

# Higgs and Electroweak Physics

## [theory status]

**Alexander Belyaev**

Southampton University & Rutherford Appleton LAB

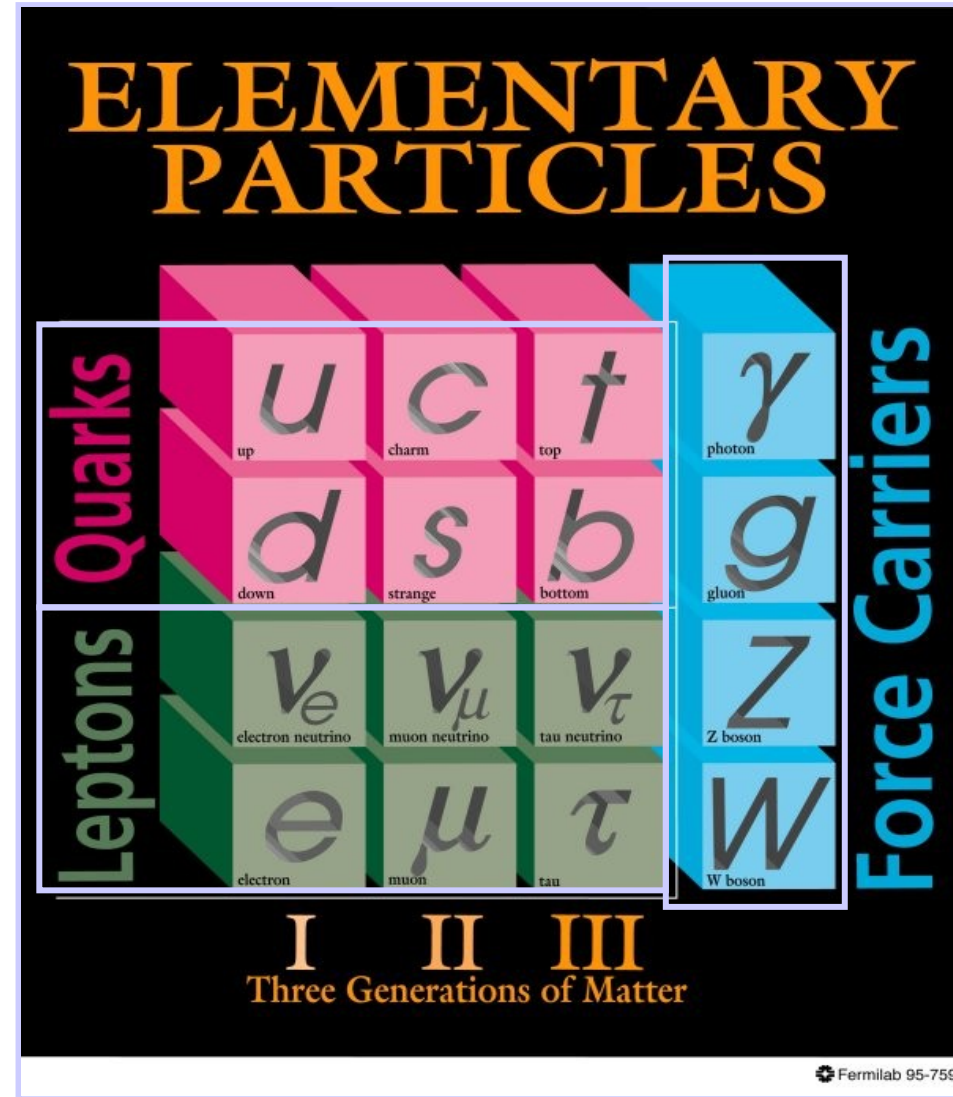


# Outline

- **Introduction**
  - ➔ *Higgs mechanism*
  - ➔ *Theory constraints*
  - ➔ *Electroweak Precision tests*
- **SM Higgs boson search**
  - ➔ *Production at the Tevatron and latest Limits*
  - ➔ *Production at the LHC and combined limits*
  - ➔ *Projections for Higgs search at the LHC*
  - ➔ *Prospects for Higgs coupling measurement*
  - ➔ *Diffraction Higgs production at the LHC*
- **EWBSB beyond the SM and its signatures**
- **Conclusions**

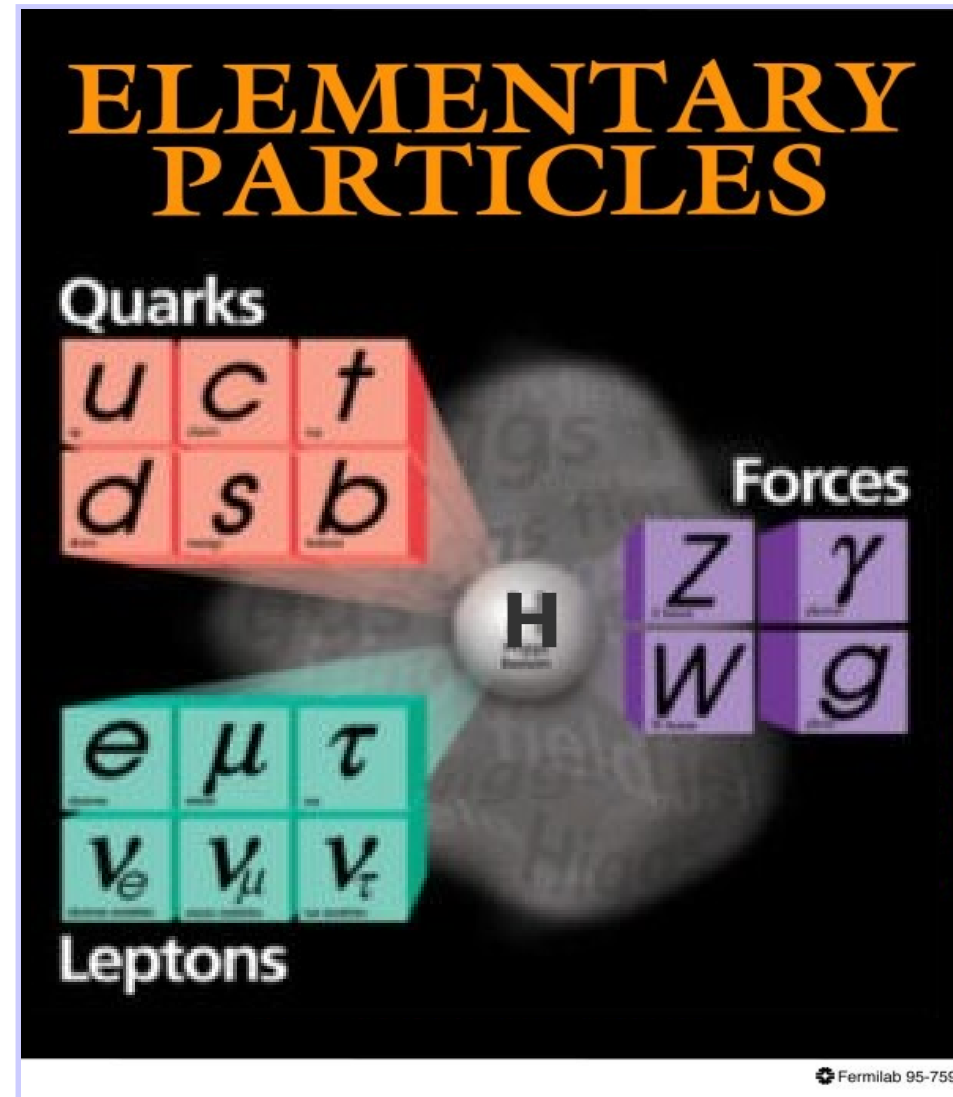
# Status of the Standard Model

- Based on  $SU(3) \times SU(2)_L \times U(1)_Y$  gauge symmetry spontaneously broken down to  $SU(3) \times U(1)_e$ :
- Matter: 3 generations of quarks and leptons



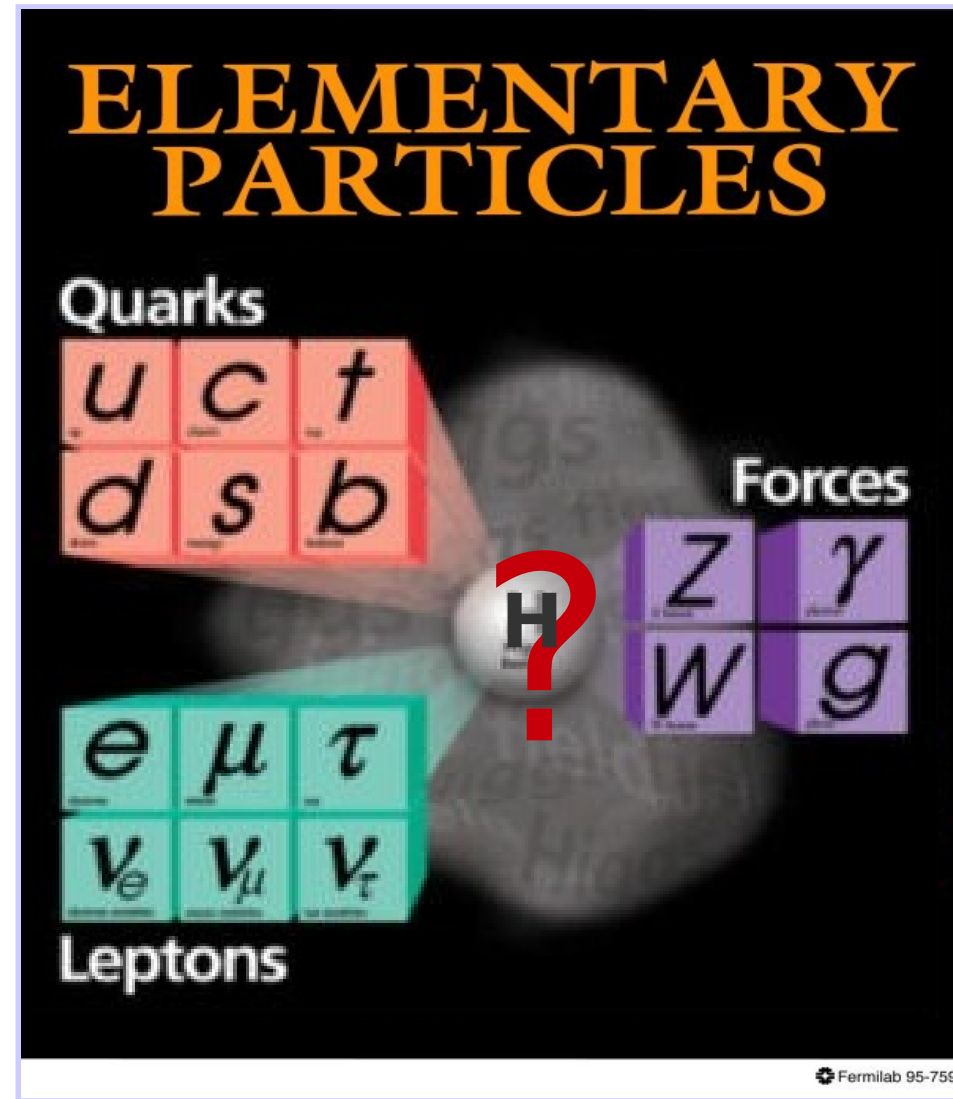
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  - *one higgs doublet, interacts with all fields*
  - *develops condensate*
  - *W, Z bosons, lepton and quarks and Higgs field itself acquires mass*



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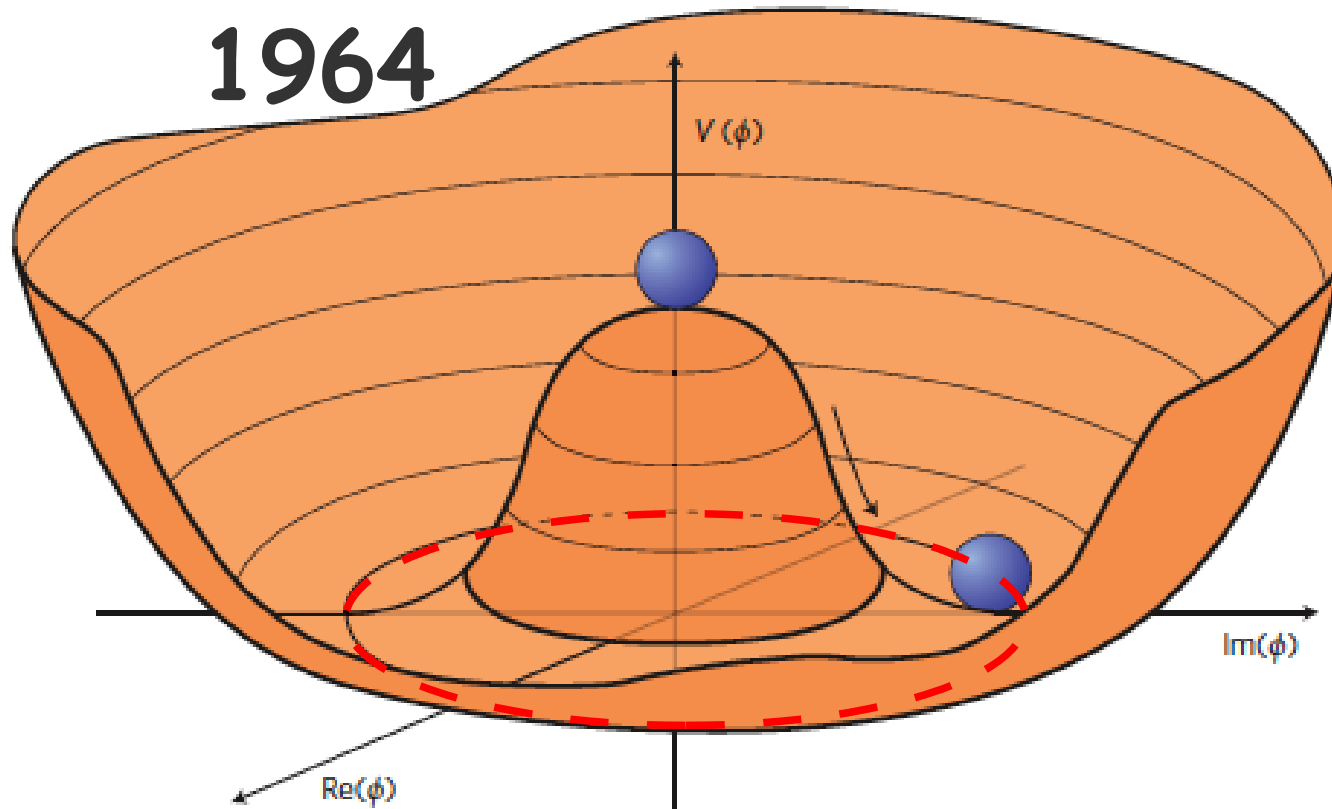
**Higgs boson is not found yet and is the most wanted particle!  
The mechanism responsible for EWSB symmetry remains unknown!**

# Theory of Electroweak Interactions

- **Status:** per-mil precision measurements confirm  $SU(2)_L \times U(1)_Y$  gauge structure
- **Unbroken Yang-Mills theory** -> vector bosons are massless.
- **Eventually it is not the case!** Explicit introduction of the massive gauge bosons breaks gauge invariance.
- **In general, there are serious problems in any Lorentz-invariant theory of massive vector bosons, unless those particles are Yang-Mills bosons and the gauge symmetry is spontaneously broken** [Nambu; Higgs; Englert, Brout; Guralnik, Hagen, Kibble].  
This is what we observe!
- **What is the mechanism of  $SU(2)_L \times U(1)_Y$  breaking?**  
 $SU(2)_L \times U(1)_Y$  does not break its own symmetry  
- couplings are weak



# Spontaneous EWSB is SM



Brout



Englert



Guralnik



Hagen



Higgs



Kibble



Nambu

# Higgs mechanism

add one scalar doublet  $\varphi$  with  $I = \frac{1}{2}$ ,  $Y = +\frac{1}{2}$

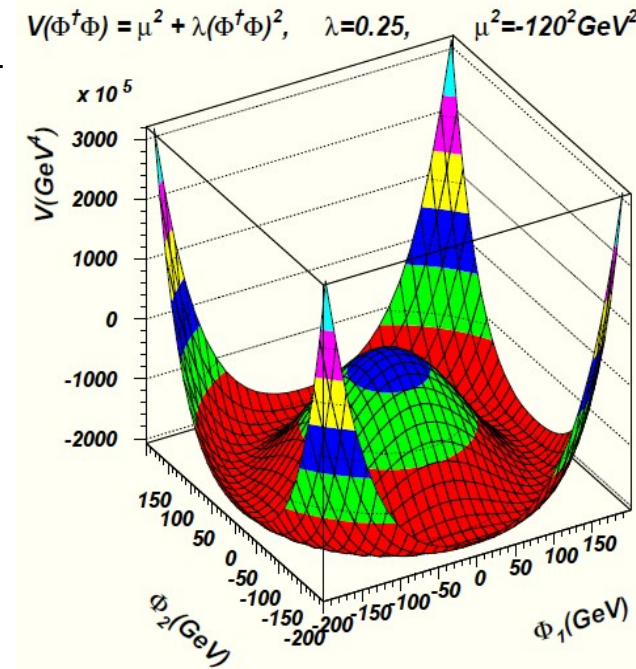
$$\mathcal{L} = |D_\mu \varphi|^2 - V(|\varphi|) - \frac{1}{4} (F_{\mu\nu}^a)^2 - \frac{1}{4} (G_{\mu\nu}^a)^2$$

+ couplings to quarks and leptons

where  $\langle \varphi \rangle \neq 0$

e.g.  $V(|\varphi|) = \mu^2 |\varphi|^2 + \lambda |\varphi|^4$

$$\mu^2 < 0$$





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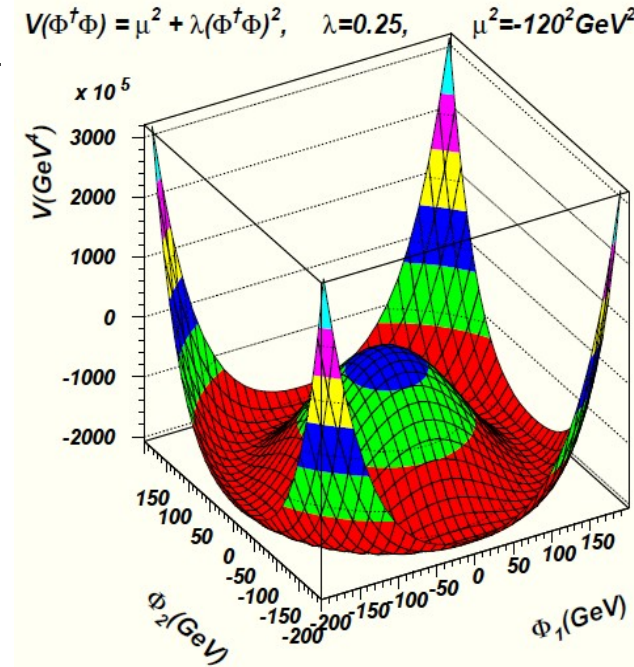
e.g.  $V(|\varphi|) = \mu^2 |\varphi|^2 + \lambda |\varphi|^4$   $\mu^2 < 0$

the field  $\varphi$  has the general structure

$$\varphi(x) = \begin{pmatrix} \pi^+(x) \\ (v + h(x) + i\pi^0(x))/\sqrt{2} \end{pmatrix}$$

which be written as (“polar decomposition”)

$$\varphi(x) = \exp\left(i \frac{\pi^a(x) \tau^a}{v}\right) \begin{pmatrix} 0 \\ (v + h(x))/\sqrt{2} \end{pmatrix}$$



$\pi^\pm$ ,  $\pi^0$  are **Goldstone bosons**  
 In the theory with **global symmetry**, they are **massless**.  
 In the theory with **gauge symmetry**, they are **gauge degrees of freedom**, and **become part of W, Z**

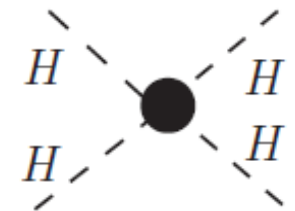
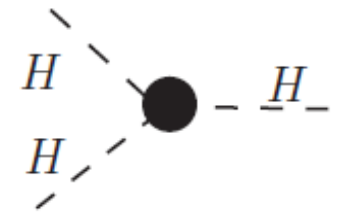
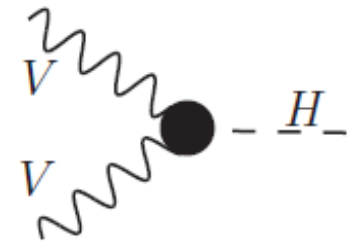
# Higgs mechanism

The choice of  $\langle \varphi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

with  $v = \sqrt{\frac{-\mu^2}{\lambda}}$  breaks the symmetry

$$\mathcal{L}_{\text{scalar}} = \frac{g^2 v^2}{4} W_{\mu}^+ W^{-\mu} + \frac{1}{2} \frac{g^2 v^2}{4 \cos^2 \theta_W} Z_{\mu} Z^{\mu}$$

$$-\frac{1}{2} (-2\mu^2) H^2 + \frac{\mu^2}{v} H^3 + \frac{\mu^2}{4v^2} H^4 + \dots$$

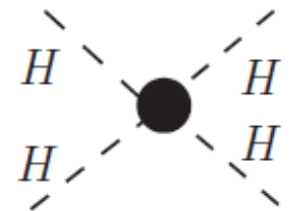
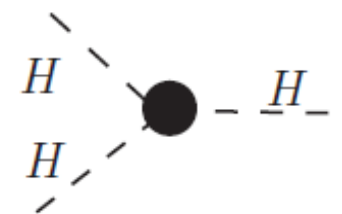
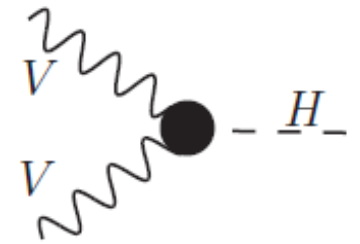


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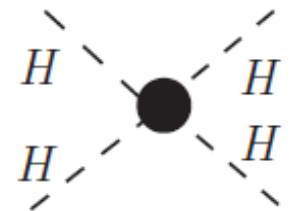
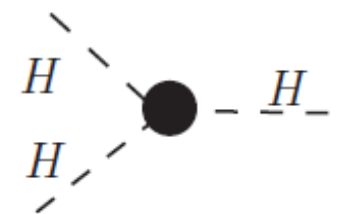
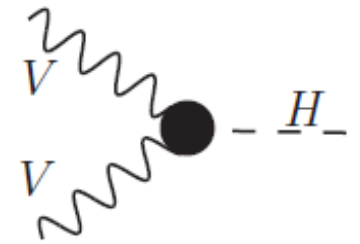


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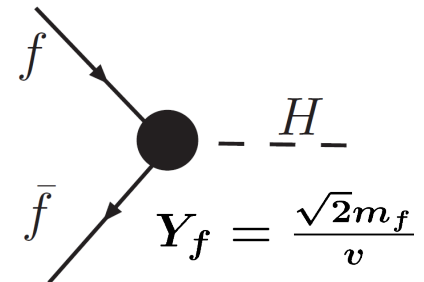
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$$\mathcal{L}_{Yukawa} = -Y_u \bar{Q}_L \Phi^c u_R - Y_d \bar{Q}_L \Phi d_R - Y_\ell \bar{L}_L \Phi l_R + h.c.$$

generates fermion masses  $m_f = Y_f \frac{v}{\sqrt{2}}$

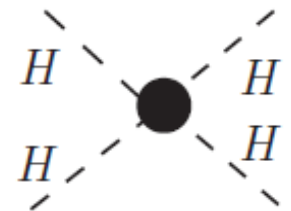
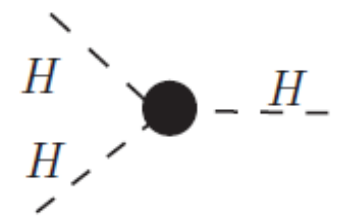
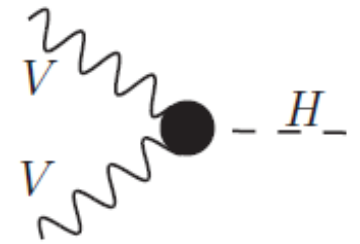


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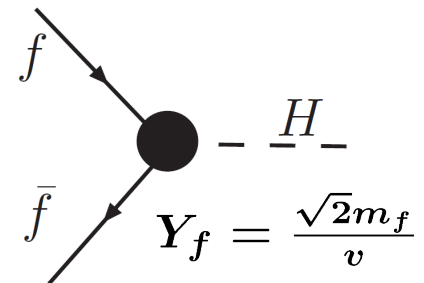
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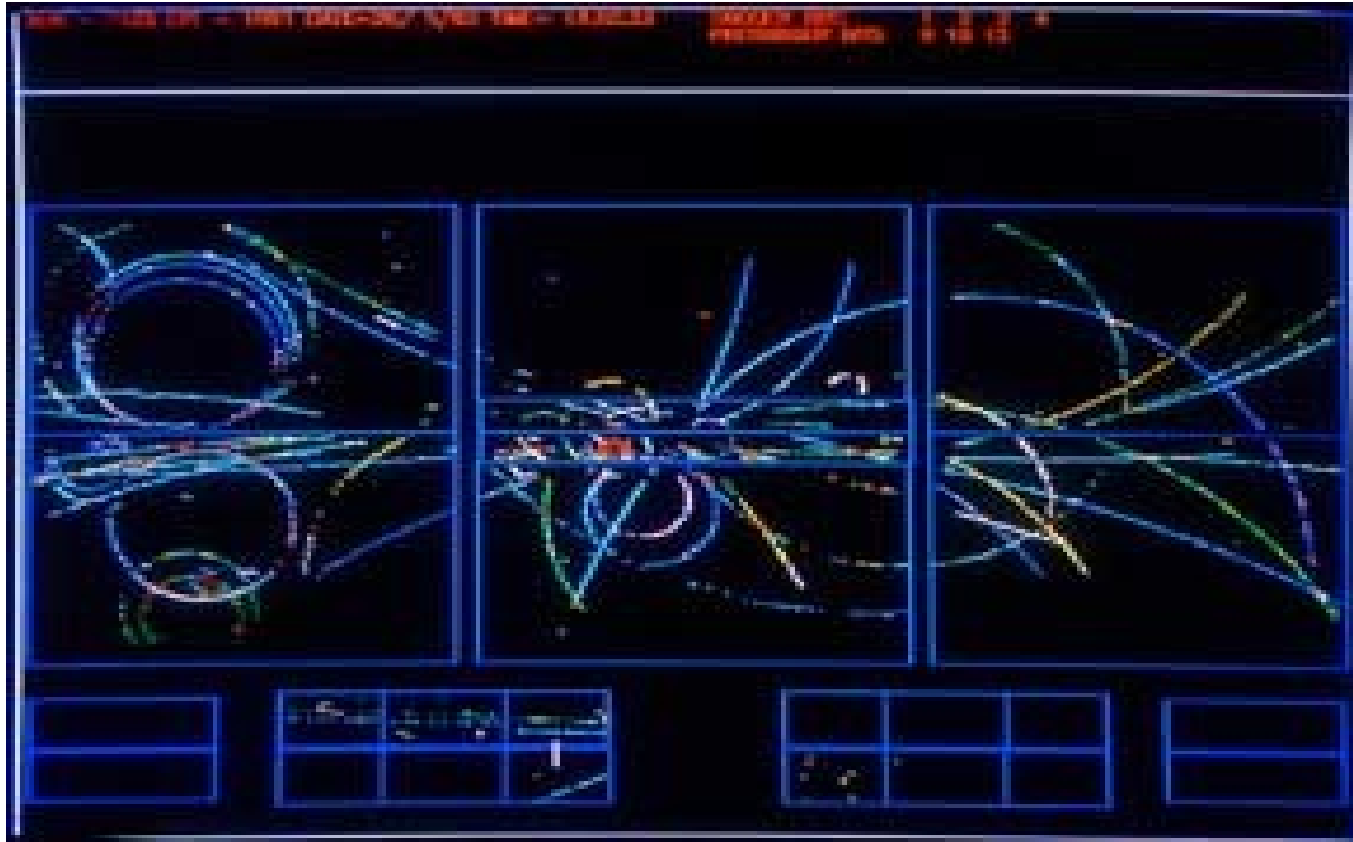


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generates fermion masses  $m_f = Y_f \frac{v}{\sqrt{2}}$



# 1983: Discovery of W- and Z- bosons at by UA1 and UA2 at SPS



Hunting for the Higgs boson started!



# Hunting for the Higgs

## The Higgs Hunter's Guide

**John F. Gunion**, *University of California, Davis*  
**Howard E. Haber**, *University of California, Santa Cruz*  
**Gordon Kane**, *University of Michigan*  
**Sally Dawson**, *Brookhaven National Laboratory*

*Frontiers in Physics Series (Volume No. 80)*

**The Higgs Hunter's Guide** is a definitive and comprehensive guide to the physics of Higgs bosons. A complete and pedagogical discussion of the properties of the Higgs boson, predicted by the Standard Model of particle physics, is presented. The appropriate techniques and experiments for discovering the Higgs boson, whatever its mass, and for exploring its properties, or showing that it does not exist, are examined in detail. Methods for studying the interactions of longitudinal  $W$  bosons in the  $TeV$  region are also reviewed. Models with non-minimal Higgs sectors are explored at length. In particular, the extended Higgs sectors required by recent theoretical approaches which go beyond the Standard Model, including supersymmetry and superstring-inspired models, and the extent to which these Higgs sectors can be probed by accelerators now in existence or being planned, are discussed.

This book is intended for practicing particle physicists, both theoretical and experimental, from advanced graduate students to active researchers in the field.

### About the Authors:

**John F. Gunion** is Professor of Physics at the University of California, Davis. He is a Fellow of the American Physical Society and has held visiting positions at the Stanford Linear Accelerator Center and the Institute for Theoretical Physics at the University of California, Santa Barbara. **Howard E. Haber** is Associate Professor of Physics at the University of California, Santa Cruz. He is also Divisional Associate Editor for *Physical Review Letters*, and is a frequent visitor at the Stanford Linear Accelerator Center Theory Group. **Gordon Kane** is Professor of Physics at the University of Michigan and is currently on the Executive Committee of the User's Organization of the SSC and on the Scientific Policy Committee of the Stanford Linear Accelerator Center. **Sally Dawson** is a member of the Theoretical Physics staff at Brookhaven National Laboratory. All have contributed to a wide range of topics in the theory of elementary particle physics, and have been active in organizing and contributing to theoretical planning for future accelerator facilities.

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Frontiers in Physics  
Lecture Note Series



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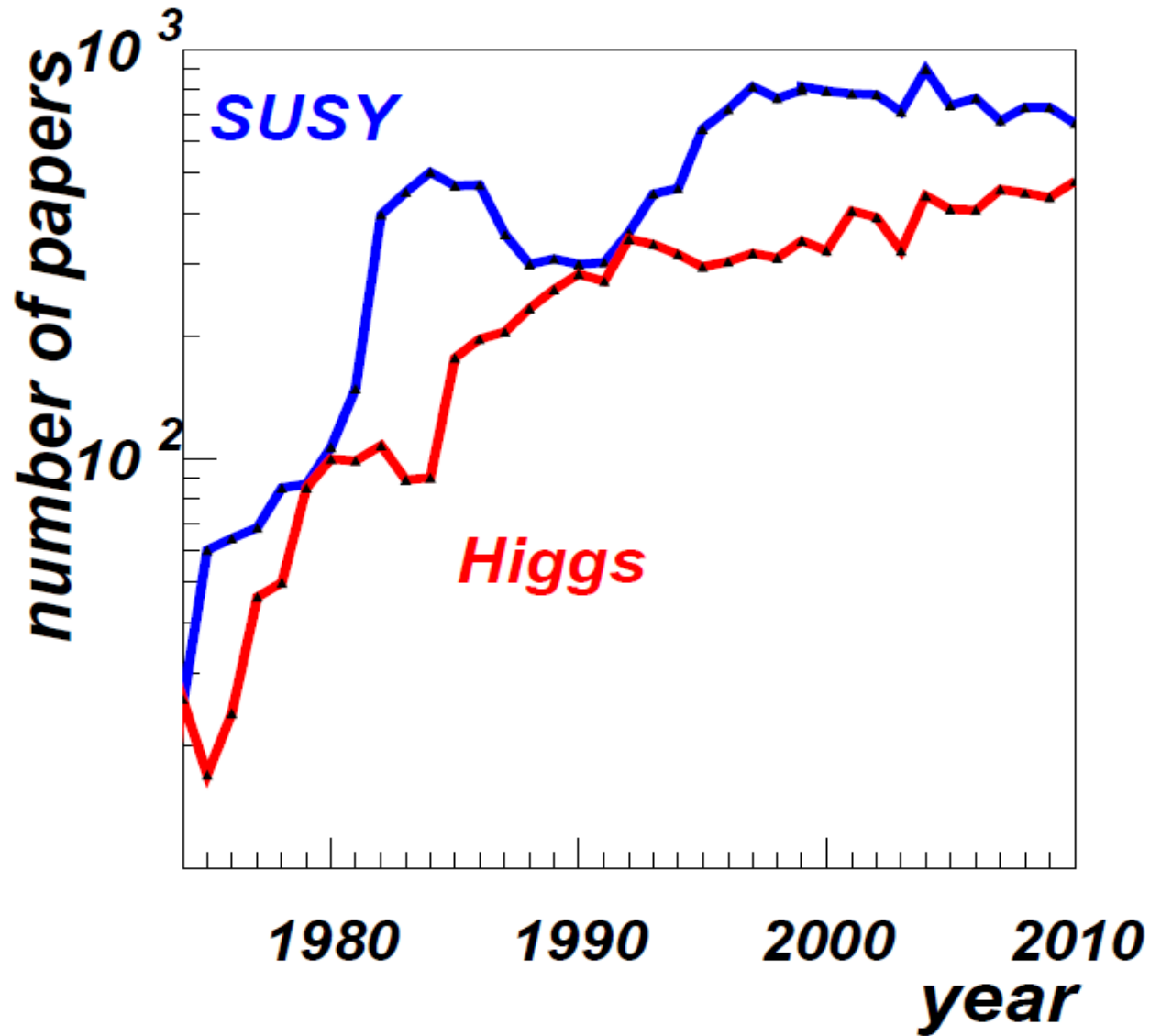
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FRONTIERS IN PHYSICS

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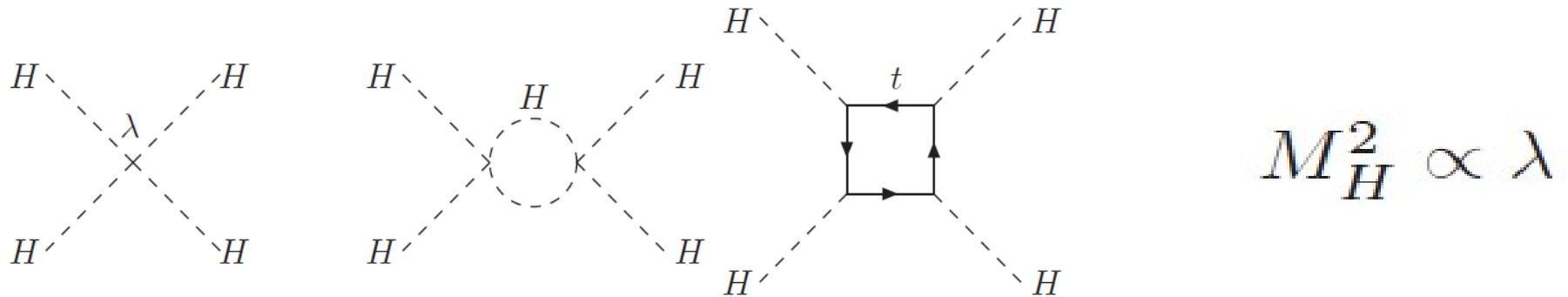
**John F. Gunion**  
**Howard E. Haber**  
**Gordon Kane**  
**Sally Dawson**

# # of Papers on Higgs boson



# Theoretical constraints

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2} \left[ \lambda^2 + \lambda y_t^2 - y_t^4 + \frac{1}{16} (2g^4 + (g^2 + g'^2)^2) \right]$$



**Large  $\lambda$ :**  $\lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\pi^2} \log\left(\frac{Q^2}{v^2}\right)}$  **from**  $\lambda(\Lambda) < \infty \Rightarrow M_H^2 \leq \frac{8\pi^2 v^2}{3 \log\left(\frac{\Lambda^2}{v^2}\right)}$   
[triviality bound]

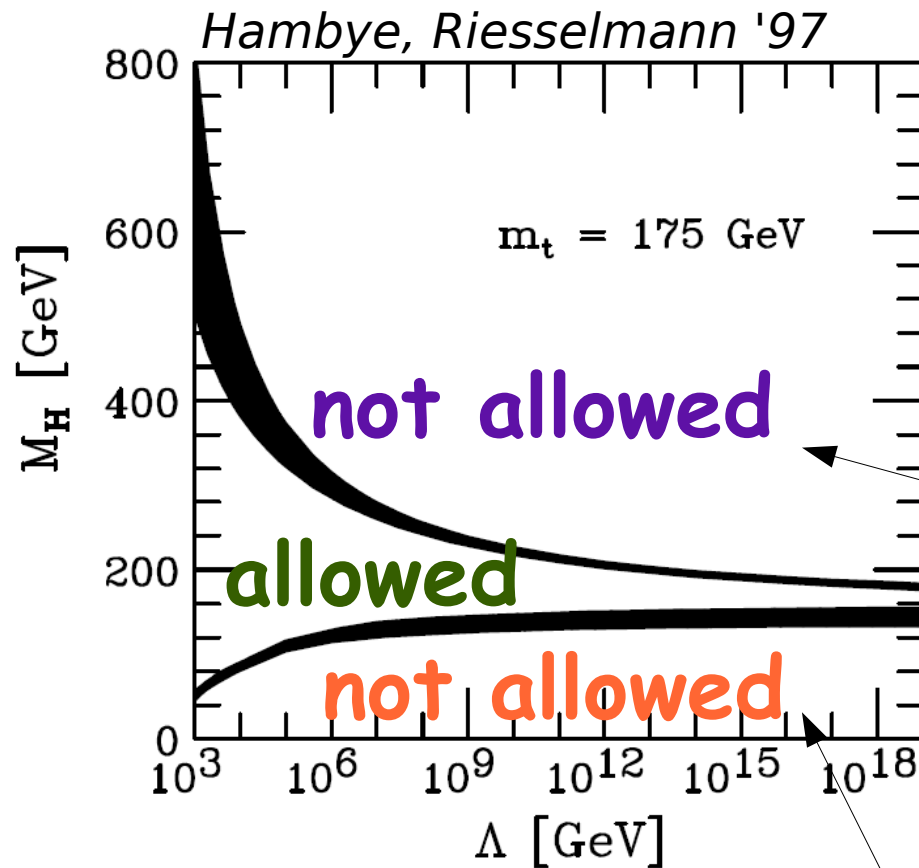
**Small  $\lambda$ :**  $\lambda(Q^2) = \lambda(v^2) \frac{3}{8\pi^2} \left[ -y_t^4 + \frac{1}{16} (2g^4 + (g^2 + g'^2)^2) \right] \log\left(\frac{Q^2}{v^2}\right)$

**from**  $\lambda(\Lambda) > 0 \Rightarrow M_H^2 > \frac{v^2}{4\pi^2} \left[ -y_t^4 + \frac{1}{16} (2g^4 + (g^2 + g'^2)^2) \right] \log\left(\frac{\Lambda^2}{v^2}\right)$   
[vacuum stability bound]



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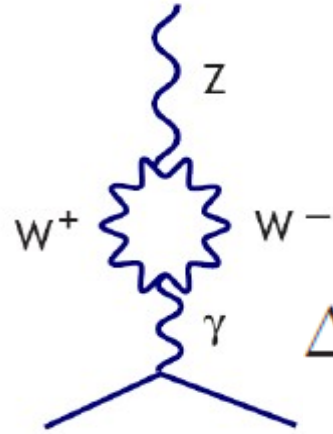
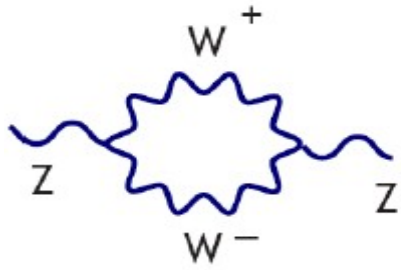
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# Electroweak Precision Fits

The level of agreement requires taking into account a-weak radiative corrections



$$M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi\alpha}{\sqrt{2}G_F} (1 + \Delta r)$$

$$\Delta r_{1\text{-loop}} = \Delta\alpha - \frac{c_w^2}{s_w^2} \Delta\rho + \Delta r_{\text{rem}}(M_H^{\text{SM}})$$

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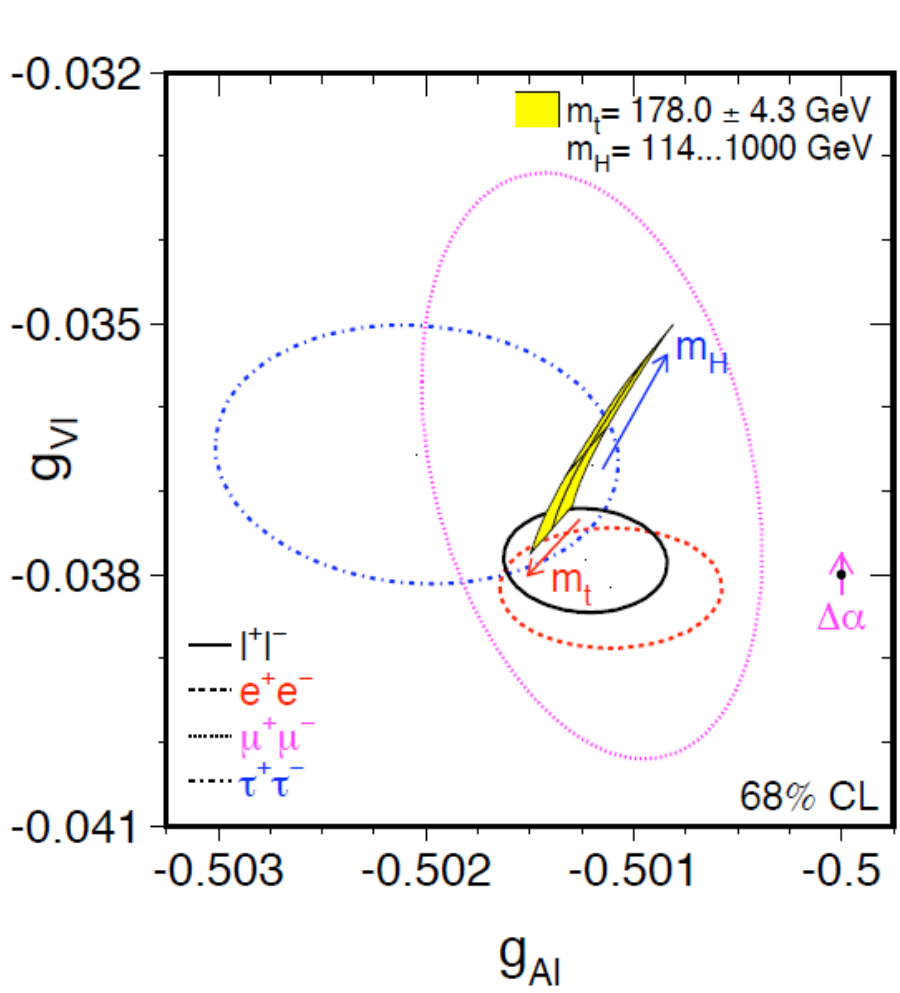
$$\Delta\rho = \frac{\Sigma^Z(0)}{M_Z^2} - \frac{\Sigma^W(0)}{M_W^2} \sim m_t^2$$

$$\Delta r_{\text{rem}} \sim \log(M_H^{\text{SM}}/M_W)$$

**Sensitivity to the top quark mass >> sensitivity to Higgs mass!**



# Electroweak Precision Fits

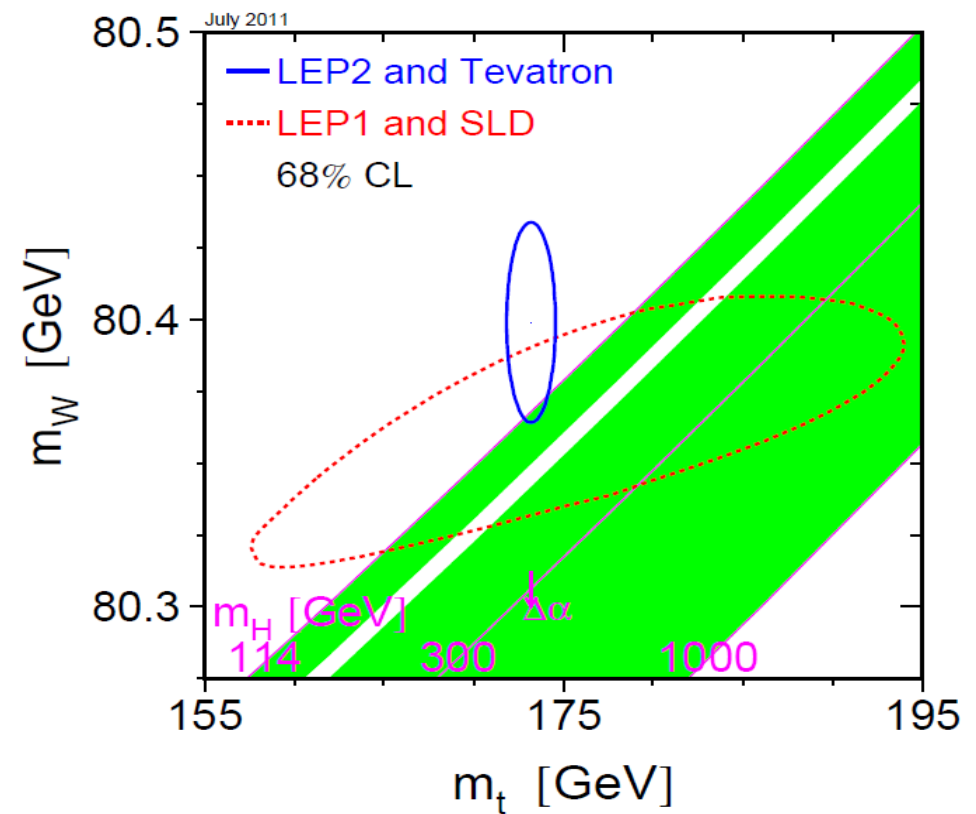
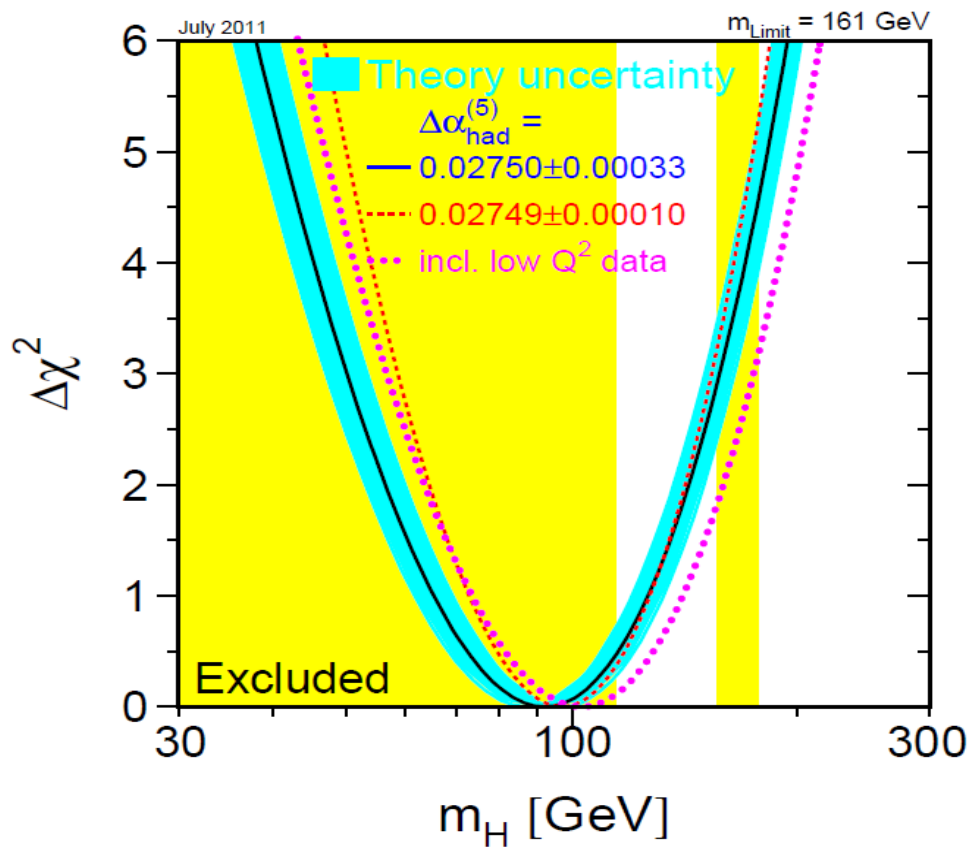


		Measurement	Fit	$ \sigma^{\text{meas}} - \sigma^{\text{fit}}  / \sigma^{\text{meas}}$
Hadronic vacuum polarization	$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	$0.02750 \pm 0.00033$	0.02759	0.0003
Z Mass	$m_Z [\text{GeV}]$	$91.1875 \pm 0.0021$	91.1874	0.0001
Z Width	$\Gamma_Z [\text{GeV}]$	$2.4952 \pm 0.0023$	2.4959	0.0007
Had. Pole Cross Section	$\sigma_{\text{had}}^0 [\text{nb}]$	$41.540 \pm 0.037$	41.478	0.062
	$R_f$	$20.767 \pm 0.025$	20.742	0.025
Lepton Asymmetries	$A_{\text{fb}}^{0,l}$	$0.01714 \pm 0.00095$	0.01646	0.0068
	$A_l(P_\tau)$	$0.1465 \pm 0.0032$	0.1482	0.0167
Left/Right Asymmetries	$R_b$	$0.21629 \pm 0.00066$	0.21579	0.0005
Forw./Backw. Asymmetries	$R_c$	$0.1721 \pm 0.0030$	0.1722	0.0001
Ratios	$A_{\text{fb}}^{0,b}$	$0.0992 \pm 0.0016$	0.1039	0.047
	$A_{\text{fb}}^{0,c}$	$0.0707 \pm 0.0035$	0.0743	0.051
Effective mixing angle	$A_b$	$0.923 \pm 0.020$	0.935	0.012
	$A_c$	$0.670 \pm 0.027$	0.668	0.002
W Mass	$A_l(\text{SLD})$	$0.1513 \pm 0.0021$	0.1482	0.031
	$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$	$0.2324 \pm 0.0012$	0.2314	0.009
W Width	$m_W [\text{GeV}]$	$80.399 \pm 0.023$	80.378	0.021
Top Mass	$\Gamma_W [\text{GeV}]$	$2.085 \pm 0.042$	2.092	0.007
	$m_t [\text{GeV}]$	$173.20 \pm 0.90$	173.27	0.004

Lepton couplings confirm universality, incl. HO corrections

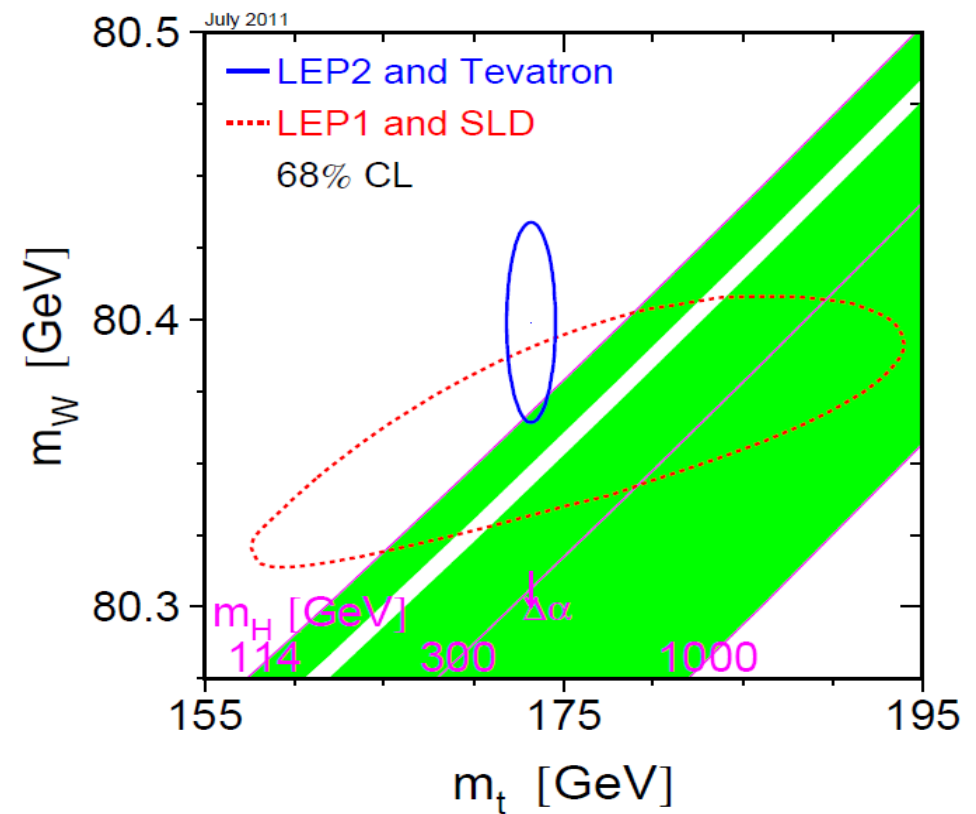
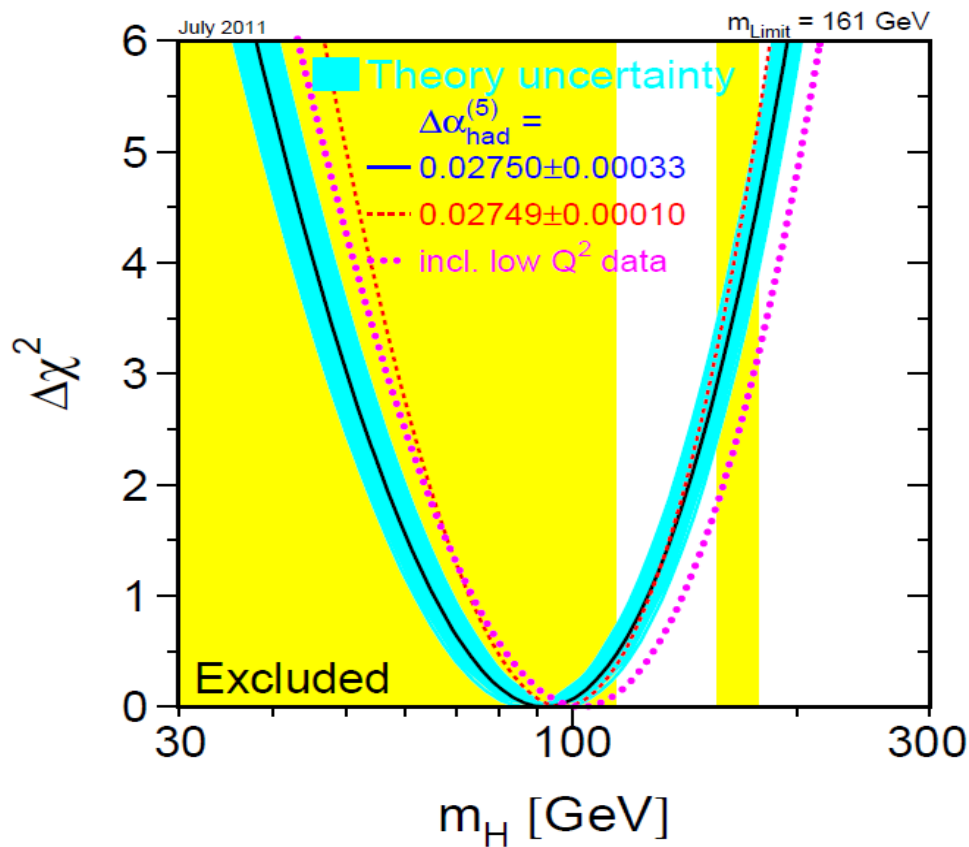
Pulls in global fit

# Sensitivity to the Higgs boson mass



- “Blue band” fit :  $M_H = 92^{+34}_{-26} \text{ GeV}$
- LEP2 direct bound:  $M_H > 114.4 \text{ GeV}$
- CDF/D0 combined @  $8.6 \text{ fb}^{-1}$  (observed):  $156 \text{ GeV} < M_H < 177 \text{ GeV}$
- ATLAS/CMS combined @  $1\text{-}2.3 \text{ fb}^{-1}$  (observed): (Claire's talk)  
 $M_H$  is excluded in  $146\text{-}288, 296\text{-}466 \text{ GeV}$  region

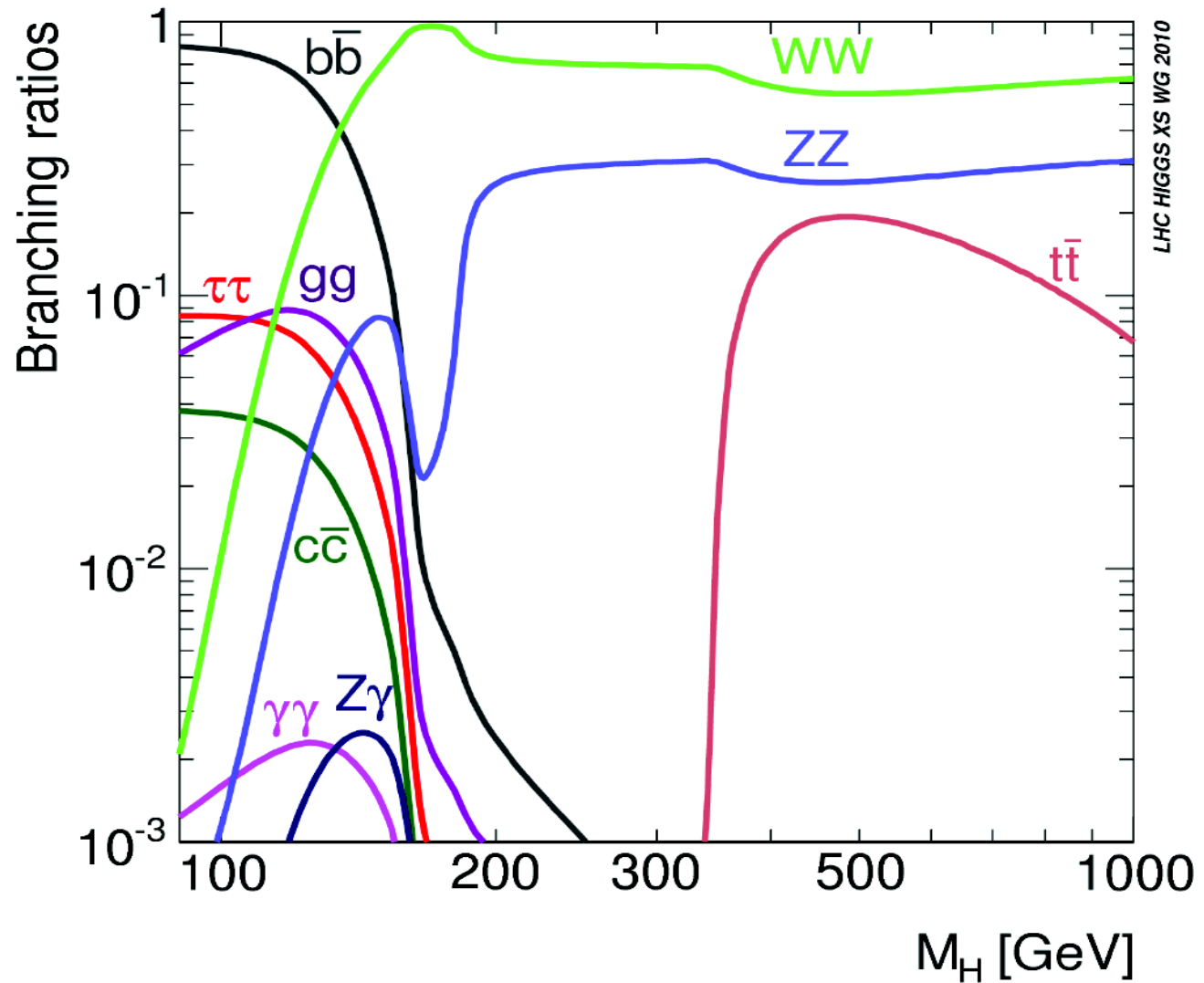
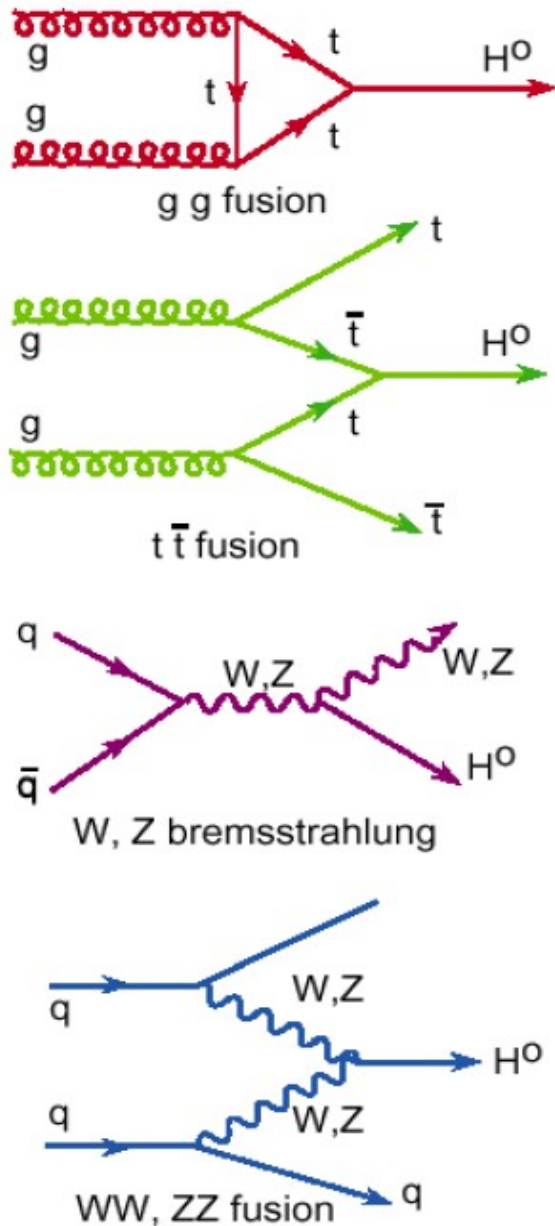
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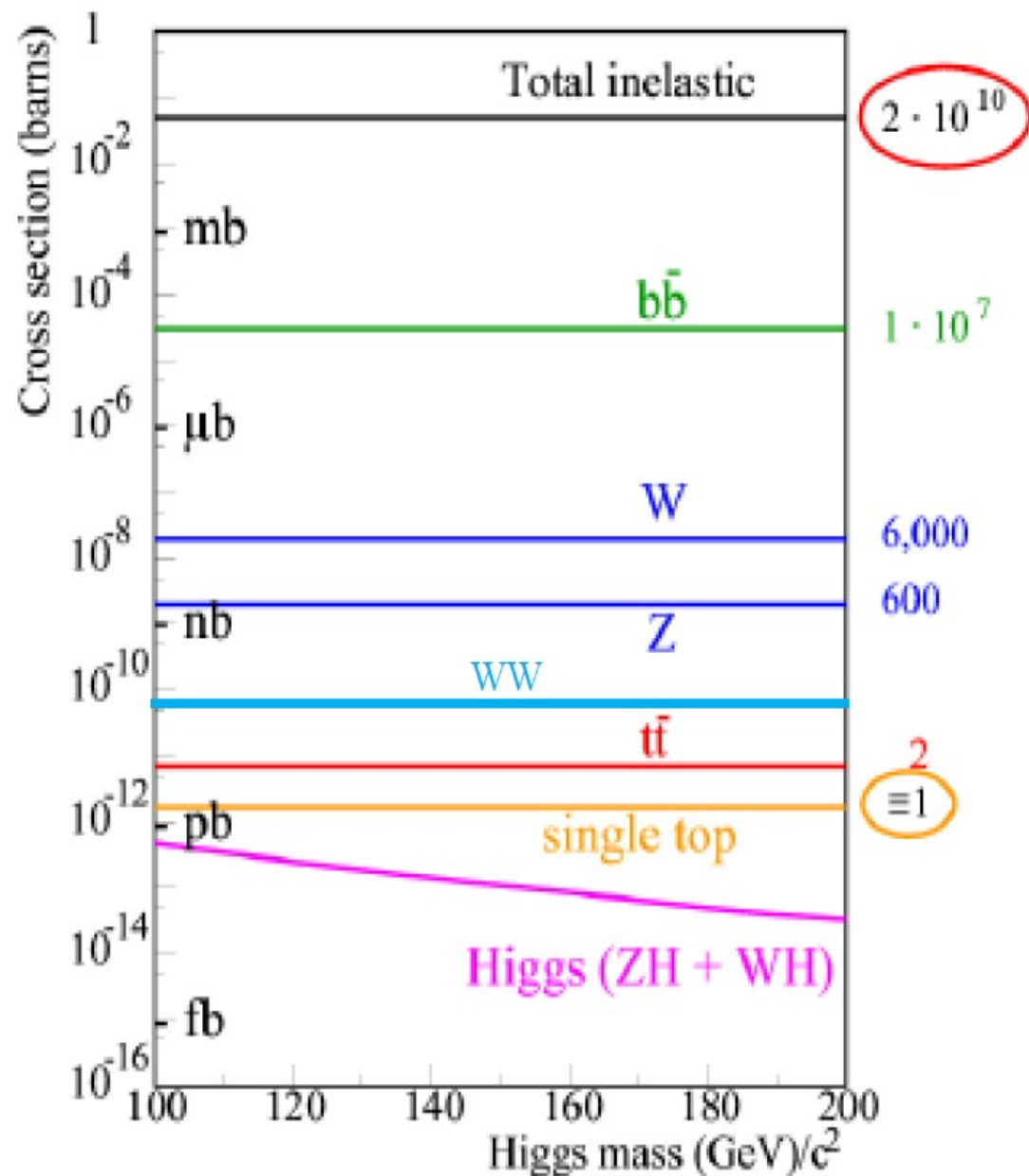
The light SM Higgs is favoured by fits but not found in direct searches ... There is still **114.4 - 146 GeV** window left for SM.

We can also conclude that New Physics with different Higgs couplings and/or Higgs sector is quite consistent with these fits too!

# SM Higgs Boson Production and decay

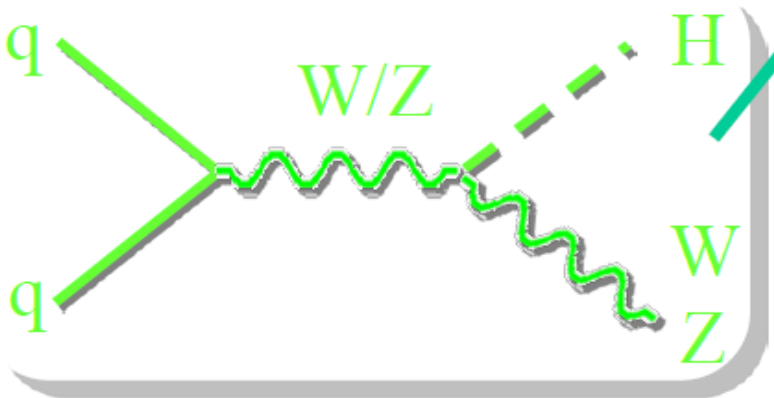
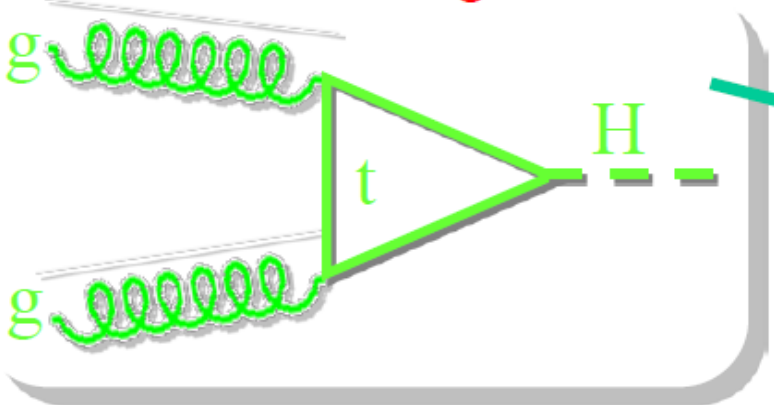


# Higgs production vs BG at the Tevatron



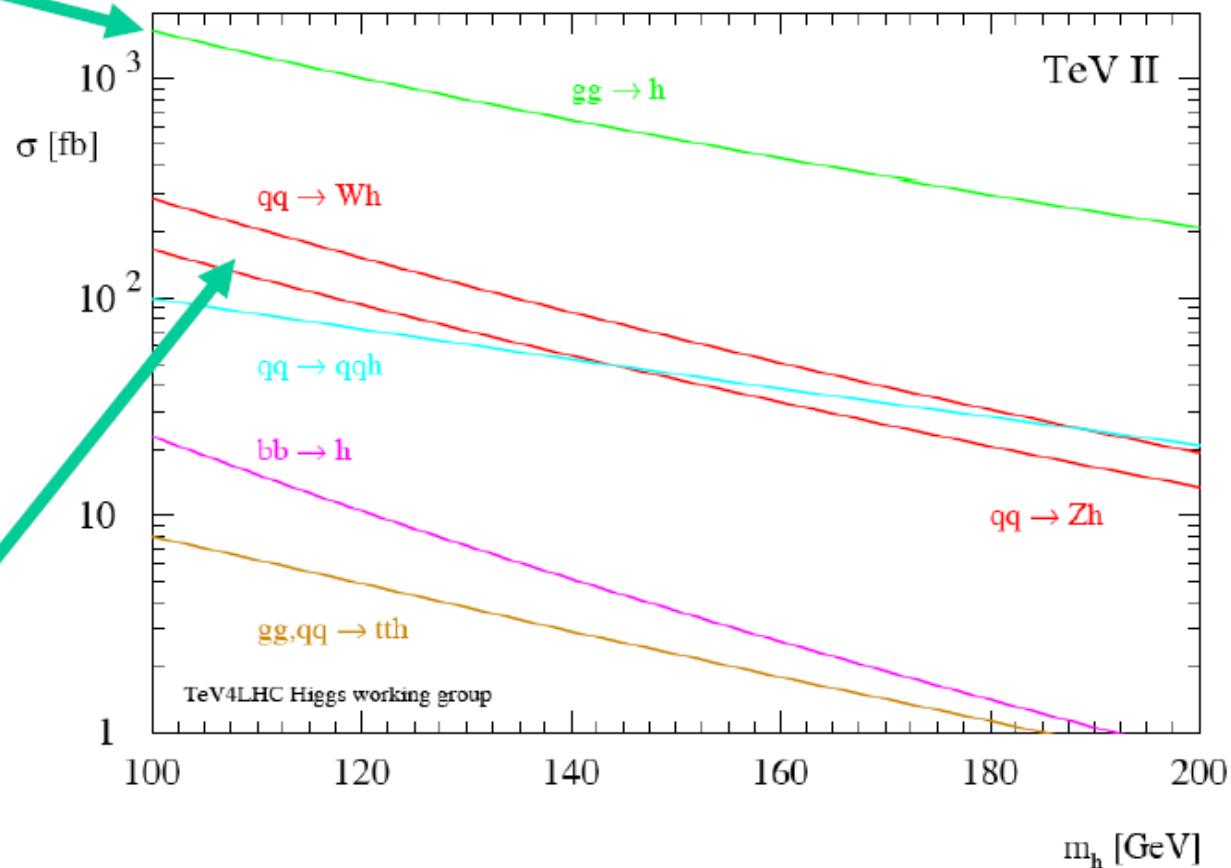
# Higgs production at the Tevatron

large cross section – huge background



small cross section – moderate background

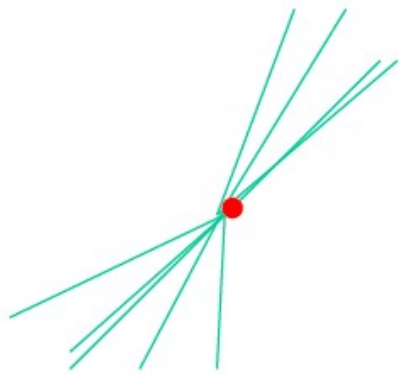
SM Higgs production





# Higgs production at the Tevatron

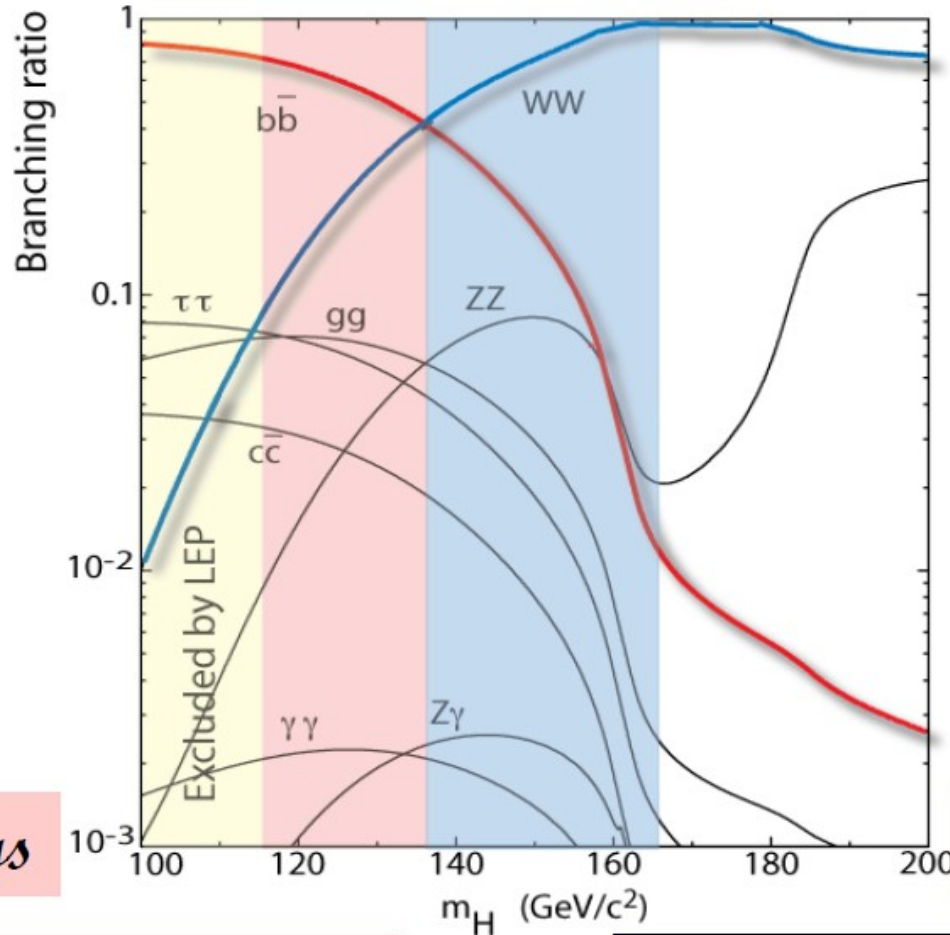
$$H \rightarrow b\bar{b}$$



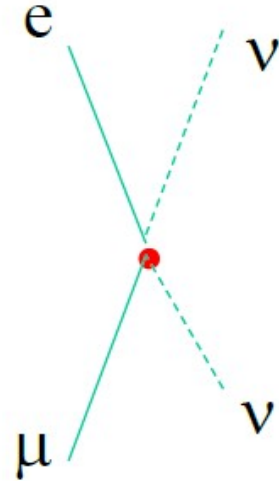
2 jets

*“low mass” Higgs*

$m_H < 135 \text{ GeV}$  ( $H \rightarrow b\bar{b}$ )  
background driven  
 $WH \rightarrow l\nu b\bar{b}$ ,  $ZH \rightarrow ll/\nu\nu b\bar{b}$



$$H \rightarrow WW$$



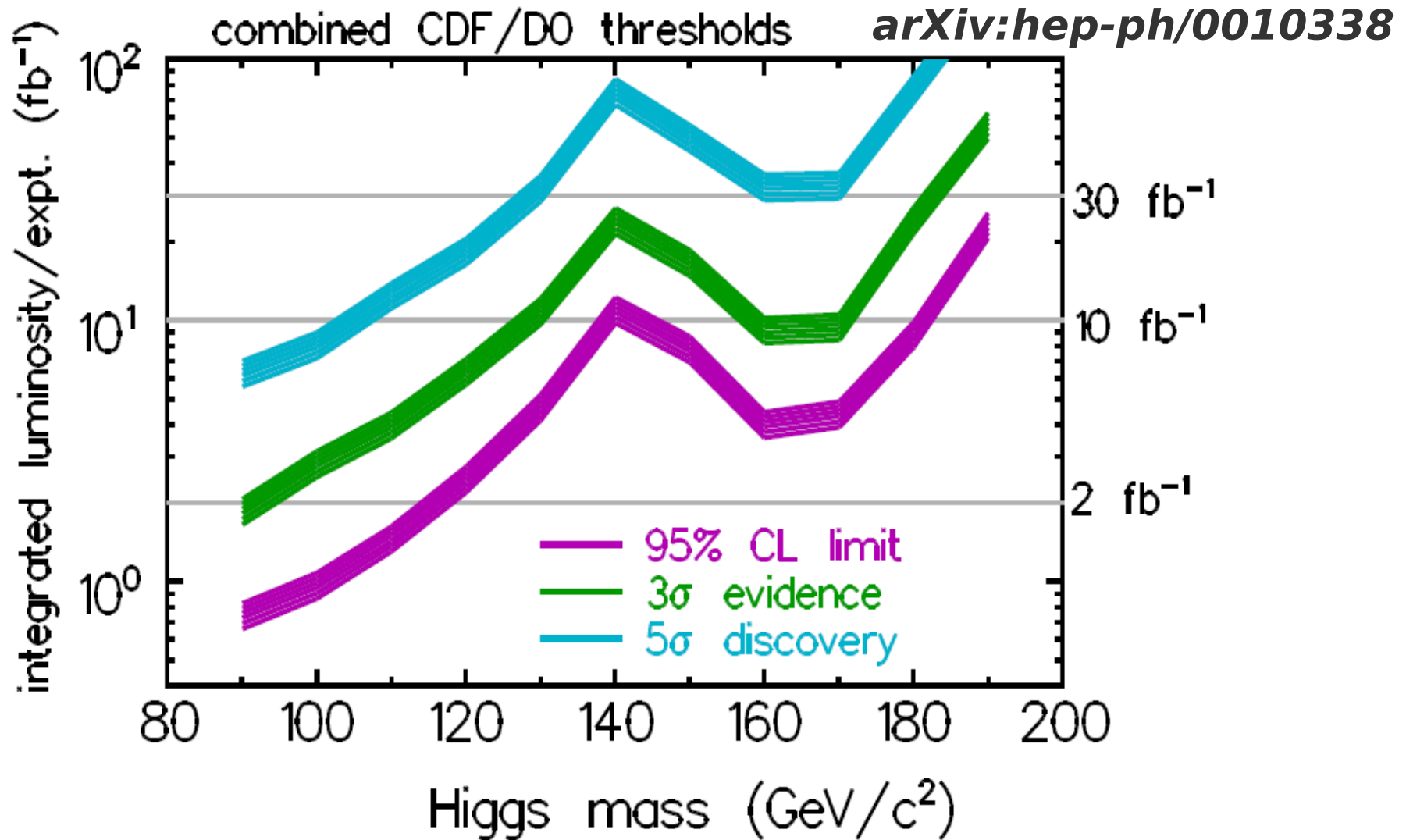
2 acollinear leptons

*“high mass” Higgs*

$m_H > 135 \text{ GeV}$  ( $H \rightarrow WW$ )  
rate driven  
all production modes

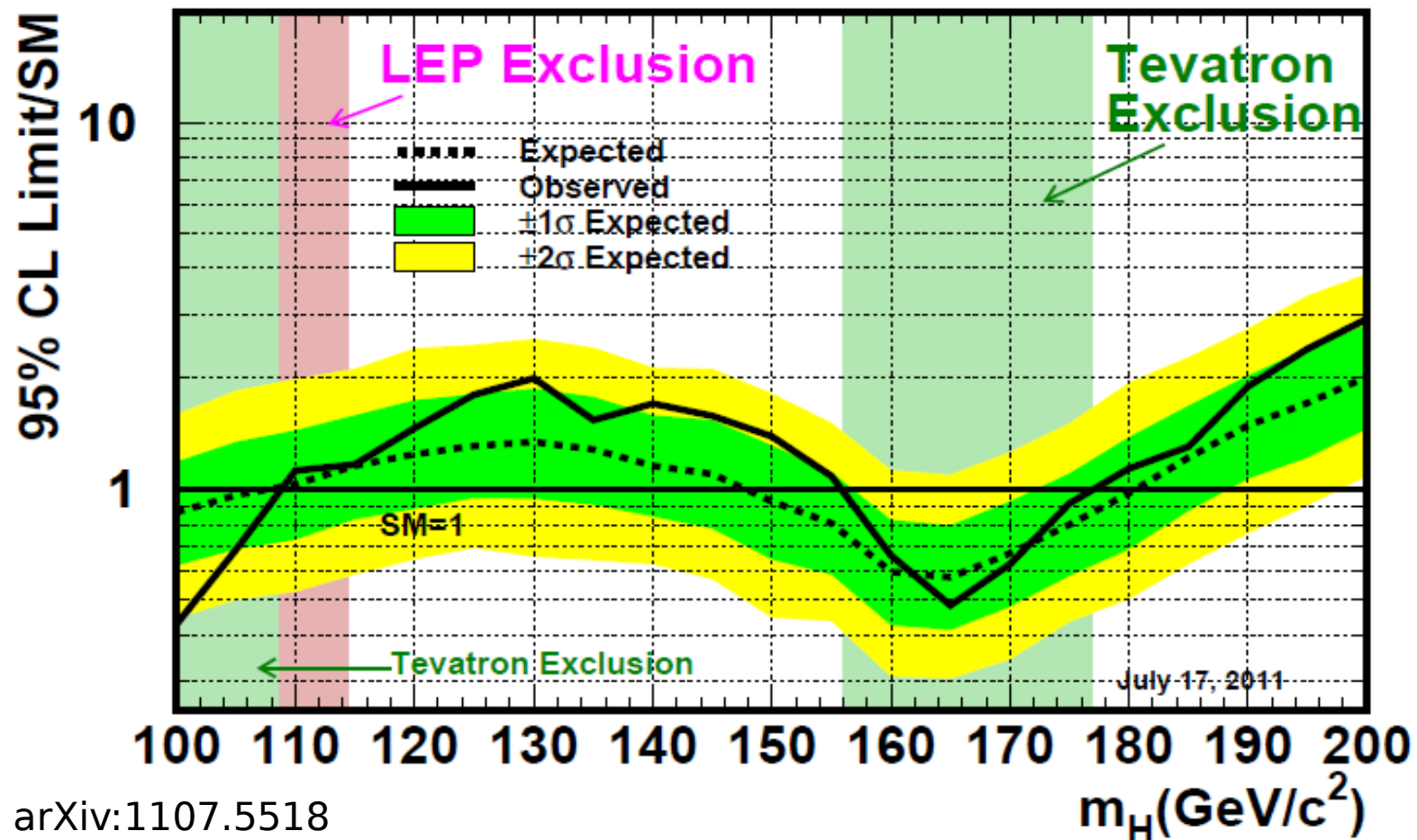
# Projected results from RUNII

## Tevatron Higgs Workshop



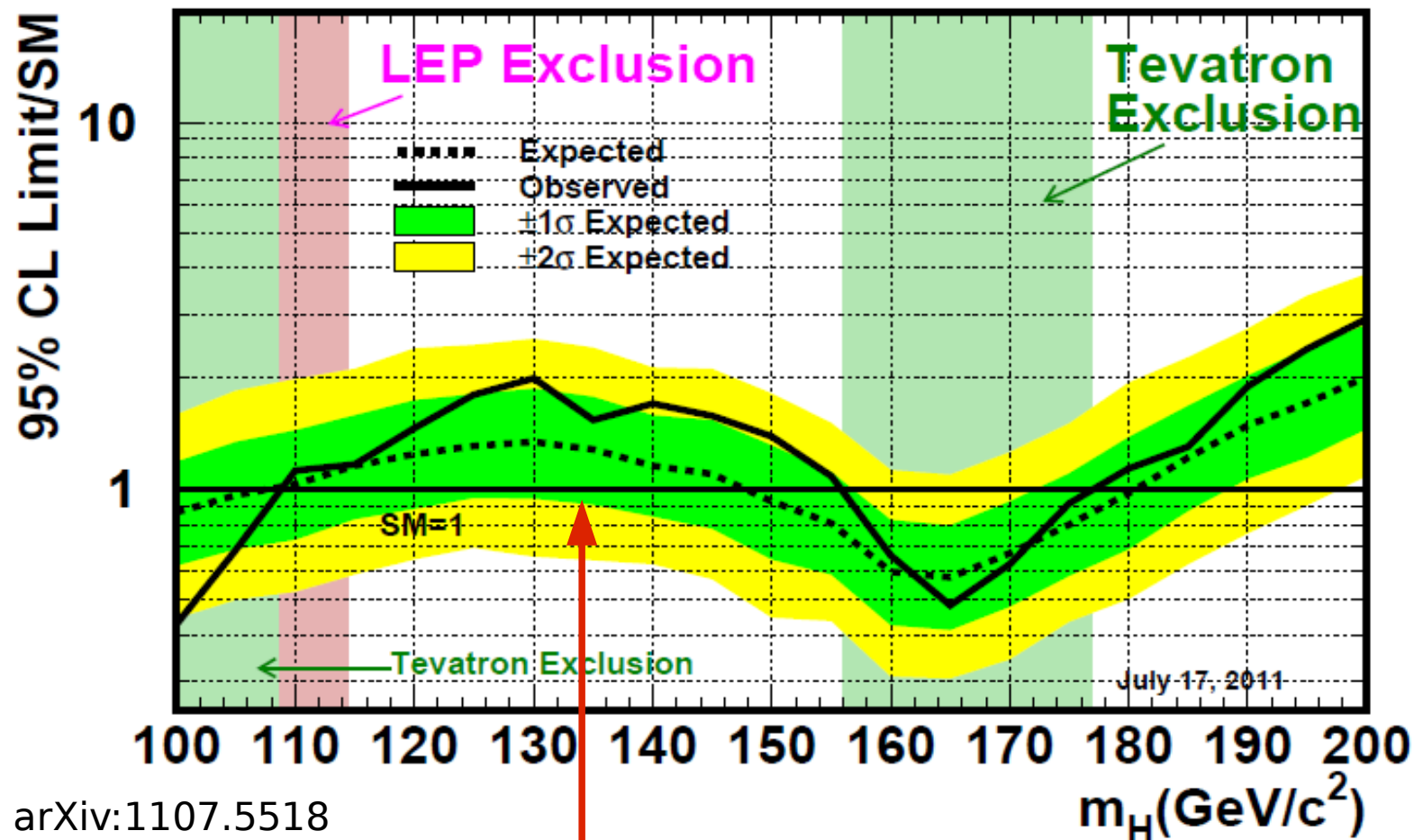
# Latest combined limit on Higgs Boson mass from CDF & D0 @ 8.6 fb<sup>-1</sup>

Tevatron Run II Preliminary,  $L \leq 8.6 \text{ fb}^{-1}$



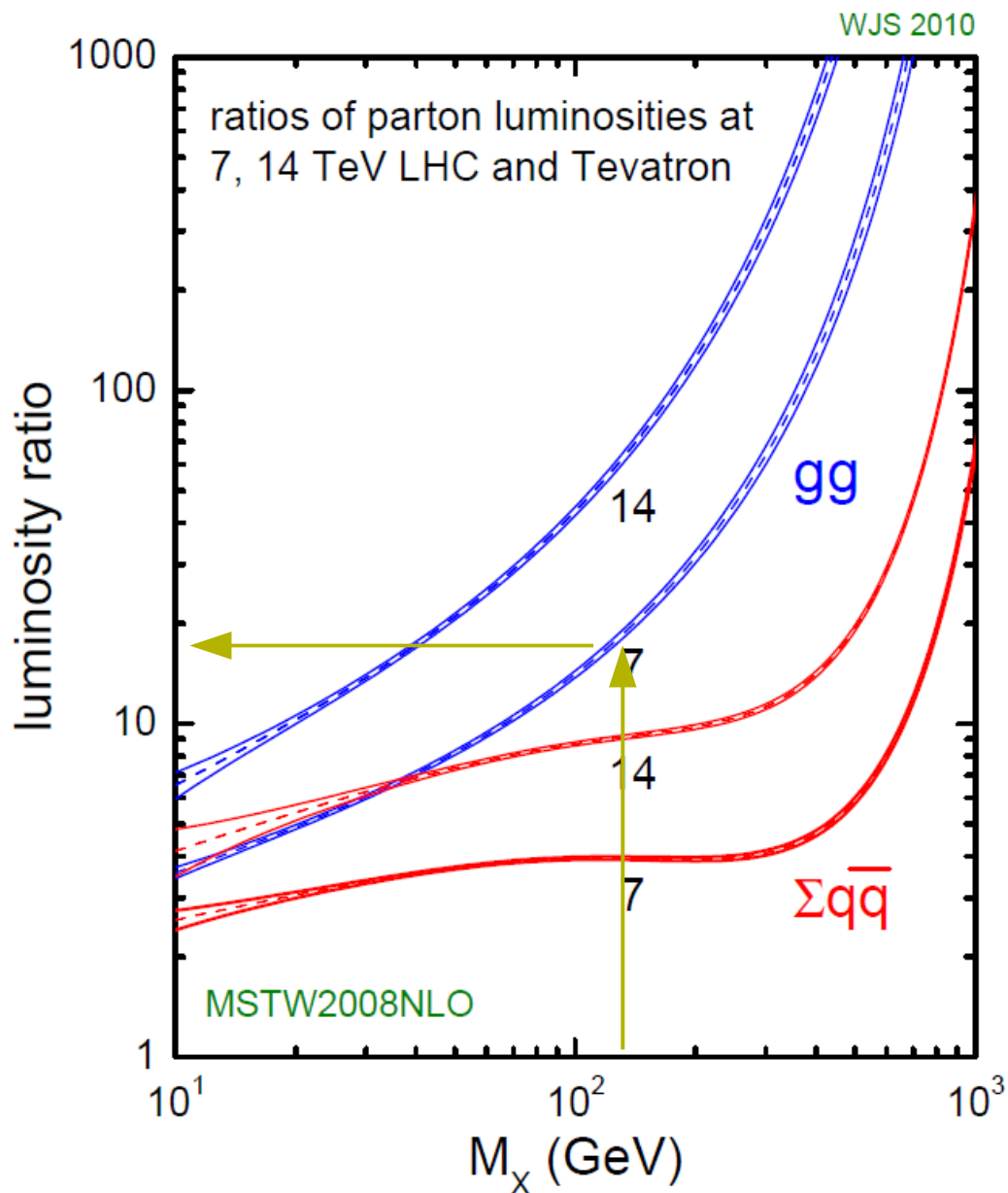
# Latest combined limit on Higgs Boson mass from CDF & D0 @ 8.6 fb<sup>-1</sup>

Tevatron Run II Preliminary, L ≤ 8.6 fb<sup>-1</sup>



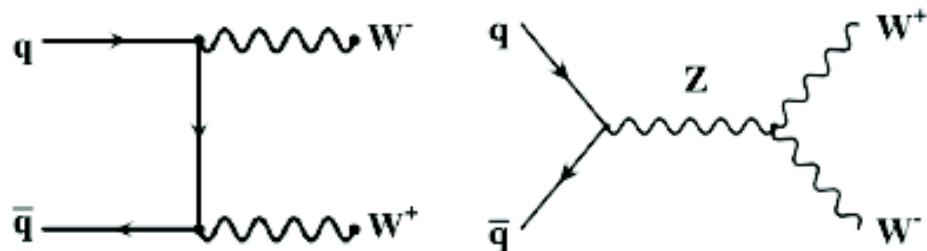
Predicted by RUN2 Tevatron Higgs Workshop.  
Systematics plays a crucial role!

# LHC vs Tevatron



**For  $M_H > 140$  GeV**  
 $gg \rightarrow H$  cross section at 7 TeV  
 is  $>15$  times that at 2 TeV

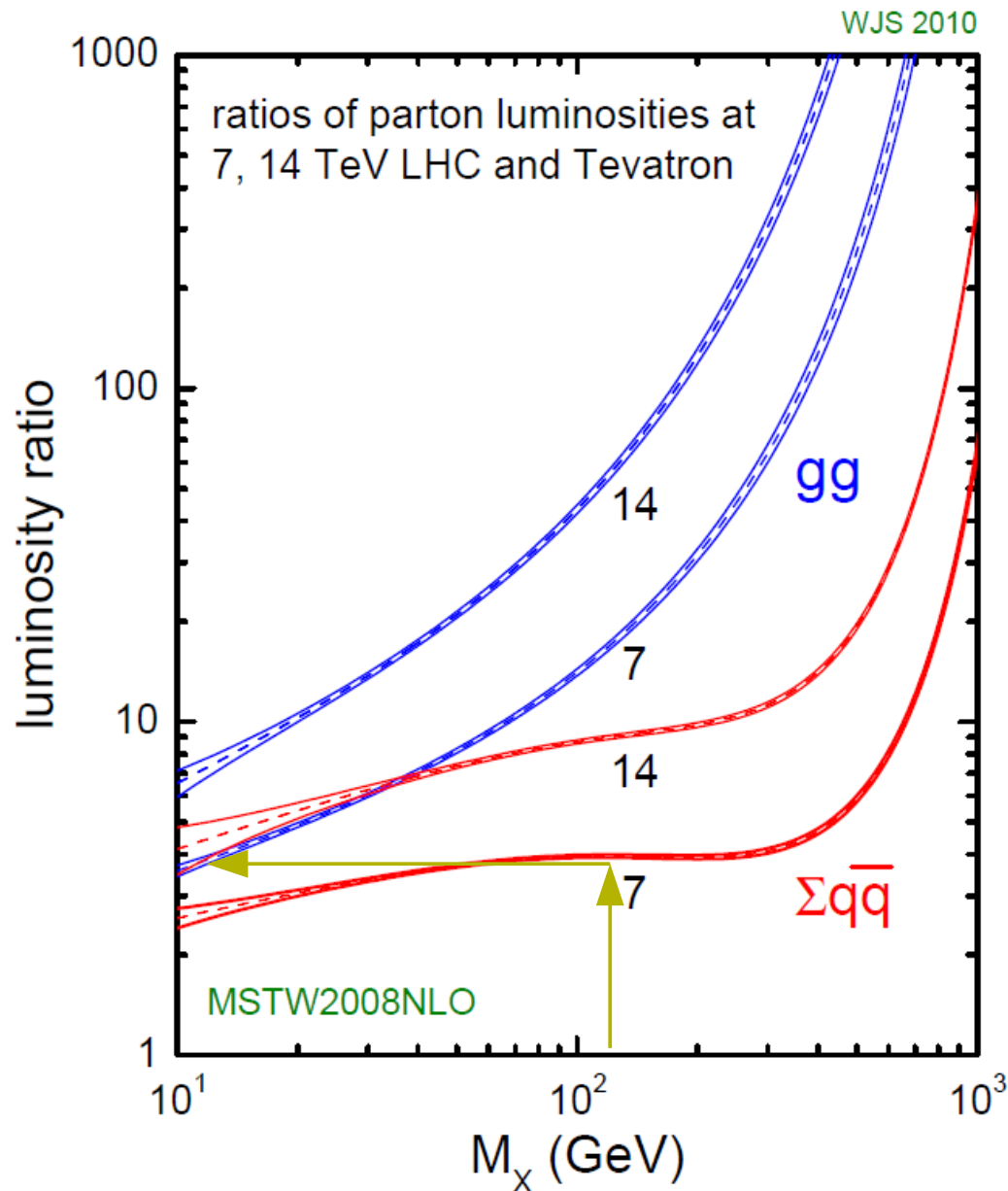
Irreducible backgrounds ( $WW, ZZ$ )  
 originate from  $q\bar{q}$  process which  
 rises relative slowly ( $pp$  vs  $p\bar{p}$ )



**$\Rightarrow$  Larger signal, better S/N**

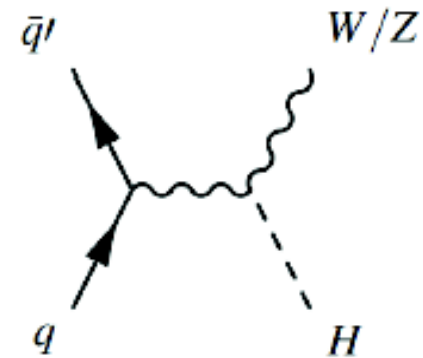


# LHC vs Tevatron



**For  $M_H < 130$  GeV**

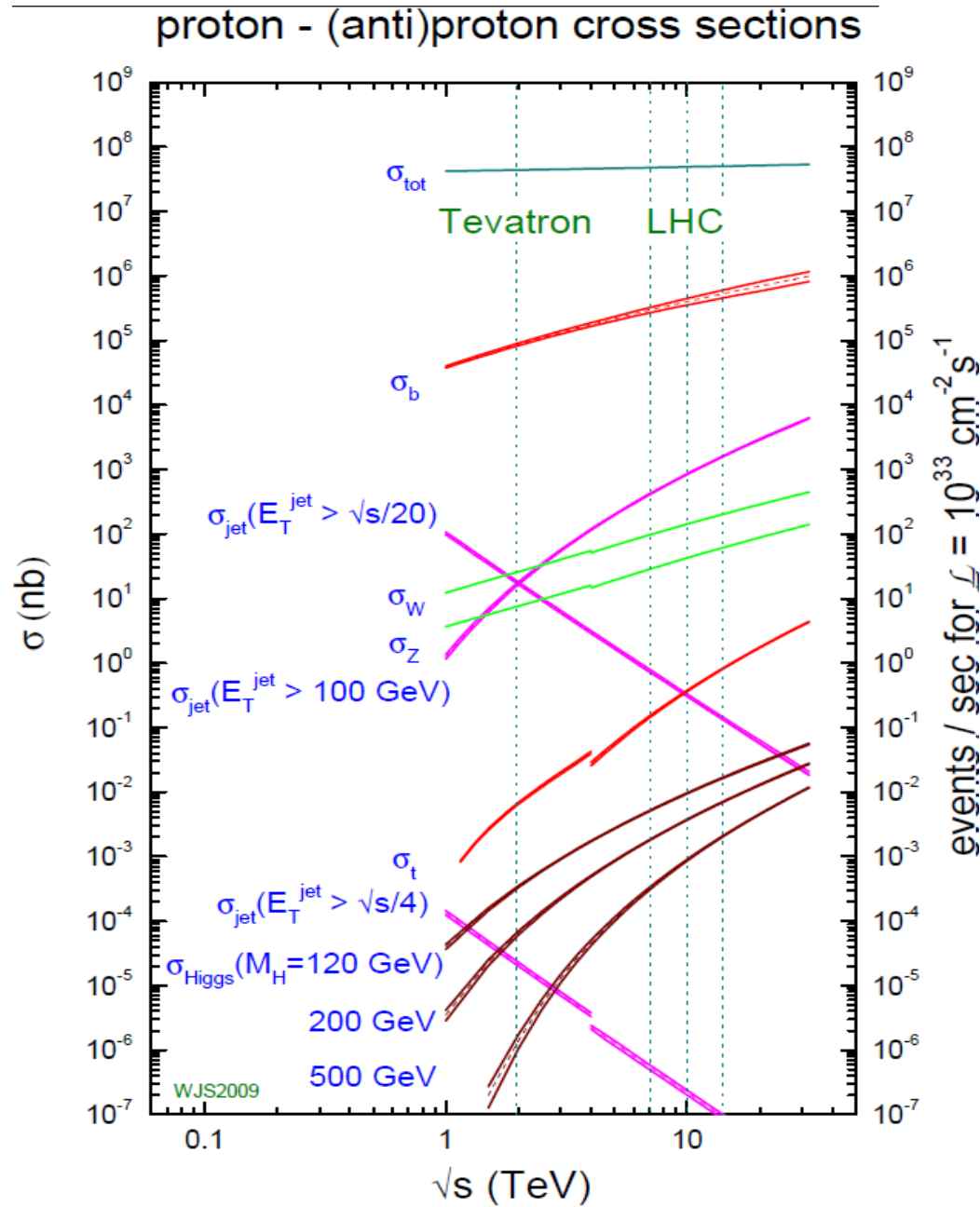
Modest rise in  $q\bar{q}$  cross section at 7 TeV,  $pp \rightarrow VH$  production only  $\times 4$  larger than at 2 TeV



Major backgrounds are  $W/Z+b\bar{b}$  &  $t\bar{t}$  which rise sharply due to rise in  $qg$  and  $gg$  cross sections

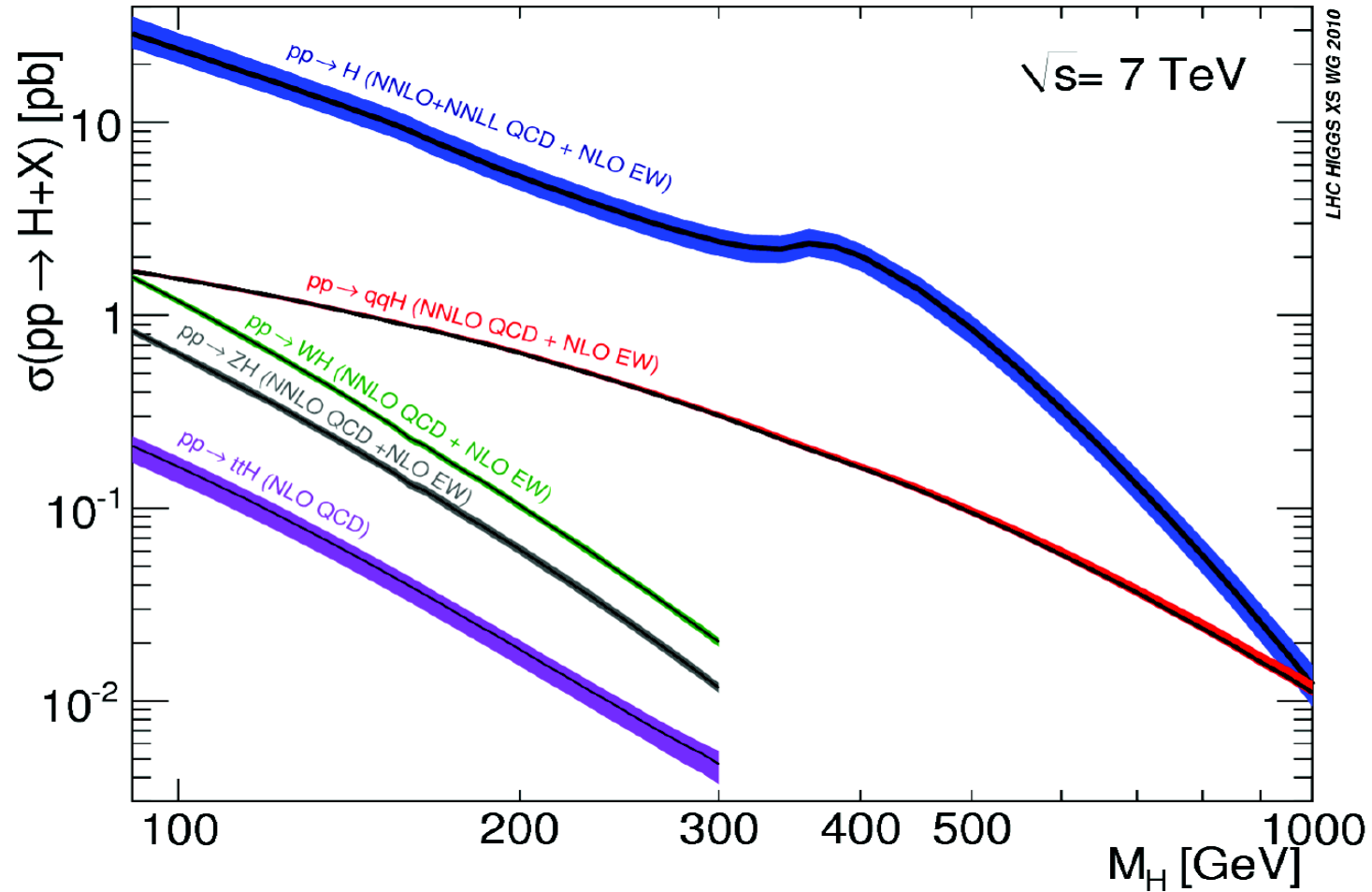
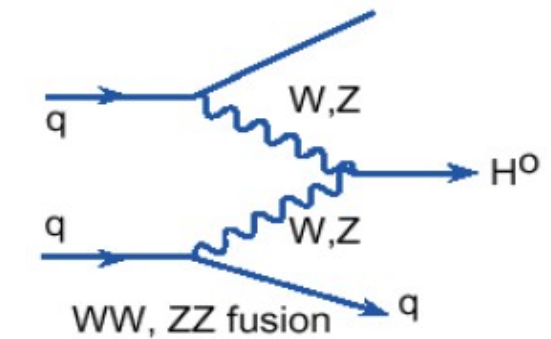
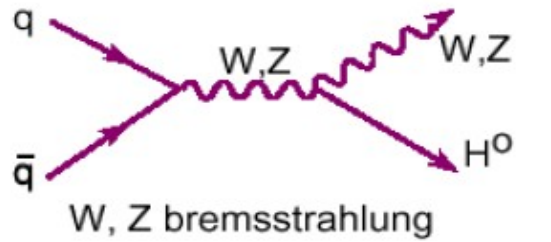
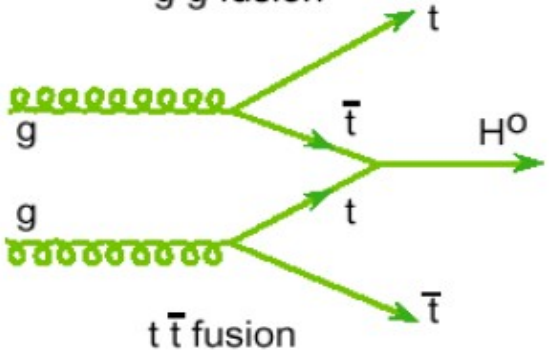
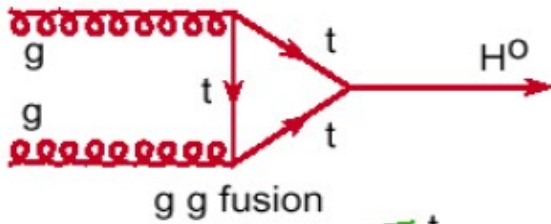
**$\Rightarrow$  Small signal, worse S/N**

# Higgs and BG rates vs Energy

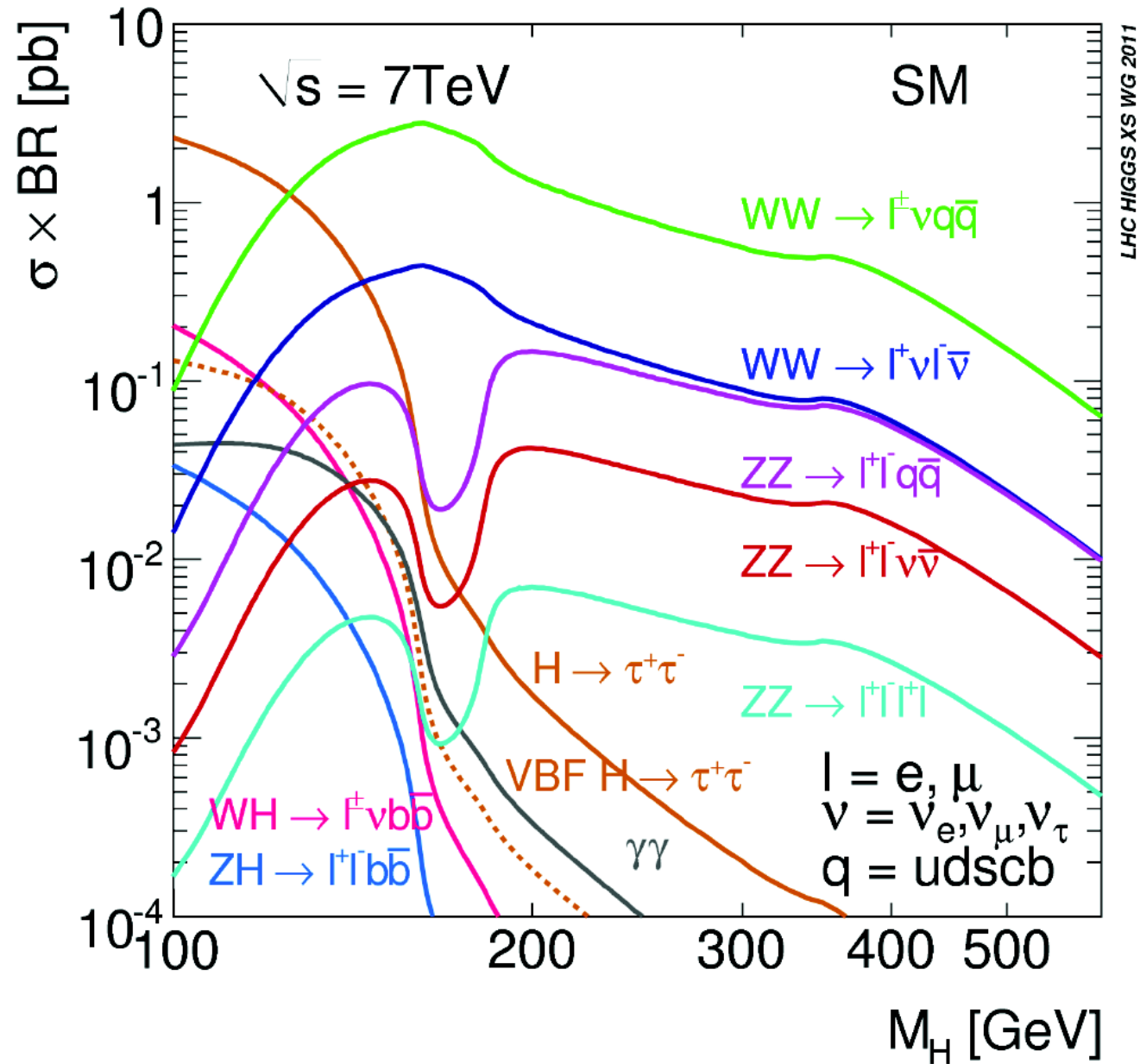




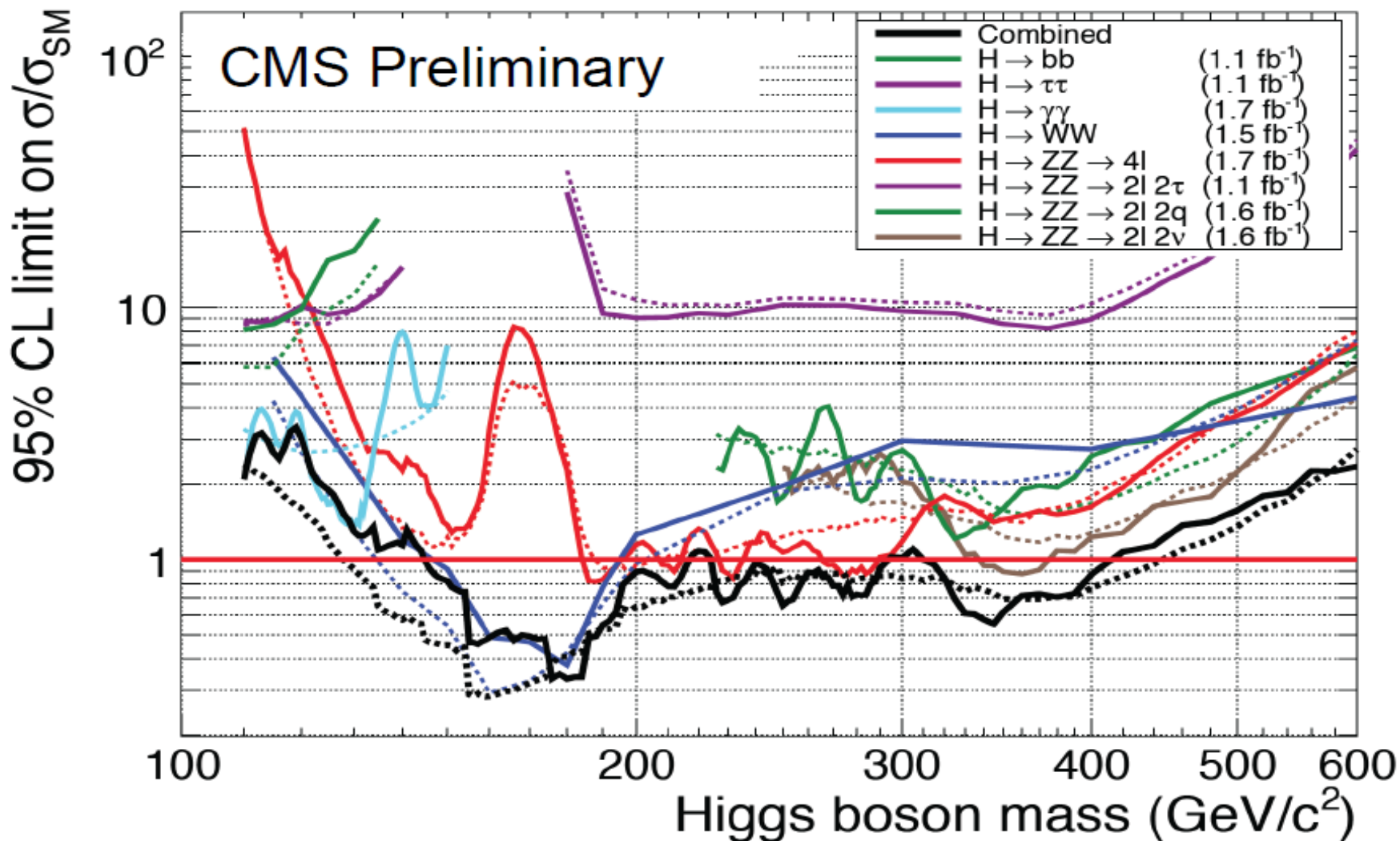
# Higgs production at the LHC



# SM Higgs Boson Production at the LHC



# Combined Limits



Conservative ATLAS+CMS combination:

146-288, 296-466 GeV

range is excluded @95% CL

[see details in Claire's talk]

# LHC projections for Higgs search

$m_H < 130$  GeV

-  $H \rightarrow \gamma\gamma$

$130 < m_H < 190$  GeV

-  $H \rightarrow W+W- \rightarrow \ell\nu\nu$

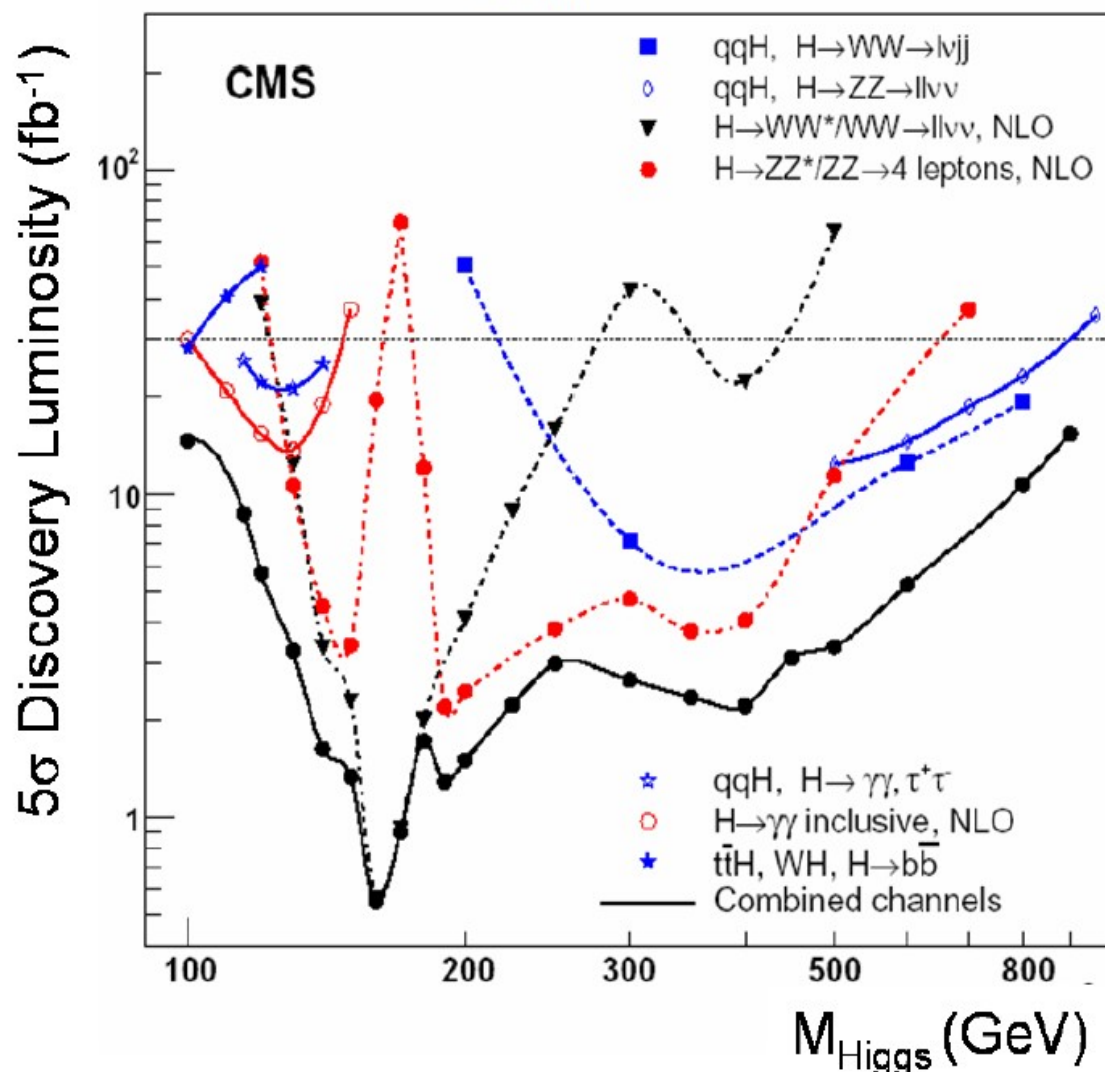
$190 < m_H < 460$  GeV

-  $H \rightarrow ZZ \rightarrow \ell\ell\ell\ell$

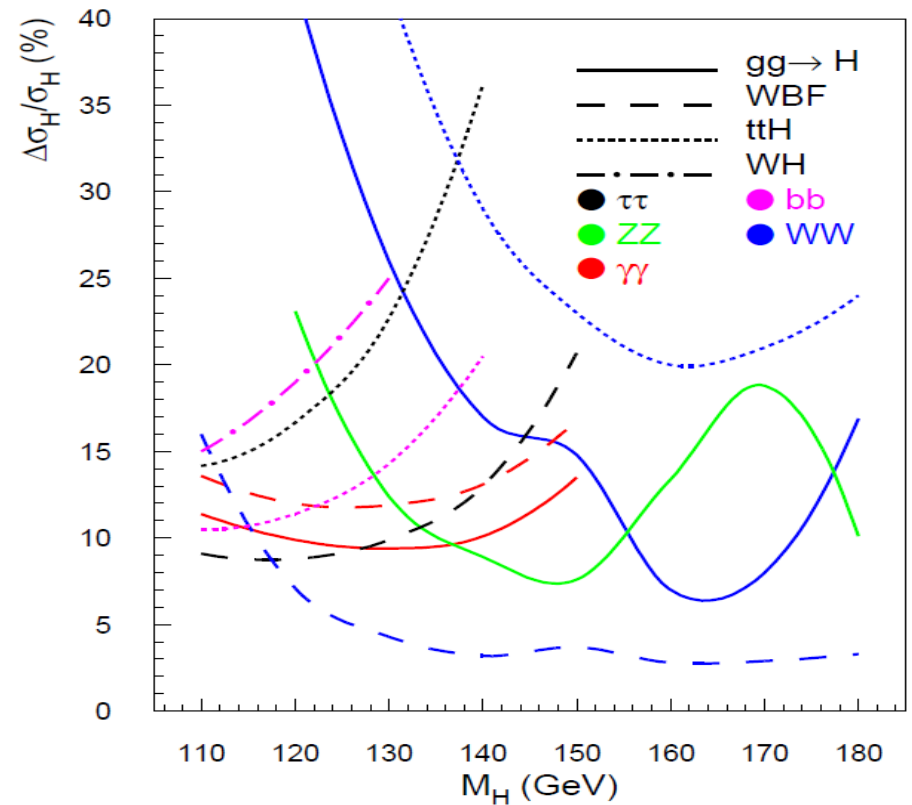
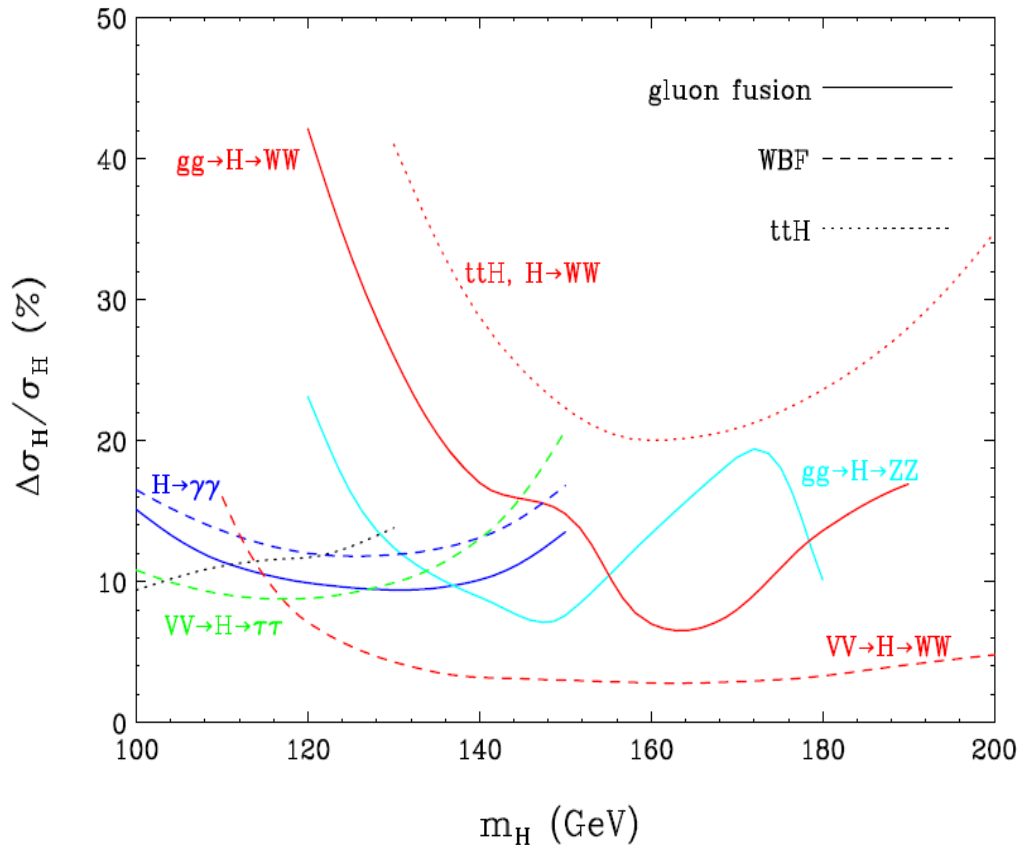
$460 < m_H < 800$  GeV

-  $H \rightarrow W+W- \rightarrow \ell\nu qq$

$E_{\text{com}} = 14$  TeV



# Measurement of Higgs couplings at the LHC



Zeppenfeld, Kinnunen, Nikitenko,  
Richter-Was 2000

AB, Reina '02

Also, Duhrssen, Heinemeyer, Logan, Rainwater, Weiglein, Zeppenfeld '04

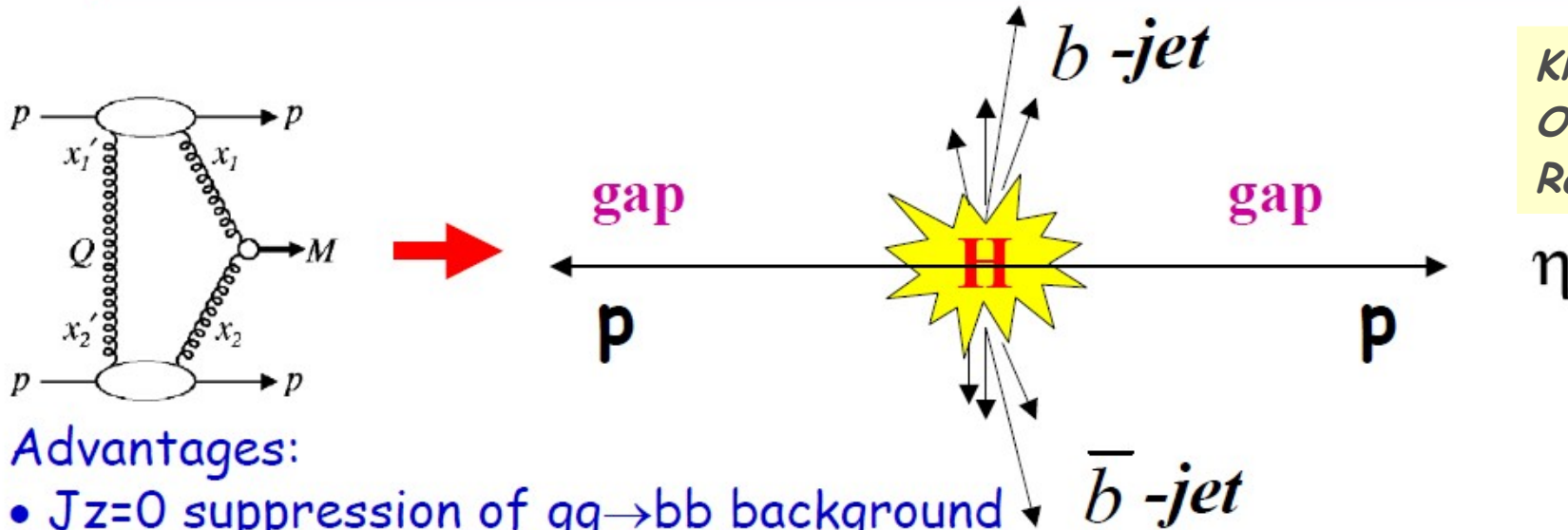
- ▷  $gg \rightarrow H, H \rightarrow \gamma\gamma$
- ▷  $qq \rightarrow qqH, H \rightarrow \gamma\gamma, \tau\tau, WW$
- ▷  $q\bar{q}, gg \rightarrow t\bar{t}H, H \rightarrow b\bar{b}, \tau\bar{\tau}$

- Assume branching ratio for Higgs decays into unexpected channels is small
- 200-300  $\text{fb}^{-1}$



# Diffraction Higgs Production

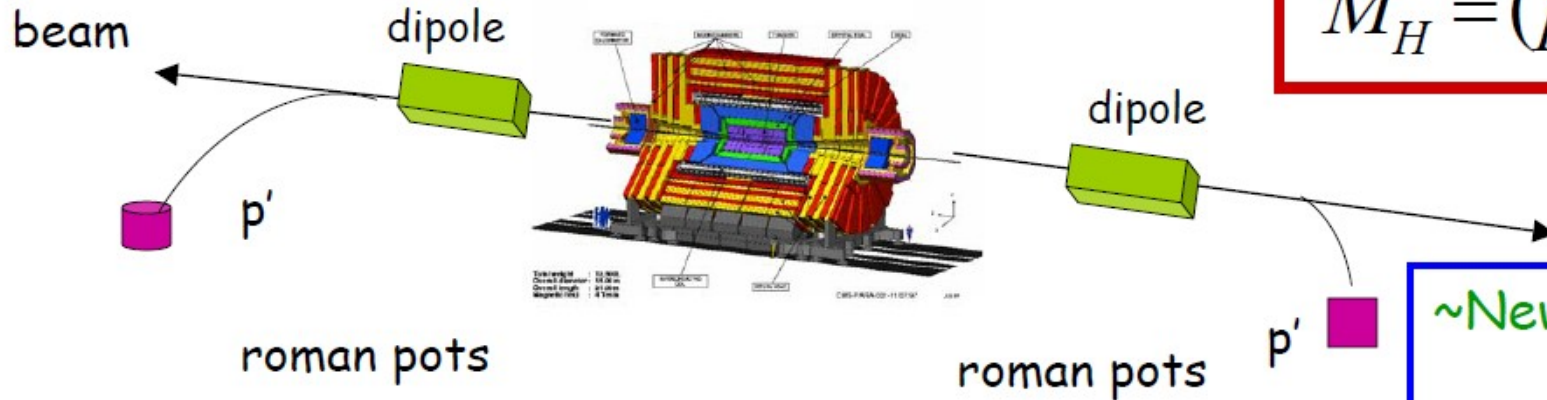
Exclusive diffractive Higgs production  $pp \rightarrow p H p$  : 3-10 fb  
 Inclusive diffractive Higgs production  $pp \rightarrow p+X+H+Y+p$  : 50-200 fb



*Khoze, Martin, Orava, Ryskin, De Roeck '02*

## Advantages:

- $J_z=0$  suppression of  $gg \rightarrow bb$  background
- Mass measurement via missing mass



$$M_H^2 = (p + \bar{p} - p' - \bar{p}')^2$$

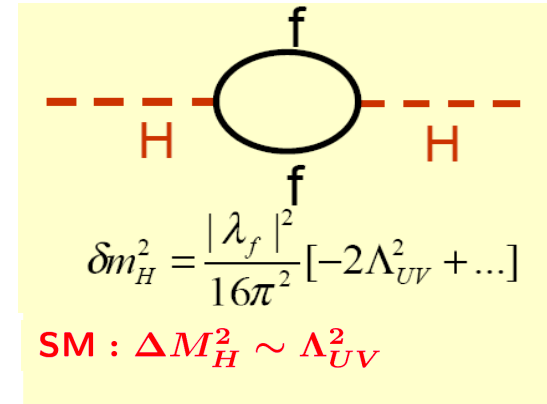
~New: Under study by many groups

Albert De Roeck (CERN)



# Beyond the SM Higgs

- SM Higgs boson accomplishes several things at once
  - ➔ Provides masses to  $W$  and  $Z$  bosons
  - ➔ Provides masses to Fermions
  - ➔ Unitarizes  $WW$  scattering
  - ➔ Provides a good quality for of EW fits if  $M_H < 200$  GeV

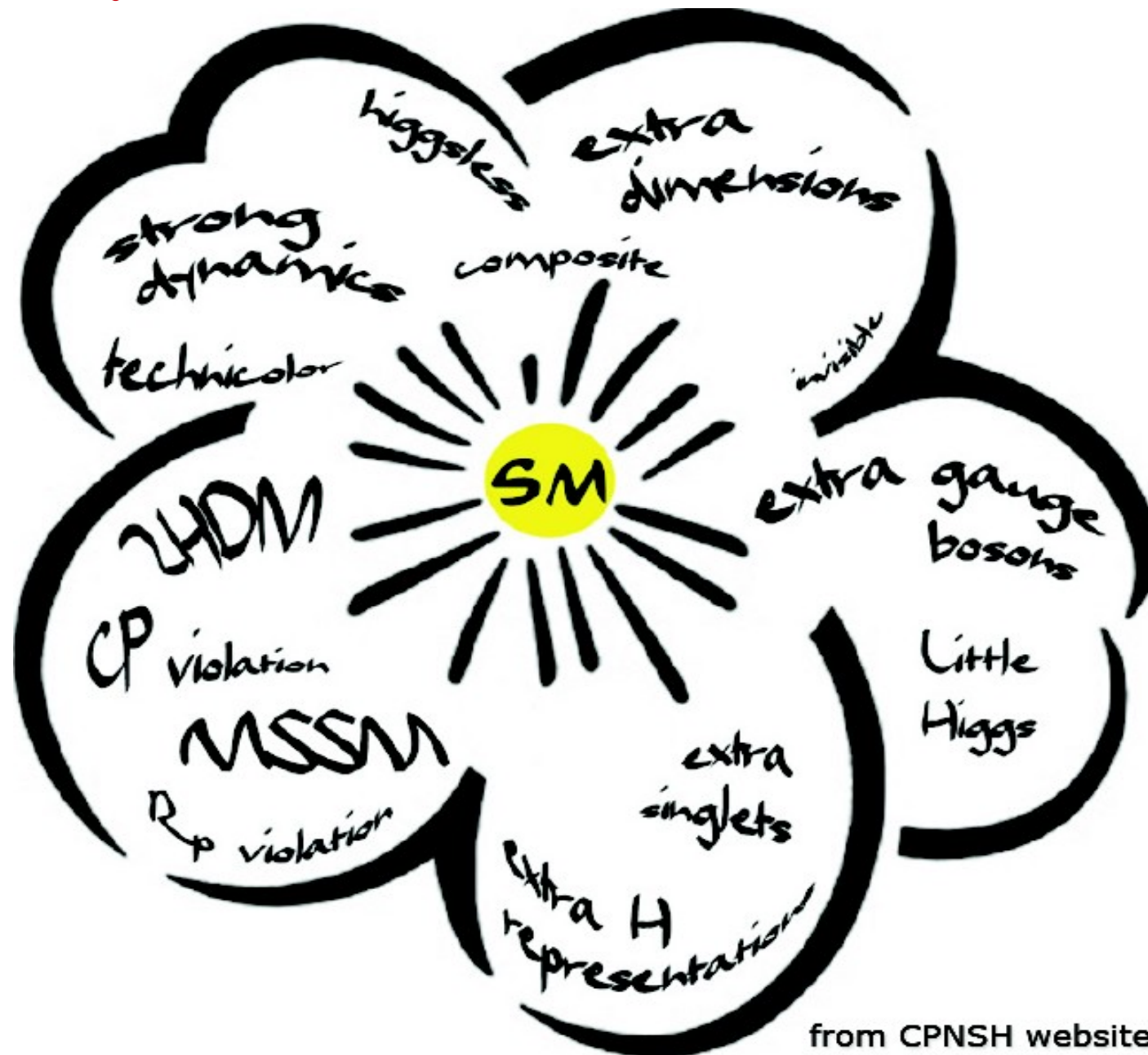


$$M_H^2 = M_{H_0}^2 - \Delta M_H^2,$$

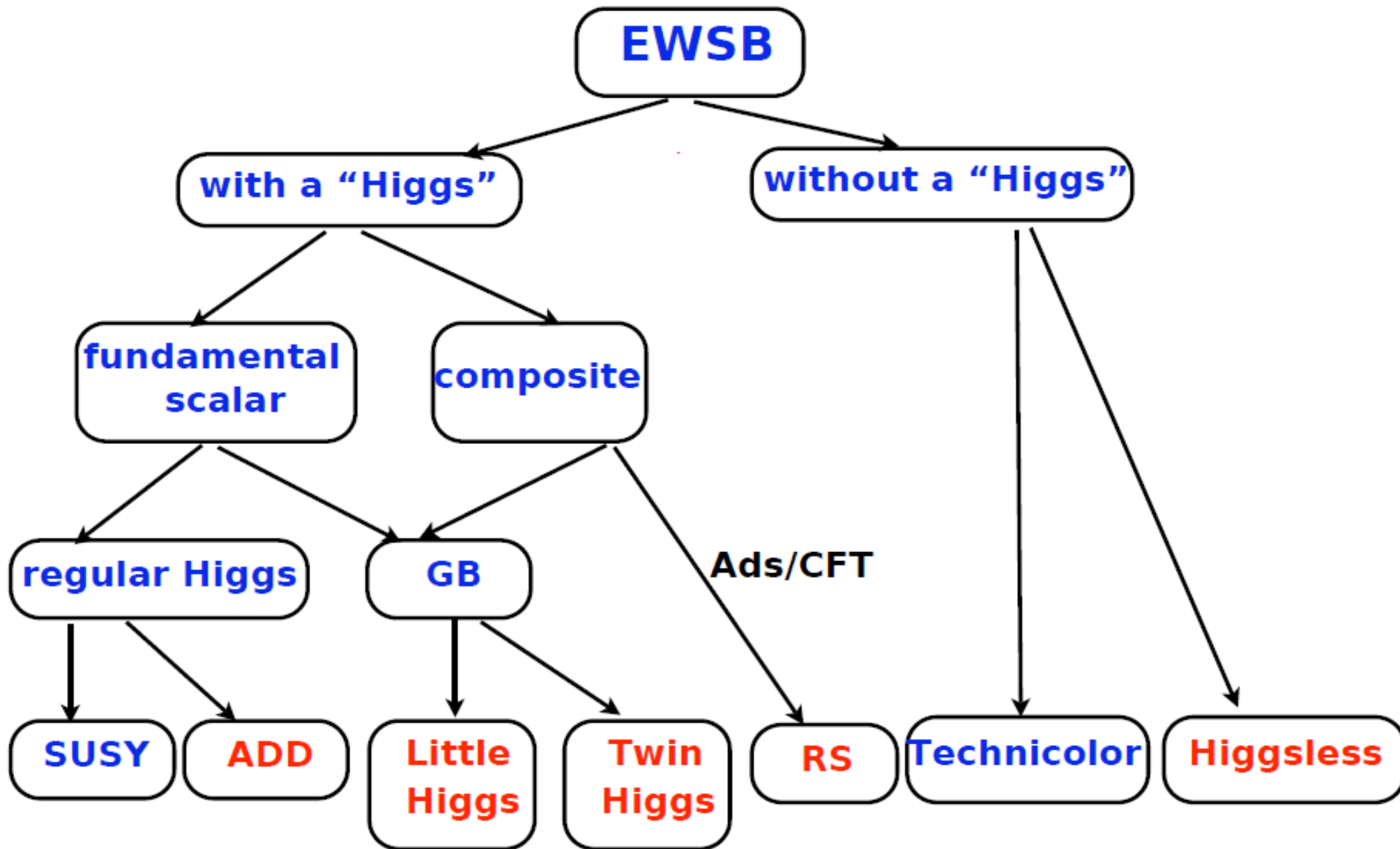
$(100 \text{ GeV})^2 = (10^{16} \text{ GeV})^2 - (10^{16} \text{ GeV})^2$   
 the cancellation is at the 28<sup>th</sup> digit  
 for  $\Lambda_{UV} \sim 10^{16} \text{ GeV}$

- Why we are not comfortable with SM Higgs?
  - ➔ Fine-tuning
  - ➔ EW Symmetry is broken "by Hand" ->  $\mu^2 < 0$
  - ➔ Fundamental Scalars never seen before

# Variety of theories with SEWSB



# Variety of theories with SEWSB



*From Sufang Su*

# Higgsless Theories

$$\varphi(x) = \exp\left(i \frac{\pi^a(x) \tau^a}{v}\right) \begin{pmatrix} 0 \\ (v + h(x))/\sqrt{2} \end{pmatrix}$$



$$\varphi(x) = \exp\left(\Sigma(x)\right) \begin{pmatrix} 0 \\ (v + h(x))/\sqrt{2} \end{pmatrix}$$

One can eliminate  $h(x)$  and still have EWSB via Sigma term  
**in the Higgsless model - non-linear Sigma model**

$$\mathcal{L}_H \rightarrow \mathcal{L}_\Sigma = \frac{v^2}{4} \text{tr} \left( [D^\mu \Sigma]^\dagger D_\mu \Sigma \right)$$

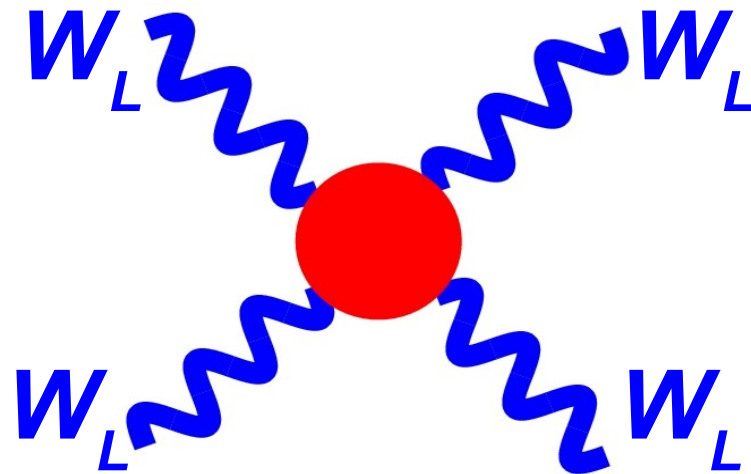
$$|D_\mu \varphi|^2$$

$$= \left( 0 \quad v/\sqrt{2} \right) \left| \frac{g}{\sqrt{2}} W^+ \sigma^+ + \frac{g}{\sqrt{2}} W^- \sigma^- + \frac{g}{2} W^0 \sigma^3 + \frac{g'}{2} B \right|^2 \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

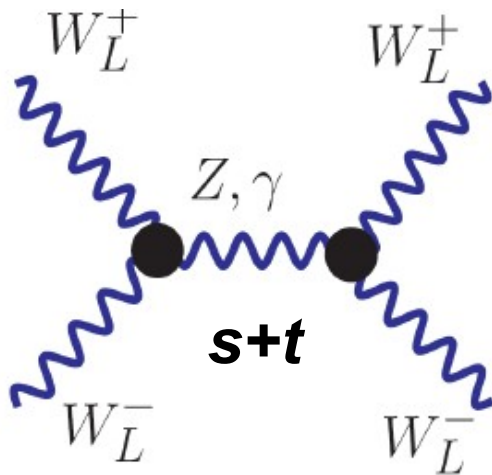
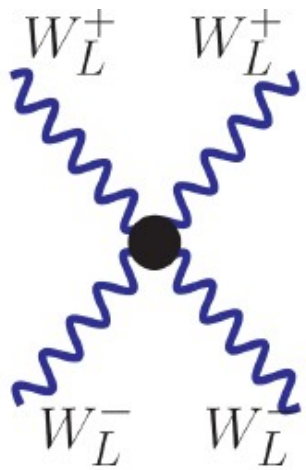
$$= \frac{v^2}{4} \left[ g^2 W^+ W^- + \frac{1}{2} (-g W^0 + g' B)^2 \right]$$

**Electroweak Symmetry Breaking  
without Higgs boson  
but within the Electroweak theory**

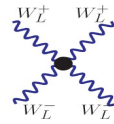
**The Loss of Unitarity and EW precision data  
is the main worry!**



# Unitarity with and without Higgs boson



Graphs



**s**

**t**

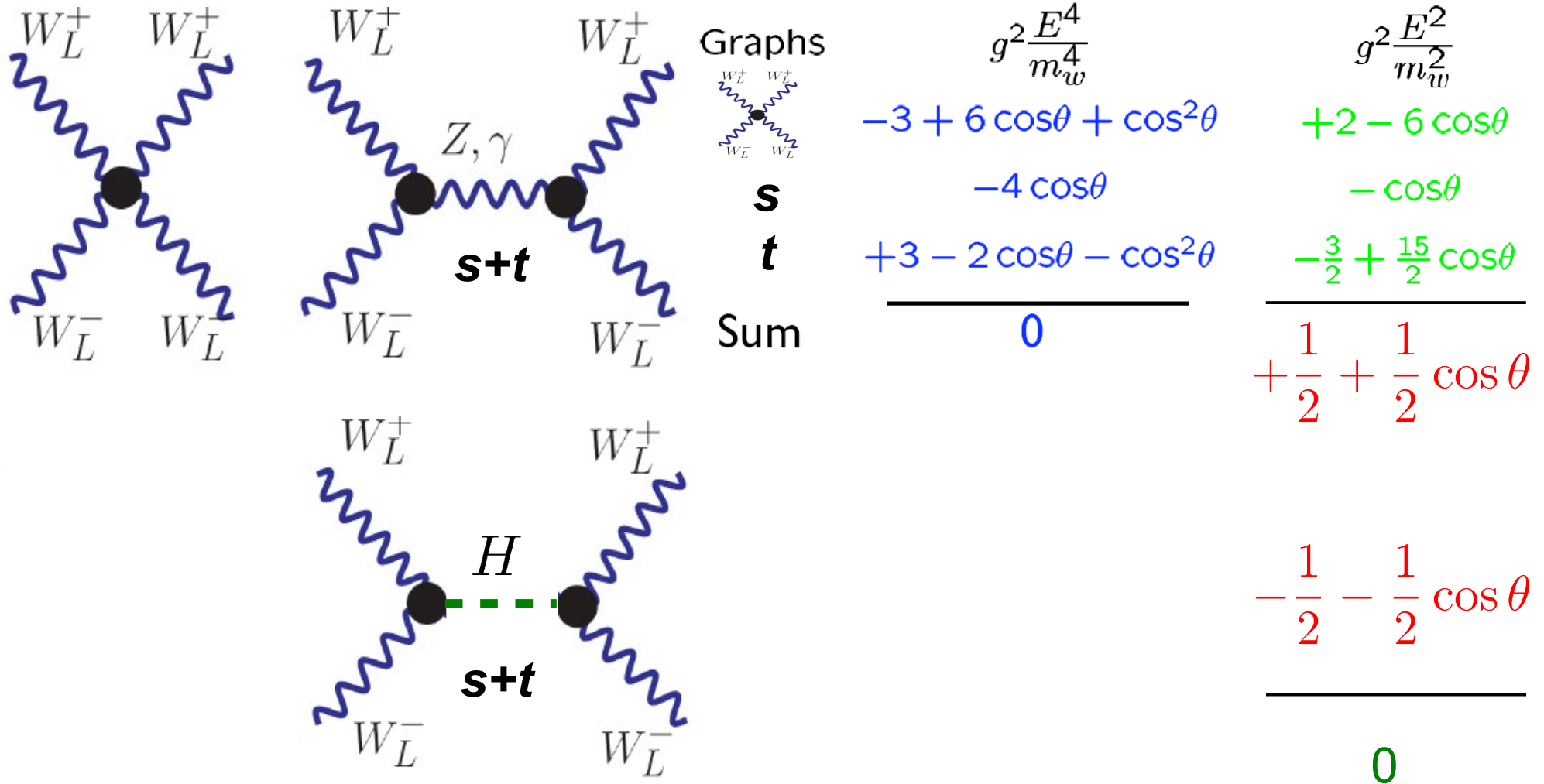
Sum

$$\begin{array}{r}
 g^2 \frac{E^4}{m_w^4} \\
 -3 + 6 \cos\theta + \cos^2\theta \\
 -4 \cos\theta \\
 +3 - 2 \cos\theta - \cos^2\theta \\
 \hline
 0
 \end{array}$$

$$\begin{array}{r}
 g^2 \frac{E^2}{m_w^2} \\
 +2 - 6 \cos\theta \\
 -\cos\theta \\
 -\frac{3}{2} + \frac{15}{2} \cos\theta \\
 \hline
 +\frac{1}{2} + \frac{1}{2} \cos\theta
 \end{array}$$



# Unitarity with and without Higgs boson



If no Higgs  $\Rightarrow \mathcal{O}(E^2) \Rightarrow E < \sqrt{8\pi}v \simeq 1.2 \text{ TeV}$

# Non-linear sigma model

There are many 4D CP-conserving operators that can be written down

$$\mathcal{L}_1 = \frac{1}{2} g^2 \alpha_1 B_{\mu\nu} \text{Tr}(TF^{\mu\nu})$$

$$\mathcal{L}_2 = \frac{1}{2} i g \alpha_2 B_{\mu\nu} \text{Tr}(T[V^\mu, V^\nu])$$

$$\mathcal{L}_3 = i g \alpha_3 \text{Tr}(F_{\mu\nu}[V^\mu, V^\nu])$$

$$\mathcal{L}_4 = \alpha_4 [\text{Tr}(V_\mu V_\nu)]^2$$

$$\mathcal{L}_5 = \alpha_5 [\text{Tr}(V_\mu V^\mu)]^2$$

$$\mathcal{L}_6 = \alpha_6 \text{Tr}(V_\mu V_\nu) \text{Tr}(TV^\mu) \text{Tr}(TV^\nu)$$

$$\mathcal{L}_7 = \alpha_7 \text{Tr}(V_\mu V^\mu) [\text{Tr}(TV_\nu)]^2$$

$$\mathcal{L}_8 = \frac{1}{4} g^2 \alpha_8 [\text{Tr}(TF_{\mu\nu})]^2$$

$$\mathcal{L}_9 = \frac{1}{2} i g \alpha_9 \text{Tr}(TF_{\mu\nu}) \text{Tr}(T[V^\mu, V^\nu])$$

$$\mathcal{L}_{10} = \frac{1}{2} \alpha_{10} [\text{Tr}(TV_\mu) \text{Tr}(TV_\nu)]^2$$

$$\mathcal{L}_{11} = \alpha_{11} \text{Tr}[(\mathcal{D}_\mu V^\mu)^2]$$

$$\mathcal{L}_{12} = \frac{1}{2} \alpha_{12} \text{Tr}(T \mathcal{D}_\mu \mathcal{D}_\nu V^\nu) \text{Tr}(TV^\mu)$$

$$\mathcal{L}_{13} = \frac{1}{2} \alpha_{13} [\text{Tr}(T \mathcal{D}_\mu V_\nu)]^2$$

$$\mathcal{L}_{14} = \alpha_{14} [\text{Tr}(F_{\mu\nu} V^\nu) \text{Tr}(TV^\mu)$$

$$- \text{Tr}(F_{\mu\nu} V^\mu) \text{Tr}(TV^\nu)]$$

$$\mathcal{L}_{15} = 2i \alpha_{15} \text{Tr}(V_\mu \mathcal{D}_\nu V^\nu) \text{Tr}(TV^\mu)$$

$$\mathcal{L}_{16} = i \alpha_{16} \text{Tr}[T(\mathcal{D}_\mu V_\nu + \mathcal{D}_\nu V_\mu)]$$

$$\times \text{Tr}(V^\mu V^\nu)$$

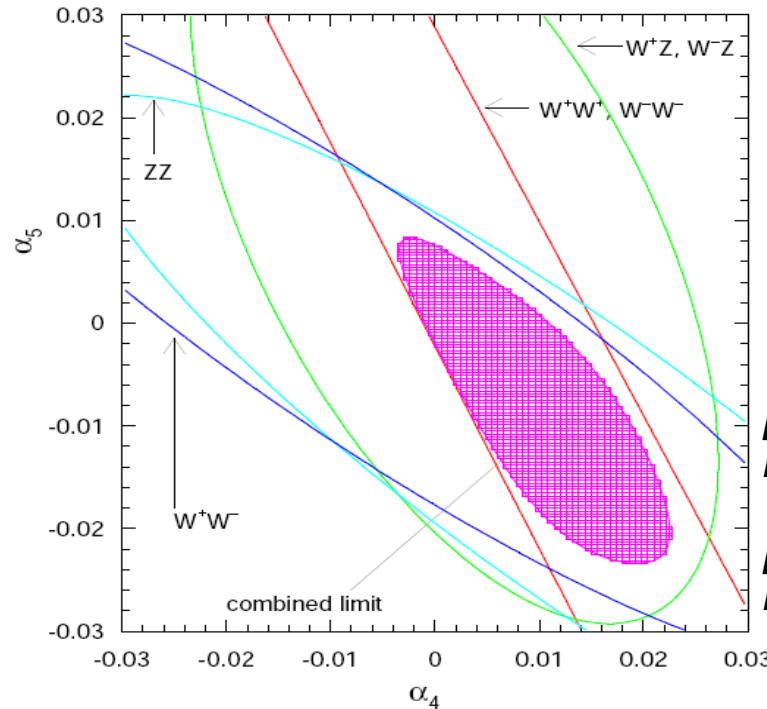
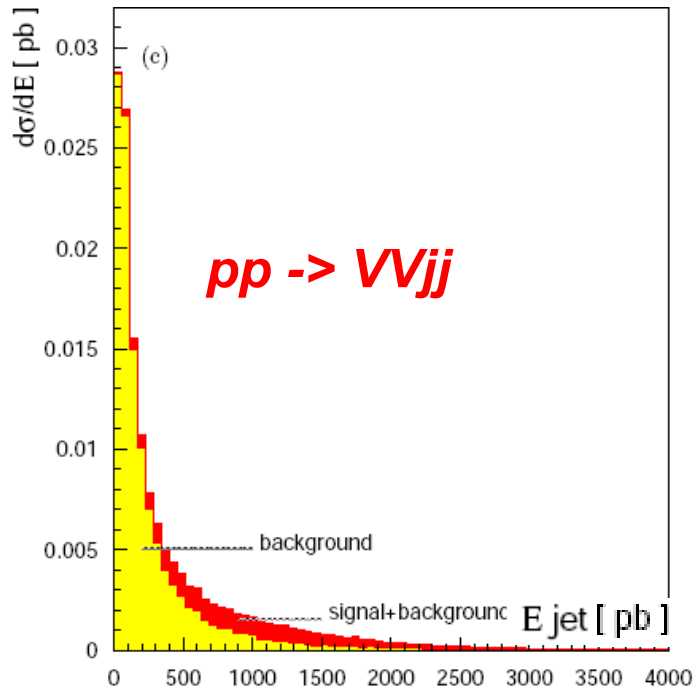
$$\mathcal{L}_{17} = \frac{1}{2} i \alpha_{17} \text{Tr}[T(\mathcal{D}_\mu V_\nu + \mathcal{D}_\nu V_\mu)]$$

$$\times \text{Tr}(TV^\mu) \text{Tr}(TV^\nu)$$

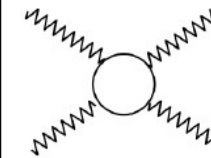
$$\mathcal{L}_{18} = \frac{1}{2} i \alpha_{18} \text{Tr}([V_\mu, T] \mathcal{D}^\mu \mathcal{D}^\nu V_\nu)$$

[Appelquist, Bernard '80 ; Longitano '80]

which can be tested at the LHC



the only quartic interactions under custodial symmetry



$$\mathcal{L}_4 = \alpha_4 (\text{tr}[V_\mu V_\nu])^2$$

$$\mathcal{L}_5 = \alpha_5 (\text{tr}[V_\mu V^\mu])^2$$

[AB, Eboli, Gonzalez-Garcia, Mizukoshi, Novaes, Zacharov '98]

[Eboli, Gonzalez-Garcia, Mizukoshi '06]

Why **do/should** we think about  
alternative way  
of Electroweak Symmetry  
Breaking?

# Example of Comparison

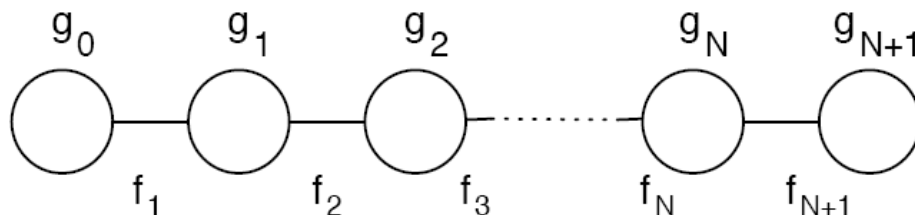
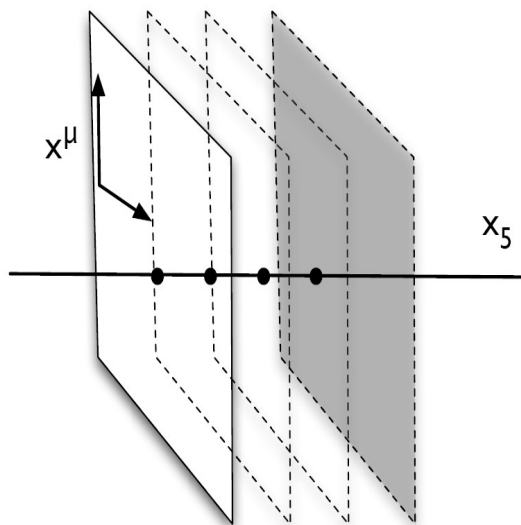
## SM Higgs vs Technicolor

- *simple and economical*
  - *GIM mechanism, no FCNC problems, EW precision data are OK for preferably light Higgs boson*
  - *SM is established, perfectly describes data*
  - *fine-tuning and naturalness problem; triviality problem*
  - *there is no example of fundamental scalar*
  - *Scalar potential parameters and yukawa couplings are inputs*
- *complicated at the effective theory level*
  - *FCNC constraints require walking, potential tension with EW precision data*
  - *no viable ETC model suggested yet, work in progress*
  - *no fine-tuning, the scale is dynamically generated*
  - *Superconductivity and QCD are examples of dynamical symmetry breaking*
  - *parameters of low-energy effective theory are derived once underlying ETC is constructed*

How one can preserve  
unitarity without Higgs ?

# DECONSTRUCTION

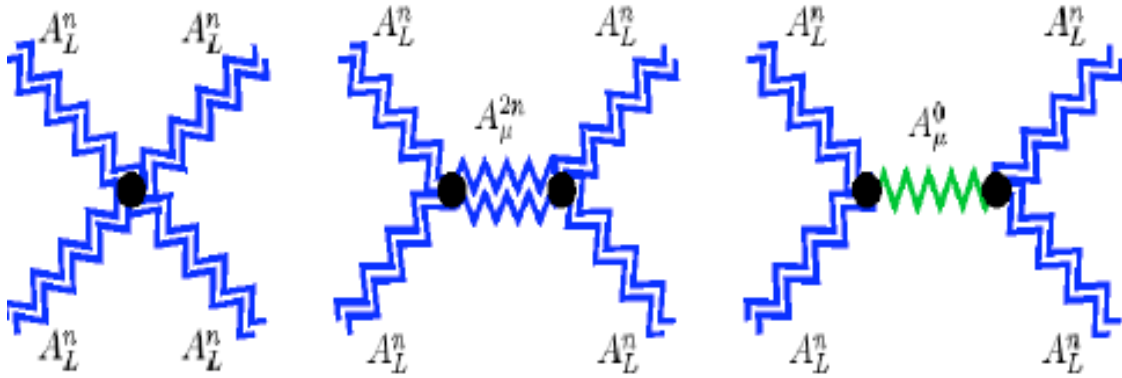
*moose diagram can be interpreted as the discretization of a continuum gauge theory in 5D along a fifth dimension*



- Discretize fifth dimension ↔
- 4D gauge group at each site ○
- Nonlinear sigma model link fields —
- To include warping: vary  $f_j$
- For spatially dependent coupling: vary  $g_k$
- Continuum Limit: take  $N \rightarrow$  infinity
- **Finite  $N$ , a 4D theory w/o 5D constraints**



# Conflict S and Unitarity

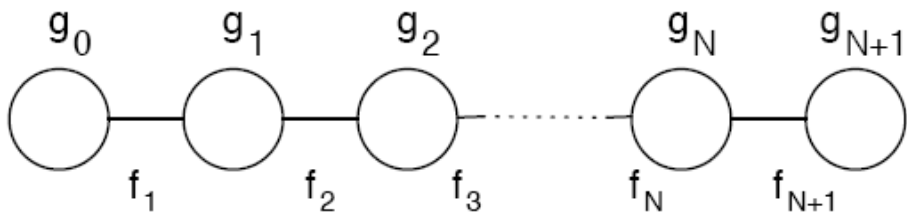


- ***Z' resonance unitarizes WW scattering, similar to what Higgs boson does in SM (Chivukula, He, Dicus)***

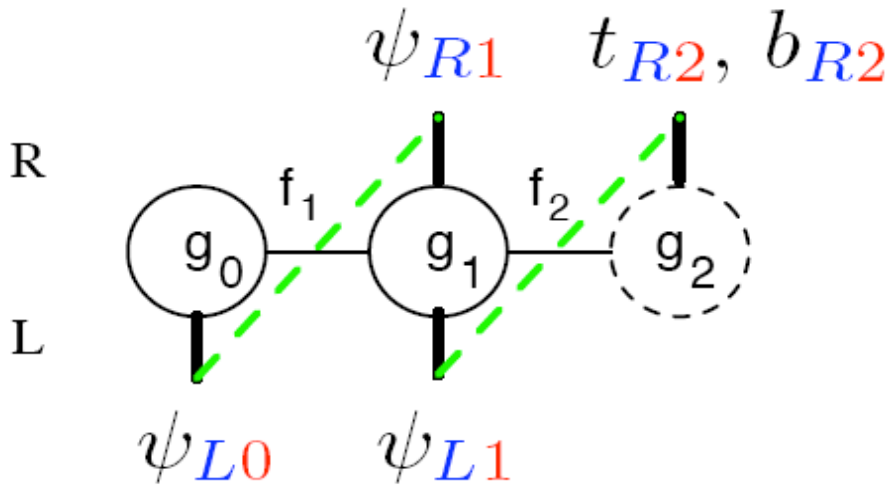
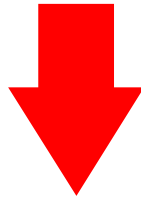
- ***Z' mass is bounded from above:  $m_{Z_1} < \sqrt{8\pi} v$***
- ***... and yields too much a value of S-parameter:  $\alpha S \geq \frac{4s_Z^2 c_Z^2 M_Z^2}{8\pi v^2} = \frac{\alpha}{2}$***   
[Chivukula, Simmons, He, Kurachi, Tanabashi]
- ***Solution – delocalization of the fermions: mixing of “brane” and “bulk” modes!***  
[Cacciapaglia, Csaki, Grojean, Reece, Terning; Foadi Gopalakrishna, Schmidt]
- ***Alternatively there could be a large contribution to T parameter [see talk by Riccardo Barbieri]***

# Three site model (TSM)

simplest, realistic, highly deconstructed, higgsless



Discretized 5<sup>th</sup> dimension written in the language of 'theory space'  
 [Arkani-Hammed, Georgi, Cohen; Hill, Pokorski, Wang]



gauge bosons: photon, Z, W, Z', W'

gauge sector is the BESS model  
 [Casalbuoni, De Curtis, Dominici, Gatto '85]

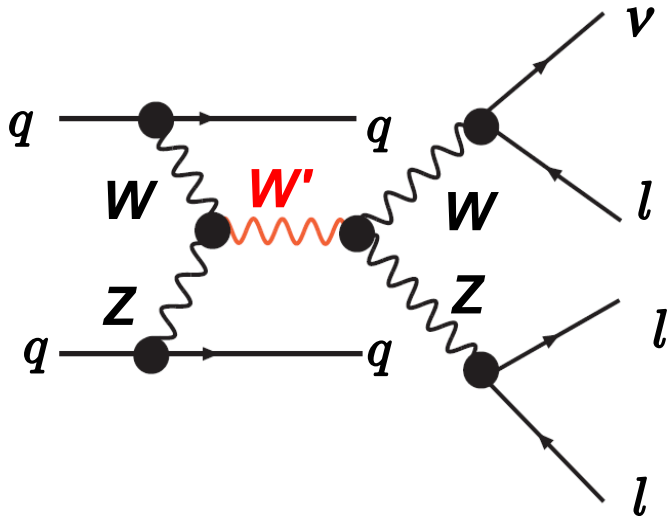
fermions: u, d, c, s, t, b  
 U, D, C, S, T, B  
 plus leptons

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

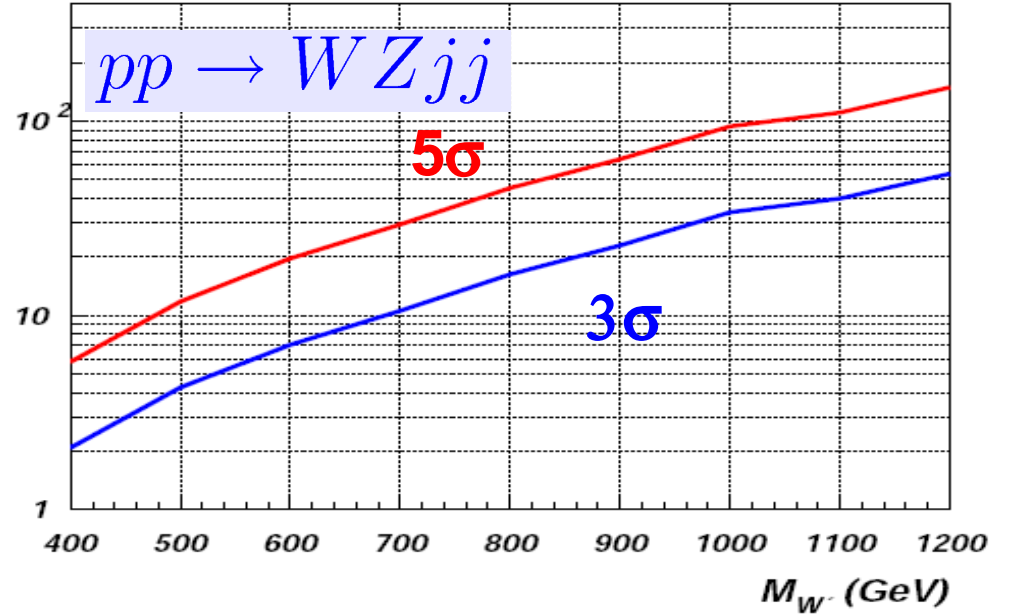
[Chivukula, Coleppa, Di Chiara, Simmons '06]

# LHC reach for $WZ \rightarrow W'$ process

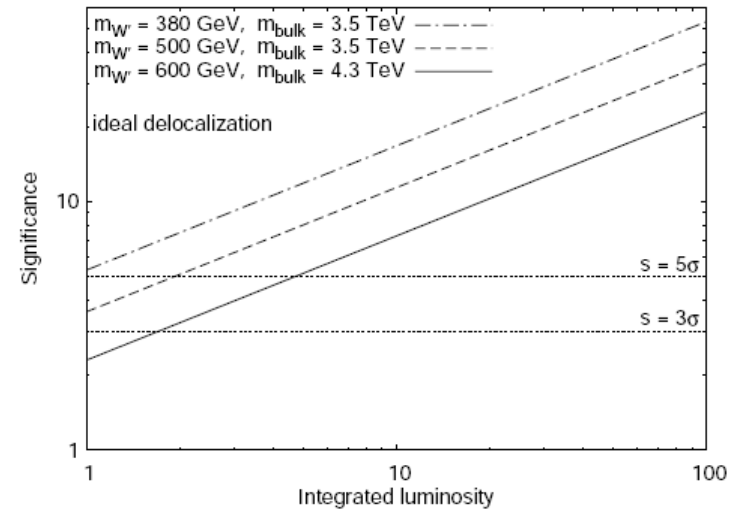
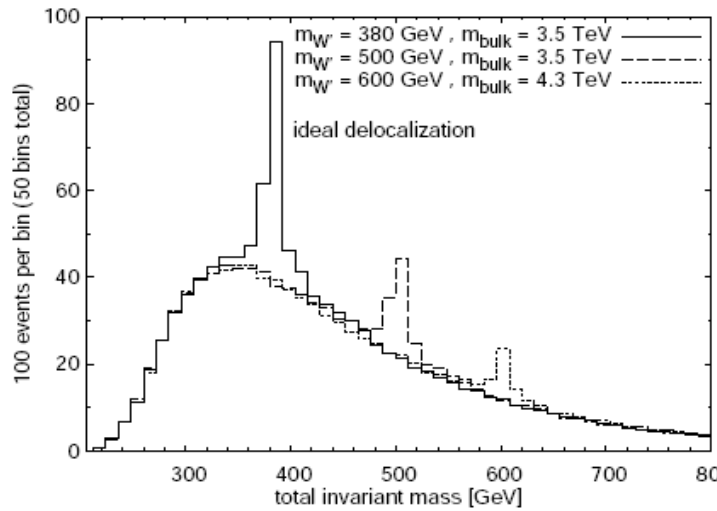
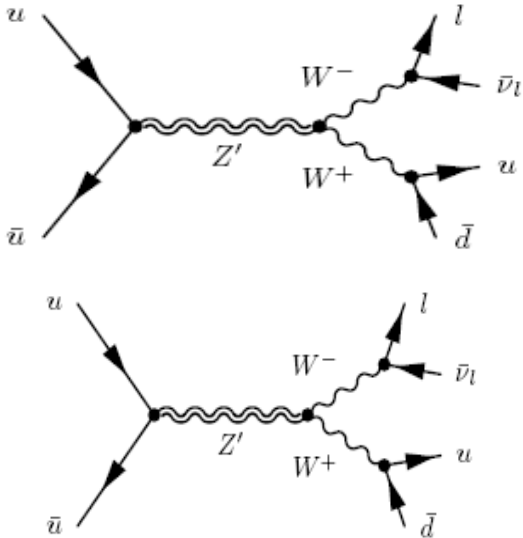
[AB, Chivukula, Christensen, He, Kuang, Pukhov, Qi, Simmons, Zhang '07]



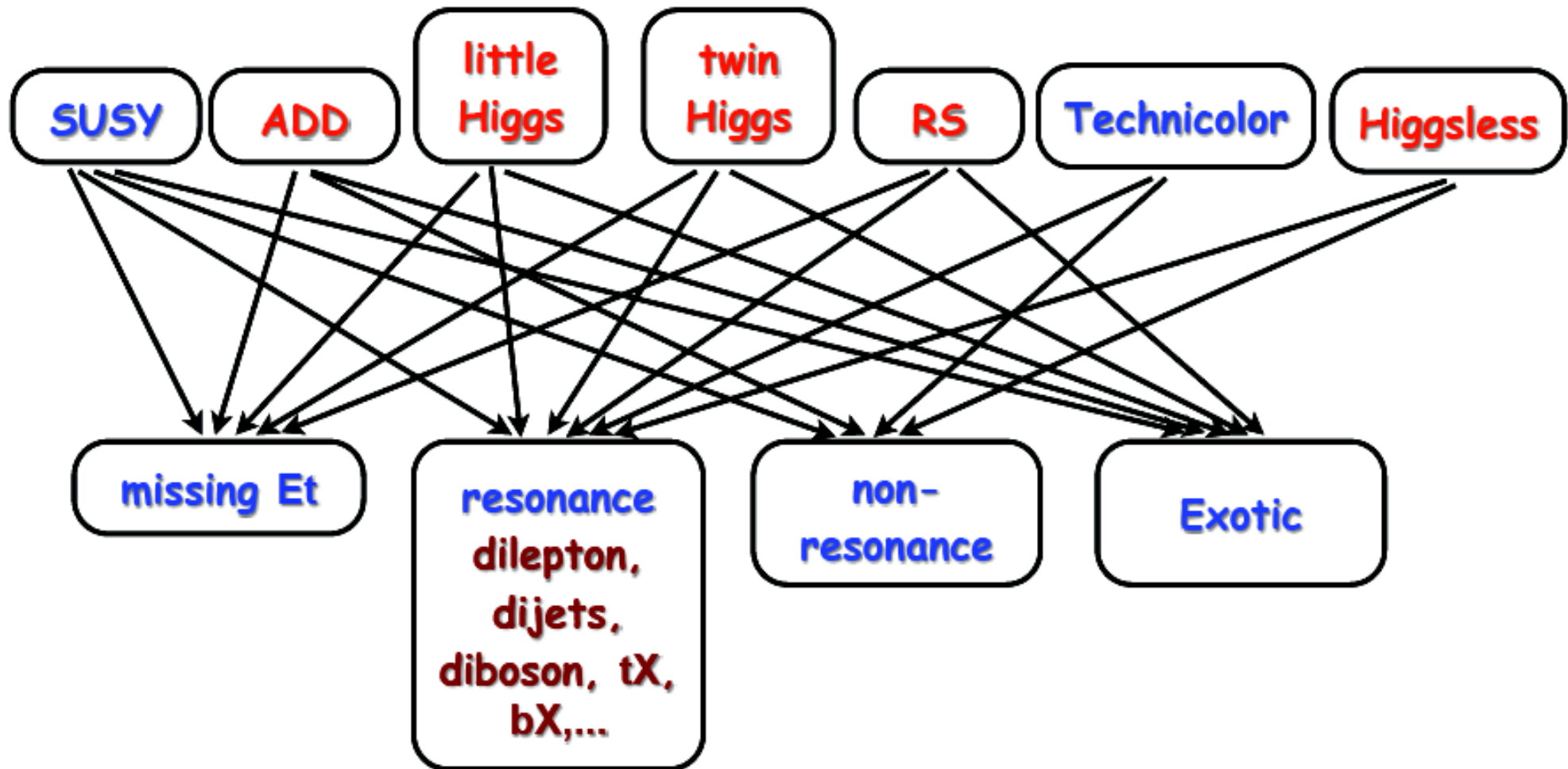
luminosity ( $\text{fb}^{-1}$ ) for discovery/observation



# LHC reach for $s$ -channel $Z'$ and $W'$ [Ohl, Speckner '08]

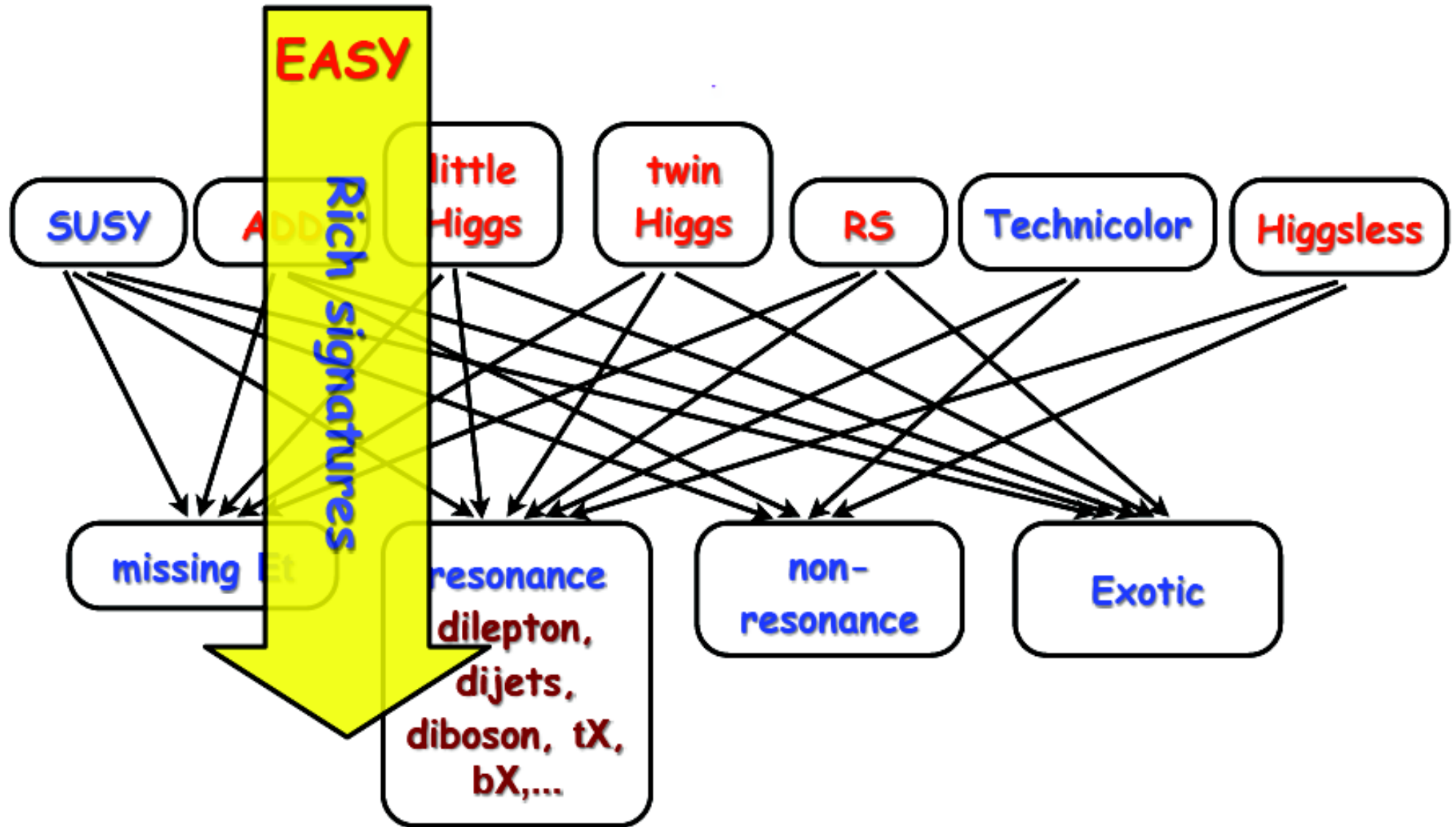


# What we should really worry about?



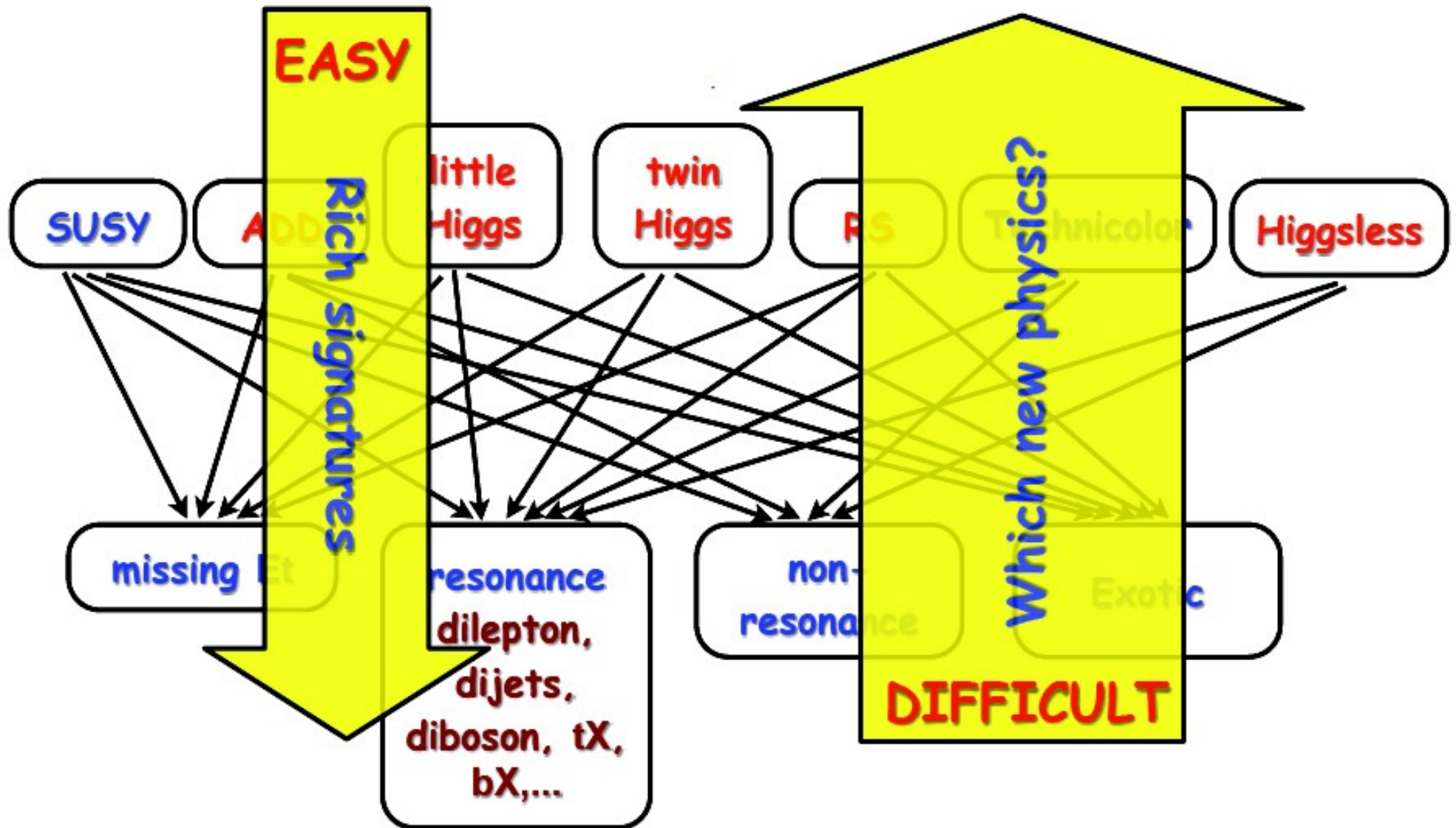
*From Sufang Su*

# What we should really worry about?



From Sufang Su

# What we should really worry about?



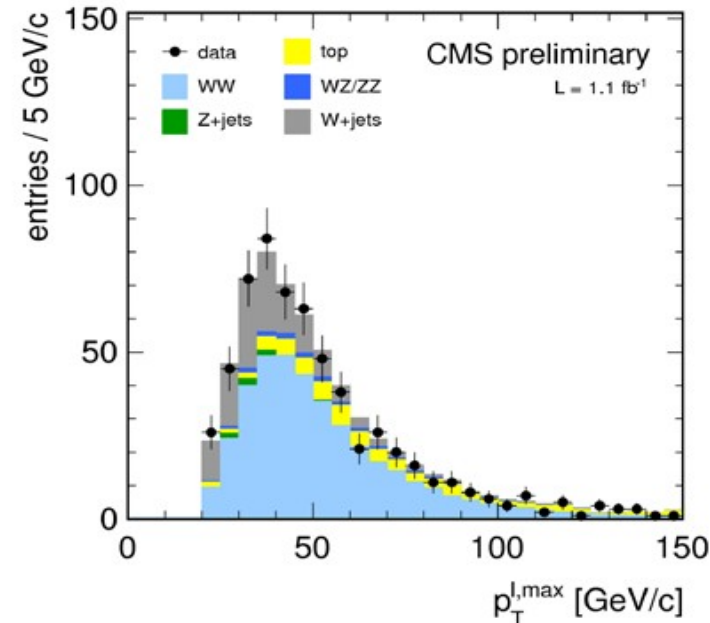
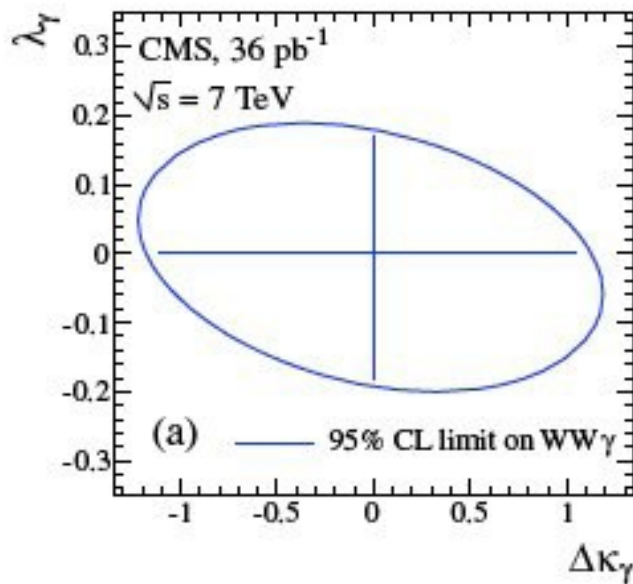
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# Reconstruction underlying theory of EWSB requires precision measurements

- Higgs couplings
- VV scattering in  $pp \rightarrow VVjj$  process
- Couplings of vector bosons to fermions

ATLAS&CMS search for deviation from expectations for TGB couplings: no anomalous coupling observed



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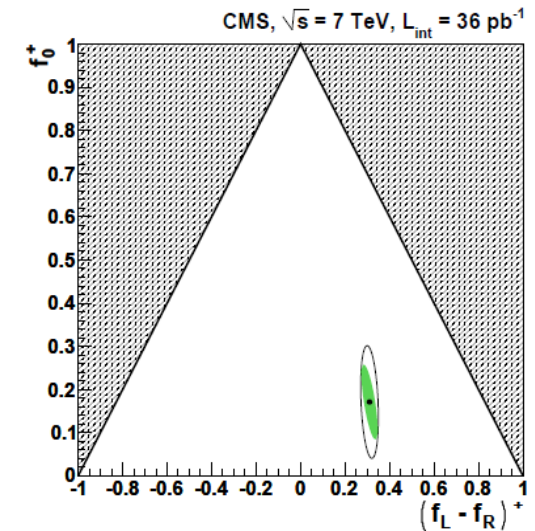
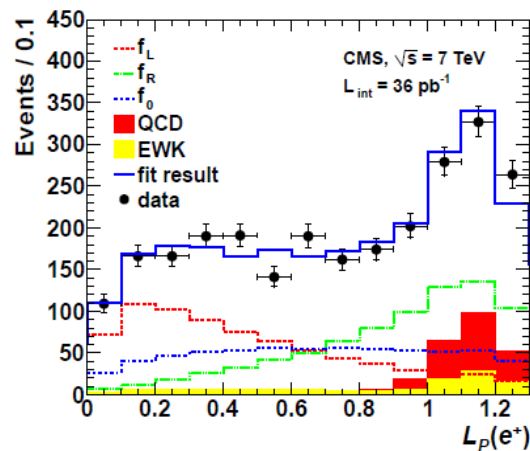
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Measurements of fermion-fermion-W couplings at CMS arXiv:1104.3829

$$\frac{dN}{d\cos\theta^*} \propto (1 + \cos^2\theta^*) + \frac{1}{2}A_0(1 - 3\cos^2\theta^*) + A_4\cos\theta^*.$$

$$L_P = \frac{\vec{p}_T(\ell) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$

$$\cos\theta^* = 2(L_P - \frac{1}{2})$$



Message to exp:

There is no factorisation for production and decay of W if  $L_P$  is used!

# Conclusions

- We are getting really close to understanding the nature of EWSB: **LHC is closing the gap!**
- Plenty different BSM scenarios are suggested and are possible. LHC has a potential to discover one or another.
- Understanding details of underlying theory of EWSB could be a tough job requiring precision measurements and generic strategy of reconstructing theory from various possible signatures