F. Zwirner
University & INFN, Padova

BSM physics at the LHC

Winter School on
Strings, Supergravity and Gauge Theories

CERN, 9-13 February 2009

Preamble: SM/BSM and the LHC

The Standard Model of strong, weak and e.m. interactions, effectively coupled to gravity near flat space, describes almost all known physics.

Even neglecting gravity and nu-oscillations
a part of the SM is still under discussion:
its symmetry-breaking sector
(must be disclosed within the TeV scale)
minimal SM: elementary scalar doublet

LHC has been built to settle this point
after the inputs from LEP and Tevatron

neutrino oscillations require only minor modifications
more serious exceptions with gravity and cosmology:
dark matter, dark energy, inflation, baryogenesis, …
none requires (one suggests) new physics at TeV scale

LHC: machine and experiments

LEP: $e^+ e^-$ collisions at $\sqrt{s} \leq 209$ GeV

Tevatron: $p\bar{p}$ collisions at $\sqrt{s} \simeq 2$ TeV

LHC: pp collisions at $\sqrt{s} = 14$ TeV

New schedule after 2008 accident being defined today:

- Collisions late 2009 to fall 2010 at 10 TeV, >200 pb^{-1}
- Then 14 TeV in 2011+, up to 10 (or more) fb^{-1}/year

Two general-purpose detectors:

ATLAS: A Toroidal Lhc ApparatuS CMS: Compact Muon Solenoid

Additional dedicated detectors:

LHCB (B physics), ALICE (heavy ions), TOTEM (forward detector)

Plan of the lectures

1. A critical overview of the SM
2. Bottom-up approaches to BSM
3. SUSY: if so, which incarnation?
4. Other BSM ideas for the LHC

SM: particle content and gauge interactions

Gauge group: G=SU(3)$_C$ × SU(2)$_L$ × U(1)$_Y$ [Q=T$_{3L}$+Y]

$$\mathcal{L}_{YM} = -\frac{1}{4} G^{\mu\nu\,A} G^{A}_{\mu\nu} - \frac{1}{4} W^{\mu\nu\,I} W^{I}_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}$$

Fermion content: 3 families of quarks and leptons

$$q_L \sim (3,2,+1/6) \quad l_L \sim (1,2,-1/2) \quad u_R \sim (3,1,+2/3) \quad d_R \sim (3,1,-1/3) \quad e_R \sim (1,1,-1)$$

$$\mathcal{L}_F = i\overline{\Psi}\gamma^\mu D_\mu \Psi \qquad D_\mu = \partial_\mu - i g_S G^A_\mu \lambda^A - i g W^I_\mu \frac{\tau^I}{2} - i g' B_\mu Y$$

unobserved global flavour symmetry: SU(3)^5 x U(1)^4

The big OPEN question is on symmetry breaking
minimal SM realization or alternative one?

Symmetry breaking in the minimal SM

$$\phi \equiv \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \sim (1,2,+1/2)$$

Elementary SM
Higgs field

$$\mathcal{L}_S = (D_\mu \phi)^\dagger (D^\mu \phi) - V \qquad V = \mu^2 \phi^\dagger \phi + \lambda \left(\phi^\dagger \phi\right)^2$$

spontaneous breaking of the gauge symmetry:

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

$$\mathcal{L}_Y = \overline{q_L}\, Y^U\, u_R\, \tilde{\phi} + \overline{q_L}\, Y^D\, d_R\, \phi + \overline{l_L}\, Y^E\, e_R\, \phi + \text{h.c.}$$

$$\tilde{\phi} \equiv (i\sigma^2 \phi^*) = \begin{pmatrix} \varphi^{0*} \\ -\varphi^- \end{pmatrix} \sim (1,2,-1/2)$$

conjugate
doublet

explicit breaking of the global flavour symmetry:

$$SU(3)^5 \times U(1)^4 \to U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

(before the modifications to account for neutrino masses)

Spectrum and interactions

$$\lambda > 0 \quad \& \quad \mu^2 < 0 \quad \Rightarrow \quad \langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8m_W^2} = \frac{1}{2v^2} \qquad \Rightarrow \qquad v \simeq 246 \text{ GeV}$$

$$m_W^2 = \frac{g^2v^2}{4} \qquad m_Z^2 = \frac{(g^2+g'^2)v^2}{4} \qquad m_\gamma = 0$$

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

undetermined

$$V \Rightarrow -\frac{\lambda}{4}v^4 + \lambda v^2h^2 + \lambda v h^3 + \frac{\lambda}{4}h^4$$

Crucial property n.1: custodial symmetry

[Sikivie-Susskind-Voloshin-Zakharov, 1980]

Minimal SM
(tree level)

$$\rho_0 \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

Veltman
rho param.

$$\left(\tan\theta_W = \frac{g'}{g}\right)$$

Can be interpreted in terms of a symmetry (also BSM)

$$\mathcal{L}_m = \frac{1}{2} m_W^2 (W_{1\mu} W_1^\mu + W_{2\mu} W_2^\mu) + \frac{1}{2} (W_{3\mu}\, B_\mu) \begin{pmatrix} M^2 & M'^2 \\ M'^2 & M''^2 \end{pmatrix} \begin{pmatrix} W_3^\mu \\ B^\mu \end{pmatrix}$$

$$m_\gamma = 0 \quad \Rightarrow \quad M^2 M''^2 = M'^4 \quad M^2 + M''^2 = m_Z^2 \quad \Rightarrow \quad \rho = 1 \leftrightarrow M^2 = m_W^2$$

$$V = V(\phi^\dagger\phi) \;\; \text{invariant under} \;\; O(4) \sim SU(2)_L \times SU(2)_R$$

$$\text{symmetry broken by} \langle\phi\rangle \text{ to } SU(2)_V \quad \Rightarrow \quad \rho_0 = 1$$

Largest SM quantum correction controlled by m_t-m_b

➔ could estimate m_t before direct top discovery

Crucial property n.2: CKM/GIM (MFV)

$$\mathcal{L}_Y \Rightarrow (\overline{u_L}\, Y^U\, u_R + \overline{d_L}\, Y^D\, d_R + \overline{e_L}\, Y^E\, e_R)\frac{(v+h)}{\sqrt{2}} + \text{h.c.}$$

Move to fermion mass eigenstates

$$u_L \to V_L^u\, u_L \qquad u_R \to V_R^u\, u_R \qquad d_L \to V_L^d\, d_L \qquad \dots$$

$$\mathcal{L}_Y \Rightarrow -(m_t\, \overline{t_L}\, t_R + m_b\, \overline{b_L}\, b_R + \dots)\left(1 + \frac{g}{2m_W}h\right) + \text{h.c.}$$

$$\mathcal{L}_{g.int} = \frac{g}{2\sqrt{2}}(J_W^\mu W_\mu^- + J_W^{\mu\dagger} W_\mu^+) + e\, J_{EM}^\mu A_\mu + \frac{g^2 + g'^2}{2} J_Z^\mu Z_\mu$$

$$J_W^\mu = 2(\overline{e_L}\gamma^\mu \nu_L + \overline{d_L}\gamma^\mu V_{CKM} u_L) \qquad (diagonal\ J_{EM}^\mu, J_Z^\mu)$$

$V_{CKM} = V_L^{d\dagger} V_L^u$ only source of flavour change/CPV

(in renormalizable operators made of minimal-SM fields)

Precision tests of EW breaking

Electroweak theory tested at the level of quantum corrections by precision measurements at SLC, LEP, Tevatron and more: large number of observables, many with per-mille accuracy

SM radiative corrections vs. m_t and m_h

For fixed values of the remaining SM input parameters:

$$\Delta m_W \simeq -(57\,MeV)\ \log X_h - (9\,MeV)\ (\log X_h)^2 + (0.54\,GeV)\ (X_t^2 - 1)$$

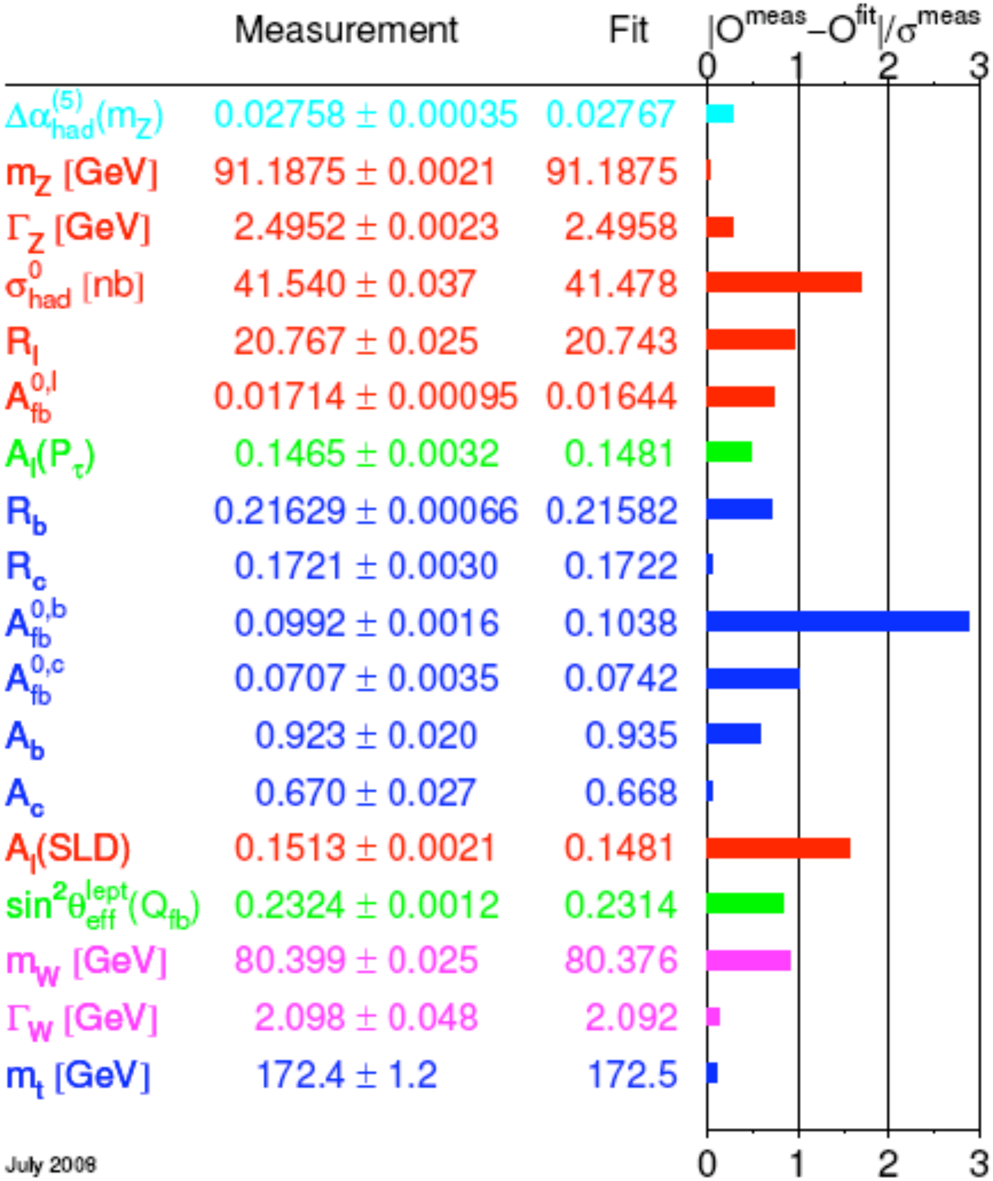
$$\Delta \sin^2_{eff} \simeq 4.9 \times 10^{-4}\ \log X_h + 3.4 \times 10^{-5}\ (\log X_h)^2 - 2.8 \times 10^{-3}\ (X_t^2 - 1)$$

$$X_h = \frac{m_h}{100\,GeV} \qquad X_t = \frac{m_t}{174.3\,GeV}$$

Now that m_t is precisely known, indirect constraints on m_h

Correlations: $m_{t\downarrow} \rightarrow m_{h\downarrow}$ $m_{W\downarrow} \rightarrow m_{h\uparrow}$ $s2w_{l\downarrow} \rightarrow m_{h\downarrow}$

SM fit to EW precision tests [Summer 2008]



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4958
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01644
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21582
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.376
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	172.4 ± 1.2	172.5

Recent update:

$M_t = 172.4 \pm 1.2$ GeV

- SM still fits well at such high precision!
- Indication for light Higgs in the SM

$M_H = 84^{+34}_{-26}$ GeV

$M_H < 154$ GeV (95%CL)

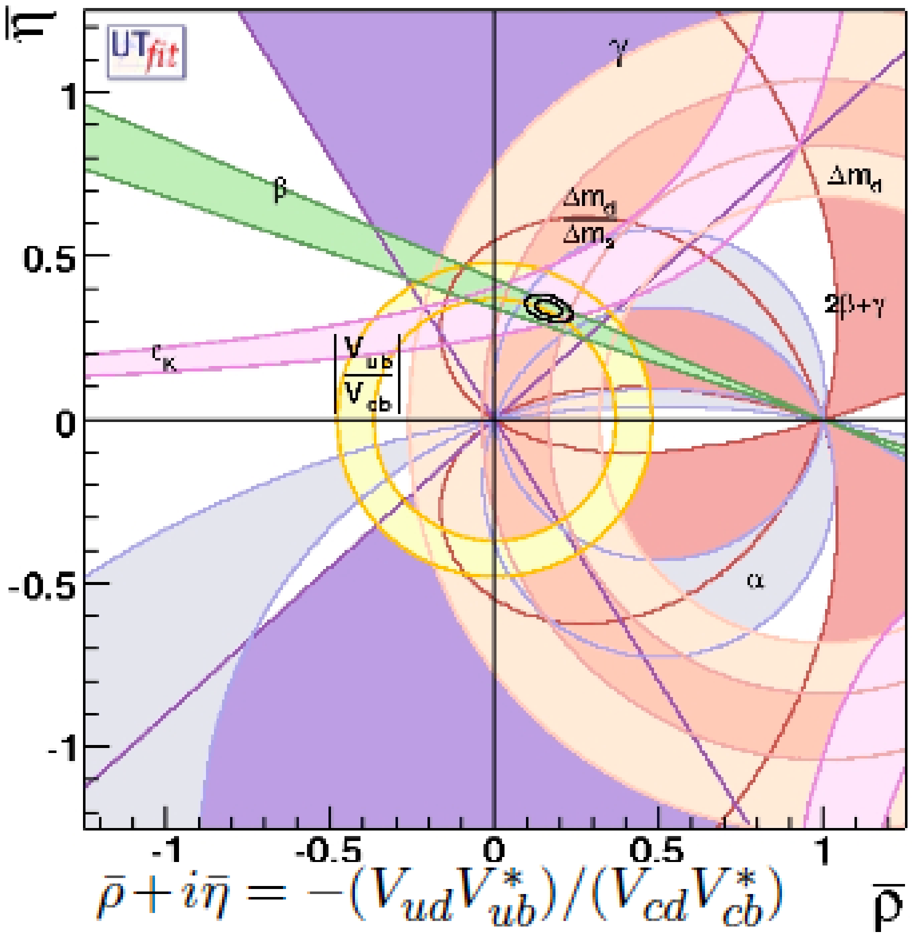
Including direct bound $M_H > 114.4$ GeV (95%cl):

$M_H < 185$ GeV (95%CL)

Precision tests of flavour breaking

Impressive recent progress (B-factories, Tevatron):
no confirmed deviation from SM (GIM, CKM) found

The unitarity triangle



$$\bar\rho + i\bar\eta = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)$$

Some examples:

Δm_s $\quad B \to \tau\nu$

$B \to X_s\gamma$ $\quad B \to X_s l^+ l^-$

$B_s \to \mu^+\mu^-$ bound

$\mu \to e\gamma$ bound

More K and B decays
CP-violation in B system
Tree-level vs. 1-loop UT

Message: little room for flavour breaking at TeV scale not in $\mathcal{L}_Y$

Two non-trivial SM tests in flavour physics

Inclusive b ➔s gamma (top-W loop):

$$BR(B \to X_S\,\gamma)^{exp}_{E_\gamma > 1.6\,GeV} = (3.52 \pm 0.25) \times 10^{-4}$$

[HFAG, 2008]

$$BR(B \to X_S\,\gamma)^{SM}_{E_\gamma > 1.6\,GeV} = (3.15 \pm 0.23) \times 10^{-4}$$

[Misiak 08]

B_s ➔ mu mu (Z-penguin dominated):

$$BR(B_s \to \mu^+\,\mu^-)^{SM} = (3.9 \pm 0.8) \times 10^{-9}$$

[0801.1833]

$$BR(B_s \to \mu^+\,\mu^-)^{exp} < 4.7 \times 10^{-8}\ (95\% cl)$$

[CDF]

One of the highlights of LHCb !

Any hints of a SM crisis (at the Fermi scale) ?

- SM incomplete because of quantum gravity
- String theory the most serious line of attack
- No solid prediction so far at the Fermi scale
- At best some plausible “stringy” scenarios

Will address here the problem more concretely:
combination experiment/theory
with more weight on experiment for now

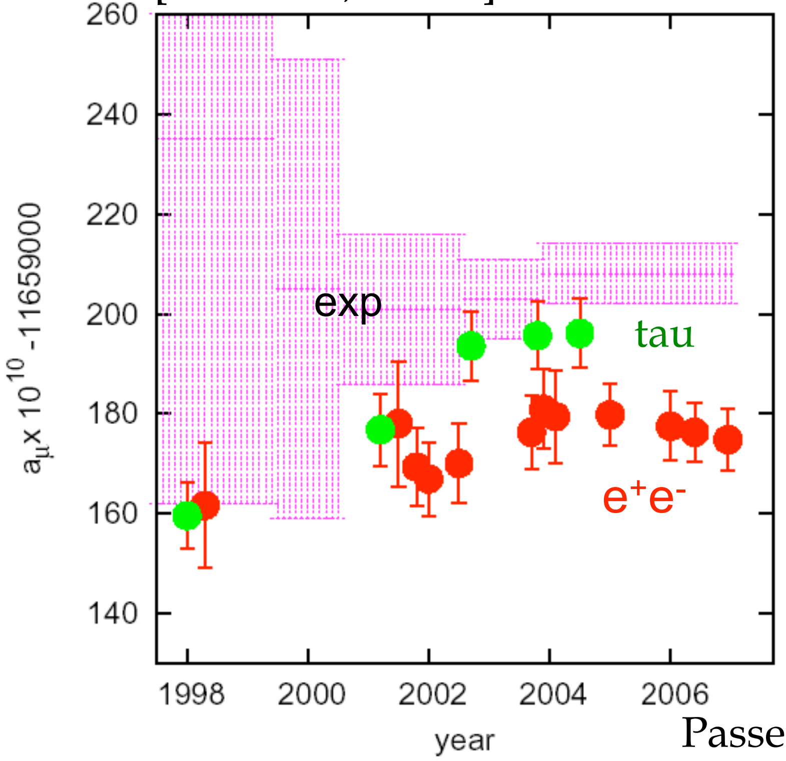
- The muon (g-2) puzzle
- Problems with EW precision tests
- Dark matter

Will add more theoretical bias in lecture 2:

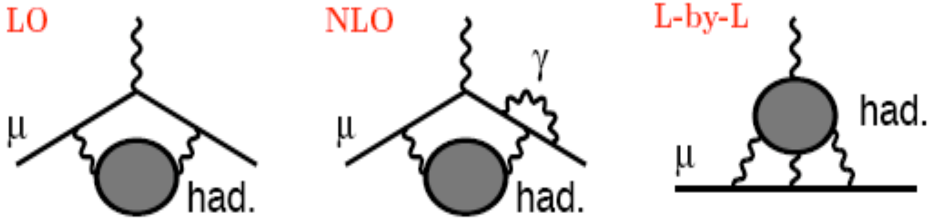
- Naturalness/Hierarchy problem

The muon (g-2) puzzle

[Gambino, EPS07]



dominant TH error: hadronic



At present, after many years:

$\sim 3\sigma$ *discrepancy*

but still evolving…

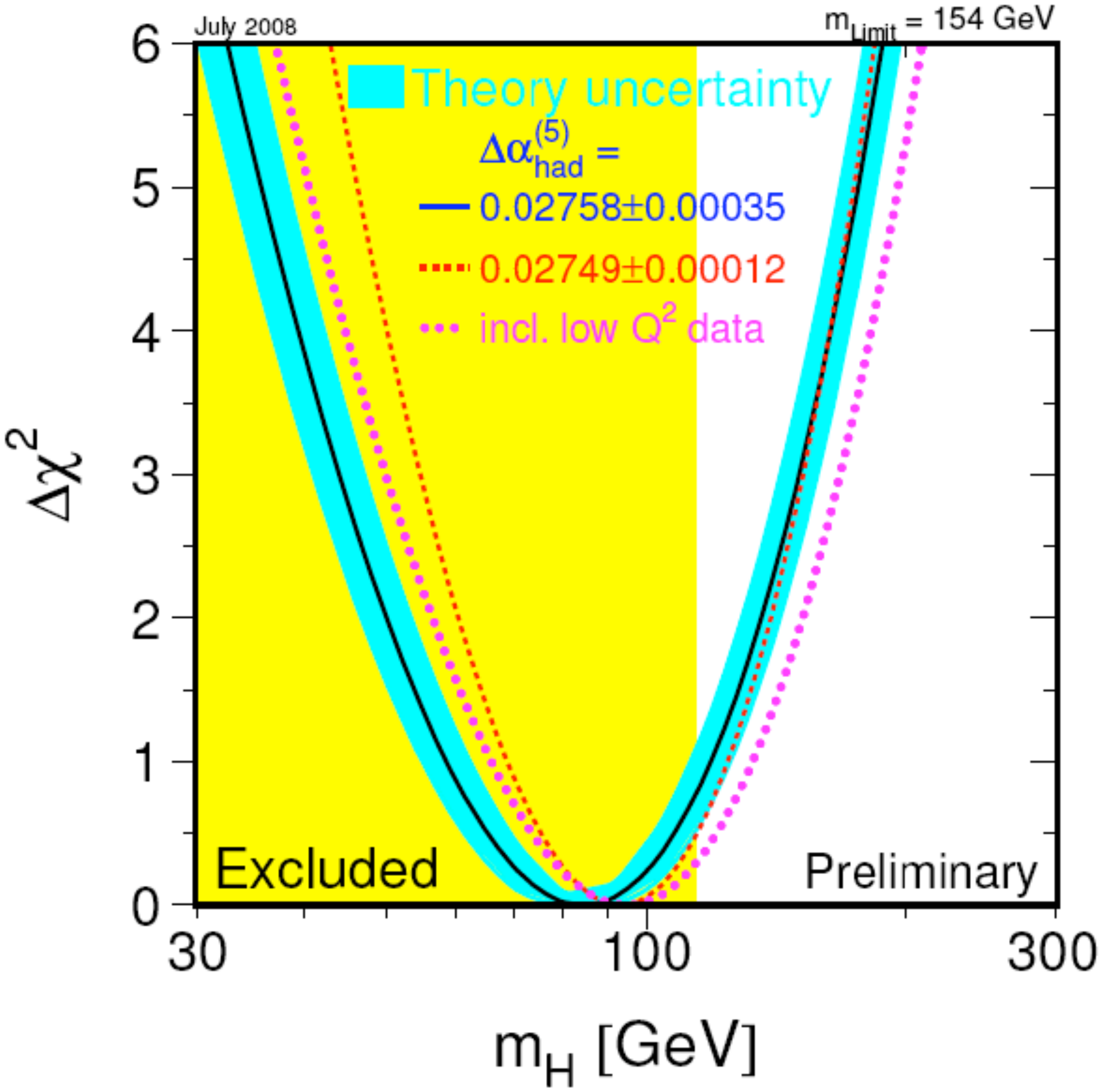
Passera, hep-ph/0702027

a_μ: Standard Model vs. measurement.

	$a_\mu^{\rm SM} \times 10^{11}$	$\Delta \times 10^{11}$	σ
[68]	116 591 763 (60)	317 (87)	3.7 $\langle 3.2 \rangle$
[69]	116 591 748 (61)	332 (88)	3.8 $\langle 3.4 \rangle$
[70]	116 591 775 (69)	305 (93)	3.3 $\langle 2.8 \rangle$
[71]	116 591 798 (63)	282 (89)	3.2 $\langle 2.7 \rangle$
[73]	116 591 961 (70)	119 (95)	1.3 $\langle 0.7 \rangle$

New Physics?
If so, SUSY?
or
Underestimated TH
(QCD) systematics?

Direct vs. Indirect Higgs mass bounds

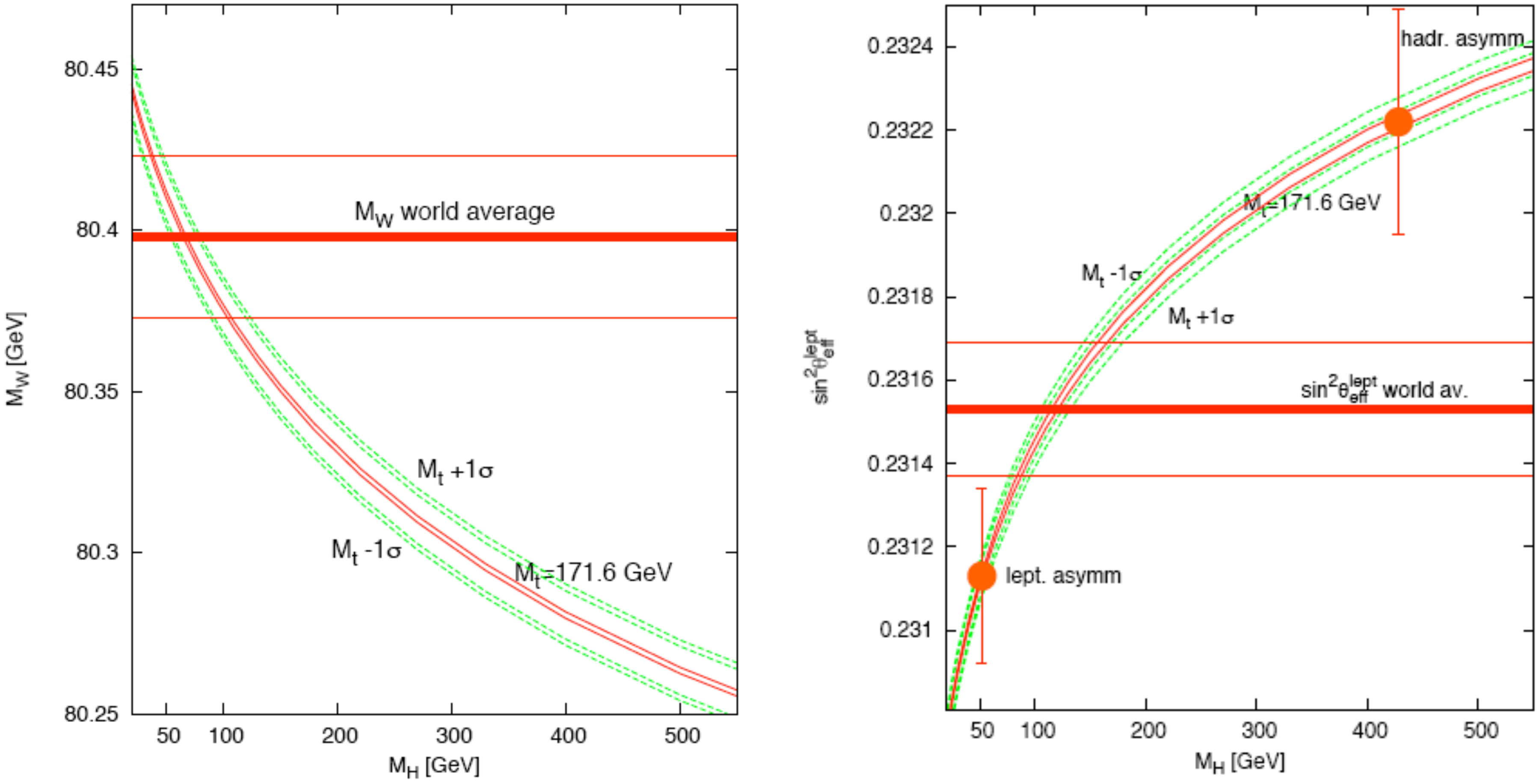


Too small m_H from fit?
Probability of
M_H>114 GeV:
~20%

Nothing dramatic,
but
how does this arise?

What prefers a light Higgs?

[Gambino]



Correlations: $M_{top\downarrow} \Rightarrow m_{H\downarrow}$ $M_{W\downarrow} \Rightarrow m_{H\uparrow}$ $s2w_{l\downarrow} \Rightarrow m_{H\downarrow}$

- M_W points to a light Higgs, with good accuracy
- Some tension in leptonic vs. hadronic asymmetries

Dark matter

Increasing evidence for dark matter over the years:

- Rotational curves of galaxies
- Cosmic microwave background
- Gravitational lensing

Should account for 20-25% of universe energy density

A possible generic dark matter candidate:
WIMP = Weakly Interacting Massive Particle
(not the only acceptable one, see e.g. the axion)

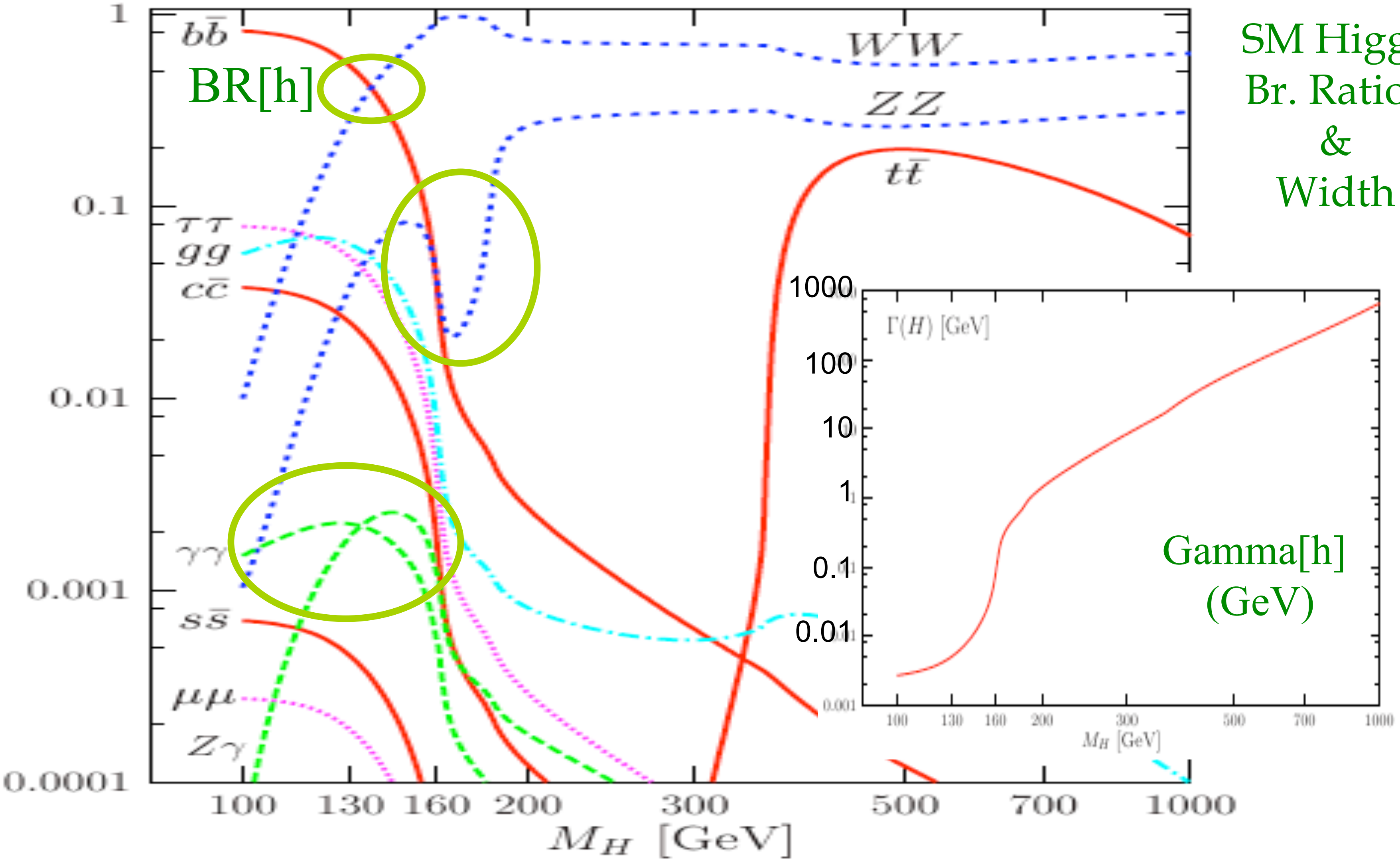
For WIMPs in thermal equilibrium after inflation need

$$\langle \sigma\, v \rangle \sim 1\,\mathrm{pb}$$

EW-size cross-section for particle with M=O($10^{2\text{-}3}$ GeV)
Another argument for new physics at the Fermi scale
(once again, quite plausible but not really compelling)

The search for the SM Higgs boson

In the SM, the only unknown parameter is m_H

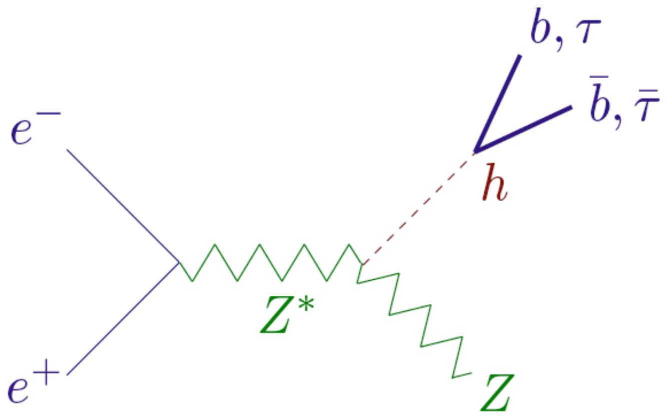


SM Higgs
Br. Ratios
&
Width

LEP Higgs searches [Aleph, Delphi, L3, Opal]

LEP signals for a SM Higgs

$$e^+\ e^- \to Z^* \to Z^*\ H^* \to f\,\overline{f}\ f'\,\overline{f'}$$



SM: $m_h > 114.4$ GeV at 95% c.l. [4 expts combined]

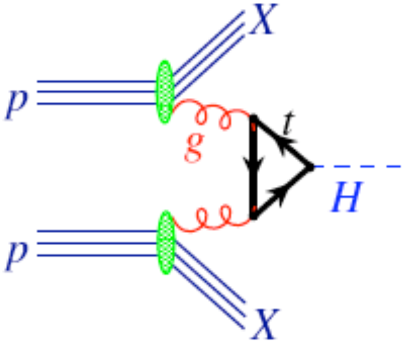
Slight ALEPH excess, mostly in 4-jets, near 115-6 GeV

Also bounds on HZZ coupling, varying m_h and decay modes

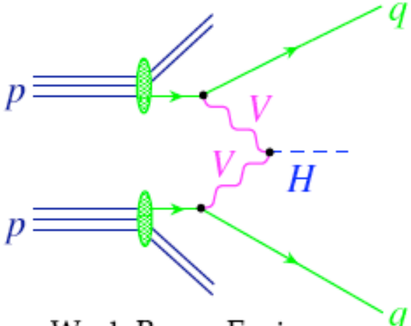
Exotic decays with SM hZZ: 100% hadronic ➔ 112.9 GeV;
100% invisible ➔ 114.4 GeV; Fermiophobic ➔ 108.2 GeV.

Higgs production at hadron colliders

g g ➔ H + X :
gluon fusion
dominant at Tevatron/LHC

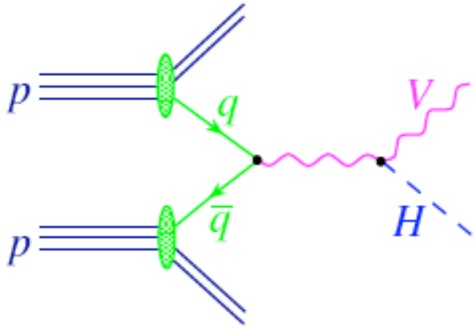


q q ➔ q q H + X :
weak boson fusion (V=W,Z)
LHC: by far the 2nd cross-section
Tevatron: competes with WH/ZH



Weak-Boson Fusion

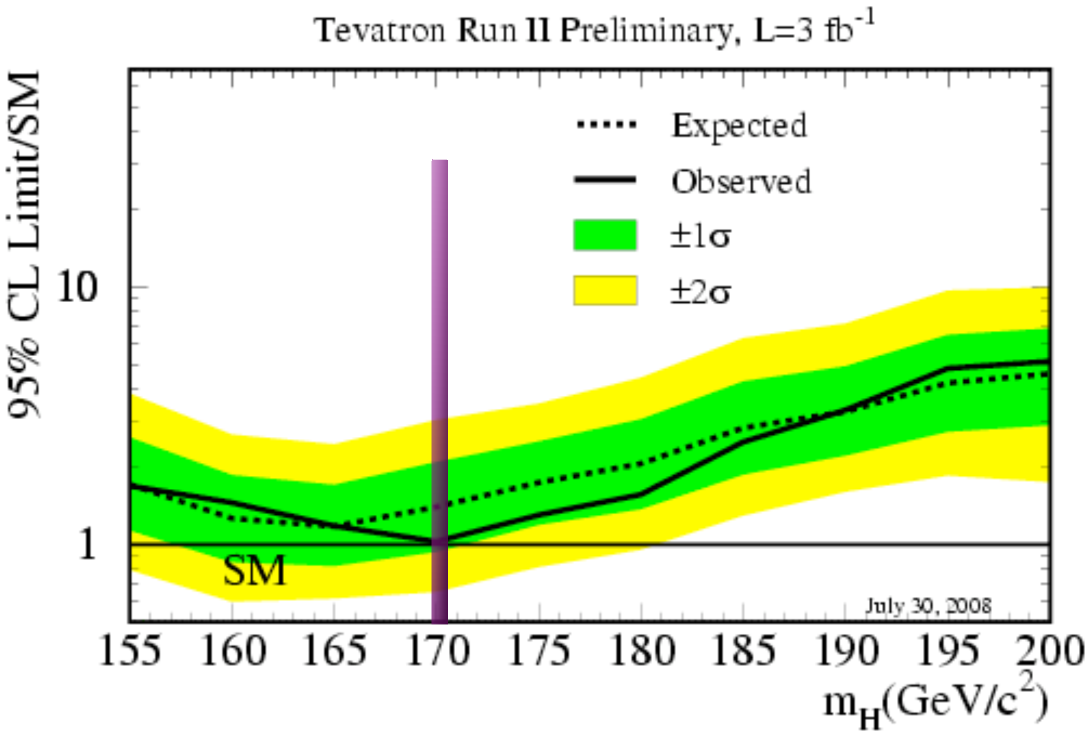
q qbar ➔ V H + X :
associated prod. with V=W,Z
Small cross-section
(especially at LHC)
but V-tagged signal!

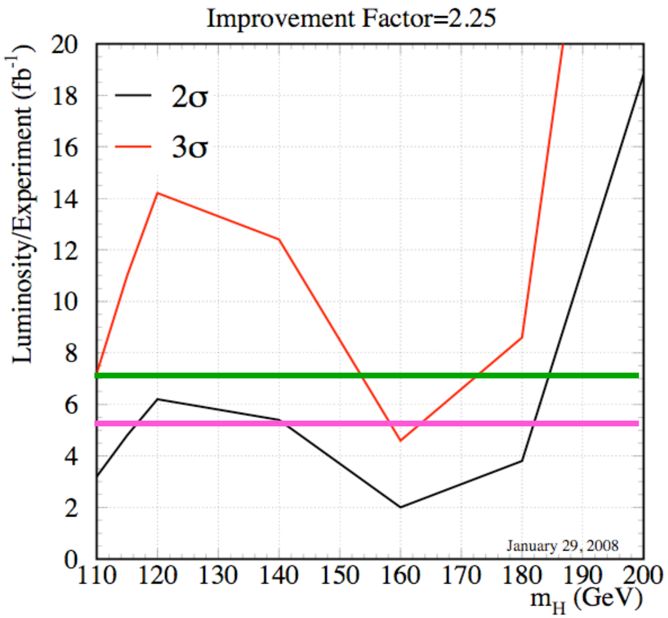


Tevatron searches [CDF, D0]

Two main branches depending on m_H:

- pp→VH, H→bbbar (m_H < 135-140 GeV)
- pp→HX, H→W^+W^- →dileptons (135-140 GeV < m_H)





With 7-8 fb^{-1} (2010)
exclude most masses

With 5.5-6 fb^{-1} (2009)
Exclude 140:180 range

SM Higgs hunting at the LHC

Gold-plated (good for $m_H > 130$ GeV)

$$p\,p \to H + X \qquad H \to Z\,Z \to l^+ l^-\, l'^+ l'^- \quad (l, l' = e, \mu)$$

Silver-plated (discovery for $150 < m_H < 180$ GeV)

$$p\,p \to H + X \qquad H \to W^+\,W^- \to l^+ \nu\, l'^- \overline{\nu}' \quad (l, l' = e, \mu)$$

What if there is a SM Higgs with $m_H < 130$ GeV ?

The most difficult region:

will take time! (luminosity, detectors, background)

$$pp \to H + X \quad H \to \gamma\gamma \qquad \Big(p\,p \to qqH \quad H \to WW/\tau\tau\Big)$$

plus other channels good only at very high luminosity

Luminosity requirements in CMS (similar ATLAS study available)