# Discovery of the Higgs boson? The role of theory 

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## supported by

Deutsche
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# The role of theory: 

- Foundations
- Calculations
- Implications


## Foundations

## BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

## Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland (Received 31 August 1964)

In a recent note ${ }^{1}$ it was shown that the Goldstone theorem, ${ }^{2}$ that Lorentz-covariant field theories in which spontaneous breakdown of

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It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons. ${ }^{8}$ It is to be expected that this feature will appear also in
${ }^{11}$ In obtaining the expression (11) the mass difference between the charged and neutral has been ignored.
${ }^{12}$ M. Ademollo and R. Gatto, Nuovo Cimento 44A, 282 (1966); see also J. Pasupathy and R. E. Marshak, Phys. Rev. Letters 17, 888 (1966).
${ }^{13}$ The predicted ratio [eq. (12)] from the current alge-
bra is slightly larger than that ( $0.23 \%$ ) obtained from the $\rho$-dominance model of Ref. 2. This seems to be true also in the other case of the ratio $\Gamma\left(\eta \rightarrow \pi^{+} \pi^{-} \gamma\right) /$ $\Gamma(\gamma \gamma)$ calculated in Refs. 12 and 14.
${ }^{14}$ L. M. Brown and P. Singer, Phys. Rev. Letters 8, 460 (1962).

## A MODEL OF LEPTONS*

## Steven Weinberg $\dagger$

Laboratory for Nuclear Science and Physics Department, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)

Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite ${ }^{1}$ these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differanoce in the macone of tha nhnton and inter-
and on a right-handed singlet

$$
\begin{equation*}
R \equiv\left[\frac{1}{2}\left(1-\gamma_{5}\right)\right] e . \tag{2}
\end{equation*}
$$

The largest group that leaves invariant the kinematic terms $-\bar{L} \gamma^{\mu} \partial_{\mu} L-\bar{R} \gamma^{\mu} \partial_{\mu} R$ of the Lagrang-
 field $\varphi_{1}$ has mass $M_{1}$ while $\varphi_{2}$ and $\varphi^{-}$have mass zero. But we can easily see that the Goldstone bosons represented by $\varphi_{2}$ and $\varphi^{-}$have no physical coupling. The Lagrangian is gauge invariant, so we can perform a combined isospin and hypercharge gauge transformation which eliminates $\varphi^{-}$and $\varphi_{2}$ everywhere ${ }^{6}$ without changing anything else. We will see that $G_{e}$ is very small, and in any case $M_{1}$ might be very large, ${ }^{7}$ so the $\varphi_{1}$ couplings will also be disregarded in the following.

The effect of all this is just to replace $\varphi$ everywhere by its vacuum expectation value

$$
\begin{equation*}
\langle\varphi\rangle=\lambda\binom{1}{0} \tag{6}
\end{equation*}
$$

The first four terms in $\mathcal{L}$ remain intact, while the rest of the Lagrangian becomes

$$
\begin{align*}
-\frac{1}{8} \lambda^{2} g^{2}\left[\left(A_{\mu}^{1}\right)^{2}+\right. & \left.\left(A_{\mu}^{2}\right)^{2}\right] \\
& -\frac{1}{8} \lambda^{2}\left(g A_{u}^{3}+g^{\prime} B_{u}\right)^{2}-\lambda G_{e} \bar{e} e \tag{7}
\end{align*}
$$

[^0]and has mass
\[

$$
\begin{equation*}
M_{W}=\frac{1}{2} \lambda g \tag{9}
\end{equation*}
$$

\]

The neutral spin-1 fields of definite mass are

$$
\begin{align*}
& Z_{\mu}=\left(g^{2}+g^{\prime 2}\right)^{-1 / 2}\left(g A_{\mu}^{3}+g^{\prime} B_{\mu}\right)  \tag{10}\\
& A_{\mu}=\left(g^{2}+g^{\prime 2}\right)^{-1 / 2}\left(-g^{\prime} A_{\mu}^{3}+g B_{\mu}\right) \tag{11}
\end{align*}
$$

Their masses are

$$
\begin{gather*}
M_{Z}=\frac{1}{2} \lambda\left(g^{2}+g^{\prime 2}\right)^{1 / 2}  \tag{12}\\
M_{A}=0 \tag{13}
\end{gather*}
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so $A_{\mu}$ is to be identified as the photon field. The interaction between leptons and spin-1

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## Citations to Weinberg's "Model of Leptons":


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# RENORMALIZABLE LAGRANGIANS FOR MASSIVE YANG-MILLS FIELDS 

G.'t HOOFT<br>Institute for Theoretical Physics, University of Utrecht

Received 13 July 1971

Abstract: Renormalizable models are constructed in which local gauge invariance is broken spontaneously. Feynman rules and Ward identities can be found by means of a path integral method, and they can be checked by algebra. In one of these models, which is studied in more detail, local $\operatorname{SU}(2)$ is broken in such a way that local $U(1)$ remains as a symmetry. A renormalizable and unitary theory results, with photons, charged massive vector particles, and additional neutral scalar particles. It has three independent parameters.

Another model has local $\mathrm{SU}(2) \otimes \mathrm{U}(1)$ as a symmetry and may serve as a renormalizable theory for $\rho$-mesons and photons.

In such models electromagnetic mass-differences are finite and can be calculated in perturbation theory.

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$\dagger$ The model of this section is due to Weinberg [13], who showed that it can describe weak interactions between leptons. His lepton model can be shown to be renormalizable.
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## Calculations

# Spontaneous Symmetry Breakdown without Massless Bosons* 

Peter W. Higgs $\dagger$<br>Department of Physics, University of North Carolina, Chapel Hill, North Carolina

(Received 27 December 1965)
We examine a simple relativistic theory of two scalar fields, first discussed by Goldstone, in which as a result of spontaneous breakdown of $U(1)$ symmetry one of the scalar bosons is massless, in conformity with the Goldstone theorem. When the symmetry group of the Lagrangian is extended from global to local $U(1)$ transformations by the introduction of coupling with a vector gauge field, the Goldstone boson becomes the longitudinal state of a massive vector boson whose transverse states are the quanta of the transverse gauge field. A perturbative treatment of the model is developed in which the major features of these phenomena are present in zero order. Transition amplitudes for decay and scattering processes are evaluated in lowest order, and it is shown that they may be obtained more directly from an equivalent Lagrangian in which the original symmetry is no longer manifest. When the system is coupled to other systems in a $U(1)$ invariant Lagrangian, the other systems display an induced symmetry breakdown, associated with a partially conserved current which interacts with itself via the massive vector boson.

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## i. Decay of a Scalar Boson into Two <br> Vector Bosons

The process occurs in first order (four of the five cubic vertices contribute), provided that $m_{0}>2 m_{1}$. Let $p$ be the incoming and $k_{1}, k_{2}$ the outgoing momenta. Then

$$
\begin{gathered}
M=i\left\{e\left[a^{* \mu}\left(k_{1}\right)\left(-i k_{2 \mu}\right) \phi^{*}\left(k_{2}\right)+a^{* \mu}\left(k_{2}\right)\left(-i k_{1 \mu}\right) \phi^{*}\left(k_{1}\right)\right]\right. \\
-e\left(i p_{\mu}\right)\left[a^{* \mu}\left(k_{1}\right) \phi^{*}\left(k_{2}\right)+a^{* \mu}\left(k_{2}\right) \phi^{*}\left(k_{1}\right)\right] \\
\left.-2 e m_{1} a_{\mu}^{*}\left(k_{1}\right) a^{* \mu}\left(k_{2}\right)-f m_{0} \phi^{*}\left(k_{1}\right) \phi^{*}\left(k_{2}\right)\right\} .
\end{gathered}
$$

Bv 11 sing Eq. (15), conservation of momontırm. and

# A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON 

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS ** CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson $H$ expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^{-} \mathrm{p} \rightarrow \mathrm{Hn}$ or $\gamma \mathrm{p} \rightarrow \mathrm{Hp}$ near threshold. If its mass is $\lesssim 300 \mathrm{MeV}$, the Higgs boson may be present in the decays of kaons with a branching ratio $\mathrm{O}\left(10^{-7}\right)$, or in the decays of one of the new particles: $3.7 \rightarrow 3.1+\mathrm{H}$ with a branching ratio $\mathrm{O}\left(10^{-4}\right)$. If its mass is $\leqslant 4 \mathrm{GeV}$, the Higgs boson may be visible in the reaction $\mathrm{pp} \rightarrow \mathrm{H}+\mathrm{X}, \mathrm{H} \rightarrow \mu^{+} \mu^{-}$. If the Higgs boson has a mass $\leqslant 2 m_{\mu}$, the decays $\mathrm{H} \rightarrow \mathrm{e}^{+} \mathrm{e}^{-}$and $\mathrm{H} \rightarrow \gamma \gamma$ dominate, and the lifetime is $\mathrm{O}\left(6 \times 10^{-4}\right.$ to $2 \times 10^{-12}$ ) seconds. As thresholds for heavier particles (pions, strange particles, new particles) are crossed, decays into them become dominant, and the lifetime decreases rapidly to $\mathrm{O}\left(10^{-20}\right)$ sec for a Higgs boson of mass 10 GeV . Decay branching ratios in principle enable the quark masses to be determined.

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We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm $[3,4]$ and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

# LIMIT ON MASS DIFFERENCES IN THE WEINBERG MODEL 

## M. VELTMAN

Institute for Theoretical Physics, University of Utrecht, Netherlands

Received 7 February 1977

Within the Weinberg model mass differences between members of a multiplet generate further mass differences between the neutral and charged vector bosons. The experimental situation on the Weinberg model leads to an upper limit of about 800 GeV on mass differences within a multiplet. No limit on the average mass can be deduced.

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$$
\left.\left.\mathrm{P}=1+\frac{G}{4 \pi^{2}}\left\{m_{1}^{2}+m_{2}^{2}-\frac{2 m_{1}^{2} m_{2}^{2}}{m_{2}^{2}-m_{1}^{2}} \ln \frac{m_{2}^{2}}{m_{1}^{2}}\right\},\right\}=1+\frac{G}{12 \pi^{2}} \frac{\left(m_{1}^{2}-m_{2}^{2}\right.}{m_{2}^{2}}\right)^{2}+\cdots
$$


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## $\square \square D$

GFitter 'I2






## Tevatron exclusion



## Tevatron exclusion



Tevatron Run II Preliminary, $\left\langle\mathrm{L}>=5.9 \mathrm{fb}^{-1}\right.$


Tevatron Run II Preliminary, $<\mathrm{L}>=5.9 \mathrm{fb}^{-1}$


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Tevatron Run II Preliminary, $<\mathrm{L}>=5.9 \mathrm{fb}^{-1}$


## Tevatron today

Tevatron Run II Preliminary, $\mathrm{L} \leq 10.0 \mathrm{fb}^{-1}$




## LHC Higgs Cross Section Working Group

$\downarrow$ LHC Higgs Cross Section Working Group
$\downarrow$ O News
$\downarrow$ Overview
$\downarrow$ CERN Reports: Handbook of LHC Higgs Cross Sections
$\downarrow$ Preprints
$\downarrow$ () Higgs cross sections at 7,8 and 14 TeV

+ Q Latest plots
$\downarrow$ O Information
+ Workshops
$\downarrow$ Communication Tools
$\downarrow$ O Organization

M. [GeV/]



M. [GeV]


## Gluon fusion



NLO: Spira, Djouadi, Graudenz, Zerwas '9I, '93
Dawson '91
NNLO: RH, Kilgore '02
Anastasiou, Melnikov '02
Ravindran, Smith, v. Neerven '03
Resummation:
Catani, de Florian, Grazzini, Nason '02 Ahrens, Becher, Neubert, Zhang '08
Electroweak:
Actis, Passarino, Sturm, Uccirati '08
Aglietti, Bonciani, Degrassi, Vicini '04
Degrassi, Maltoni '04
Djouadi, Gambino '94
Mixed EW/QCD:
Anastasiou, Boughezal, Petriello '09
Fully differential NNLO:
Anastasiou, Melnikov, Petriello '04
Catani, Grazzini '07

## Gluon fusion



NLO: Spira, Djouadi, Graudenz, Zerwas '9I, '93
Dawson '9|
~80\%
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Catani, Grazzini '07

## Gluon fusion



$$
\sigma_{\infty}^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}\left(m_{t}\right)\left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}}\right)_{m_{t} \rightarrow \infty}
$$

NLO: Spira, Djouadi, Graudenz, Zerwas '9I, '93
Dawson '91
~80\%

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Anastasiou, Melnikov, Petriello '04
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Effective Theory:



## Effective Theory:


$m_{t} \gg M_{H}$
$C\left(m_{t}, \alpha_{s}\right) \times$

$$
\sigma_{\infty}^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}\left(m_{t}\right)\left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}}\right)_{m_{t} \rightarrow \infty}
$$



$$
\mathrm{M}_{\mathrm{H}}[\mathrm{GeV}]
$$

## Effective Theory:




$$
\sigma_{\infty}^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}\left(m_{t}\right)\left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}}\right)_{m_{t} \rightarrow \infty}
$$

what about higher orders?


## Gluon fusion: recent progress

- Higgs line shape

Goria, Passarino, Rosco 'I2; Anastasiou, Buehler, Herzog, Lazopoulos 'II

- Signal/Background interference

Glover, v.d. Bij '89; Binoth, Ciccolini, Kauer, Krämer '06;
Campbell, Ellis, Williams 'II; Kauer 'I2; Passarino 'I2;
S.P. Martin 'I3; Bonfini, Caola, Forte, Melnikov, Ridolfi 'I3

- validity of effective $\mathrm{I} / \mathrm{mt}$ theory

RH, Mantler, Marzani, Ozeren '09; Pak, Rogal, Steinhauser '09
Alwall, Li, Maltoni ' I I; Bagnaschi, Degrassi, Slavich,Vicini 'I I
RH, Neumann, Wiesemann 'I2

- jet veto uncertainties

Anastasiou, Dissertori, Grazzini, Stöckli,Webber '09
Stewart, Tackmann 'II
Banfi, Monni, Salam, Zanderighi 'I2; Becher, Neubert 'I2
Tackmann,Walsh, Zuberi 'I2

## Towards NNNLO



## Towards NNNLO

Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser '09
Lee, Smirnov, Smirnov 'I0
Gehrmann, Glover, Huber, Ikizlerli, Studerus '09


## Towards NNNLO

Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser '09
Lee, Smirnov, Smirnov 'I0
Gehrmann, Glover, Huber, Ikizlerli, Studerus '09
(ع) $\begin{aligned} & \text { Anastasiou, Bühler, Duhr, Herzog 'I2 } \\ & \text { Hoschele, Hoff, Pak, Steinhauser, Ueda 'I2 }\end{aligned}$


## Towards NNNLO

Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser '09
Lee, Smirnov, Smirnov 'I0
Gehrmann, Glover, Huber, Ikizlerli, Studerus '09

O(ع) Anastasiou, Bühler, Duhr, Herzog 'I2
(ع) Hoschele, Hoff, Pak, Steinhauser, Ueda 'I2

Anastasiou, Duhr, Dulat, Mistlberger 'I3

## Towards NNNLO

Baikov, Chetyrkin, Smirnov, Smirnov, Steinhauser '09
Lee, Smirnov, Smirnov 'IO
Gehrmann, Glover, Huber, Ikizlerli, Studerus '09
(ع) Anastasiou, Bühler, Duhr, Herzog 'I2 $\begin{aligned} & \text { Hoschele, Hoff, Pak, Steinhauser, Ueda 'I2 }\end{aligned}$

Anastasiou, Duhr, Dulat, Mistlberger 'I3



Boughezal, Caola, Melnikov, Petriello, Schulze 'I3

## Approximate NNNLO:

Higgs hadron-level cross section


## Gluon fusion: uncertainties

- perturbative (scale variation)
- $\operatorname{PDF} / \alpha_{s}$
- bottom loop/Yukawa coupling









## Gluon fusion: uncertainties

- perturbative (scale variation)
- $\operatorname{PDF} / \alpha_{s}$
- bottom loop/Yukawa coupling



## Influence of theory errors








## March 2013

Signal strength ( $\mu$ )


## highly unofficial and scetchy!



## highly unofficial and scetchy!



## highly unofficial and scetchy!

## Differential quantities

## Transverse momentum:



HqT Bozzi, Catani, de Florian, Grazzini '03
see also: de Florian, Kulesza, Vogelsang '06
Kulesza, Sterman, Vogelsang ’03
Berger, Qiu '03

## Transverse momentum:



HqT Bozzi, Catani, de Florian, Grazzini '03
see also: de Florian, Kulesza, Vogelsang '06
Kulesza, Sterman, Vogelsang '03
Berger, Qiu '03

## including decay:


de Florian, Ferrera, Grazzini, Tommasini ' $\mid$ I



$$
\sigma_{\infty}^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}\left(m_{t}\right)\left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}}\right)_{m_{t} \rightarrow \infty}
$$

what about NNLO?



$$
\sigma_{\infty}^{\mathrm{HO}} \equiv \sigma^{\mathrm{LO}}\left(m_{t}\right)\left(\frac{\sigma^{\mathrm{HO}}}{\sigma^{\mathrm{LO}}}\right)_{m_{t} \rightarrow \infty}
$$

what about NNLO?


see also Spira, Djouadi, Graudenz, Zerwas '93
Keung, Petriello '09; Brein 'l0;
Bagnasci, Degrassi, Slavich,Vicini 'II Anastasiou, Bucherer, Kunszt '09

see also Spira, Djouadi, Graudenz, Zerwas '93 Keung, Petriello '09; Brein 'IO;

Bagnasci, Degrassi, Slavich,Vicini 'II Anastasiou, Bucherer, Kunszt '09



## Other processes

# Higgs Strahlung 



NLO: Han, Willenbrock '90
NNLO: Brein, Djouadi, RH '03
EW: Ciccolini, Dittmaier, Krämer ’03
vh@nnlo: Brein, RH, Zirke 'I2

# Higgs Strahlung 



## Higgs Strahlung



(c)

Brein, RH,Wiesemann, Zirke 'II




Kniehl '90




Kniehl '90
NLO: Altenkamp, Dittmaier, RH, Rzehak, Zirke 'I2

@ NLO:



Altenkamp, Dittmaier, RH, Rzehak, Zirke 'I2

## Higgs Strahlung: fully differential NNLO


$\mathrm{d} \sigma / \mathrm{d} p_{\mathrm{T}, \mathrm{H}}[\mathrm{fb} / \mathrm{GeV}]$
Ferrera, Grazzini, Tramontano 'I2


$\delta_{\mathrm{EW}}[\%]$
Denner, Dittmaier, Kallweit, Mück 'II

$t \bar{t} H$

NLO:
Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas 'OI;
Dawson, Reina, Wackeroth, Orr, Jackson '01-'03;



NLO:
Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas ' ${ }^{\prime}$ I;
Dawson, Reina, Wackeroth, Orr, Jackson 'OI-'03;

NLO+PS:
Frederix, Frixione, Hirschi, Maltoni, Pittau,Torielli 'l2 $\rightarrow$ alMC@NLO Garzelli, Kardos, Papadopoulos, Trócsányi 'll $\rightarrow$ PowHel


## Weak Boson Fusion



NLO QCD: Figy, Oleari, Zeppenfeld '03 $\rightarrow$ vbfnlo NLO QCD+EW: Ciccolini, Denner,

Dittmaier '08 $\rightarrow$ HAWK
NLO SUSY: Figy, Palmer, Weiglein 'IO


## Weak Boson Fusion: Beyond NLO

- gluon fusion/WBF interference

Andersen, Binoth, Heinrich, Smillie '07; Bredenstein, Hagiwara, Jäger ’08

- gluon induced WBF

RH,Vollinga, Weber '08

- DIS-like NNLO (inclusive)

Bolzoni, Maltoni, Moch, Zaro 'II


- missing:



Bolzoni, Maltoni, Moch, Zaro 'II

## BSM


sensitive to heavy particle spectrum

sensitive to heavy particle spectrum
e.g. 4th generation:

sensitive to heavy particle spectrum
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$$
\sigma \stackrel{m_{t} \gg M_{H}}{256 \sqrt{2}}\left(\frac{\alpha_{s}}{\pi}\right)^{2}\left(\frac{y_{t}}{m_{t}}\right)^{2}
$$


sensitive to heavy particle spectrum
e.g. 4th generation:

$$
\sigma \stackrel{m_{t} \gg M_{H}}{\pi} \frac{\pi}{256 \sqrt{2}}\left(\frac{\alpha_{s}}{\pi}\right)^{2}\left(\frac{y_{t}}{m_{t}}+\frac{y_{t^{\prime}}}{m_{t^{\prime}}}+\frac{y_{b^{\prime}}}{m_{b^{\prime}}}\right)^{2}
$$


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e.g. 4th generation:

$$
\sigma \stackrel{m_{t} \gg M_{H}}{256 \sqrt{2}}\left(\frac{\alpha_{s}}{\pi}\right)^{2}\left(\frac{m_{t}}{m_{t}}+\frac{m_{t^{\prime}}}{m_{t^{\prime}}}+\frac{m_{b^{\prime}}}{m_{b^{\prime}}}\right)^{2}
$$


sensitive to heavy particle spectrum
e.g. 4th generation:

$$
\begin{aligned}
\sigma \stackrel{m_{t} \gg}{\longrightarrow} M_{H} & \pi \\
256 \sqrt{2} & \left(\frac{\alpha_{s}}{\pi}\right)^{2}\left(\frac{m_{t}}{m_{t}}+\frac{m_{t^{\prime}}}{m_{t^{\prime}}}+\frac{m_{b^{\prime}}}{m_{b^{\prime}}}\right)^{2} \\
& =9 \frac{\pi}{256 \sqrt{2}}\left(\frac{\alpha_{s}}{\pi}\right)^{2}
\end{aligned}
$$


sensitive to heavy particle spectrum
e.g. 4th generation:

$$
\begin{aligned}
& \sigma \stackrel{m_{t} \gg M_{H}}{ } \frac{\pi}{256 \sqrt{2}}\left(\frac{\alpha_{s}}{\pi}\right)^{2}\left(\frac{m_{t}}{m_{t}}+\frac{m_{t^{\prime}}}{m_{t^{\prime}}}+\frac{m_{b^{\prime}}}{m_{b^{\prime}}}\right)^{2} \\
&=9 \frac{\pi}{256 \sqrt{2}}\left(\frac{\alpha_{s}}{\pi}\right)^{2}
\end{aligned}
$$


sensitive to heavy particle spectrum

## Supersymmetry


sensitive to heavy particle spectrum

## Supersymmetry


sensitive to heavy particle spectrum
LHC Higgs XSWG:
$\sigma^{\mathrm{MSSM}}(\operatorname{gg} \rightarrow \phi)=\left(\frac{g_{\mathrm{t}}^{\mathrm{MSSM}}}{g_{\mathrm{t}}^{\mathrm{SM}}}\right)^{2} \sigma_{\mathrm{tt}}(\mathrm{gg} \rightarrow \phi)+\left(\frac{g_{\mathrm{b}}^{\mathrm{MSSM}}}{g_{\mathrm{b}}^{\mathrm{SM}}}\right)^{2} \sigma_{\mathrm{bb}}(\operatorname{gg} \rightarrow \phi)+\frac{g_{\mathrm{t}}^{\mathrm{MSSM}}}{g_{\mathrm{t}}^{\mathrm{SM}}} \frac{g_{\mathrm{b}}^{\mathrm{MSSM}}}{g_{\mathrm{b}}^{\mathrm{SM}}} \sigma_{\mathrm{tb}}(\mathrm{gg} \rightarrow \phi)$,

## Supersymmetry


sensitive to heavy particle spectrum
LHC Higgs XS WG:
$\sigma^{\mathrm{MSSM}}(\mathrm{gg} \rightarrow \phi)=\left(\frac{g_{\mathrm{t}}^{\mathrm{MSSM}}}{g_{\mathrm{t}}^{\mathrm{SM}}}\right)^{2} \sigma_{\mathrm{tt}}(\mathrm{gg} \rightarrow \phi)+\left(\frac{g_{\mathrm{b}}^{\mathrm{MSSM}}}{g_{\mathrm{b}}^{\mathrm{SM}}}\right)^{2} \sigma_{\mathrm{bb}}(\operatorname{gg} \rightarrow \phi)+\frac{g_{\mathrm{t}}^{\mathrm{MSSM}}}{g_{\mathrm{t}}^{\mathrm{SM}}} \frac{g_{\mathrm{b}}^{\mathrm{MSSM}}}{g_{\mathrm{b}}^{\mathrm{SM}}} \sigma_{\mathrm{tb}}(\operatorname{gg} \rightarrow \phi)$,

All contributions for NLO MSSM Higgs known:

## Supersymmetry



## sensitive to heavy particle spectrum

## LHC Higgs XSWG:

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## All contributions for NLO MSSM Higgs known:

NLO: RH, Steinhauser '04; Anastasiou, Beerli, Daleo '08; + Bucherer, Kunszt '06;
Mühlleitner, Rzehak, Spira '07/'08; Aglietti, Bonciani, Degrassi,Vicini '06;
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## Supersymmetry



## sensitive to heavy particle spectrum

## LHC Higgs XSWG:

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Even NNLO: RH, Steinhauser '03; Pak, Steinhauser, Zerf 'I2
－SusHi
－Changelog
－Examples
－Contact
－Download

## SusHi

## Download

Version 1.0 .5 （13．03．2013）is available here：Download

## Details

SusHi（Supersymmetric Higgs）is a Fortran code，which calculates Higgs cross sections in gluon fusion and bottom－quark annihilation at hadron colliders in the SM and the MSSM．Apart from inclusive cross sections up to NNLO QCD，differential cross sections with respect to the Higgs＇transverse momentum and（pseudo）rapidity can be calculated． In case of gluon fusion，SusHi contains NLO QCD contributions from the third family of quarks and squarks，NNLO corrections due to top－quarks，approximate NNLO corrections due to top squarks and electro－weak effects．It supports various renormalization schemes for the sbottom sector and the bottom Yukawa coupling，as well as resummation effects of higher order $\tan$（beta）－enhanced sbottom contributions．SusHi provides a link to FeynHiggs for the calculation of Higgs masses in the MSSM．

Starting with V 1．0．2 gluon fusion and bottom－quark annihilation cross sections for the 2 －Higgs－Doublet－Model（2HDM）can be calculated．Our notation is shortly explained here．
For example input and output files regarding recent MSSM benchmark scenarios we refer to the＂Examples＂page as well．

## Reference

If you use SusHi for your publication，please refer to the following paper：
SusHi：A program for the calculation of Higgs production in gluon fusion and bottom－quark annihilation in the Standard Model and the MSSM
Robert V．Harlander，Stefan Liebler，Hendrik Mantler
M Google Mail YahoolMail Wupper!Mail Albums mac home

- SusHi
- Changelog
- Examples
- Contact
- Download


## SusHi

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Version $1.0 .5(13.03 .2013)$ is availa

## Details

SusHi (Supersymmetric Higgs) is a in gluon fusion and bottom-quark an MSSM. Apart from inclusive cross s with respect to the Higgs' transverse In case of gluon fusion, SusHi conte of quarks and squarks, NNLO corre due to top squarks and electro-weal for the sbottom sector and the botto higher order tan(beta)-enhanced sb for the calculation of Higgs masses

Starting with V 1.0 .2 gluon fusion an for the 2-Higgs-Doublet-Model ( 2 H shortly explained here.

For example input and output files r we refer to the "Examples" page as

- full MSSM @ NLO
- SM @ NNLO
- 2HDM
- bbh
- various ren. schemes
- link to FeynHiggs
- link to LHAPDF
- ... RH, Liebler, Mantler 'I2


## Reference

If you use SusHi for your publication, please refer to the following paper:
SusHi: A program for the calculation of Higgs production in gluon fusion and bottom-quark annihilation in the Standard Model and the MSSM
Robert V. Harlander, Stefan Liebler, Hendrik Mantler


## Implications



Hambye, Riesselmann '97


Hambye, Riesselmann '97


Hambye, Riesselmann '97


Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

## What about fine tuning?




Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12


Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12

Shaposhnikov, Wetterich '10
 at zero. This results in $m_{H}=m_{\min }=126 \mathrm{GeV}$, with only a few GeV uncertainty. This ls of the short distance running and holds for a wide class of extensions of the SM as well.

## Will our universe end in a 'big slurp'? Higgs-like particle suggests it might



## Conclusions

- Heuer: I think we have it! RH: Me too.
- importance of theory undeniable
- error estimates will become crucial
- revival of precision physics? hopefully not...


## NNLO jet veto:

## $\sigma(0-j e t)=\sigma(t o t a l)-\sigma(\geq I-j e t)$



NNLO


NLO

Catani, de Florian, Grazzini '02


Anastasiou, Dissertori, Grazzini, Stöckli,Webber '09


Stewart, Tackmann 'II

## Jet veto efficiency:

$$
\begin{gathered}
\epsilon^{(a)}\left(p_{\mathrm{t}, \text { veto }}\right) \equiv \frac{\Sigma_{0}\left(p_{\mathrm{t}, \text { veto }}\right)+\Sigma_{1}\left(p_{\mathrm{t}, \text { veto }}\right)+\Sigma_{2}\left(p_{\mathrm{t}, \text { veto }}\right)}{\sigma_{0}+\sigma_{1}+\sigma_{2}} \\
\epsilon^{(b)}\left(p_{\mathrm{t}, \text { veto }}\right) \equiv \frac{\Sigma_{0}\left(p_{\mathrm{t}, \text { veto }}\right)+\Sigma_{1}\left(p_{\mathrm{t}, \text { veto }}\right)+\bar{\Sigma}_{2}\left(p_{\mathrm{t}, \text { veto }}\right)}{\sigma_{0}+\sigma_{1}} \\
\epsilon^{(c)}\left(p_{\mathrm{t}, \text { veto }}\right) \equiv 1+\frac{\bar{\Sigma}_{1}\left(p_{\mathrm{t}, \text { veto }}\right)}{\sigma_{0}}+\left(\frac{\bar{\Sigma}_{2}\left(p_{\mathrm{t}, \text { veto }}\right)}{\sigma_{0}}-\frac{\sigma_{1}}{\sigma_{0}^{2}} \bar{\Sigma}_{1}\left(p_{\mathrm{t}, \text { veto }}\right)\right) \\
\text { perturbatively equivalent }
\end{gathered}
$$

Higgs production ( $\mathrm{m}_{\mathrm{H}}=125 \mathrm{GeV}$ ), NNLO


Banfi, Salam, Zanderighi 'I2

## Resummation:


see also
Becher, Neubert 'I2
Tackmann, Walsh, Zuberi 'l2

Banfi, Monni, Salam, Zanderighi 'I2


$$
\begin{aligned}
m_{t} & =173.2 \mathrm{GeV}, \\
M_{\mathrm{SUSY}} & =1000 \mathrm{GeV}, \\
\mu & =200 \mathrm{GeV}, \\
M_{2} & =200 \mathrm{GeV}, \\
X_{t}^{\mathrm{OS}} & =1.5 M_{\text {SUSY }} \text { (FD calculation) }, \\
X_{t}^{\overline{\mathrm{MS}}} & =1.6 M_{\text {SUSY }} \text { (RG calculation) }, \\
A_{b} & =A_{\tau}=A_{t} \\
m_{\tilde{g}} & =1500 \mathrm{GeV}, \\
M_{\tilde{l}_{3}} & =1000 \mathrm{GeV} .
\end{aligned}
$$

Carena, Heinemeyer, Stål, Wagner, Weiglein '13


- collinear logarithms:
$\sim \alpha_{s} \operatorname{In}\left(m_{b} / M_{H}\right) \sim \alpha_{s} \ln (5 / 200)$
- resummation:
bottom quarks as partons


4FS


5FS








Santander matching:

$$
\begin{aligned}
\sigma & =\frac{\sigma^{4 F S}+w \sigma^{5 F S}}{1+w} \\
w & =\log \frac{M_{H}}{m_{b}}-1
\end{aligned}
$$

RH, Krämer, Schumacher 'II
see also
Maltoni, Ridolfi, Ubiali ' 12


## Santander matching

RH, Krämer, Schumacher 'II

NNLO jet veto:



[^0]:    ferannoc in the maconanf thanhntonn and inter-

