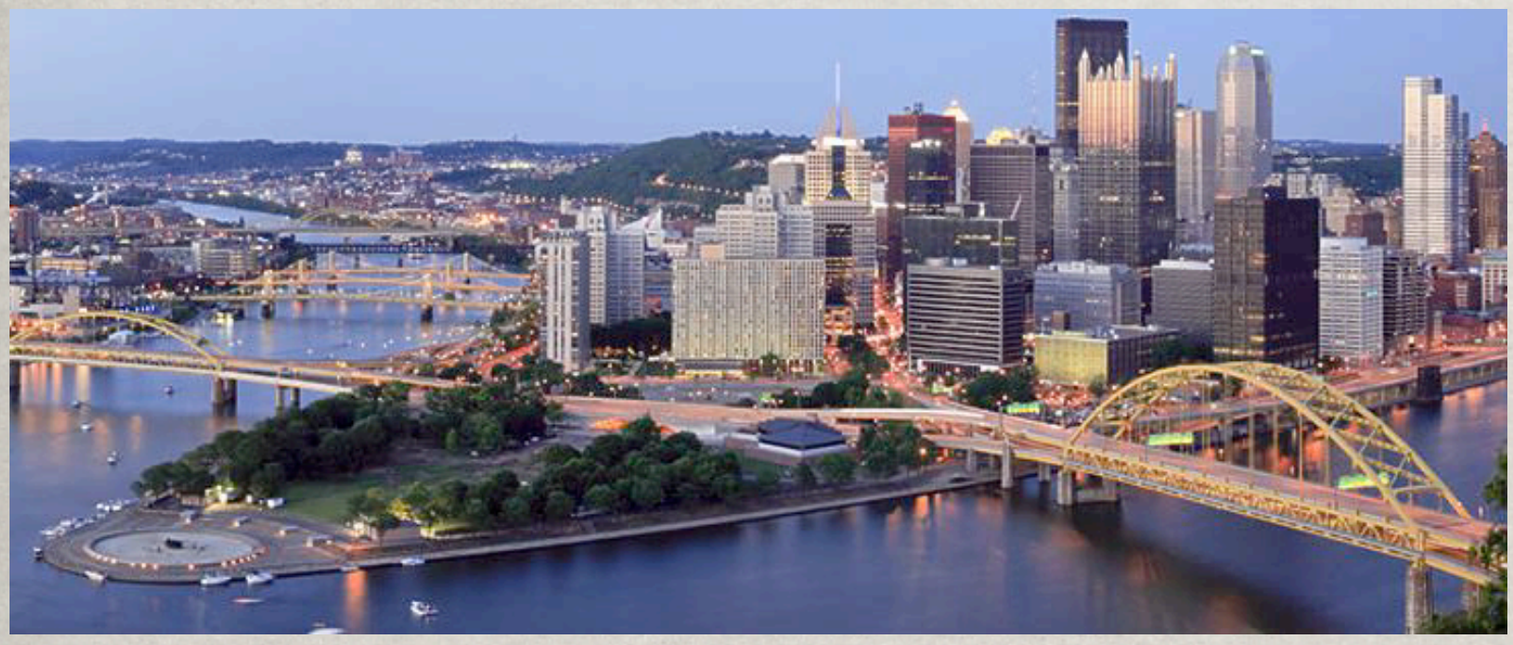
Higgsology:
Theory and Practice

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

DPG School on
Heavy Particles at LHC
Bad Honnef
Sept. 16-21, 2012

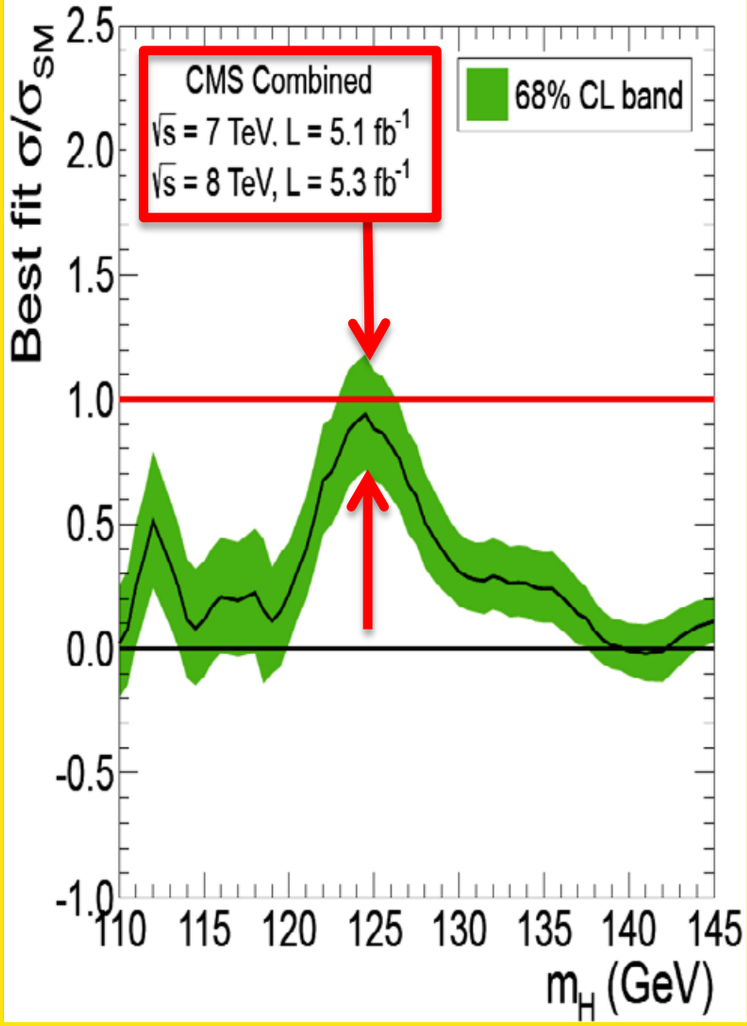




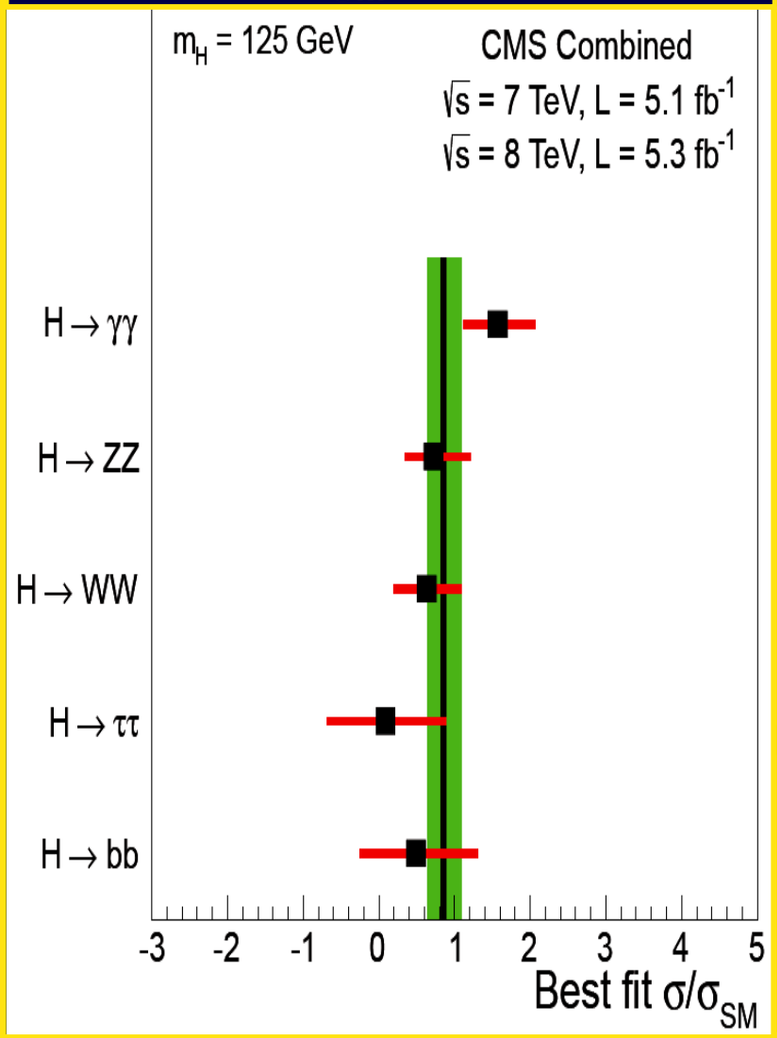
It is one of the most exciting times:

Compatibility with SM Higgs boson

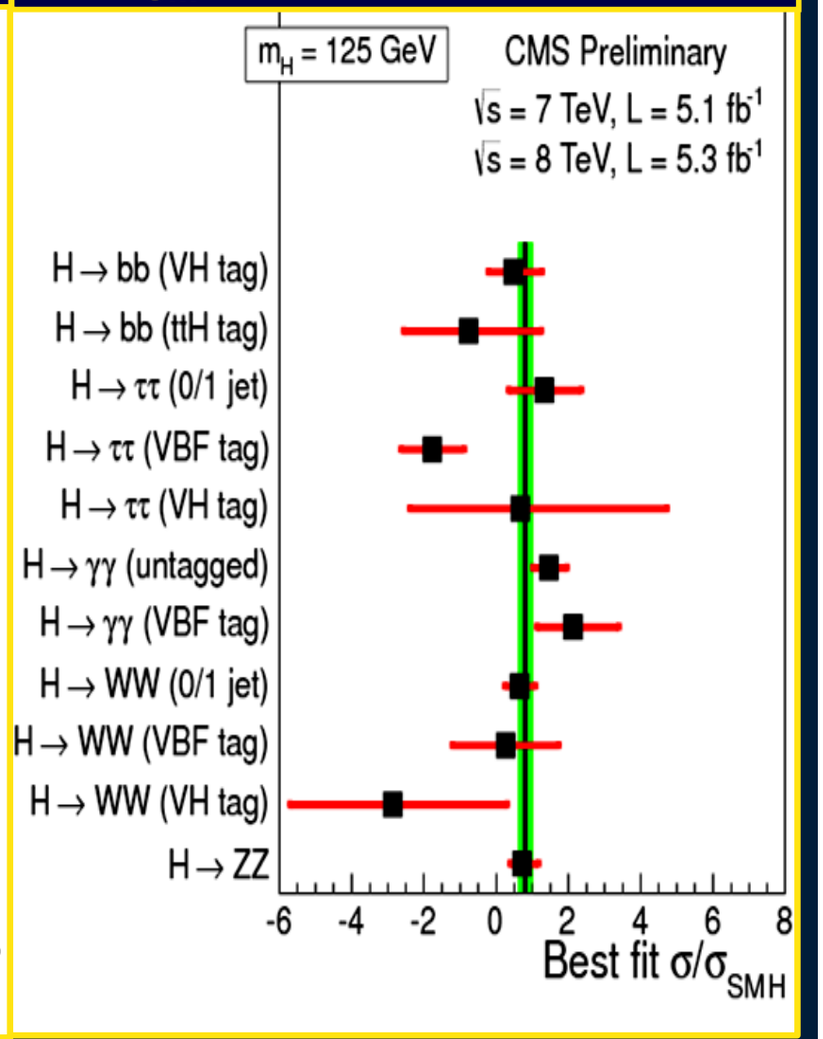
Overall strength σ/σ_{SM}



Best Fit σ/σ_{SM} by decay mode

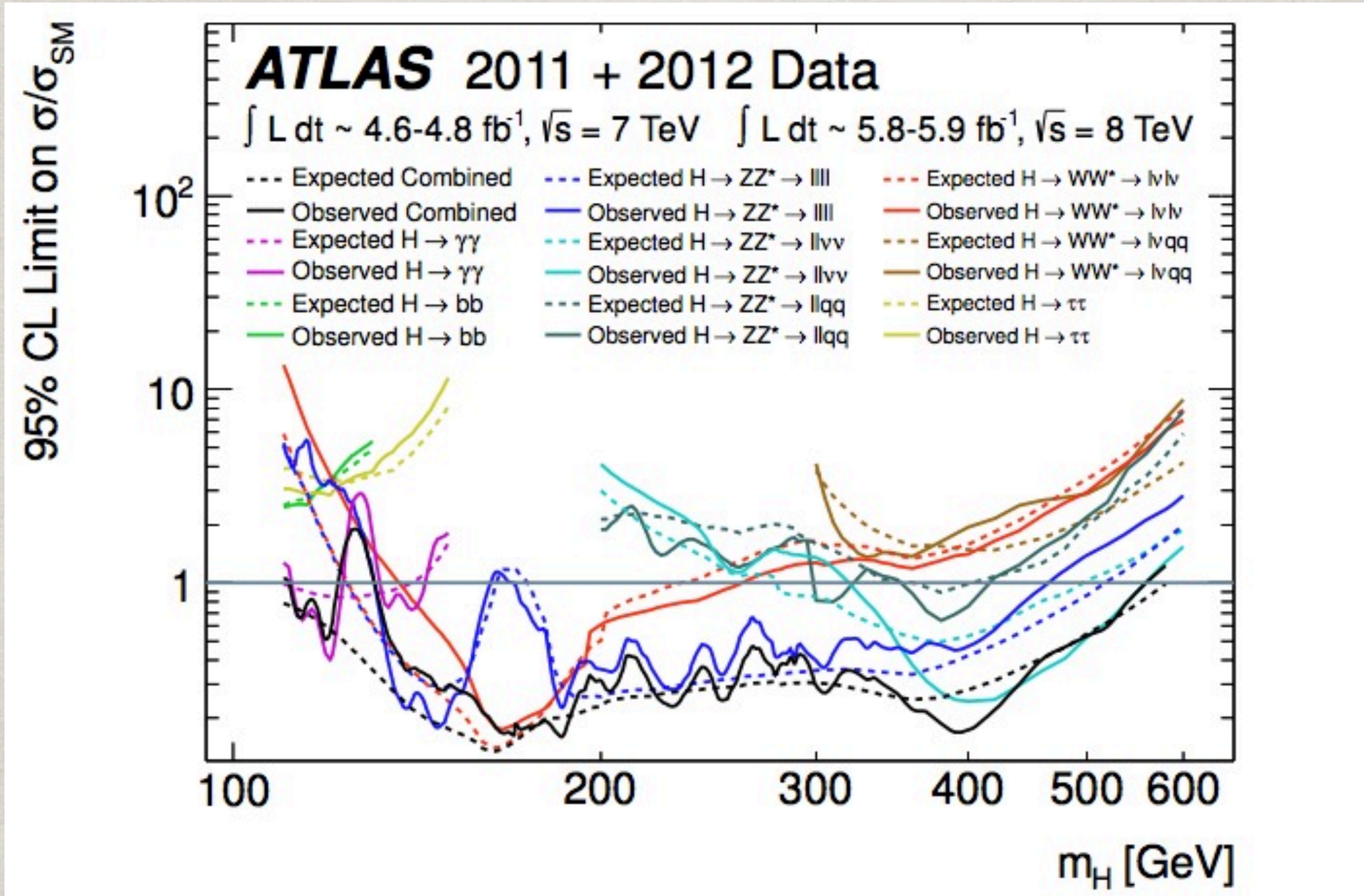


σ/σ_{SM} by prod. + decay mode



Overall best-fit signal strength: $\sigma/\sigma_{SM} = 0.87 \pm 0.23$

Signal strength σ/σ_{SM} in different modes is self-consistent, but some modes require more data to distinguish a SM signal from background



Exclusion between 111 and 559 GeV, except between 122 and 131 GeV

When I first accepted to lecture here, I did not except the Higgs discovery!
(so soon)

Now we have
a new "standard candle",
a new "lamp post"!

This discovery opens up
a new era in HEP!

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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

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Lecture I: Higgs Physics in the SM

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-- A historical count

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A. The Higgs Mechanism

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Lecture II: Higgs and Beyond

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-- Motivations for physics beyond SM

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A. A Weakly Coupled Light Scalar?

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C. New Physics Scenarios

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C. New Physics Scenarios associated with the Higgs

Lect I. Higgs Sector in the SM
A. The Higgs Mechanism

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1. A historical Count:

(a). Deep Root in QED

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Lorentz invariance, U(1) Gauge Invariance



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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!‡

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

‡ Still with dispute: physical? redundancy?

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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^+

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

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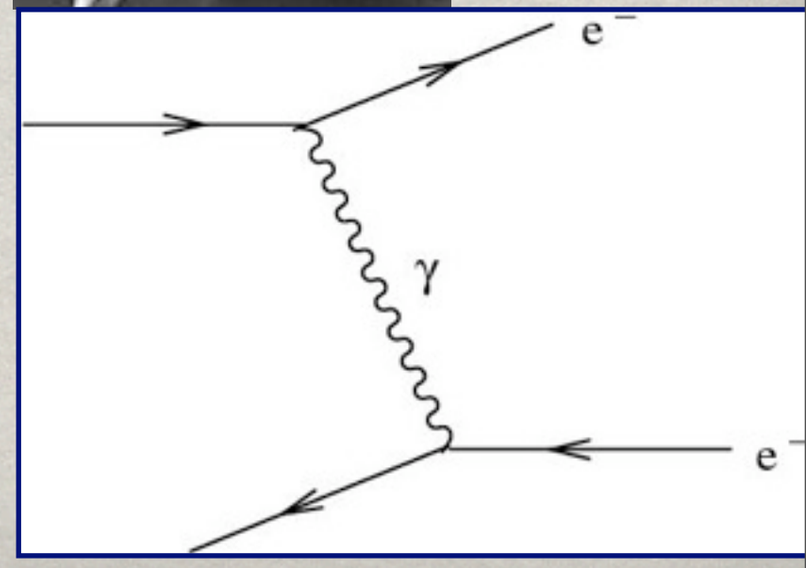
➔ Renormalization







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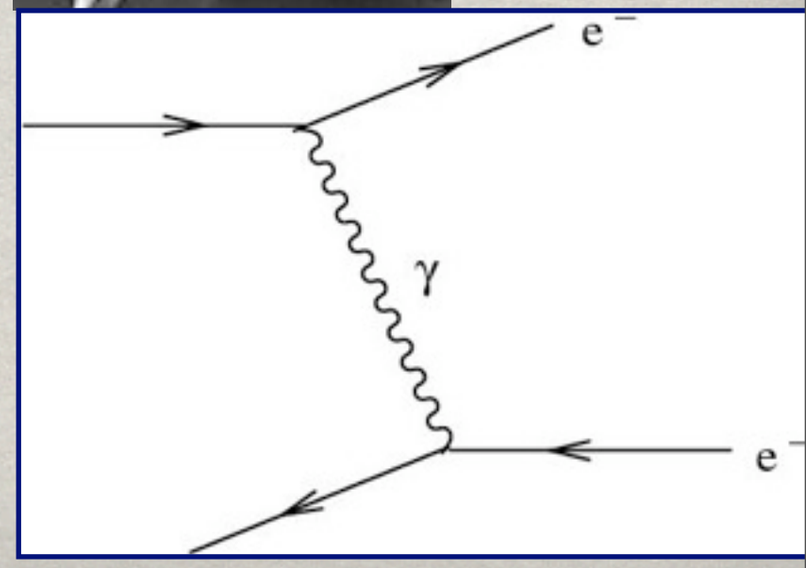






* The perturbation theory, thus Feynman diagram approach, the most successful aspect.

* 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:

$$e^+ e^- \to \phi^+ \phi^-$$

(b). Build up the weak Interactions

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

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Parity violation ➔ V-A interactions

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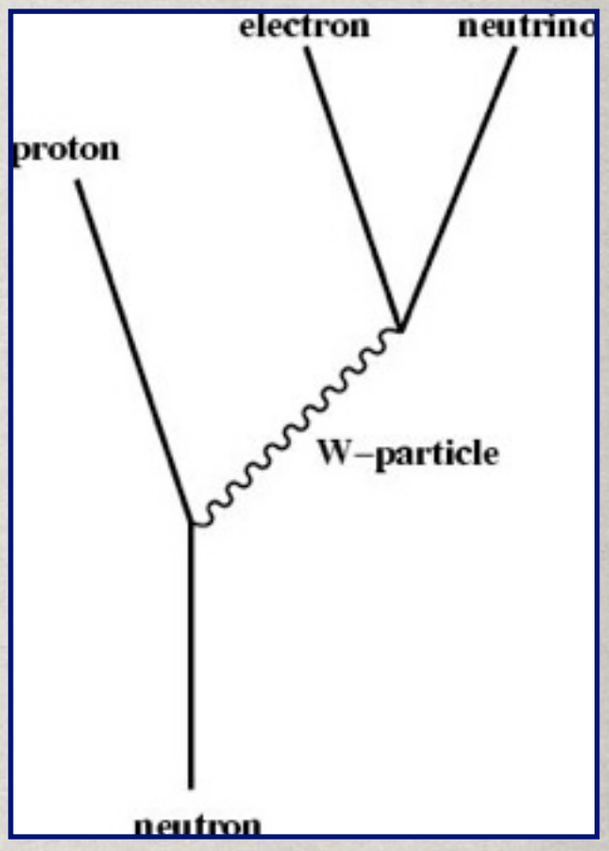
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ν N ->ν N ➔ Neutral current interaction: Z^0

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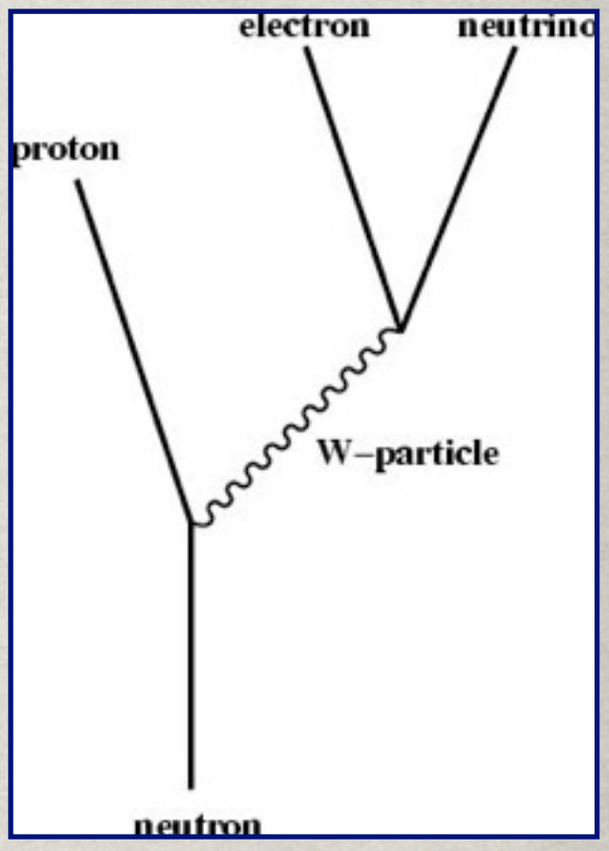
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The fact $G_F = (300\ \text{GeV})^{-2}$ implies that:

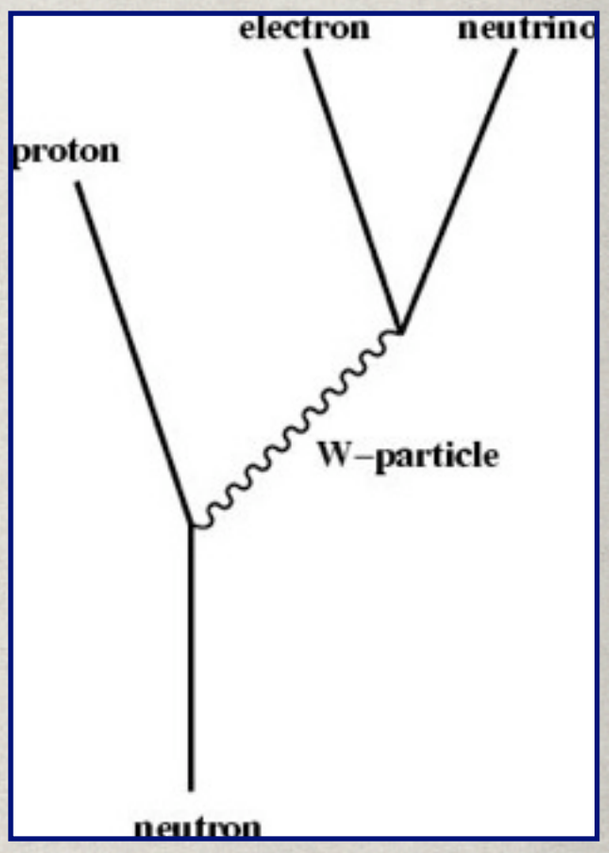
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2. Partial-wave Unitarity requires new physics below

$E < 300$ GeV

Exercise 2:

Assume that the ν e -> ν e scattering amplitude to be

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

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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

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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 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).

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A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 17 October 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 and on a right-handed singlet

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

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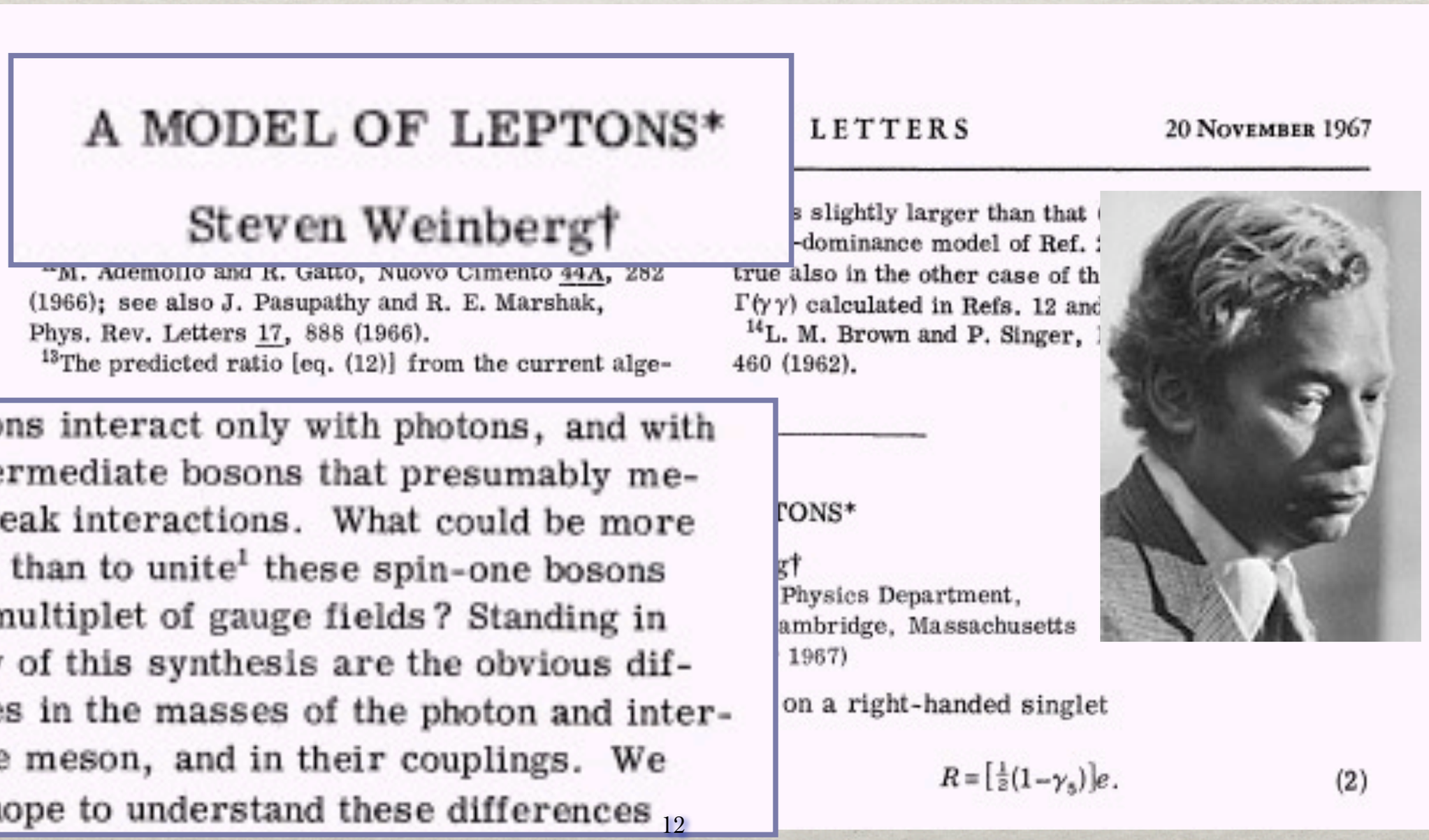
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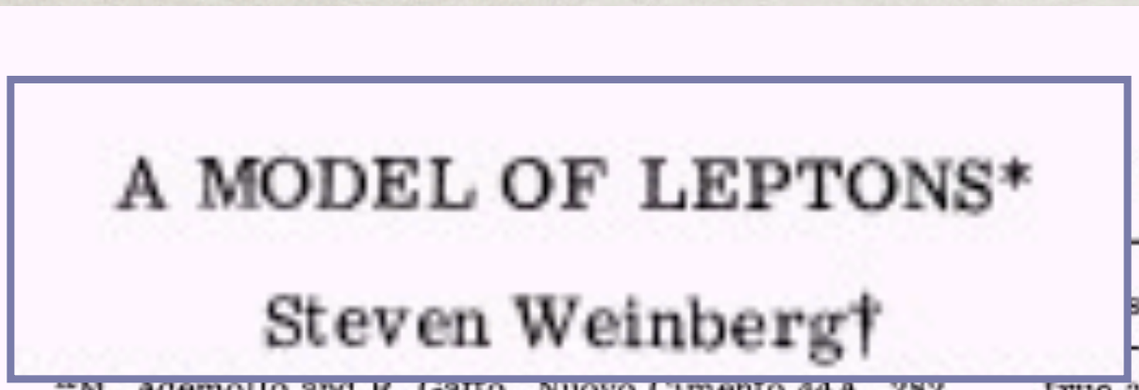
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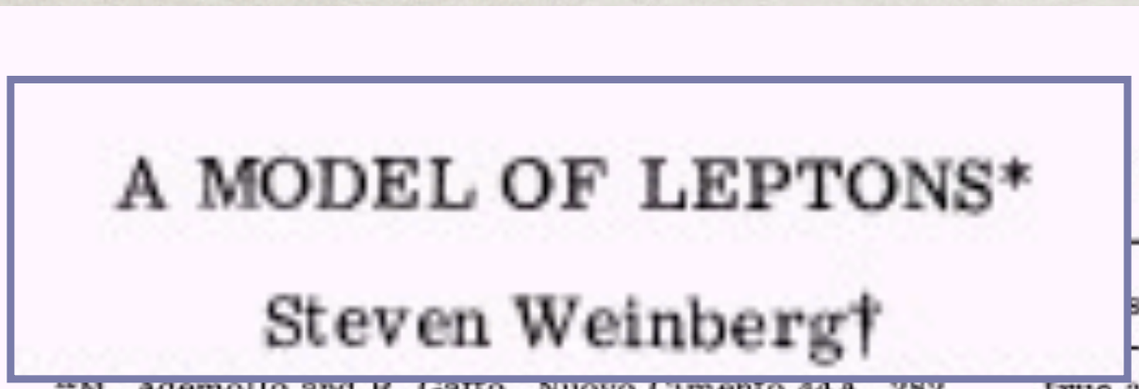
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The EW Unifcation I: Couplings

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$\mathrm{SU(2)_L} \otimes \mathrm{U(1)_Y}$ interactions

$e = g \sin\theta_W$ coupling unification

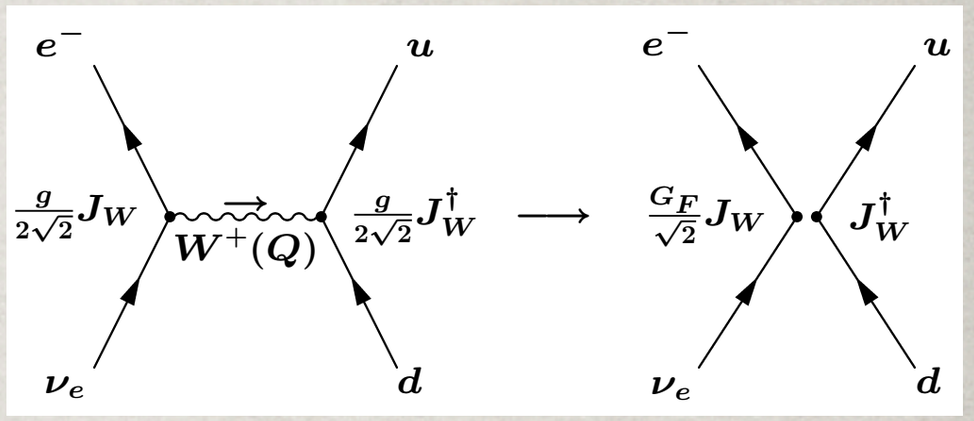
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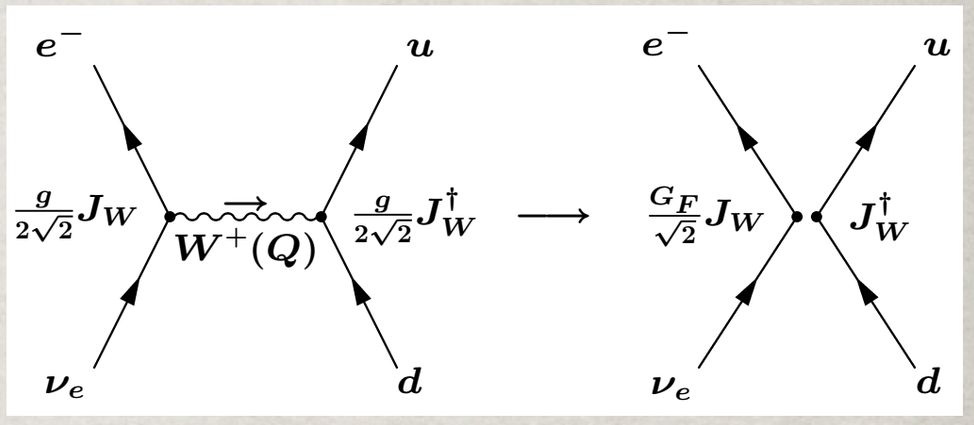


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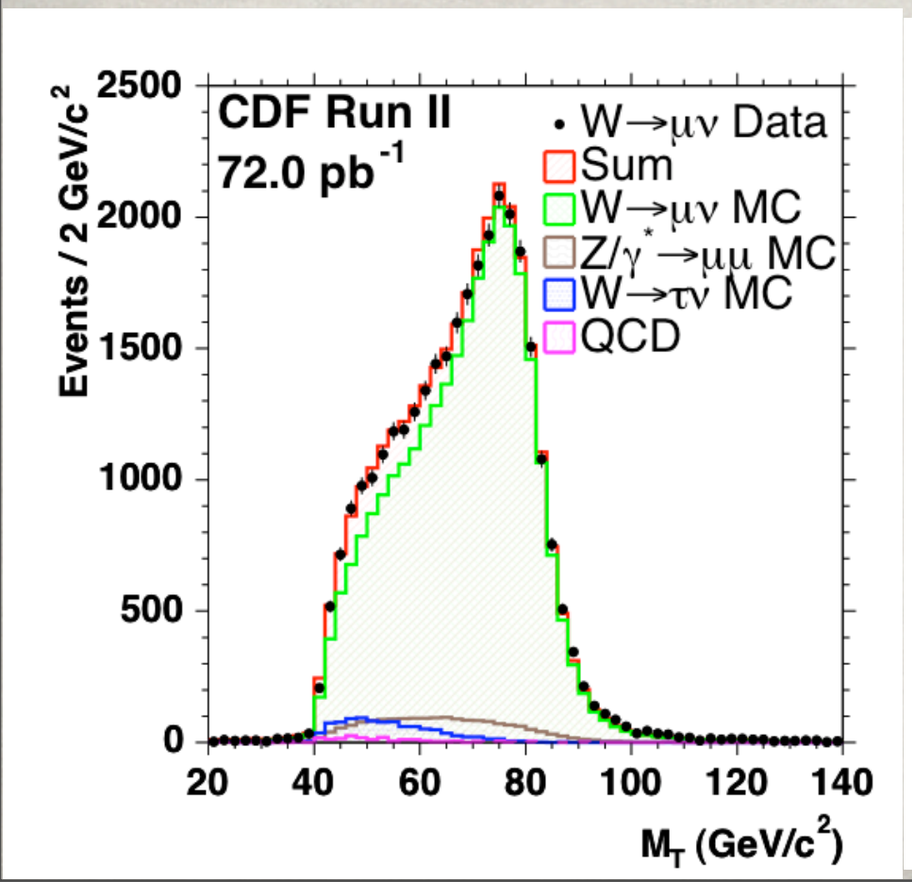
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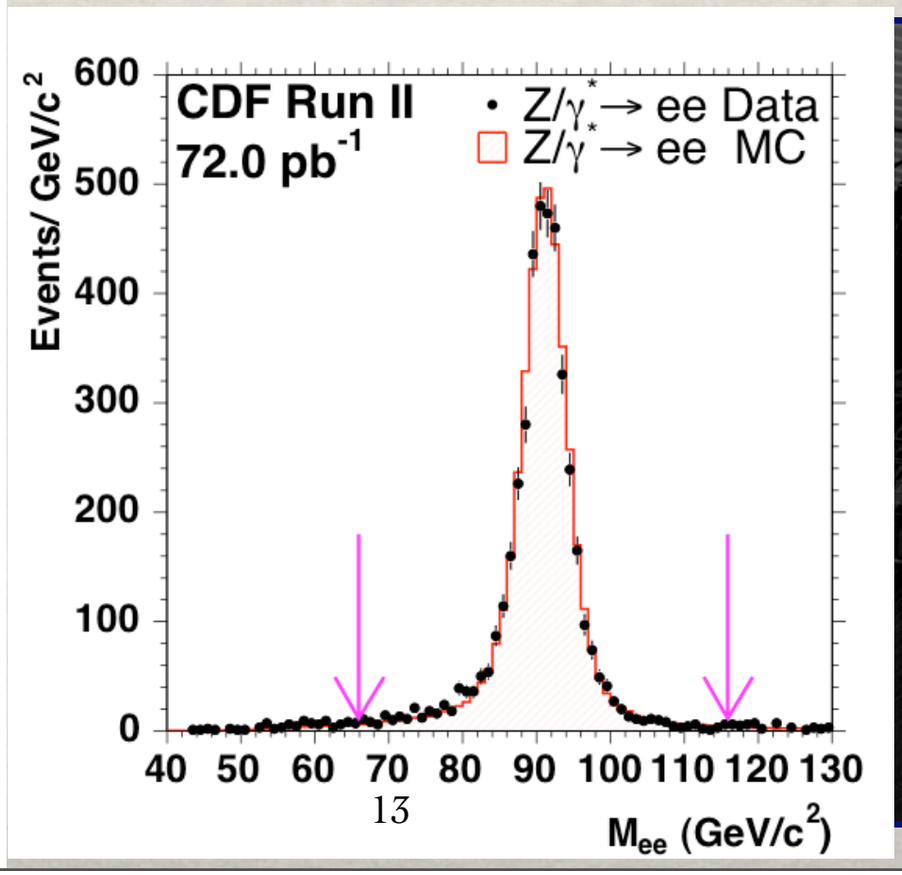
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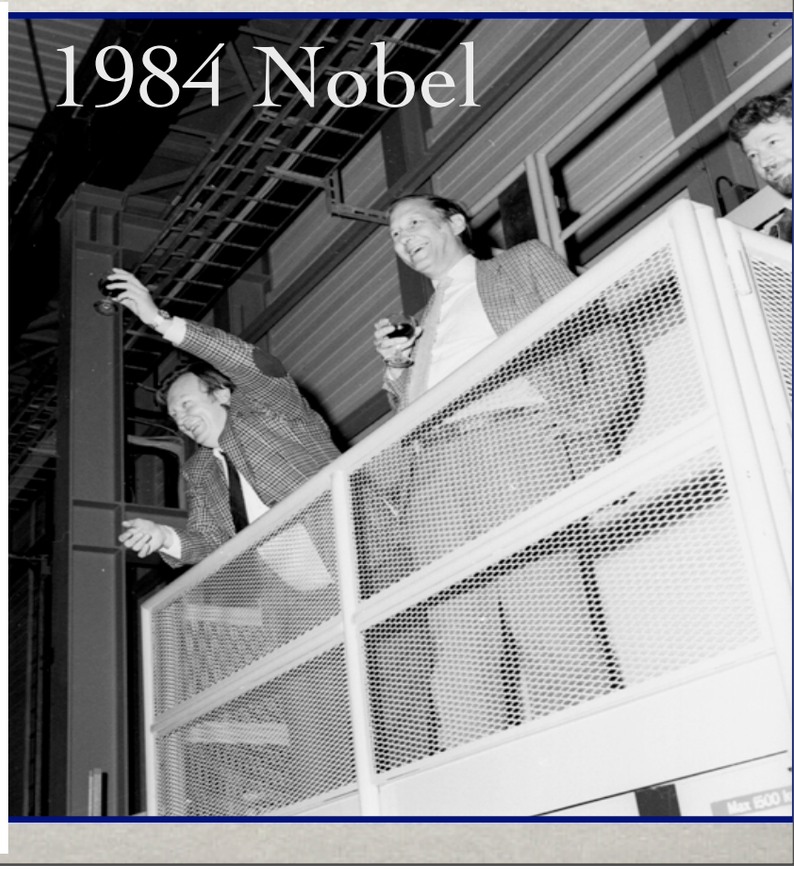
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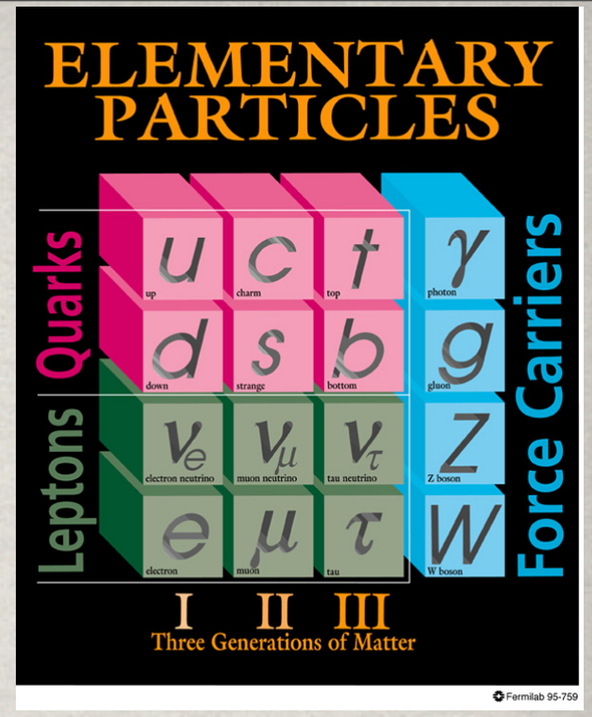
The EW scale is fully open up:







The EW Unifcation II: Particle representation



- Simple structure and particle contents:

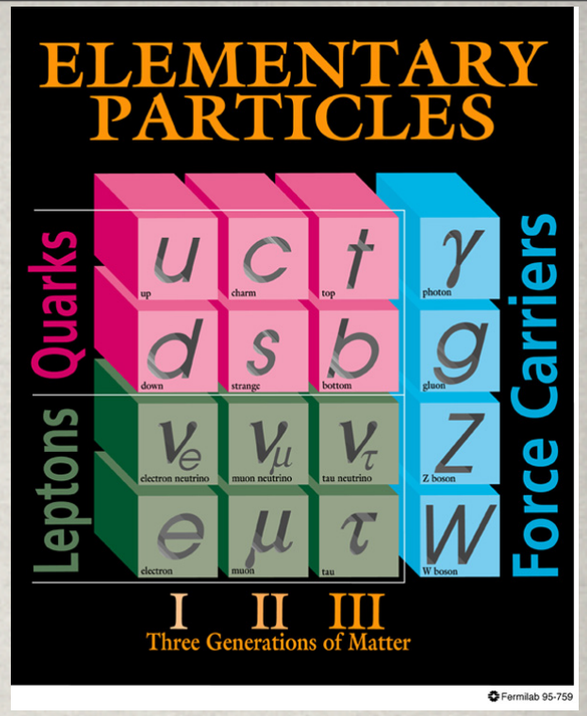
Leptons:

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

Quarks:

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

The EW Unifcation II: Particle representation



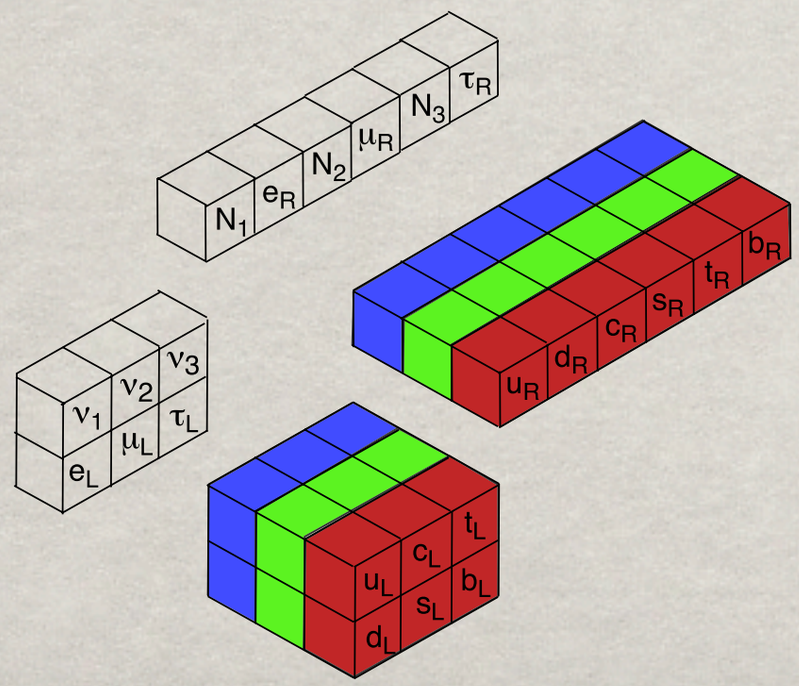
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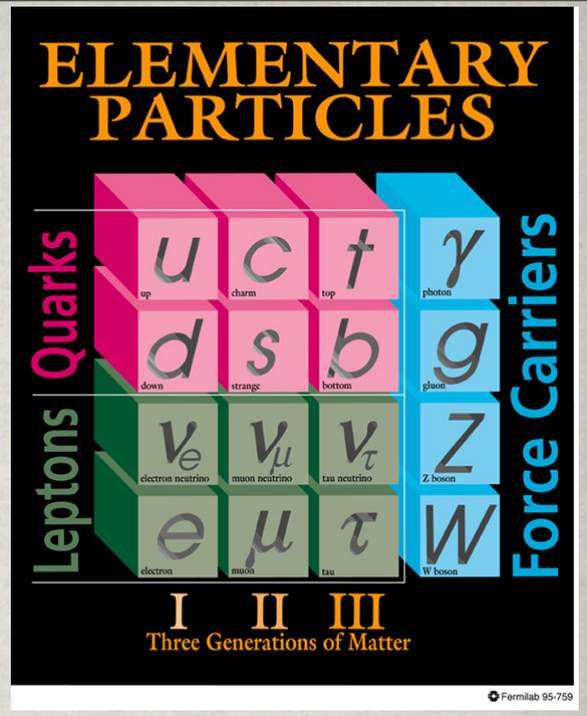
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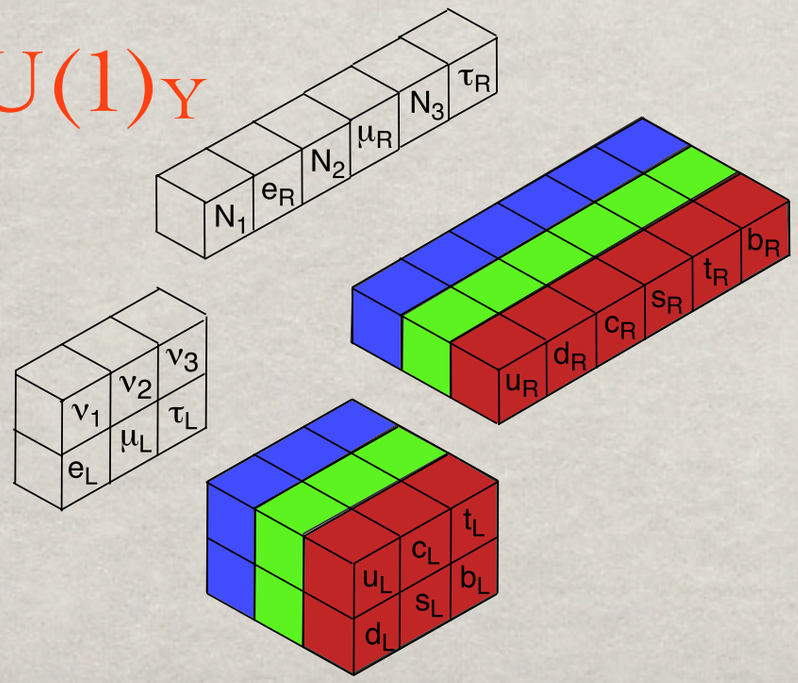
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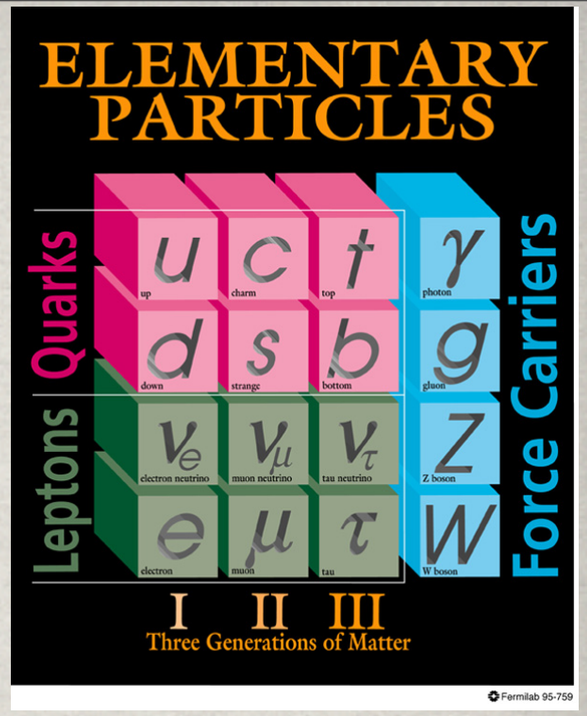
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$U(1)_Y$



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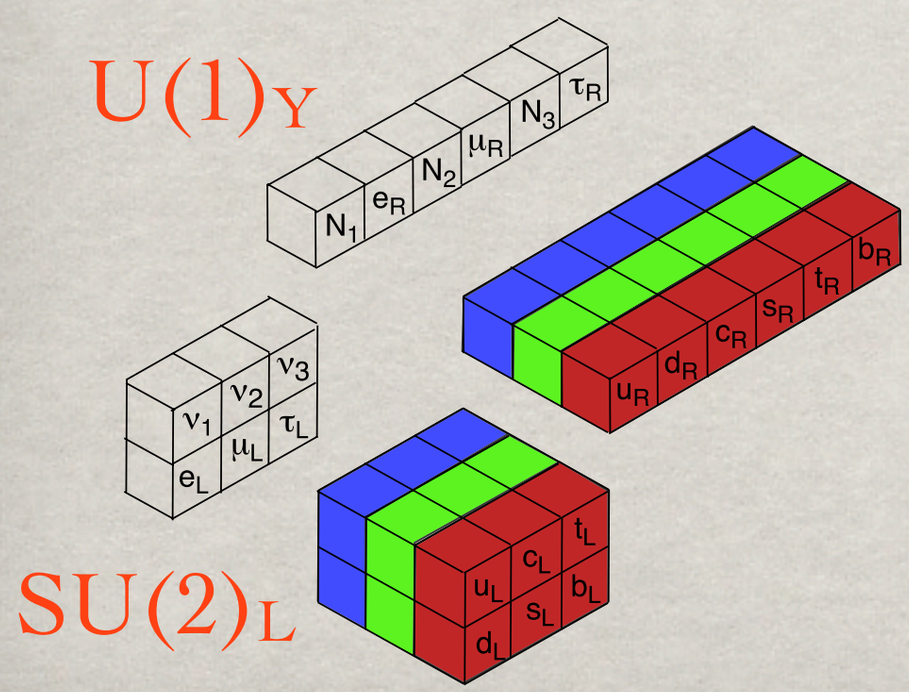
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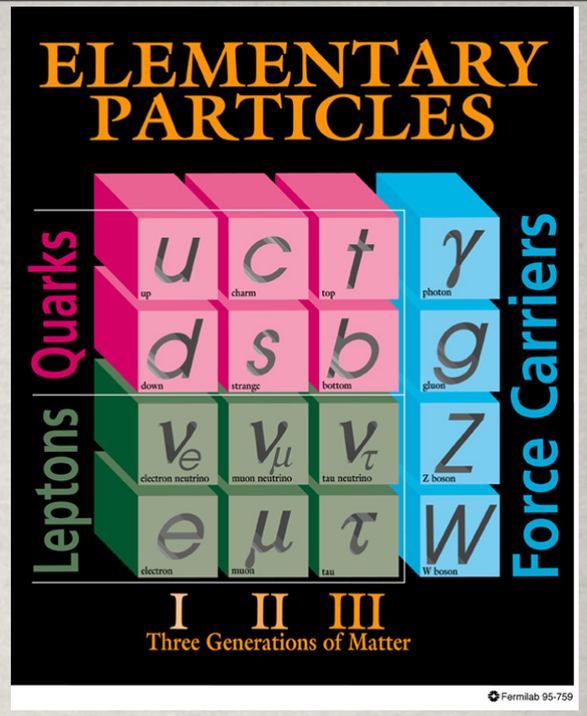
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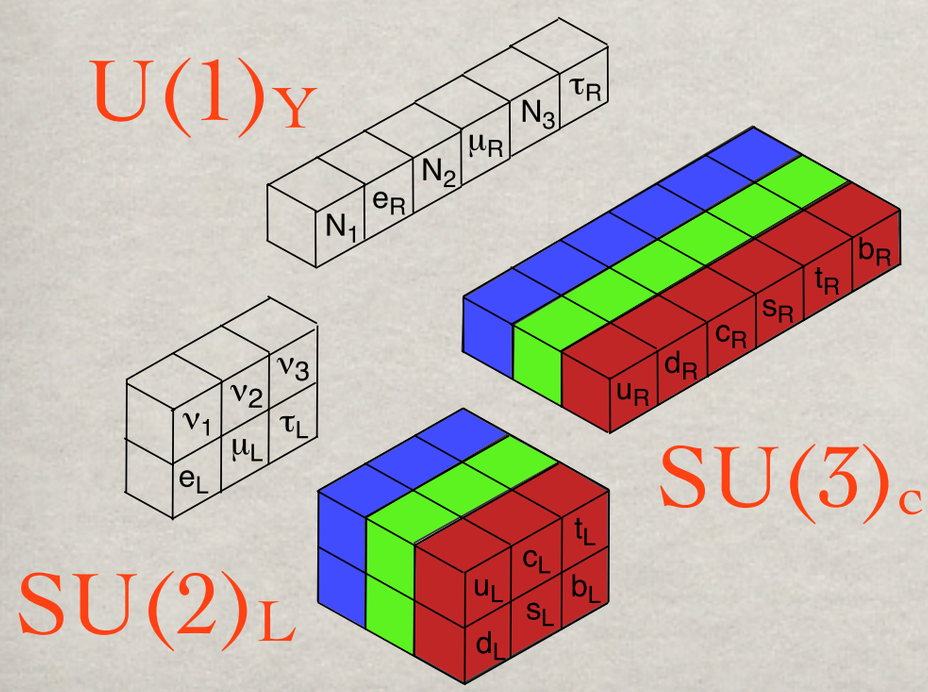
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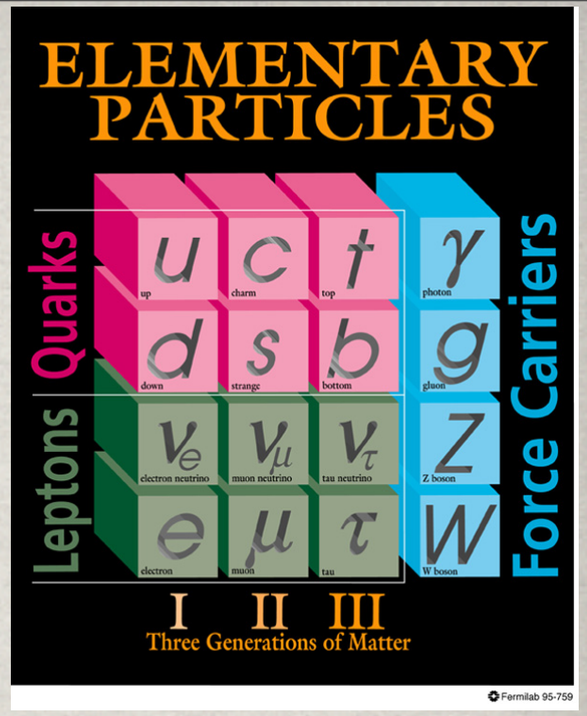
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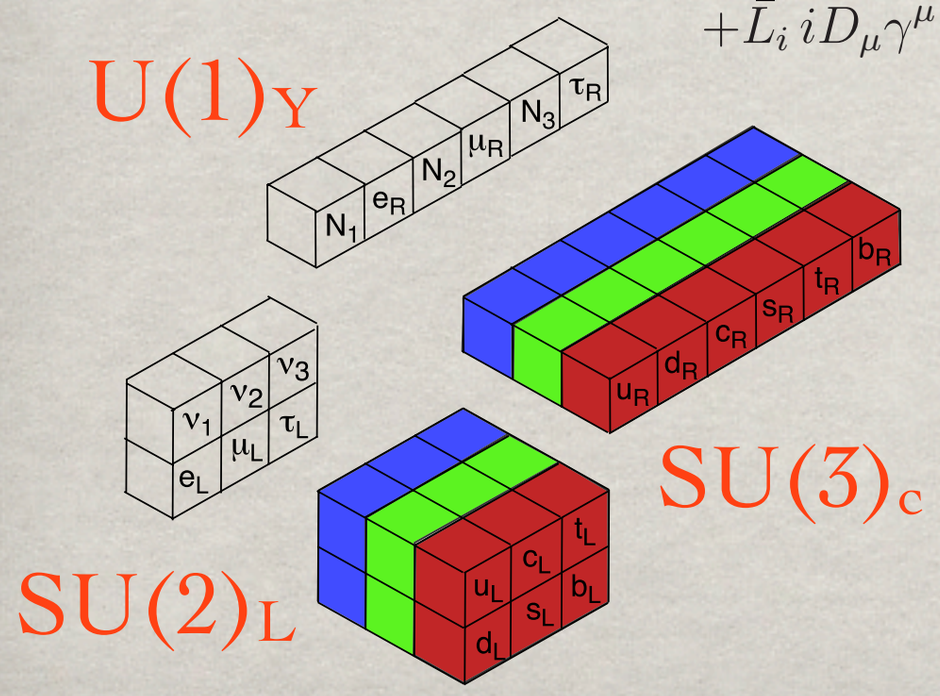
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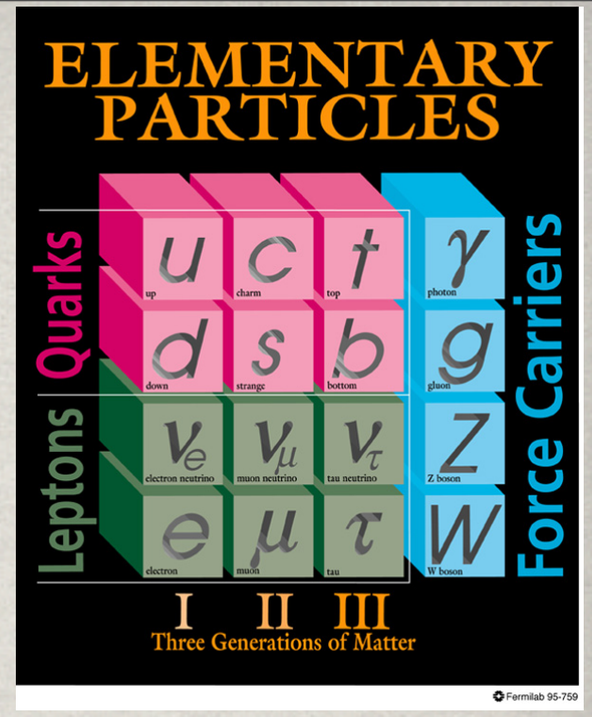
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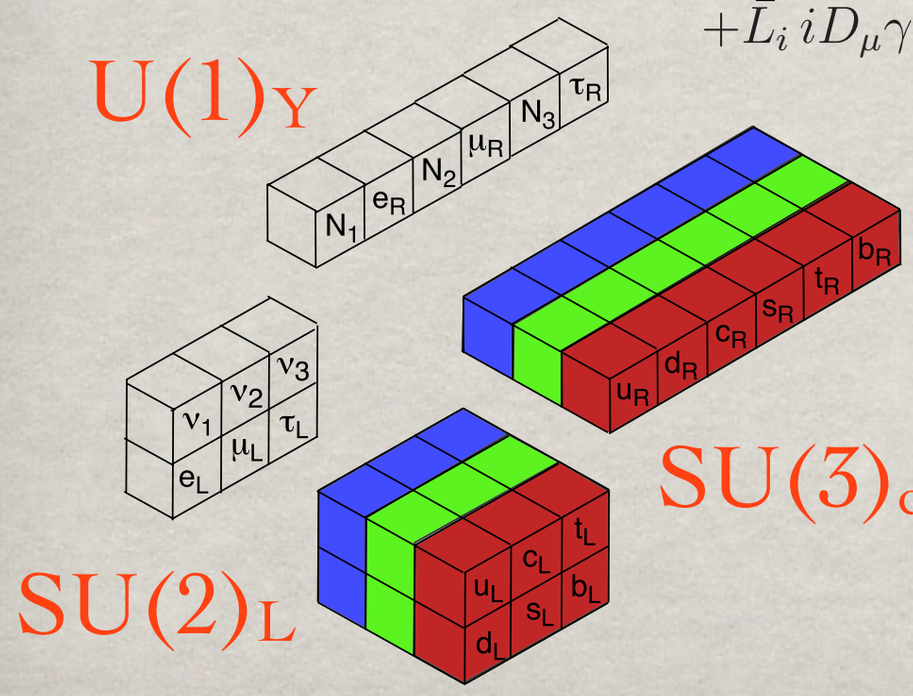
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The local gauge symmetry prevents gauge bosons from acquiring masses!

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

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Domains Before Magnetization


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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)

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The concept of SSB: profound, common.

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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).

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The Goldstone Theorem (continued)

Broken Symmetries*

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Trinity College, Cambridge University, Cambridge, England

AND

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

(Received March 16, 1962)

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

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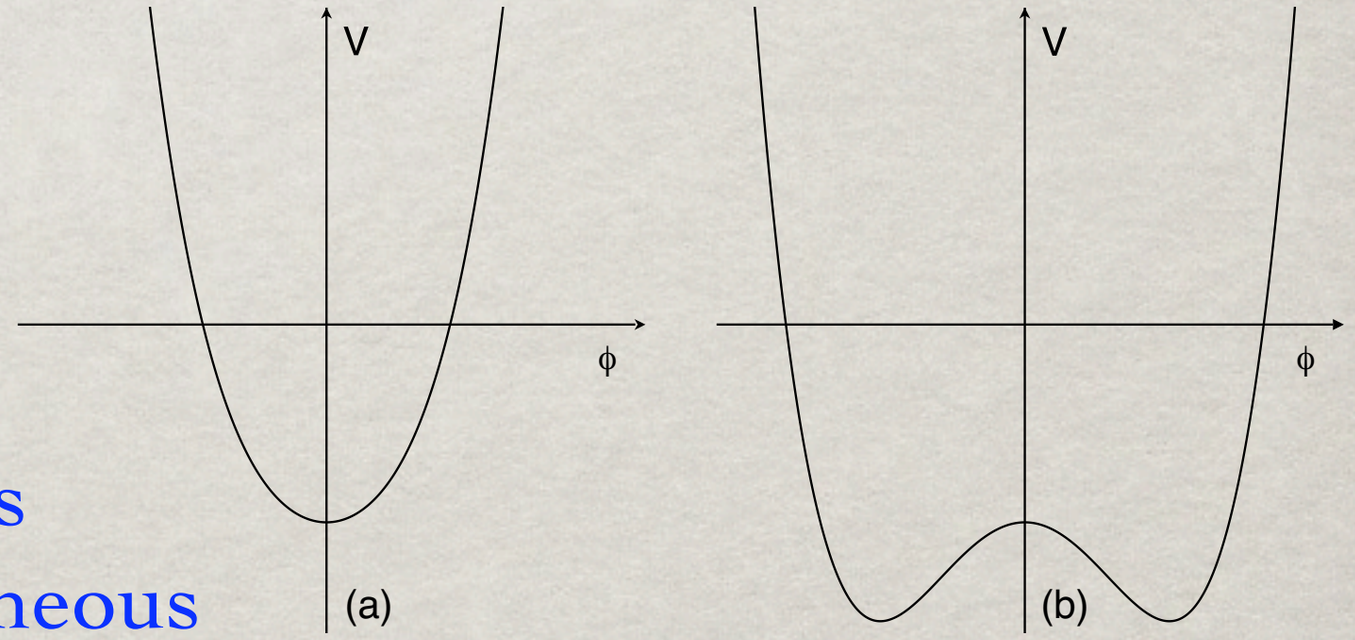
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For $\mu^2 > 0$, the vacuum is shifted, and thus spontaneous symmetry breaking.

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

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

Particle spectrum:[§]

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

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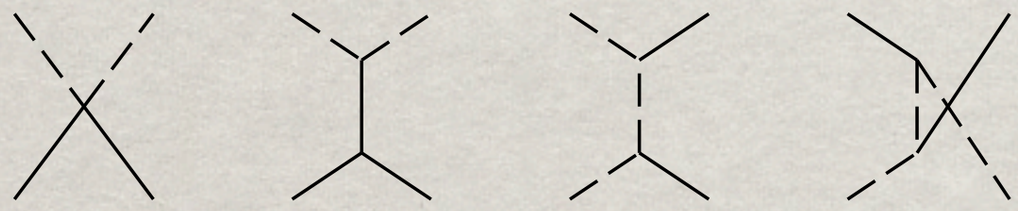
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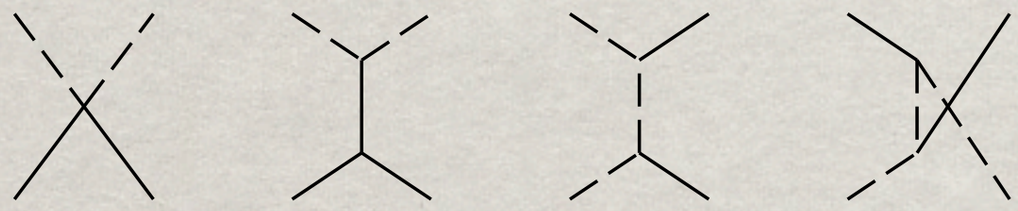
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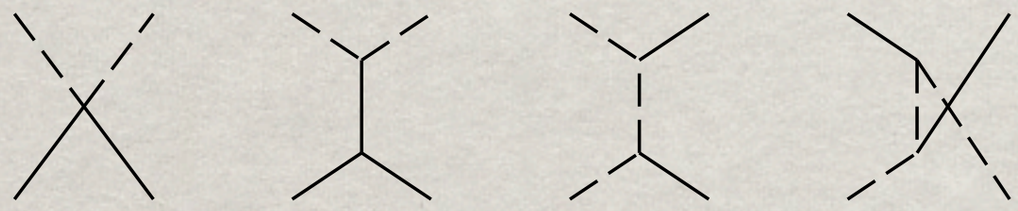
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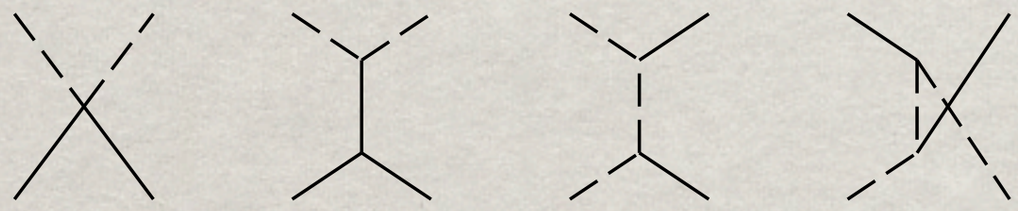
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Exercise 4: Show this result by an explicit calculation.

[§] C. Burgges, hep-ph/9812468

(b). Field Φ Re-definition:

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Define:

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

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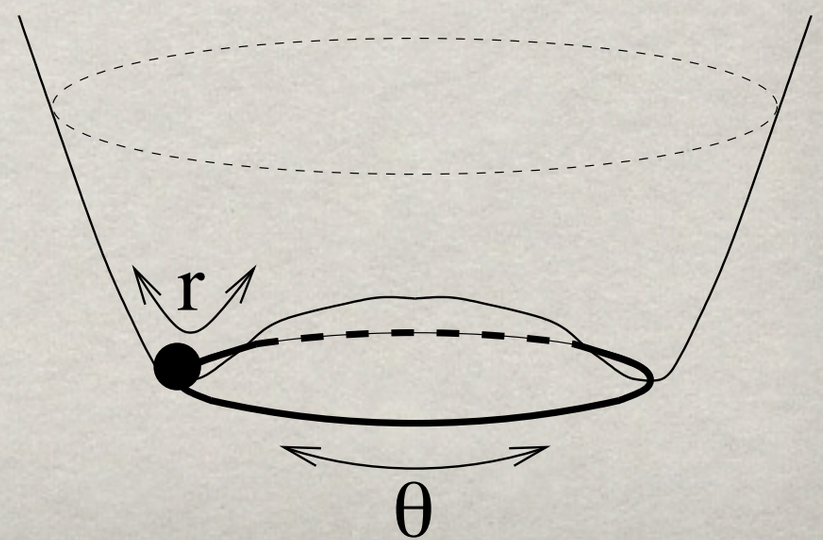
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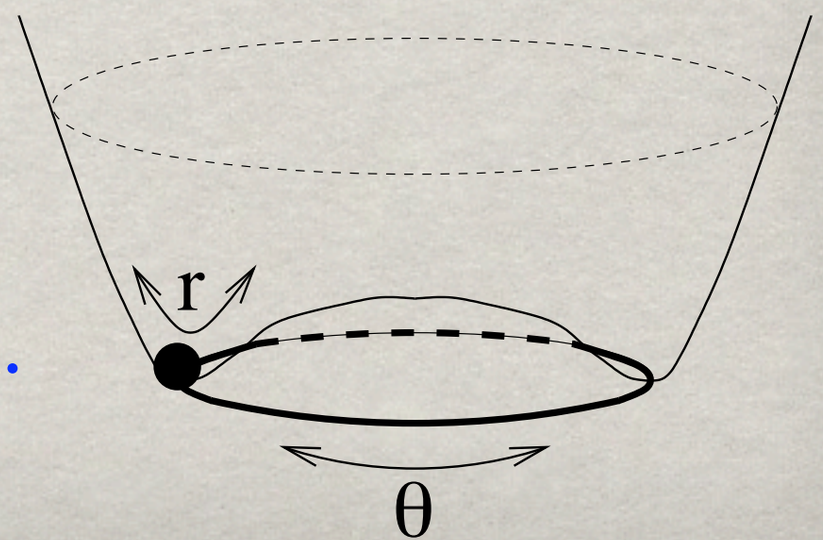
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$$\begin{pmatrix} u \\ d \end{pmatrix} \to \left(U_L\,\gamma_L + U_R\,\gamma_R\right)\begin{pmatrix} u \\ d \end{pmatrix} \Rightarrow SU(2)_L \otimes SU(2)_R$$

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.

Known example: Chiral symmetry breaking

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

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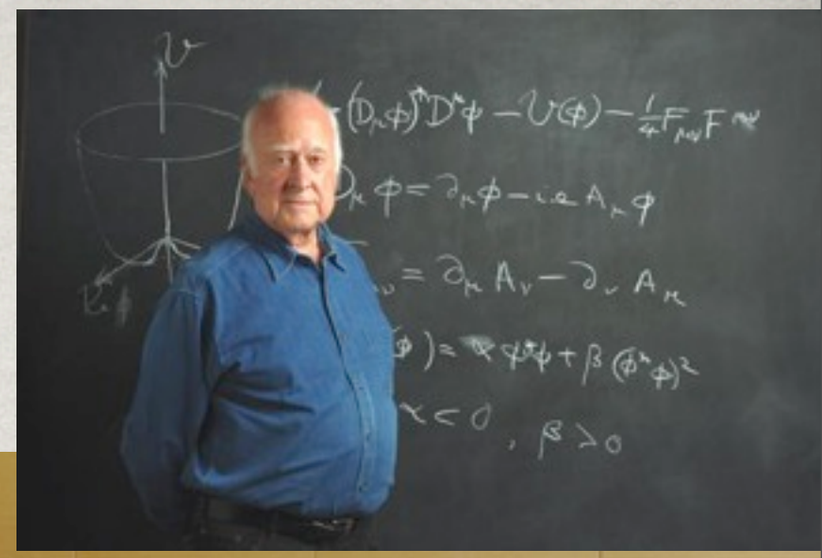
Except the photon, no massless boson (a long-range force carrier) has been seen in particle physics!

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

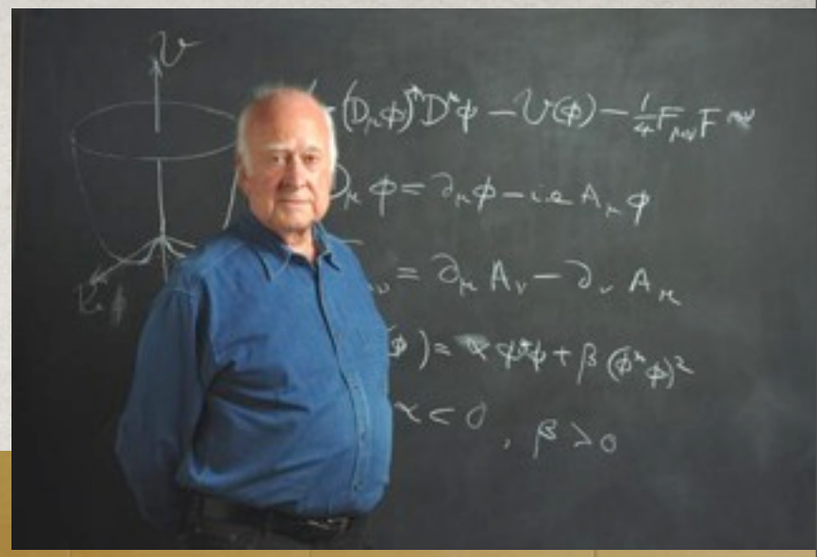
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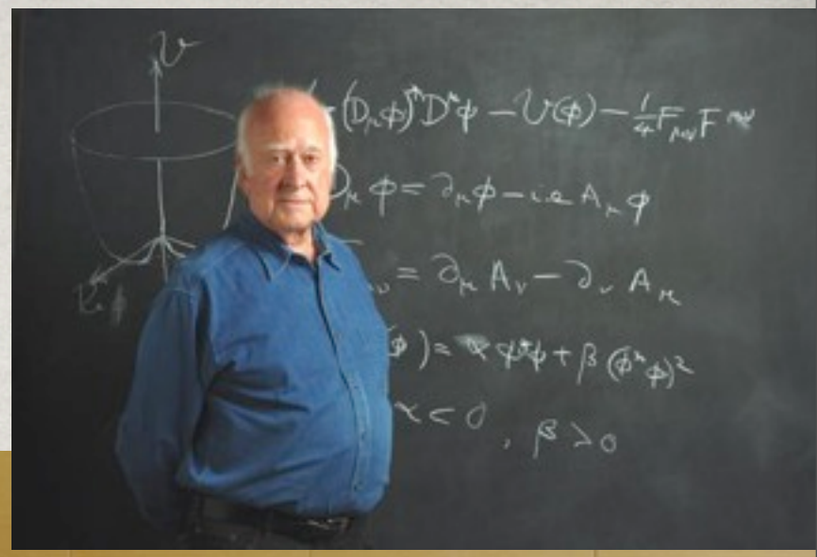
BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

PRL

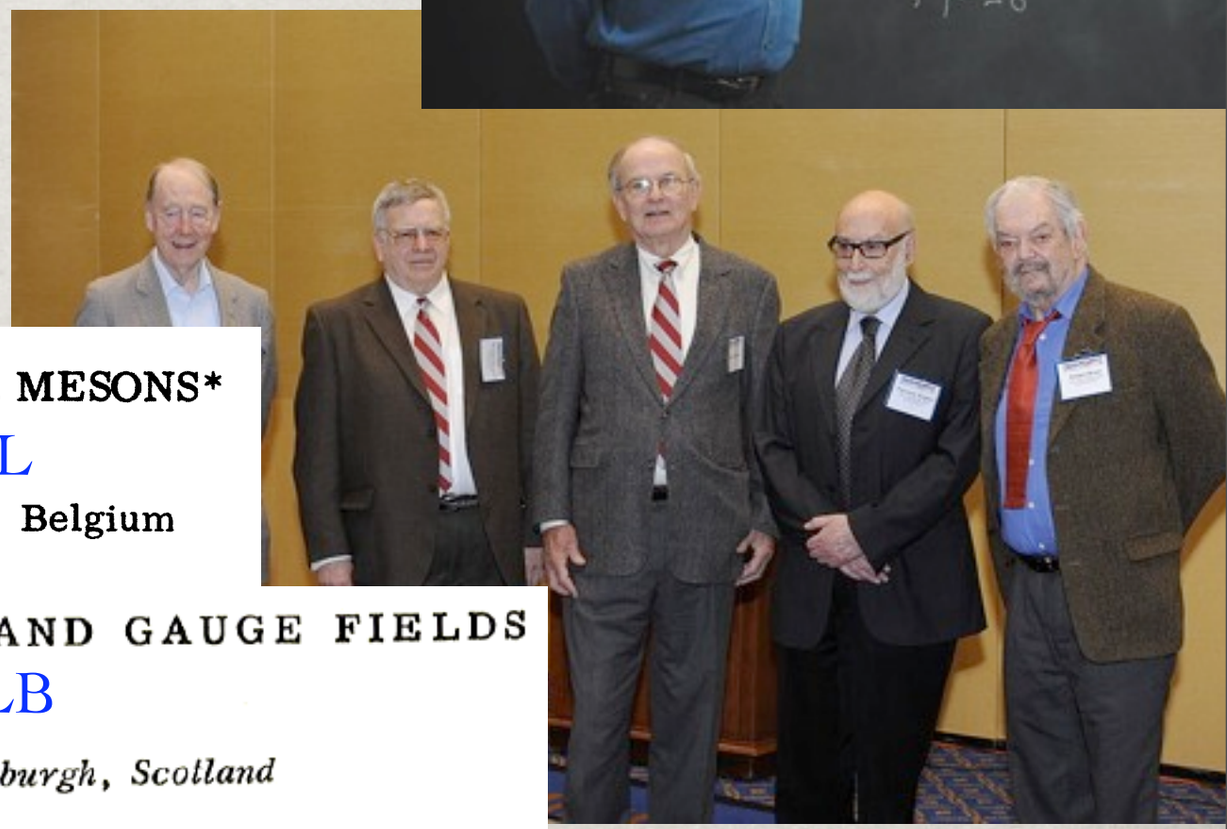
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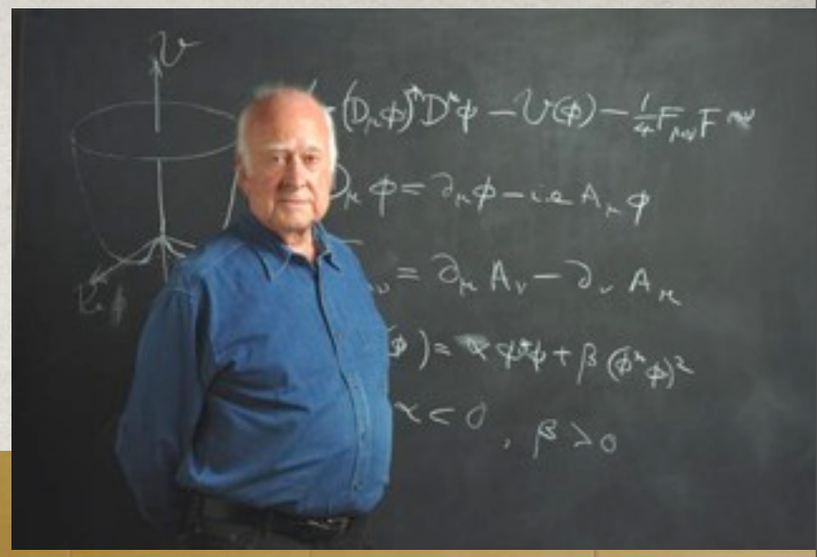
BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

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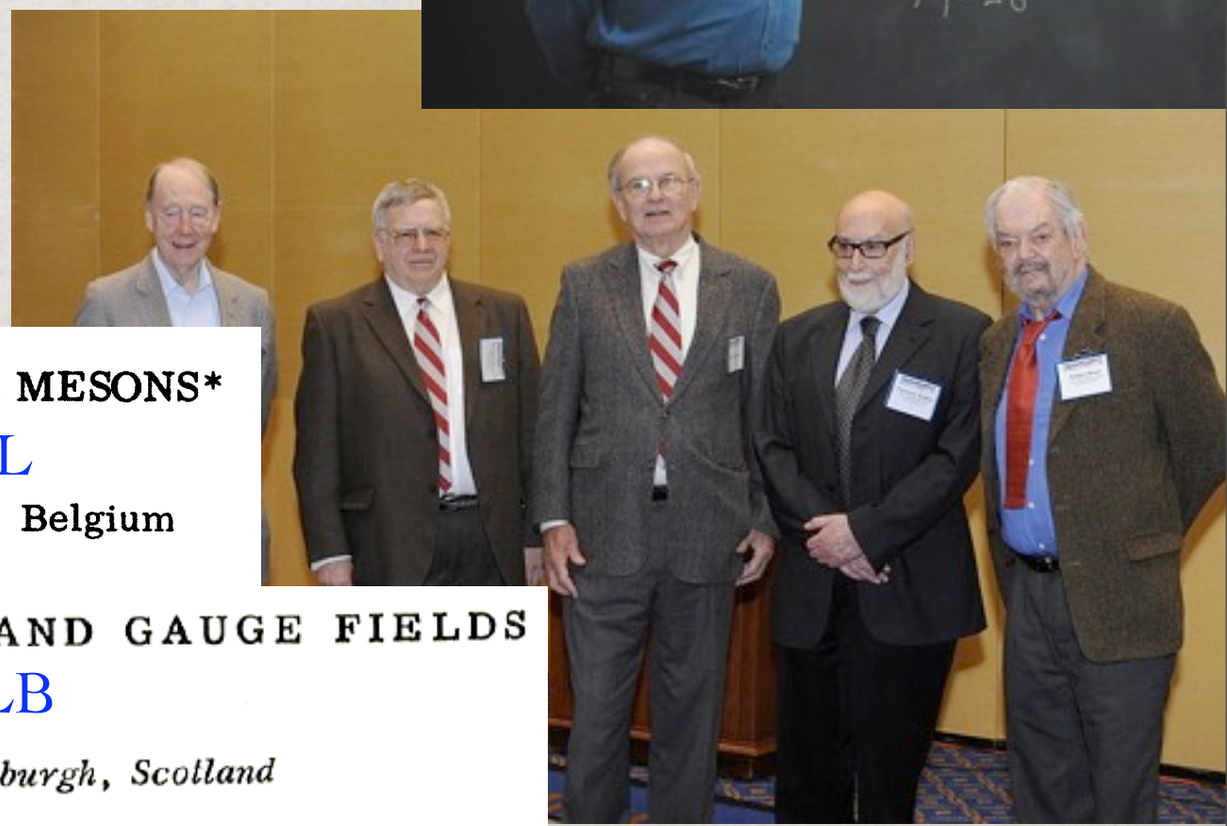
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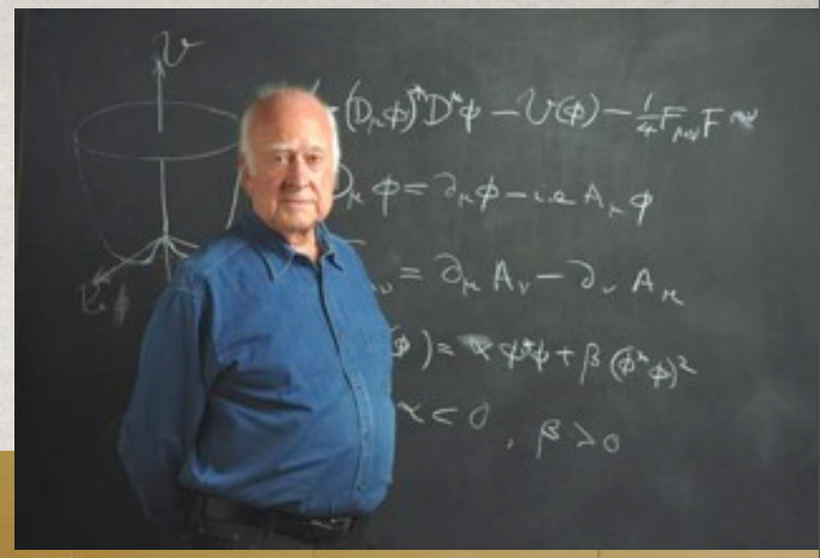
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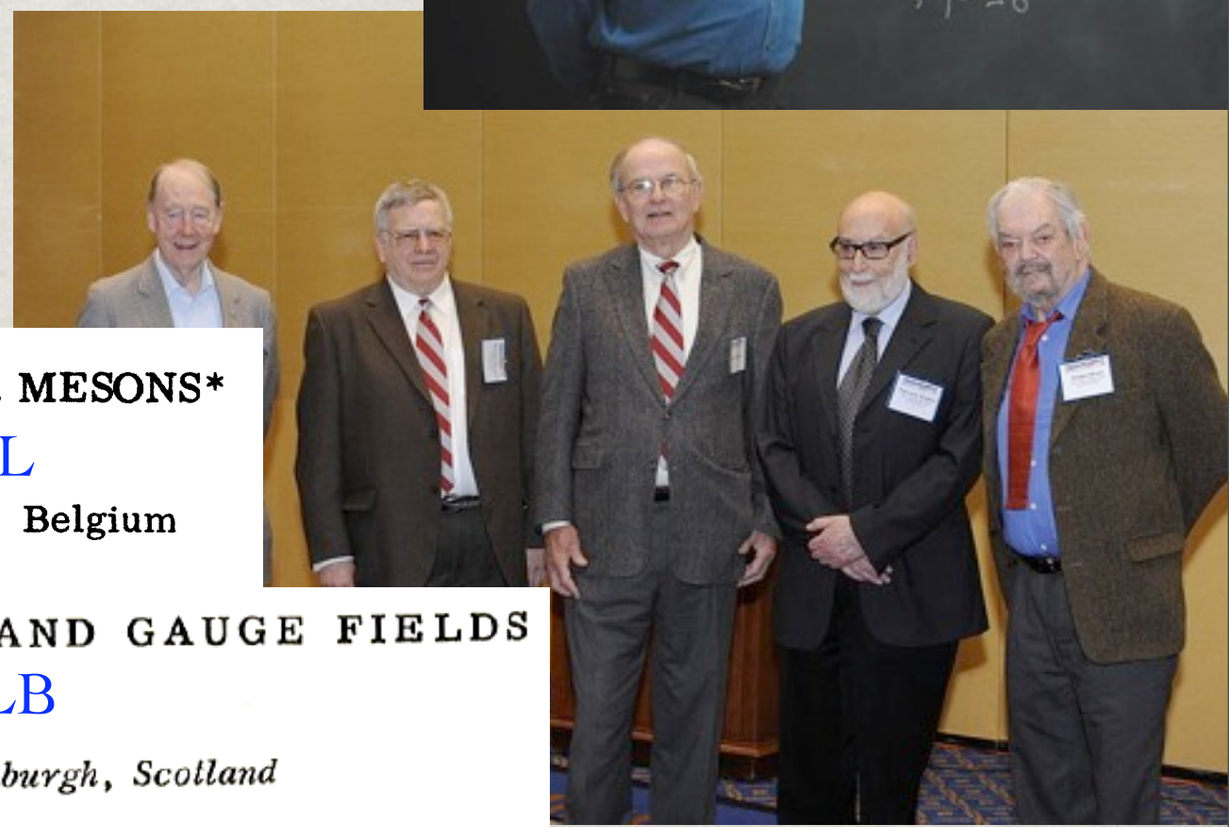
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GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

PRL

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble

Department of Physics, Imperial College, London, England

(Received 12 October 1964)

A illustrative (original) Model:¶

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

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

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

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

and under the local gauge transformations

$$\phi(x) \rightarrow \phi'(x) = e^{iq\alpha(x)}\phi(x),$$

$$A_{\mu}(x) \rightarrow A'_{\mu}(x) = A_{\mu}(x) - \partial_{\mu}\alpha(x).$$

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

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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

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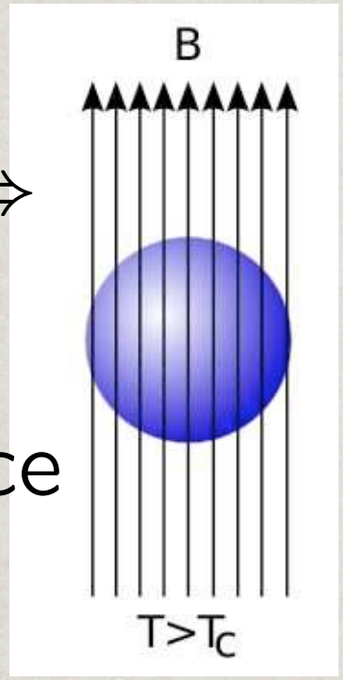
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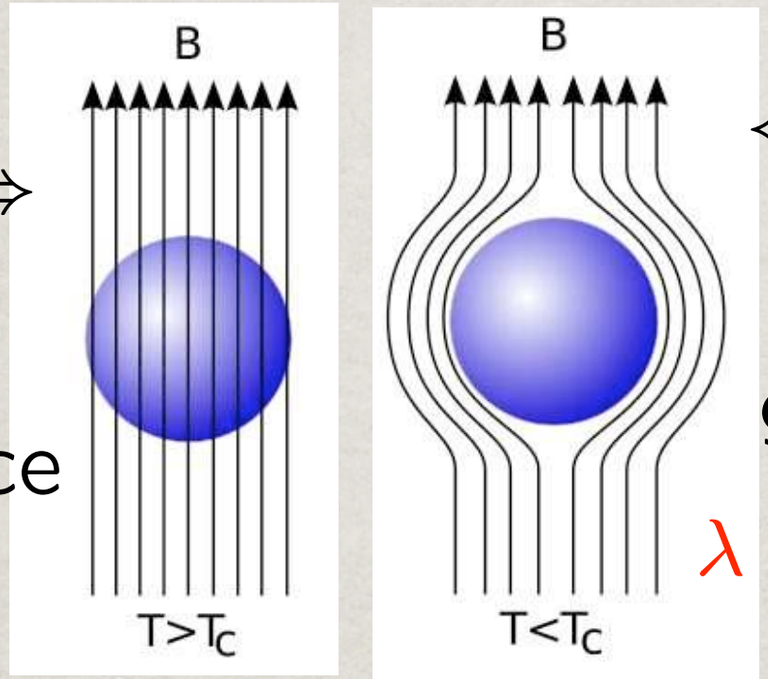


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⇐Superconducting phase

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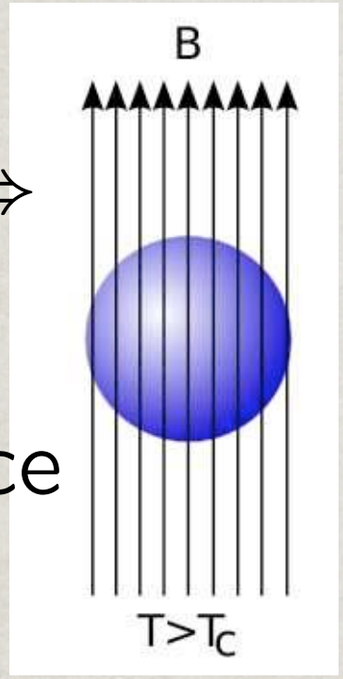
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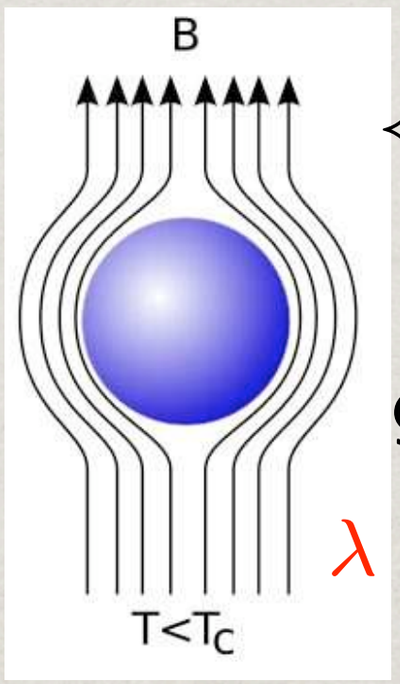
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In "conventional" electro-magnetic superconductivity:

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

In "electro-weak superconductivity":

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

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

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‡ **Spontaneous Symmetry Breakdown without Massless Bosons***

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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. ↩

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B. Higgs Phenomenology

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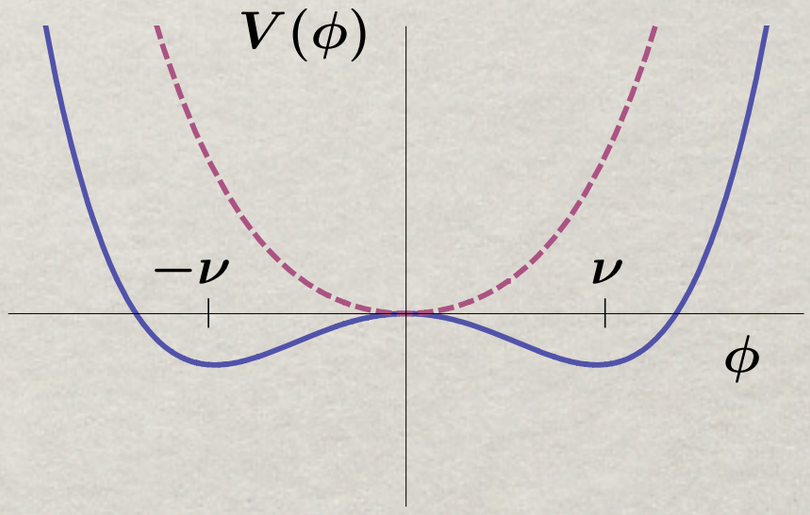
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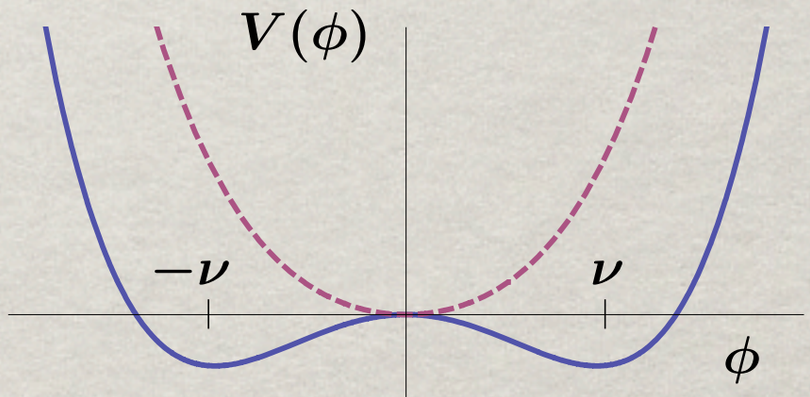
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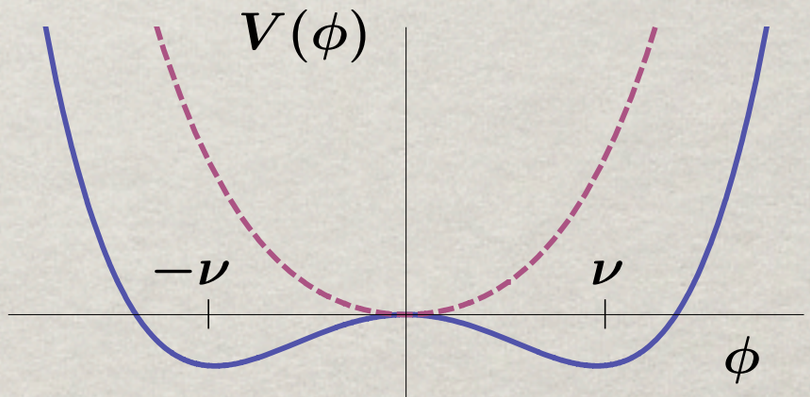
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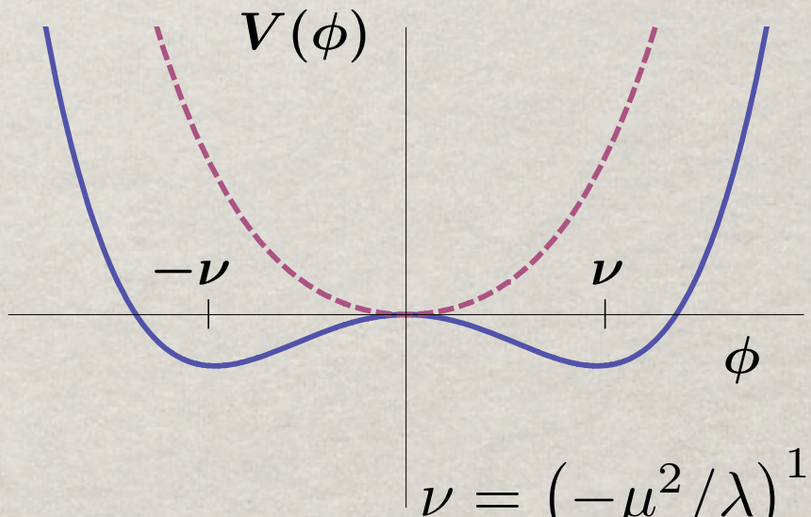
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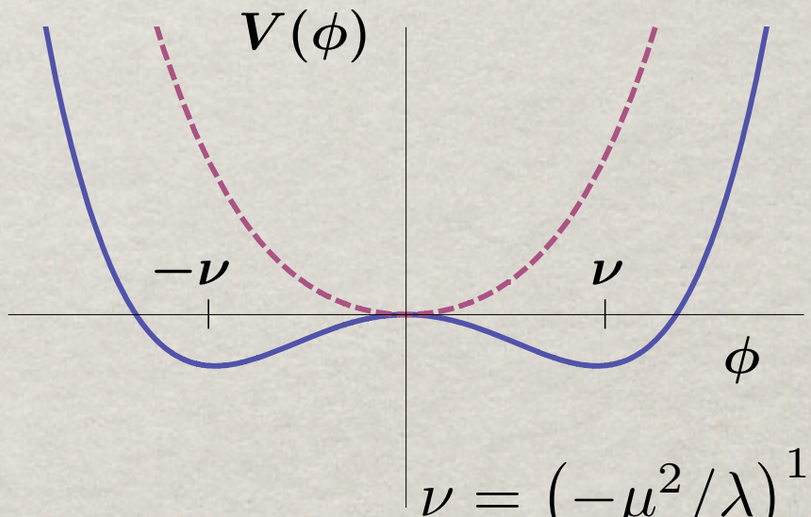
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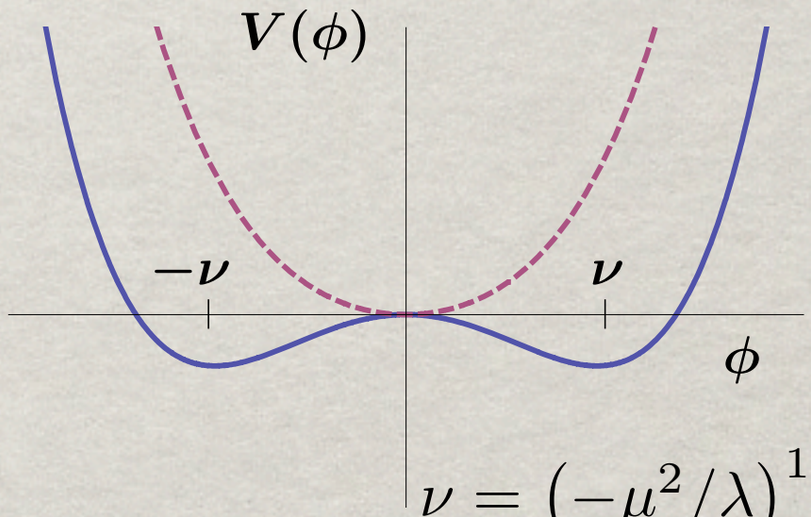
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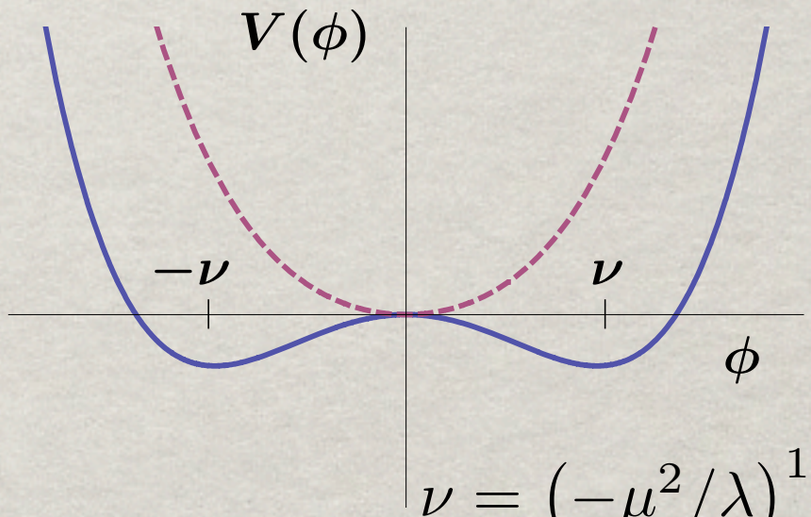
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Need something like a doublet:

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that's the Higgs doublet!

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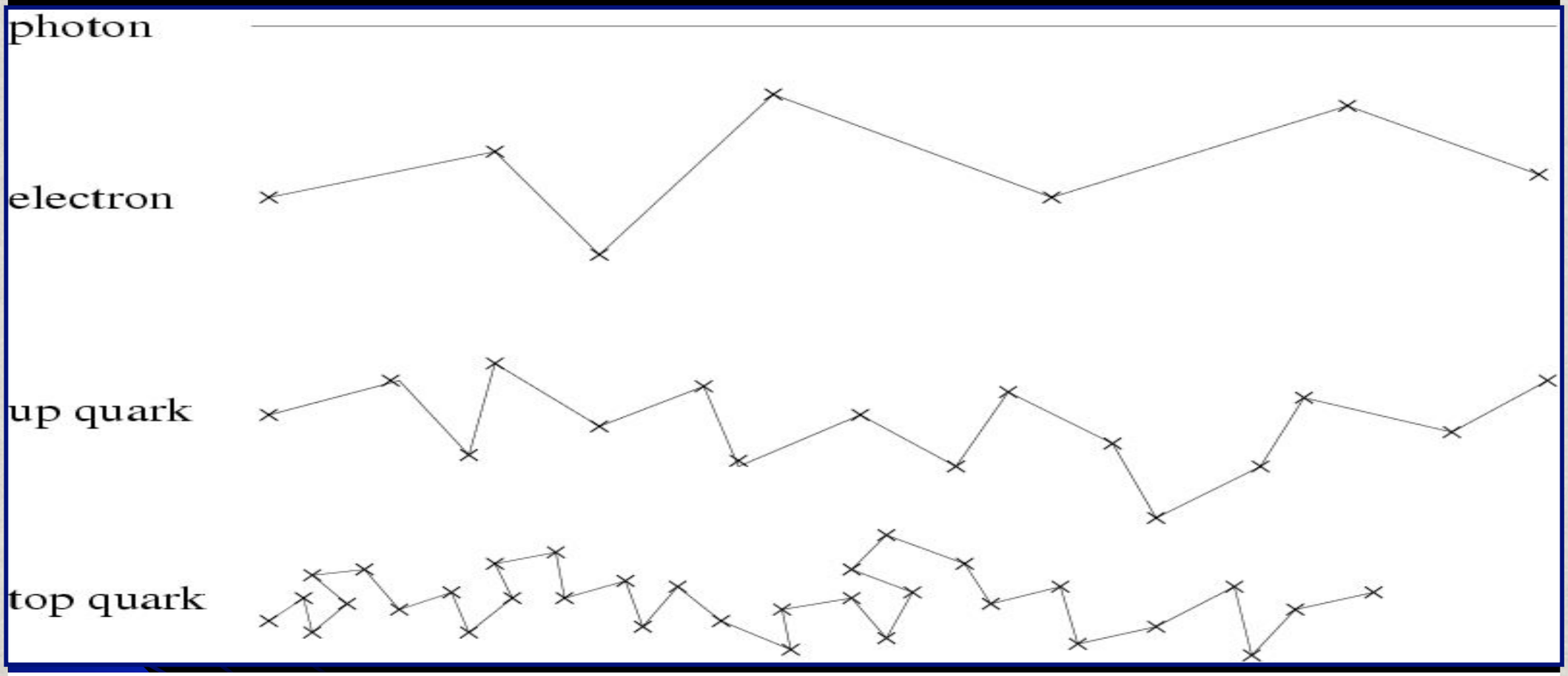
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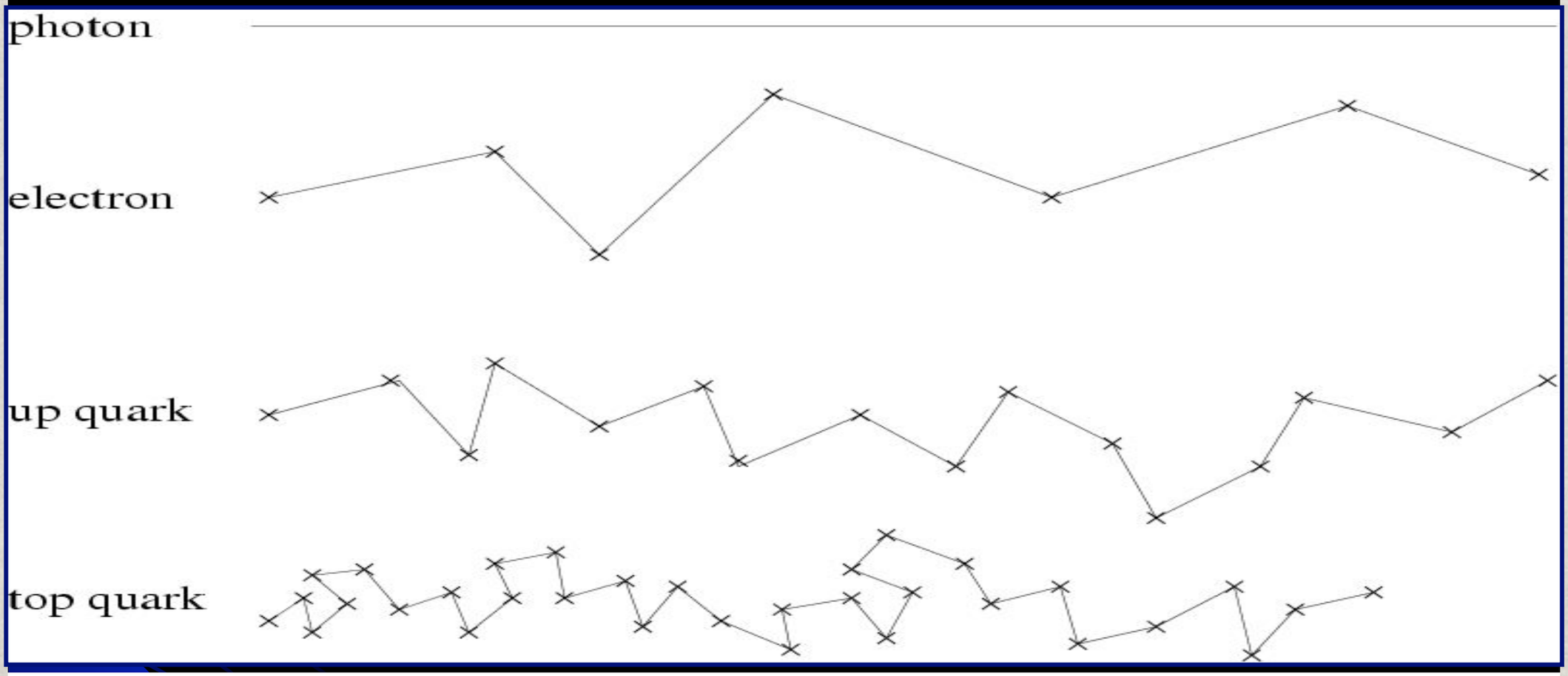
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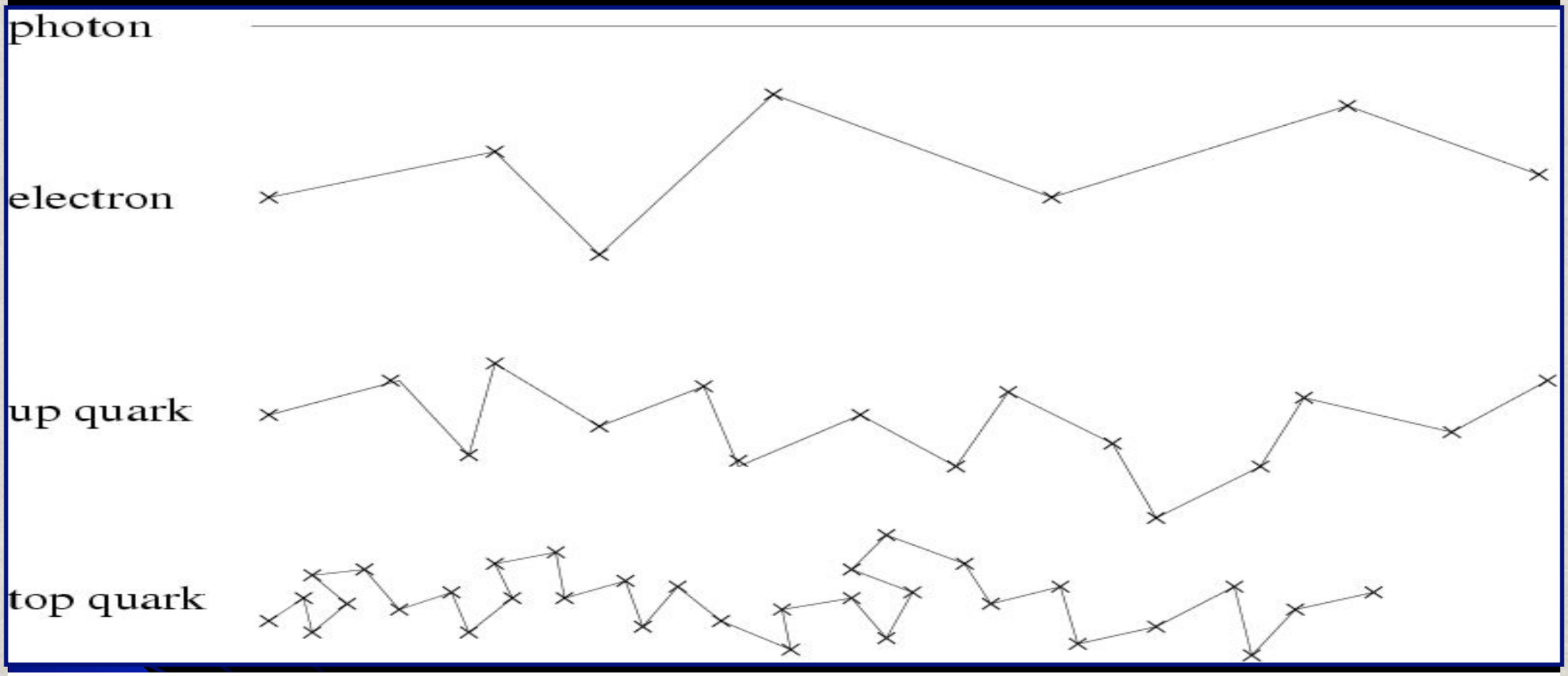


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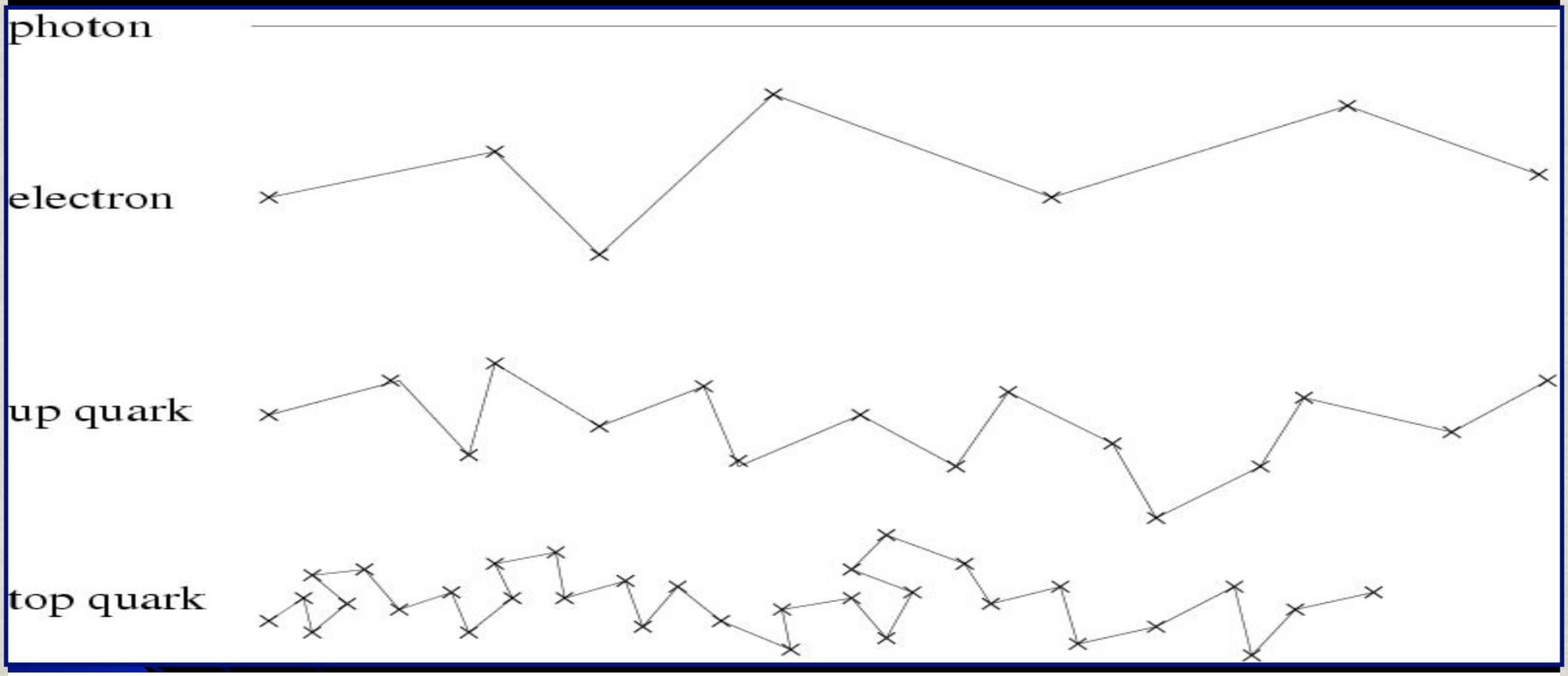
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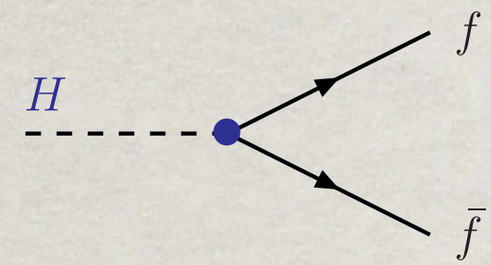


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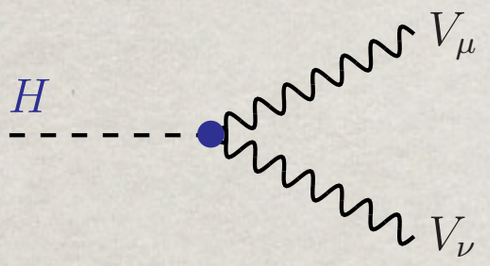
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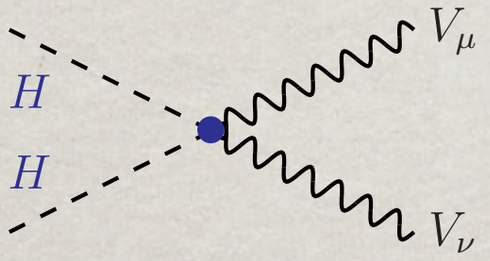
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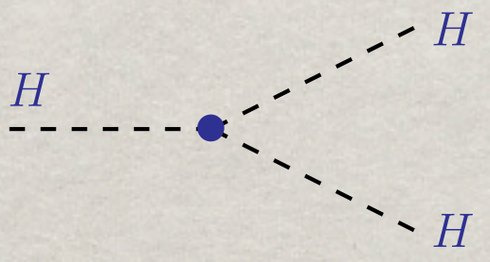
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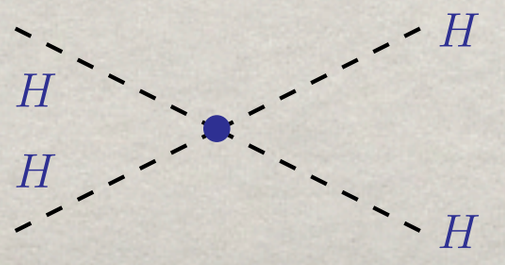
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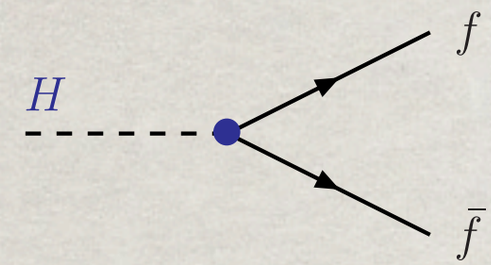


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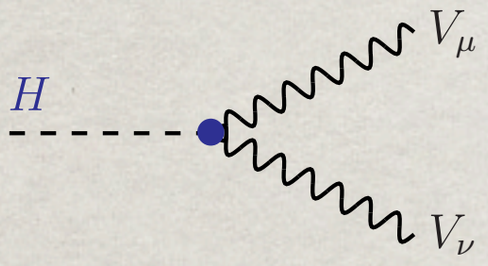


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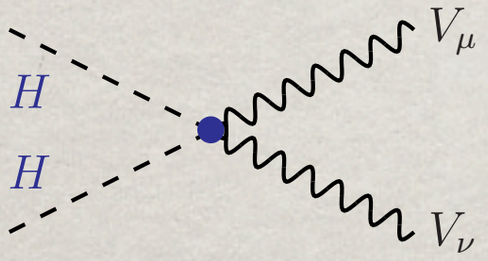
Feynman rules:



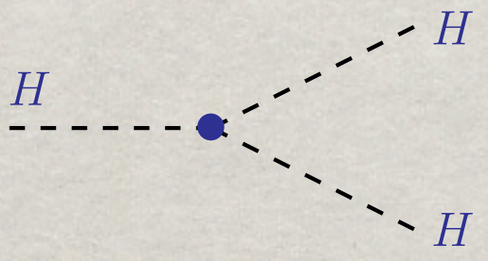
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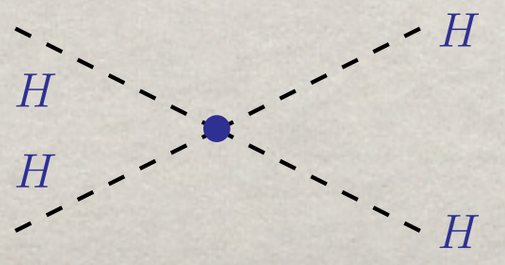
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Caution: Very often, we say at high energies, M_W -> 0.
Rigorously speaking, we mean: g, M_W -> 0, but M_W/g -> v/2.

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:

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Exercise 7: Verify the Goldstone-boson Equivalence Theorem by examining the HWW vertex.

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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.

Outline

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Lecture I: Higgs Physics in the SM

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-- A historical count

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A. The Higgs Mechanism

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A. The Higgs Mechanism

B. Higgs Phenomenology

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A. A Weakly Coupled Light Scalar?

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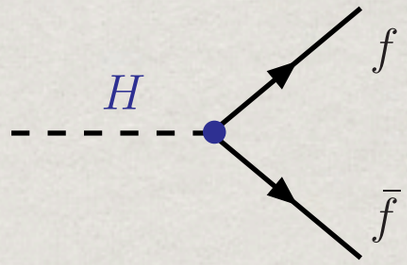
C. New Physics Scenarios
associated with the Higgs

3. Higgs Boson Decay§

§ L. Reina, TASI lectures, 2011.

3. Higgs Boson Decay§

Decay to fermions:

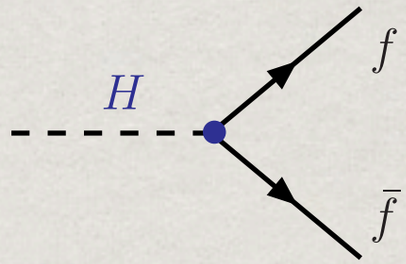


$$\Gamma_{\rm Born}(A \to f\bar{f}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H\, m_f^2\, \beta_f$$

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3. Higgs Boson Decay§

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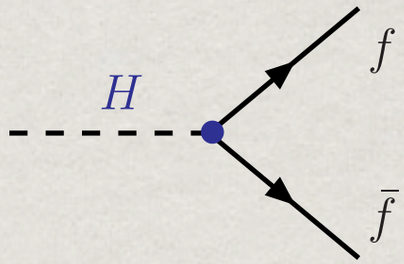
The largest higher-order effect is the quark running mass:

$$\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}} \\
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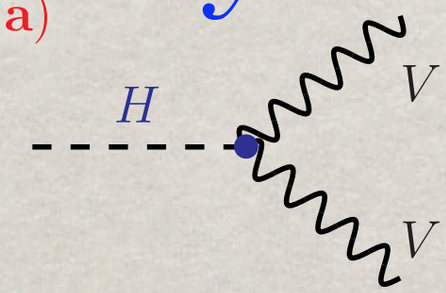
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Decay to WW,ZZ:

a)

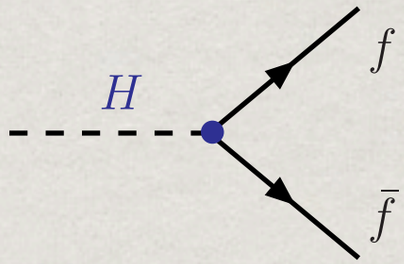


$$\Gamma(H \to VV) = \frac{G_\mu M_H^3}{16\sqrt{2}\pi}\,\delta_V\,\sqrt{1-4x}\,(1-4x+12x^2)\;, \quad x = \frac{M_V^2}{M_H^2}$$

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3. Higgs Boson Decay§

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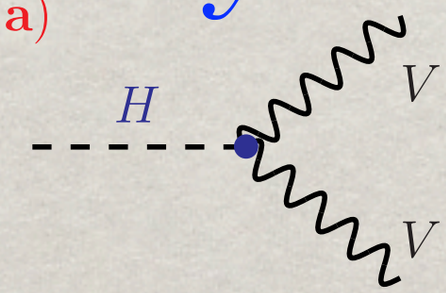
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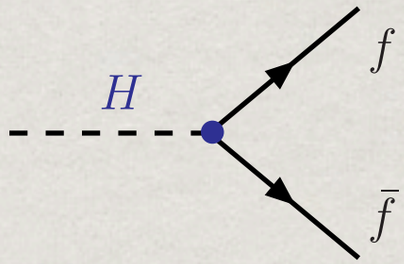
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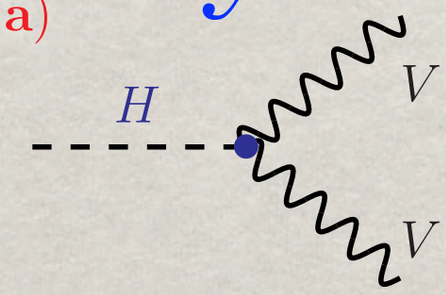
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Exercise 8: Calculate the Higgs decay to polarized pairs V_TV_T, V_LV_T, and V_LV_L.

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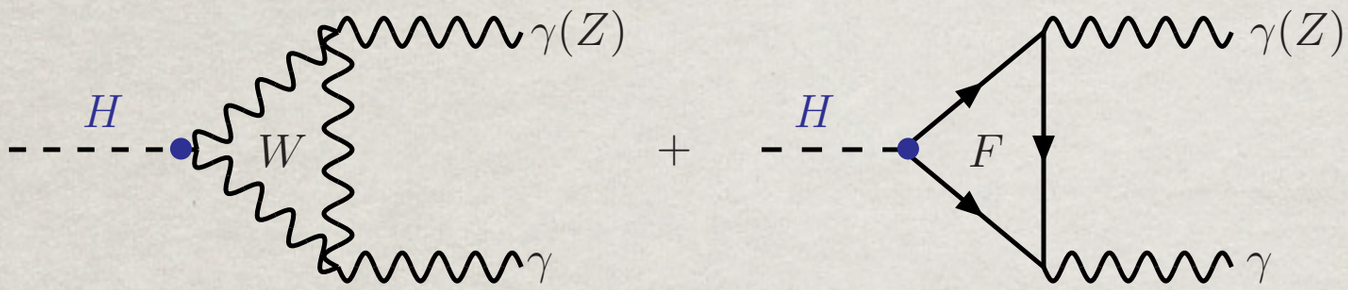
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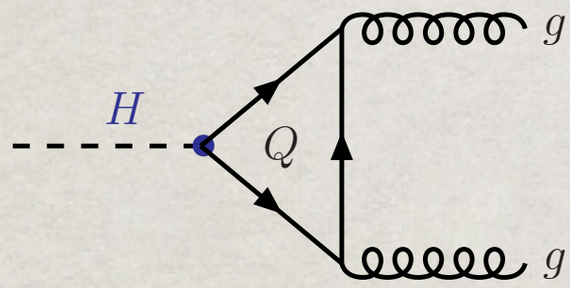
3. Higgs Boson Decay§

Decay through loops:

a)



b)



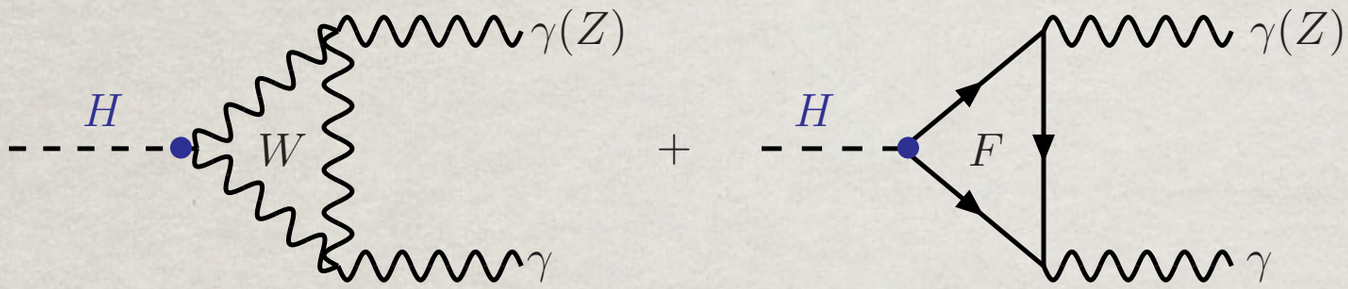
Sensitive to new charged (Q,L), colored (Q) heavy states in loops.

§ L. Reina, TASI lectures, 2011.

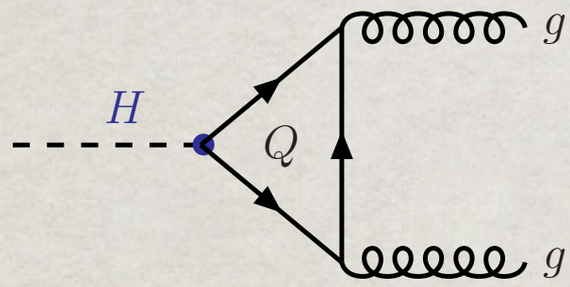
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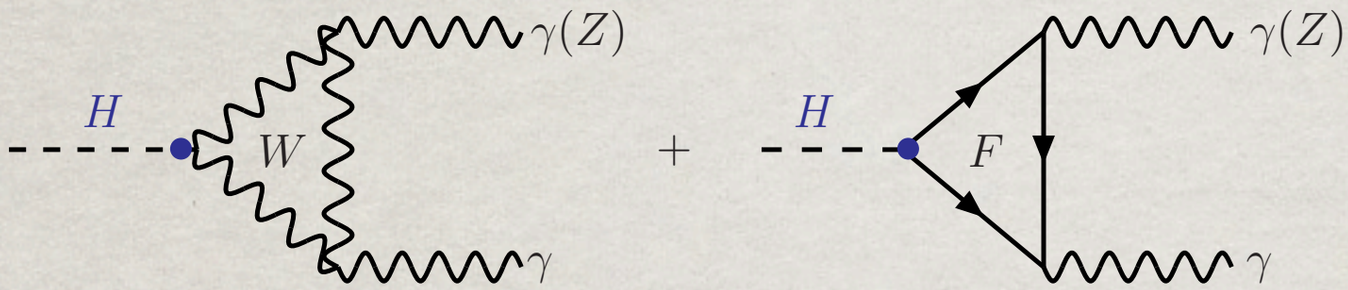
$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha^2 M_H^3}{128\sqrt{2}\pi^3} \left| \sum_f N_c^f Q_f^2 A_f^H(\tau_f) + A_W^H(\tau_W) \right|^2$$

§ L. Reina, TASI lectures, 2011.

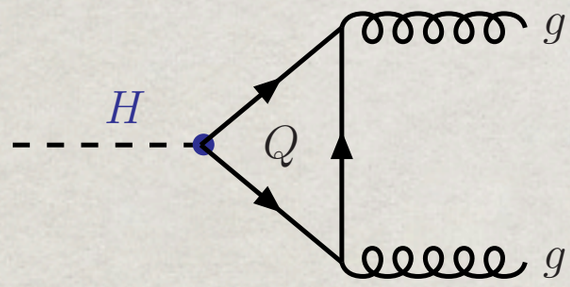
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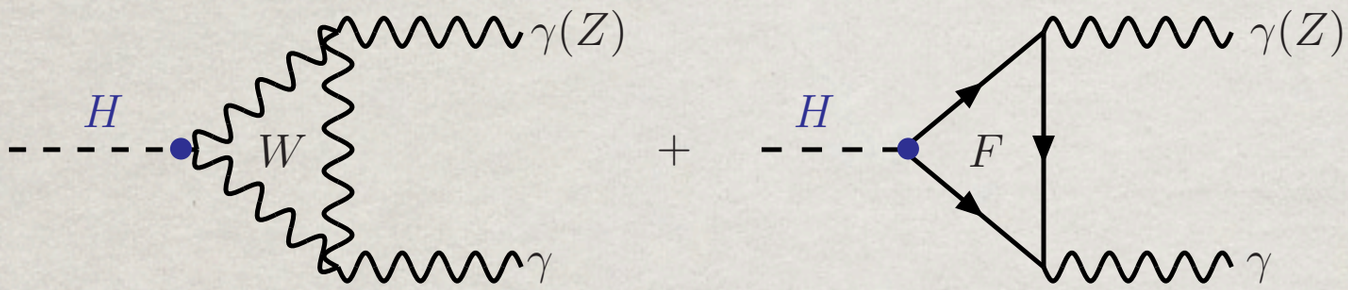
$$\Gamma(H \to \gamma Z) = \frac{G_F^2 M_W^2 \alpha M_H^3}{64\pi^4} \left(1 - \frac{M_Z^2}{M_H^2}\right)^3 \left| \sum_f A_f^H(\tau_f, \lambda_f) + A_W^H(\tau_W, \lambda_W) \right|^2$$

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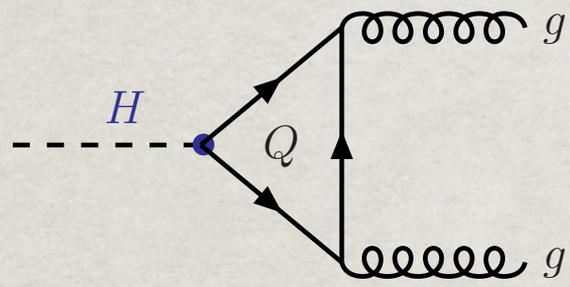
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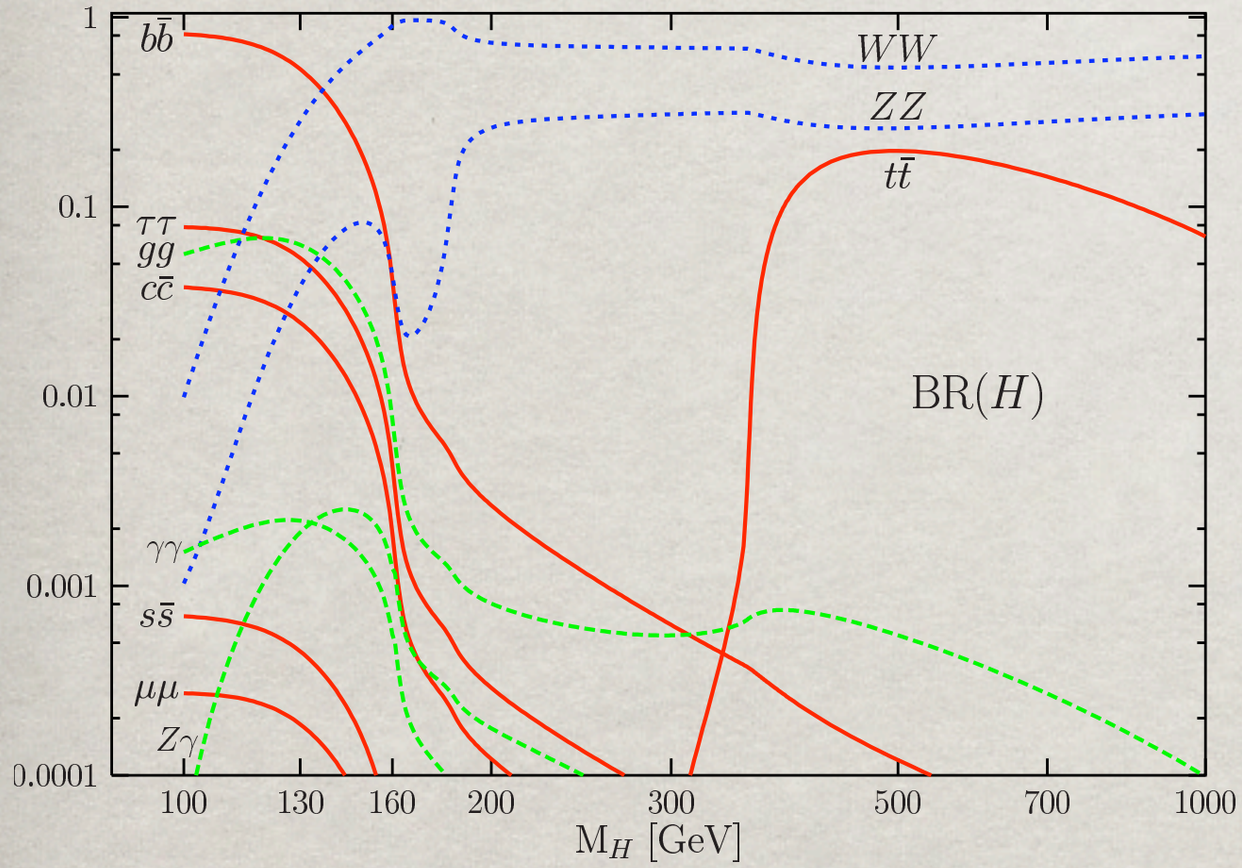
$$\Gamma(H \to gg) = \frac{G_F \alpha_s^2 M_H^3}{36\sqrt{2}\pi^3} \left| \frac{3}{4} \sum_q A_q^H(\tau_q) \right|^2$$

§ L. Reina, TASI lectures, 2011.

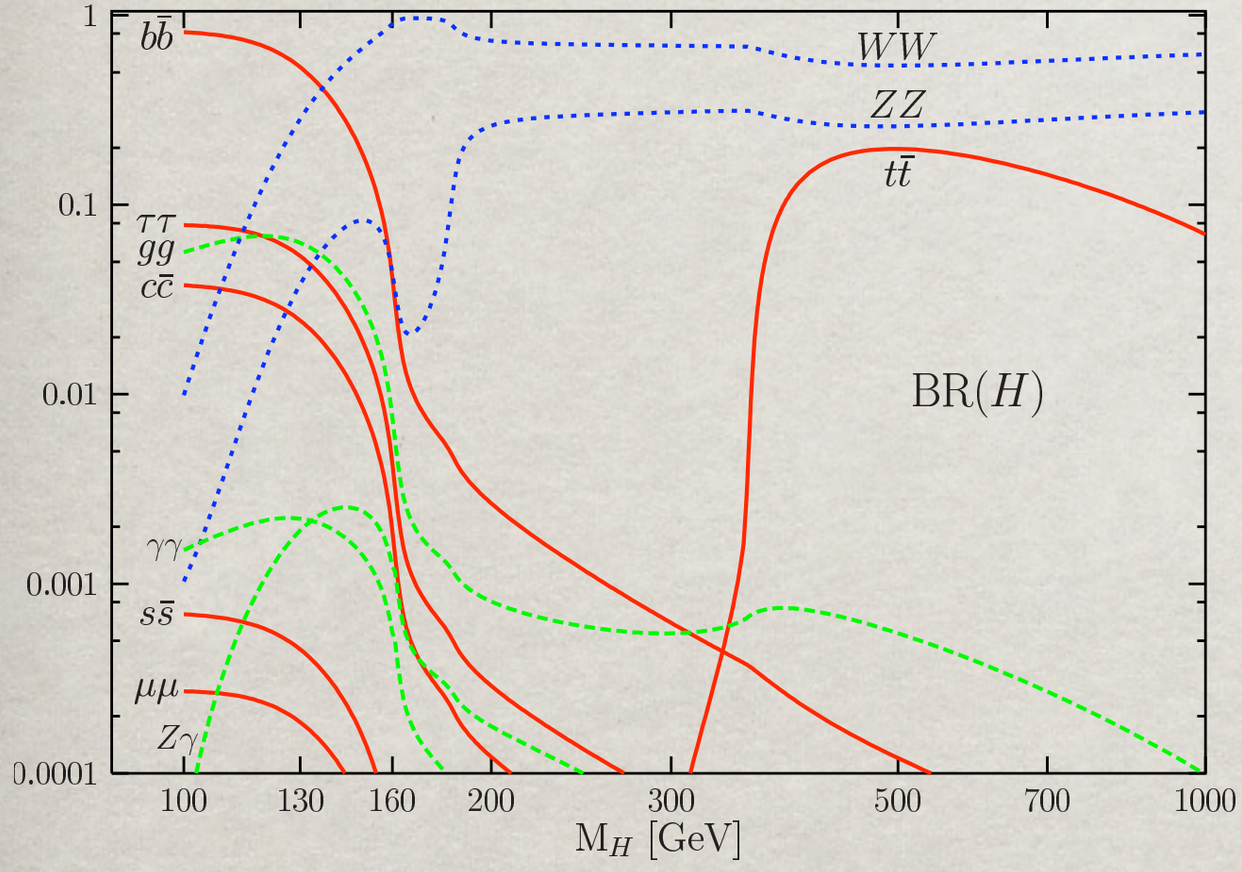
As the results for a SM Higgs:

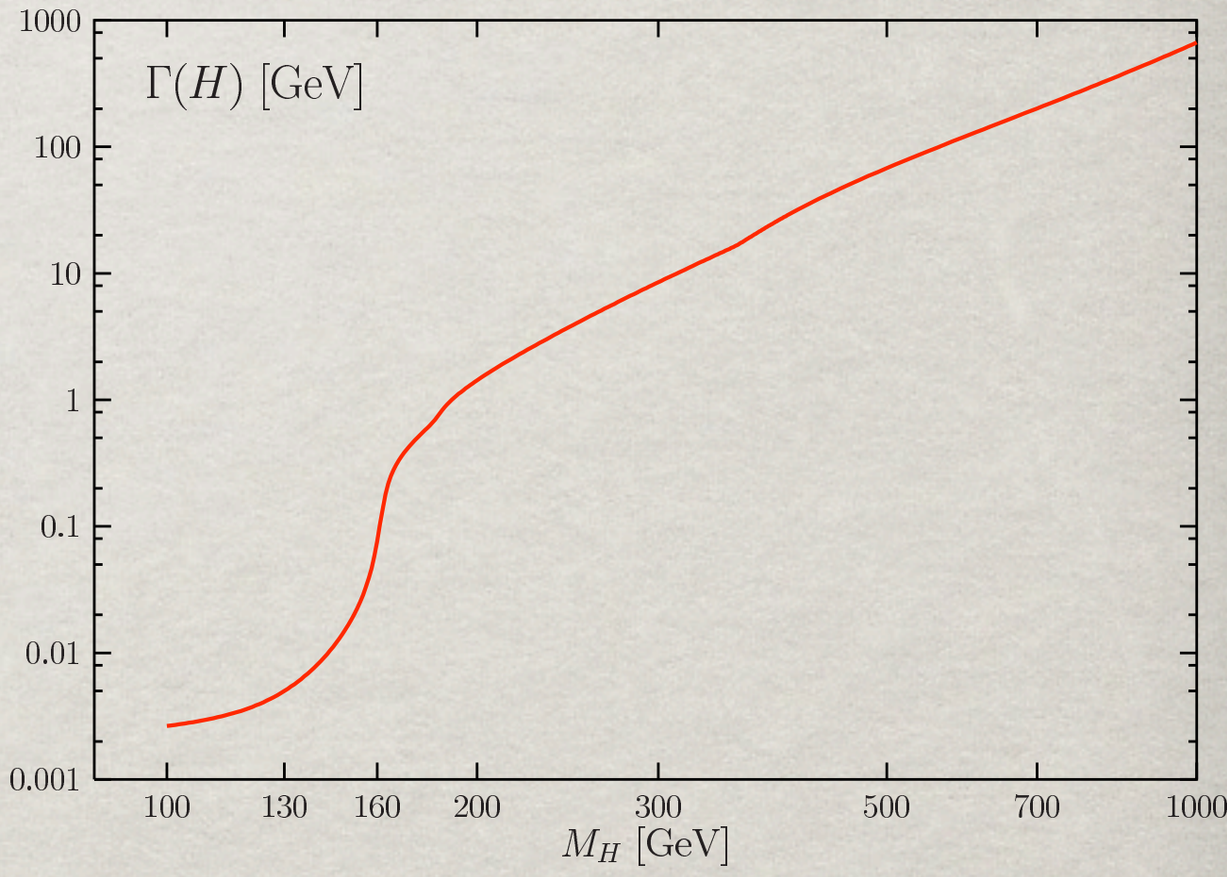
As the results for a SM Higgs:
The branching fractions and total width

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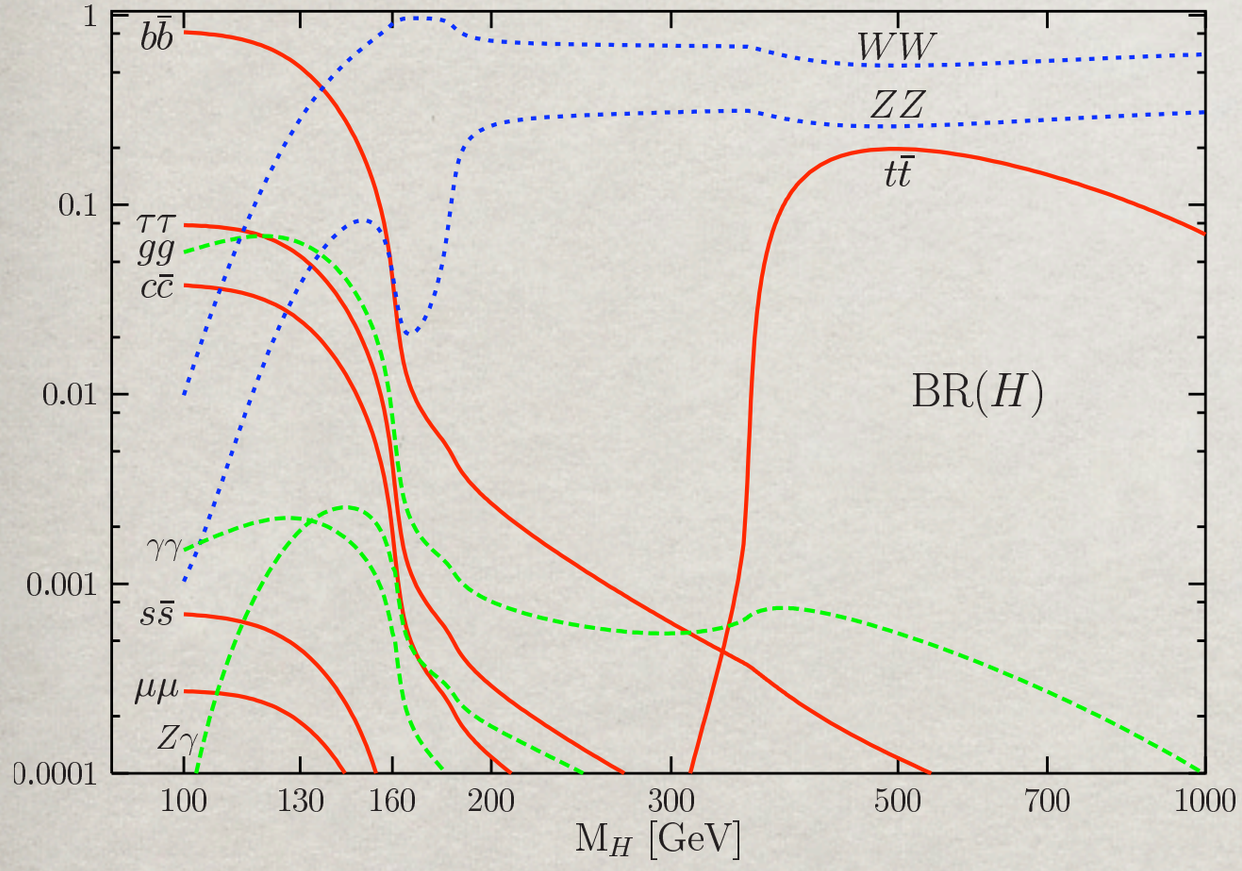


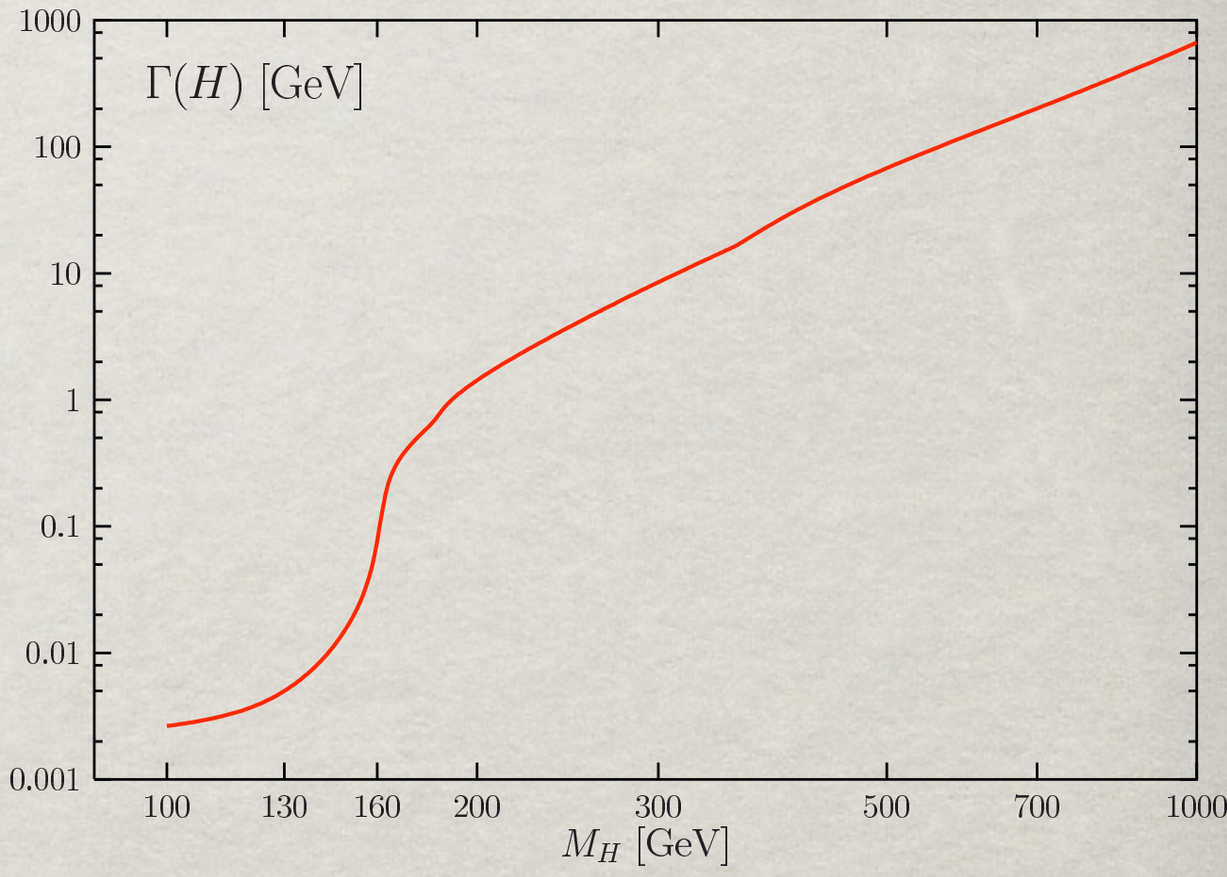
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As the results for a SM Higgs: The branching fractions and total width





For m_H = 125 GeV, Γ(total) ≈ 4 MeV

BR(bb) ≈ 60%

BR(WW) ≈ 21%

BR(gg) ≈ 9%

BR(ττ) ≈ 8%

BR(ZZ) ≈ 2%

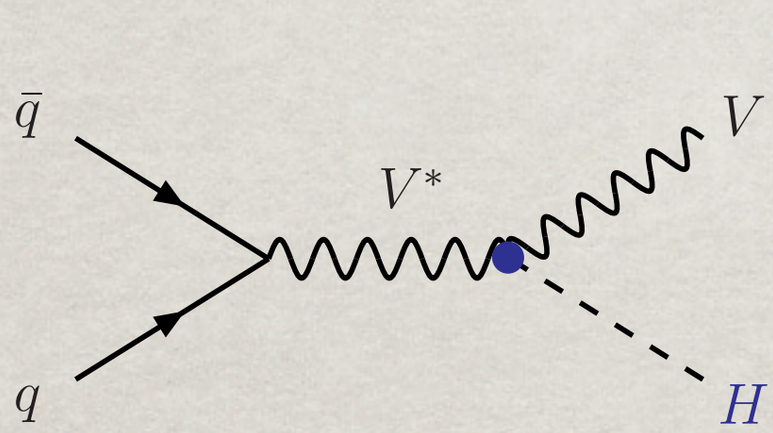
BR(γγ) ≈ 0.22%

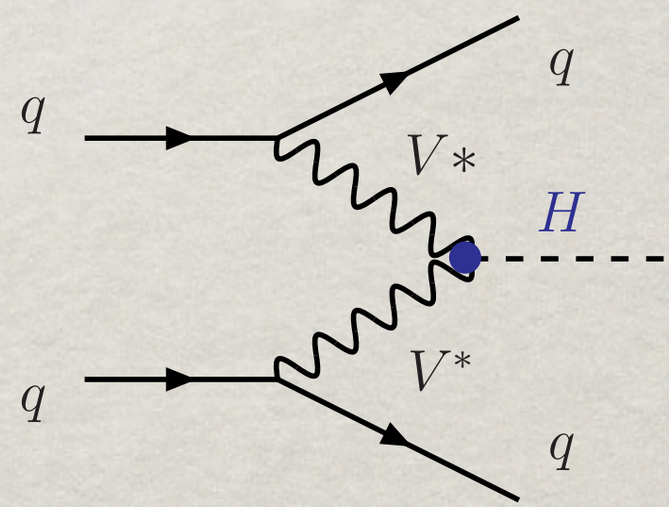
$$\text{associated production with } W/Z: \quad q\bar{q} \longrightarrow V + H$$

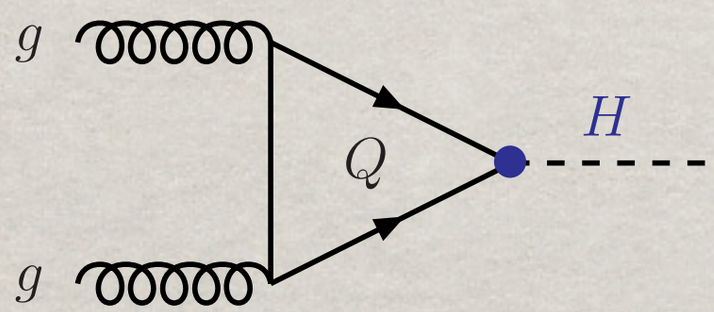
$$\text{vector boson fusion}: \quad qq \longrightarrow V^*V^* \longrightarrow qq + H$$

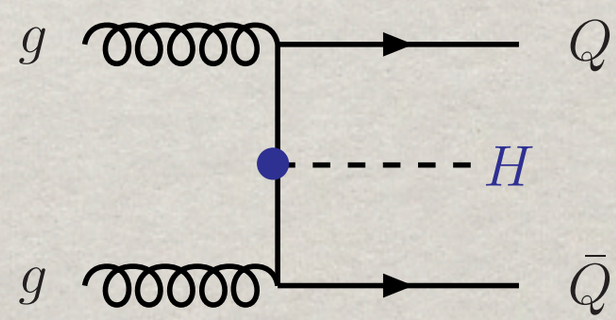
$$\text{gluon} - \text{gluon fusion}: \quad gg \longrightarrow H$$

$$\text{associated production with heavy quarks}: \quad gg, q\bar{q} \longrightarrow Q\bar{Q} + H$$





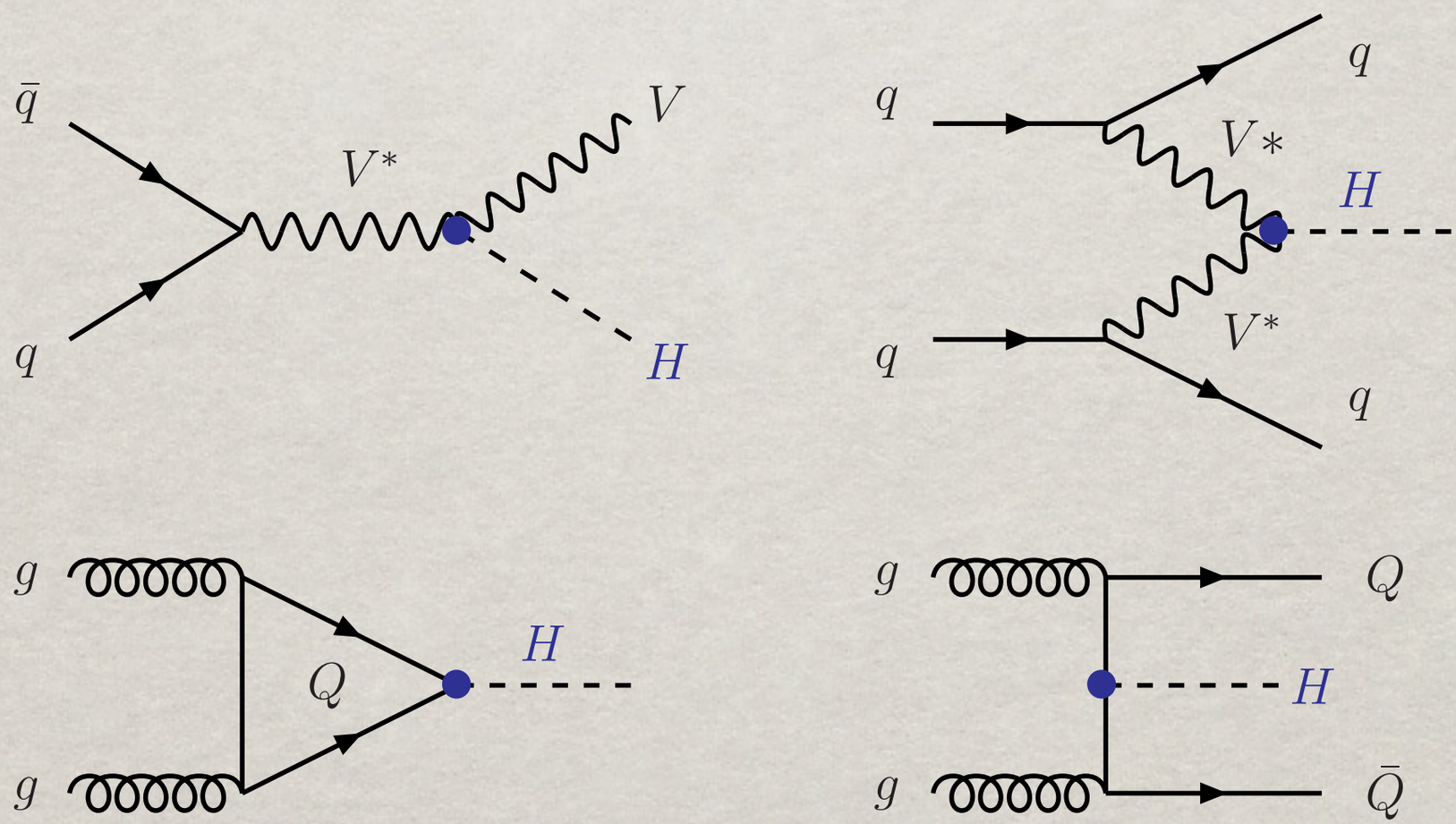




4. Higgs Boson Production at LHC

Recall that the Higgs couples preferably to heavier particles.

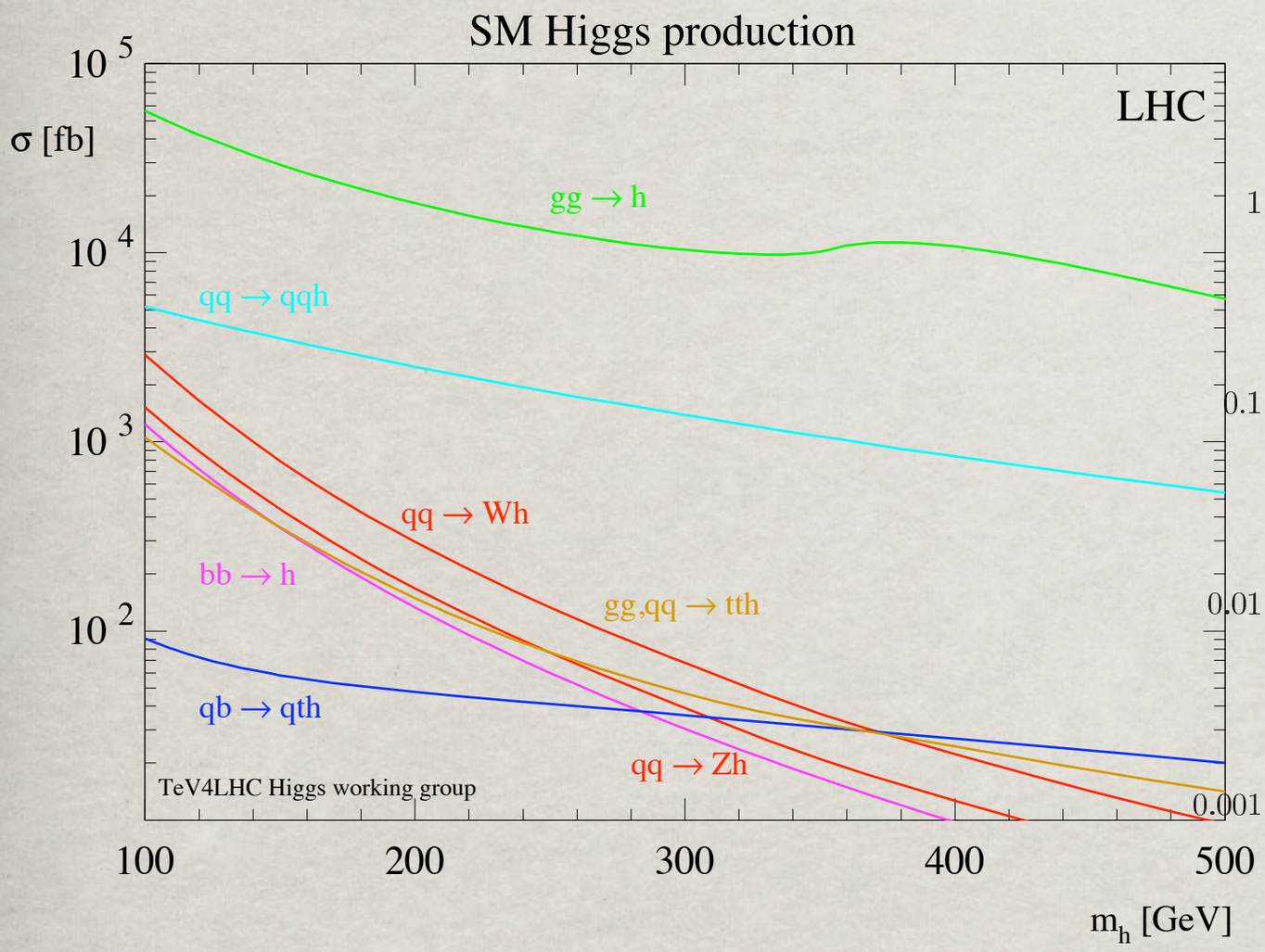
$$\begin{aligned}
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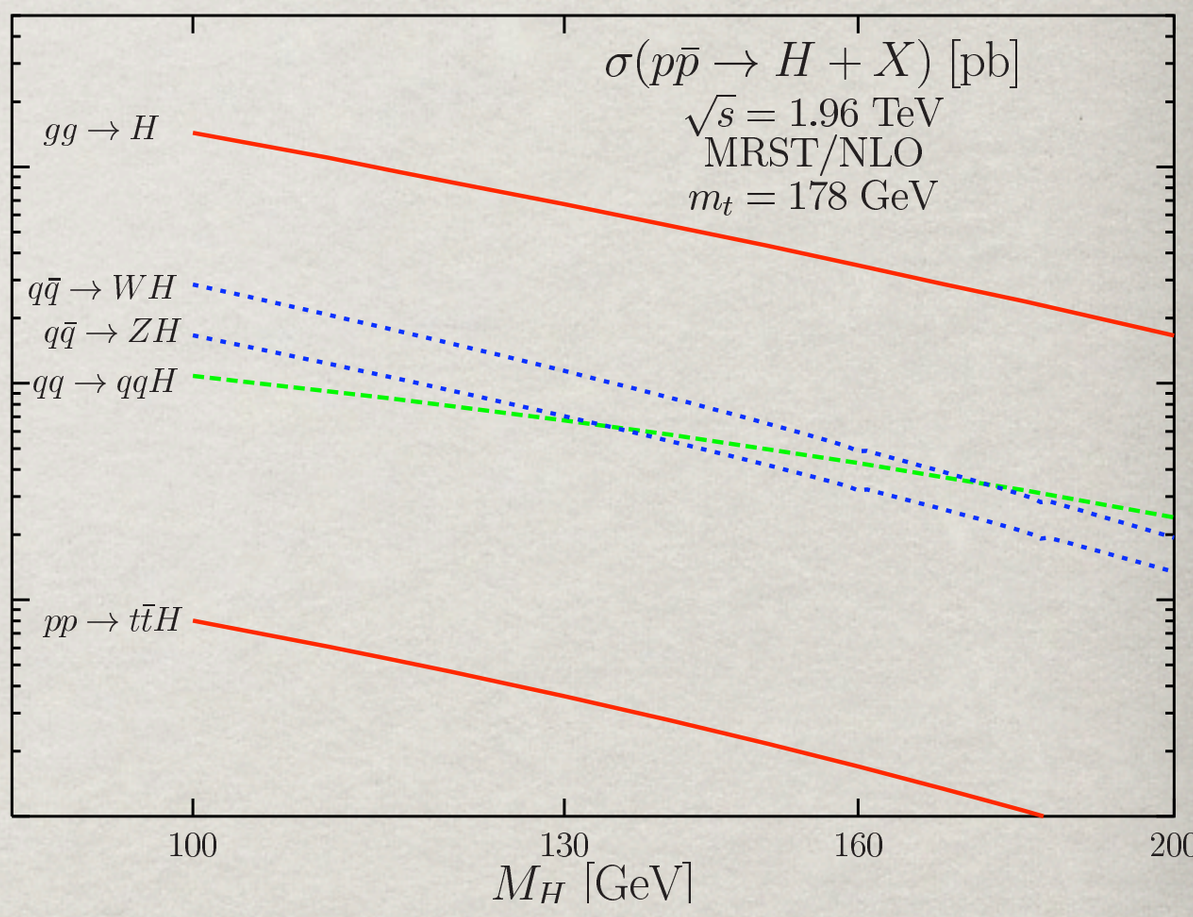


process	$\sigma_{NLO,NNLO}$ by
$gg \to H$	S.Dawson, NPB 359 (1991), A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser *et al.*, JHEP 0212 (2002); V.Ravindran *et al.*, NPB 634 (2002) D. de Florian *et al.*, PRL 82 (1999) R.Harlander, W.Kilgore, PRL 88 (2002) (NNLO) C.Anastasiou, K.Melnikov, NPB 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)

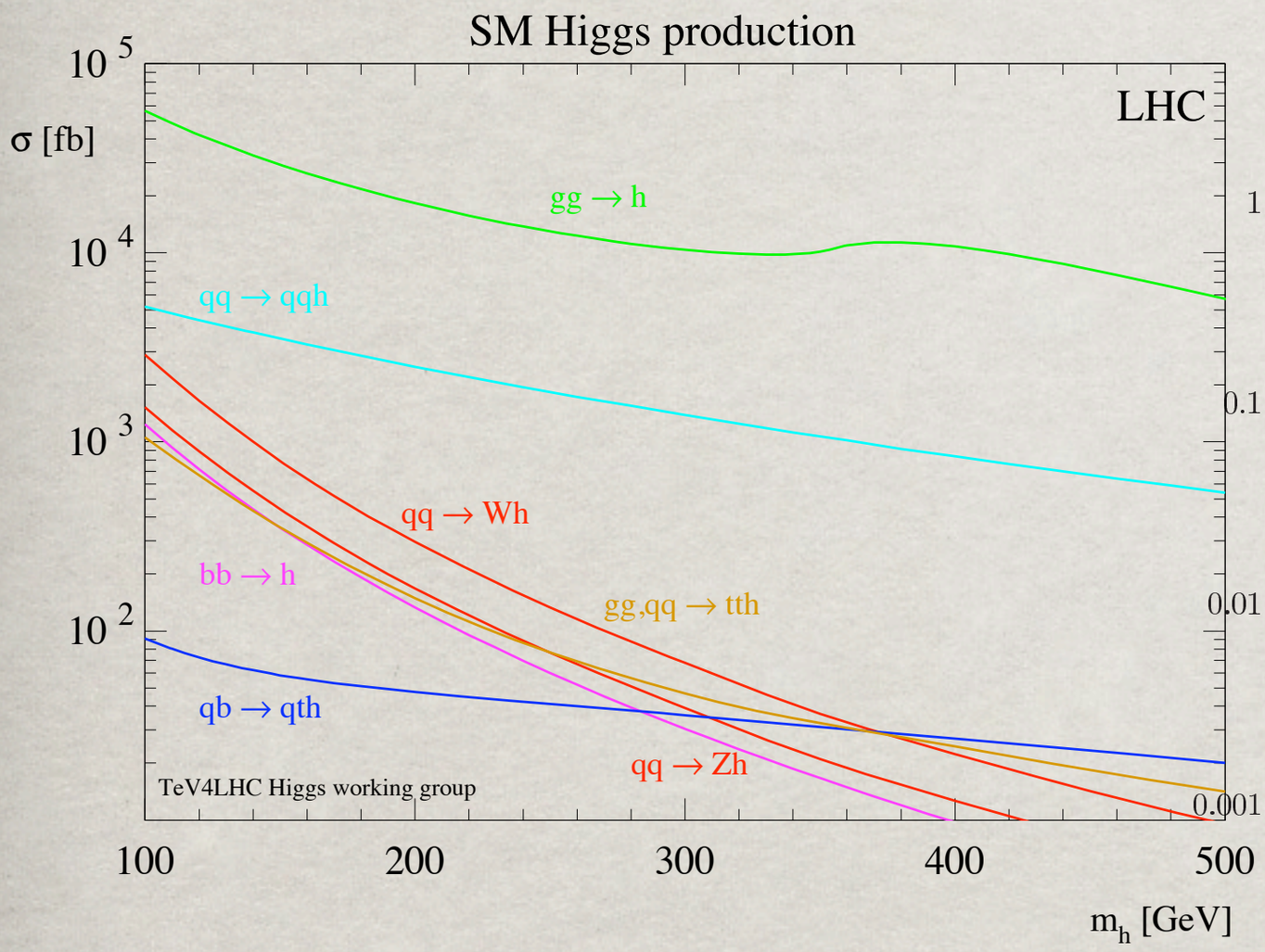
Calculation history and references compiled by Laura Reina

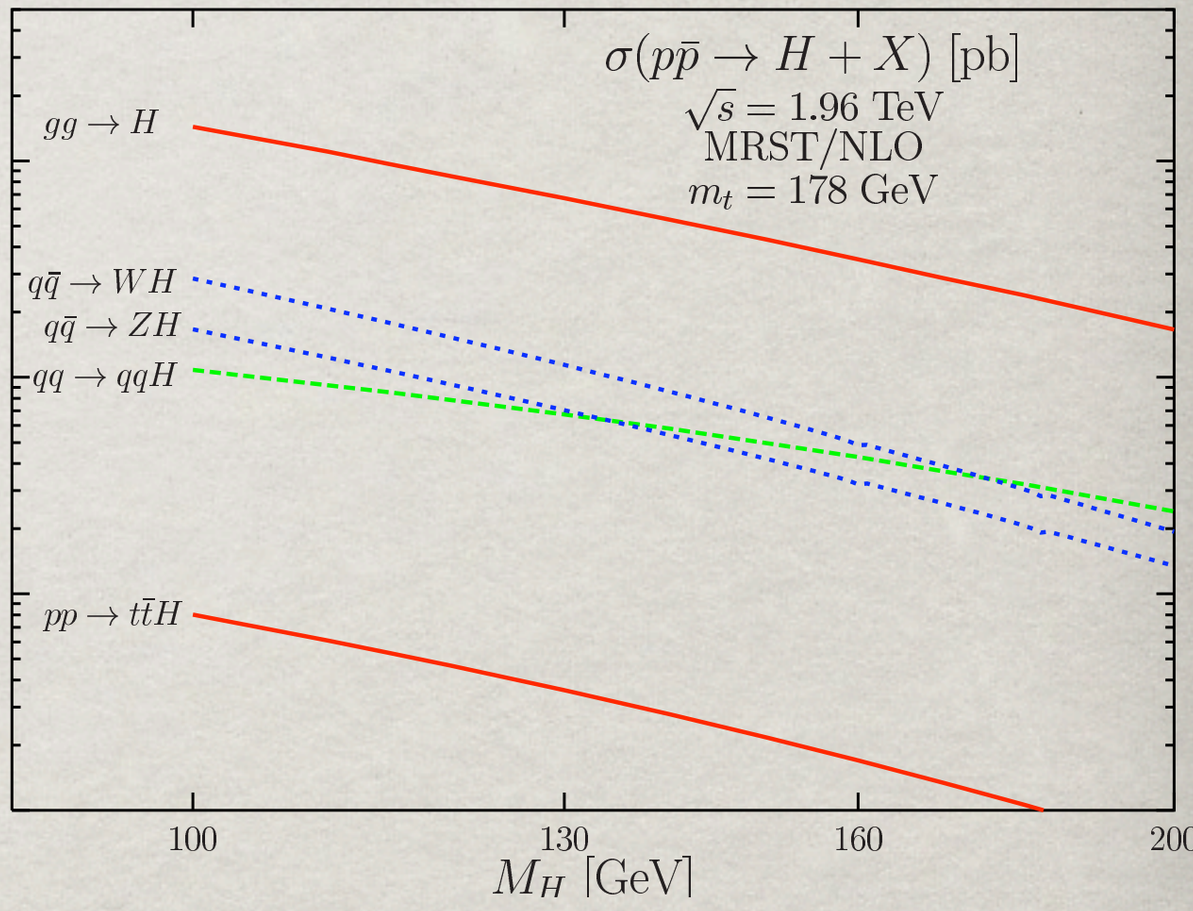
process	$\sigma_{NLO,NNLO}$ by
$gg \to H$	S.Dawson, NPB 359 (1991), A.Djouadi, M.Spira, P.Zerwas, PLB 264 (1991) C.J.Glosser *et al.*, JHEP 0212 (2002); V.Ravindran *et al.*, NPB 634 (2002) D. de Florian *et al.*, PRL 82 (1999) R.Harlander, W.Kilgore, PRL 88 (2002) (NNLO) C.Anastasiou, K.Melnikov, NPB 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)
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SM Higgs production
LHC
σ [fb]
gg → h
qq → qqh
qq → Wh
bb → h
gg,qq → tth
qb → qth
qq → Zh
TeV4LHC Higgs working group
m_h [GeV]


σ(pp̄ → H + X) [pb]
√s = 1.96 TeV
MRST/NLO
m_t = 178 GeV
gg → H
qq̄ → WH
qq̄ → ZH
qq → qqH
pp → tt̄H
M_H [GeV]

Production cross sections at hadron colliders:

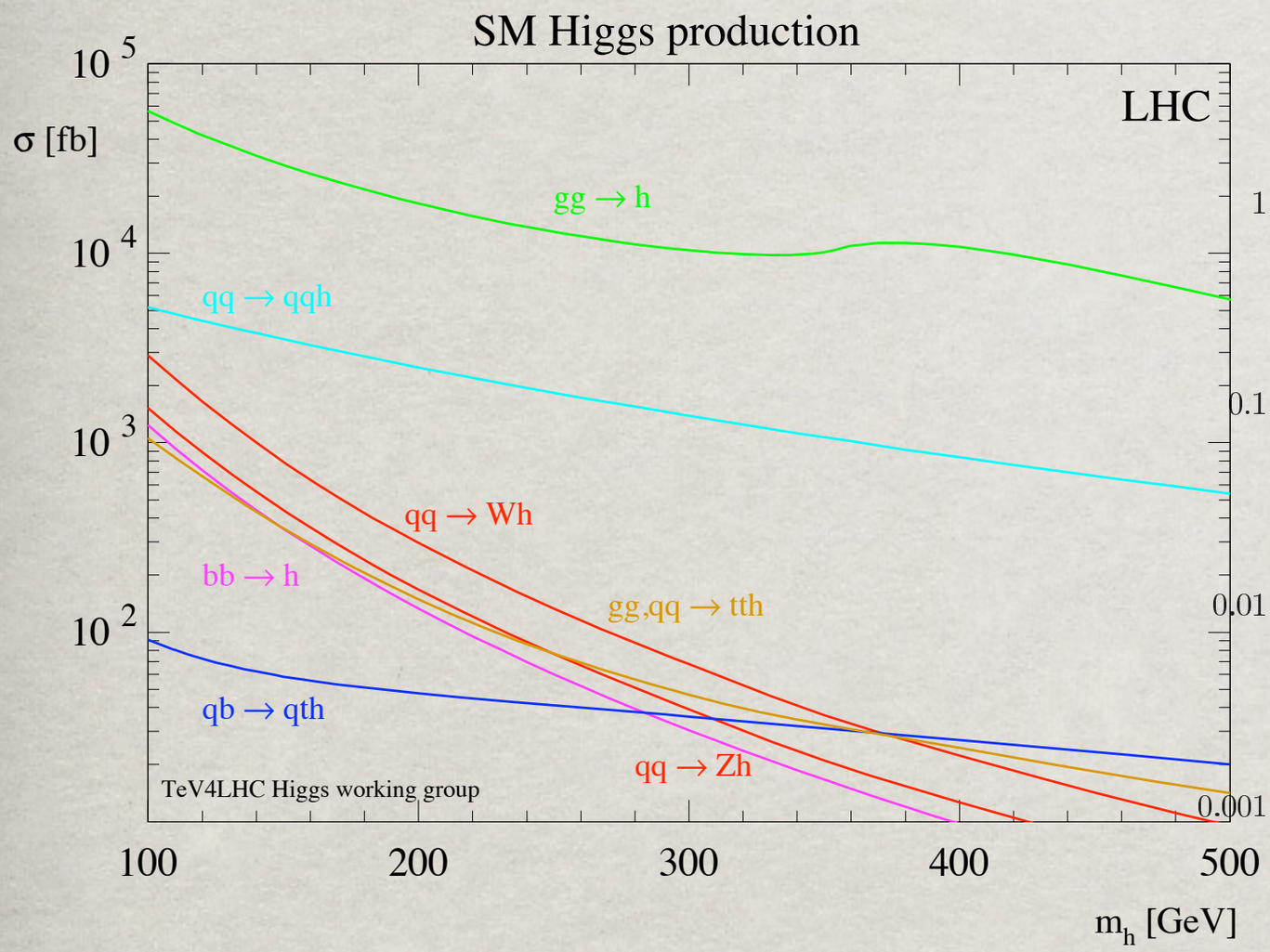


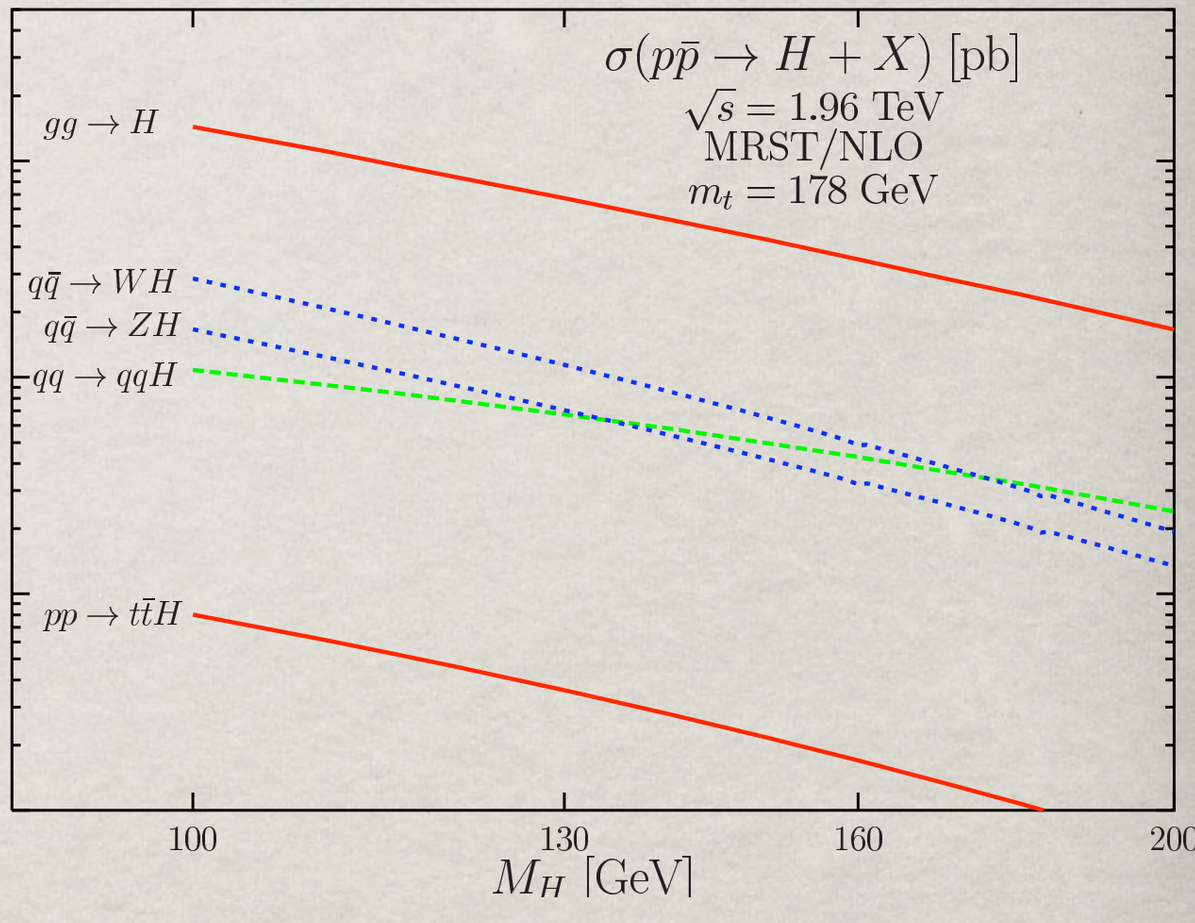


§ L. Reina, TASI lectures, 2011.

A. Djouadi, hep-ph/0503172.

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.

C. Higgs Boson Search & Study at LHC

1. Signal Search Strategy:

C. Higgs Boson Search & Study at LHC

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Searching for the Higgs boson at the LHC

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In experiments:‡

‡ See the authoritative lectures Vivek Sharma.

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In experiments:‡

- specify a (good) final state from H decay;

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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)

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Salute to theorists/experimentalists:

We Made It!

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We want to know more:

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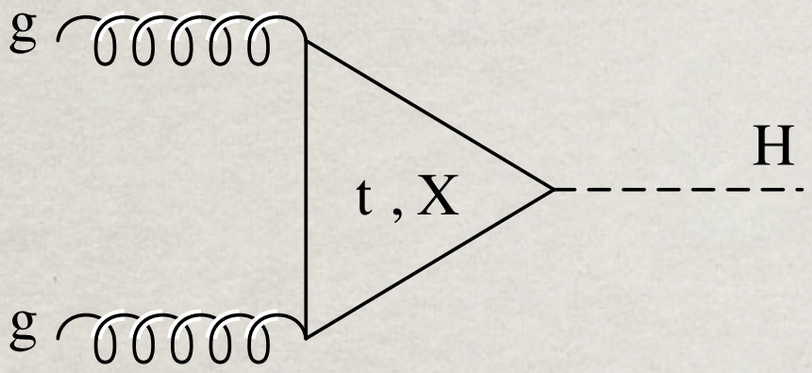
- Is there more than one Higgs boson?
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Still a lot of hard, but fun work to do!

2. Signal Characteristics:

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(a). Gluon fusion: The leading production channel

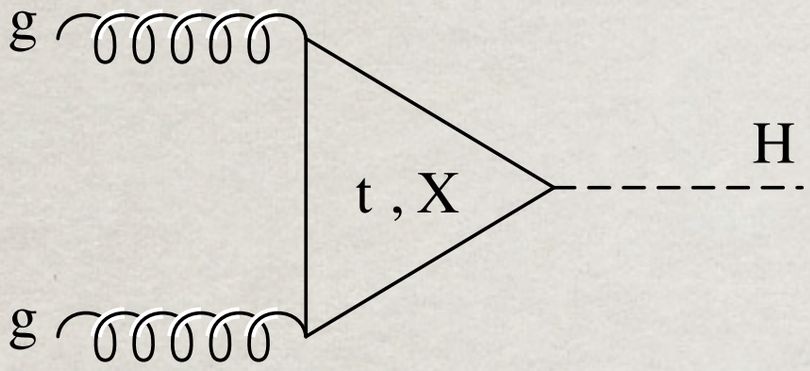


$\sigma(125\ \text{GeV}@\ 8\ \text{TeV}) \approx 20\ \text{pb}$

$\sigma(125\ \text{GeV}@14\ \text{TeV}) \approx 40\ \text{pb}$

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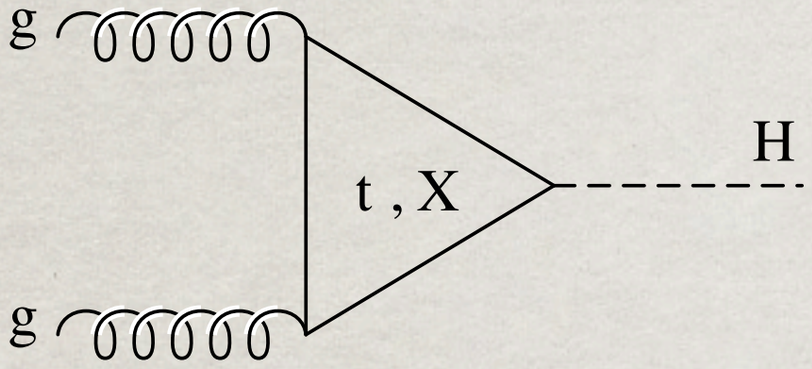
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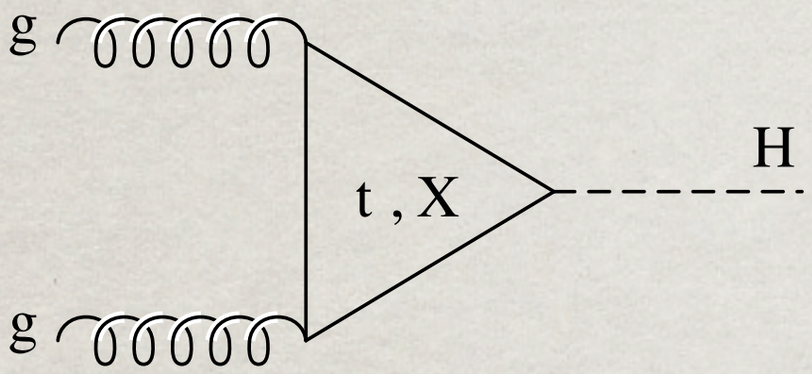
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§ L. Reina, TASI lectures, 2011.

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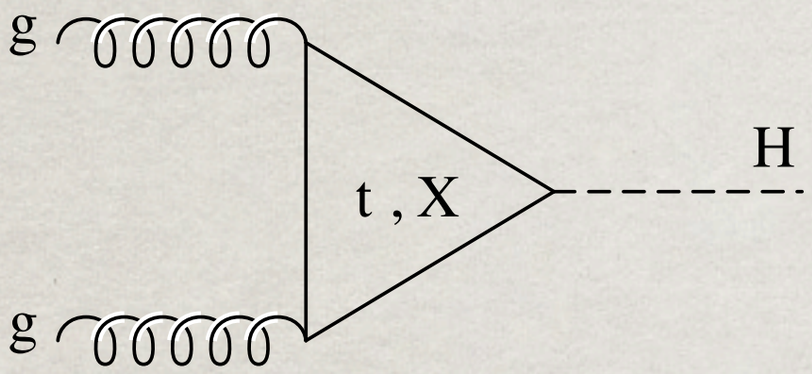
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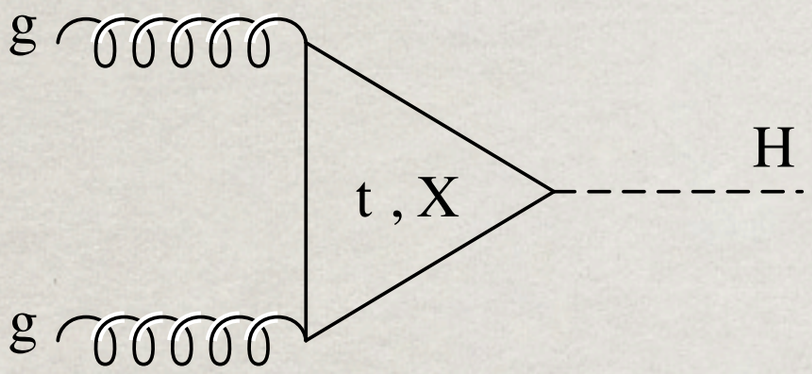
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  gg -> H sensitive to new colored states: Q

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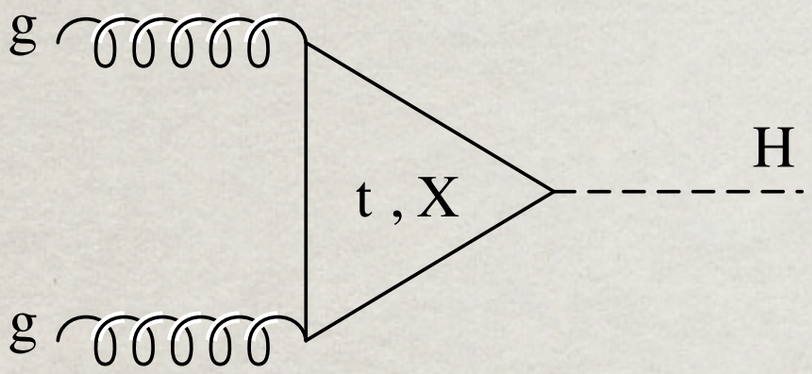
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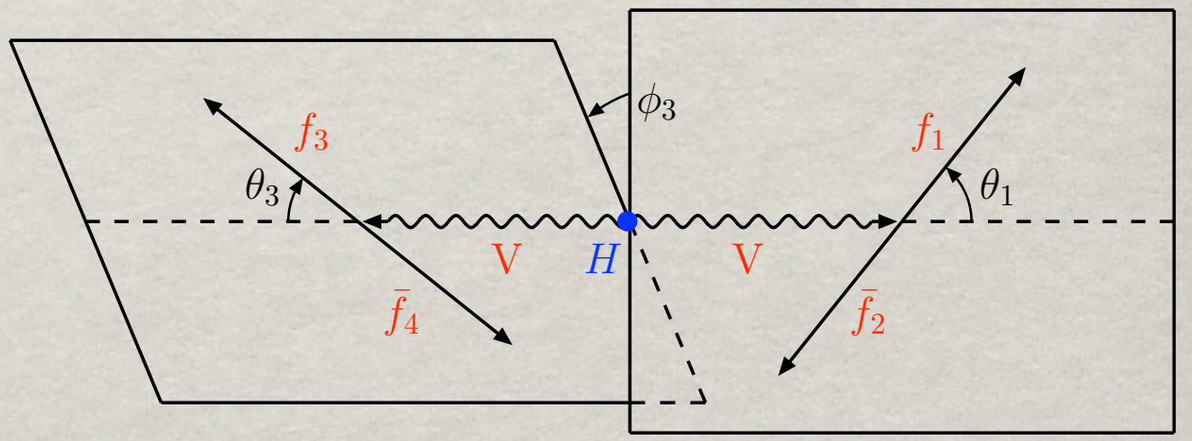
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  H -> γγ sensitive to new charged states: Q, L

  H -> ZZ -> 4 leptons

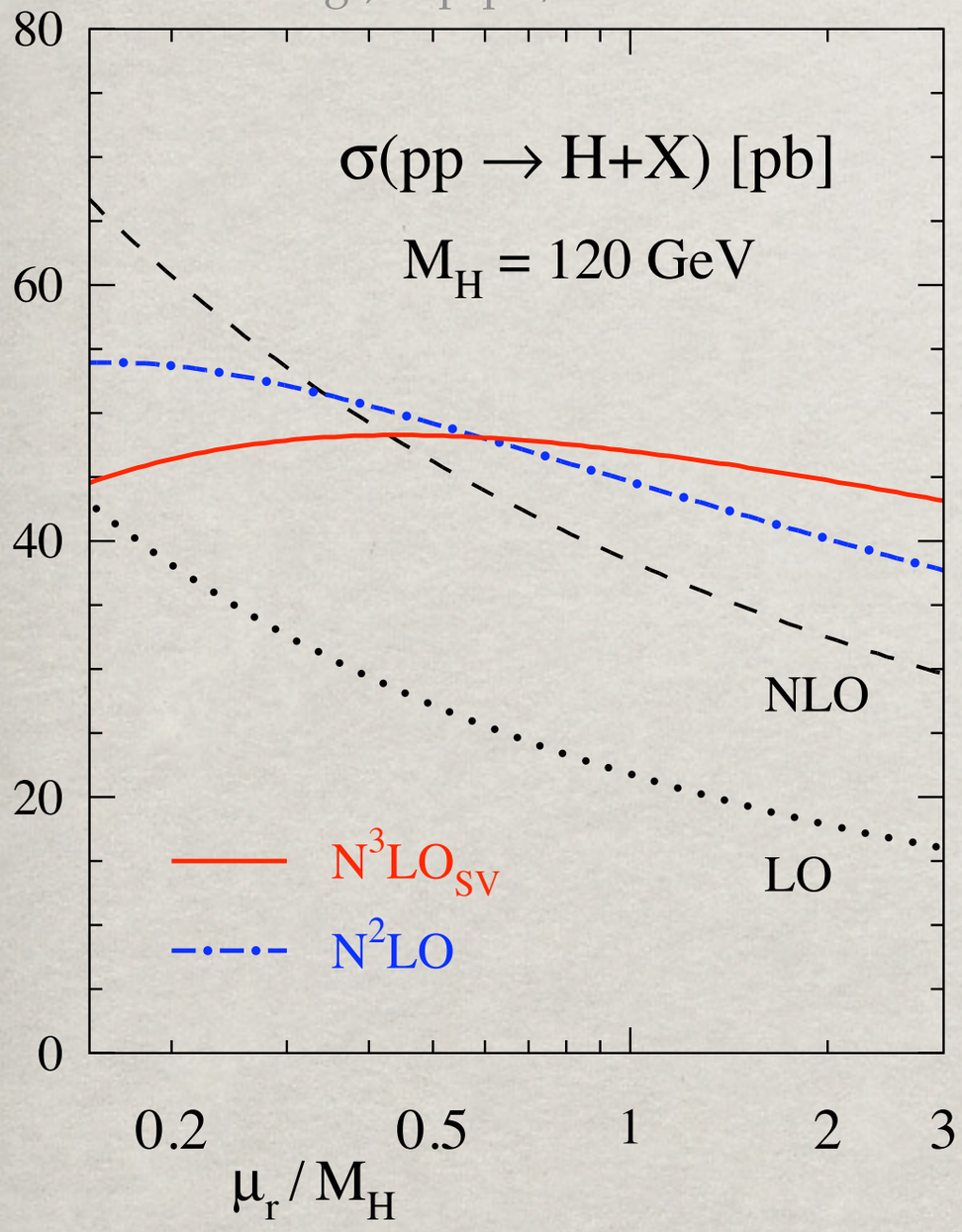
  best to study the Higgs CP properties:



§ L. Reina, TASI lectures, 2011.

QCD corrections to $gg \to H$

Moch & Vogt, hep-ph/0508265

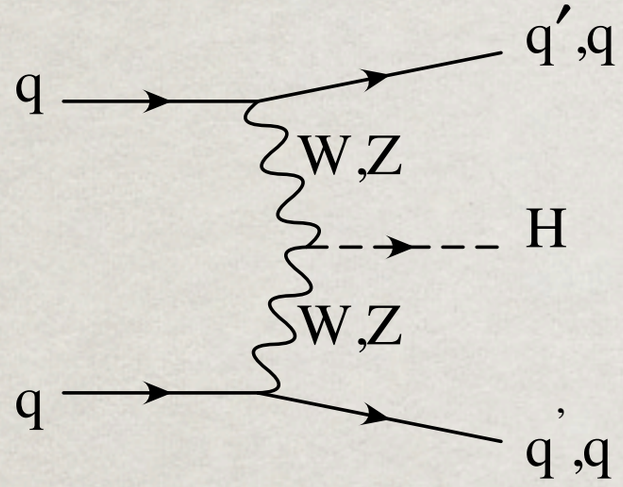


- Large QCD corrections: K-factor of about 2
- Stabilization of scale dependence needs N^3LO or at least NNLO corrections
- Cross section estimate for $m_H = 126$ GeV at 8 TeV from LHC XS WG, determined at NNLL QCD and NLO EW

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

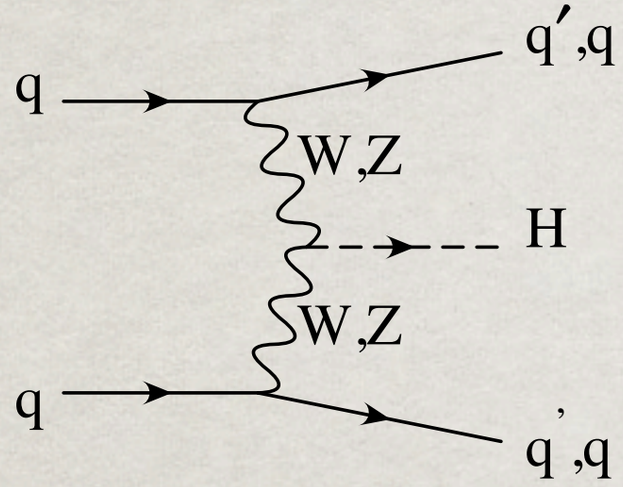
- Error is linear combination of $\approx 7.5\%$ scale uncertainty and $\approx 7.2\%$ from gluon pdf and α_s error
- Additional uncertainty from use of effective hgg vertex (heavy top approximation) is estimated to be below 2%

(b). The Vector Boson Fusion:



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

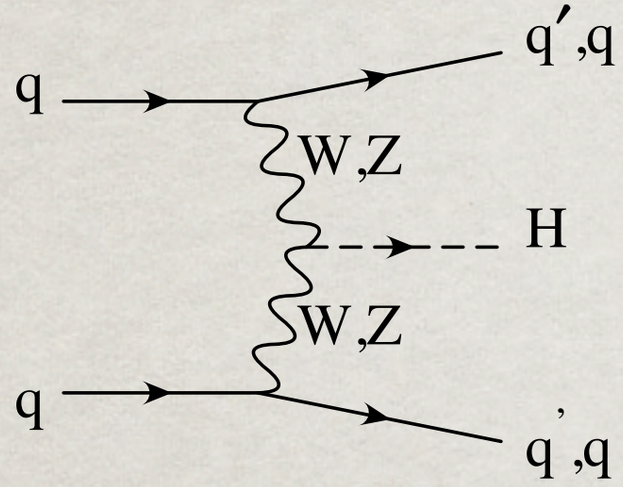
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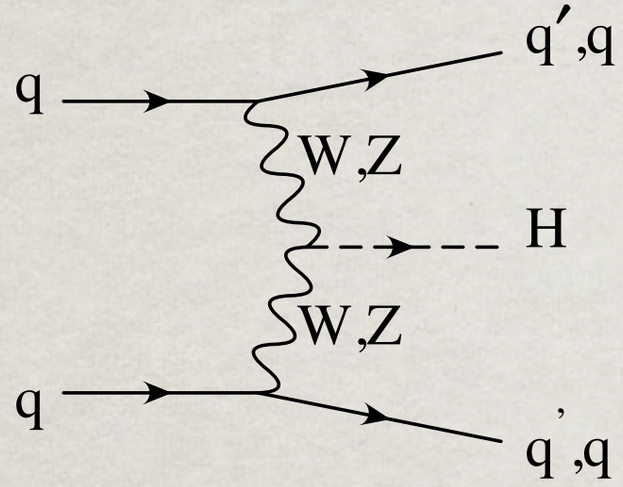
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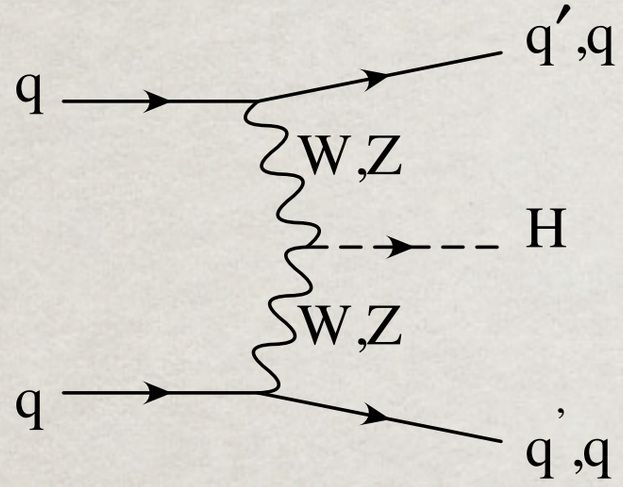
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  -> color singlet exchange, low jet activities.

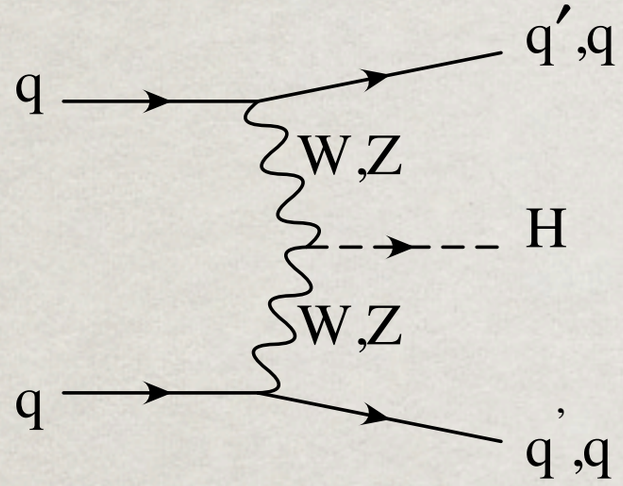
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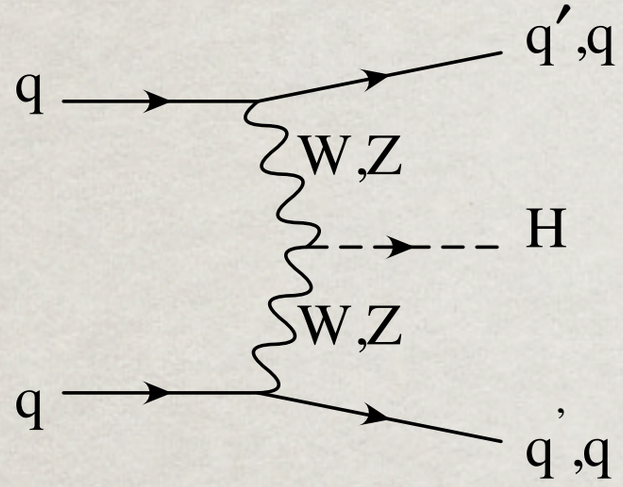
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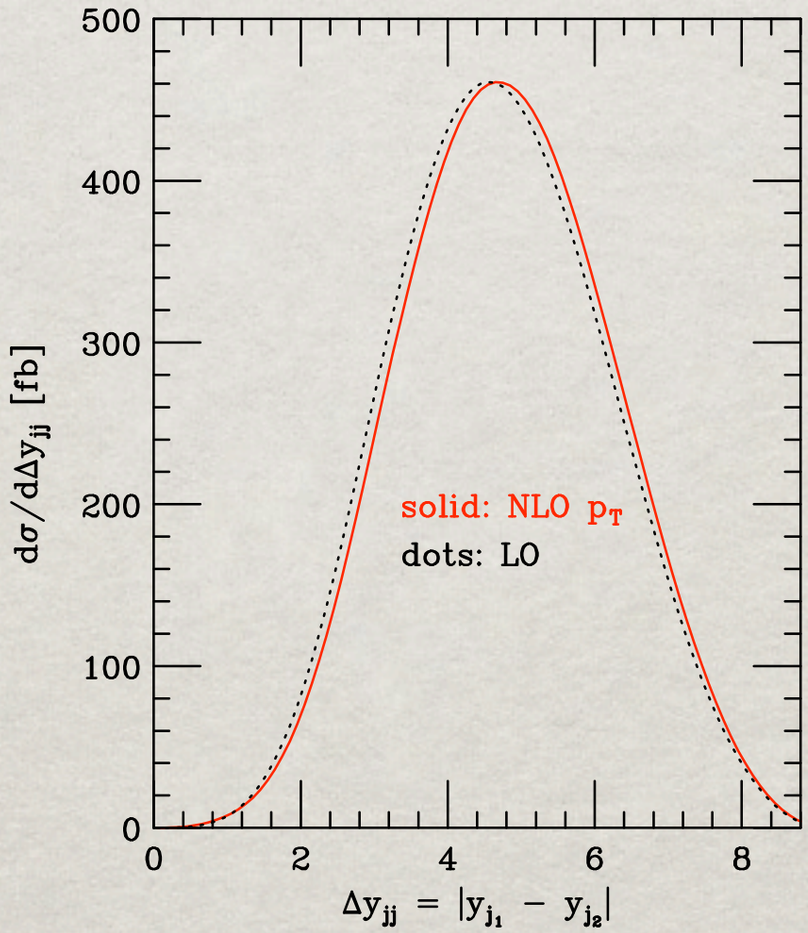
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- A bit lower rate, but unique kinematics

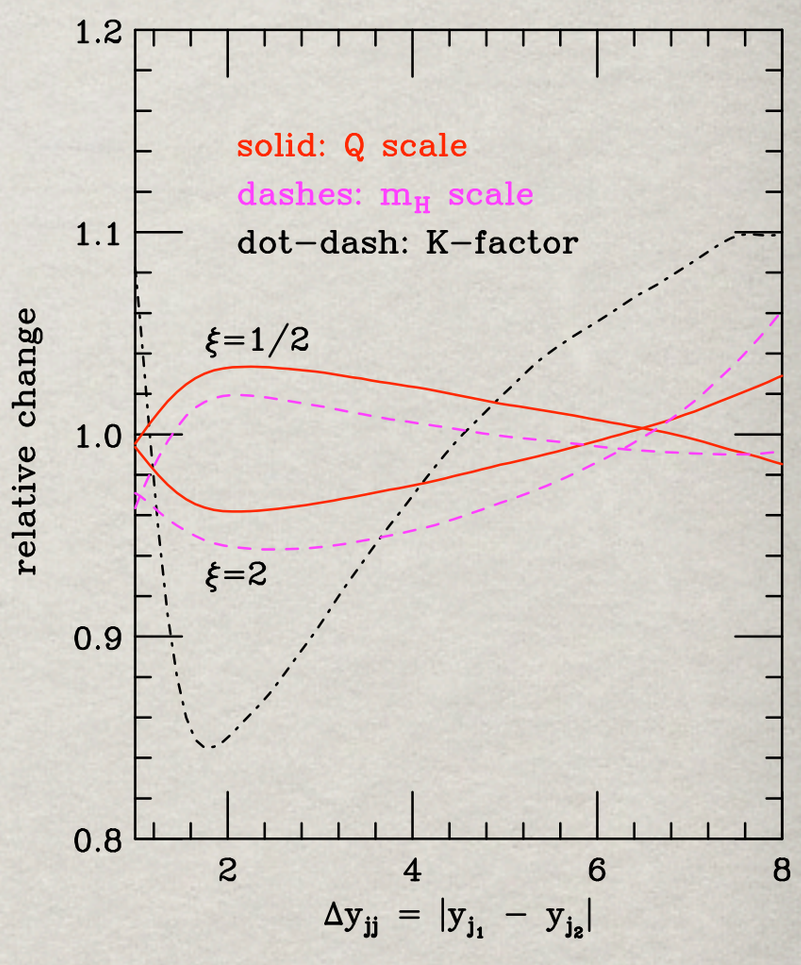
NLO corrections to VBF

- 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

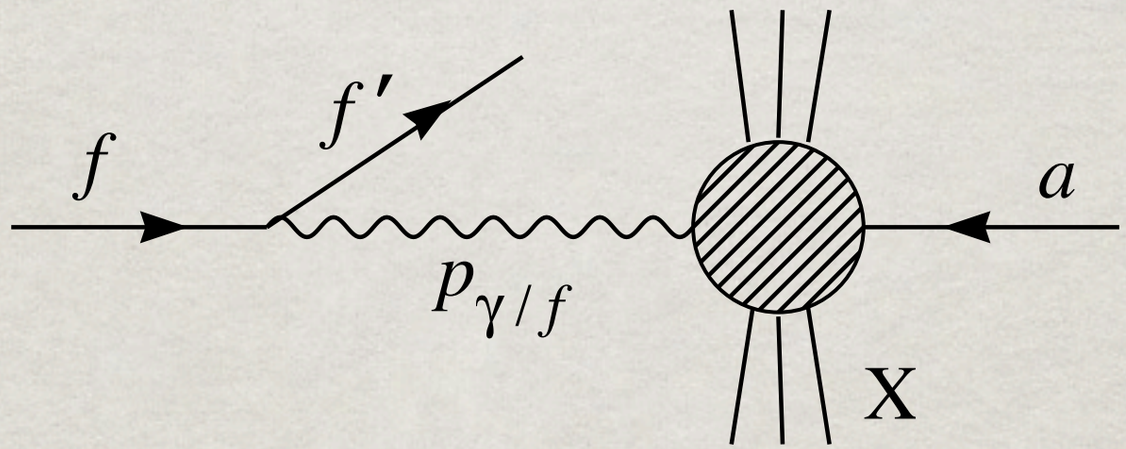




$m_H = 120$ GeV, typical VBF cuts

Basic feature: V radiation off a quark

The familiar Weizsäcker-Williams approximation



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

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

- 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},

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

At high-p_{jT},

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

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

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},

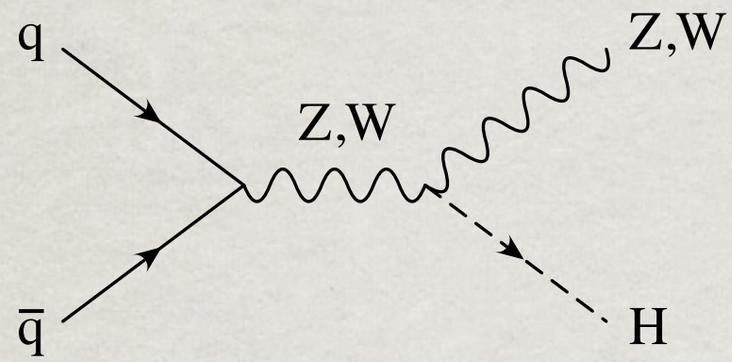
$$\left.\begin{array}{l} p_{jT}^2 \approx (1-x)M_V^2 \\ E_j \sim (1-x)E_q \end{array}\right\} forward\ jet\ tagging$$

At high-p_{jT},

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

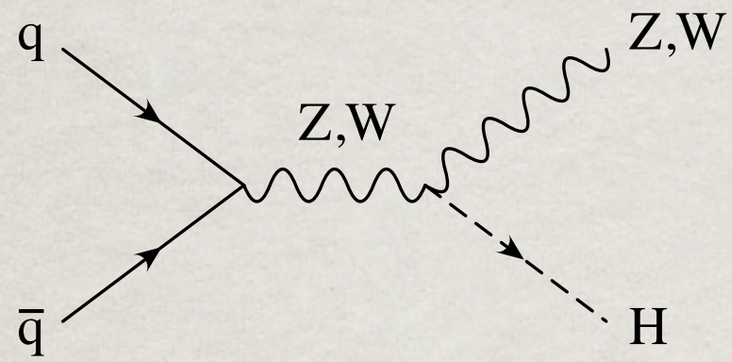
has become important tools for Higgs searches, single-top signal etc.

(c). VH Associate production:



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

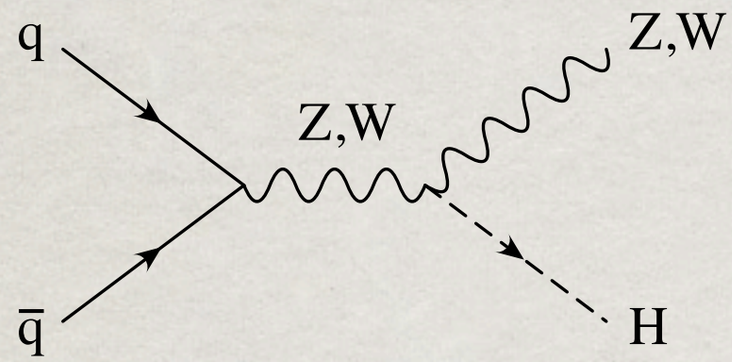
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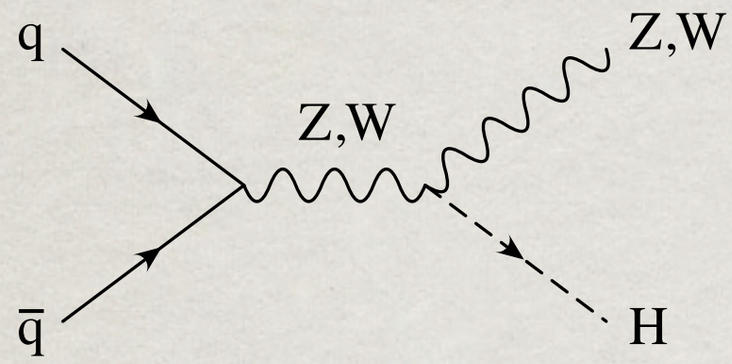
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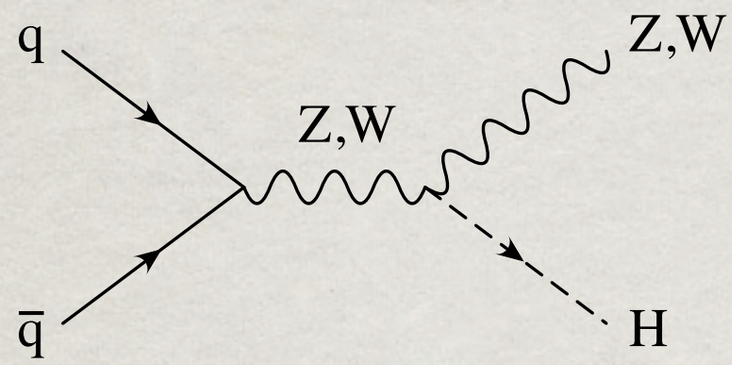
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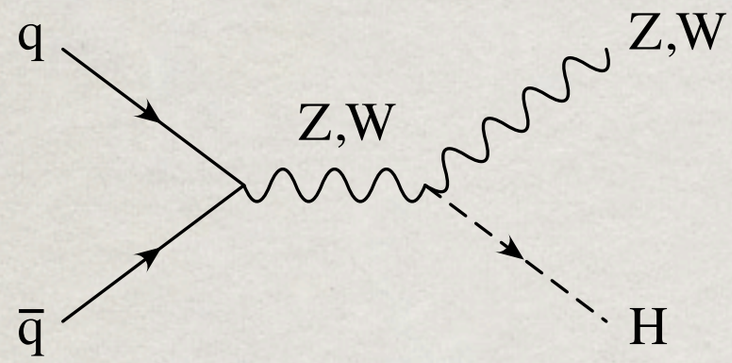
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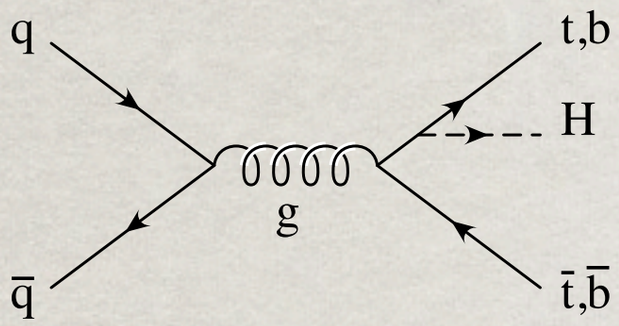
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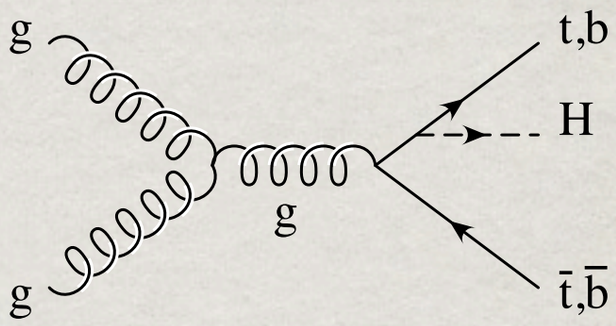


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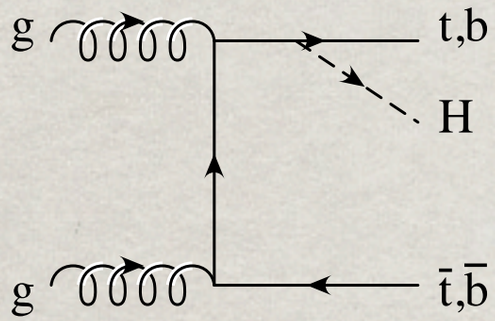
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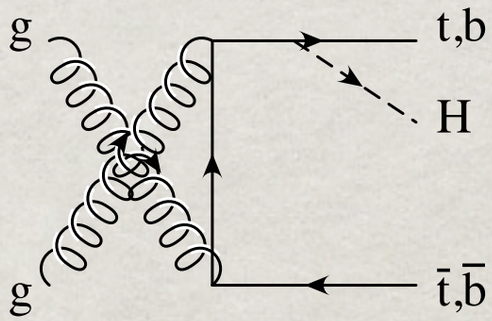
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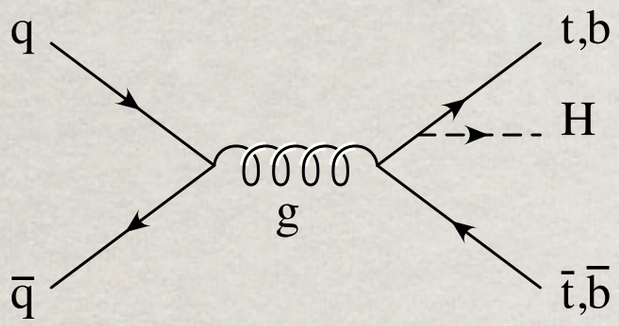


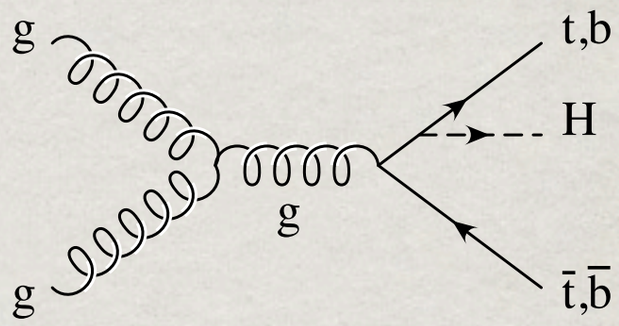
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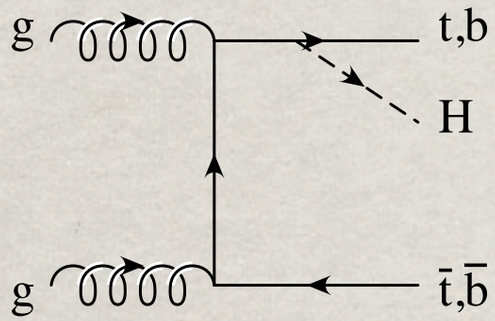


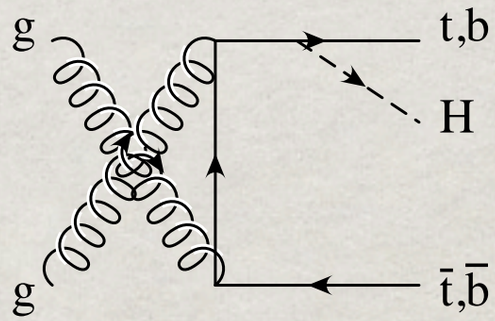


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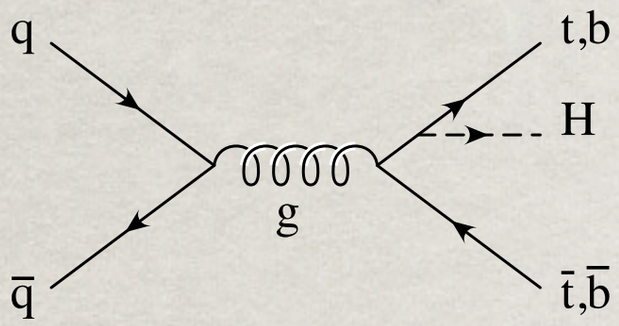


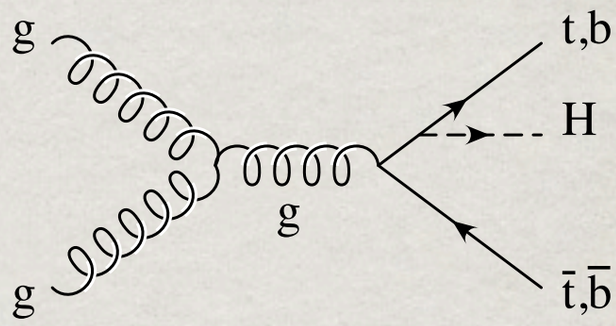


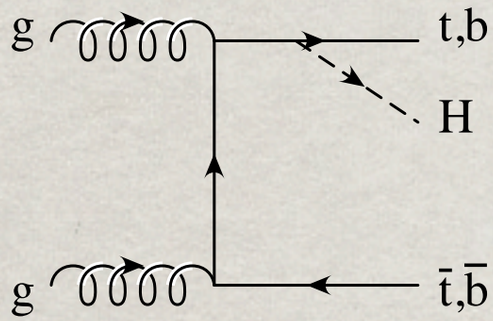
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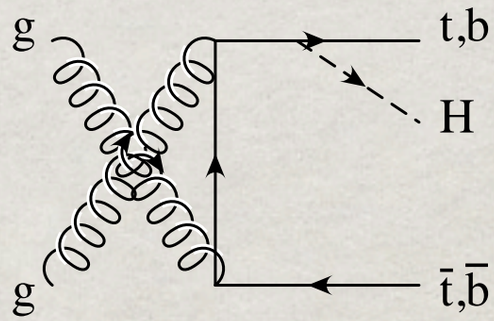
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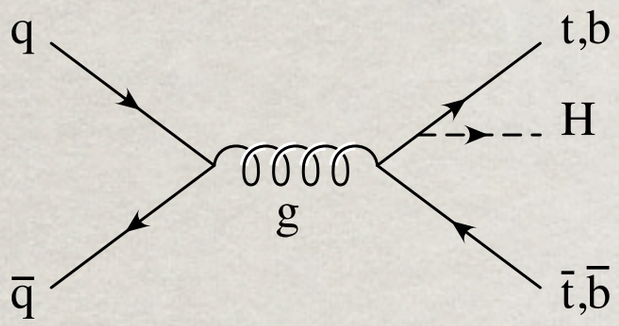


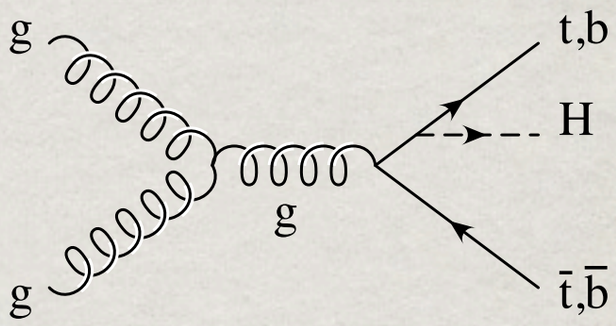


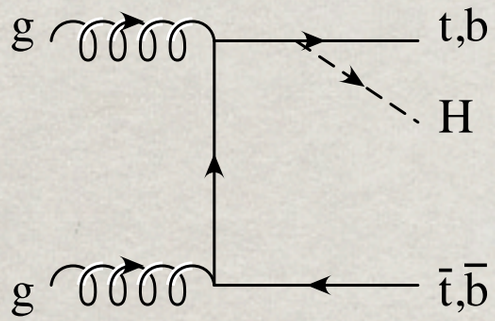
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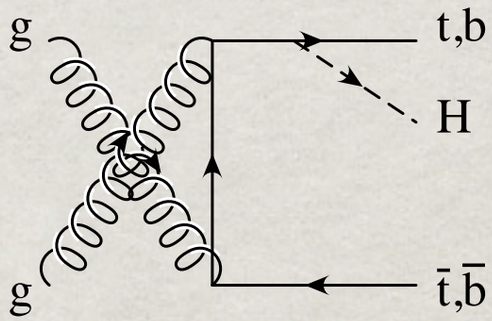
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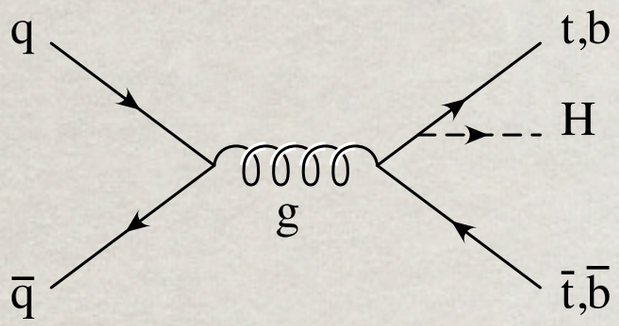


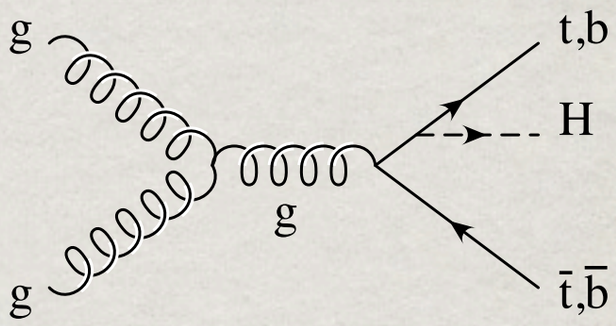


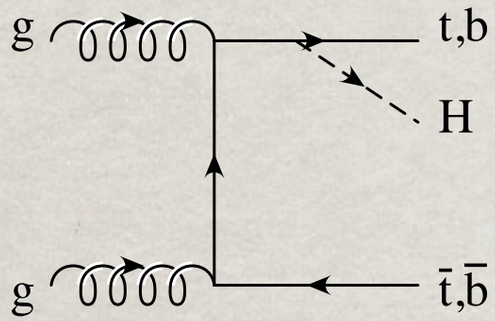
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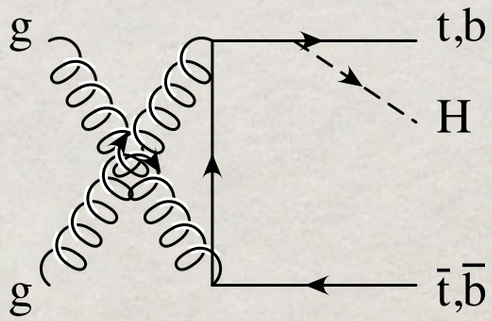
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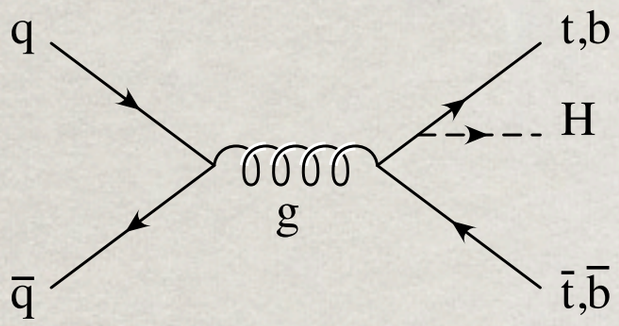


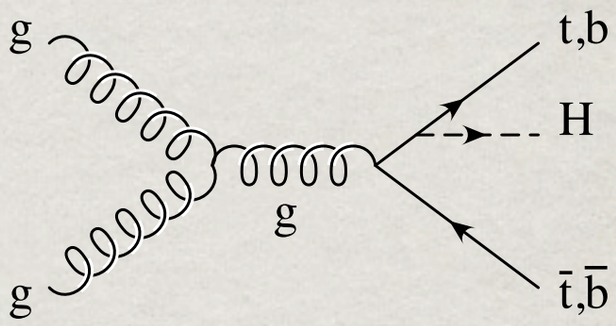


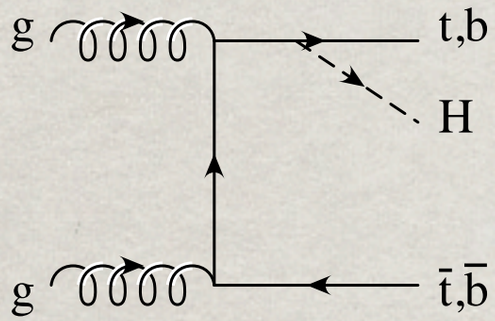
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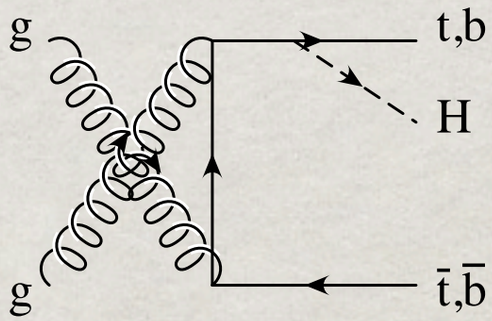
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-- Motive for Physics Beyond SM

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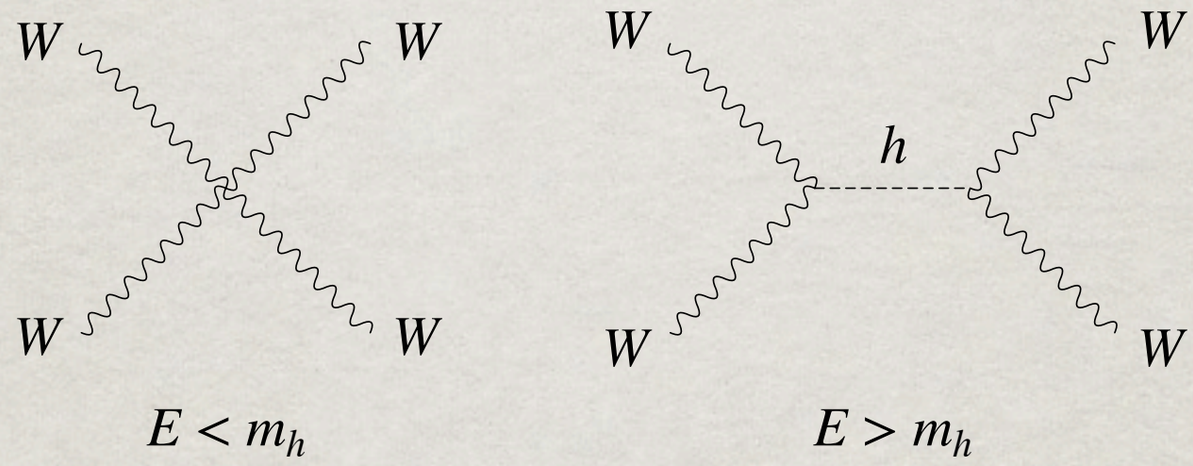
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(fermion masses can be accommodated similarly)

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Consider the massive gauge boson scattering:



$E < m_h$ (a) $E > m_h$ (b)

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

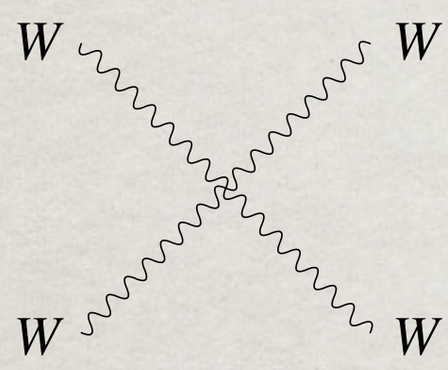
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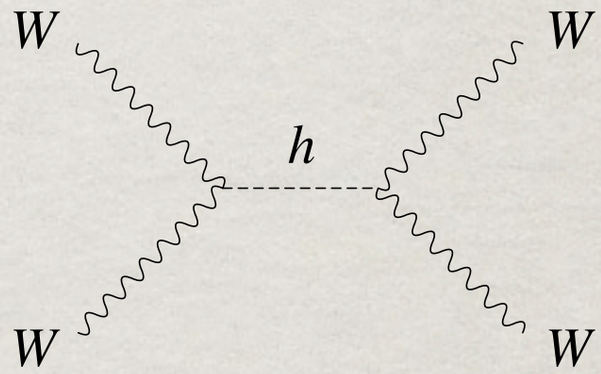
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Exercise 11: Verify this unitarity bound by an explicit partial wave analysis.

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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?
- or dynamically generated by a new strong force?

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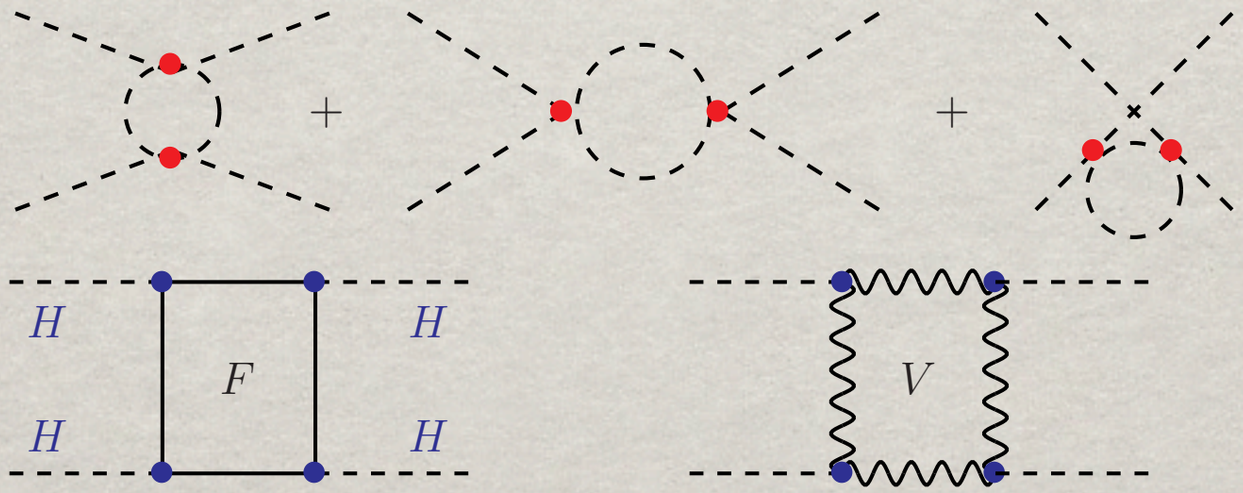
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Renormalization Group Equation Evolution at NLO:

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

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



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

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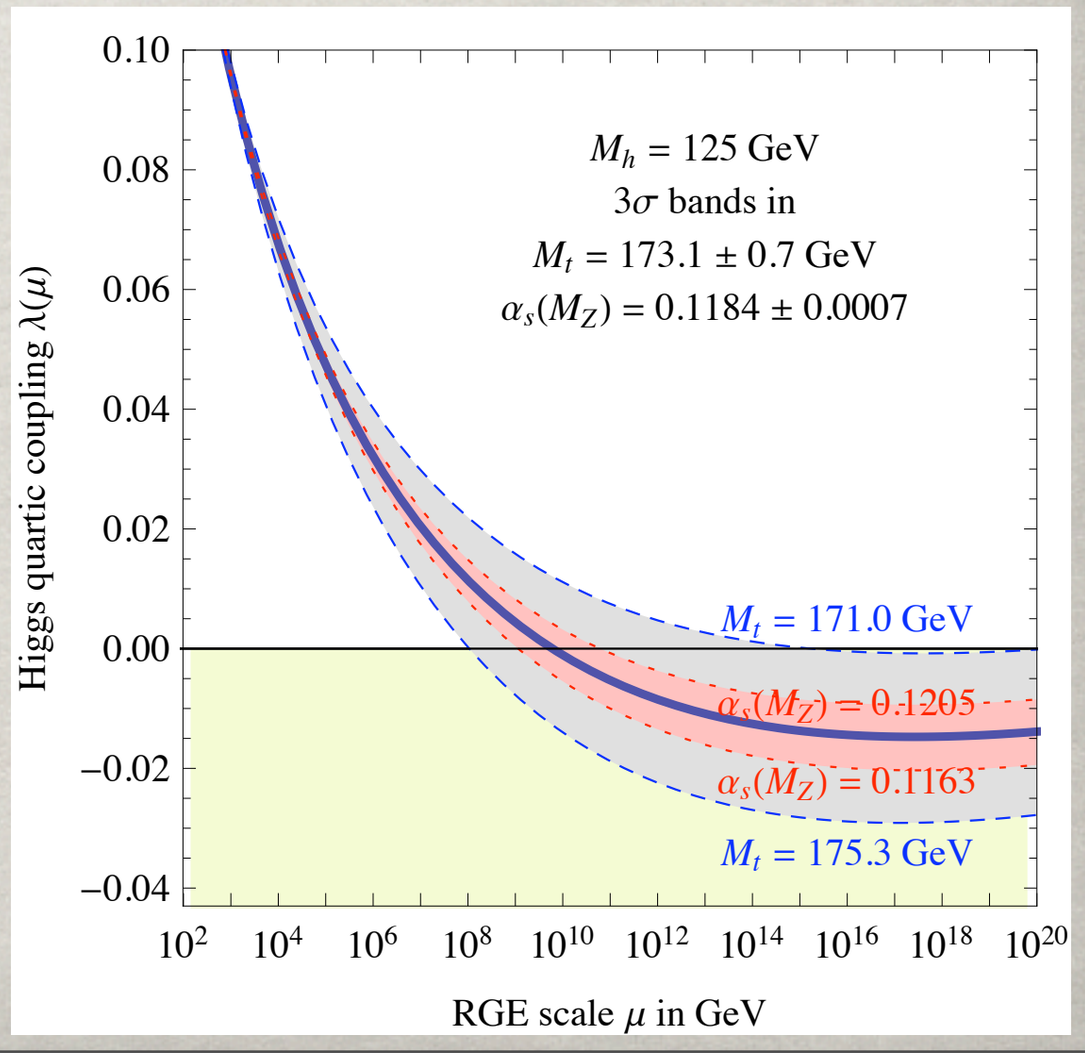
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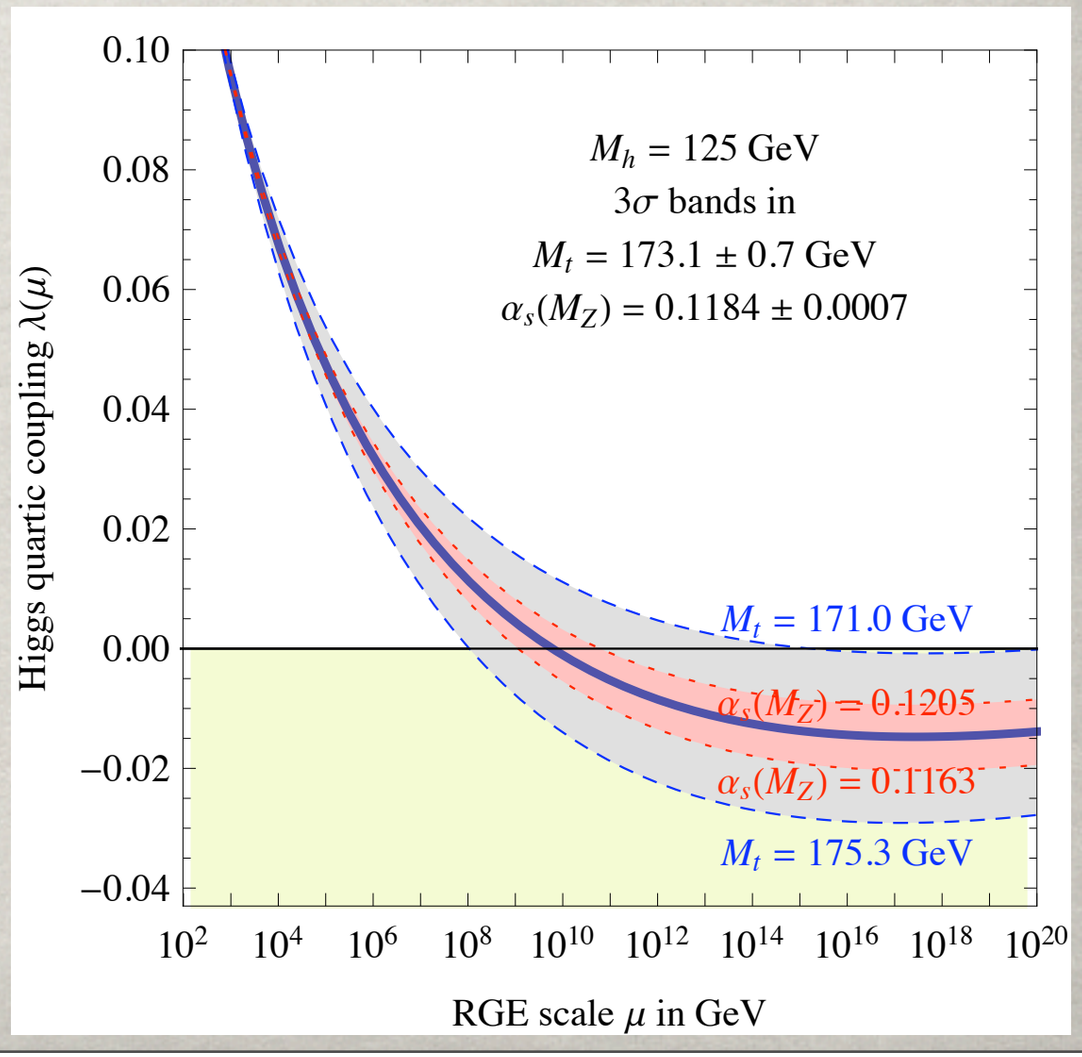
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For M_H = 125 GeV,
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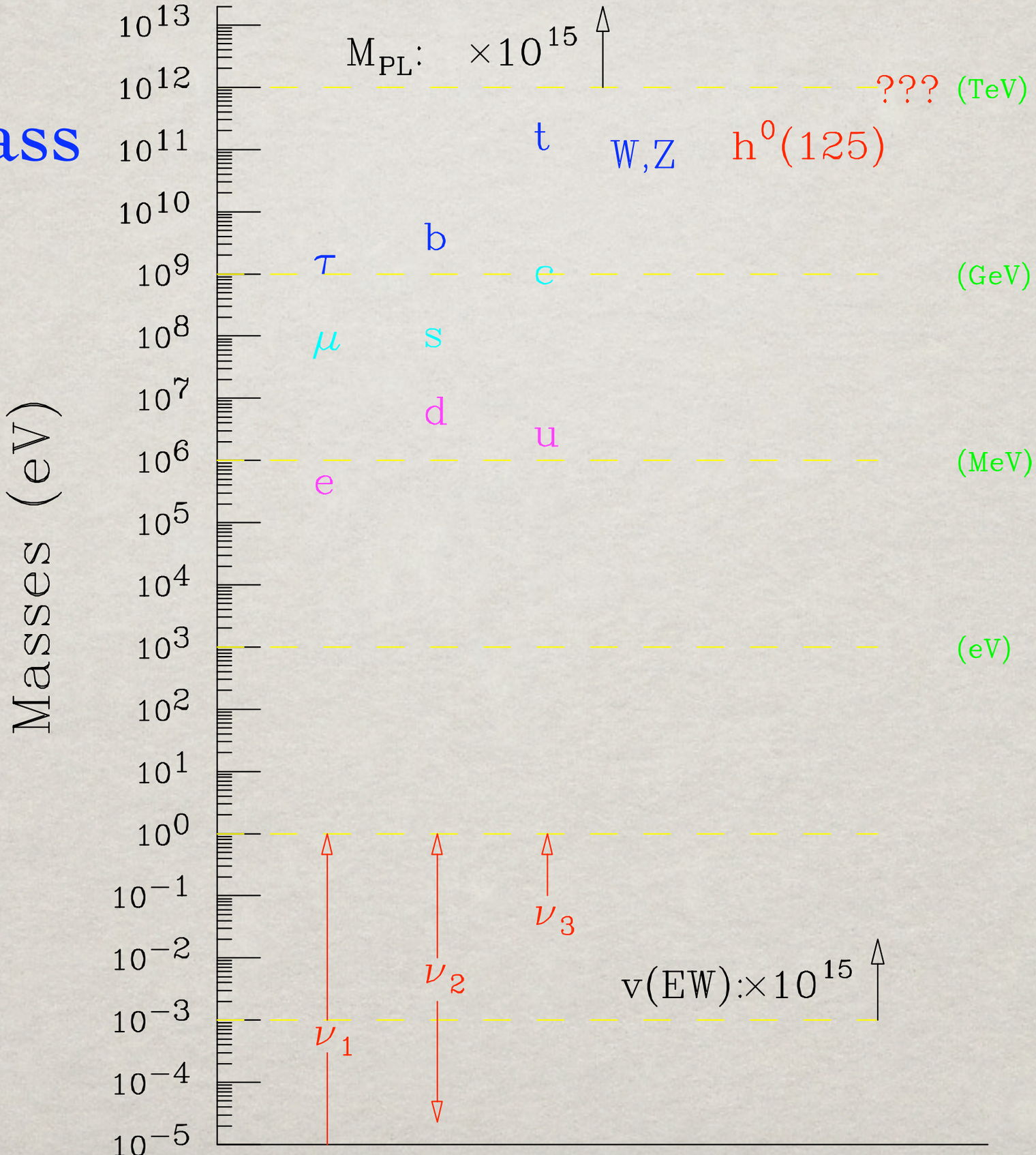
Personal Statement II:

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

However,

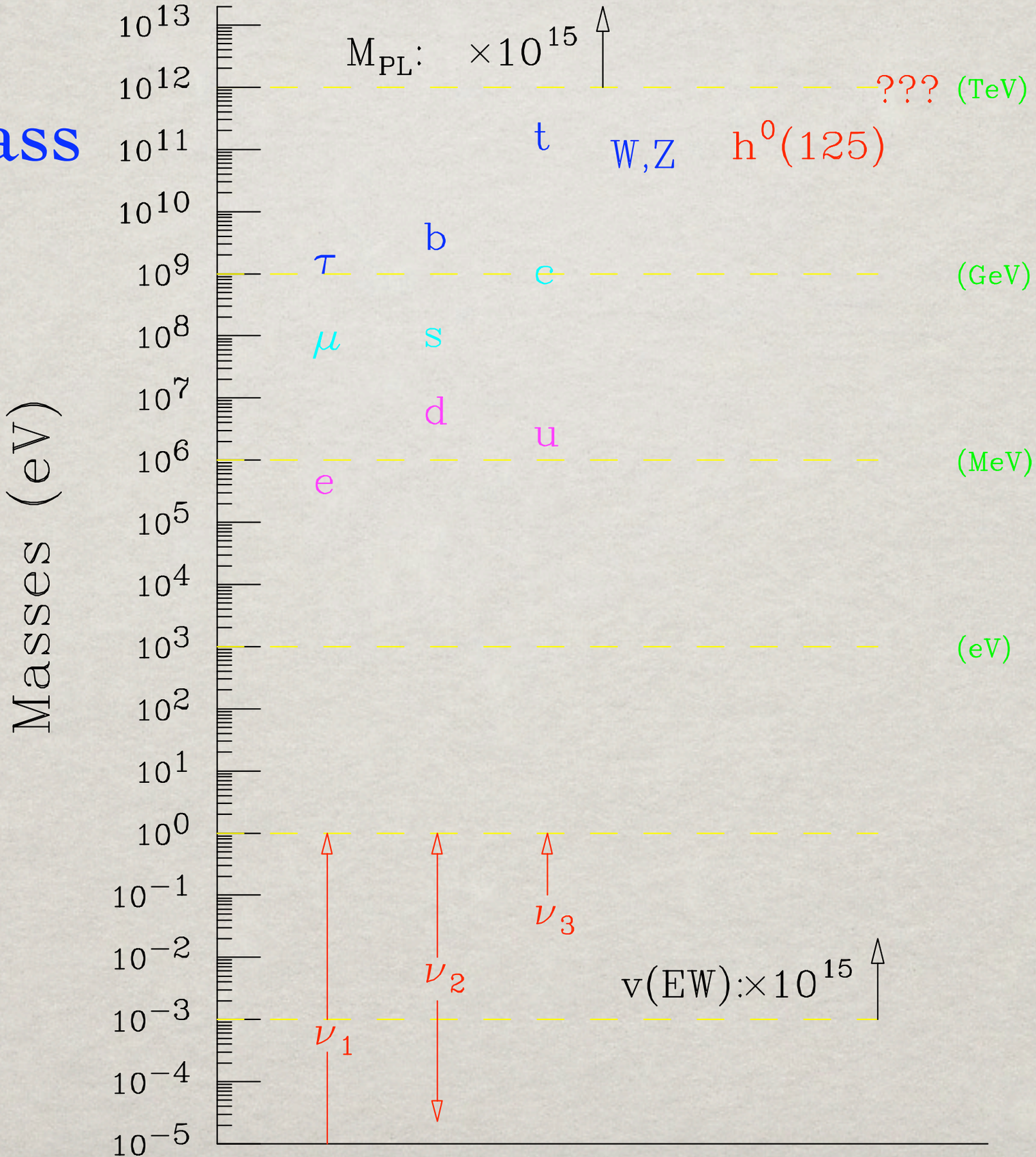
1. the scale maybe too high for LHC physics;
2. a quasi-stable universe would evade a relevant scale.

Particle mass hierarchy:



3. "Naturalness" argument:

Particle mass hierarchy:



Since all the masses are generated like ~ 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 ...

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

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

Dynamical scale generation is natural!

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

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

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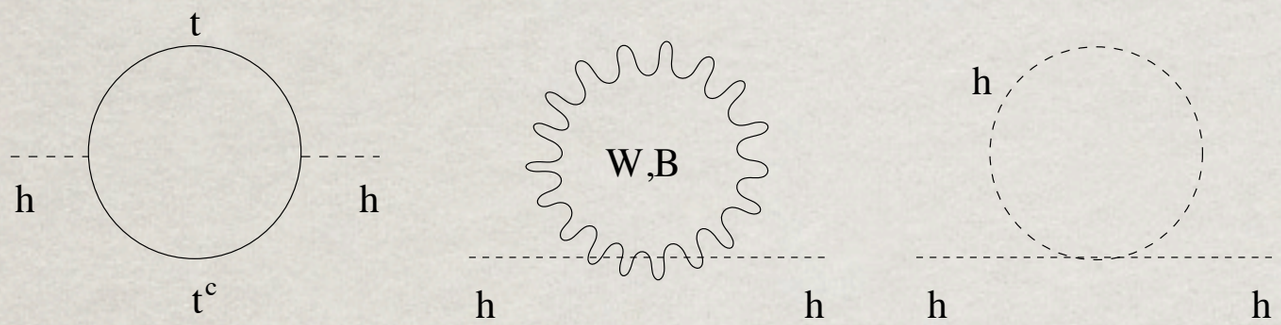
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However, this picture (Technicolor and variations) doesn't work (well) in EW:

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

A light SM-like Higgs unnatural!

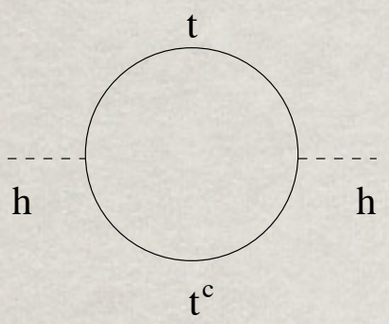
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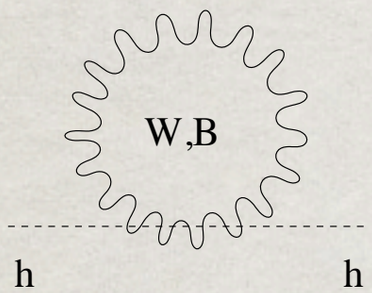
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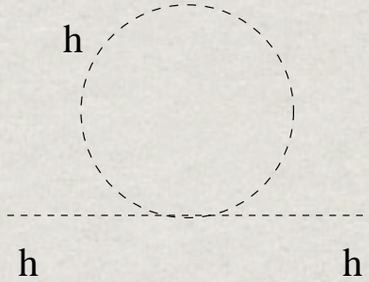
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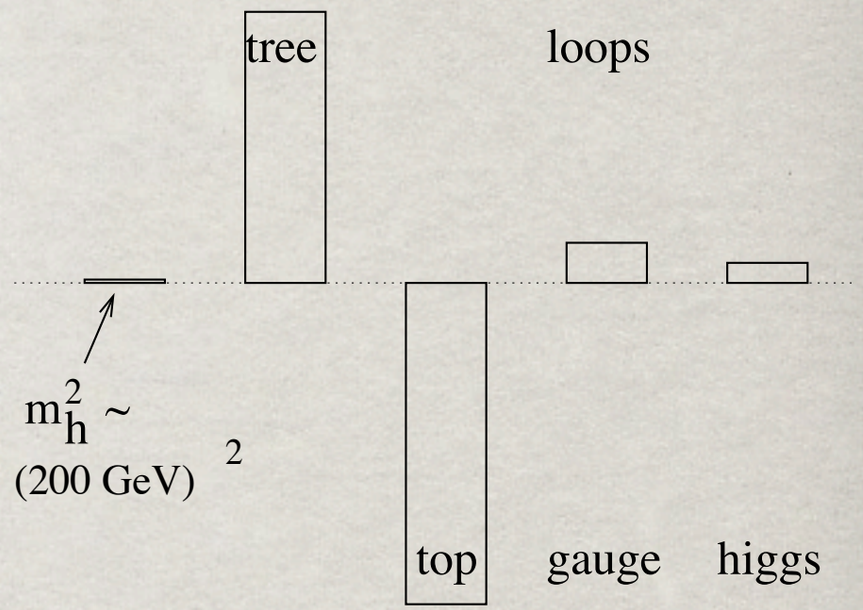
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(b)



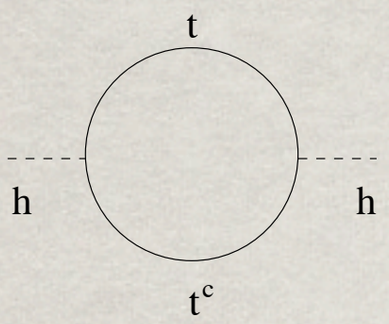
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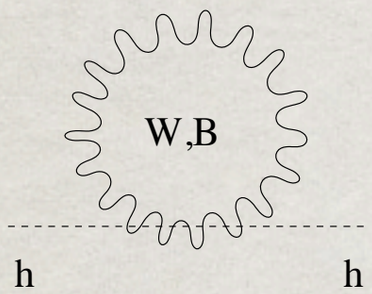
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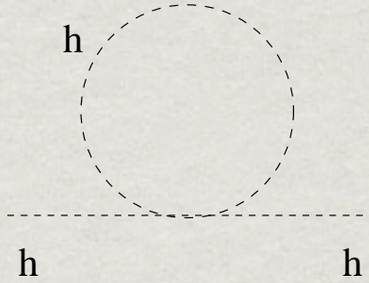
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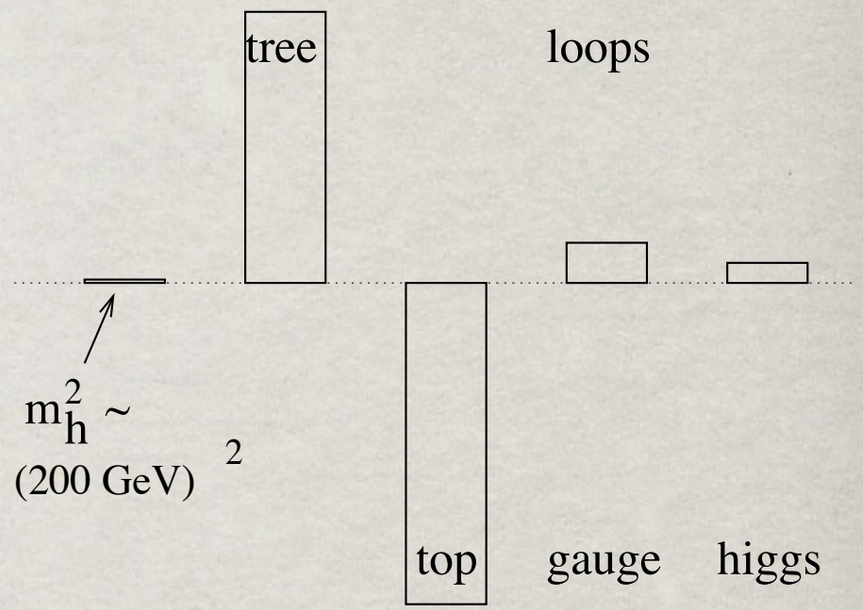
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$$(200\ \text{GeV})^2 = m_{H0}^2 + [-(2\ \text{TeV})^2 + (700\ \text{GeV})^2 + (500\ \text{GeV})^2] \left(\frac{\Lambda_{t,W,H}}{10\ \text{TeV}}\right)^2$$

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)

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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".

C. New Physics Scenarios associated with the Higgs Sector

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§ See, Graham Krib's lectures.

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

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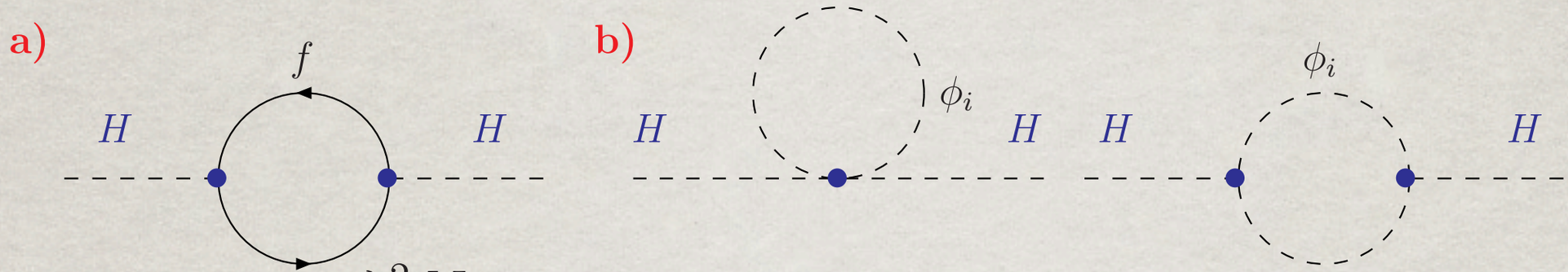
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$\hat{G}_a$	8	1	0	G_a^μ, $\tilde{G}_a$
$\hat{W}_a$	1	3	0	W_a^μ, $\tilde{W}_a$
$\hat{B}$	1	1	0	B^μ, $\tilde{B}$

Superfield	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Particle content
$\hat{Q}$	3	2	$\frac{1}{3}$	(u_L, d_L), $(\tilde{u}_L, \tilde{d}_L)$
$\hat{U}^c$	$\overline{3}$	1	$-\frac{4}{3}$	$\overline{u}_R$, $\tilde{u}_R^*$
$\hat{D}^c$	$\overline{3}$	1	$\frac{2}{3}$	$\overline{d}_R$, $\tilde{d}_R^*$
$\hat{L}$	1	2	-1	(ν_L, e_L), $(\tilde{\nu}_L, \tilde{e}_L)$
$\hat{E}^c$	1	1	2	$\overline{e}_R$, $\tilde{e}_R^*$
$\hat{H}_1$	1	2	-1	$H_1, \tilde{H}_1$
$\hat{H}_2$	1	2	1	$H_2, \tilde{H}_2$



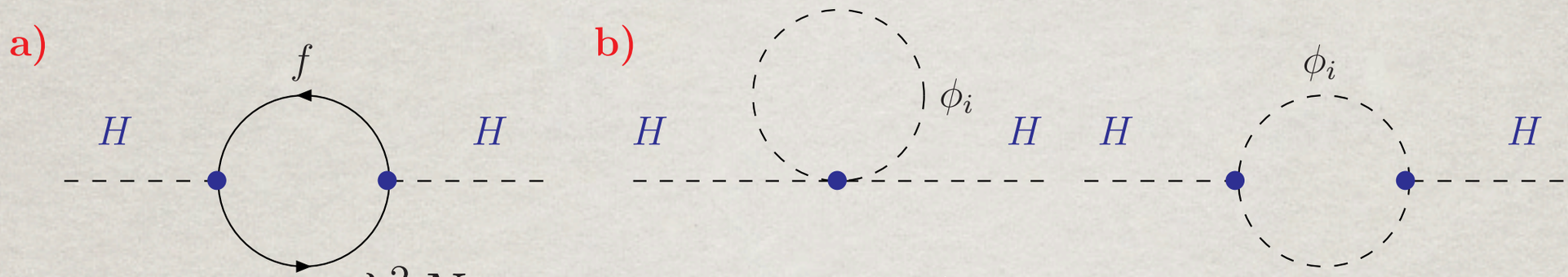
$$\Delta M_H^2 = \frac{\lambda_f^2 N_f}{4\pi^2}\left[(m_f^2 - m_S^2)\log\left(\frac{\Lambda}{m_S}\right) + 3m_f^2\log\left(\frac{m_S}{m_f}\right)\right].$$

- predict TeV scale new physics:
  light Higgs bosons, SUSY partners...
- imply a (possible) grand desert in
  $M_{SUSY} - M_{GUT}$, and unification
- radiative EWSB:

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

- SUSY dark matter with R-parity conservation

Thus the Higgs mass corrections:

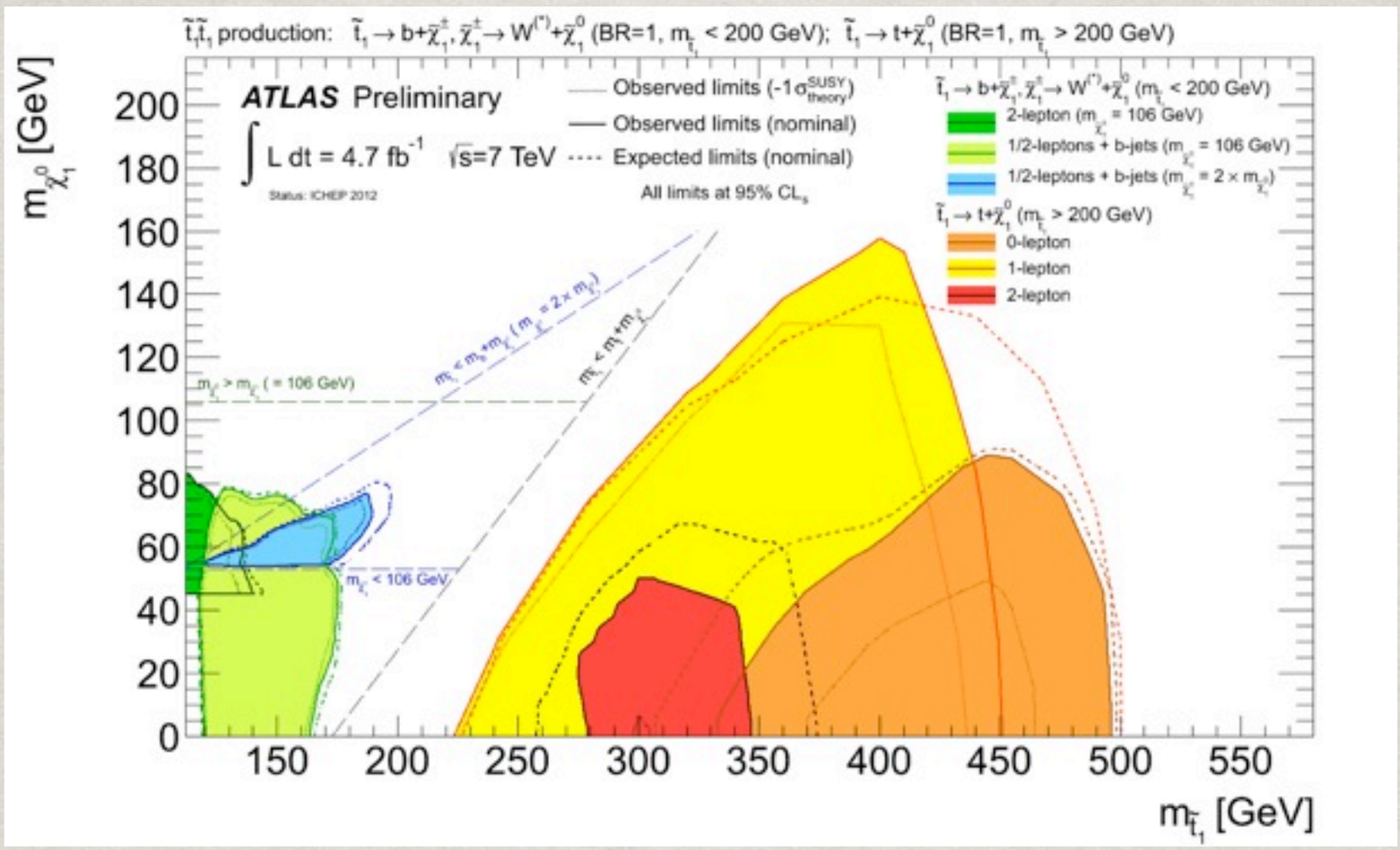


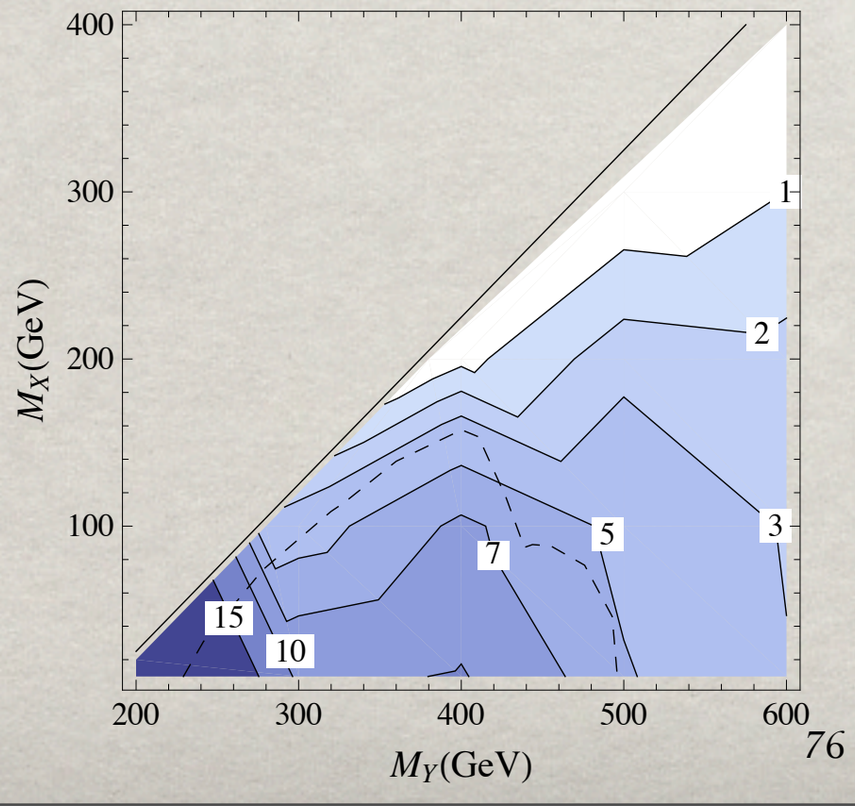
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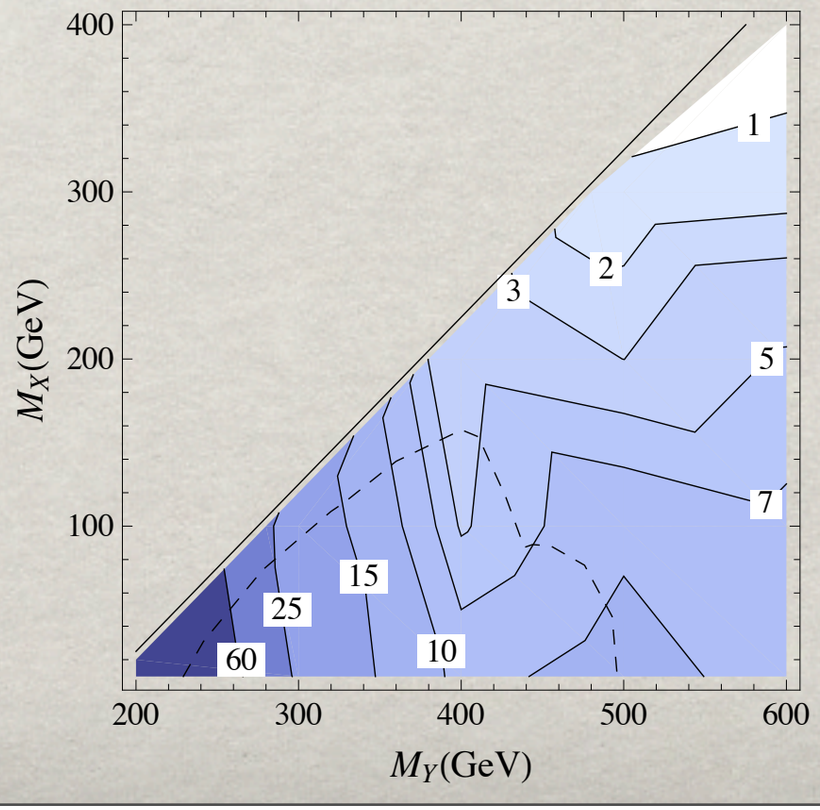
* In SUSY limit, the correction vanishes.
* In soft SUSY breaking case, $m_S \sim$ O(1 TeV).
  - predict TeV scale new physics:
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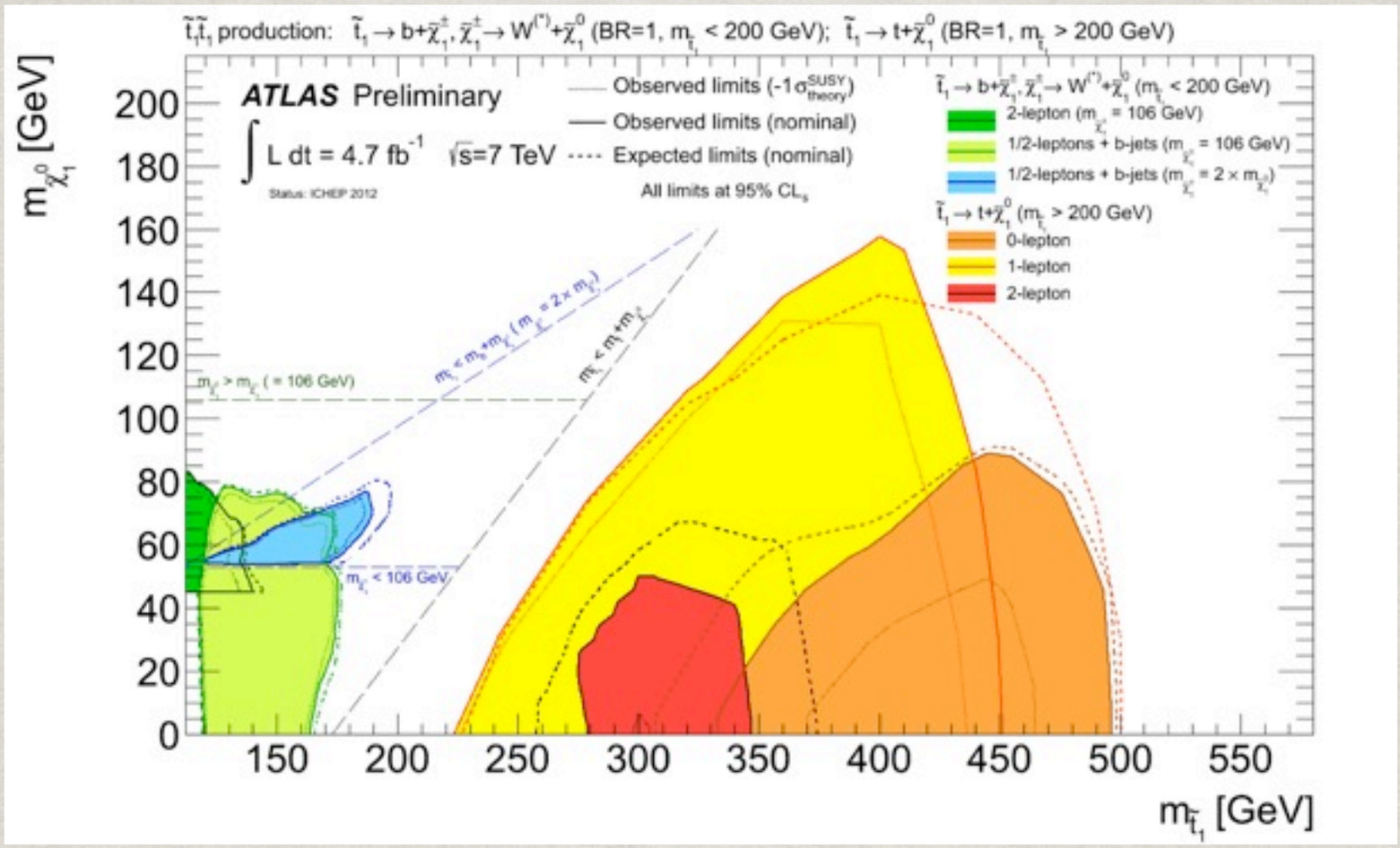
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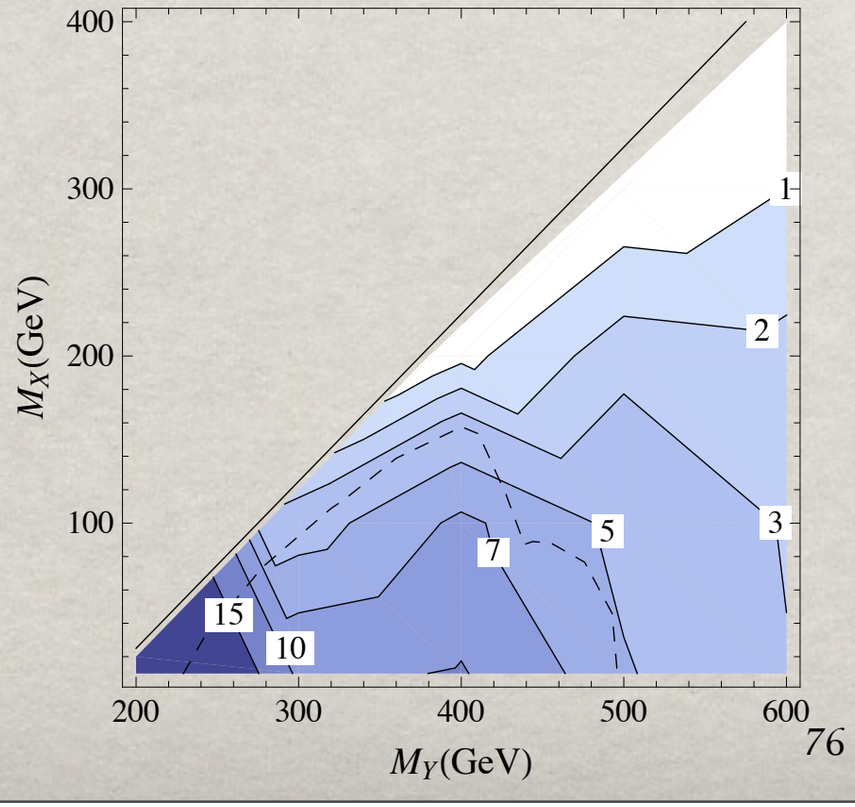

$\tilde{t}_1\tilde{t}_1$ production: $\tilde{t}_1 \to b+\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \to W^{(*)}+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1} < 200$ GeV); $\tilde{t}_1 \to t+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1} > 200$ GeV)
ATLAS Preliminary
$\int L\,dt = 4.7\ fb^{-1}$ $\sqrt{s}$=7 TeV
Status: ICHEP 2012
Observed limits ($-1\sigma^{SUSY}_{theory}$)
Observed limits (nominal)
Expected limits (nominal)
All limits at 95% CL_s
$\tilde{t}_1 \to b+\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \to W^{(*)}+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1} < 200$ GeV)
2-lepton ($m_{\tilde{\chi}_1^0}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^0}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^0} = 2 \times m_{\tilde{\chi}_1^{\pm}}$)
$\tilde{t}_1 \to t+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1} > 200$ GeV)
0-lepton
1-lepton
2-lepton
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^{\pm}}$ (= 106 GeV)
$m_{\tilde{t}_1} < m_b + m_{\tilde{\chi}_1^{\pm}}$ ($m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$)
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^{\pm}} < 106$ GeV
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]

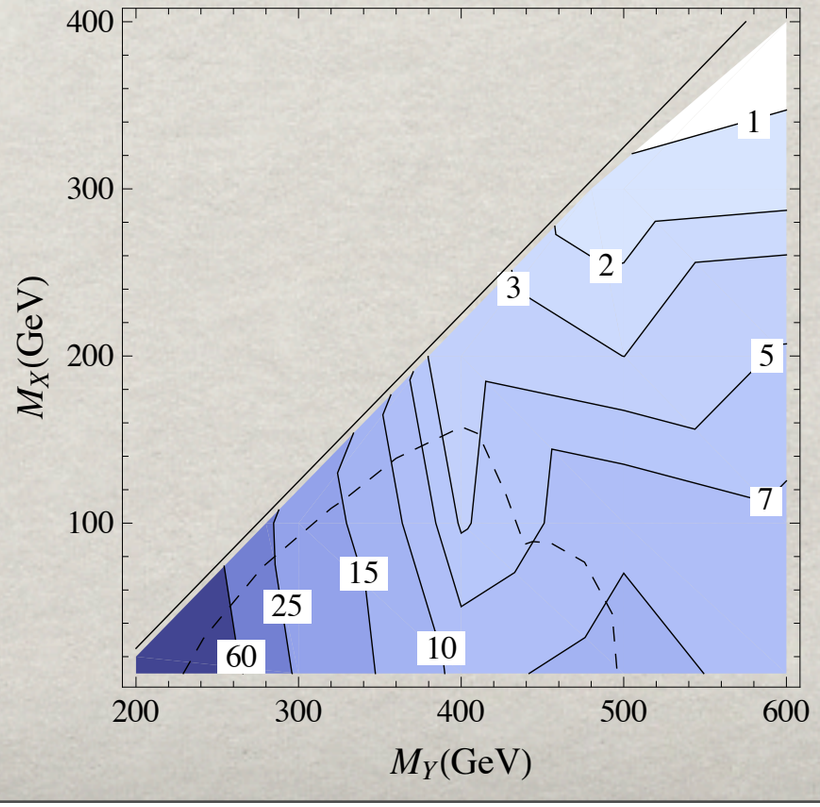

M_X(GeV)
M_Y(GeV)
1
2
3
5
7
10
15


M_X(GeV)
M_Y(GeV)
1
2
3
5
7
10
15
25
60

Thus, top-partner is most likely suspect!







2. Two Higgs Doublets in the MSSM

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

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

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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:

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

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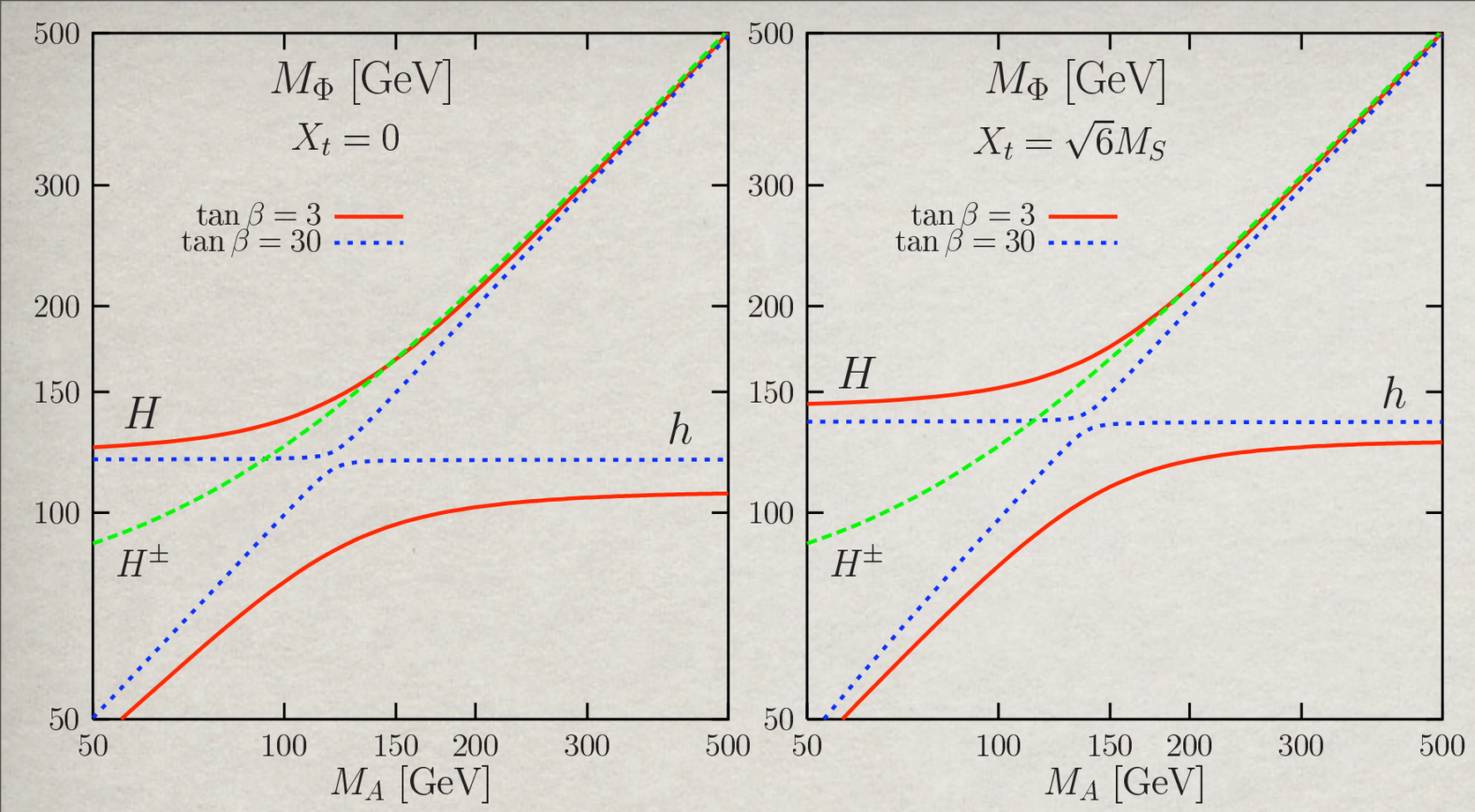
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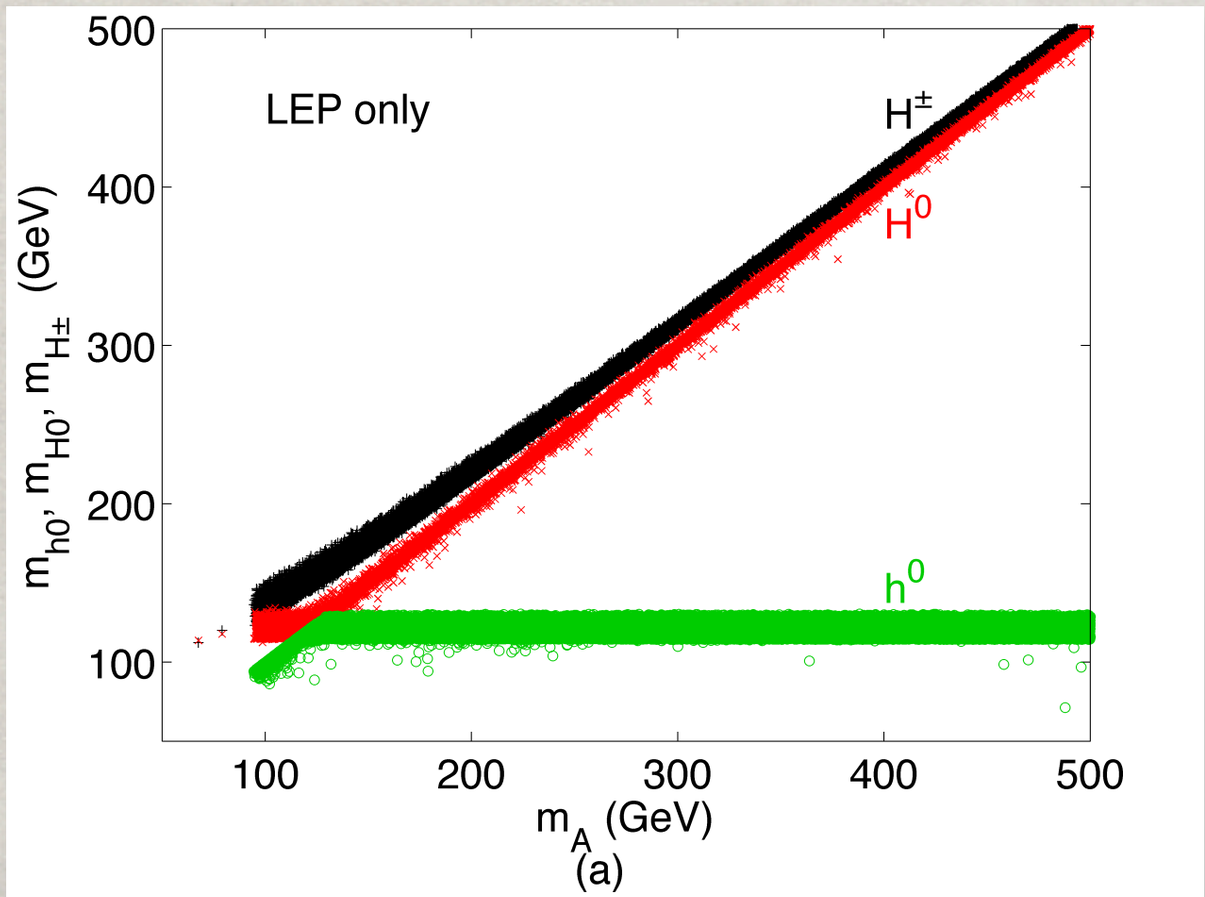
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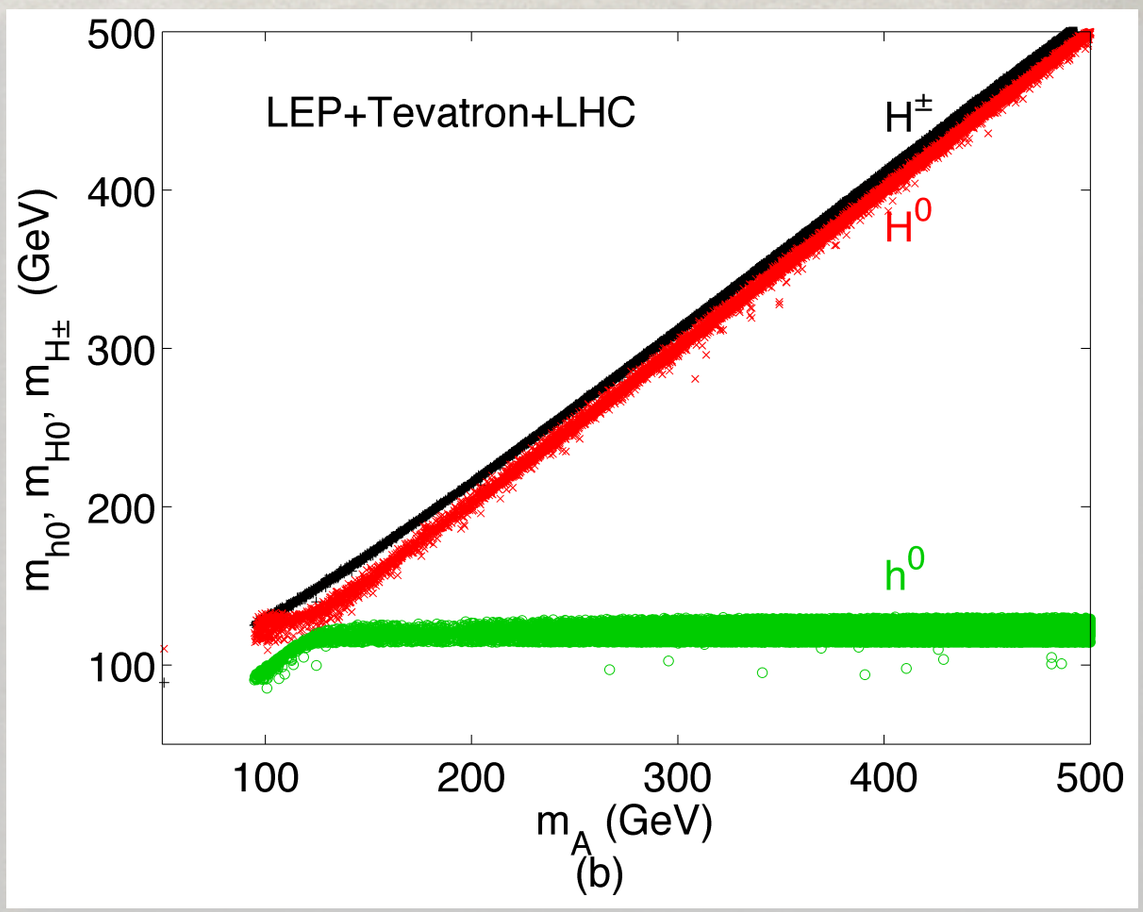
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can be as large as 50%!

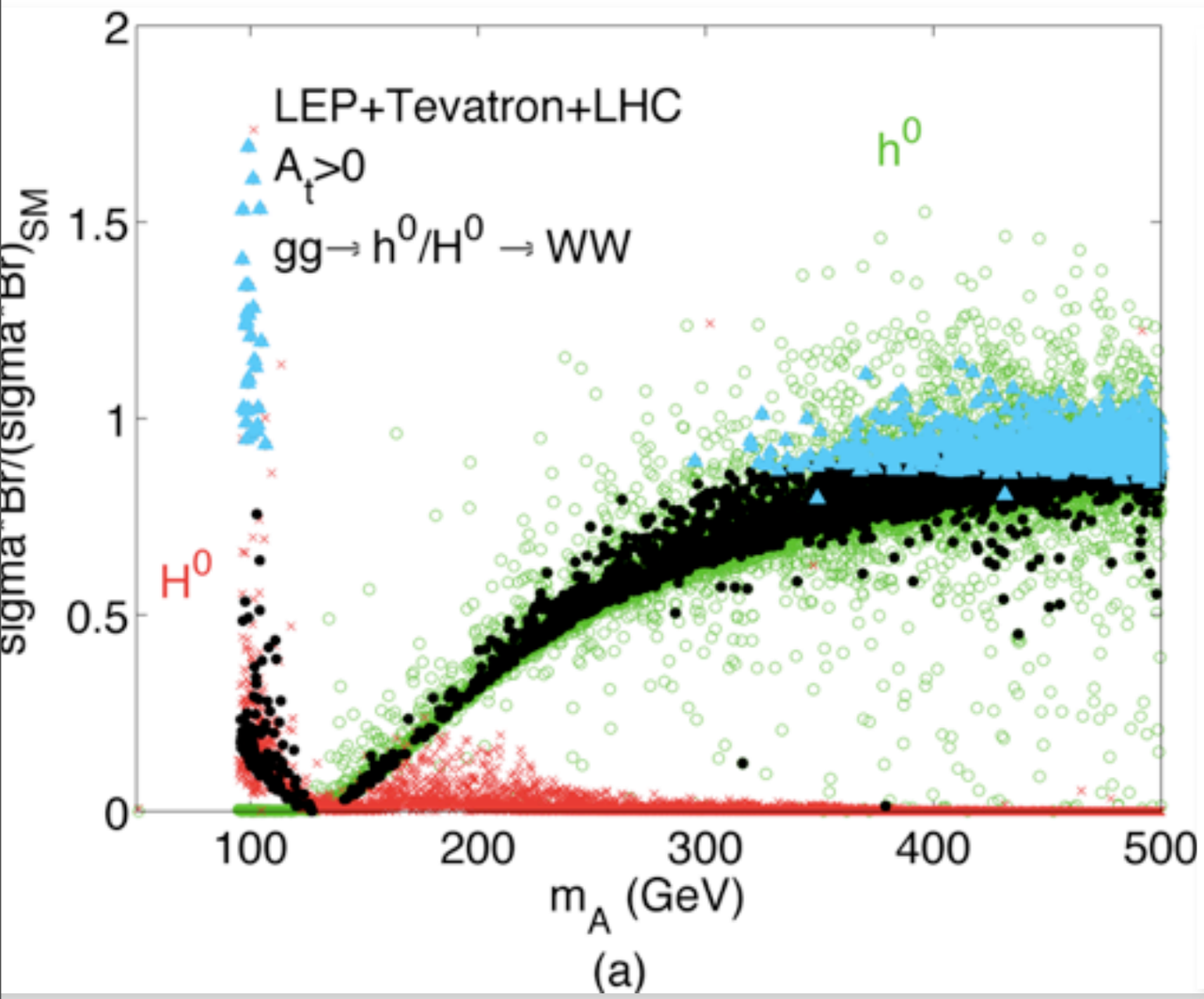


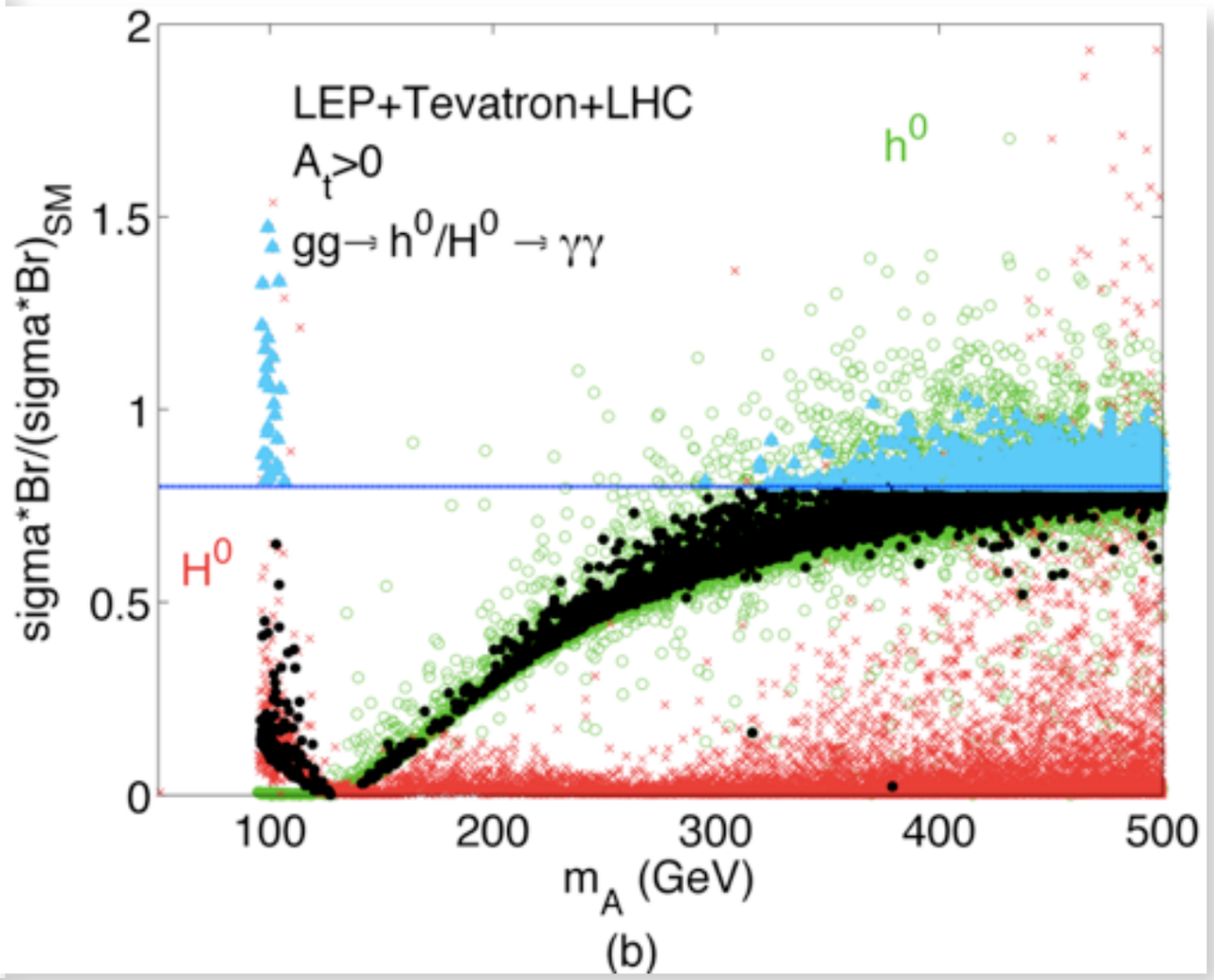
- Updated results: arXive:1203.3207





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





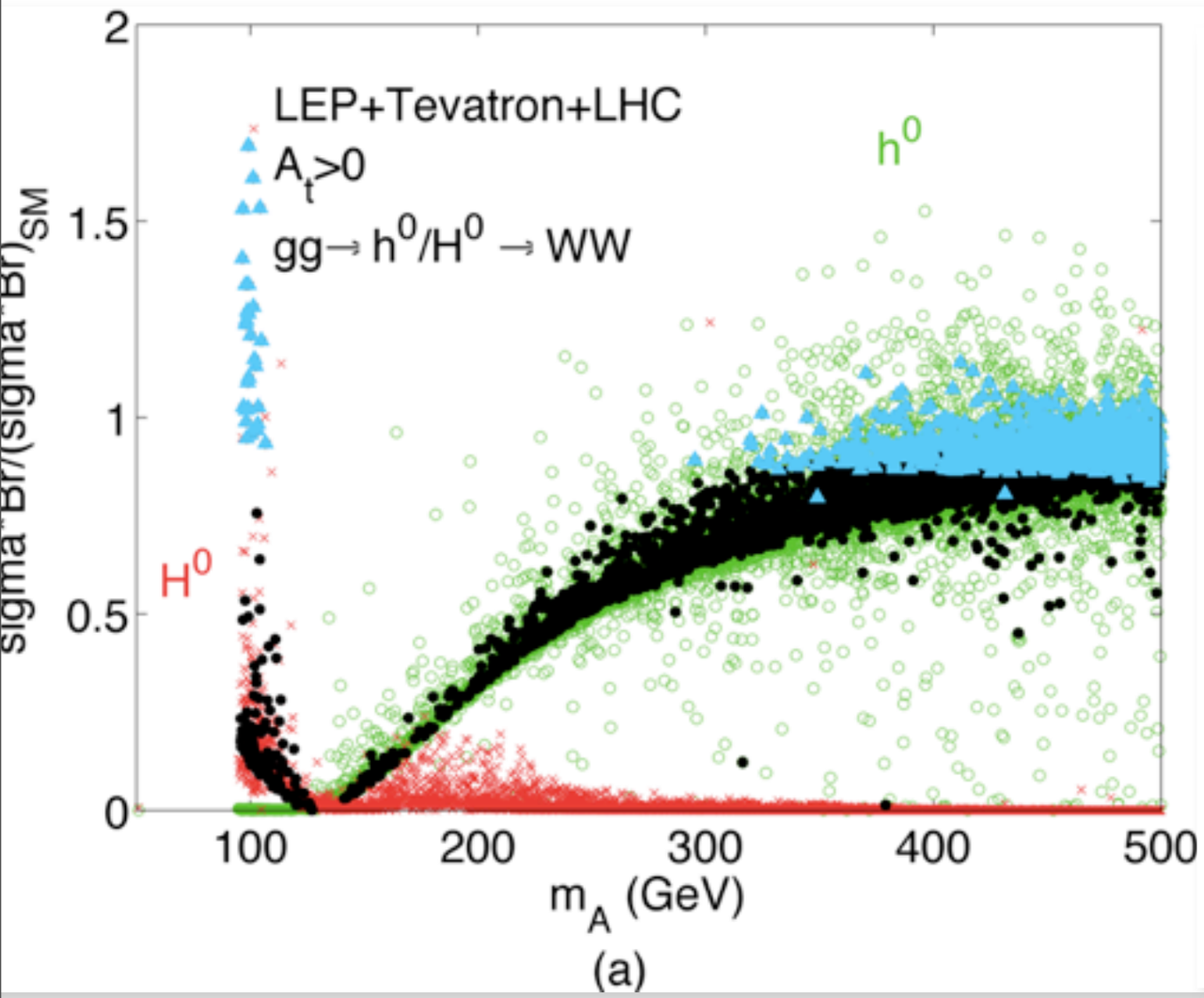
black dots: $123 < m_{h0}$ or $m_{H0} < 127$ GeV

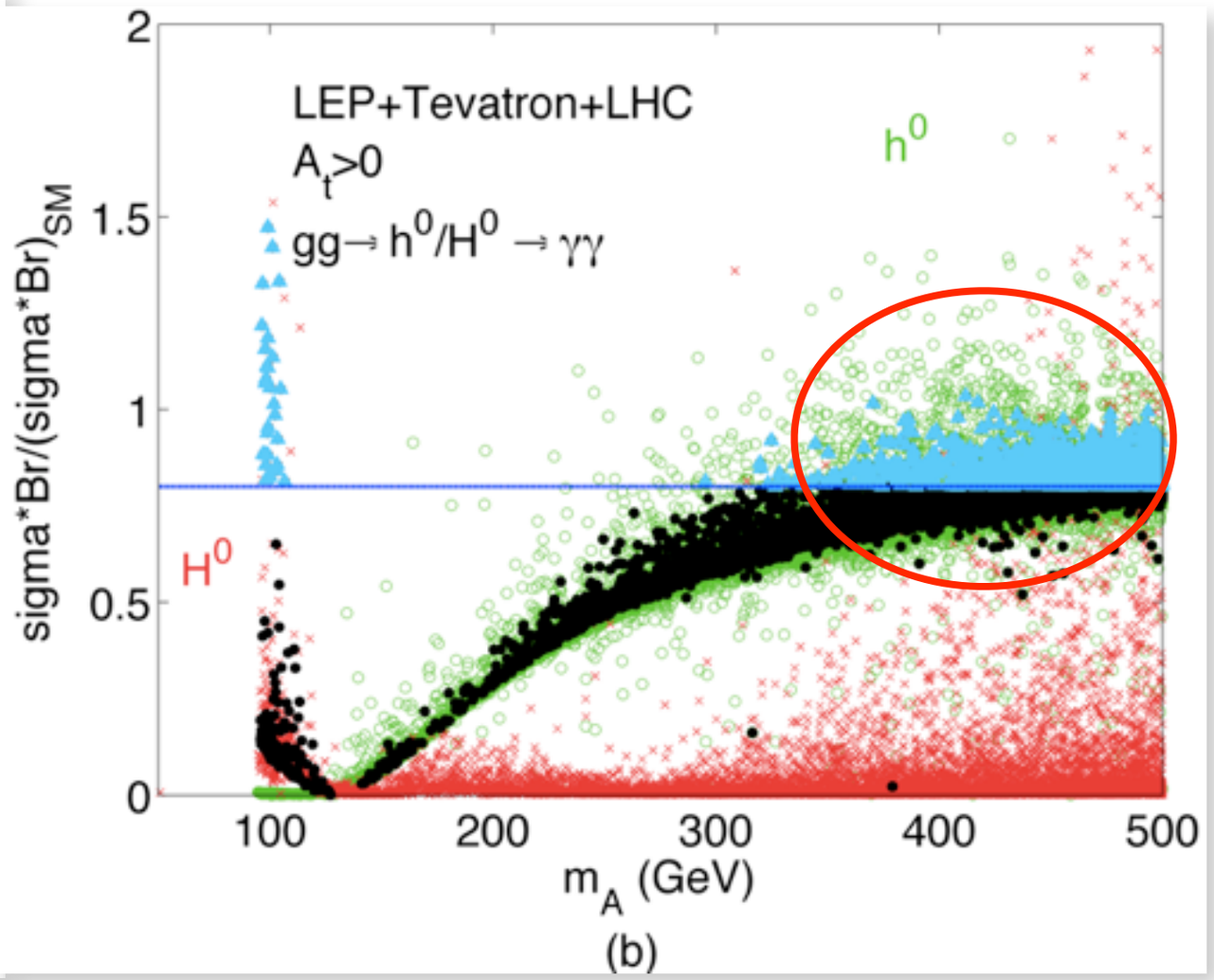
blue dots: $\sigma XBr(gg \to h^0, H^0 \to \gamma\gamma)_{MSSM} > 80\% (\sigma XBr)_{SM}$

Tao Han

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decoupling region





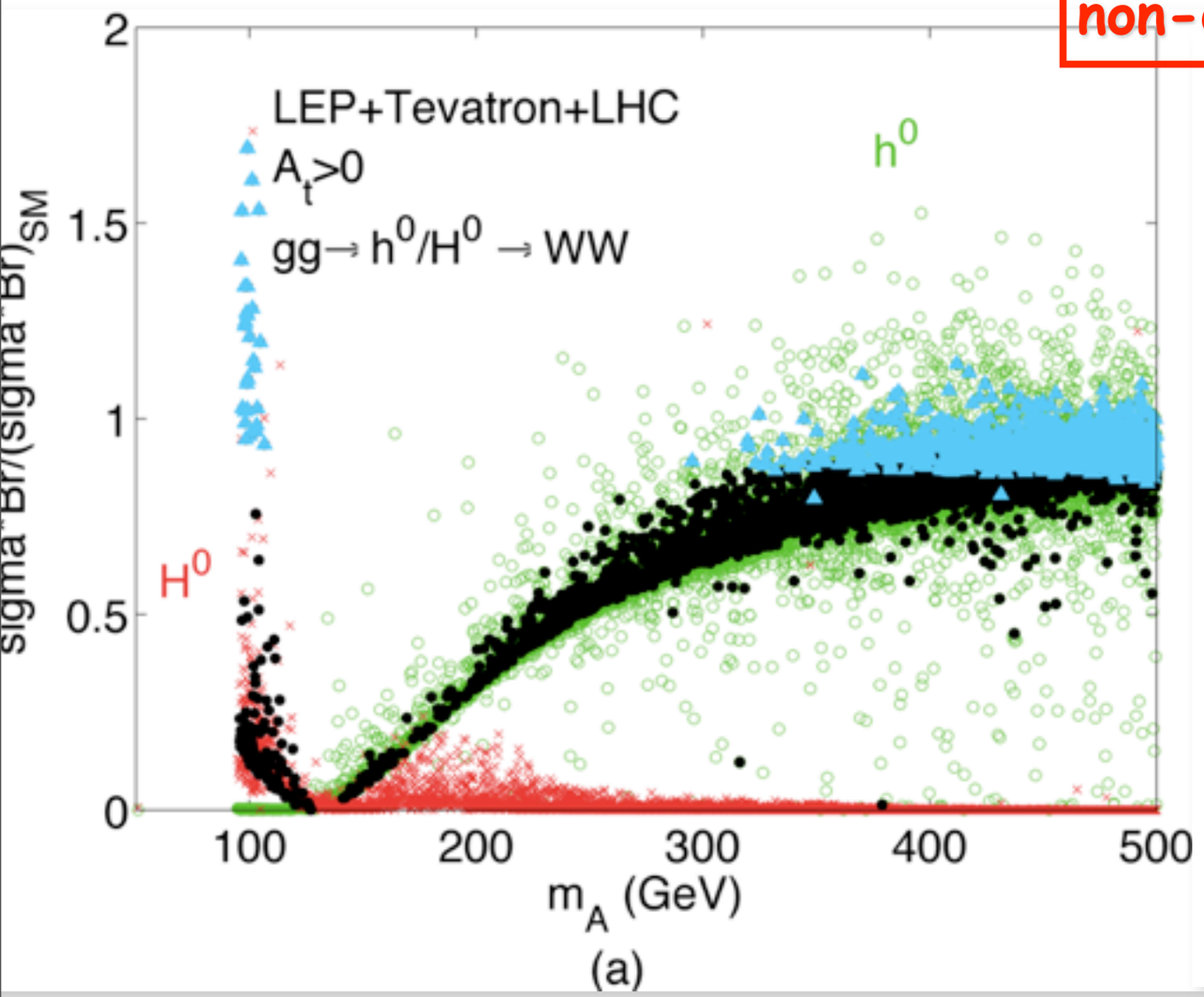
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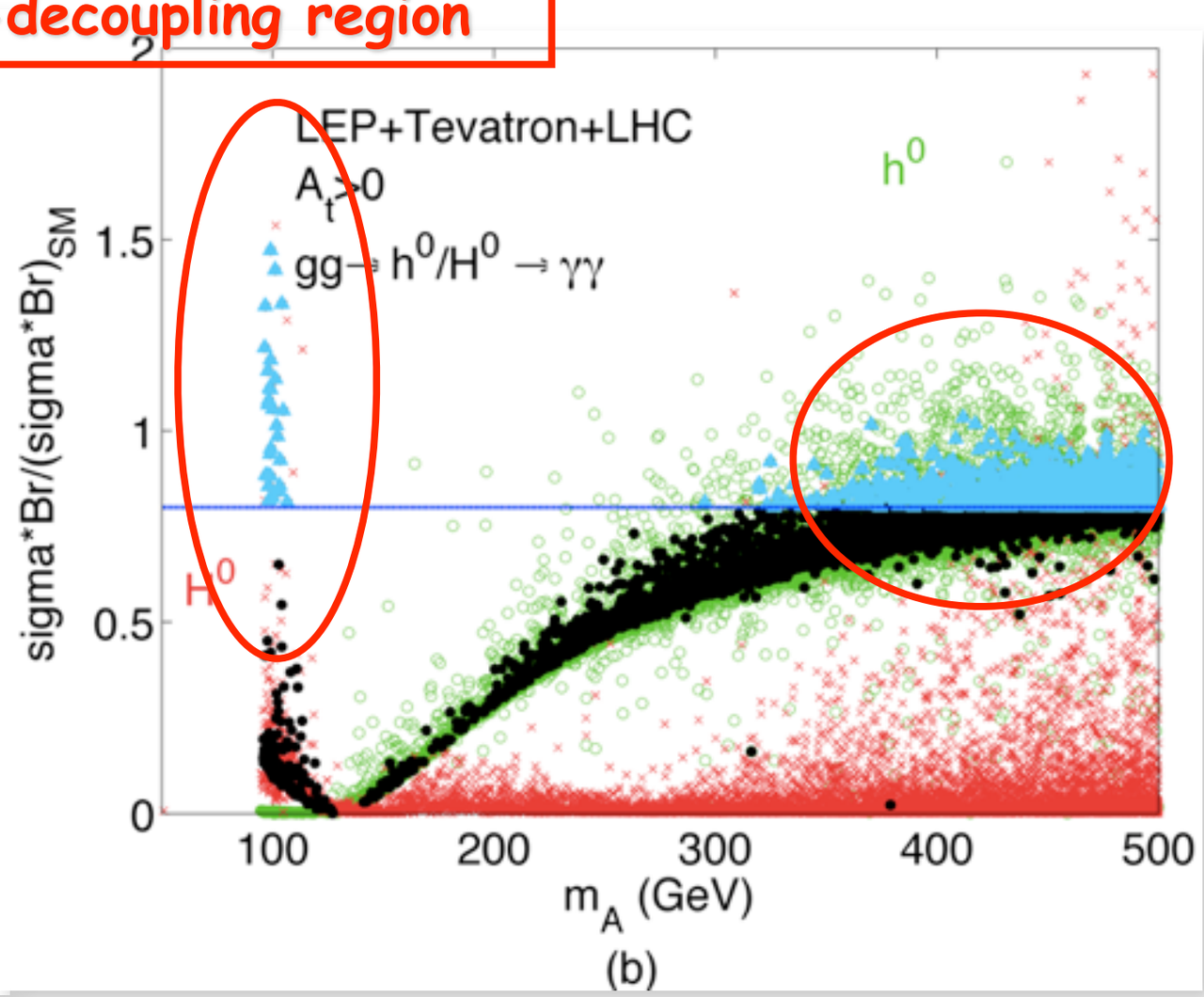
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decoupling region

non-decoupling region





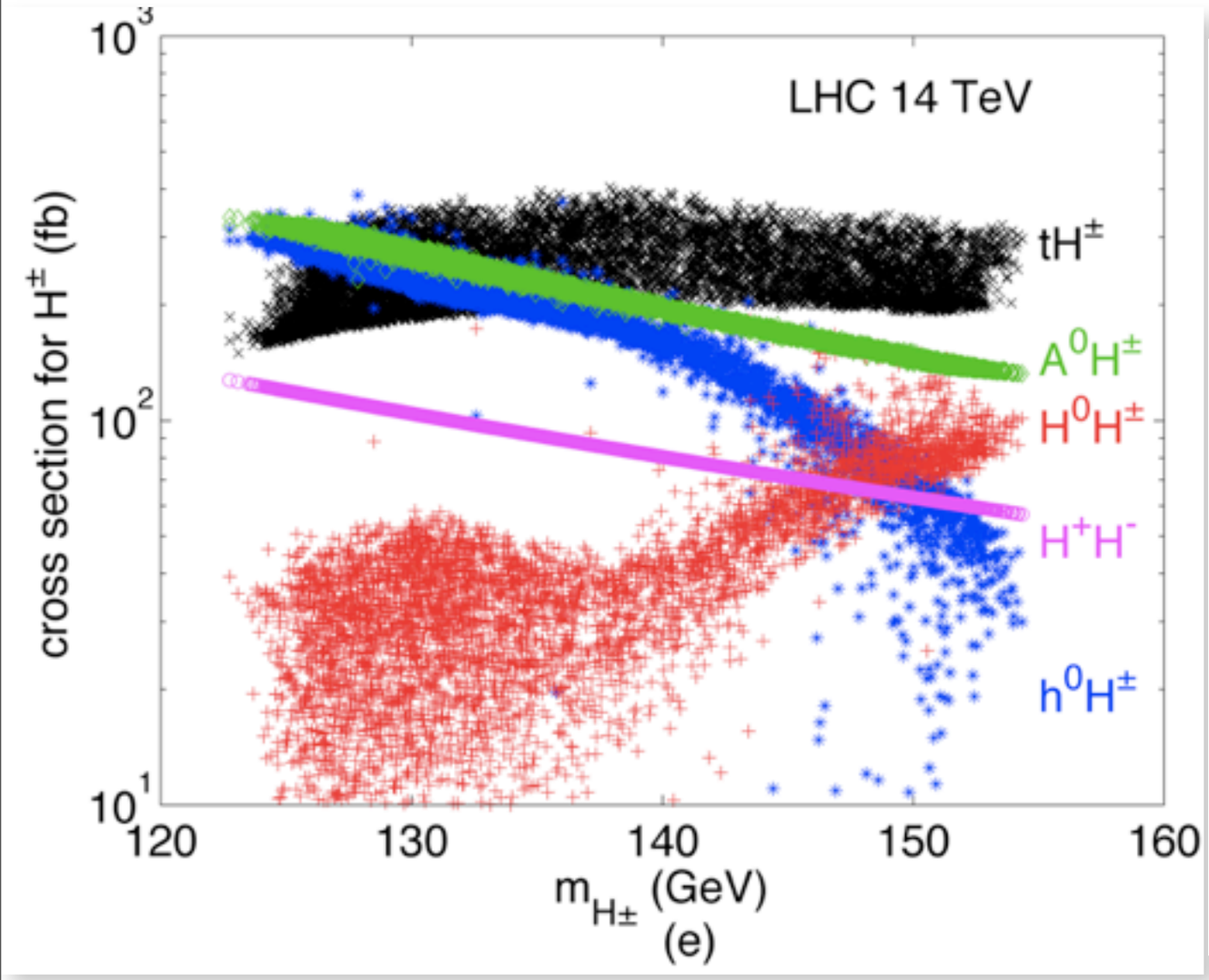
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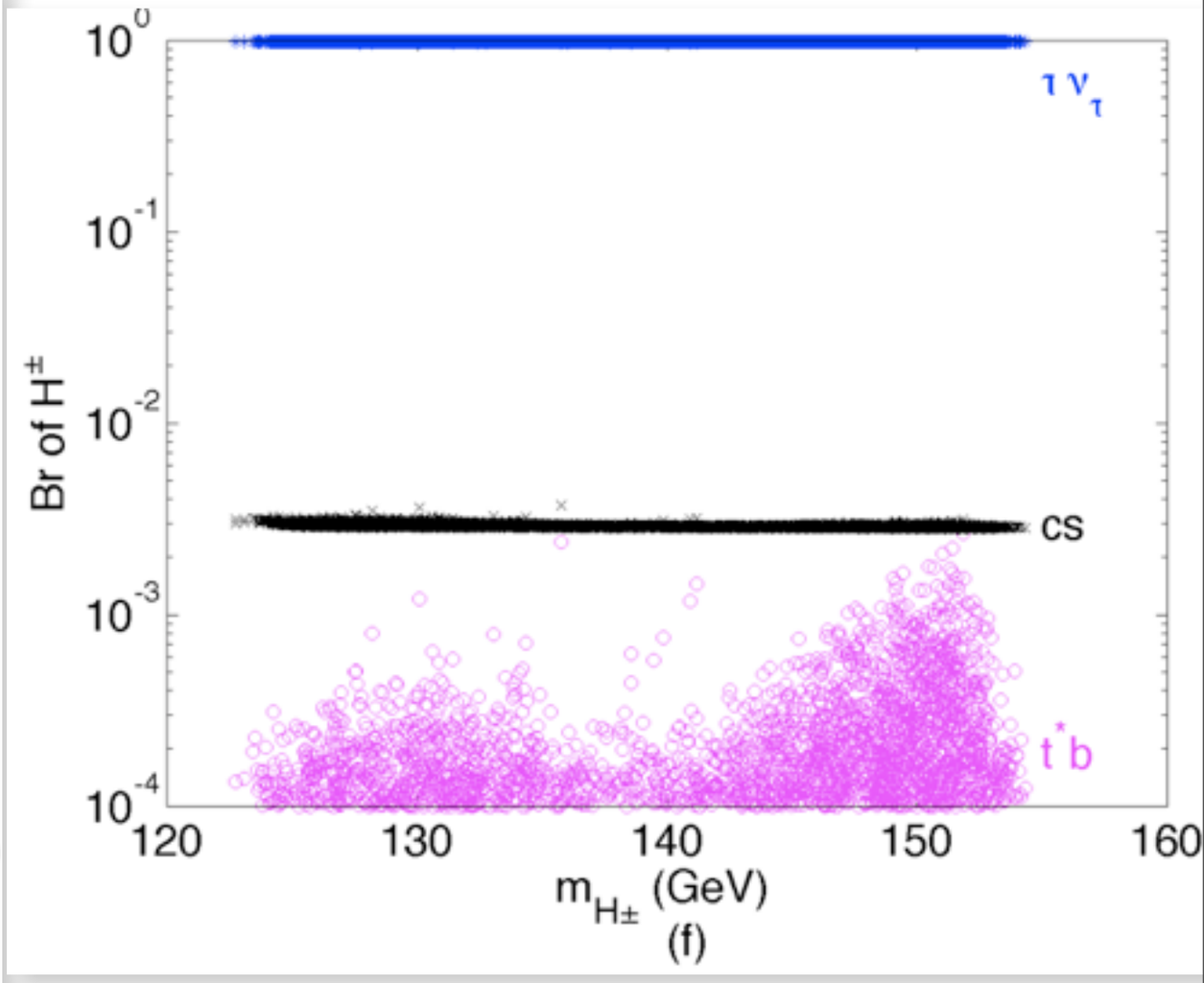
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Tao Han

Higgs Pair Production

- non-decoupling region:

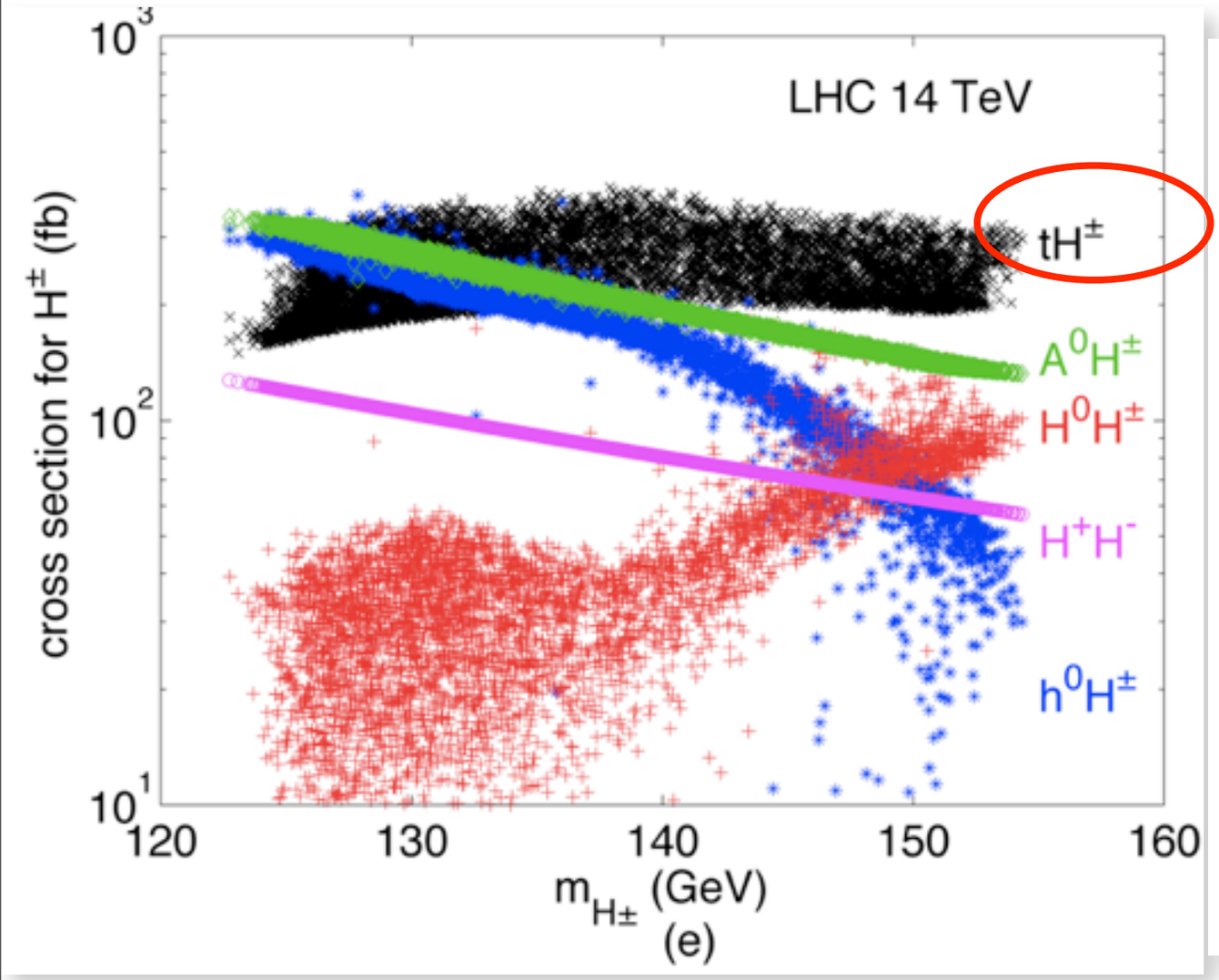


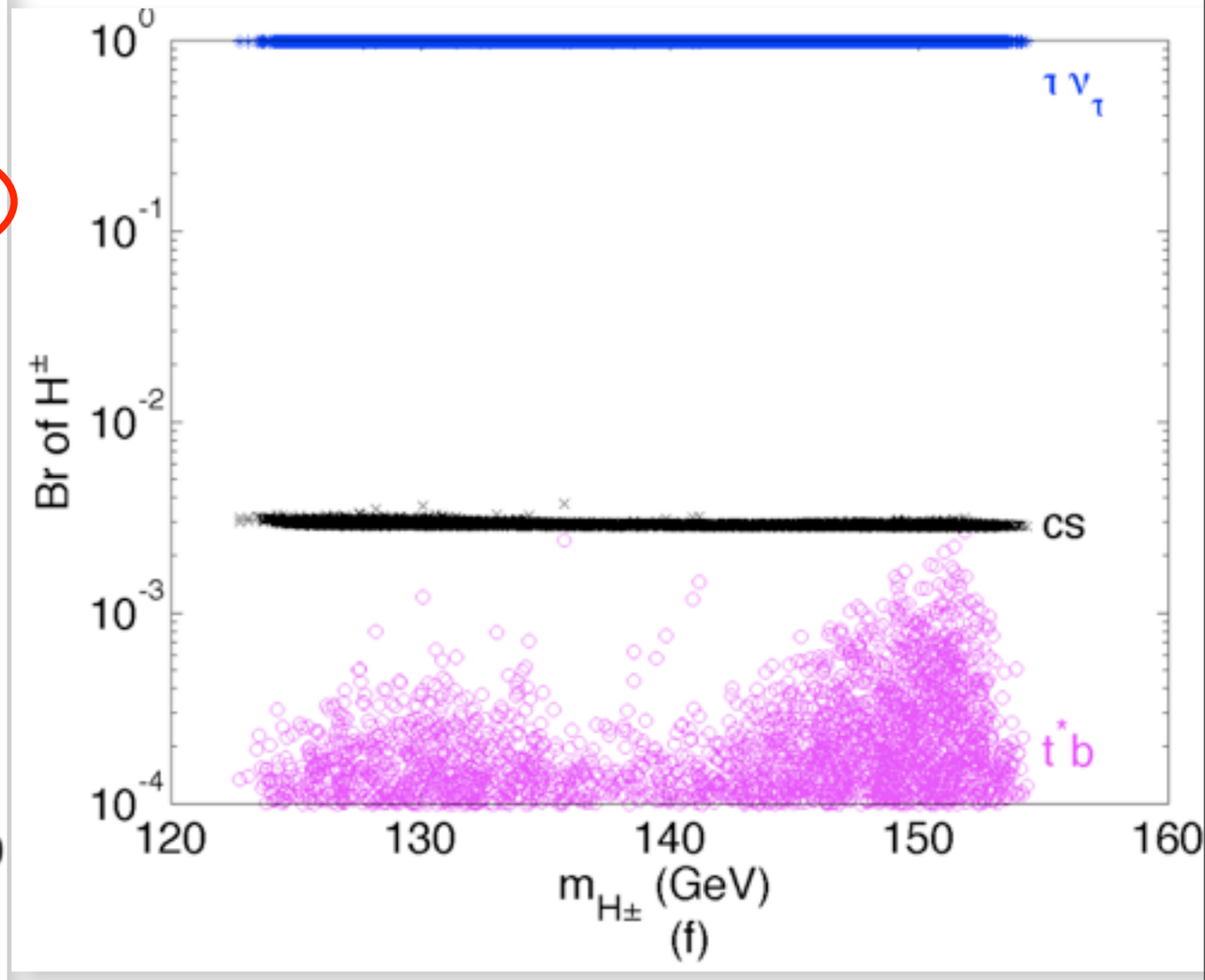


Tao Han

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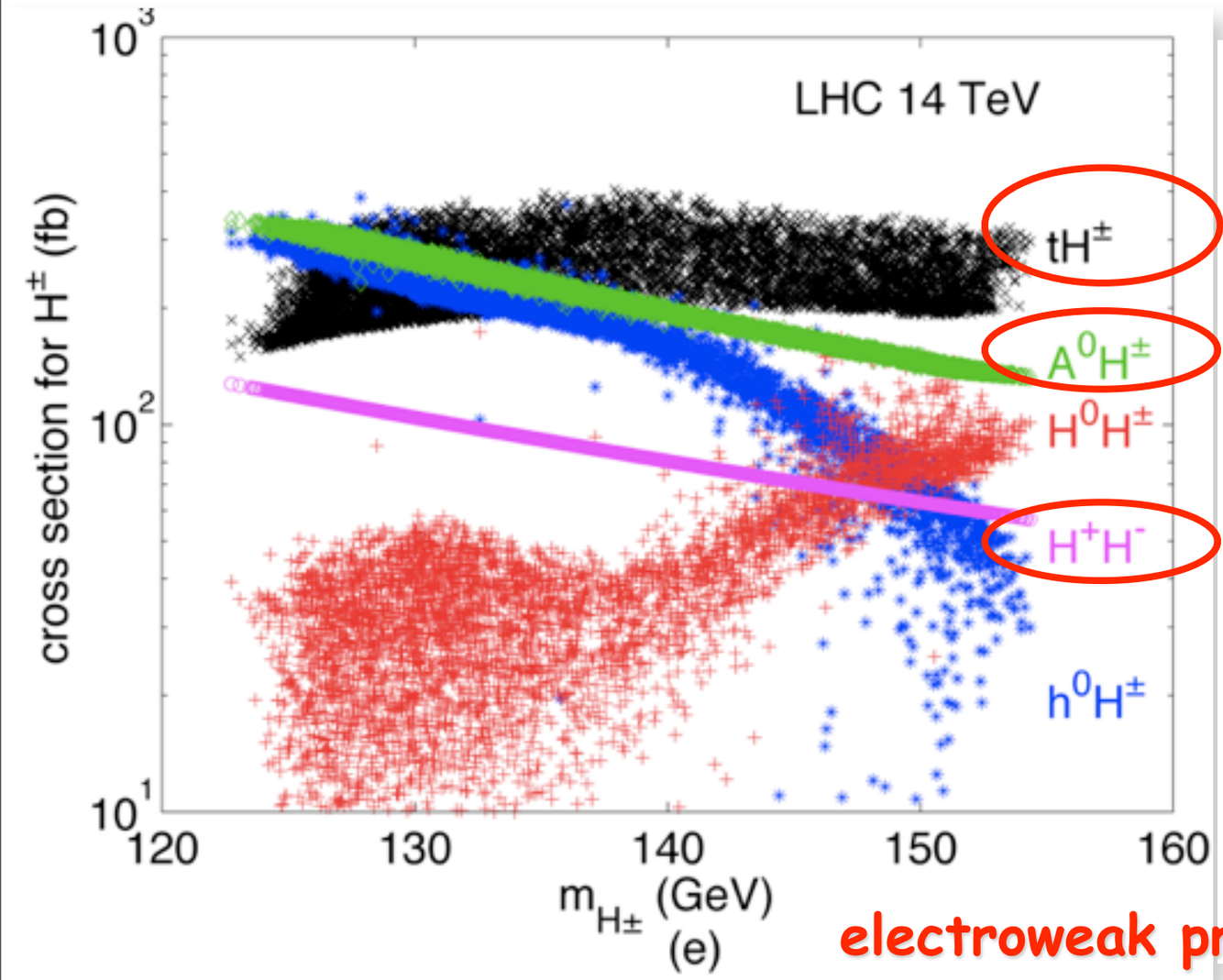


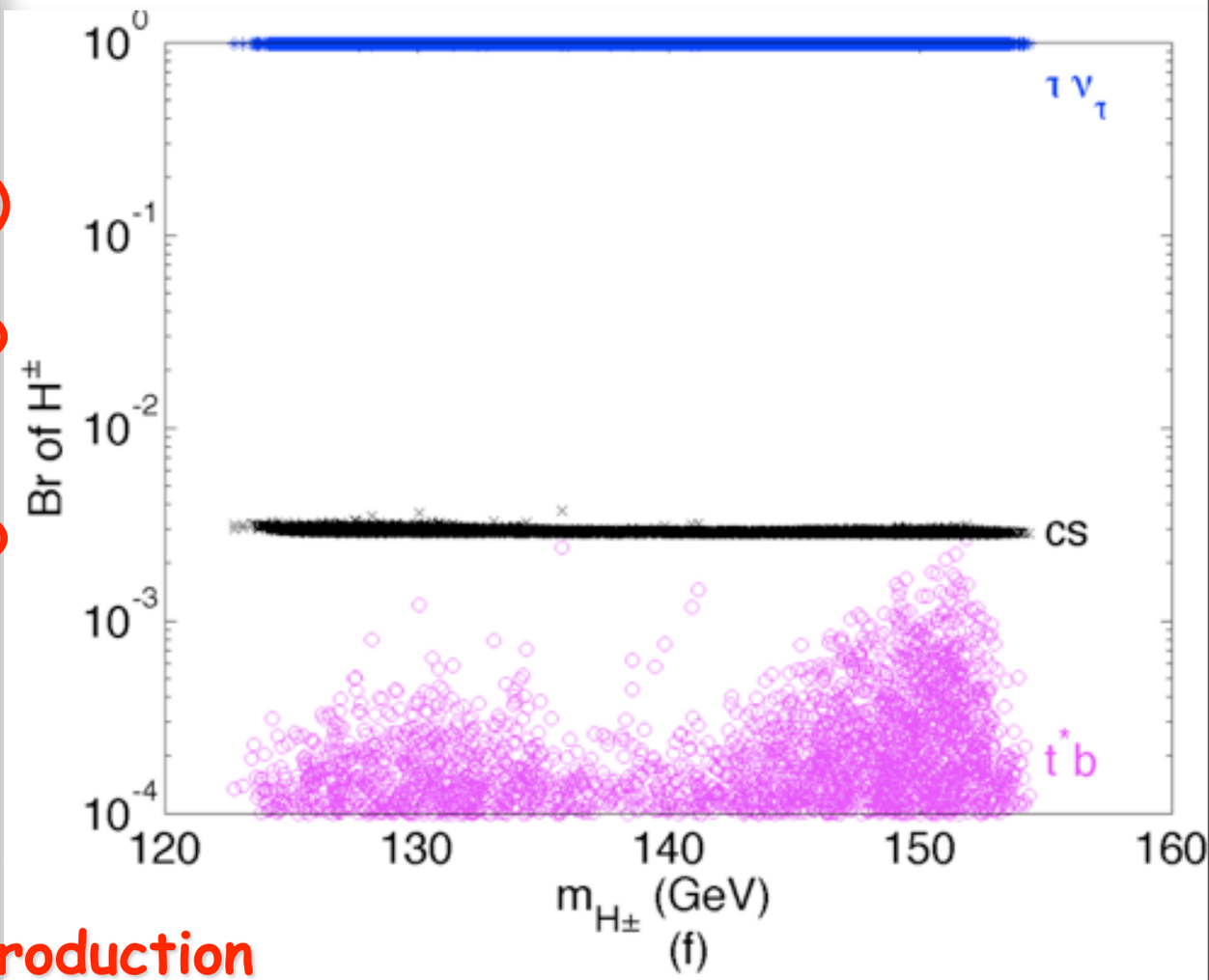
Tao Han

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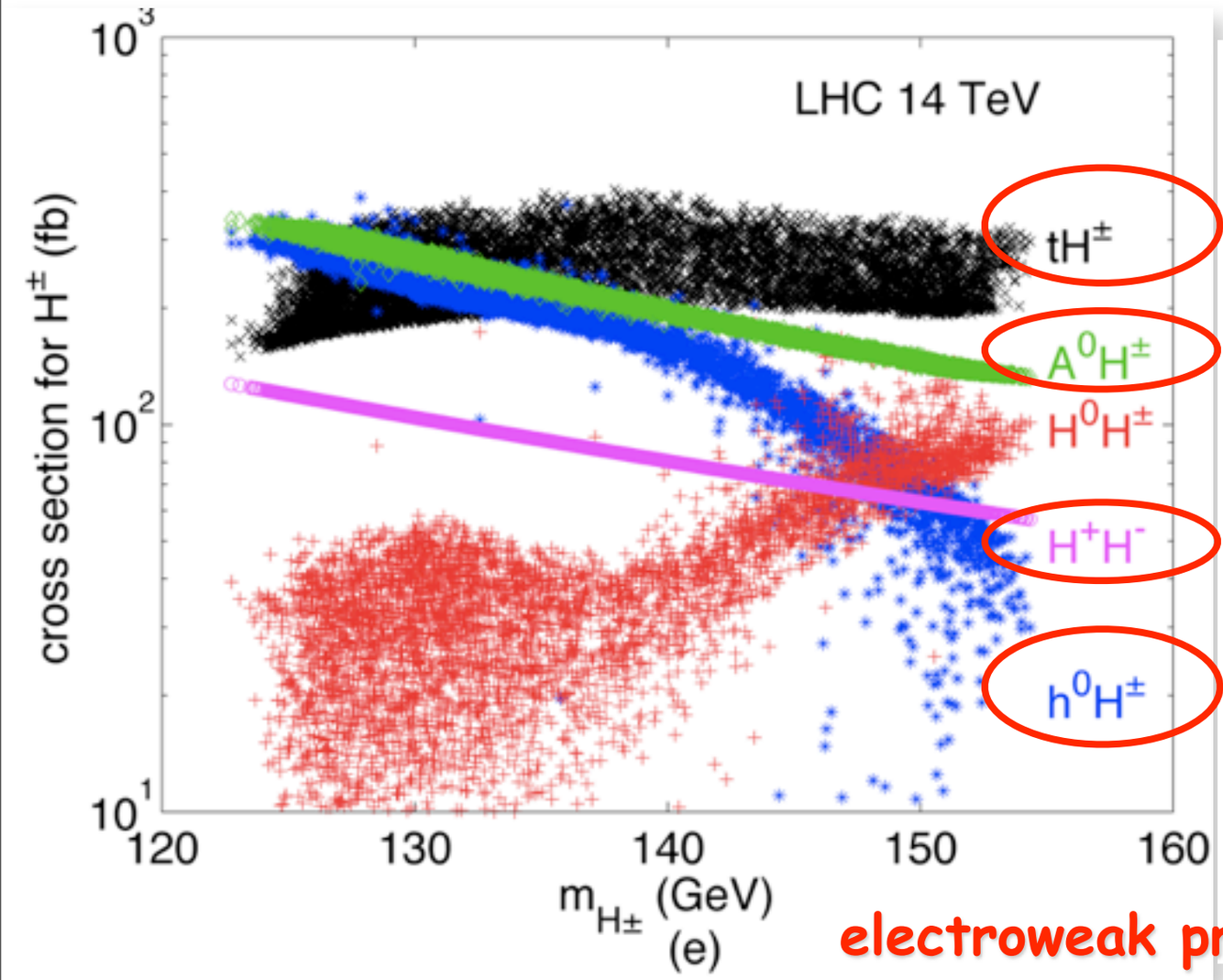
electroweak production

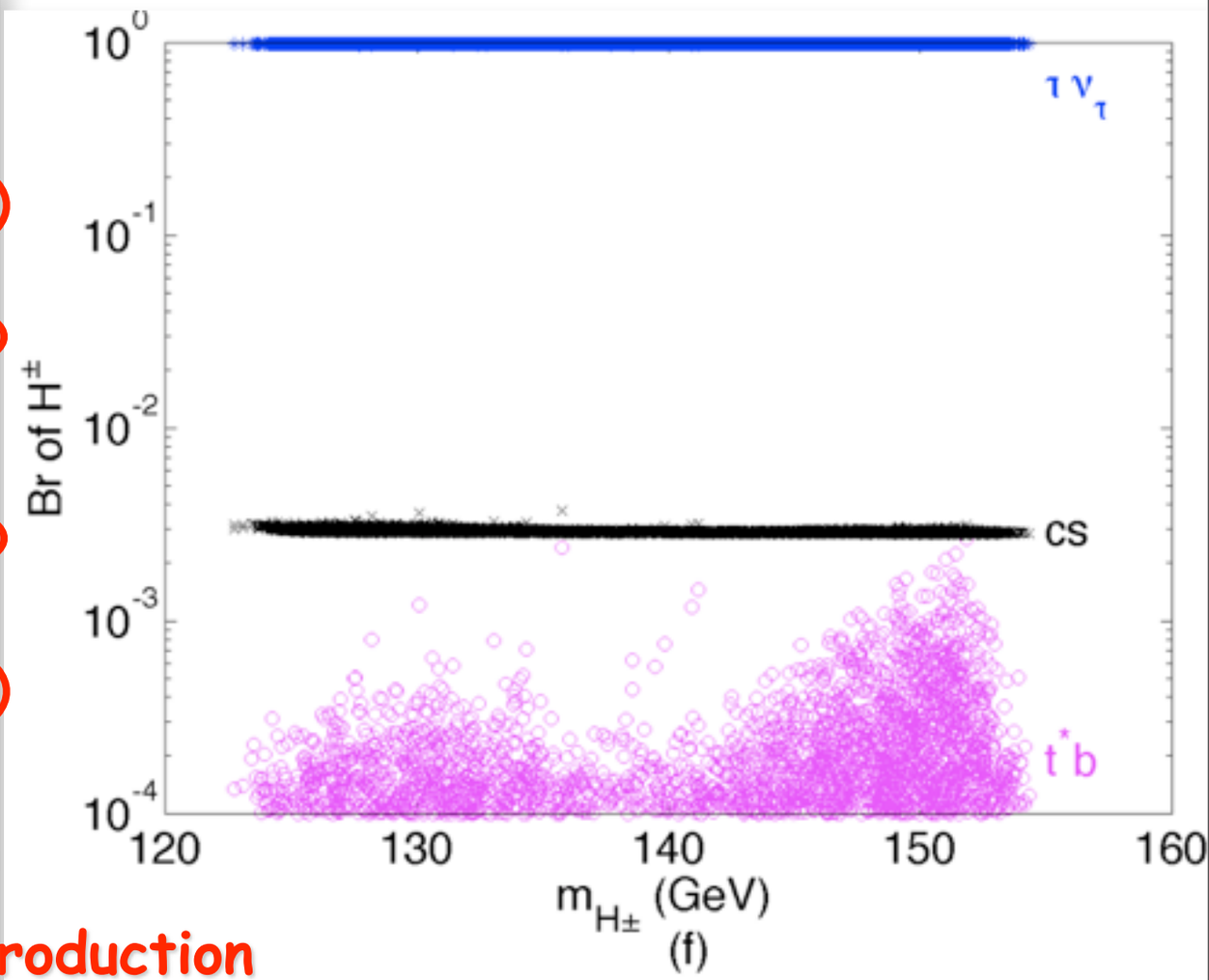
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SUSY parameter depndt: $pp \to H^\pm h^0,\ A^0 h^0,$





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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!)

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

Most interesting of all,
the top fermionic partner T:

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

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

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.

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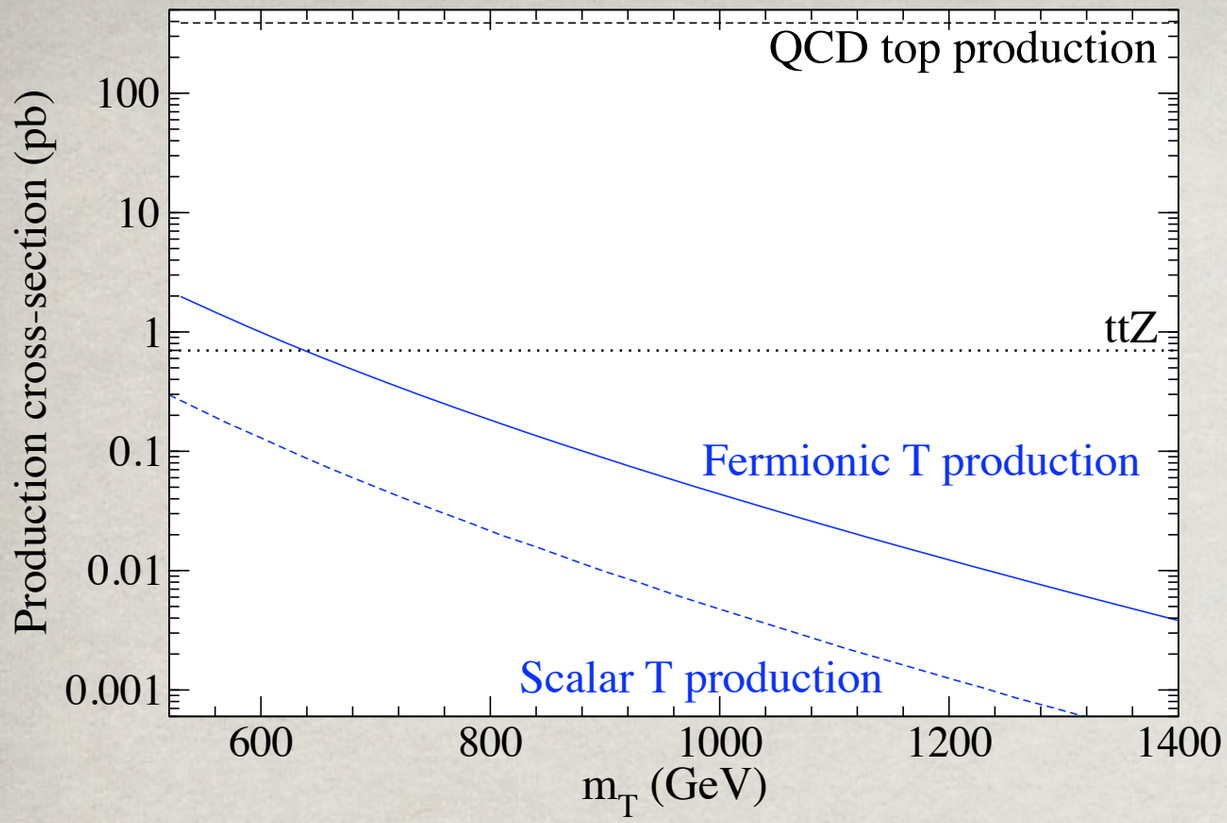
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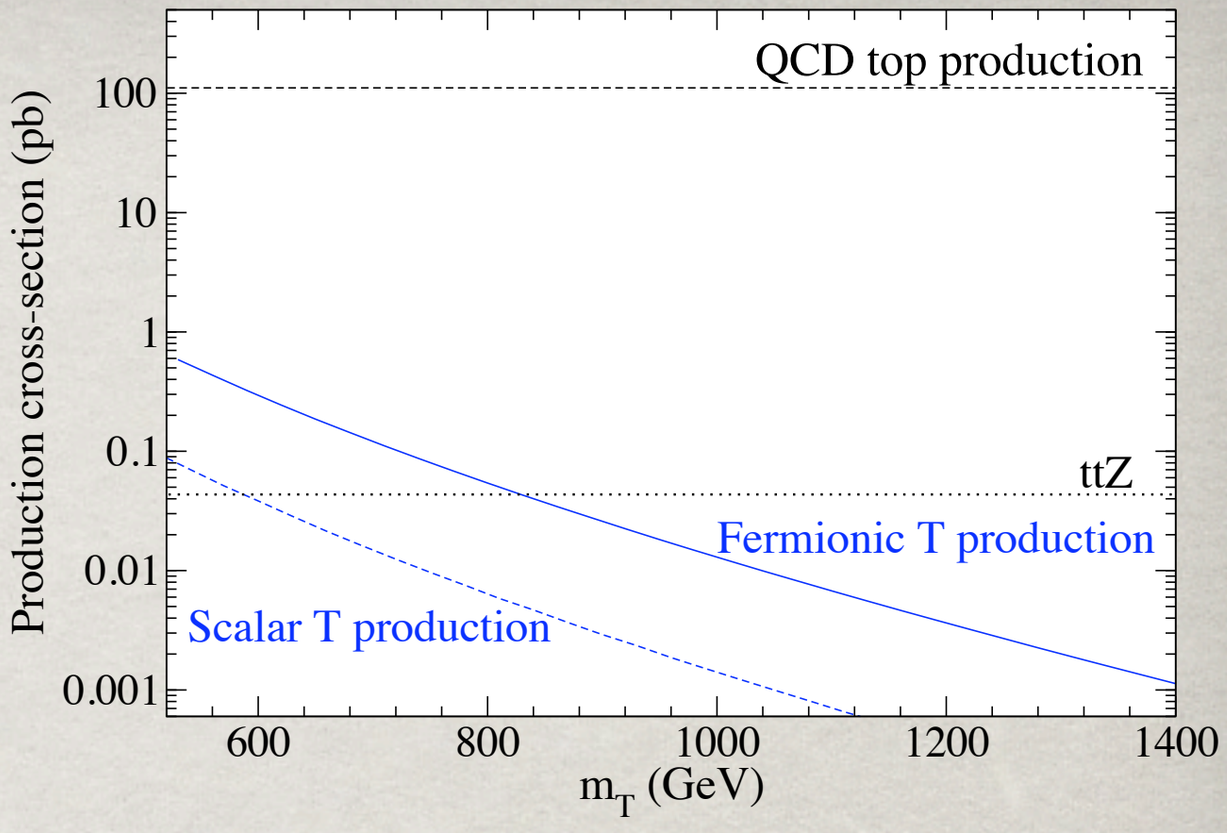
$$\lambda_{h^4} = \frac{a}{8}\left[\frac{g^2}{s^2c^2} + \frac{g'^2}{s'^2c'^2}\right] + 2a'\lambda_1^2 = \frac{1}{4}\lambda_{\phi^2}.$$

Most interesting of all, the top fermionic partner T:

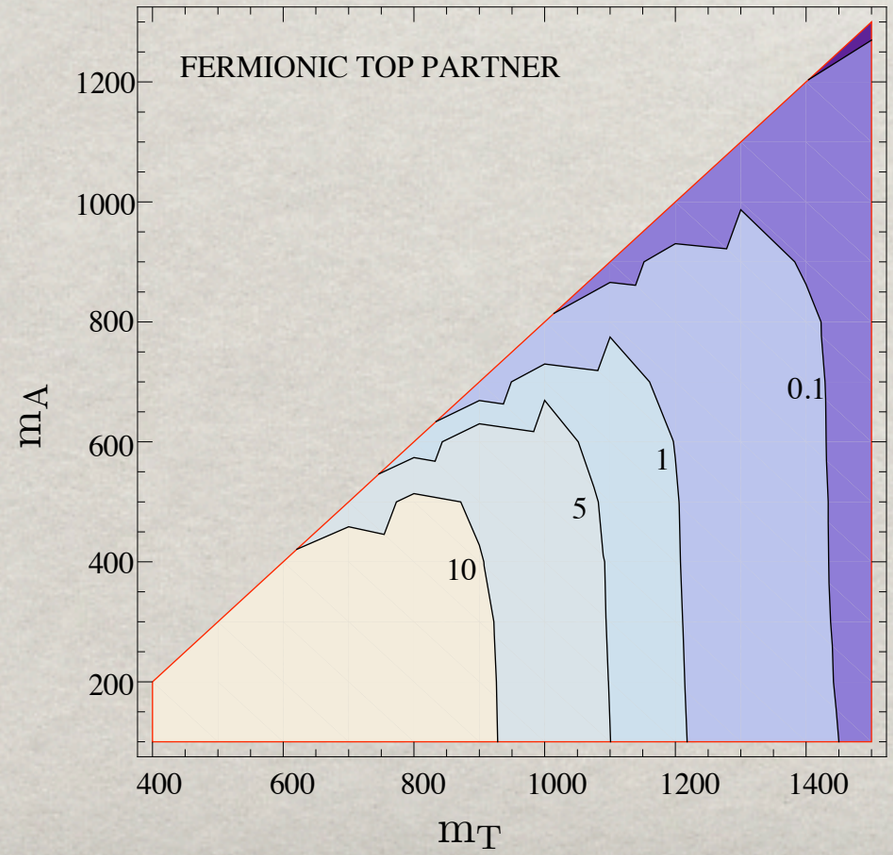
$$m_t = \frac{i\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}}v\left\{1 + \frac{v^2}{f^2}\left[-\frac{1}{3} + \frac{fv'}{v^2}\right.\right.$$

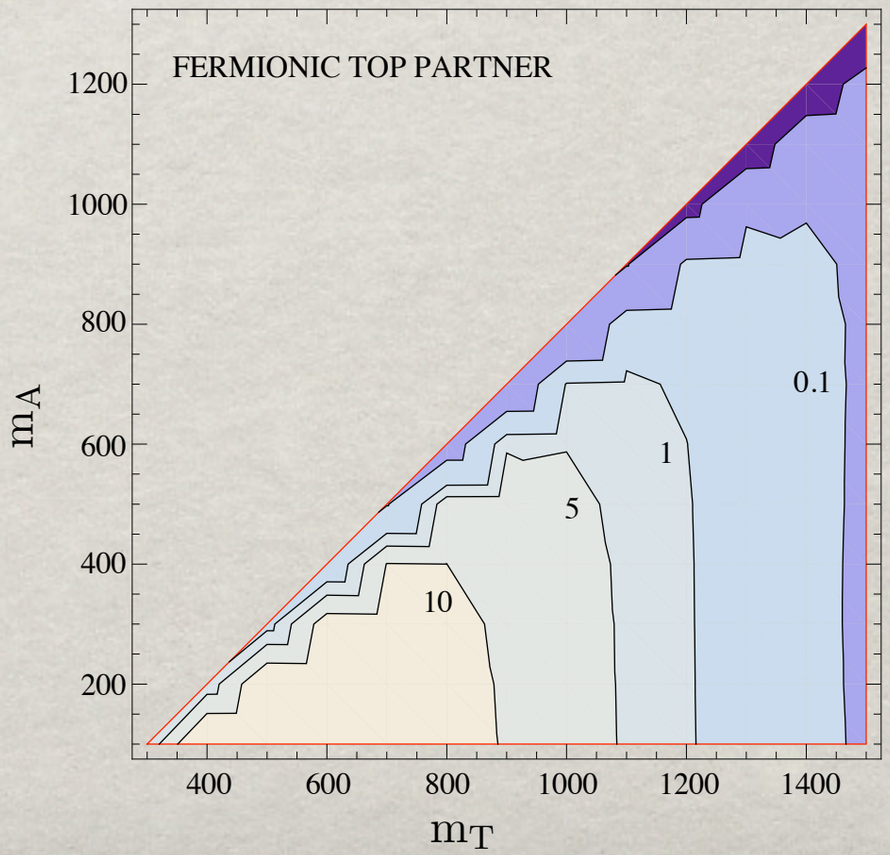
$$M_T = -f\sqrt{\lambda_1^2+\lambda_2^2}\left[1 + \mathcal{O}(v^2/f^2)\right].$$





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



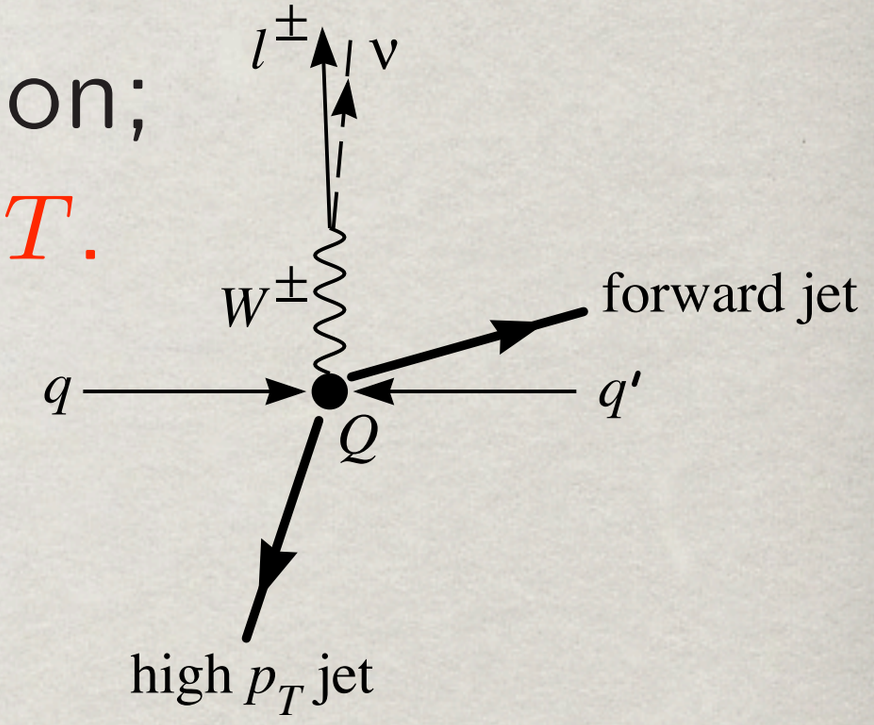


Single production:

Single production:

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

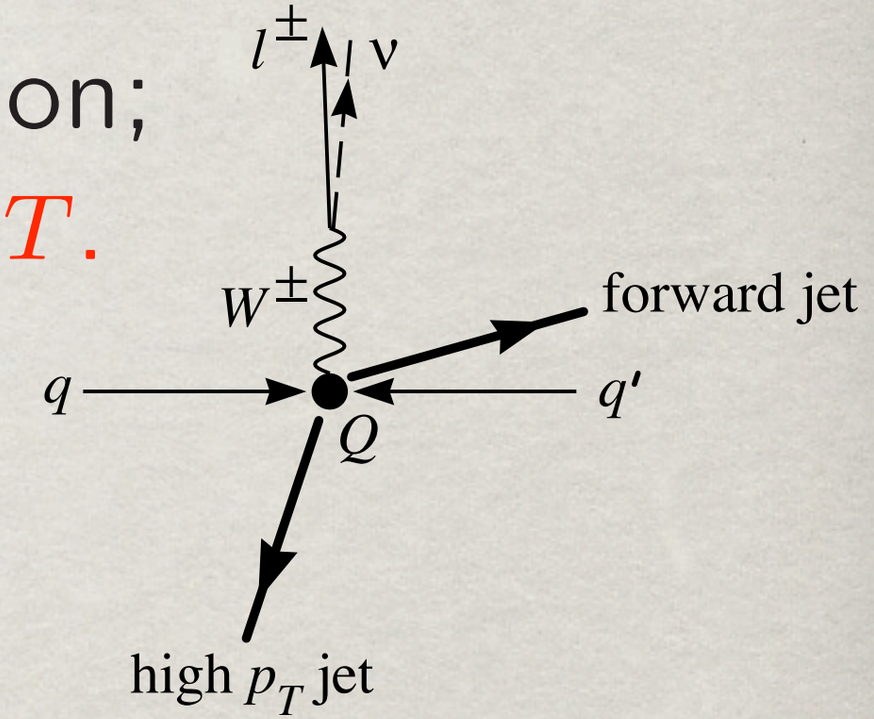
$qb \to q'T$ via t-channel $W_L b \to T$.

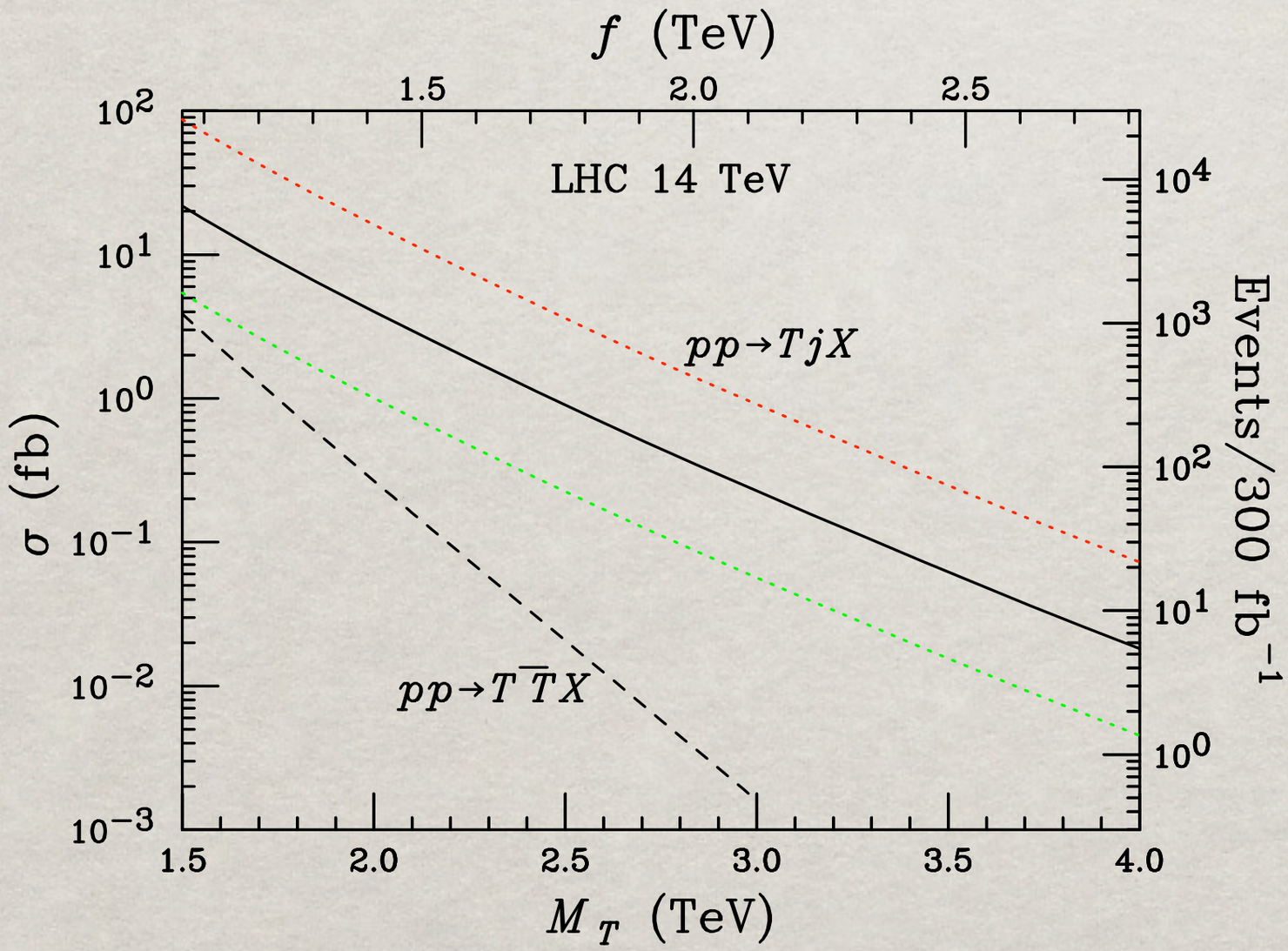


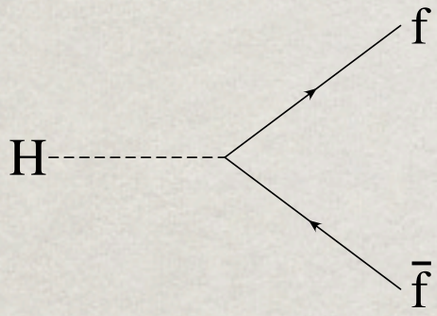
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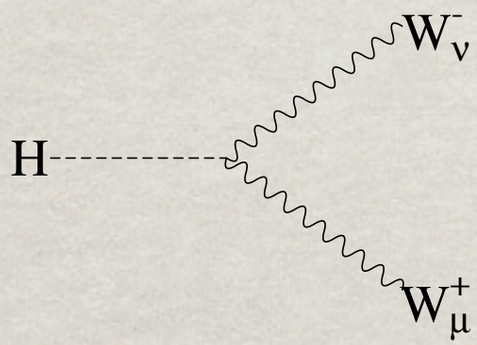
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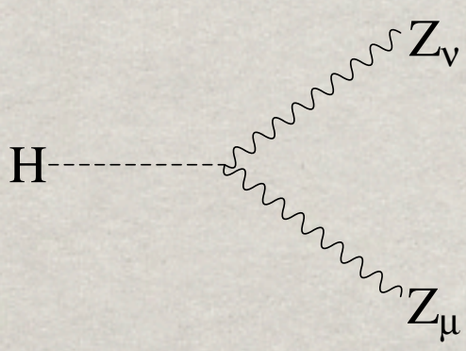




$$-i\frac{m_f}{v}\left(1+\Delta_f\right)$$



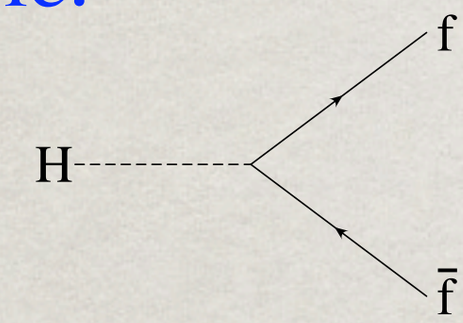
$$ig\,m_W\,(1+\Delta_W)g_{\mu\nu}$$



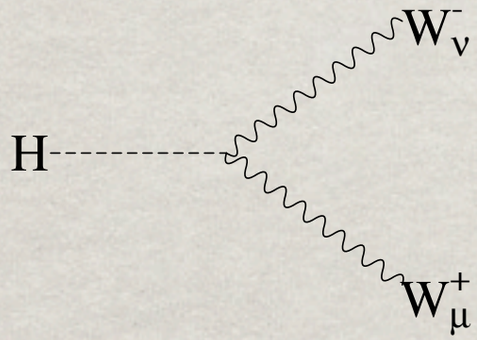
$$i\,g\,\frac{1}{\cos\theta_W}\,m_Z\,(1+\Delta_Z)g_{\mu\nu}$$

4. Higgs Couplings:

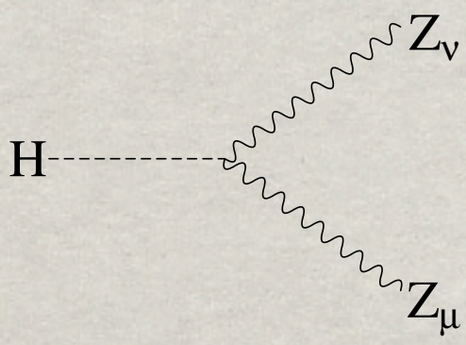
No matter there is new physics BSM seen or not, Higgs couplings need to be measured as accurate as possible.



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



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



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

SFitter analysis of Higgs couplings at LHC

- Parameterize deviations from SM couplings

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

- 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

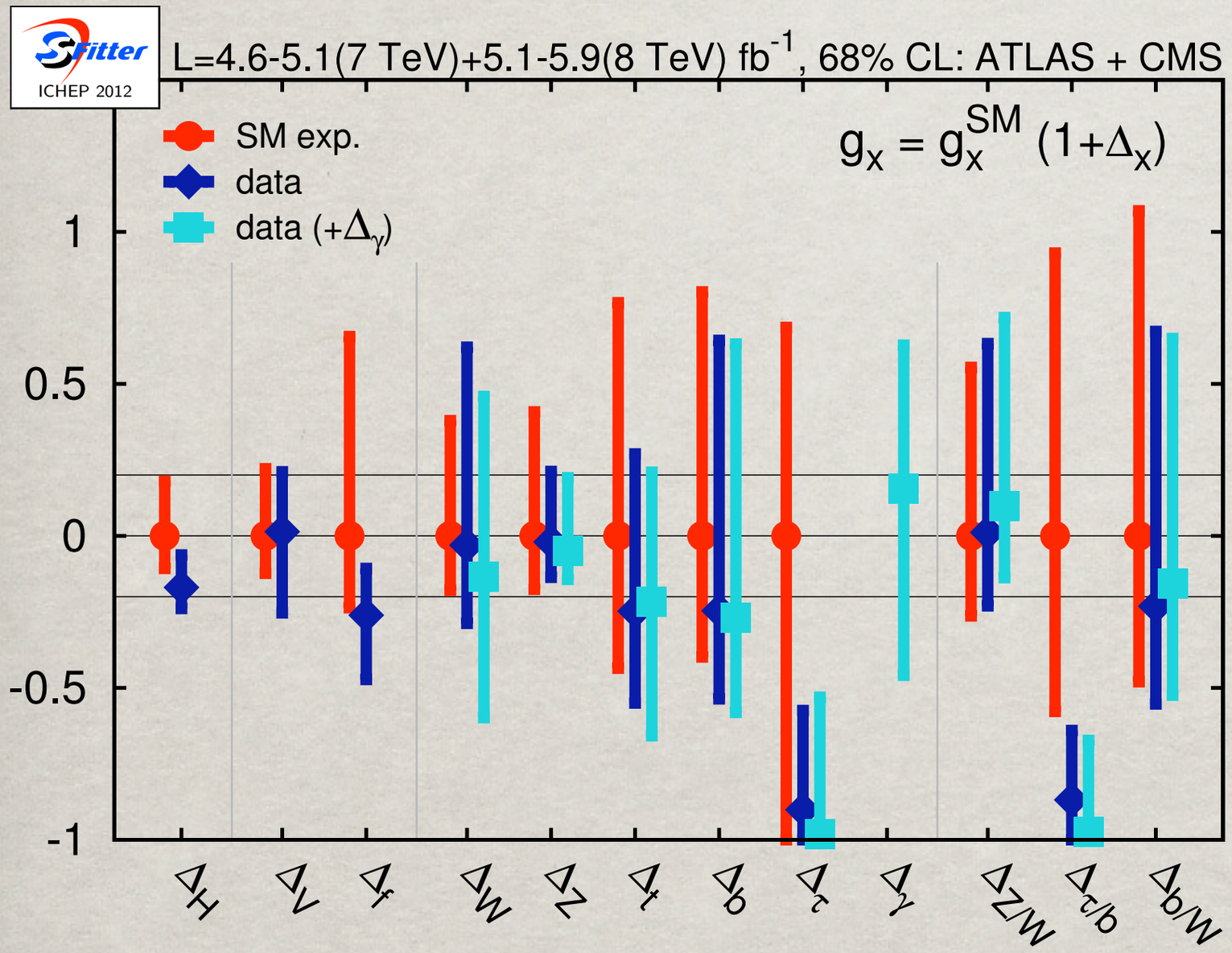
- Background expectations, exp. errors, etc. from published analyses
- cross-checked with exclusion and signal-strength plots

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)

Central values and errors on couplings



- 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: $\chi^2/\text{d.o.f.} = 27.7/49$

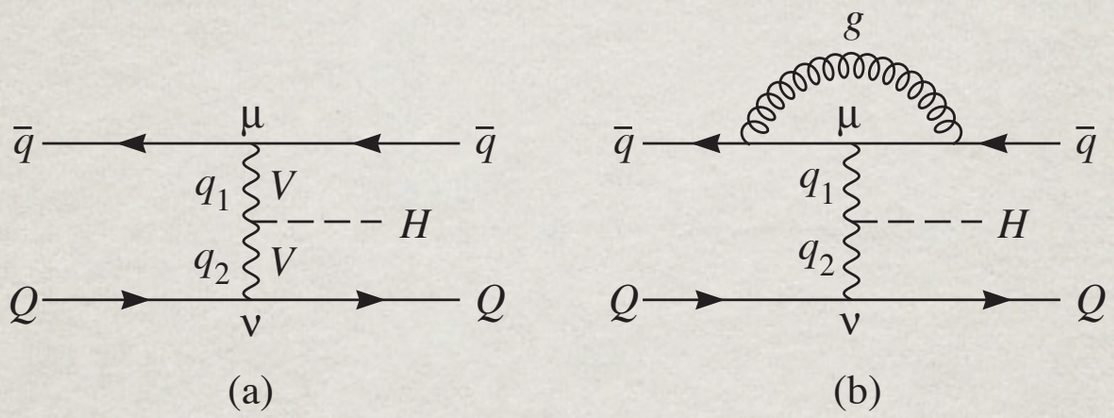
$$\frac{m_f}{v} H \bar{f} (1 + \epsilon \gamma_5) f$$

More general couplings:

$$\frac{m_f}{v} H \bar{f} (1 + \epsilon \gamma_5) f$$

More general couplings:

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



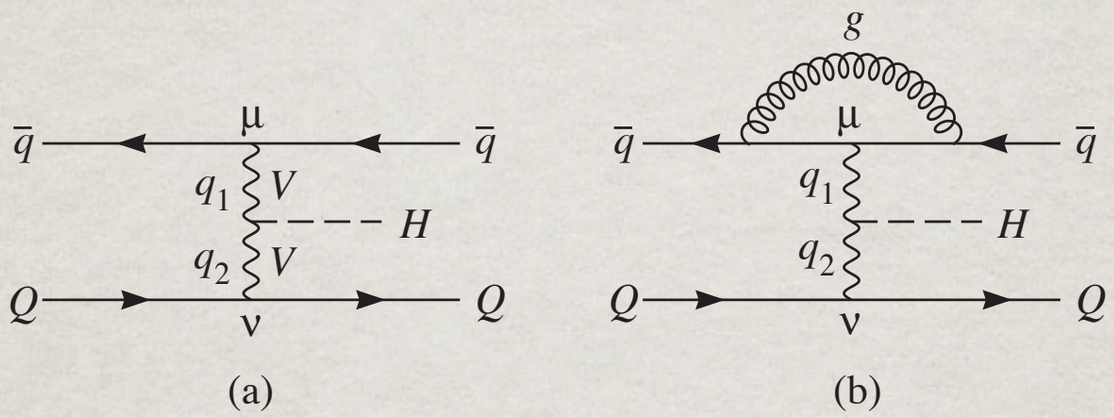
$$
\begin{aligned}
T^{\mu\nu} \quad = \quad & a_1 \, g^{\mu\nu} \; + \\
& a_2 \; (q_1 \cdot q_2 \, g^{\mu\nu} - q_1^\nu q_2^\mu) + \\
& a_3 \; \varepsilon^{\mu\nu\rho\sigma} \; q_{1\rho} q_{2\sigma}
\end{aligned}
$$

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

$$\frac{m_f}{v} H \bar{f}(1 + \epsilon\gamma_5) f$$

More general couplings:

Most general HVV vertex $T^{\mu\nu}(q_1, q_2)$



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

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

For Hff : $\dfrac{m_f}{v} H \bar{f}(1 + \epsilon\gamma_5) f$

So far, I have not totally updated you:

a. N-MSSM Higgs sector
   (very interesting!);
b. Dilaton/Radion (less likely);
c. Other states: H -> invisible modes
   (DM connection!)
d. ... ...

Summary:

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  The Higgs mechanism ...

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Go LHC!