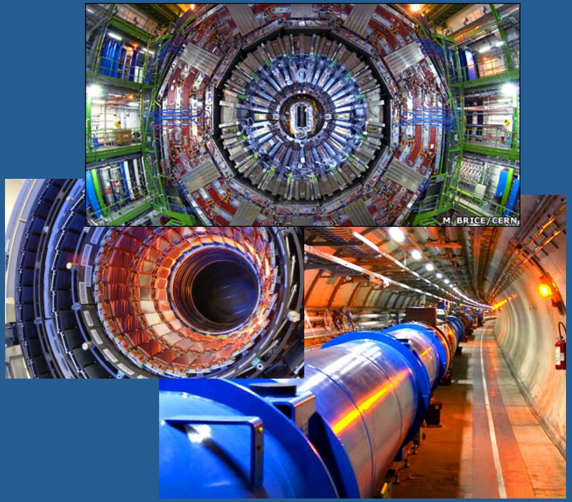
The Interplay Between the Top Quark and the Higgs Boson:

How a discovery from a generation ago can help us understand the latest discovery in particle physics

Prof. Chris Neu
Department of Physics
University of Virginia



4 July 2012: A Coming Out Party

Celebrations on
4 July 2012

CERN and Melbourne
and many other places
around the globe

Both CMS and ATLAS reporting
5 sigma evidence for a new
particle with mass ~ 125 GeV

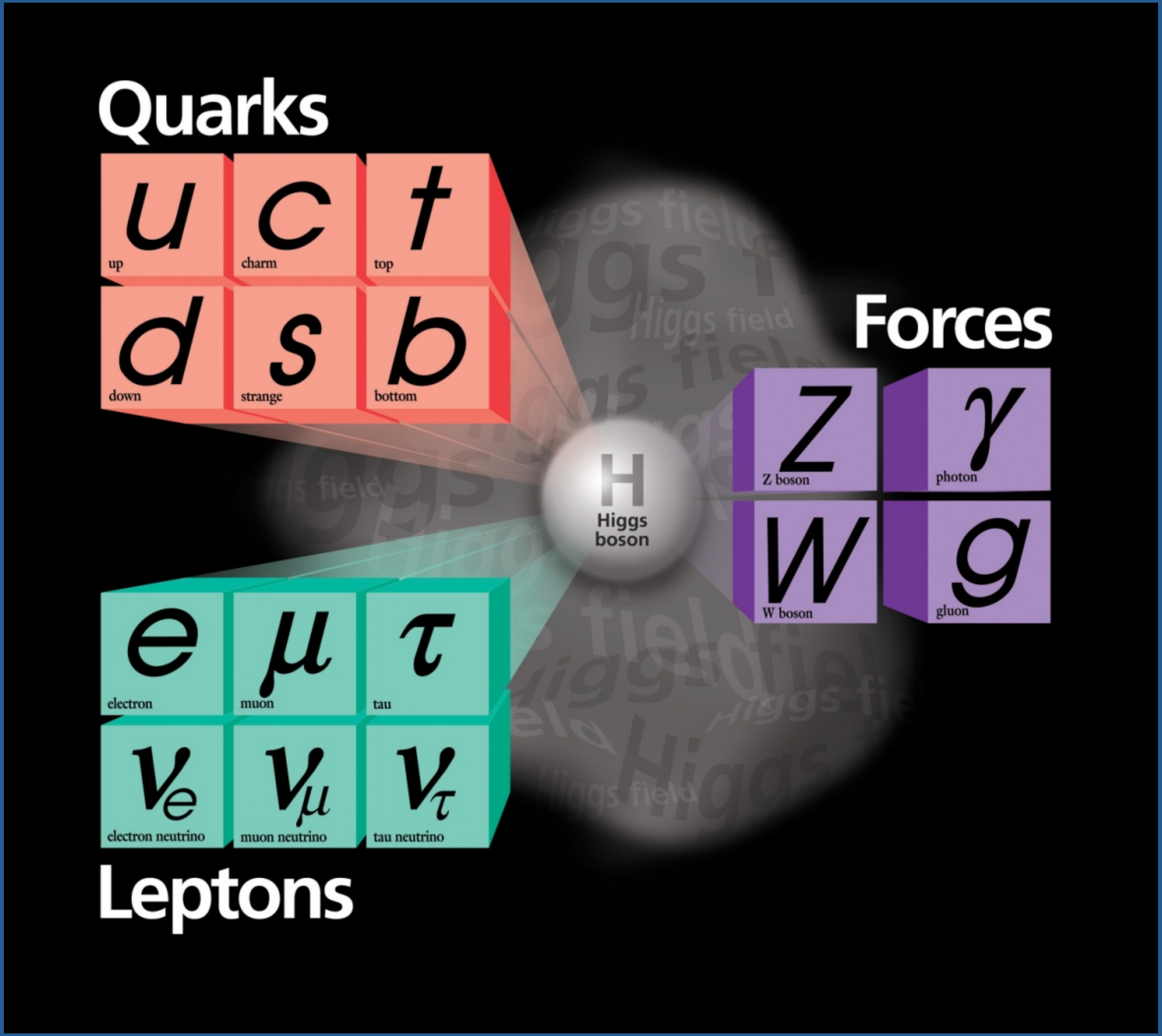
2 March 1995: A Coming Out Party

2 March 1995: A Coming Out Party

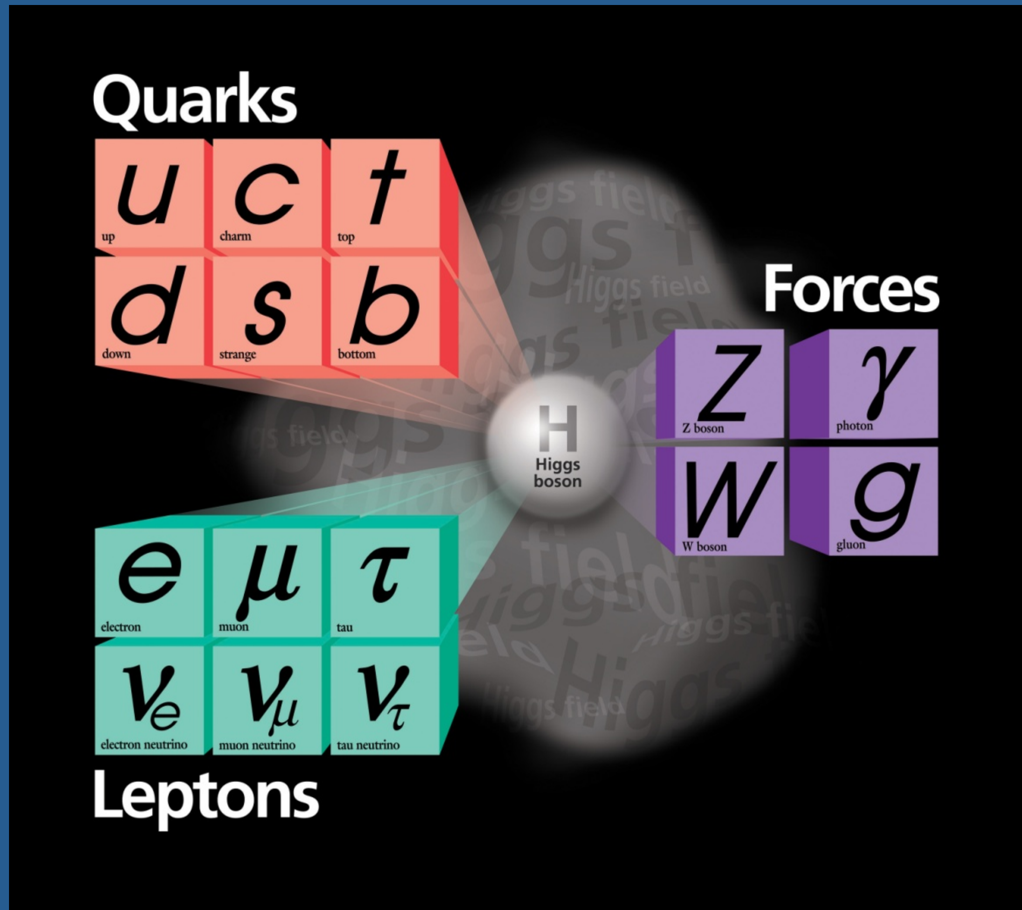
Can this discovery
from nearly 20 years ago
help us understand
the new boson
discovered at the LHC?

http://www-visualmedia.fnal.gov/

The Standard Model



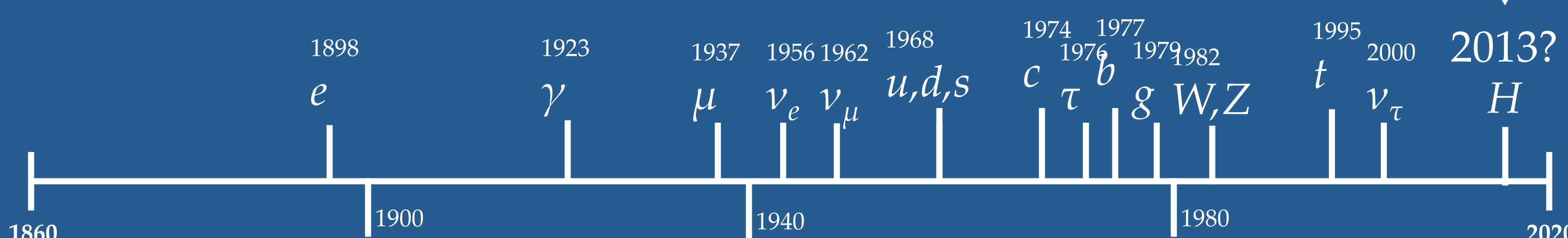
The History of Discoveries



One remaining piece to complete the puzzle

H:

the Higgs boson -- the last piece of the standard model.



The Electromagnetic and Weak Forces

Elegant feature of the SM:

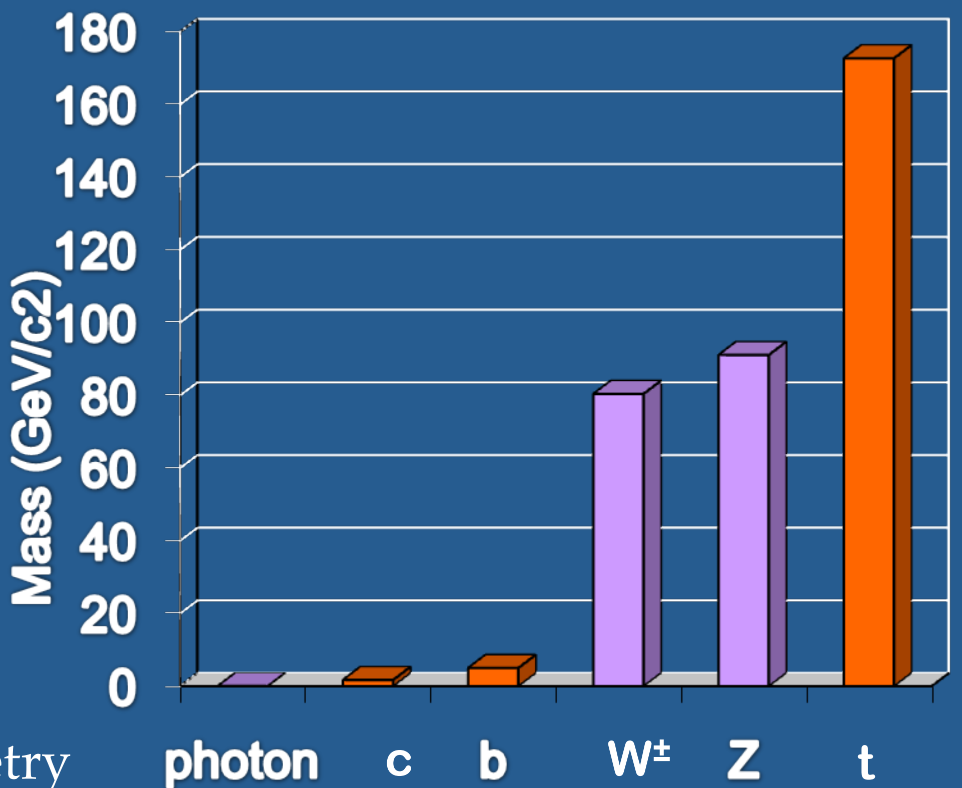
- Electromagnetic and Weak forces are unified: electroweak interaction

Symmetry is *broken* however:

- Photon massless
- *W, Z* very massive
- **How?**

Higgs Mechanism:

- Higgs field breaks EWK symmetry
- Explains masses of *W, Z* and photon
- Other particles interact with the Higgs field and acquire mass
- Additional consequence:
  new particle predicted to exist, the so-called Higgs boson



Remember these masses, at least qualitatively…

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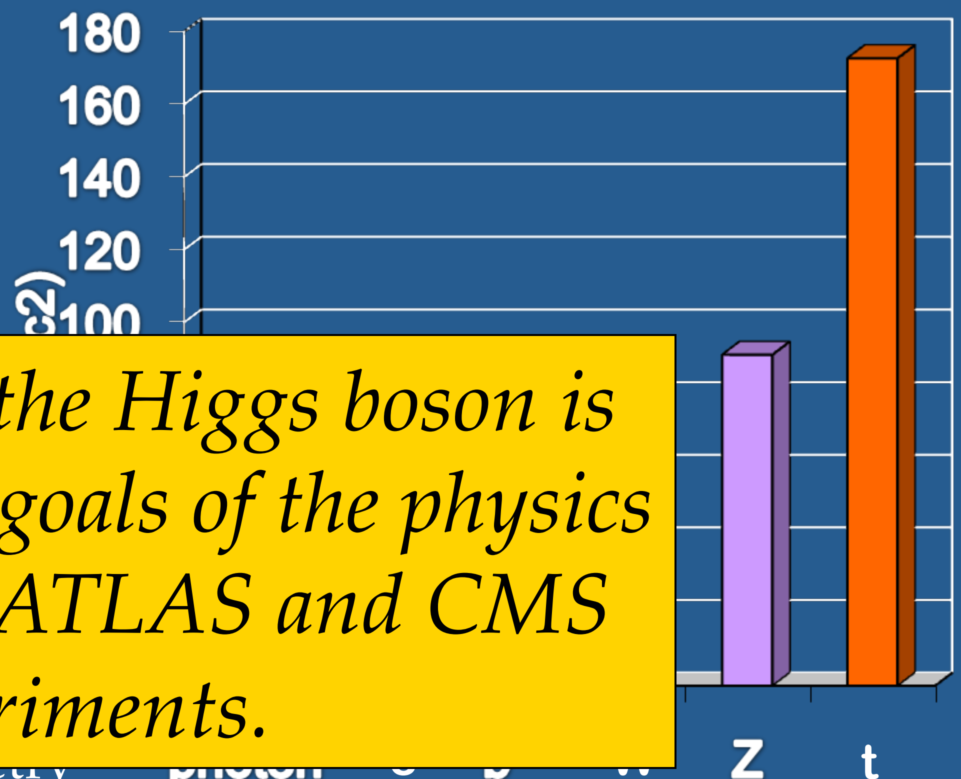


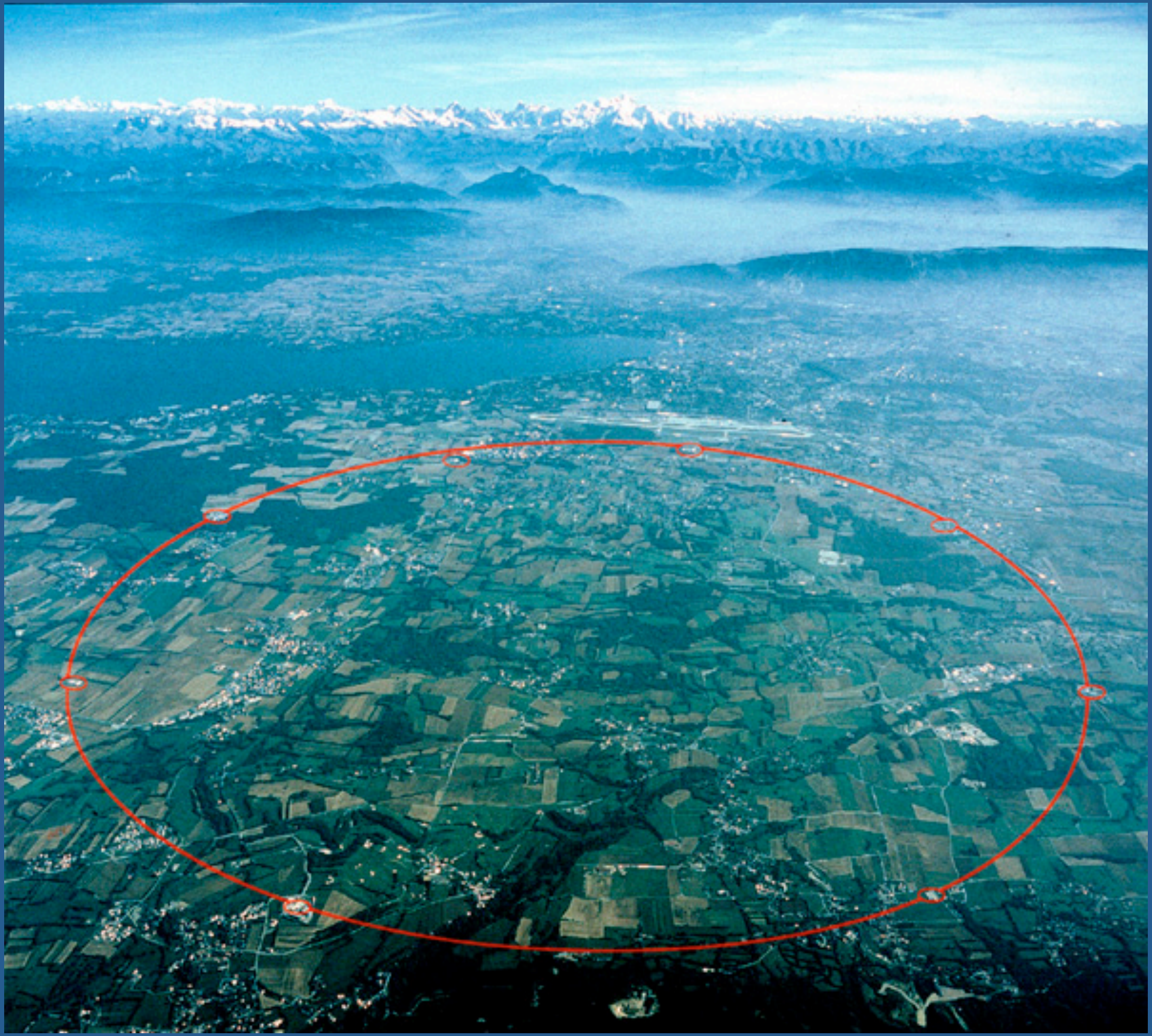
The search for the Higgs boson is one of the main goals of the physics mission of the ATLAS and CMS experiments.

Remember these masses, at least qualitatively…

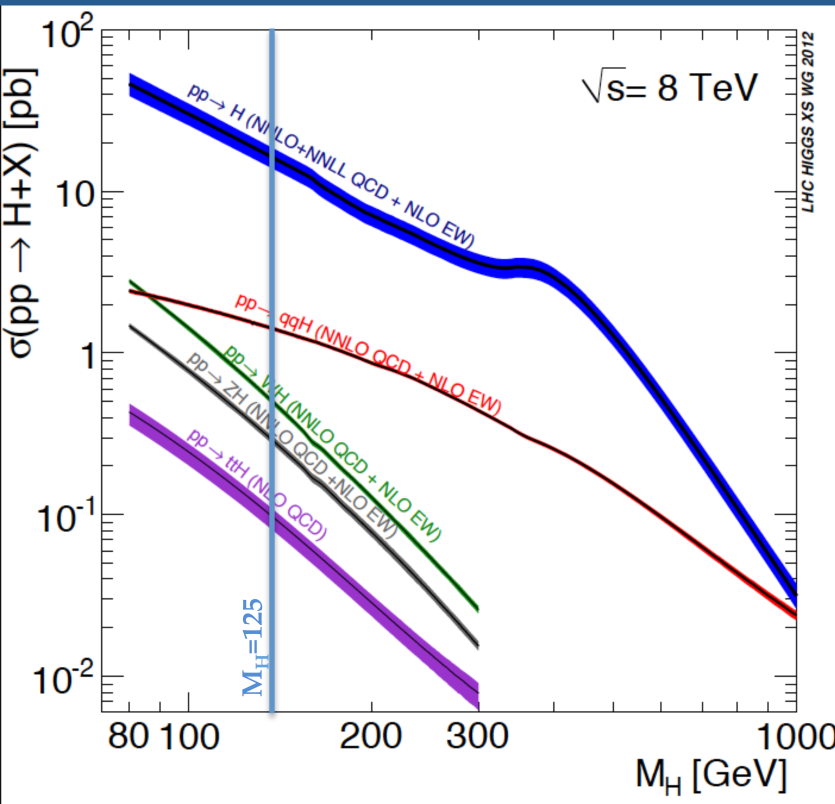
The Large Hadron Collider

- A proton-proton collider
  - 27 km in circumference
  - beamlines ~100m underground
  - Four active interaction regions
  - proton-proton collisions with up to 7+7 = 14 TeV

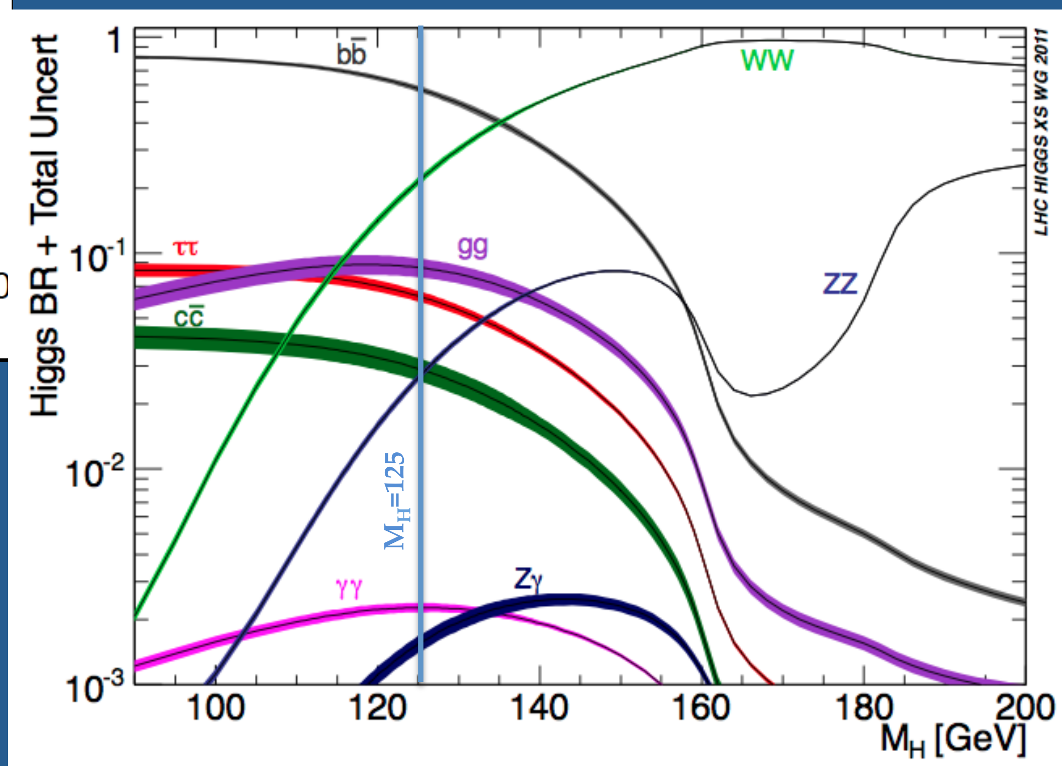
- Significant opportunity for discovery:
  - highest energies ever achieved…
  - …at unprecedented collision rate
  - *a perfect place for searching for the Higgs*



The Search for the Higgs Boson at the LHC

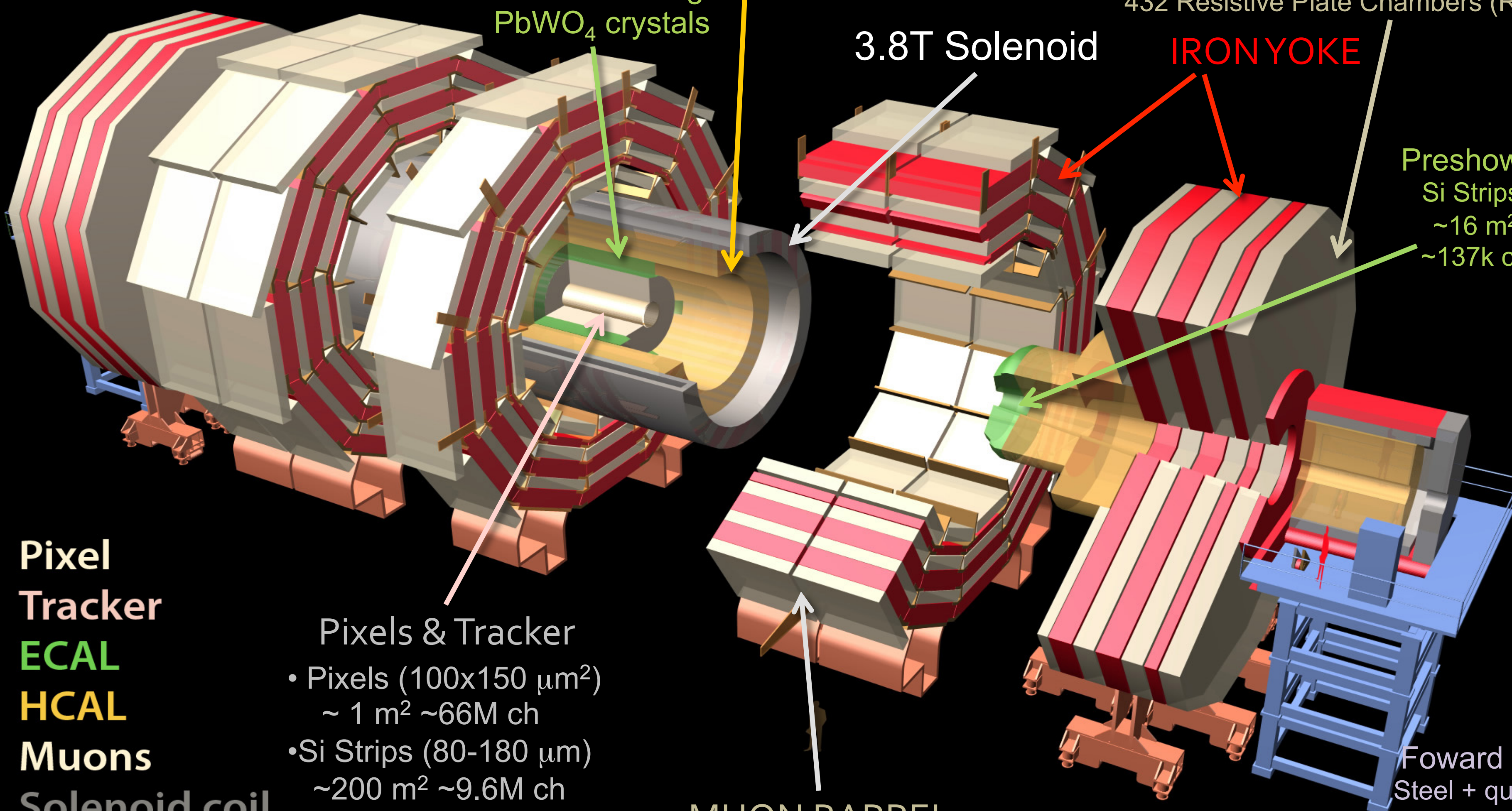


Various production mechanisms and decay modes, each with its own challenges.



Overall search campaign executed in many channels

The CMS Detector



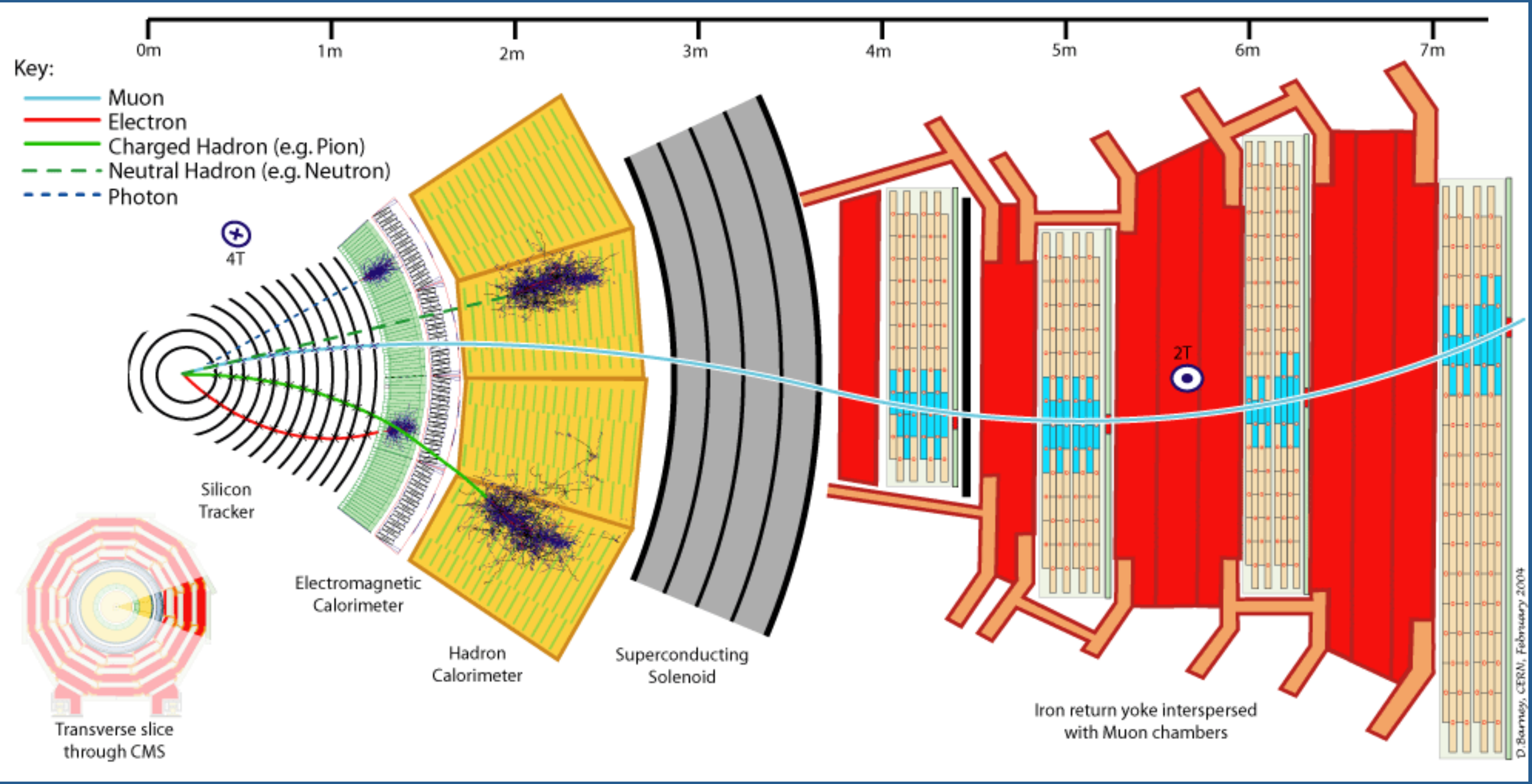
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Pixels & Tracker

- Pixels (100x150 μm^2)
  ~ 1 m^2 ~66M ch
- Si Strips (80-180 μm)
  ~200 m^2 ~9.6M ch

Total weight	14000 t
Overall diameter	15 m
Overall length	28.7 m

Particle Detection and Subsystems



Higgs search campaign
utilizes every CMS subsystem

Higgs Search: Latest Results from CMS

Decay Mode	Production Mechanism	Lumi (fb^{-1}) 7 + 8 TeV	SM-Sensitivity or SM-Significance Expected	Observed	Signal Strength $\mu = \sigma/\sigma_{SM}$
$H \rightarrow bb$	VH	5 + 12	$\geq 1.2x\, \sigma_{SM}$	$\geq 2.5x\, \sigma_{SM}$	$1.3^{+0.7}_{-0.6}$
$H \rightarrow WW$	ggF, VBF	4.9 + 19.5	5.1σ	4.1σ	0.76 ± 0.21 ★
$H \rightarrow \tau\tau$	ggF, VBF, VH	5 + 19	2.6σ	2.9σ	1.1 ± 0.4
$H \rightarrow ZZ$	ggF, VBF	5.1 + 19.6	7.2σ ★	6.7σ	$0.91^{+0.30}_{-0.24}$
$H \rightarrow \gamma\gamma$	ggF, VBF	5.1 + 19.6	4.2σ	3.2σ	$0.78^{+0.28}_{-0.26}$

- Results current, best available numbers as of updated results for Moriond QCD 2013 (~four weeks ago)
- Many other analyses not included here:
  - Rare decay modes
  - High-mass optimized channels
  - BSM Higgs searches

Higgs Results: Assessment

CERN Accelerating science

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New results indicate that particle discovered at CERN is a Higgs boson

14 Mar 2013

Geneva, 14 March 2013. At the Moriond Conference today, the ATLAS and CMS collaborations at CERN[1]'s Large Hadron Collider (LHC) presented preliminary new results that further elucidate the particle discovered last year. Having analysed two and a half times more data than was available for the discovery announcement in July, they find that the new particle is looking more and more like a Higgs boson, the particle linked to the mechanism that gives mass to elementary particles. It remains an open question, however, whether this is the Higgs boson of the Standard Model of particle physics, or possibly the lightest of several bosons predicted in some theories that go beyond the Standard Model. Finding the answer to this question will take time.

Whether or not it is a Higgs boson is demonstrated by how it interacts with other particles, and its quantum properties. For example, a Higgs boson is postulated to have spin 0, and in

Identifying the SM Higgs Boson

Characteristic
Spin 0
Parity +
Decay Modes
Couplings

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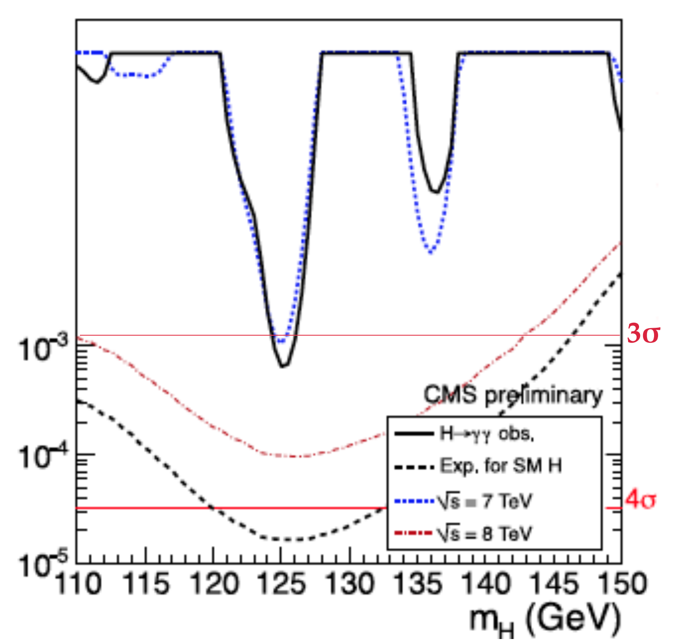
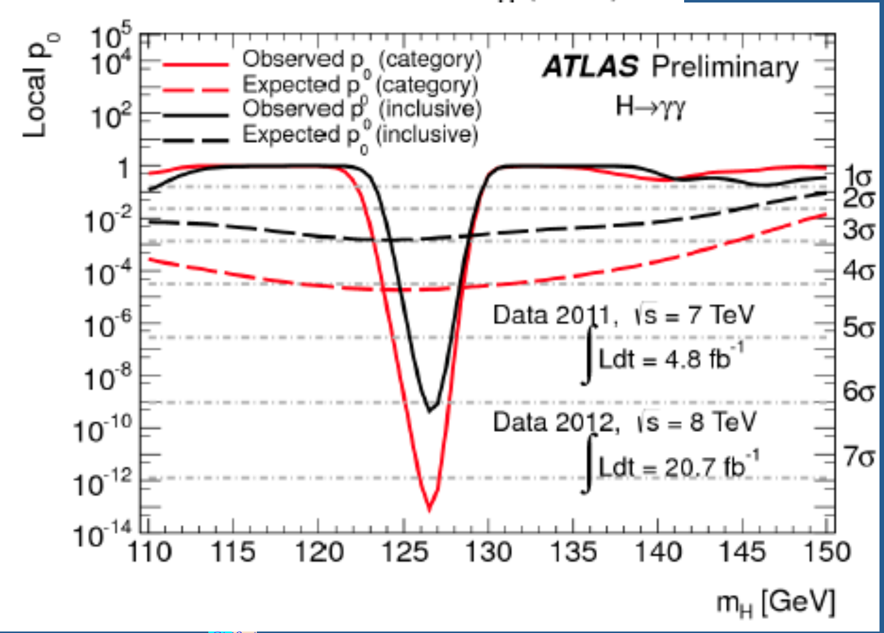


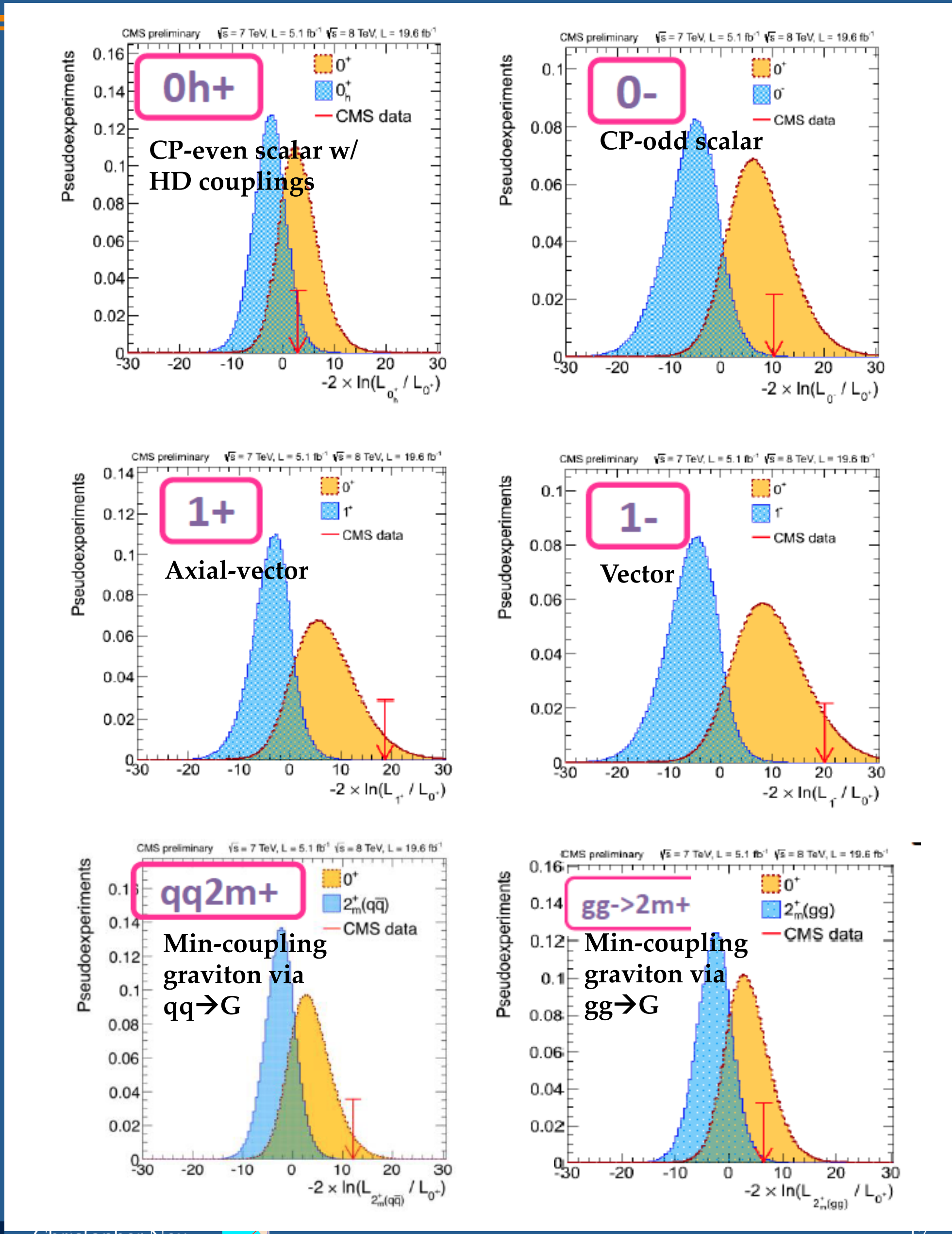


Spin 1 hypothesis disallowed by H→γγ

Photons have J=1 but $m_J=\pm1$

Identifying the SM Higgs Boson

Characteristic
Spin 0
Parity +
Decay Modes
Couplings



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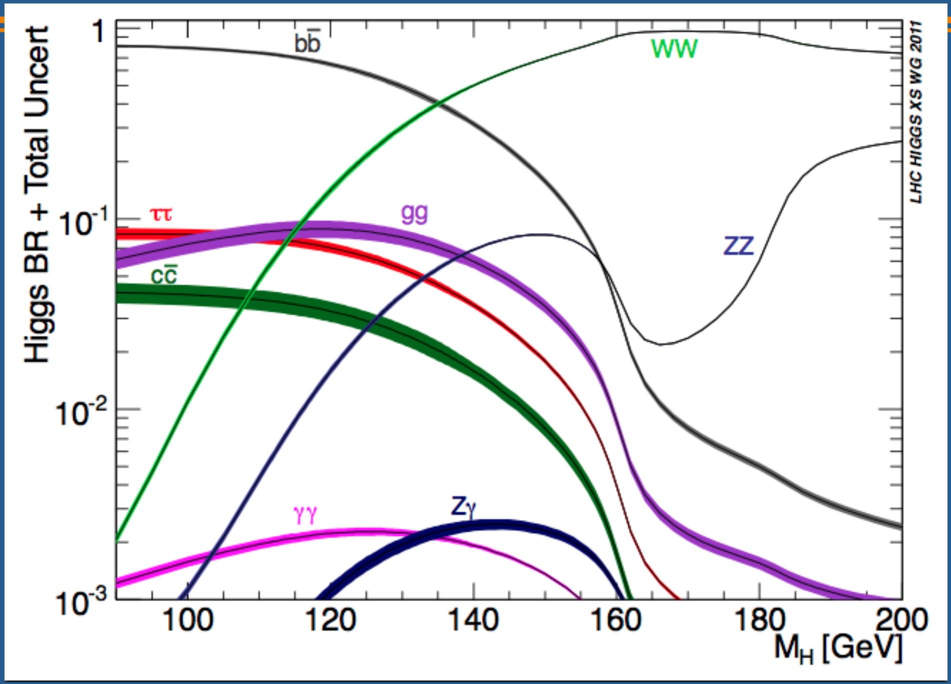


This is an ongoing campaign, clearly.

ATLAS and CMS have identified H→γγ, ZZ and WW at greater than 3σ. CMS H→ττ close to 3σ.

H→bb, despite largest BR, not quite there. Tevatron experiments contributed as well.

Identifying the SM Higgs Boson

Characteristic
Spin 0
Parity +
Decay Modes
Couplings

- Every Higgs channel has two coupling factors
- Survey of analyses from different production and decay modes have insight into various accessible couplings
- In the SM:

$$\lambda_f = \sqrt{2}\frac{m_f}{v} \qquad \lambda_V = 2\frac{M_V^2}{v}$$

- Global fits have been executed by CMS, ATLAS, independent theory groups using the reported signal strengths from LHC, Tevatron

Identifying the SM Higgs Boson

Characteristic
Spin 0
Parity +
Decay Modes
Couplings

- Ellis, et al., (arXiv:1303.3879) approach the problem by introducing adjustments to the SM couplings:

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{v'}\right)^{1+\varepsilon} \qquad \lambda_V = 2\left(\frac{M_V^{2(1+\varepsilon)}}{\left(v'\right)^{1+2\varepsilon}}\right)$$

- These reduce to SM couplings in the limits when:

$$\varepsilon \rightarrow 0 \qquad v' \rightarrow v = 246\ \text{GeV}$$

- Their global fit prefers:

$$\varepsilon = 0.022^{+0.042}_{-0.021} \qquad v' = 244^{+20}_{-10}\ \text{GeV}$$

More on the Higgs Couplings

- So the couplings are all understood then, yes?

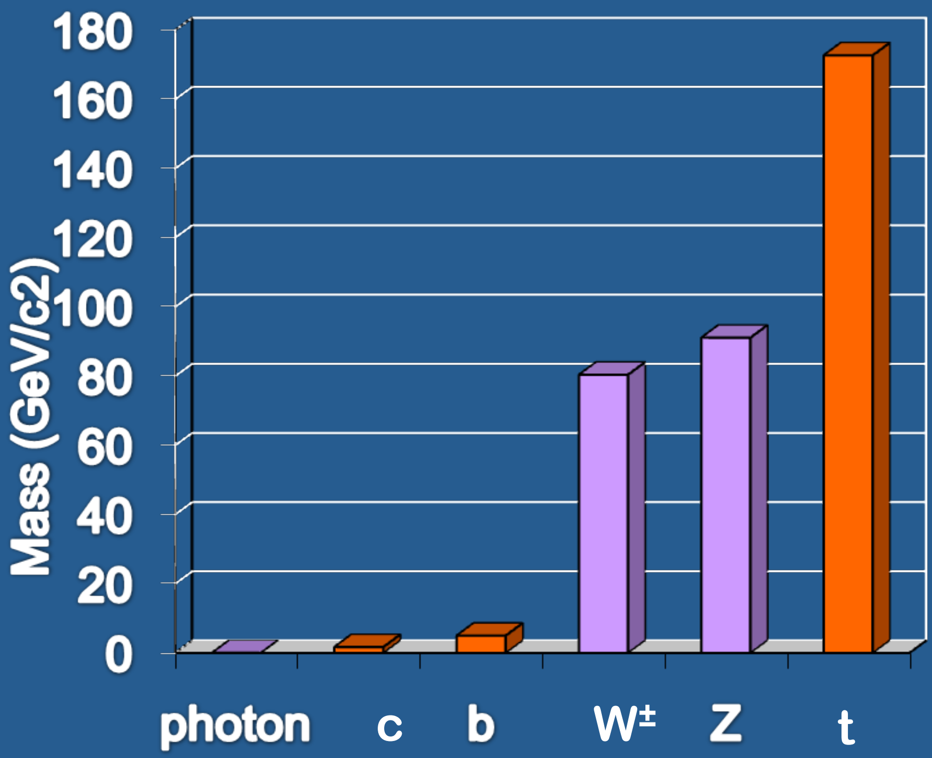
More on the Higgs Couplings

- So the couplings are all understood then, yes?

No

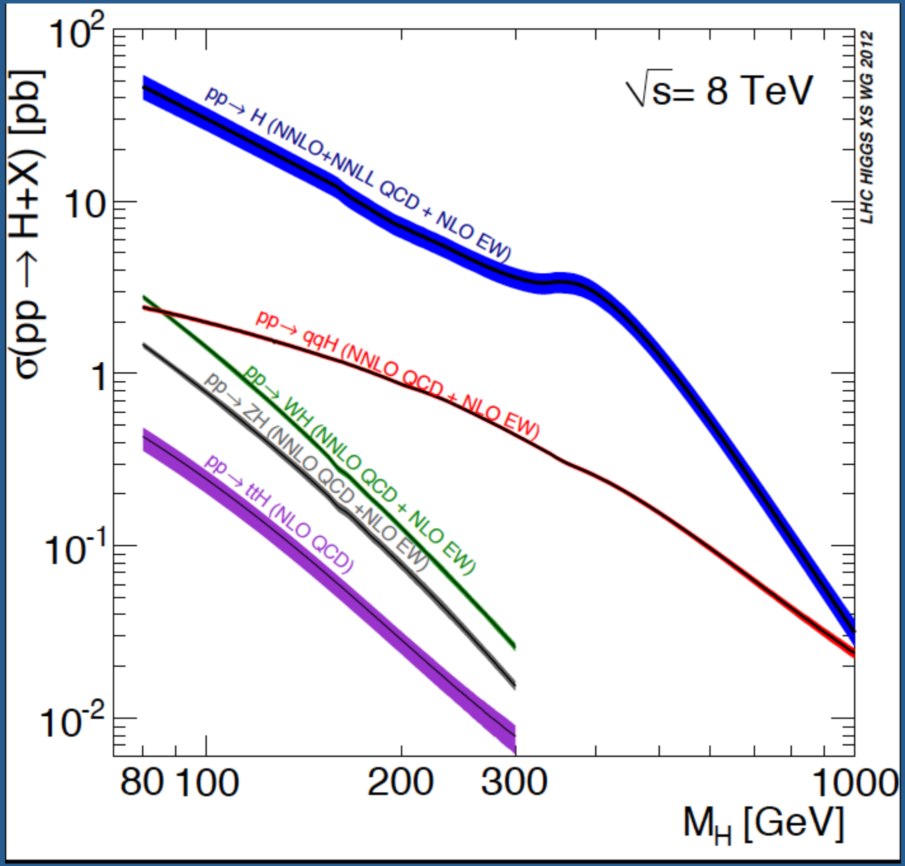
More on the Higgs Couplings

- **Fermionic couplings:**
  - LHC analyses have so far only been able to probe λ_b and λ_τ directly
    - Via H→bb and H→ττ decay modes
    - Sensitivity still unsatisfying
- Within the SM, the Higgs coupling to top, λ_t, is predicted to be **by far the largest** of all the fermionic couplings
  - ~x30 larger than λ_b
  - ~x100 larger than λ_τ

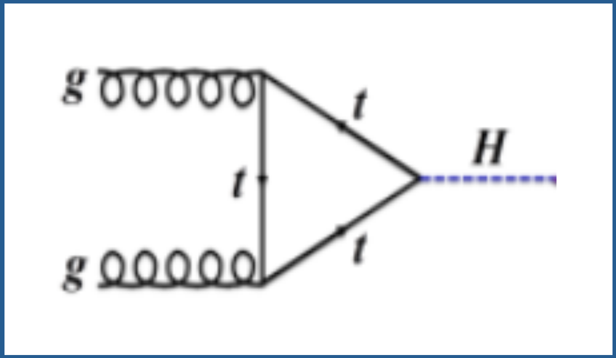


Imperative:
Absolutely need to measure λ_t directly to know the true nature of the couplings of the new boson.

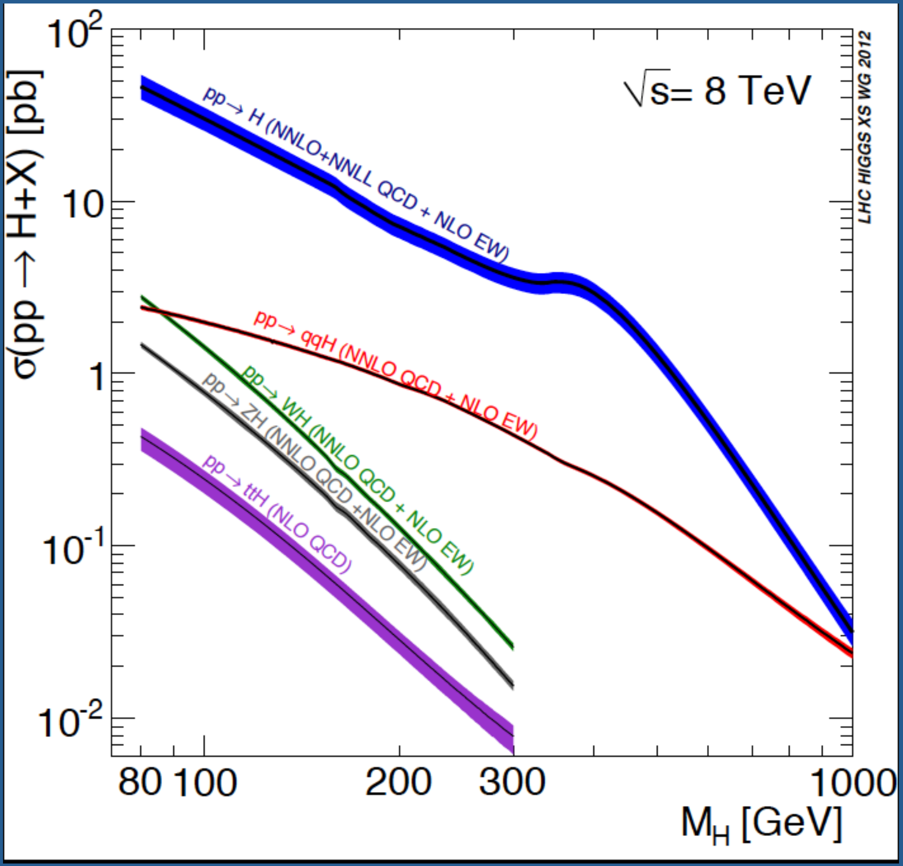
Higgs and Top



- Workhorse analyses already probe the top-Higgs coupling, though there are issues…
- Consider gluon fusion:



Higgs and Top



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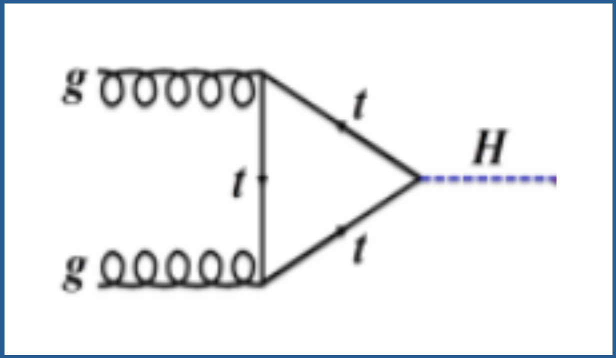
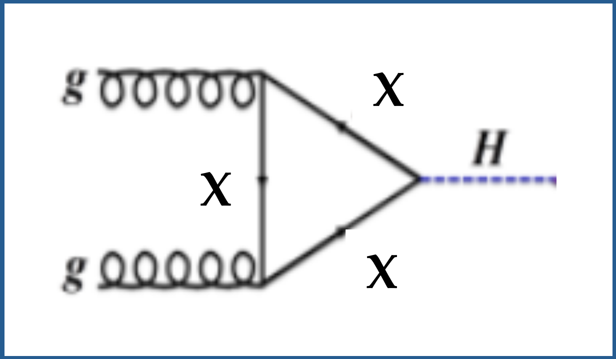
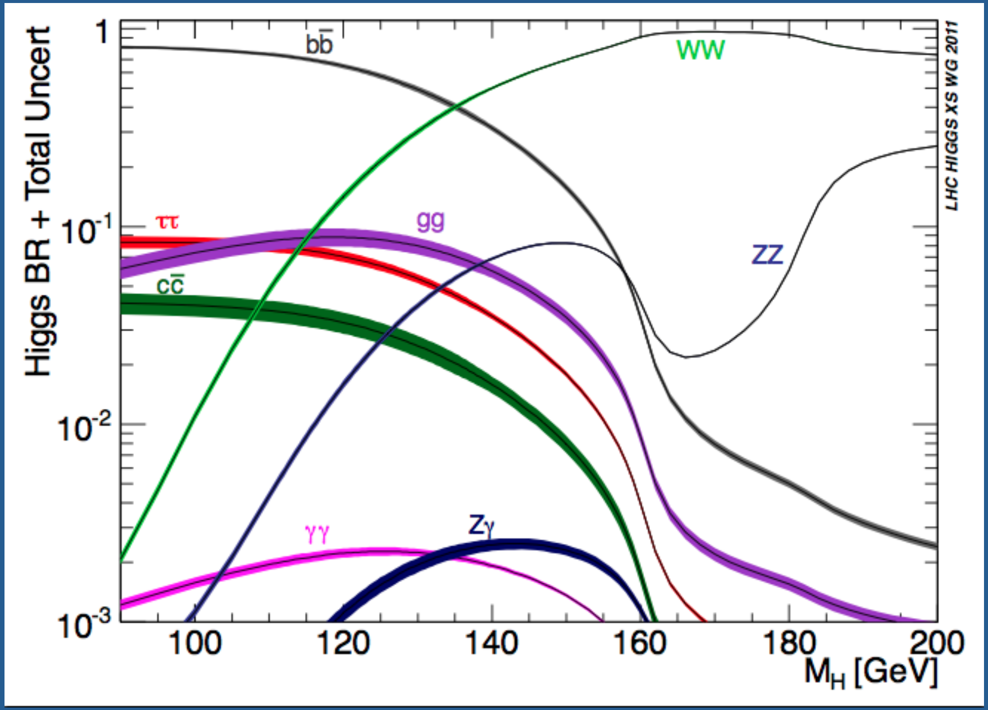


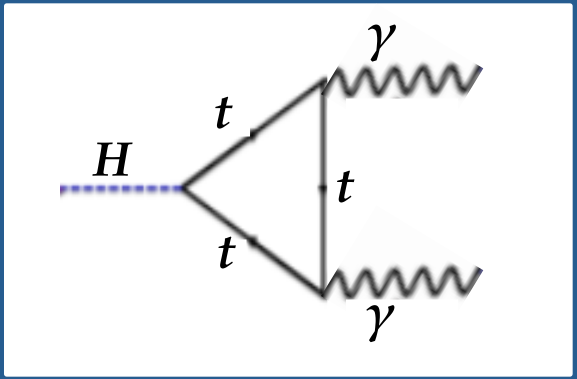
- But what about this?



Higgs and Top



- Similar problems on the decay side:



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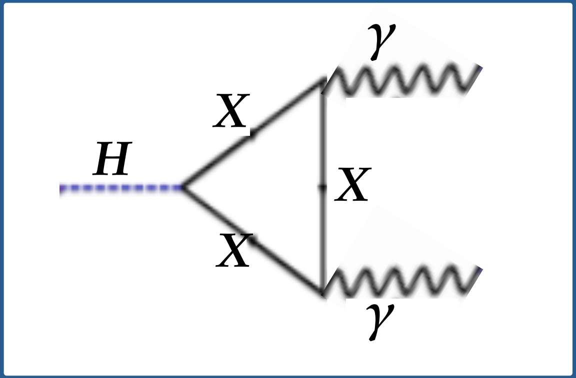
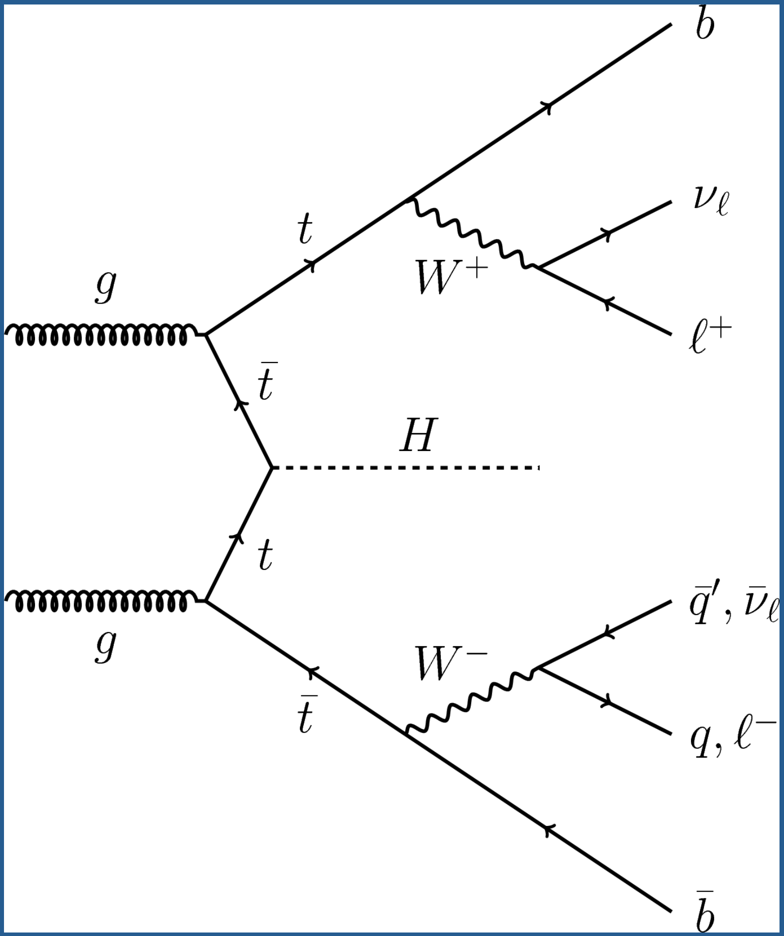


The results of global fits such as that of Ellis, et al., simply say that the new boson has couplings that "are SM-like".

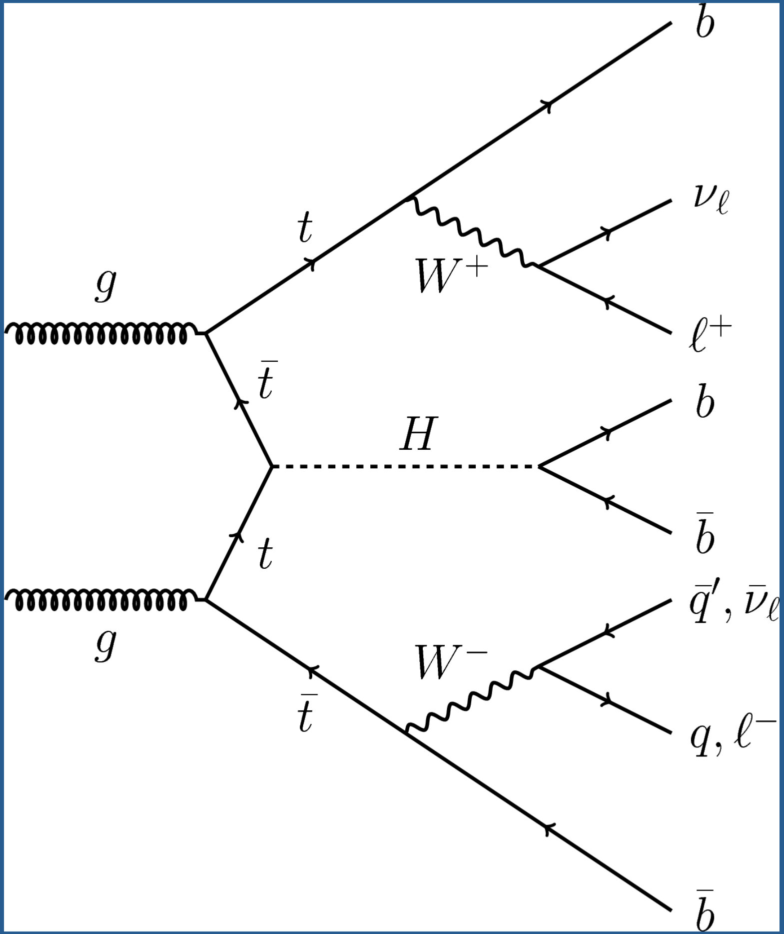
To really know what is going on, **we need a direct probe** of the top-Higgs coupling…

ttH Production



- Higgs production in association with a top-quark pair
  - comparatively small production cross section
  - Spectacular signature – rich final state
- Virtues:
  - Alternative to VH channel for H→bb
  - Can extract λ_t through comparison to other channels in same decay mode
    - Eg: ZH, H→bb vs. ttH, H→bb
  - With sufficient luminosity, allows access to every possible decay mode
- Challenges:
  - Small yield
  - Difficult backgrounds

ttH Search at CMS

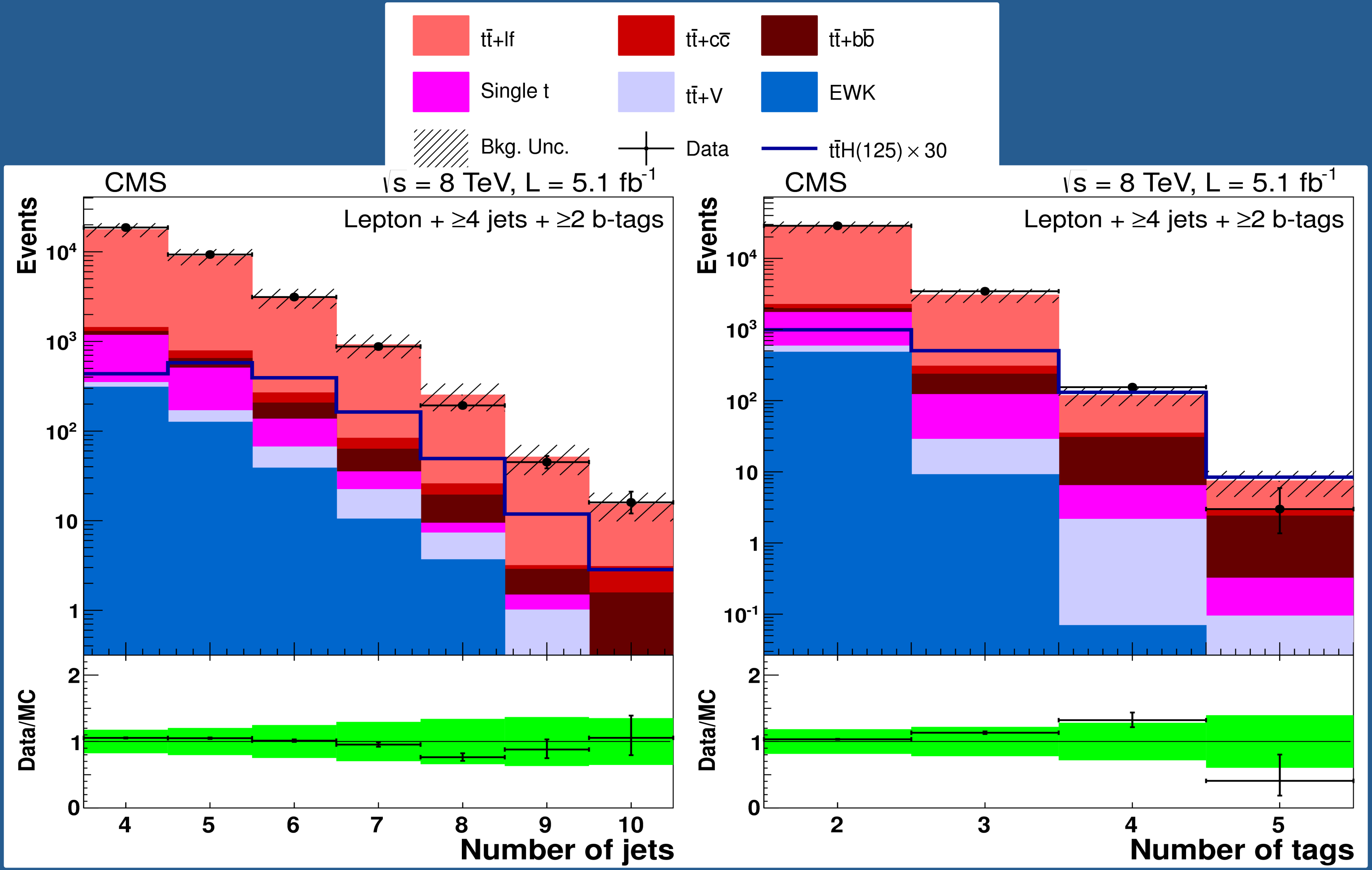


Analysis performed in 5/fb samples from both 7 TeV and 8 TeV

Submitted to JHEP, see arXiv:1303.0763

- Initial focus:
  - Optimized for low M_H and H→bb decay mode
  - Exploit both lepton+jets (LJ) and dilepton (DIL) ttbar channels
- Event selection:
  - One (two) isolated charged leptons w/ $p_T > 30$ (20) GeV
  - Veto events in the LJ channel w/ a second charged lepton
  - No explicit MET requirement
  - LJ: At least 3 jets w/ $p_T > 40$ and a fourth jet with $p_T > 30$
  - DIL: At least two jets with $p_T > 30$
  - Require presence of b-tagged jets in the event

ttH Search at CMS: Sample Categorization



Categorize events according to jet and tag multiplicity…

$t\bar{t}H$ Search at CMS: Sample Composition

Expected signal and background yields for LJ channel at 8 TeV in 5/fb:

	≥6 jets 2 b-tags	4 jets 3 b-tags	5 jets 3 b-tags	≥6 jets 3 b-tags	4 jets 4 b-tags	5 jets ≥4 b-tags	≥6 jets ≥4 b-tags
$t\bar{t}H(125)$	11.7 ± 1.9	3.9 ± 1.8	6.1 ± 2.8	6.9 ± 3.1	0.6 ± 0.3	1.5 ± 0.7	2.5 ± 1.2
$t\bar{t}$+lf	3460 ± 940	1320 ± 280	870 ± 210	570 ± 170	18.0 ± 5.1	27.6 ± 8.6	41 ± 15
$t\bar{t}+b\bar{b}$	61 ± 34	35 ± 19	43 ± 24	35 ± 20	2.5 ± 1.7	8.4 ± 5.3	15.4 ± 9.4
$t\bar{t}+c\bar{c}$	62 ± 17	19.6 ± 5.1	25.0 ± 6.9	25.9 ± 7.7	0.6 ± 0.4	0.8 ± 0.9	3.7 ± 1.8
$t\bar{t}$ V	35.7 ± 7.5	4.5 ± 1.1	6.1 ± 1.4	8.6 ± 2.1	0.1 ± 0.1	0.7 ± 0.2	1.5 ± 0.4
Single t	79 ± 18	56 ± 11	25.6 ± 6.2	10.3 ± 2.9	0.3 ± 0.6	3.1 ± 2.2	1.0 ± 0.6
V+jets	53 ± 40	5.9 ± 6.0	0.8 ± 0.9	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Diboson	1.2 ± 0.4	1.8 ± 0.6	0.5 ± 0.2	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Total bkg	3760 ± 980	1440 ± 300	970 ± 230	650 ± 190	21.5 ± 6.1	41 ± 12	63 ± 21
Data	3503	1646	1116	686	28	56	74

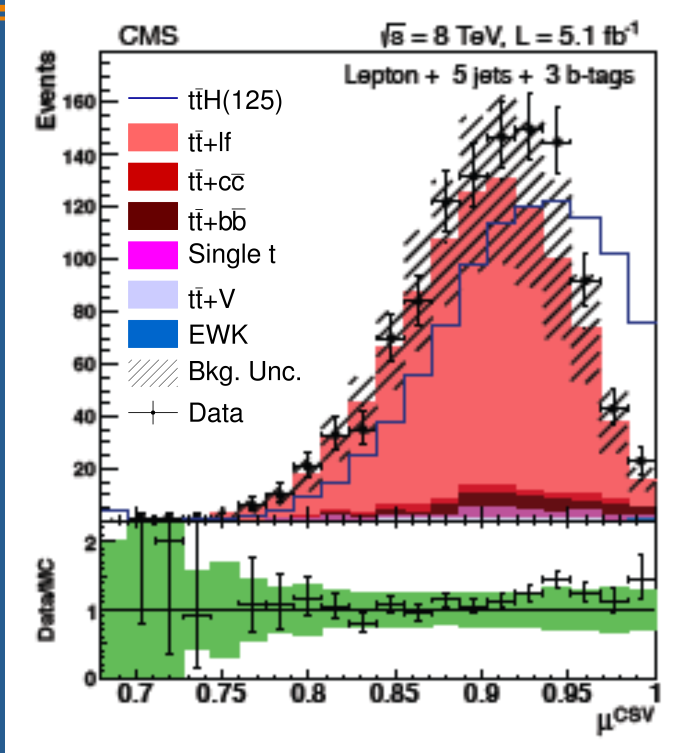
- Sample composition predictions from simulation
- Different S/B in each jet-tag category
- Largest background in every category: $t\bar{t}$+jets, specifically $t\bar{t}$+light flavor jets ($t\bar{t}$+LF)

ttH Search at CMS: Signal Extraction

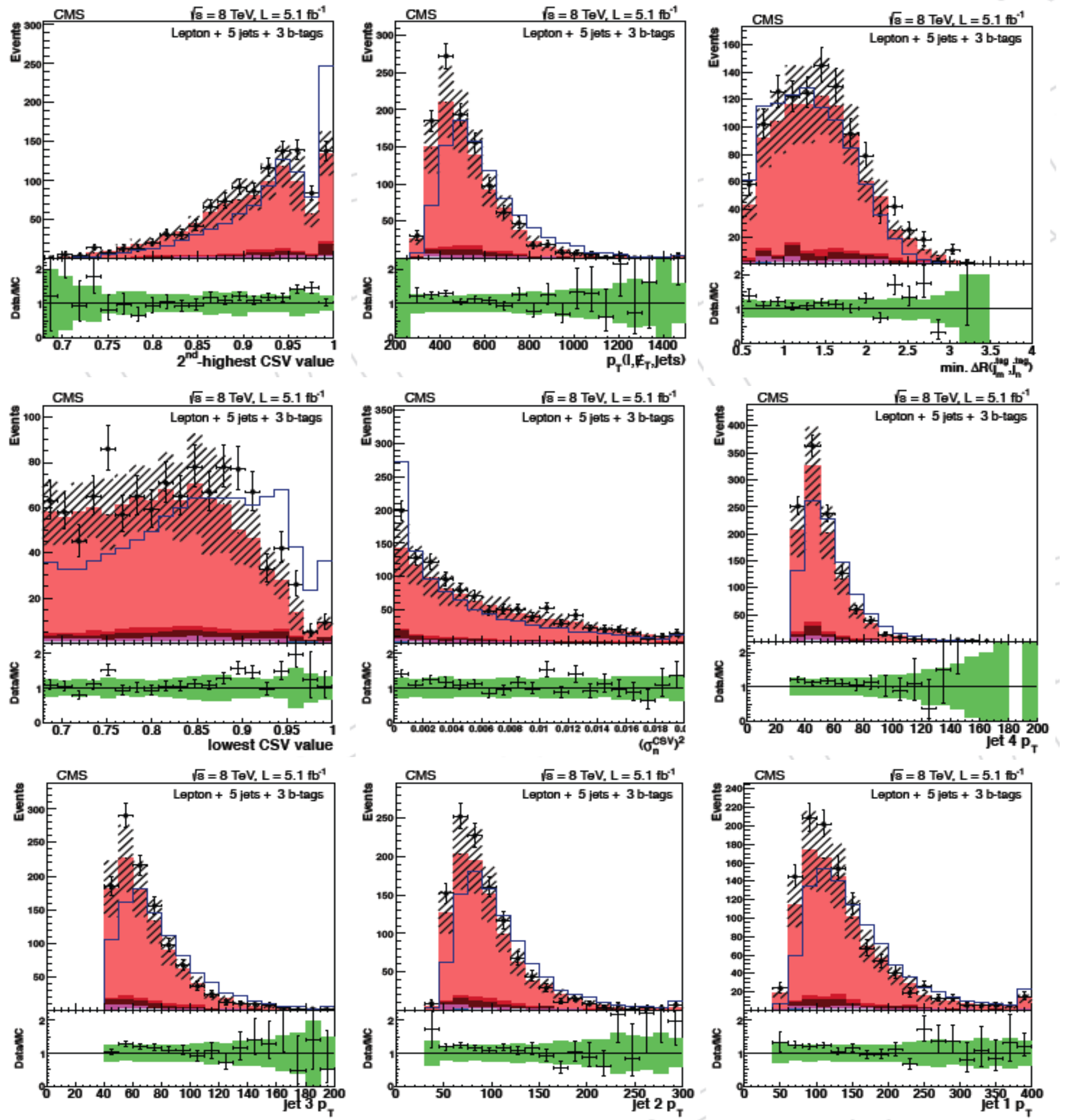
	Lepton+Jets							Dilepton	
Jets	≥6	4	5	≥6	4	5	≥6	2	≥3
Tags	2	3	3	3	4	≥4	≥4	2	≥3
Jet 1 p_T		✓	✓		✓			★	✓
Jet 2 p_T		✓	✓						
Jet 3 p_T	✓	✓	✓			✓			
Jet 4 p_T	✓	✓	✓			✓			
N_{jets}									✓
$p_T(\ell, E_T^{miss}, jets)$		★	✓		✓	✓		✓	✓
$M(\ell, E_T^{miss}, jets)$	✓	✓		✓	✓		✓		
Average $M((j_m^{untag}, j_n^{untag}))$	✓			✓					
$M((j_m^{tag}, j_n^{tag})_{closest})$							✓		
$M((j_m^{tag}, j_n^{tag})_{best})$							✓		
Average $\Delta R(j_m^{tag}, j_n^{tag})$				✓	✓	✓	✓		
Minimum $\Delta R(j_m^{tag}, j_n^{tag})$			✓					✓	✓
$\Delta R(\ell, j_{closest})$						✓	✓	✓	✓
Sphericity	✓			✓			✓		
Aplanarity	✓				✓				
H_0	✓								
H_1	✓				✓				
H_2				✓			✓		
H_3	★			✓			✓		
μ^{CSV}	✓	✓	★	★	★	★	★	✓	★
$(\sigma_n^{CSV})^2$		✓	✓	✓	✓	✓			
Highest CSV value						✓			
2^{nd}-highest CSV value		✓	✓	✓	✓	✓	✓		
Lowest CSV value		✓	✓	✓	✓	✓	✓		

- Artificial neural networks (ANNs) used in each jet-tag category to enhance signal discrimination
- Input variables:
  - Event kinematics
  - Event shapes
  - B-tagging information
- Separate ANNs for each category
  - Different S:B, different topologies translate to different optimal inputs
- Inputs chosen from a large pool of candidates variables

ttH Search at CMS: ANN Inputs for 5j3t



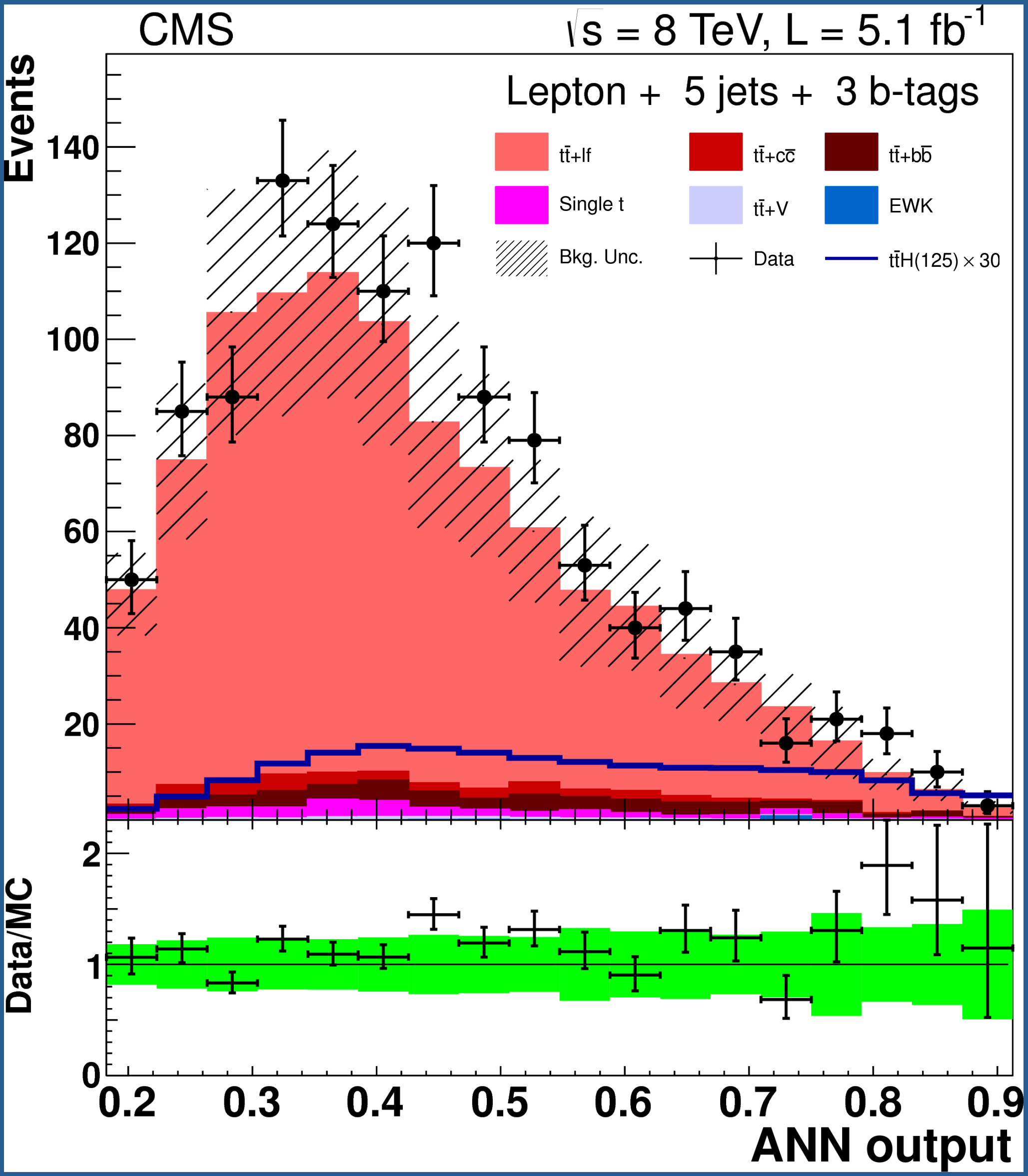
signal norm'd to bkgd



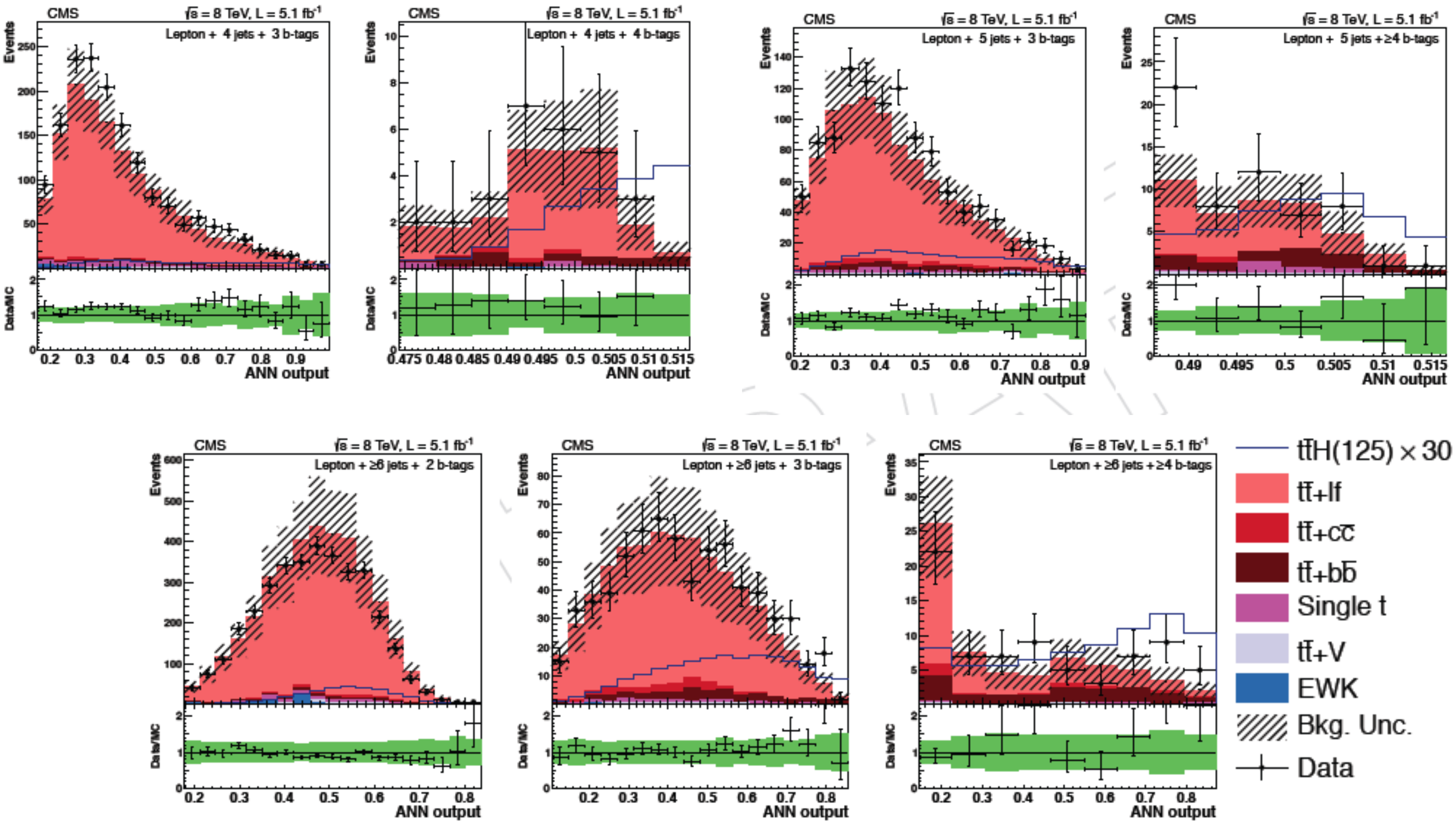
- Most important inputs in this category:
  - jet- and event-level b-tagging variables

ttH Search at CMS: ANN Output for 5j3t

- ANN exploits multidimensional correlations in attempt to discriminate between signal and background
- Trained with simulated event samples
- ANN output:
  - reduce multi-dimensional characterization into single discriminant
  - 0 implies background-like, 1 implies signal-like
- ANN output distribution in each jet-tag category



ttH Search at CMS: LJ ANN Summary



$t\bar{t}$H Search at CMS: Systematic Uncertainties

- Maximum likelihood fit in the ANN output distributions from the nine LJ+DIL jet-tag categories

- Background-dominated categories serve to constrain the bkgd contribution in signal-enhanced categories

Source	Rate Uncertainty	Shape	Remarks
Luminosity (7 TeV)	2.2%	No	All signal and backgrounds
Luminosity (8 TeV)	4.4%	No	All signal and backgrounds
Lepton ID/Trig	4%	No	All signal and backgrounds
Pileup	1%	No	All signal and backgrounds
Additional Pileup Corr.	–	Yes	All signal and backgrounds
Jet Energy Resolution	1.5%	No	All signal and backgrounds
Jet Energy Scale	0–60%	Yes	All signal and backgrounds
b-Tag SF (b/c)	0–33.6%	Yes	All signal and backgrounds
b-Tag SF (mistag)	0–23.5%	Yes	All signal and backgrounds
MC Statistics	–	Yes	All backgrounds
PDF (gg)	9%	No	For gg initiated processes ($t\bar{t}$, $t\bar{t}$Z, $t\bar{t}$H)
PDF ($q\bar{q}$)	4.2–7%	No	For $q\bar{q}$ initiated processes ($t\bar{t}$W, W, Z).
PDF (qg)	4.6%	No	For qg initiated processes (single top)
QCD Scale ($t\bar{t}$H)	15%	No	For NLO $t\bar{t}$H prediction
QCD Scale ($t\bar{t}$)	2–12%	No	For NLO $t\bar{t}$ and single top predictions
QCD Scale (V)	1.2–1.3%	No	For NNLO W and Z prediction
QCD Scale (VV)	3.5%	No	For NLO diboson prediction
Madgraph Scale ($t\bar{t}$)	0–20%	Yes	$t\bar{t}$ + jets/$b\bar{b}$/$c\bar{c}$ uncorrelated. Varies by jet bin.
Madgraph Scale (V)	20–60%	No	Varies by jet bin.
$t\bar{t} + b\bar{b}$	50%	No	Only $t\bar{t} + b\bar{b}$.

- Uncertainties treated as nuisance parameters which are profiled in limit extraction

- Shape variations are handled through template morphing

ttH Search at CMS: Systematic Uncertainties

Source	Rate Uncertainty	Shape	Remarks
Luminosity (7 TeV)	2.2%	No	All signal and backgrounds
Luminosity (8 TeV)	4.4%	No	All signal and backgrounds
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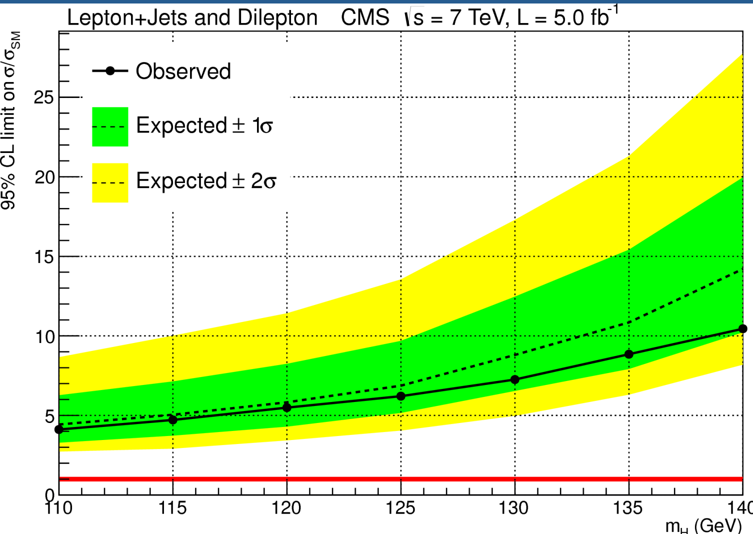
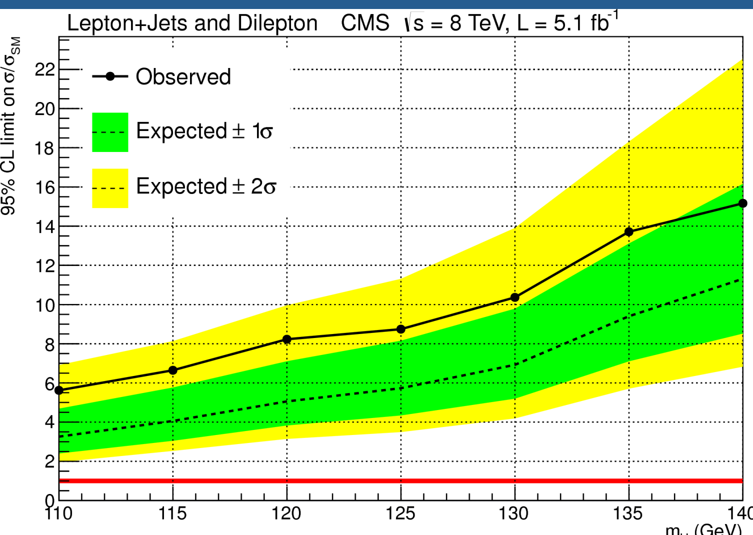
Jet Energy Resolution	1.5%	No	All signal and backgrounds
Jet Energy Scale	0–60%	Yes	All signal and backgrounds
b-Tag SF (b/c)	0–33.6%	Yes	All signal and backgrounds
b-Tag SF (mistag)	0–23.5%	Yes	All signal and backgrounds
MC Statistics	–	Yes	All backgrounds
PDF (gg)	9%	No	For gg initiated processes ($t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$)
PDF ($q\bar{q}$)	4.2–7%	No	For $q\bar{q}$ initiated processes ($t\bar{t}W$, W, Z).
PDF (qg)	4.6%	No	For qg initiated processes (single top)
QCD Scale ($t\bar{t}H$)	15%	No	For NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	2–12%	No	For NLO $t\bar{t}$ and single top predictions
QCD Scale (V)	1.2–1.3%	No	For NNLO W and Z prediction
QCD Scale (VV)	3.5%	No	For NLO diboson prediction
Madgraph Scale ($t\bar{t}$)	0–20%	Yes	$t\bar{t}$ + jets/$b\bar{b}$/$c\bar{c}$ uncorrelated. Varies by jet bin.
Madgraph Scale (V)	20–60%	No	Varies by jet bin.
$t\bar{t}+b\bar{b}$	50%	No	Only $t\bar{t}+b\bar{b}$.

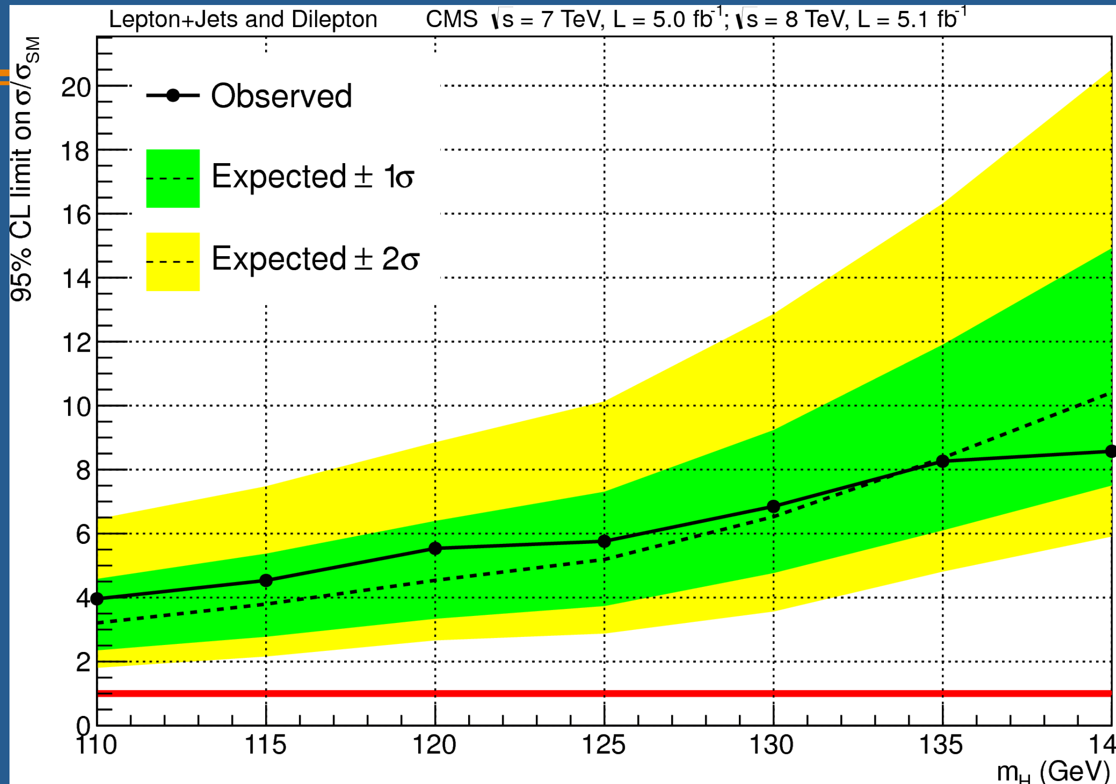
Leading Experimental Uncertainties

Leading Theoretical Uncertainties

ttH Search at CMS: Results







7 TeV + 8 TeV Lepton+Jets and Dilepton combined				
		Expected		
m_H	Observed	Median	68% CL Range	95% CL Range
110 GeV	4.0	3.2	[2.4, 4.6]	[1.8, 6.5]
115 GeV	4.5	3.8	[2.8, 5.4]	[2.2, 7.5]
120 GeV	5.5	4.5	[3.3, 6.4]	[2.7, 8.9]
125 GeV	5.8	5.2	[3.7, 7.3]	[2.9, 10.1]
130 GeV	6.8	6.5	[4.8, 9.2]	[3.6, 12.9]
135 GeV	8.3	8.4	[6.1, 11.9]	[4.8, 16.3]
140 GeV	8.6	10.4	[7.5, 14.9]	[5.9, 20.5]

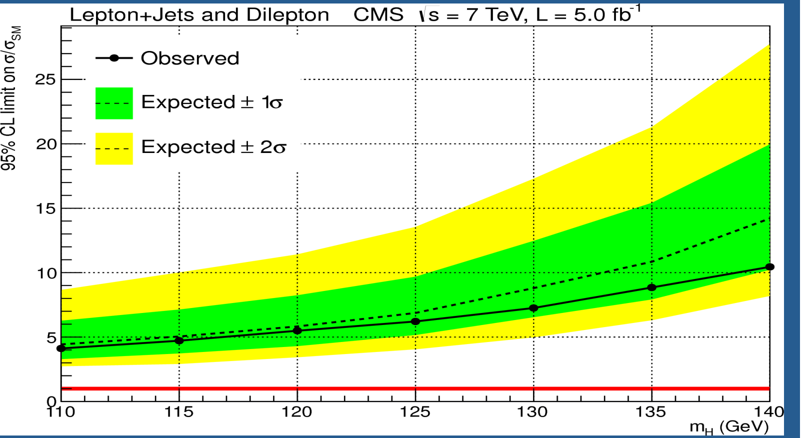
Combined 7+8 TeV result:

Observed (expected) upper limit $M_H = 125$: $\sigma/\sigma_{SM} < 5.8\ (5.2)$

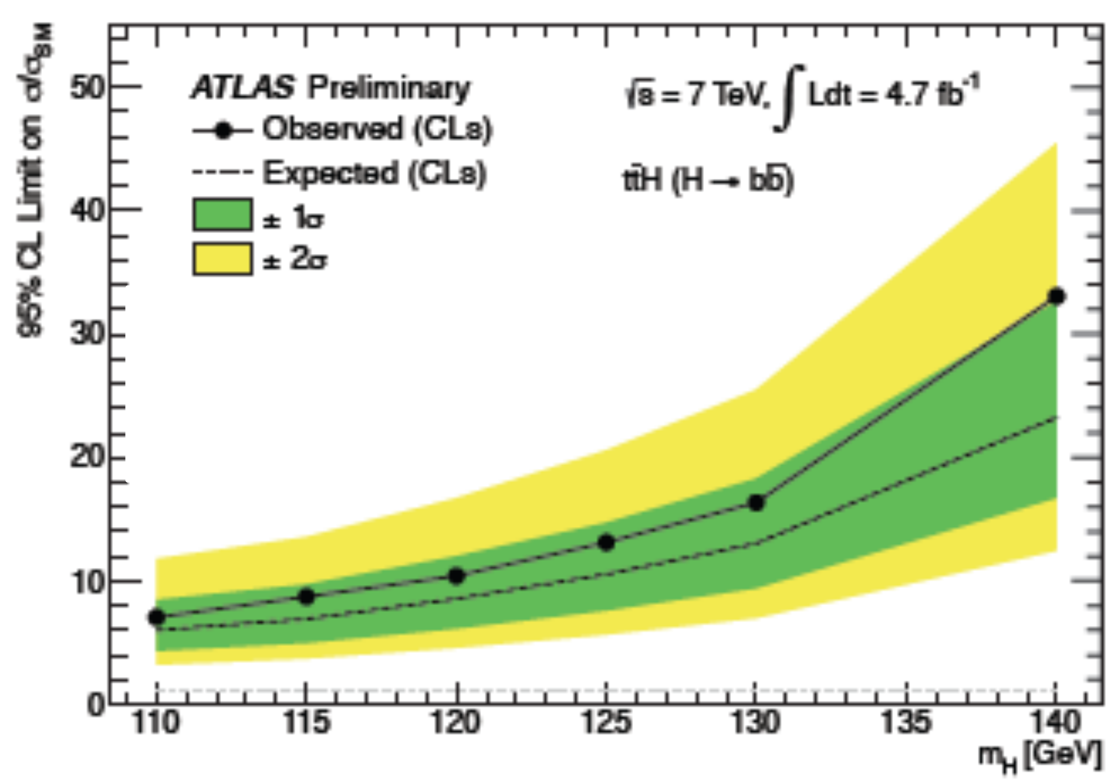
Comparison: CMS and ATLAS

ATLAS has a preliminary ttH result

- 7 TeV analysis in 4.7/fb
- Scaling below to aid visual comparison



Upper limit $M_H = 125$: $\sigma/\sigma_{SM} < 6.2$ (6.9)



Upper limit $M_H = 125$: $\sigma/\sigma_{SM} < 13.1$ (10.5)

Differences:

- CMS analysis uses LJ+DIL, ATLAS only LJ – small effect
- ATLAS: lower jet, lepton p_T thresholds; QCD mitigation from MET, M_T cuts
- CMS: higher acceptance for signal, lower acceptance for bkgd in some categories
- ATLAS fits single best variable, CMS uses MVA
- CMS b-tag efficiency systematic uncertainty smaller than ATLAS

Outlook

- x4 more data in the 8 TeV sample – more data and analysis improvements
  - Will it be enough to achieve SM sensitivity?
  - When will we be able to measure λ_t?
  - What else is in store in this rich signature?
    - *Good questions!*

- Going forward, for ttH w/ H→bb, statistics is not the only issue:
  - Need improved theoretical insight on the modeling of tt+b-jet production
    - Currently, although NLO calculations exist, events processed through shower MC program are not yet available (computationally expensive)
  - Alternative:
    - Build off of strong tt+X measurement campaign at CMS
    - Synthesize measurement and search endeavors
    - Build a coherent approach in which measurements of background processes and searches using same signature are performed simultaneously

Summary

- The new boson discovered at the LHC is looking more and more like the Higgs boson of the Standard Model
- Several characteristics need to be pinned down with higher precision, in particular the couplings to the other SM particles
- The coupling between the top quark and the Higgs is predicted to be large; if this new boson is indeed the Higgs of the SM, we absolutely need to measure it – for which study of ttH production is our only avenue
- The CMS search in this channel is underway. Not quite achieving SM sensitivity but with more data, improved analysis techniques and improvements in our modeling, this channel will play an important role in characterizing this new particle.

Backup

The Standard Model

- This so-called "standard model" is a real achievement
  - mathematical description of the building blocks of the universe and its interactions – matter and forces
  - accommodates nearly all of the observed phenomena we see in our every day world
  - explains nearly all of the observations we have made in the exotic conditions created in particle physics experiments
  - particularly elegant feature: the unification of two of the four known forces into a single interaction

The Nobel Prize in Physics 1979 was awarded jointly to Sheldon Lee Glashow, Abdus Salam and Steven Weinberg "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".

nobelprize.org

It’s a Very Nice Picture, But…

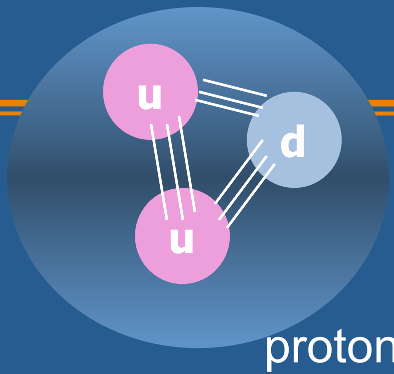
- The model has some gaping holes and open questions:
  - Already observed physics beyond-the-standard-model
  - Mathematics of the model work out perfectly well when assuming the masses of the fundamental particles are all zero – which is manifestly not the case.
  - Large corrections expected in PT to EWK observables, but this is manifestly not the case.
  - 95% of the universe is made of stuff that cannot be explained by the standard model – so-called dark matter and dark energy.
  - Three out of four interactions isn’t bad – but what about gravity?

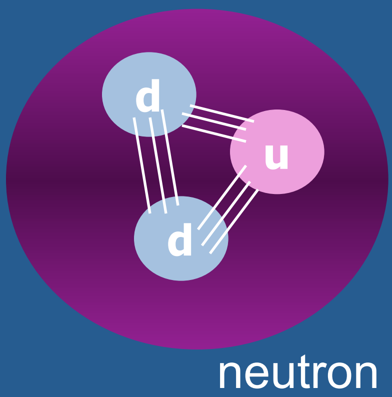
These are big questions!

These questions are why we build immense particle colliders and participate in these huge international endeavors.

Mass – What's the Big Deal?

- Higgs boson credited with the **"origin of mass"**
- **This is not the complete story**
  - **Most of the visible universe** is protons and neutrons
  - Protons (*p*) and neutrons (*n*) are a bound state of *u, d* quarks (~3-8 MeV apiece)
  - The *p, n* masses (938 and 940 MeV) come mostly from the **strong force** holding the quarks together
  - Strong force proceeds with or without the Higgs





- **However,** what if the fundamental particles were massless?
  - If $m_u = m_d = 0$, then $M_{proton} > M_{neutron}$

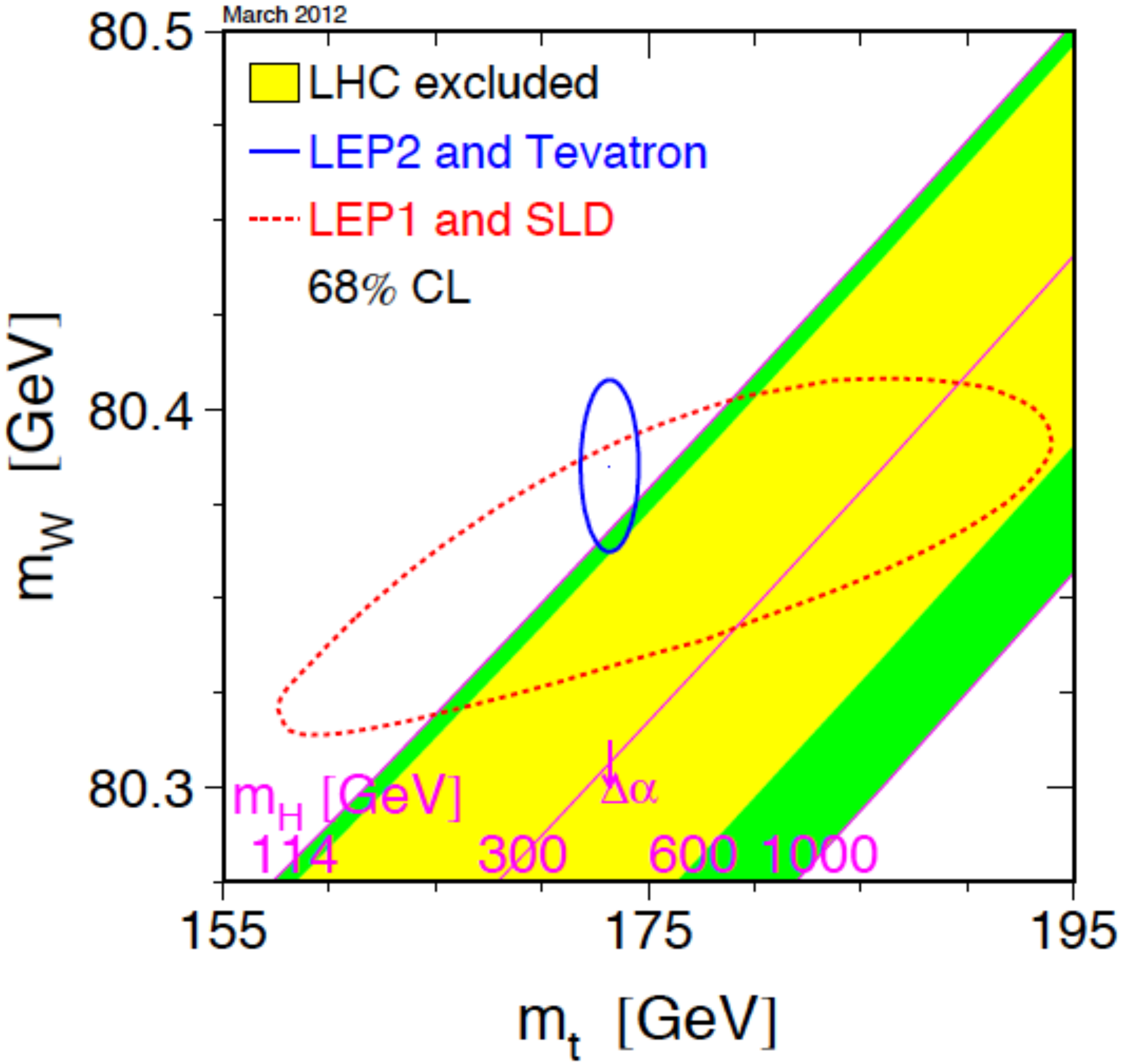
$$p \rightarrow n e^{+} \nu_{e}$$

– This would be bad.

  - If $m_e = 0$, the Bohr radius of atoms would be large
    - Chemistry as we know it would not exist! This too would be bad.

$$a \equiv \frac{4\pi\varepsilon_0 \hbar^2}{m_e e^2}$$

Higgs and Top



ttH Search at CMS: Best ANN Inputs per Category