Theory for the LHC:
Adventures with the Higgs Cross Section Working Group

Heather Logan
Carleton University

Pizza and a Prof talk
Carleton University Physics Society
January 25, 2016

A little about me

Undergrad at U. California Davis 1989–1993

Started out interested in astronomy,
quickly switched to physics.
Was interested in astroparticle physics.

Graduate school (Ph.D.) at U. California Santa Cruz 1993–1999

Worked on Higgs physics

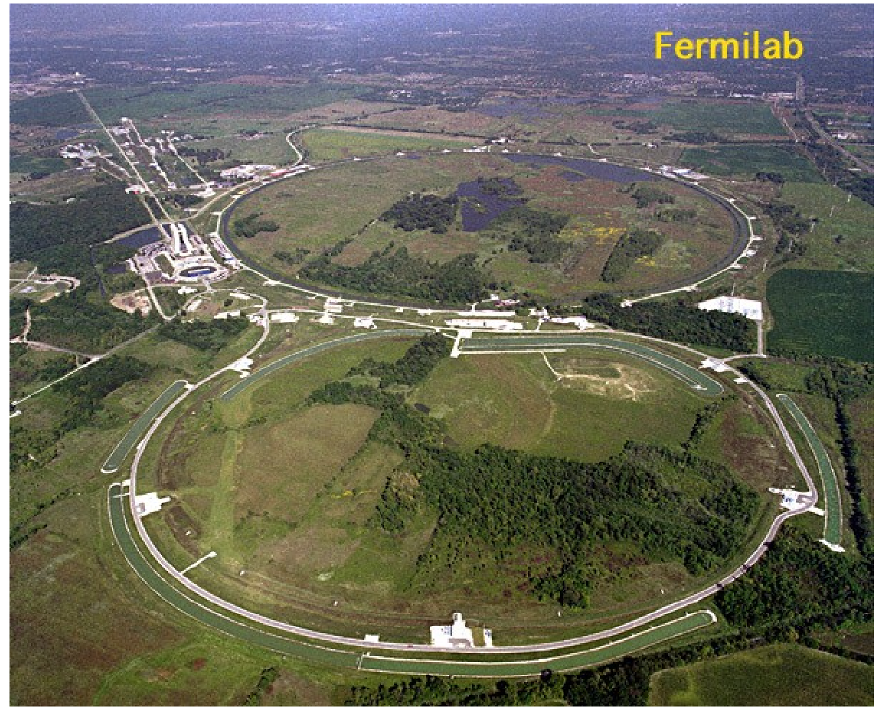
Postdoc at Fermilab 1999–2002

Research job!

Short-term contract: 3 years.

Continued learning: more Higgs, supersymmetry, B physics.

Mentoring by experts in the field.



Postdoc at U. Wisconsin Madison 2002–2005

Short-term contract: 3 years.

Continued learning: Higgs at LHC, Little Higgs models.

Mentoring by different experts.

Professor at Carleton 2005–now

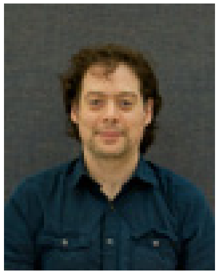
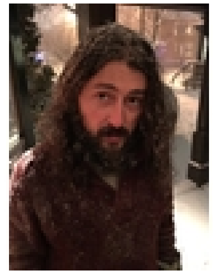
Joined the Theoretical Particle Physics group

Working on research:
- Models with extra Higgs bosons & their properties
- Studying signals and backgrounds at colliders using simulation
- Models with dark matter: what it could be; searching at LHC

Also Grad Chair: talk to me if you need info about grad school

Carleton Theoretical Particle Physics Group

* 4 active faculty members

Profs. Thomas Grégoire, Steve Godfrey, Heather Logan, & Daniel Stolarski (new Winter 2016!)

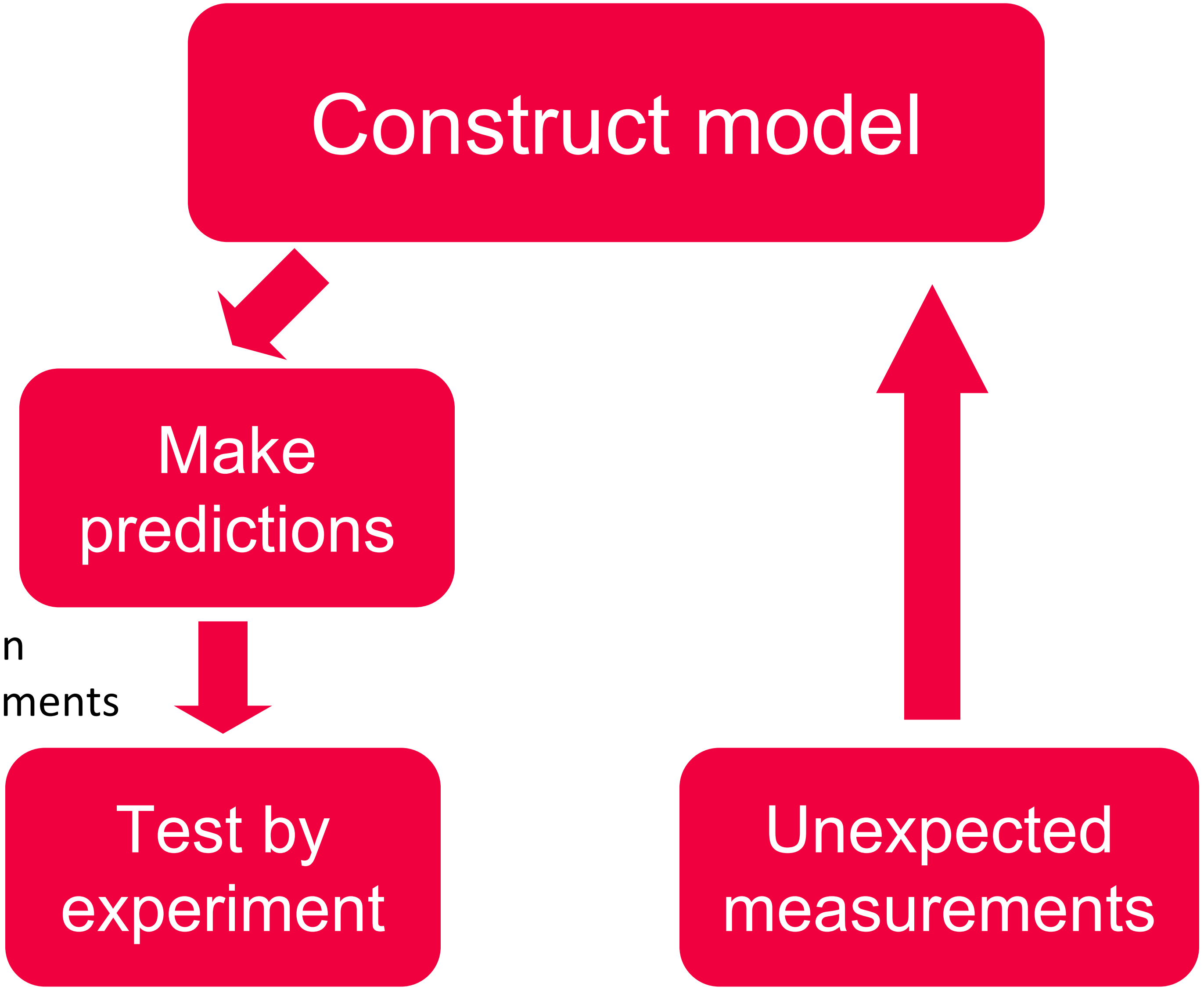
* 2 postdoctoral research associates

Drs. Andrea Peterson and Alejandro de la Puente

* 10 graduate students

MSc: Gage Bonner, Robyn Campbell, Hassan Easa, Ben Keeshan, Will Scott, & Rouz Modarresi Yazdi

PhD: Hugues Beauchesne, Kevin Earl, Terry Pilkington, & Alex Poulin



Give input to experiments on what measurements to make

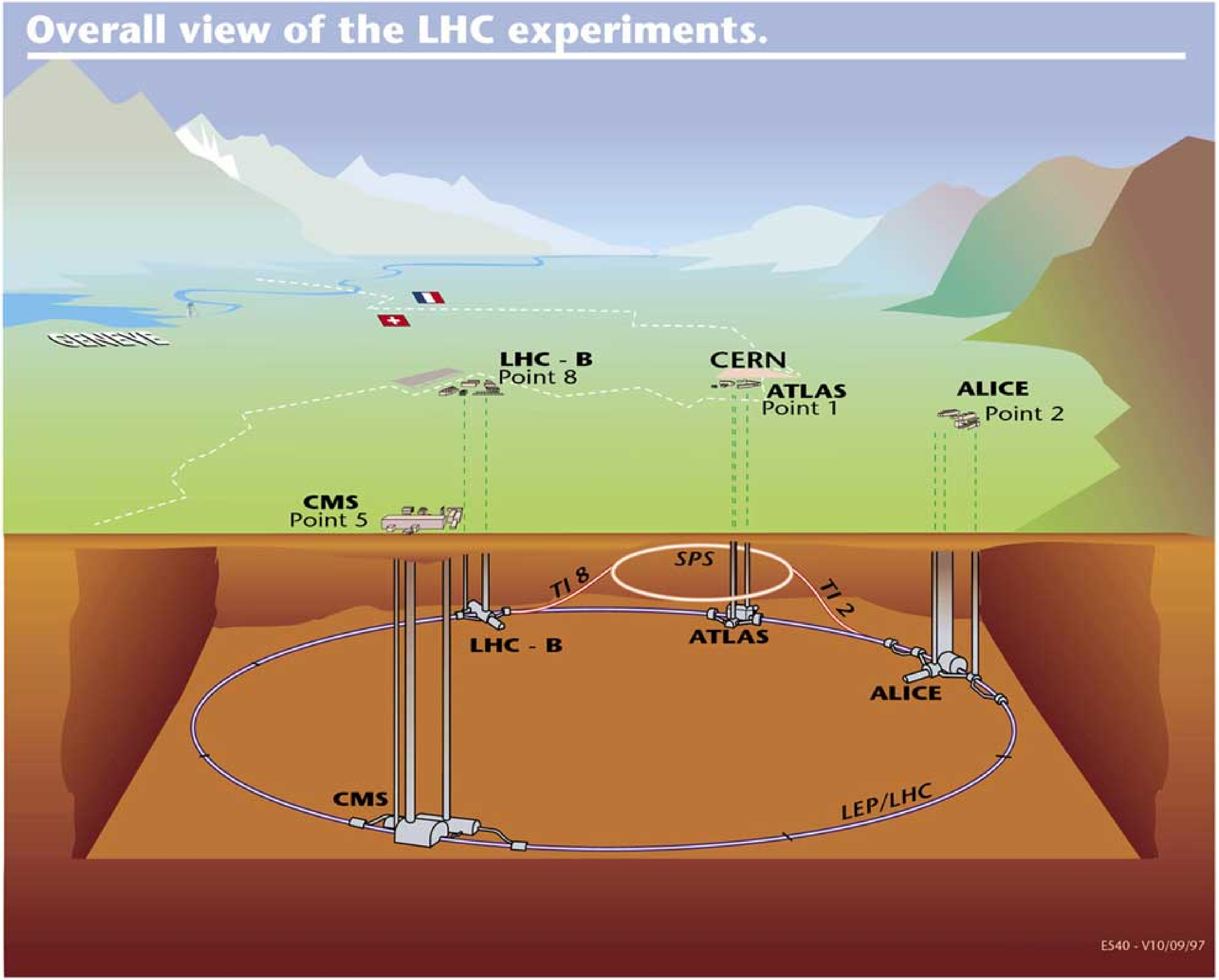
Cooperation between theorists and experimentalists is essential

photo: Snowmass 2013 community planning study

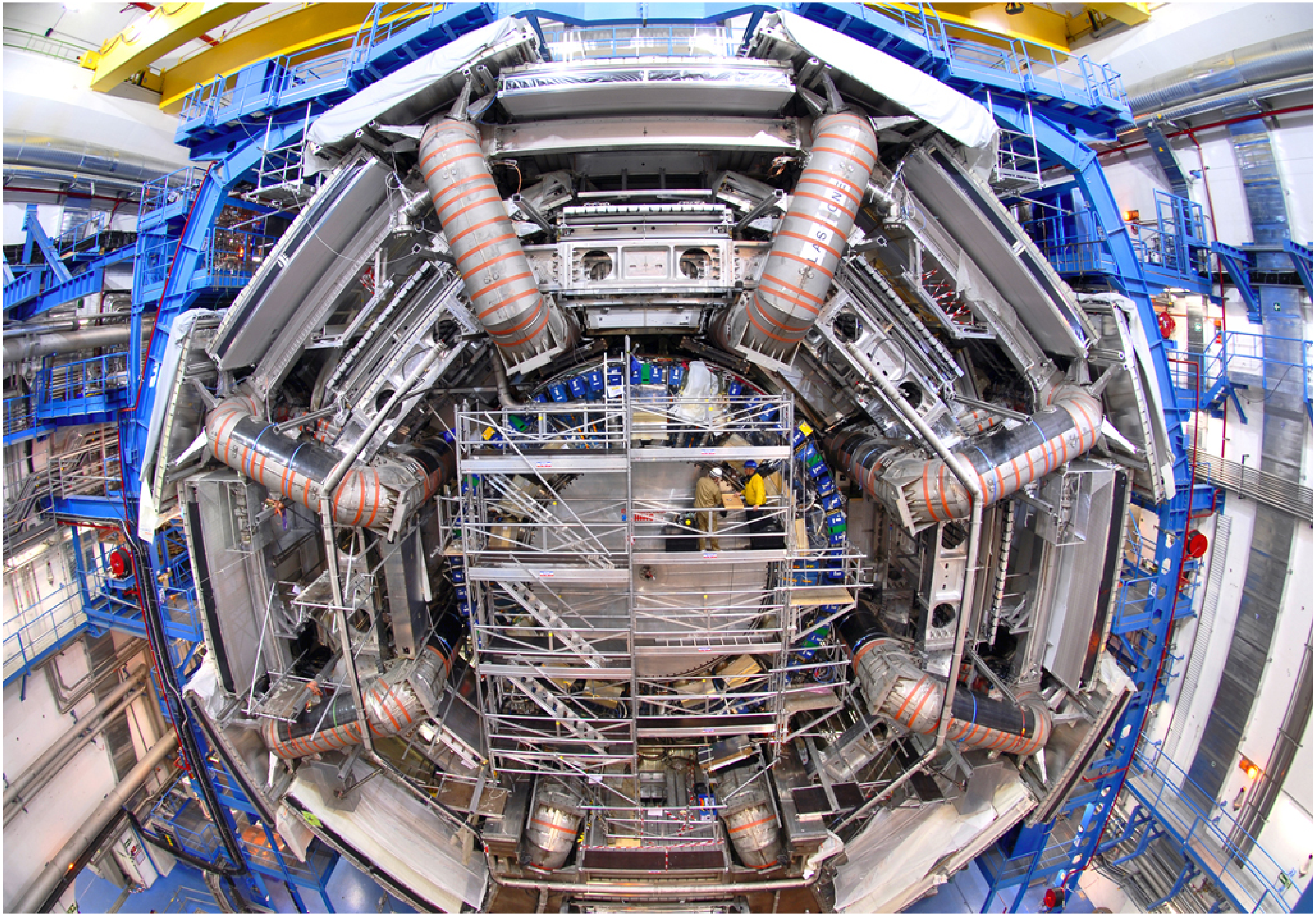
- creation of sensible, interesting, and self-consistent models of New Physics

- computer-simulation software to make detailed predictions for Standard Model physics and New Physics signals at colliders

CERN

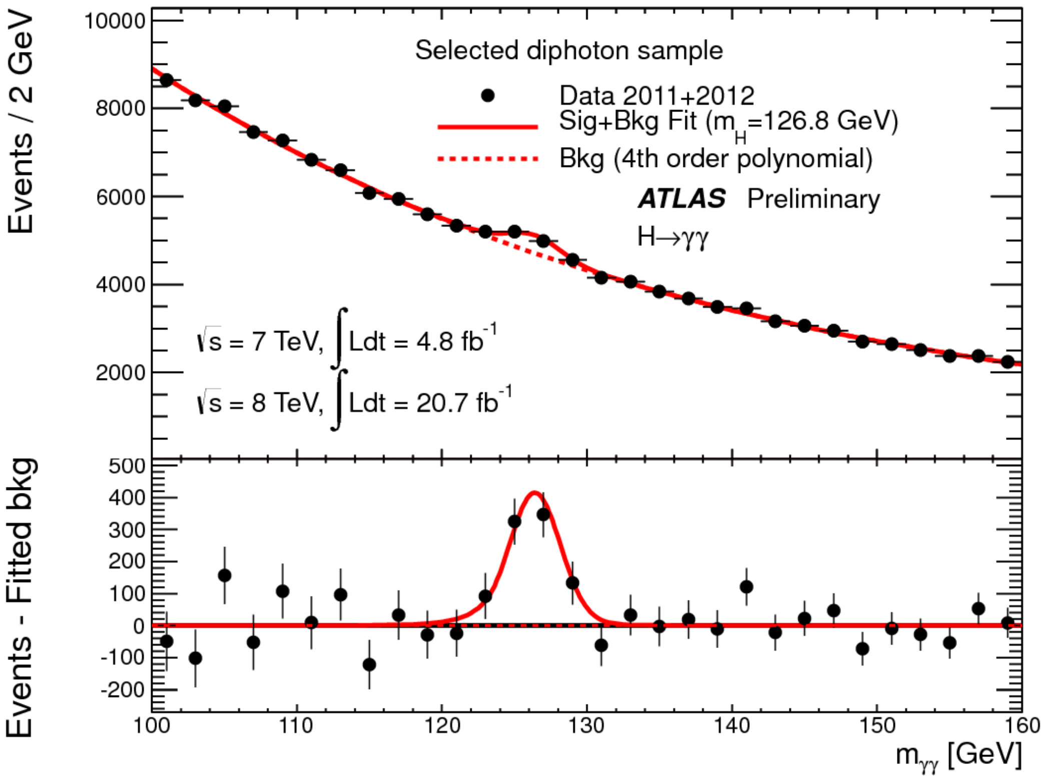

Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

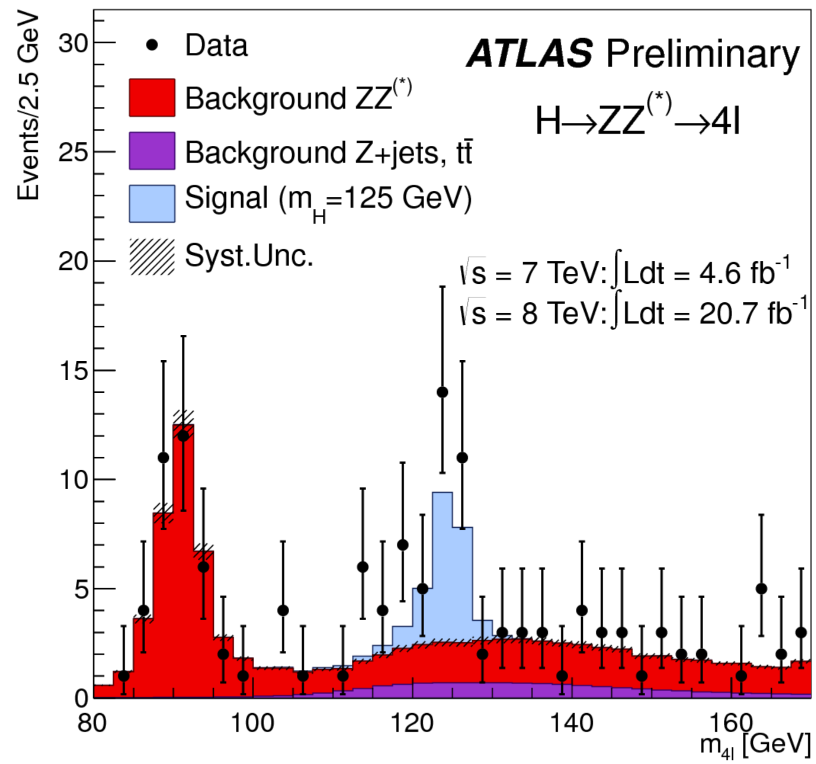
CERN



ATLAS detector installation, February 2007

Higgs boson discovery, July 2012

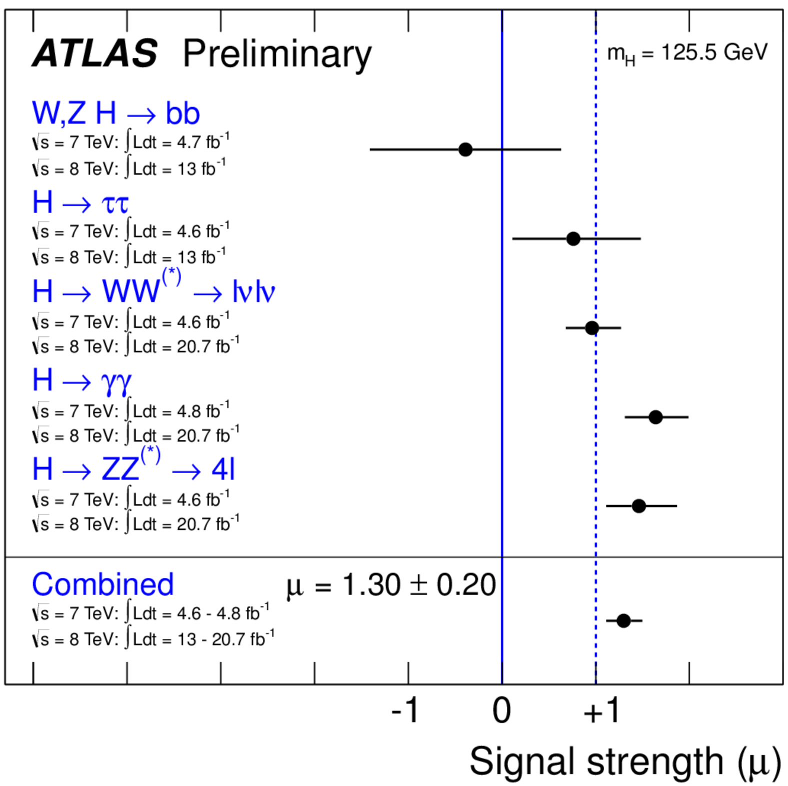


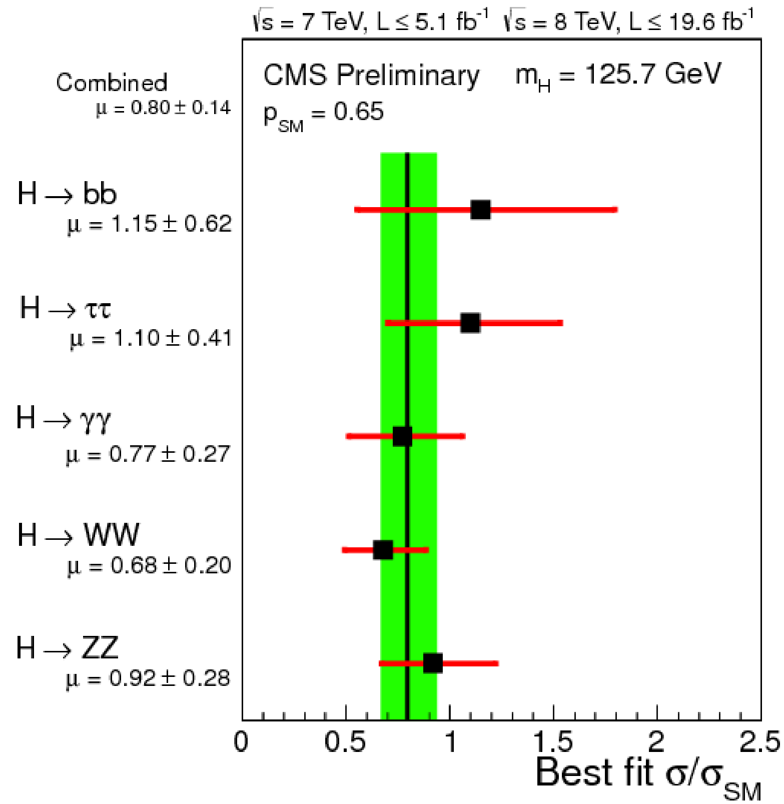


ATLAS results (CMS has similar plots)

On the x-axis: the two-photon or four-lepton *invariant mass*.

Measurements so far consistent with Standard Model Higgs





- Event rates in the expected production/decay processes are just about right (within uncertainties)

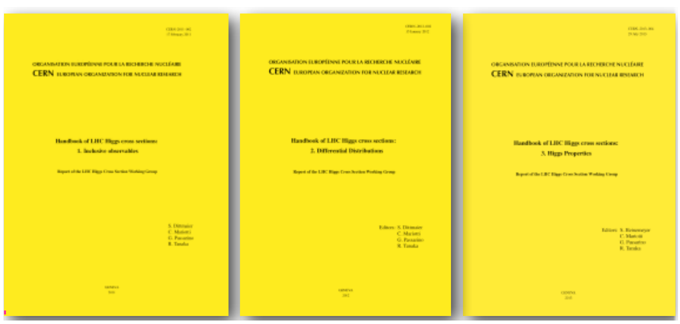
- Angular distributions look like they should [not shown here]

LHC Higgs Cross Section Working Group (HXSWG)

Created January 2010
- Aim was to produce theory *agreements* on cross sections, branching ratios, etc (and their uncertainties!) relevant to SM and MSSM Higgs boson(s)

Restructured spring 2012 ← I got involved here
- Goal of discussing Higgs properties/measurements and beyond-the-SM extensions

Has produced 3 big "yellow reports": facilitated the comparison and combination of Higgs results at LHC



YR1: 64 authors, 153 pages
YR2: 120 authors, 275 pages
YR3: 156 authors, 404 pages ← incl me

(the 4th report is in preparation!)

I was involved in the beyond-the-SM working group but was relatively clueless.

Focus was on the electroweak-singlet extension of the SM:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ v + \phi_3 + i\phi_4 \end{pmatrix}, \qquad S$$

Physical particles:

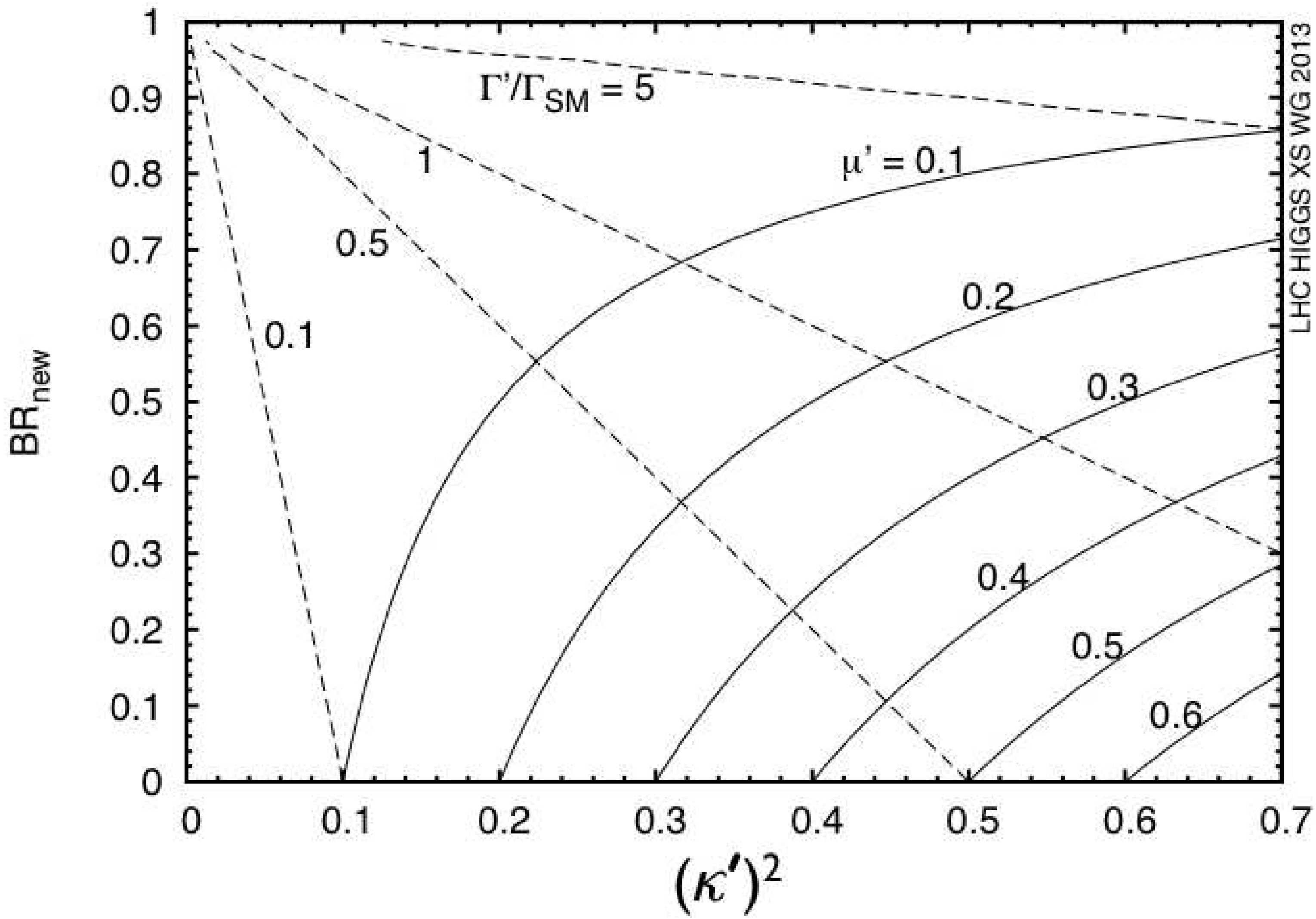
$$h^0 = \phi_3 \cos\theta - S \sin\theta, \qquad H^0 = \phi_3 \sin\theta + S \cos\theta$$

Q: If h^0 is the discovered Higgs boson, how do you search for H^0?

The answers seemed super obvious to me (due to being clueless!) Many video-conferences later...

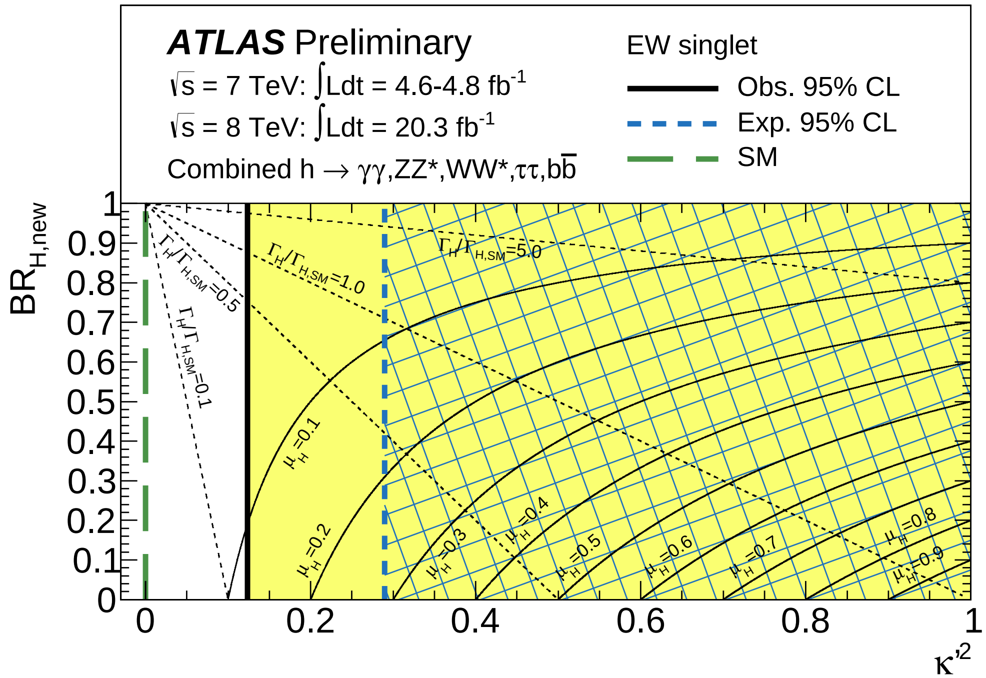
1. With what rate is H^0 produced (as a function of its mass)
2. What is the total width of H^0 (the breadth of the "bump")
3. How is H^0 production rate related to h^0 measurements

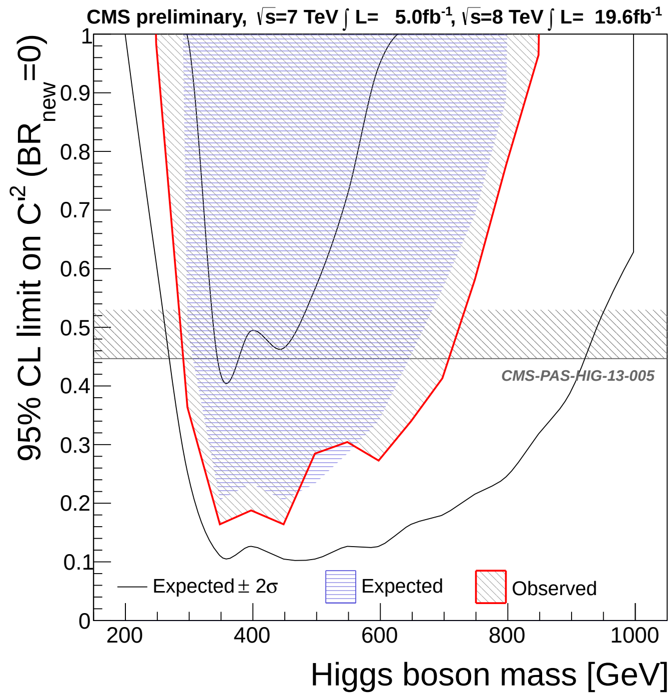
Only 3 parameters: m_H, $\sin\theta \equiv \kappa'$ or C', and BR$_{\rm new}$ $(H \to hh)$



HXSWG, arXiv:1307.1347

The experiments used our stuff!!!





I finally started to understand what the experimentalists were looking for all along: simple, explicit parameterizations in which to express their search constraints!

So when I started working on another model...

Georgi-Machacek model

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs bidoublet + two isospin-triplets in a bitriplet:

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{pmatrix} \qquad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}$$

under a global SU(2)$_L\times$SU(2)$_R$

Physical spectrum:

- Two custodial singlets $\to h^0$, H^0 m_h, m_H $\leftarrow$ very similar
- Custodial triplet $\to (H_3^+, H_3^0, H_3^-)$ m_3 $\leftarrow$ to 2HDM

- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5 $\leftarrow$ new!

$\to$ Focus on direct searches for H_5 states

First step: "work out the model"

$$\begin{aligned}
V(\Phi, X) \; = \; & \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger \Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1 [\mathrm{Tr}(\Phi^\dagger \Phi)]^2 \\
& + \lambda_2 \mathrm{Tr}(\Phi^\dagger \Phi)\mathrm{Tr}(X^\dagger X) + \lambda_3 \mathrm{Tr}(X^\dagger X X^\dagger X) \\
& + \lambda_4 [\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5 \mathrm{Tr}(\Phi^\dagger \tau^a \Phi \tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\
& - M_1 \mathrm{Tr}(\Phi^\dagger \tau^a \Phi \tau^b)(U X U^\dagger)_{ab} - M_2 \mathrm{Tr}(X^\dagger t^a X t^b)(U X U^\dagger)_{ab}
\end{aligned}$$

9 parameters, 2 fixed by G_F and m_h $\rightarrow$ 7 free parameters

Need to work out relationships between the free parameters and the physical masses & couplings of the Higgs particles...

K. Hartling, K. Kumar, and H. E. Logan, "The decoupling limit in the Georgi-Machacek model," Phys. Rev. D 90, 015007 (2014)

...and the constraints due to existing experimental measurements at lower energies...

K. Hartling, K. Kumar, and H. E. Logan, "Indirect constraints on the Georgi-Machacek model and implications for Higgs couplings," Phys. Rev. D 91, 015013 (2015)

GMCALC
A calculator for the Georgi-Machacek model

Description:

The Georgi-Machacek model adds scalar triplets to the Standard Model Higgs sector in such a way as to preserve custodial SU(2) symmetry in the scalar potential. This allows the triplets to have a non-negligible vacuum expectation value while satisfying constraints from the rho parameter. Depending on the parameters, the 125 GeV neutral Higgs particle can have couplings to WW and ZZ larger than in the Standard Model due to mixing with the triplets. The model also contains singly- and doubly-charged Higgs particles that couple to vector boson pairs at tree level (WZ and like-sign WW, respectively).

GMCALC is a self-contained FORTRAN program that, given a set of input parameters, calculates the particle spectrum and tree-level couplings, checks theoretical and indirect constraints on the model, and computes the branching ratios and total widths of the scalars. It also generates a param_card.dat file for MadGraph5 (both LO and NLO versions) to be used with the corresponding FeynRules model implementation.

Authors:

- Katy Hartling, Kunal Kumar, Heather E. Logan, and Andrea D. Peterson (v1.2.x)
- Katy Hartling, Kunal Kumar, and Heather E. Logan (v1.0.x, 1.1.x)

Downloads:

- GMCALC v1.2.0 (.tar.gz, includes manual and changes log)
- Manual (pdf)
- Log of changes (txt)

K. Hartling, K. Kumar, and H. E. Logan, "GMCALC: a calculator for the Georgi-Machacek model," arXiv:1412.7387 [hep-ph]

Drafted back into HXSWG in Feb 2014:
This time, I knew what I wanted to accomplish!

Physical spectrum:

- Two custodial singlets $\rightarrow h^0$, H^0 m_h, m_H $\leftarrow$ very similar
- Custodial triplet $\rightarrow (H_3^+, H_3^0, H_3^-)$ m_3 $\leftarrow$ to 2HDM

- Custodial fiveplet $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$ m_5 $\leftarrow$ new!

$\rightarrow$ Focus on direct searches for H_5 states

Experiments need:

1. What parameters are relevant
2. Predictions for production cross sections & decay widths

$$
\begin{aligned}
V(\Phi, X) \;=\; & \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 \\
& +\lambda_2\mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) + \lambda_3\mathrm{Tr}(X^\dagger X X^\dagger X) \\
& +\lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\
& -M_1\mathrm{Tr}(\Phi^\dagger\tau^a\Phi\tau^b)(UXU^\dagger)_{ab} - M_2\mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}
\end{aligned}
$$

7 free parameters: too messy.

⇒ Specify a "benchmark scenario":

Fixed parameters	Variable parameters	Dependent parameters
$G_F = 1.1663787 \times 10^{-5}$ GeV^{-2}	$m_5 \in [200, 3000]$ GeV	$\lambda_2 = 0.4(m_5/1000\text{ GeV})$
$m_h = 125$ GeV	$s_H \in (0, 1)$	$M_1 = \sqrt{2}s_H(m_5^2 + v^2)/v$
$\lambda_3 = -0.1$		$M_2 = M_1/6$
$\lambda_4 = 0.2$		

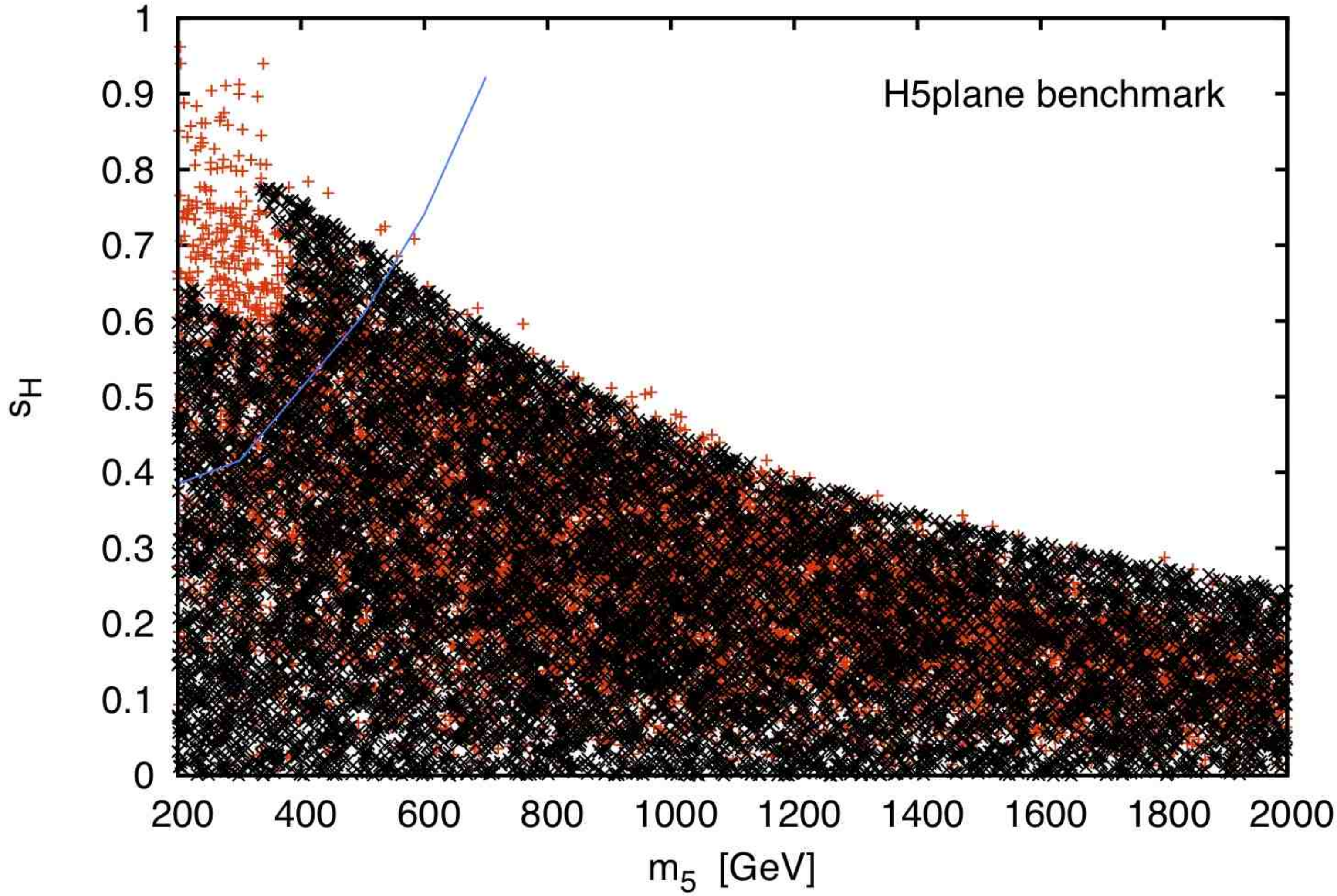
Table 6.1: Specification of the H5plane benchmark for the Georgi-Machacek model. These input parameters correspond to `INPUTSET = 4` in GMCALC [252].

- Vary the parameters that matter most

m_5 = mass of H_5, s_H controls production cross section & total width

- Make sure remaining parameters are set to reasonable values

parameter point makes sense theoretically; not ruled out



Red points: full scan of GM model done using GMCALC!

Black points: "H5plane" benchmark scenario

Region above blue line excluded by ATLAS VBF $W^{\pm}W^{\pm}$ xsec: Chiang et al 1407.5053

VBF $\to H_5$ cross sections (NNLO QCD, LO EW, onshell H_5) and H_5 decay widths (LO) for $H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--}$

Update of numbers in LHCHXSWG-2015-001 (H. Logan & M. Zaro), consistent with H5plane benchmark scenario

m_5 [GeV]	$\sigma_1^{\rm NNLO}(H_5^0)$ [fb]	$\sigma_1^{\rm NNLO}(H_5^+)$ [fb]	$\sigma_1^{\rm NNLO}(H_5^-)$ [fb]
200.	$1375.^{+0.35\%}_{-0.20\%} \pm 1.8\% \pm 0.51\%$	$1770.^{+0.30\%}_{-0.18\%} \pm 1.6\% \pm 0.46\%$	$1148.^{+0.36\%}_{-0.21\%} \pm 2.2\% \pm 0.54\%$
210.	$1288.^{+0.33\%}_{-0.19\%} \pm 1.8\% \pm 0.49\%$	$1662.^{+0.28\%}_{-0.17\%} \pm 1.7\% \pm 0.45\%$	$1073.^{+0.34\%}_{-0.21\%} \pm 2.2\% \pm 0.53\%$
220.	$1209.^{+0.30\%}_{-0.18\%} \pm 1.8\% \pm 0.48\%$	$1564.^{+0.26\%}_{-0.17\%} \pm 1.7\% \pm 0.44\%$	$1004.^{+0.32\%}_{-0.20\%} \pm 2.2\% \pm 0.52\%$
230.	$1136.^{+0.28\%}_{-0.17\%} \pm 1.8\% \pm 0.47\%$	$1473.^{+0.25\%}_{-0.16\%} \pm 1.7\% \pm 0.43\%$	$940.9^{+0.31\%}_{-0.19\%} \pm 2.2\% \pm 0.51\%$
240.	$1069.^{+0.26\%}_{-0.17\%} \pm 1.8\% \pm 0.46\%$	$1388.^{+0.25\%}_{-0.15\%} \pm 1.7\% \pm 0.42\%$	$883.0^{+0.29\%}_{-0.18\%} \pm 2.3\% \pm 0.50\%$
250.	$1006.^{+0.27\%}_{-0.16\%} \pm 1.8\% \pm 0.46\%$	$1311.^{+0.25\%}_{-0.14\%} \pm 1.7\% \pm 0.41\%$	$829.6^{+0.27\%}_{-0.17\%} \pm 2.3\% \pm 0.49\%$
260.	$948.9^{+0.27\%}_{-0.15\%} \pm 1.8\% \pm 0.45\%$	$1239.^{+0.25\%}_{-0.14\%} \pm 1.7\% \pm 0.40\%$	$780.4^{+0.27\%}_{-0.17\%} \pm 2.3\% \pm 0.48\%$

m_5 [GeV]	$\sigma_1^{\rm NNLO}(H_5^{++})$ [fb]	$\sigma_1^{\rm NNLO}(H_5^{--})$ [fb]
200.	$2511.^{+0.24\%}_{-0.14\%} \pm 1.9\% \pm 0.40\%$	$1070.^{+0.33\%}_{-0.21\%} \pm 2.9\% \pm 0.54\%$
210.	$2364.^{+0.24\%}_{-0.14\%} \pm 1.9\% \pm 0.39\%$	$997.0^{+0.31\%}_{-0.20\%} \pm 2.9\% \pm 0.53\%$
220.	$2229.^{+0.23\%}_{-0.13\%} \pm 1.9\% \pm 0.38\%$	$930.3^{+0.29\%}_{-0.19\%} \pm 3.0\% \pm 0.52\%$
230.	$2104.^{+0.24\%}_{-0.13\%} \pm 1.9\% \pm 0.37\%$	$869.2^{+0.27\%}_{-0.19\%} \pm 3.0\% \pm 0.51\%$
240.	$1988.^{+0.24\%}_{-0.12\%} \pm 1.9\% \pm 0.35\%$	$813.3^{+0.25\%}_{-0.18\%} \pm 3.0\% \pm 0.51\%$
250.	$1881.^{+0.24\%}_{-0.11\%} \pm 1.9\% \pm 0.34\%$	$762.0^{+0.25\%}_{-0.18\%} \pm 3.1\% \pm 0.50\%$
260.	$1781.^{+0.24\%}_{-0.10\%} \pm 1.9\% \pm 0.33\%$	$714.8^{+0.25\%}_{-0.18\%} \pm 3.1\% \pm 0.49\%$

Uncertainty on σ from uncalculated NLO EW corrs $\simeq \pm 7\%$

m_5 [GeV]	$\Gamma_1^{\rm tot}(H_5^{\pm\pm})$ [GeV]	$\Gamma_1^{\rm tot}(H_5^{\pm})$ [GeV]	$\Gamma_1^{\rm tot}(H_5^{0})$ [GeV]	${\rm BR}(H_5^0 \to W^+W^-)$
200.	1.006	0.8608	0.8008	$0.4187^{+14.\%}_{-14.\%}$
210.	1.275	1.118	1.071	$0.3969^{+15.\%}_{-14.\%}$
220.	1.578	1.410	1.362	$0.3863^{+15.\%}_{-14.\%}$
230.	1.921	1.737	1.686	$0.3799^{+15.\%}_{-14.\%}$
240.	2.307	2.105	2.051	$0.3749^{+15.\%}_{-15.\%}$
250.	2.739	2.516	2.459	$0.3714^{+16.\%}_{-15.\%}$
260.	3.219	2.975	2.912	$0.3685^{+16.\%}_{-15.\%}$

to appear in YR4

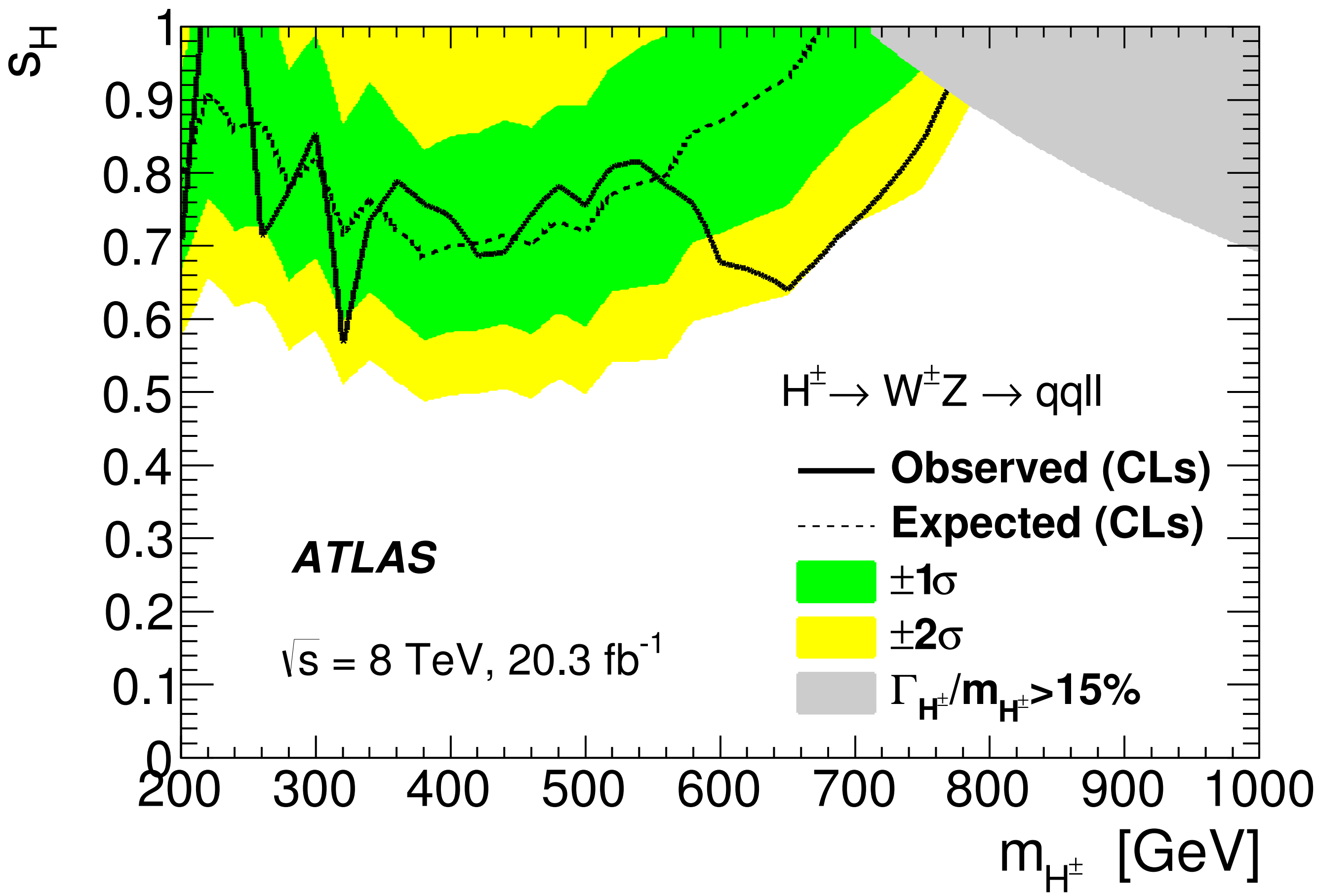
Uncertainty on Γ from uncalculated NLO EW corrs $\simeq \pm 12\%$

s_H dependence incorporated via $\sigma \equiv s_H^2 \sigma_1$, $\Gamma \equiv s_H^2 \Gamma_1$

ATLAS search for Georgi-Machacek model fiveplet state $H_5^\pm$

- Production via vector boson fusion, cross section $\propto s_H^2$

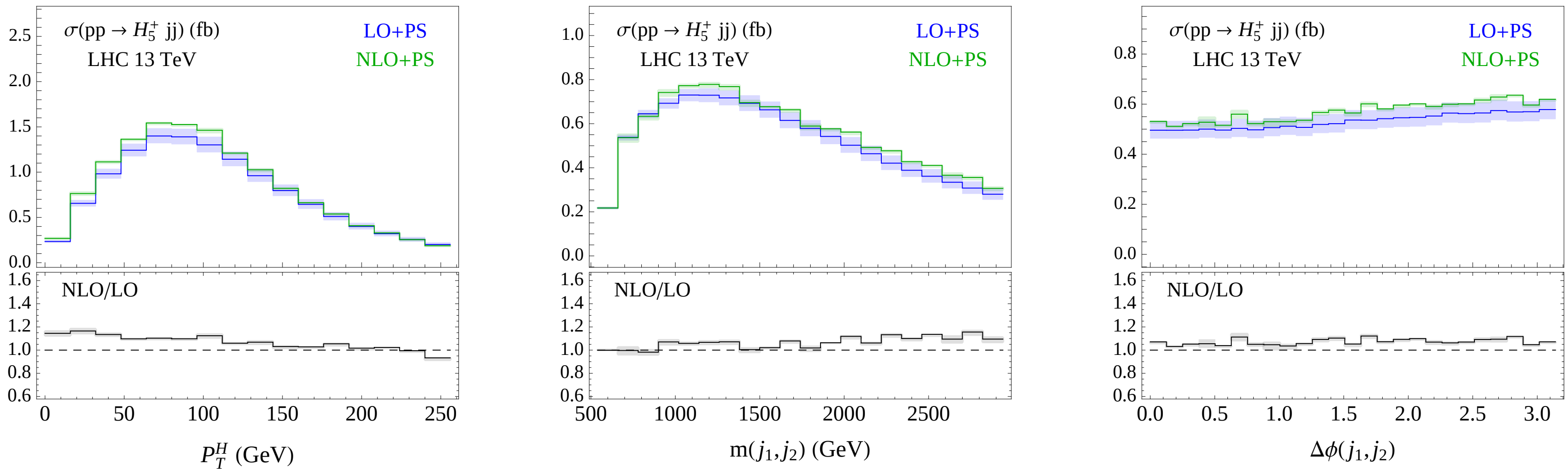
  $s_H^2 =$ fraction of M_W^2 and M_Z^2 coming from the triplet



ATLAS Collaboration, Phys. Rev. Lett. 114, 231801 (2015)

Our latest stuff:

Studying effects of QCD corrections on kinematic distributions



C. Degrande, K. Hartling, H. E. Logan, A. D. Peterson and M. Zaro, "Automatic predictions in the Georgi-Machacek model at next-to-leading order accuracy," arXiv:1512.01243 [hep-ph]

MadGraph model file publicly released

https://feynrules.irmp.ucl.ac.be/wiki/GeorgiMachacekModel

(still a little debugging to do, will not affect published results)

Summing up... and the future

Working with the Higgs Cross Section Working Group has changed the way I do physics (at least a little bit :)

What's next for me with the HXSWG?

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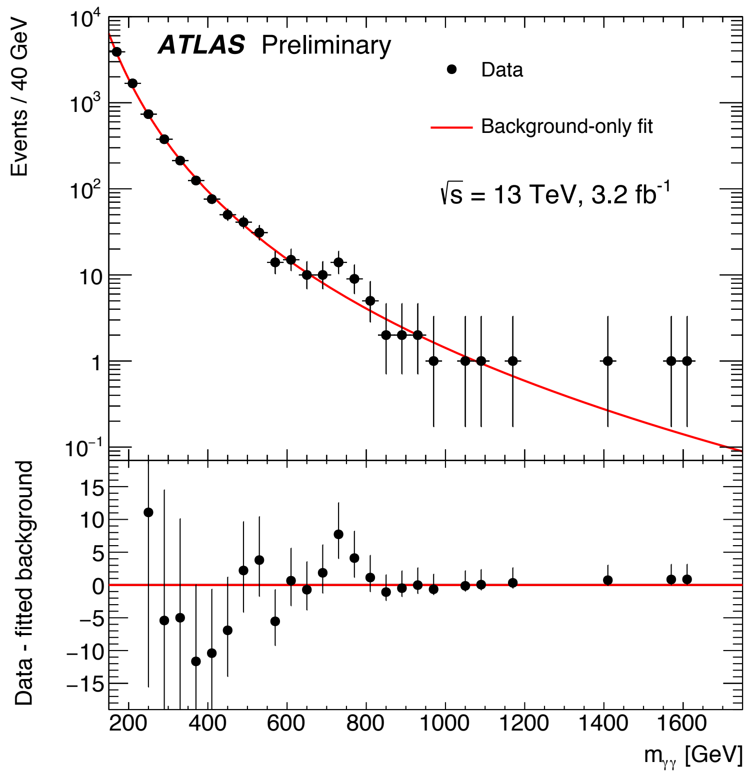


⇐ OMG What is That??!

- Experiments request an extended-Higgs benchmark to interpret their two-photon resonance search

- Fabbrichesi & Urbano, arXiv:1601.02447 claims the bump can be accommodated in the Georgi-Machacek model

⇒ Work out a benchmark scenario

⇒ Recruit some experts for un-studied part of the cross-section prediction

BACKUP SLIDES

Experimental particle physics at Carleton

- ATLAS experiment at the CERN Large Hadron Collider

Profs. Bellerive, Gillberg, Koffas, Oakham, & Vincter

- EXO - are neutrinos their own antiparticles?

Profs. Graham, Gornea, & Sinclair + Koffas

- DEAP - search for Dark Matter

Profs. Boulay & Graham

- ILC (International Linear Collider) detector development

Prof. Bellerive

Student research opportunities

* Summer research positions

NSERC USRA summer research fellowships

- applications are usually due in January
- generally need at least 3rd year QM, E&M, dynamics for theory
- awards based on CGPA: work hard & keep your grades up!

* 4th-year Honours Projects

PHYS 4909 – research project under direct guidance of a faculty member

* Grad student positions (MSc, PhD)

We are always looking for strong students!

For non-physics students: check with your department.

There are many opportunities to get involved in research during your undergrad career!

Introduction: the descriptive version

The Higgs field is a new kind of field that fills all space

Kind of like a magnetic field, but without a direction

It carries weak gauge charges (isospin and hypercharge):
the W and Z bosons interact with it and thereby become massive

It interacts with different fermions with different strengths:
thereby the quarks and leptons all acquire their different masses

(except probably for neutrinos: that's another story)

This is the description in the Standard Model:
only just starting to be tested!

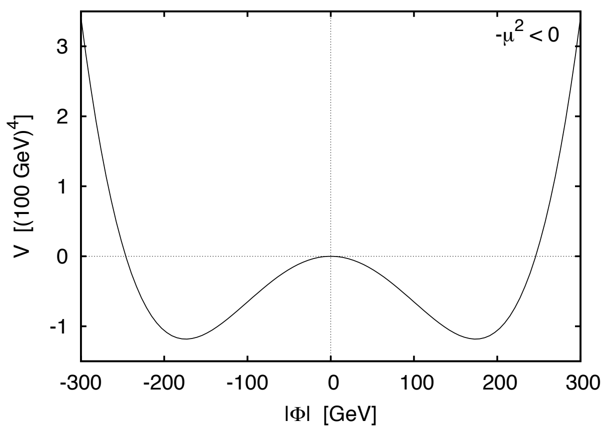
Introduction: the mathy version

A one-line theory:

$$\mathcal{L}_{Higgs} = |\mathcal{D}_\mu H|^2 - [-\mu^2 H^\dagger H + \lambda (H^\dagger H)^2] - [y_f \bar{f}_R H^\dagger F_L + \text{h.c.}]$$

Most general, renormalizable, gauge-invariant theory involving a single spin-zero (scalar) field with isospin 1/2, hypercharge 1.

$-\mu^2$ term: electroweak symmetry spontaneously broken; Goldstone bosons can be gauged away leaving 1 physical particle h.



$$H = \begin{pmatrix} G^+ \\ (v + h + iG^0)/\sqrt{2} \end{pmatrix}$$

Mass and vacuum expectation value of h are fixed by minimizing the Higgs potential:

$$v^2 = \mu^2/\lambda \qquad\qquad M_h^2 = 2\lambda v^2 = 2\mu^2$$

Introduction: the mathy version

SM Higgs couplings to SM particles are fixed by the mass-generation mechanism.

W and Z: $g_Z \equiv \sqrt{g^2 + g'^2}$, $v = 246$ GeV

$$\mathcal{L} = |\mathcal{D}_\mu H|^2 \;\rightarrow\; (g^2/4)(h+v)^2 W^+ W^- + (g_Z^2/8)(h+v)^2 ZZ$$
$$M_W^2 = g^2 v^2/4 \qquad hWW: \; i(g^2 v/2) g^{\mu\nu}$$
$$M_Z^2 = g_Z^2 v^2/4 \qquad hZZ: \; i(g_Z^2 v/2) g^{\mu\nu}$$

Fermions:

$$\mathcal{L} = -y_f \bar{f}_R H^\dagger F_L + \cdots \;\rightarrow\; -(y_f/\sqrt{2})(h+v)\bar{f}_R f_L + \text{h.c.}$$
$$m_f = y_f v/\sqrt{2} \qquad h\bar{f}f: \; i m_f/v$$

Gluon pairs and photon pairs:
induced at 1-loop by fermions, W-boson.

All predicted in the Standard Model, with no free parameters!

There is a lot more work to do on the Higgs.

- Precision measurements of Higgs boson properties need more data!

- Are there more Higgs-like particles? Hunt for them!

And there are still many other mysteries to solve.

- Dark matter? Dark energy??

- Matter/antimatter asymmetry of the universe?

- Neutrino masses? (probably not coming solely from the Higgs)

- Why 3 generations of quarks & leptons?

- New forces? New dimensions of space??

Most general scalar potential:

Aoki & Kanemura, 0712.4053

Chiang & Yagyu, 1211.2658; Chiang, Kuo & Yagyu, 1307.7526

Hartling, Kumar & HEL, 1404.2640

$$
\begin{aligned}
V(\Phi, X) = & \frac{\mu_2^2}{2}\mathrm{Tr}(\Phi^\dagger\Phi) + \frac{\mu_3^2}{2}\mathrm{Tr}(X^\dagger X) + \lambda_1[\mathrm{Tr}(\Phi^\dagger\Phi)]^2 \\
& +\lambda_2 \mathrm{Tr}(\Phi^\dagger\Phi)\mathrm{Tr}(X^\dagger X) + \lambda_3 \mathrm{Tr}(X^\dagger X X^\dagger X) \\
& +\lambda_4[\mathrm{Tr}(X^\dagger X)]^2 - \lambda_5 \mathrm{Tr}(\Phi^\dagger \tau^a \Phi \tau^b)\mathrm{Tr}(X^\dagger t^a X t^b) \\
& -M_1 \mathrm{Tr}(\Phi^\dagger \tau^a \Phi \tau^b)(UXU^\dagger)_{ab} - M_2 \mathrm{Tr}(X^\dagger t^a X t^b)(UXU^\dagger)_{ab}
\end{aligned}
$$

9 parameters, 2 fixed by M_W and m_h $\rightarrow$ free parameters are m_H, m_3, m_5, v_χ, α plus two triple-scalar couplings.

Dimension-3 terms usually omitted by imposing Z_2 sym. on X.
These dim-3 terms are essential for the model to possess a decoupling limit!

$(UXU^\dagger)_{ab}$ is just the matrix X in the Cartesian basis of SU(2), found using

$$
U = \begin{pmatrix} -\frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \\ -\frac{i}{\sqrt{2}} & 0 & -\frac{i}{\sqrt{2}} \\ 0 & 1 & 0 \end{pmatrix}
$$

Theory constraints

Perturbative unitarity: impose $|\mathrm{Re}\, a_0| < 1/2$ on eigenvalues of coupled-channel matrix of $2 \to 2$ scalar scattering processes. Constrain ranges of λ_{1-5}.

Aoki & Kanemura, 0712.4053

Bounded-from-belowness of the scalar potential: consider all combinations of fields nonzero. Further constraints on λ_{1-5}.

Hartling, Kumar & HEL, 1404.2640

Absence of deeper custodial SU(2)-breaking minima: numerical check that desired minimum is the deepest (1-dim scan over finite parameter range). Constraints involve all 9 parameters.

Hartling, Kumar & HEL, 1404.2640

(we do not consider situations in which the desired vacuum is metastable)

Indirect constraints

Hartling, Kumar & HEL, 1410.5538

R_b: known a long time in GM model; same form as Type-I 2HDM

HEL & Haber, hep-ph/9909335; Chiang & Yagyu, 0902.4665; Type-I: Grant, hep-ph/9410267

B_s–$\bar{B}_s$ mixing: adapted from Type-I 2HDM

Mahmoudi & Stal, 0907.1791

* $b \to s\gamma$: adapted from Type-I 2HDM

Barger, Hewett & Phillips, PRD41, 3421 (1990)

F. Mahmoudi, SuperIso

$B_s \to \mu^+\mu^-$: adapted from new calculation for Aligned 2HDM

Li, Lu & Pich, 1404.5865

S parameter: marginalize over T Gunion, Vega & Wudka, PRD43, 2322 (1991)

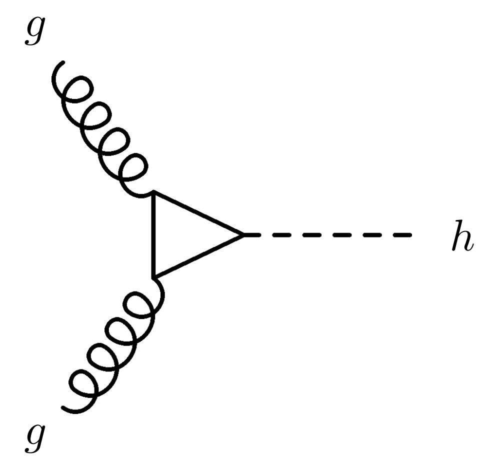
* strongest

Higgs couplings at the LHC: top 4 production modes

1) Gluon fusion
(90% of Higgs production at LHC)

Top quark in the loop gives most important contribution (bottom quark few-%)

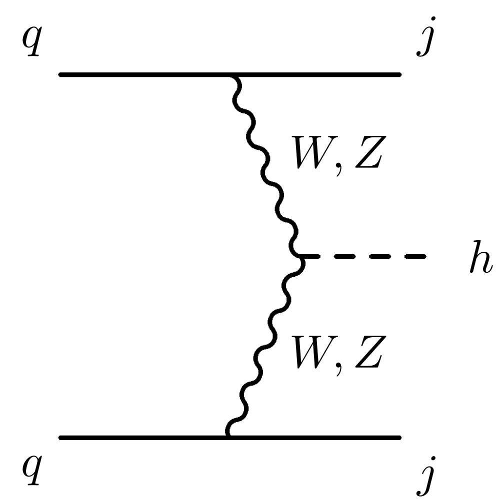
Just Higgs produced: need distinctive decays:
$\gamma\gamma$, $ZZ \to 4\ell$



2) Weak boson fusion
($\sim$10% of Higgs production at LHC)

Higgs couples to WW or ZZ

Two energetic "tagging jets" produced: distinctive production signature

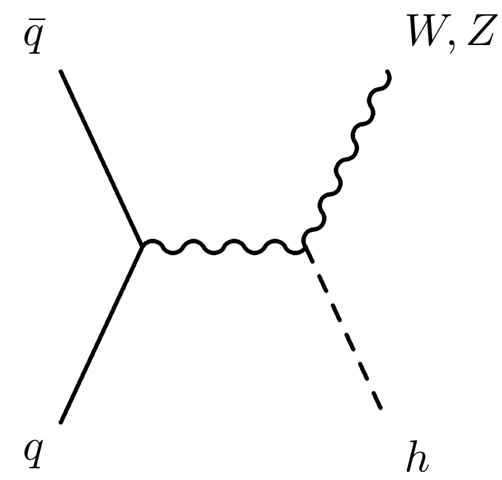


Higgs couplings at the LHC: top 4 production modes

3) Associated production of $h + W$, $h + Z$
(a couple percent of total Higgs rate)

Higgs couples to WW or ZZ

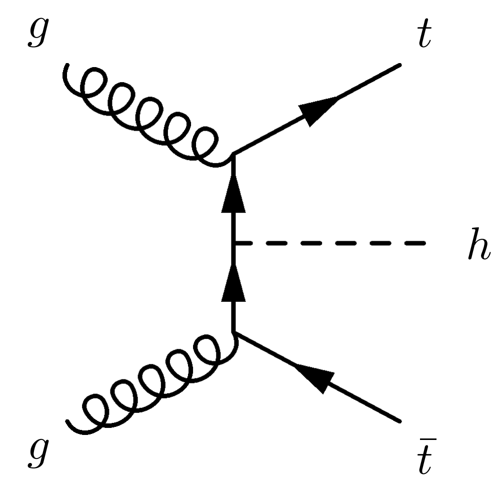
$W \to \ell\nu$ or $Z \to \ell^+\ell^-$ provide distinctive tags: essential if Higgs decay is similar to backgrounds!



4) Associated production of $h + t\bar{t}$
(rare: only 1% of total Higgs rate at 13 TeV)

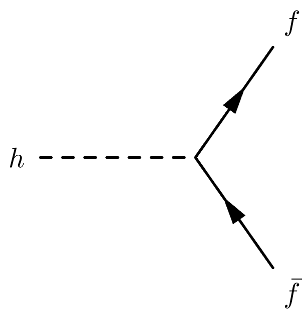
Higgs couples to $t\bar{t}$: cleaner probe of $ht\bar{t}$ coupling than gluon fusion

Two top quarks provide distinctive tags

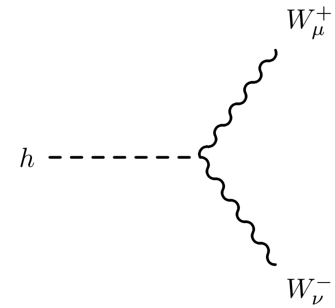


Higgs couplings at the LHC: decays

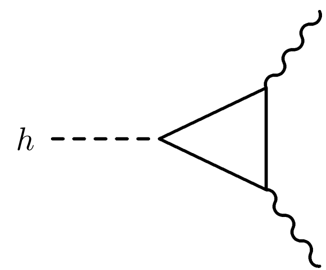
2 fermions:
$b\bar{b}$, $\tau\tau$, $c\bar{c}$



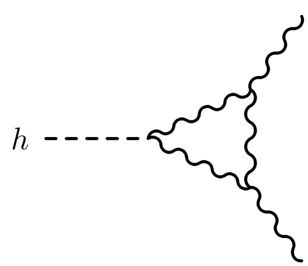
$WW \to \ell\nu\ell\nu$
or $ZZ \to 4\ell$, $2\ell2\nu$

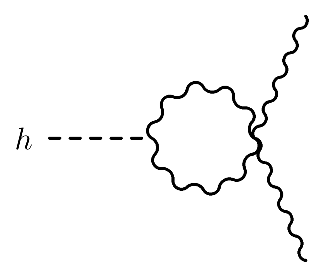


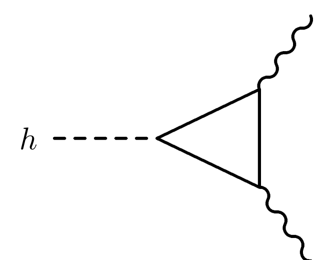
2 gluons, mainly through a top quark loop (bottom loop a few percent)



2 photons, mainly through a W boson loop; top quark loop interferes destructively (-30%), small contribution from bottom loop







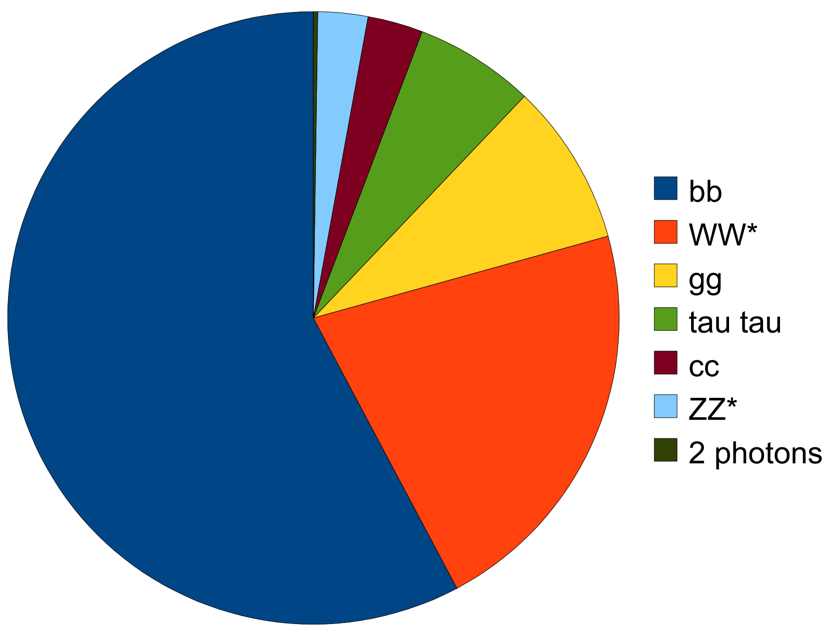
Higgs couplings at the LHC: decays

Predict the decay rate Γ_i into each final state i.

Total decay rate is $\Gamma_{\text{tot}} \equiv \sum_i \Gamma_i$.

Fraction of Higgs decays into a particular final state is

$$\text{BR}_i \equiv \frac{\Gamma_i}{\Gamma_{\text{tot}}}$$ "branching ratio"



Why Higgs couplings are interesting: search for new physics!

We know that the Standard Model cannot be the whole story.

Problems from data:

- Dark matter (and dark energy?!?)
  Higgs portal; $h \to$ invisible
- Matter-antimatter asymmetry
  Electroweak baryogenesis, need modified Higgs potential

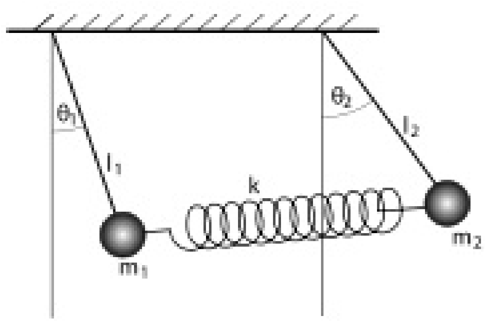
Problems from theory:

- Hierarchy problem
  SUSY; composite Higgs/Randall-Sundrum; little Higgs; fine tuning??
- Neutrino masses (why so very tiny?)
  Type-2 seesaw scalar triplet; neutrino-coupled doublet
- Flavour (origin of quark and lepton masses, mixing, CP violation?)
  Clues from fermion couplings to Higgs?

Three general possibilities:

1) More than one Higgs field in the vacuum

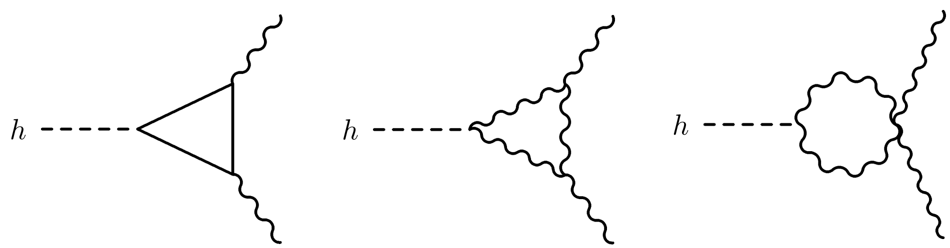
Each one has excitations, in general they are coupled together:
$\rightarrow$ there are more Higgs states (including electrically-charged!)
$\rightarrow$ physical particles are mixtures



Couplings of physical Higgs h are modified due to mixing:
parameterize by multiplicative factors κ_i

Three general possibilities:

2) New particles that interact with the Higgs



Like top squarks, charginos in Supersymmetry:
They run in the loops that cause ggh and $h\gamma\gamma$ couplings

Modified loop-induced couplings: probe for new physics through its virtual effects!

Three general possibilities:

3) New particles that the Higgs can decay into

The Higgs can interact with new particles that don't interact via the strong, weak, or electromagnetic interactions.
$\rightarrow$ Dark matter?

Can also interact with light new particles that have so far evaded direct searches.
$\rightarrow$ New light particles that decay to non-distinctive final states, like QCD jets

The Higgs could be our window to new physics!

New decays add to $\Gamma_{\rm tot}$: affect the "visible" Higgs branching ratios via

$$\mathrm{BR}_i \equiv \frac{\Gamma_i}{\Gamma_{\rm tot}} = \frac{\Gamma_i}{\Gamma_{\rm SM} + \Gamma_{\rm new}}$$

Extracting Higgs couplings from LHC data

Measure event rates at LHC: sensitive to production and decay couplings. Narrow width approximation:

$$\text{Rate}_{ij} = \sigma_i \, \text{BR}_j = \sigma_i \frac{\Gamma_j}{\Gamma_{\text{tot}}}$$

Coupling dependence (at leading order):

$$\sigma_i = \kappa_i^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_j = \kappa_j^2 \times (\text{SM coupling})^2 \times (\text{kinematic factors})$$
$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum \kappa_k^2 \Gamma_k^{\text{SM}}$$

Each rate depends on multiple couplings. $\rightarrow$ correlations

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$$\Gamma_{\text{tot}} = \sum \Gamma_k = \sum_{\text{SM}} \kappa_k^2 \Gamma_k^{\text{SM}} + \sum_{\text{new}} \Gamma_k^{\text{new}}$$

Each rate depends on multiple couplings. $\rightarrow$ correlations

Non-SM decays could also be present:

- invisible final state (can look for this with dedicated searches)
- "unobserved" final state (e.g., $h \rightarrow$ jets)