matter how much you say you are against it, some people will think you are a little too interested. -- Steven Weinberg

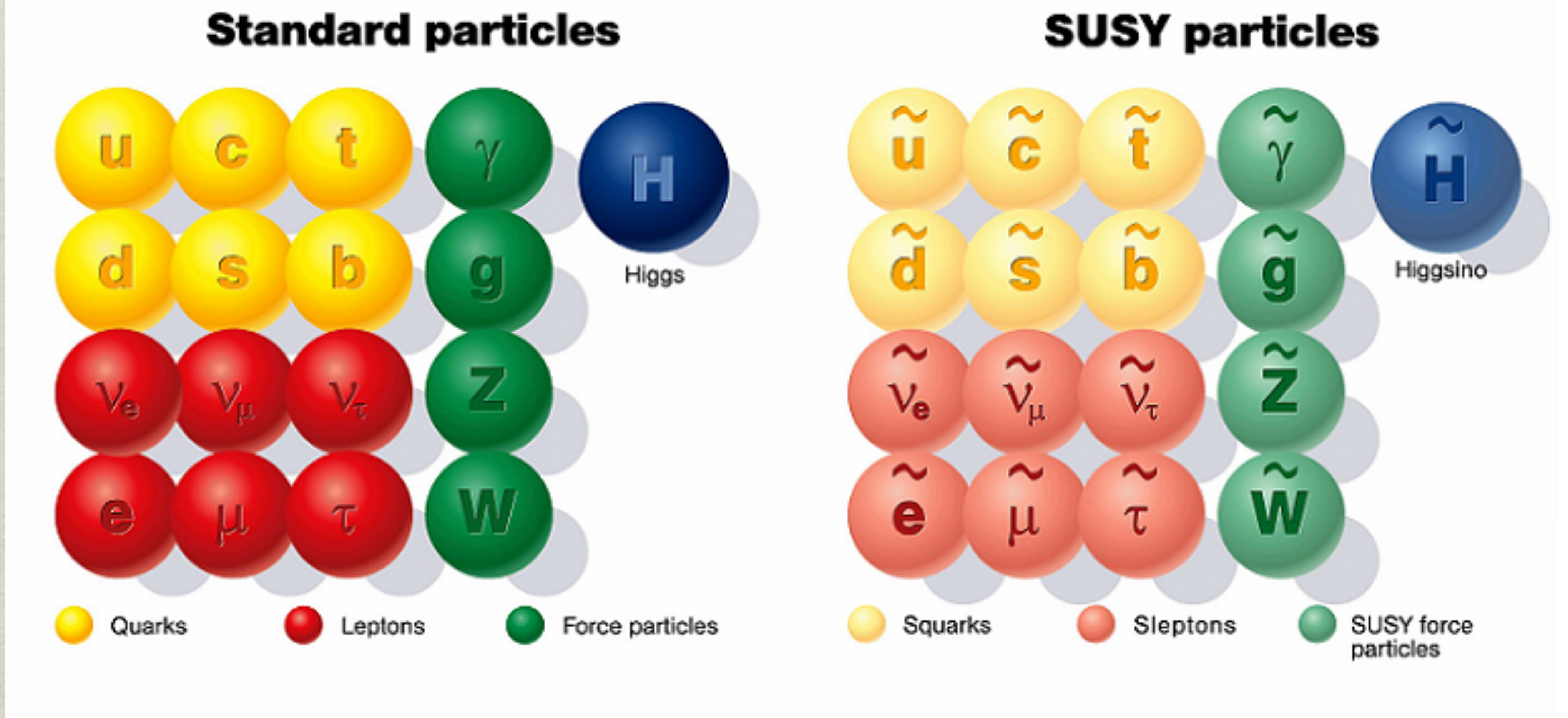
Or

C. New Physics Scenarios associated with the Higgs Sector

1. Supersymmetry:

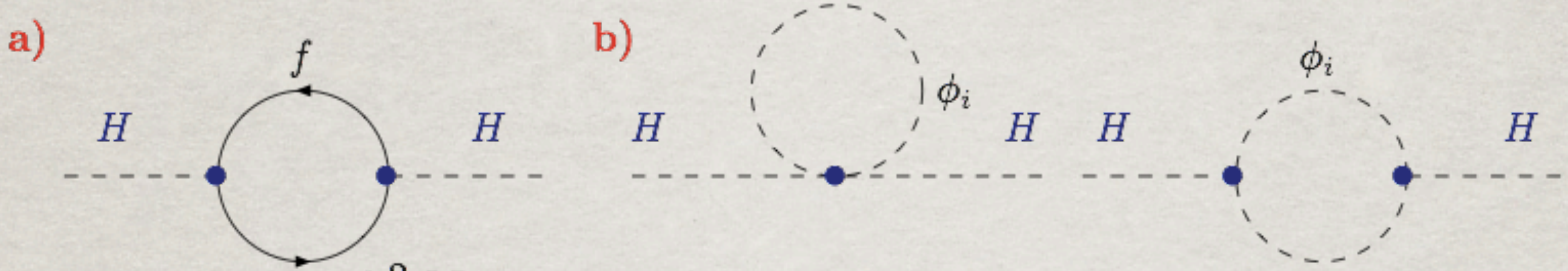
The SUSY generators $\mathcal{Q}$ transform fermions into bosons and vice–versa

$$\mathcal{Q}|\mathrm{Fermion}\rangle >= |\mathrm{Boson}\rangle \quad , \quad \mathcal{Q}|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle$$



See Sudhir Vempati

Thus the Higgs mass corrections:



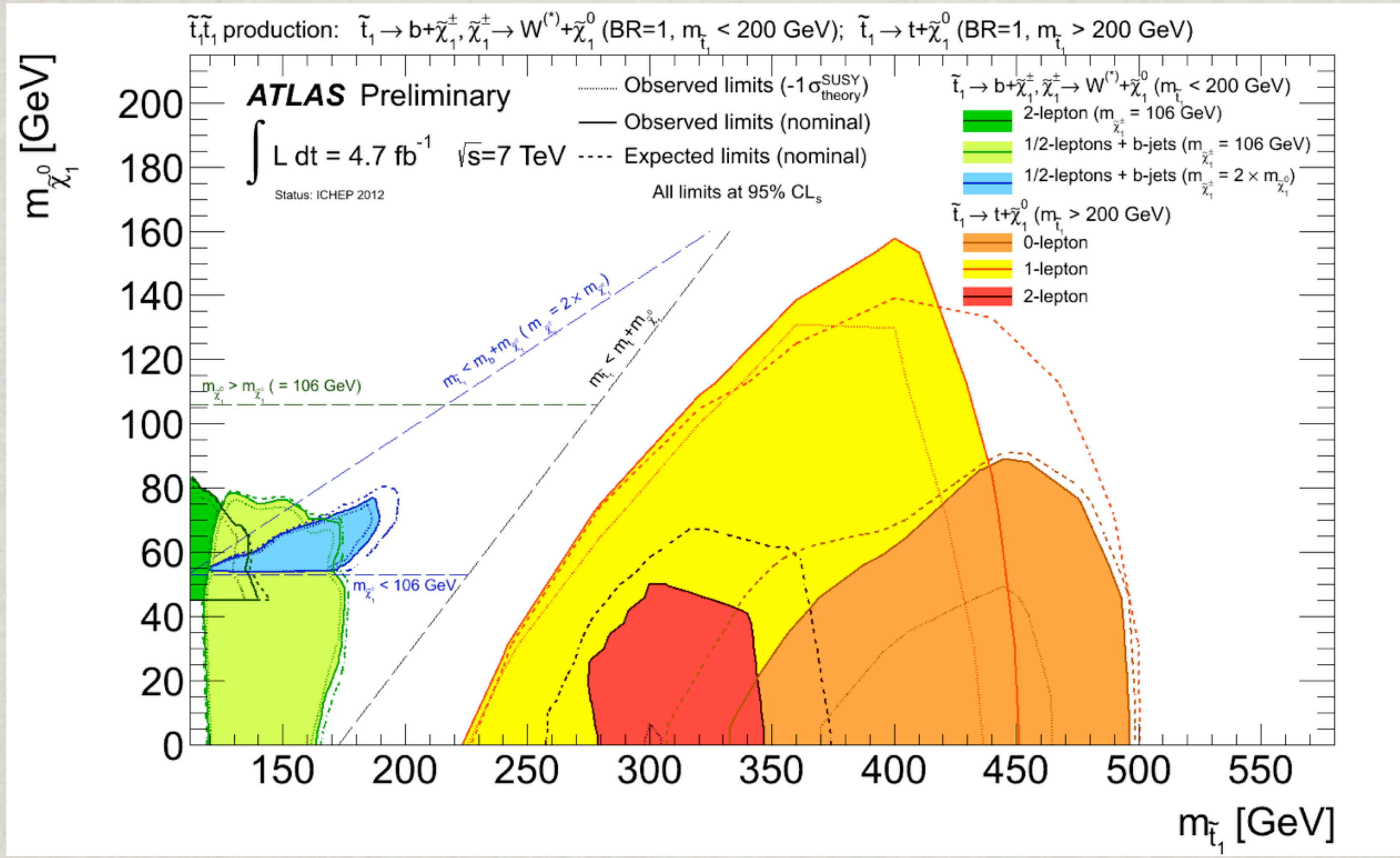
$$\Delta M_H^2 = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right]$$

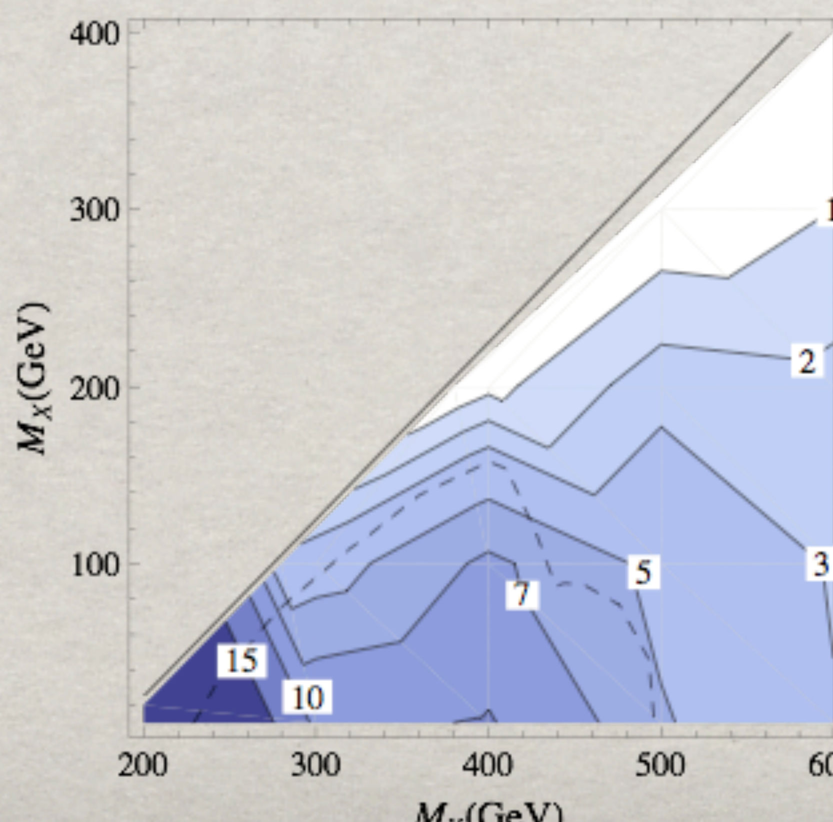
* In SUSY limit, the correction vanishes.
* In soft SUSY breaking case, $m_S \sim O(1\text{ TeV})$.
  - predict TeV scale new physics: light Higgs bosons, SUSY partners...
  - imply a (possible) grand desert in $M_{SUSY} - M_{GUT}$, and unification
  - radiative EWSB:

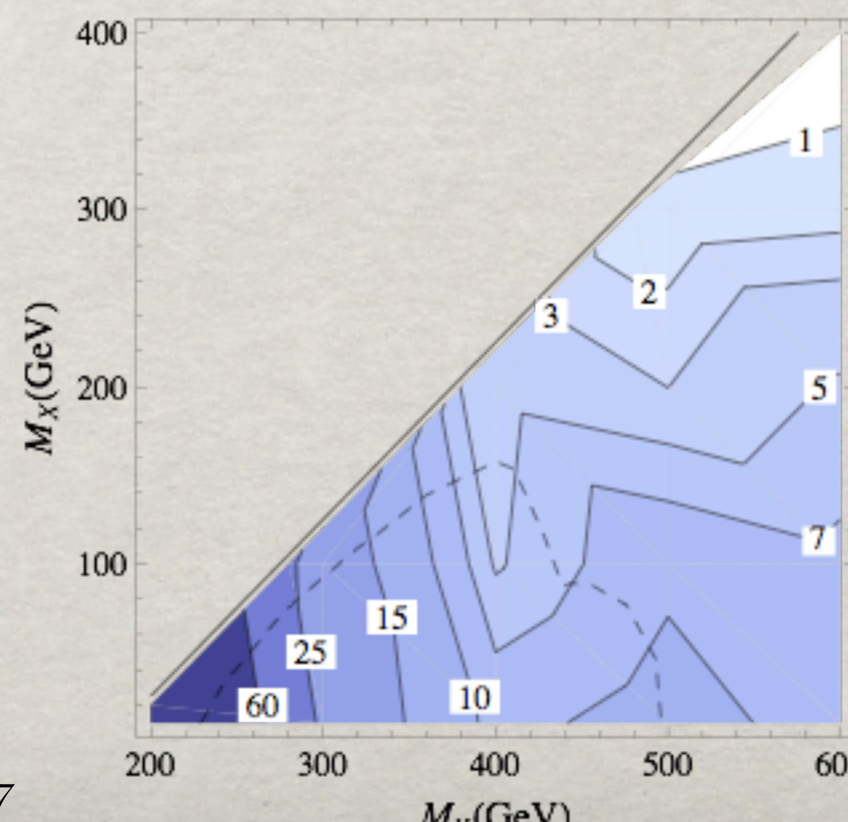
$$M_Z^2/2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2.$$

- SUSY dark matter with R-parity conservation

Thus, top-partner is most likely suspect!







2. Two Higgs Doublets in the MSSM

In the MSSM, we need two doublets of complex scalar fields of opposite hypercharge

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \text{ with } Y_{H_1} = -1 \quad , \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \text{ with } Y_{H_2} = +1$$

$$\langle H_1^0 \rangle = \frac{v_1}{\sqrt{2}} \quad , \quad \langle H_2^0 \rangle = \frac{v_2}{\sqrt{2}} \qquad (v_1^2 + v_2)^2 = v^2 = \frac{4M_Z^2}{g_2^2 + g_1^2} = (246 \text{ GeV})^2$$

$$\tan\beta = \frac{v_2}{v_1} = \frac{(v\sin\beta)}{(v\cos\beta)} \qquad \lambda = \frac{g_2^2 + g_1^2}{8}$$

Lead to 3 Goldstone bosons, and five "Higgses":

$$h^0,\ H^0,\ A^0,\ H^\pm$$

Tree-level masses given by $M_A,\ \tan\beta$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$M_h \ \leq \ \min(M_A, M_Z) \cdot |\cos 2\beta| \leq M_Z$$

Large radiative corrections:

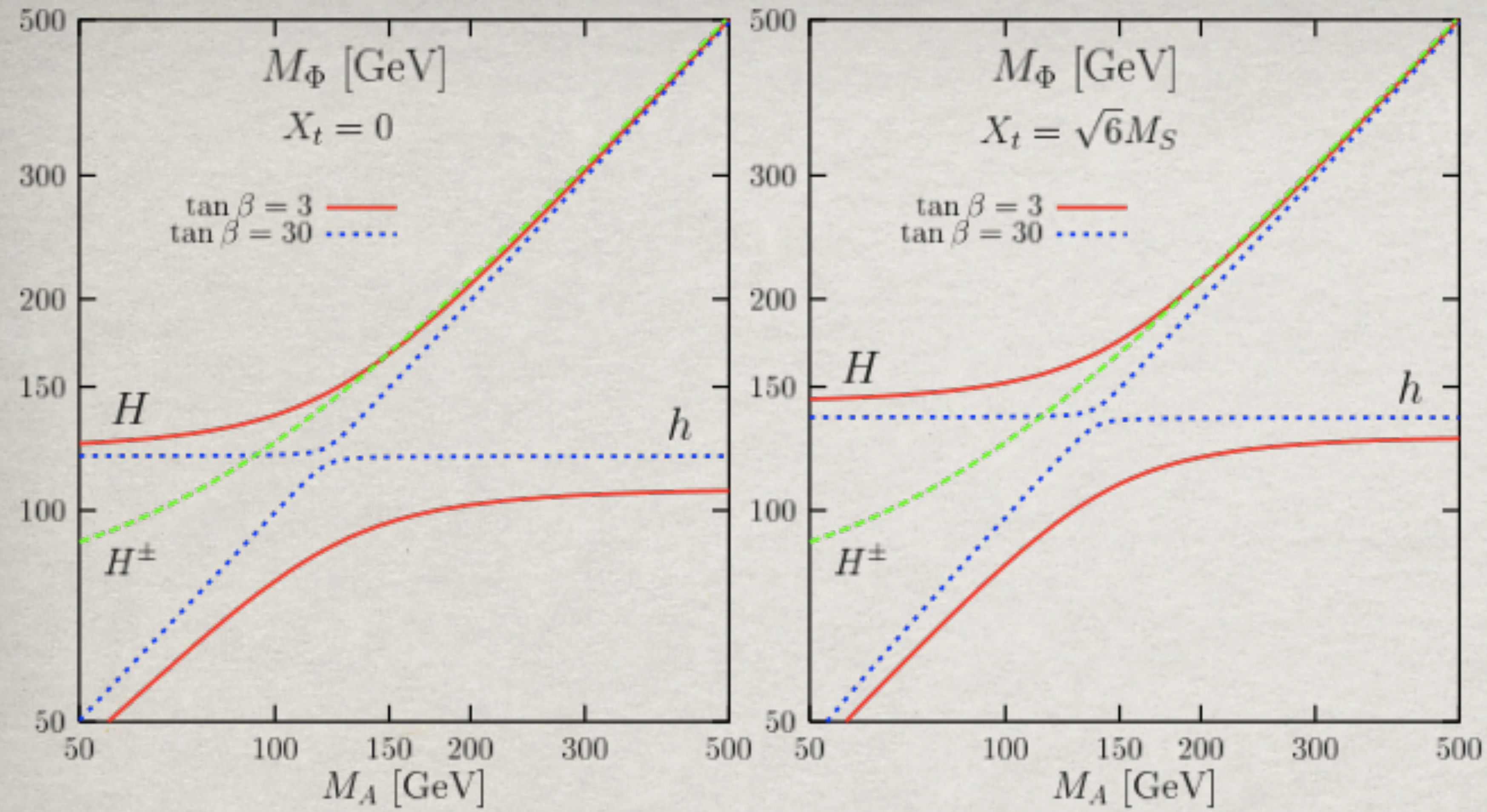
$$\Delta m_{h^0}^2 \approx \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right)+\frac{\tilde{A}_t^2}{M_S^2}\left(1-\frac{\tilde{A}_t^2}{12M_S^2}\right)\right]+\ldots,$$

where the mixing in the stop sector is given by

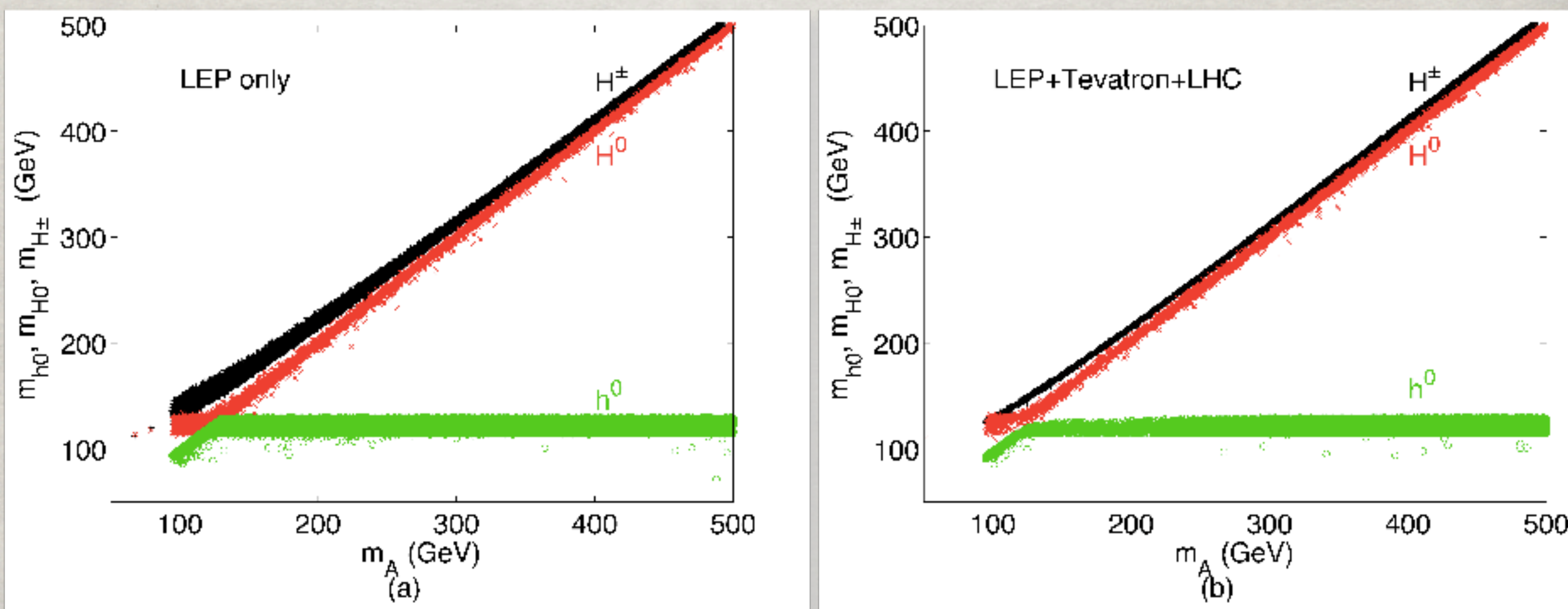
$$\tilde{A}_t = A_t - \mu\cot\beta.$$

- Very sensitive to $m_t, \quad \delta m_t \approx \delta m_H.$
- Sensitive to stop-mixing: large
- Sensitive to SUSY -breaking: heavy
- Sensitive to: μ, light Higgsino

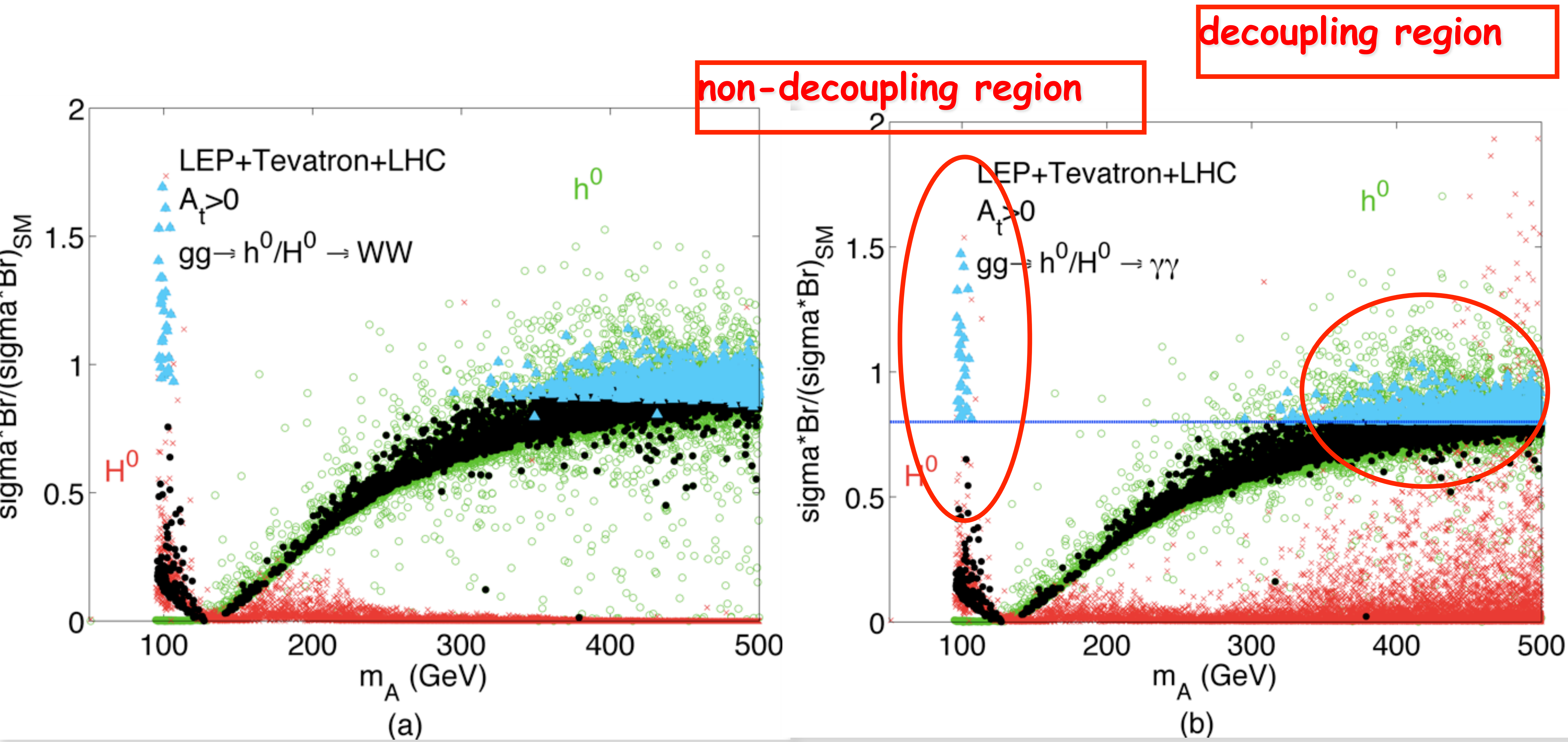
can be as large as 50%!



- Updated results: arXive:1203.3207



Allowed Region: $gg \to h^0, H^0 \to \gamma\gamma$, WW



black dots: $123 < m_{h0}$ or $m_{H0} < 127$ GeV

blue dots: $\sigma X Br\,(gg \to h^0, H^0 \to \gamma\gamma)_{MSSM} > 80\%\,(\sigma X Br)_{SM}$

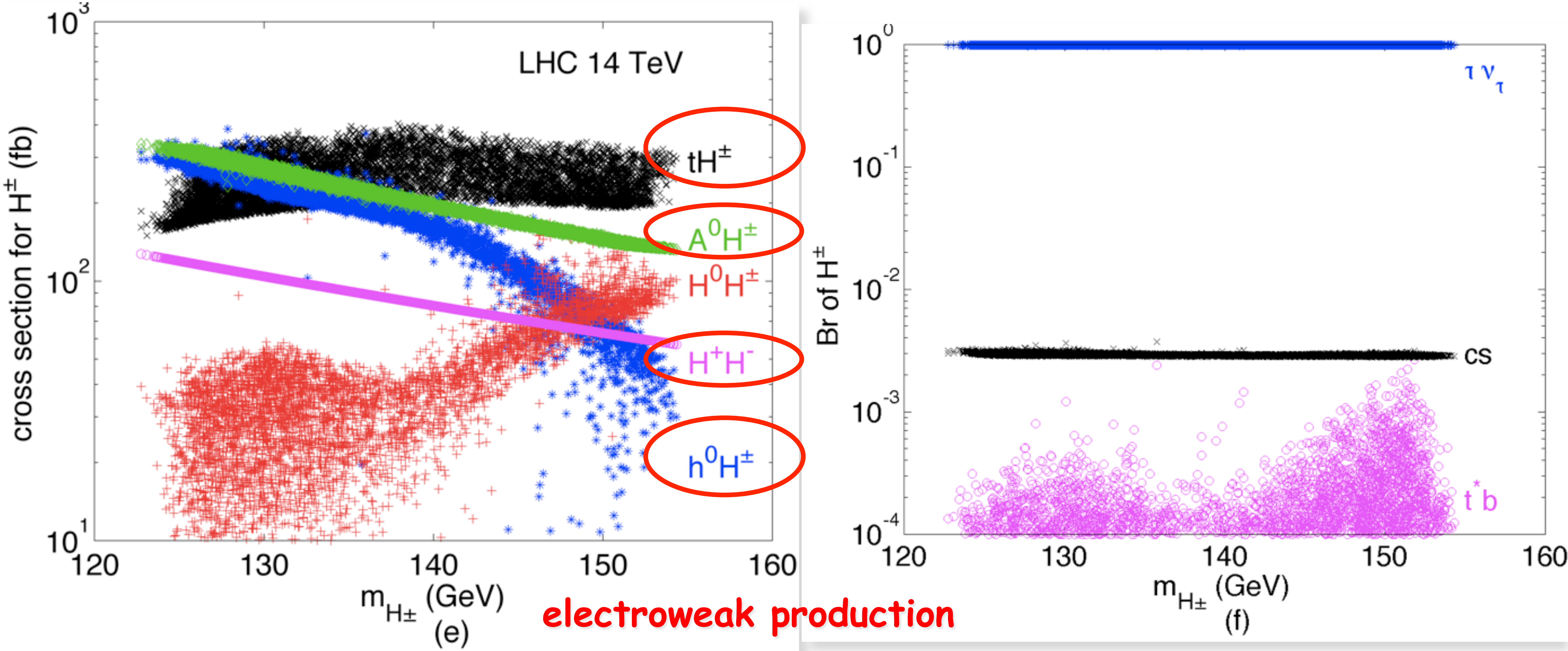
Tao Han

Higgs Pair Production

◉ non-decoupling region:

EW gauge interactions: $pp \to H^\pm A^0,\ H^+ H^-$

SUSY parameter depndt: $pp \to H^\pm h^0,\ A^0 h^0,$



electroweak production

Tao Han

3. Composite Higgs:
--- The Little Higgs Model

A very interesting idea§ is to make the Higgs a "pseudo-Nambu-Goldstone" boson.

§ H. Georgi and David B Kaplan, 1984.

A less ambitious approach: Little Higgs Models

Accept the existence of a light Higgs;

keep the Higgs boson "naturally" light (at 1-loop level).

Higgs is a pseudo-Goldstone boson from global symmetry breaking (at scale $4\pi f$)‡

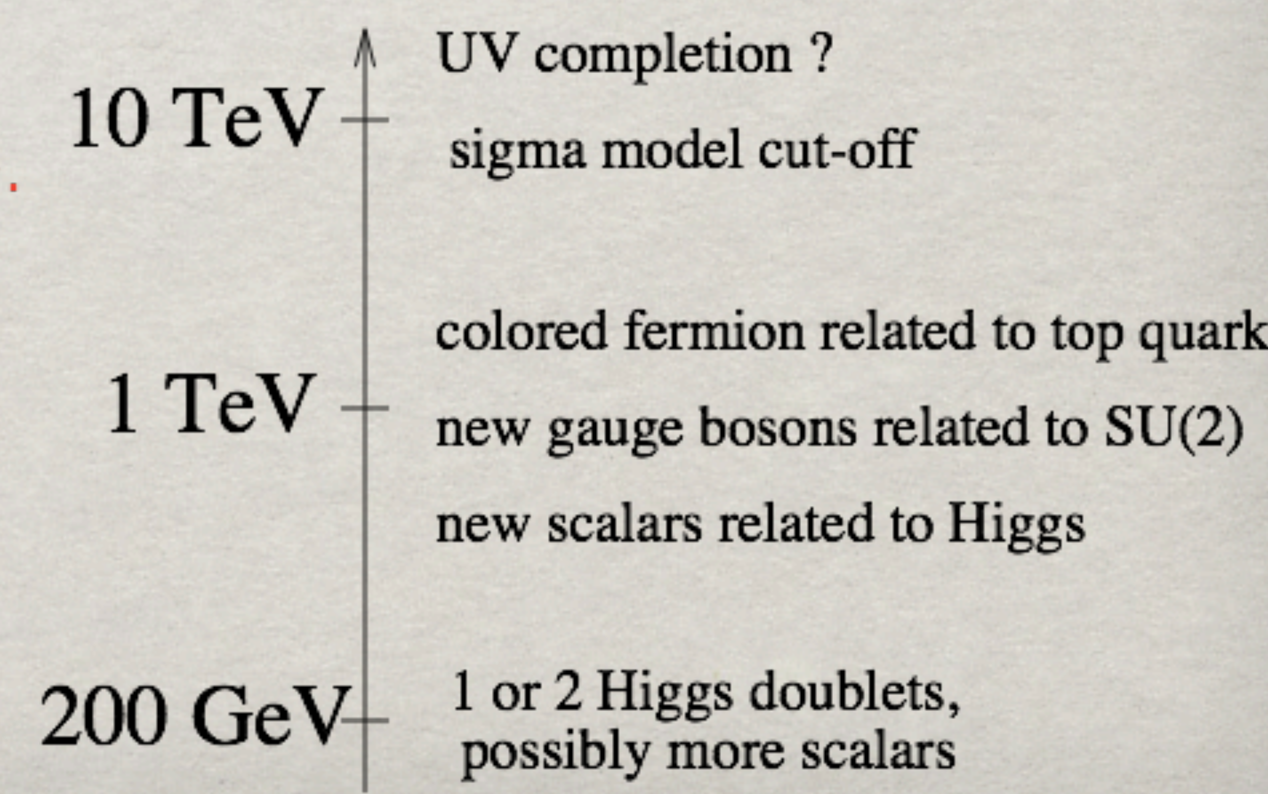
Higgs acquires a mass radiatively at the EW scale v, by collective explicit breaking

Consequently, quadratic divergences absent at one-loop level*

$W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$

(cancellation among same spin states!)

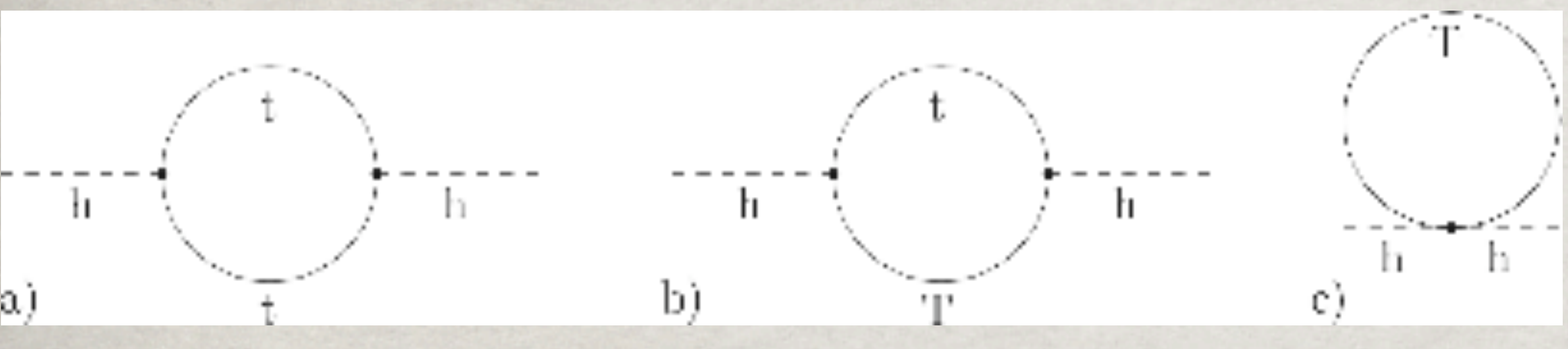
$$\lambda_{h^4} = \frac{a}{8}\left[\frac{g^2}{s^2c^2} + \frac{g'^2}{s'^2c'^2}\right] + 2a'\lambda_1^2 = \frac{1}{4}\lambda_{\phi^2}.$$



In Little Higgs Models,

Most interesting of all, the top fermionic partner T:

$$\mathcal{L} = -\lambda_T T_R^\dagger \tilde{H} Q_3 + \frac{\lambda_t^2 + \lambda_T^2}{2m_T}(H^\dagger H) T_L^\dagger T_R + \text{ h.c.}$$



$$m_t = \frac{i\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}} v \left\{1 + \frac{v^2}{f^2}\left[-\frac{1}{3} + \frac{fv'}{v^2}\right.\right.$$

$$M_T = -f\sqrt{\lambda_1^2+\lambda_2^2}\left[1 + \mathcal{O}(v^2/f^2)\right].$$

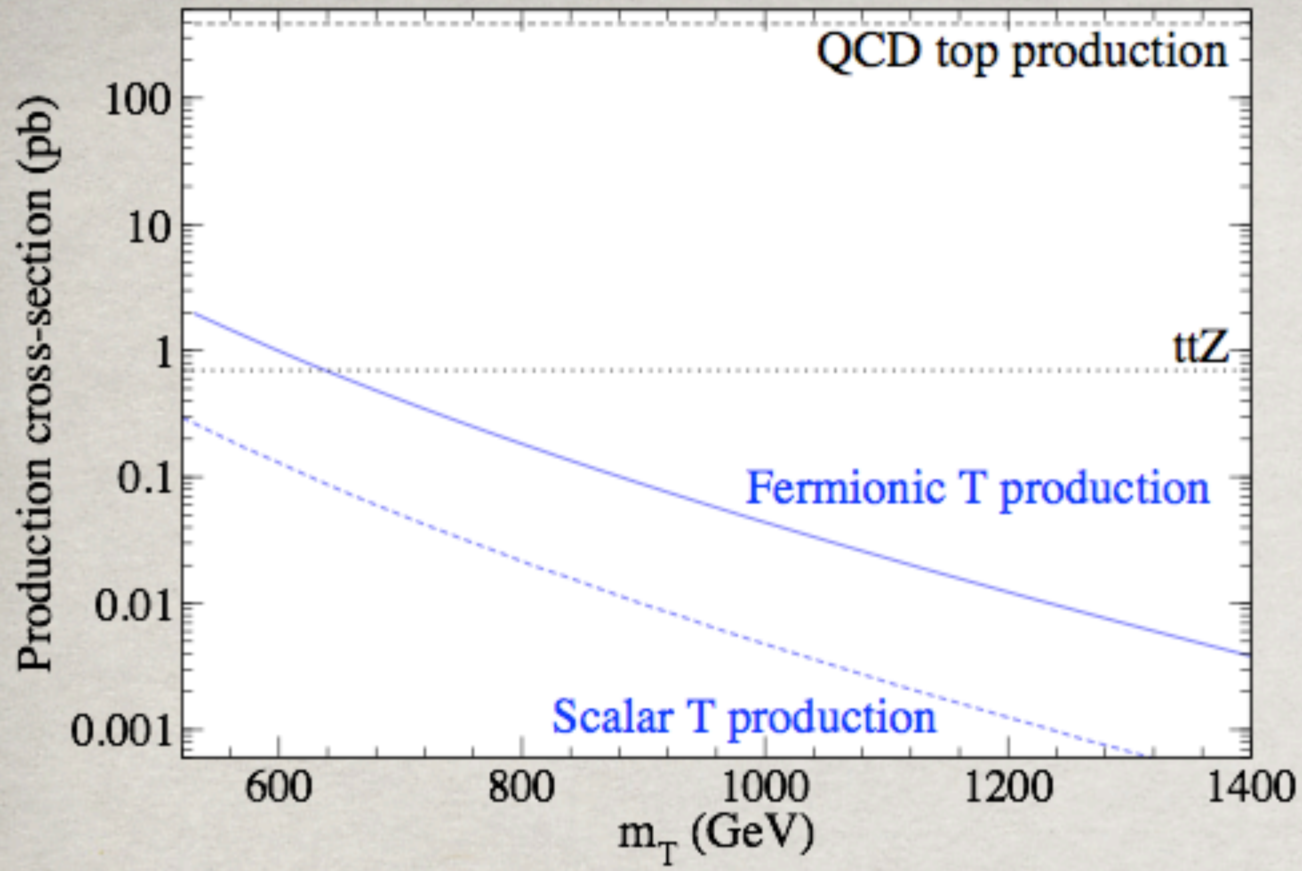
=> The quadratic divergence is then cancelled at one loop level

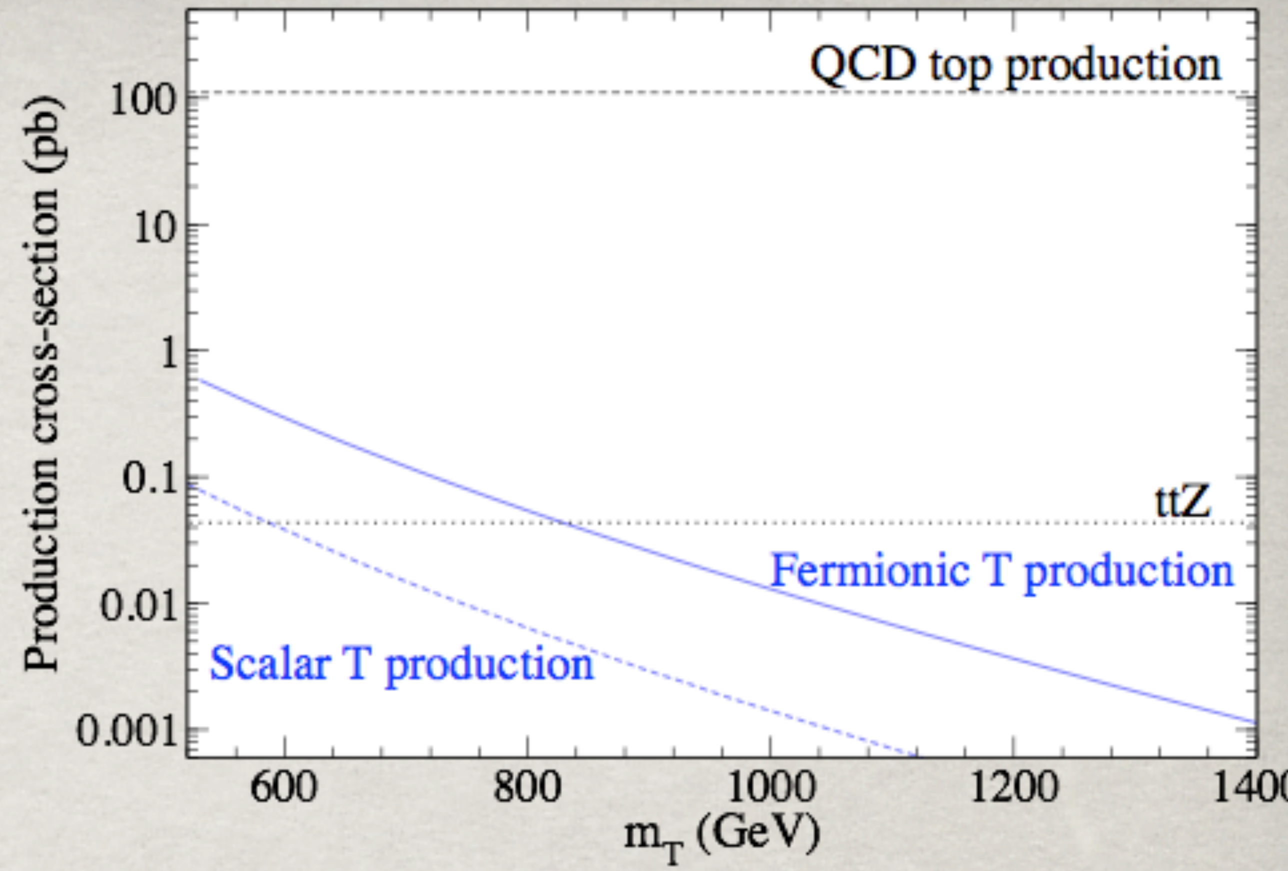
Then the logarithmically contribution to the Higgs mass square

$$m_h^2 \sim 6\frac{\lambda_t^2 m_T^2}{8\pi^2}\log\frac{\Lambda^2}{m_T^2}$$

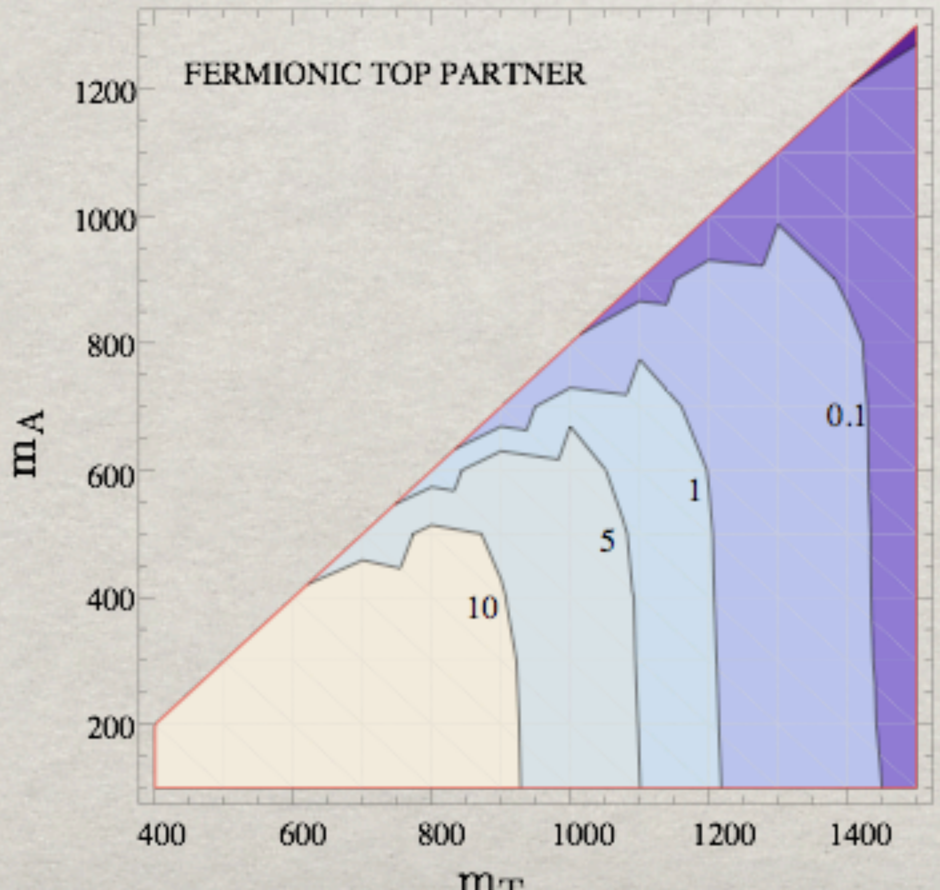
m_h = 125 GeV → mT < 1TeV

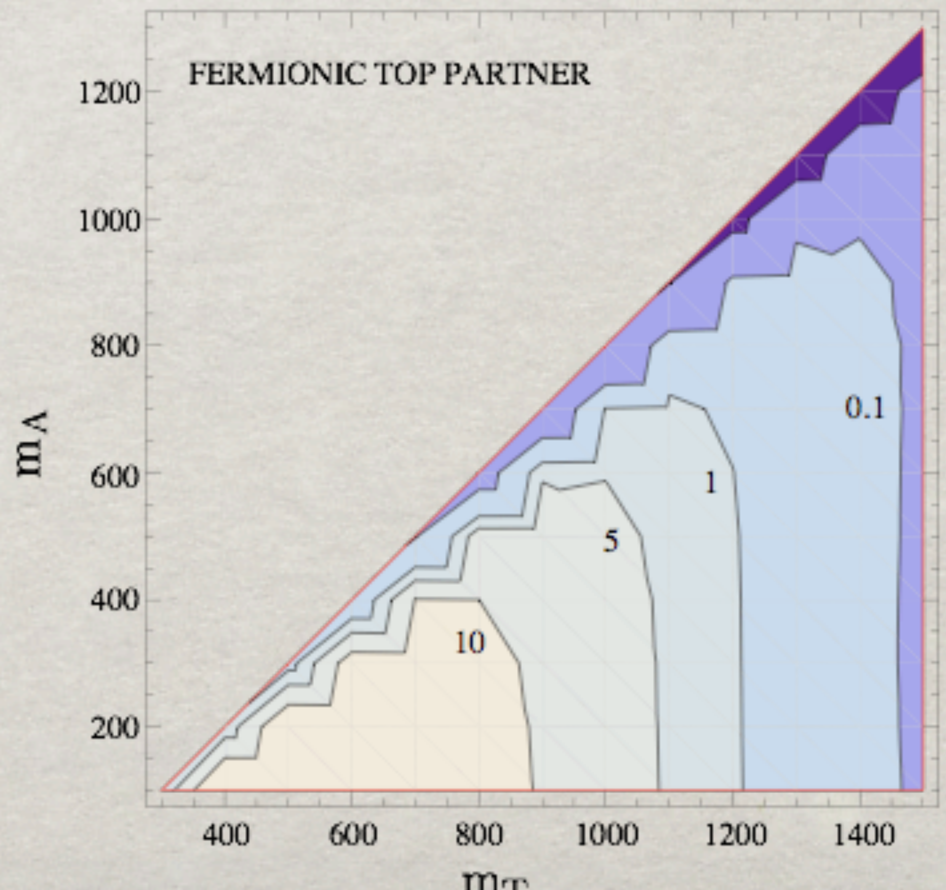
(J Berger, J. Hubisz and M. Perelstein, 2012)





$$q\bar{q},\ gg \to T\bar{T} \to t\bar{t}\ A^0 A^0 X \to b j_1 j_2\ \bar{b}\ \ell^- \bar{\nu}\ A^0 A^0\ X + c.c.$$

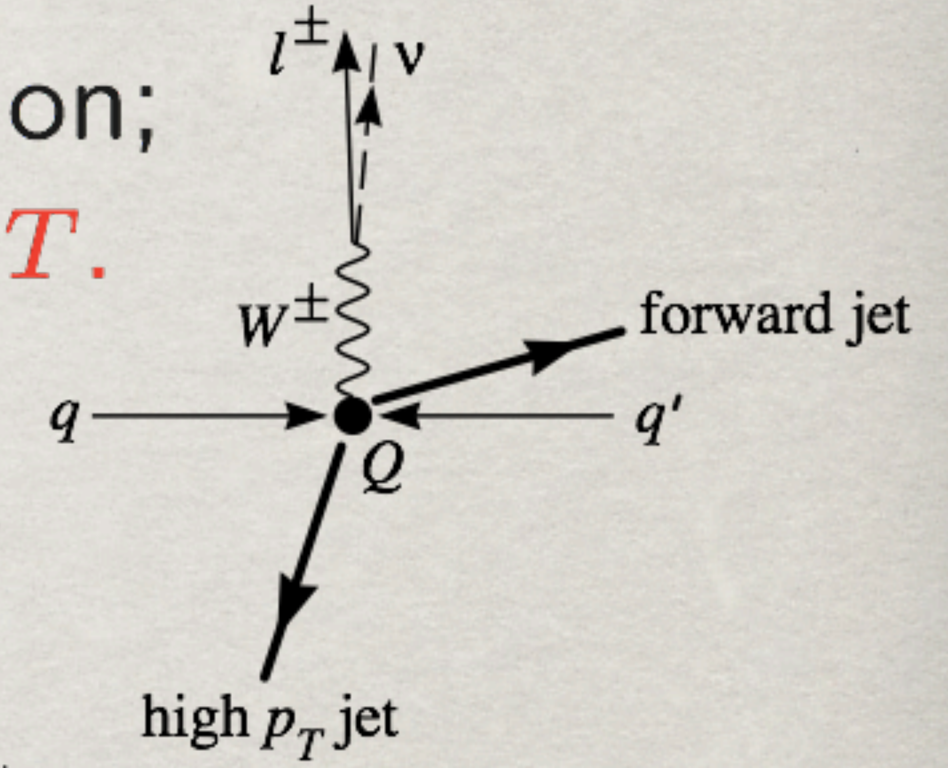


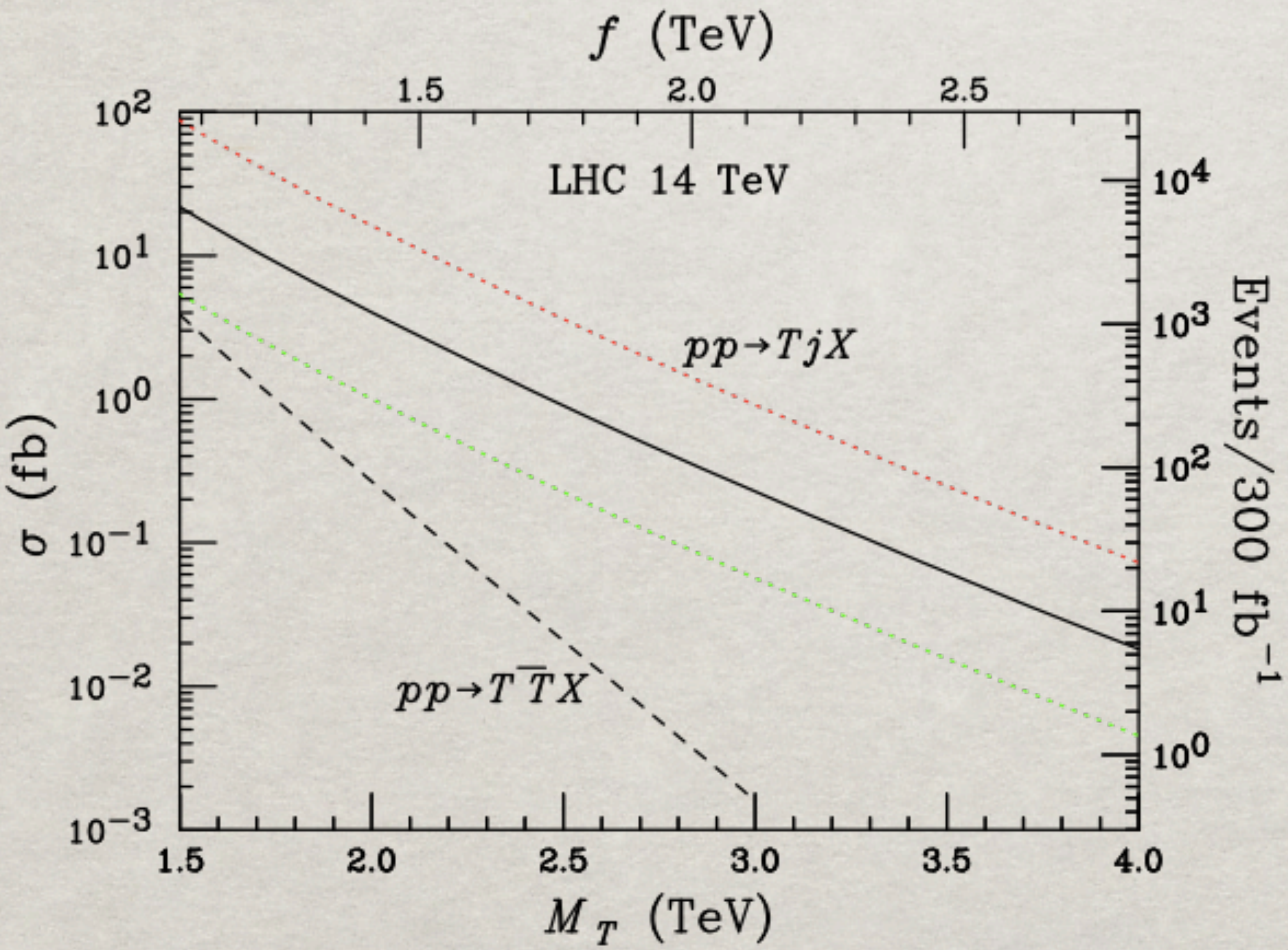


Single production:

$gg \to T\bar{T}$ phase-space suppression;

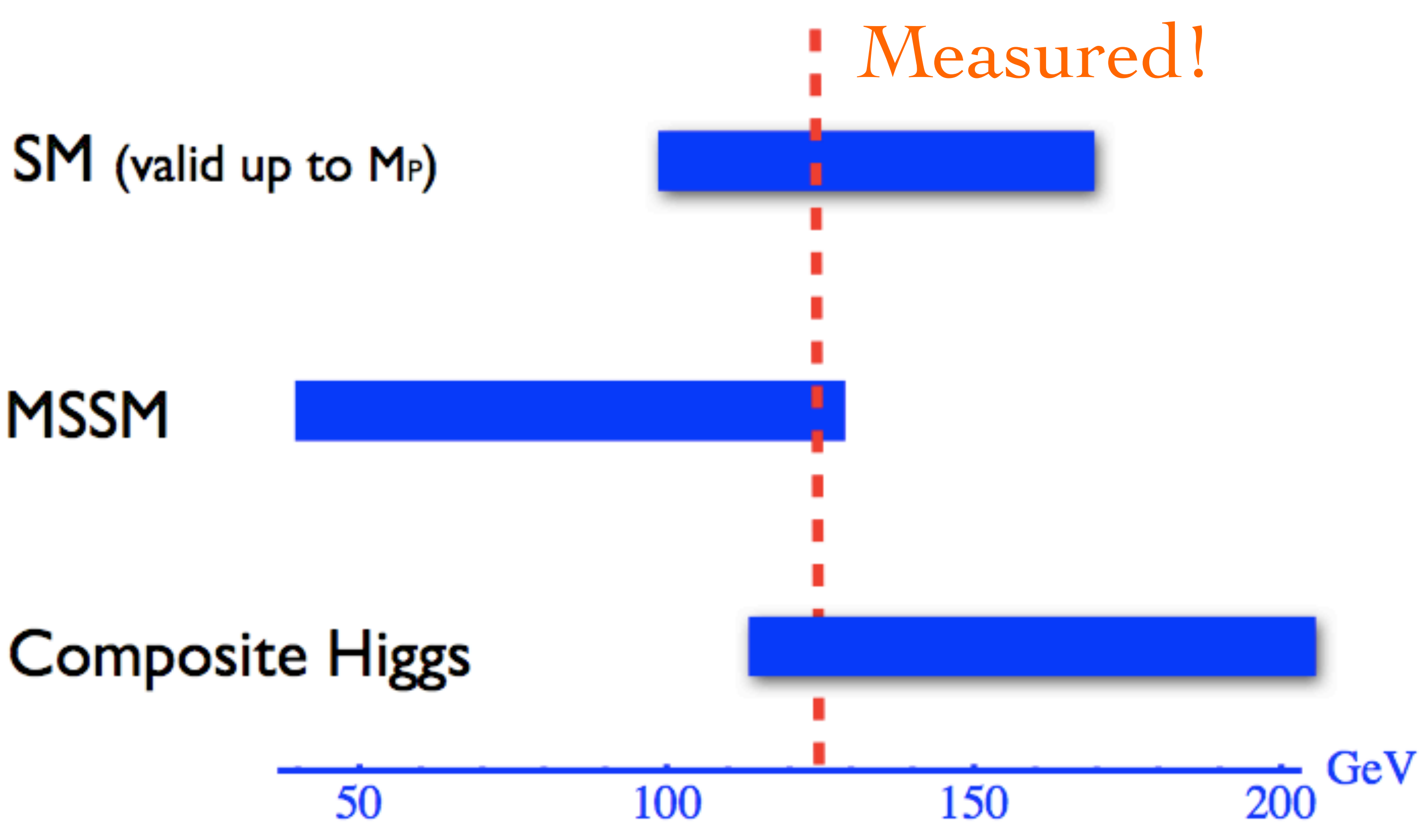
$qb \to q'T$ via t-channel $W_L b \to T$.





The fact that $M_H \approx 126$ GeV
has already provides non-trivial test to some models.

In a given theory with additional symmetries, one may be able
- to calculate (in a weakly coupled theory – SUSY)
- to (g)estimate (in a strongly coupled theory – composite)



$$M_H^2 = M_Z^2 \cos^2 2\beta + \Delta_{SUSY}^2$$

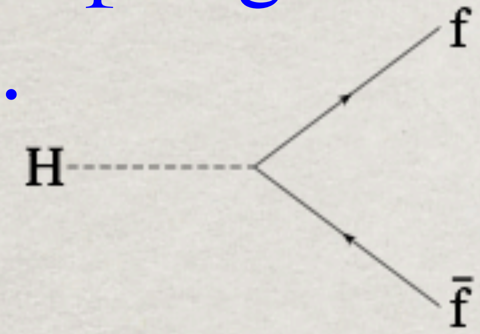
$$M_H^2 \approx \frac{3}{\pi} \frac{m_t^2 M_T^2}{f^2}$$

Pomarol, ICHEP'12

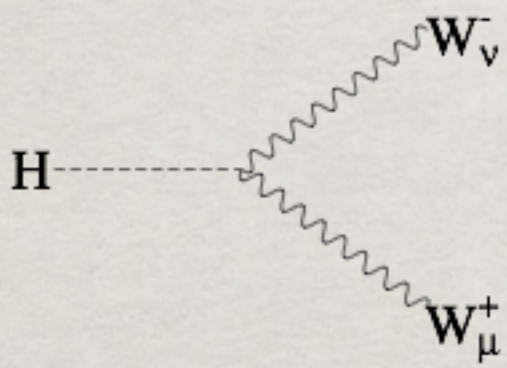
Both suffer from some degree of fine-tune (already).

4. Higgs Coupling Deviations:

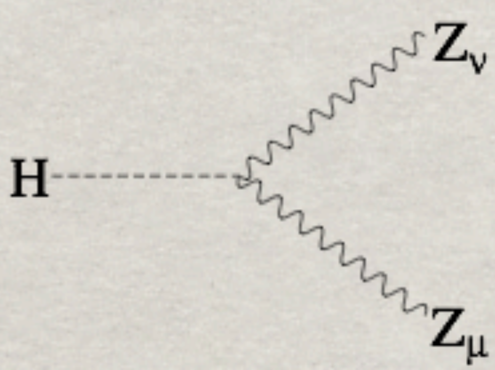
No matter there is new physics BSM seen or not, Higgs couplings need to be measured as accurate as possible.



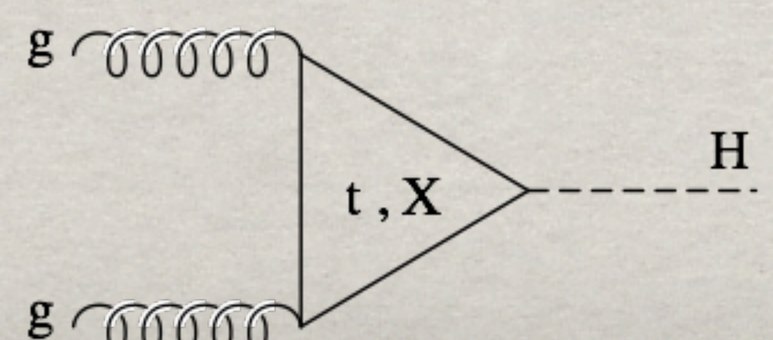
$$-i\frac{m_f}{v}\left(1+\Delta_f\right)$$

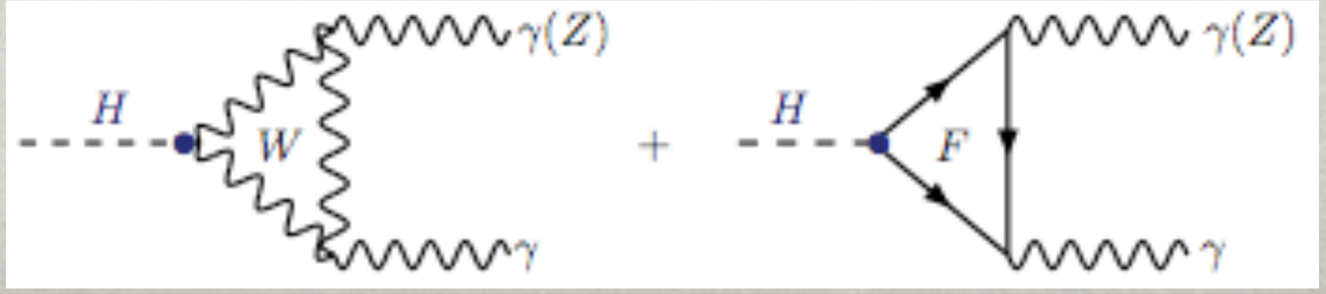


$$ig\, m_W\, (1+\Delta_W) g_{\mu\nu}$$



$$i\, g\, \frac{1}{\cos\theta_W}\, m_Z\, (1+\Delta_Z) g_{\mu\nu}$$





SFitter analysis of Higgs couplings at LHC

- Parameterize deviations from SM couplings

$$g_i = g_i^{\mathrm{SM}}\ (1 + \Delta_i)$$

- Five free parameters $i = W, Z, t, b, \tau$ plus generation universality
- Loop-induced couplings change from modifying contributing tree-level couplings
- Δ_H: common parameter modifying all (tree-level) couplings
- Assume no add. contribution to total width

- Background expectations, exp. errors, etc. from published analyses
- cross-checked with exclusion and signal-strength plots

List of input channels for 2011 data

ATLAS		CMS	
$\gamma\gamma$		$\gamma\gamma$	
$ZZ \to 4\ell$		$\gamma\gamma$	di-jet
WW	0-jet	$ZZ \to 4\ell$	
WW	1-jet	WW	0-jet
WW	2-jet	WW	1-jet
$\tau\tau$	0-jet	WW	2-jet
$\tau\tau$	1-jet	$\tau\tau$	0/1-jet
$\tau\tau$	VBF	$\tau\tau$	Boosted
$\tau\tau$	VH	$\tau\tau$	VBF
$b\bar{b}$	WH	$b\bar{b}$	WH
$b\bar{b}$	$Z(\to \ell\bar{\ell})H$	$b\bar{b}$	$Z(\to \ell\bar{\ell})H$
$b\bar{b}$	$Z(\to \nu\bar{\nu})H$	$b\bar{b}$	$Z(\to \nu\bar{\nu})H$

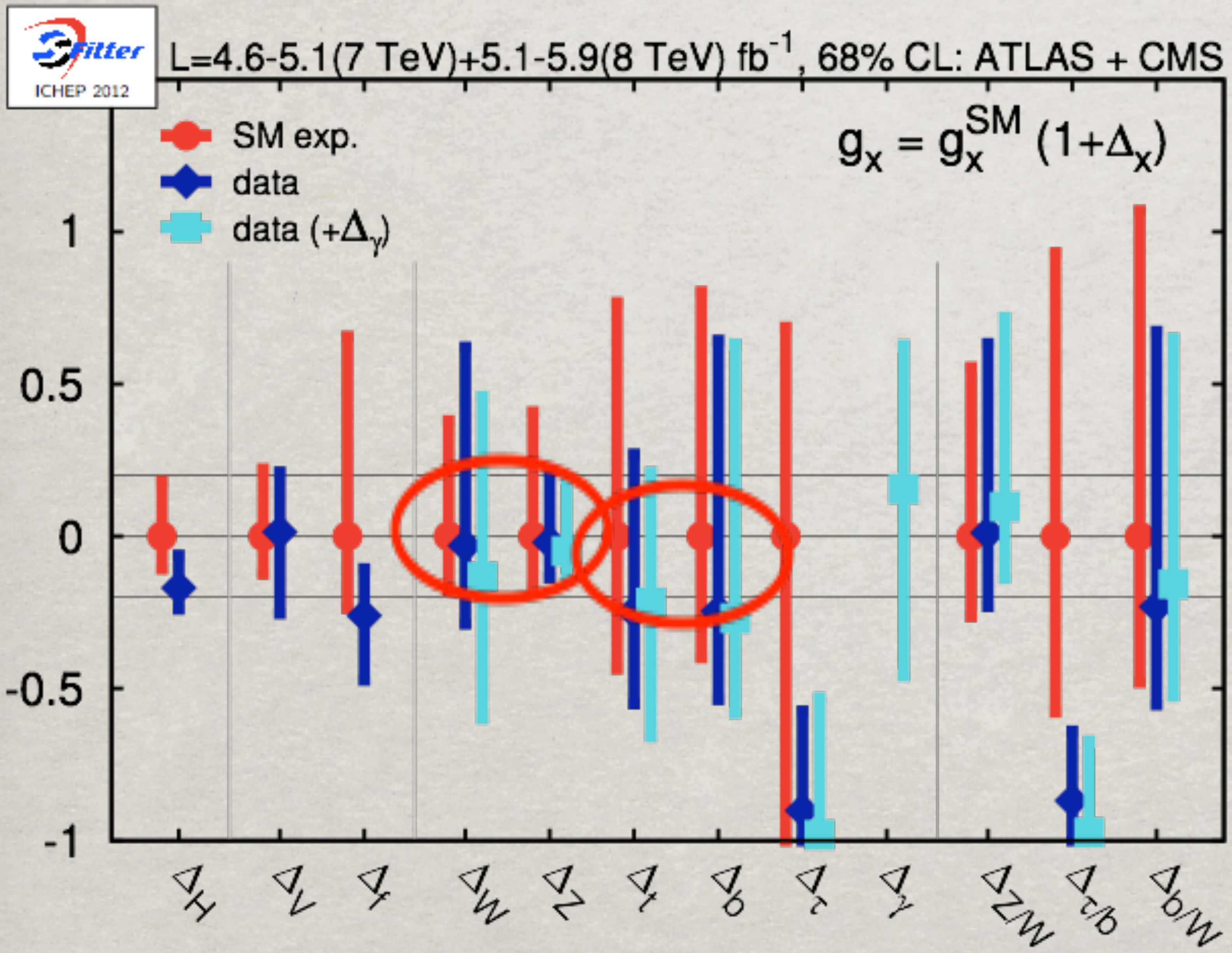
plus inclusion of 2012 data (ICHEP)

Current accuracies:

Central values and errors on couplings

Assuming SM:

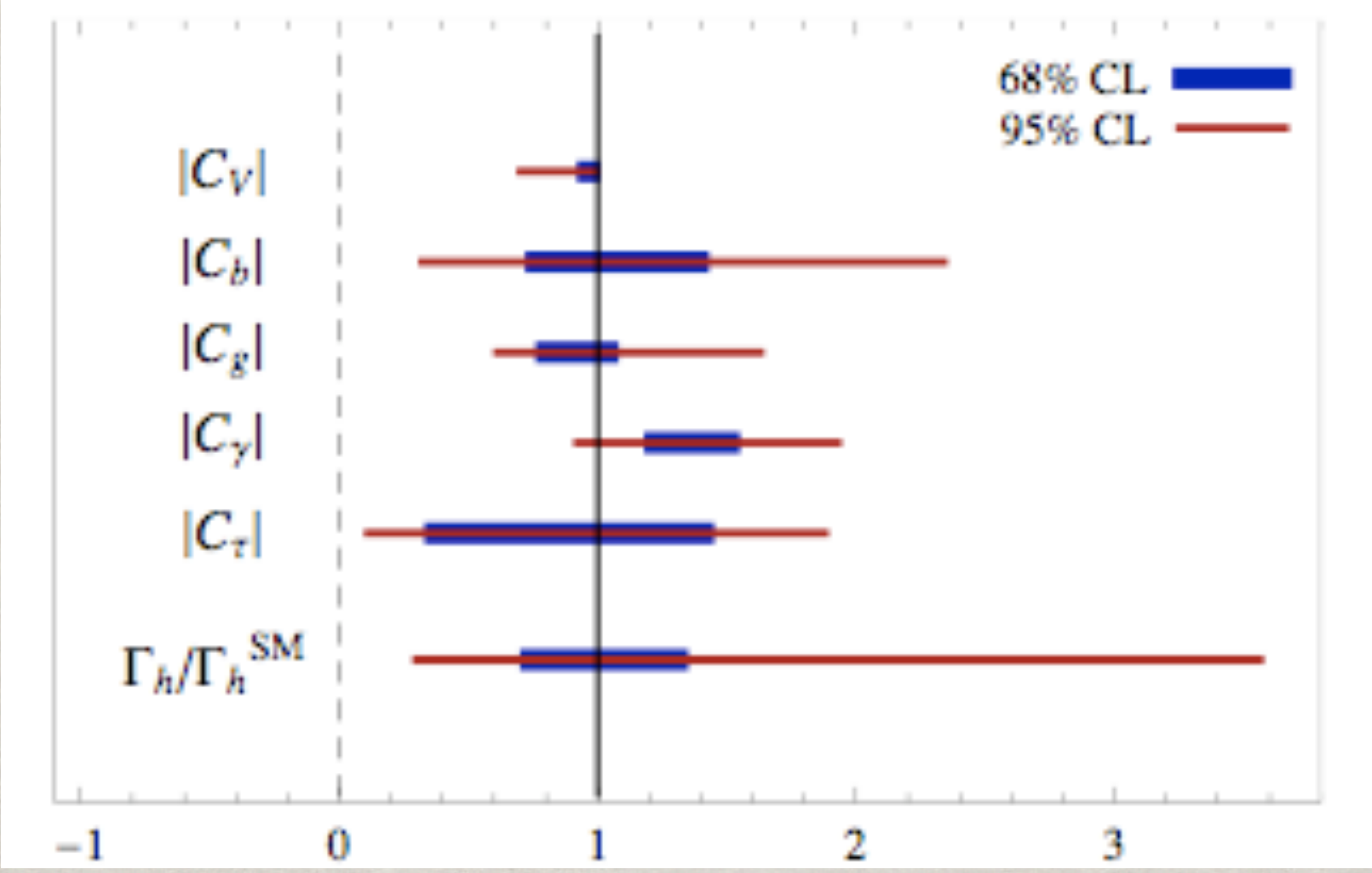
SFitter: T. Plehn et al., 2012.



- SM provides good overall description
- Two parameter fit with $\Delta_V \equiv \Delta_W = \Delta_Z$ and $\Delta_f \equiv \Delta_b = \Delta_\tau = \Delta_t$ gives improvement to $\chi^2/\text{d.o.f.} = 29.0/52$
- Five parameter fit does not give further improvement: $\chi^2/\text{d.o.f.} = 27.7/49$

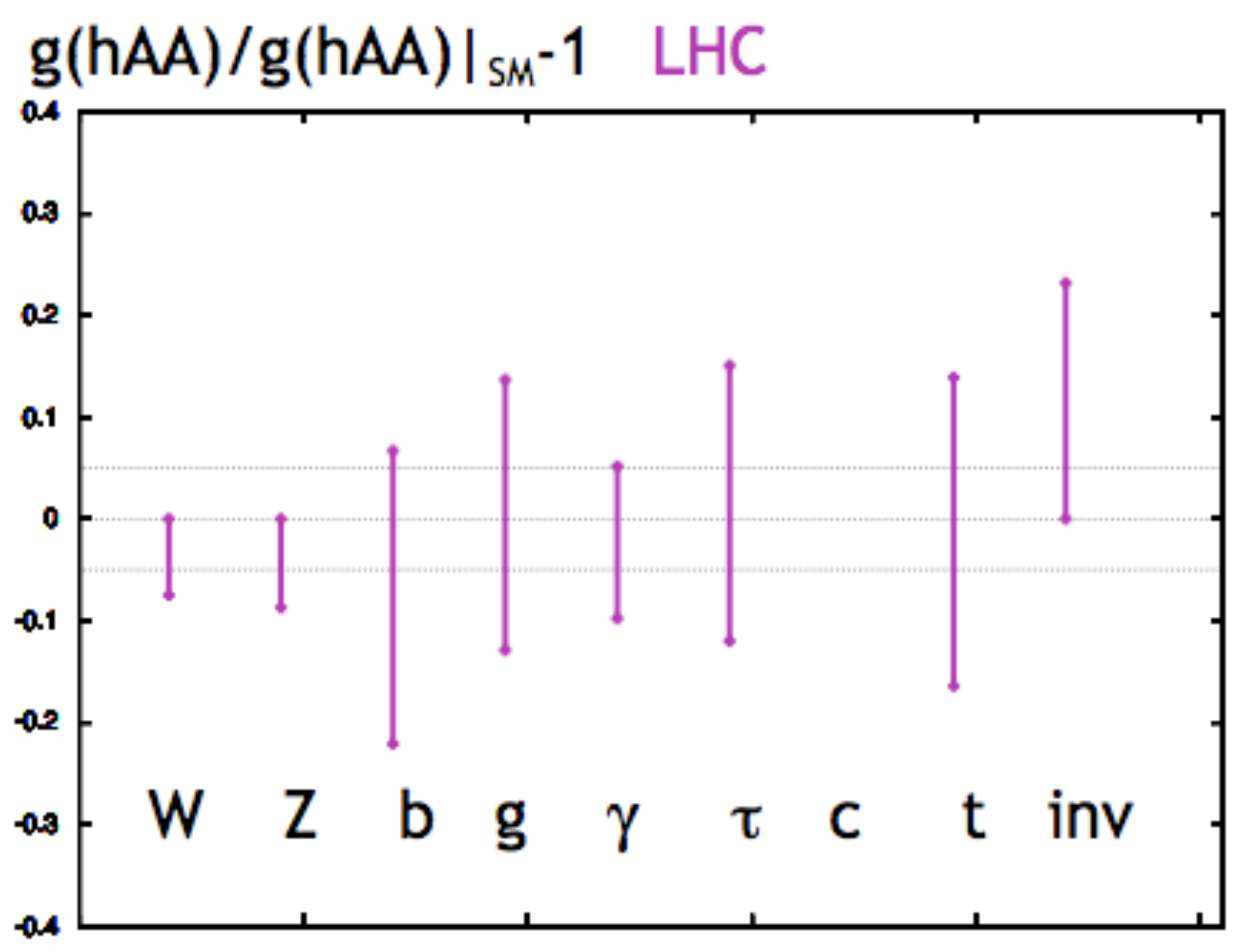
COUPLINGS & TOTAL WIDTH

Assuming $\Gamma_{W,Z} < (\Gamma_{W,Z})^{SM}$, one can derive bounds on Γ_{tot} based on the LHC data



Dobrescu & Lykken, arXiv:1210.3342.

Future LHC sensitivities:



14 TeV LHC with 300 fb^{-1}.

Peskin, arXiv:1207.2516; arXiv:1208.5152.

What if,
Not-So Natural Higgs Sector

Integrating out the heavy states at the scale M ≈ 1 TeV,
we expect the tree-level corrections:

$$\Delta_i \equiv \frac{g_i}{g_{SM}} - 1 \sim \mathcal{O}(v^2/M^2) \approx \text{a few } \%$$

We illustrate the possible effects
in a few specific models.

For each model, we aim at the mass scale M
which is not easily accessible by
14 TeV LHC with 300 fb^{-1}.

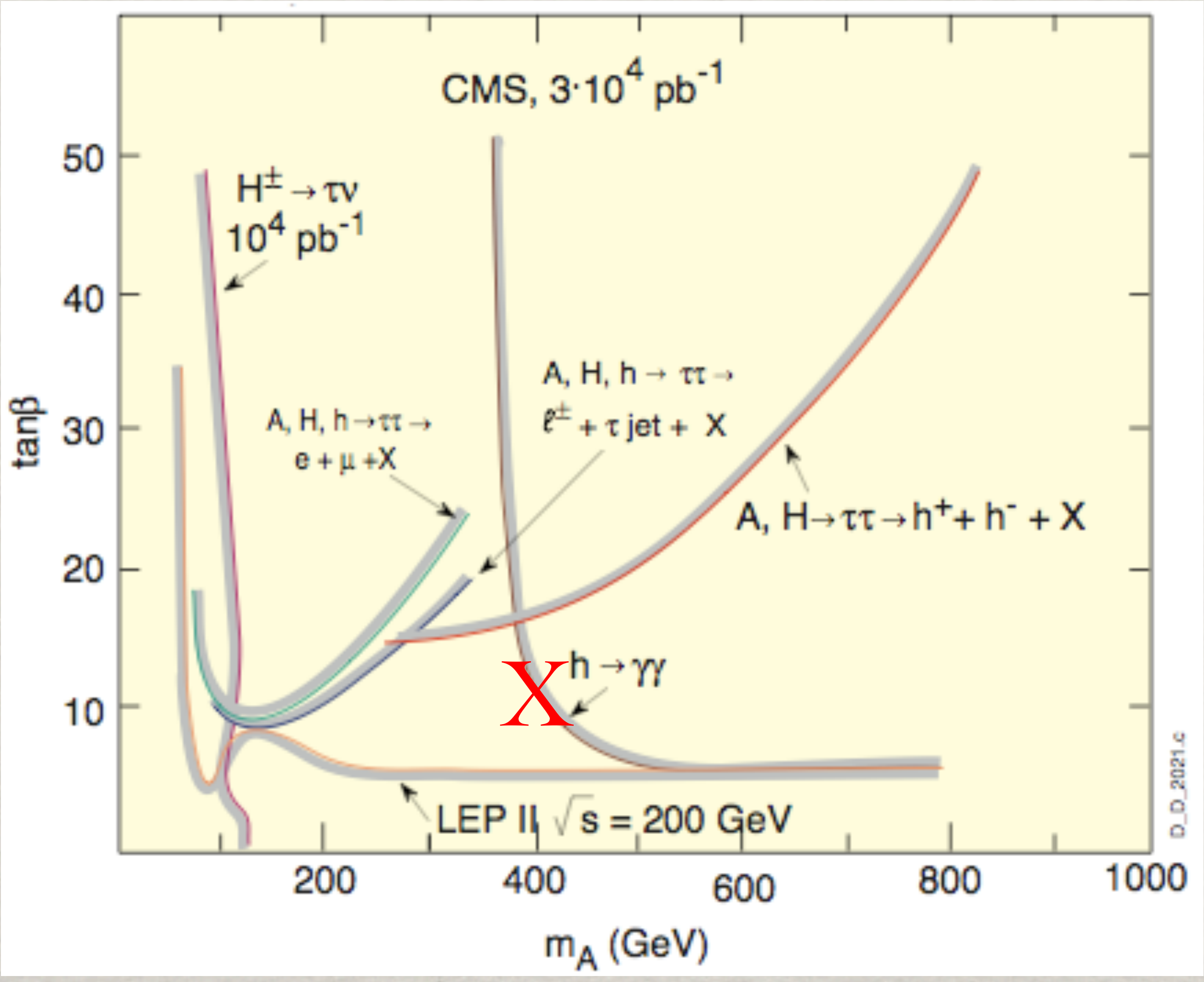
Example 1: Extended Higgs Sector:

The decoupling limit in MSSM: H. Haber, hep-ph/9501320.

$$\Delta_{VVH} \sim \mathcal{O}(M_Z^4/M_A^4), \quad \Delta_{ffH} \sim \mathcal{O}(M_Z^2/M_A^2).$$

(Similar decoupling limit also exists in 2HDM)

A^0, H^0, $H^\pm$ may be out of LHC detection:

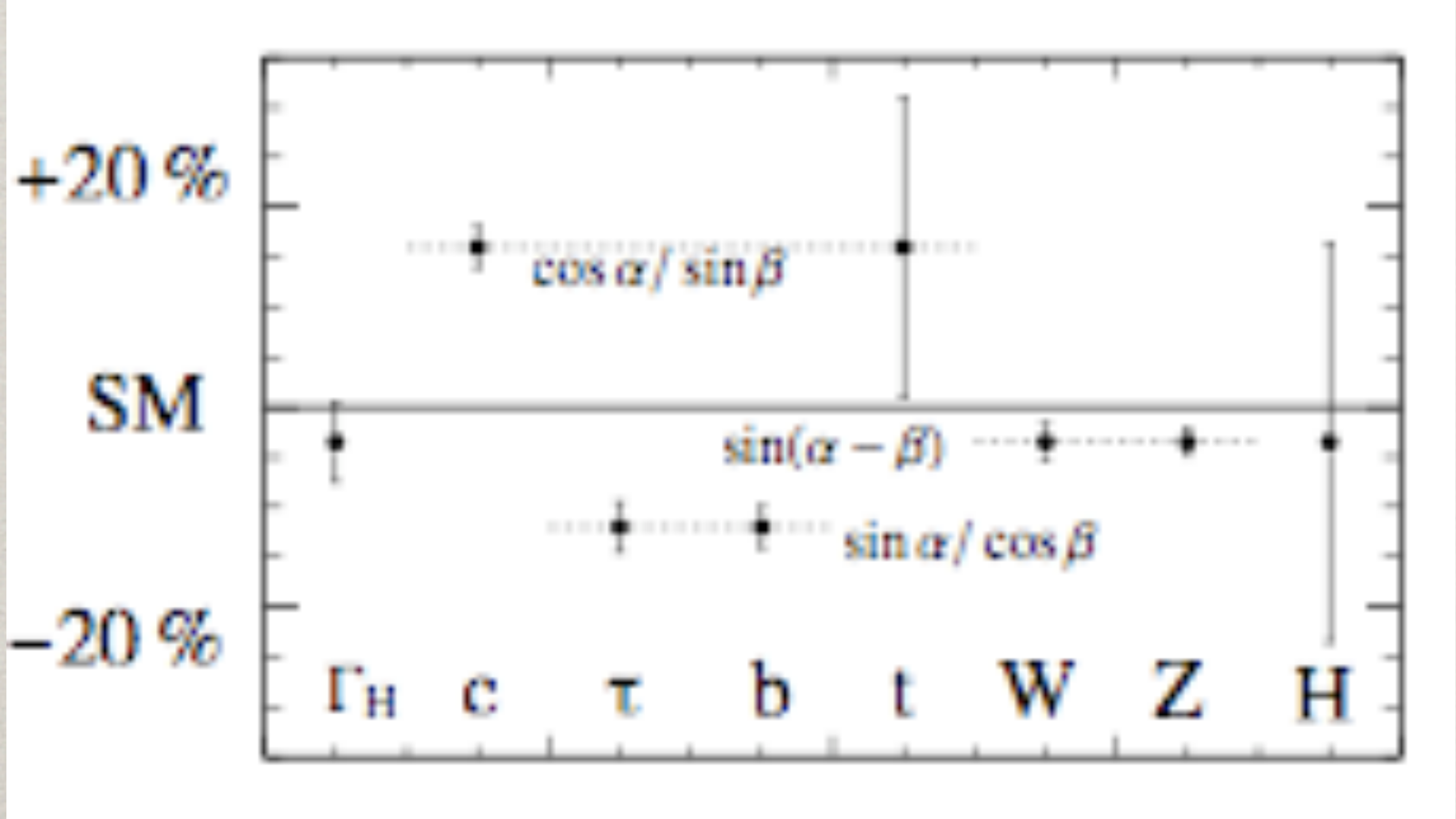


Corrections in the MSSM decoupling limit:

Carena, Haber et al., 2002

Δ_{hVV}	Δ_{htt}	$\Delta_{hbb,h\tau\tau}$
$\frac{-2M_Z^4}{m_A^4 \tan^2\beta}$	$\frac{-2M_Z^2}{m_A^2 \tan^2\beta}$	$\frac{2M_Z^2}{m_A^2}$
$-5\cdot 10^{-5}(\frac{10}{\tan^2\beta})^2(\frac{400\ \mathrm{GeV}}{m_A})^4$	$-10^{-3}(\frac{10}{\tan^2\beta})^2(\frac{400\ \mathrm{GeV}}{m_A})^2$	$10\%(\frac{400\ \mathrm{GeV}}{m_A})^2$

Corrections in the 2HDM decoupling limits:



J.Brau et al.,
arXiv:1210.0202

Not-So Natural Higgs Sector

Example 2: Top quark partner

The top quark partners are most wanted to cancel the quadratic sensitivity to the quantum corrections of M_H.

	Δ_{hgg}	$\Delta_{h\gamma\gamma}$
SUSY $\tilde{t}$	$1.4\%(\frac{1\ \text{TeV}}{m_{\tilde{t}}})^2$	$-0.4\%(\frac{1\text{TeV}}{m_{\tilde{t}}})^2$
Little Higgs T	$-10\%(\frac{1\ \text{TeV}}{M_T})^2$	$-6\%(\frac{1\text{TeV}}{M_T})^2$

Peskin, arXiv:1208.5152;
TH, Logan, McElrath, Wang, 2004

Not-So Natural Higgs Sector

Example 3. Composite Higgs

The Higgs boson as a pseudo-Goldstone boson,
so that it is much lighter than the dynamical scale f ~ TeV.

The Higgs boson couplings may receive corrections from the other heavy states

Contino, Nomura, Pomarol, 2003;
Agashe, Contino, Pomarol, 2005.

$$\Delta_i \sim \mathcal{O}(v^2/f^2)$$

	Δ_{hVV}	Δ_{hff}
Minimal Composite Higgs	$-3\%(\frac{1\ \mathrm{TeV}}{f})^2$	$-(3-9)\%(\frac{1\ \mathrm{TeV}}{f})^2$

Espinosa, Grojean, Muhlleitner; 2010;
Gupta, Rzehak, Wells, arXiv:1206.3560.

Not-So Natural Higgs Sector

Example 4. Missing MSSM at LHC

For an illustration:

Peskin et al., 2012, to appear.

$M_A = 1\ \text{TeV},\ \tan\beta = 5,\ m_{\tilde{t}} = 900\ \text{GeV}:$

MSSM	Δ_{hVV}	$\Delta_{hbb,\ h\tau\tau}$
Tree-level	10^{-4}	3%
	Δ_{hgg}	$\Delta_{h\gamma\gamma}$
Loop induced	-2.7%	0.2%

Carena, Heinemeyer, Wagner, Weiglein, 1999;
Carena, Haber, Logan, Mrenna, 2002.

SUSY is a weakly coupled theory,
thus with modest corrections.

Not-So "Standard" Higgs Sector

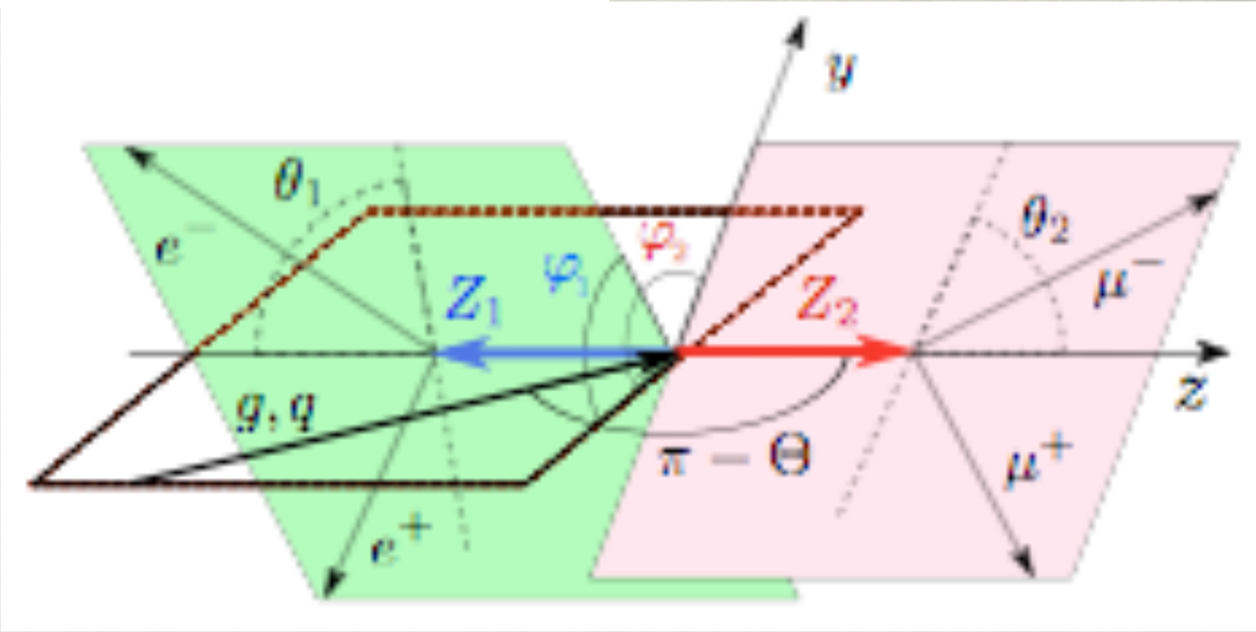
Precision measurements may be (surprisingly) rewarding !

Most general $V^\mu V^\nu H$ coupling:

$$T^{\mu\nu} = a_1\, g^{\mu\nu} + a_2\, (q_1 \cdot q_2\, g^{\mu\nu} - q_1^{\nu} q_2^{\mu}) + a_3\, \varepsilon^{\mu\nu\rho\sigma}\, q_{1\rho} q_{2\sigma}$$

The $a_i = a_i(q_1, q_2)$ are scalar form factors

$$H \to Z Z^* \to \mu^+ \mu^- \; e^+ e^-$$



Test Higgs spin-parity property, search for CP violation (may not be larger than 10^{-3}).

De Rujula, Lykken, Spiropulu et al., 2010.

Not-So "Standard" Higgs Sector

Most general $Hf\bar{f}$ coupling:

$$H\bar{t}(a + ib\gamma_5)t$$

$$gg,\ q\bar{q} \to t\bar{t}H,\ \text{with } H \to b\bar{b},\ \tau\bar{\tau},\ \gamma\gamma$$

Gunion and He, 1996.

It will be very challenging
to study the $H\bar{t}t$ coupling at the LHC:
20%?

What we need to achieve …

To go beyond the LHC direct search,

1. Precision Higgs physics at a few %: Δ_{VVH} for composite dynamics;
   $\Delta_{bbH,\ \tau\tau H}$ for decoupling H^0, A^0;
   $\Delta_{ggH,\ \gamma\gamma H}$ for color/charge loops.

2. Reach 10% for H → invisible.

3. Determine Γ_{tot} to 10%.

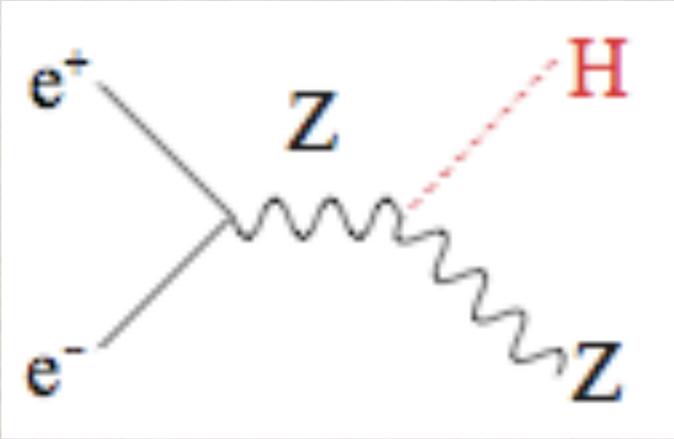
A Word of Expectations

1. LHC: $\sigma_{obs} \propto g_{in}^2 \frac{\Gamma_{final}}{\Gamma_{tot}}$

- σ_{obs}/σ_{SM} measured at 10% level.
- $Br(h \to \bar{N}N,\ \chi\chi,\ ...)$ sensitive to 20% level.
- No model-independent measure for $\Gamma_i,\ \Gamma_{tot}$

2. e^+e^- Higgs factory:

- model-independent for g_{ZZh} at 1.5% level
- Extraction for $\Gamma_{tot} \equiv \Gamma_{ZZ}/BR_{ZZ}$



3. $\mu^+\mu^-$ Higgs factory:

- Direct measurement of Γ_{tot} by scanning.

Summary:

- We are a lucky generation to have experienced the revolutionary discovery!

- We have learned a lot about Nature!
  Spontaneous symmetry breaking;
  The Higgs mechanism ...

- We are still puzzled!

"Naturally speaking":

- It should not be a lonely particle; has an "interactive friend circle": $t,\ W^{\pm},\ Z$ and partners $\tilde{t},\ \tilde{W}^{\pm},\ \tilde{Z},\ \tilde{H}^{\pm,0}$ ...
- If we do not see them at the LHC, they may reveal their existence from Higgs coupling deviations from the SM values at a few percentage level.

THE DISCOVERY OF THE HIGGS-LIKE BOSON IS MERELY A BEGINNING OF A LONG, EXCITING JOURNEY!