LUND UNIVERSITY

Higgsportal

Johan Rathsman

The "Higgs" discovery - a portal to new physics

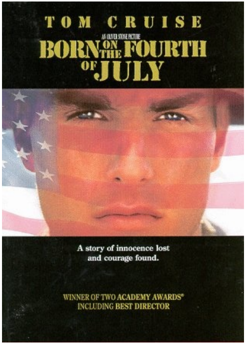
Johan Rathsman

Department of astronomy and theoretical physics, 2012-10-17

The “Higgs” discovery

July 4th 2012 - a historic day in many ways . . .

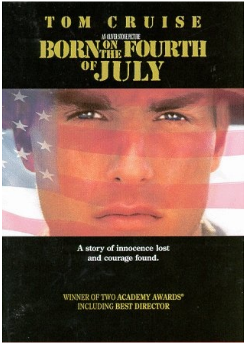
July 4th 2012 - a historic day in many ways . . .

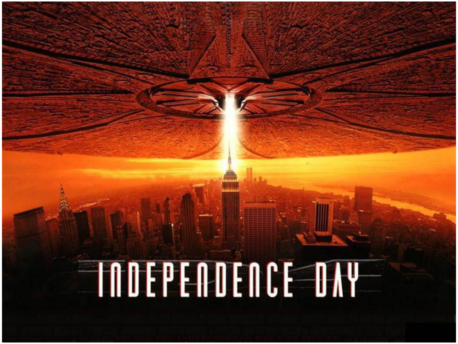


Higgsportal

Johan Rathsman

July 4th 2012 - a historic day in many ways . . .



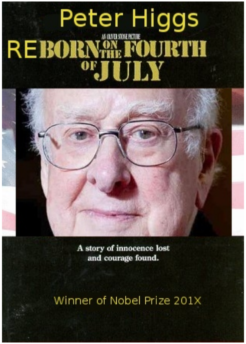


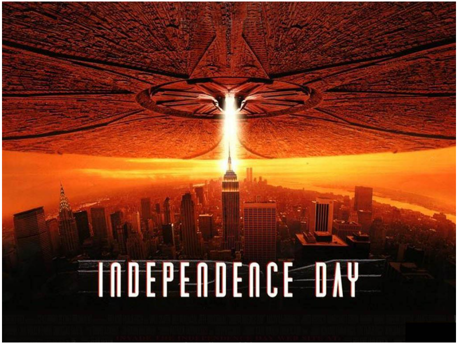
LUND UNIVERSITY

Higgsportal

Johan Rathsman

July 4th 2012 - a historic day in many ways . . .



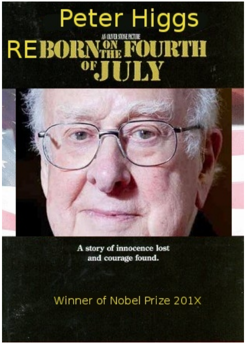


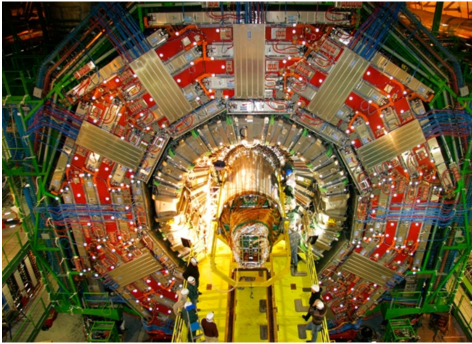
Now also in the world of particle physics

Higgsportal

Johan Rathsman

July 4th 2012 - a historic day in many ways . . .





Now also in the world of particle physics

and in Lund

LUND UNIVERSITY

Higgsportal

Johan Rathsman

Published


HOME PAGE | TODAY'S PAPER | VIDEO | MOST POPULAR | U.S. Edition

Log In | Register Now

MARCJACOBS.COM

The New York Times

Wednesday, July 4, 2012 Last Update: 4:00 AM ET

TRY A TIMES DIGITAL SUBSCRIPTION: 4 WEEKS FOR 99¢. CLICK HERE

Search

Follow Us | Personalize Your Weather

WORLD
U.S.
POLITICS
NEW YORK
BUSINESS
DEALBOOK
TECHNOLOGY
SPORTS
SCIENCE
HEALTH
ARTS
STYLE
OPINION

Autos
Blogs
Books
Cartoons
Classifieds
Crosswords
Dining & Wine
Education
Event Guide
Fashion & Style
Home & Garden
Jobs
Magazine
Movies
Music
Obituaries

Rapid H.I.V. Home Test Wins Federal Approval

By DONALD G. McNEIL Jr.

The OraQuick test, which uses a cheek swab and gives results in 20 to 40 minutes, is the first chance for Americans to learn in the privacy of their own homes whether they are infected.

DEALBOOK

As Bank Frames a Defense, Barclays' C.E.O. Resigns

By BEN PROTESS and MARK SCOTT

Ahead of a British parliamentary hearing, senior Barclays executives said they thought they had implicit approval from regulators to manipulate interest rates.

- A Chief With Flair Falls

Top Judge Helped Egyptian Military

Pool photo by Denis Balibouse

New Particle Could Be Physics' Holy Grail

By DENNIS OVERBYE 4 minutes ago

If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva, could explain the universe's origin.

Fears of Fires Take Fireworks Out of July 4th Celebrations

By DAN FROSCH

Many U.S. cities and towns across the country have decided to scrap their displays, driven by parched

As Symbols Clash, Fireworks Lose Out to a Hamlet's Bald Eagles

By AARON EDWARDS

The Fire Department in Narrowsburg, N.Y., canceled its annual display after planned fireworks were said to

OPINION »

EDITORIAL

Too Quiet, Again, on Health Care

The Obama campaign has not forcefully countered Republican misinformation on the reform law.

- Dowd: Gaelic Guerrilla
- Friedman: Morsi, Israel
- Douthat: Books for Obama
- Fixes: Rwanda's Miracle
- Kurt Andersen: The Downside of Liberty
- Op-Ed: Anderson Cooper

MARKETS » At 4:02 AM ET

Britain	Germany	France
FTSE 100	DAX	CAC 40
5,673.04	6,553.19	3,248.93
−14.69	−25.02	−22.27
−0.26%	−0.38%	−0.68%

Data delayed at least 15 minutes

GET QUOTES My Portfolios »

Stock, ETFs, Funds Go

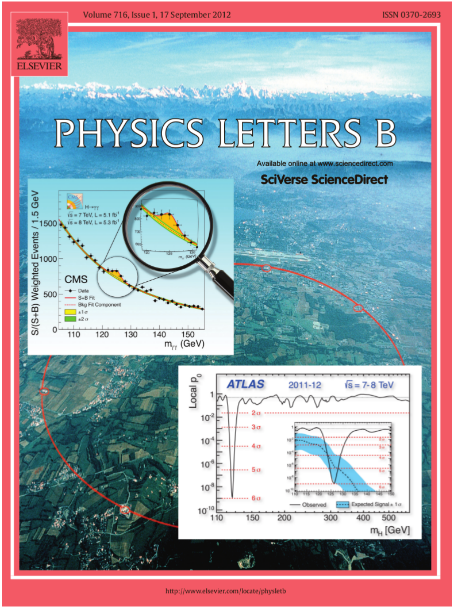
The New York Times TRY IT NOW 4 WEEKS FOR 99¢ CLICK HERE

INTRODUCING NEW YORK TIMES CORPORATE DIGITAL SUBSCRIPTIONS.
From insight comes inspiration.

Published

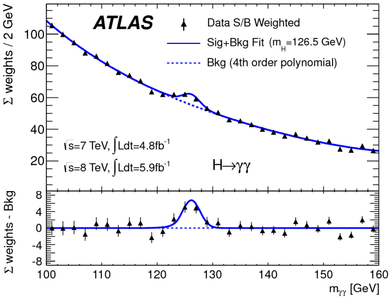

The Economist
JULY 7TH–13TH 2012
Economist.com
In praise of charter schools
Britain's banking scandal spreads
Volkswagen overtakes the rest
A power struggle at the Vatican
When Lonesome George met Nora
A giant leap for science
Finding the Higgs boson

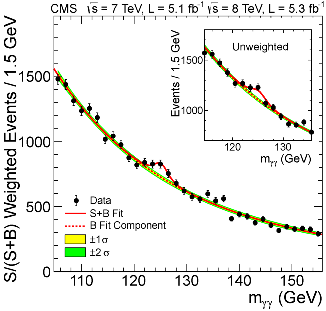
Published


Volume 716, Issue 1, 17 September 2012
ISSN 0370-2693
ELSEVIER
PHYSICS LETTERS B
Available online at www.sciencedirect.com
SciVerse ScienceDirect
CMS
S/(S+B) Weighted Events / 1.5 GeV
$m_{\gamma\gamma}$ (GeV)
Data
S+B Fit
Bkg Fit Component
±1σ
±2σ
ATLAS
2011-12
√s = 7-8 TeV
Local p_0
m_H [GeV]
Observed
Expected Signal ± 1σ
http://www.elsevier.com/locate/physletb

LHC data in $H \to \gamma\gamma$ channel

- proton proton collider with 7/8 TeV center of mass energy
- Two multipurpose experiments: ATLAS and CMS

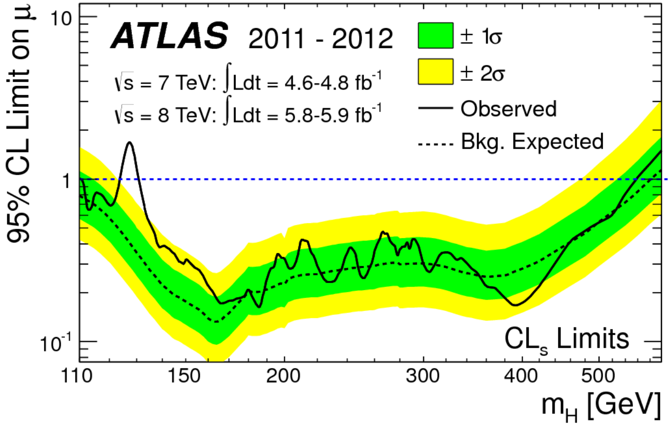




- $H \to \gamma\gamma$ on-shell $\Rightarrow$ spin 0 or 2

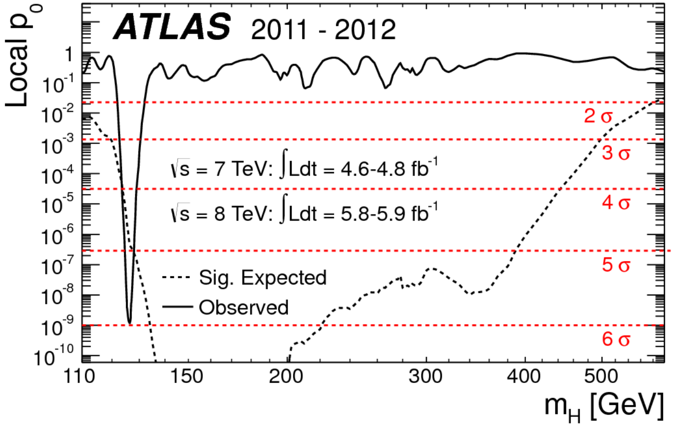
ATLAS data – exclusion

Standard Model Higgs particle excluded (95 % CL):
$111 < m_H < 122$ GeV and $131 < m_H < 559$ GeV



ATLAS data – signal

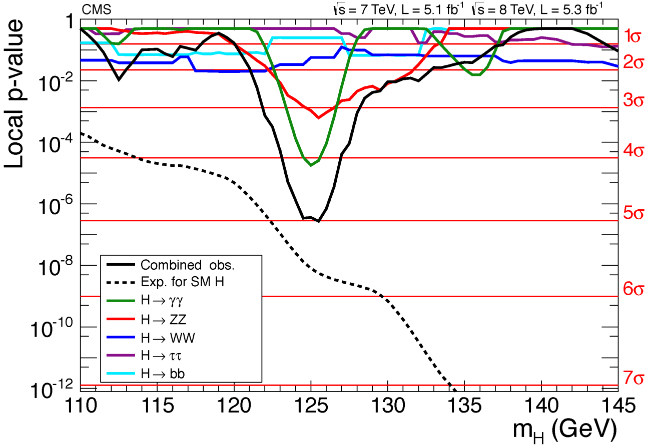
Compatibility with background only hypothesis:
observed and expected in standard model



$\Rightarrow m_H = 126.0 \pm 0.4(\text{stat}) \pm 0.4(\text{sys})$ GeV

CMS data – signal

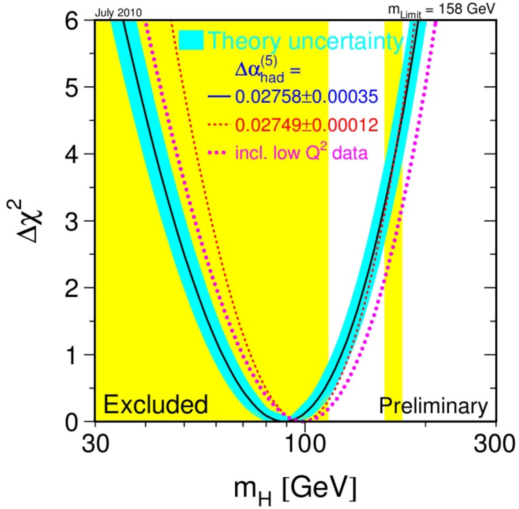
Compatibility with background only hypothesis:
observed and expected in standard model



$\Rightarrow m_H = 125.3 \pm 0.4(\text{stat}) \pm 0.5(\text{sys})$ GeV

preLHC experimental results in standard model

- Direct LEP-limit: $m_H > 114$ GeV (95% CL)
- Indirect electroweak precision tests: $m_H < 158$ GeV (95% CL)

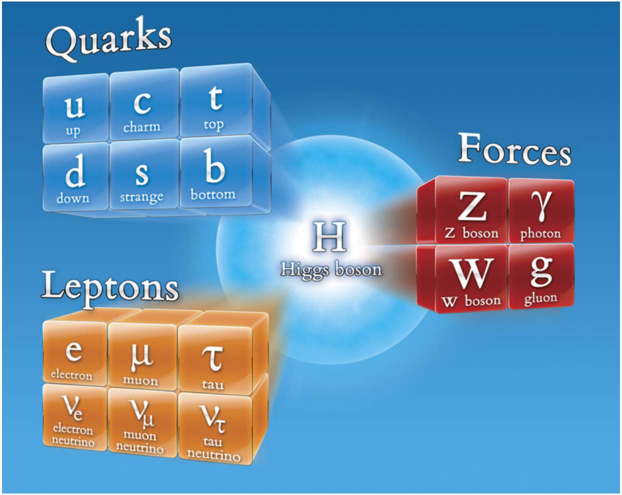


- very good agreement with direct detection!

The standard model of particle physics

The particle content of the standard model

Describes the electromagnetic, weak and strong forces



All particles observed – that's it?

Gauge symmetries and Lagrangians

- dynamics of relativistic quantum field theory described by Lagrangian (density) $\mathcal{L} = K - V$
- standard model with $\mathrm{U}(1)_\mathrm{Y} \otimes \mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{SU}(3)_\mathrm{C}$ gauge symmetry (local transf. of type $e^{iY_f \alpha(x)/2}$, $Y_f = 2Q_f - 2I_f^3$)

$$
\begin{aligned}
\mathcal{L}_\mathrm{SM} &= (\bar{u}_\mathrm{L}, \bar{d}_\mathrm{L}) \mathrm{i} \not{D} \begin{pmatrix} u_\mathrm{L} \\ d_\mathrm{L} \end{pmatrix} + \bar{u}_\mathrm{R} \mathrm{i} \not{D} u_\mathrm{R} + \bar{d}_\mathrm{R} \mathrm{i} \not{D} d_\mathrm{R} + \ldots \\
&\quad - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu}
\end{aligned}
$$

where ($e = g_1 g_2 / \sqrt{g_1^2 + g_2^2}$, $\sin\theta_w = g_1/\sqrt{g_1^2 + g_2^2}$):

$$
\begin{aligned}
D_\mu &= \partial_\mu - \mathrm{i} g_1 \frac{Y_f}{2} B_\mu - \mathrm{i} g_2 \frac{\sigma_i}{2} W^i_\mu - \mathrm{i} g_s \frac{\lambda_a}{2} G^a_\mu \\
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\
W^i_{\mu\nu} &= \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + g_2 \epsilon^{ijk} W^j_\mu W^k_\nu \\
G^a_{\mu\nu} &= \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu
\end{aligned}
$$

- explicit mass terms would break $\mathrm{SU}(2)_\mathrm{L}$ gauge symmetry

$$
\mathcal{L}_\mathrm{mass} = -m_u(\bar{u}_\mathrm{R} u_\mathrm{L} + \bar{u}_\mathrm{L} u_\mathrm{R}) + \frac{1}{2} M_V^2 W^3_\mu W^{3\mu} + \ldots
$$

Englert–Brout–Higgs–Guralnik–Hagen–Kibble–... mechanism

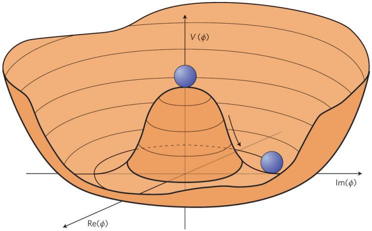
Spontaneous breaking of $\mathrm{SU}(2)_\mathrm{L}$ gauge symmetry

- weak force carriers W and Z massive
- quarks and leptons can be given masses through Yukawa interaction with Higgs field
- one more massive particle – the Higgs boson

Spontaneous breaking of global symmetry

Complex field ϕ with $\mathcal{L} = \partial_\mu \phi \partial^\mu \phi - V(\phi)$ and potential

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



- $\mathcal{L}$ unchanged under $\phi \to \phi e^{i\alpha}$
- minimum: $v = \frac{\mu}{\sqrt{\lambda}}$
- expand around minimum $\phi = v + H + iG$ and identify term in front of H^2 and G^2
  $\Rightarrow$ "Higgs" mass: $m_H = \sqrt{2\lambda}v$ (radial excitations)
  Nambu-Goldstone mass: $m_G = 0$ (angular excitations)
- Symmetry broken by ground state
  – spontaneous symmetry breaking (Nobel prize 2008)
  $\Rightarrow$ equations of motion unchanged
- If the symmetry is local ($\phi \to \phi e^{i\alpha(x)}$) the Nambu-Goldstone boson is "eaten" by the gauge field making it massive

Electroweak symmetry breaking in Standard Model

Higgs sector in Standard Model

Add complex doublet $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^+ \\ v + H + \mathrm{i} G^0 \end{pmatrix}$

with Lagrangian $\mathcal{L}_{\mathrm{Higgs}} = |D_\mu \Phi|^2 - V(\Phi)$ where

$D_\mu \Phi = \left(\partial_\mu - \mathrm{i} g_1 \frac{Y_f}{2} B_\mu - \mathrm{i} g_2 \frac{\sigma_i}{2} W^i_\mu \right) \Phi$

and the potential contains all the self-interactions of Φ

$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \frac{1}{2} \lambda \left(\Phi^\dagger \Phi \right)^2$

Higgs mechanism in Standard Model

- $\mu^2 > 0 \Rightarrow$ vacuum expectation value $v \approx 246$ GeV/c^2
  $\Rightarrow \mathrm{SU}(2)_{\mathrm{L}} \otimes \mathrm{U}(1)_{\mathrm{Y}}$ "spontaneously" broken to $\mathrm{U}(1)_{\mathrm{e.m.}}$
- three would be Nambu-Goldstone bosons G^0 and $G^\pm$ (longitudinal components of Z and W)
- one massive Higgs field H, $m_H^2 = \lambda v^2$

Higgsportal

Johan Rathsman

Vector boson masses and interactions with Higgs field

In unitary gauge $\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$

$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp \mathrm{i} W_\mu^2)$ and $Z_\mu = \frac{1}{\sqrt{g_1^2+g_2^2}}(g_2 W_\mu^3 - g_1 B_\mu)$

couple to the Higgs field through

$$|D_\mu \Phi|^2 = \frac{1}{4} g_2^2 W_\mu^+ W^{-\mu}(v+H)^2 + \frac{1}{8}(g_1^2+g_2^2) Z_\mu Z^\mu (v+H)^2 + \ldots$$

giving masses

$$m_W = \frac{1}{2} g_2 v \quad , \qquad m_Z = \frac{1}{2}\sqrt{g_1^2+g_2^2}\, v$$

and interactions

$$\mathcal{L}_{|D_\mu \Phi|^2,\mathrm{int}} = \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H + \frac{2m_Z^2}{v} Z_\mu Z^\mu H + \ldots$$

Fermion masses and interactions with Higgs field

Add Yukawa type interaction (example d-quark)

$$\mathcal{L}_{\mathrm{Y}} = -y_d(\bar{u}, \bar{d})_{\mathrm{L}} \Phi d_R + \mathrm{h.c.}$$

In unitary gauge

$$\mathcal{L}_{\mathrm{Y}} = -y_d \frac{v}{\sqrt{2}}(\bar{d}_{\mathrm{L}} d_{\mathrm{R}} + \bar{d}_{\mathrm{R}} d_{\mathrm{L}}) \left(1 + \frac{H}{v}\right) = -m_d \bar{d} d \left(1 + \frac{H}{v}\right)$$

giving mass

$$m_d = y_d \frac{v}{\sqrt{2}}$$

and coupling to Higgs

$$\mathcal{L}_{\mathrm{Y,int}} = -\frac{m_d}{v} \bar{d} d H$$

Why is the Higgs boson so "light"?

- Standard Model is an effective theory $\Rightarrow$ expect it to break down at some high scale Λ (e.g. Planck mass $\sim 10^{19}$ GeV)
- Calculating the one-loop corrections to the Higgs boson mass one finds

$$m_H^2 = m_{H,0}^2 + \frac{3\Lambda^2}{8\pi^2 v^2}\left(4m_t^2 - 2m_W^2 - 4m_Z^2 - m_H^2\right)$$

$\Rightarrow$ "natural scale" for Higgs boson mass given by Λ and not v (tree-level $m_H^2 = \lambda v^2$)

- Solutions:
  - fine-tuning – $m_{H,0}^2$ cancels one-loop correction "exactly"
  - Higgs boson is not a fundamental scalar (*e.g.* Technicolor)
  - There is a symmetry that protects the Higgs boson from acquiring a large mass

Theory beyond the standard model

Supersymmetry - one possible solution

Why is this not a problem for fermions?

Protected by Chiral symmetry:
the Lagrangian gets an additional symmetry if $m_f \to 0$
$\Rightarrow$ higher order corrections have to be proportional to m_f
$\Rightarrow$ only $\log(\Lambda)$ dependence $\Rightarrow$ no fine-tuning

SUSY solution

- introduce Higgsino – SUSY fermion partner to Higgs boson
- Higgsino mass $m_{\tilde{H}}$ is protected by the Chiral symmetry
- Imposing (exact) SUSY $m_H = m_{\tilde{H}}$ is also stabilized

SUSY complications

- Anomaly cancelation and analytic structure of SUSY Lagrangian $\Rightarrow$ the SM cannot be supersymmetrized as is – have to add an additional Higgs doublet
- No supersymmetric partners observed $\Rightarrow$ Supersymmetry has to be softly broken $\Rightarrow$ plethora of parameters

Particle content minimal supersymmetric model

FERMIONS			BOSONS		
spin	Name	Symbols	Name	Symbols	spin
½	leptons	e, ν_{eL}	sleptons	$\tilde{e}_L, \tilde{e}_R, \tilde{\nu}_{eL}$	0
		$\mu, \nu_{\mu L}$		$\tilde{\mu}_L, \tilde{\mu}_R, \tilde{\nu}_{\mu L}$	
		$\tau, \nu_{\tau L}$		$\tilde{\tau}_L, \tilde{\tau}_R, \tilde{\nu}_{\tau L}$	
½	quarks	u, d	squarks	$\tilde{u}_L, \tilde{d}_L, \tilde{u}_R, \tilde{d}_R$	0
		c, s		$\tilde{c}_L, \tilde{s}_L, \tilde{c}_R, \tilde{s}_R$	
		t, b		$\tilde{t}_L, \tilde{b}_L, \tilde{t}_R, \tilde{b}_R$	
½	gluinos	$\tilde{g}$	gluons	g	1
½	charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	EW bosons	$\gamma, Z^0, W^\pm$	1
½	neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	higgs	$h^0, H^0, A^0, H^\pm$	0

SM particles (observed) | SM particles (not yet observed) | Super Partners (not yet observed)

Higgs sector of minimal supersymmetric model

- Two complex Higgs doublets: H_u and $H_d \Rightarrow$ 5 scalar degrees of freedom after electroweak symmetry breaking
- CP conserved: h, H (CP-even, $m_h \leq m_H$), A (CP-odd), $H^{\pm}$
- supersymmetry $\Rightarrow$ Higgs potential very constrained – only two parameters at tree-level:

$$m_{H^{\pm}} \quad , \qquad \tan\beta = \frac{v_u}{v_d} = \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}$$

- Other masses determined at tree-level

$$\begin{aligned} m_A^2 &= m_{H^{\pm}}^2 - m_W^2 \\ m_{h,H}^2 &= \frac{1}{2}\left\{ m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta} \right\} \end{aligned}$$

$\Rightarrow m_h^2 \leq m_Z^2 \cos^2 2\beta$ (equality in decoupling limit, $m_{H^{\pm}} \to \infty$)

- approximate custodial symmetry $m_A \approx m_H \approx m_{H^{\pm}}$

Couplings and mixings

mixing of CP-even Higgs bosons

- $\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_d^0 \\ H_u^0 \end{pmatrix}$
- at tree-level $\sin 2\alpha = -\frac{m_H^2 + m_h^2}{m_H^2 - m_h^2} \sin 2\beta$

Couplings relative to standard model

- ZZh, WWh: $\sin(\beta - \alpha)$
- ZZH, WWH: $\cos(\beta - \alpha)$
- uuh : $\cos(\alpha)/\sin(\beta) = \sin(\beta - \alpha) + \cot\beta \cos(\beta - \alpha)$
- uuH : $\sin(\alpha)/\sin(\beta) = \cos(\beta - \alpha) - \cot\beta \sin(\beta - \alpha)$
- ddh : $-\sin(\alpha)/\cos(\beta) = \sin(\beta - \alpha) - \tan\beta \cos(\beta - \alpha)$
- ddH : $\cos(\alpha)/\cos(\beta) = \cos(\beta - \alpha) + \tan\beta \sin(\beta - \alpha)$

standard model limit: $\sin(\beta - \alpha) \to 1,\ m_{H^\pm} \to \infty$

LUND UNIVERSITY

Higgsportal

Johan Rathsman

Higher order corrections to Higgs sector

- All particles enter through loops
- Sensitivity to supersymmetry breaking parameters

$$m_h^2 = m_{h,tree}^2 + \frac{3m_t^4}{2\pi^2 v_u^2}\left\{\log\frac{m_S^2}{m_t^2} + \frac{X_t^2}{m_S^2}\left(1 - \frac{X_t^2}{12m_S^2}\right)\right\} + \dots$$

  where
  - $m_S = \dfrac{m_{\tilde{t}_1} + m_{\tilde{t}_2}}{2}$ with $\tilde{t}_{1,2}$ the two stop mass eigenstates
  - $X_t = A_t - \mu\cot\beta$, A_t is a supersymmetry breaking contribution to the Higgs-stop-stop coupling, μ is the Higgsino mass parameter
- Maximal mixing: $X_t^2 = 6m_S^2 \Rightarrow m_h \lesssim 135$ GeV
- No mixing: $X_t^2 = 0 \Rightarrow m_h \lesssim 120$ GeV

Supersymmetry predicts at least one light Higgs boson

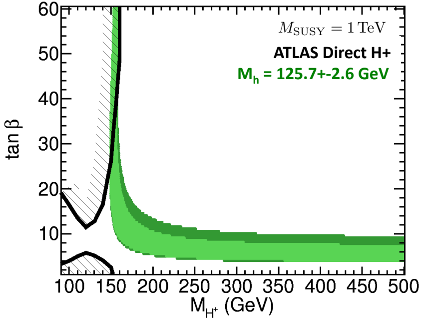
Interpretation of data beyond the standard model

The Higgs mass constrains the MSSM parameters

- M_h is an increasing function of the tree-level parameters M_{H+}, tan β

$$M_h^2 = M_{h,\mathrm{tree}}^2\,(M_{H^\pm}, \tan\beta) + \Delta M_h^2(M_{\mathrm{SUSY}}, X_t, \ldots)$$

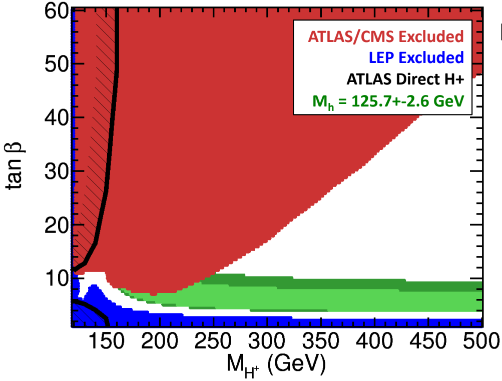
- For a given SUSY mass scale M_{SUSY}, maximize the contributions to ΔM_h from radiative corrections -> M_h-max scenario



courtesy Oscar Stål (Stockholm) from H^+2012 in Uppsala

Including exclusion limits

- MSSM Higgs exclusion (at 95% CL) taken into account using HiggsBounds [3.8.0] http://higgsbounds.hepforge.org -> Talk by T. Stefaniak



Most sensitive LHC limit

$$H/A \to \tau\tau$$

MSSM mass relation

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

Lower MSSM limit:

$$M_{H^\pm} > 161\,\mathrm{GeV}$$

$$\tan\beta > 4$$

2012-10-10 cHarged 2012 15

courtesy Oscar Stål (Stockholm) from H^+2012 in Uppsala

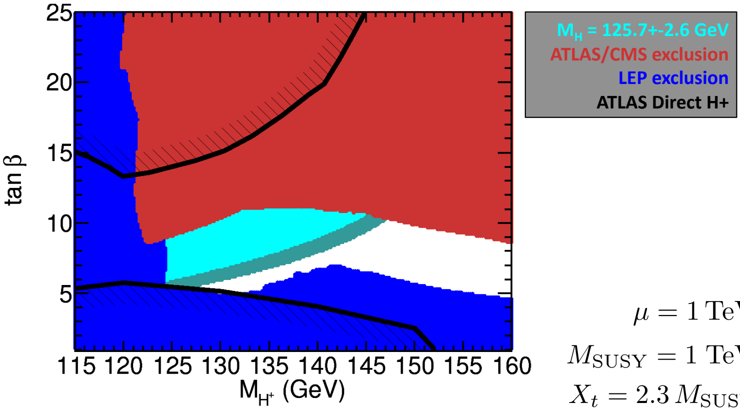
Lund University

Higgsportal

Johan Rathsman

Alternative MSSM interpretation: M_H = 126 GeV

- Viable to have the heavier CP-even Higgs boson at 126 GeV?
  -> Yes, in a limited region of parameter space!



$\mu = 1\,\mathrm{TeV}$

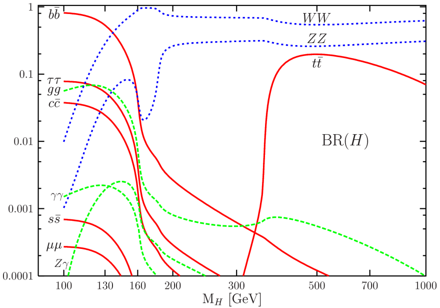
$M_{\mathrm{SUSY}} = 1\,\mathrm{TeV}$

$X_t = 2.3\,M_{\mathrm{SUSY}}$

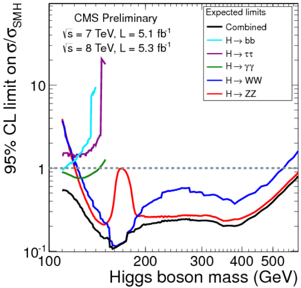
courtesy Oscar Stål (Stockholm) from H^+2012 in Uppsala

Different "Higgs" boson decay channels

Branching fraction in SM



Experimental sensitivity

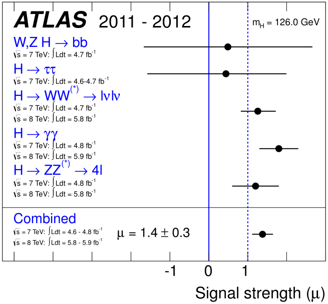


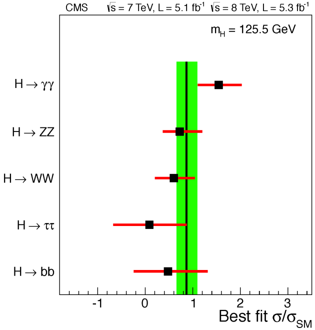
LUND UNIVERSITY

Higgsportal

Johan Rathsman

Signal strength relative to standard model expectation



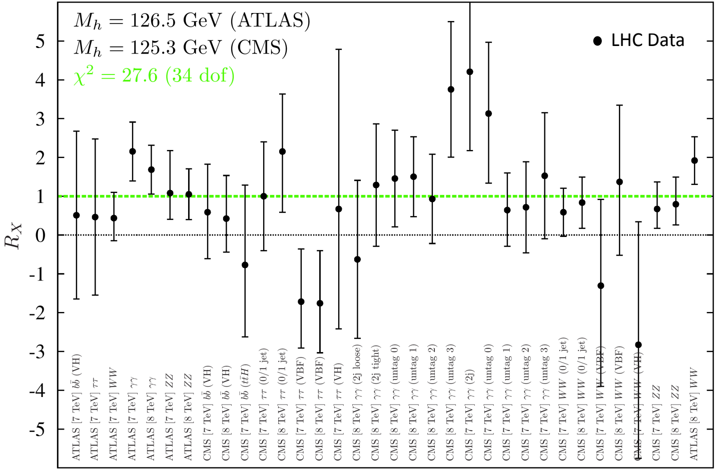


depends also on production mode (gluon-gluon fusion, vector-boson fusion (VBF) , Higgs strahlung (VH))

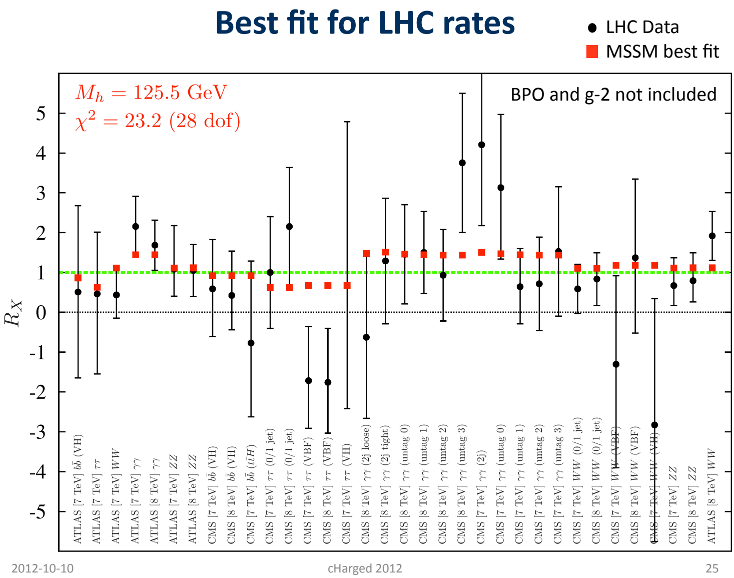
Higgsportal

Johan Rathsman

LHC data set



courtesy Oscar Stål (Stockholm) from H^+2012 in Uppsala

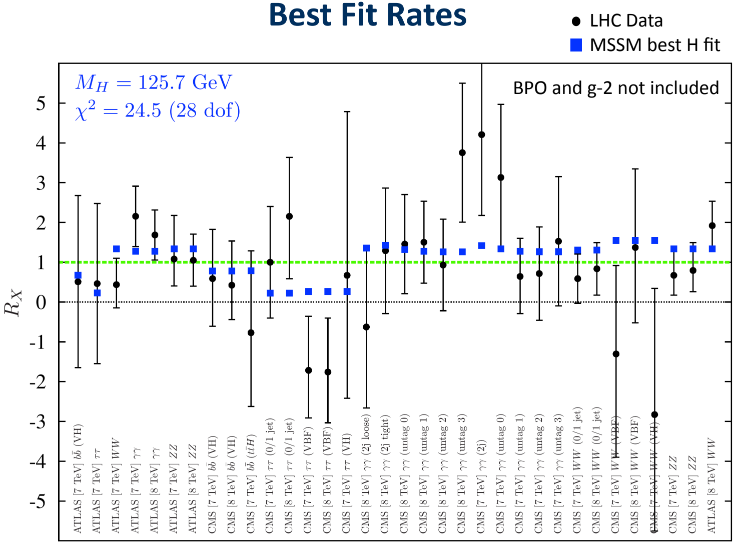


courtesy Oscar Stål (Stockholm) from H^+2012 in Uppsala

Higgsportal

Johan Rathsman

Best Fit Rates



courtesy Oscar Stål (Stockholm) from H^+2012 in Uppsala

Conclusions

- The discovery of a Higgs-like particle marks a new era in (particle) physics
- Completes the particle content of the standard model – time to look beyond
- So far experimental data in agreement with standard model expectations – still room for surprises
- Supersymmetric models give equal or better description of available data
- Precision measurements of all possible combinations of production and decay channels will test if standard model is correct at LHC energies
- Higgs physics has gone from discovery mode to precision measurements (also possible at hadron collider)
- LHC will continue running until February 2013 and then have a break until November 2014 to go to design energy
- Stay tuned