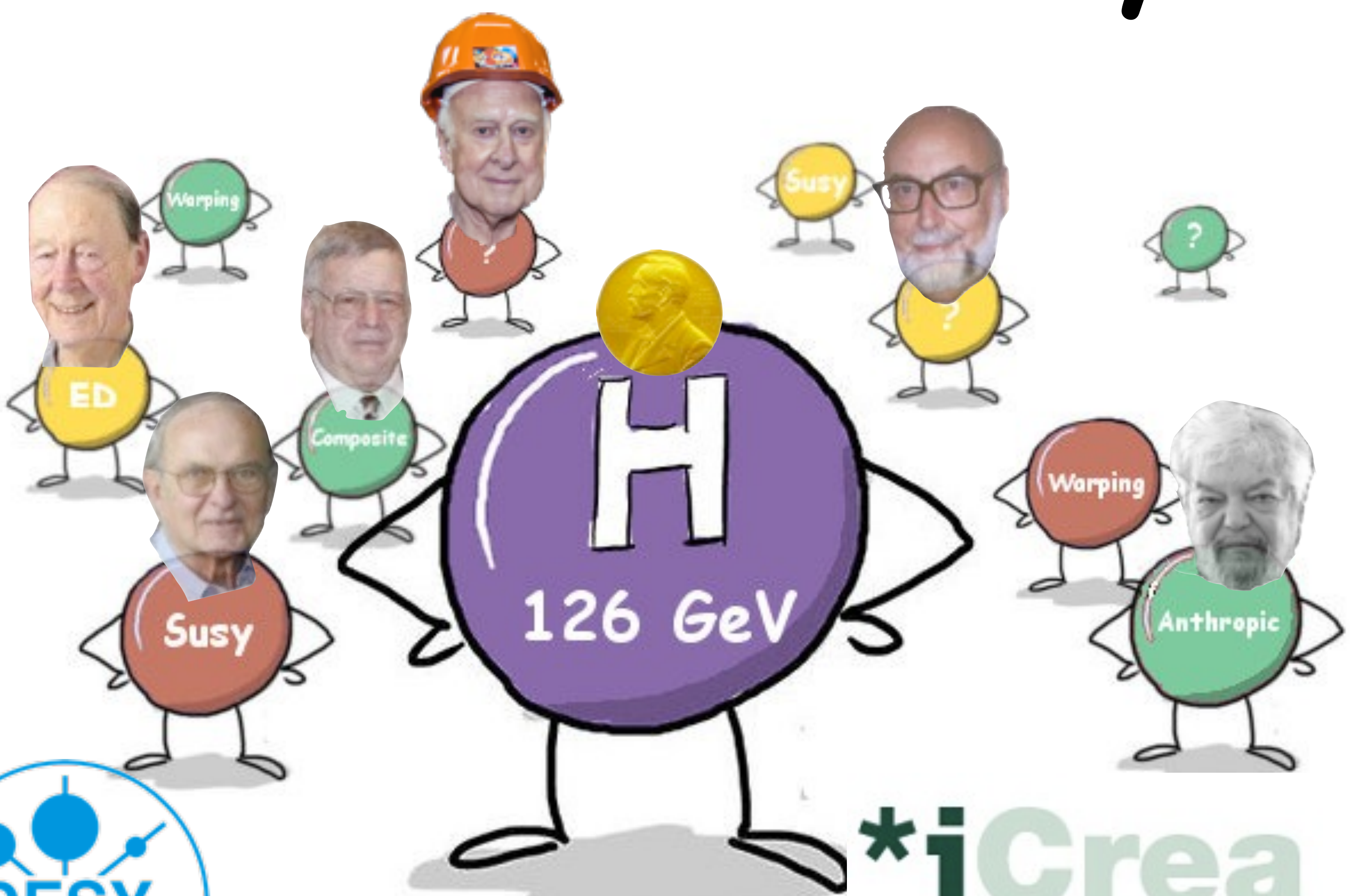
Higgs Physics within and beyond the SM



P. Cámara/C. Grojean

IFIC, Valencia, May 2015

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INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

Disclaimer

These are slides that I've prepared for some lectures at the CERN-Latin American School of High Energy Physics last March in Ecuador.

There is partial overlap with what I covered during my blackboard lectures at IFIC even though some parts are missing in these notes.

Do not hesitate to contact me by email if you have any comments or questions. And please, report any typo/mistake that you might find in these notes.

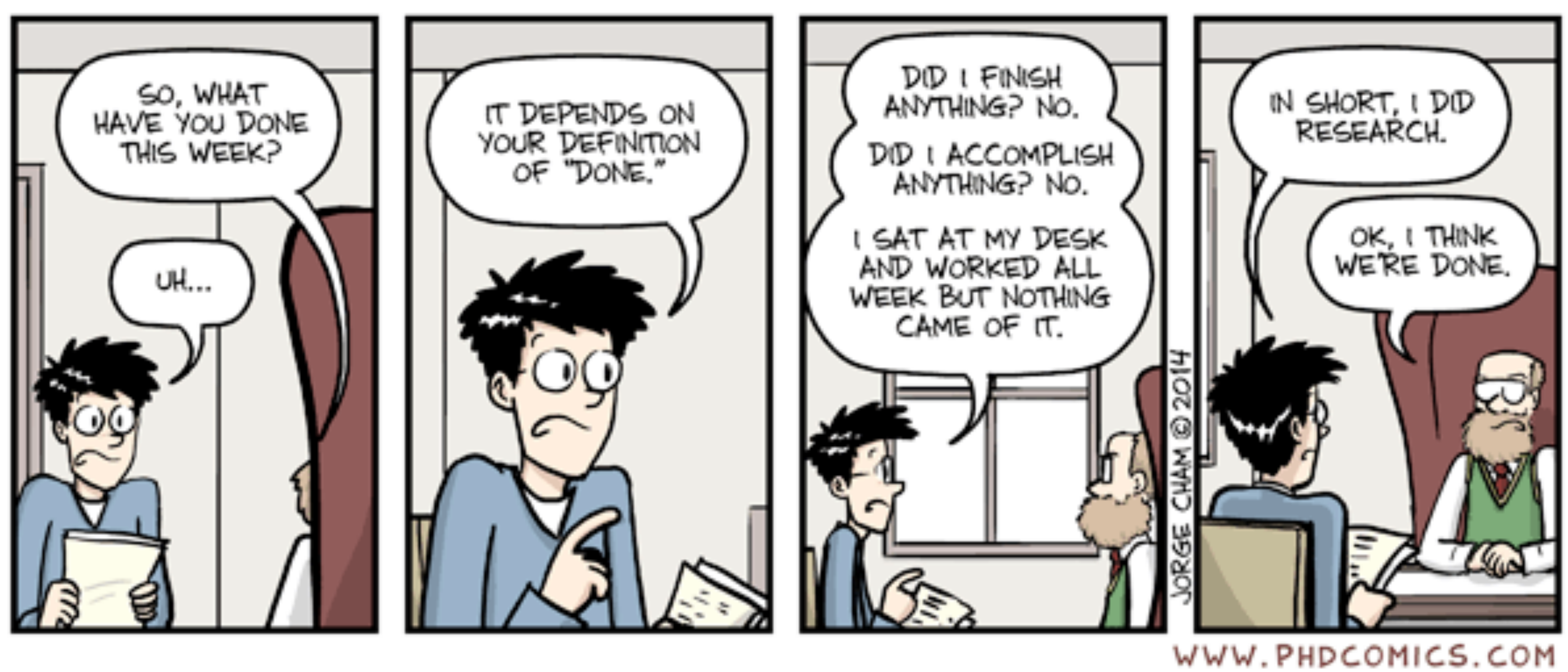
To help you reading these notes...

- Some exercises

  - do them by yourself!
  - ... or ask the discussion leaders to help you

- Some hyperlinks
  - ➲ and ⇡⇠⇢ to navigate through the pdf
  - text written in "red" (in particular all the references)

Your work, as PhD students, is to question all what you are listening during the lectures...



Lecture Outline

1 First Lecture ➲

- Standard Model and EW symmetry breaking ➲
- Higgs mechanism - custodial symmetry ➲
- Goldstone equivalence theorem ➲
- What is the Higgs boson the name of? ➲
- SM Higgs @ colliders ➲
- UV behavior of the Higgs boson (triviality, stability, naturality) ➲
- Symmetries for a natural EWSB ➲

2 Second Lecture ➲

- Implications for SUSY ➲
- Composite Higgs models ➲
- Precision Higgs couplings ➲
- Future Higgs channels:
  - Boosted and off-shell channels ➲
  - Multi-Higgs ➲

1 2

[pictures: courtesy of NYT]

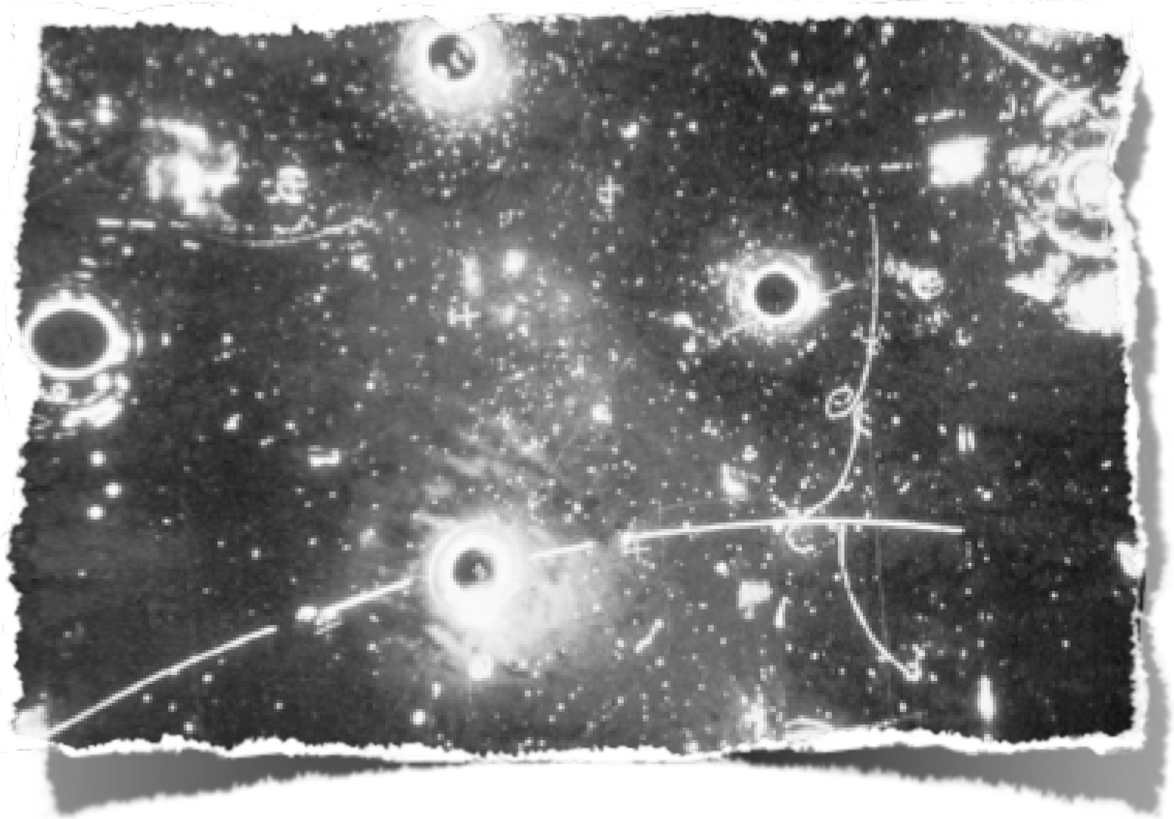
1

Standard Model & EW Symm. Breaking

The Standard Model

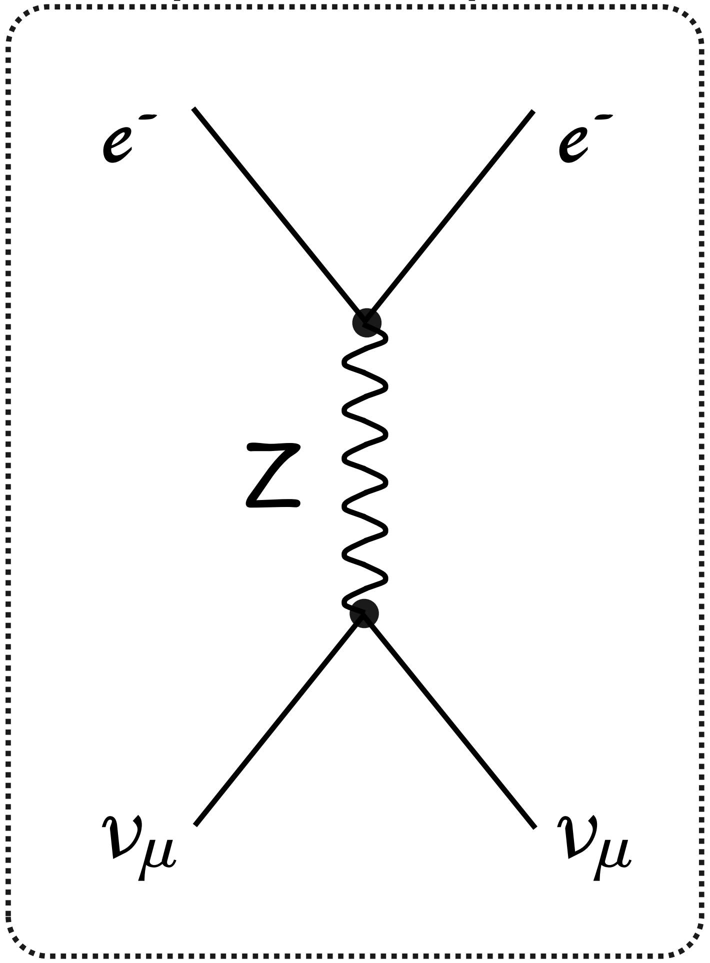
the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$



Gargamelle collaboration, '73

$\nu_\mu e^- \to \nu_\mu e^-$

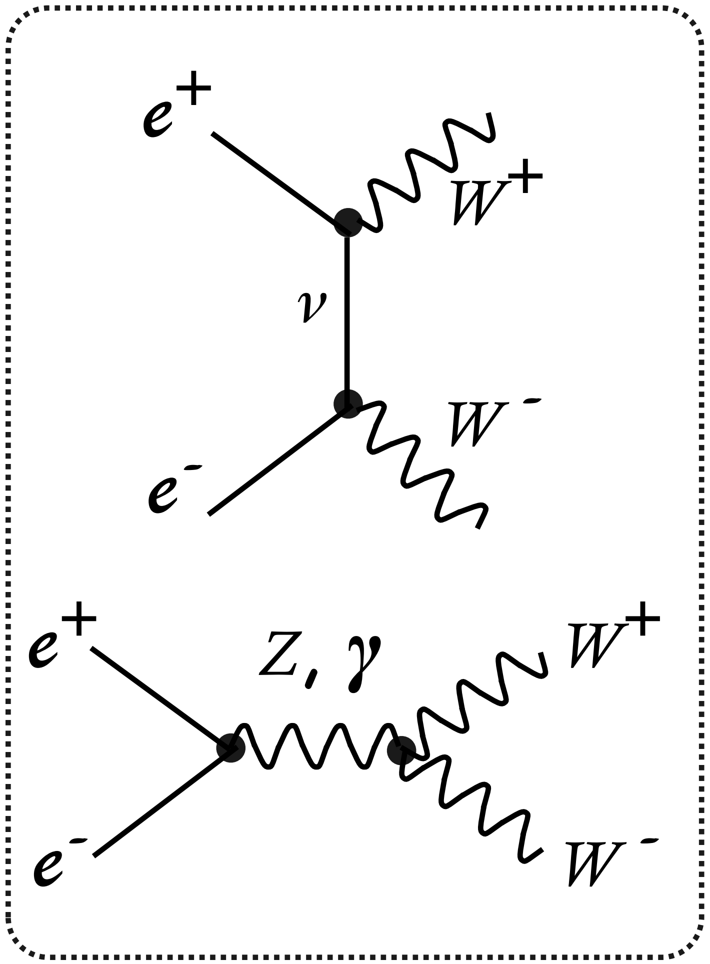


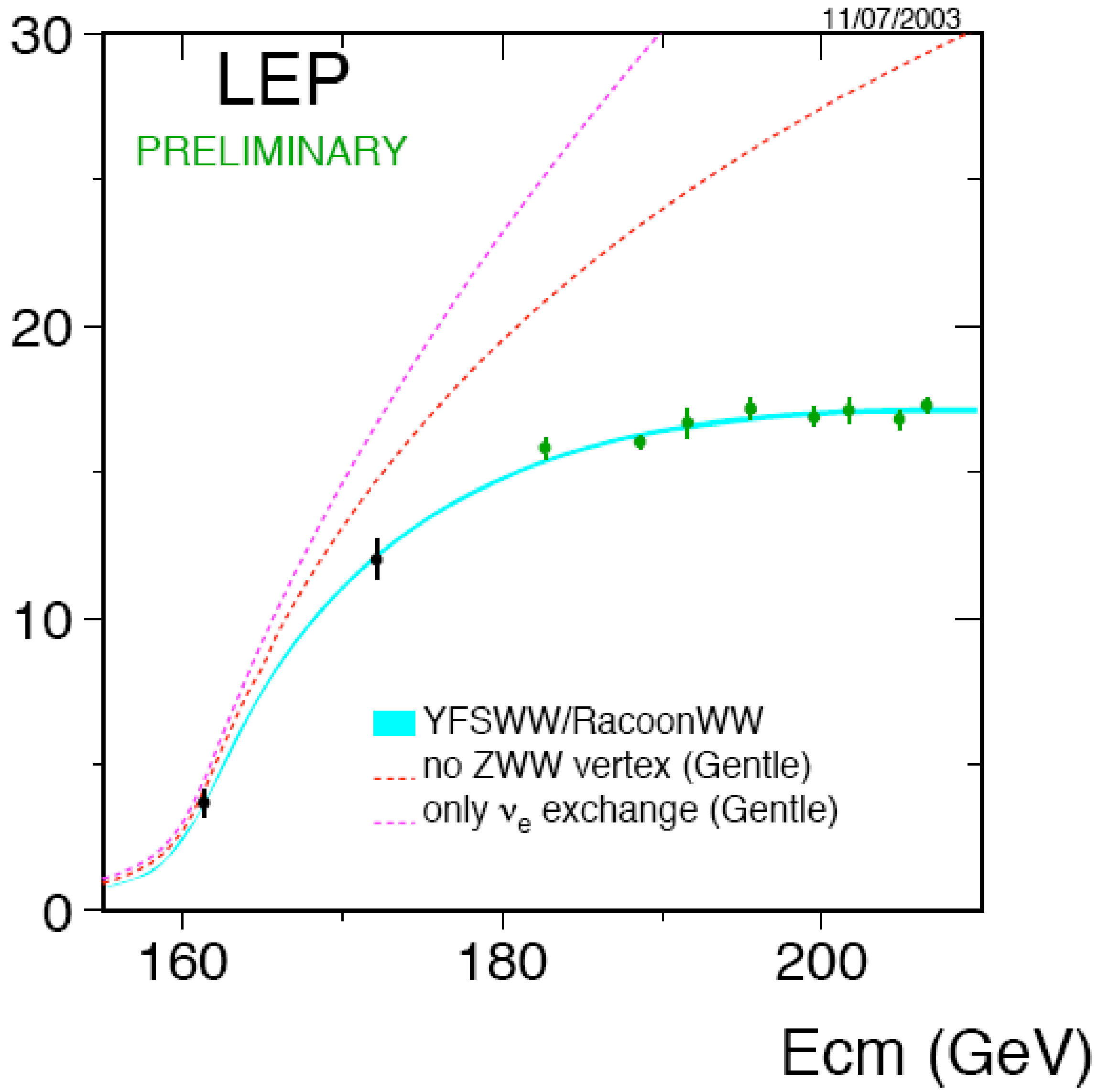
The Standard Model

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

$e^+e^- \to W^+W^-$





The Standard Model and the Mass Problem

the strong, weak and electromagnetic interactions of the elementary particles are described by gauge interactions

$SU(3)_C \times SU(2)_L \times U(1)_Y$

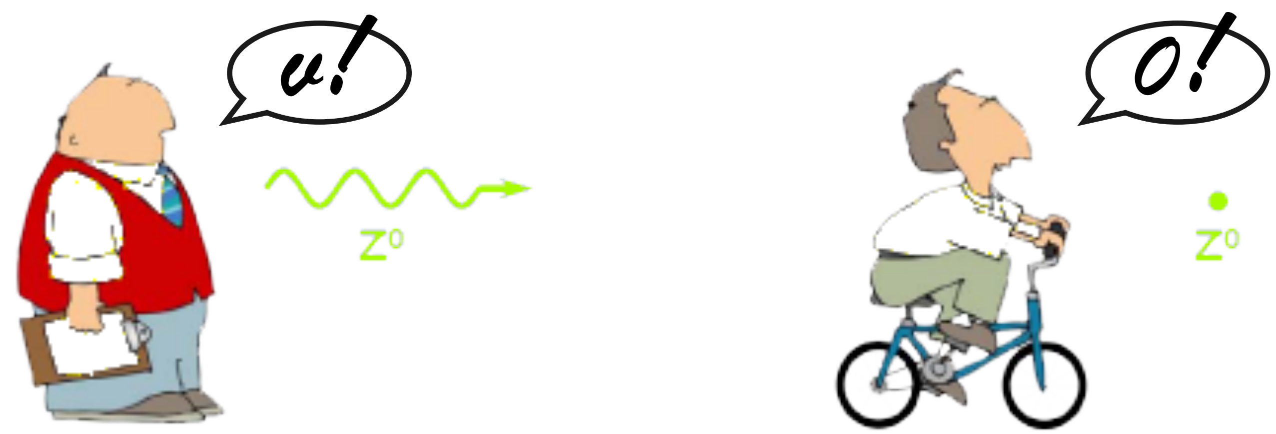
the masses of the quarks, leptons and gauge bosons don't obey the full gauge invariance

- $\begin{pmatrix} \nu_e \\ e \end{pmatrix}$ is a doublet of $SU(2)_L$ but $m_{\nu_e} \ll m_e$
- a mass term for the gauge field isn't invariant under gauge transformation $\delta A^a_\mu = \partial_\mu \epsilon^a + g f^{abc} A^b_\mu \epsilon^c$

⇒ spontaneous breaking of gauge symmetry ⇐

The longitudinal polarization of massive W, Z

a massless particle is never at rest: always possible to distinguish (and eliminate!) the longitudinal polarization



the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

symmetry breaking: new phase with more degrees of freedom

$$\epsilon_{\parallel} = \left(\frac{|\vec{p}|}{M}, \frac{E}{M} \frac{\vec{p}}{|\vec{p}|} \right)$$ polarization vector grows with the energy

The longitudinal polarization of massive W, Z

a massless particle is never at rest: … distinguish

(and elimin… …

3=2+1 Guralnik et al '64

the longitudinal polarization is physical for a massive spin-1 particle

(pictures: courtesy of G. Giudice)

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[pictures: courtesy of NYT]

2

Higgs Mechanism. Custodial symmetry

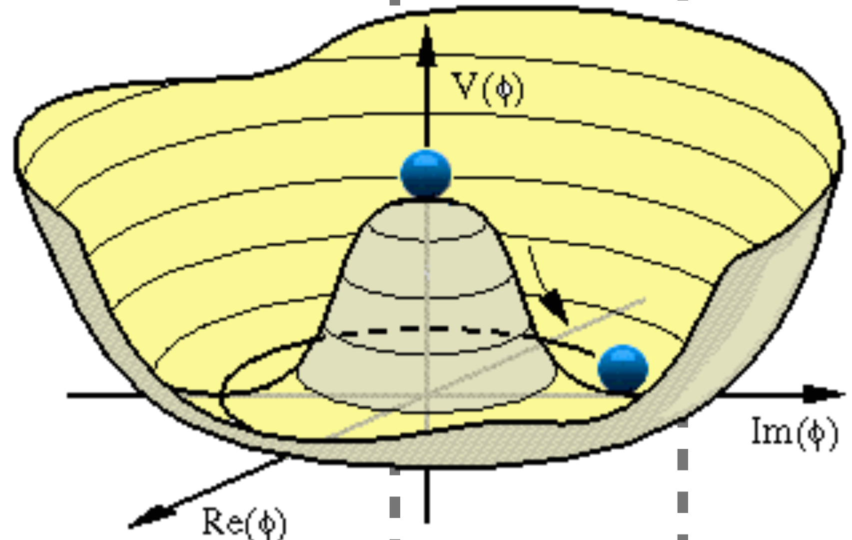
Higgs Mechanism

Symmetry of the Lagrangian

$$SU(2)_L \times U(1)_Y$$

Higgs Doublet

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$



Symmetry of the Vacuum

$$U(1)_{e.m.}$$

Vacuum Expectation Value

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \quad \text{with} \quad v \approx 246 \text{ GeV}$$

$$D_\mu H = \partial_\mu H - \frac{i}{2} \begin{pmatrix} g W_\mu^3 + g' B_\mu & \sqrt{2} g W_\mu^+ \\ \sqrt{2} g W_\mu^- & -g W_\mu^3 + g' B_\mu \end{pmatrix} H \quad \text{with} \quad \mathrm{W}_\mu^\pm = \frac{1}{\sqrt{2}} (\mathrm{W}_\mu^1 \mp \mathrm{W}_\mu^2)$$

$$|D_\mu H|^2 = \frac{1}{4} g^2 v^2 W_\mu^+ W^{-\,\mu} + \frac{1}{8} (W_\mu^3 \; B_\mu) \begin{pmatrix} g^2 v^2 & -g g' v^2 \\ -g g' v^2 & g'^2 v^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

- Gauge boson spectrum
  - electrically charged bosons $M_W^2 = \frac{1}{4} g^2 v^2$
  - electrically neutral bosons

$$Z_\mu = c W_\mu^3 - s B_\mu$$
$$\gamma_\mu = s W_\mu^3 + c B_\mu$$

Weak mixing angle

$$c = \frac{g}{\sqrt{g^2 + g'^2}} \qquad s = \frac{g'}{\sqrt{g^2 + g'^2}}$$

$$M_Z^2 = \frac{1}{4} (g^2 + g'^2) v^2$$

$$M_\gamma = 0$$

Custodial Symmetry

Sikivie et al, '80

- Rho parameter

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_w} = \frac{\frac{1}{4} g^2 v^2}{\frac{1}{4}(g^2+g'^2)v^2 \frac{g^2}{g^2+g'^2}} = 1$$

- Consequence of an approximate global symmetry of the Higgs sector

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$ Higgs doublet = 4 real scalar fields

$$V(H) = \lambda \left(H^\dagger H - \frac{v^2}{2} \right)^2$$ is invariant under the rotation of the four real components

$$SO(4) \sim SU(2)_L \times SU(2)_R$$

$SU(2)_R$ (acting from above), $SU(2)_L$ (acting from the left):

$$\left(i\sigma^2 H^\star \quad H \right) = \Phi$$

2x2 matrix

$$\Phi^\dagger \Phi = H^\dagger H \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$V(H) = \frac{\lambda}{4} \left(\mathrm{tr}\Phi^\dagger\Phi - \mathrm{v}^2 \right)^2$$

explicitly invariant under $SU(2)_L \times SU(2)_R$

Custodial Symmetry

Sikivie et al, '80

Higgs vev

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \qquad \langle \Phi \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 1 & \\ & 1 \end{pmatrix}$$

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

unbroken symmetry in the broken phase

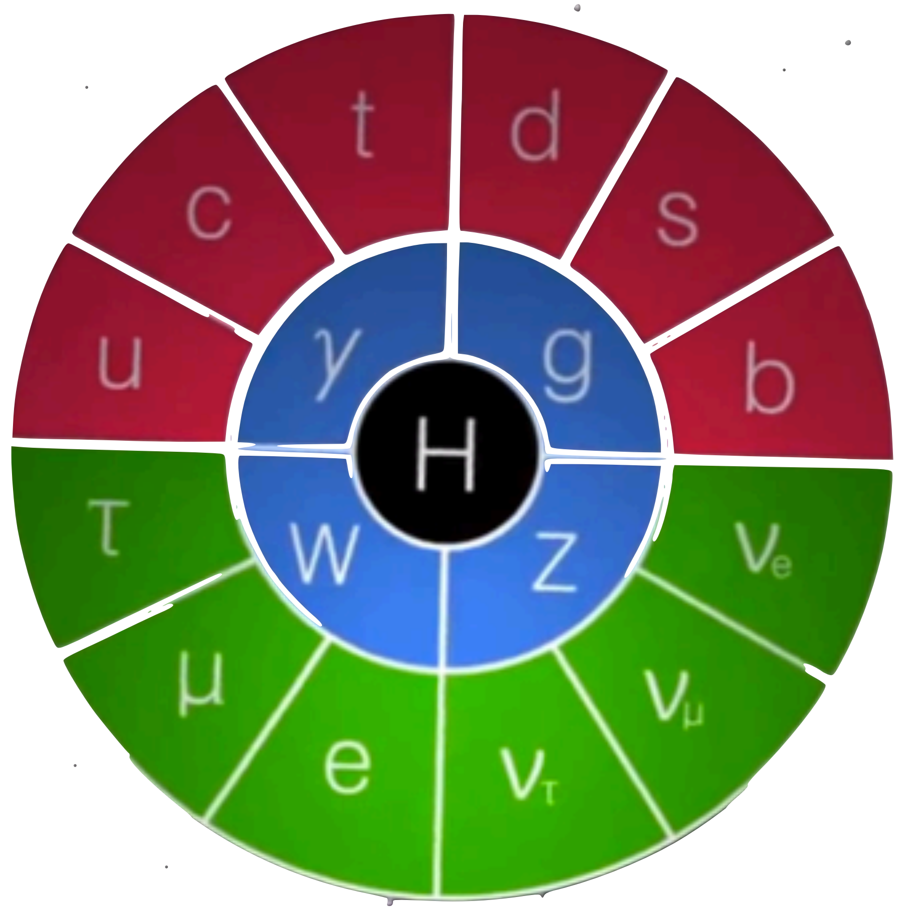
$$(W_\mu^1, W_\mu^2, W_\mu^3) \quad \text{transforms as a triplet}$$

$$(Z_\mu \, \gamma_\mu) \begin{pmatrix} M_Z^2 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} Z^\mu \\ \gamma^\mu \end{pmatrix} = (W_\mu^3 \, B_\mu) \begin{pmatrix} c^2 M_Z^2 & -csM_Z^2 \\ -csM_Z^2 & s^2 M_Z^2 \end{pmatrix} \begin{pmatrix} W^{3\,\mu} \\ B^\mu \end{pmatrix}$$

The $SU(2)_V$ symmetry imposes the same mass term for all W^i thus $c^2 M_Z^2 = M_W^2$

$$\rho = 1$$

The hypercharge gauge coupling and the Yukawa couplings break the custodial $SU(2)_V$, which will generate a (small) deviation to $\rho = 1$ at the quantum level.



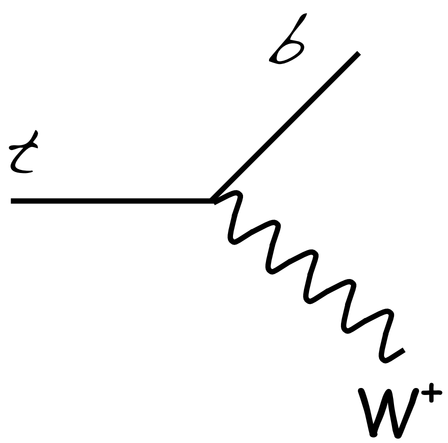
[pictures: courtesy of D.E. Kaplan @ particle fever]

3

Goldstone equivalence theorem

The BEH mechanism: “V_L=Goldstone bosons”

At high energy, the physics of the gauge boson becomes simple



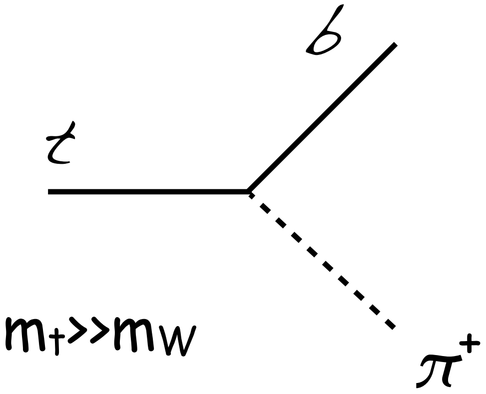
$$\Gamma(t \to bW_L) = \frac{g^2}{64\pi}\frac{m_t^2}{m_W^2}\frac{(m_t^2 - m_W^2)^2}{m_t^3}$$

$$\Gamma(t \to bW_T) = \frac{g^2}{64\pi}\frac{2(m_t^2 - m_W^2)^2}{m_t^3}$$

democratic decay at threshold

at high energy ($m_t \gg m_W$), W_L dominates the decay

$m_t \gg m_W$



Goldstone equivalence theorem

$W^\pm_L$, $Z_L \approx SO(4)/SO(3)$

LEP already established the BEH mechanism

The pending question was: how it is realized?

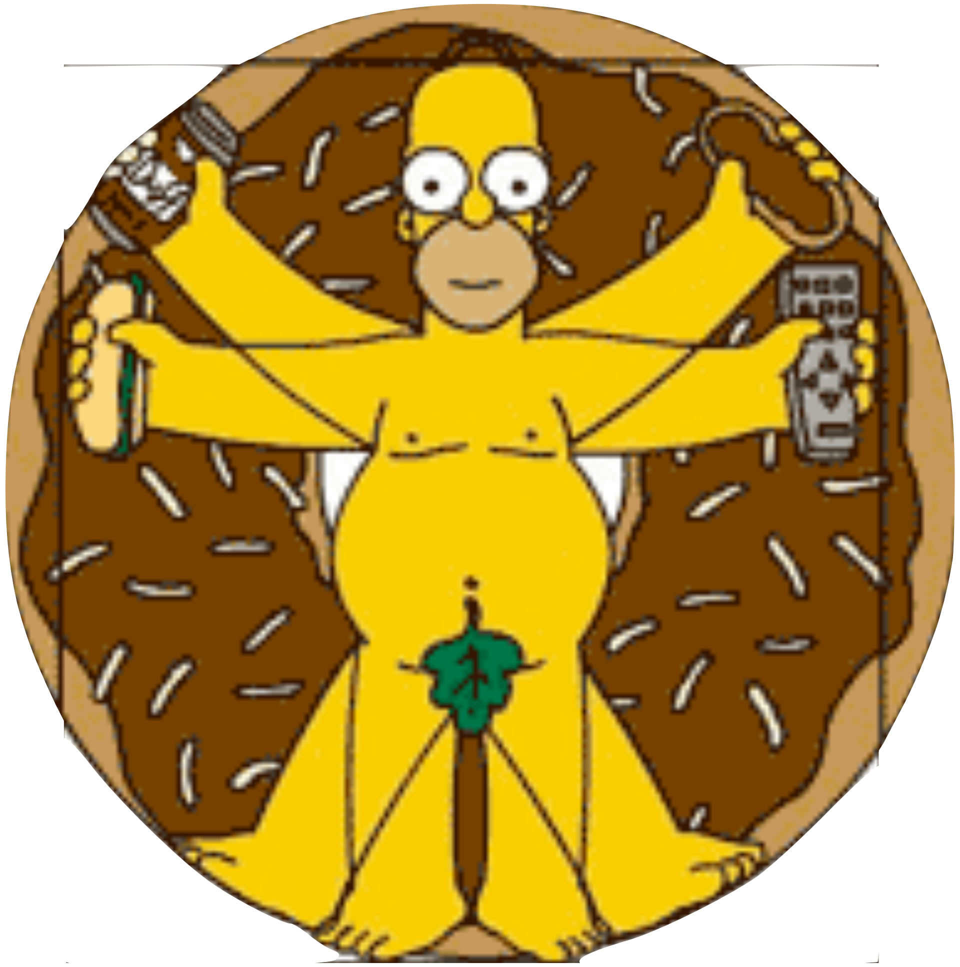
Via a fundamental EW doublet? A la technicolor?

Is there a Higgs boson in addition to the 3 Goldstone bosons?

In other words, LEP established a simple description of EWSB in the energy range

$$m_W \ll E \ll 4\pi v = \frac{8\pi m_W}{g}$$

The goal of the LHC was/is to understand what comes next



[pictures: courtesy of I. Low]

4

What is the SM Higgs boson?

The UV behavior of the weak Goldstone

symmetry breaking: new phase with more degrees of freedom

massive $W^\pm$, Z: 3 physical polarizations=eaten Goldstone bosons $\frac{SU(2)_L \times SU(2)_R}{SU(2)_V}$

⟹ UV behavior of these Goldstone's? ⟸

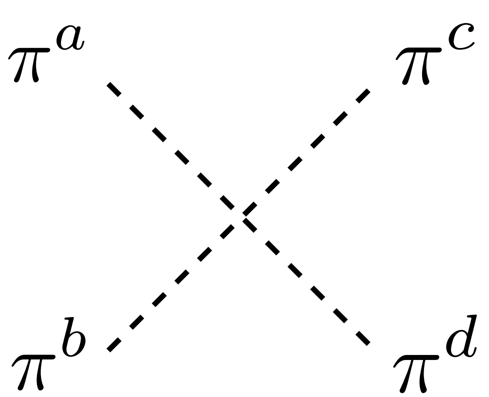
$$\mathcal{L}_{\rm mass} = m_W^2 W_\mu^+ W^{\mu\,-} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu = \frac{v^2}{4} \mathrm{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)$$

$\Sigma = e^{i\sigma^a \pi^a / v}$

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm mass} = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6v^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \ldots$$

contact interaction growing with energy



$$\mathcal{A}\left(\pi^a \pi^b \to \pi^c \pi^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

$$\mathcal{A}(s,t,u) = \frac{s}{v^2}$$ Weinberg's LET

the behavior of this amplitude is not consistent above $4\pi v$ (≈1÷3TeV)

Lee, Quigg & Thacker '77

A QCD antecedent

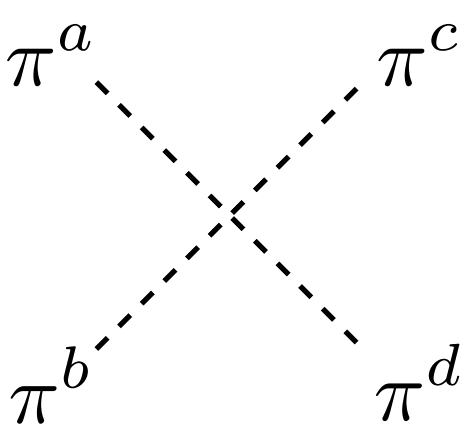
QCD pions are Goldstone bosons associated to $SU(2)_L \times SU(2)_R / SU(2)_V$

$$U = e^{i\pi^a \sigma^a / f_\pi} \begin{pmatrix} 0 \\ \frac{f_\pi}{\sqrt{2}} \end{pmatrix}$$

kinetic terms for U ⇔ interaction terms for π^a

$$\mathcal{L} = |\partial_\mu U|^2 = \frac{1}{2}(\partial_\mu \pi^a)^2 - \frac{1}{6 f_\pi^2}\left((\pi^a \partial_\mu \pi^a)^2 - (\pi^a)^2 (\partial_\mu \pi^a)^2\right) + \ldots$$

contact interaction growing with energy



$$\mathcal{A}\left(\pi^a \pi^b \to \pi^c \pi^d\right) = \mathcal{A}(s,t,u)\delta^{ab}\delta^{cd} + \mathcal{A}(t,s,u)\delta^{ac}\delta^{bd} + \mathcal{A}(u,t,s)\delta^{ad}\delta^{bc}$$

$$\mathcal{A}(s,t,u) = \frac{s}{f_\pi^2}$$

$$f_\pi = 93 \text{ MeV}$$

⇒ unitarity bound

$$\sqrt{s} \sim 4\sqrt{\pi} f_\pi = 660 \text{ MeV}$$

rho meson (m=770 MeV) is restoring unitarity

Longitudinal polarization of a massive spin 1

a massive spin 1 particle has 3 physical polarizations:

$$k^\mu = (E, 0, 0, k)$$

with $k_\mu k^\mu = E^2 - k^2 = M^2$

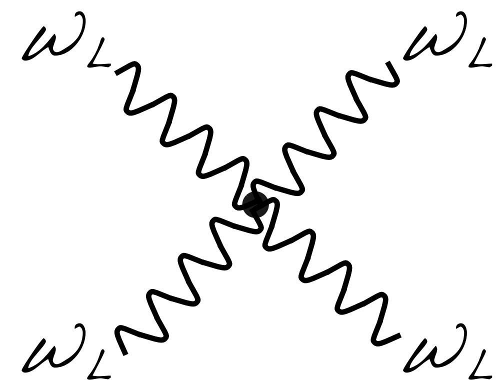
$$A_\mu = \epsilon_\mu \; e^{i k_\mu x^\mu}$$

$$\epsilon^\mu \epsilon_\mu = -1 \qquad k^\mu \epsilon_\mu = 0$$

- 2 transverse: $\begin{cases} \epsilon_1^\mu = (0,1,0,0) \\ \epsilon_2^\mu = (0,0,1,0) \end{cases}$
- 1 longitudinal: $\epsilon_{||}^\mu = (\frac{k}{M}, 0, 0, \frac{E}{M}) \approx \frac{k^\mu}{M} + \mathcal{O}(\frac{E}{M})$

(in the R-ξ gauge, the time-like polarization ($\epsilon^\mu \epsilon_\mu = 1 \quad k^\mu \epsilon_\mu = M$) is arbitrarily massive and decouple)

Bad UV behavior for the scattering of the longitudinal polarizations

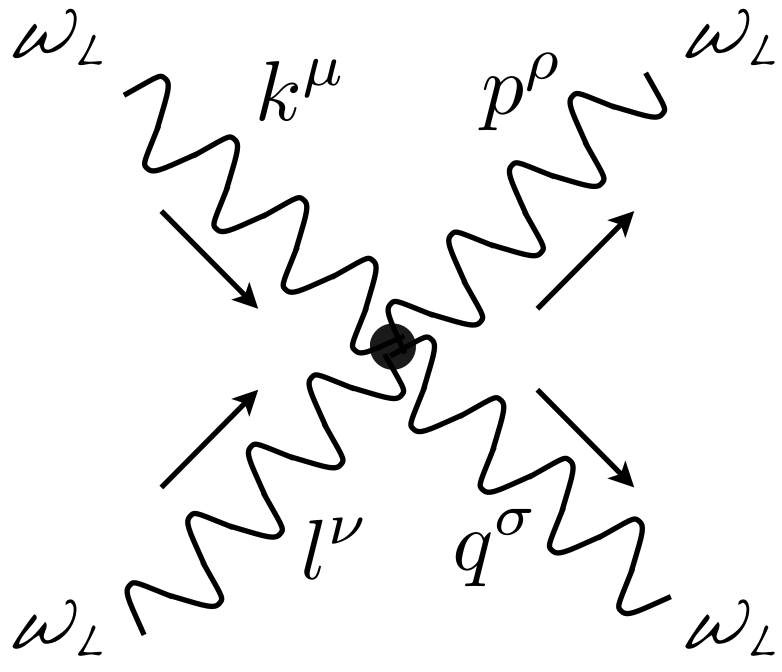


Why do we need a Higgs ?

NO LOSE THEOREM

The W and Z masses are inconsistent with the known particle content! Need more particles to soften the UV behavior of massive gauge bosons.

Bad UV behavior for
the scattering of the longitudinal polarizations

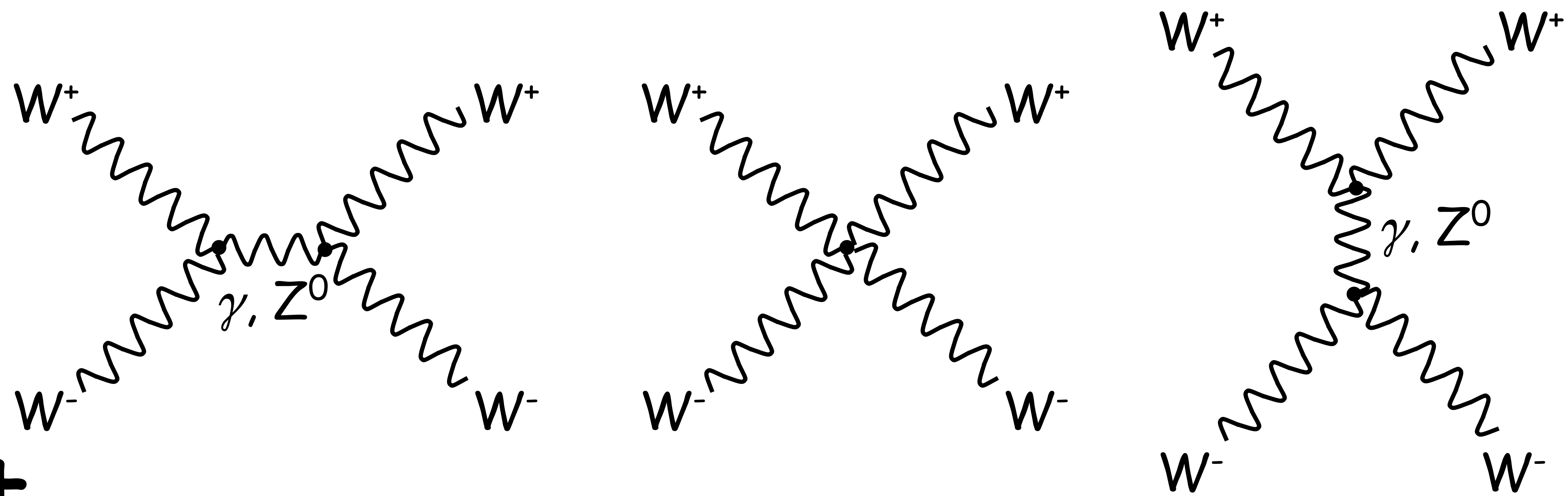


$$\mathcal{A} = \epsilon^\mu_{||}(k)\epsilon^\nu_{||}(l)\, ig^2(2\eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho})\,\epsilon^\rho_{||}(p)\epsilon^\sigma_{||}(q)$$

$$\mathcal{A} = g^2 \frac{E^4}{4M_W^4}$$

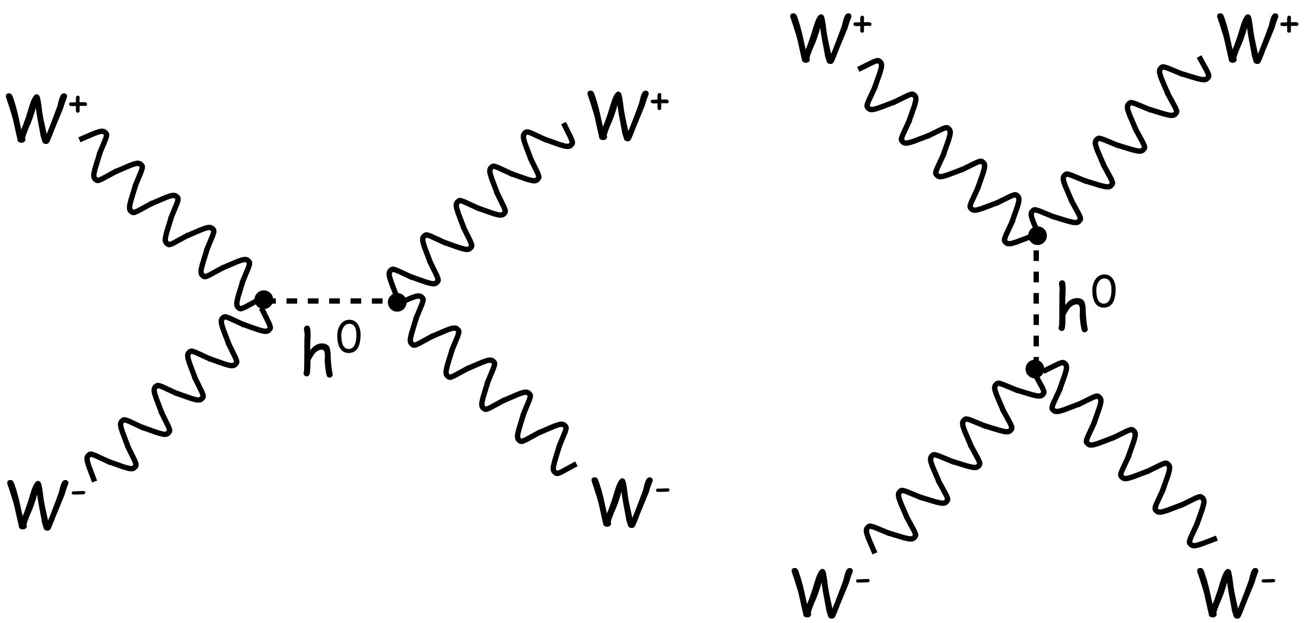
violations of perturbative unitarity around E ~ M

Why do we need a Higgs ?



$$\mathcal{A} = g^2 \left(\frac{E}{M_W}\right)^2$$

+



+

$$\mathcal{A} = -g^2 \left(\frac{E}{M_W}\right)^2$$

$$\mathcal{A} = g^2 \left(\frac{M_H}{2M_W}\right)^2$$

The Higgs boson unitarize the W scattering
(if its mass is below ~ 1 TeV)

W_L scattering = pion scattering
Goldstone equivalence theorem

Lewellyn Smith '73
Dicus, Mathur '73
Cornwall, Levin, Tiktopoulos '73
Lee, Quigg, Thacker '77

Higgs as UV moderator

massless W, Z ⟷ gauge invariance

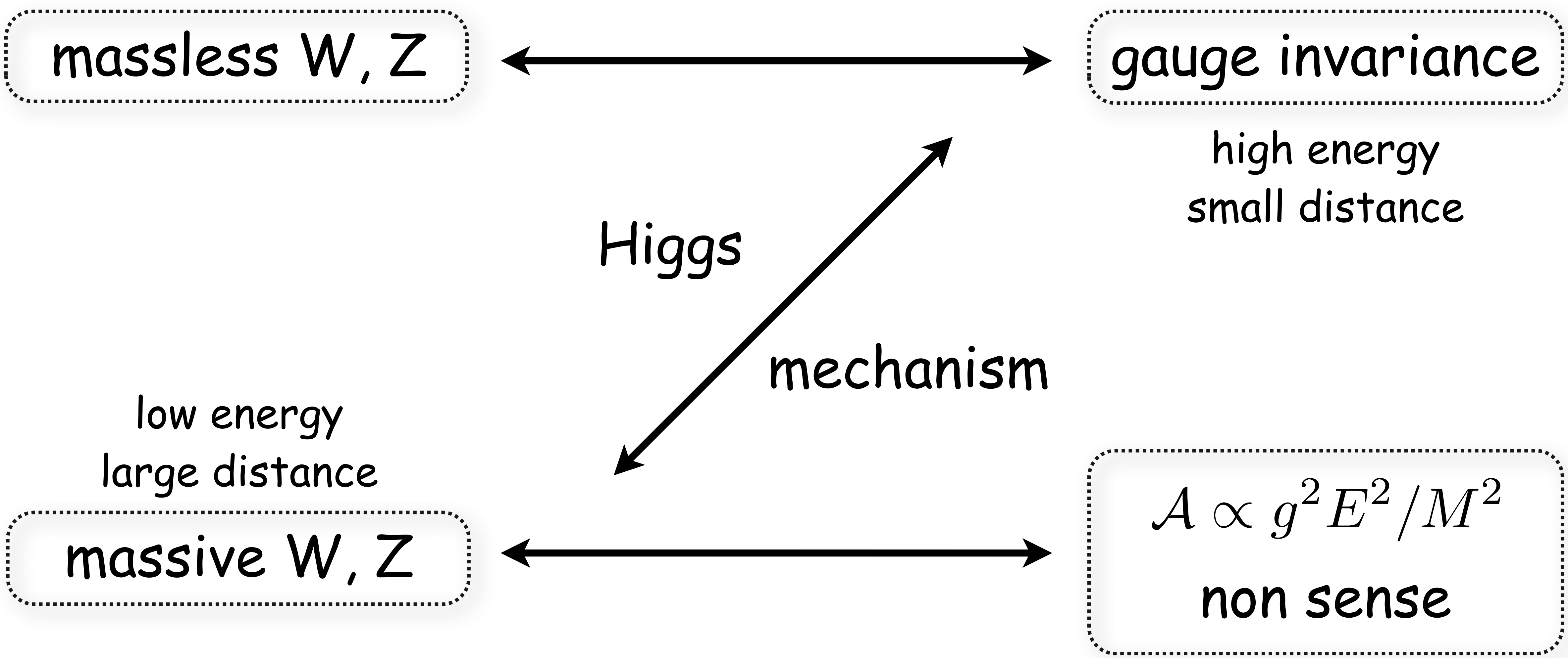
high energy
small distance

Puzzle:
compatibility between
high and low energy

low energy
large distance

massive W, Z ⟷ $\mathcal{A} \propto g^2 E^2 / M^2$
non sense

Higgs as UV moderator



Unitarity Bound

Lee, Quigg, Thacker '77
Chanowitz, Gaillard '85

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|\mathcal{A}|^2$$

Partial wave amplitude decomposition:

$$\mathcal{A} = 16\pi \sum_{l=0}^{\infty}(2l+1)P_l(\cos\theta)\, a_l \qquad a_l = \frac{1}{32\pi}\int_{-1}^{+1} d(\cos\theta) P_l(\cos\theta)\mathcal{A}$$

$$\sigma = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2$$

$P_0(x) = 1,\ P_1(x) = x,\ P_2(x) = 3x^2/2 - 1/2 \ldots$

$\int_{-1}^{1} dx P_l(x) P_{l'}(x) = \frac{2}{2l+1}\delta_{ll'}$

Optical theorem:

$$\sigma = \mathrm{Im}\left(\mathcal{A}_{|\theta=0}\right)/s \Rightarrow \mathrm{Im}\,(a_l) = |a_l|^2 \Rightarrow (\mathrm{Im}\,(a_l) - 1/2)^2 + (\mathrm{Re}\,(a_l))^2 = 1/4$$

$$|\mathrm{Re}\,(a_l)\,| \leq 1/2$$

$W^+ W^- \to W^+ W^-$ $\qquad \mathcal{A} = \mathcal{A}(s) + \mathcal{A}(t)$

SM without a Higgs $\quad \mathcal{A}(s) = s/v^2$

$$a_0 = \frac{s}{8\pi v^2} \Rightarrow \sqrt{s} = 2E \leq 4\sqrt{\pi}v \approx 1.7\ \mathrm{TeV}$$

SM with a Higgs $\quad \mathcal{A}(s) = (s - s^2/(s-m_h^2))/v^2$

$$a_0 = \frac{m_h^2}{16\pi v^2} \Rightarrow m_h \leq 2\sqrt{2\pi}v \approx 1.2\ \mathrm{TeV}$$

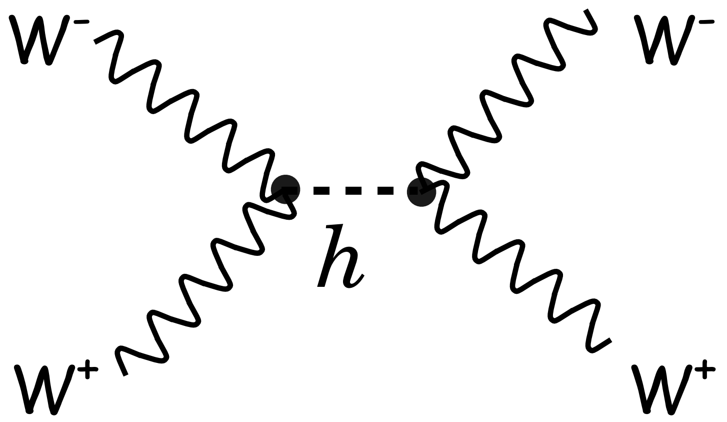
Stronger Bound
$2W^+W^- + ZZ$ scattering
$m_h \leq 4\sqrt{\pi/3}v \approx 1.0\ \mathrm{TeV}$

What is the Higgs the name of?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} {\rm Tr} \left(D_\mu \Sigma^\dagger D_\mu \Sigma \right) \left(1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} \right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c \frac{h}{v} \right)$$

'a', 'b' and 'c' are arbitrary free couplings



$$\mathcal{A} = \frac{1}{v^2} \left(s - \frac{a^2 s^2}{s - m_h^2} \right)$$

growth cancelled for
a = 1
restoration of
perturbative unitarity

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10

$$\Sigma = e^{i \sigma^a \pi^a / v}$$

Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$

$$D_\mu \Sigma \approx W_\mu$$

What is the Higgs the name of?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

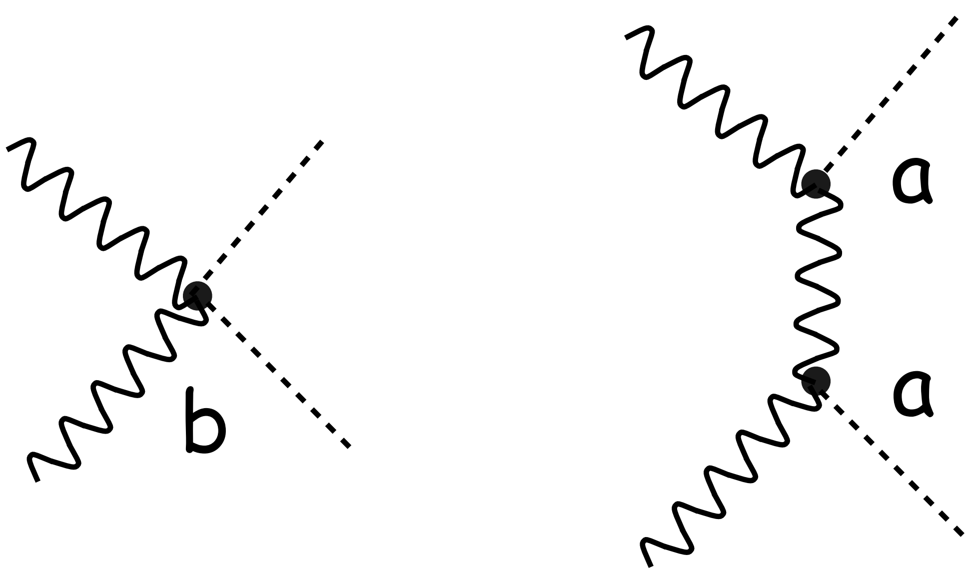
'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels $WW \to WW$

For $b = a^2$: perturbative unitarity in inelastic channels $WW \to hh$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



What is the Higgs the name of?

A single scalar degree of freedom neutral under $SU(2)_L \times SU(2)_R / SU(2)_V$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings

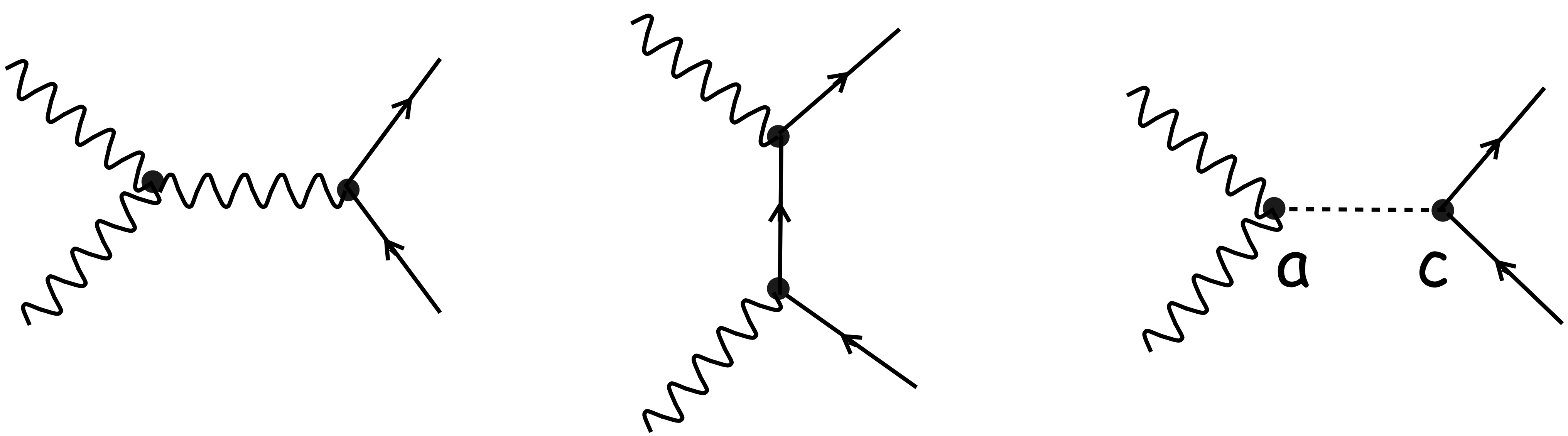
For a=1: perturbative unitarity in elastic channels WW $\to$ WW

For b = a^2: perturbative unitarity in inelastic channels WW $\to$ hh

For ac=1: perturbative unitarity in inelastic WW $\to$ $\psi\,\psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



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$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} \text{Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings

For a=1: perturbative unitarity in elastic channels WW → WW

For b = a^2: perturbative unitarity in inelastic channels WW → hh

For ac=1: perturbative unitarity in inelastic WW → $\psi\,\psi$

'a=1', 'b=1' & 'c=1' define the SM Higgs

Higgs properties are fixed once all masses are known (including m_H)

$\mathcal{L}_{\rm EWSB}$ can be rewritten as $D_\mu H^\dagger D_\mu H$

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \pi^a / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

h and π^a (ie W_L and Z_L) combine to form a linear representation of $SU(2)_L \times U(1)_Y$

What is the Higgs the name of?

The SM Higgs couplings are fixed to restore unitarity with mass

$\Sigma = e^{i\sigma^a \pi^a / v}$ Goldstone of $SU(2)_L \times SU(2)_R / SU(2)_V$ $D_\mu \Sigma = g V_\mu$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4} {\rm Tr}\left(D_\mu \Sigma^\dagger D_\mu \Sigma\right) \left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2}\right) - \lambda \bar{\psi}_L \Sigma \psi_R \left(1 + c\frac{h}{v}\right)$$

'a', 'b' and 'c' are arbitrary free couplings

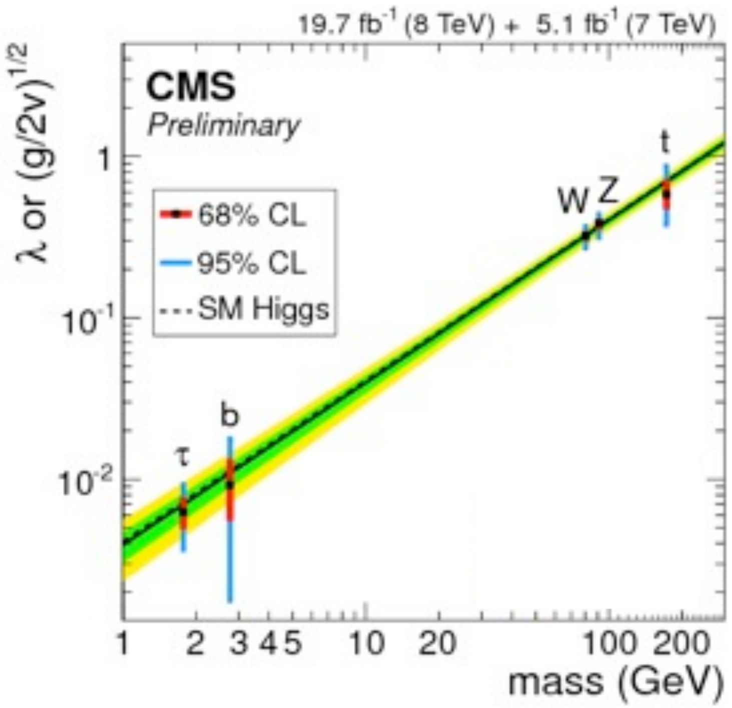
For a=1: perturbative unitarity in elastic channels WW → WW

For b=a²: perturbative unitarity in inelastic channels WW → hh

For ac=1: perturbative unitarity in inelastic WW → $\psi\,\psi$

Cornwall, Levin, Tiktopoulos '73

Contino, Grojean, Moretti, Piccinini, Rattazzi '10



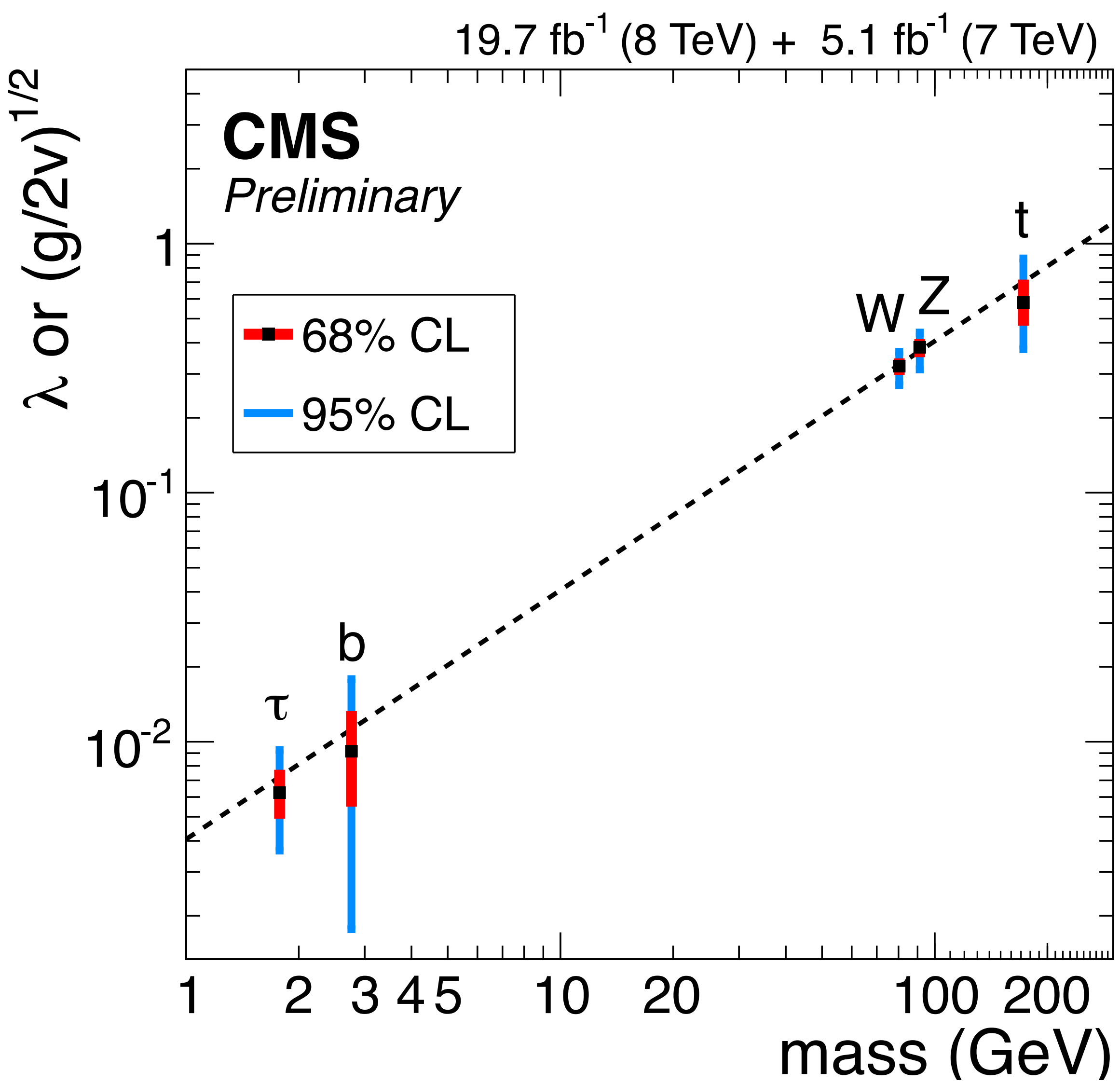
CMS PAS-HIG-14-009

Higgs couplings
are proportional
to the masses of the particles

$$\lambda_\psi \propto \frac{m_\psi}{v}\,, \qquad \lambda_V^2 \equiv \frac{g_{VVh}}{2v} \propto \frac{m_V^2}{v^2}$$

What is the Higgs the name of?

The SM Higgs couplings are fixed to restore unitarity with mass



Higgs group @ Snowmass '13

Facility	LHC	HL-LHC
$\sqrt{s}$ (GeV)	14,000	14,000
$\int \mathcal{L} dt$ (fb^{-1})	300/expt	3000/expt
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_ℓ	$6-8\%$	$2-5\%$
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$

~ Is this fit theoretically consistent? ~

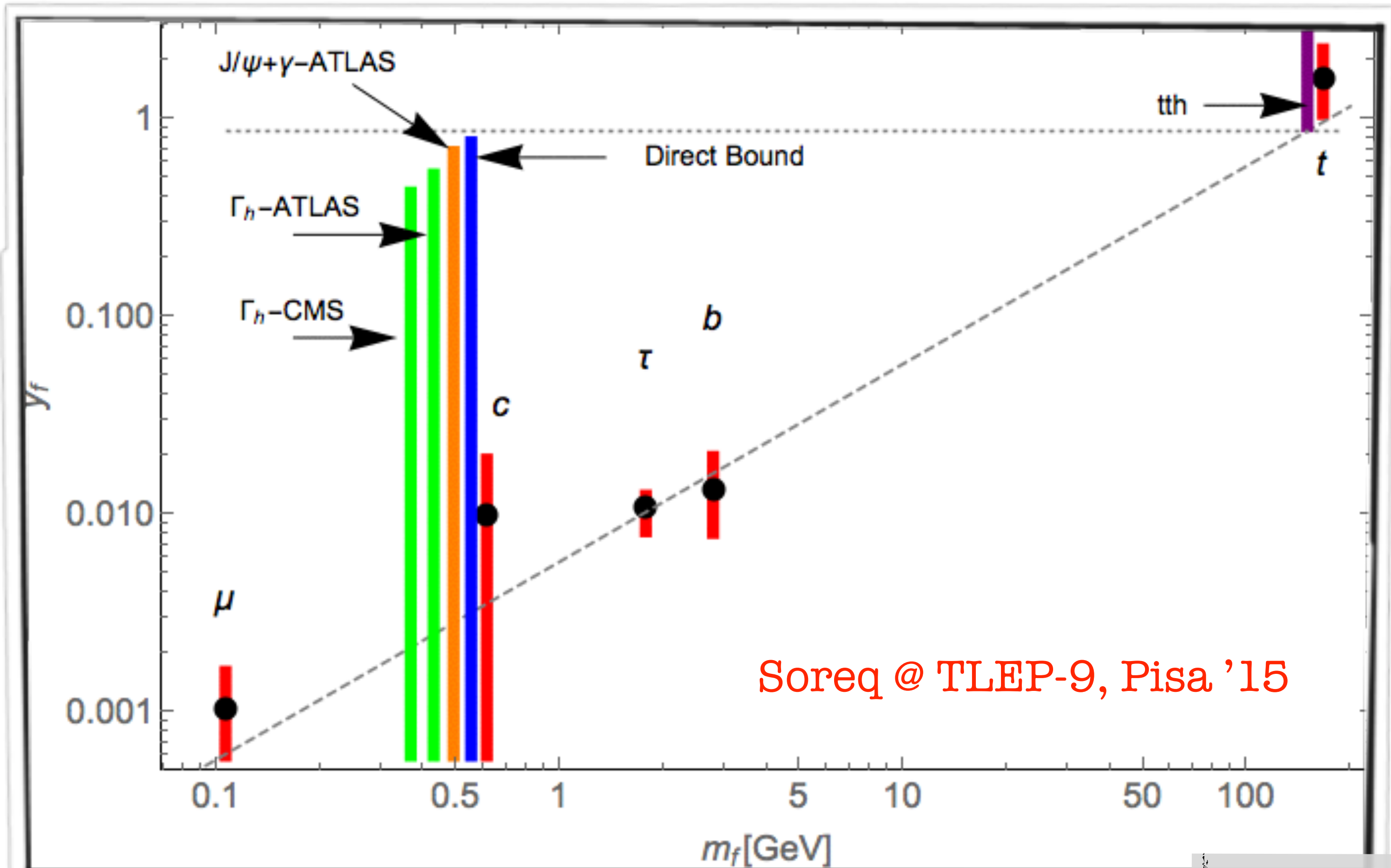
can you generate a 500% deviations

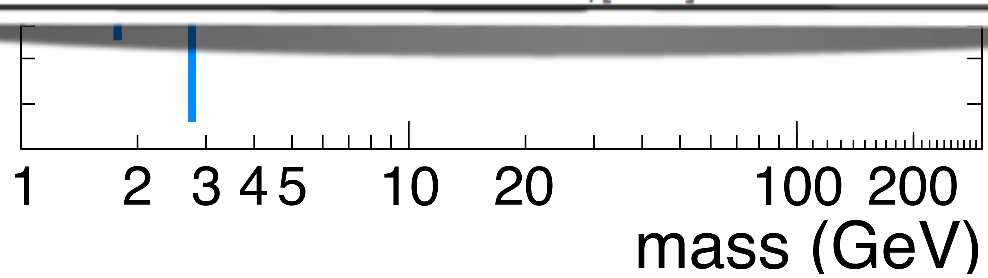
in the bottom coupling without generating other coupling

structures not taken into account in the fit?

What is the Higgs the name of?

The SM Higgs couplings are fixed to restore unitarity with mass





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~ Is this fit theoretically consistent? ~

can you generate a 500% deviations

in the bottom coupling without generating other coupling

structures not taken into account in the fit?

missing information to complete the picture

° width measurement?

° couplings to light particles?

inclusive (e.g. c-tagging) or exclusive ($h \to J/\Psi + \gamma$)

° coupling to top?

known indirectly ($gg \to h$) or via difficult tth channel

Higgs and Flavor

In SM, the Yukawa interactions are the only source of the fermion masses

$$y_{ij}\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\bar{f}_{L_i}f_{R_j} + \frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

mass — higgs-fermion interactions

both matrices are simultaneously diagonalizable

⇩ ⇩ ⇩

no tree-level Flavor Changing Current induced by the Higgs

Not true anymore if the SM fermions mix with vector-like partners (*) or for non-SM Yukawa

$$y_{ij}\left(1+c_{ij}\frac{|H|^2}{f^2}\right)\bar{f}_{L_i}Hf_{R_j} = \frac{y_{ij}v}{\sqrt{2}}\left(1+c_{ij}\frac{v^2}{2f^2}\right)\bar{f}_{L_i}f_{R_j} + \left(1+3c_{ij}\frac{v^2}{2f^2}\right)\frac{y_{ij}}{\sqrt{2}}h\bar{f}_{L_i}f_{R_j}$$

Look for SM forbidden Flavor Violating decays $h \to \mu\tau$ and $t \to hc$

- weak indirect constrained by flavor data (e.g. $\mu \to e\gamma$): BR<10% — Blankenburg, Ellis, Isidori '12
- ATLAS and CMS have the sensitivity to set bounds O(1%) — Harnik et al '12; Davidson, Verdier '12; CMS-PAS-HIG-2014-005
- ILC/CLIC/FCC-ee can certainly do much better

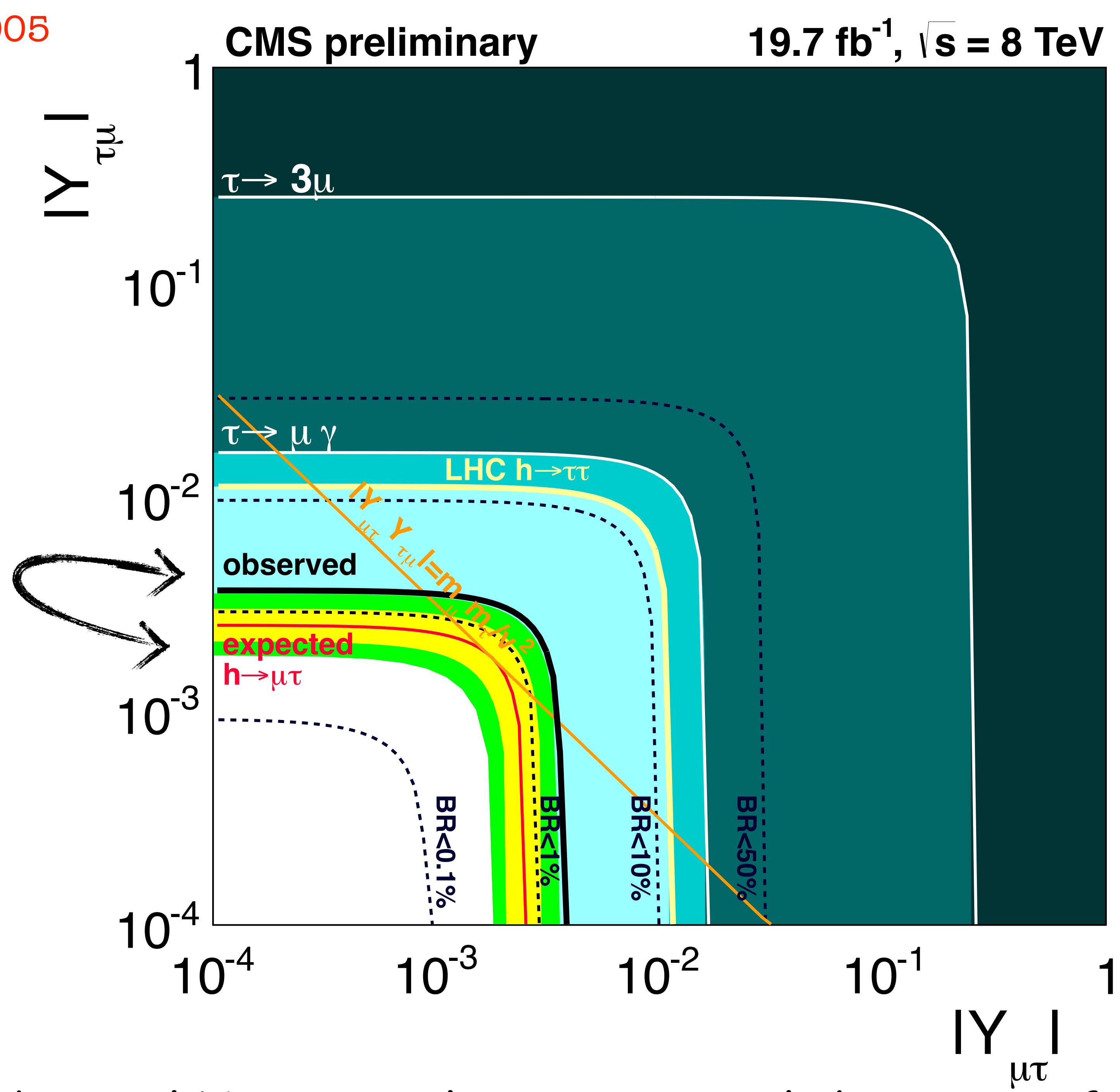
(*) e.g. Buras, Grojean, Pokorski, Ziegler '11

Higgs and Flavor

In SM, the Yukawa interactions are the only source of the fermion masses

CMS-PAS-HIG-2014-005

by the way:
2.3σ excess!



Off-diagonal Higgs couplings can reveal the origin of flavor

The interesting models of flavor ($Y_{ij} \approx \sqrt{(m_i m_j / v^2)}$) start being probed by the experimental data

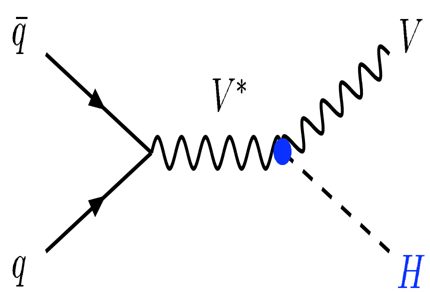
5

SM Higgs @ colliders

(SM) Higgs Production

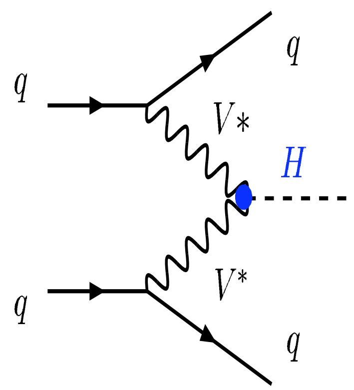
(see for instance A. Djouadi, hep-ph/0503172)

Higgs-strahlung



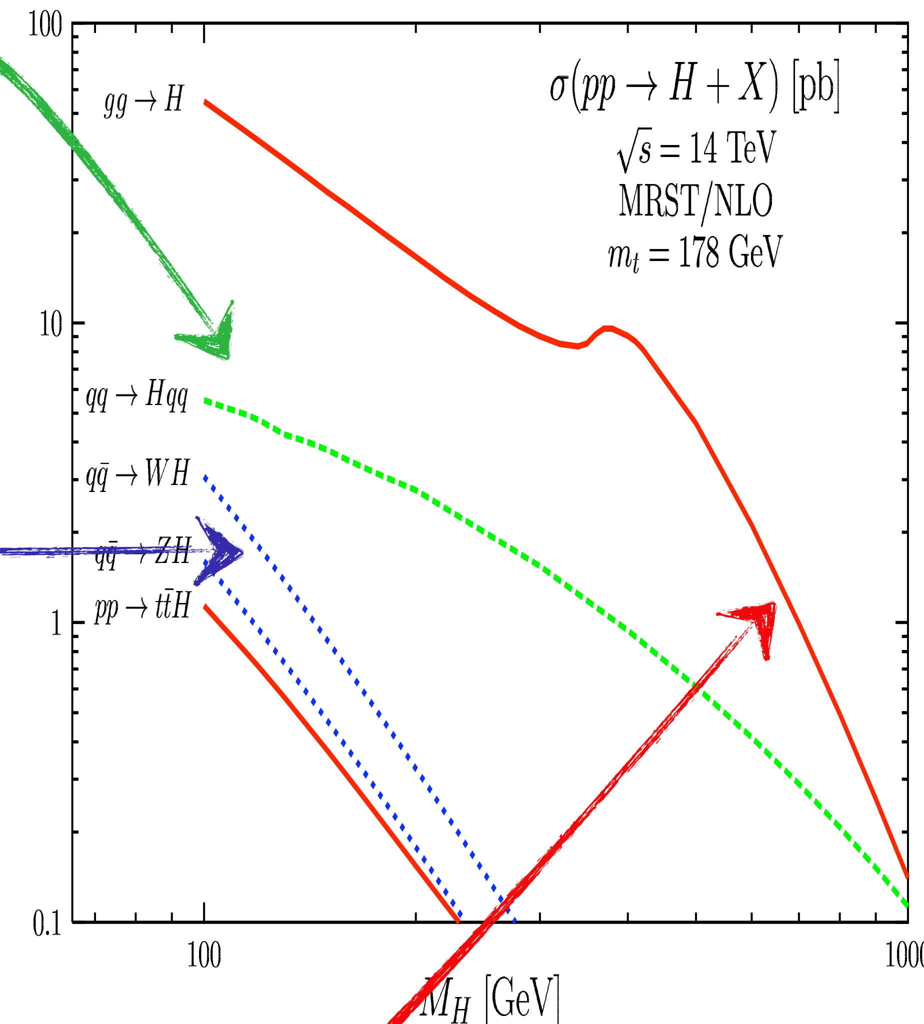
$\propto$ 1/s: Tevatron, ~~LHC~~

Vector boson fusion

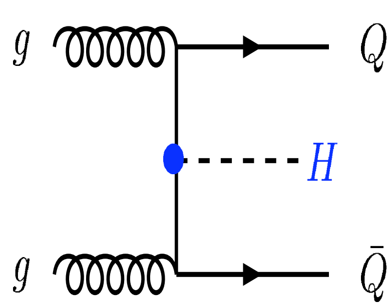


forward jet tagging
central jet veto
small hadronic activity

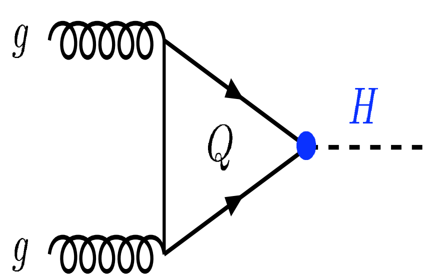
Higgs production @ LHC



QQ associated production



Gluon fusion



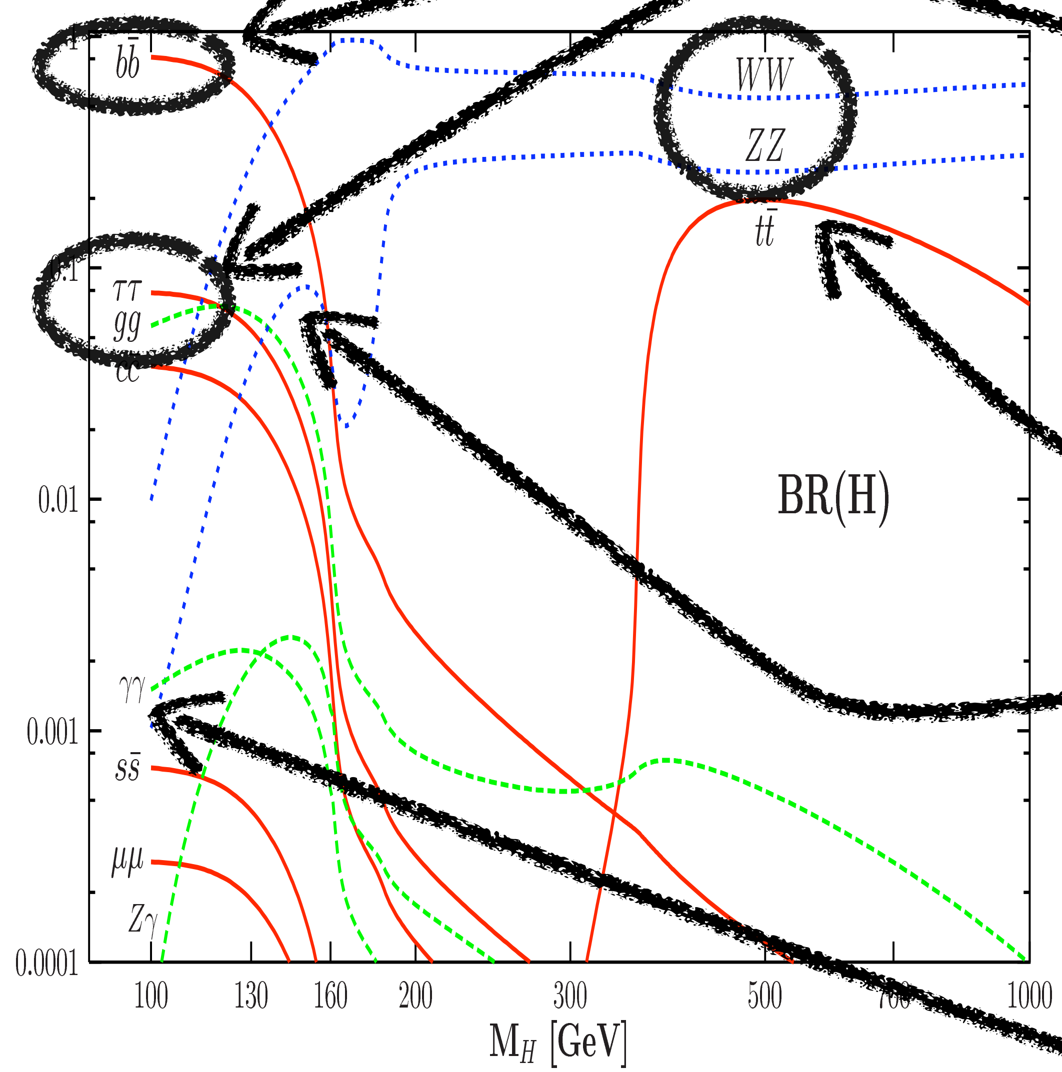
single final state
large NLO enhancement

(SM) Higgs Decays

Higgs couples proportionally to masses:

it decays into the heaviest particle available by phase space

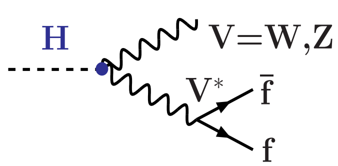
BRs



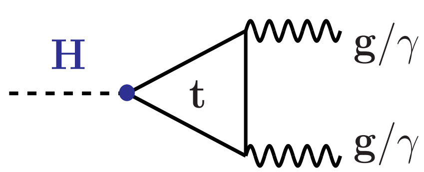
light Higgs

heavy Higgs

decay into VV below threshold

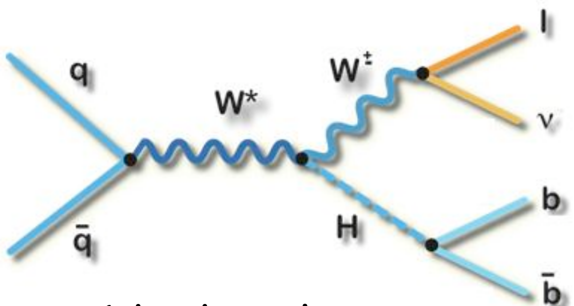


decay into massless particles (γ, gluons) at 1-loop

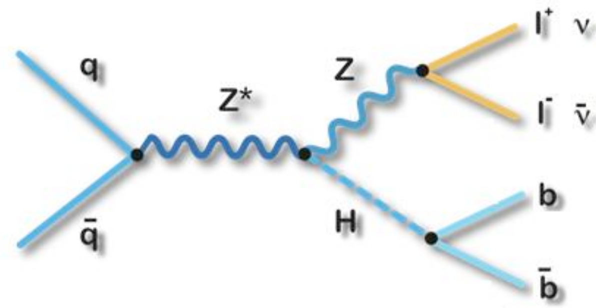


(SM) Higgs Searches @ Tevatron

Low Mass Higgs



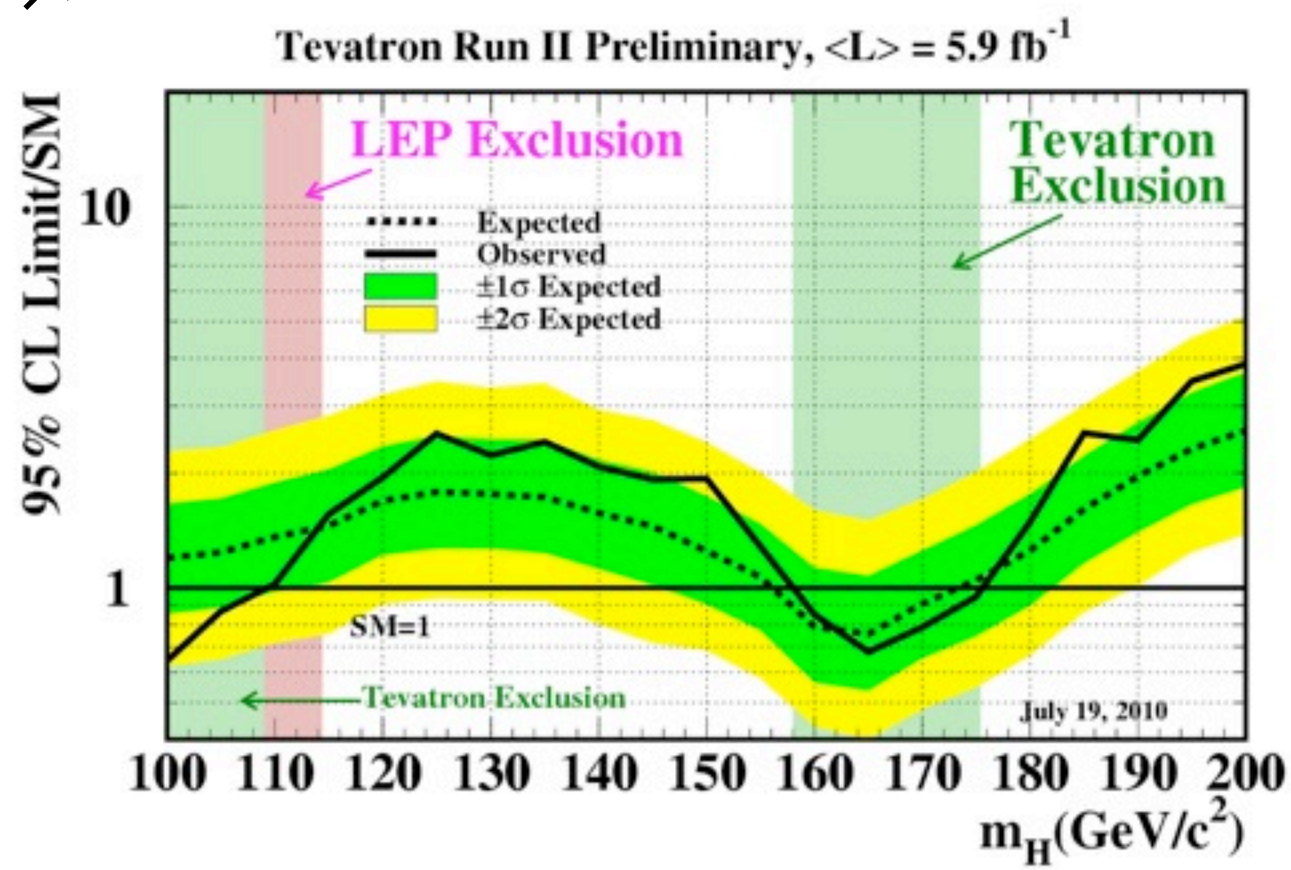
1 high p_T lepton
$\not{E}_T$
2 b-jets



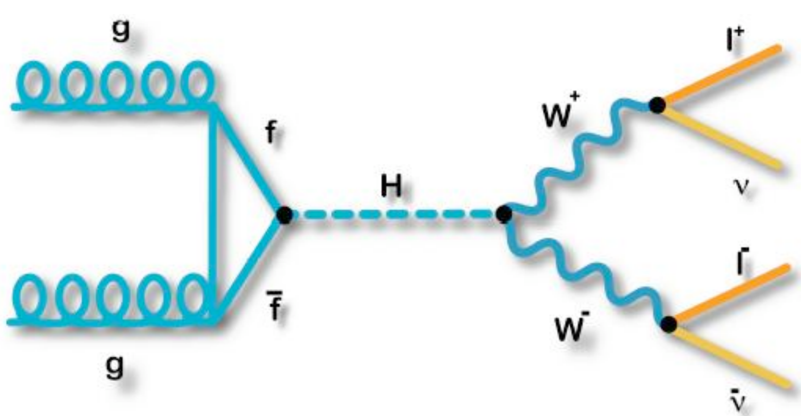
2 high p_T leptons/high $\not{E}_T$
2 b-jets

Issues:

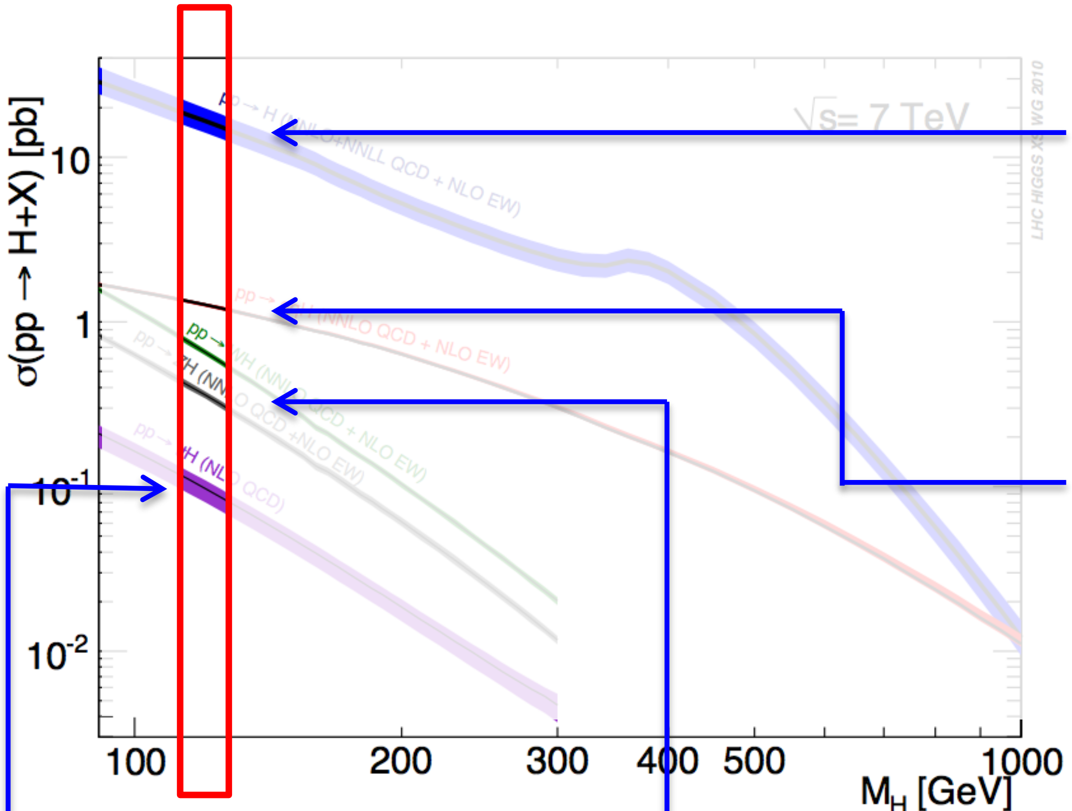
- lepton identification
- b-tagging performance
- dijet mass resolution

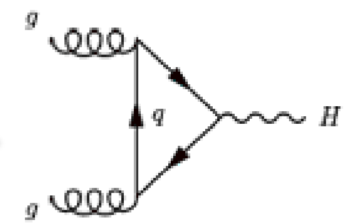


Higg Mass Higgs



(SM) Higgs Searches @ the LHC



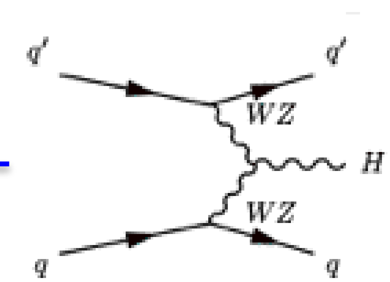


- Gluon fusion process :

Dominant process known at

NNnLO TH uncertainty ~O(10%)

~0.5 M events produced!

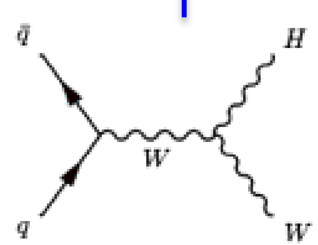


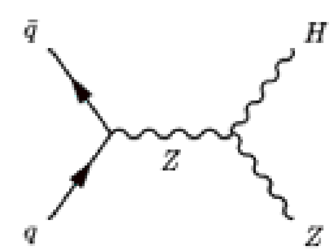
- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

Distinctive features with two forward jets and a large rapidity gap

~40 k events produced!



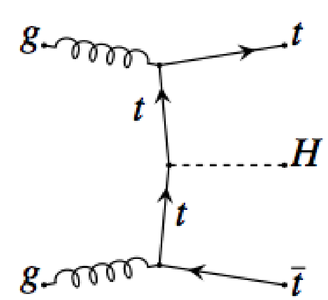


- W and Z Associated Production :

known at NNLO TH uncertainty ~O(5%)

Very distinctive feature with a Z or W decaying leptonically

~20 k events produced!



~3 k events produced!

- Top Associated Production :

known at NLO TH uncertainty ~O(15%)

Quite distinctive but also quite crowded

slide courtesy of M. Kado, CERN ATC '14

(SM) Higgs Searches @ the LHC

- Dominant decay mode b (57%)

Very large backgrounds, associated production W,Z H and Boost!

- The $\tau\tau$ channel (6.3%)

VBF, VH, but also ggF with new mass reconstruction techniques

- The $\gamma\gamma$ channel (0.2%)

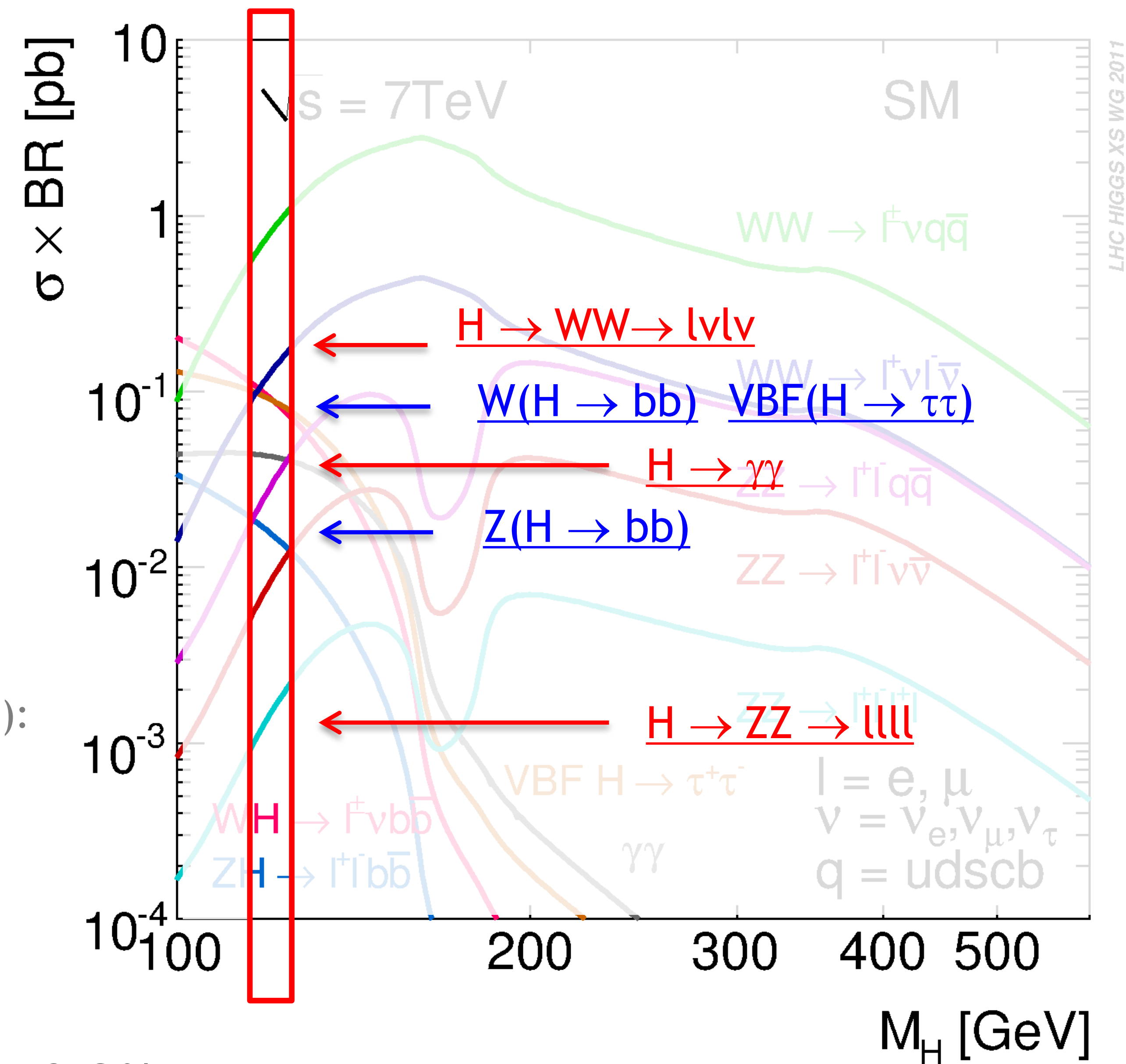
Discovery channel, high mass resolution (High stat, and backgrounds)

- The ZZ Channel (3%)

- Subsequent all leptons decays (low statistics): golden channel
- llqq and llvv sensitive mostly at high mass

- The WW Channel (22%)

- Subsequent lvlv very sensitive channel
- lvqq sensitive mostly at high mass



- The $\mu\mu$ channel (0.02%) and Zγ (0.2%)

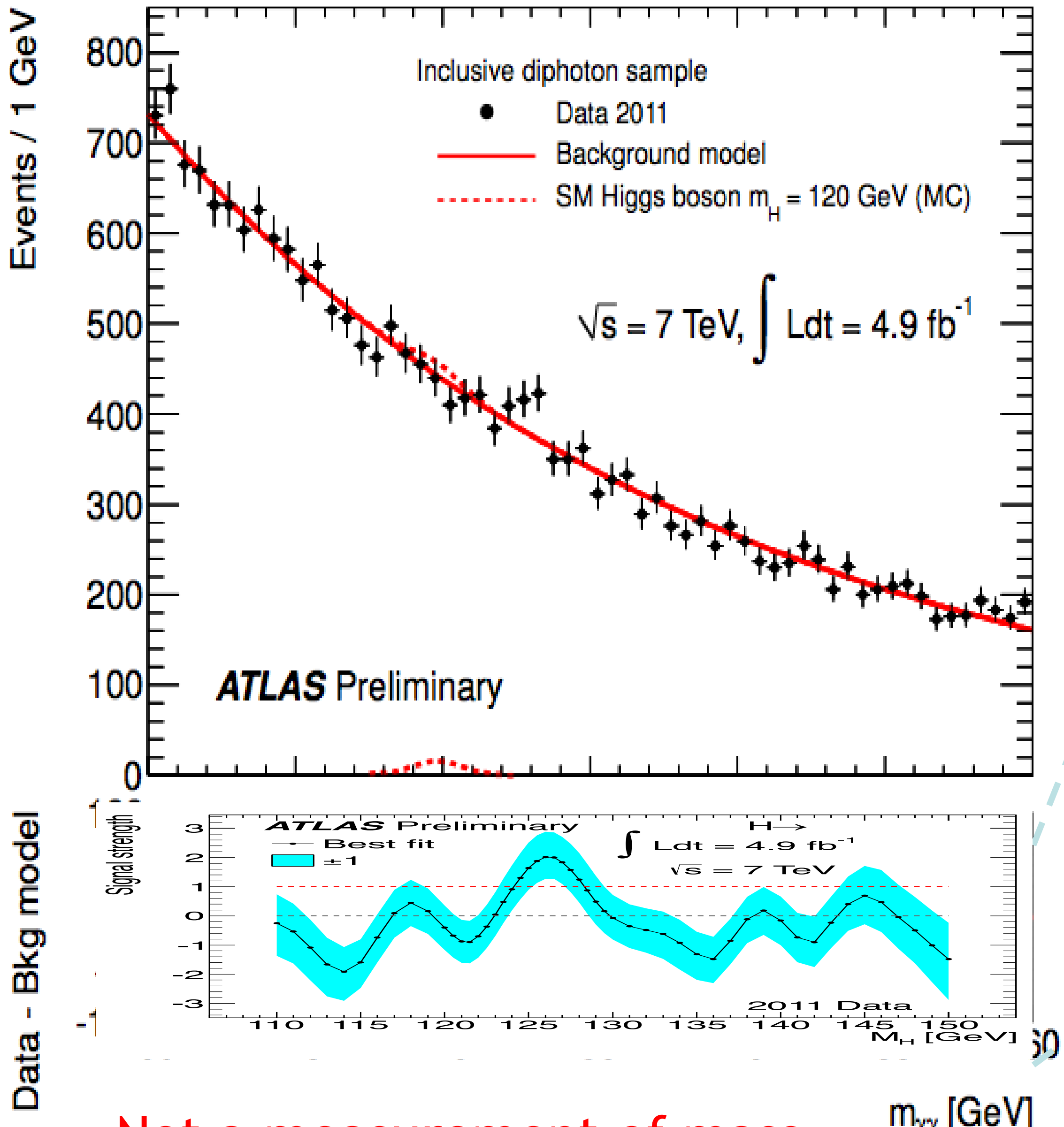
Low statistics from the low branching in $\mu\mu$ or both the low branching and subsequent decay in leptons (Zγ)

- The cc channel (3%) Very difficult

slide courtesy of M. Kado, CERN ATC '14

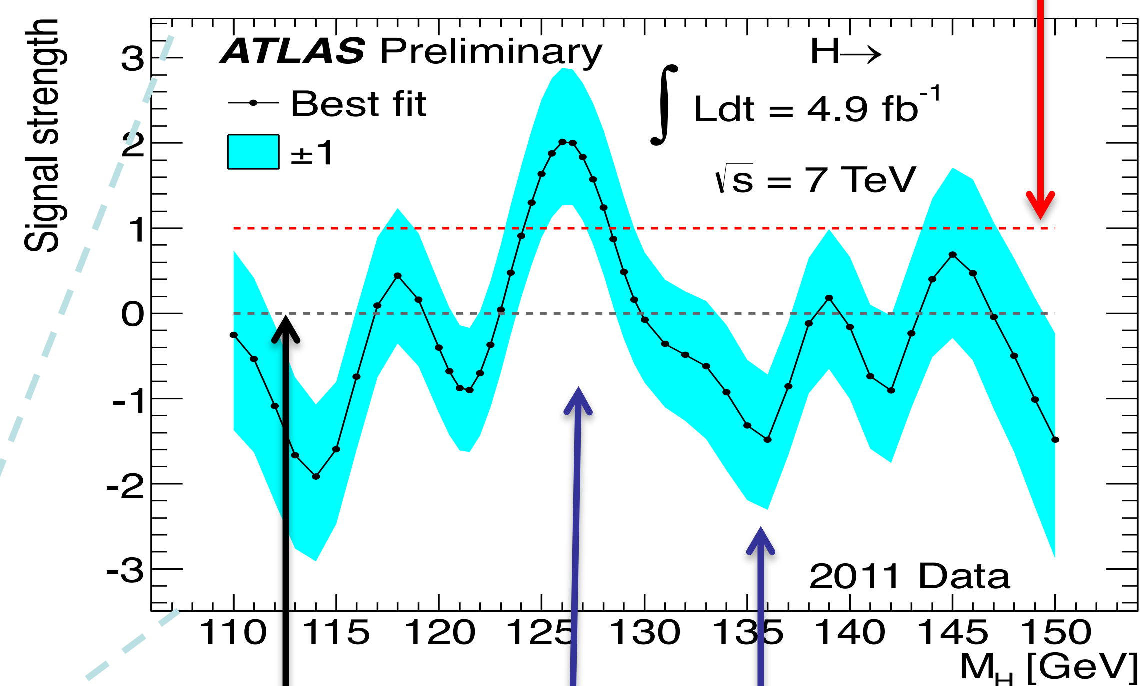
The Higgs discovery @ the LHC

$$gg \to H \to \gamma\gamma$$



Relate to Higgs mass hypothesis

Expected Signal



Not a measurement of mass

Not a measurement of cross section

Expected Background

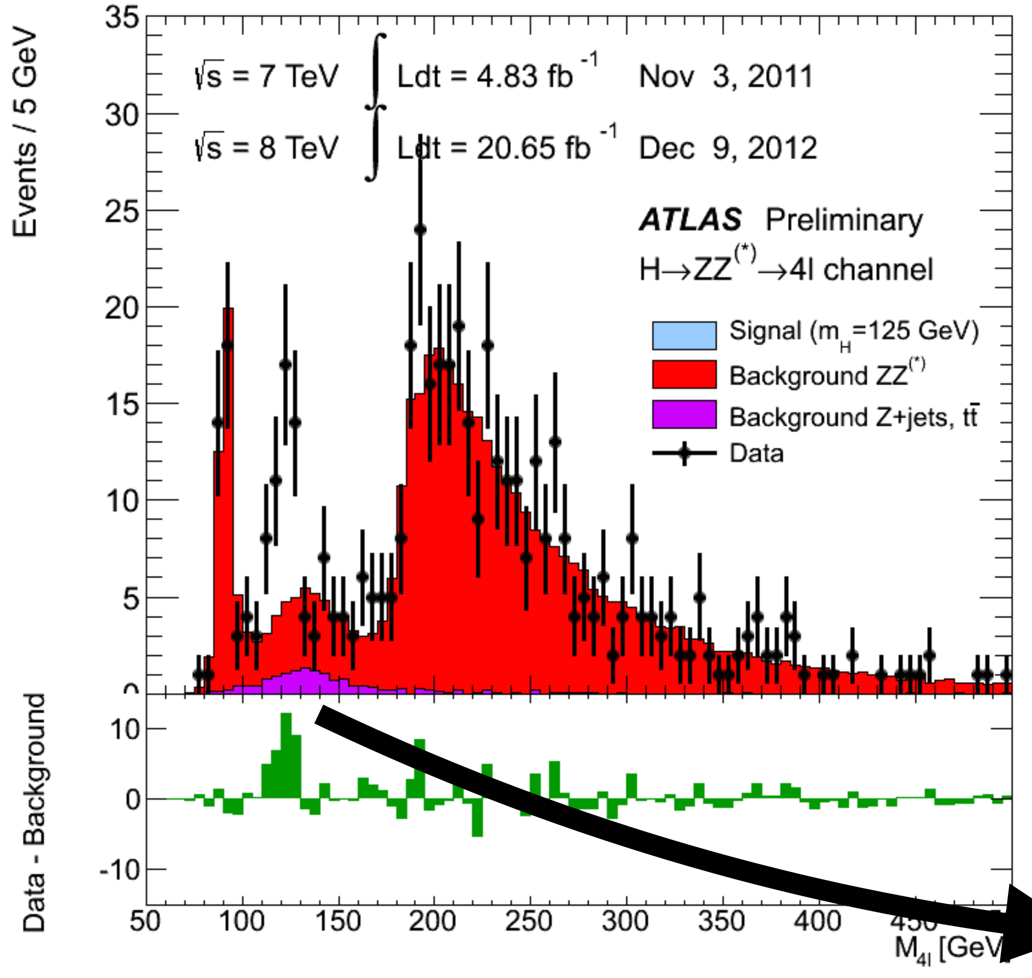
Excess

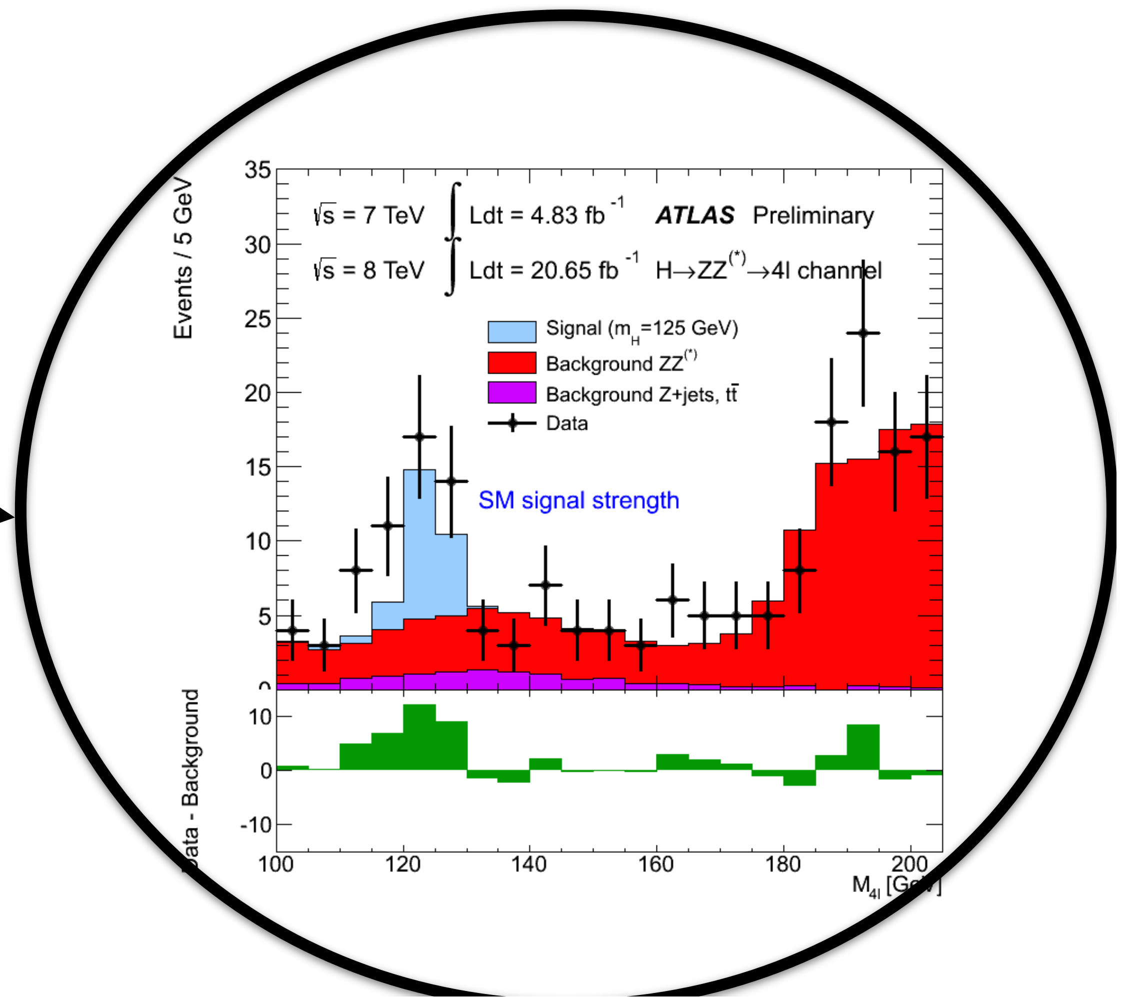
Deficit

slide courtesy of M. Kado, CERN ATC '14

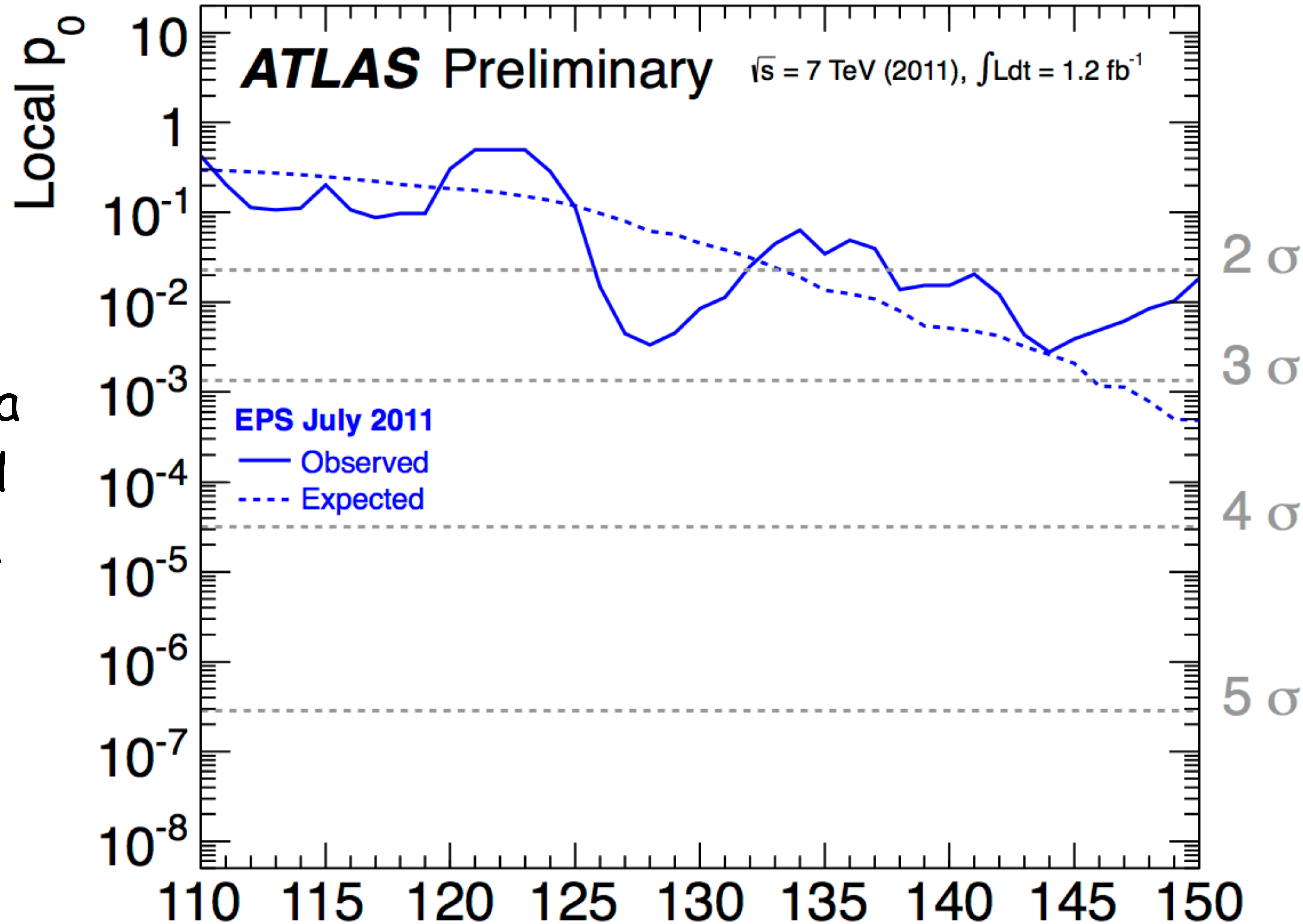
The Higgs discovery @ the LHC

$$gg \to H \to ZZ^* \to 4l$$





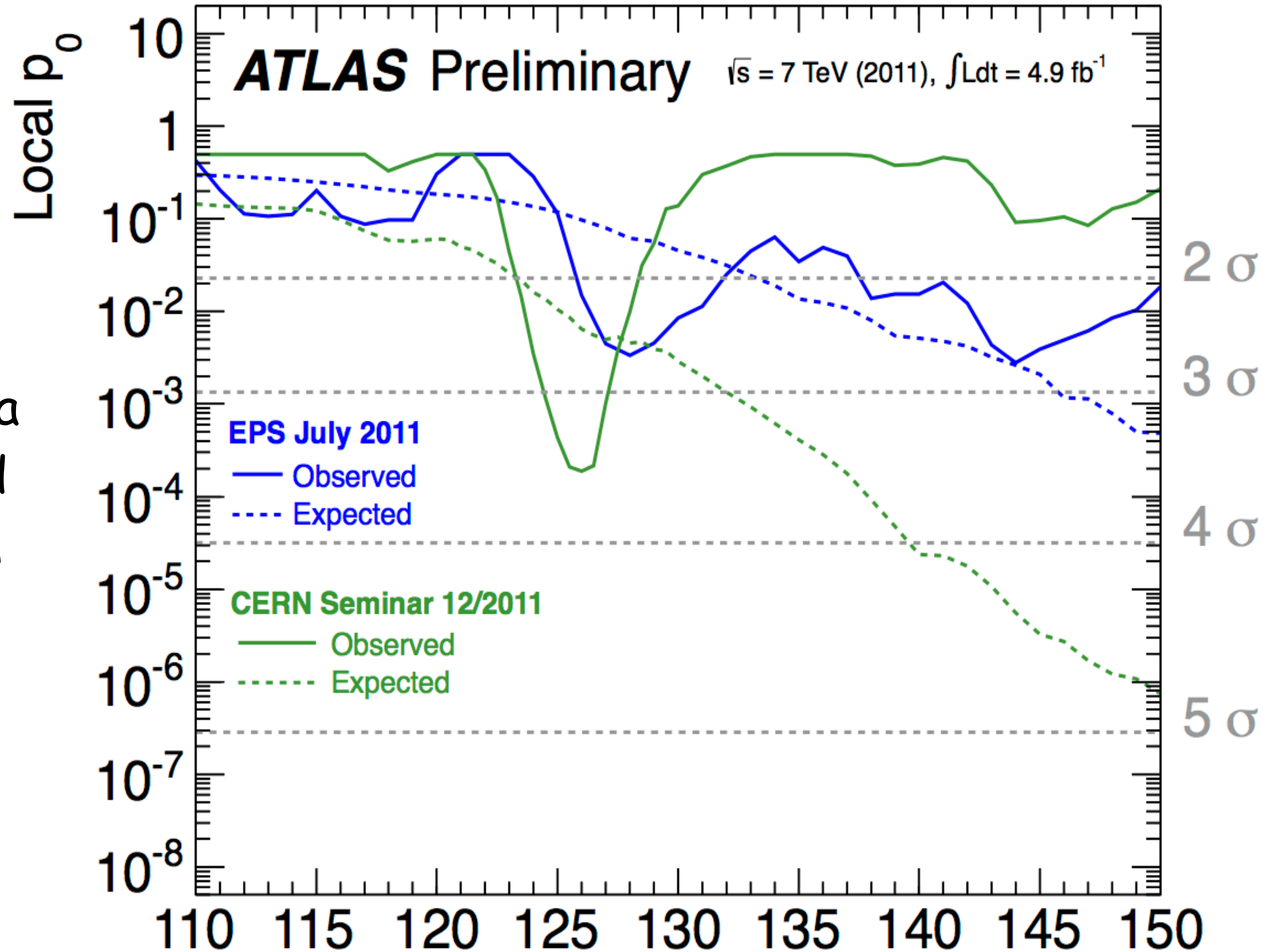
Higgs Discovery Reloaded



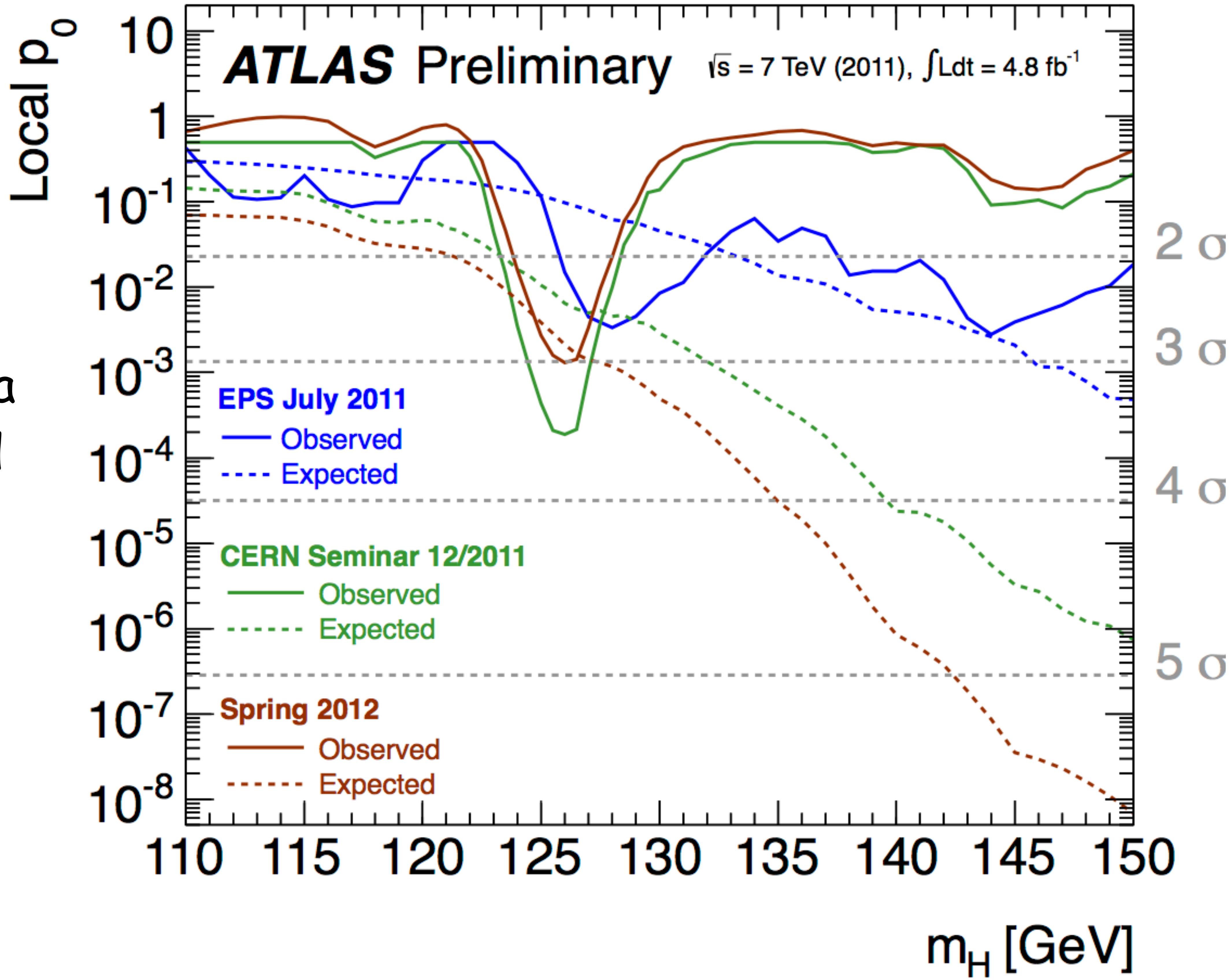
probability to observe a background fluctuation instead of the signal

Higgs Discovery Reloaded

probability to observe a background fluctuation instead of the signal



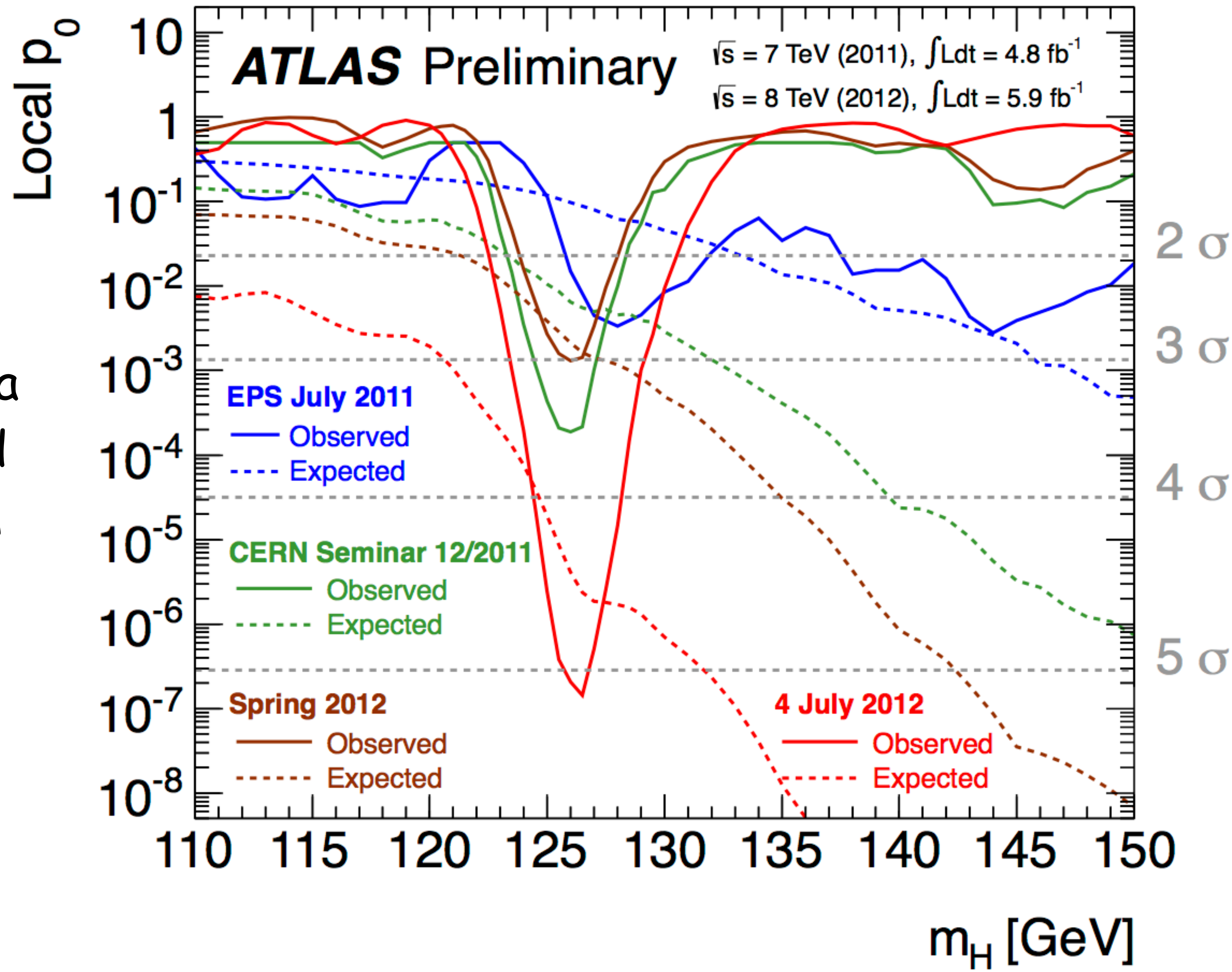
Higgs Discovery Reloaded



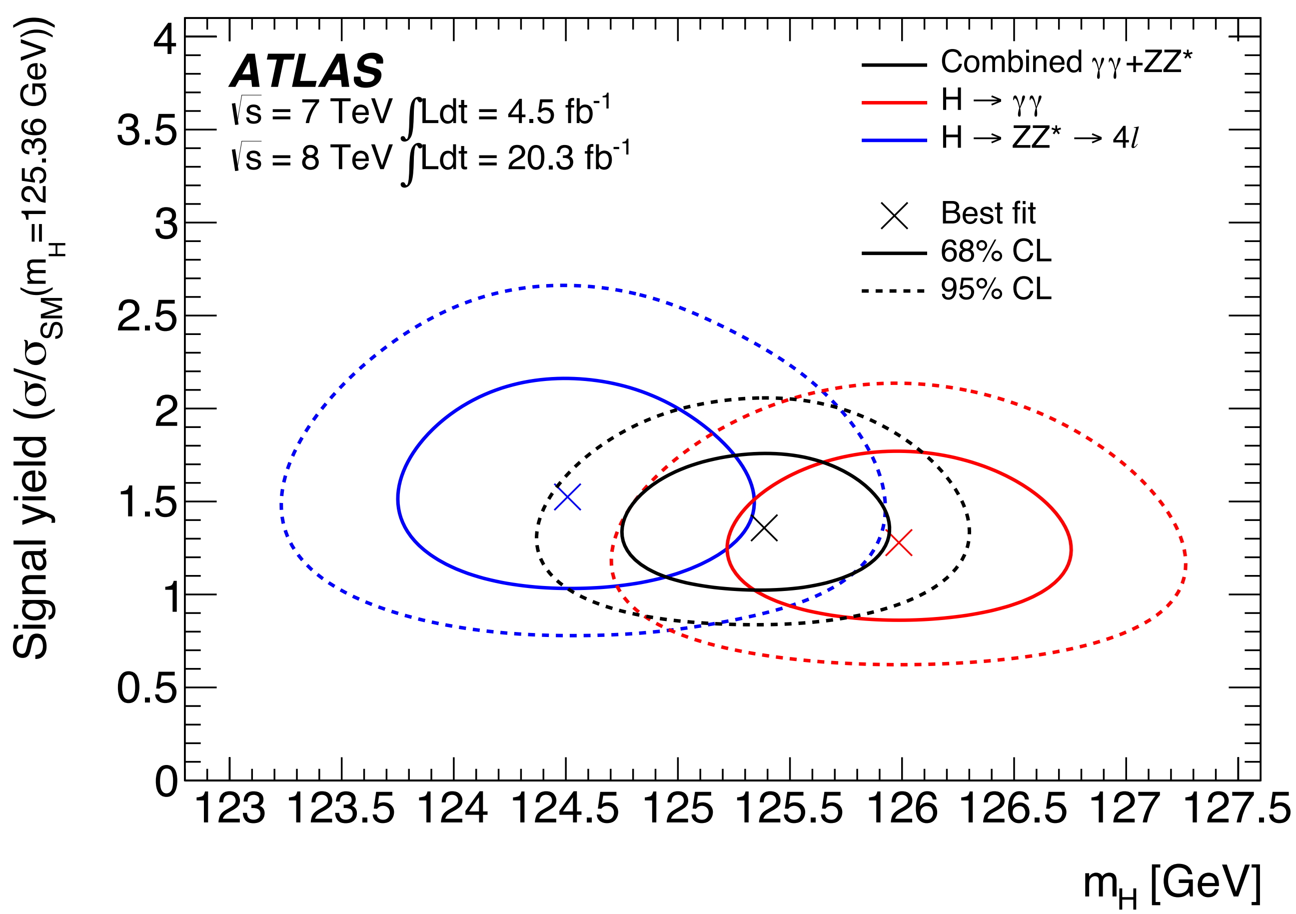
probability to observe a background fluctuation instead of the signal

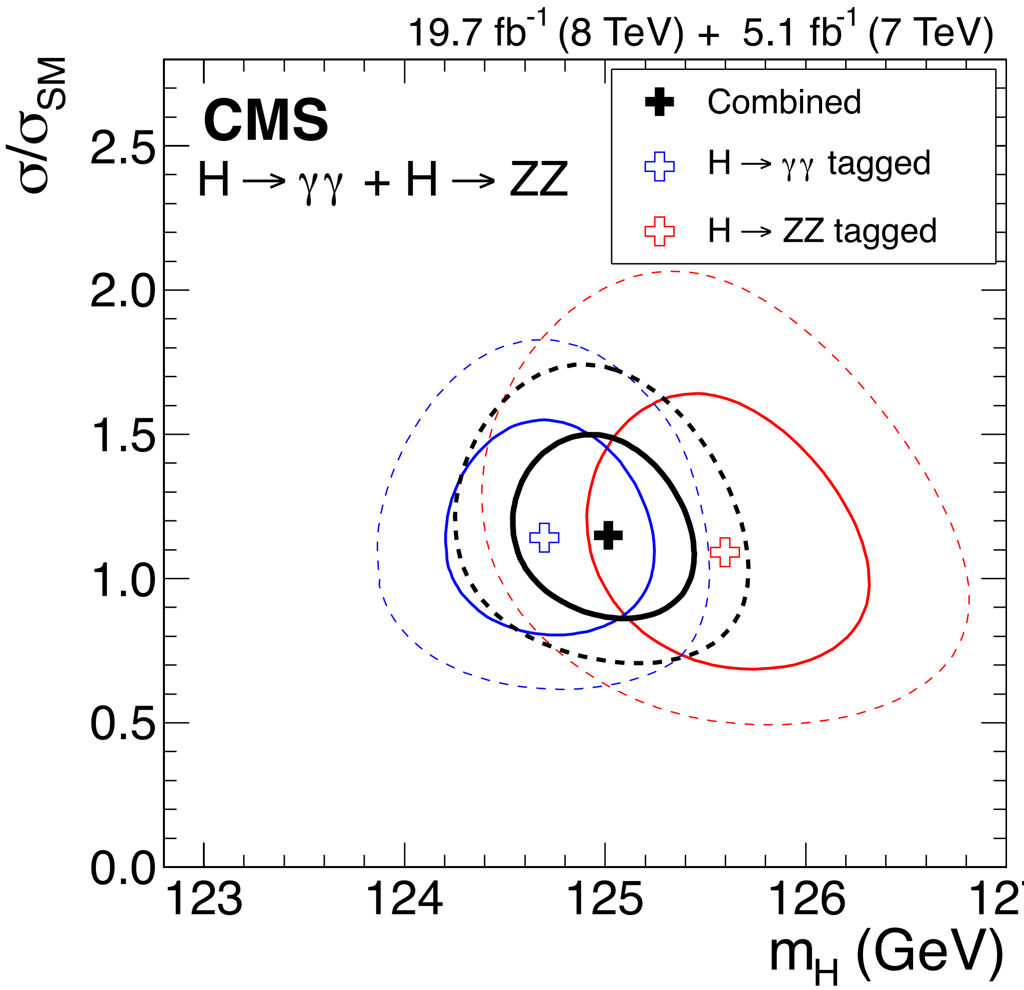
Higgs Discovery Reloaded

probability to observe a background fluctuation instead of the signal



Towards Higgs measurements





Experiment	$H \to \gamma\gamma$	$H \to ZZ^* \to 4\ell$	combined
ATLAS	125.98±0.42(stat.)±0.28(syst.)	124.51±0.52(stat.)±0.06 (syst.)	125.36±0.37(stat.)±0.18 (syst.)
CMS	124.70±0.31(stat.)±0.15(syst.)	125.59±0.42(stat.)±0.17(syst.)	125.02±0.27(stat.)±0.15(syst.)

The Higgs program

" With great power comes great responsibility "

Voltaire & Spider-Man

which, in particle physics, really means

" With great discoveries come great measurements "

BSMers desperately looking for anomalies

(true credit: F. Maltoni)

The Higgs has access to EW coupled New Physics
which is less constrained by direct searches than strongly coupled NP

1

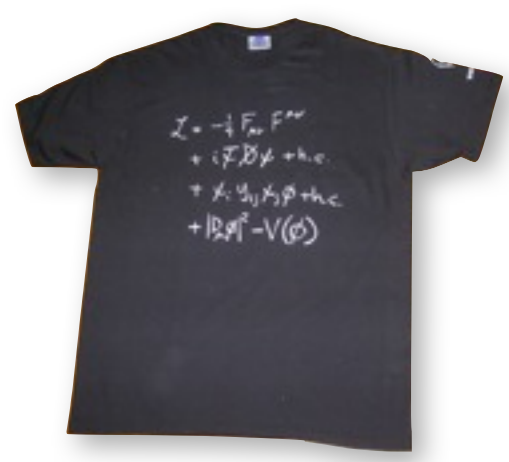
Higgs properties

J^{PC}

Important & nice to see progresses but "this question carries a similar potential for surprise as a football game between Brazil and Tonga" Resonaances

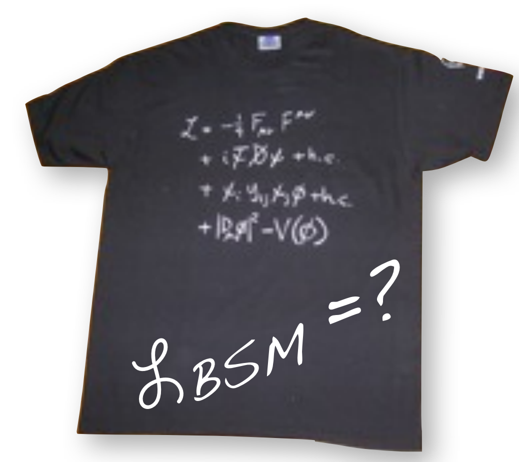
2

Higgs couplings



3

BSM implications



[pictures: courtesy of G. Giudice]

6

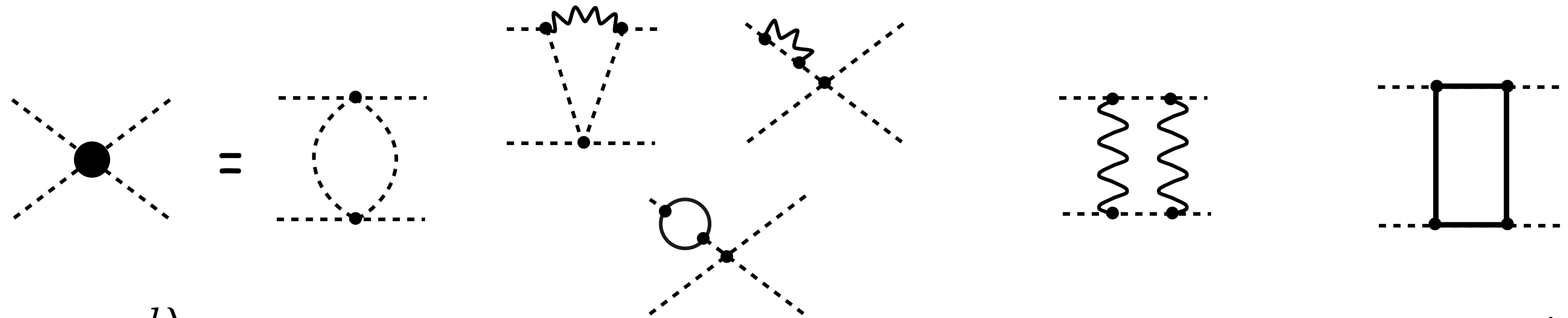
UV behaviour of the Higgs boson

(triviality, stability, hierarchy)

Quantum Behavior of the Higgs^4 Coupling (I)

$$V(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$

vev: $v^2 = \mu^2/\lambda$ mass: $m_H^2 = 2\lambda v^2$



$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

Large mass (λ dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2$$

λ increases with Q: IR-free coupling

$$\lambda(Q) = \frac{m_H^2}{2v^2 - \frac{3}{2\pi^2} m_H^2 \ln(Q/v)}$$

Quantum Behavior of the Higgs^4 Coupling (I)

$$V(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$

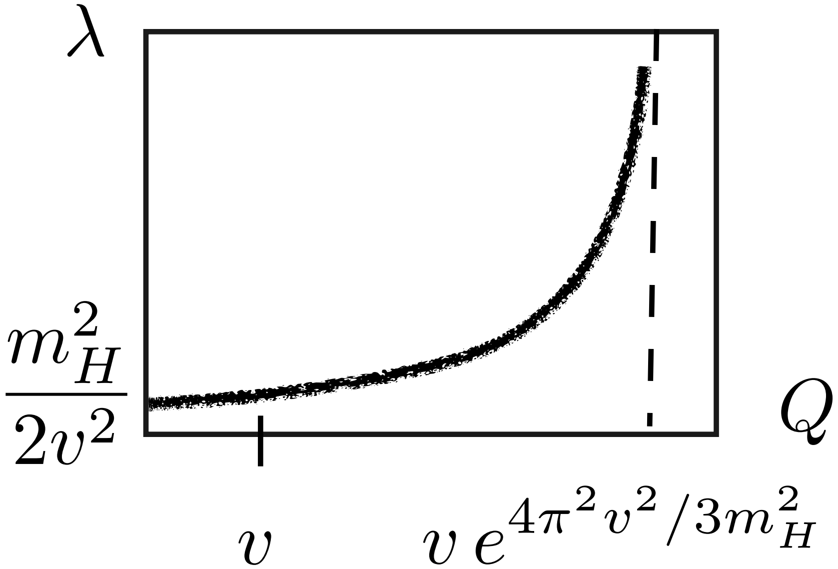
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

Large mass (λ dominated RGE)

$$\lambda(Q) = \frac{m_H^2}{2v^2 - \frac{3}{2\pi^2} m_H^2 \ln(Q/v)}$$

Wilson '71
Wilson, Kogut '74

Landau pole



Triviality bound

$$\Lambda \leq v\, e^{4\pi^2 v^2/3m_H^2}$$

New physics should appear before that point to restore stability

for m_H fixed, upper bound on Λ
for Λ fixed, upper bound on m_H

No microscopic description: for $\Lambda \to \infty$, trivial theory (λ=0)

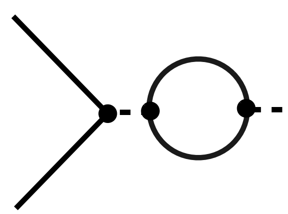
Quantum Behavior of the Higgs^4 Coupling (II)

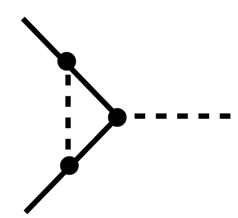
$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

Small mass (y_t dominated RGE)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = -6y_t^4$$

λ decreases with Q.





$$\left(16\pi^2 \frac{dy_t}{d\ln Q} = \frac{9}{2}\, y_t^3 + \text{Higher loops Small Yukawa} \qquad y^2(Q) = \frac{y^2(Q_0)}{1 - \frac{9}{16\pi^2} y^2(Q_0) \ln \frac{Q}{Q_0}}\right)$$

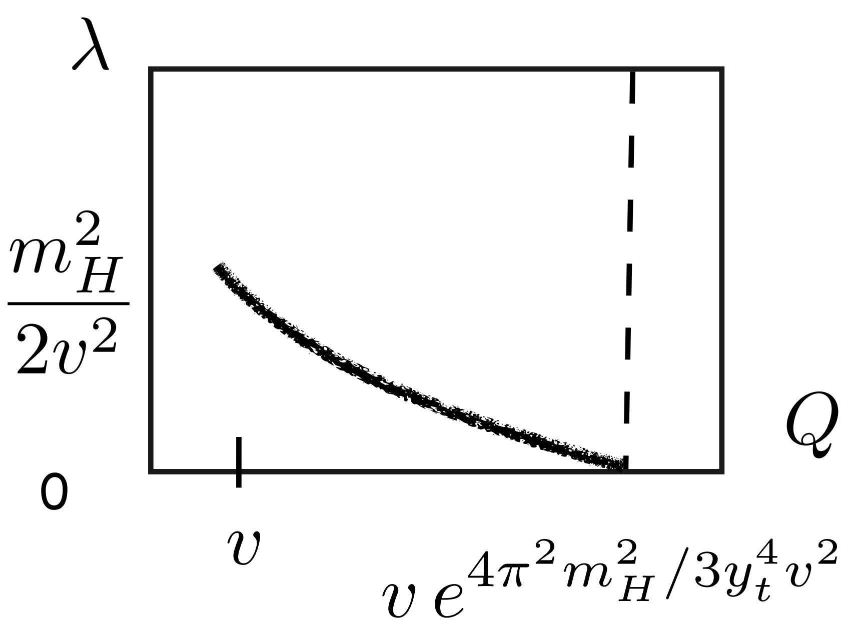
$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln \frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln \frac{Q}{Q_0}}$$

Quantum Behavior of the Higgs^4 Coupling (II)

$$16\pi^2 \frac{d\lambda}{d\ln Q} = 24\lambda^2 - (3g'^2 + 9g^2 - 12y_t^2)\lambda + \tfrac{3}{8}g'^4 + \tfrac{3}{4}g'^2 g^2 + \tfrac{9}{8}g^4 - 6y_t^4 +$$ Higher loops Small Yukawa

Small mass (y_t dominated RGE)

$$\lambda(Q) = \lambda_0 - \frac{\frac{3}{8\pi^2} y_0^4 \ln\frac{Q}{Q_0}}{1 - \frac{9}{16\pi^2} y_0^2 \ln\frac{Q}{Q_0}}$$



$\lambda < 0$ ⇛ potential unbounded from below

$\lambda(Q) = 0$ for $\lambda_0 \approx \frac{3}{8\pi^2} y_0^4 \log\frac{Q}{Q_0}$

New physics should appear before that point to restore stability

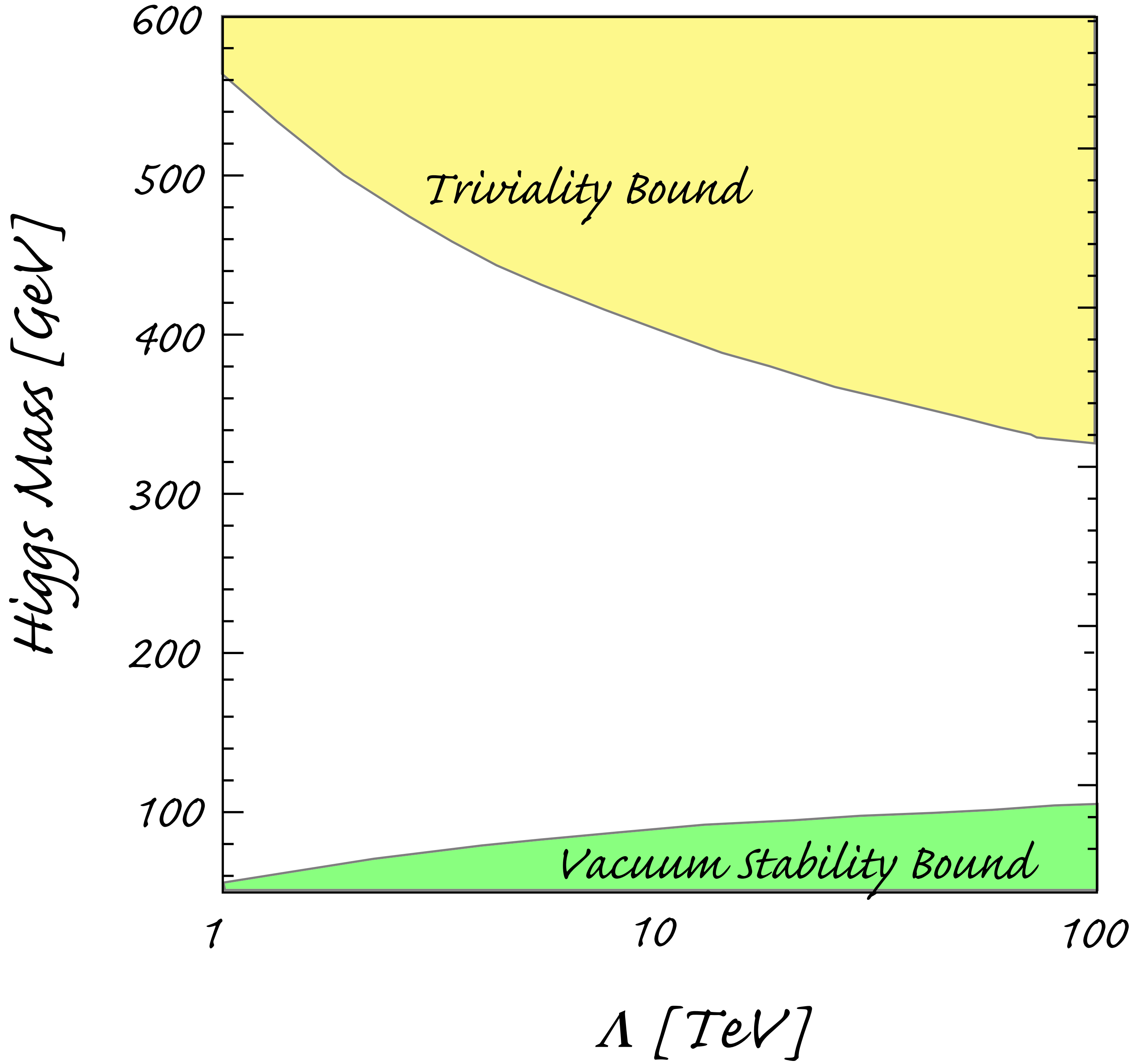
Stability bound

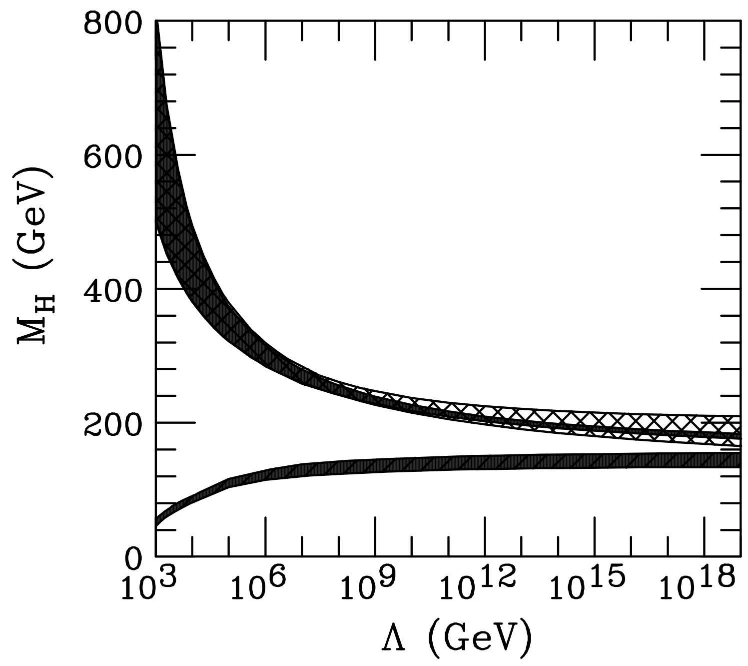
$$\Lambda \leq v\, e^{4\pi^2 m_H^2/3y_t^4 v^2}$$

for Λ fixed, lower bound on m_H

Linde '76, '80
Weinberg '76
Maini et al '78, '79
Politzer, Wolfram '79
Lindner '86
+...

Solving exactly the RG equation, we obtain the maximum domain of validity of the SM

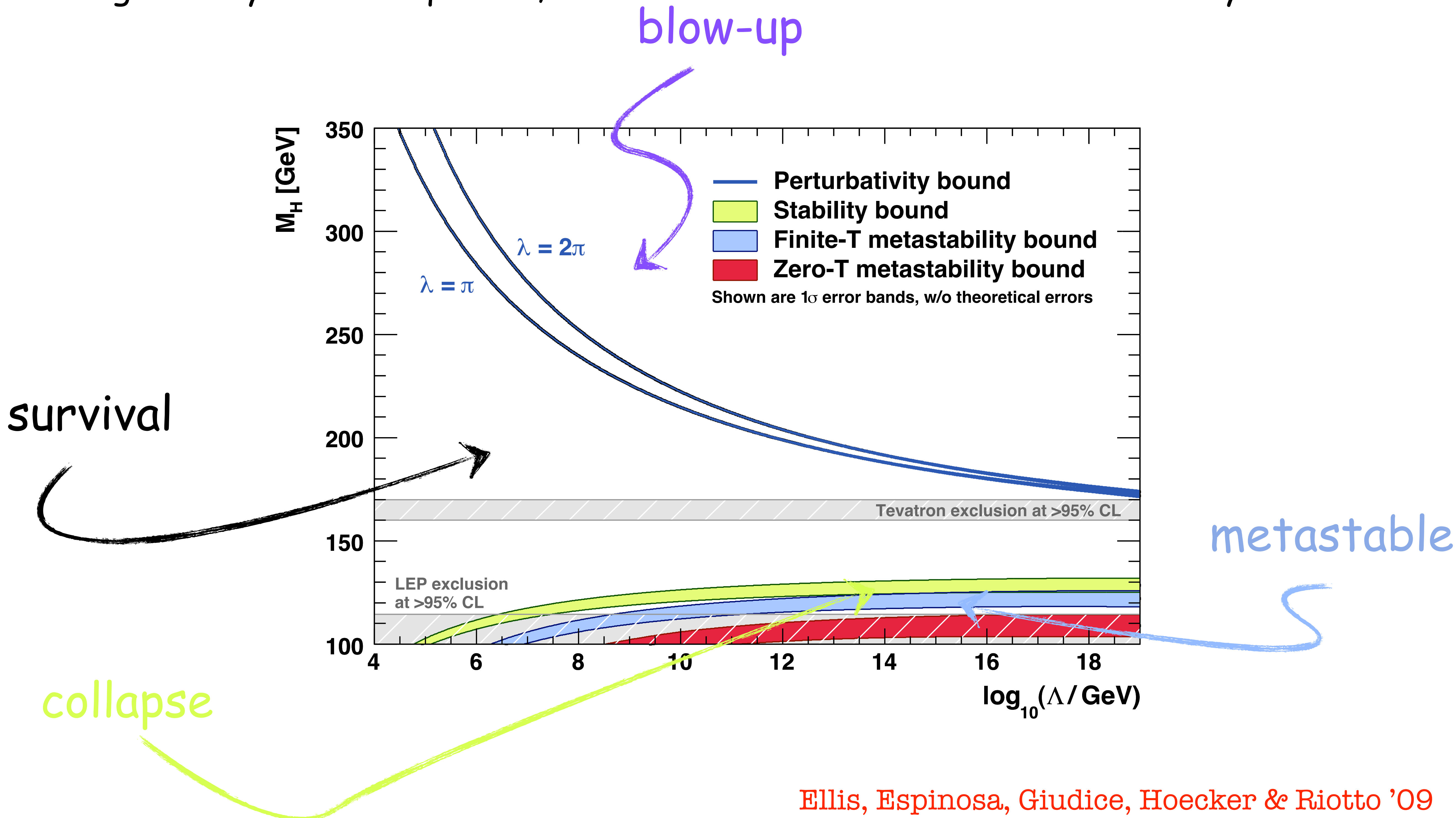




Hambye, Riesselmann '97

Only a light Higgs (130 GeV<m_H<170 GeV) allows for the absence of New Physics at low energy

Solving exactly the RG equation, we obtain the maximum domain of validity of the SM

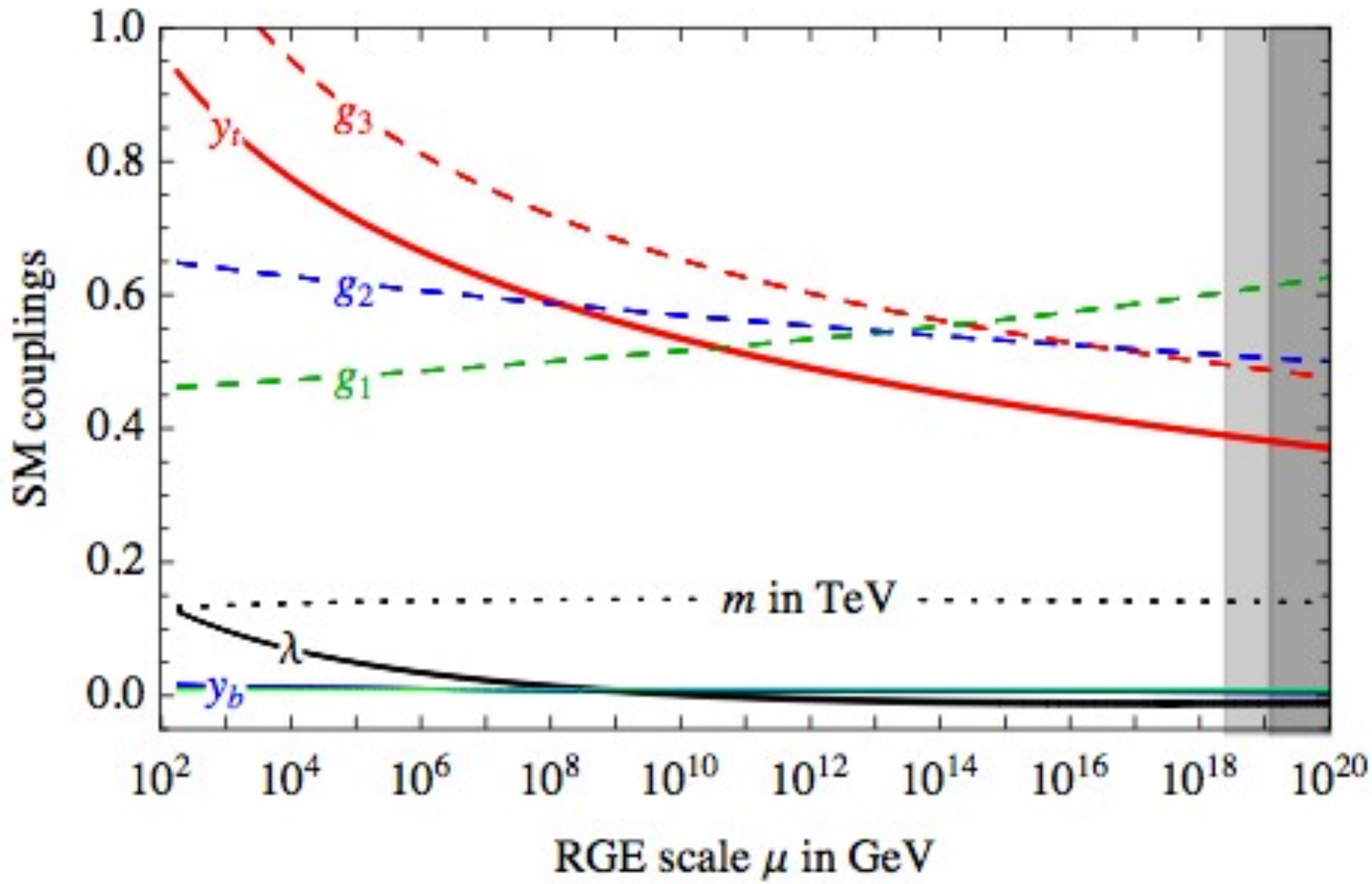


Ellis, Espinosa, Giudice, Hoecker & Riotto '09

Only a light Higgs (130 GeV$<m_H<$170 GeV) allows for the absence of New Physics at low energy

... and for m_H=125GeV

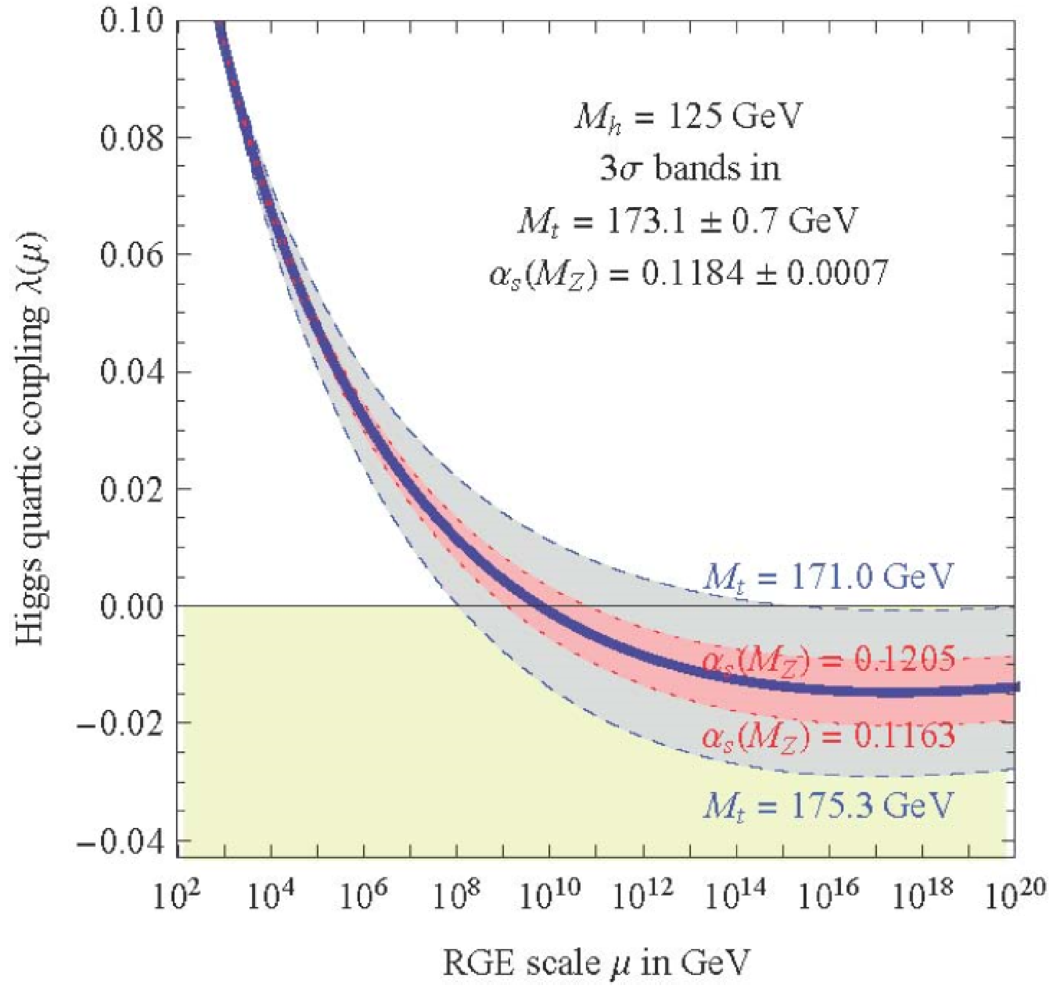
Buttazzo et al '13

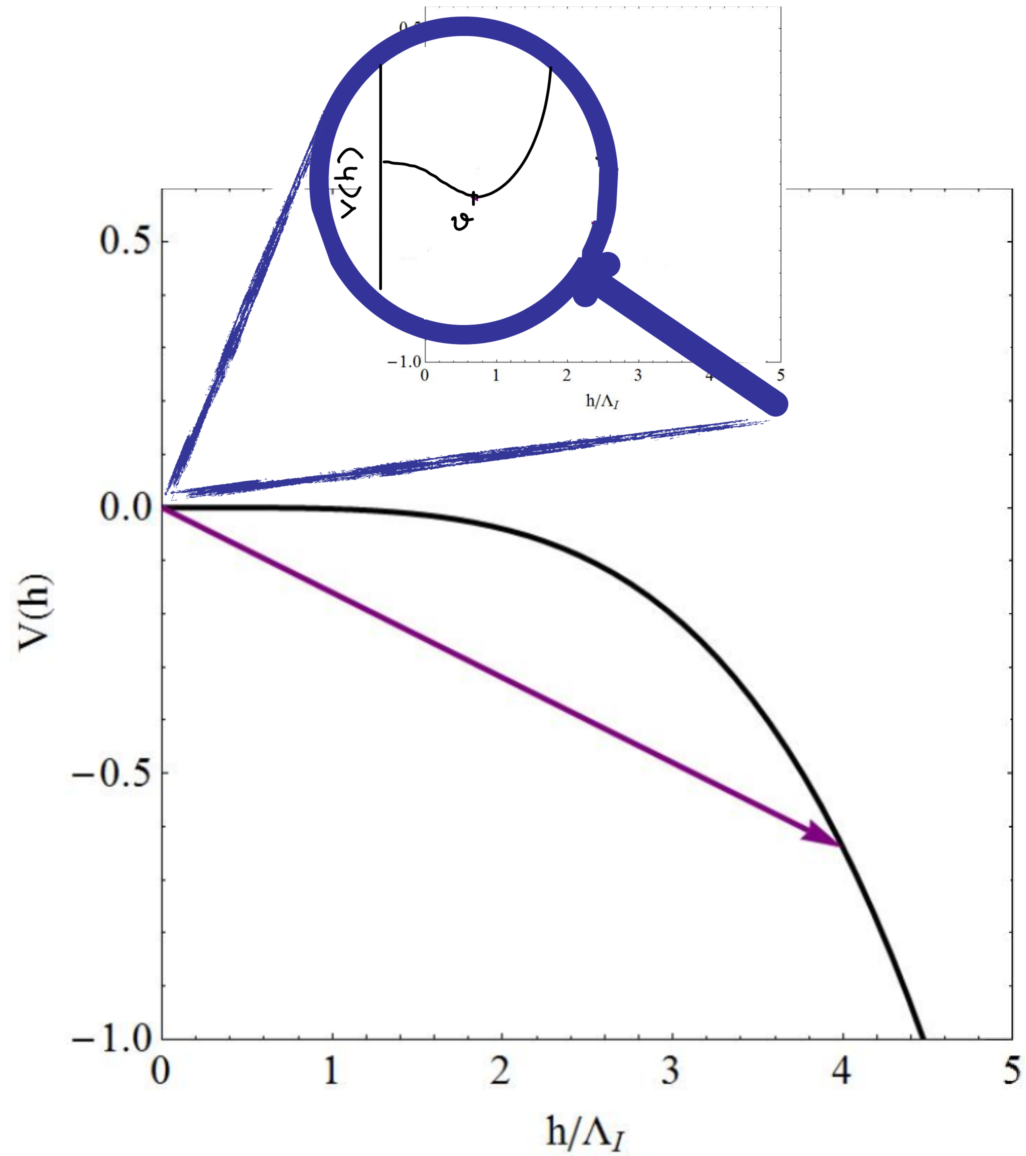


Can the SM (without new physics)
be valid up to M_{Pl} and remain weakly coupled?

Stability vs Metastability

Degrassi et al '12





Life time of the EW vacuum?

delicate computation!

exp(-bounce action)

prefactors also matter

needs to control all cosmological history of the Universe

thermal fluctuations?

Stability vs Metastability: a question of precision!

NNLO STABILITY BOUND

Lower bound on M_h for stability up to M_{Pl} :

State-of-the-art NNLO calculation:

- 2-loop V_{eff} (Ford, Jack, Jones [ph/0111190])
- 3-loop RGES (..., Chetyrkin, Zoller [ph/1205.2892], Bednyakov, Pikelner, Velizhanin [ph/1212.6829])
- 2-loop matching in $\lambda \leftrightarrow M_h^2$; $h_t \leftrightarrow M_t$ (..., Shaposhnikov et al [ph/1205.2893], , Degrassi et al [ph/1205.6497], , Buttazzo et al [ph/1307.3536])

For stability up to M_{Pl} :

$$M_h\,[\text{GeV}] > 129.4 + 1.4\left(\frac{M_t(\text{GeV}) - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{th}$$

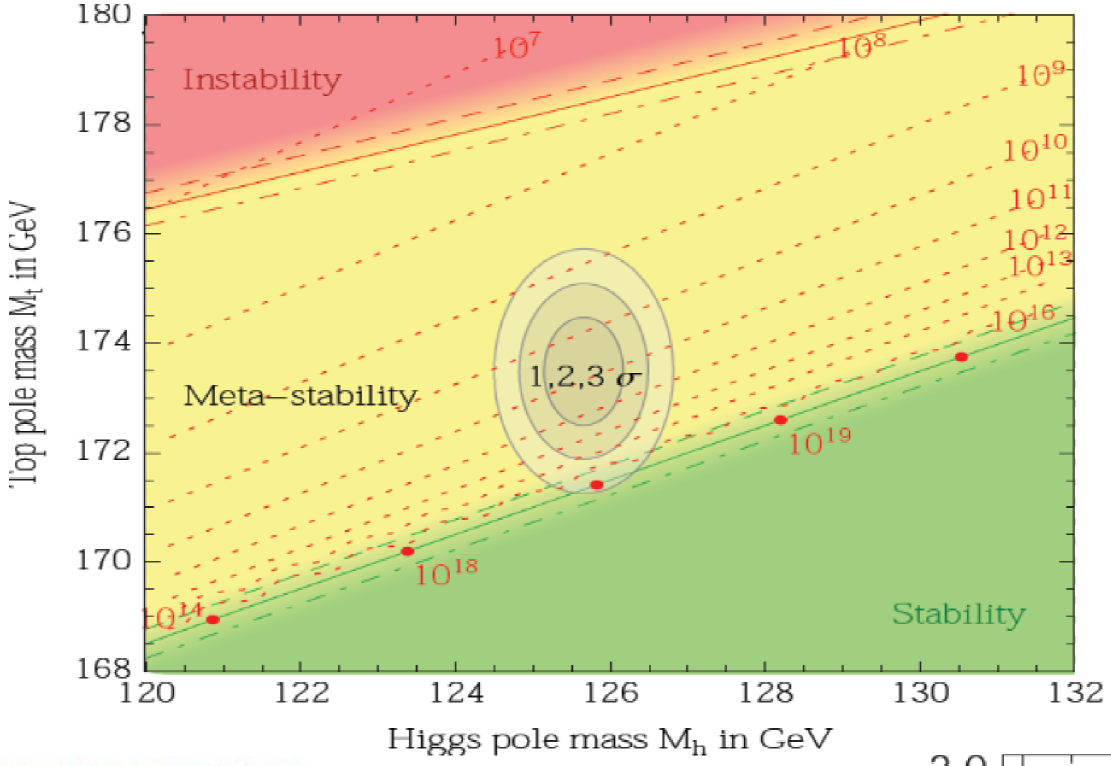
Degrassi et al '12

$$M_h\,[\text{GeV}] > 129.6 + 2\left(\frac{M_t(\text{GeV}) - 173.35}{1}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 0.3_{th}$$

Buttazzo et al '13

slide courtesy @ J.R. Espinosa, Lattice '13

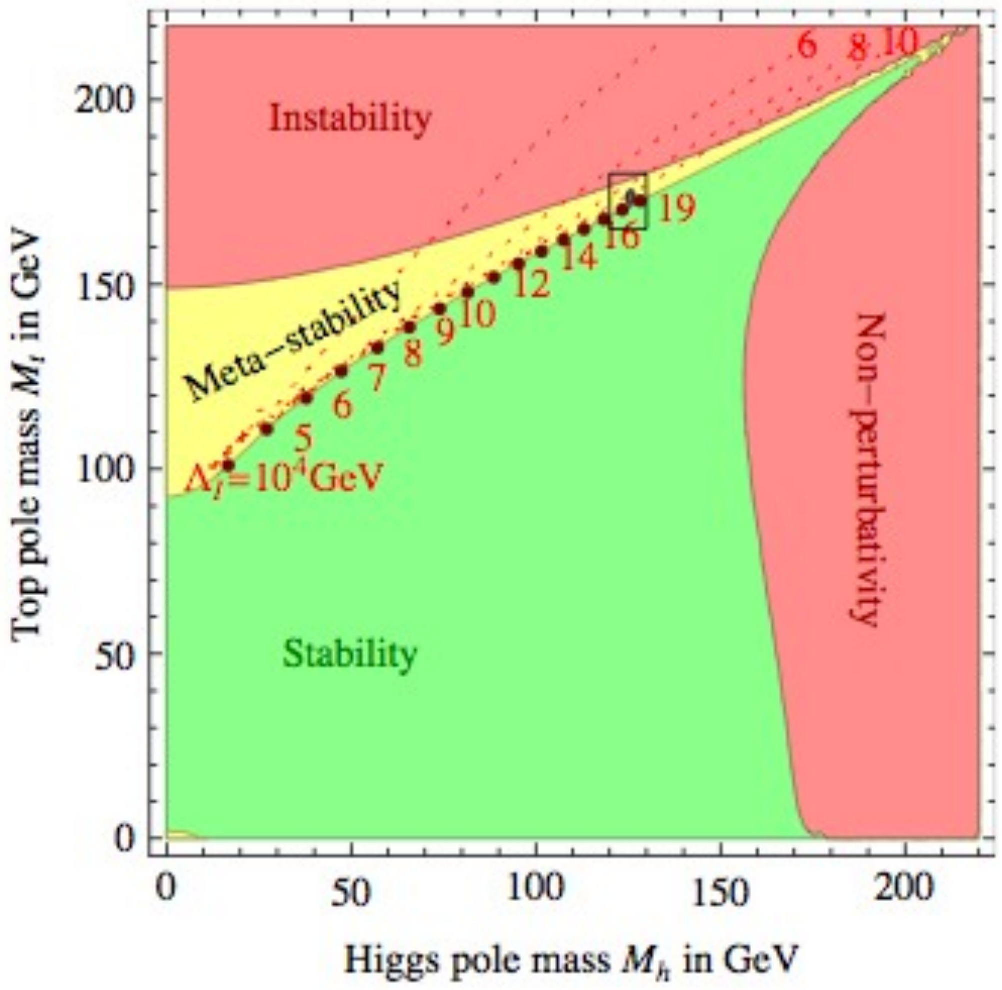
Are we living at a edge of the phase diagram?

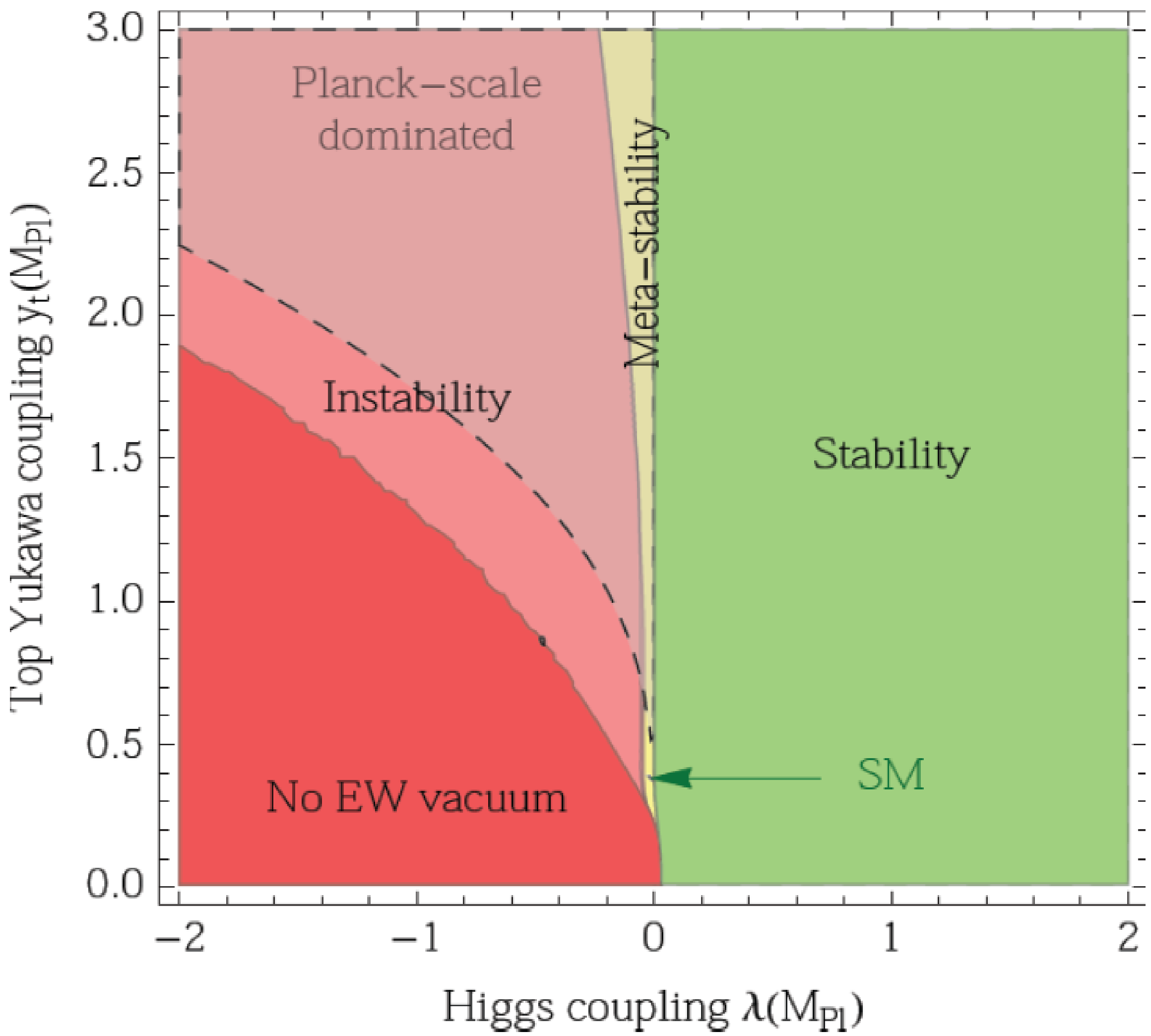


Bezrukov et al '12

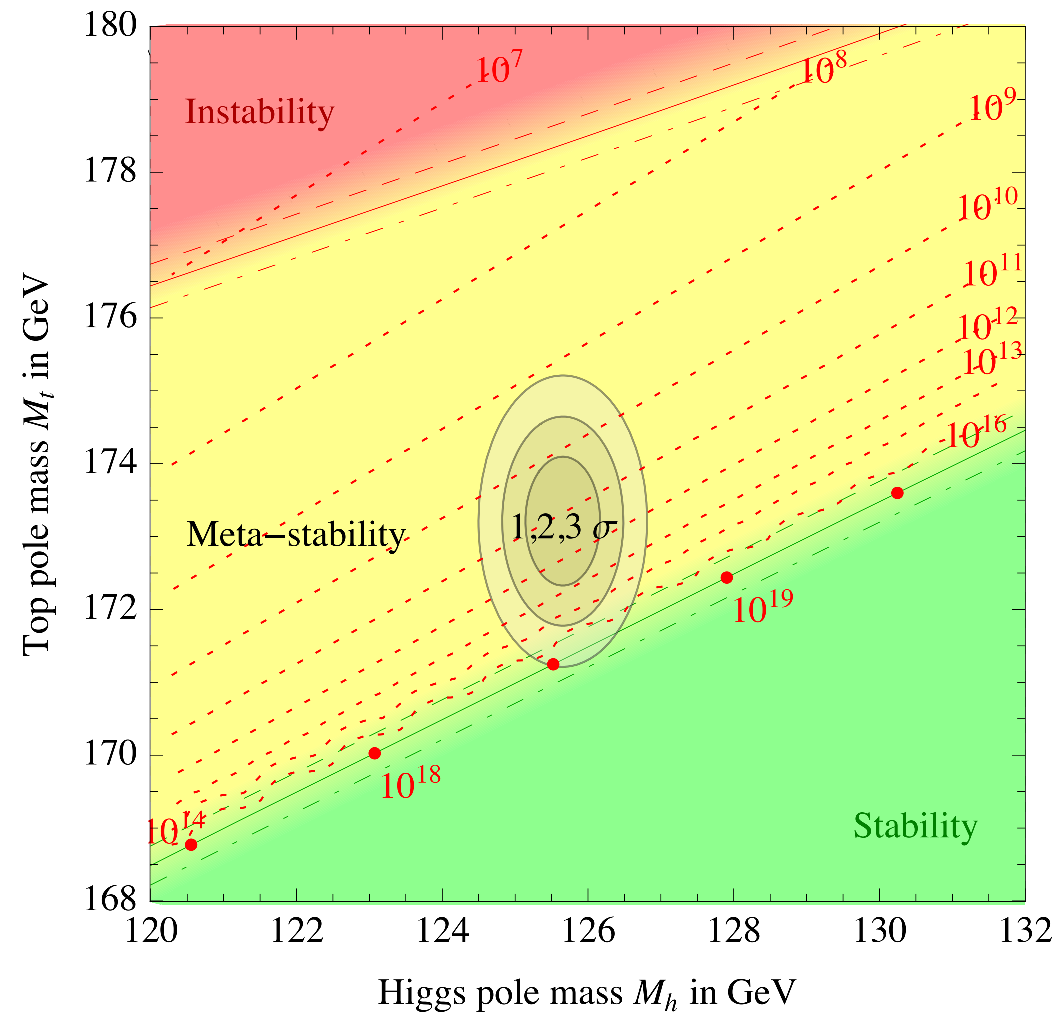
Degrassi et al '12

Buttazzo et al '13





The fate of the EW vacuum



Buttazzo et al '13

It is almost certain (>4σ) that $m_H > M_{mestability}$ and totally certain that $m_H < M^{h^3}_{Landau}$

(even though this certainty might by questioned by threshold effects at the Planck scale Holthausen, Lim and Lindner '12)

Not totally clear yet if m_H is above $M_{stability}$, but rather important question since

- ☑ if $m_H > M_{stability}$, the Higgs could serve as an inflaton
- ☑ if $m_H = M_{stability}$ the SM is asymptotically safe, ie consistent up to arbitrary high energy

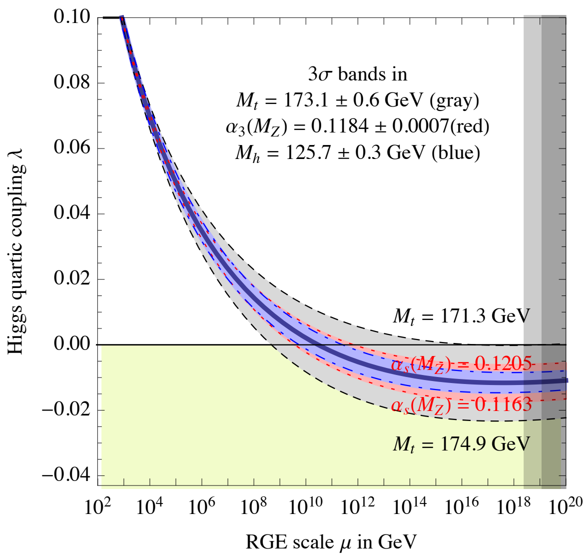
Bezrukov et al '12

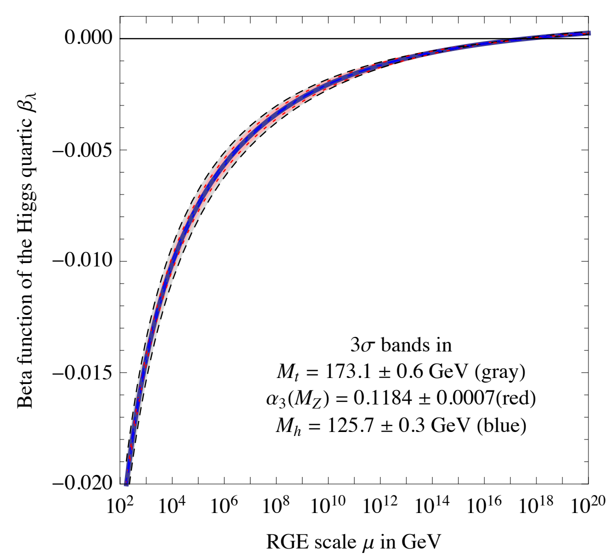
need precise Higgs&top mass/couplings (and α_s) measurements (ILC, μ coll.)

and better understanding of pole vs MS top mass Alekhin, Djouadi, Moch '12

From the EW scale to M_{Pl}... and return

Many of my theory colleagues started wild speculations/extrapolations





$$\lambda(M_{\rm Pl}) = -0.0113 - 0.0065\left(\frac{M_t}{\rm GeV} - 173.10\right) + 0.0018\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007} + 0.0029\left(\frac{M_h}{\rm GeV} - 125.66\right)$$

Buttazzo et al '13

Is the Higgs potential vanishing potential at M_{Pl}?

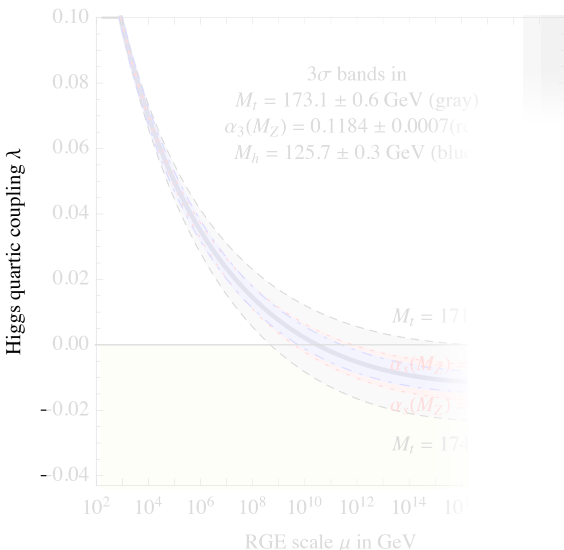
Froggatt, Nielsen, Takanishi '01
Arkani-Hamed et al '08
Shaposhnikov, Wetterich '09

EWSB determined by Planck physics? M_{Pl} calculable from weak scale non-gravitational quantities?
absence of new energy scale between the Fermi and the Planck scale?
Anthropic vs. natural EWSB...

But these implications are based on the assumptions
(1) that the 126 GeV particle observed is *exactly* the SM Higgs
(2) that the Dark Matter sector is decoupled from the weak sector

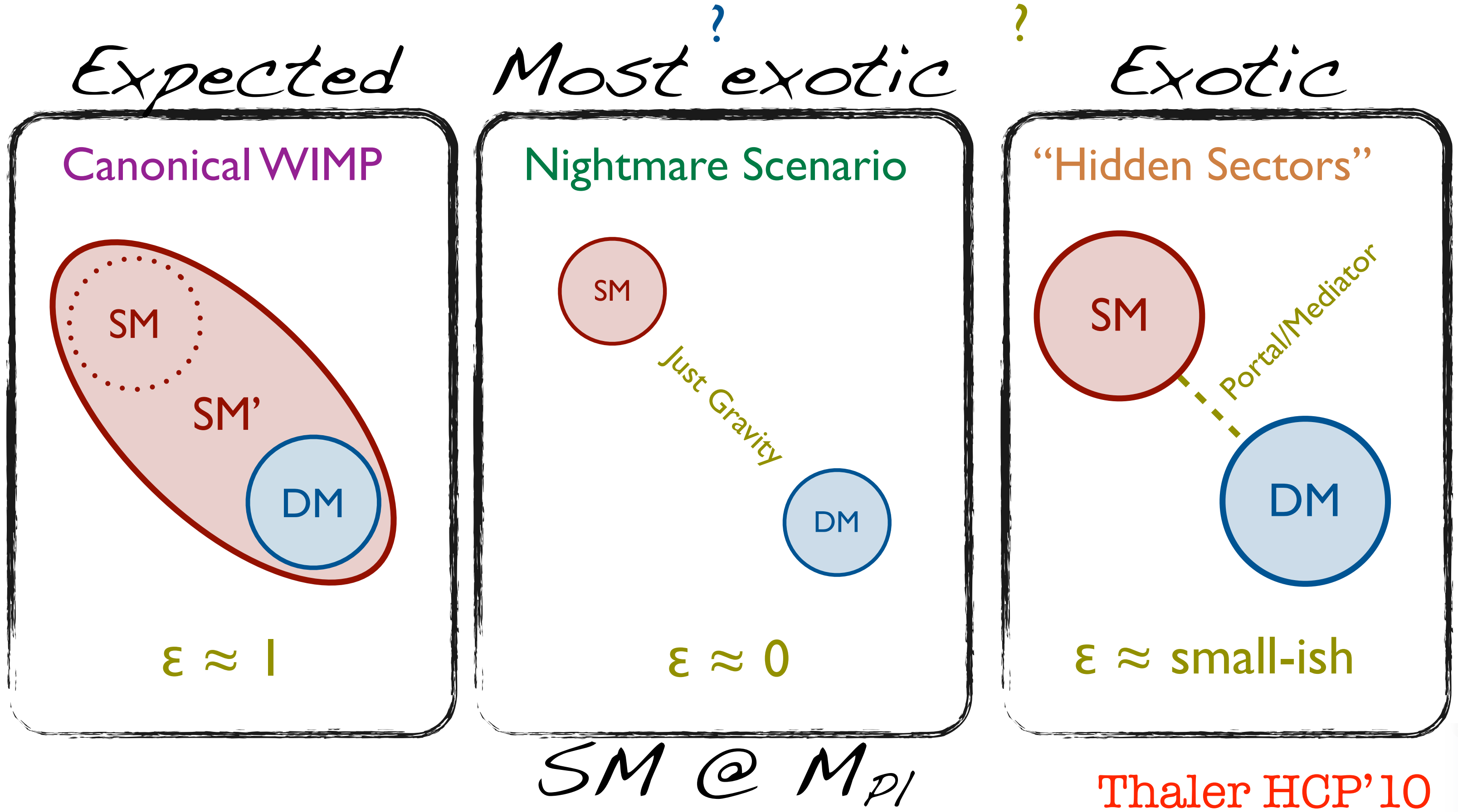
From the EW scale to M_{Pl}... and return

Many of my theory colleagues started wild speculations/extrapolations



SM/DM Couplings

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm DM} + \epsilon\, \mathcal{O}_{\rm SM}\, \mathcal{O}_{\rm DM}$$



Thaler HCP'10

Buttazzo et al '13

EWSB determine ... absen...

...vitational quantities? ...ck scale?

How robust is the conclusion?

BSM & STABILITY

Even without naturalness, BSM must exist...

Its impact on the Higgs instability can be

Example

IRRELEVANT — See-saw neutrinos $M_R \lesssim 10^{13}$ GeV

MAKE IT WORSE — See-saw neutrinos $M_R \gtrsim 10^{13}$ GeV

CURE IT — See-saw neutrinos $M_R \sim \langle S \rangle$ & $\lambda_{HS} |H|^2 |S|^2$

Lebedev '12, Elias-Miro et al. '12

slide courtesy @ J.R. Espinosa, Lattice '13

Solution to the Higgs^4 Coupling Instabilities

find a symmetry such that

$$\lambda \equiv g^2$$

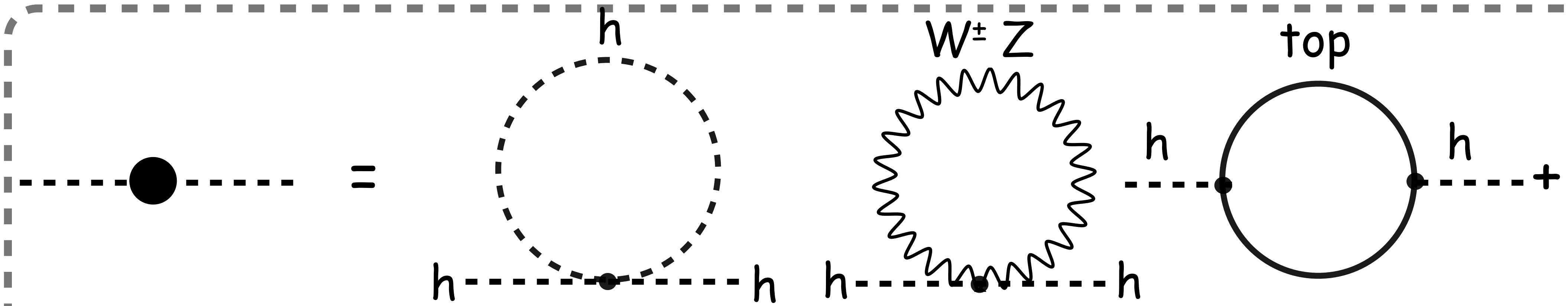
the Higgs quartic will inherit the good UV asymptotically free behavior of the gauge coupling

Examples of such symmetry:

- supersymmetry
- gauge-Higgs unification: the Higgs is identified as a component of the gauge field along some extra-dimensions.

Quantum Instability of the Higgs Mass

so far we looked only at the RG evolution of the Higgs quartic coupling (dimensionless parameter). The Higgs mass has a totally different behavior: it is higly dependent on the UV physics, which leads to the so called hierarchy problem



Higher loops
Smaller Yukawa

$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{(k^2 - m^2)^2} \propto \Lambda^2$$

Weisskopf ’39
‘t hooft ’79

$$\delta m_H^2 = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \frac{3G_F\Lambda^2}{8\sqrt{2}\pi^2}$$

$$m_H^2 \sim m_0^2 - (115 \text{ GeV})^2 \left(\frac{\Lambda}{700 \text{ GeV}}\right)^2$$

Λ^2 from the Coleman-Weinberg Potential

$$V(h) = \int \frac{d^4 k_E}{2(2\pi)^4} \mathrm{STr} \ln\left(k_E^2 + M^2(h)\right)$$

$$V(h) = -\frac{\Lambda^4}{128\pi^2}\mathrm{STr}1 + \frac{\Lambda^2}{32\pi^2}\mathrm{STr}M^2(h) + \frac{1}{64\pi^2}\mathrm{STr}M^4(h)\ln\frac{M^2(h)}{\Lambda^2}$$

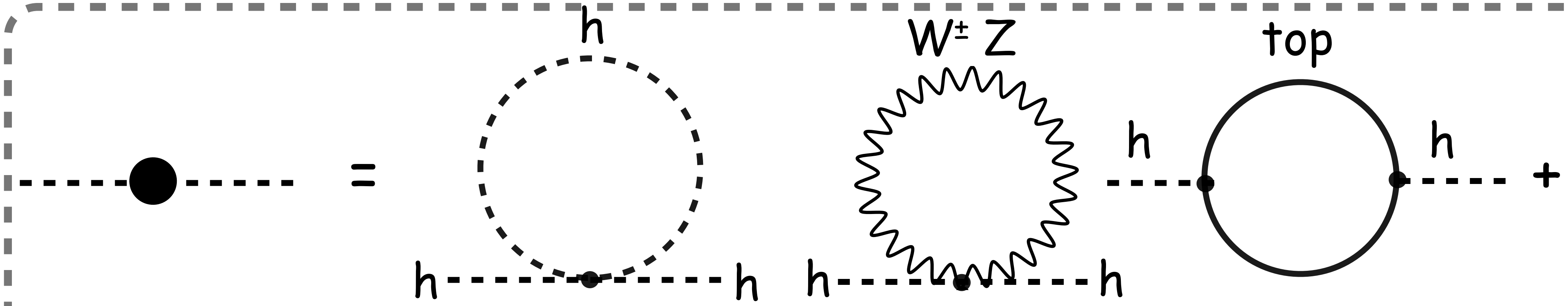
$M_W^2 = \frac{1}{4}g^2h^2$	$M_Z^2 = \frac{1}{4}(g^2+g'^2)h^2$	$M_t^2 = \frac{1}{2}y_t^2h^2$	$M_H^2 = \lambda\left(3h^2 - v^2\right)$	$M_G^2 = \lambda\left(h^2 - v^2\right)$
2x3	3	4x3	1	3

h dependent masses away from the true vacuum
(for h=v, we recover the usual expression
for the Higgs mass
and the Goldstone are massless)

$$V(h) = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)\frac{3G_F\Lambda^2}{32\sqrt{2}\pi^2}h^2$$

in agreement with the loop computation

Quantum Instability of the Higgs Mass



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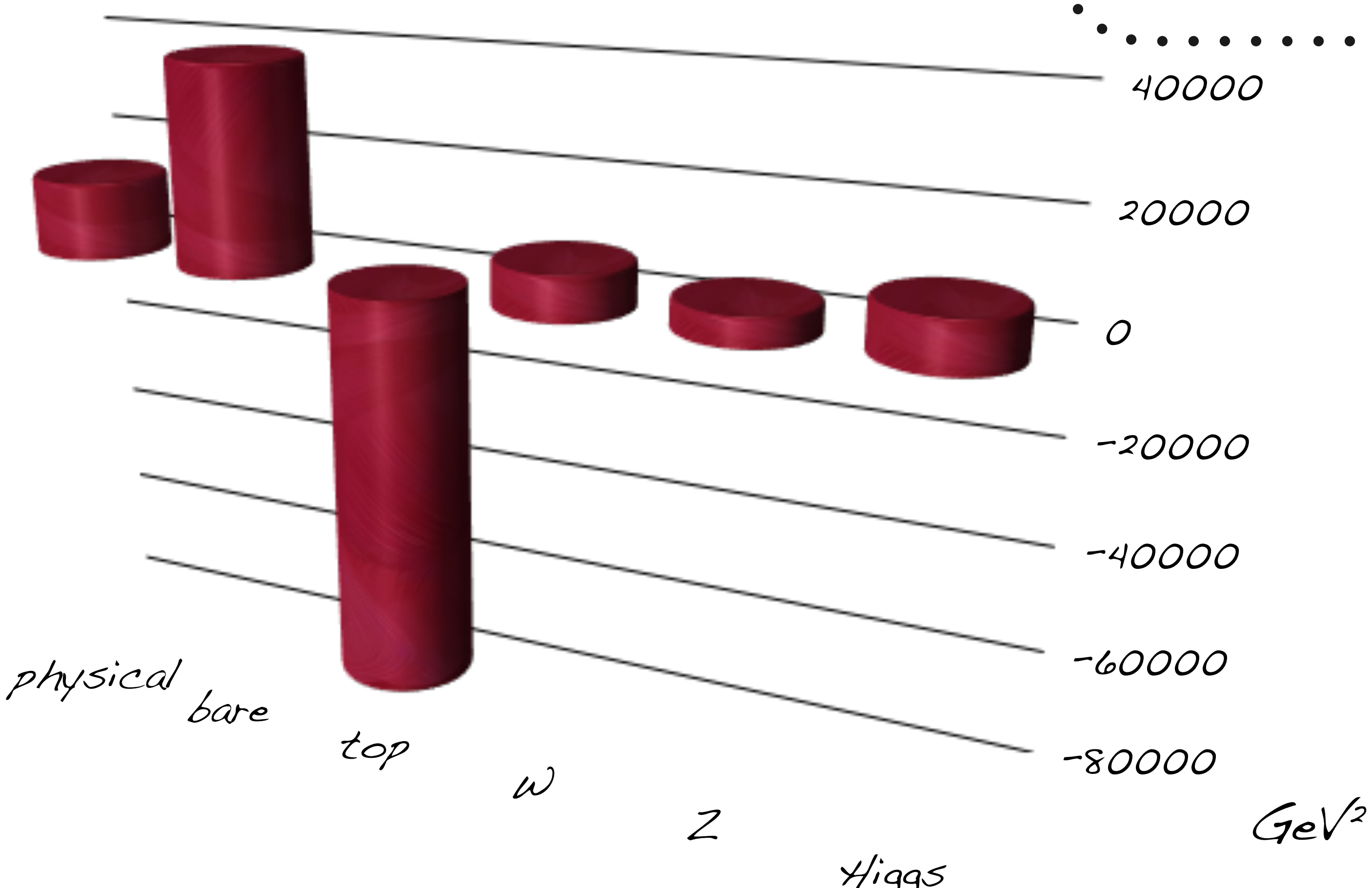
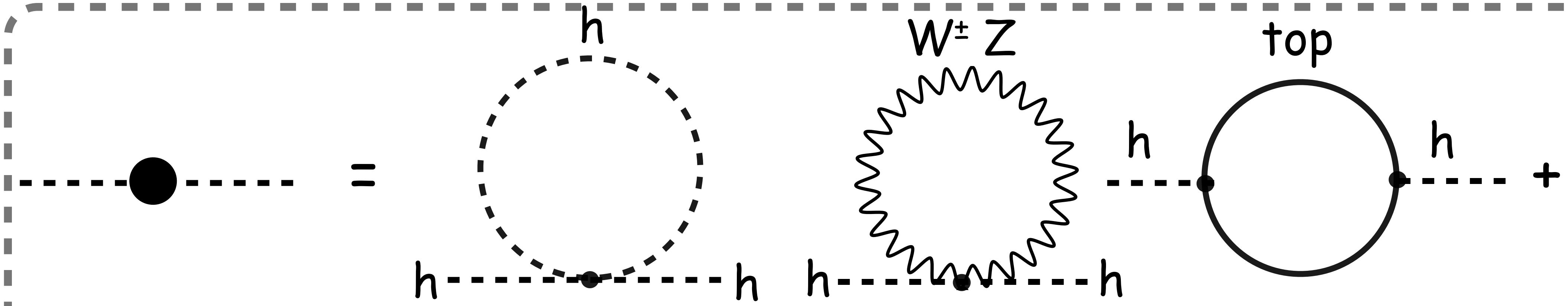
$$m_H^2 \sim m_0^2 - (115\ \mathrm{GeV})^2 \left(\frac{\Lambda}{700\ \mathrm{GeV}} \right)^2$$

$\Lambda = 1$ TeV



Quantum Instability of the Higgs Mass

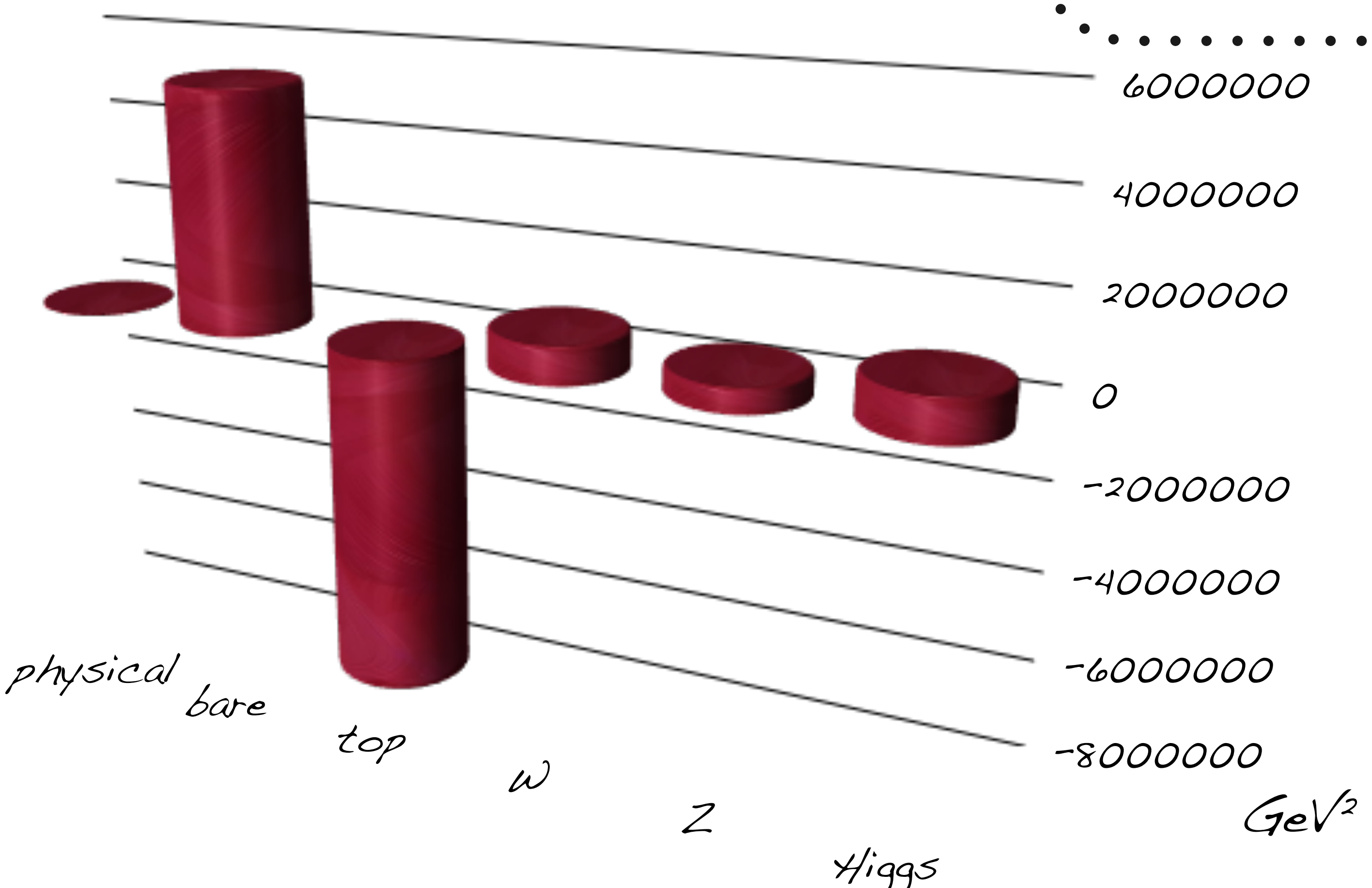


Higher loops
Smaller Yukawa

$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2 \qquad \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{(k^2 - m^2)^2} \propto \Lambda^2$$

$$m_H^2 \sim m_0^2 - (115\ \text{GeV})^2 \left(\frac{\Lambda}{700\ \text{GeV}}\right)^2$$

Λ = 10 TeV



Playing with Λ^2: Veltman throat

$$\delta m_H^2 = \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \frac{3G_F\Lambda^2}{16\sqrt{2}\pi^2}$$

People taking the Λ^2 terms literally would say it is possible to cure the hierarchy pb if

$$m_H^2 = 4m_t^2 - 2m_W^2 - m_Z^2 \approx (320\ \mathrm{GeV})^2$$

This is a too naive interpretation

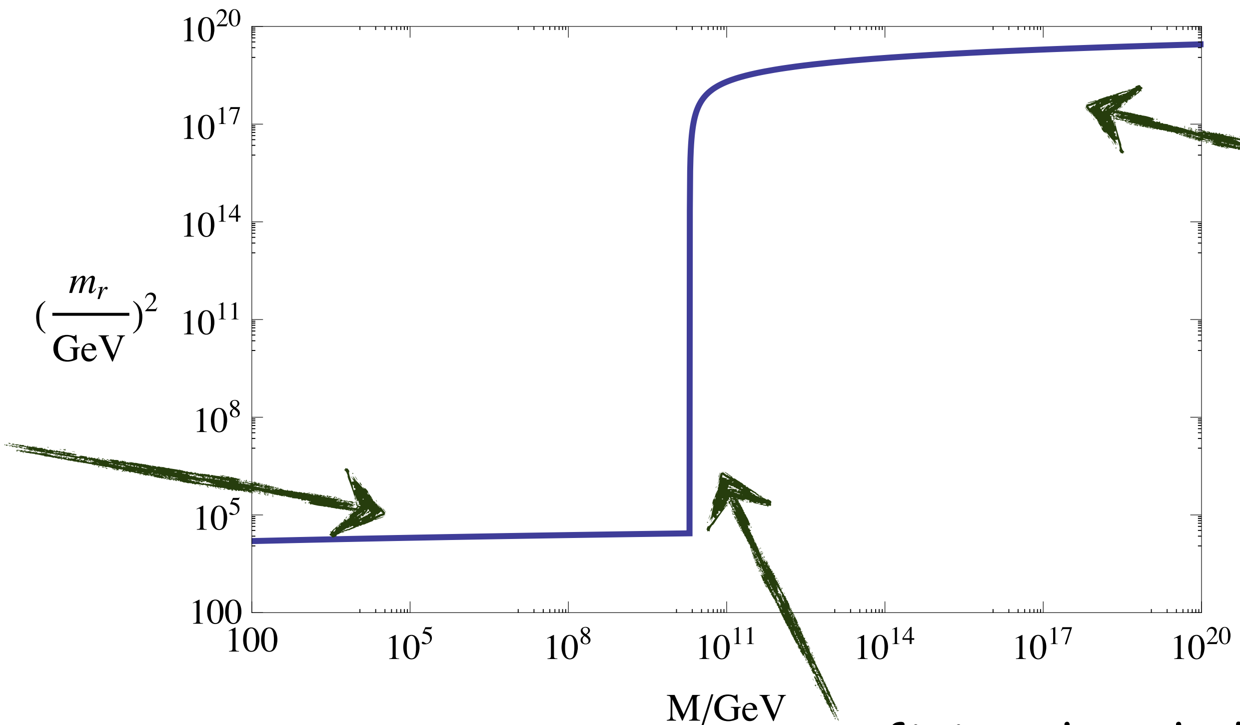
- in the absence of any symmetry, there is no reason to use the same cutoff for all particles
- the throat doesn't survive at higher loop order
- it would anyway require a very particular value of the Higgs mass that it is not dictated by any symmetry

What the hell is the meaning of Λ^2 ?

It is often argued that Λ^2 terms have no meaning since they are put to 0 in dim. reg.
hence the believe that there is no hierarchy pb!
THIS IS TRUE IN THE SM
the hierarchy pb exists only when multiple scales are present

The hierarchy pb can be seen when dealing with the renormalized running Higgs mass

e.g. Barbieri '13



innocuous
Log running

innocuous
Log running

finite threshold correction $O((\lambda_* M_*)^2/16\pi^2)$
induced by a new particle of mass M_*
with a coupling λ_* to the Higgs

Need to tune $O((m_h/M_*)^2)$ the value of m_H at high scale to reproduce m_H(EW)
UV sensitivity

[picture courtesy of A. Weiler]

7

Symmetries for a natural EWSB

How to Stabilize the Higgs Potential

Goldstone's Theorem

spontaneously broken global symmetry ⇨ massless scalar

... but the Higgs has sizable non-derivative couplings

The spin trick

a particle of spin s: 2s+1 polarization states

...with the only exception of a particle moving at the speed of light

... fewer polarization states

Spin 1 Gauge invariance ⟶ no longitudinal polarization ↘ $m=0$

Spin 1/2 Chiral symmetry ⟶ only one helicity ↗ $m=0$

... but the Higgs is a spin 0 particle

Naturalness

't Hooft naturality: a number is naturally small when the symmetry of the theory increases as the parameter is set to zero

Spin 1/2 $\begin{pmatrix} \chi \\ \psi \end{pmatrix}$

$$-i\bar{\chi}\bar{\sigma}^\mu \partial_\mu \chi - i\psi\sigma^\mu\partial_\mu\bar{\psi} + m\left(\chi\psi + \bar{\chi}\bar{\psi}\right)$$

invariant under $\chi \to e^{i\alpha}\chi$, $\psi \to e^{-i\alpha}\psi$

if $m=0$, also invariant under $\chi \to e^{i\alpha}\chi$, $\psi \to e^{i\alpha}\psi$

Spin 1

$$-\frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)(\partial^\mu A^\nu - \partial^\nu A^\mu) - \frac{1}{2}m^2 A_\mu A^\mu$$

iff $m=0$, invariant under $A_\mu \to A_\mu + \partial_\mu \epsilon$

Symmetries to Stabilize a Scalar Potential

Supersymmetry

fermion ~ boson

Higher Dimensional Lorentz invariance

⇚ gauge-Higgs unification models

[Manton '79, Fairlie 79, Hosotani '83 +...]

$$A_\mu \sim A_5$$

4D spin 1 ↗ ↖ 4D spin 0

These symmetries cannot be exact symmetry of the Nature. They have to be broken. We want to look for a soft breaking in order to preserve the stabilization of the weak scale.

Other symmetries?

Ghost symmetry

Grinstein, O'Connell, Wise '07

SM particle ~ ghost

It was known since Pauli-Villars that ghosts can soften the UV behavior of the propagators. But they are unstable per se.

Lee-Wick in the 60's proposed a trick to stabilize the ghosts (at the price of of a violation of causality at the microscopic scale).

What amount conformal invariance?

SM is nearly scale invariant classically
and scale invariance will forbid any Higgs mass term
SM mass and running couplings break conformal invariance
but maybe conformal symmetry is only "softly" broken and restored at high energy

Bardeen '95

$U(1)_Y$ and gravity grow in the UV ⇒ large conformal breaking

one needs a transition between SM and Conformal Field Theory behavior

w/ particles @ transition scale
⇓
usual hierarchy pb

w/o particles @ transition scale
⇓
it was shown that the anomalous dimensions
of the operators coupled to the Higgs
change at the threshold
and this reintroduces a fine-tuning
unless the threshold is around the weak scale

Marques Tavares, Schmaltz, Skiaba '13

Not totally impossible scenario but requires some unknown dynamics

EWSB might be unnatural

nothing to say but the usual words:

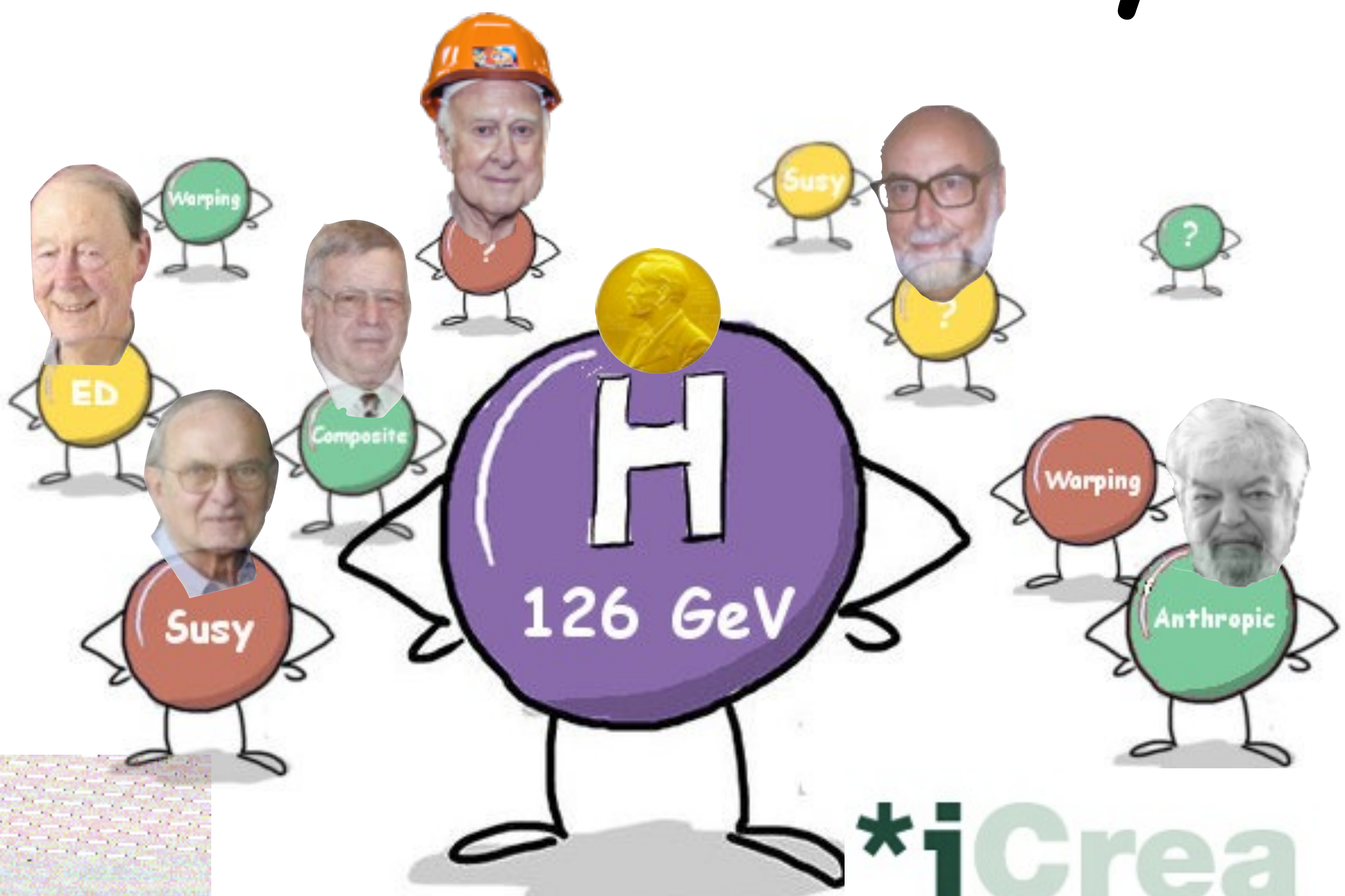
- cosmological constant problem...
- multiverse...
- landscape of vacua...
- laws of physics are environmental...
- anthropic solution...
- end of reductionism...

will be tested to an unprecedented level (10^{-4})

if we lose naturalness,
what should be the guiding principle towards our understanding of physics at higher and higher energies?

1 2

Higgs Physics within and beyond the SM



P. Cámara/C. Grojean

IFIC, Valencia, May 2015

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*iCrea
INSTITUCIÓ CATALANA DE RECERCA I ESTUDIS AVANÇATS

Disclaimer

These are slides that I've prepared for some lectures at the CERN-Latin American School of High Energy Physics last March in Ecuador.

There is partial overlap with what I covered during my blackboard lectures at IFIC even though some parts are missing in these notes.

Do not hesitate to contact me by email if you have any comments or questions.
And please, report any typo/mistake that you might find in these notes.

Lecture Outline

1. First Lecture ⮌
   - Standard Model and EW symmetry breaking ⮌
   - Higgs mechanism - custodial symmetry ⮌
   - Goldstone equivalence theorem ⮌
   - What is the Higgs boson the name of? ⮌
   - SM Higgs @ colliders ⮌
   - UV behavior of the Higgs boson (triviality, stability, naturality) ⮌
   - Symmetries for a natural EWSB ⮌
2. Second Lecture ⮌
   - Implications for SUSY ⮌
   - Composite Higgs models ⮌
   - Precision Higgs couplings ⮌
   - Future Higgs channels:
     - Boosted and off-shell channels ⮌
     - Multi-Higgs ⮌

1 2

We all have a Post higgs Depression

For the first time in the history of physics,
we have a *consistent* description of the fundamental constituents of matter and their interactions and this description can be extrapolated to very high energy (up M_{Planck}?)

My key message

MLM@Aspen'14

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

Where and how does the SM break down?
Which machine(s) will reveal this breakdown?

HEP with a Higgs boson

"If you don't have the ball, you cannot score"

HEP with a Higgs boson

"If you don't have the ball, you cannot score"

Now with the Higgs boson in their hands,
particle physicists can... play as well as the Barça players

Higgs as a target

- observe it in as many channels as possible to measure its properties
- check of the coupling structure of the SM and its deformations
- interpret deviations of Higgs couplings as a sign of NP

Higgs as a tool

- a portal to New Physics
- in initial states: rare decays (BSM Higgs decays)

  e.g., $h \to \mu\tau$, $h \to J/\Psi+\gamma$

- in final states as an object that can be reconstructed and tagged (BSM Higgs productions)

  e.g., $t \to h+c$, $H \to hh$

Profound change in paradigm:
missing SM particle ⇨ tool to explore SM and venture into physics landscape beyond

1

Implications for SUSY

Is SUSY/MSSM Natural?

The Higgs mass is calculable in the MSSM

$$m_h^2 = M_Z^2 \cos^2 2\beta + \delta_t^2$$

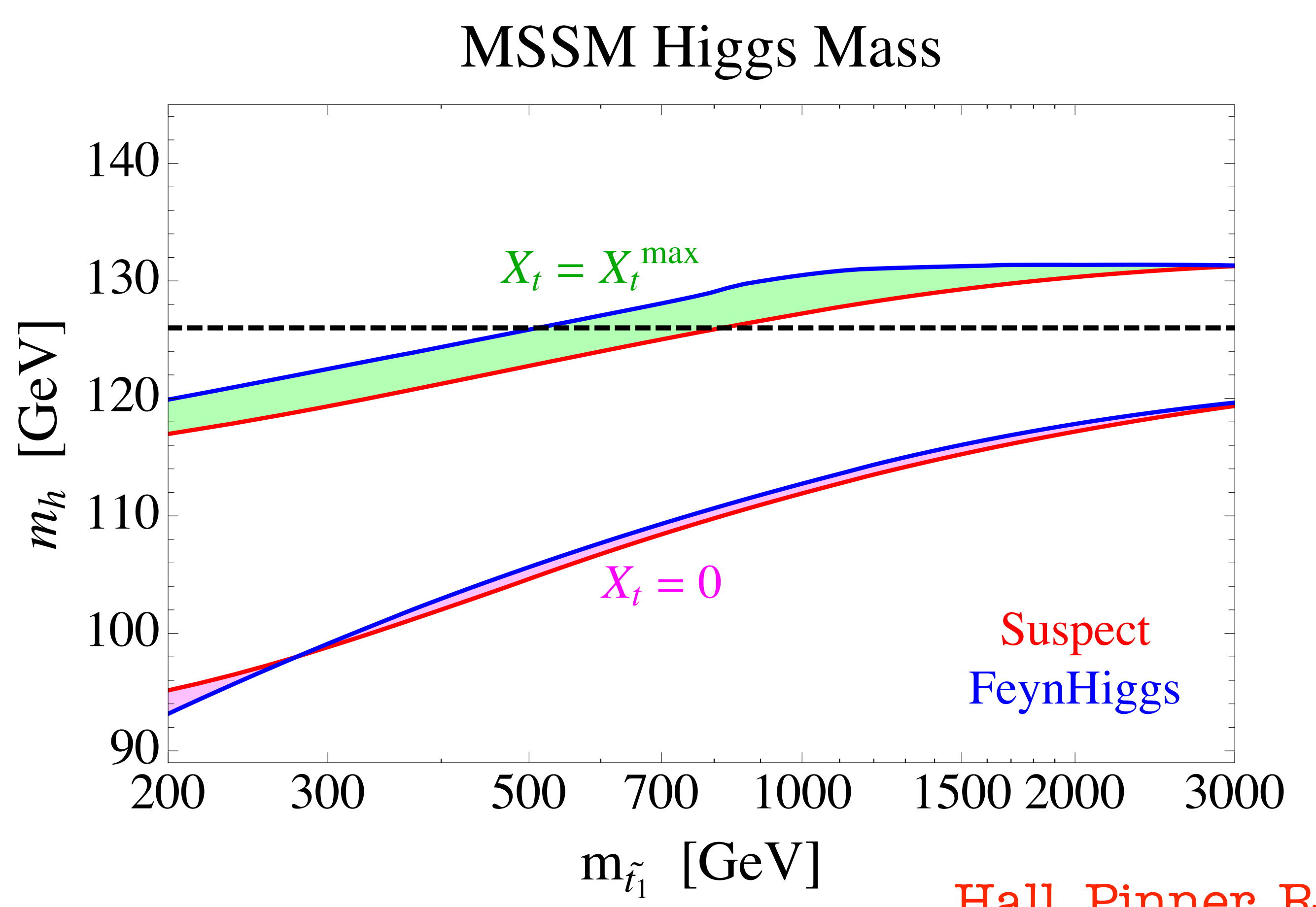
$$\delta_t^2 \approx \frac{3\sqrt{2} G_F M_t^4}{16\pi^2}\left[\log\frac{M_{\tilde{t}}^2}{M_t^2} + \frac{X_t^2}{M_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 M_{\tilde{t}}^2}\right)\right]$$

$M_{\tilde{t}}$ stop mass (degenerate)

X_t stop mixing

$(125\ \text{GeV})^2$ $\qquad$ $(\gtrsim 87\text{GeV})^2$

substantial loop contribution from stops



Hall, Pinner, Ruderman '11
+ many similar analyses

large mixing
heavy stops

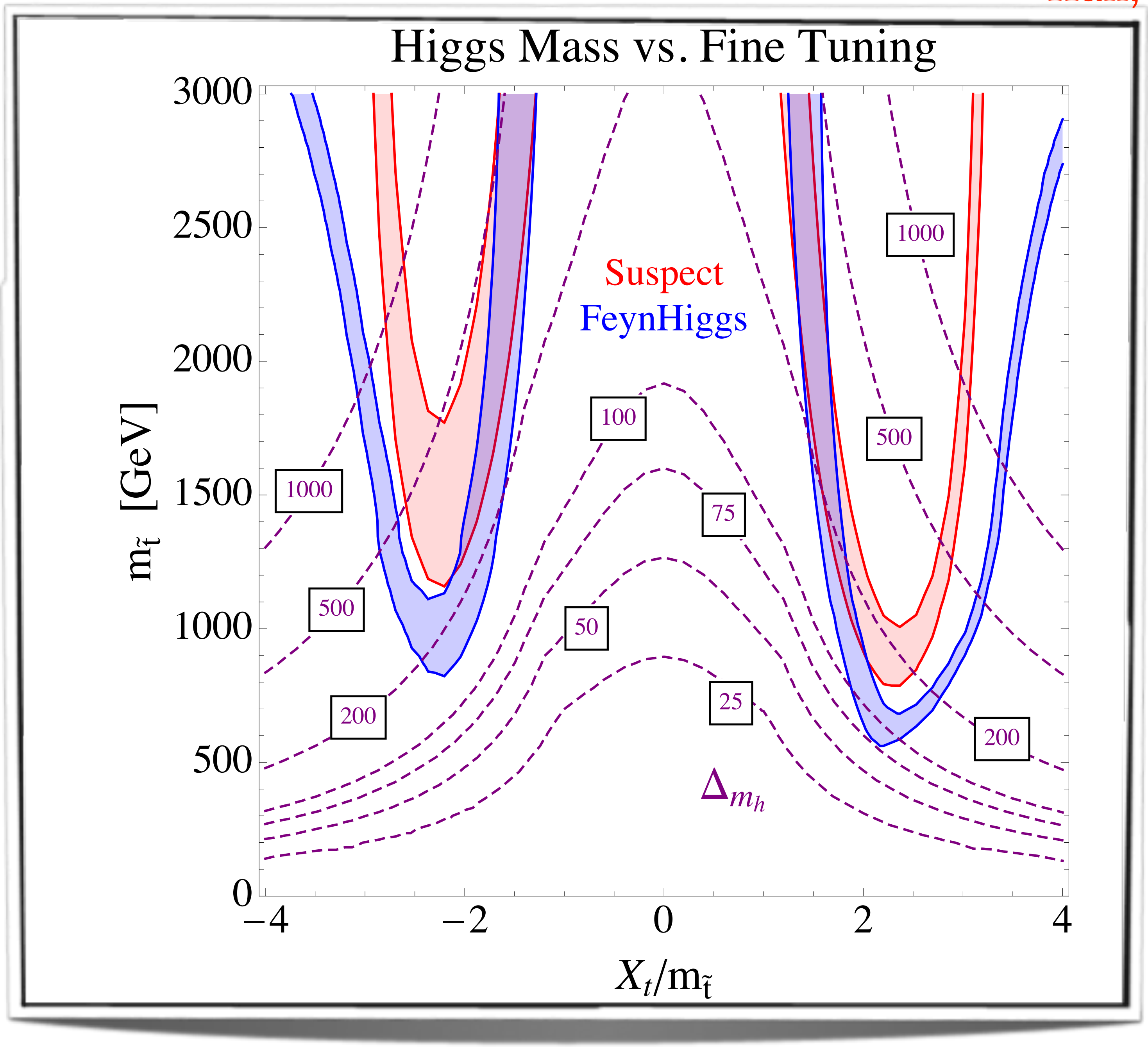
$$\sqrt{m_{Q_3} m_{u_3}} \gtrsim 700\ \text{GeV}$$

$\Downarrow$ $\qquad$ $\Downarrow$

fine-tuning $\gtrsim$ 1%

MSSM fine-tuning

Hall, Pinner, Ruderman '11



maximal mixing requires engineering

$$m_{\tilde{t}}^2(M_Z) \simeq 5.0 M_3^2(M_G) + 0.6 m_{\tilde{t}}^2(M_G)$$
$$A_t(M_Z) \simeq -2.3 M_3(M_G) + 0.2 A_t(M_G)$$

⇢ generically $|A_t/m_{\tilde{t}}| \leq 1$

Fermisek, Kim '06

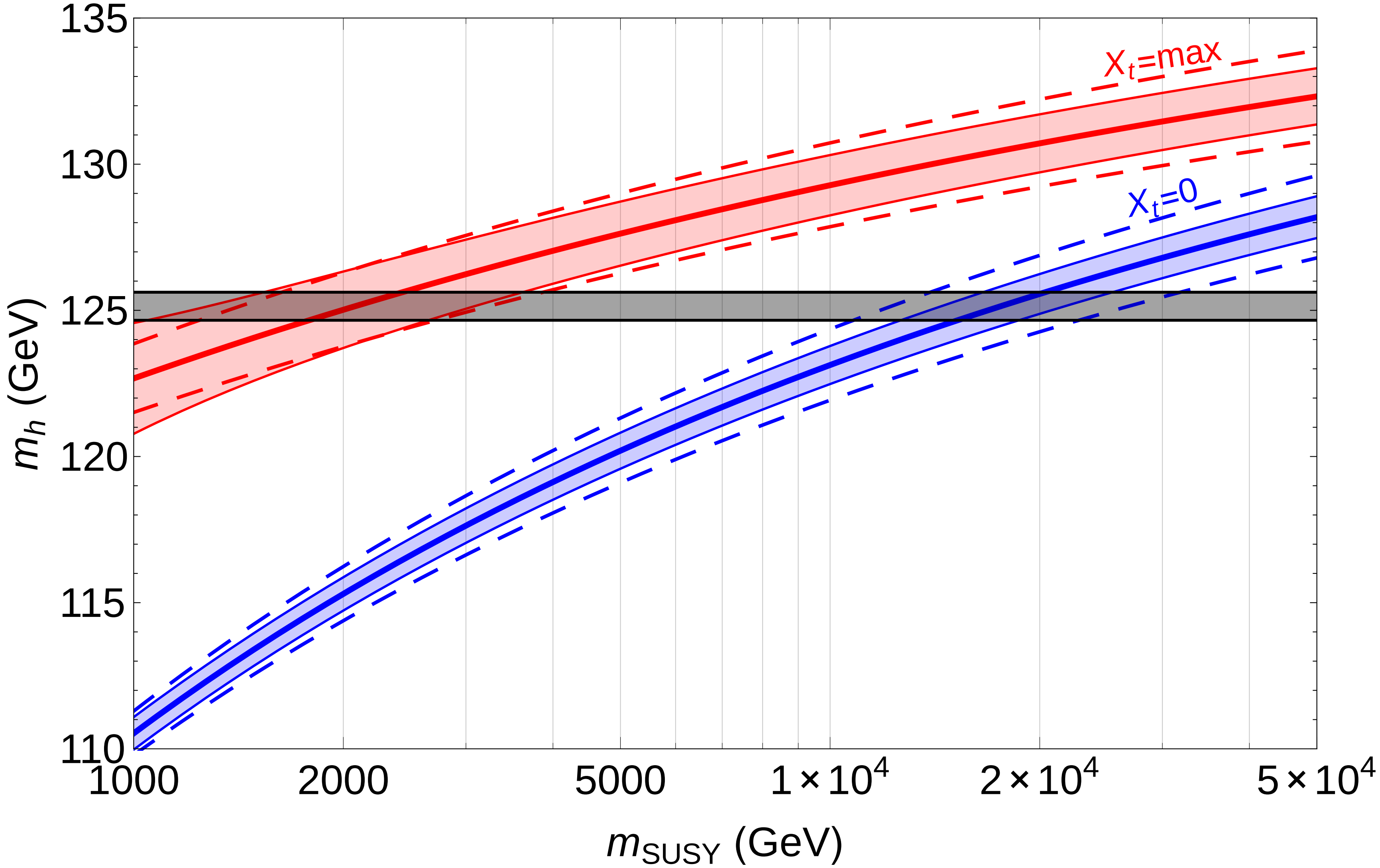
Towards precise prediction of MSSM Higgs mass

further improved predictions (full 2-loop QCD corrections)

Bagnaschi et al '14

Degrassi et al '14

Pedro Vega, Villadoro 'to appear



requires
even heavier stops
to accommodate
a 125GeV Higgs

[plot from J. Padro Vega and G. Villadoro, 'to appear]

Saving SUSY

SUSY is Natural
but not plain vanilla

- ~~CMSSM~~
- pMSSM
- NMSSM
- Hide SUSY, e.g. smaller phase space
  - reduce production (eg. split families) Mahbubani et al
  - reduce MET (e.g. ~~R-parity~~, compressed spectrum) Csaki et al
  - dilute MET (decay to invisible particles with more invisible particles)
  - soften MET (stealth susy, stop -top degeneracy) Fan et al

$LHC_{100fb^{-1}}$ will tell!

Good coverage of
hidden natural susy

- mono-top searches (DM, flavored naturalness - mixing among different squark flavors-, stop-higgsino mixings)
- mono-jet searches with ISR recoil (compressed spectra)
- precise tt inclusive measurement+ spin correlations (stop → top + very soft neutralino)
- multi-hard-jets (RPV, hidden valleys, long decay chains)

2

Composite Higgs models

Why should you care about compositeness?

Higgs compositeness means new fundamental interactions

Pospelov's 38 years rule...

38 years rule = new forces of nature are discovered every 38 years for the last 150 yrs

1. 1860s – first papers of Maxwell on EM. Light is EM excitation. E & M unification.
2. 1897 – Becquerel discovers radioactivity – first evidence of weak charged currents (in retrospect).
3. 1935 – Chadwick gets NP for his discovery of neutron with subsequent checks that there exists strong n-p interaction. Strong force is established.
4. 1973 – Gargamelle experiment sees the evidence for weak neutral currents in nu-N scattering
5. 2011/2012 Discovery of the Higgs, i.e. new Yukawa force.
6. *Prediction: Discovery of a new dark force – 2050?*

(+/- 2 years or so).

M. Pospelov, SHiP collab. meeting, Naples '15

Why should you care about compositeness?

All SM shortcomings are intimately linked to the Higgs elementary nature

$$\mathcal{L}_{\rm Higgs} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar{\psi}_{Li}\psi_{Rj}H + h.c.\right)$$

vacuum energy
cosmological constant
$V_0 \approx (2\times 10^{-3}\ \text{eV})^4 \ll M_{\rm PL}^4$

String?

hierarchy problem
$m_H \approx 100\ \text{GeV} \ll M_{\rm Pl}$

SUSY?
TeV New Physics?

triviality/stability
of EW vacuum

mass and mixing
hierarchy

flavour & CP:
no FCNC, small CP

well described
experimentally by CKM
(up to a few exceptions: $A_{FB}^{t\bar{t}}$, ΔA_{CP}^{c}...)

Why should you care about compositeness?

All SM shortcomings are intimately linked to the Higgs elementary nature

$$\mathcal{L}_{\text{Higgs}} = V_0 - \mu^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \left(y_{ij}\bar{\psi}_{Li}\psi_{Rj}H + h.c.\right)$$

vacuum energy
cosmological constant
$V_0 \approx (2 \times 10^{-3}\ \text{eV})^4 \ll M_{\text{PL}}^4$

hierarchy problem
$m_H \approx 100\ \text{GeV} \ll M_{\text{Pl}}$

triviality/stability of EW vacuum

mass and mixing hierarchy

flavour & CP: no FCNC, small CP

> All these problems because the Higgs boson would be the first elementary particle whose interactions are not endowed with a gauge structure

Higgs = Elementary or Composite?

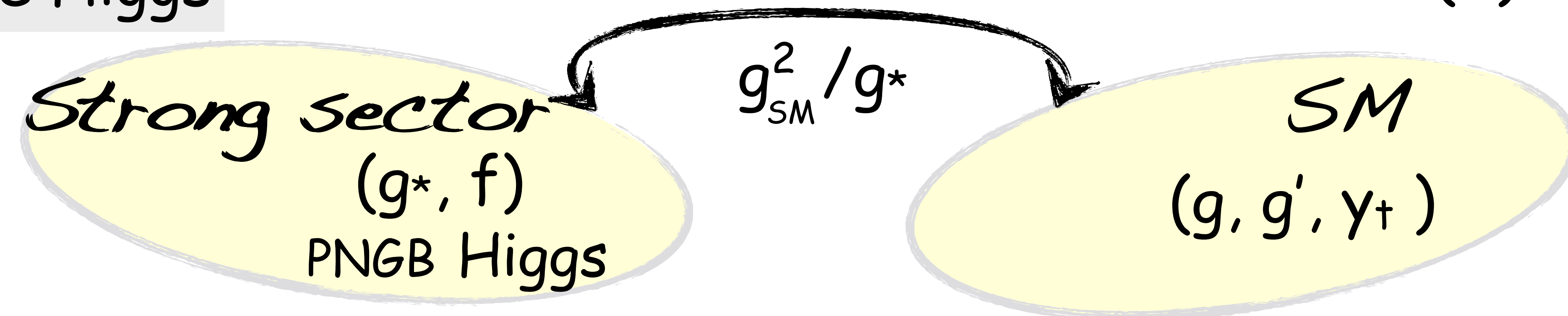
Which composite scenario?

Minimal Composite Higgs

ex: SO(5)/SO(4)

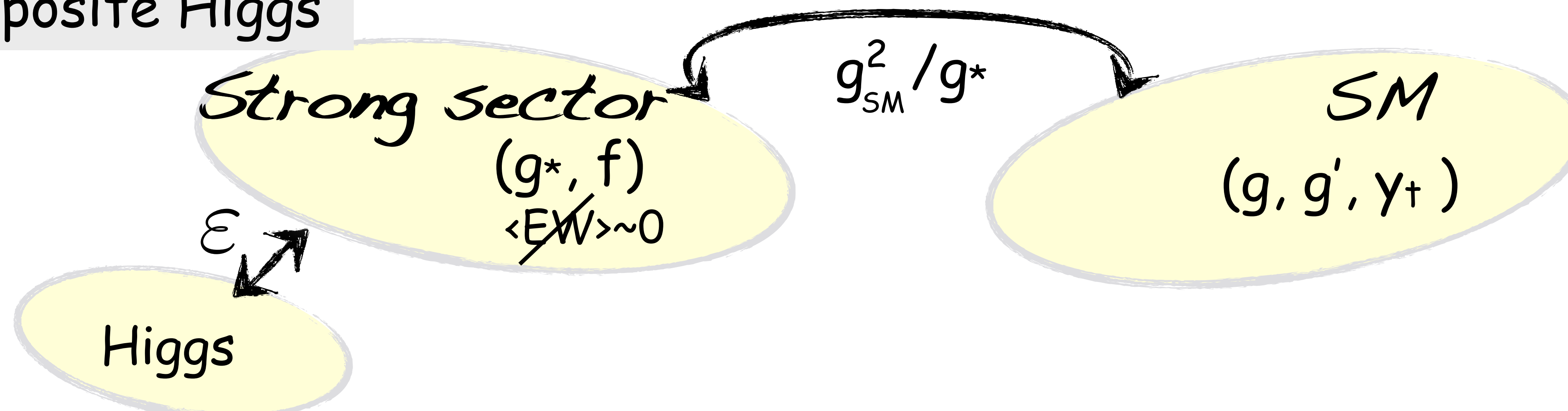
SILH

$$\xi = \frac{v^2}{f^2} \ll 1$$



Partly Composite Higgs

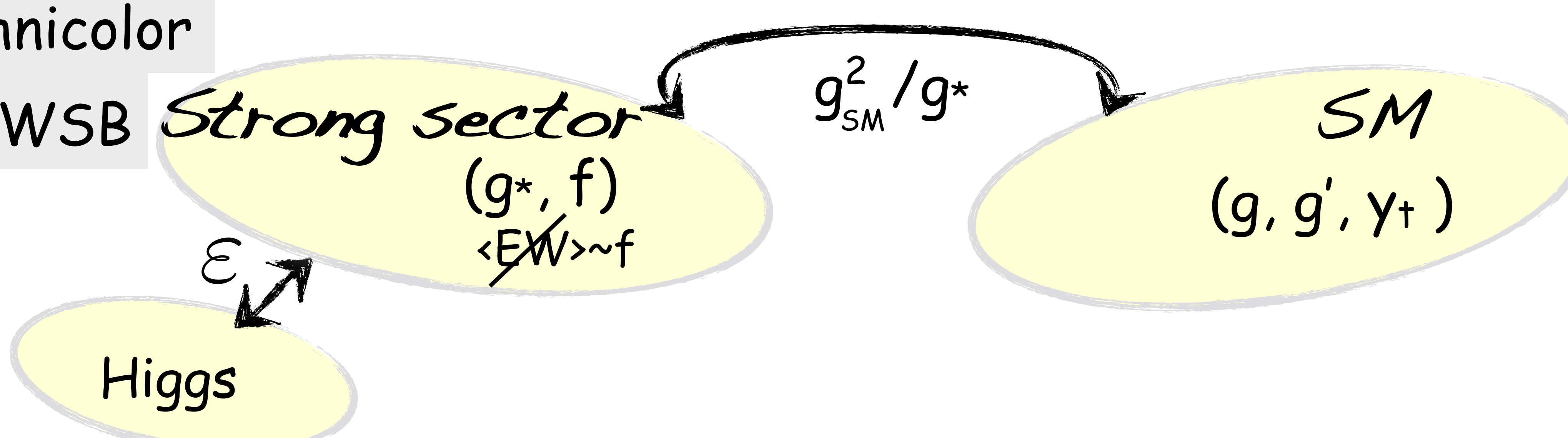
$$\xi = \frac{v^2}{f^2} \ll 1$$



Bosonic Technicolor

Induced EWSB

$$\varepsilon = \frac{f}{v} \ll 1$$



Which composite scenario?

Minimal Composite Higgs

SILH

$$\frac{1}{f^2}\left(\partial_\mu |H|^2\right)^2 \qquad \frac{\lambda_4}{f^2}|H|^6$$

$$\xi = \frac{v^2}{f^2} \ll 1$$

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}} = 1+\xi \qquad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\mathrm{SM}}} = 1+\xi$$

Partly Composite Higgs

$$\frac{\varepsilon^4}{f^2}\left(\partial_\mu |H|^2\right)^2 \qquad \frac{\varepsilon^6}{f^2}|H|^6$$

$$\xi = \frac{v^2}{f^2} \ll 1$$

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}} = 1+\varepsilon^4\xi \qquad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\mathrm{SM}}} = 1+\varepsilon^2\frac{g_*^2 v^2}{m_h^2}\varepsilon^4\xi$$

Bosonic Technicolor

Induced EWSB

$$\frac{\varepsilon^4}{f^2}\left(\partial_\mu |H|^2\right)^2 \qquad \frac{\varepsilon^6}{f^2}|H|^6$$

$$\varepsilon = \frac{f}{v} \ll 1$$

$$\kappa_V \equiv \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}} = 1+\varepsilon^2 \qquad \kappa_3 \equiv \frac{g_{hhh}}{g_{hhh}^{\mathrm{SM}}} = 1+\mathcal{O}(1)$$

Patterns of Higgs coupling deviations

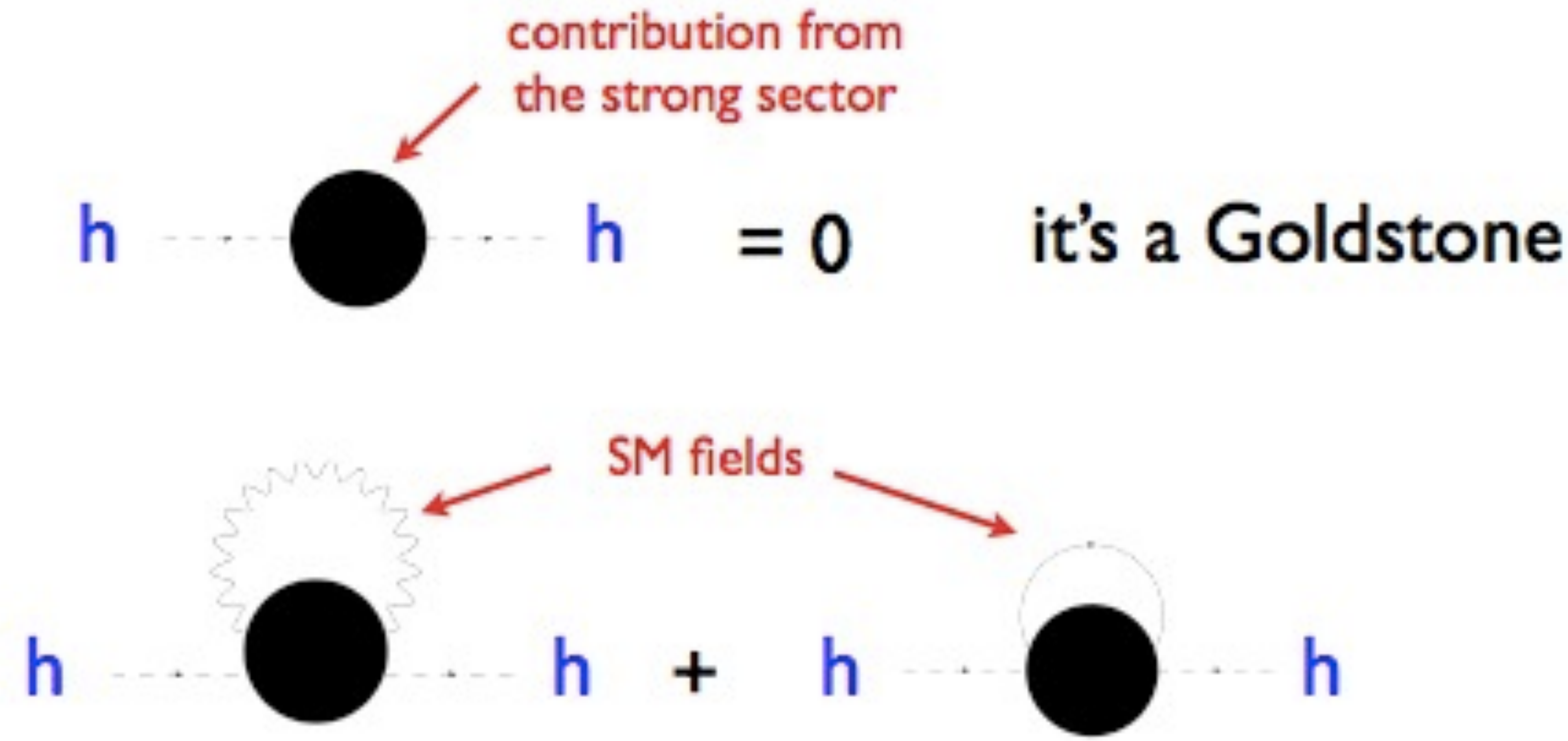
expected largest relative deviations

	hff	hVV	hγγ	hγZ	hGG	h^3
MSSM	√		√	√	√	
NMSSM	√	√	√	√	√	
PGB Composite	√	√		√		√
SUSY Composite	√	√	√	√	√	√
SUSY partly-composite			√	√	√	√
“Bosonic TC”						√
Higgs as a dilaton			√	√	√	√

A. Pomarol, Naturalness ’15

Light composite Higgs from "light" resonances

The interactions between the strong sector and the SM generate a potential for the Higgs



Impossible to compute the details of the potential from first principles
but using general properties on the asymptotic behavior of correlators
(saturation of Weinberg sum rules with the first few lightest resonances)
it is possible to estimate the Higgs mass

Pomarol, Riva '12

$$m_h^2 \approx \frac{3}{\pi^2} \frac{m_t^2 m_Q^2}{f_{G/H}^2}$$

Marzocca, Serone, Shu '12

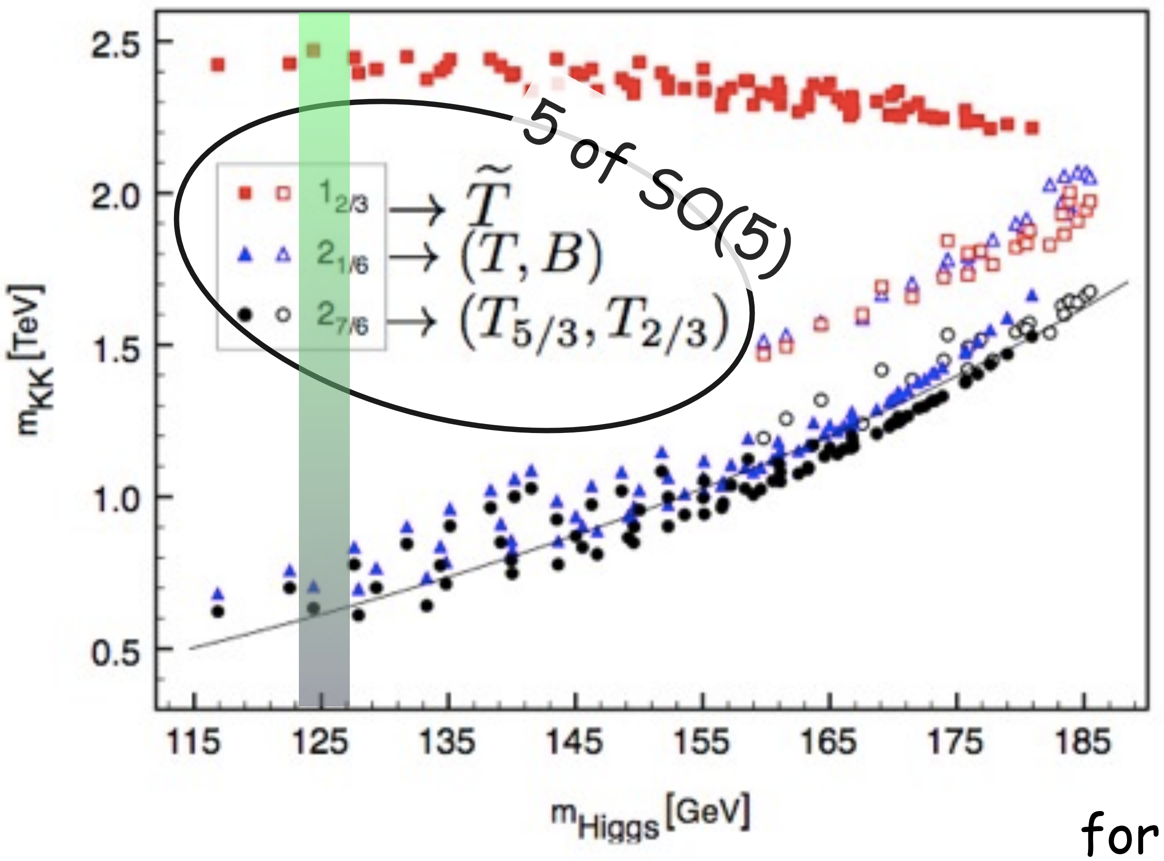
$$m_Q \lesssim 700 \text{ GeV} \left(\frac{m_h}{125 \text{ GeV}}\right) \left(\frac{160 \text{ GeV}}{m_t}\right) \left(\frac{f}{500 \text{ GeV}}\right)$$

fermionic resonances below ~ 1 TeV
vector resonances ~ few TeV (EW precision constraints)
~ for a natural (<20% fine-tuning) set-up ~

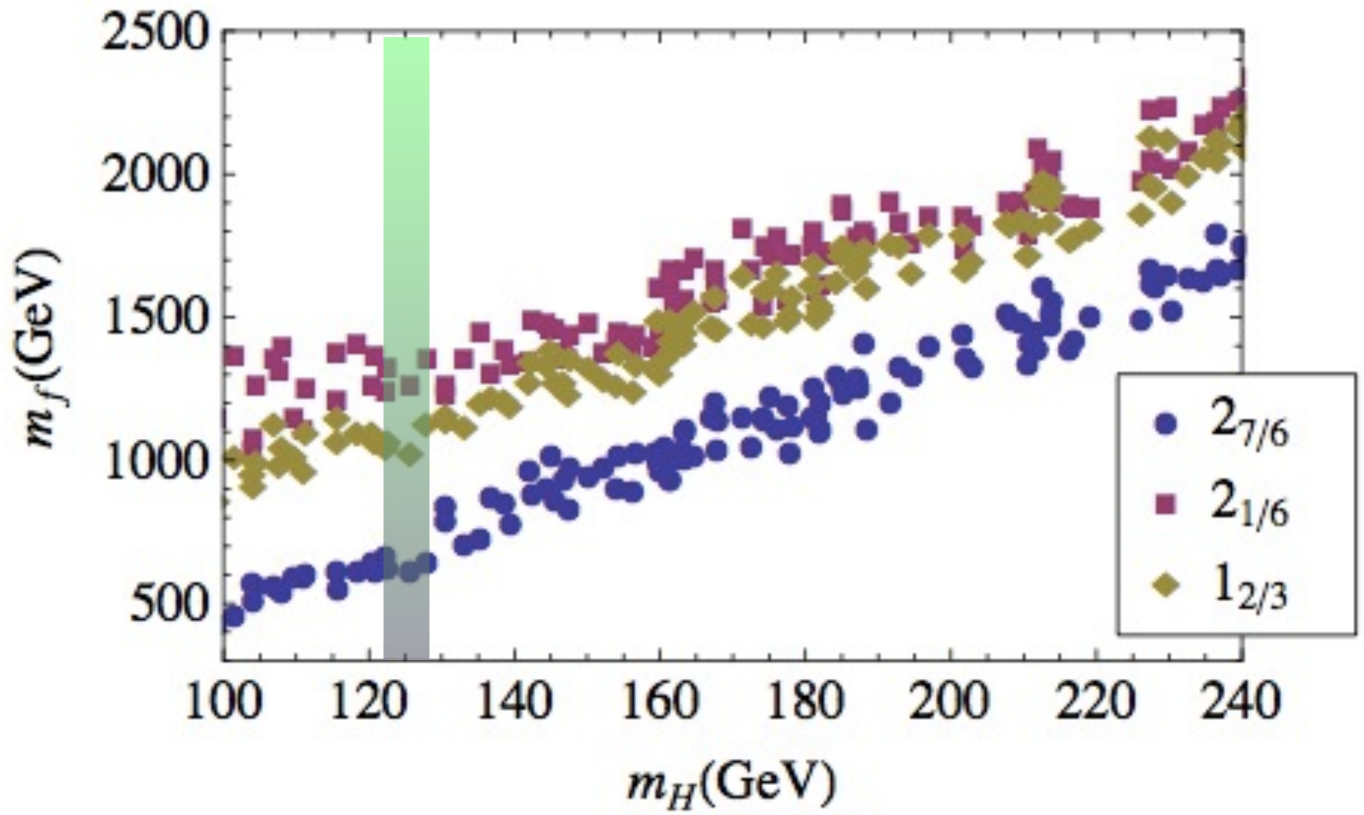
Light composite Higgs from "light" resonances

true spectrum in explicit realizations

Contino, Da Rold, Pomarol '06



De Curtis, Redi, Tesi '11



for similar results, see also

Matsedonskyi, Panico, Wulzer '12 & Marzocca, Serone, Shu '12

Nice AdS/CFT interpretation

$$\mathrm{Dim}[\mathcal{O}_\Psi] = \frac{3}{2} + |M_\Psi + \frac{1}{2}|$$

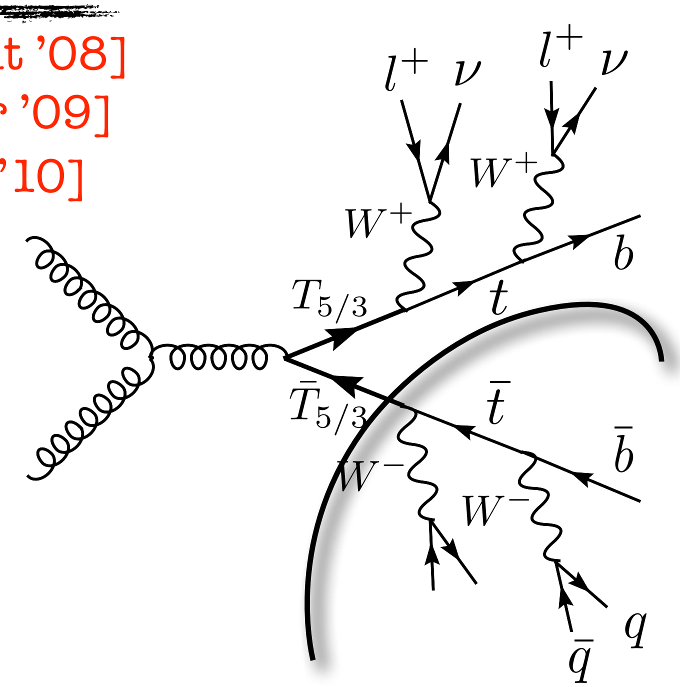
$$M_\Psi = 1/2 \leftrightarrow \dim[\mathcal{O}_\Psi] = 3/2 \leftrightarrow \text{light free field decoupled from CFT}$$

Rich phenomenology of the top partners

Search in same-sign di-lepton events

[Contino, Servant '08]
[Mrazek, Wulzer '09]
[Dissertori et al '10]

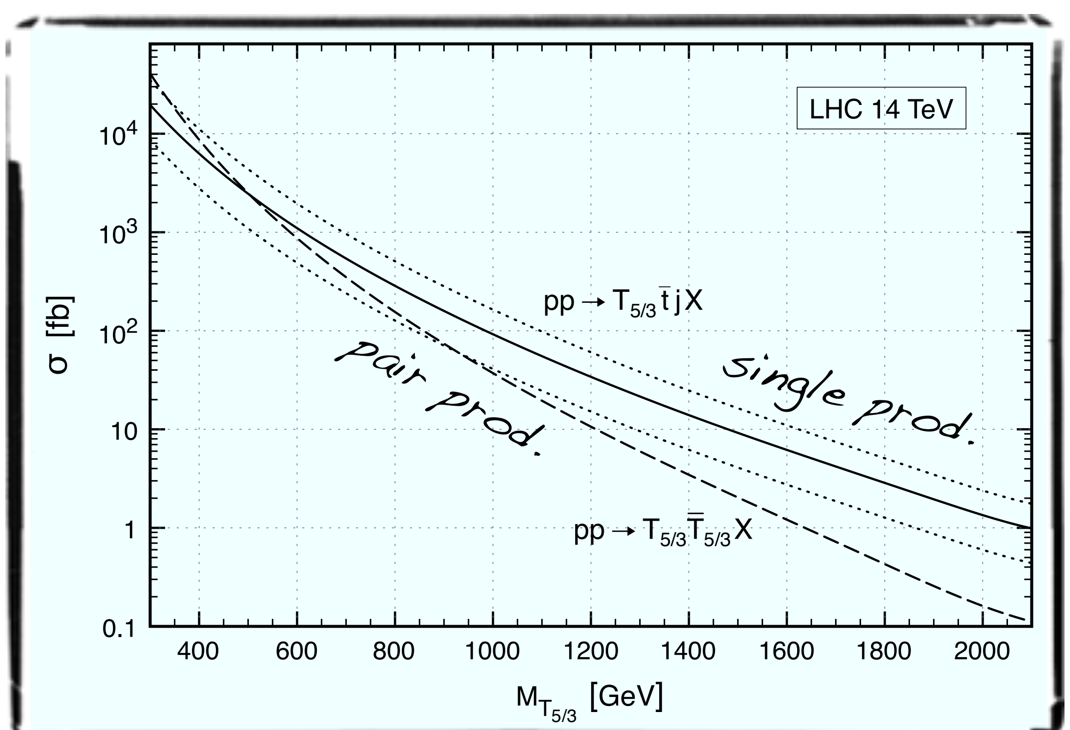
- *tt+jets* is not a background [except for charge mis-ID and fake e^-]
- the resonant (tW) invariant mass can be reconstructed



discovery potential (LHC_{14TeV})

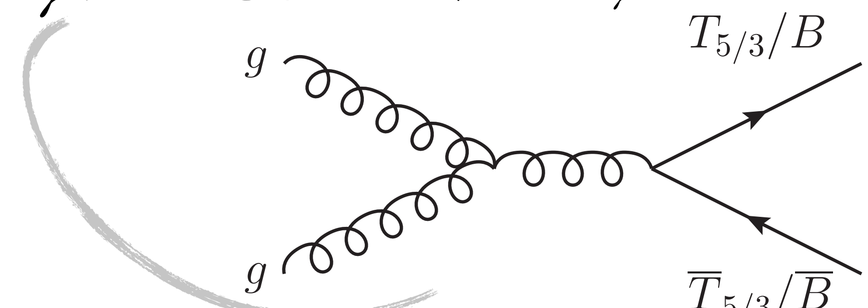
$M_{5/3}$=500 GeV (σxBR≈100/fb) → 56 pb^{-1}

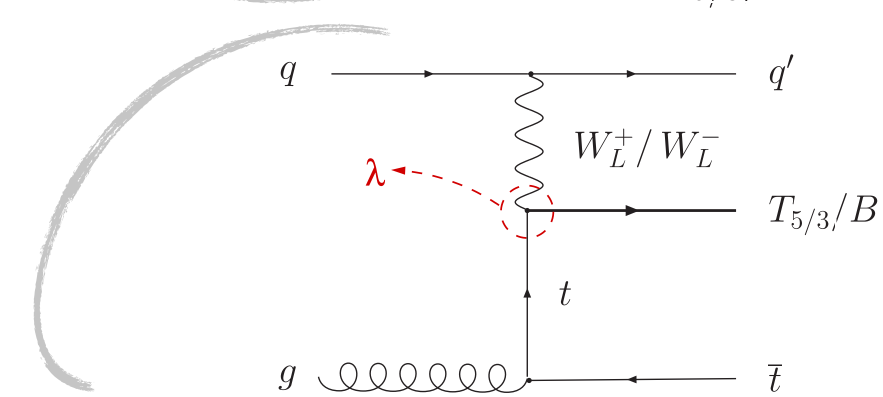
$M_{5/3}$=1 TeV (σxBR≈2/fb) → 15 fb^{-1}



[Contino, Servant '08]

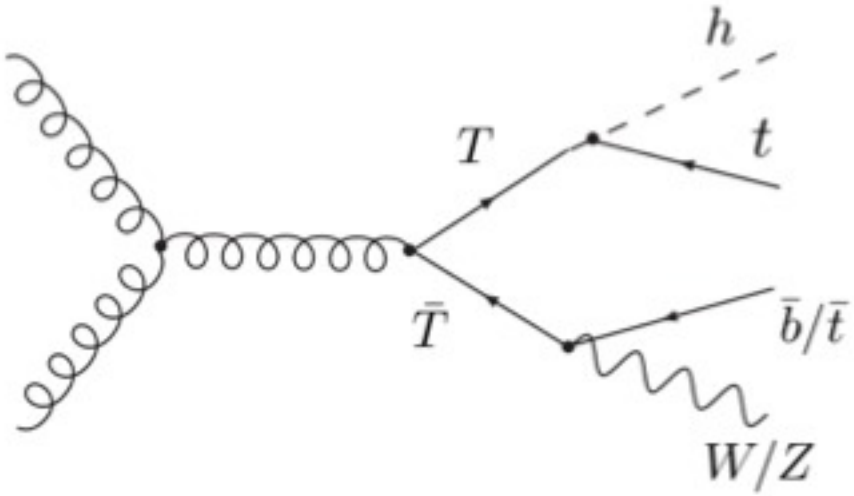
Pair production (model independent)





Single production (model dependent)

Rich phenomenology of the top partners



l± + 4b final state

Aguilar-Saavedra '09

$$T\bar{T} \to HtW^-\bar{b} \to HW^+bW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}',$$
$$T\bar{T} \to HtV\bar{t} \to HW^+bVW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}', V \to q\bar{q}/\nu\bar{\nu}$$

l± + 6b final state

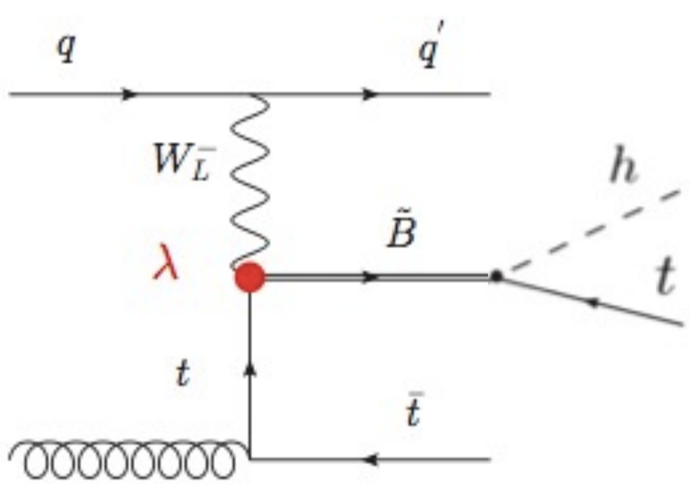
Aguilar-Saavedra '09

$$T\bar{T} \to HtH\bar{t} \to HW^+bHW^-\bar{b} \qquad H \to b\bar{b}, WW \to \ell\nu q\bar{q}'$$

$\gamma\gamma$ final state

Azatov et al '12

$$thbW/thtZ/thth,\ h \to \gamma\gamma$$



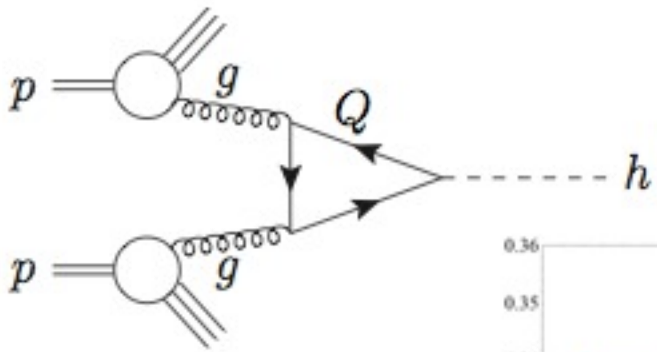
l± + 4b final state

Vignaroli '12

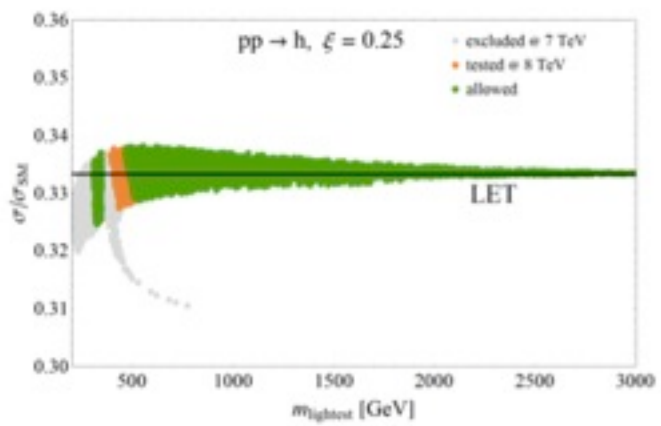
$$pp \to (\tilde{B} \to (h \to bb)b)t + X$$

Top partners & Higgs physics

~ current single higgs processes are insensitive to top partners ~



$\sigma^{SM}_{14\text{TeV}} \approx 50$ pb



two competing effects that cancel:

- ☑ T's run in the loops
- ☑ T's modify top Yukawa coupling

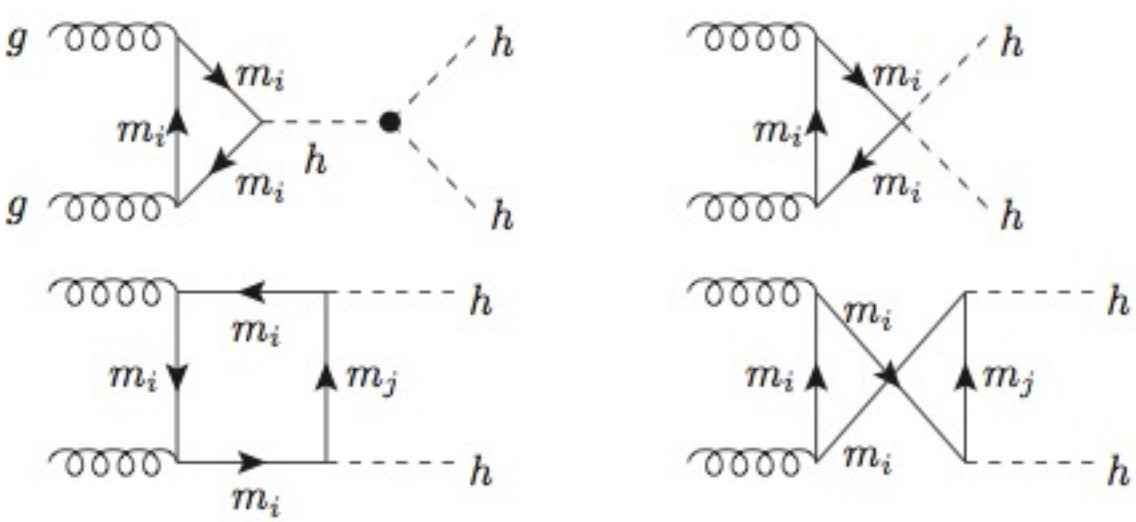
Falkowski '07

Azatov, Galloway '11

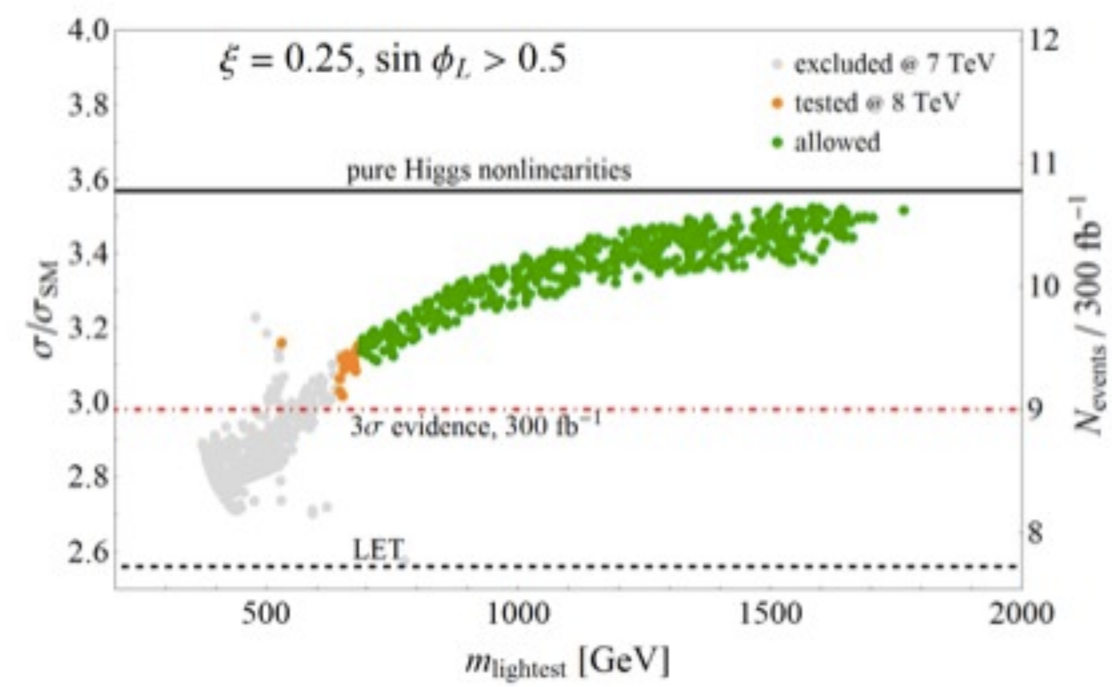
Delaunay, Grojean, Perez, '13

~ sensitivity in double Higgs production ~

Gillioz, Grober, Grojean, Muhlleitner, Salvioni '12



$\sigma^{SM}_{14\text{TeV}} = 17.9\text{fb}$



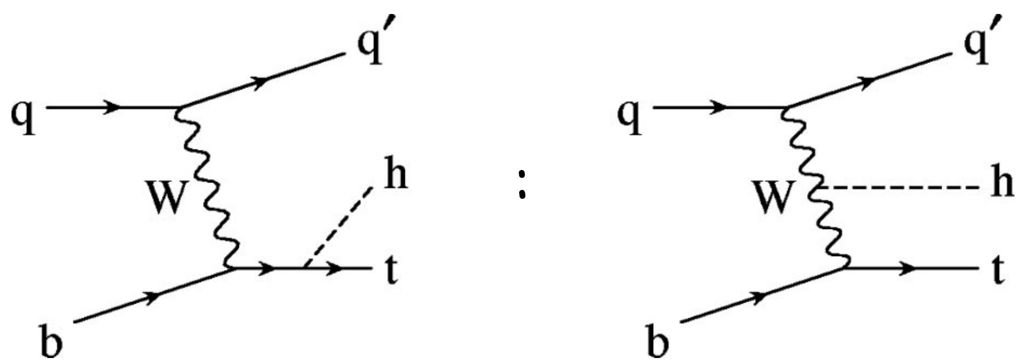
Top partners & Higgs physics

direct measurement of top-higgs coupling

htt is important but challenging channel

may be easier channel to look at

qb→q'th



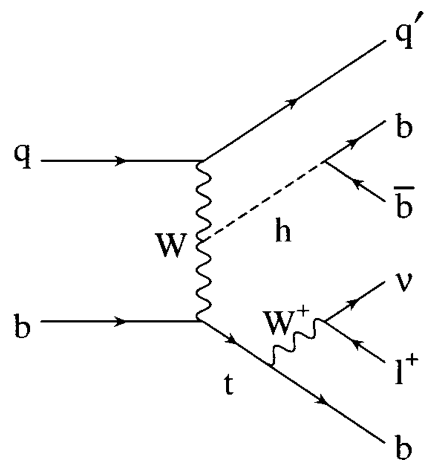
@m_H=125GeV $$\frac{|\mathcal{A}_W - \mathcal{A}_t|^2}{|\mathcal{A}_W + \mathcal{A}_t|^2} \approx 13$$

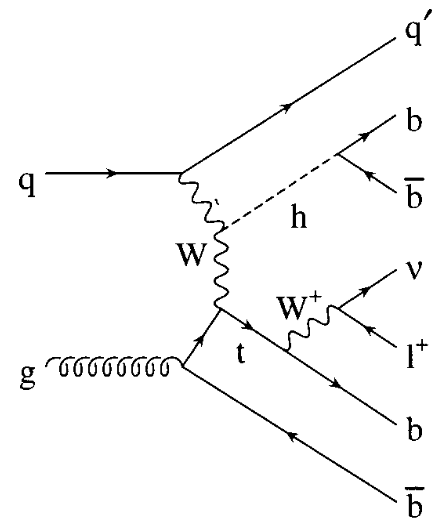
Farina, Grojean, Maltoni, Salvioni, Thamm '12

	$\sigma(pp \to tjh)$ [fb]		$\sigma(pp \to tjh\bar{b})$ [fb]	
	$c_F = 1$	$c_F = -1$	$c_F = 1$	$c_F = -1$
8 TeV	17.3	252.7	12.14	181.4
14 TeV	80.6	1042	59.6	828.5

look at final states:

$3\, b + 1\,\text{fwd jet} + l^{\pm} + \not{p}^T$. $4\, b + 1\,\text{fwd jet} + l^{\pm} + \not{p}^T$.

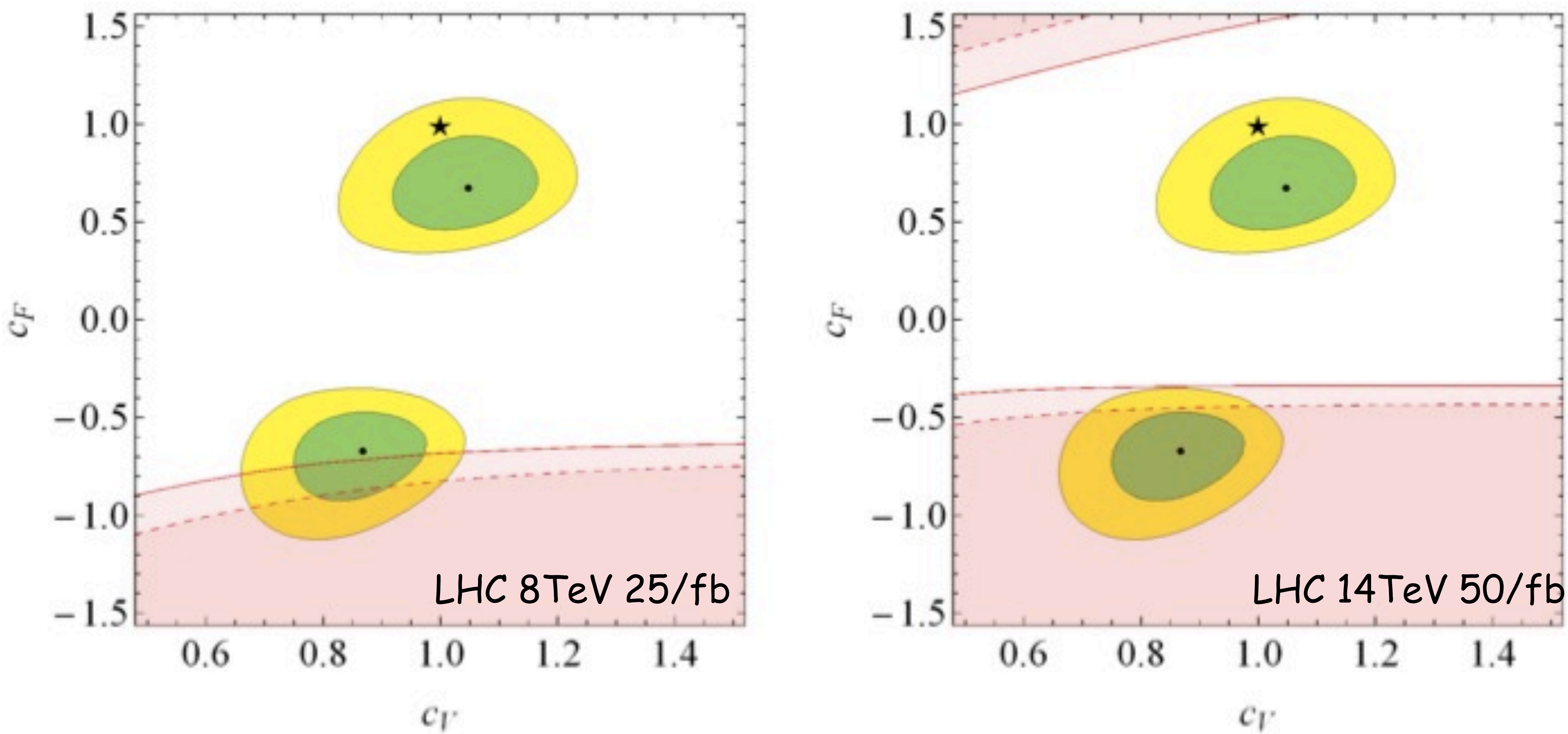




Top partners & Higgs physics

direct measurement of top-higgs coupling

single-top in association with Higgs



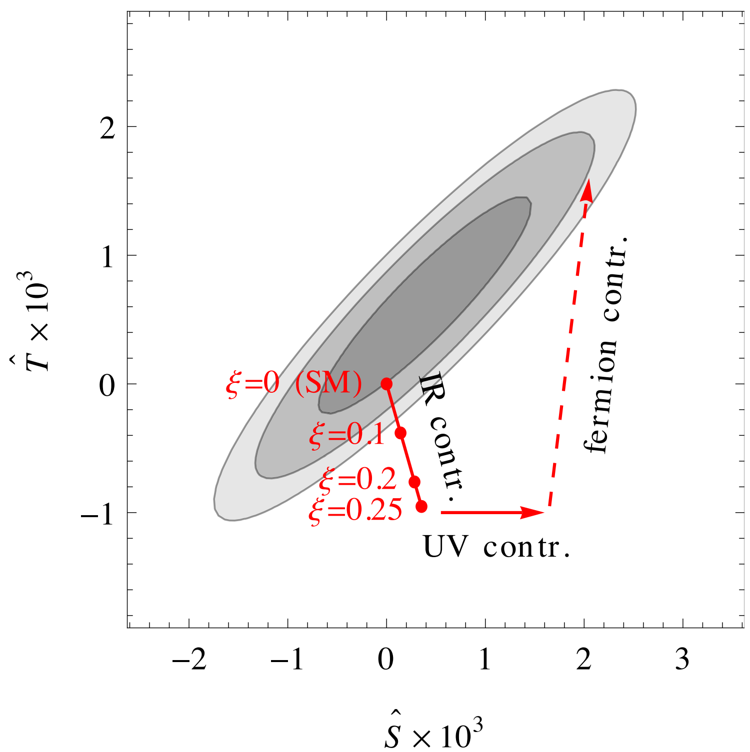
68% and 95% CL exclusion region vs current Higgs coupling fit

Farina, Grojean, Maltoni, Salvioni, Thamm '12

Top partners & EWPT

Grojean, Matsedonskyi, Panico '13

Oblique parameters



tree-level contribution

$$\Delta\widehat{S} \simeq \frac{g^2}{g_*^2}\xi \simeq \frac{m_w^2}{m_*^2}$$

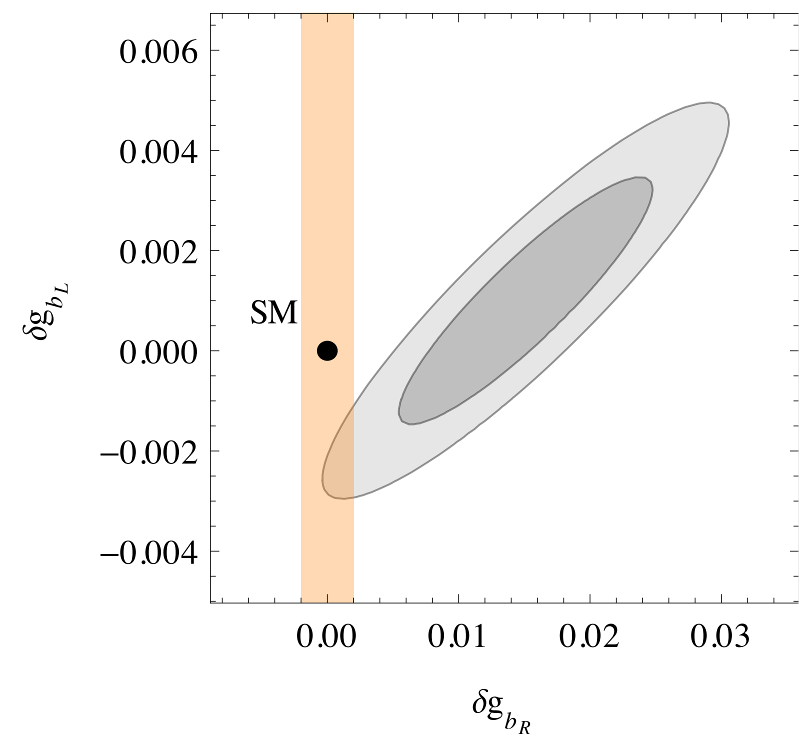
Higgs loop

$$\Delta\widehat{S} = \frac{g^2}{192\pi^2}\xi\log\left(\frac{m_*^2}{m_h^2}\right) \simeq 1.4\cdot 10^{-3}\,\xi \qquad \Delta\widehat{T} = -\frac{3g'^2}{64\pi^2}\xi\log\left(\frac{m_*^2}{m_h^2}\right) \simeq -3.8\cdot 10^{-3}\,\xi$$

fermion loop

$$\Delta\widehat{S}^{div}_{ferm} = \frac{g^2}{8\pi^2}(1-2c^2)\,\xi\log\left(\frac{m_*^2}{m_4^2}\right) \qquad \Delta\widehat{T} \simeq \frac{N_c}{16\pi^2}y_t^2\,\xi \simeq 2\cdot 10^{-2}\,\xi$$

Zb_Lb_L



tree-level contribution

$$\frac{\delta g_{b_L}}{g_{b_L}^{SM}} \sim \frac{y_L^2 f^2}{m^2}\frac{m_z^2}{m_*^2} \simeq 8\cdot 10^{-4}\,\frac{f}{m}\left(\frac{4\pi}{g_*}\right)^2\xi$$

fermion loop

$$\frac{\delta g_{b_L}}{g_{b_L}^{SM}} \simeq \frac{y_t^2}{16\pi^2}\xi\log\left(\frac{m_*^2}{m_4^2}\right) \simeq 2\cdot 10^{-2}\,\xi$$

ξ<0.1 ➪ we might have to wait LHC-HL to see any new physics in Higgs data

BSM Higgs precision era

3

Precision program in single Higgs processes

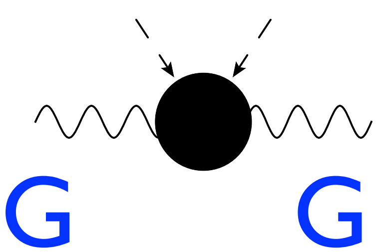
(assuming a mass gap between weak scale and new physics scale)

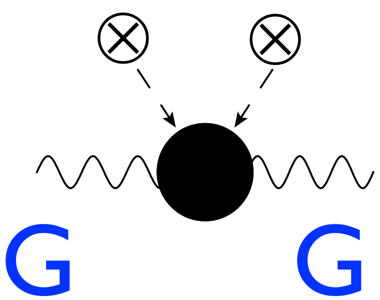
Higgs/BSM Primaries

Several deformations away from the SM are harmless in the vacuum and need a Higgs field to be probed

e.g. $$\frac{1}{g_s^2}G_{\mu\nu}^2 + \frac{|H|^2}{\Lambda^2}G_{\mu\nu}^2 \rightarrow \left(\frac{1}{g_s^2} + \frac{v^2}{\Lambda^2}\right)G_{\mu\nu}^2$$

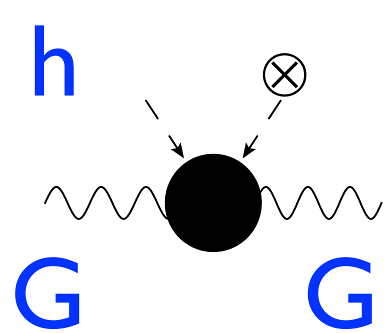
operator is not visible in the vacuum
(redefinition of input parameter)





(courtesy of A. Pomarol@HiggsHunting2014)

But can affect h physics:



affects GG →h!

Higgs/BSM Primaries

How many of these effects can we have?

Pomarol, Riva '13

Elias-Miro et al '13

Gupta, Pomarol, Riva '14

As many as parameters in the SM: **8** for one family

(assuming CP-conservation)

(courtesy of A. Pomarol@HiggsHunting2014)

g_s	$\|H\|^2 G^A_{\mu\nu} G^{A\mu\nu}$	→ GGh coupling
g	$\|H\|^2 B_{\mu\nu} B^{\mu\nu}$	→ hγγ coupling
g'	$\|H\|^2 W^a_{\mu\nu} W^{\mu\nu\, a}$	→ hZγ coupling
m_W	$\|H\|^2 \|D_\mu H\|^2$	→ hVV* (custodial invariant)
m_h	$\|H\|^6$	→ h^3 coupling
m_f (f=t,b,τ)	$\|H\|^2 \bar{f}_L H f_R + h.c.$	→ htt, hbb, hττ

yet to be measured at the LHC

the 6 others have been measured (~15%) up to a flat direction between between the top/gluon/photon couplings

Higgs/BSM Primaries

How many of these effects can we have?

Pomarol, Riva '13

Elias-Miro et al '13

Gupta, Pomarol, Riva '14

8 for one family

(assuming CP-conservation)

Almost a 1-to-1 correspondence with the 8 κ's in the Higgs fit

Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
κ_t	22%	21%	20%	11%	8.5%	7.6%
κ_b	23%	22%	22%	12%	11%	10%
κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
κ_g	14%	12%	11%	9.1%	6.5%	5.3%
κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

Atlas projection

With some important differences:

1) width approximation built-in

2) κ_W/κ_Z is not a primary (constrained by $\Delta\rho$ and TGC)

3) κ_g, κ_γ, $\kappa_{Z\gamma}$ do not separate UV and IR contributions

- **GGh coupling**
- **hγγ coupling**
- **hZγ coupling**
- **hVV* (custodial invariant)**
- **h^3 coupling**
- **htt, hbb, h$\tau\tau$**

yet to be measured at the LHC

Don't forget LEP!

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables

$$\mathcal{L} \supset \frac{1}{f^2}|H|^2|D_\mu H|^2$$

$$\Rightarrow a = \kappa_V = 1 + \frac{v^2}{2f^2}$$

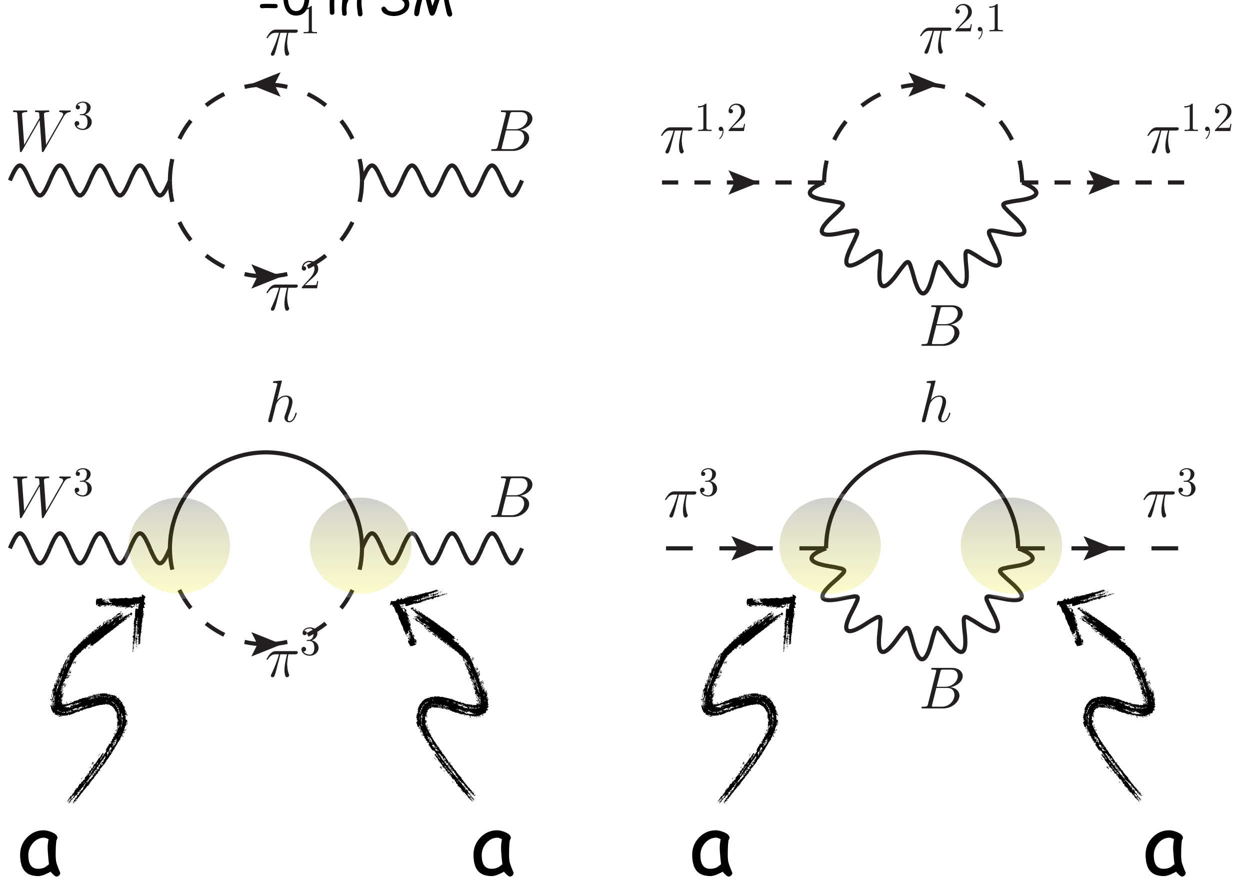
$$\epsilon_{1,3} = c_{1,3}\log(m_Z^2/\mu^2) - c_{1,3}\, a^2 \log(m_h^2/\mu^2) - c_{1,3}(1-a^2)\log(m_\rho^2/\mu^2) + \text{finite terms}$$

=0 in SM

$$c_1 = +\frac{3}{16\pi^2}\frac{\alpha(m_Z)}{\cos^2\theta_W} \qquad c_3 = -\frac{1}{12\pi}\frac{\alpha(m_Z)}{4\sin^2\theta_W}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\,(1-a^2)\log(m_\rho^2/m_h^2)$$

Barbieri, Bellazzini, Rychkov, Varagnolo '07



Log. div. cancel only for a=1 (SM)

a≠1 log. sensitivity on the scale of new physics

Don't forget LEP!

The parameter 'a' controls the size of the one-loop IR contribution to the LEP precision observables

$$\mathcal{L} \supset \frac{1}{f^2}|H|^2|D_\mu H|^2$$

$$\Rightarrow a = \kappa_V = 1 + \frac{v^2}{2f^2}$$

$$\Delta\epsilon_{1,3} = -c_{1,3}\left(1 - a^2\right)\log(m_\rho^2/m_h^2)$$

Barbieri, Bellazzini, Rychkov, Varagnolo '07

EW fit:

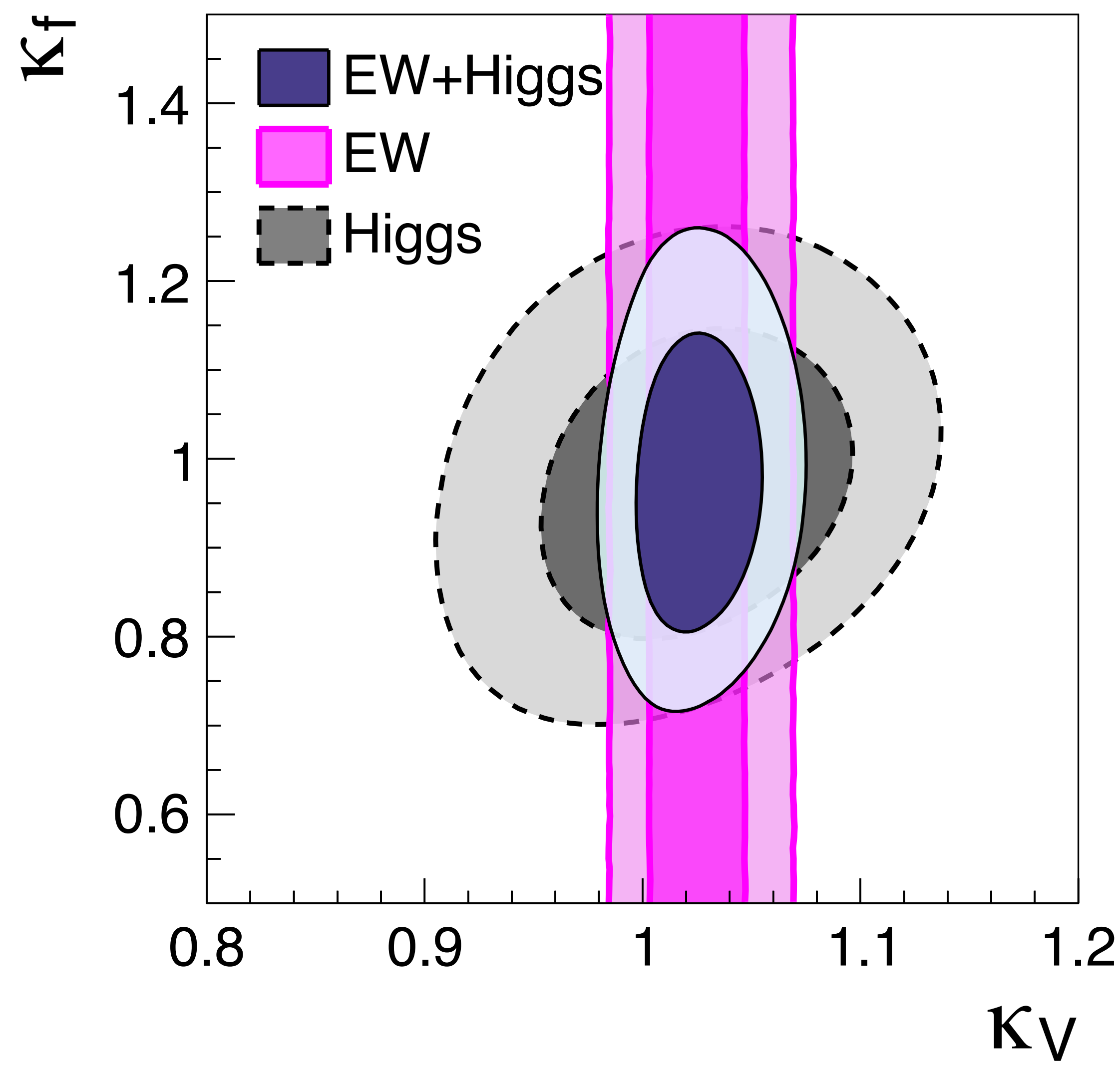
$$0.98 \leq a^2 \leq 1.12$$

Ciuchini et al '13

see also Grojean et al '13

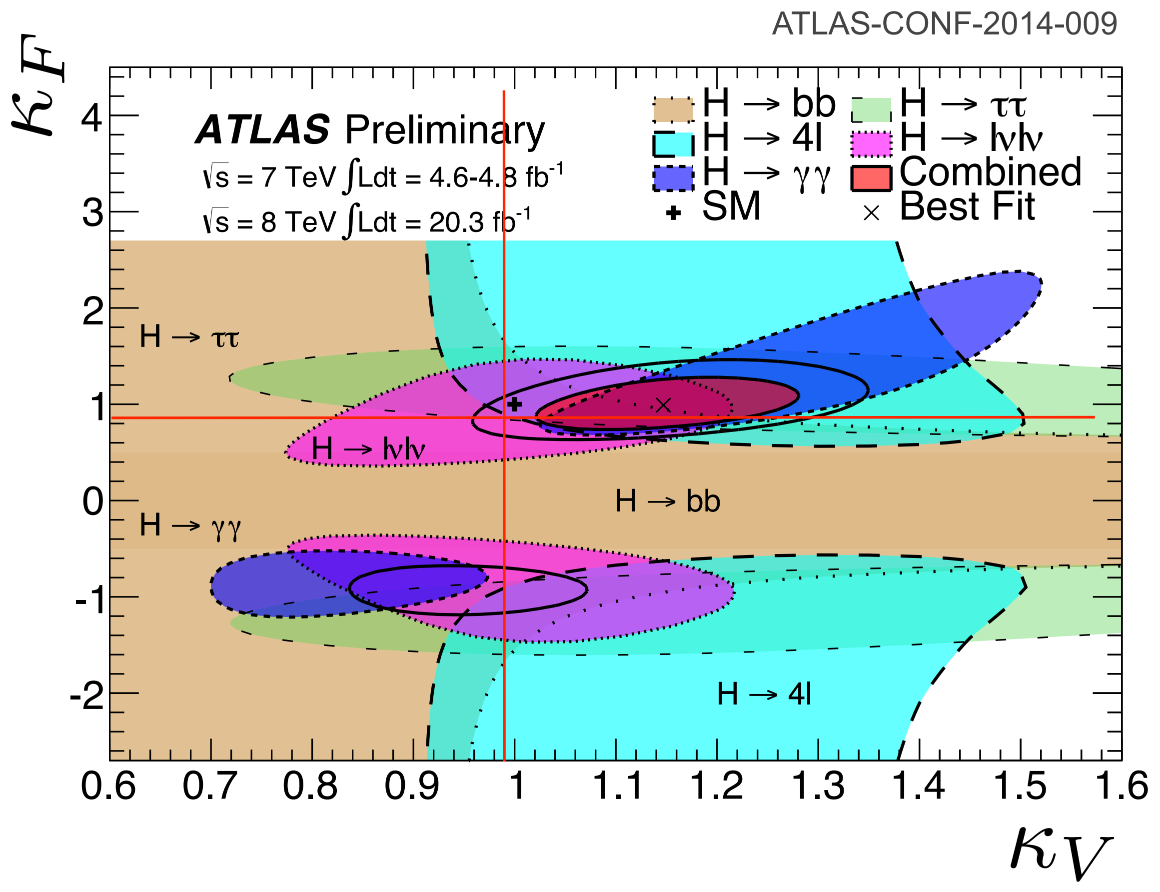
The LEP indirect constraints on the other BSM primaries are not competitive

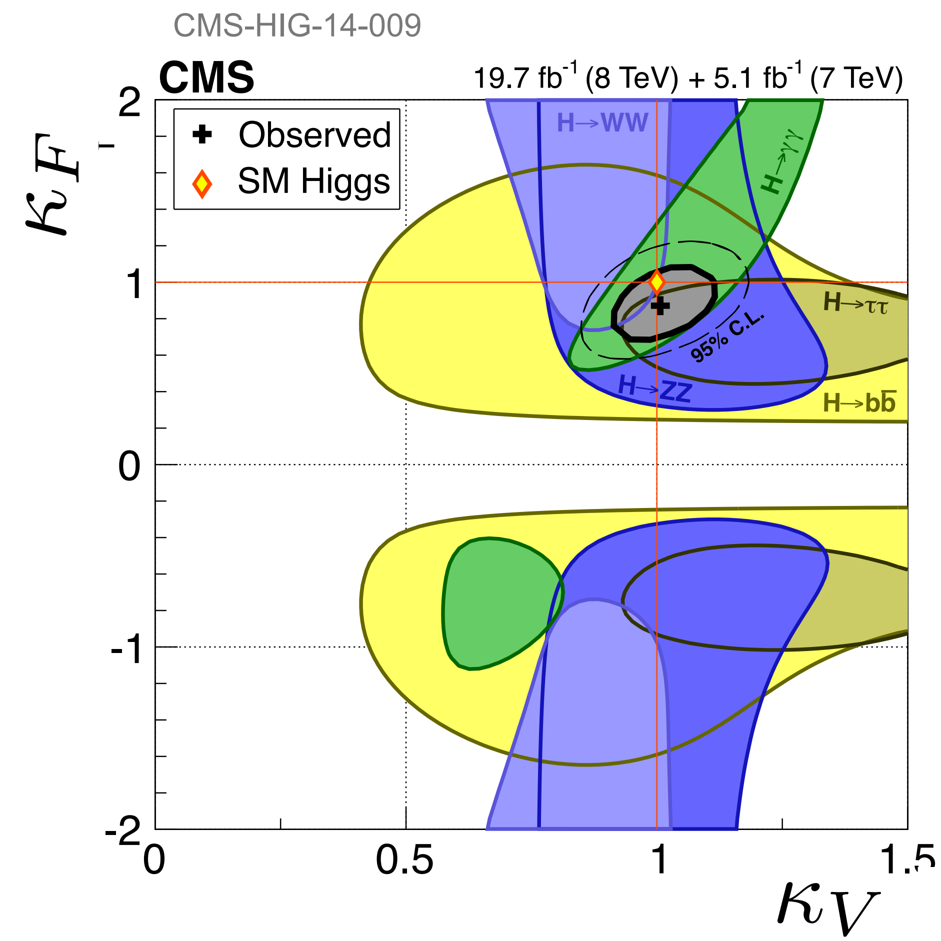
Elias-Miro et al '13



Ciuchini et al '13

Experimental results





CP violation in Higgs physics?

Is CP a good symmetry of Nature? 2 CP-violating couplings in the SM:

V_{CKM} (large, O(1)), but screened by small quark masses) and θ_{QCD} (small, $O(10^{-10})$)

Can the 0^+ SM Higgs boson have CP violating couplings?

Among the 59 irrelevant directions, 6 $\not{C}$P Higgs/BSM primaries

$$\Delta\mathcal{L}_{\rm BSM} = i\delta\tilde{g}_{hff}\, h\bar{f}_L f_R + h.c. \qquad \text{(f=b, } \tau\text{, t)}$$

$$+\tilde{\kappa}_{GG}\frac{h}{v}G^{\mu\nu}\tilde{G}_{\mu\nu} \qquad (\tilde{F}_{\mu\nu} \equiv \epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma})$$

$$+\tilde{\kappa}_{\gamma\gamma}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{\gamma}_{\mu\nu}$$

$$+\tilde{\kappa}_{\gamma Z}\frac{h}{v}F^{\gamma\,\mu\nu}\tilde{F}^{Z}_{\mu\nu}$$

CP violation in Higgs physics?

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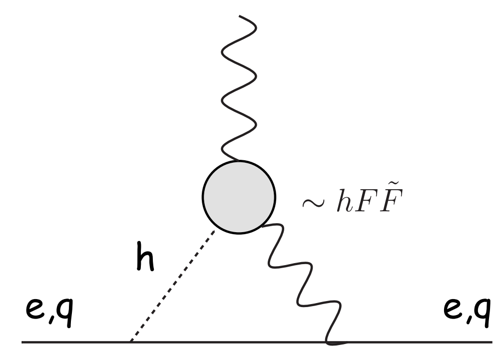
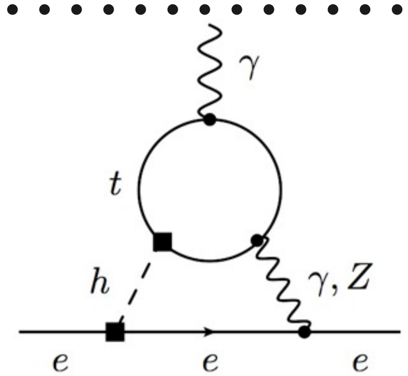
operators with γ:
already severely constrained
by e and q EDMs
McKeen, Pospelov, Ritz '12



$$\tilde{\kappa}_{\gamma\gamma} \sim \tilde{\kappa}_{\gamma Z} \leq 10^{-4}$$

$\Lambda_{\not{CP}}$ > 25 TeV

operators with top:
already severely constrained
by e and q EDMs
Brod, Haisch, Zupan '13



$$\delta\tilde{g}_{htt} \leq 0.01$$

$\Lambda_{\not{CP}}$ > 2.5 TeV

Caveats: h couplings to light particles can be significantly reduced

4

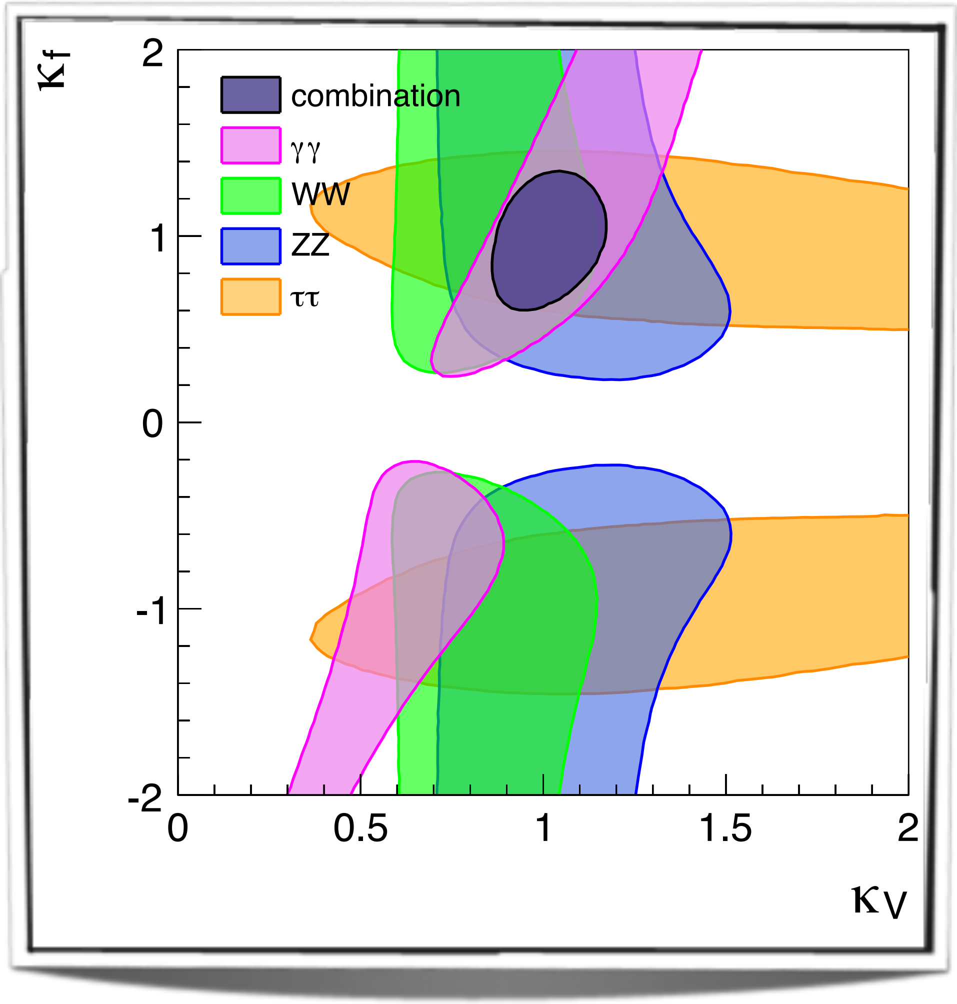
Boosted and off-shell Higgs channels

Why going beyond inclusive Higgs processes?

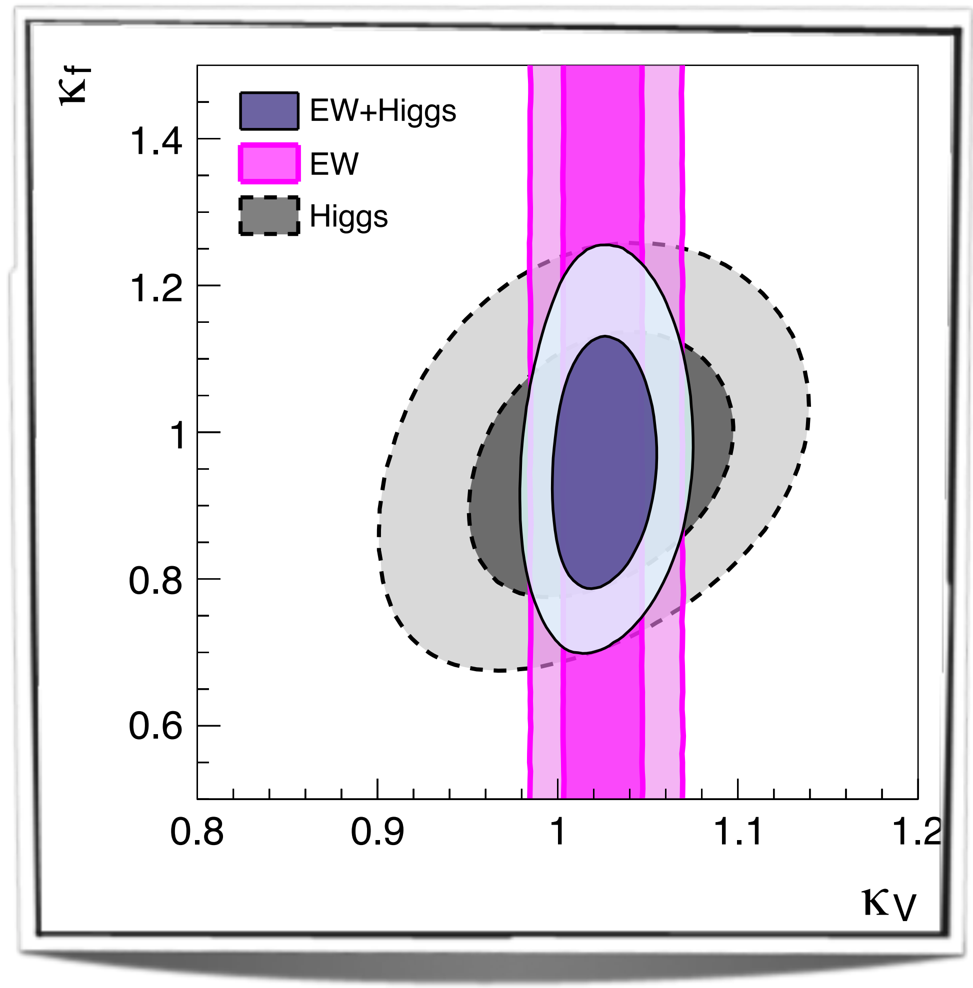
So far the LHC has mostly produced Higgses on-shell
in processes with a characteristic scale $\mu \approx m_H$

⇩ ⇩

access to Higgs couplings @ m_H



Ciuchini et al '13



Ciuchini et al '13

Why going beyond inclusive Higgs processes?

So far the LHC has mostly produced Higgses on-shell
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⇩ ⇩

access to Higgs couplings @ m_H

Producing a Higgs with boosted additional particle(s)
probe the Higgs couplings @ large energy
(important to check that the Higgs boson ensures perturbative unitarity)

Probing new corrections to the SM Lagrangian?

on-shell Z @ LEP1

constraints on
S and T oblique corrections

off-shell Z @ LEP2
constraints on
W and Y oblique corrections
(same order as S and T but cannot be probed @ LEP1)

But... off-shell Higgs data do not probe new corrections
that cannot be constrained by on-shell data

Boosted Higgs

inability to resolve the top loops

- the bearable lightness of the Higgs: rich spectroscopy w/ multiple decays channels
- the unbearable lightness: loops saturate and don't reveal the physics @ energy physics (*)

m_H(GeV)	$\frac{\sigma_{NLO}(m_t)}{\sigma_{NLO}(m_t\to\infty)}$	$\frac{\sigma_{NLO}(m_t,m_b)}{\sigma_{NLO}(m_t\to\infty)}$
125	1.061	0.988
150	1.093	1.028
200	1.185	1.134

e.g. Grazzini, Sargsyan '13

(*) unless it doesn't decouple (e.g. 4th generation)

the inclusive rate doesn't "see" the finite mass of the top

⇛ cannot disentangle
- long distance physics (modified top coupling)
- short distance physics (new particles running in the loop) ⇚

$$\mathcal{L} = \frac{\alpha_s c_g}{12\pi}|H|^2 G_{\mu\nu}^{a\,2} + \frac{\alpha c_\gamma}{2\pi}|H|^2 F_{\mu\nu} + y_t c_t \bar{q}_L \tilde{H} t_R |H|^2$$

$$\frac{\sigma(gg\to h)}{\text{SM}} = (1+(c_g-c_t)v^2)^2 \qquad \frac{\Gamma(h\to\gamma\gamma)}{\text{SM}} = (1+(c_\gamma-4c_t/9)v^2)^2$$

fermionic top-partners in composite Higgs models exactly lead to $\Delta c_t = \Delta c_g = \frac{9}{4}\Delta c_\gamma$.

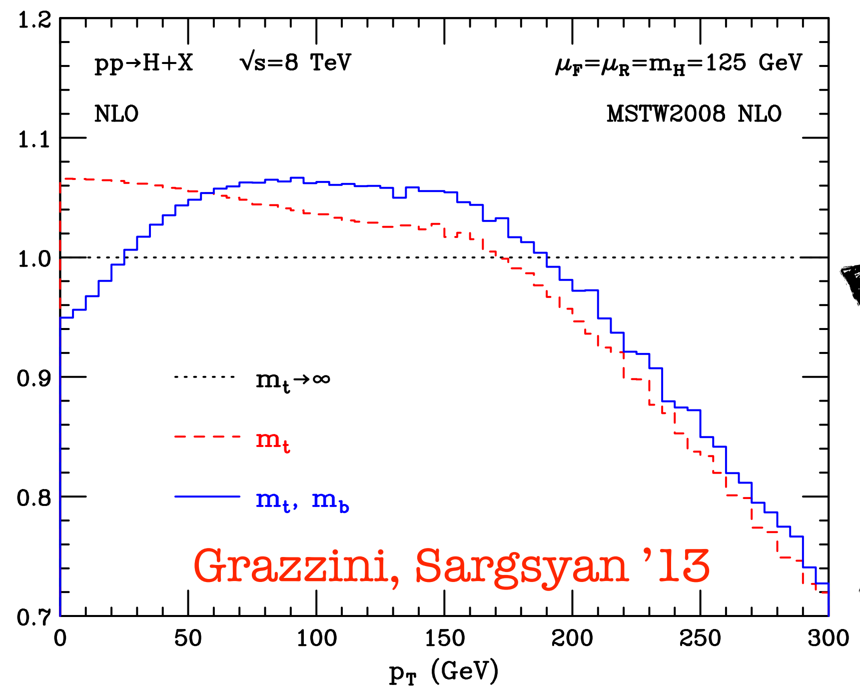
having access to $ht\bar{t}$ final state will resolve this degeneracy
but notoriously difficult channel
14%-4% @ LHC^{14}_{300}-LHC^{14}_{3000} vs 10%-4% @ ILC^{500}_{500}-ILC^{1000}_{1000}

Resolving top loop: Boosted Higgs

cut open the top loops

high p_T ≈ Higgs off-shell
we "see" the details of the particles
running inside the loops

Baur, Glover '90
Langenegger, Spira, Starodumov, Trueb '06



Note: LO only
NLO_{m_t} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

the high p_T tail
is tens' % sensitive
to the mass of top

Resolving top loop: Boosted Higgs

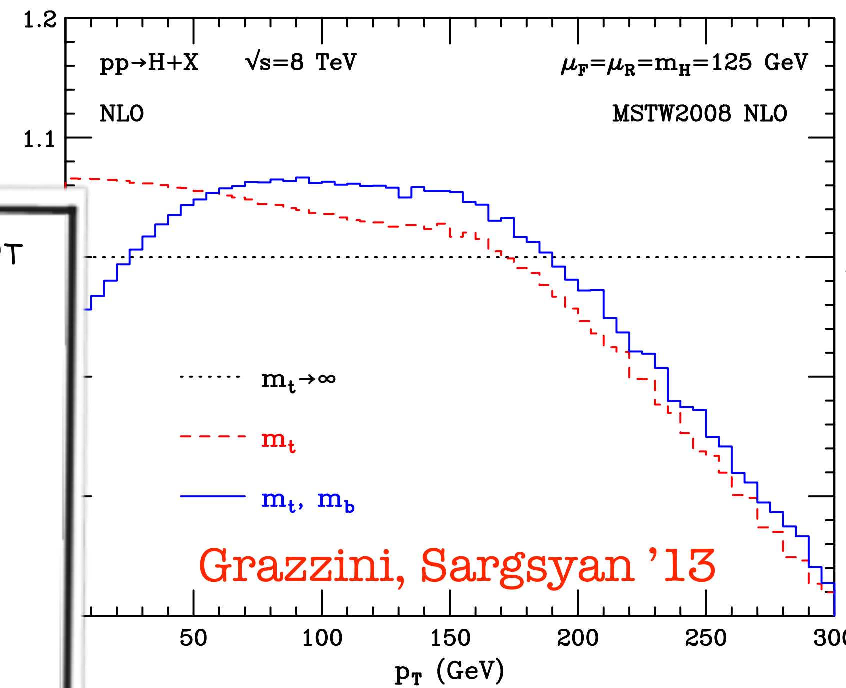
cut open the top loops

Don't think it is easy to produce a Higgs with high p_T

$\sqrt{s}$ [TeV]	$p_T^{\rm min}$ [GeV]	$\sigma^{\rm SM}_{p_T^{\rm min}}$ [fb]	δ	ϵ	gg, qg [%]
	100	2200	0.016	0.023	67, 31
	150	830	0.069	0.13	66, 32
	200	350	0.20	0.31	65, 34
	250	160	0.39	0.56	63, 36
	300	75	0.61	0.89	61, 38
	350	38	0.86	1.3	58, 41
	400	20	1.1	1.8	56, 43
14	450	11	1.4	2.3	54, 45
	500	6.3	1.7	2.9	52, 47
	550	3.7	2.0	3.6	50, 49
	600	2.2	2.3	4.4	48, 51
	650	1.4	2.6	5.2	46, 53
	700	0.87	3.0	6.2	45, 54
	750	0.56	3.3	7.2	43, 56
	800	0.37	3.7	8.4	42, 57

×1000 reduction

Grojean, Salvioni, Schlaffer, Weiler '13



Grazzini, Sargsyan '13

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high $p_T \approx$ Higgs off-shell
we "see" the details of the particles
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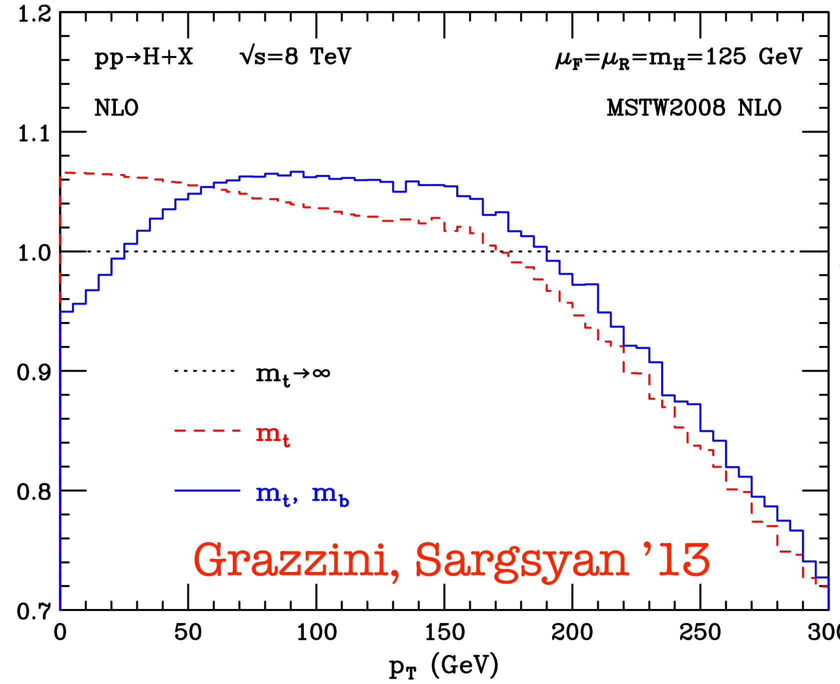


Note: LO only
NLO_{mt} is not known
$1/m_t$ corrections known $O(\alpha_s^4)$
few % up to p_T~150 GeV

Harlander et al '12

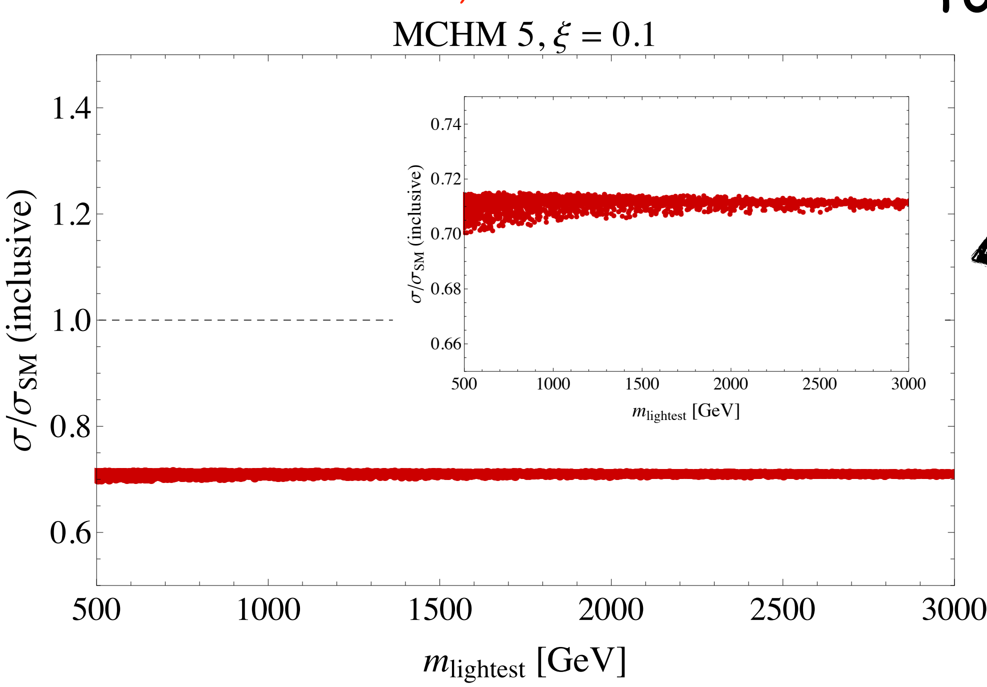
the high p_T tail
is tens' % sensitive
to the mass of top

Composite Higgs Model

see also Banfi, Martin, Sanz '13
see also Azatov, Paul '13

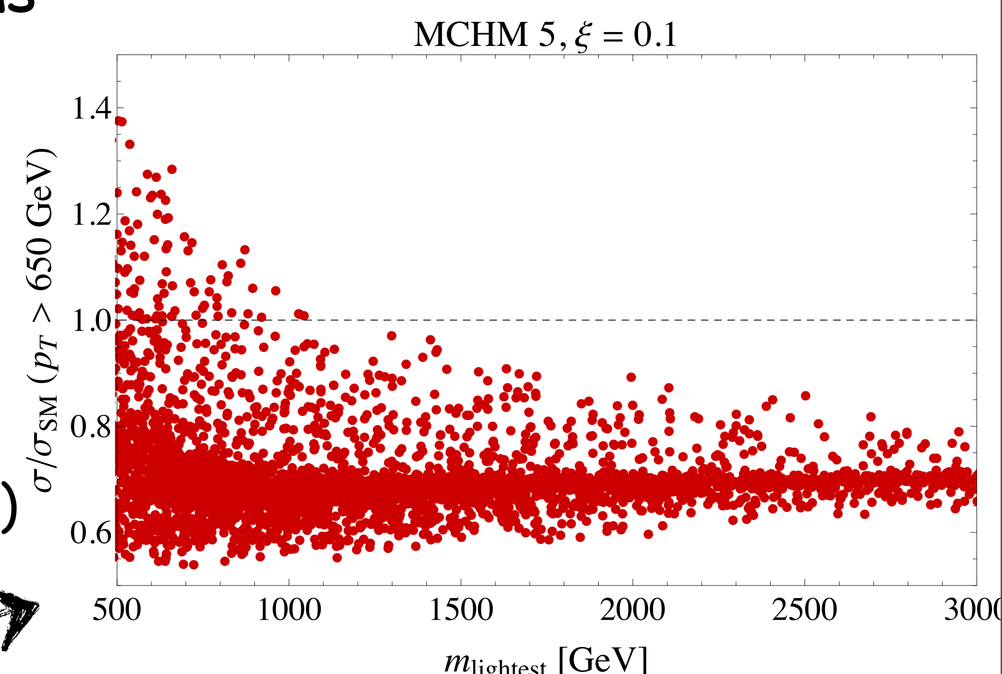
top partners contributions

Grojean, Salvioni, Schlaffer, Weiler '13



inclusive rate: O(%)

with high-p_T cut: O(x10'%)



high-p_T tail "sees" the top partners that are missed by the inclusive rate

Boosted Higgs

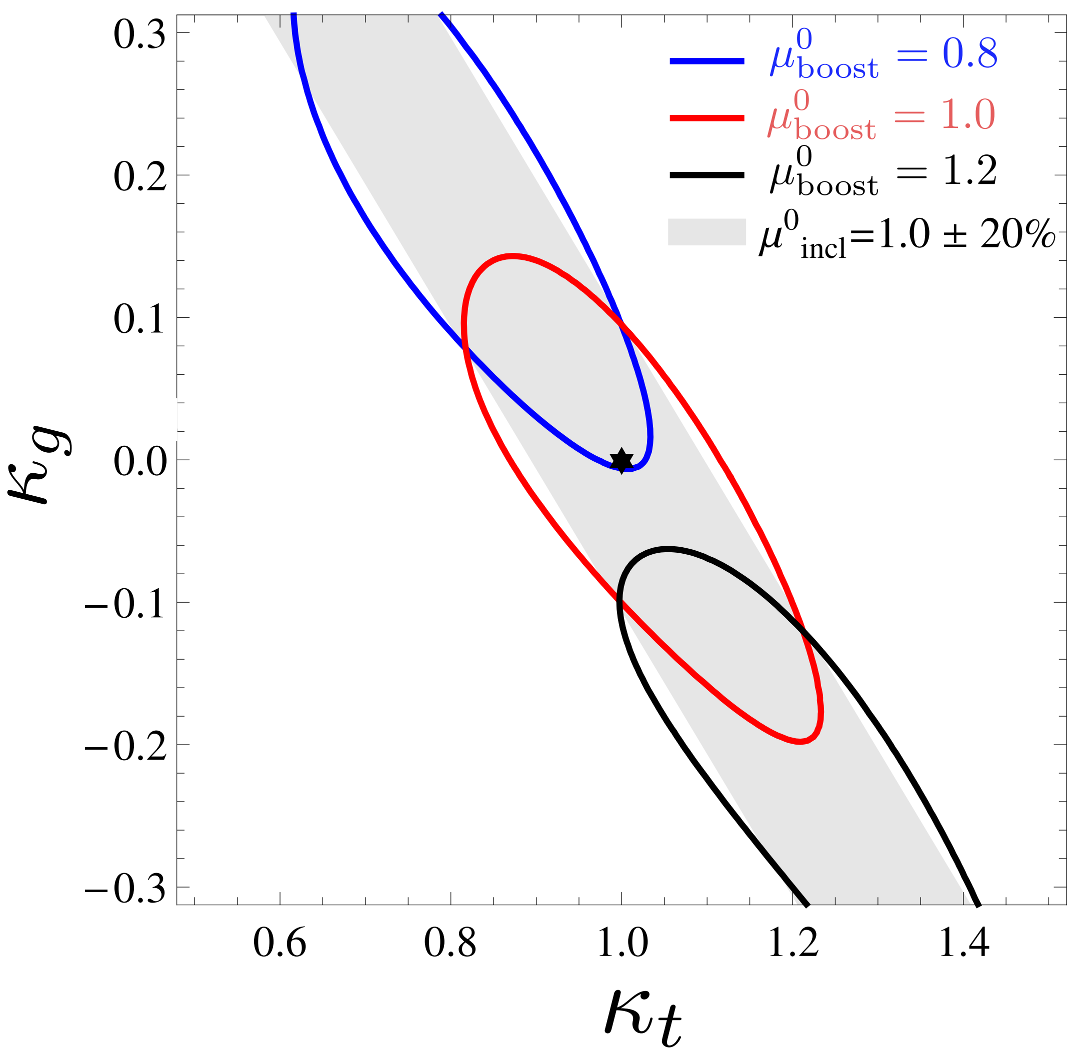
see also Azatov, Paul '13

high p_T tail discriminates short and long distance physics contribution to $gg \to h$

$$\sqrt{s} = 14 \text{ TeV}, \int dt\, \mathcal{L} = 3\text{ab}^{-1}, p_T > 650 \text{ GeV}$$

(partonic analysis in the boosted "ditau-jets" channel)

see Schlaffer et al '14 for a more complete analysis including WW channel



Grojean, Salvioni, Schlaffer, Weiler '13

10-20% precision on κ_t

⇓ ⇓

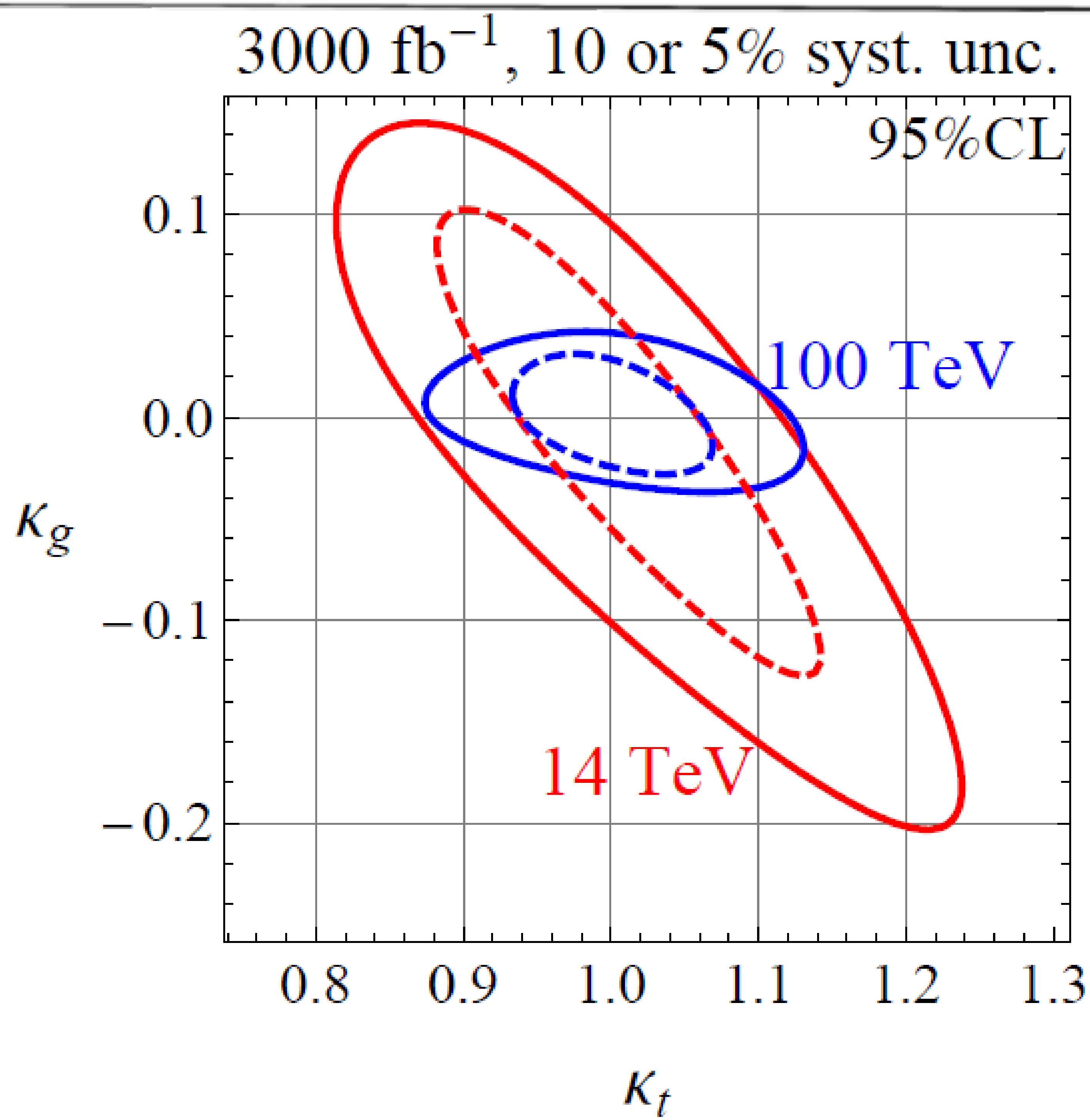
competitive/complementary to htt channel for the measure the top-Higgs coupling

Are the NLO_m QCD corrections (not known) going to destroy all the sensitivity?
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

Boosted Higgs

see also Azatov, Paul '13

high p_T tail discriminates short and long distance physics contribution to $gg \to h$



Grojean, Salvioni, Schlaffer, Weiler '13

A perfect case for a very energetic machine

tth increases by 10 from 14 to 100TeV

$h+j_{pT>600GeV}$ increases by 210

$$\mathcal{R}_{14} = \frac{\sigma(p_T > 650\ \text{GeV})}{\sigma(p_T > 150\ \text{GeV})}$$

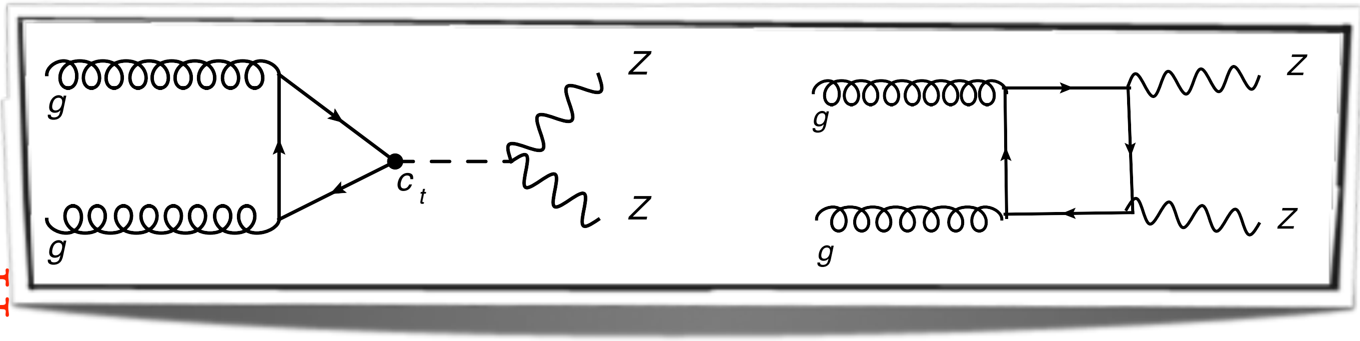
$$\mathcal{R}_{100} = \frac{\sigma(p_T > 2000\ \text{GeV})}{\sigma(p_T > 500\ \text{GeV})}$$

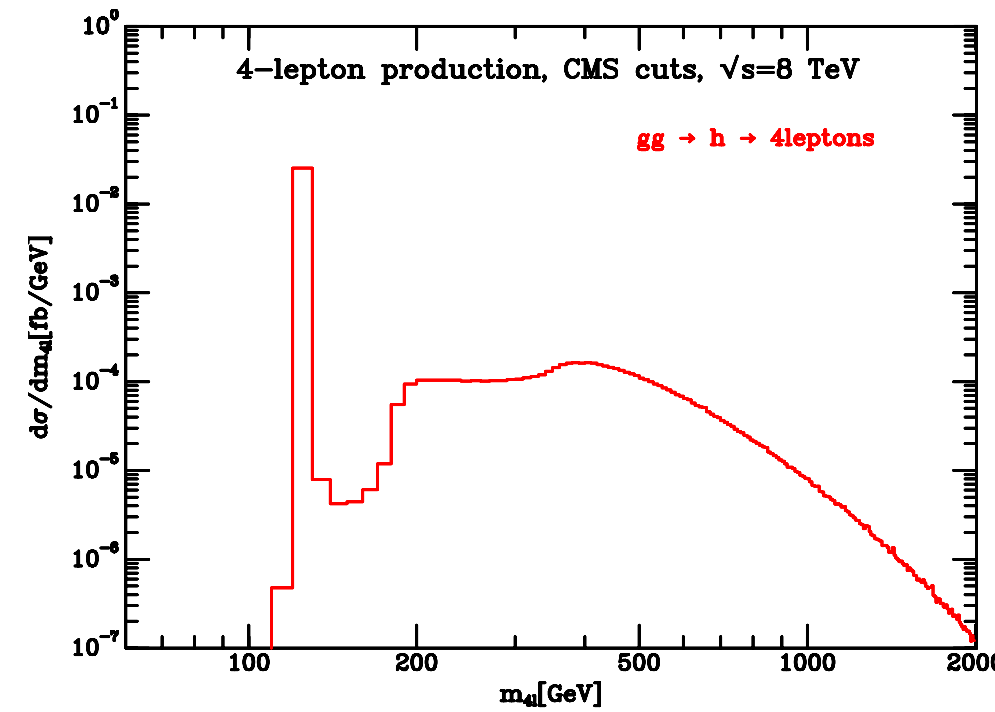
Frontier priority: N^3LO_∞ for inclusive xs or NLO_{mt} for pT spectrum?

Off-shell Higgs: $gg \to h^* \to ZZ \to 4l$

off-shell effects enhanced by the particular couplings of H to V_L

Glover, van der Bij '89





$$\mathcal{M}^{++00}_{\rm Higgs} \sim \log^2 \frac{\hat{s}}{m_t^2} \qquad \mathcal{M}^{++00}_{\rm box} \sim -\log^2 \frac{\hat{s}}{m_t^2}$$

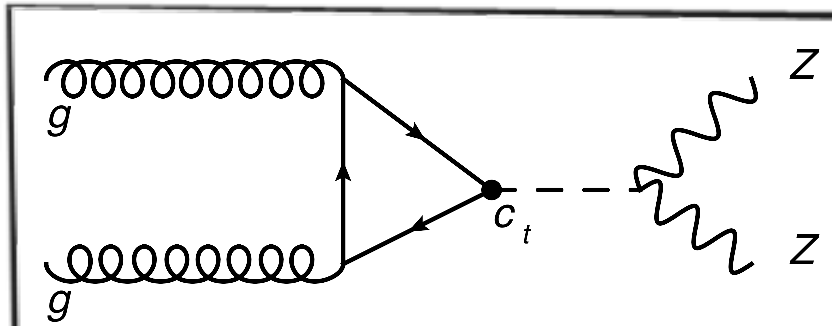
SM: cancelation forced by unitarity

BSM: deviations of Higgs couplings at large s will be amplified

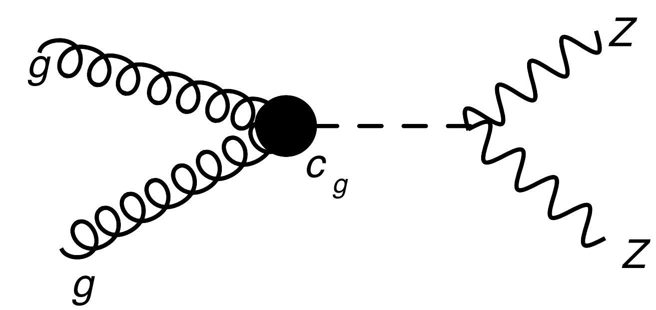
Azatov, Grojean, Paul, Salvioni '14

CMS interpretation in terms of bounds of the Higgs width is limited

data can be better used to measure the structure of the couplings at high √s



$$\mathcal{M}^{++00}_{c_t} \sim \log^2 \frac{\hat{s}}{m_t^2}$$

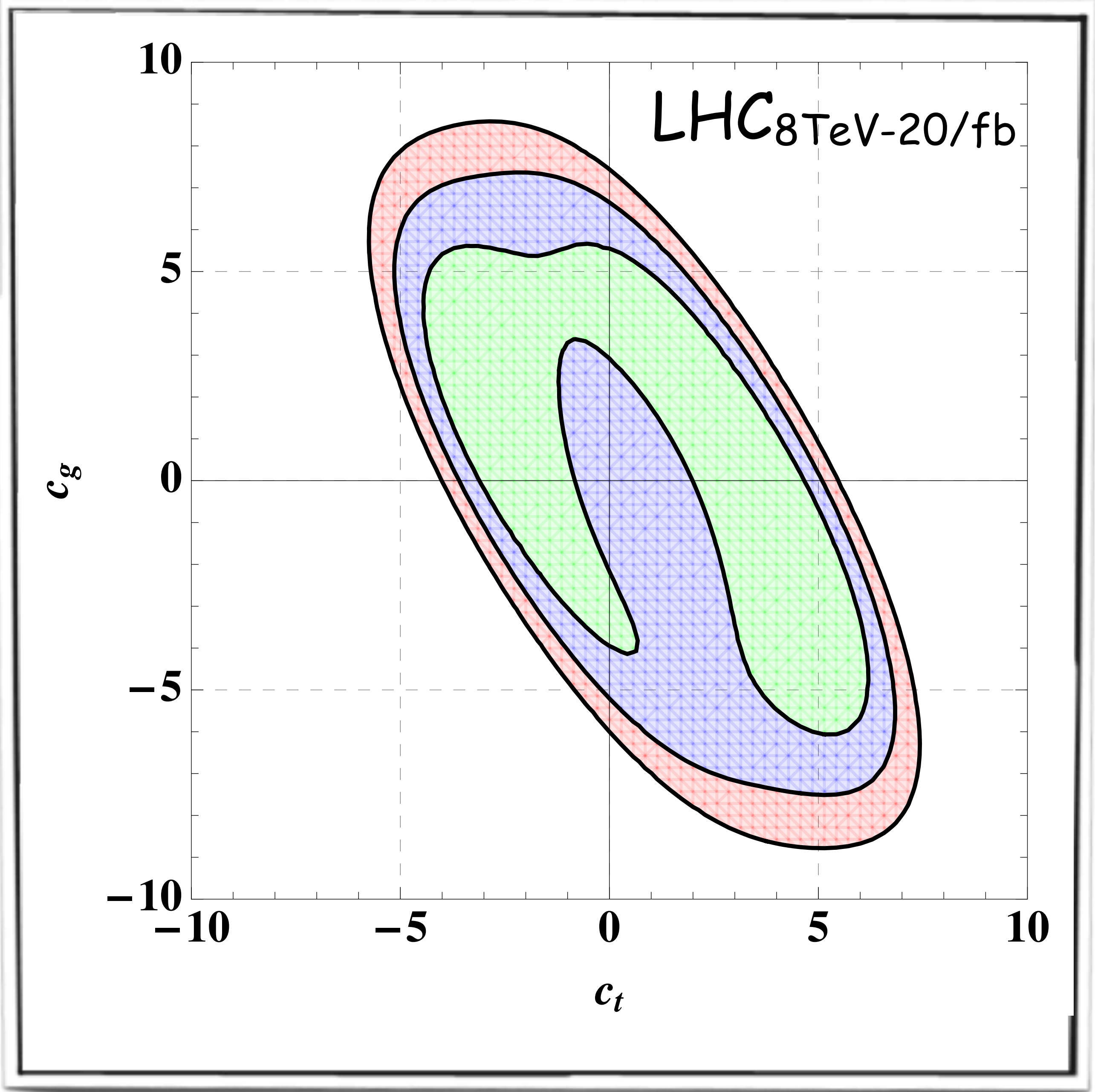


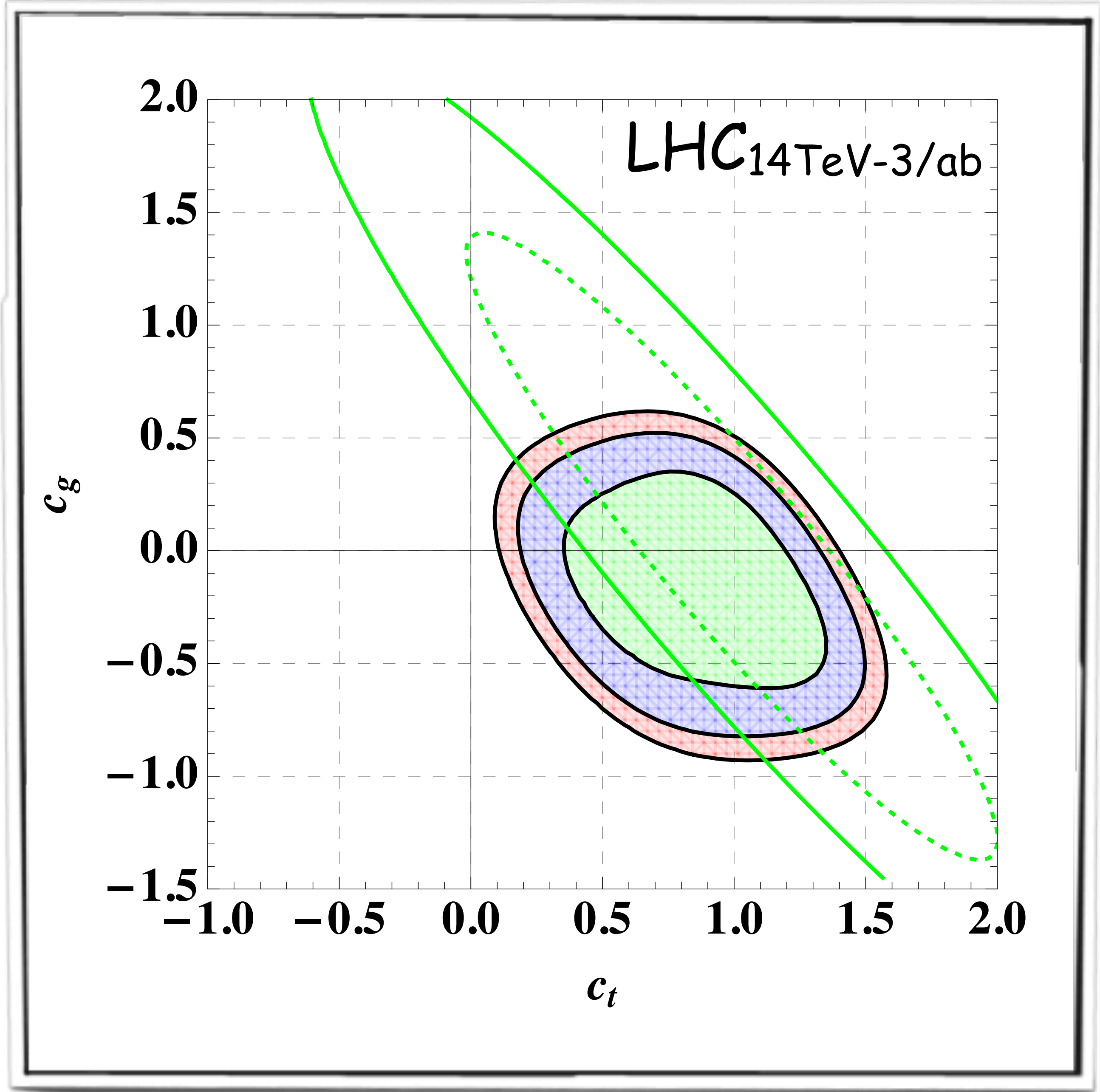
$$\mathcal{M}^{++00}_{c_g} \sim \hat{s}$$

Off-shell Higgs: $gg \to h^* \to ZZ \to 4l$

off-shell effects enhanced by the particular couplings of H to V_L

Azatov, Grojean, Paul, Salvioni '14



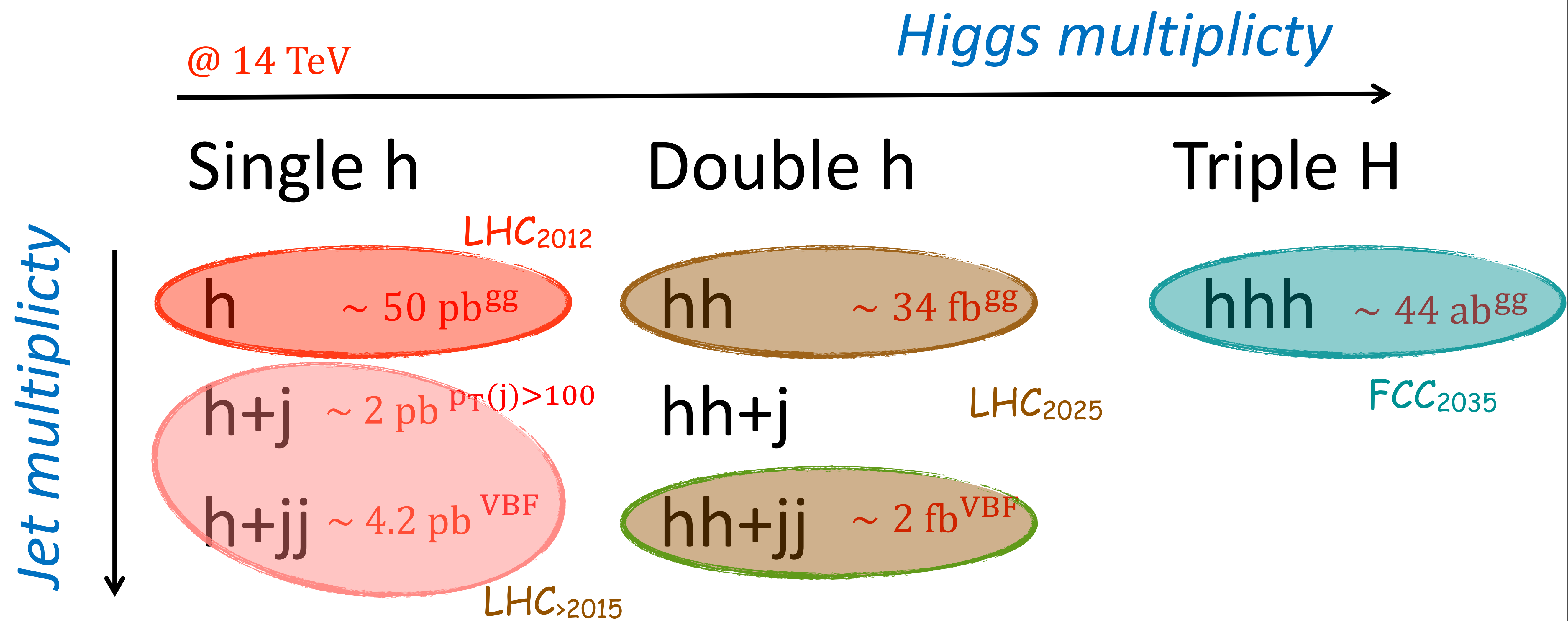


5

Multi-Higgs channels

Beyond single Higgs processes

Producing one Higgs is good. Producing H+X is better



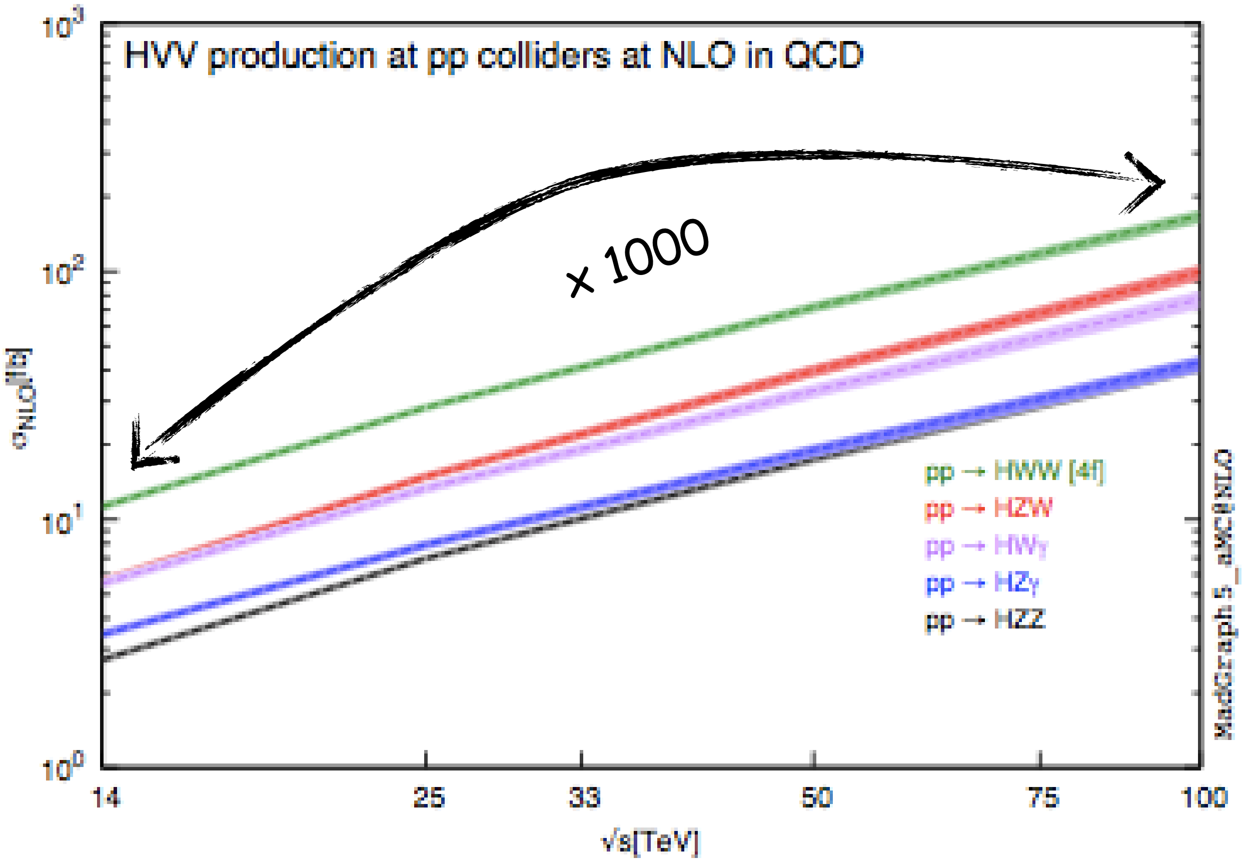
- also roughly indicates possible initial states/related kinematics
- Jet multiplicity might be replaced with V=W,Z, top, etc…

(adapted from M. Son@Planck2014)

Beyond single Higgs processes

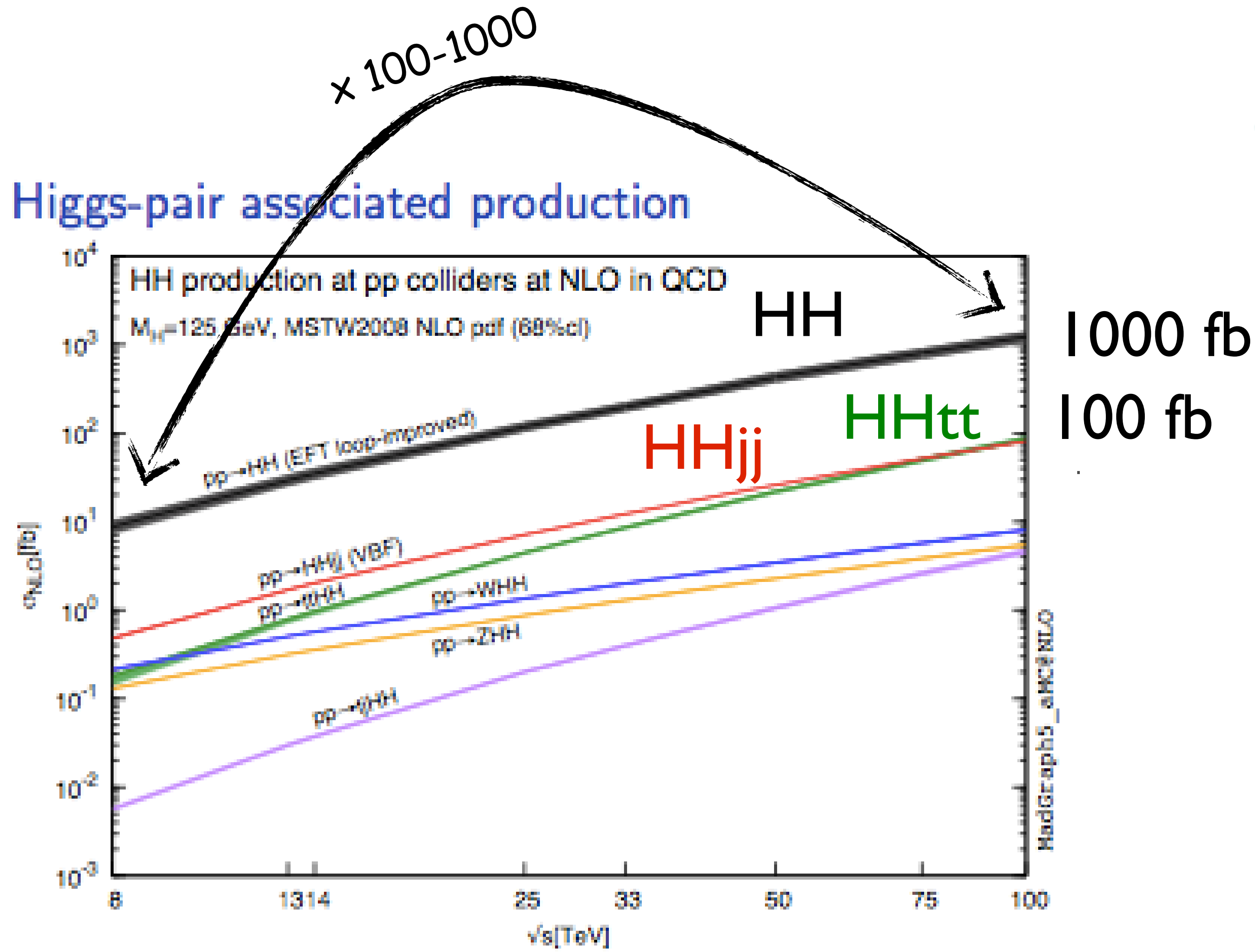
Producing one Higgs is good. Producing H+X is better
A long term plan?

Higgs-diboson associated production



FCC = H+X factory

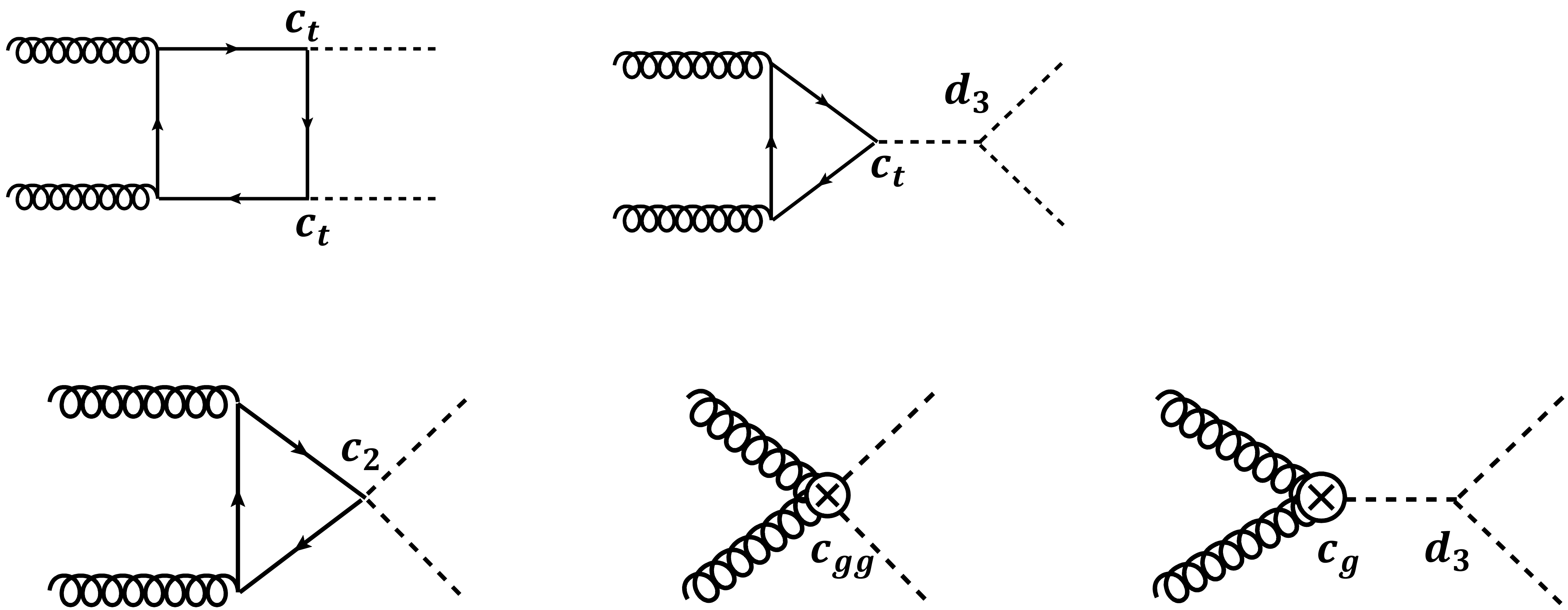
Higgs-pair associated production



(Plots from P. Torrielli and MLM, CERN'14)

What do we learn from gg→HH?

in principle gg→HH gives access to many new couplings, including non-linear couplings

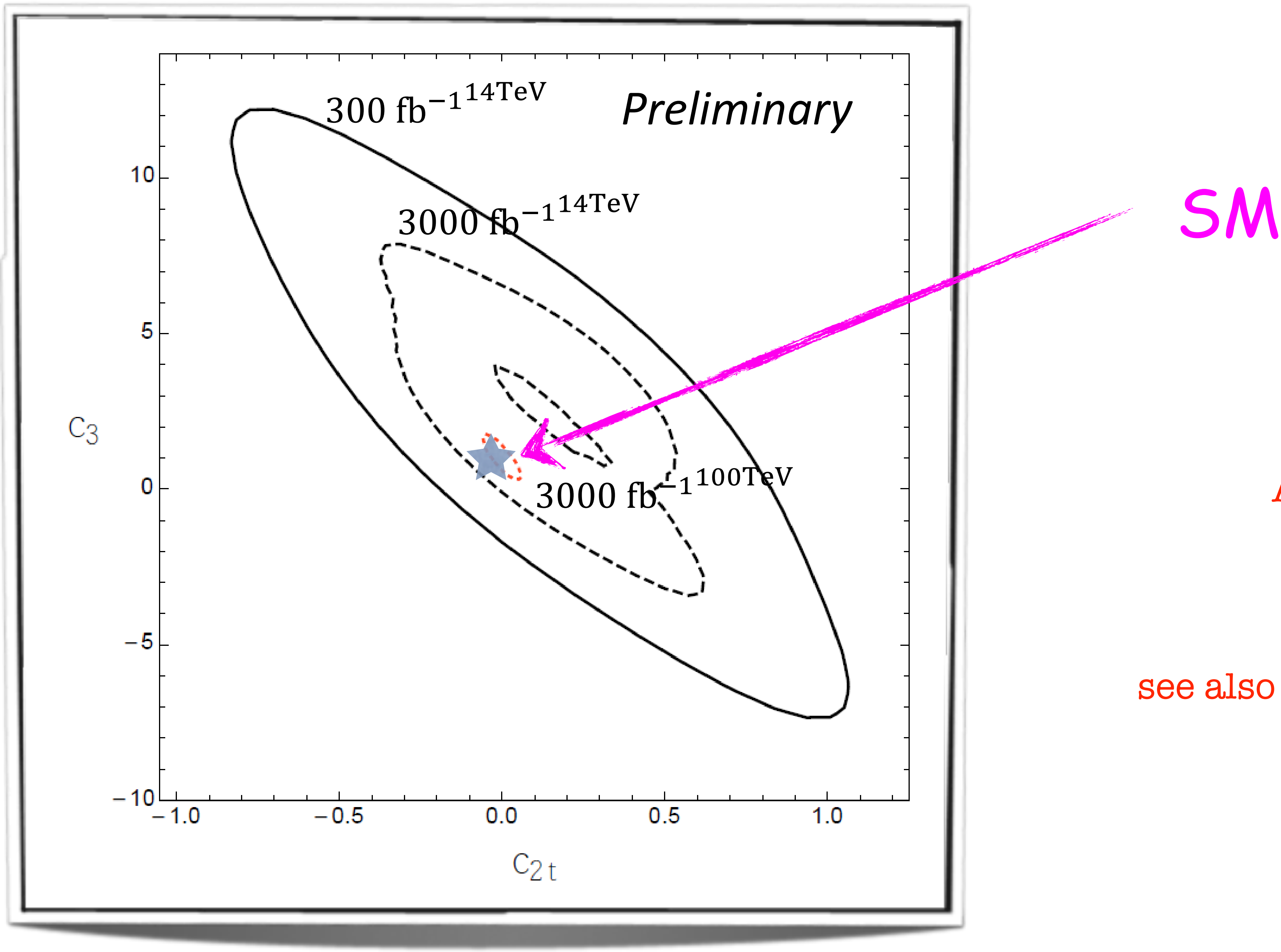


In practice, if the Higgs is part of an EW doublet,
these new couplings are related to single-Higgs couplings

$$c_{2t} = 3(c_t - 1) \qquad c_{gg} = c_g$$

Examples of connection between 1-Higgs and 2-Higgs vertices
Important to measure independently these vertices
and check the relations imposed by structure/symmetries/dynamics of the theory

What do we learn from gg→HH?



Azatov, Contino, Panico, Son ’15

see also Goertz, Papaefstathiou, Yang, Zurita ’14

Remarks:

- unique access to c_3 but sensitivity is limited (within the validity of EFT?).
- statistically limited, with more luminosity

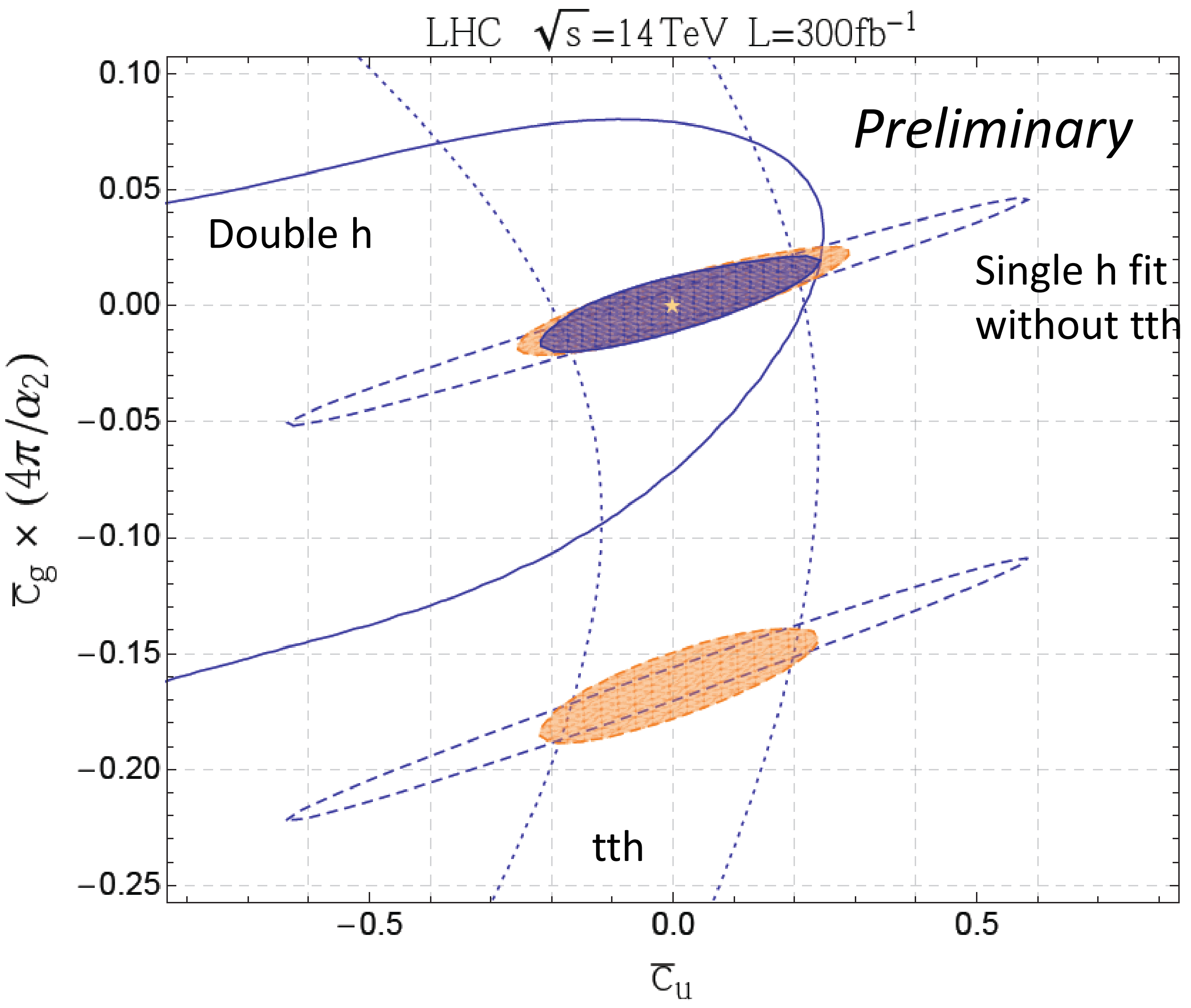
⇛ access to distribution

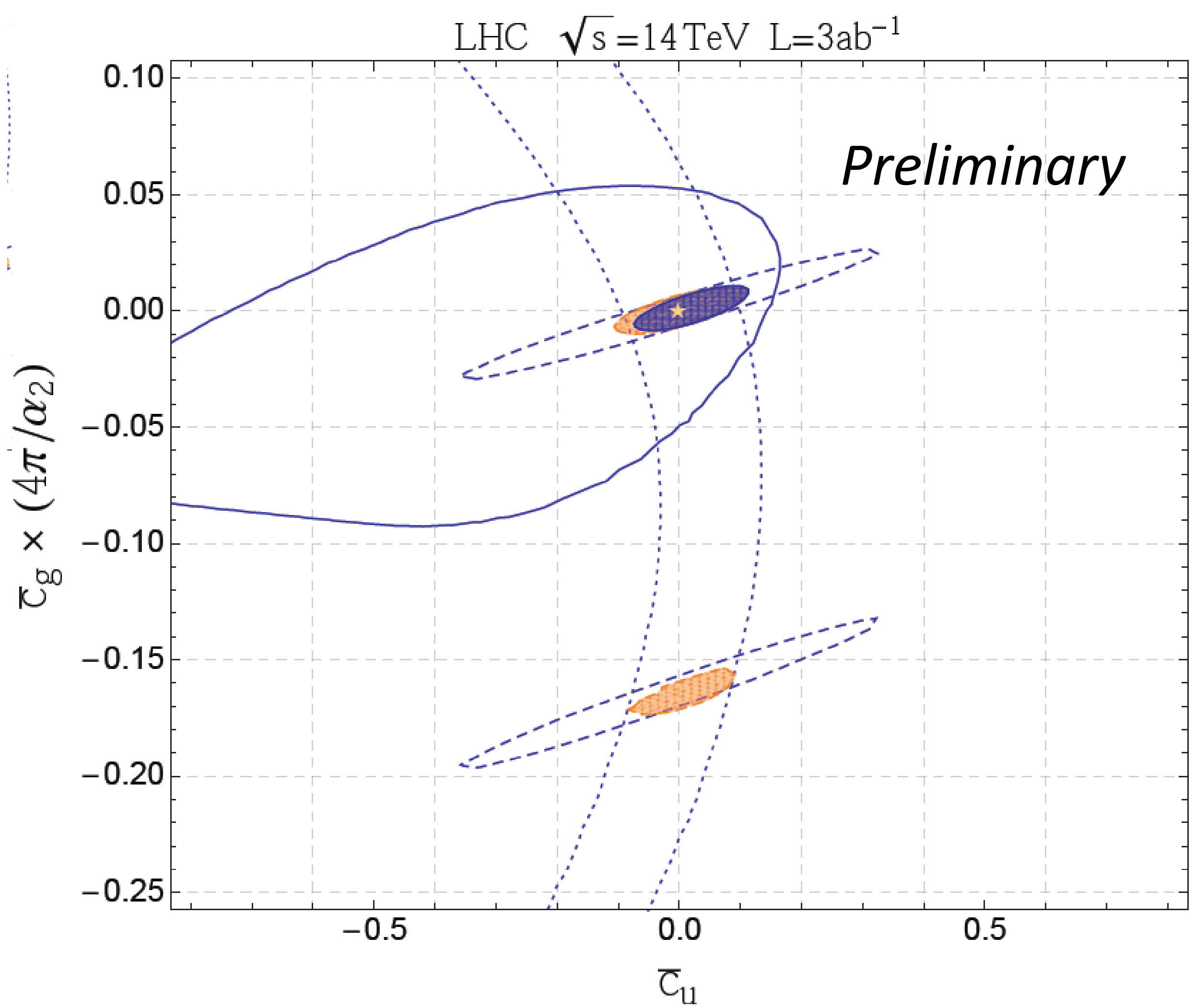
⇛ discriminating power c_3 vs. c_{2t} vs c_g

What do we learn from gg→HH?

in principle gg→HH gives access to many new couplings, including non-linear couplings

after marginalizing over c_3, HH channel provides additional infos on single Higgs couplings





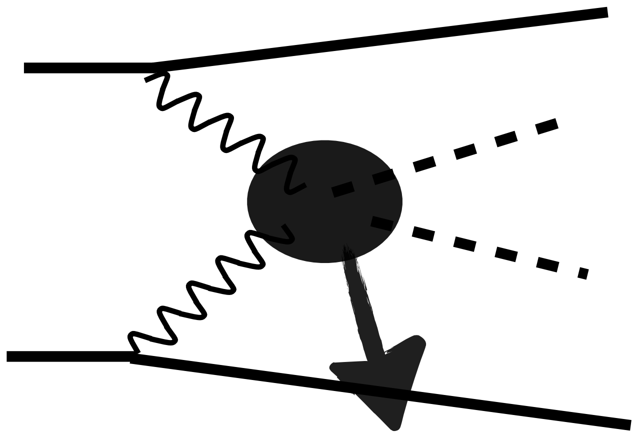
Azatov, Contino, Panico, Son 'to appear

HH channel is useful to break the degeneracy
between 2 minima in the fit of single Higgs processes

Multiple Higgs interactions in WW→HH

in the SM, the Higgs is essential to prevent strong interactions in EWSB sector

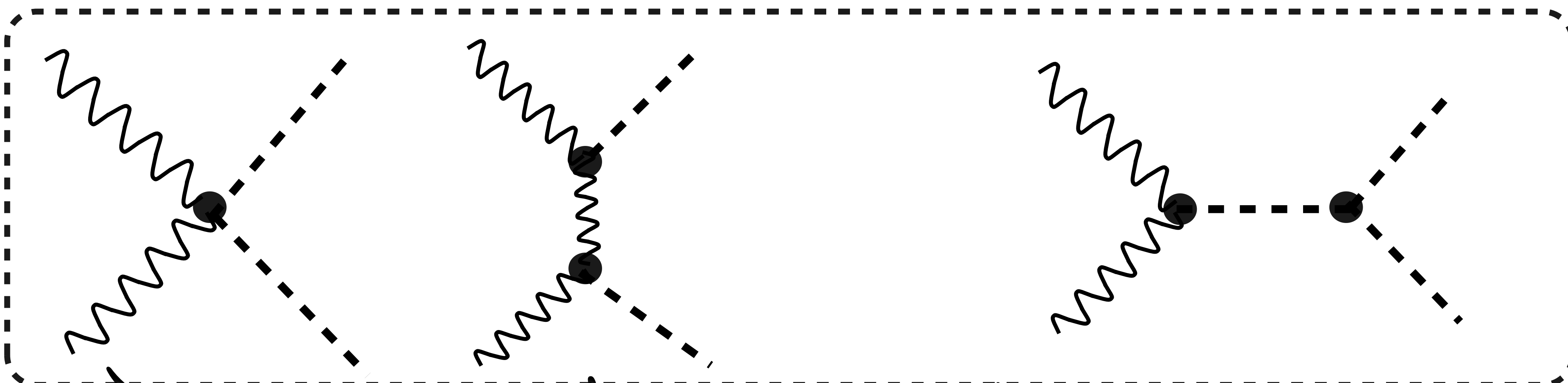
(e.g. WW scattering) Contino, Grojean, Moretti, Piccini, Rattazzi '10



SM: $a=b=d_3=d_4=1$

$$\mathcal{L}_{\rm EWSB} = \frac{v^2}{4}{\rm Tr}\left(D_\mu\Sigma^\dagger D_\mu\Sigma\right)\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}\right)$$

$$V(h) = \frac{1}{2}m_h^2 h^2 + d_3\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4+\ldots$$



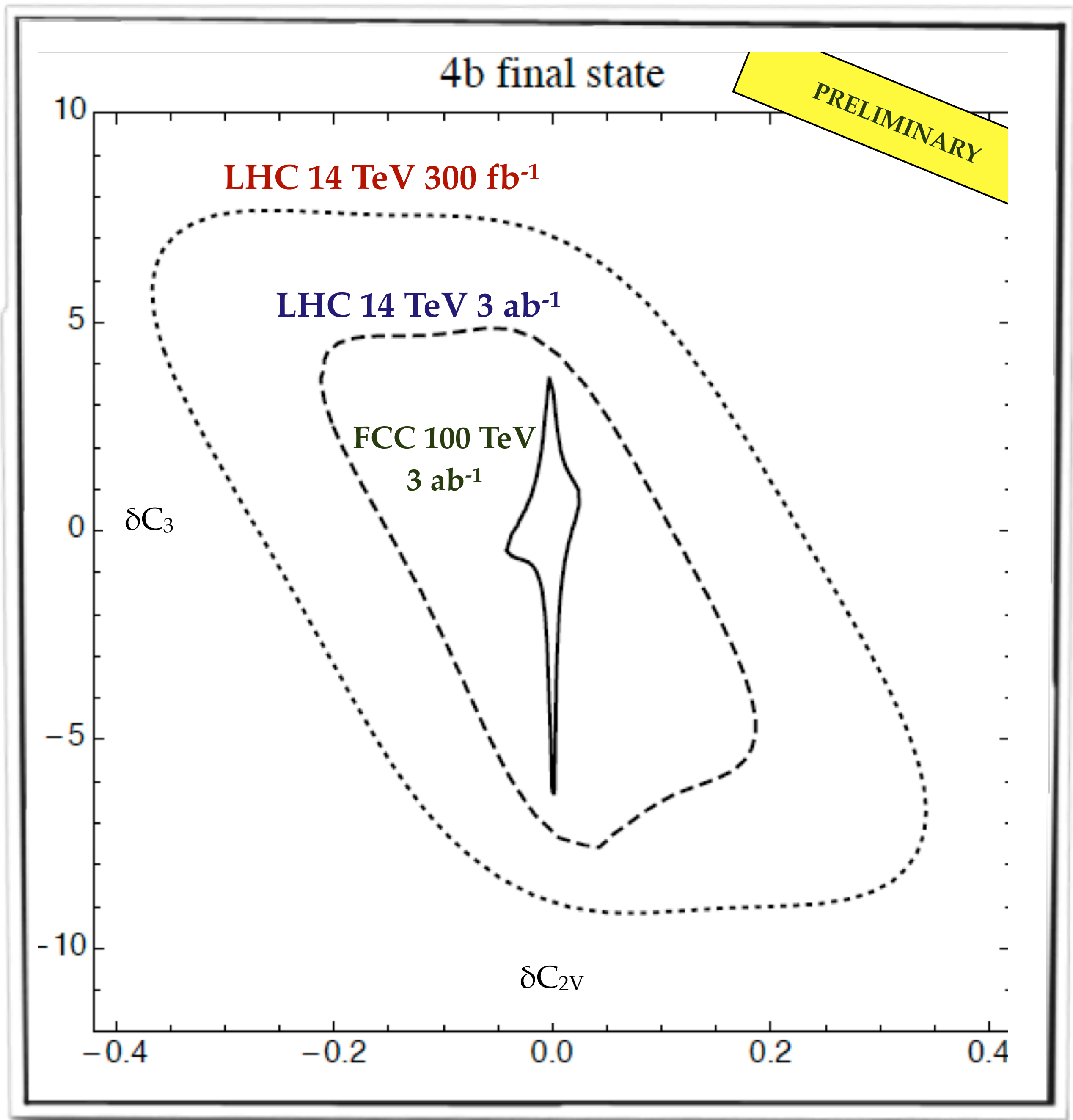
$$\mathcal{A} \underset{m_{hh}^2\gg m_W^2}{\sim} (b-a^2)\,\frac{4m_{hh}^2}{v^2}$$

asymptotic behavior
sensitive to strong interaction

$$\mathcal{A} \underset{m_{hh}^2\sim 4m_h^2}{\sim} {\rm cst.} + 3ad_3\frac{m_h^2}{v^2}$$

threshold effect
anomalous coupling'

Multiple Higgs interactions in WW→HH



Bondu, Contino, Massironi, Rojo 'to appear

Conclusions: Higgs & New Physics - a love affair

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13

NP

typical mass scale

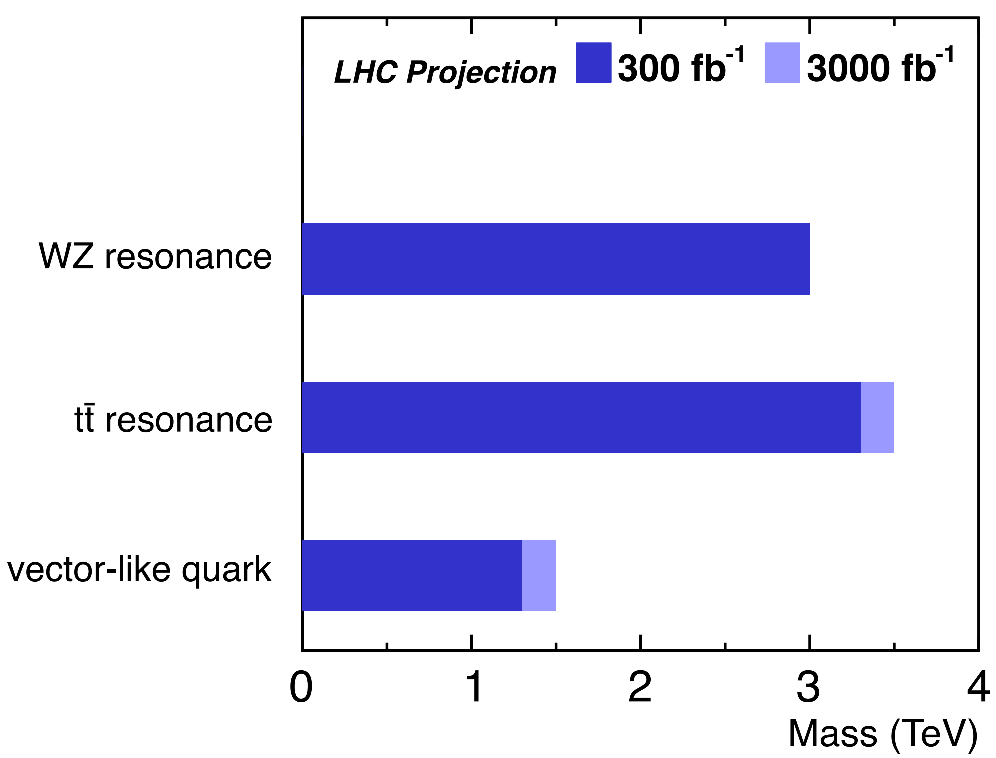
$M = g_* f$

SM

EW scale v=246GeV

g, g', y_t

g_{SM}^2 / g_*



LHC direct search

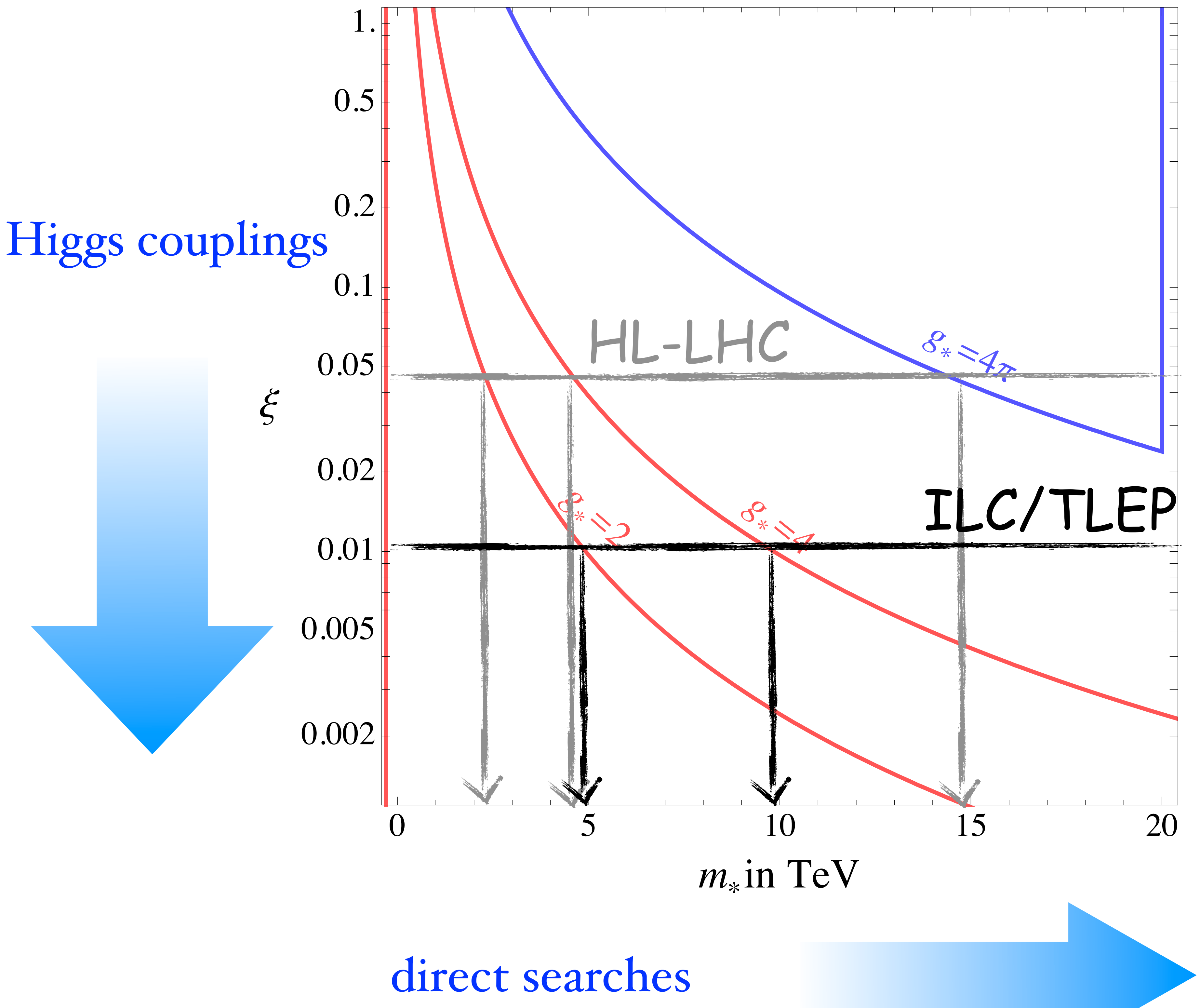
- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$

Which one is doing best?
it depends on value of g_*

Conclusions: Higgs & New Physics - a love affair

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13



- nice complementarity between direct searches and precision Higgs physics

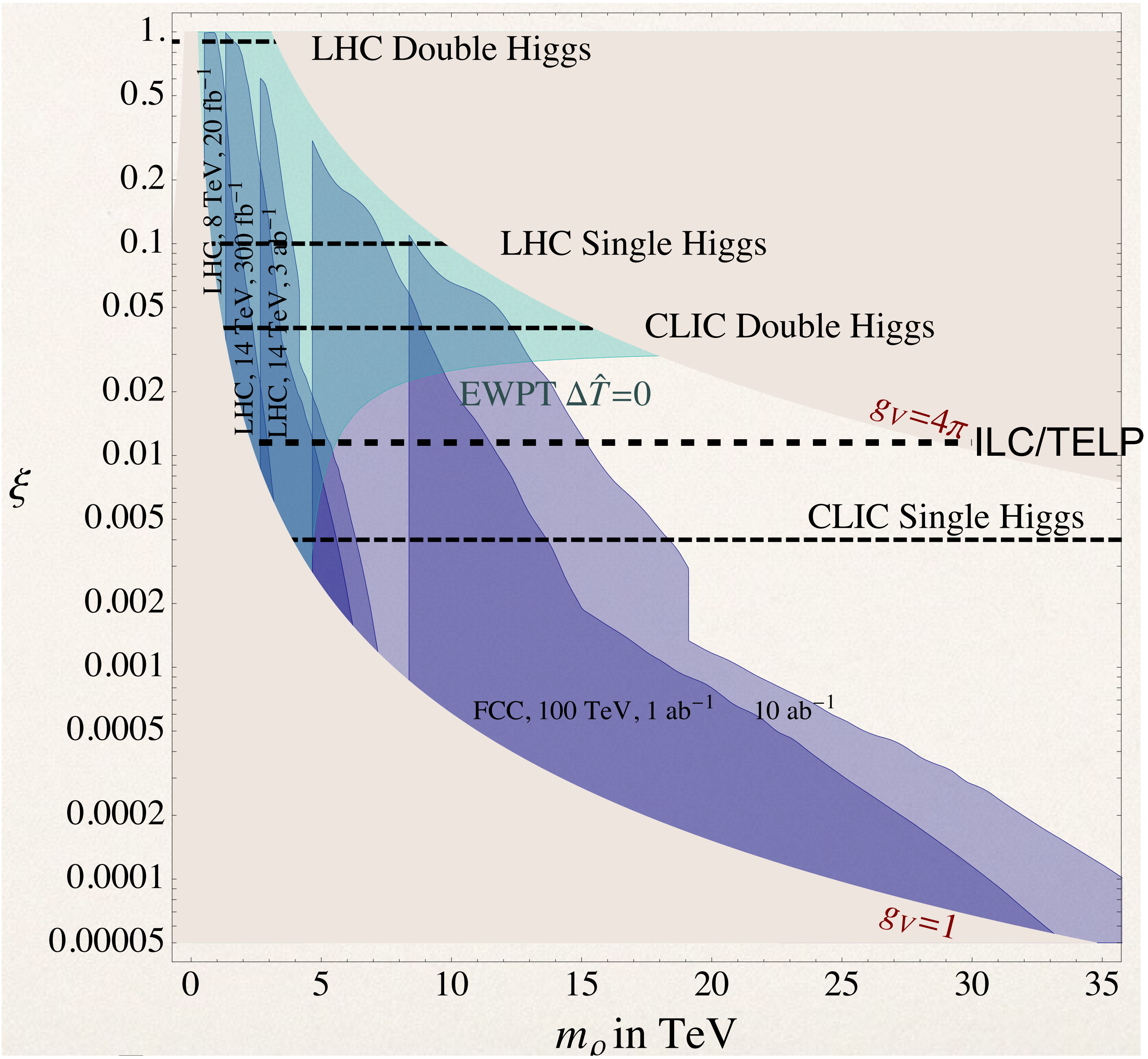
Rattazzi, BSM@100TeV, CERN '14

Conclusions: Higgs & New Physics - a love affair

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

- large region of parameter space already disfavored by EW precision data

- complementarity between direct searches @ hadron machine and indirect higgs measurements @ lepton machine



Contino, Grojeam, Pappadopulo, Rattazzi, Thamm '13

Torre, Thamm, Wulzer '14

a deviation in Higgs couplings also teaches us on the maximum mass scale to search for!

e.g. 10% deviation ⇛ m_V < 10TeV i.e. resonance within the reach of FCC-hh

Conclusions

"Higgs = emergency tire of the SM"

Altarelli @ Blois'10

[picture courtesy to Andreas Weiler]

Soon the LHC run 2 will start exploring a new energy domain...
while waiting for other big machines (ILC, CLIC, FCC-ee, FCC-hh).
You have a chance to be part of this exciting adventure.
Good luck!