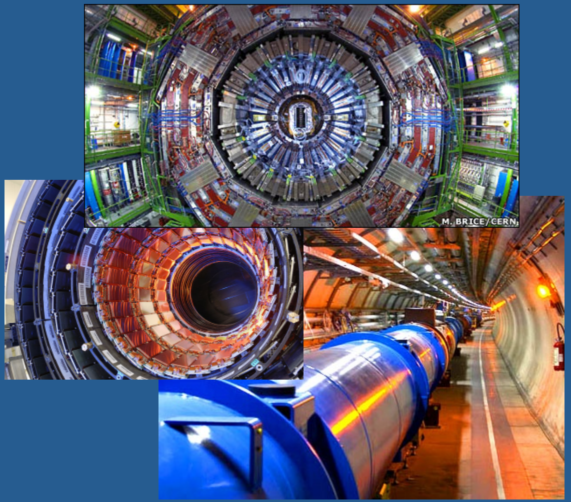
The Interplay Between the Top Quark and the Higgs Boson:

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



Discovery of a New Particle

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: Discovery of a New Particle

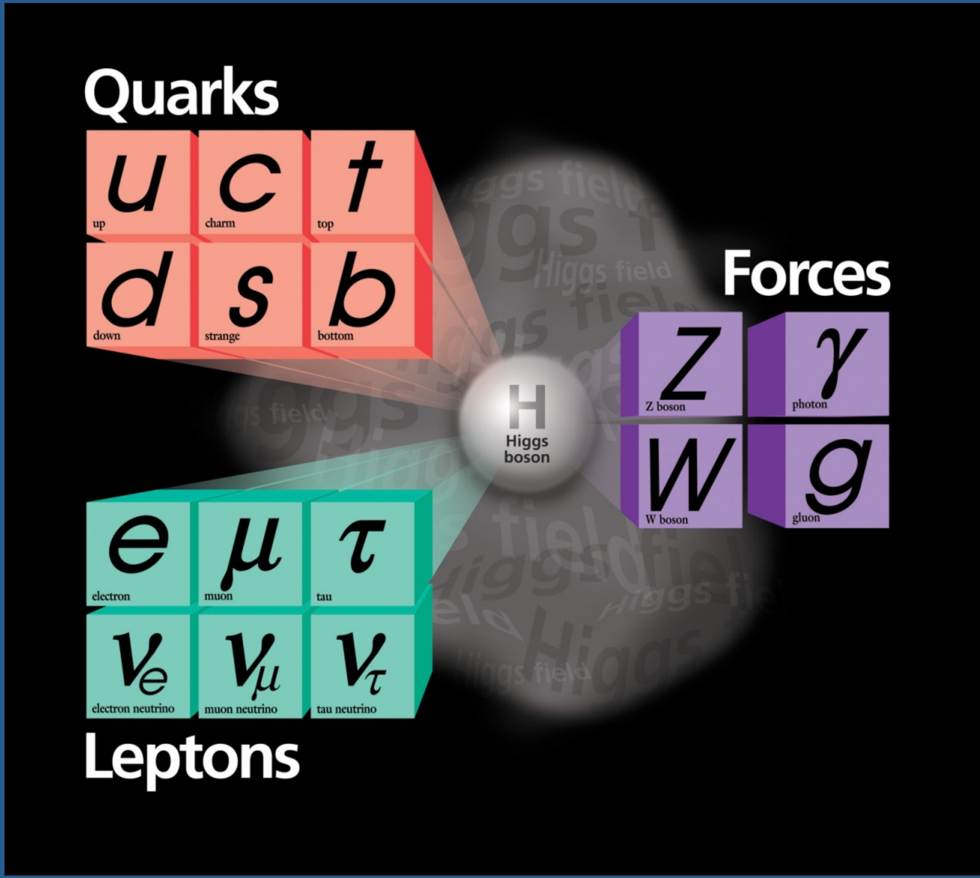
2 March 1995: Discovery of a New Particle

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

The Standard Model

- Mathematical description of the building blocks of the universe and its interactions – **matter and forces**
  - Matter: Quarks, leptons
  - Forces: Gauge bosons

- **Very successful model:**
  - 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 Higgs boson is the last of the fundamental particles predicted by the Standard Model to be observed.

The Electromagnetic and Weak Forces

Symmetry in description of Electromagnetic and Weak forces allows unification:

electroweak interaction

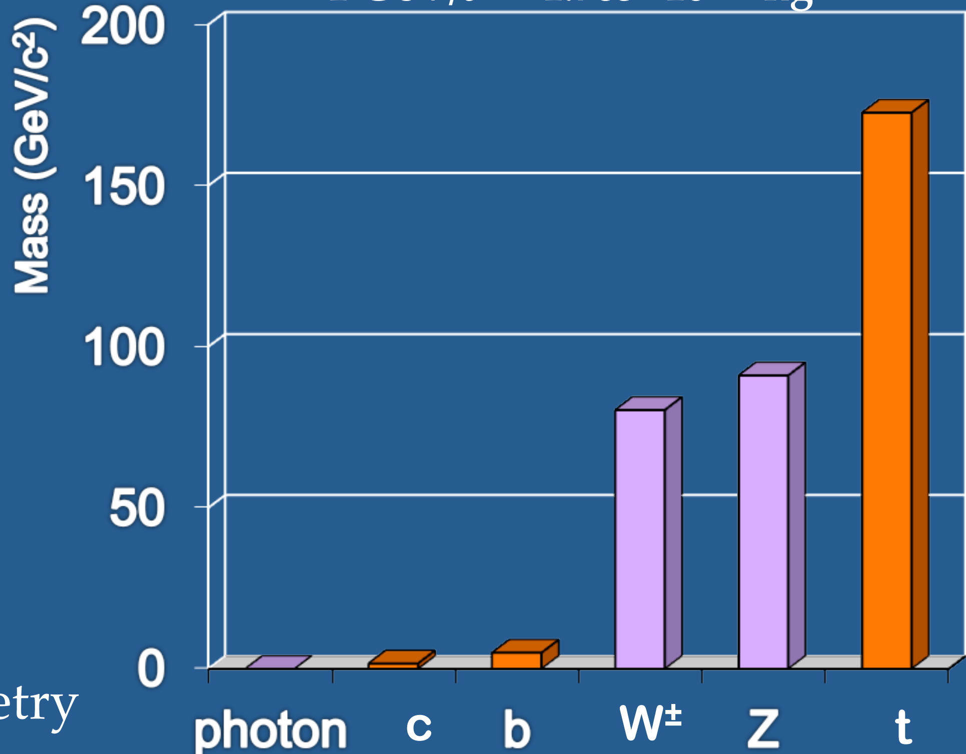
Symmetry is *broken* however:

- 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*

$1\ \text{GeV}/c^2 = 1.783\times10^{-27}$ kg

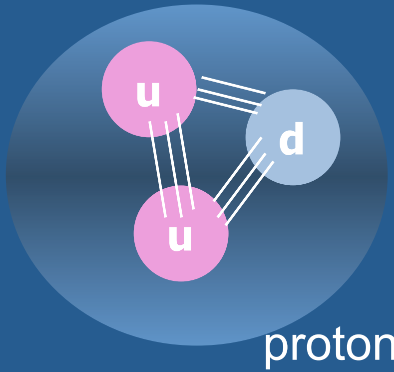


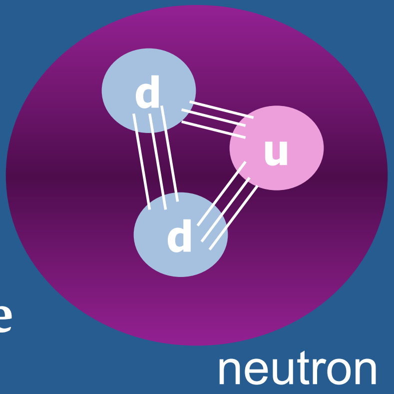
Higgs boson:
Mathematical curiosity or something more?

Mass – What's the Big Deal?

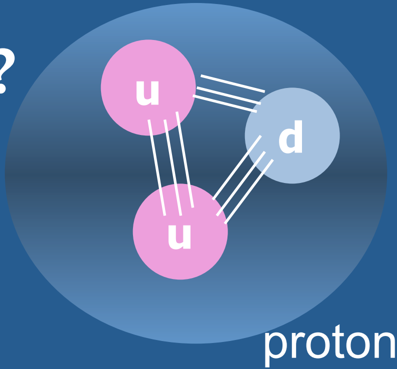
- Higgs boson credited with the "**origin of mass**"

- **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 (~a few MeV apiece)
  - The *p, n* masses (938 and 940 MeV) are much larger than the constituent quarks alone
    - Measured mass comes mostly from the **strong force** holding the quarks together
    - Strong force proceeds with or without the Higgs

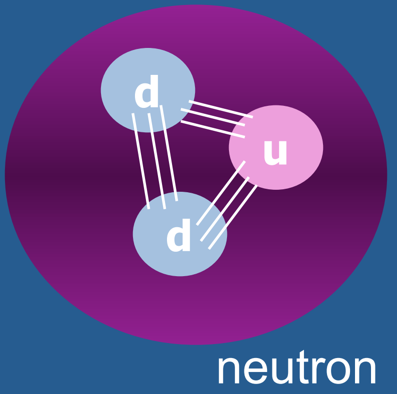




However…



- **What if the fundamental particles were massless?**
- Quark masses:
  - The up and down quark masses have been measured:
    - $m_u = 2.3^{+0.7}_{-0.5}$ MeV and $m_d = 4.8^{+0.5}_{-0.3}$ MeV
  - Important point: $\mathbf{m_d > m_u}$
    - This small difference forces the neutron mass to be slightly larger than that of the proton
  - If $m_u = m_d = 0$, then $M_{proton} > M_{neutron}$, allowing…



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

<u>This would be bad.</u>

- Lepton masses:
  - If $m_e = 0$, the Bohr radius of atoms would be large
    - Chemistry as we know it would not exist!

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

<u>This too would be bad.</u>

However…

- **What if the fundamental particles were massless?**
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  - The u
    - m
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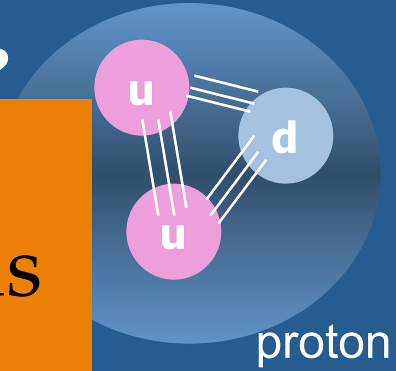
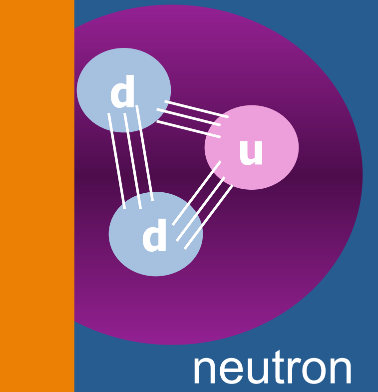




Understanding **electroweak symmetry breaking and mass** is among the most significant puzzles in modern physics.

Hence, the search for the Higgs boson was one of the **primary goals of modern particle physics experiments!**

- Lepton
  - If m_e
    - Chemistry as we know it would not exist!

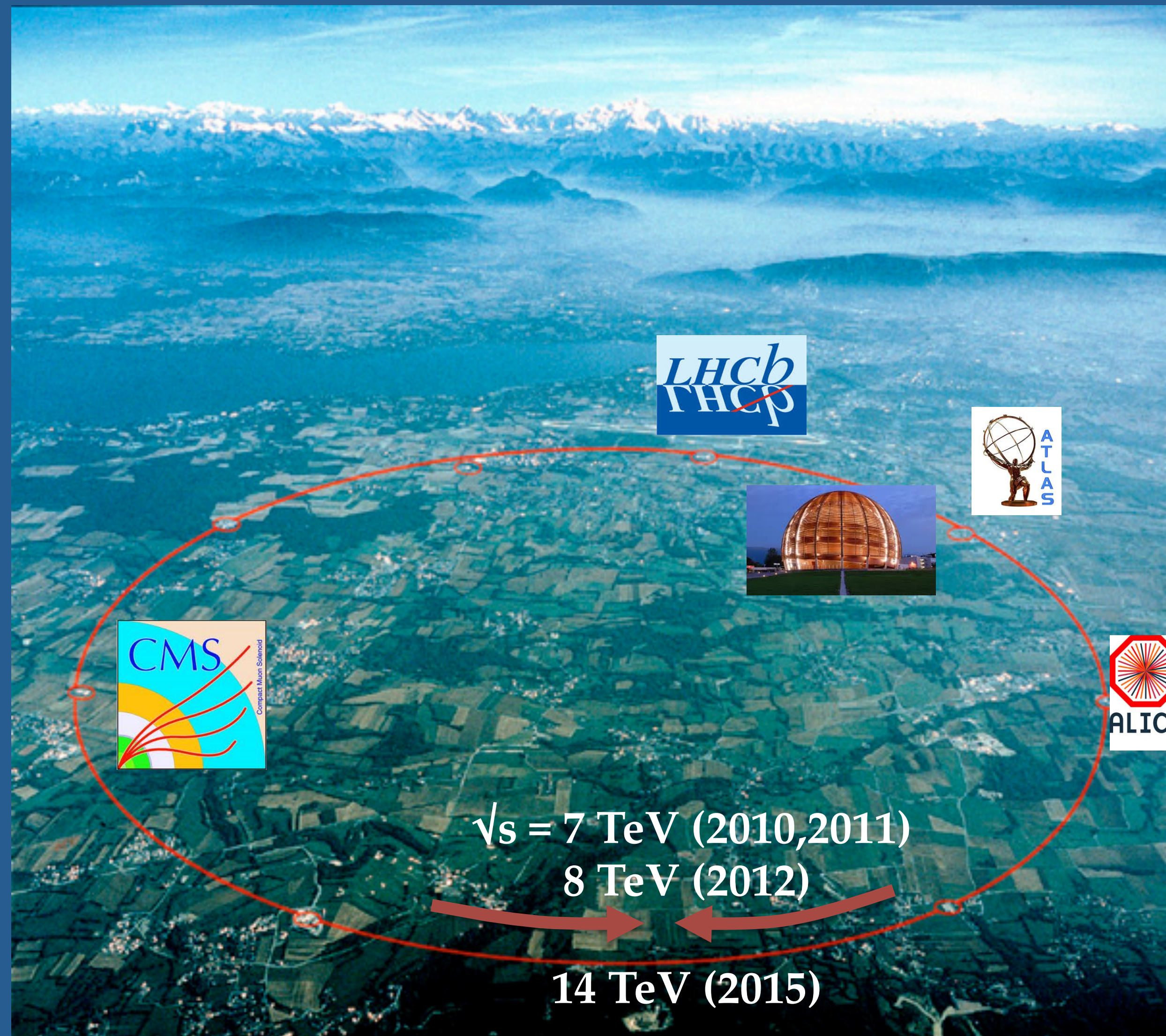
  This too would be bad.

$$\frac{\ldots_0\hbar^2}{m_e e^2}$$

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*



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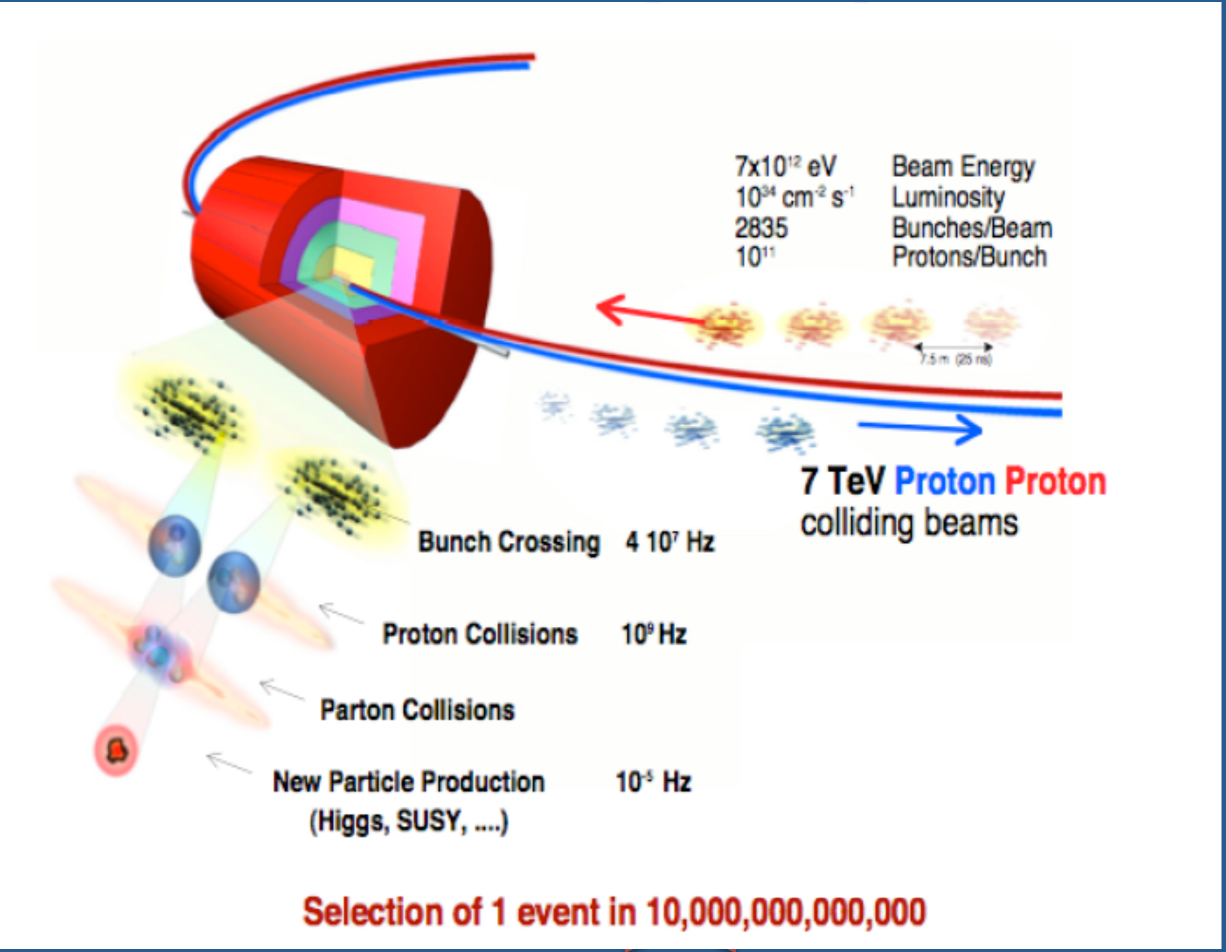

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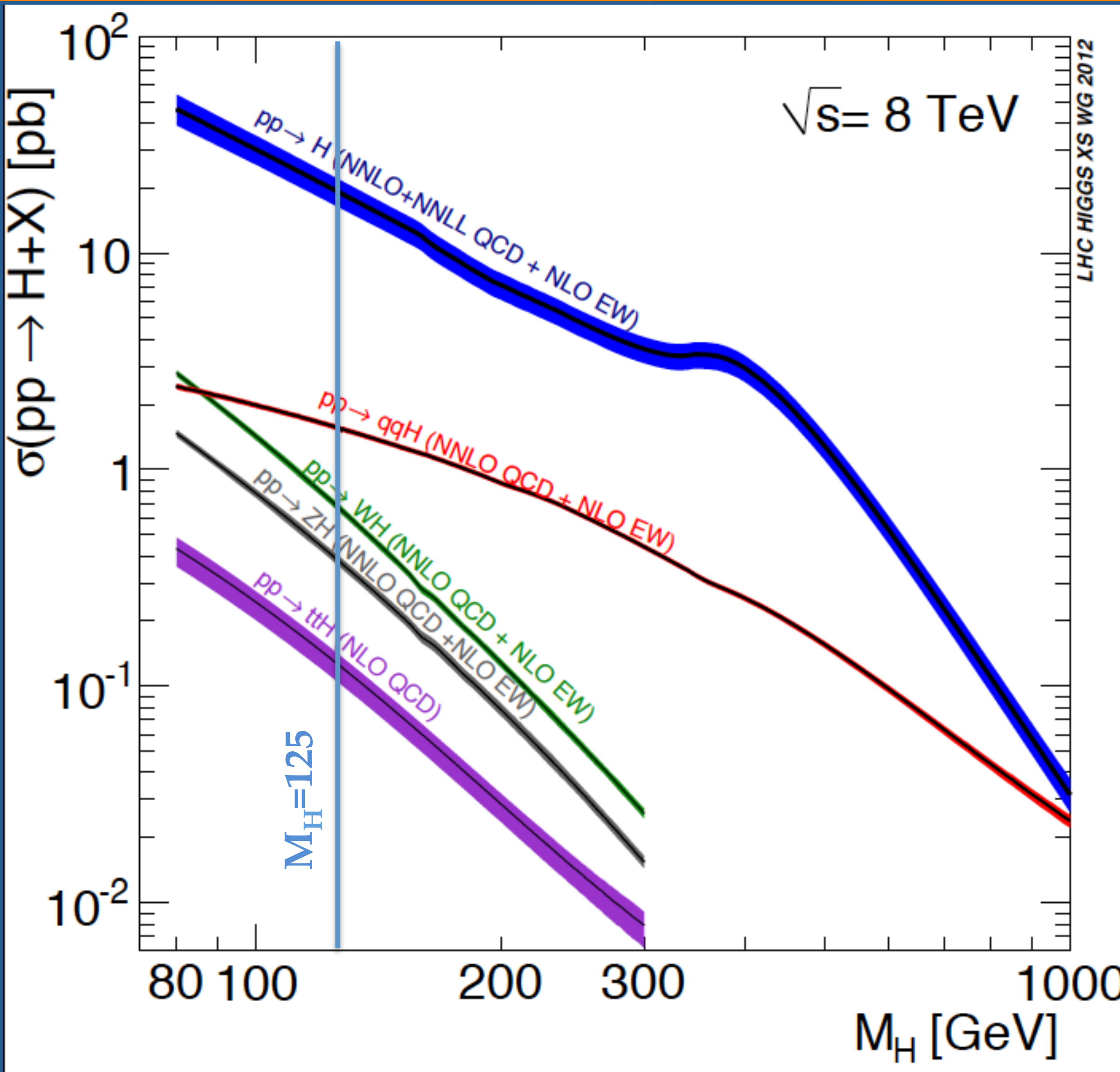
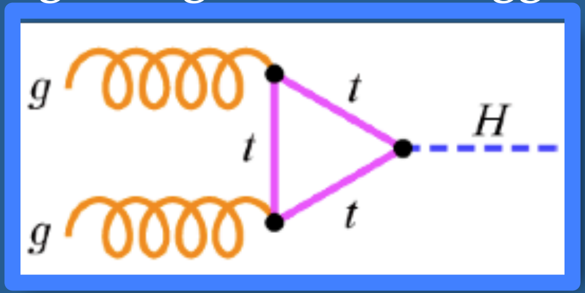
Higgs Boson Production at the LHC

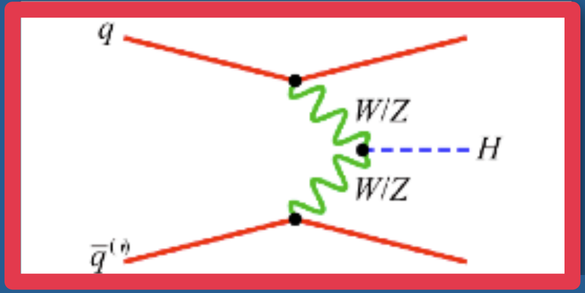


σ = cross section, like rate of production

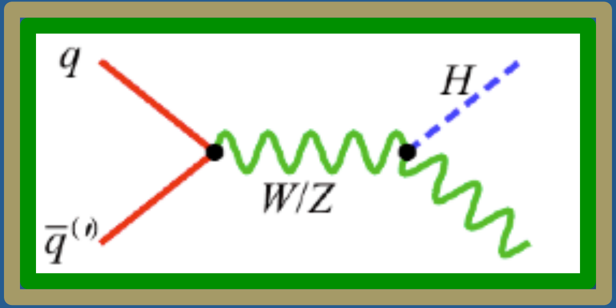
gluon-gluon fusion (ggF)



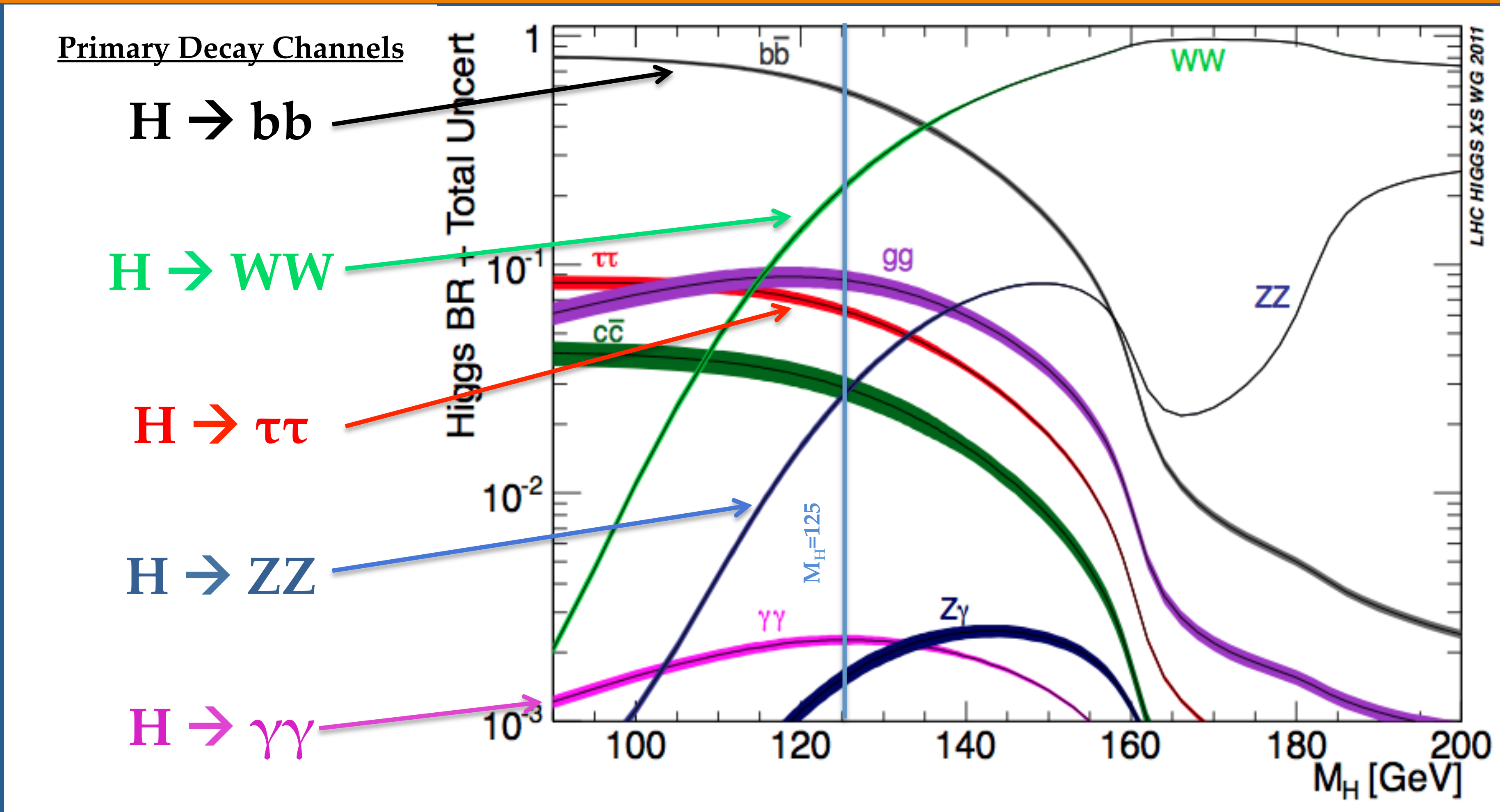
vector-boson fusion (VBF)



W/Z associated production (VH)

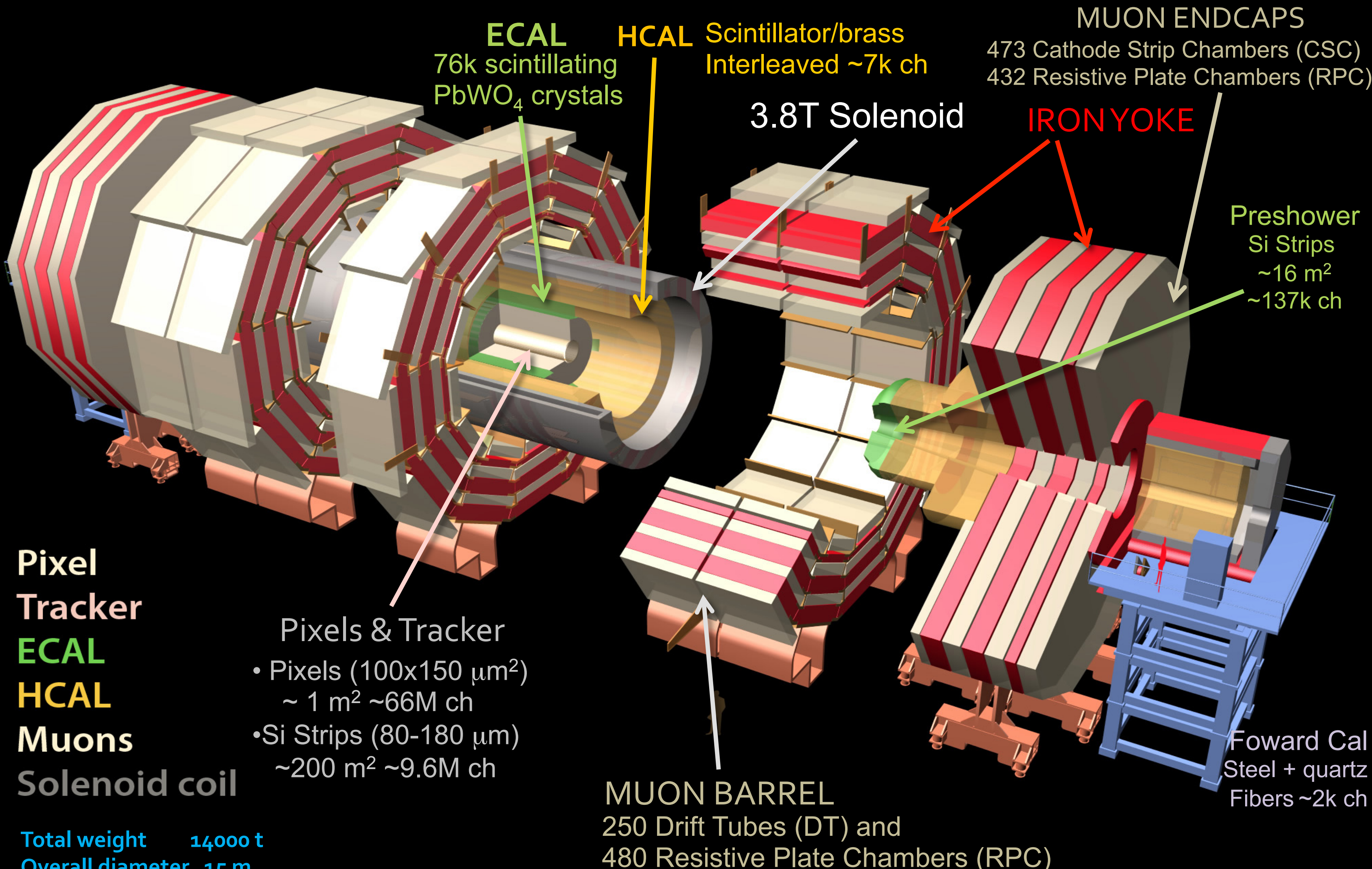


The Search for the Higgs Boson at the LHC



Rarer decay modes suffer from statistics but generally have lower levels of mundane processes ("background") obscuring the signal AND have a higher resolution on the mass of the Higgs before decay.

The CMS Detector



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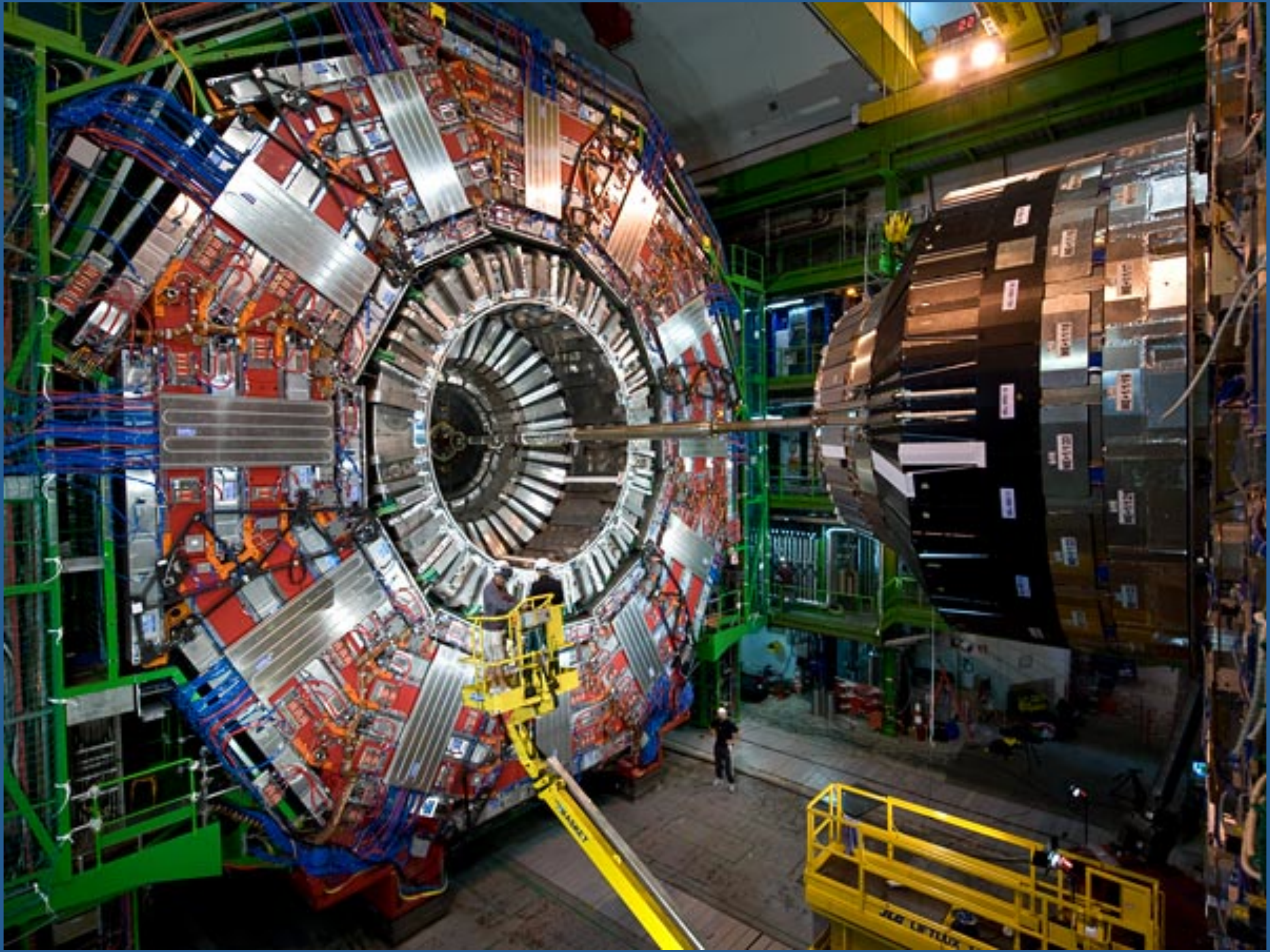
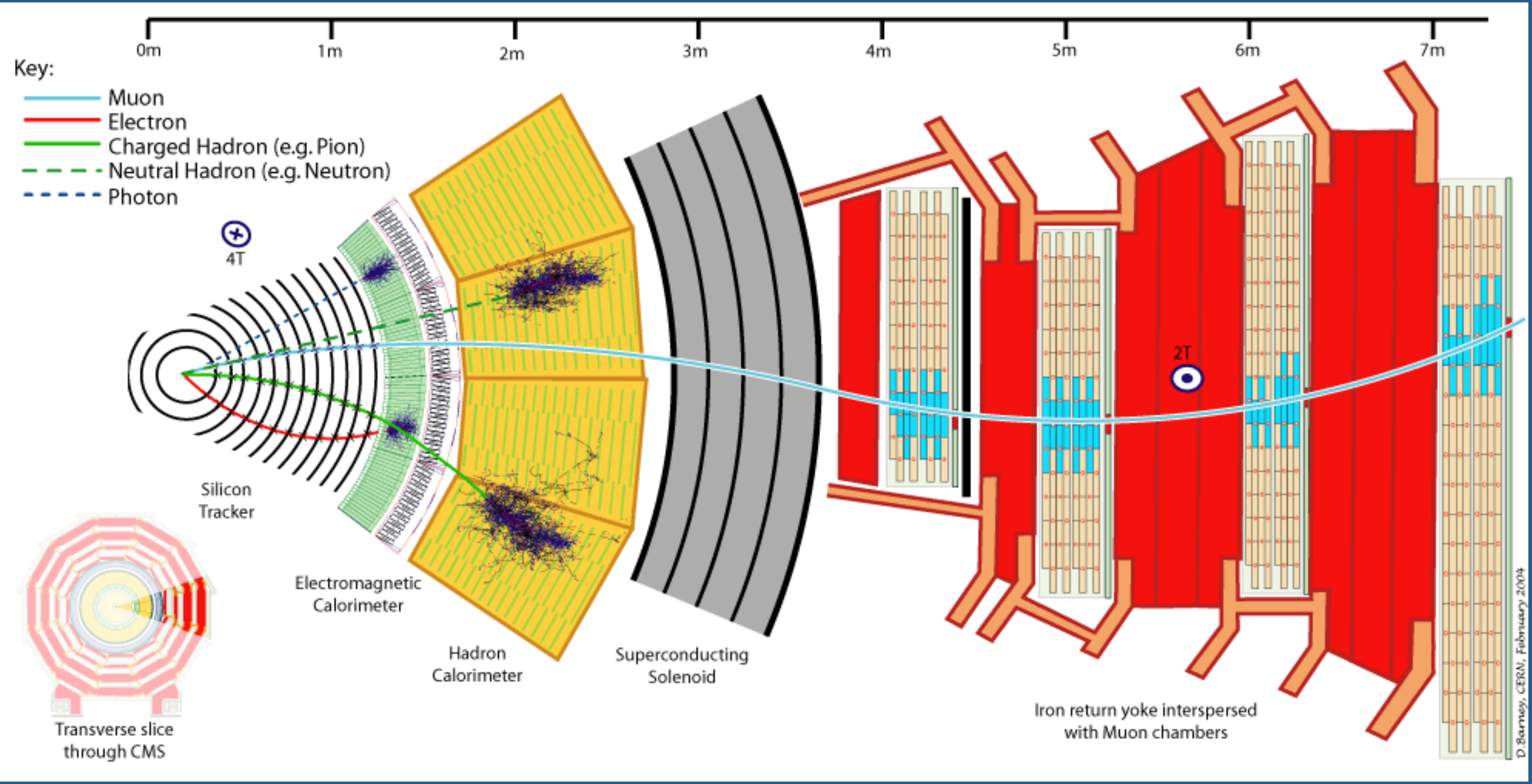
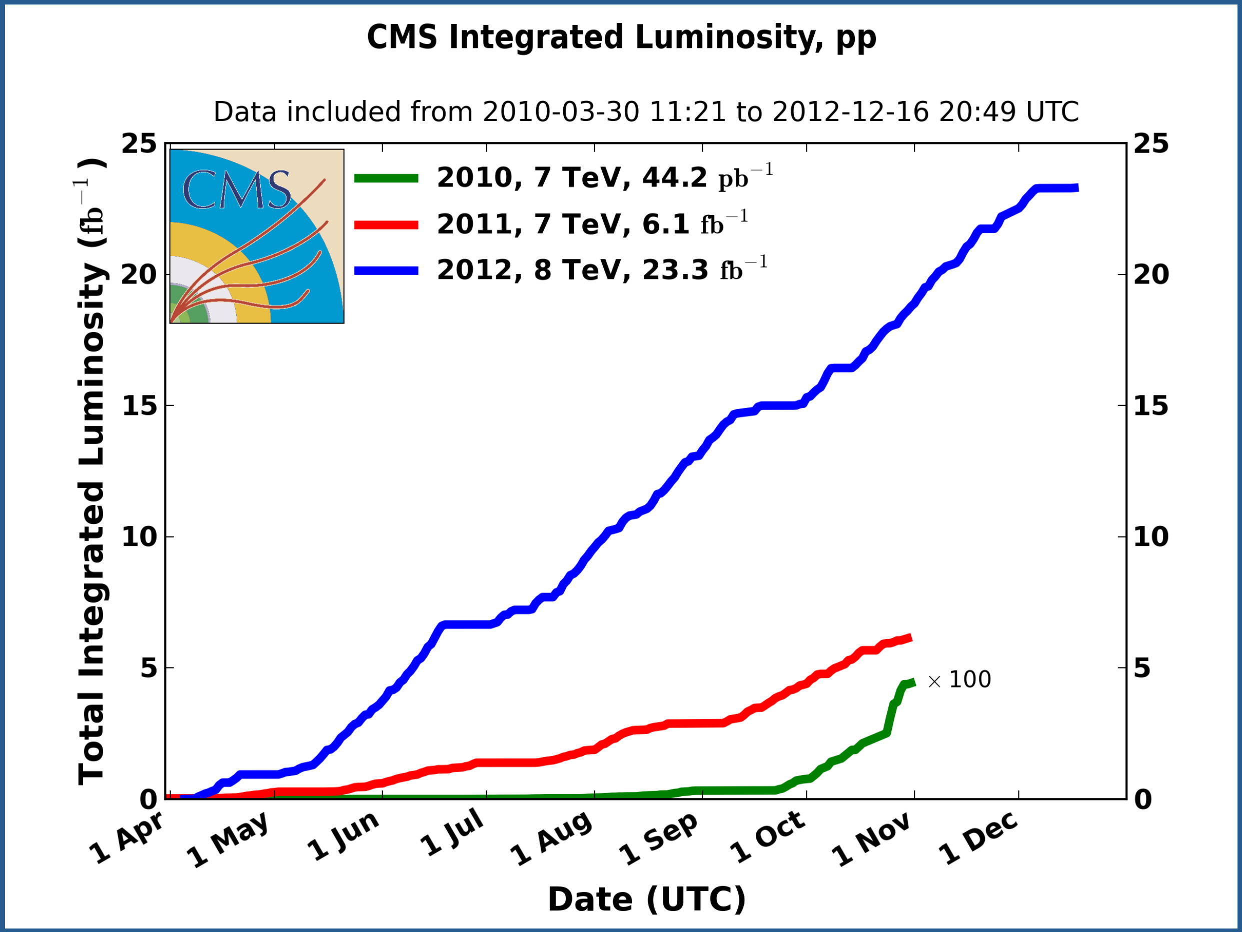


Particle Detection and Subsystems



Higgs search campaign
utilizes every CMS subsystem

The Cumulative CMS Data Sample



Integrated Luminosity, *L*: measure of number of collisions. Units: pb^{-1} "inverse pico-barns"

Related to **cross-section, σ**: "Rate" of a certain process. Units: pb

For some process, *i*:

$$N_{\text{events},\, i} = \sigma_i \cdot \mathcal{L}$$

Higgs Search: Latest Results from CMS

$M_H = 125$ GeV

Decay Mode	Production Mechanism	Lumi (fb^{-1}) 7 + 8 TeV	Significance of Observation (σ = standard deviation) Expected	Observed	Signal Strength $\mu = \sigma/\sigma_{SM}$
H→bb	VH	5 + 19	2.1σ	2.1σ	1.0 ± 0.5
H→WW	ggF, VBF	4.9 + 19.5	5.1σ	4.1σ	0.76 ± 0.21
H→ττ	ggF, VBF, VH	5 + 19	2.6σ	2.9σ	1.1 ± 0.4
H→ZZ	ggF, VBF	5.1 + 19.6	7.2σ	6.7σ	$0.91^{+0.30}_{-0.24}$
H→γγ	ggF, VBF	5.1 + 19.6	4.2σ	3.2σ	$0.78^{+0.28}_{-0.26}$

- **Significance of Observation:**
  - "3σ significance" implies only 1 in 740 probability for background-only data to fluctuate to produce observed excess.
  - "5σ significance" = 1 in 3.5 million
- **Signal Strength, μ:**
  - How much signal is observed, in units of the amount predicted from the Standard Model for each search channel **(μ = 1.0 implies SM level)**

Higgs Results: Assessment

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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, howe whether this is the Higgs boson of the Standard Model of particle physics, or possibly t lightest of several bosons predicted in some theories that go beyond the Standard Mod 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 part and its quantum properties. For example, a Higgs boson is postulated to have spin 0, and in

"…is a Higgs boson."

What does that mean?

Identifying the SM Higgs Boson

Characteristic
Electric Charge 0
Spin 0
Parity +
Decay Modes
Couplings to Other Fundamental Particles
Self Coupling

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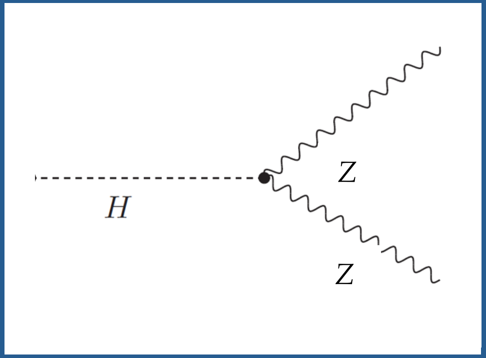
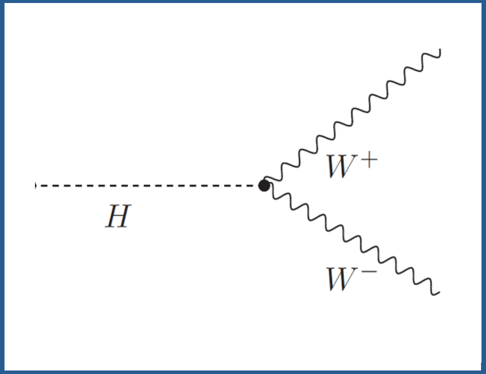
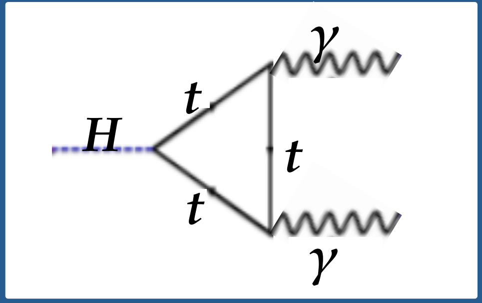
Observation modes all consistent with Higgs being charge 0







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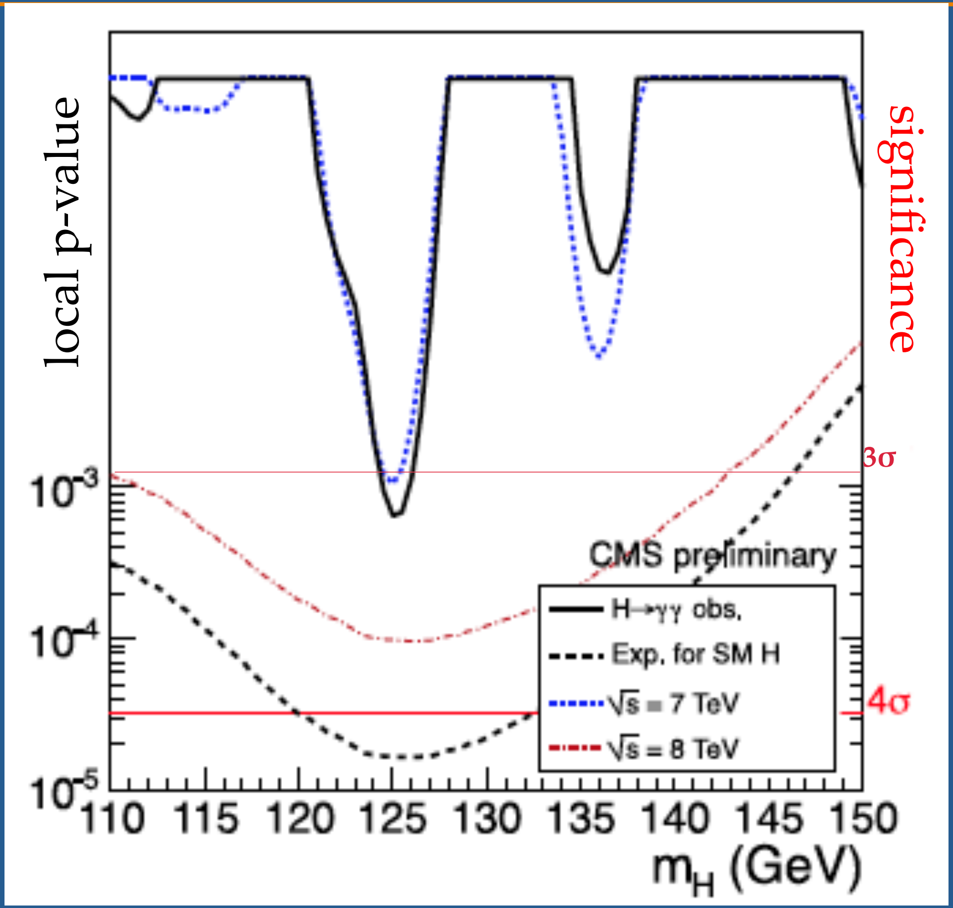

Spin 1 hypothesis disallowed by observation of H→γγ:
Photons have J=1 but only m_J=±1.

What about spin 2?

Identifying the SM Higgs Boson

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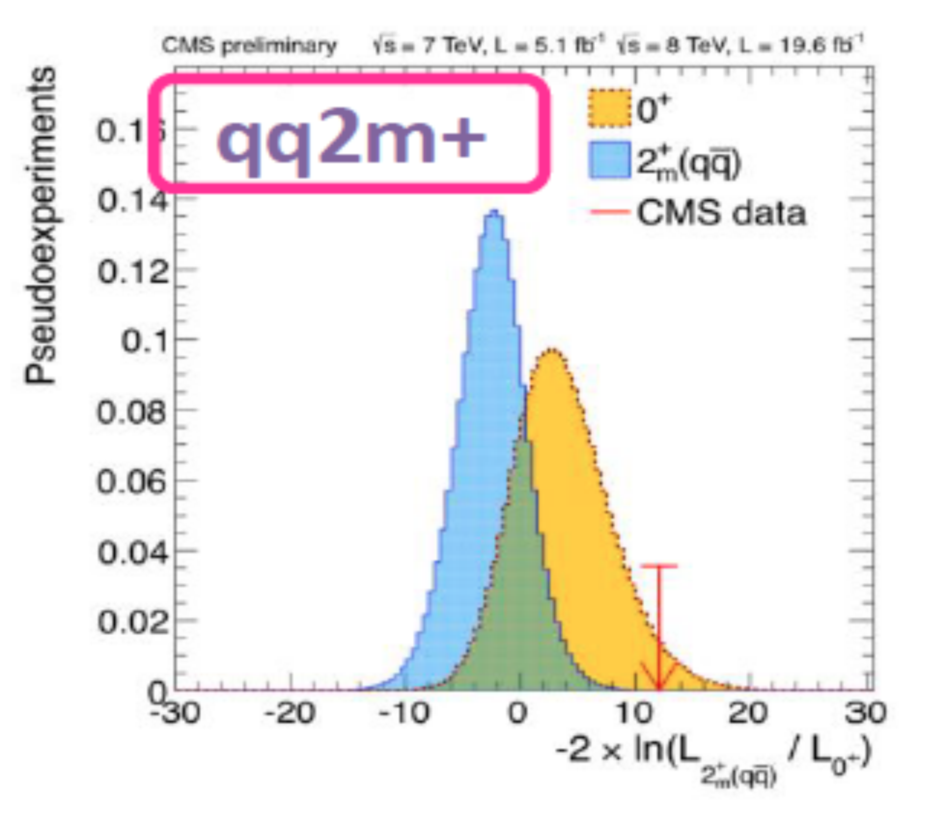
No known fundamental particle has spin 2. Many models predict them, however.

Candidate: Spin-2 Graviton



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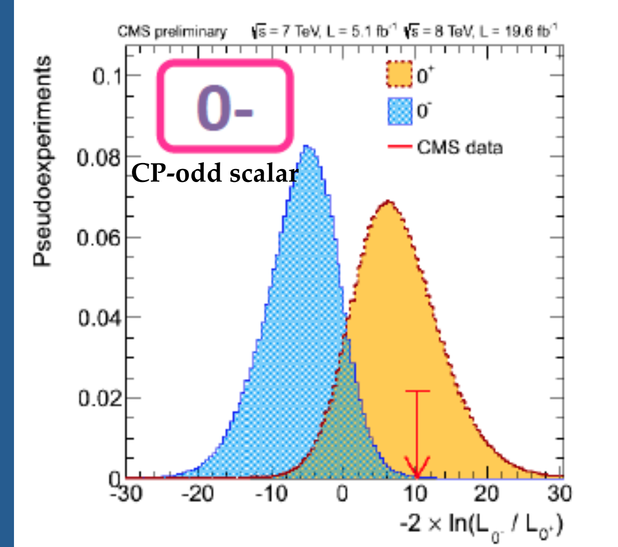

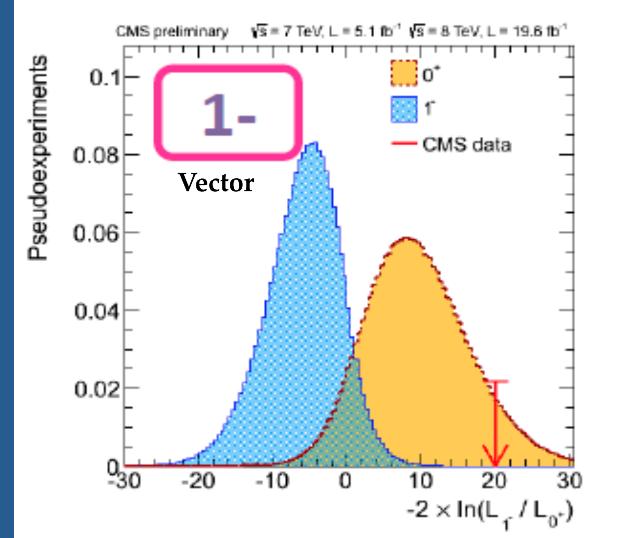

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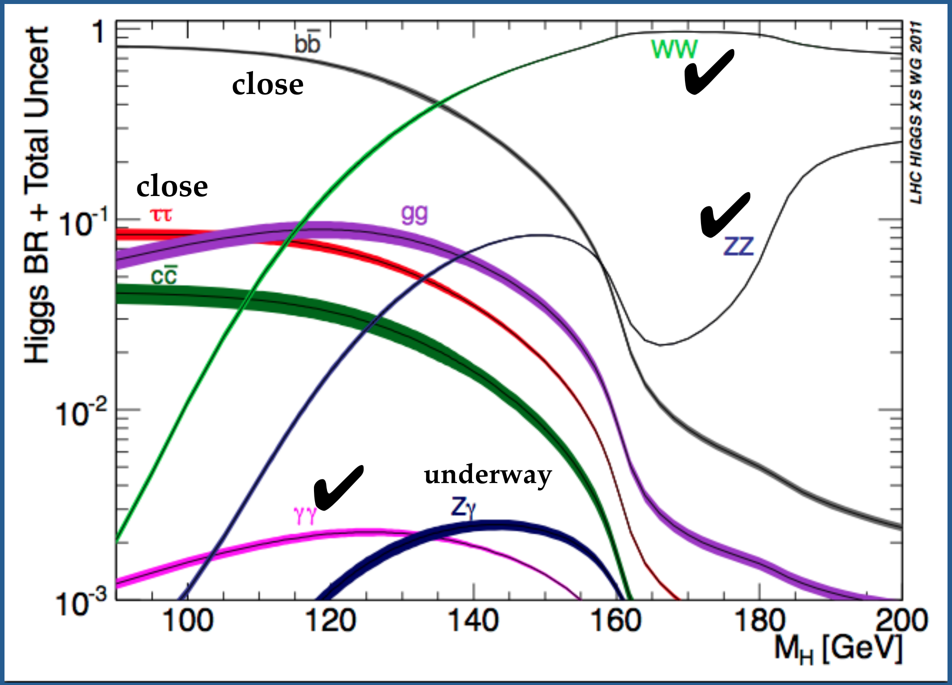

This is an ongoing campaign, clearly.

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

Identifying the SM Higgs Boson

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- 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

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

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

- These reduce to SM couplings in the limits when:

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

- 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 to the other fundamental particles are all understood then, yes?

More on the Higgs Couplings

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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 the top quark, 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

leptons quarks gauge bosons

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

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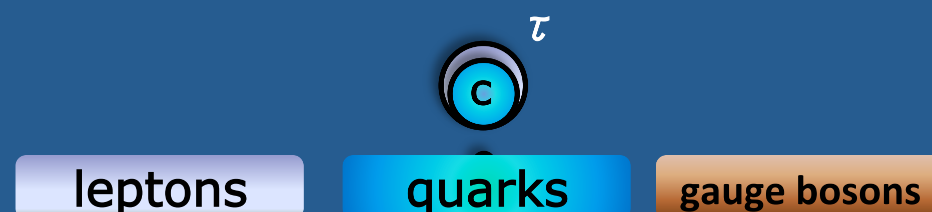

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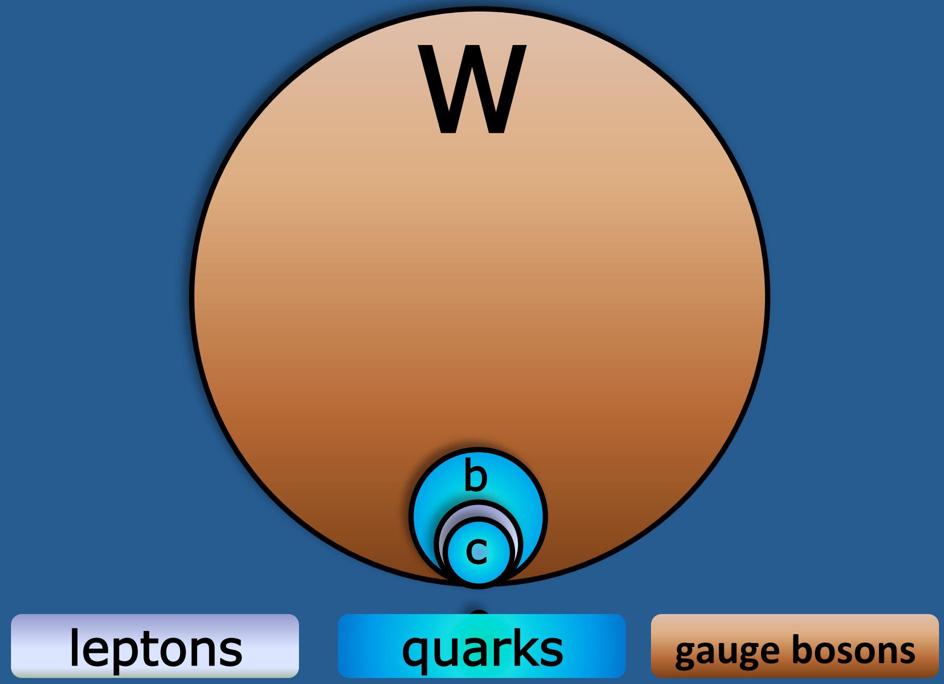

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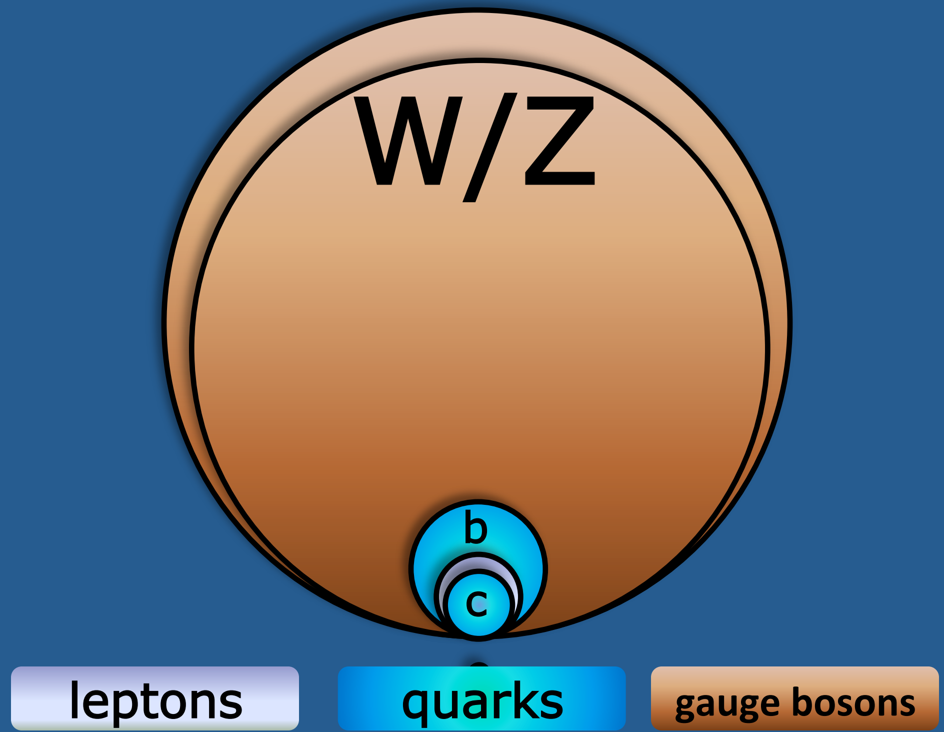

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More on the Higgs Couplings

1 atom of Au:
mass= ~180 GeV/c^2
^{197}Au = 118 n, 79 p, 79 e^-

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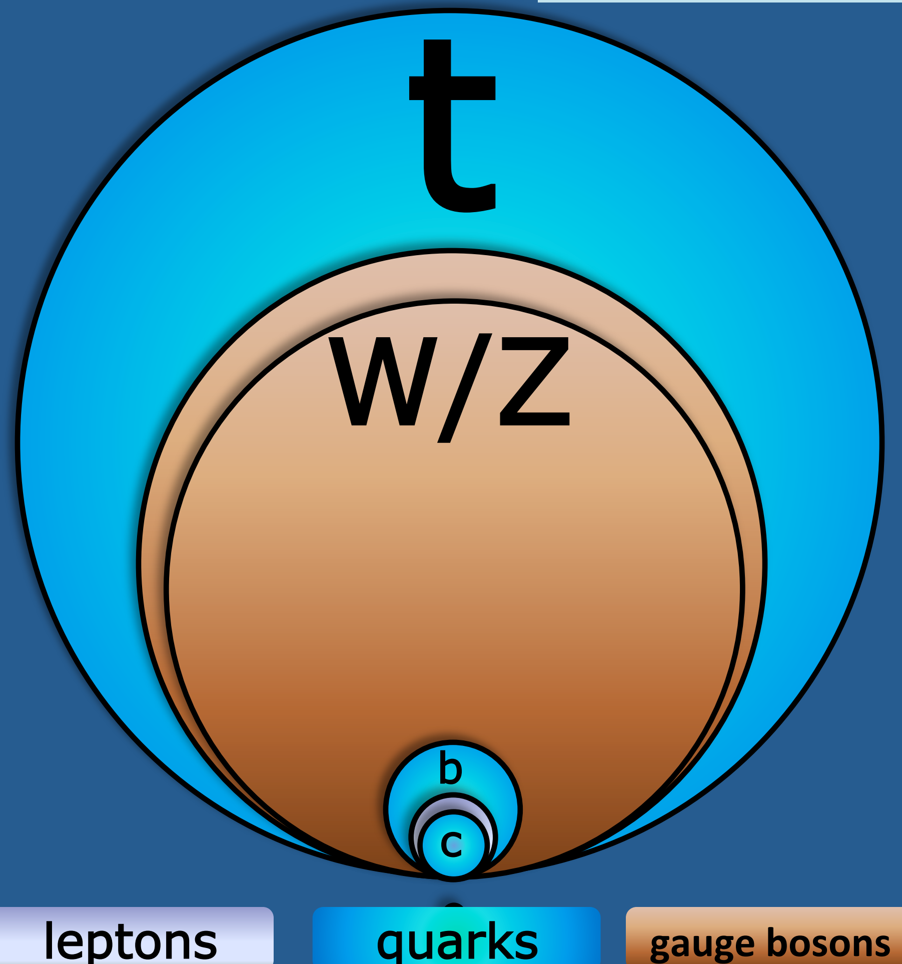

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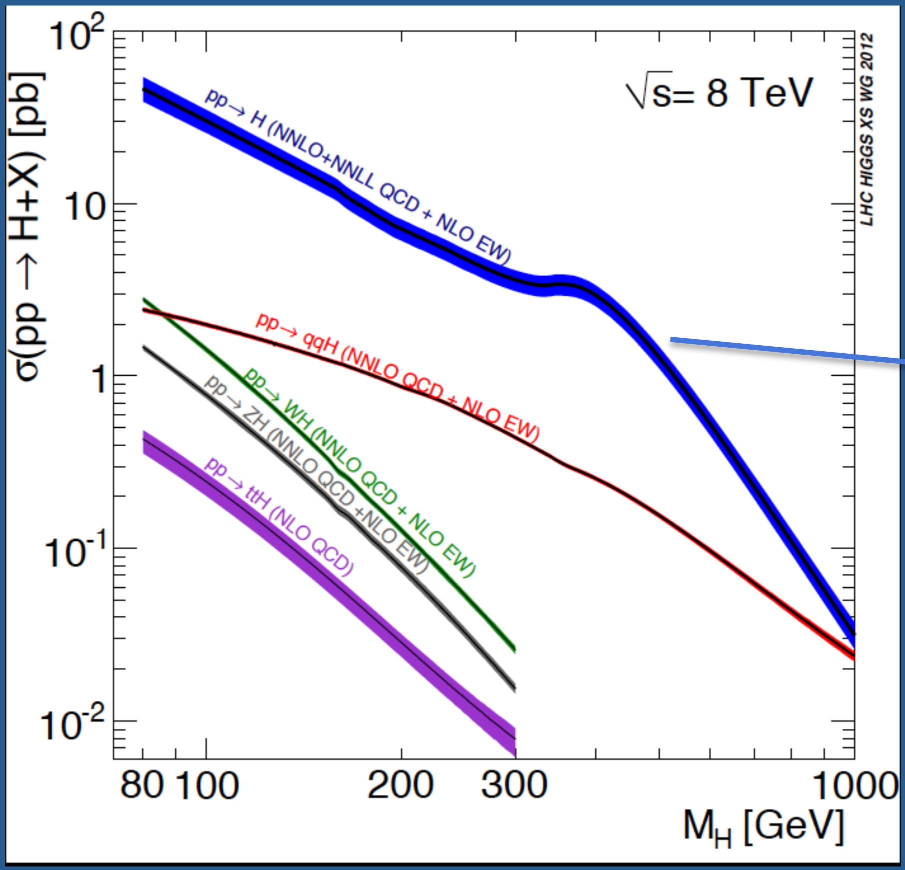
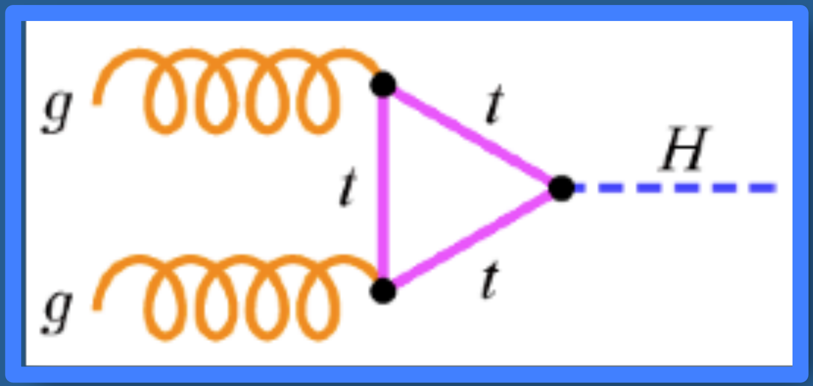
Higgs and Top



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



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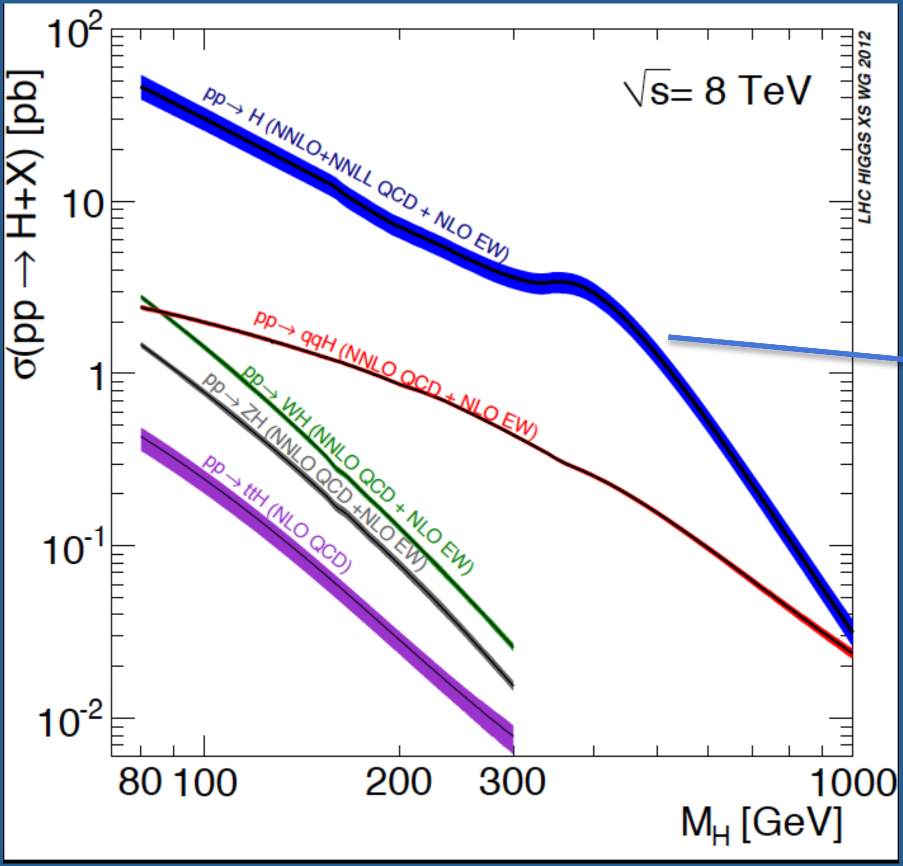

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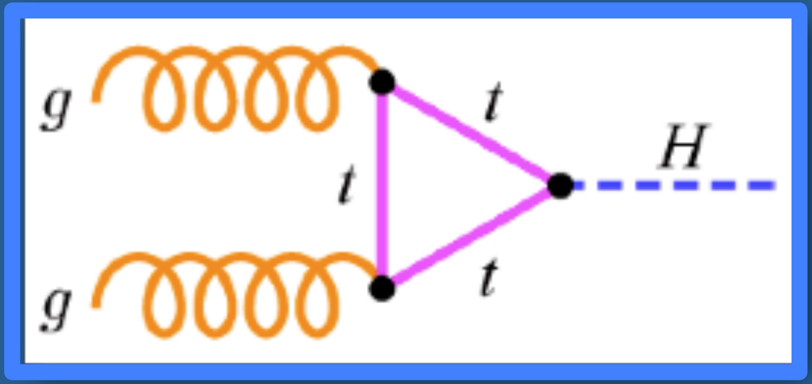
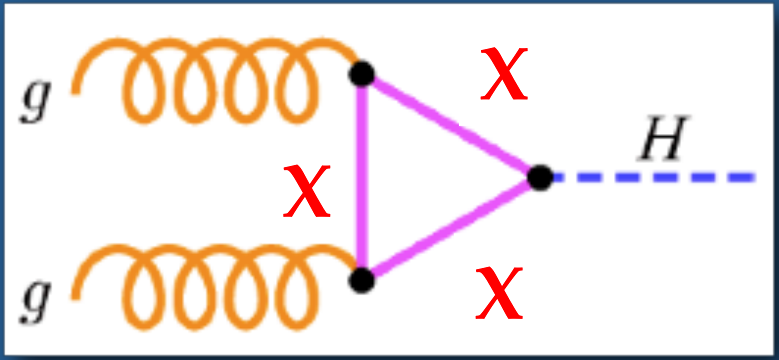
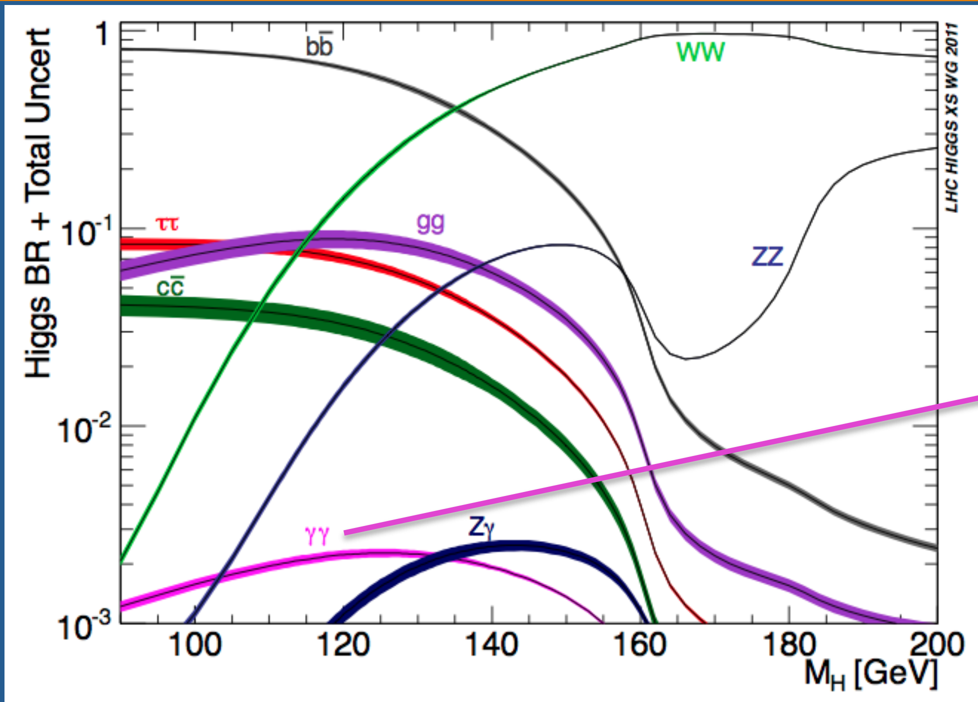


- But what about this?

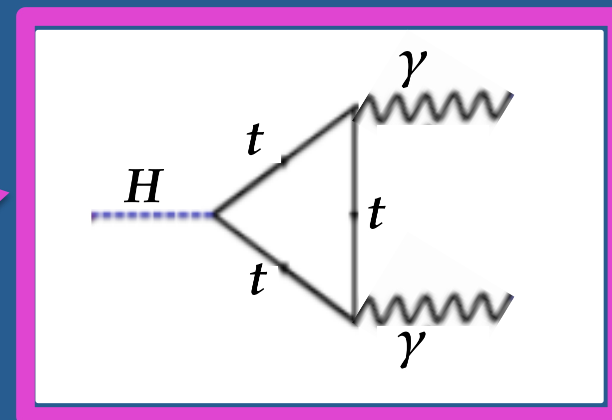


We assume gluon-fusion proceeds through a top-quark loop…but we don't really know!

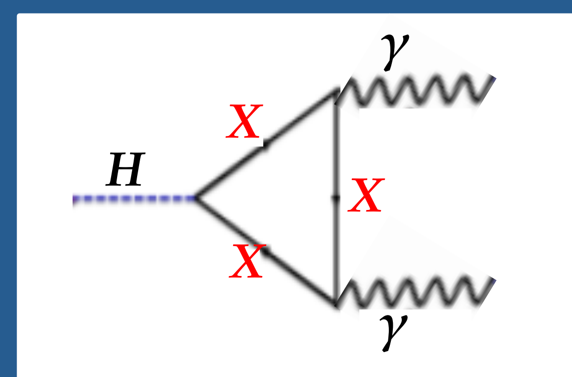
Higgs and Top



- Similar problems on the decay side:

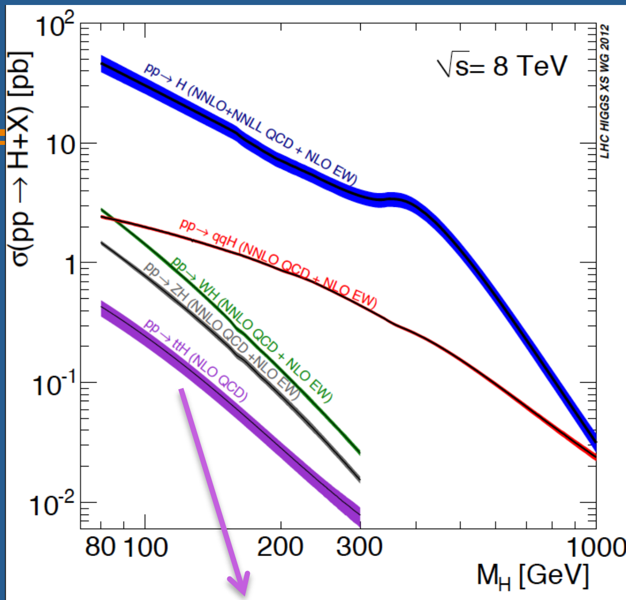


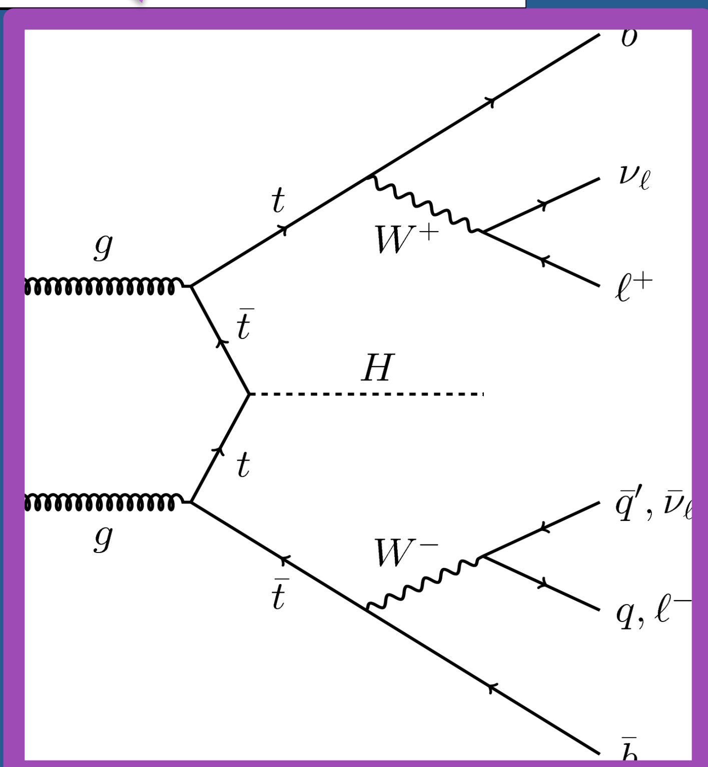
…but what about…



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…

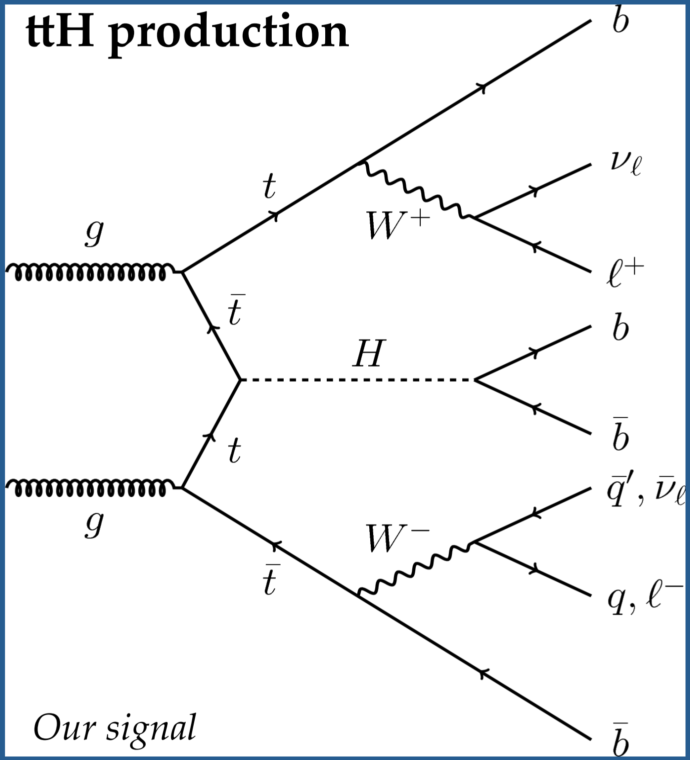


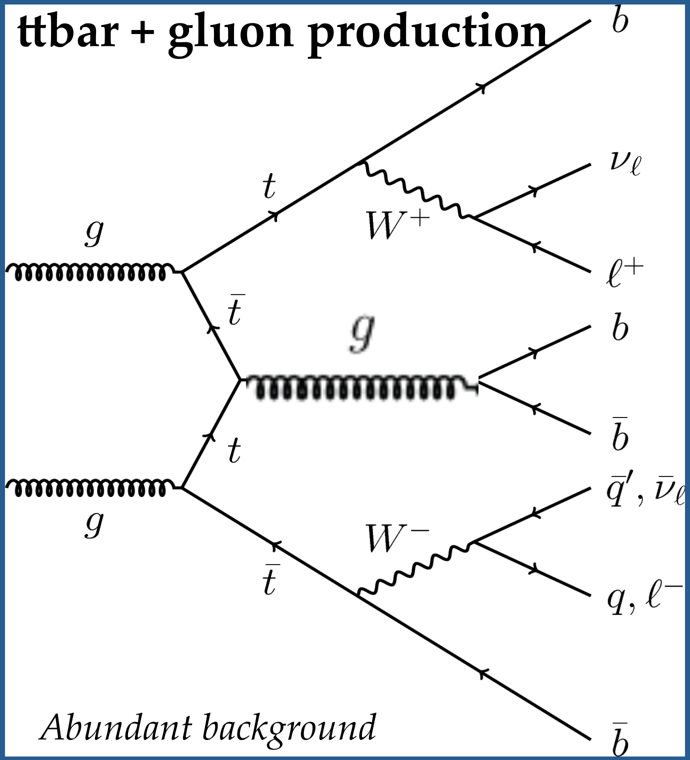


ttH Production

- 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

Backgrounds Are a Problem



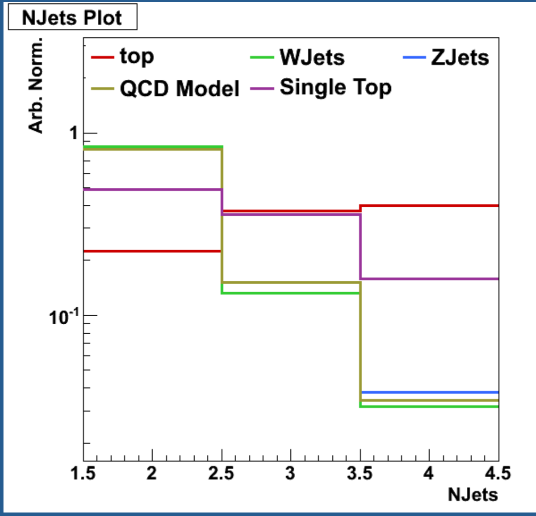


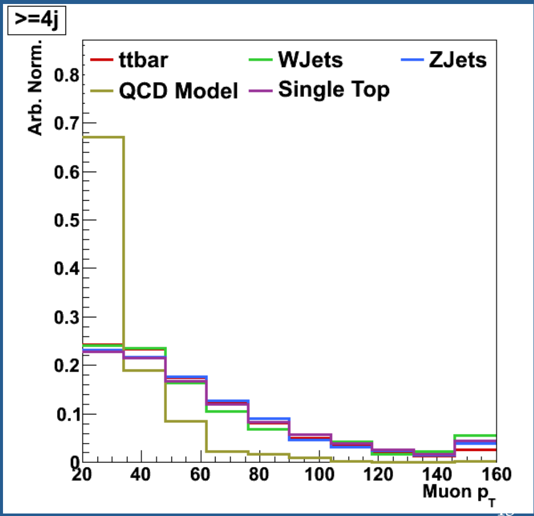
- Overwhelming background from ttbar+gluon production
  - Expected cross section for inclusive ttbar production is x2000 higher than that of ttH
- Need solid understanding of inclusive ttbar production in order for ttH search to succeed

Top-Quark Physics at UVa

UVa Postdoc
Sarah Boutle

- Initial focus upon joining CMS: Top-quark physics
  - Goal: **Study ttbar production in detail** in preparation for performing the ttH search once sufficient statistics would be accumulated
- First entrypoint (2010):
  - Measurement of the production cross section for ttbar events in the 2010 CMS data sample
  - Simultaneous QCD, W+jets and Top (SQWaT):
    - The dominant contributors to the selected sample are W+jets, QCD and ttbar
    - Use discriminating variables to perform a max likelihood fit to determine the contribution from each process simultaneously





$$\sigma(t\bar{t}) = 156.2 \pm 18.7(\text{stat.})^{+42.1}_{-38.4}(\text{syst.}) \pm 17.2(\text{lumi.})\ \text{pb.}$$

Eur. Phys. J. C. 71, 1721 (2011)

Top-Quark Physics at UVa

- My contributions to the early top-quark physics program were recognized by the management of the CMS experiment
  - Primary author of first top-quark physics measurement paper at the LHC (2010) [Phys. Lett. B 695, 424-443 (2011)](#)
  - I was chosen as convener of the top-quark cross sections measurement group (2010-2013)
    - Important component of CMS physics program
    - Coordinated efforts of more than 100 physicists form 20 institutes across the collaboration
    - Resulted in 25 preliminary results and 10 papers

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First measurement of the cross section for top-quark pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration

CERN, Switzerland

ARTICLE INFO

Article history:
Received 30 October 2010
Received in revised form 18 November 2010
Accepted 26 November 2010
Available online xxxx
Editor: M. Doser

Keywords:
CMS
LHC
Physics
Top quark
Cross section

ABSTRACT

The first measurement of the cross section for top-quark pair production in pp collisions at the Large Hadron Collider at centre-of-mass energy $\sqrt{s} = 7$ TeV has been performed using a data sample corresponding to an integrated luminosity of 3.1 ± 0.3 pb^{-1} recorded by the CMS detector. This result utilizes the final state with two isolated, highly energetic charged leptons, large missing transverse energy, and two or more jets. Backgrounds from Drell–Yan and non-W/Z boson production are estimated from data. Eleven events are observed in the data with 2.1 ± 1.0 events expected from background. The measured cross section is 194 ± 72(stat.) ± 24(syst.) ± 21(lumi.) pb, consistent with next-to-leading order predictions.

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Since its discovery [1,2], the properties of the top quark have been subject to numerous detailed studies [3], which until recently have only been possible at the Tevatron proton–antiproton collider. With the advent of the Large Hadron Collider (LHC) era [4], top-quark processes can be studied for the first time in multi-TeV proton–proton collisions. In both $p\bar{p}$ and pp collisions, top quarks are expected to be produced primarily via the strong interaction in top–antitop ($t\bar{t}$) pairs. At the LHC, the $t\bar{t}$ production mechanism is expected to be dominated by a gluon fusion process, whereas at the Tevatron, top-quark pairs are predominantly produced through quark–antiquark annihilation. Measurements of top-quark production at the LHC are therefore important new tests of our understanding of the $t\bar{t}$ production mechanism. This is a crucial component of the early LHC physics program, since many signatures of new physics models accessible at the LHC either suffer from top-quark production as a significant background or contain top quarks themselves.

In this Letter we present the first measurement of the cross section for $t\bar{t}$ production in proton–proton collisions at the LHC at center-of-mass energy $\sqrt{s} = 7$ TeV. The results are based on a data sample corresponding to an integrated luminosity of 3.1 ± 0.3 pb^{-1} [5] recorded by the CMS experiment [6] between March and August 2010. This measurement is an important milestone for CMS, demonstrating the experiment's capabilities in extracting an intricate signature.

Within the standard model, the top quark decays via the weak process $t \to Wb$ almost exclusively. Experimentally, top-quark pair events are categorized according to the decay of the two W bosons: the all-hadronic channel, in which both W bosons decay into quarks; the lepton + jets channel, in which one W boson decays leptonically, the other into quarks; and the dilepton channel, in which both W bosons decay into leptons. The measurement described herein is performed using the e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ dilepton $t\bar{t}$ modes. These modes comprise $(6.45 \pm 0.11)\%$ [7] of the total branching fraction for $t\bar{t}$ when including contributions from tau leptons that subsequently decay to electrons and muons, as is done here. Therefore, the final state studied in this analysis contains two oppositely charged leptons (electrons or muons), two neutrinos from the W boson decays, and at least two jets of particles resulting from the hadronization of the b quarks. Similar measurements have been performed recently at the Tevatron [8,9].

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. The bore of the solenoid is outfitted with various particle detection systems. Charged particle trajectories are measured by the silicon pixel and strip tracker, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan\theta/2]$, with θ being the polar angle of the trajectory of the particle with respect to the beam direction. A crystal electromagnetic calorimeter (ECAL)

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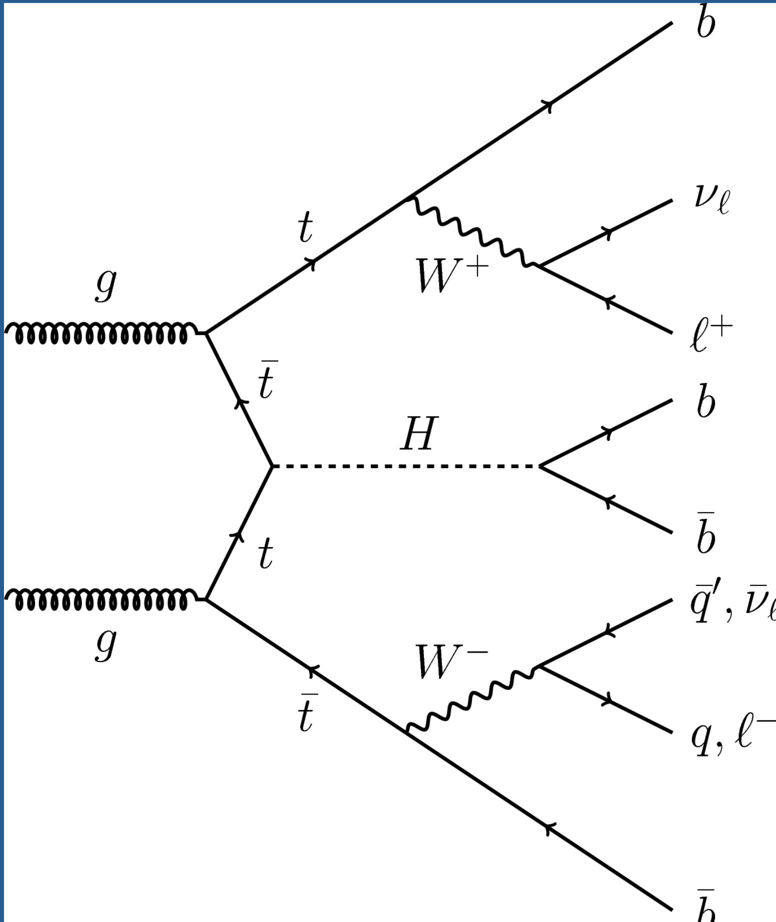
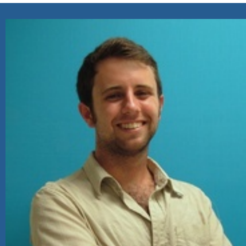
doi:10.1016/j.physletb.2010.11.058

Please cite this article in press as: CMS Collaboration, First measurement of the cross section for top-quark pair production in proton–proton collisions at $\sqrt{s} = 7$ TeV, Physics Letters B (2010), doi:10.1016/j.physletb.2010.11.058

ttH Search at CMS



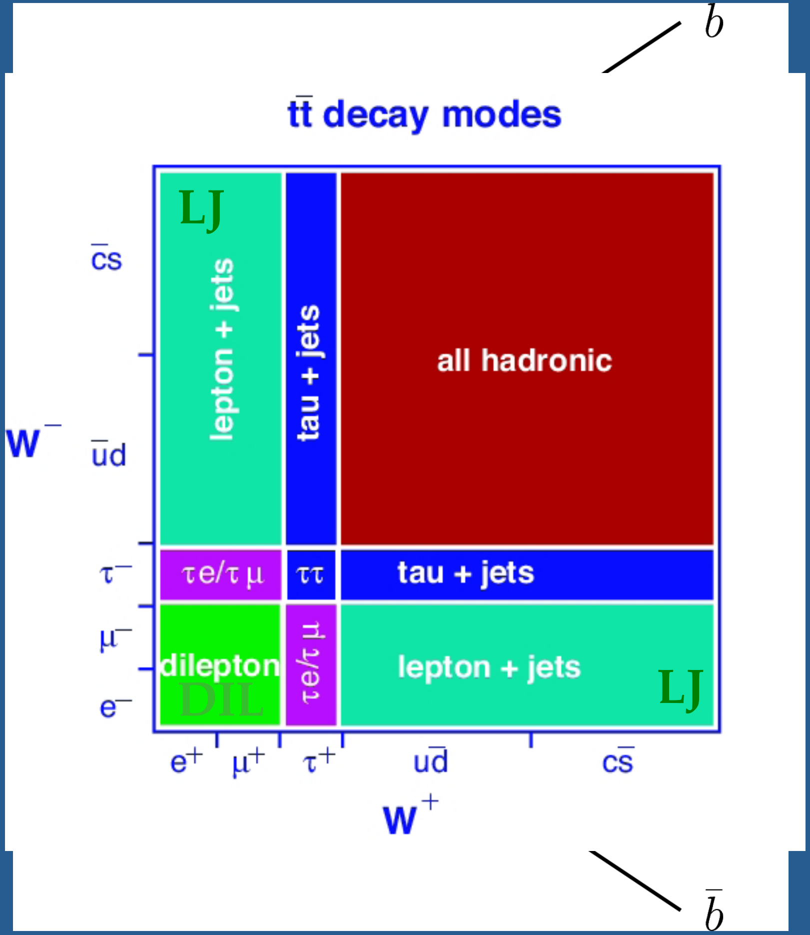


UVa PhD student
John Wood

UVa Postdoc
Sarah Boutle

- **Initial focus:**
  - Optimized for low M_H and H→bb decay mode
  - Exploit both lepton+jets (LJ) and dilepton (DIL) ttbar channels
  - Combine 5/fb samples from 2011 (7 TeV) and 2012 (8 TeV)
- **Event selection:**
  - One (two) isolated charged leptons w/ $p_T > 30$ (20) GeV
  - Veto events in the LJ channel w/ a second charged lepton
  - 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



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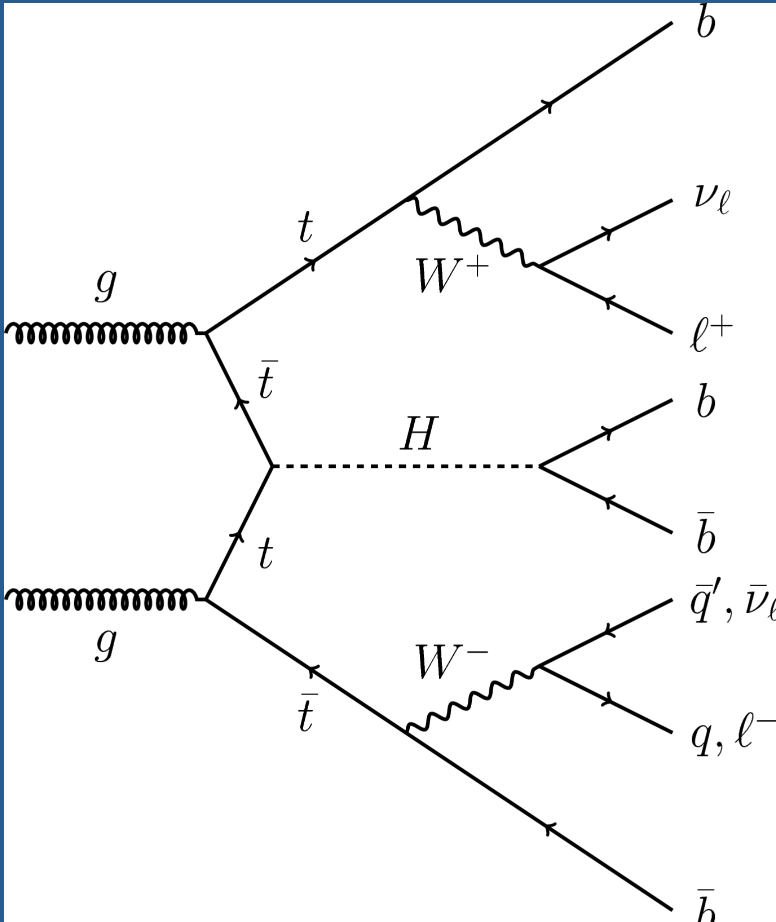

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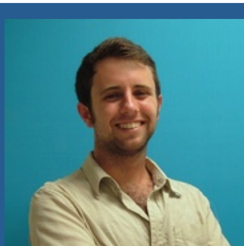
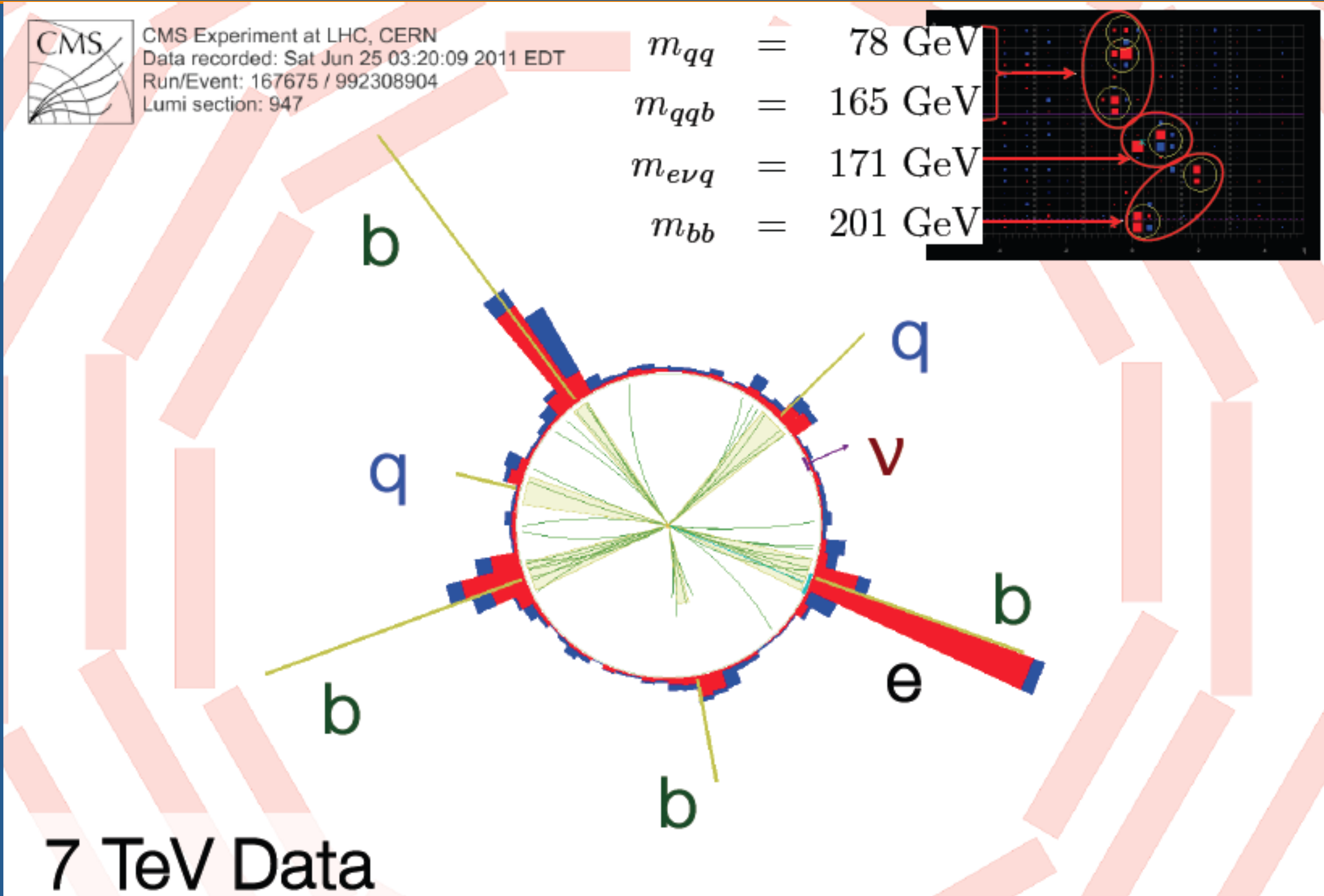


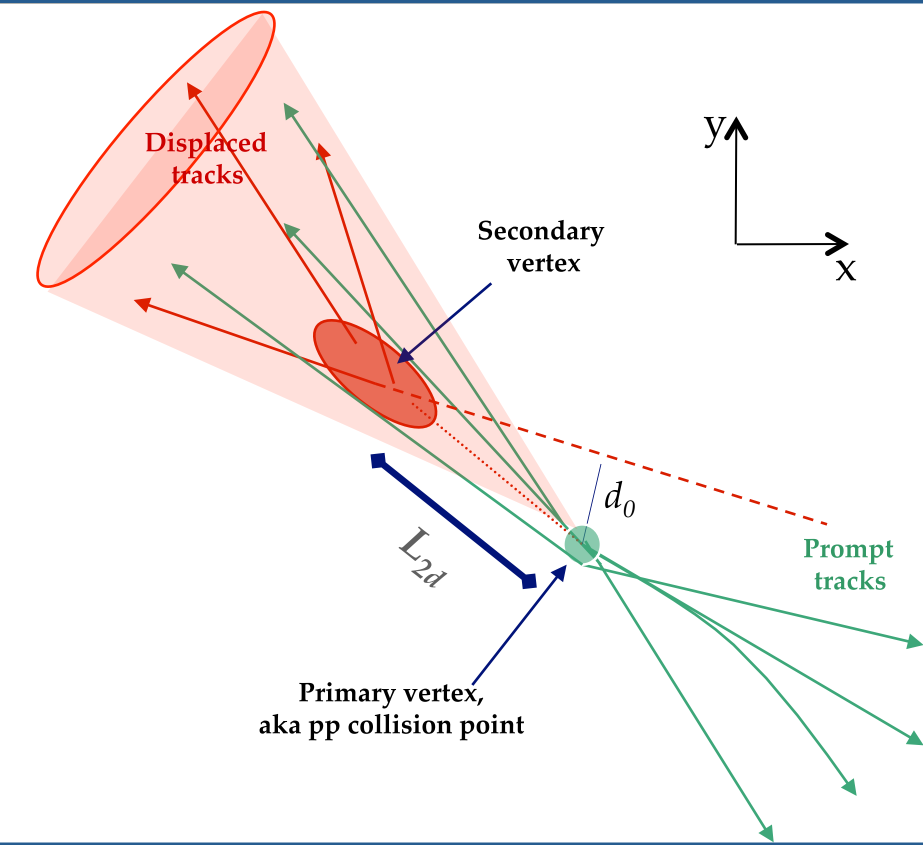
UVa PhD student John Wood

UVa Postdoc Sarah Boutle

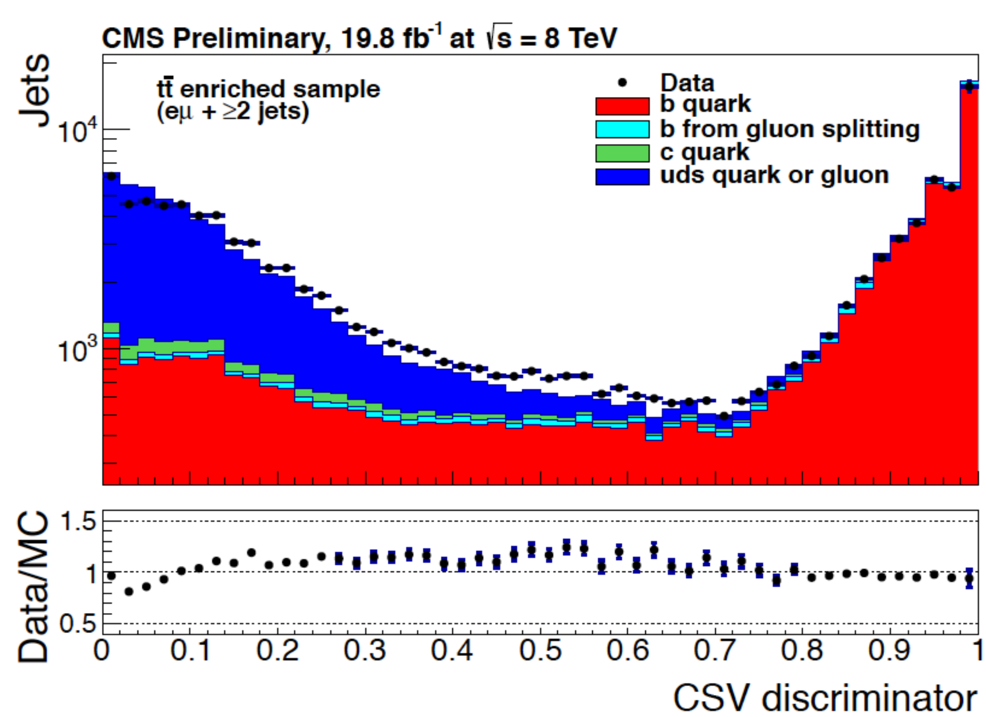
A $t\bar{t}H$ Candidate Event



Identifying b-Quark Jets at CMS

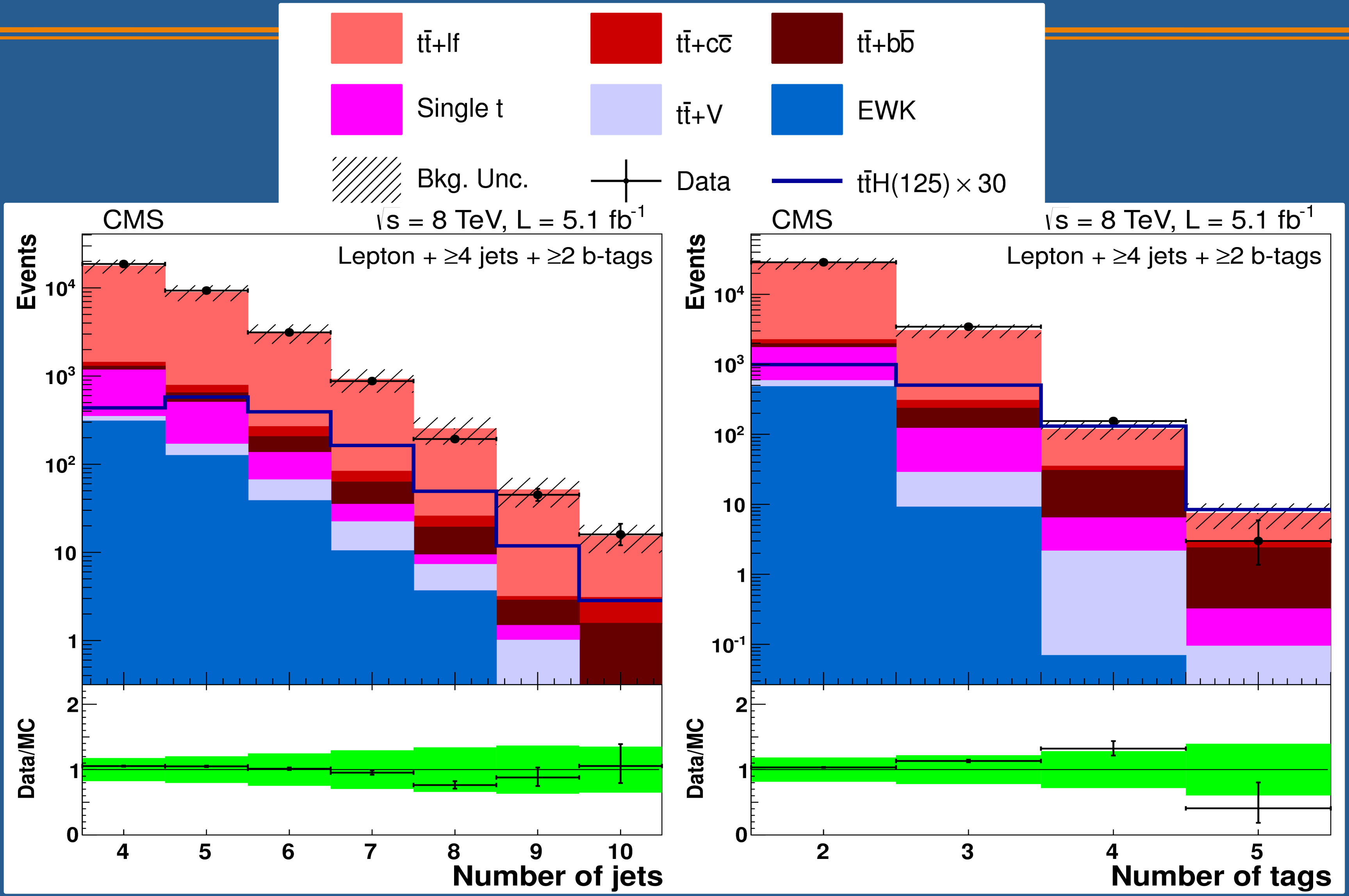


CMS-BTV-13-001



- Generally, the ttH process produces more b-quark jets than the dominant generic ttbar+gluon background
- Can exploit the long lifetime of the b quark to discriminate jets from b-quark production from jets from other sources
- CSV b-tagging discriminant:
  - Per-jet likelihood discriminant from different discriminating qualities of b-quark jets

tt̄H 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
$S/\sqrt{B}$	**0.19**	**0.10**	**0.20**	**0.27**	**0.13**	**0.23**	**0.31**

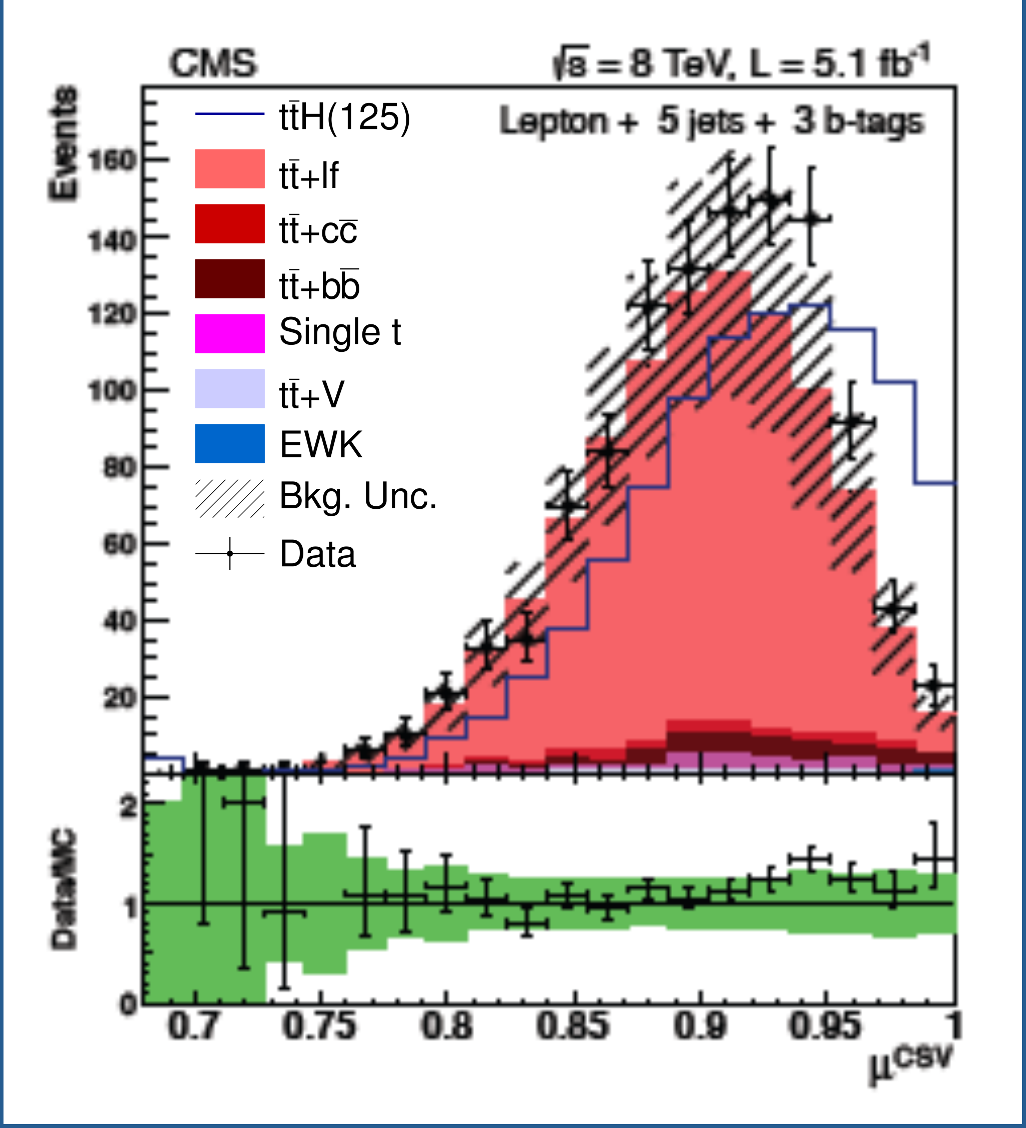
- Sample composition predictions from simulation
- Different $S/\sqrt{B}$ in each jet-tag category
- Largest background in every category: tt+jets, specifically tt+light flavor jets (tt+LF)

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}									✓
$p_T(\ell, E_T^{miss}, \text{jets})$		★	✓		✓	✓		✓	✓
$M(\ell, E_T^{miss}, \text{jets})$	✓	✓		✓	✓		✓		
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

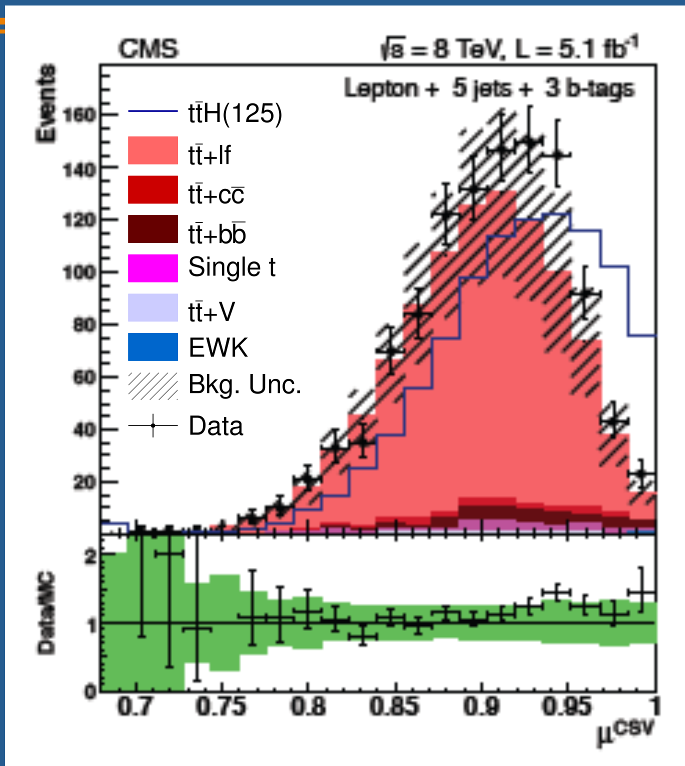
ttH Search at CMS: Most Powerful ANN Input for 5j3t



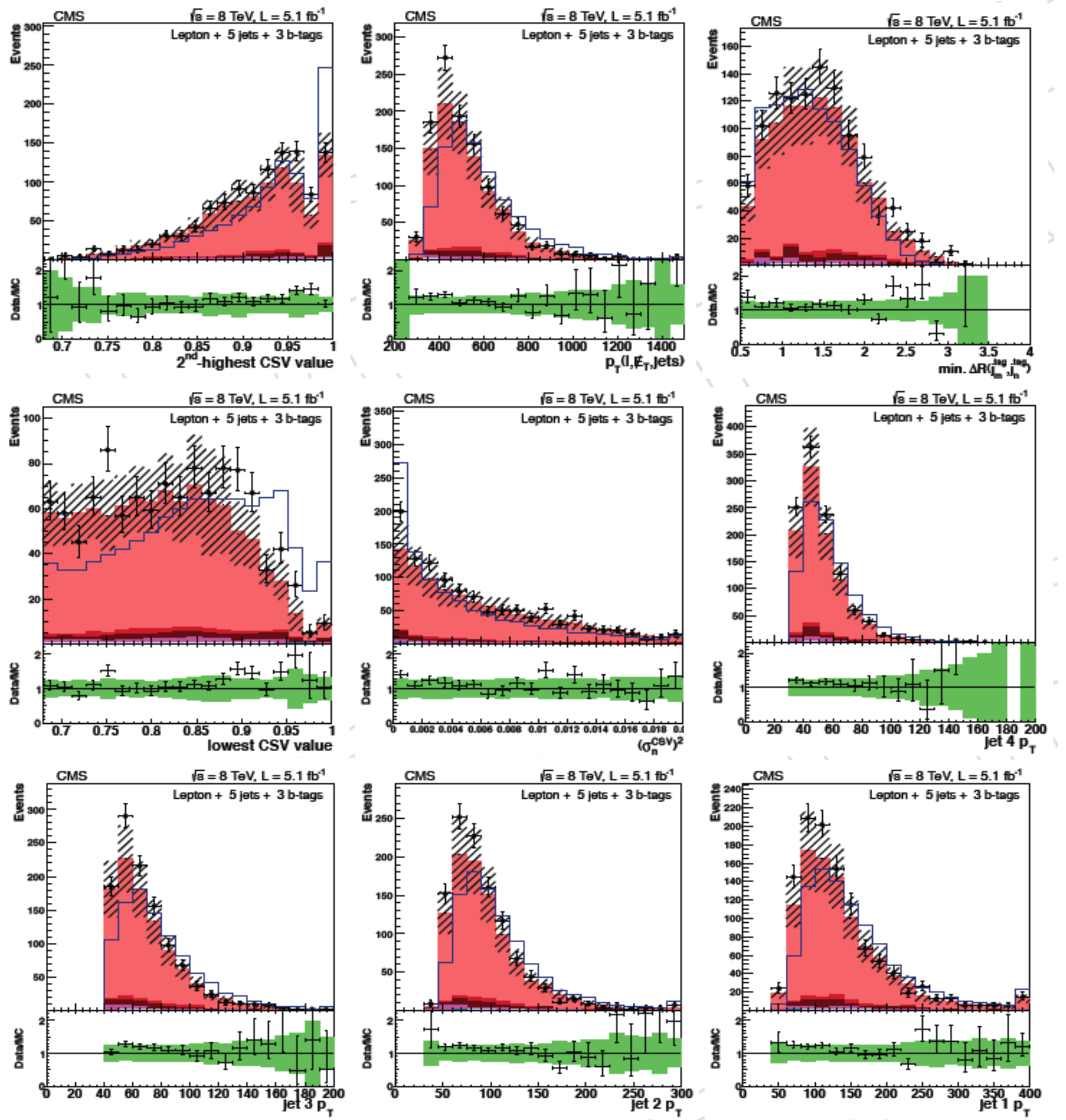
signal norm'd to bkgd

- Examine more closely the 5-jet, 3-tagged-jet category
  - Good compromise between sensitivity and statistics
- Most important inputs in this category:
  - jet- and event-level b-tagging variables
- Eg., the average CSV discriminant value among the 5 selected jets (μ^{CSV}):
  - Events with a large number of b-quark jets will favor higher values
  - Events with fewer b-quark jets will favor lower values

ttH Search at CMS: ANN Inputs for 5j3t



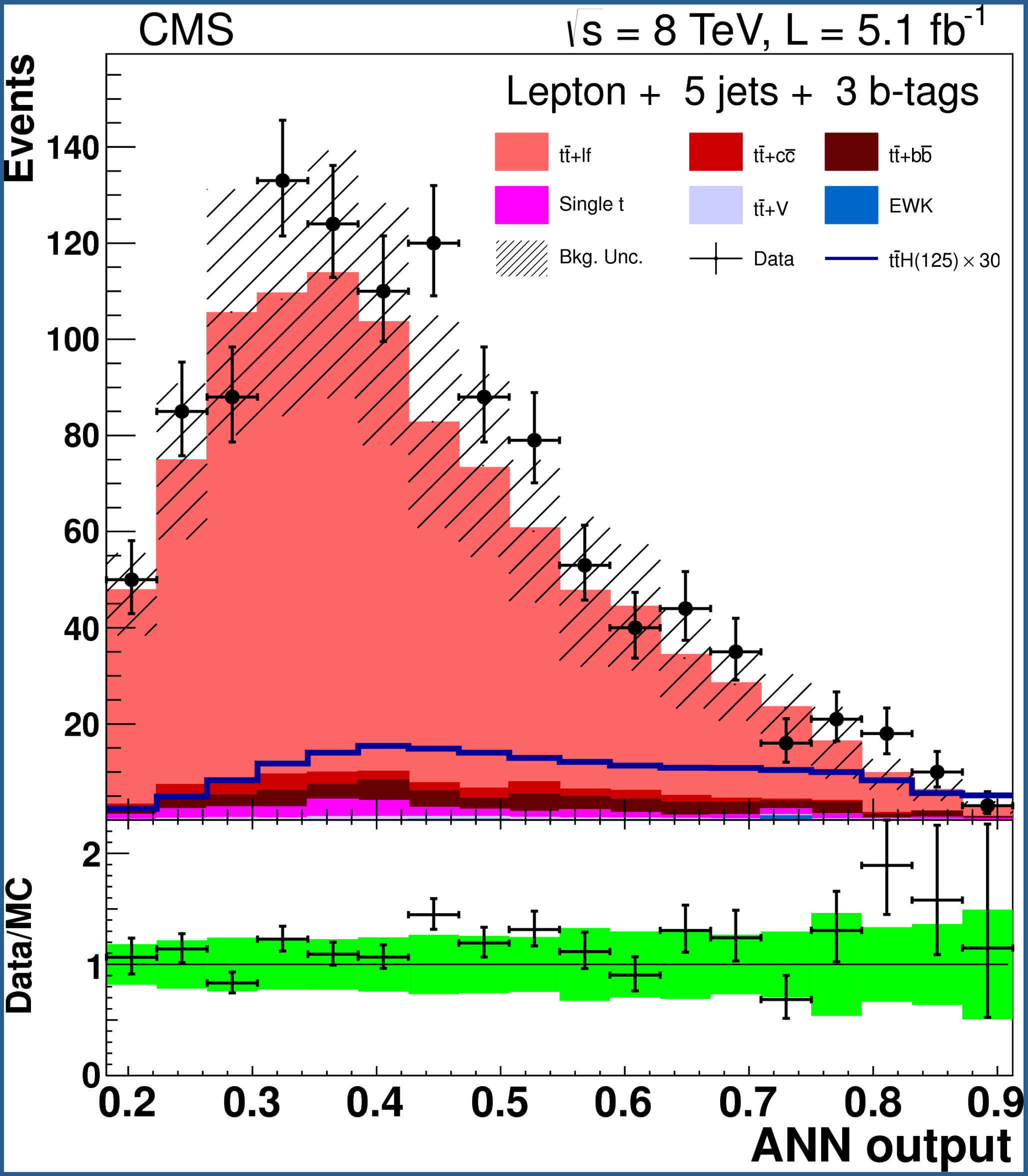
signal norm'd to bkgd



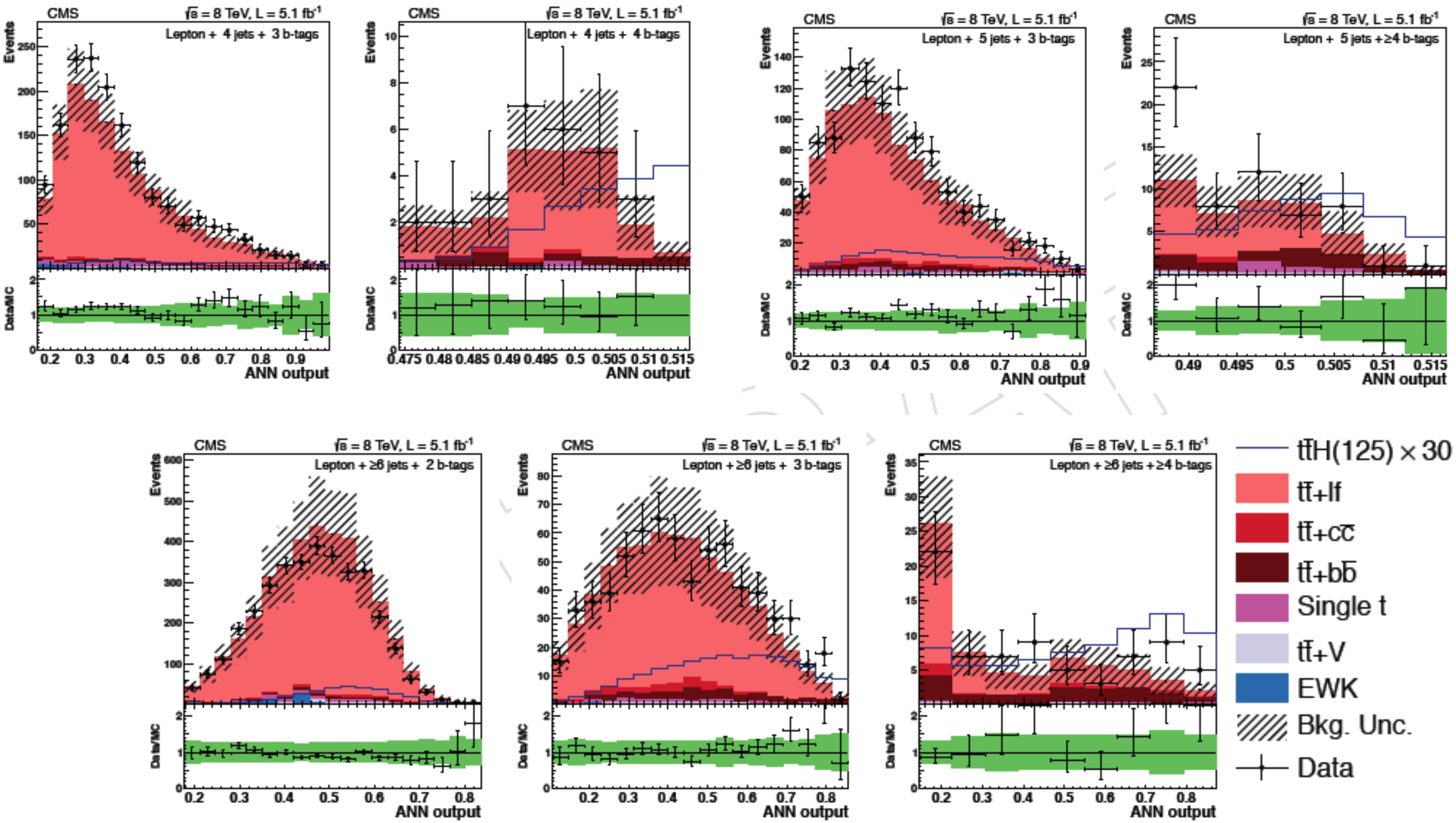
- Total of ten input variables used to train the ANN in each category

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 discriminating variable
  - output = 0 implies background-like,1 implies signal-like
- One 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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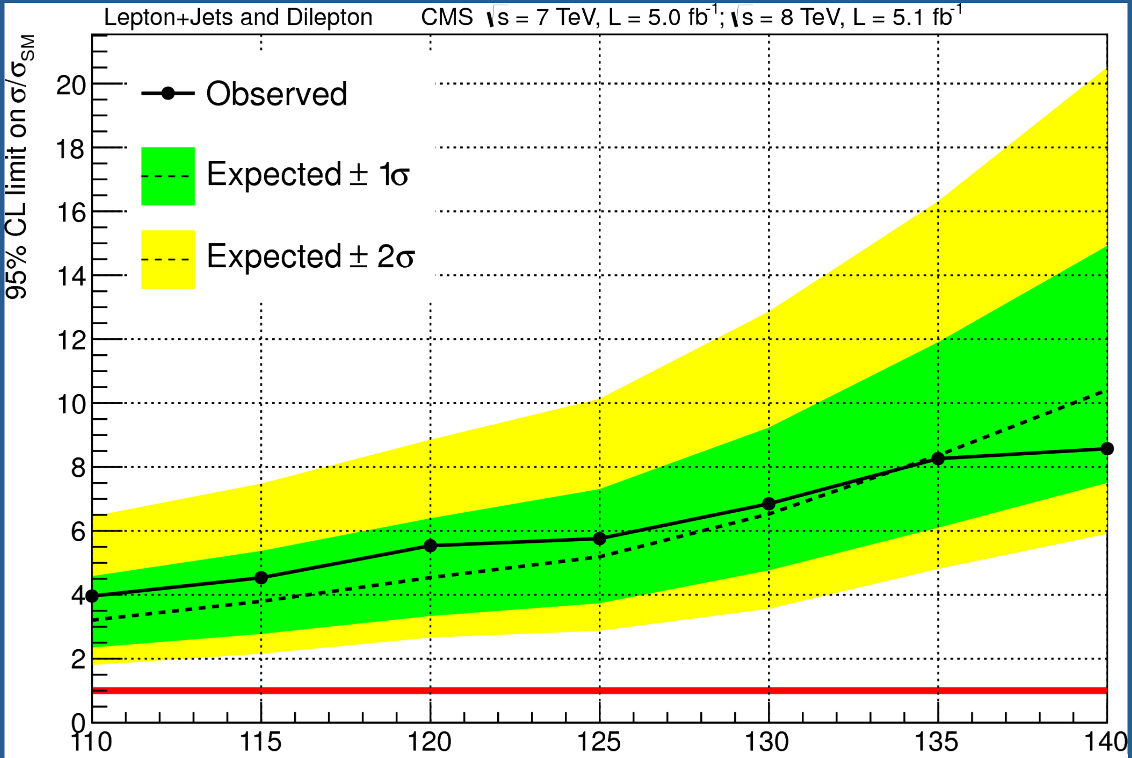
Madgraph Scale (V)	20–60%	No	Varies by jet bin.
$t\bar{t} + b\bar{b}$	50%	No	Only $t\bar{t} + b\bar{b}$.

Leading Experimental Uncertainties

Leading Theoretical Uncertainties

ttH Search at CMS: Upper Limit Results

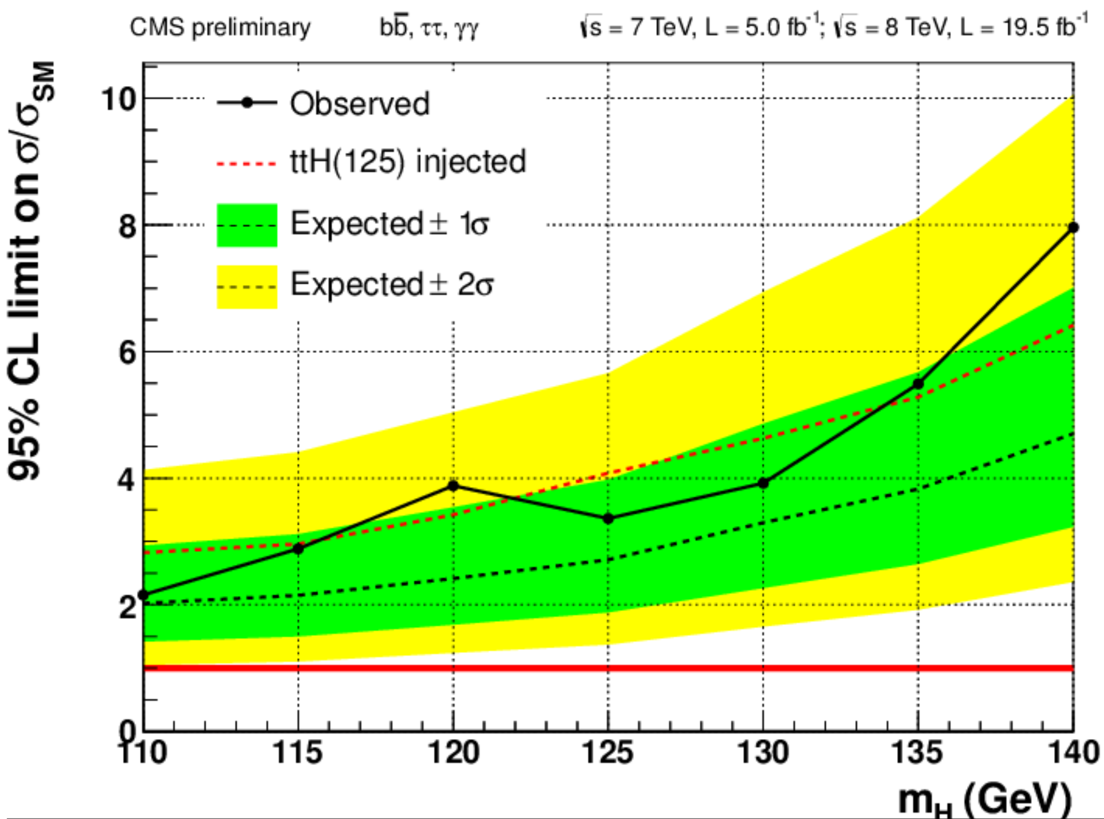


7 TeV + 8 TeV Lepton+Jets and Dilepton combined

m_H	Observed	Expected 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]

- Search for ttH at CMS has **not yet achieved sensitivity to expected SM level of production**
- **See no significant excess,** hence set an upper limit on the amount of ttH that the data contains
  - Observed (expected) upper limit M_H = 125 :
    $\sigma/\sigma_{SM} < 5.8\ (5.2)$
- This work described in Jour. HEP. 05, 145 (2013), the first published results on any ttH search at the LHC.

ttH Search at CMS: Full 2012 Sample Results



Higgs Mass	Observed	Expected Median	68% C.L. Range	95% C.L. Range
110 GeV/c^2	2.2	2.0	[1.4,2.9]	[1.0,4.1]
115 GeV/c^2	2.9	2.1	[1.5,3.1]	[1.1,4.4]
120 GeV/c^2	3.9	2.4	[1.7,3.5]	[1.2,5.0]
125 GeV/c^2	3.4	2.7	[1.9,4.0]	[1.4,5.7]
130 GeV/c^2	3.9	3.3	[2.3,4.9]	[1.7,6.9]
135 GeV/c^2	5.5	3.8	[2.6,5.7]	[1.9,8.1]
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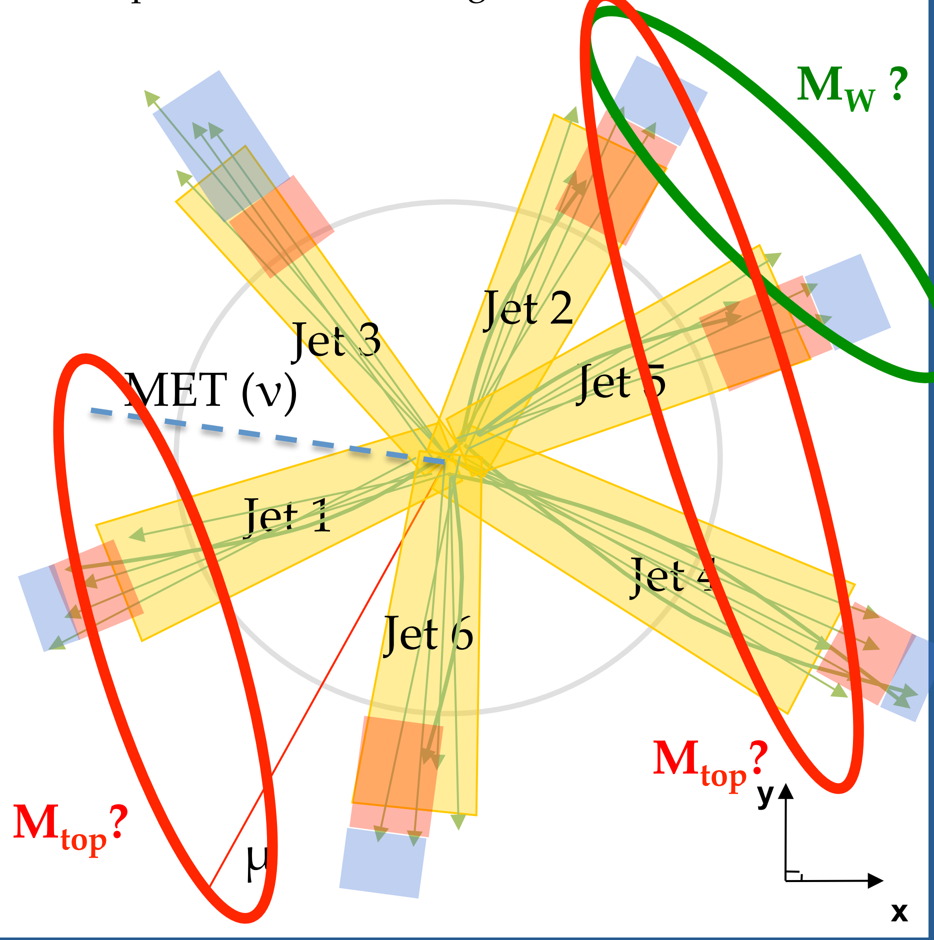
- Analysis described herein exploits only first 5/fb of 2012 CMS data
- Analysis of complete 2012 sample completed with new features:
  - Improved signal extraction technique
  - New signal discriminating variables
  - Improved b-tagging discriminant
  - Added H→γγ, ττ channels
- Small, statistically insignificant excess
- Improvement in upper limit
- Publication in preparation

ttH Search at CMS: Next Steps

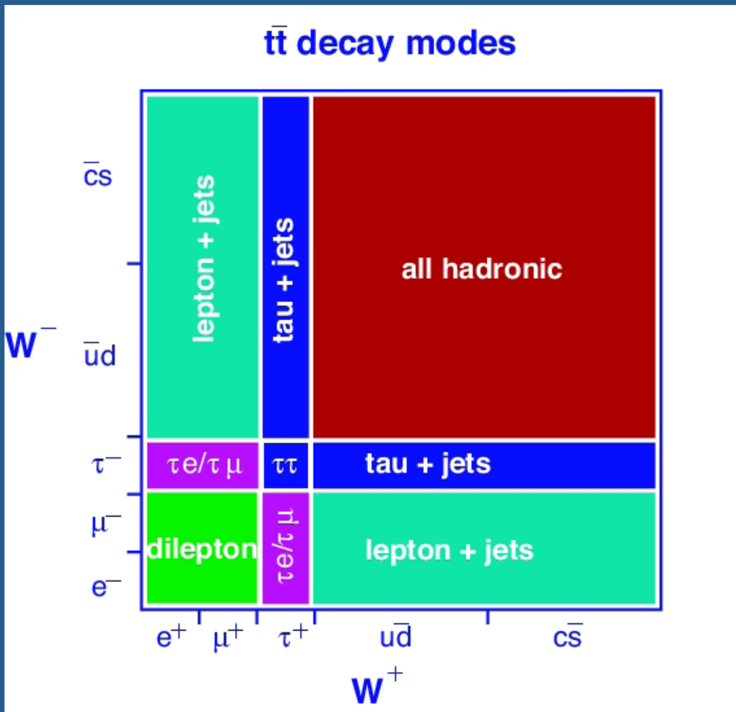
- These results are not the end of the story!
- There is opportunity for optimization of the signal extraction technique in the LJ channel
  - So many final state objects
  - Do they pair together to corroborate the hypothesis of top-quark pair production in the event?
    - Kinematic fitting
    - Re-optimized discriminant design
  - Subject of John Wood's thesis project

Concept of kinematic fitting:



If you can identify the objects from the top quarks, the remaining objecrts have distinct features in ttH production.

ttH Search at CMS: Next Steps

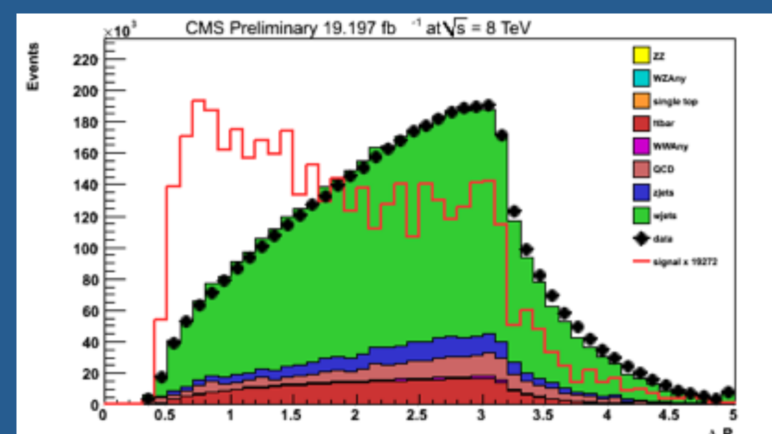


- **New ttbar channel:**
  - All-hadronic ttbar mode:
    - largest component of ttbar decays!
    - As yet not pursued in ttH at CMS
  - Extremely technically challenging
    - Overwhelming amount of hadronic jet backgrounds
  - Research project of undergraduate student Catherine Jones
  - Expect results in next 6 months

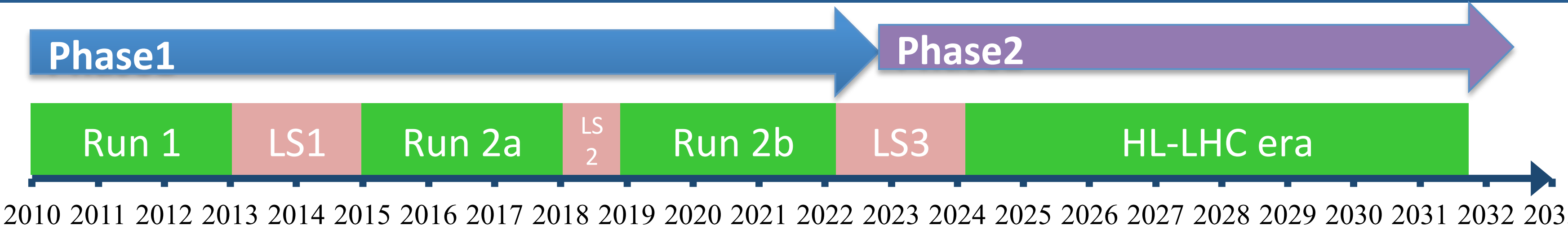
UVa Undergrad
Catherine Jones

- **New Higgs decay to consider:**
  - Look for H → WW → lvjj in ttH events
  - Search for this decay in ggF is subject of Joey Goodell's Ph.D. thesis project
  - Synthesize ideas from that analysis for use in ttH

UVa PhD student
Joey Goodell



ttH Search at CMS: The Next LHC Run



- Currently the LHC is in shutdown and upgrade mode
- Collisions resume in 2015
  - $\sqrt{s}$ = 13 or 14 TeV
  - L_{inst} = 1E34 $cm^{-2}s^{-1}$
    - Significant increase in beam energies, moderate increase in instantaneous luminosity
  - 50/fb recorded per year
  - All new conditions in which to execute measurements and searches
  - ttH: essential aspect of physics program in Run 2 at the LHC – **UVa will play a major role!**

Ultimate Characterization of the Higgs

Characteristic
Electric Charge 0
Spin 0
Parity +
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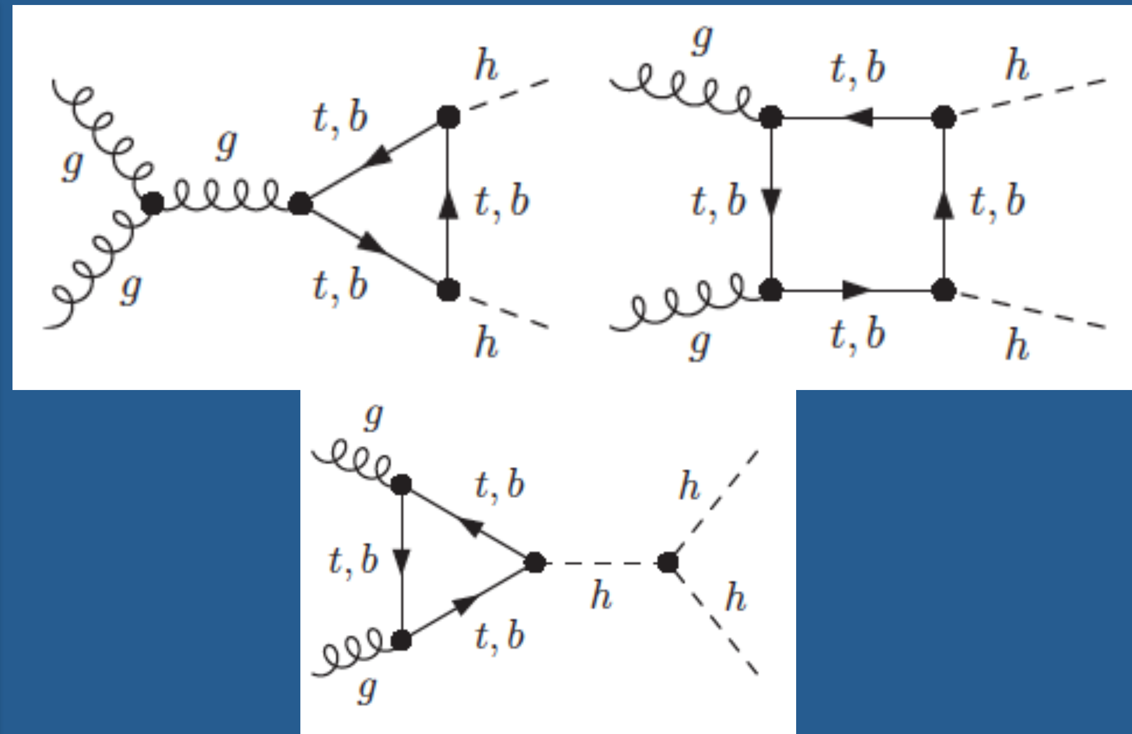
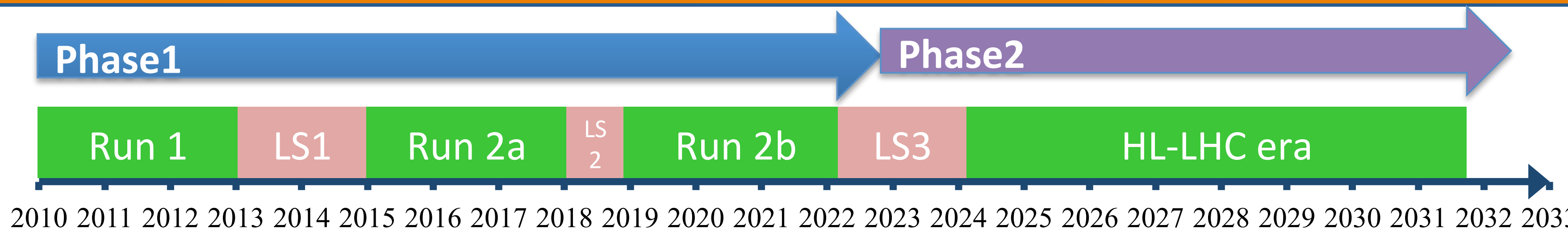
http://arxiv.org/pdf/1206.5001v2.pdf

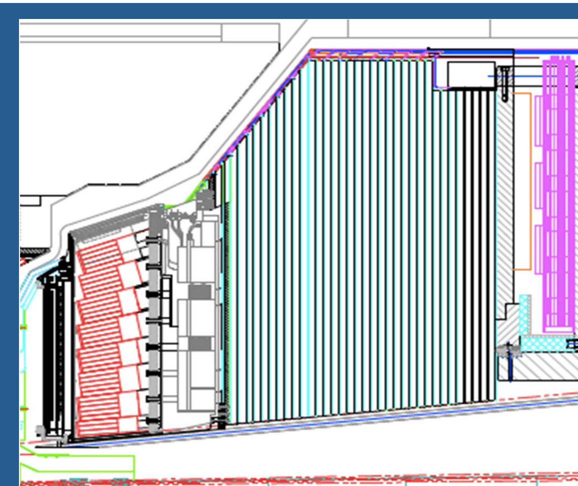


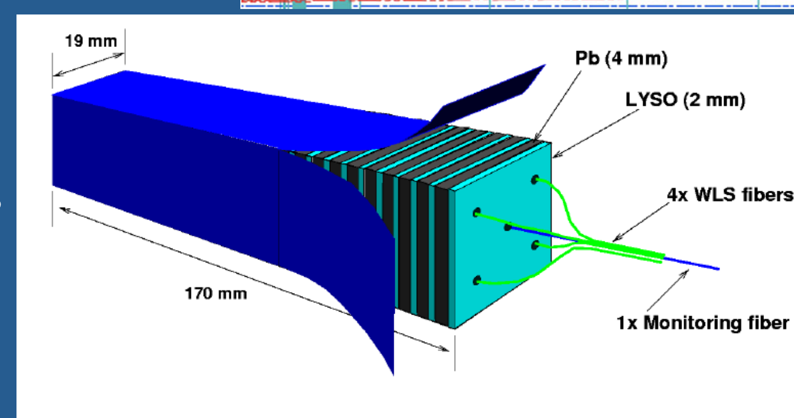
- Very low production cross section for Higgs pair production
- Need significant increase in integrated luminosity:
  - **High-luminosity LHC era**

Ultimate Characterization: Self-Coupling

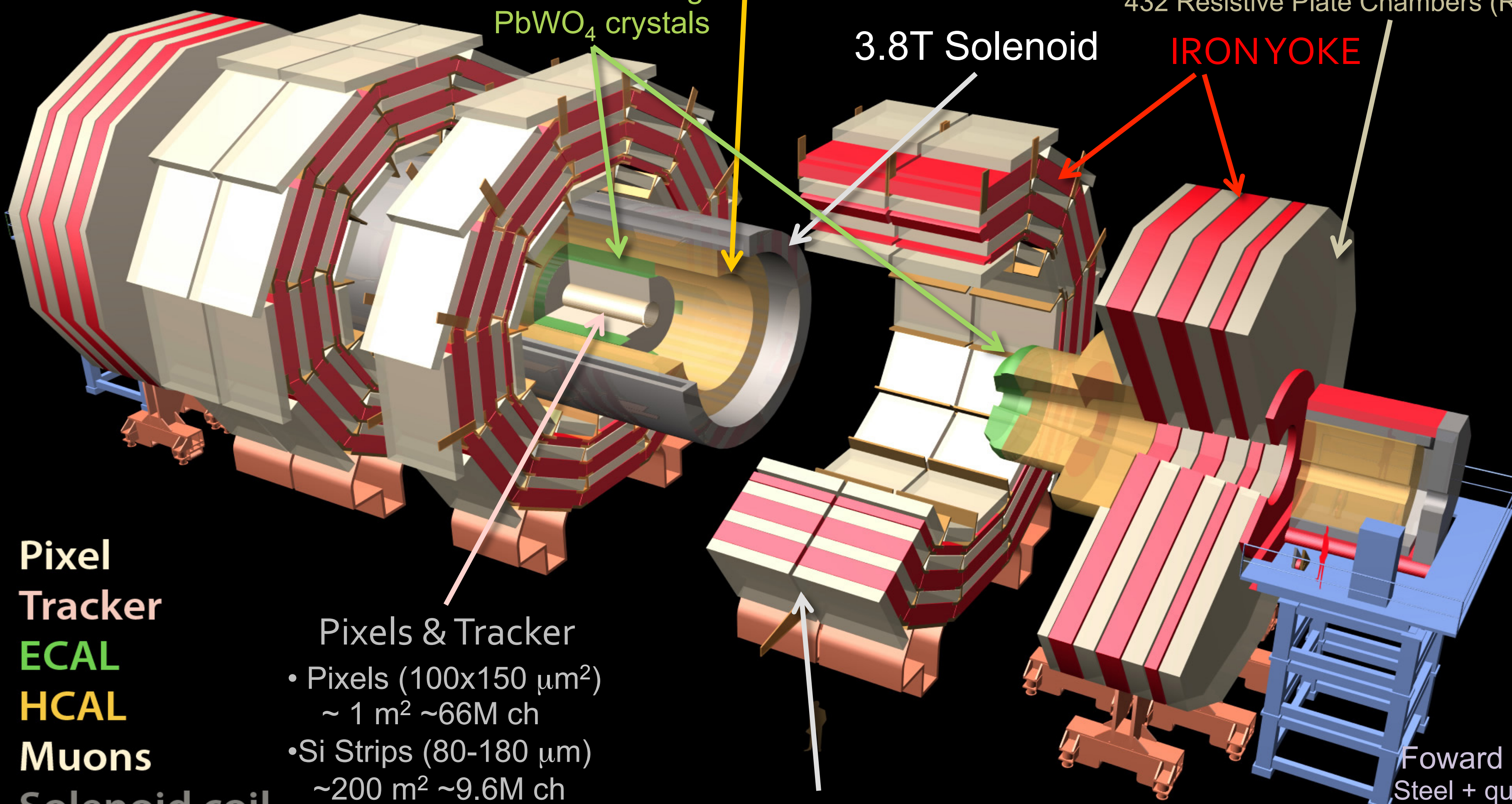


- HL-LHC era:
  - $L_{inst} = 5E34\ cm^{-2}s^{-1}$
  - 250/fb recorded per year
  - 140 pp interactions per beam crossing
- Phase II upgrade:
  - Harsh radiation environment means replacements for many CMS components will be necessary, esp. close to beamline
- UVa role in 2013-14 and beyond:
  - Radiation-tolerant Ga-based photodetectors
  - Simulations of calorimetry upgrade options
  - Test beam exposures to prototypes



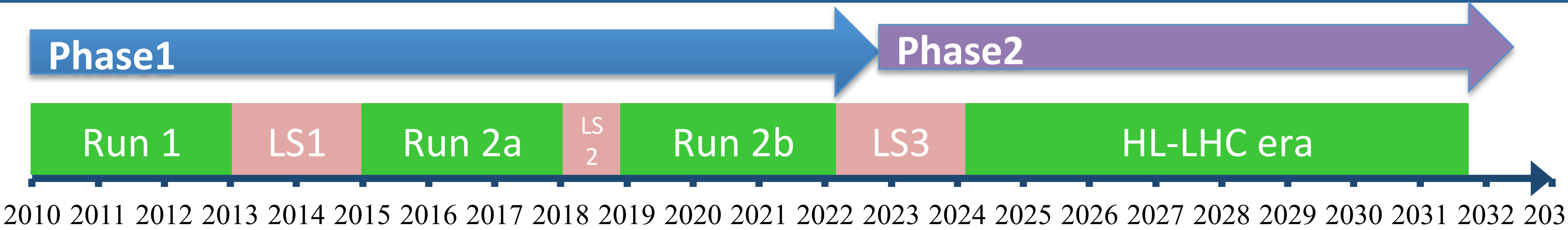


The CMS Detector



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

Ultimate Characterization: Self-Coupling



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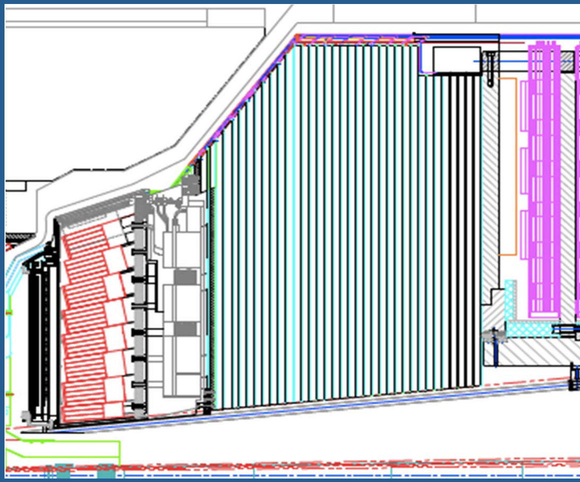
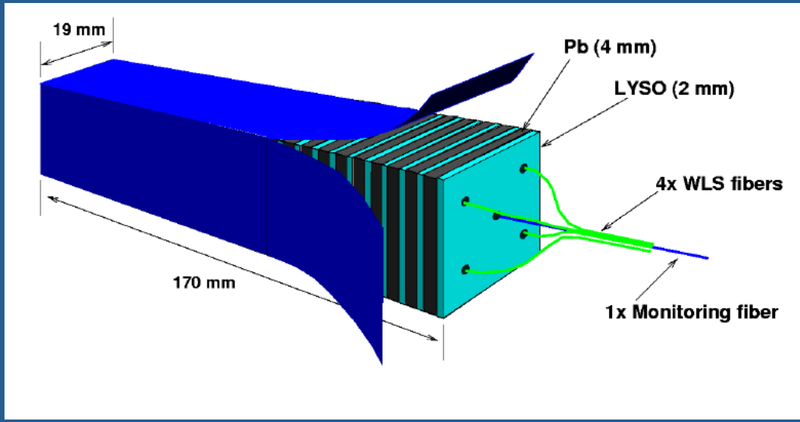


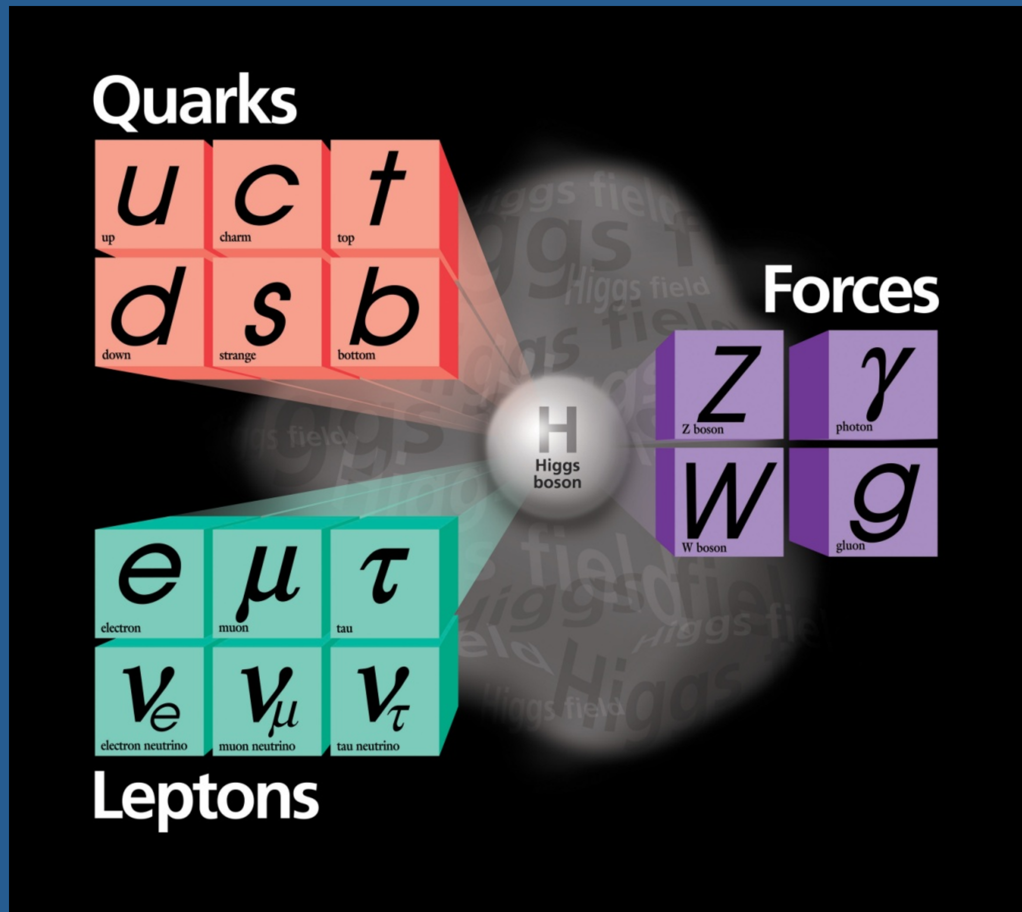


Summary

- 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 fundamental fermions
- 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 proceeding rapidly. Not yet achieving SM sensitivity – but with more data, improved analysis techniques and improvements in our modeling, we will get there.
- This channel will be essential in characterizing this new particle – and UVa will be playing a leading role.

Backup

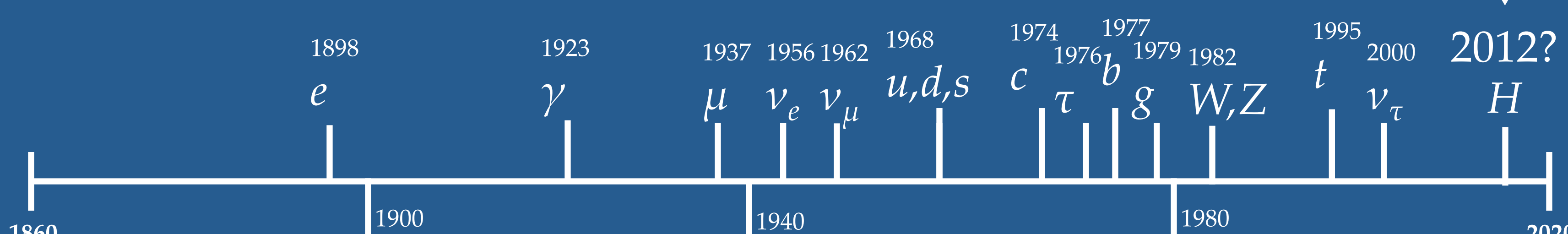
The History of Discoveries



One remaining piece to complete the puzzle

H:

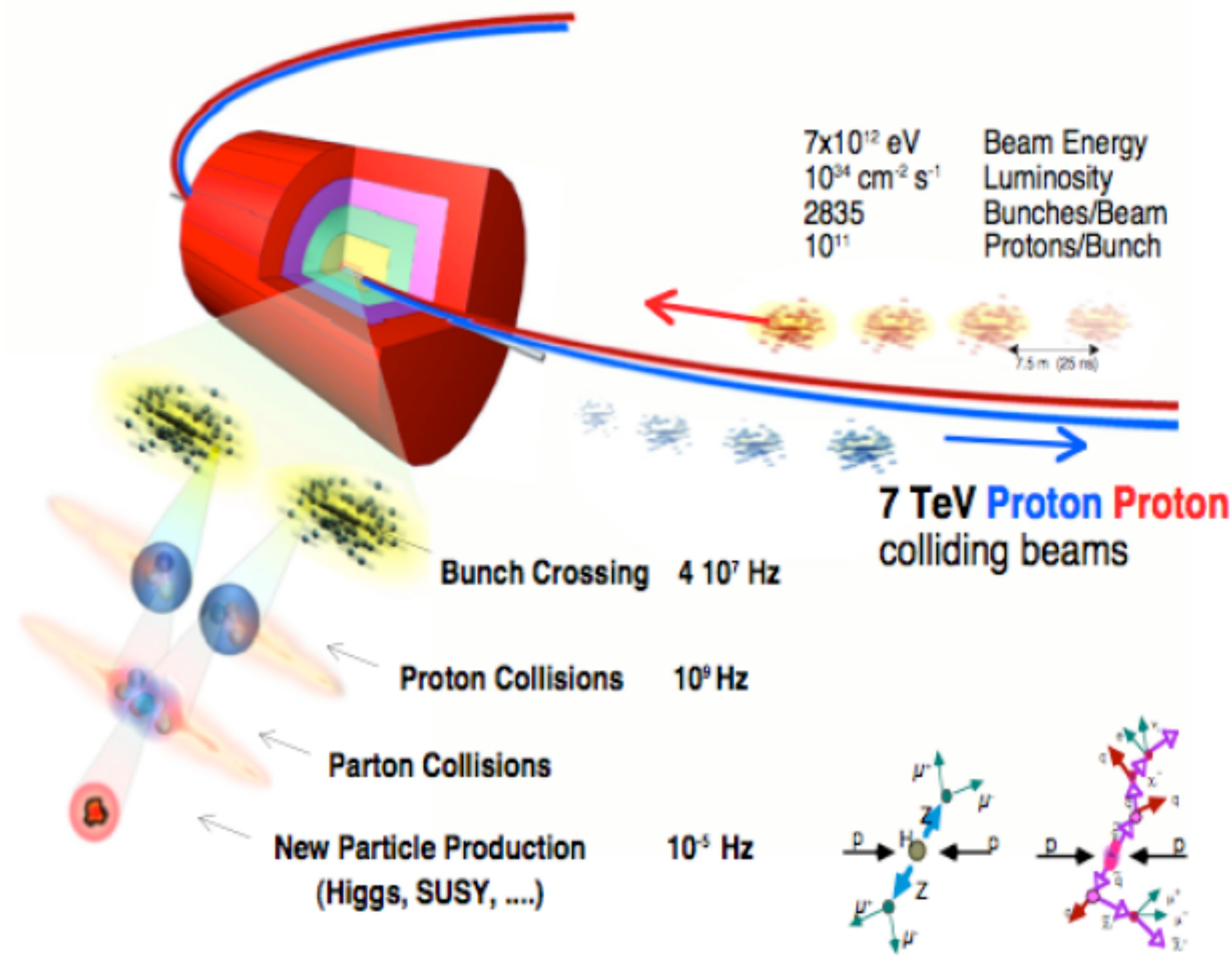
the Higgs boson -- the last piece of the standard model.



It's a Very Nice Picture, But…

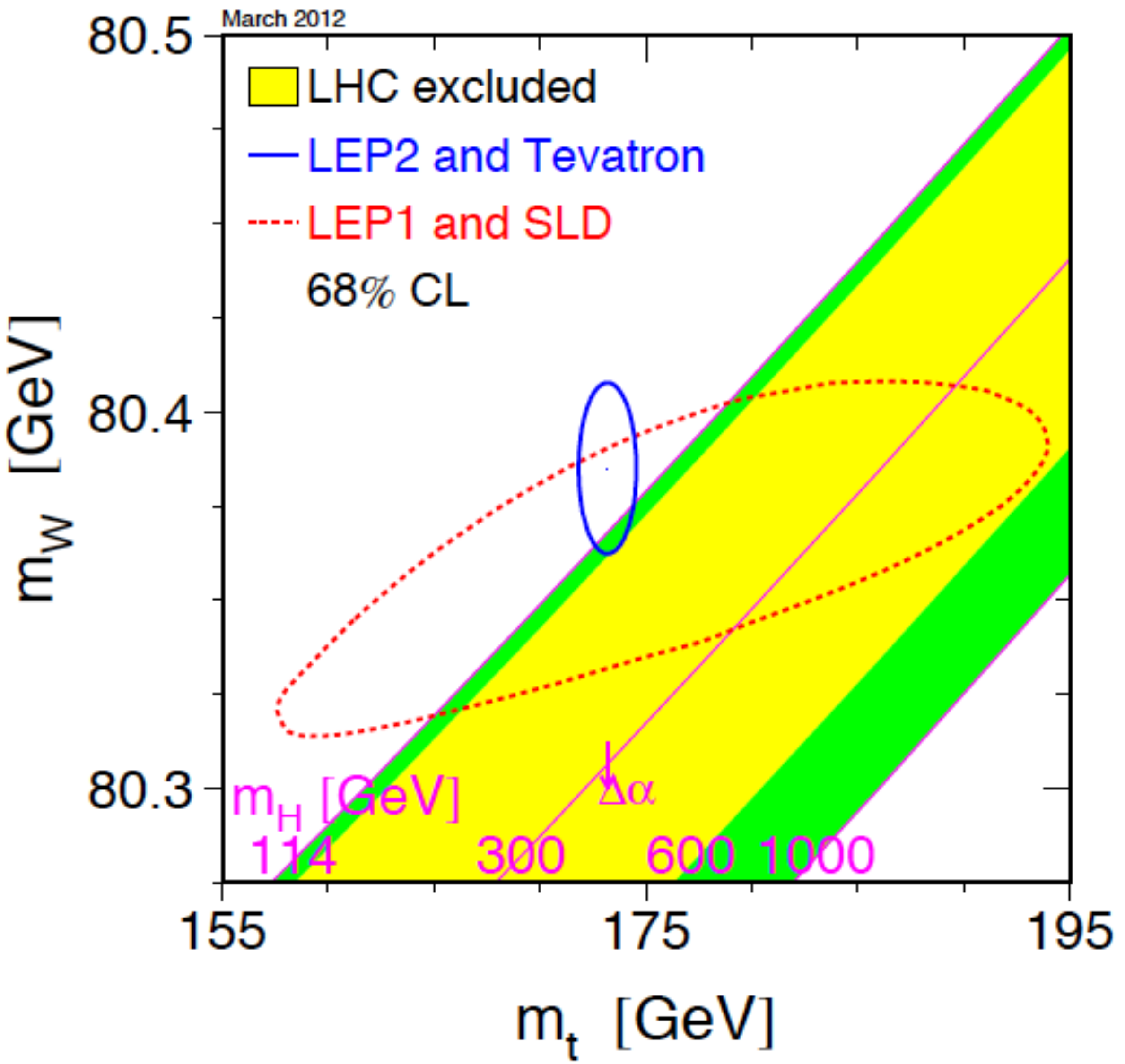
- The model has some gaping holes and open questions:
  - Already observed phenomena that the standard-model cannot explain
  - Mathematics of the model work out perfectly well when assuming the masses of the fundamental particles are all zero – which is manifestly not the case.
  - Large corrections expected in perturbation theory 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*.
  - The SM offers no preference for matter over antimatter – why does matter clearly dominate?
  - Three out of four interactions isn't bad – but what about gravity?

Colliding Beam Experiment

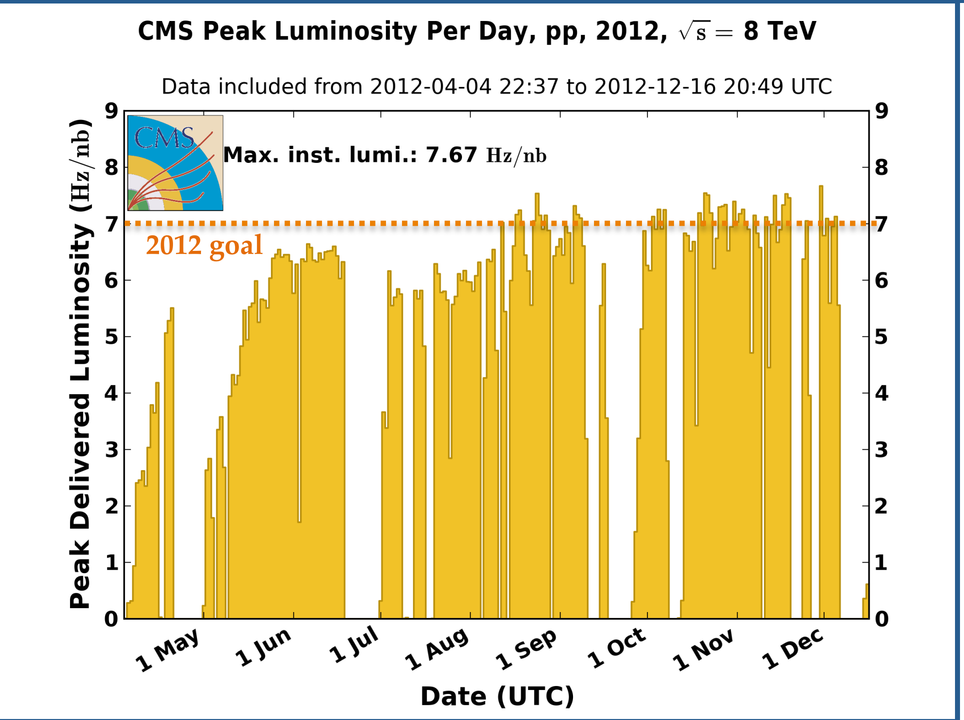


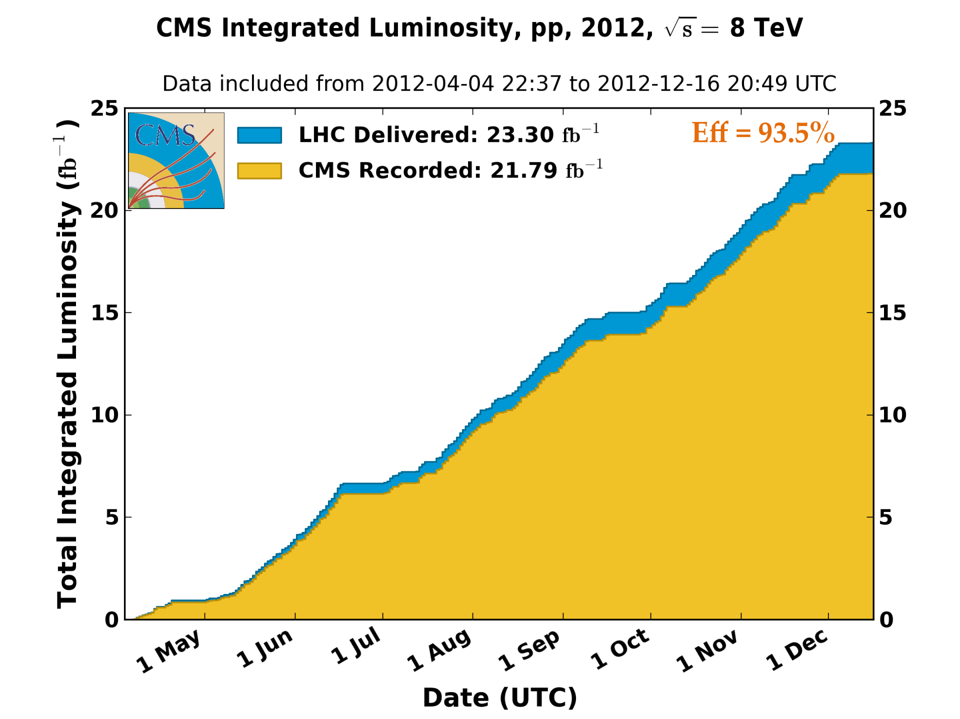
Selection of 1 event in 10,000,000,000,000 (the rest are less interesting)

Higgs and Top



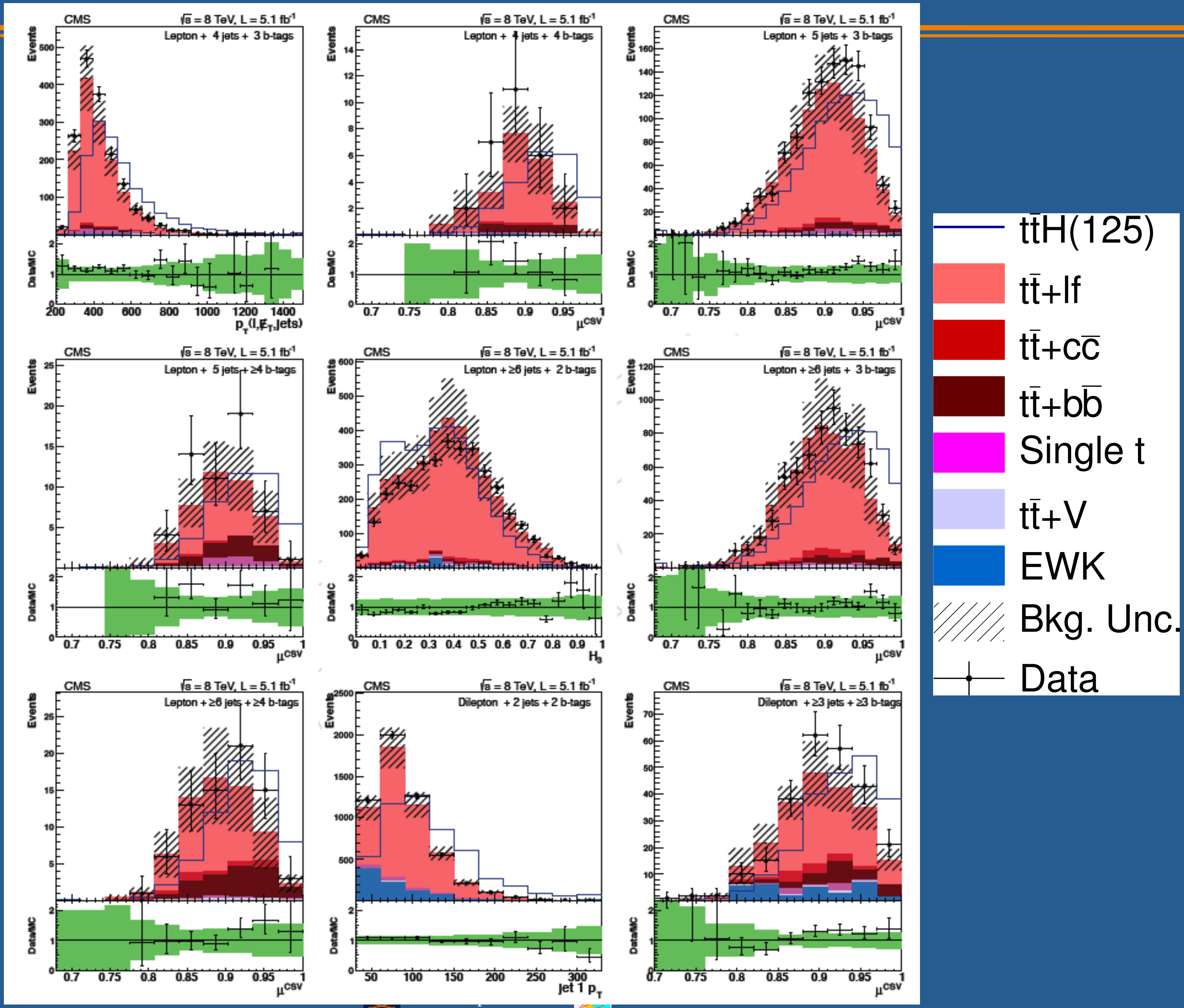
Higgs Search Depends on LHC Performance



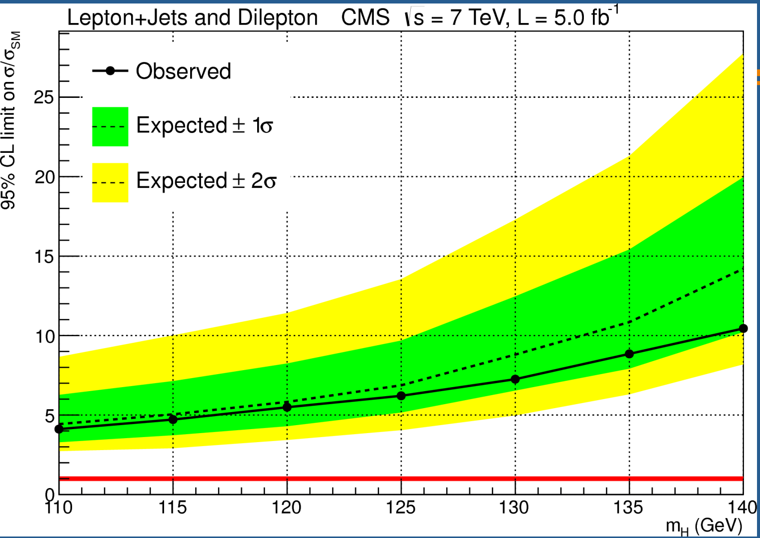


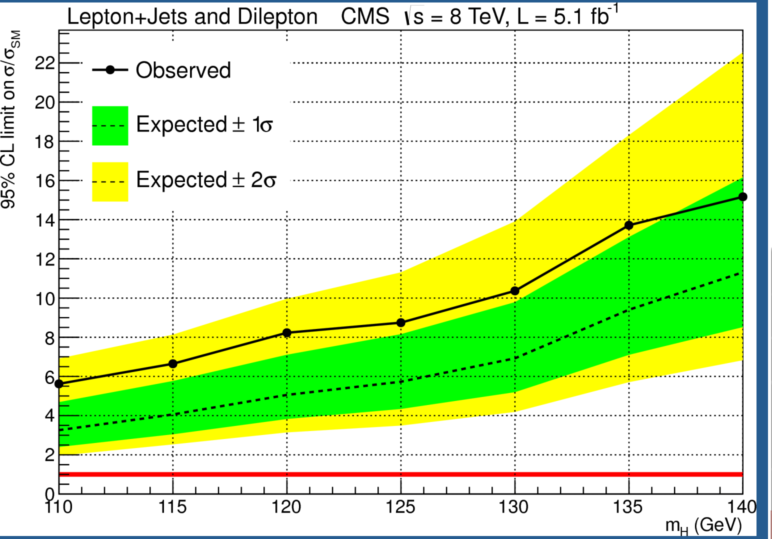
- Incredible performance of LHC in 2012:
  - Instantaneous luminosity goal of 7E33/cm^{2}s achieved in August
  - Higgs discovery only possible with stable and reliable LHC running
- LHC in 2013 is in shutdown + upgrade mode
  - More on this later in the talk

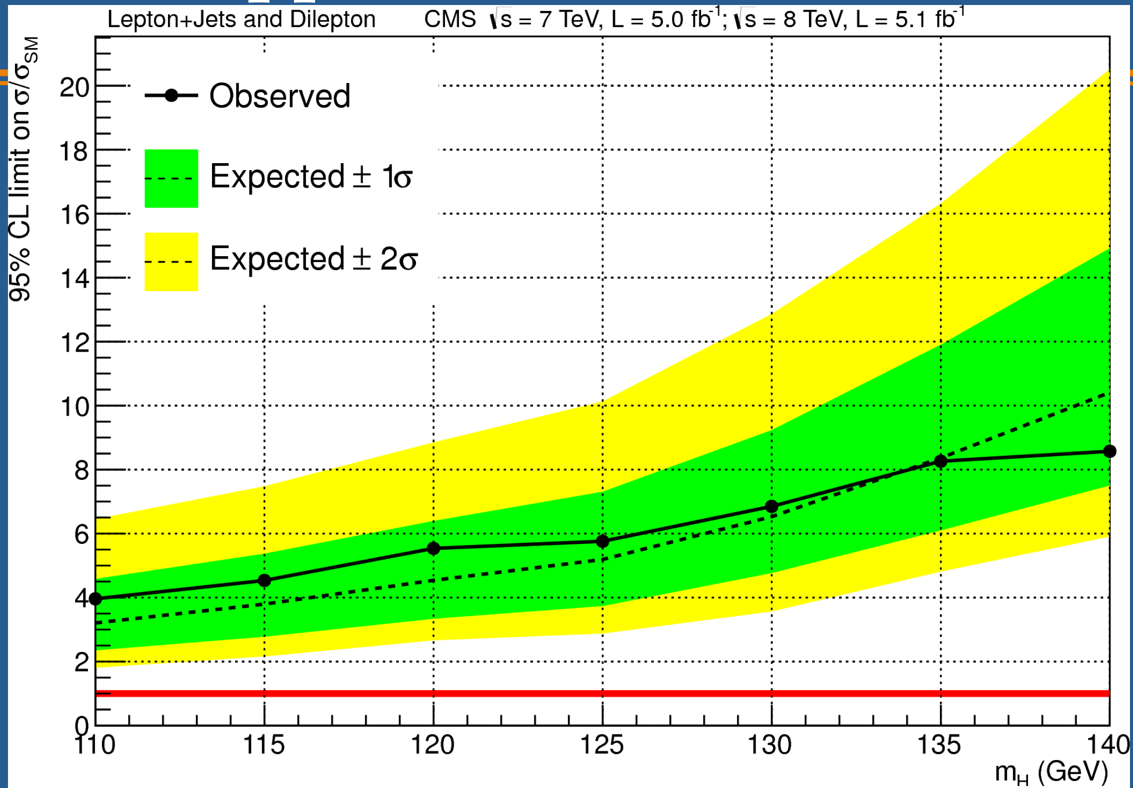
t̄tH Search at CMS: Best ANN Inputs per Category



ttH Search at CMS: Upper Limit Results







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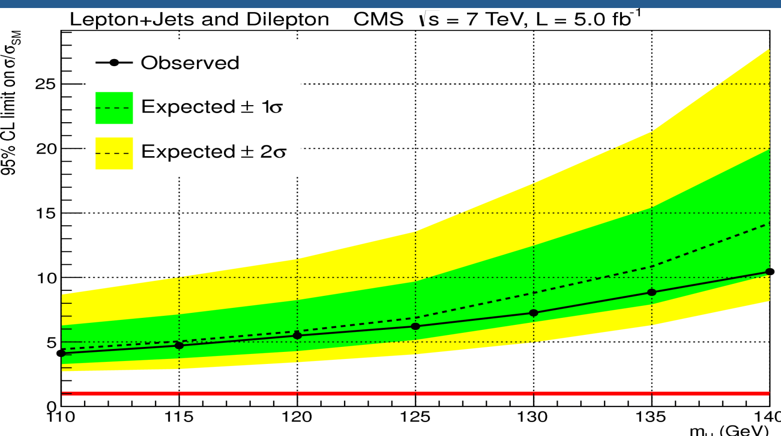
Combined 7+8 TeV result:

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

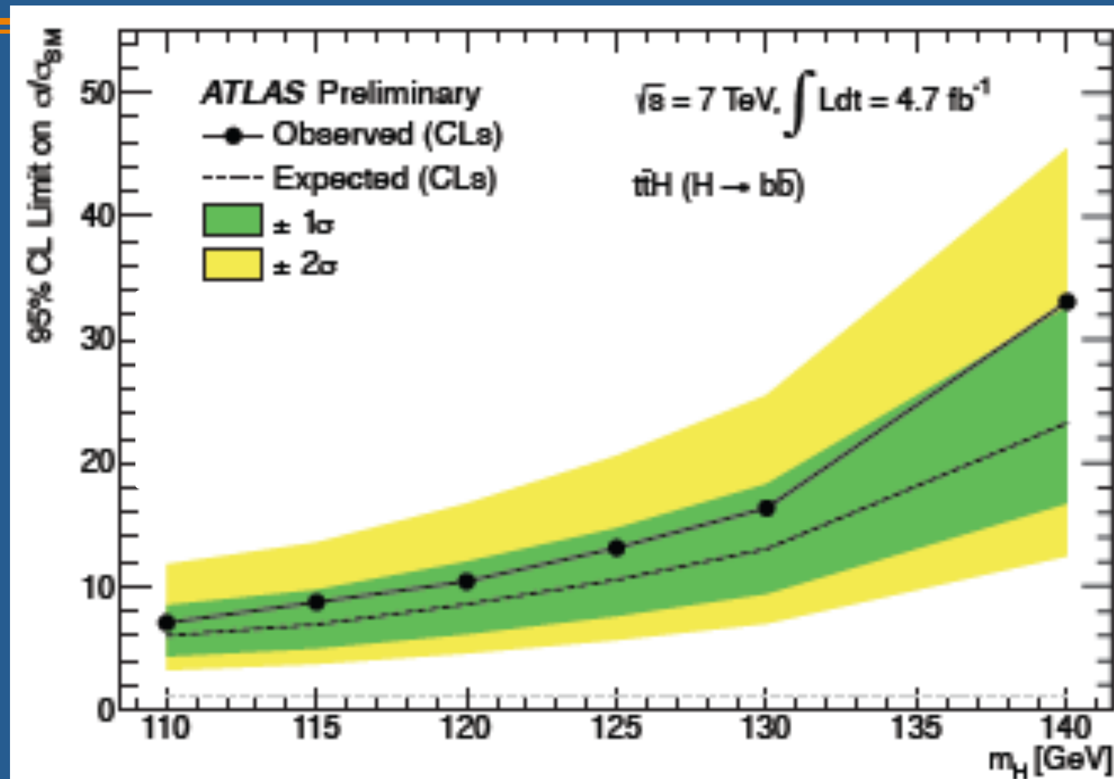
Comparison: CMS and ATLAS

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