EFFECTIVE LAGRANGIAN FOR HIGGS INTERACTIONS

Concha Gonzalez-Garcia

(YITP Stony Brook & ICREA U. Barcelona)

MPIK Heidelberg, July 24th 2013

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arXiv:1207.1344, 1211.4580, 1304.1151

http://hep.if.usp.br/Higgs

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OUTLINE

Introduction: the SM Higgs Boson

Effective Lagrangian for SM-like Higgs Boson

Data Driven Choice of Operator Basis

Application to Present Analysis of Higgs Data

Summary

Introduction: the Standard Model

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- The SM is a gauge theory based on the symmetry group

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

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With matter made of 3 fermion generations with quantum numbers

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

And the gauge bosons *carriers* of the strong, weak and electromagnetic interactions

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And the gauge bosons *carriers* of the strong, weak and electromagnetic interactions

$$g \quad W^{\pm} \; Z^0 \quad \gamma$$

- In a gauge theory the Lagrangian is fully determined by symmetry
- In 90's we tested fermion-GB interactions to better than 1%
- Also we have tested GB self-interactions to 5-10%

Introduction: SM

- Plus: Gauge Theories are renormalizable (theoretically sound)
- Minus: GS forbids mass for gauge-bosons (for SM group also for fermions)

  $V_\mu V^\mu$ or $\bar{f}_R f_L$ are not Gauge Invariant

- But we know that many particles have mass:

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- To give mass to these states without spoiling renormalizability:

  $\Rightarrow$ Spontaneous Symmetry Breaking

  $\equiv$ It is the ground state (vacuum) which breaks the symmetry

  $\equiv$ Vacuum is invariant only under a subgroup of the GS

  $\Rightarrow$ There will be massless excitations

  $\Rightarrow$ In presence of long range forces massless excitations disappear and the force becomes short ranged

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- In SM EWSSB: $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$

Introduction: Higgs Mechanism of EWSB

- To allow for EWSB we need to add *something* to parametrize this non-trivial vacuum

  Lorentz Invariance $\Rightarrow$ *something* cannot have spin $\equiv$ scalar

  EWSB $\Rightarrow$ *something* must be non-singlet $SU(2)_L$ but colorless and elec neutral

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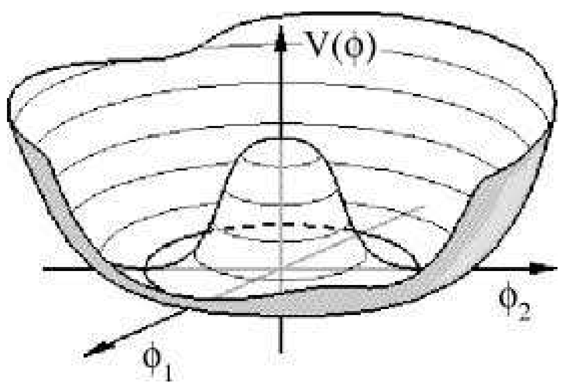
  something$\equiv$ *fundamental scalar* $SU(2)$ *doublet*: $\Phi\,(1,2)_{\frac{1}{2}} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

  With particular form of the potential [Englert& Brout;Higgs:Guralnik&Hagen&Kibble]

$$\mathcal{L}_\Phi = (D_\mu \Phi)(D^\mu \Phi)^\dagger - (\mu^2|\Phi|^2 + \lambda|\Phi|^4)$$

with $\mu^2 < 0$



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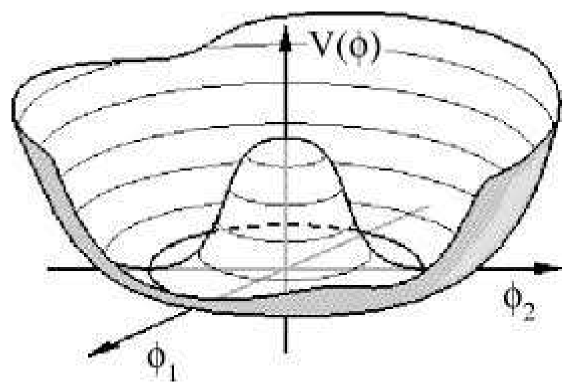


- SSB $\equiv$ choice of vacuum: $\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

About this vacuum

$\Rightarrow$ W and Z become massive

$\Rightarrow$ fermions can acquire a mass via Yukawa interactions $\lambda_f \bar{f} f \Phi$

$\Rightarrow$ Physical scalar excitation $h(x)$: $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$

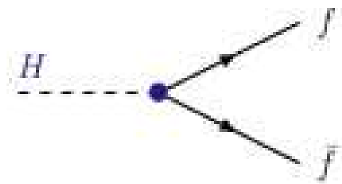
The Higgs Boson

Intro: The Higgs Boson

- A few properties of the Higgs Boson

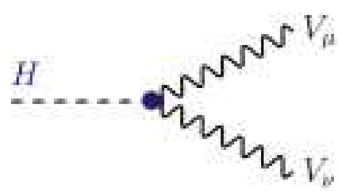
  - ∗ Neutral Scalar with CP=+1 0^+

  - ∗ Its mass is the only free parameter $m_H = \sqrt{2\lambda}\, v$

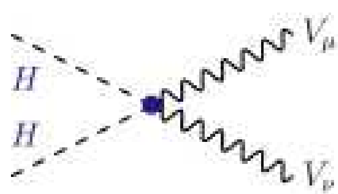


$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f \quad \times (-i)$$

  - ∗ Interactions with GB
    and fermions
    proportional to their masses



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



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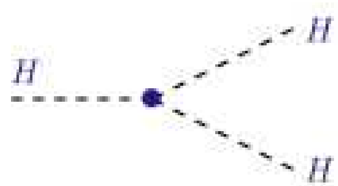
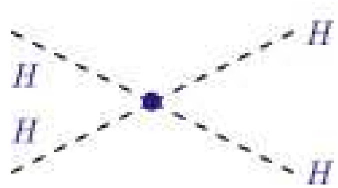


$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2} M_H^2 \quad \times (-i)$$



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

Intro: Higgs Decay Modes

$$\Gamma(h \to f\bar{f}) = \frac{G_F m_f^2 (N_c)}{4\sqrt{2}\pi} M_h \left(1 - r_f\right)^{\frac{3}{2}} \qquad r_i \equiv \frac{4M_i^2}{M_h^2}$$

$$\Gamma(h \to W^+W^-) = \frac{G_F M_h^3}{8\pi\sqrt{2}} \sqrt{1 - r_W}\left(1 - r_W + \tfrac{3}{4} r_W^2\right)$$

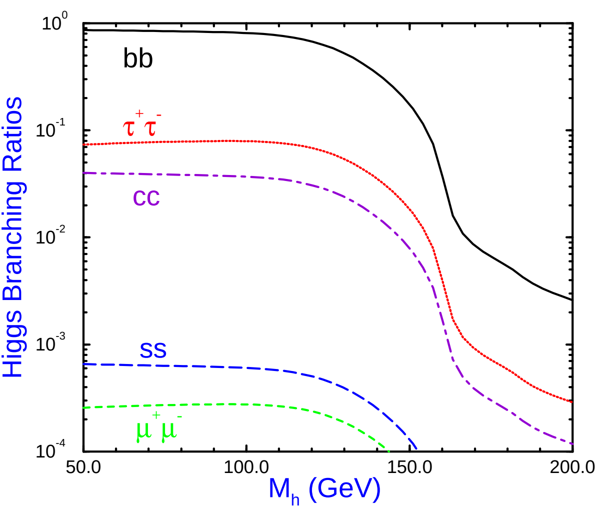
$$\Gamma(h \to ZZ) = \frac{G_F M_h^3}{8\pi\sqrt{2}} \sqrt{1 - r_Z}\left(1 - r_Z + \tfrac{3}{4} r_Z^2\right)$$

$$\Gamma_0(h \to gg) = \frac{G_F \alpha_s^2 M_h^3}{64\sqrt{2}\pi^3} \left| \sum_q F_{1/2}(r_q) \right|^2 \qquad \Gamma(h \to \gamma\gamma) = \frac{\alpha^2 G_F}{128\sqrt{2}\pi^3} g_V M_h^3 \left| \sum_{q,W} N_{ci} Q_i^2 F_i(r_i) \right|^2$$

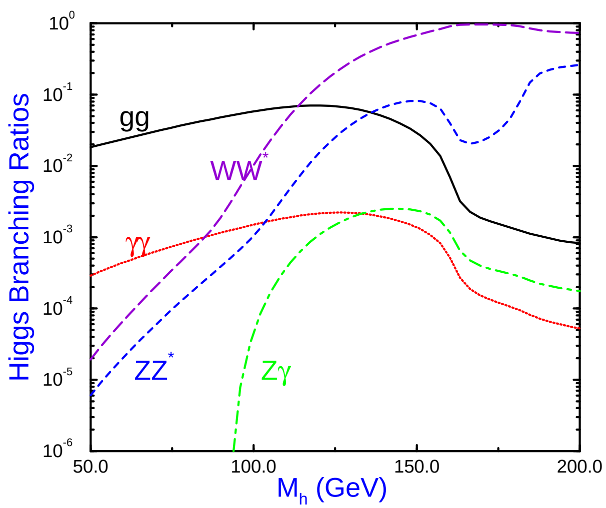
$$F_{1/2}(r_q) \equiv -2r_q[1 + (1 - r_q)f(r_q)] \qquad f(x) = \begin{cases} \sin^{-2}(\sqrt{1/x}), & \text{if } x \geq 1 \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-x}}{1-\sqrt{1-x}}\right) - i\pi\right]^2, & \text{if } x < 1, \end{cases}$$

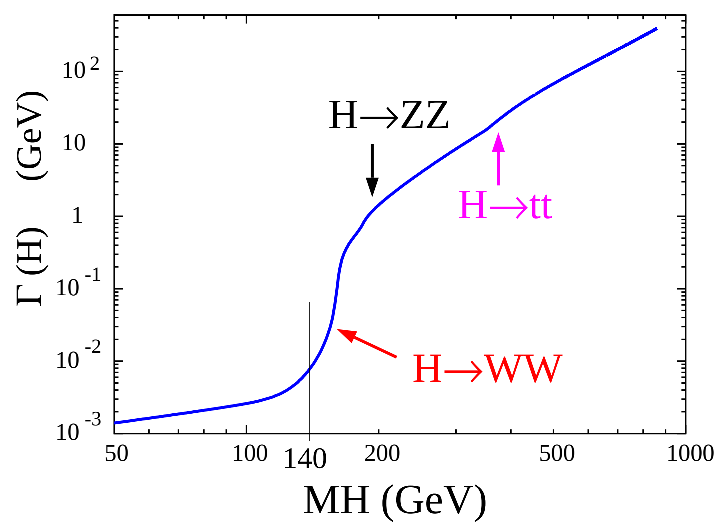
$$F_W(r_W) = 2 + 3r_W[1 + (2 - r_W)f(r_W)]$$

Higgs Branching Ratios to Fermion Pairs



Higgs Branching Ratios to Gauge Boson Pairs

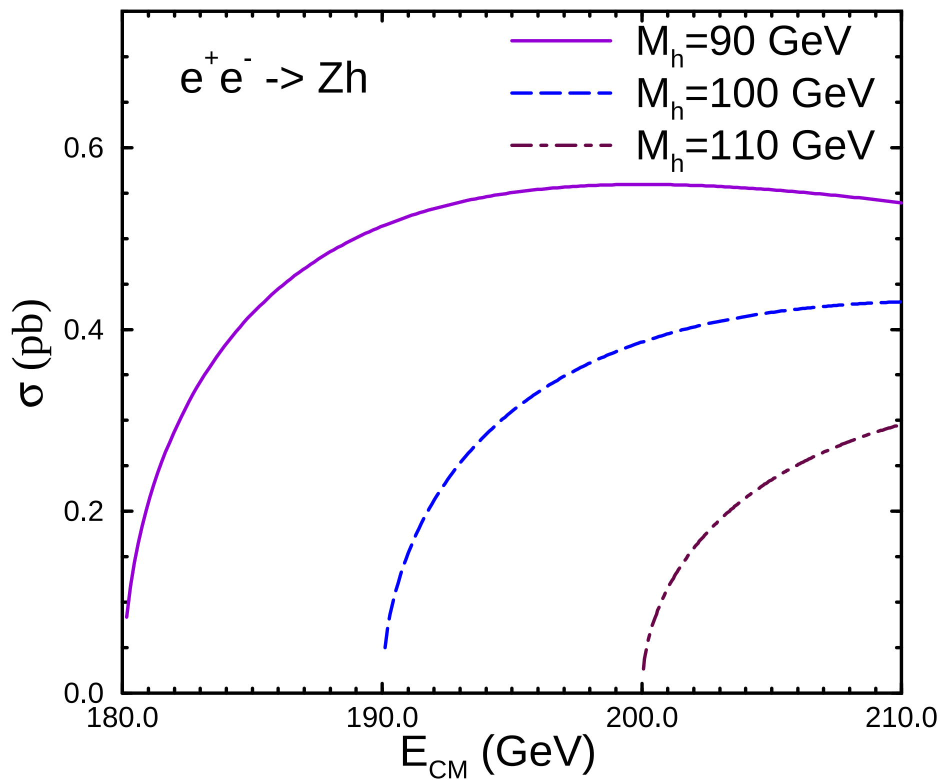




Intro: Higgs at e^+e^-

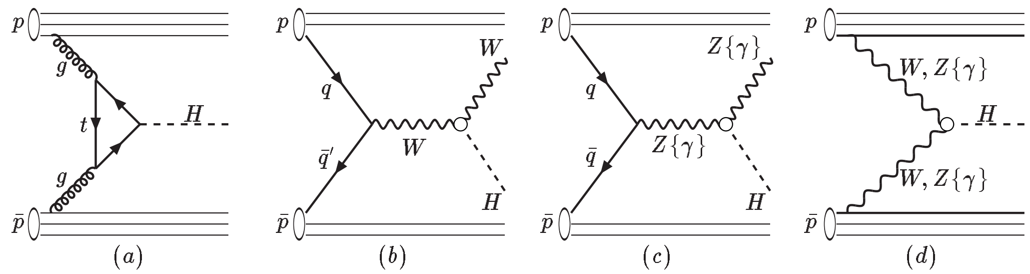
$$\sigma(e^+e^- \to Zh) = \frac{\pi\alpha^2\lambda_{Zh}^{1/2}[\lambda_{Zh} + 12\frac{M_Z^2}{s}][1 + (1 - 4\sin^2\theta_W)^2]}{192 s \sin^4\theta_W \cos^4\theta_W (1 - M_Z^2/s)^2}$$

$$\lambda_{Zh} \equiv (1 - \frac{M_h^2 + M_Z^2}{s})^2 - \frac{4M_h^2 M_Z^2}{s^2} \qquad s = (p_{e^+} + p_{e^-})^2$$

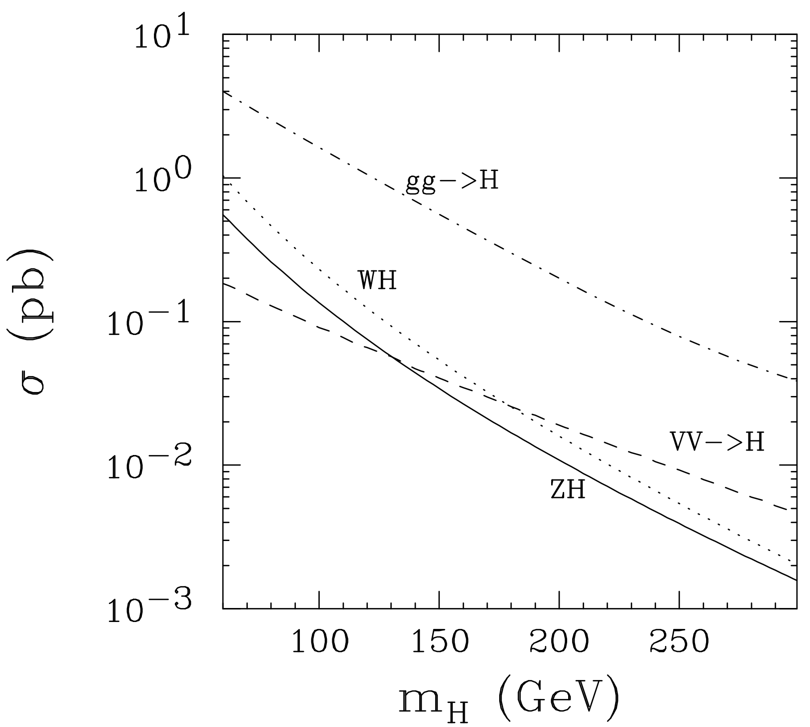


Searches at LEP ($e^+e^-\ \sqrt{s} = 90 - 210$ GeV) $\Rightarrow M_H \geq 114.4$ GeV

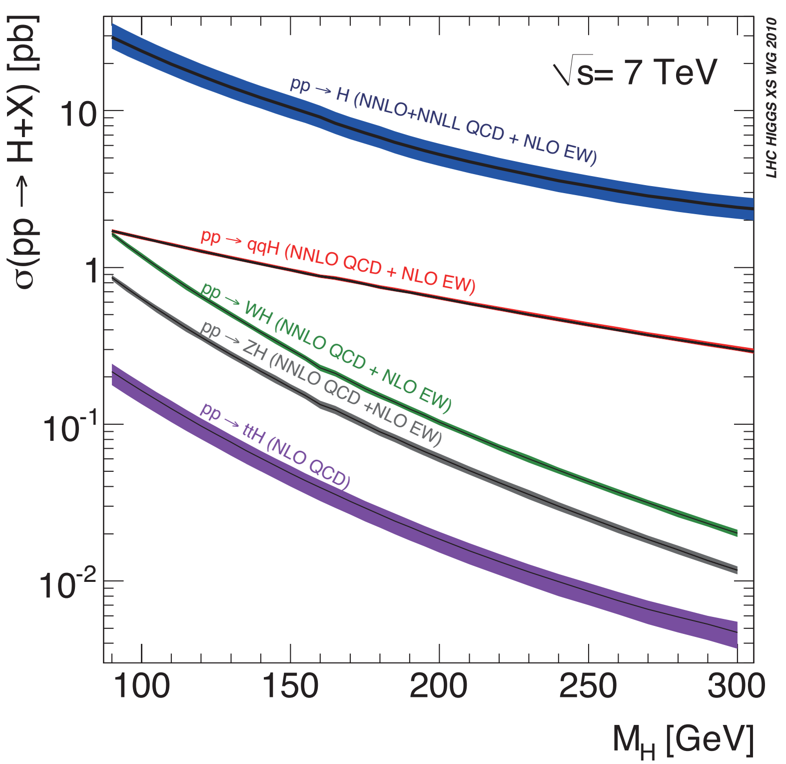
Intro: Higgs at Hadron Colliders



Tevatron ($p\bar{p}$ $\sqrt{s} = 2$ TeV)



LHC (pp $\sqrt{s} = 7$–14 TeV)



Intro: Higgs at LHC7-8

- SM main discovery modes for a light Higgs:

$$pp \to \gamma\gamma$$

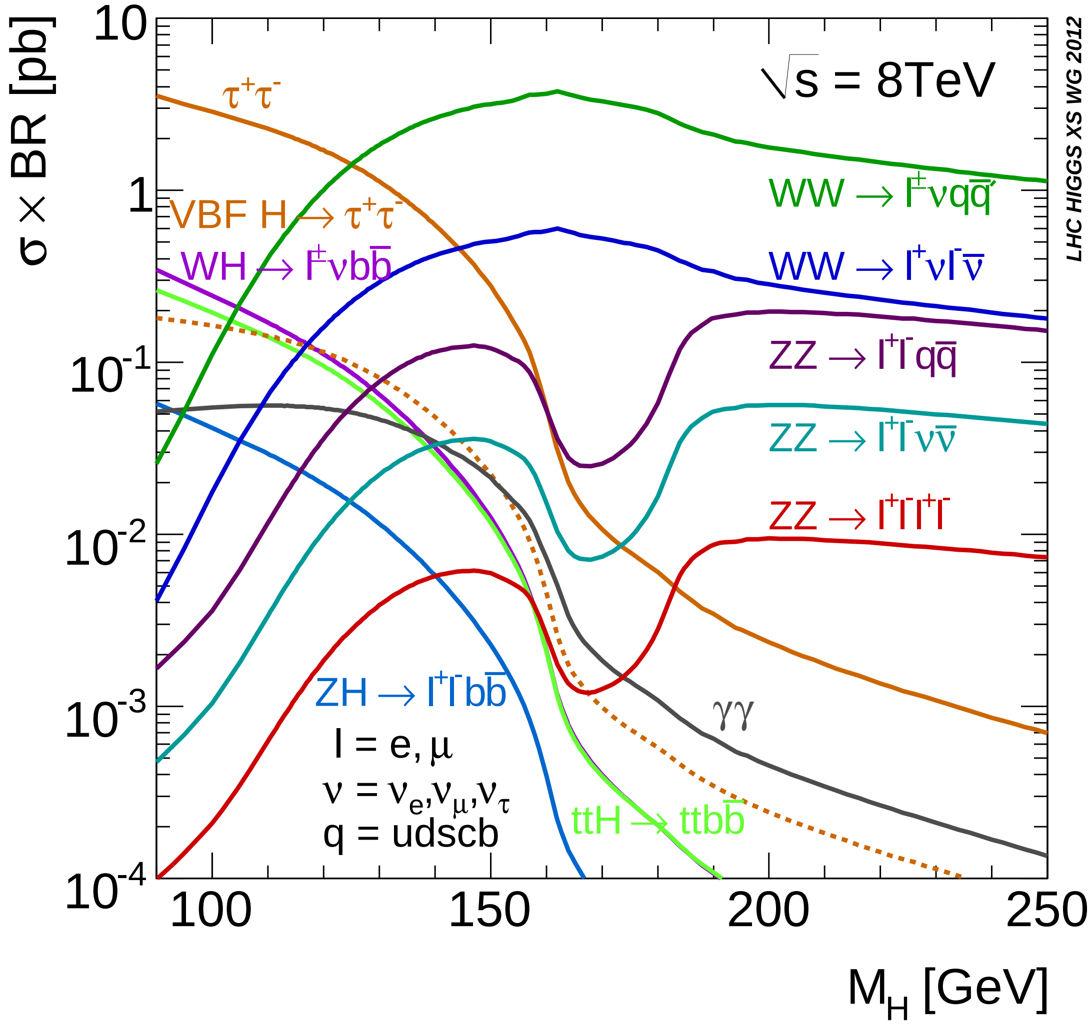
$$pp \to ZZ \to \ell\ell\ell\ell$$

$$pp \to WW \to \ell\nu\ell\nu$$

Also:

$$pp \to b\bar{b}$$

$$pp \to \tau\bar{\tau}$$



Eureka!

The INDEPENDENT
HOMOPHOBIA, HIP-HOP, AND THE STAR WHO CAME OUT
THE L'OREAL FILES: COULD SARKOZY GO DOWN?
MURRAY ONE MATCH FROM THE FINAL
EUREKA!
It has taken nearly 50 years and cost £2.6bn. Now, at last, the Higgs boson particle has been found and a new chapter in our understanding of the universe can begin
theguardian
Osborne accuses Labour over rate-fixing scandal
The New York Times
TRY A TIMES DIGITAL SUBSCRIPTION: 4 WEEKS FOR 99¢
Rapid H.I.V. Home Test Wins Federal Approval
INTRODUCING
EL PAÍS
Hallada la partícula clave para la comprensión del universo
LA VANGUARDIA
La 'partícula de Dios' abre nuevas puertas a la física
El juez imputa a Rato y 32 consejeros de Bank

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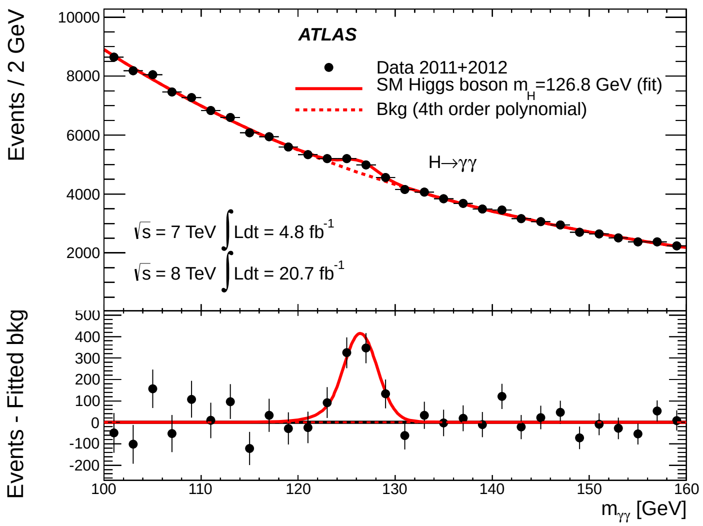
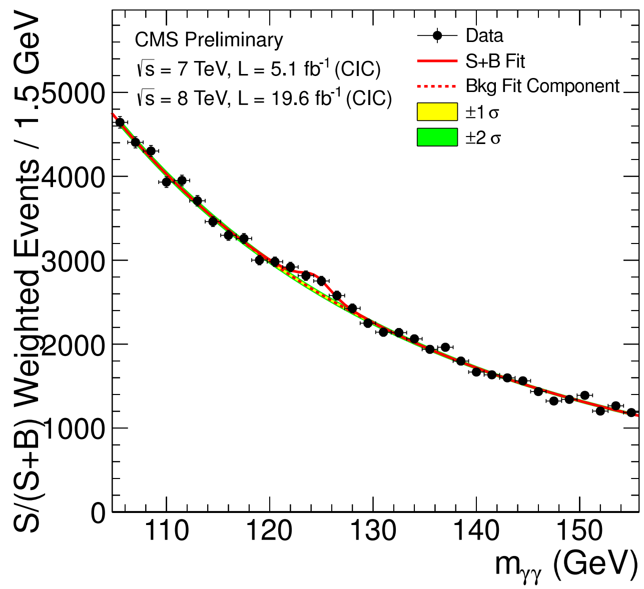
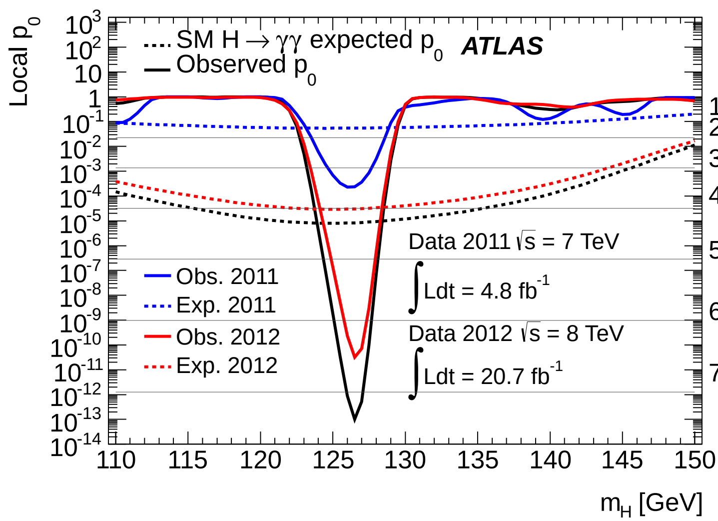
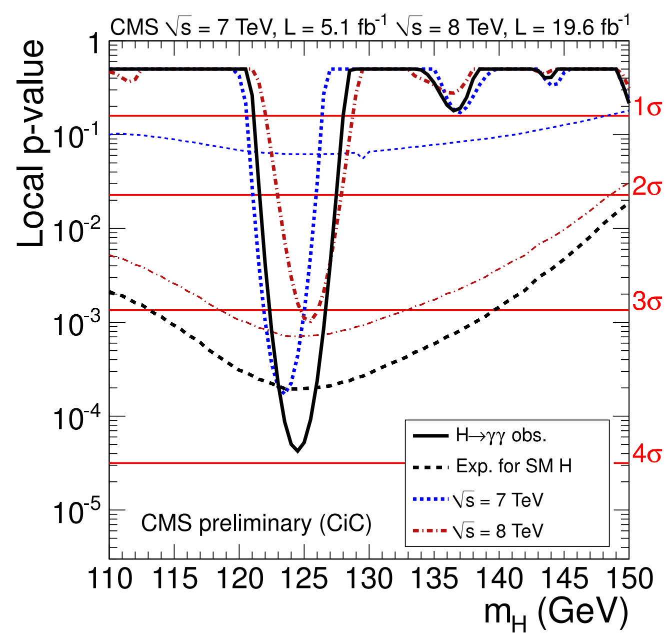
- 48 years between EWSB theory and discovery
- 1964: THEORY [Englert& Brout;Higgs:Guralnik&Hagen&Kibble]
- 2013: DATA Signal in many channels $\gamma\gamma$, ZZ, WW, $b\bar{b}$, $\tau\bar{\tau}$ $\ldots$

Intro: $H \to \gamma\gamma$

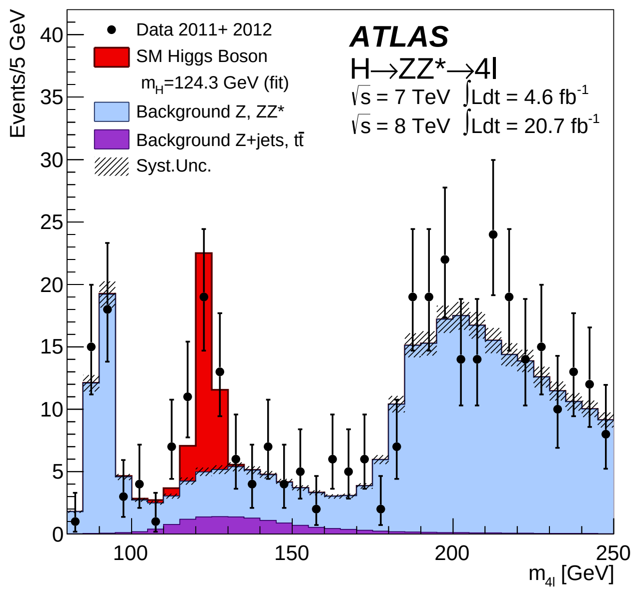


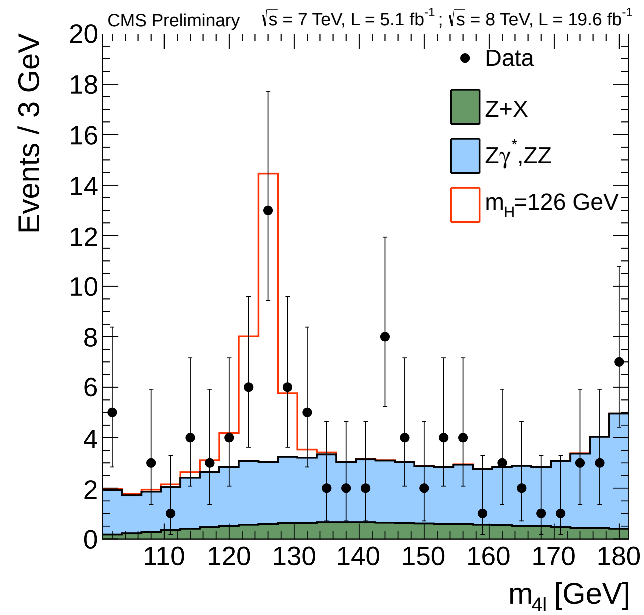


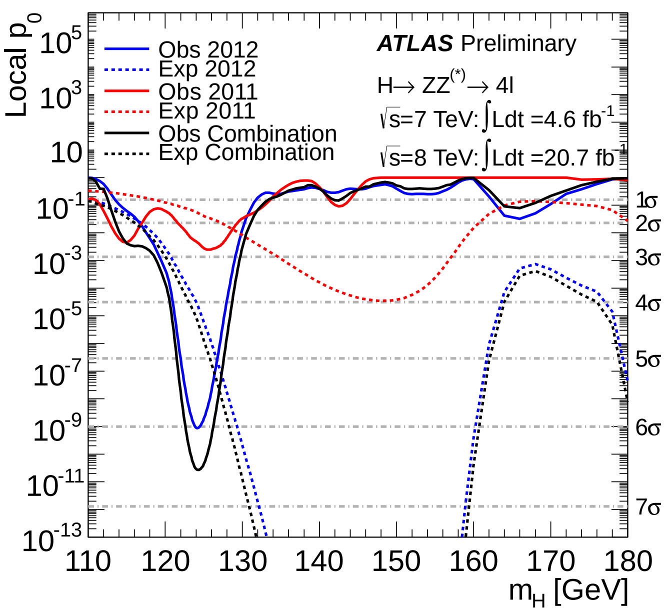


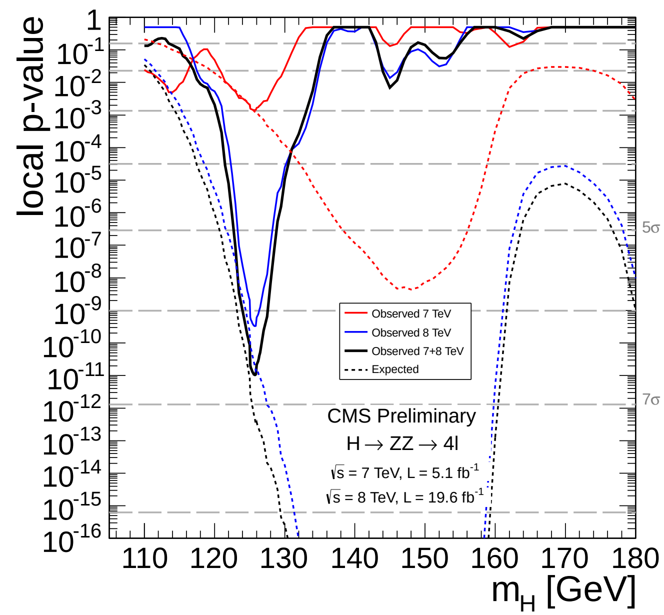


Intro: $H \to ZZ^* \to 4l$



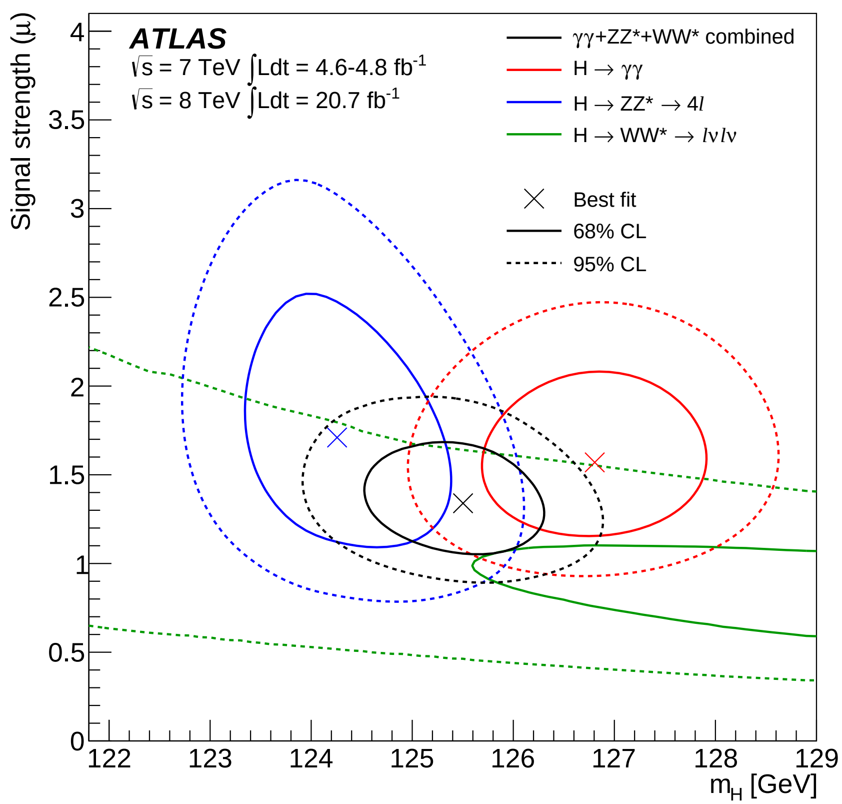




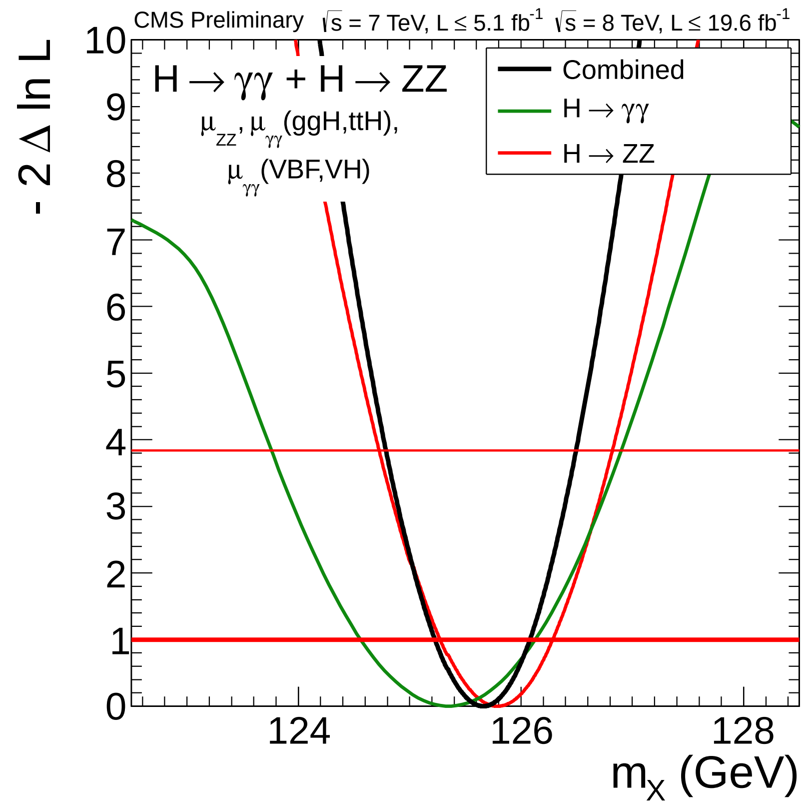


Intro: Mass

ATLAS



CMS



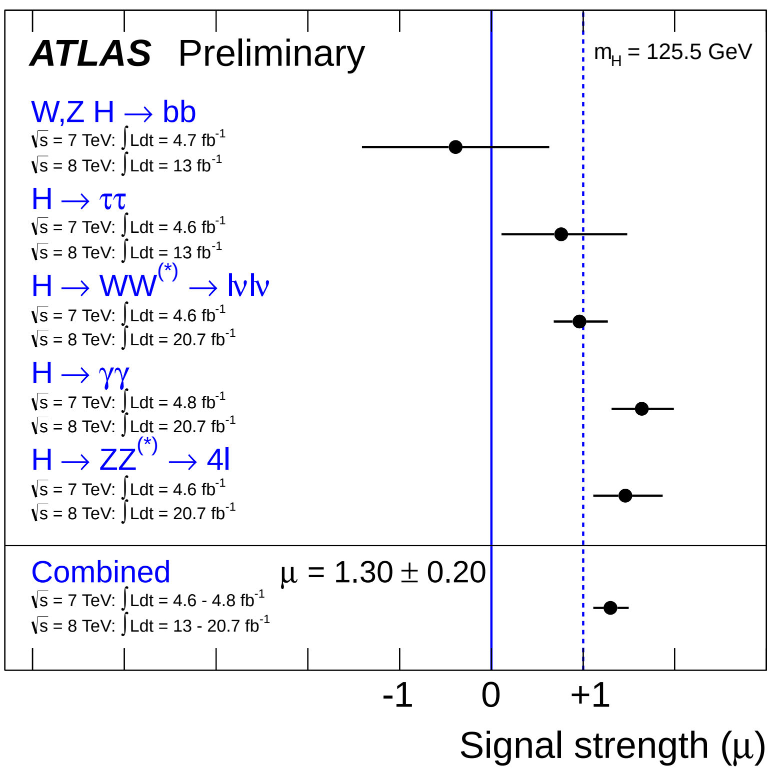
$M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{sys}$ GeV

$M_H = 125.5 \pm 0.3_{stat} \pm 0.3_{sys}$ GeV

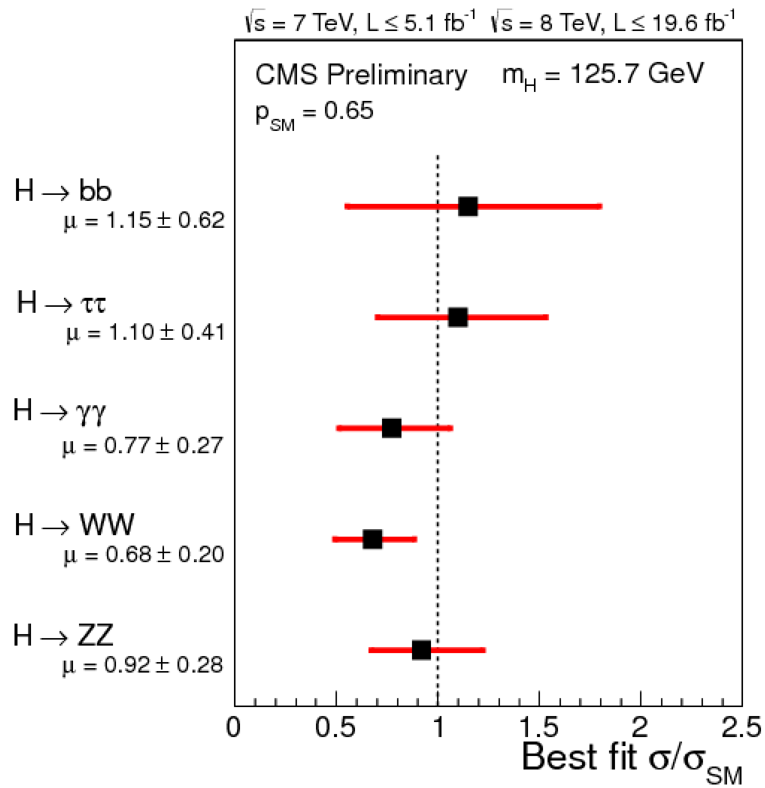
Intro: Summary of Other Channels

- Signal Strengths: $\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$

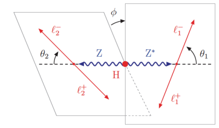
ATLAS



CMS

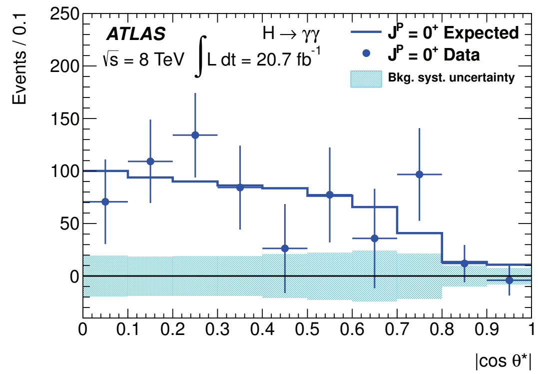


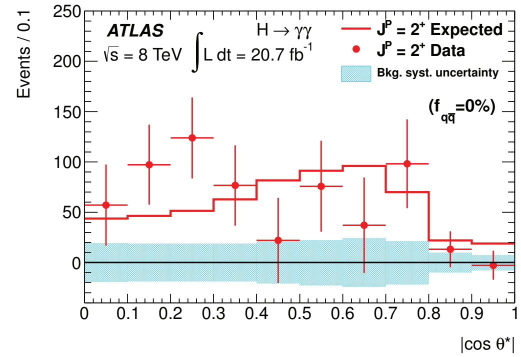
Spin-Parity Determination



Analyzed channels:

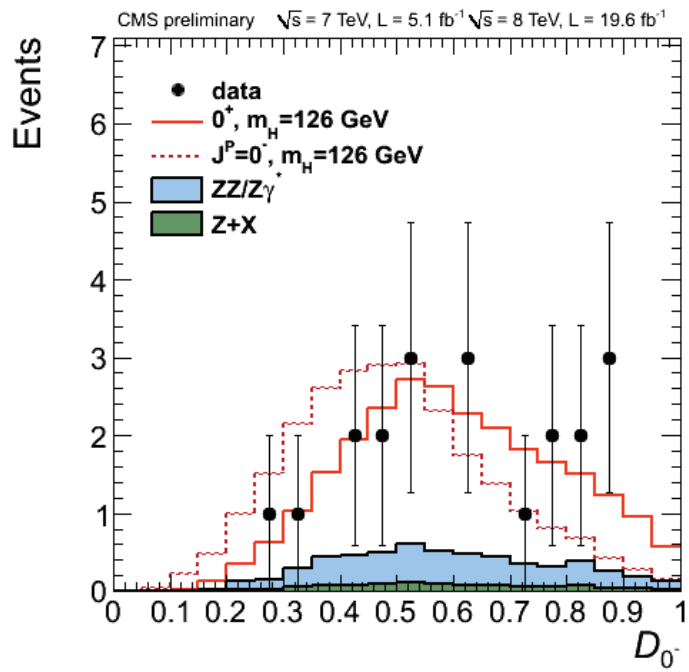
- H→ γγ decay angle cos(θ*) in Collins-Sopper frame sensitive to J





- H → WW* → ℓνℓν Several variables sensitive to J^P
  - $\Delta\phi_{\ell\ell}$, $M_{\ell\ell}$, ..
  - Combined with Boosted-Decision-Tree (BDT)

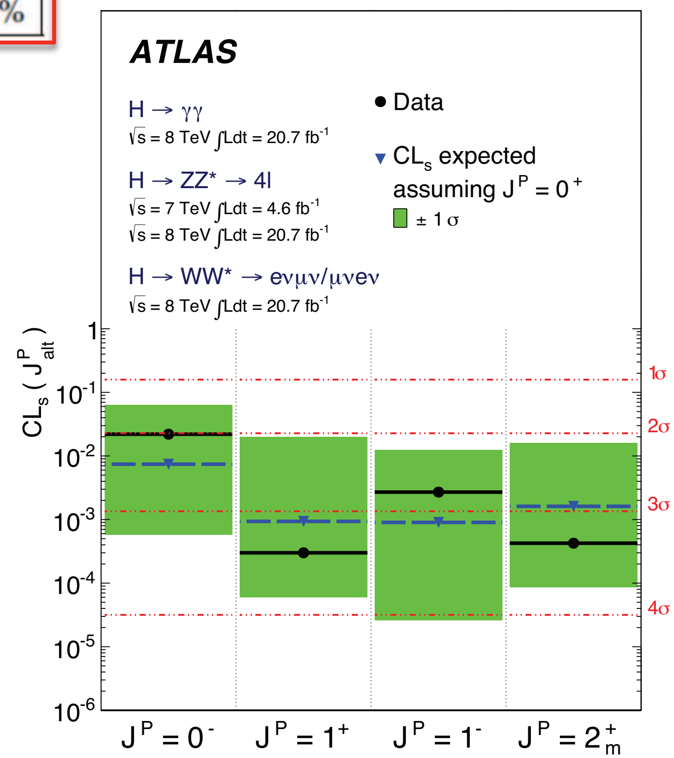
- H → ZZ* →4ℓ: Full final state reconstruction sensitive to J^P
  - 2 masses (M_{Z1},M_{Z2}) and 5 angles
  - Combined with BDT or Matrix-Element-based discriminant D_{JP}



Spin-Parity ATLAS - CMS Overview

CMS ZZ*(4ℓ)

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2_{mgg}^+	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2_{mq\bar{q}}^+$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%



ATLAS and CMS: *"bosonic"* decay modes

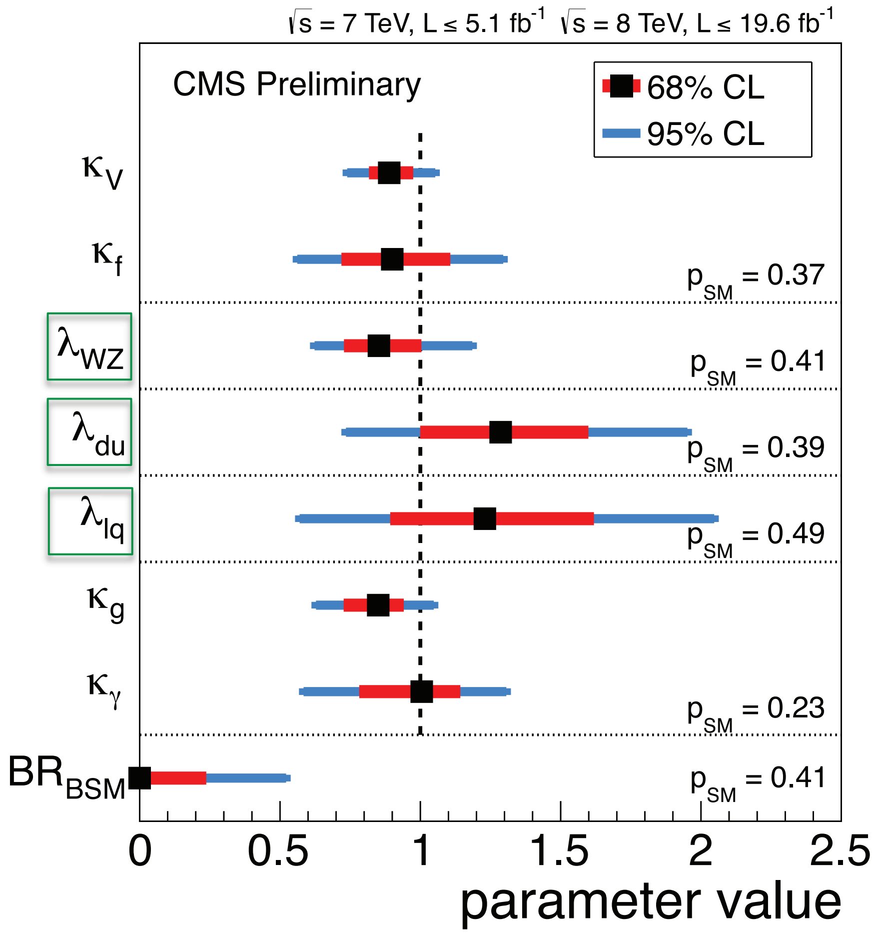
Strongly favor $J^P = 0^+$ SM quantum numbers

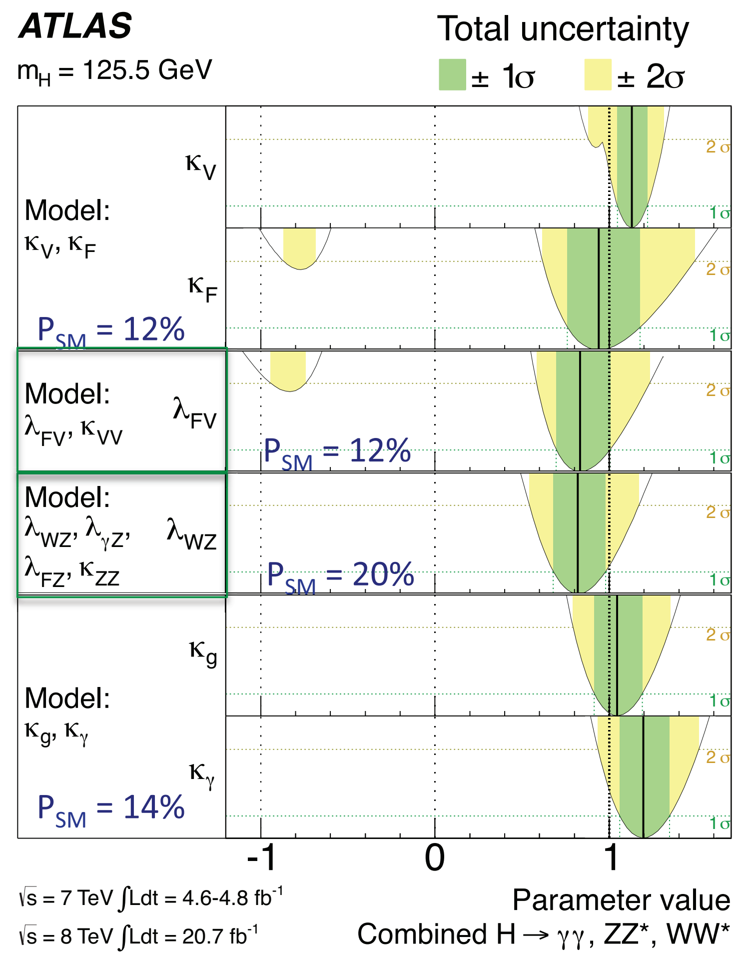
All alternative J^P models tested:

Excluded @ >95% CL

Couplings Overview

Assumption only one or two couplings varied at a time





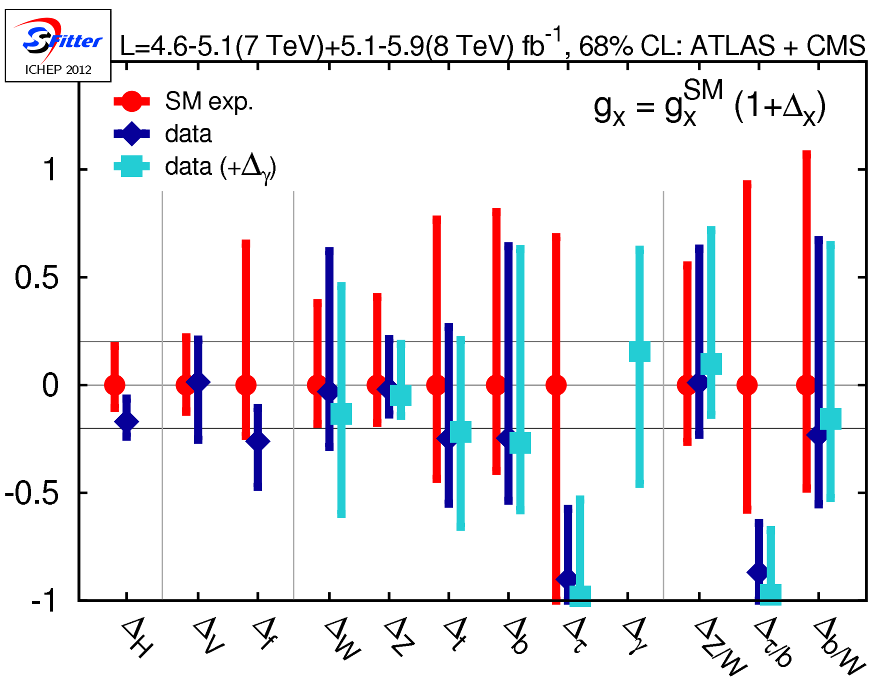
- Different *Sectors* of the New Boson Couplings tested: P_{SM}>12%

<u>All compatible with SM Higgs expectations</u>

Intro: Couplings

- Several phenomenological multi-coupling analysis
- In general assumed re-scaled/shifted SM couplings:

$gg \to H$ $qq \to qqH$ $gg \to t\bar{t}H$ $qq' \to VH$	$\longleftrightarrow$	$g_{HXX} = g_{HXX}^{SM}\ (1 + \Delta_X)$	$\longleftrightarrow$	$H \to ZZ$ $H \to WW$ $H \to b\bar{b}$ $H \to \tau^+\tau^-$ $H \to \gamma\gamma$



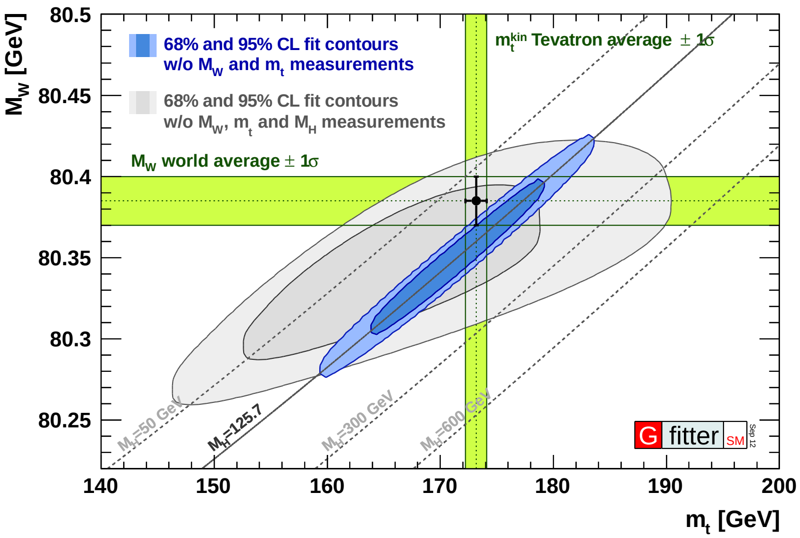
SFitter-Higgs (Dursssen),Klute,Lafaye,Plhen,Rauch, Zerwas

• July 4th 2012 marks the dawning of new era

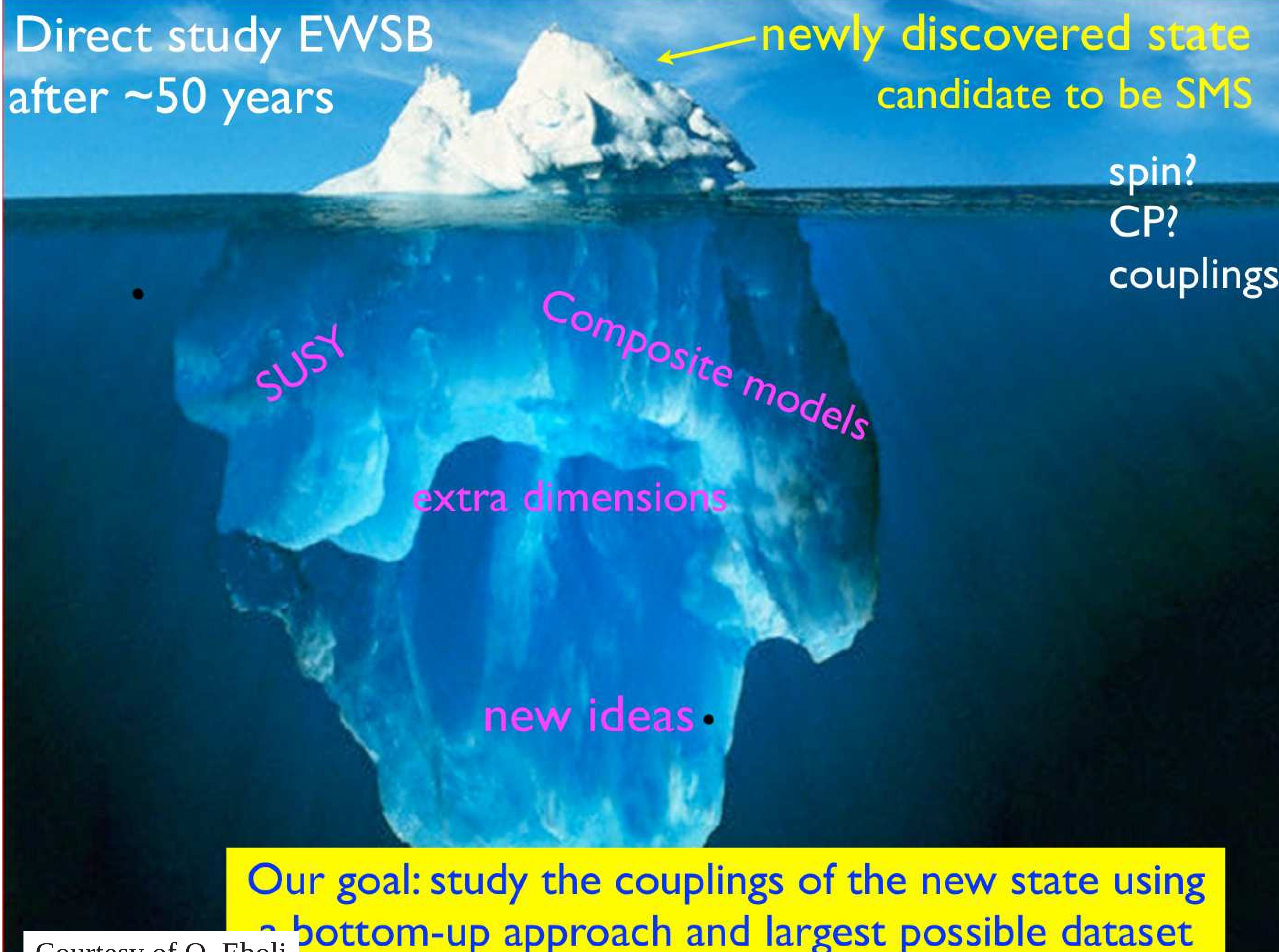
• 48 years between EWSB theory and discovery

• 1964: THEORY [Englert& Brout;Higgs:Guralnik&Hagen&Kibble]

• 2013: DATA Signal in many channels $\gamma\gamma$, ZZ, WW, $b\bar{b}$, $\tau\bar{\tau}$ ...



New state fits the global SM picture [Gfitter arXiv:1209.2716]

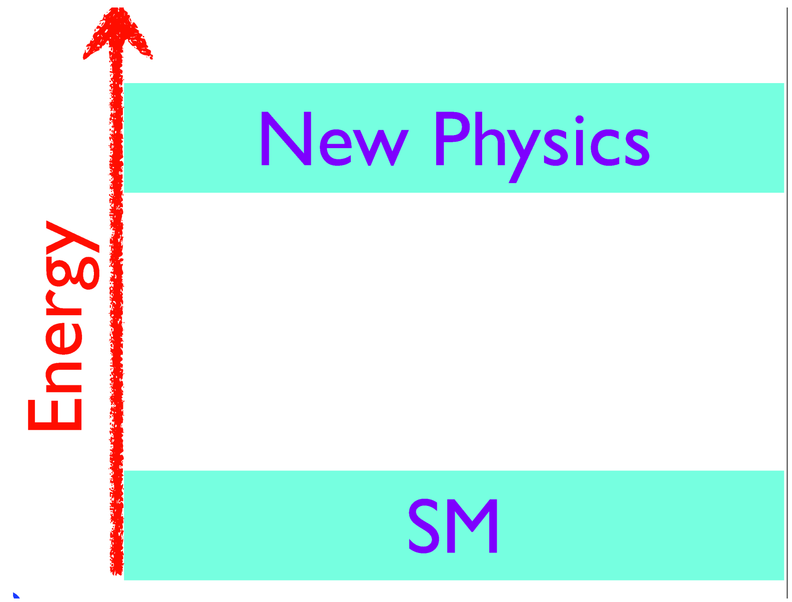


Courtesy of O. Eboli

Effective Lagrangian for a SM-like Higgs Boson

- Some *conservative/realistic/agnostic* assumptions

- There is a mass gap
  between SM and NP



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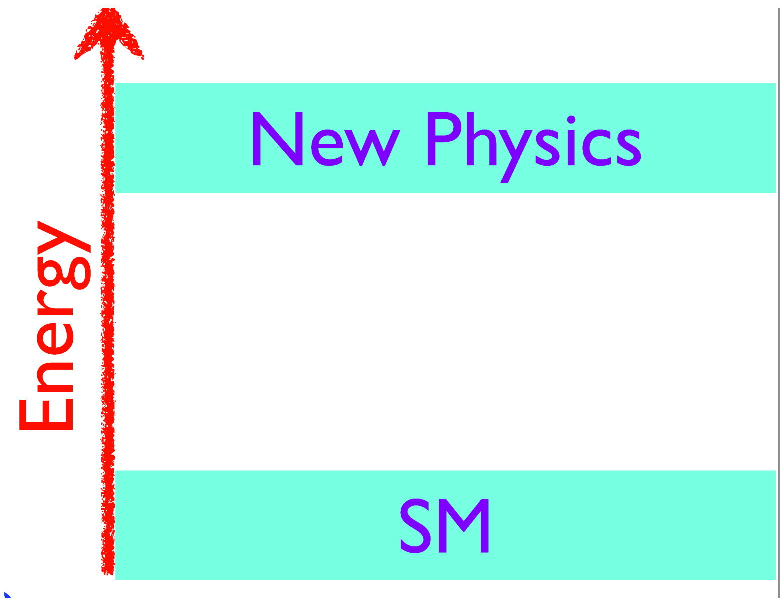

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- New State belongs to $SU(2)$ doublet: Φ

- $SU(2) \times U(1)$ is realized linearly as in the SM

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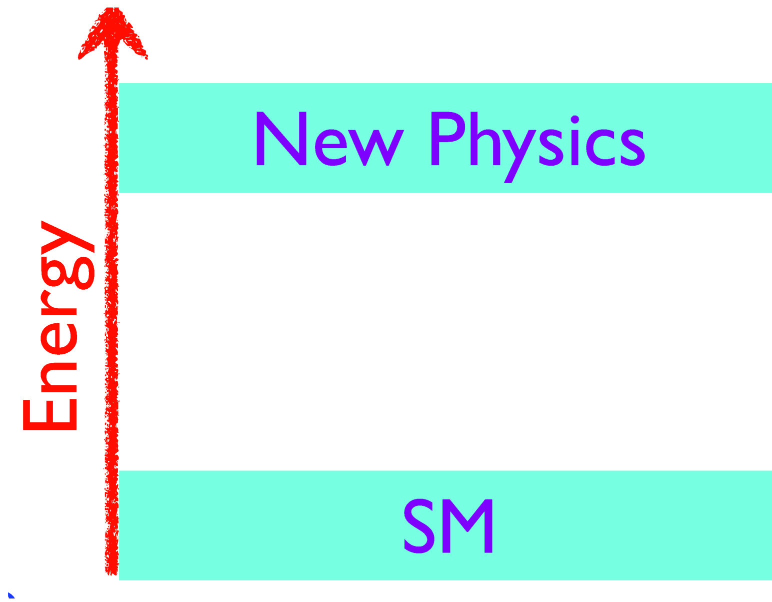

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- Building Blocks of $\mathcal{L}_{\text{eff}}$:

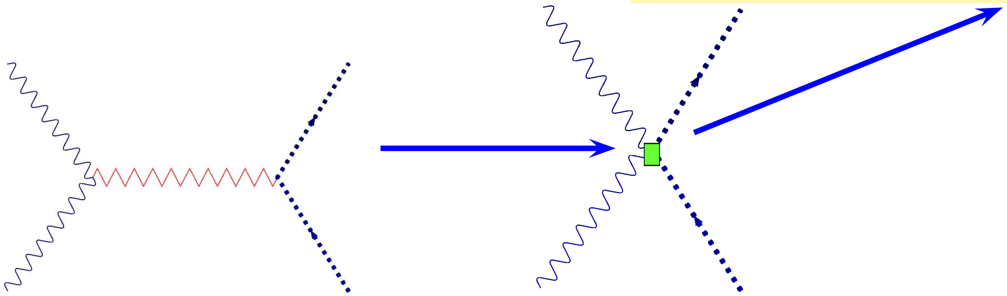
$$\Phi \qquad D_\mu \Phi$$

$$\hat{B}_{\mu\nu} = i\frac{g'}{2} B_{\mu\nu} \qquad \hat{W}_{\mu\nu} = i\frac{g}{2}\sigma^a W^a_{\mu\nu} \qquad G^a_{\mu\nu}$$

$$\ldots \qquad \ldots \qquad \ldots$$

- To parametrize departures from the SM predictions we write

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{f_i}{\Lambda^2}\mathcal{O}_i + \dots$$



Dimension-6 operators Summarizing NP effects of scale Λ

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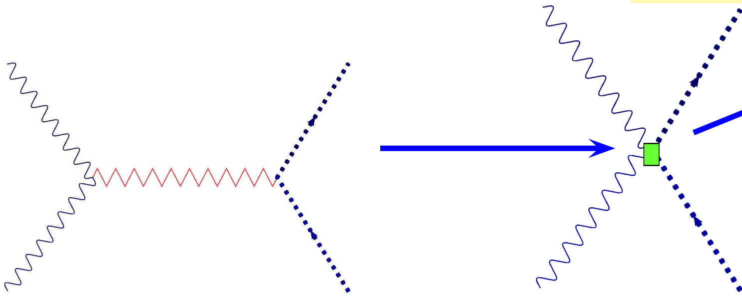

Dimension-6 operators Summarizing NP effects of scale Λ

• There are 59 *independent* dimension-6 operators

[Buchmuller&Wyler;Gradzkowski et al arXiv:1008.4884]

$\Rightarrow$ There is freedom in choosing the operator basis

$\Rightarrow$ Possible to choose a basis to make best use of all available data

Application to Higgs pheno: Hagiwara, Szalapski, Zeppenfeld, hep-ph/9308347;
de Campos *etal* hep-ph/9707511,9806307; MCG-G hep-ph/9902321; Eboli *etal* hep-ph/9802408,0001030

- A partial list of operators involving the scalar and SM gauge bosons

$$\mathcal{O}_{GG} = \Phi^\dagger \Phi \; G^a_{\mu\nu} G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \Phi^\dagger \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{BB} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{B}^{\mu\nu} \Phi$$

$$\mathcal{O}_{BW} = \Phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \Phi \qquad \mathcal{O}_{W} = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_{B} = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{O}_{\Phi,1} = (D_\mu \Phi)^\dagger \, \Phi \, \Phi^\dagger \, (D^\mu \Phi) \qquad \mathcal{O}_{\Phi,2} = \frac{1}{2} \partial^\mu \left(\Phi^\dagger \Phi\right) \partial_\mu \left(\Phi^\dagger \Phi\right) \qquad \mathcal{O}_{\Phi,4} = (D_\mu \Phi)^\dagger \, (D^\mu \Phi) \left(\Phi^\dagger \Phi\right)$$

- In Unitary Gauge $\quad \Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$

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(a) Operators with Higgs and its Derivatives $[\; D_\mu \Phi = \left(\partial_\mu + i \frac{1}{2} g' B_\mu + i g \frac{\sigma_a}{2} W^a_\mu\right) \Phi \;]$

$\ast$ Scalar Field Redefinition Required

$$H = h \left[1 + \frac{v^2}{2\Lambda^2} \left(f_{\Phi,1} + 2 f_{\Phi,2} + f_{\Phi,4} \right) \right]$$

$\Rightarrow$ Rescale of all the Couplings of the Higgs

$\ast$ $\mathcal{O}_{\Phi,1}$:

$\Rightarrow \Delta T \propto f_{\Phi,1}$

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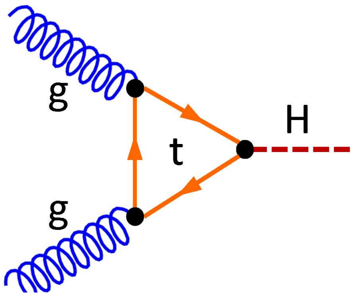
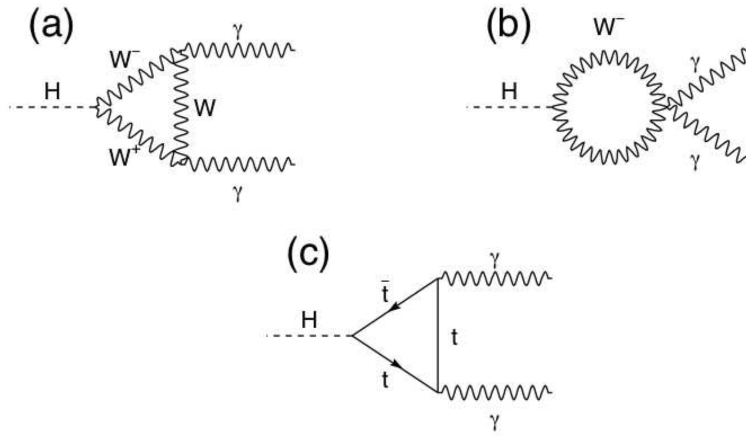
(b) Operators Inducing Higgs-Gauge Boson Couplings which are 1-loop in SM

∗ Coupling to Gluons: $\mathcal{O}_{GG}$ In SM



∗ Coupling to Photons: $\mathcal{O}_{BW}$ $\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ In SM



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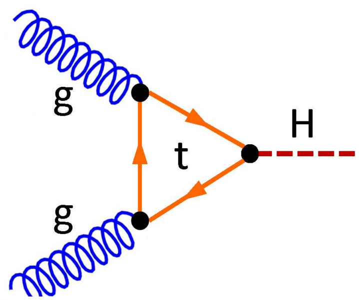

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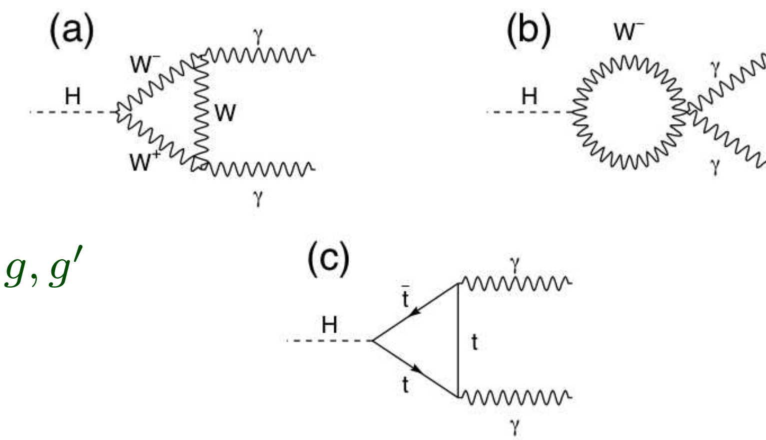

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Removed by W, Z and g, g' redefinitions

$\Rightarrow$ Also HVV VVV VVVV

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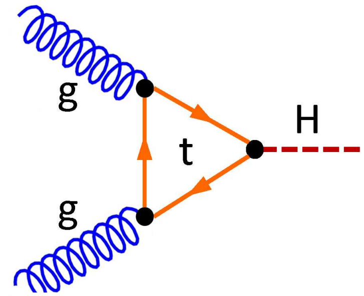

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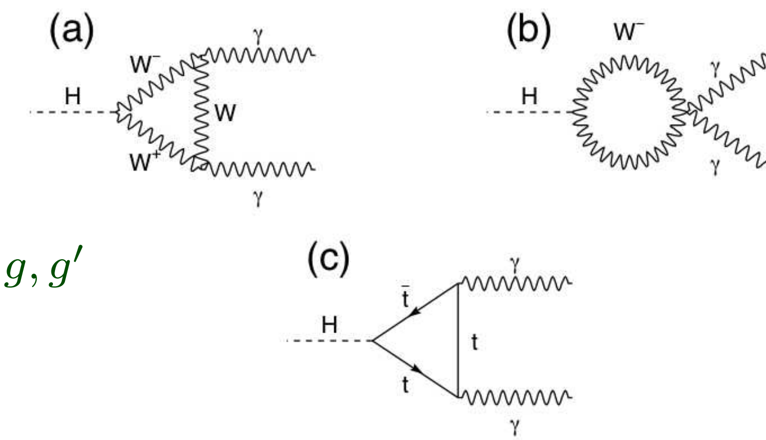

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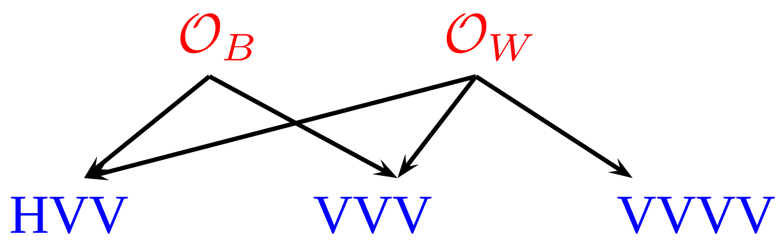
(c) Operators with GB Stress Tensors and $D_\mu\Phi$ [$D_\mu\Phi = \left(\partial_\mu + i\frac{1}{2}g' B_\mu + ig\frac{\sigma_a}{2}W^a_\mu\right)\Phi$]

⇒



• Higgs Coupl to Fermions are Modified by: [$D_\mu \Phi = (\partial_\mu + i\frac{1}{2} g' B_\mu + ig\frac{\sigma_a}{2} W^a_\mu)\,\Phi$]

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger \Phi)(\bar{L}_i \Phi e_{R_j})$$
$$\mathcal{O}_{u\Phi,ij} = (\Phi^\dagger \Phi)(\bar{Q}_i \tilde{\Phi} u_{R_j})$$
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These Modify the Yukawa Couplings

These Modify the Fermion Couplings to Gauge Bosons

• All the Operators Contaning the Higgs are **Not Independent**
Related by the Equations of Motion

Operator Basis:The Right of Choice

- Operators related by EOM lead to the same S matrix elements

[Politzer;Georgi;Artz;Simma]

- The EOM lead to the relations

$$2\mathcal{O}_{\Phi,2} - 2\mathcal{O}_{\Phi,4} = \sum_{ij} \left(y^e_{ij} \mathcal{O}_{e\Phi,ij} + y^u_{ij} \mathcal{O}_{u\Phi,ij} + y^d_{ij} (\mathcal{O}_{d\Phi,ij})^\dagger + \text{h.c.} \right)$$

$$2\mathcal{O}_{\mathcal{B}} + \mathcal{O}_{BW} + \mathcal{O}_{BB} + g'^2 \left(\mathcal{O}_{\Phi,1} - \tfrac{1}{2} \mathcal{O}_{\Phi,2} \right) = -\frac{g'^2}{2} \sum_i \left(-\frac{1}{2} \mathcal{O}^{(1)}_{\Phi L,ii} + \frac{1}{6} \mathcal{O}^{(1)}_{\Phi Q,ii} - \mathcal{O}^{(1)}_{\Phi e,ii} + \frac{2}{3} \mathcal{O}^{(1)}_{\Phi u,ii} - \frac{1}{3} \mathcal{O}^{(1)}_{\Phi d,ii} \right)$$

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EOM allow to Eliminate 3 Operators

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$$2\mathcal{O}_{W} + \mathcal{O}_{BW} + \mathcal{O}_{WW} + g^2 \left(\mathcal{O}_{\Phi,4} - \tfrac{1}{2}\mathcal{O}_{\Phi,2} \right) = -\frac{g^2}{4} \sum_i \left(\mathcal{O}^{(3)}_{\Phi L,ii} + \mathcal{O}^{(3)}_{\Phi Q,ii} \right)$$

EOM allow to Eliminate 3 Operators

Data Driven Approach to Choice of Basis:

⇒ Avoid Theoretical Prejudice (tree vs. loop, etc...)

⇒ Choose Operator Basis Easiest to Relate to Available Data

⇒ Keep Operators Most Directly Constrained by Existing Data

- Z-pole physics, Atomic Parity Violation . . . constrain

$$\mathcal{O}^{(1)}_{\Phi L,ij} = \Phi^\dagger (i\overleftrightarrow{D}_\mu \Phi)(\bar{L}_i \gamma^\mu L_j) \qquad \mathcal{O}^{(3)}_{\Phi L,ij} = \Phi^\dagger (i\overleftrightarrow{D}^a_\mu \Phi)(\bar{L}_i \gamma^\mu \sigma_a L_j)$$

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Z (left column) — Z, W (right column)

- Z-pole physics, Atomic Parity Violation … constrain

Z

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Z, W

- EWPD Bounds: At tree level $\alpha\Delta S = -\hat{e}^2\frac{v^2}{\Lambda^2}f_{BW} \quad \alpha\Delta T = -\hat{e}^2\frac{v^2}{2\Lambda^2}f_{\Phi,1}$

• Z-pole physics, Atomic Parity Violation … constrain

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Z (left operators) ; Z, W (right operators)

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• Bounds on FCNC Constrain the Off-Diagonal Elements of

$$\mathcal{O}_{e\Phi,ij} = (\Phi^\dagger\Phi)(\bar{L}_i\Phi e_{R_j}) \quad \mathcal{O}_{u\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\tilde{\Phi}u_{R_j}) \quad \mathcal{O}_{d\Phi,ij} = (\Phi^\dagger\Phi)(\bar{Q}_i\Phi d_{Rj})$$

$$\Rightarrow \mathcal{L}^{Hff} = g^f_{Hij}\bar{f}_{Li}f_{Rj}H \text{ with } g^f_{Hij} = -\frac{m^f_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}f_{f\Phi,ij}$$

- Operators $\mathcal{O}_W$ and $\mathcal{O}_B$ modify Triple Gauge Boson Vertex

$$\mathcal{O}_W = (D_\mu \Phi)^\dagger \hat{W}^{\mu\nu} (D_\nu \Phi) \qquad \mathcal{O}_B = (D_\mu \Phi)^\dagger \hat{B}^{\mu\nu} (D_\nu \Phi)$$

$$\mathcal{L}_{WWV} = -i g_{WWV} \left\{ g_1^V \left(W^+_{\mu\nu} W^{-\,\mu} V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \ldots \right\}$$

with

$$\Delta g_1^Z = g_1^Z - 1 = \frac{g^2 v^2}{8 c^2 \Lambda^2} f_W$$

$$\Delta \kappa_\gamma = \kappa_\gamma - 1 = \frac{g^2 v^2}{8 \Lambda^2} \left(f_W + f_B \right)$$

$$\Delta \kappa_Z = \kappa_Z - 1 = \frac{g^2 v^2}{8 c^2 \Lambda^2} \left(c^2 f_W - s^2 f_B \right)$$

and we have data on TGV so we keep them

- Using the EOM we eliminate: $\mathcal{O}_{\Phi,2}$, $\mathcal{O}_{\Phi,4}$, $\mathcal{O}_{BB}$

  and choose the basis:

$$\mathcal{O}_{GG} \;\; , \;\; \mathcal{O}_{BW} \;\; , \;\; \mathcal{O}_{WW} \;\; , \;\; \mathcal{O}_{W} \;\; , \;\; \mathcal{O}_{B} \;\; , \;\; \mathcal{O}_{\Phi,1} \;\; , \;\; \mathcal{O}_{f\Phi} \;\; , \;\; \mathcal{O}^{(1)}_{f\Phi} \;\; , \;\; \mathcal{O}^{(3)}_{f\Phi}$$

• Using the EOM we eliminate: $\mathcal{O}_{\Phi,2}$, $\mathcal{O}_{\Phi,4}$, $\mathcal{O}_{BB}$

and choose the basis:

$$\mathcal{O}_{GG} \;,\; \mathcal{O}_{BW} \;,\; \mathcal{O}_{WW} \;,\; \mathcal{O}_{W} \;,\; \mathcal{O}_{B} \;,\; \mathcal{O}_{\Phi,1} \;,\; \mathcal{O}_{f\Phi} \;,\; \mathcal{O}^{(1)}_{f\Phi} \;,\; \mathcal{O}^{(3)}_{f\Phi}$$

• Using *pre-Higgs* data most strongly constrained :

- Using the EOM we eliminate: $\mathcal{O}_{\Phi,2}$, $\mathcal{O}_{\Phi,4}$, $\mathcal{O}_{BB}$

  and choose the basis:

$$\mathcal{O}_{GG} \;,\; \mathcal{O}_{BW} \;,\; \mathcal{O}_{WW} \;,\; \mathcal{O}_{W} \;,\; \mathcal{O}_{B} \;,\; \mathcal{O}_{\Phi,1} \;,\; \mathcal{O}_{f\Phi} \;,\; \mathcal{O}^{(1)}_{f\Phi} \;,\; \mathcal{O}^{(3)}_{f\Phi}$$

- Using *pre-Higgs* data ✗ most strongly constrained :

- After Discarding the Constrained Operators ⇒ 13

  - ∗ 4 Involving Gauge Bosons: $\mathcal{O}_{GG} \;,\; \mathcal{O}_{WW} \;,\; \mathcal{O}_{W} \;,\; \mathcal{O}_{B}$

  - ∗ 9 Involving Fermions: $\mathcal{O}_{e\Phi,ii} \;,\; \mathcal{O}_{u\Phi,ii} \;,\; \mathcal{O}_{d\Phi,ii}$

    Neglecting effects of couplings to first and second generation

    Due to small statistics on ttH associate production

    effects of $\mathcal{O}_{u\Phi,33}$ reabsorbed in redefinitions of coefficients of $\mathcal{O}_{WW}$,$\mathcal{O}_{GG}$

    ⇒ two relevant fermion operators left: $\mathcal{O}_{d\Phi,33}$,$\mathcal{O}_{e\Phi,33}$

• In Summary

$$\mathcal{L}_{eff} = -\frac{\alpha_s v}{8\pi}\frac{f_g}{\Lambda^2}\mathcal{O}_{GG} + \frac{f_{WW}}{\Lambda^2}\mathcal{O}_{WW} + \frac{f_W}{\Lambda^2}\mathcal{O}_W + \frac{f_B}{\Lambda^2}\mathcal{O}_B + \frac{f_{\rm bot}}{\Lambda^2}\mathcal{O}_{d\Phi,33} + \frac{f_\tau}{\Lambda^2}\mathcal{O}_{e\Phi,33}$$

coefficients related by gauge invariance →

	hgg	$h\gamma\gamma$	$h\gamma Z$	hZZ	hW^+W^-	γW^+W^-	ZW^+W^-
$\mathcal{O}_{GG}$	✓						
$\mathcal{O}_{WW}$		✓	✓	✓	✓		
$\mathcal{O}_B$			✓	✓		✓	✓
$\mathcal{O}_W$			✓	✓	✓	✓	✓

supplemented by shifts in the Yukawa couplings of bottom and τ

• In Summary for Analysis of Higgs Data

$$\mathcal{L}_{\rm eff}^{\rm H} = g_{Hgg}\, H G^a_{\mu\nu} G^{a\mu\nu} + g_{H\gamma\gamma}\, H A_{\mu\nu} A^{\mu\nu} + g^{(1)}_{HZ\gamma}\, A_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZ\gamma}\, H A_{\mu\nu} Z^{\mu\nu}$$
$$+ g^{(1)}_{HZZ}\, Z_{\mu\nu} Z^\mu \partial^\nu H + g^{(2)}_{HZZ}\, H Z_{\mu\nu} Z^{\mu\nu} + g^{(0)}_{HZZ}\, H Z_\mu Z^\mu$$
$$+ g^{(1)}_{HWW}\, \left(W^+_{\mu\nu} W^{-\,\mu} \partial^\nu H + \text{h.c.}\right) + g^{(2)}_{HWW}\, H W^+_{\mu\nu} W^{-\,\mu\nu} + g^{(0)}_{HWW}\, H W^+_\mu W^{-\,\mu}$$
$$+ \sum_{f=\text{bot},\tau} \left(g^f_{Hff} \bar{f}_L f_R H + \text{h.c.}\right)$$

with

$$g^{(0)}_{HZZ} = M_Z^2 (\sqrt{2} G_F)^{1/2} \qquad g^{(0)}_{HWW} = M_W^2 (\sqrt{2} G_F)^{1/2}$$

$$g_{Hgg} = \frac{f_{GG} v}{\Lambda^2} \equiv -\frac{\alpha_s}{8\pi} \frac{f_g v}{\Lambda^2} \qquad g_{H\gamma\gamma} = -\left(\frac{g^2 v s^2}{2\Lambda^2}\right) \frac{f_{WW}}{2}$$

$$= \frac{s}{2c} g^{(2)}_{HZ\gamma} = \frac{s^2}{c^2} g^{(2)}_{HZZ} = \frac{s^2}{2} g^{(2)}_{HWW}$$

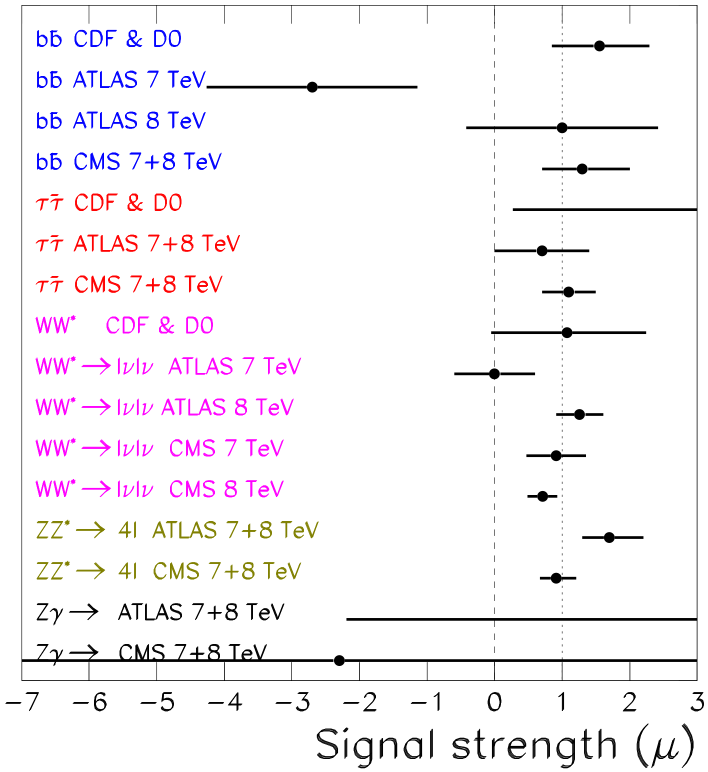
$$g^{(1)}_{HZ\gamma} = \left(\frac{g^2 v}{2\Lambda^2}\right) \frac{s(f_W - f_B)}{2c}$$

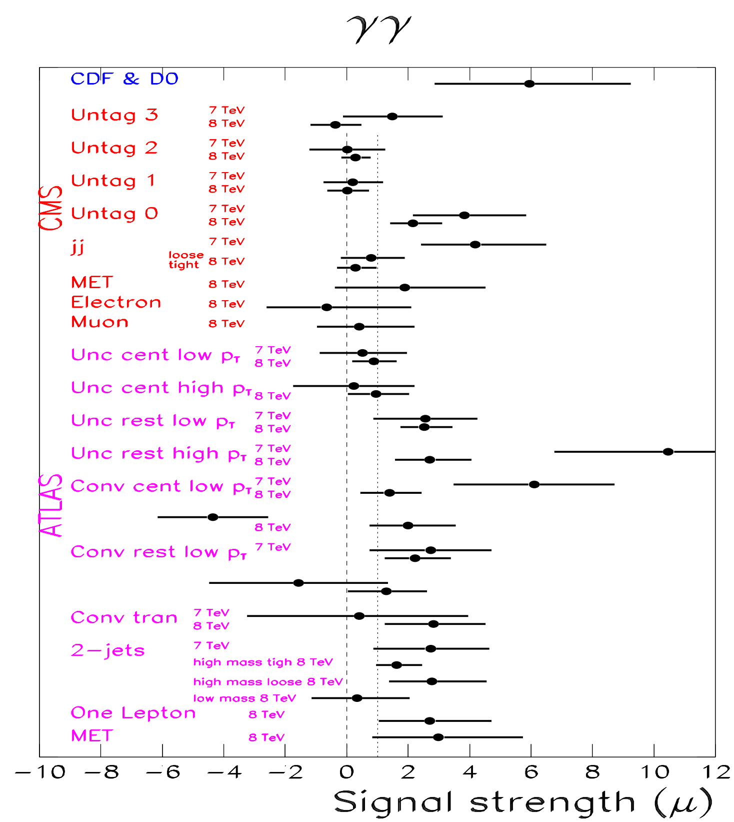
$$g^{(1)}_{HZZ} = \left(\frac{g^2 v}{2\Lambda^2}\right) \frac{c^2 f_W + s^2 f_B}{2c^2} \qquad g^{(1)}_{HWW} = \left(\frac{g^2 v}{2\Lambda^2}\right) \frac{f_W}{2}$$

$$g^f_{Hff} = -\frac{m^f}{v} + \frac{v^2}{\sqrt{2}\Lambda^2} f_f$$

Analysis of Higgs Data

- Inputs: signal strength for the different channels $\mu = \dfrac{\sigma_{obs}}{\sigma_{SM}}$





Analysis of Higgs Data

- With all the data points we construct

$$\chi^2 = \min_{\xi_{pull}} \sum_j \frac{(\mu_j - \mu_j^{\exp})^2}{\sigma_j^2} + \sum_{pull} \left(\frac{\xi_{pull}}{\sigma_{pull}} \right)^2$$

* Where

$$\mu_F = \frac{\epsilon^F_{gg}\sigma^{ano}_{gg}(1+\xi_g)+\epsilon^F_{VBF}\sigma^{ano}_{VBF}(1+\xi_{VBF})+\epsilon^F_{WH}\sigma^{ano}_{WH}(1+\xi_{VH})+\epsilon^F_{ZH}\sigma^{ano}_{ZH}(1+\xi_{VH})+\epsilon^F_{t\bar{t}H}\sigma^{ano}_{t\bar{t}H}}{\epsilon^F_{gg}\sigma^{SM}_{gg}+\epsilon^F_{VBF}\sigma^{SM}_{VBF}+\epsilon^F_{WH}\sigma^{SM}_{WH}+\epsilon^F_{ZH}\sigma^{SM}_{ZH}+\epsilon^F_{t\bar{t}H}\sigma^{SM}_{t\bar{t}H}} \otimes \frac{\text{Br}^{ano}[h\to F]}{\text{Br}^{SM}[h\to F]}$$

$\ast$ Production factors ϵ^F_{Prod} are given by the collaborations

$\ast$ σ_i^{SM} and Γ_j^{SM} are known to one or two–loops

$\ast$ For anomalous contributions we scale the higher-order (h-o) effects as in SM :

$$\sigma_Y^{ano} = \left.\frac{\sigma_Y^{ano}}{\sigma_Y^{SM}}\right|_{tree} \left.\sigma_Y^{SM}\right|_{h-o}$$

$$\Gamma^{ano}(h \to X) = \left.\frac{\Gamma^{ano}(h \to X)}{\Gamma^{SM}(h \to X)}\right|_{tree} \left.\Gamma^{SM}(h \to X)\right|_{h-o}$$

- Also combined with

TGV Bounds: f_W, f_B

$$\mathcal{L}_{WWV} = -ig_{WWV}\left\{ g_1^V \left(W^+_{\mu\nu} W^{-\,\mu} V^\nu - W^+_\mu V_\nu W^{-\,\mu\nu} \right) + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \ldots \right\}$$

with

$$\begin{aligned} \Delta g_1^Z &= g_1^Z - 1 = \frac{g^2 v^2}{8c^2\Lambda^2} f_W \\ \Delta\kappa_\gamma &= \kappa_\gamma - 1 = \frac{g^2 v^2}{8\Lambda^2}\left(f_W + f_B\right) \\ \Delta\kappa_Z &= \kappa_Z - 1 = \frac{g^2 v^2}{8c^2\Lambda^2}\left(c^2 f_W - s^2 f_B\right) \end{aligned}$$

(from LEPEWWG for this scenario)

$$\kappa_\gamma = 0.984^{+0.049}_{-0.049} \quad g_1^Z = 1.004^{+0.024}_{-0.025} \quad \text{with} \quad \rho = 0.11$$

- Also combined with

  EWPD: (with f_{WW}, f_W, f_B at 1-loop) [Hagiwara,et al; Alam, Dawson, Szalapski]

$$\alpha\Delta S = \frac{1}{6}\frac{e^2}{16\pi^2}\Bigg\{3(f_W+f_B)\frac{m_H^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right) + + 2\left[(5c^2-2)f_W-(5c^2-3)f_B\right]\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right)$$
$$-\left[(22c^2-1)f_W-(30c^2+1)f_B\right]\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_Z^2}\right) - 24c^2 f_{WW}\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right)\Bigg\},$$

$$\alpha\Delta T = \frac{3}{4c^2}\frac{e^2}{16\pi^2}\Bigg\{f_B\frac{m_H^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right) + (c^2 f_W+f_B)\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right)$$
$$+\left[2c^2 f_W+(3c^2-1)f_B\right]\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_Z^2}\right)\Bigg\},$$

$$\alpha\Delta U = -\frac{1}{3}\frac{e^2 s^2}{16\pi^2}\Bigg\{(-4f_W+5f_B)\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_H^2}\right) + (2f_W-5f_B)\frac{m_Z^2}{\Lambda^2}\log\left(\frac{\Lambda^2}{m_Z^2}\right)\Bigg\}$$

More model-dependent: tree vs one-loop?, finite part?, Λ does not factorize

- Also combined with

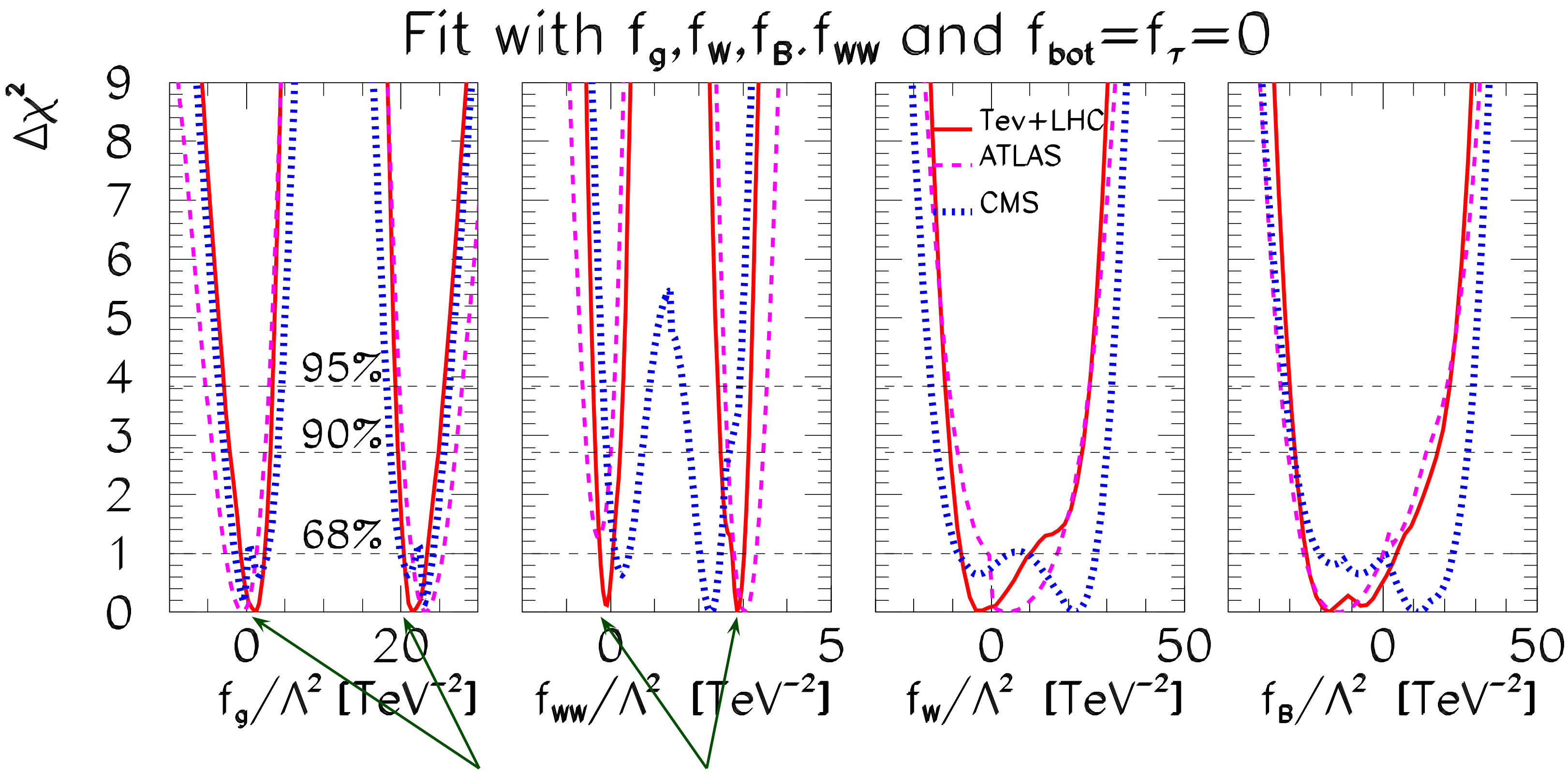
EWPD: (with f_{WW}, f_W, f_B at 1-loop) [Hagiwara,et al; Alam, Dawson, Szalapski]

$$\Delta S = 0.00 \pm 0.10 \qquad \Delta T = 0.02 \pm 0.11 \qquad \Delta U = 0.03 \pm 0.09$$

$$\rho = \begin{pmatrix} 1 & 0.89 & -0.55 \\ 0.89 & 1 & -0.8 \\ -0.55 & -0.8 & 1 \end{pmatrix}$$

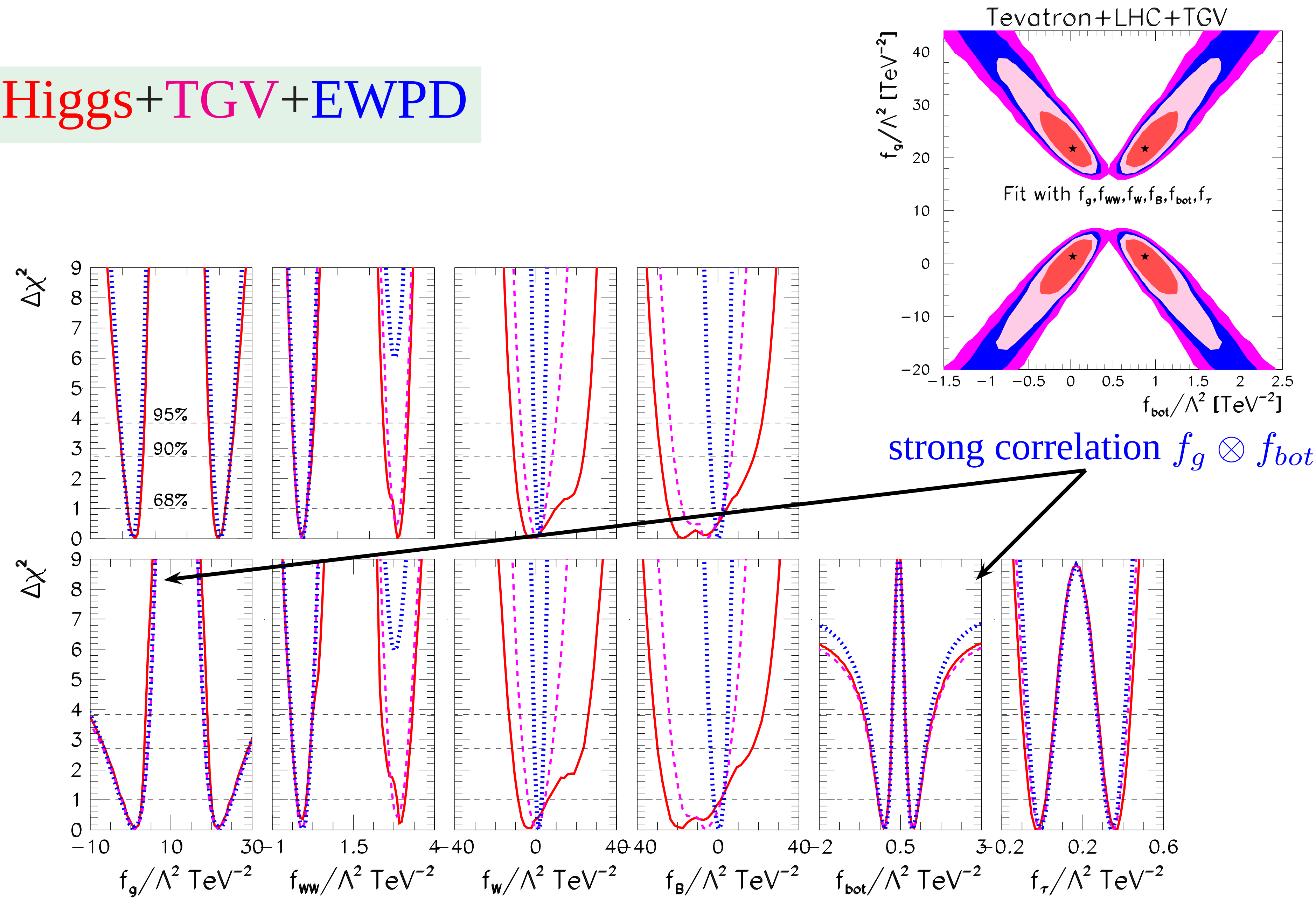
Results

- First Scenario: f_g , f_{WW} , f_W , f_B , $f_{bot} = 0,$, $f_\tau = 0$
- Second Scenario: f_g , f_{WW} , f_W , f_B , f_{bot} , f_τ



Interference with SM contribution leads to (near) degeneracy

Higgs+TGV+EWPD



Best Fit and 90% CL ranges

- From Tevatron+LHC+TGV

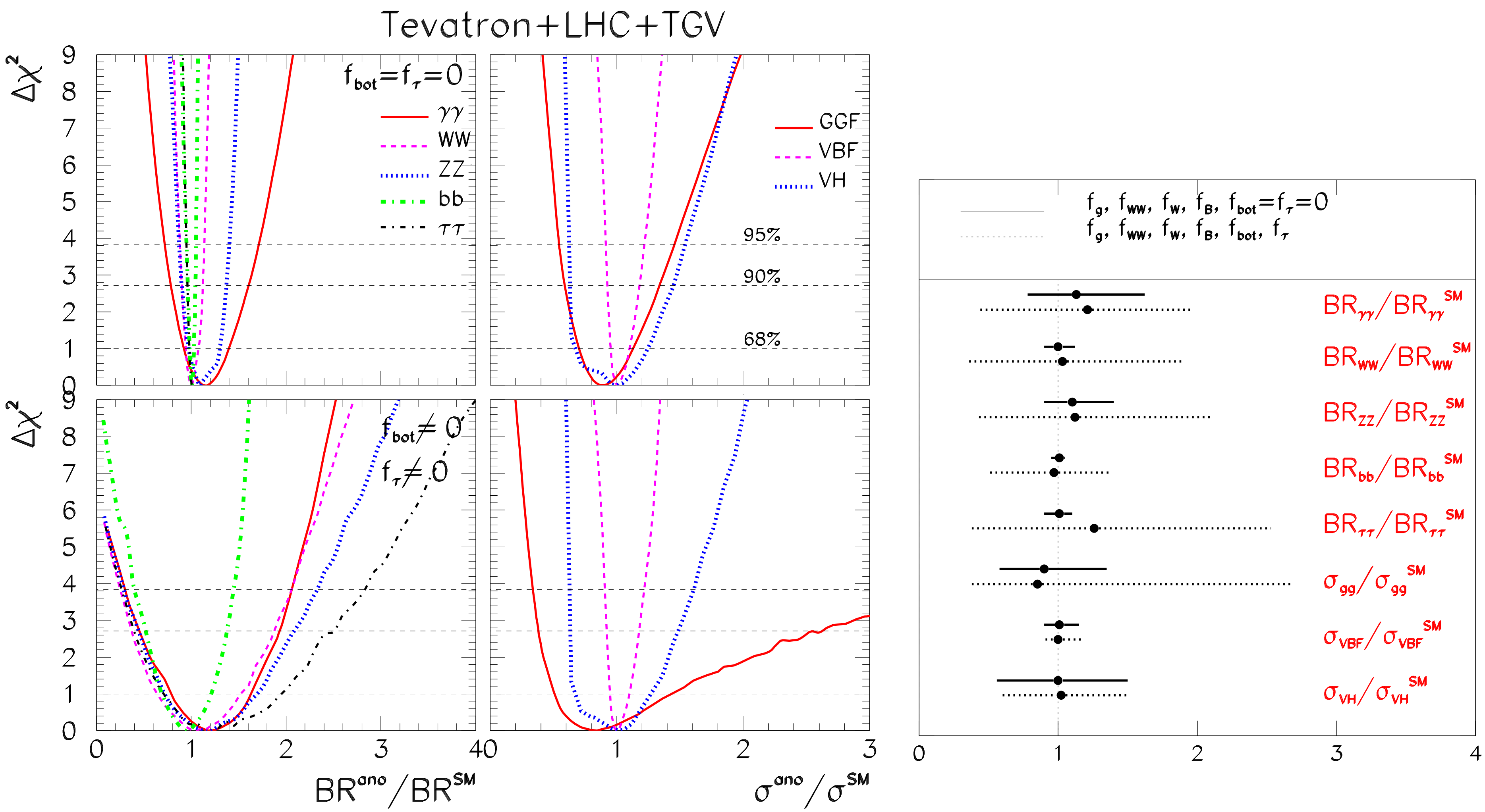
	Fit with $f_{bot} = f_\tau = 0$		Fit with f_{bot} and f_τ	
	Best fit	90% CL allowed range	Best fit	90% CL allowed range
f_g/Λ^2 (TeV^{-2})	0.64, 22.1	$[-1.8, 2.7] \cup [20, 25]$	0.71, 22.0	$[-6.2, 4.4] \cup [18, 29]$
f_{WW}/Λ^2 (TeV^{-2})	-0.083	$[-0.35, 0.15] \cup [2.6, 3.05]$	-0.095	$[-0.39, 0.19]$
f_W/Λ^2 (TeV^{-2})	0.35	$[-6.2, 8.4]$	-0.46	$[-7.1, 6.5]$
f_B/Λ^2 (TeV^{-2})	-5.9	$[-22, 6.7]$	-0.46	$[-7.1, 6.5]$
f_{bot}/Λ^2 (TeV^{-2})	—	—	0.01, 0.89	$[-0.34, 0.23] \cup [0.67, 1.2]$
f_τ/Λ^2 (TeV^{-2})	—	—	-0.01, 0.34	$[-0.07, 0.05] \cup [0.28, 0.40]$

SM predictions within 68% CL range for all couplings

Unitarity Violation in $V_L V_L$ scattering due to $f_{W,B}$ at 90%CL $\Rightarrow$ $\Lambda \lesssim 2$ TeV

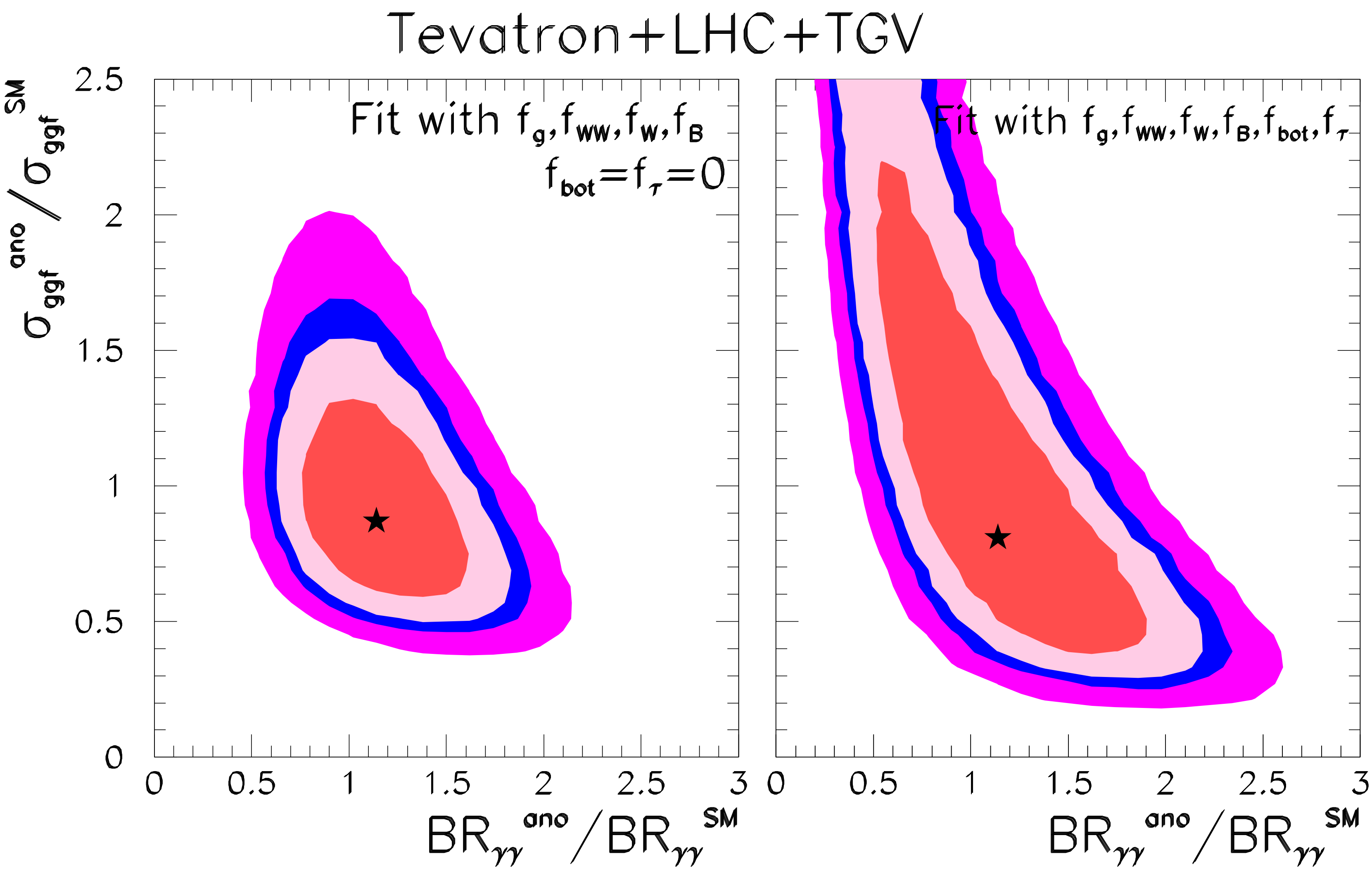
Cross Sections and Branching Ratios

- From full $\chi^2(f_i)$ one can derive allowed ranges for σ_i^{ano} and Γ_j^{ano}



90% CL ranges

Interesting Correlations



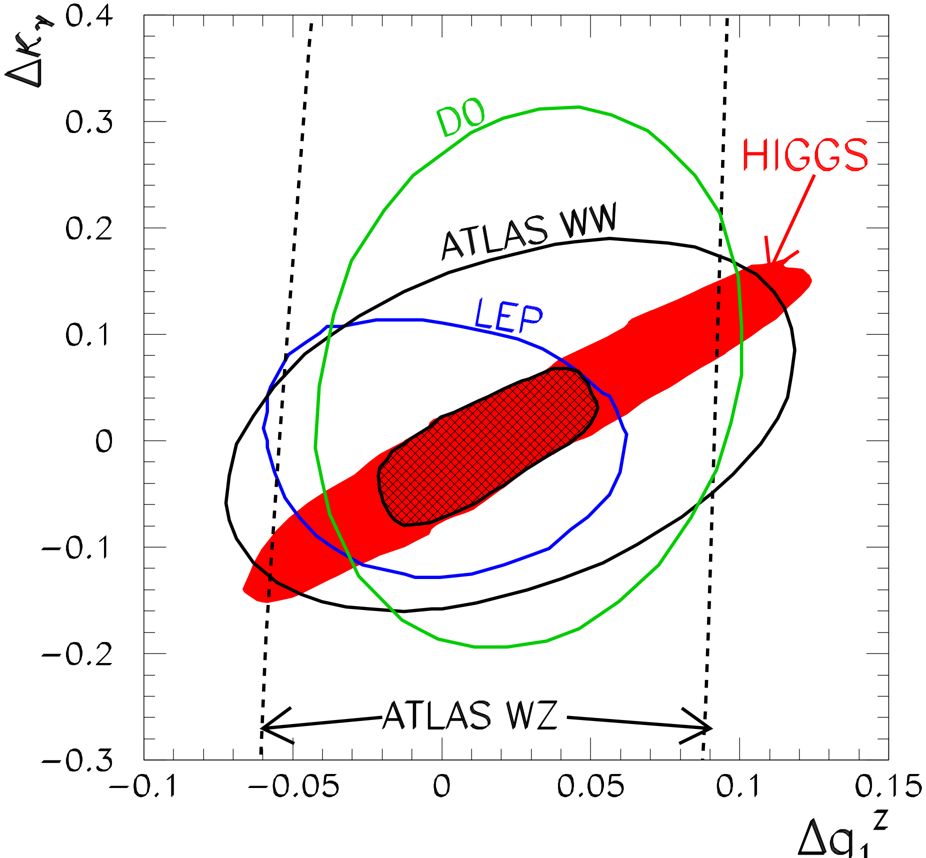
Due to diphoton channel

Constraints on TGV from Higgs Results

- Gauge Invariance $\Rightarrow$ TGV and Higgs couplings are related: $\mathcal{O}_W, \mathcal{O}_B$
- Analysis of Higgs results marginalizing over $f_g, f_{WW}, f_{bot}, f_\tau$

$\Rightarrow$ bounds on $f_W \otimes f_B \equiv \Delta\kappa_\gamma \otimes \Delta g_1^Z$

95% CL



$$\Delta g_1^Z = g_1^Z - 1 = \frac{g^2 v^2}{8c^2\Lambda^2} f_W$$
$$\Delta\kappa_\gamma = \kappa_\gamma - 1 = \frac{g^2 v^2}{8\Lambda^2}\left(f_W + f_B\right)$$
$$\Delta\kappa_Z = \kappa_Z - 1 = \frac{g^2 v^2}{8c^2\Lambda^2}\left(c^2 f_W - s^2 f_B\right)$$

Comparison to constraints from TGV analysis in LEP, Tevatron and ATLAS

What Next?

- To combine full Higgs and TGV 7+8 TeV data in this framework

- To exploit the different Lorentz structure of the anomalous operators

  Analysis of full kinematical distributions not only signal strengths

  Only possible within the collaborations

- To study the most promising signals for LHC-14 still allowed

  $H \to Z\gamma$? $H \to f_i \bar{f}_j$?

$\ldots$

Concluding Remarks

• After 5 decades we have finally observed a state which seems the one responsible for EW SSB

• So far all observations consistent with state having quantum numbers of SM Higgs Boson

$\Rightarrow$ Consistent to parametrize NP in scalar sector as $SU(2) \times U(1)$ GI $\mathcal{L}_{eff}$

• Freedom of choice of basis of operators for $\mathcal{L}_{eff}$

$\Rightarrow$ In absence of theoretical prejudice it pays to be **data driven**

• This framework consistently accounts for relations between Higgs couplings and GB self-couplings due to GI

$\Rightarrow$ interesting complementarity in experimental searches