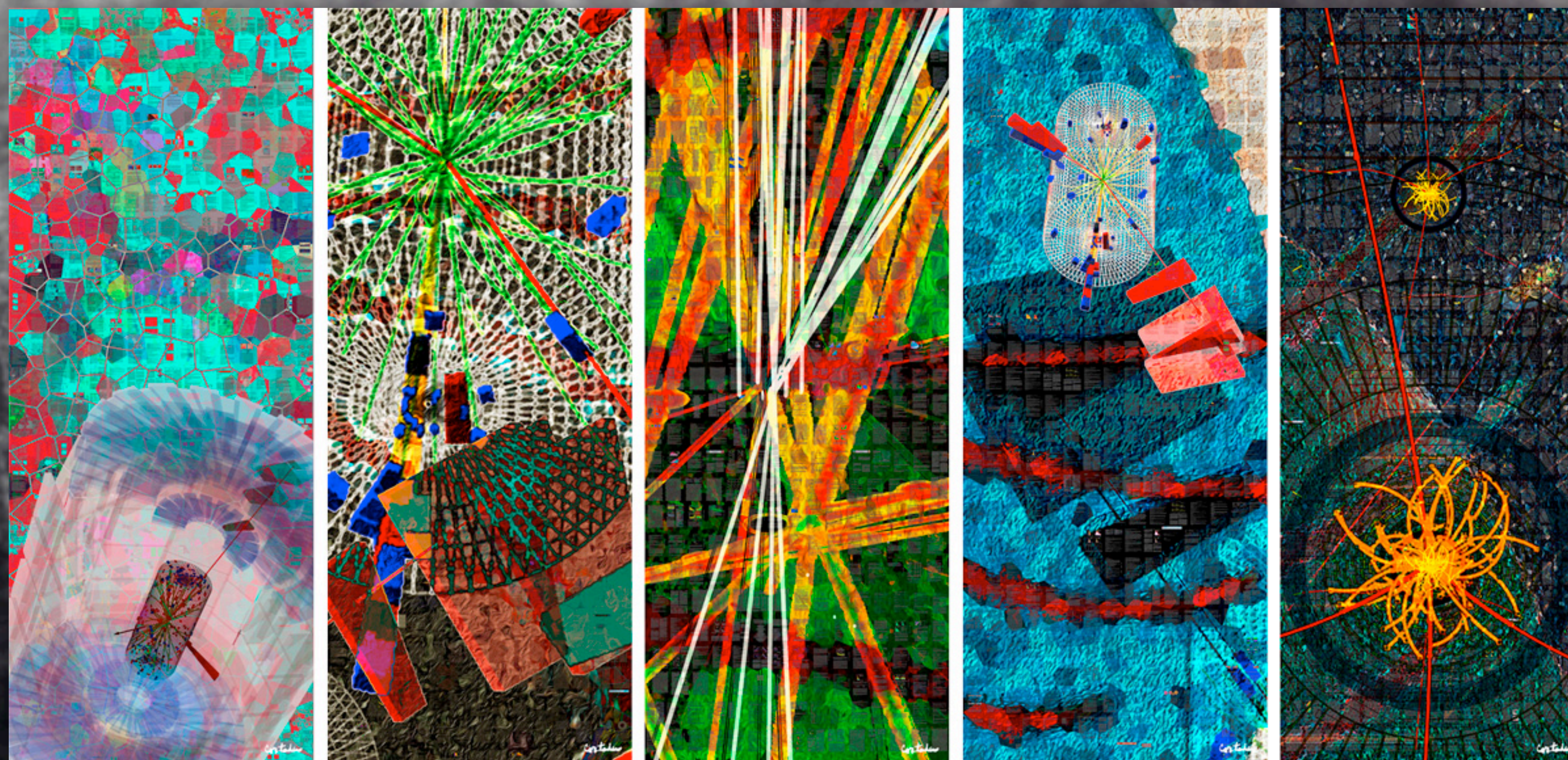
SM Higgs @ LHC

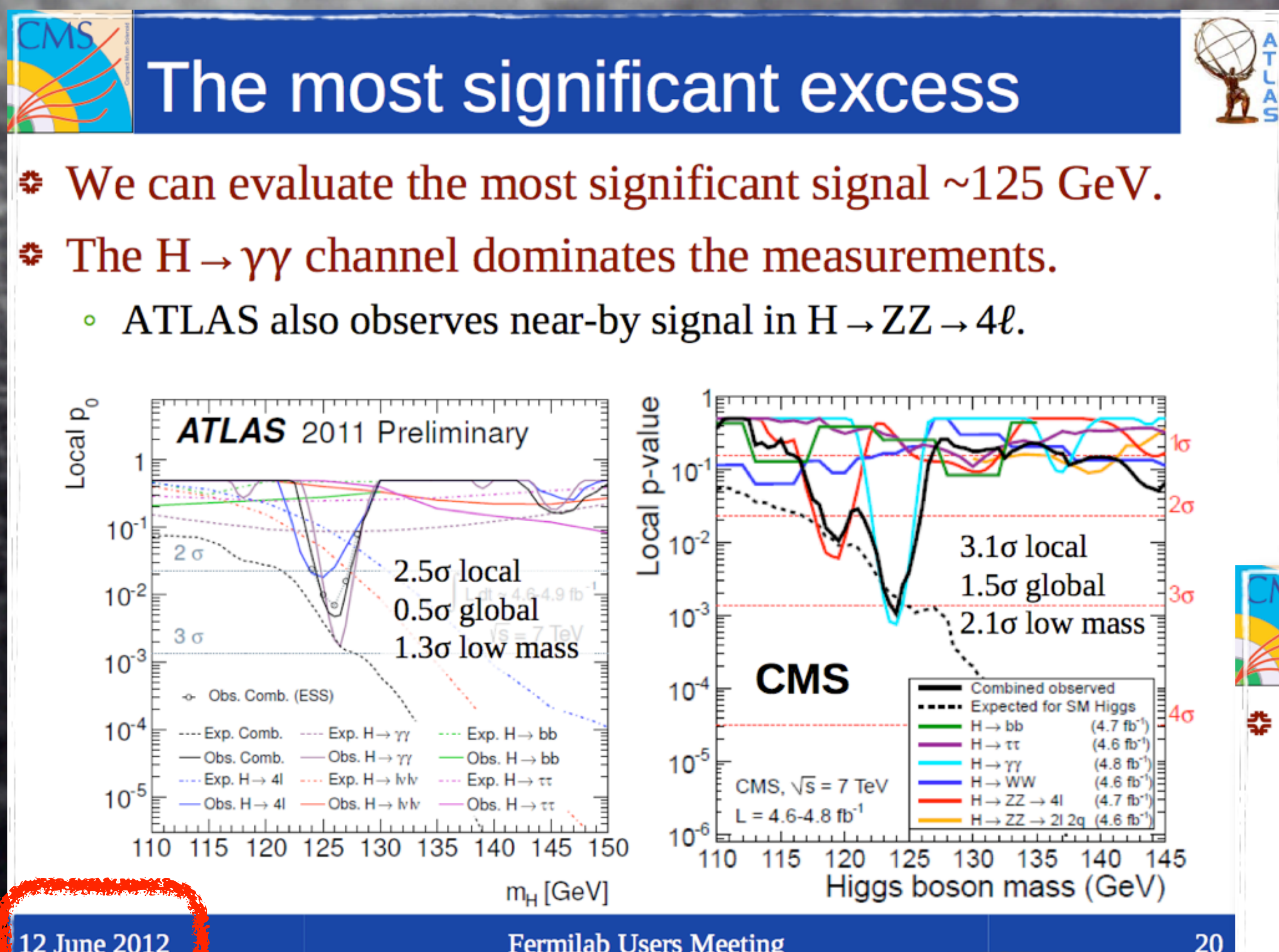


Xavier Cortada (with the participation of physicist Pete Markowitz)

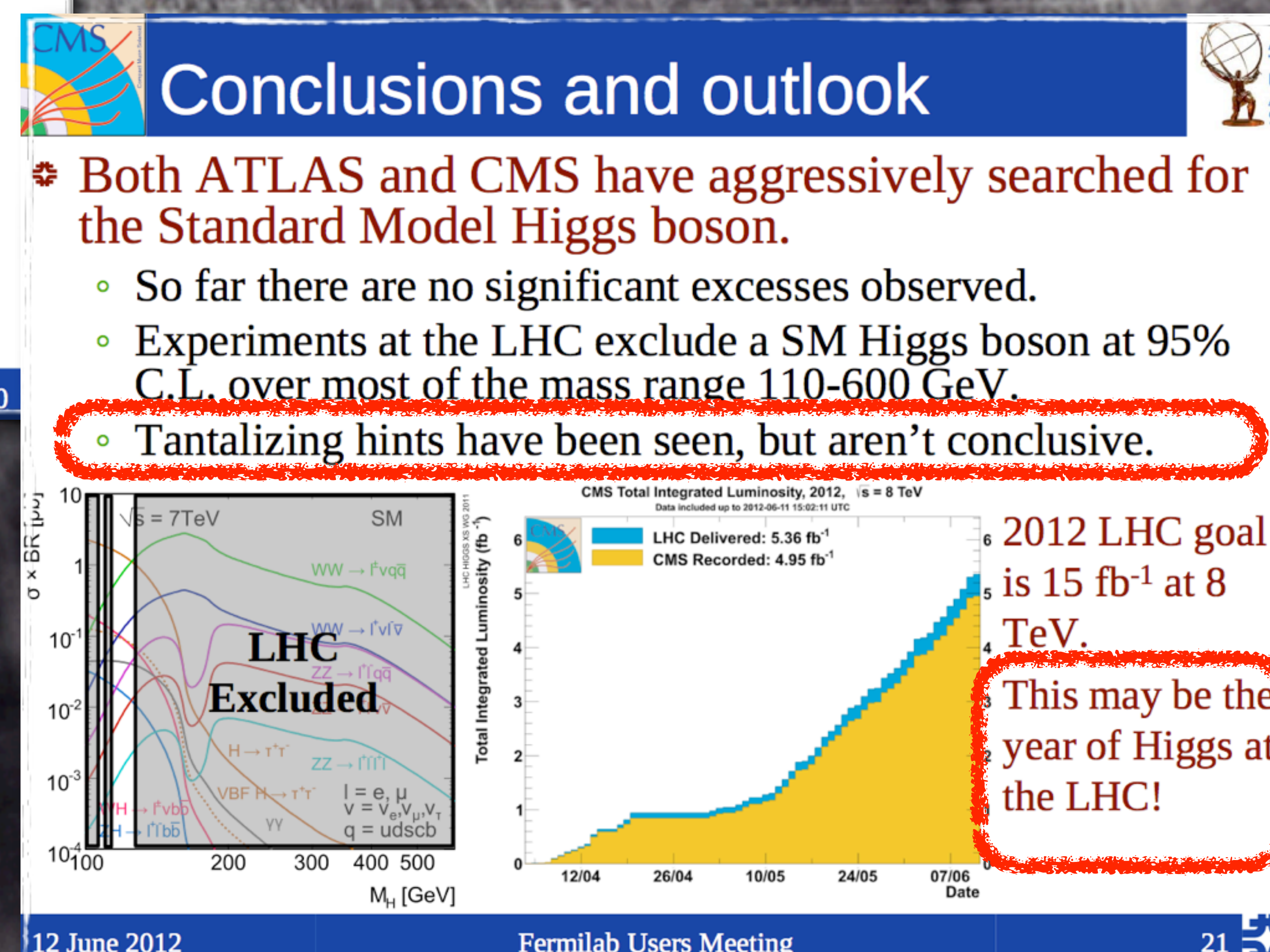
2013 Fermilab Users meeting

Jacobo Konigsberg
U. of Florida
6/12/13

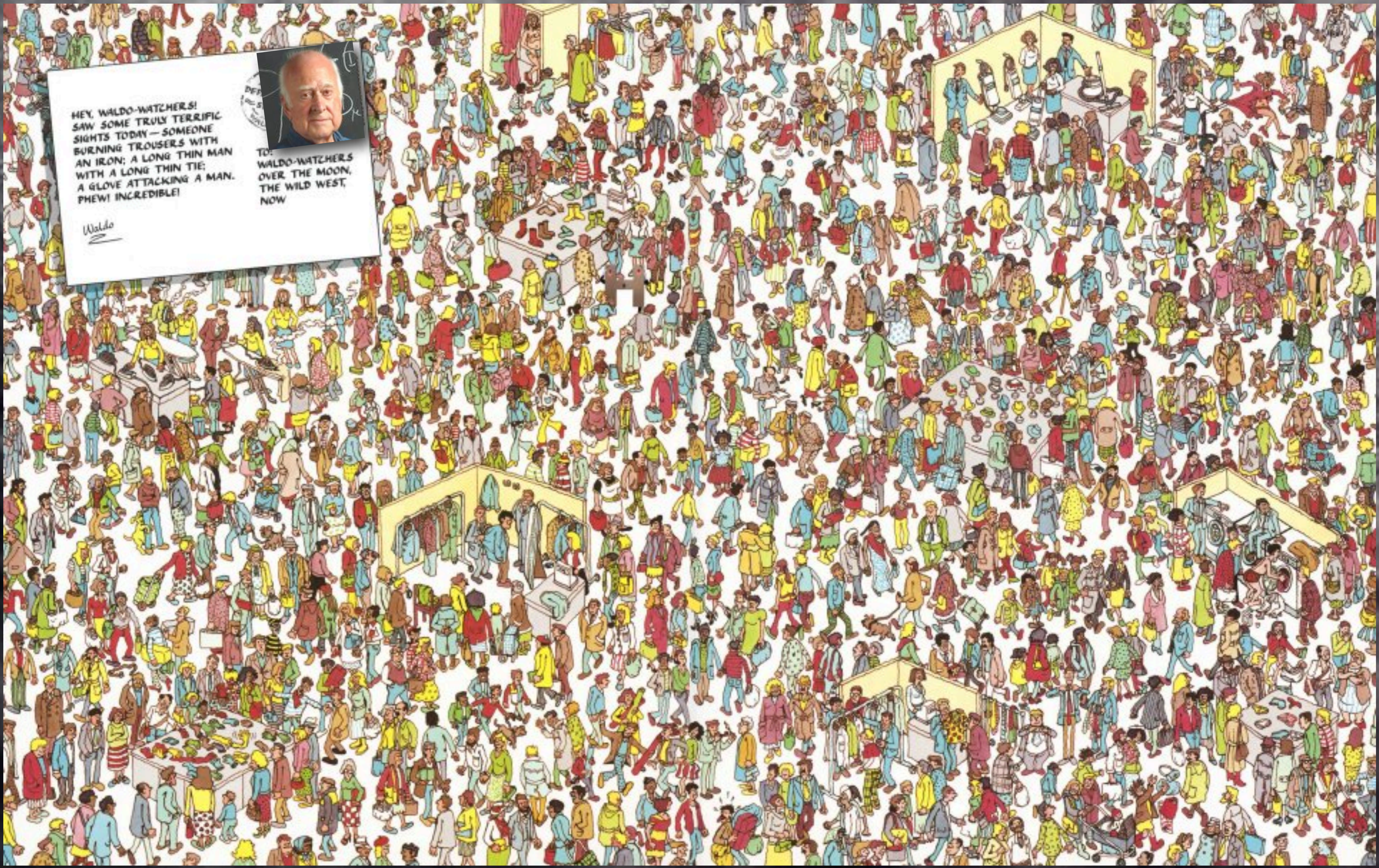
Exactly a year ago...



J. Anderson's talk
@ 2012 FNAL Users Meeting



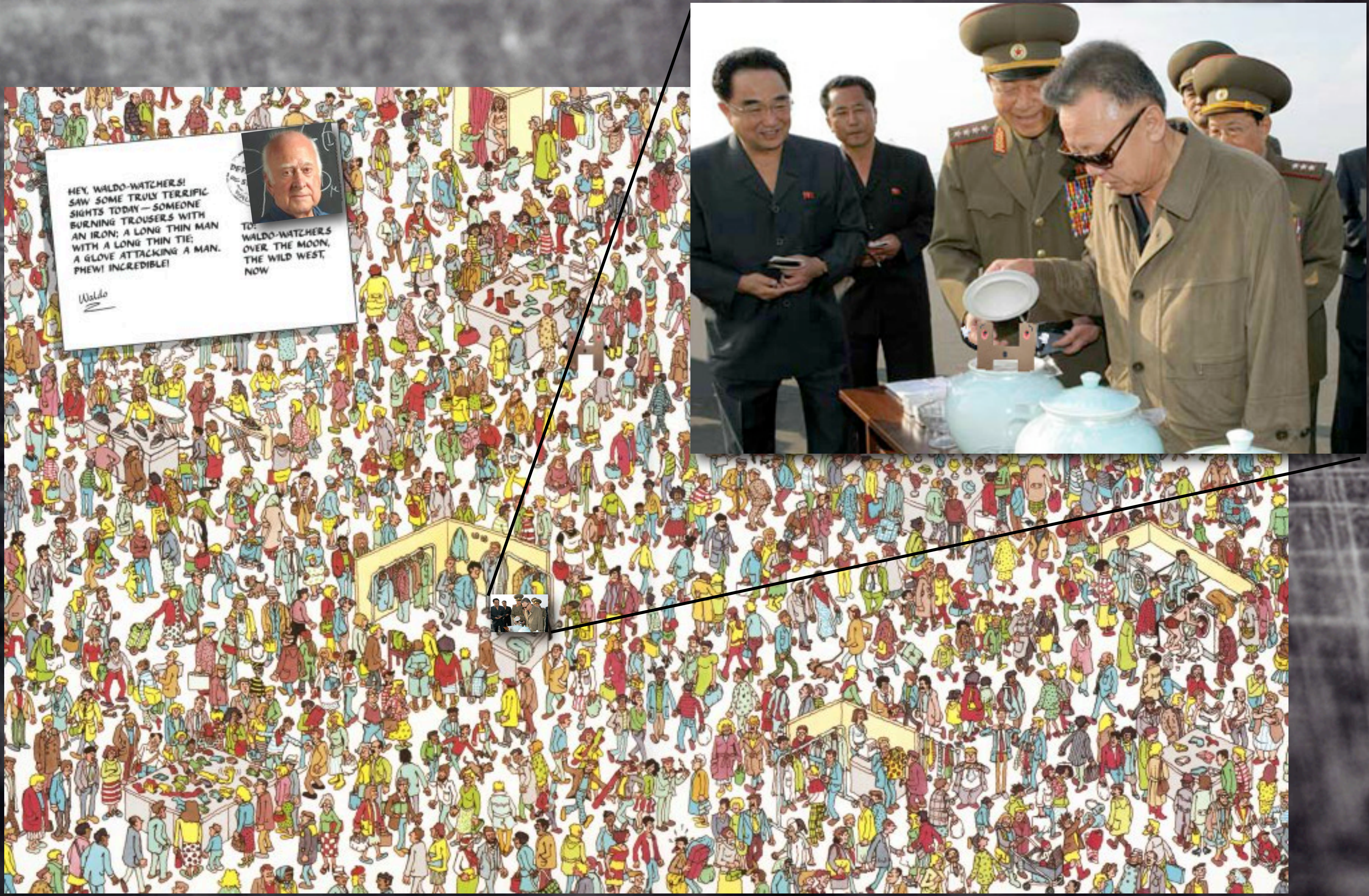
So we looked further



symmetry mag

So we looked further

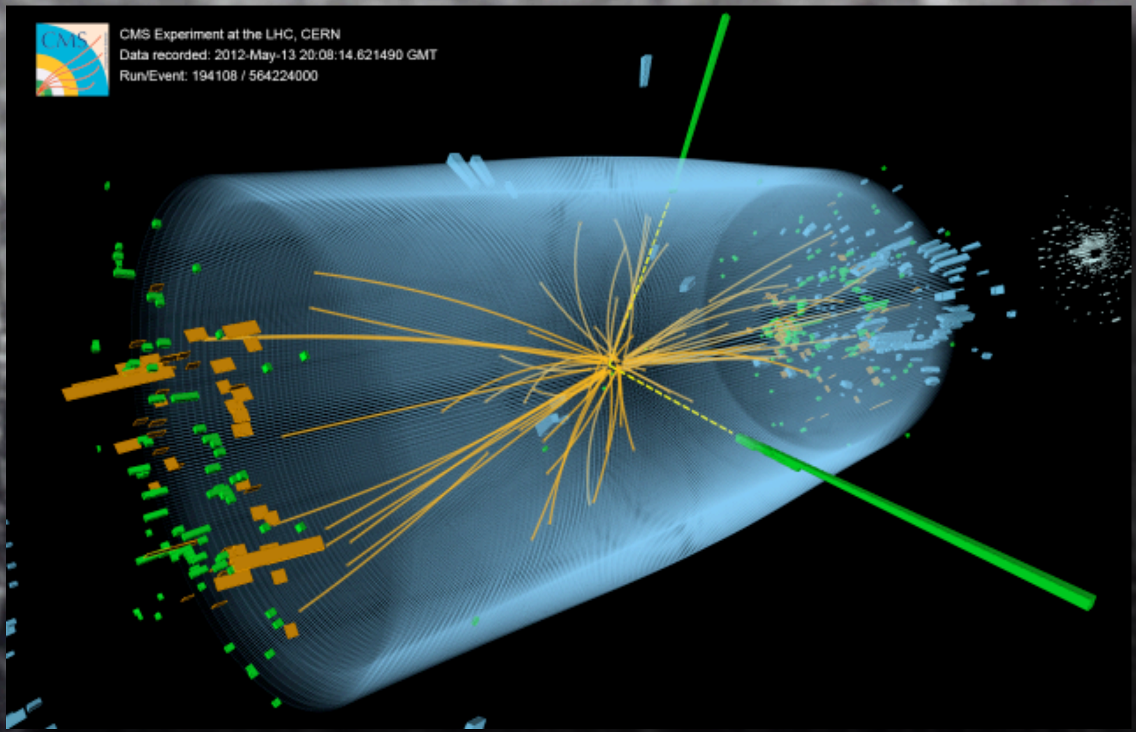
until...

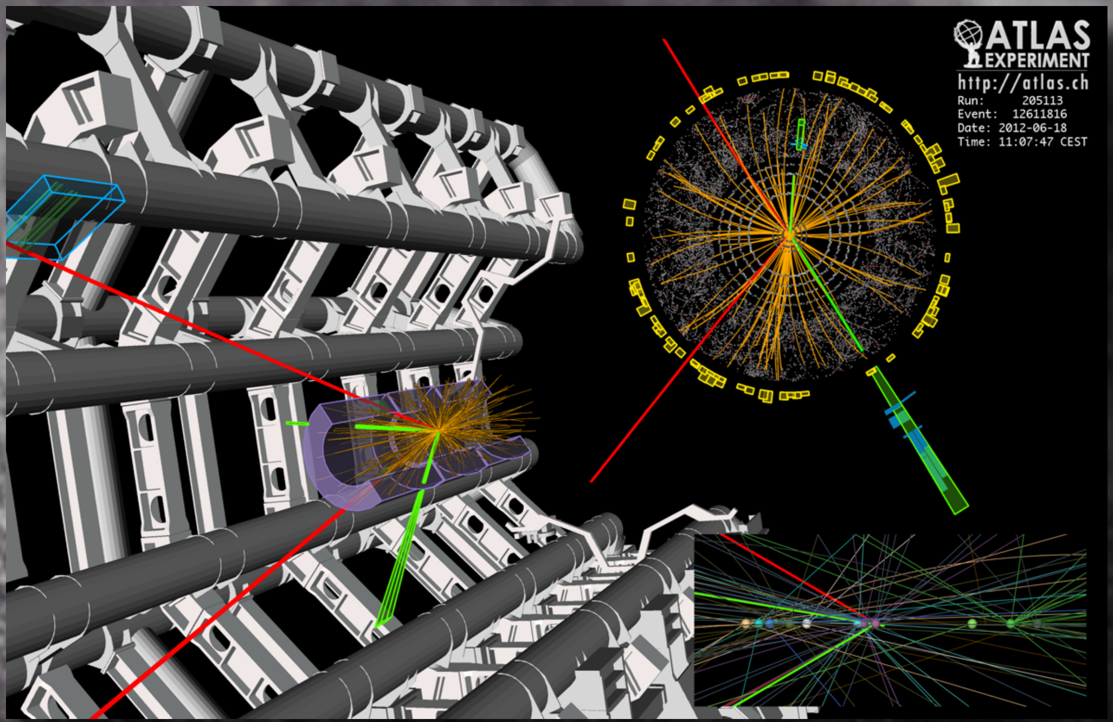


symmetry mag

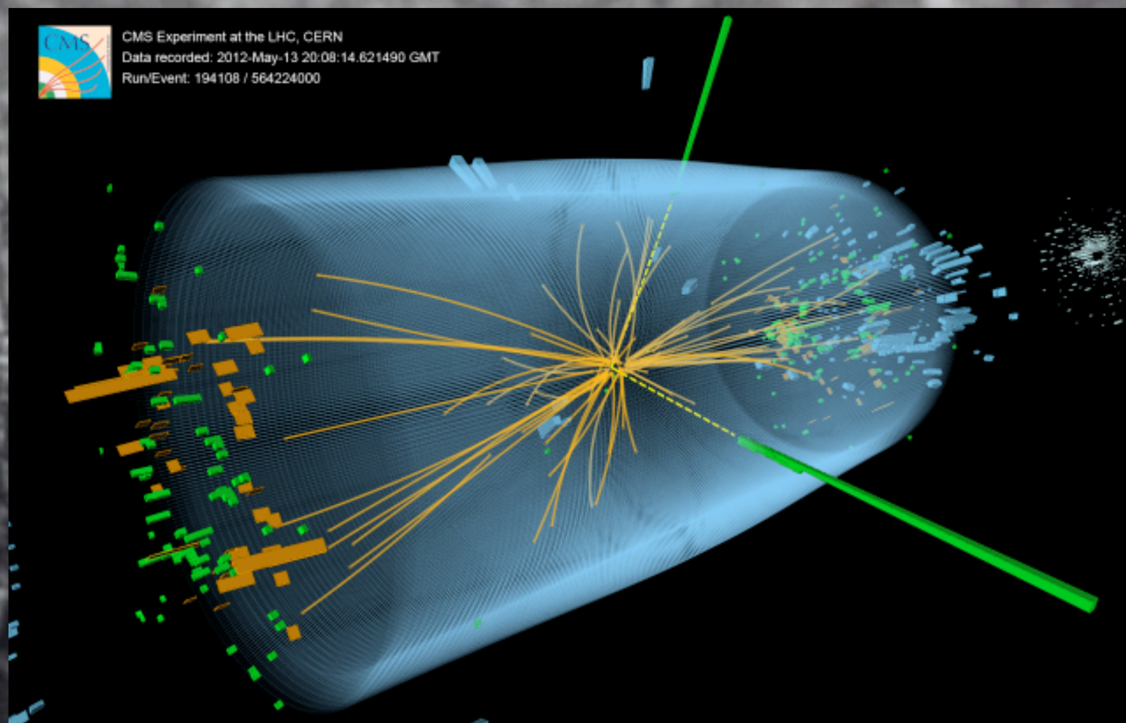
until... July 4th, 2012

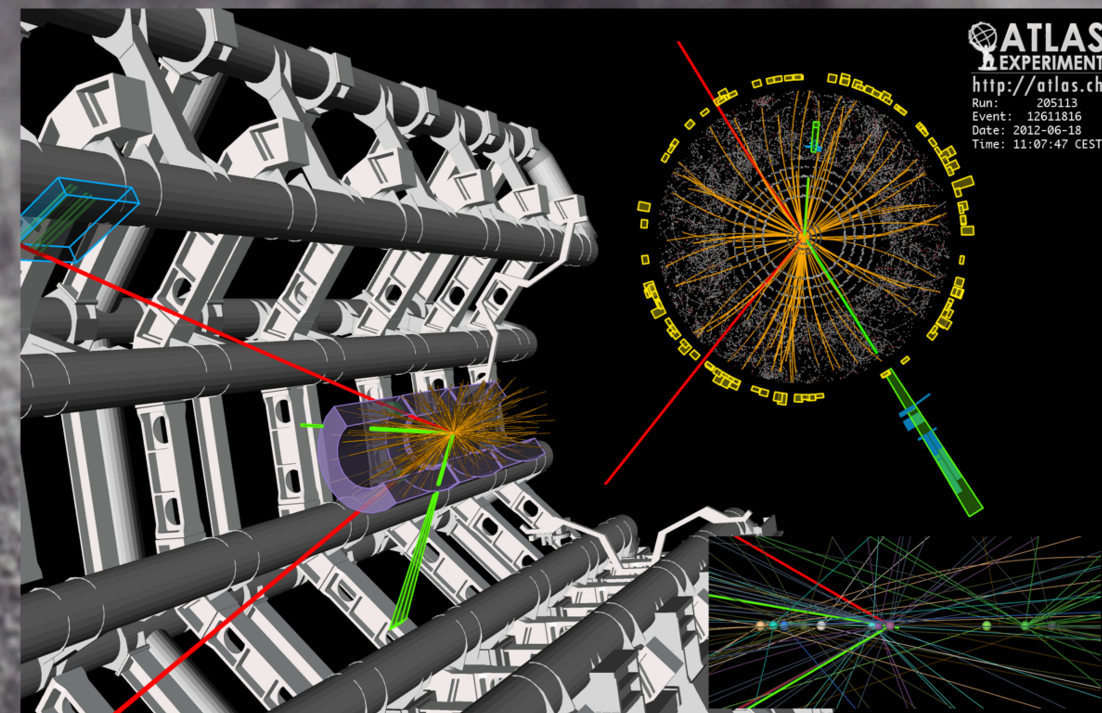
until… July 4th, 2012





until... July 4th, 2012





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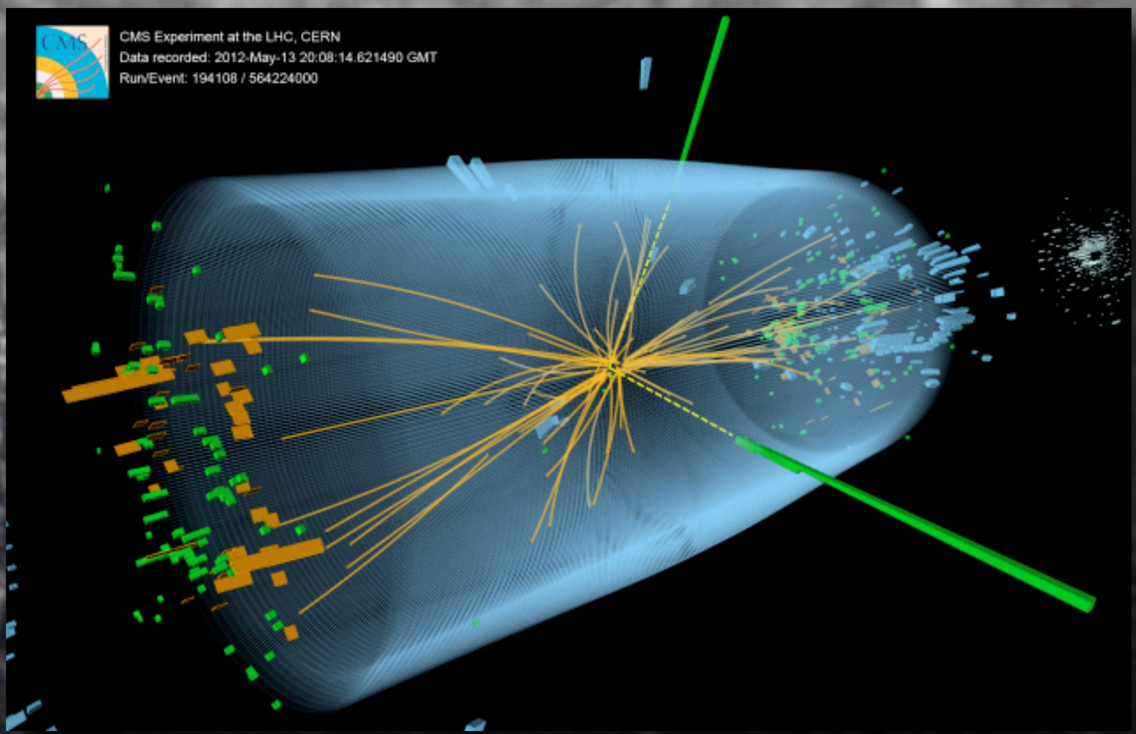

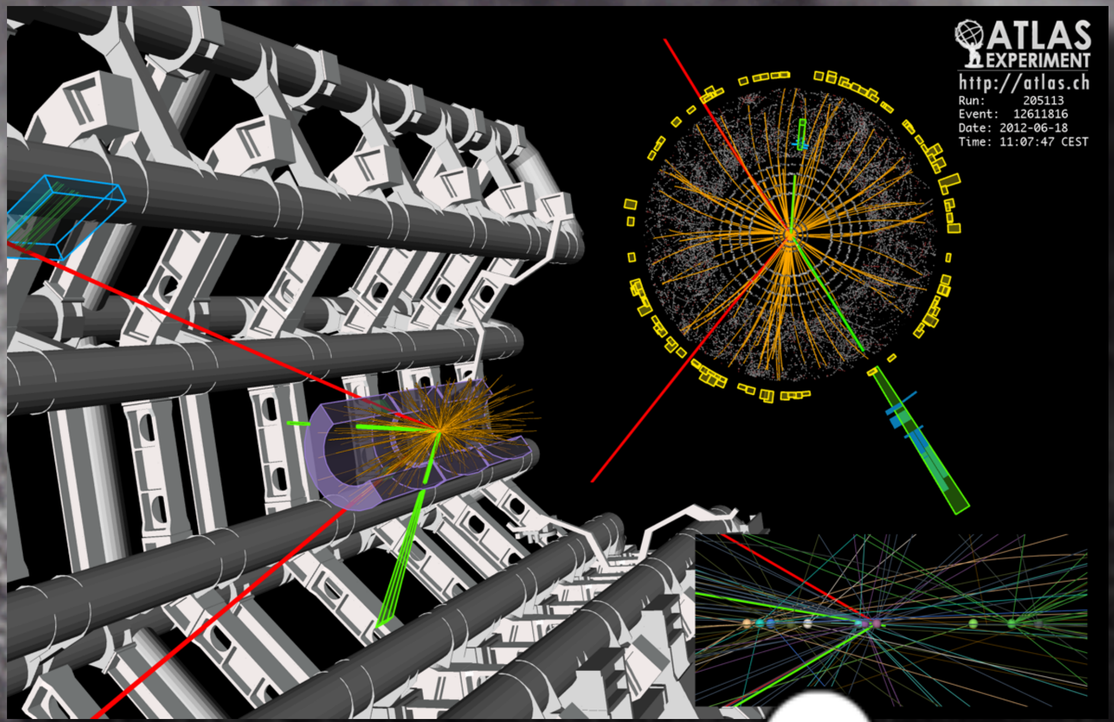

A triumph for HEP

[http://goo.gl/49c0c] [http://goo.gl/suJzZ] [http://goo.gl/ShJJG]

symmetry dimensions of particle physics

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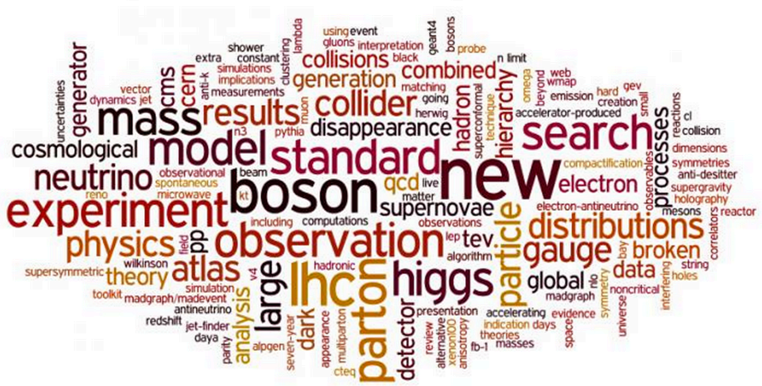

signal to background

May 12, 2013

The top 40 physics hits of 2012

The Higgs boson is a popular subject among the most-cited physics papers of 2012, but a particle simulation manual takes the top spot.

2012 reports for eprints

1. 568 citations in 2012
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jul 2012. 24 pp.
Published in **Phys.Lett. B716 (2012) 1-29**
CERN-PH-EP-2012-218
DOI: 10.1016/j.physletb.2012.08.020
e-Print: **arXiv:1207.7214 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; Link to all figures including auxiliary figures

2. 558 citations in 2012
Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012.
Published in **Phys.Lett. B716 (2012) 30-61**
CMS-HIG-12-028, CERN-PH-EP-2012-220
DOI: 10.1016/j.physletb.2012.08.021
e-Print: **arXiv:1207.7235 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service; Link to PRESSRELEASE

3. 433 citations in 2012
Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s}=7$ TeV
CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Feb 2012.
Published in **Phys.Lett. B710 (2012) 26-48**
CMS-HIG-11-032, CERN-PH-EP-2012-023
DOI: 10.1016/j.physletb.2012.02.064
e-Print: **arXiv:1202.1488 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service

4. 381 citations in 2012
Combined search for the Standard Model Higgs boson using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s}=7$ TeV with the ATLAS detector at the LHC
ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Feb 2012. 8 pp.
Published in **Phys.Lett. B710 (2012) 49-66**
CERN-PH-EP-2012-019
DOI: 10.1016/j.physletb.2012.02.044
e-Print: **arXiv:1202.1408 [hep-ex]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.

FREE ACCESS

The Discovery of the Higgs Boson

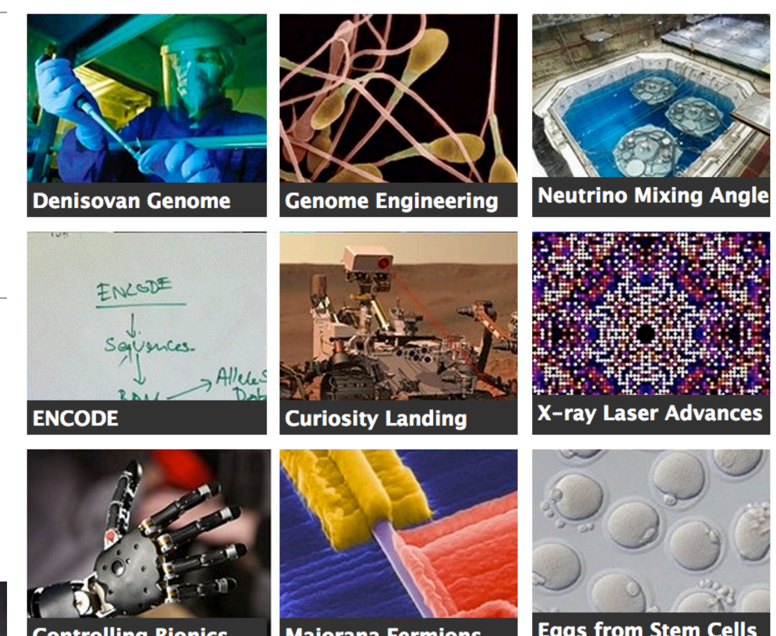
A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

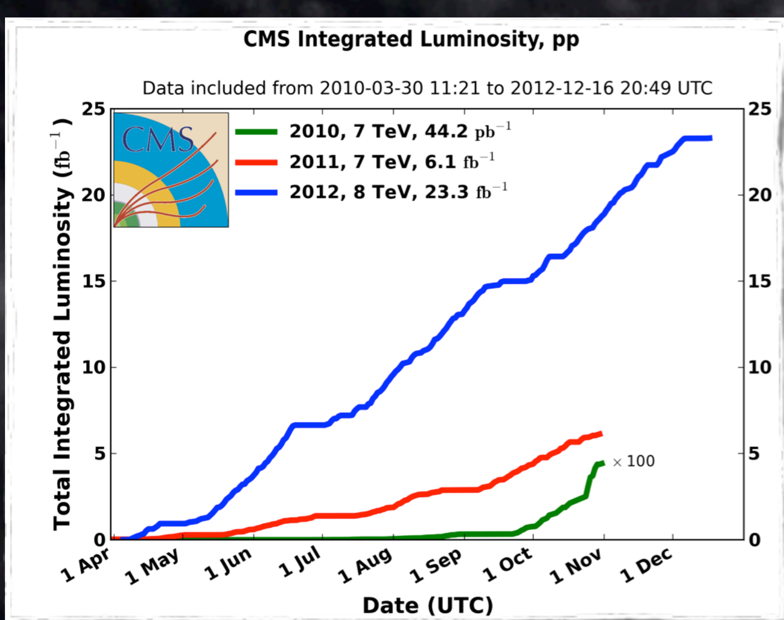
Runners-Up FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

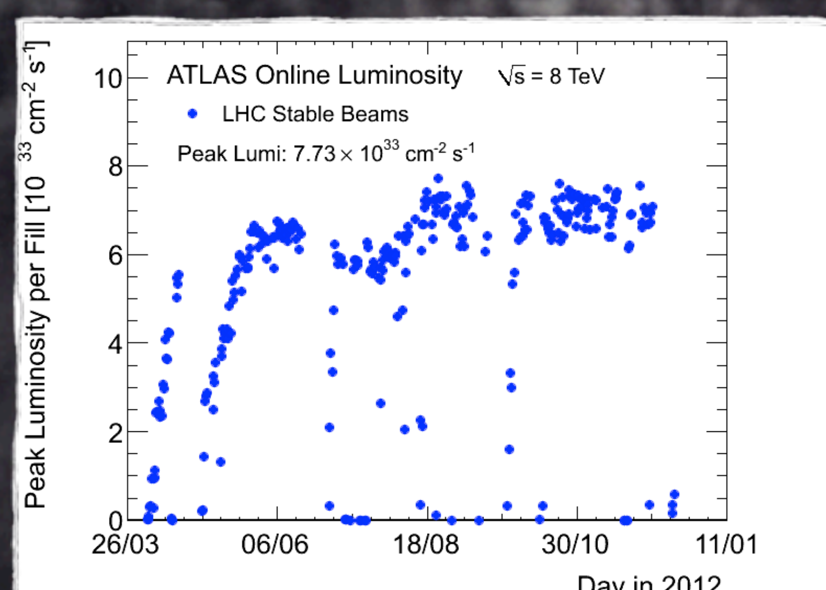


LHC performance

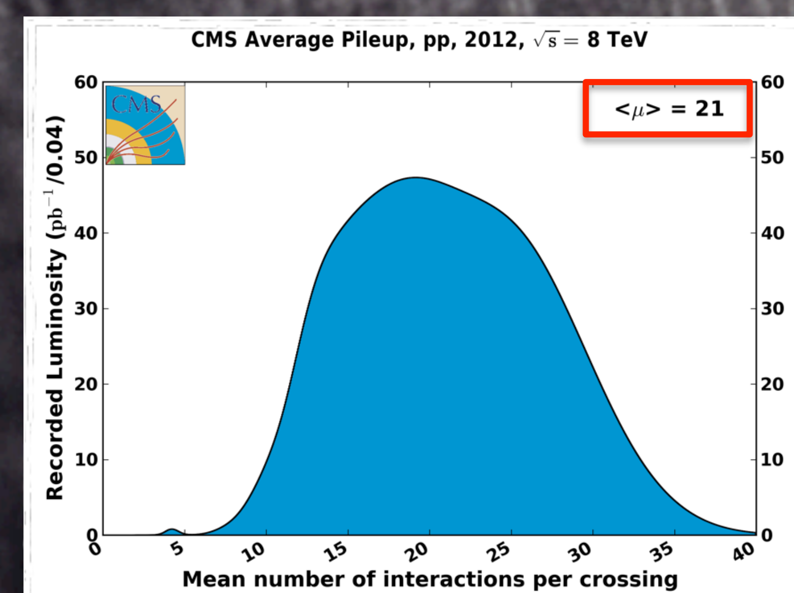
Integrated luminosity



Peak instantaneous lum
7.7 x10^{33} cm^{-2} s^{-1}



"pileup"

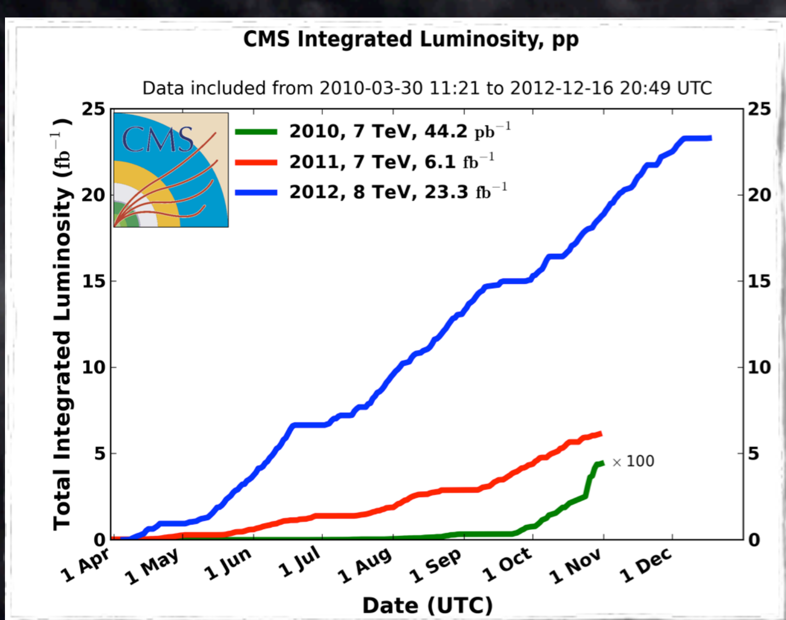


LHC performance

pp collisions
2011: ~6 fb^{-1} @ 7 TeV
2012: ~23 fb^{-1} @ 8 TeV

Approx. 250 Higgs evts/hr

Integrated luminosity



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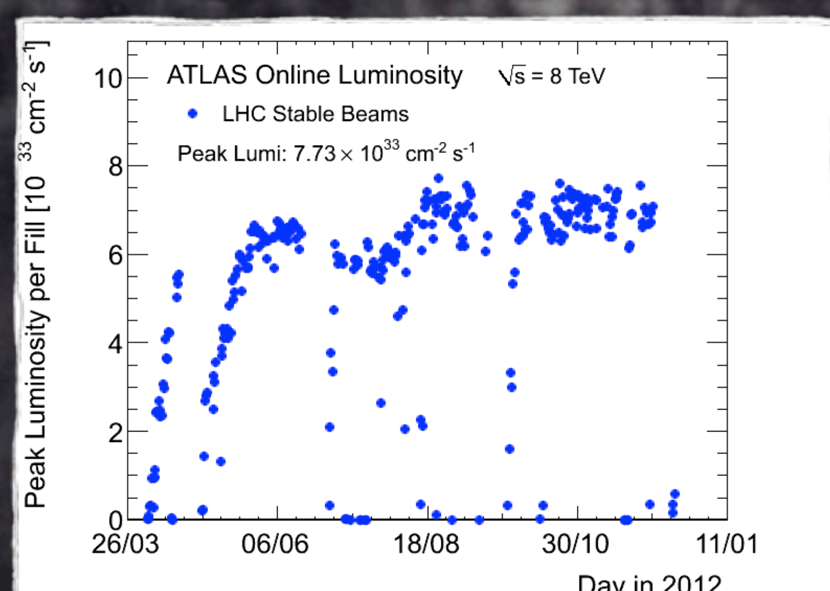
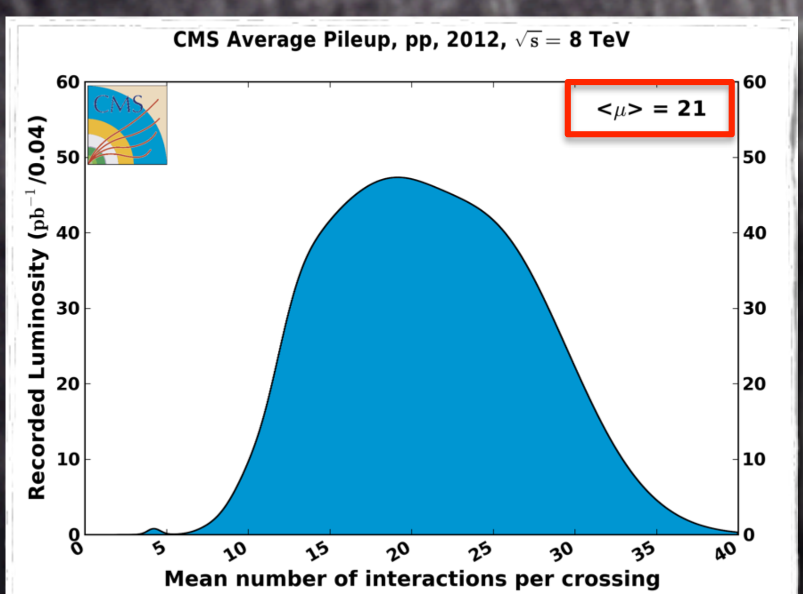
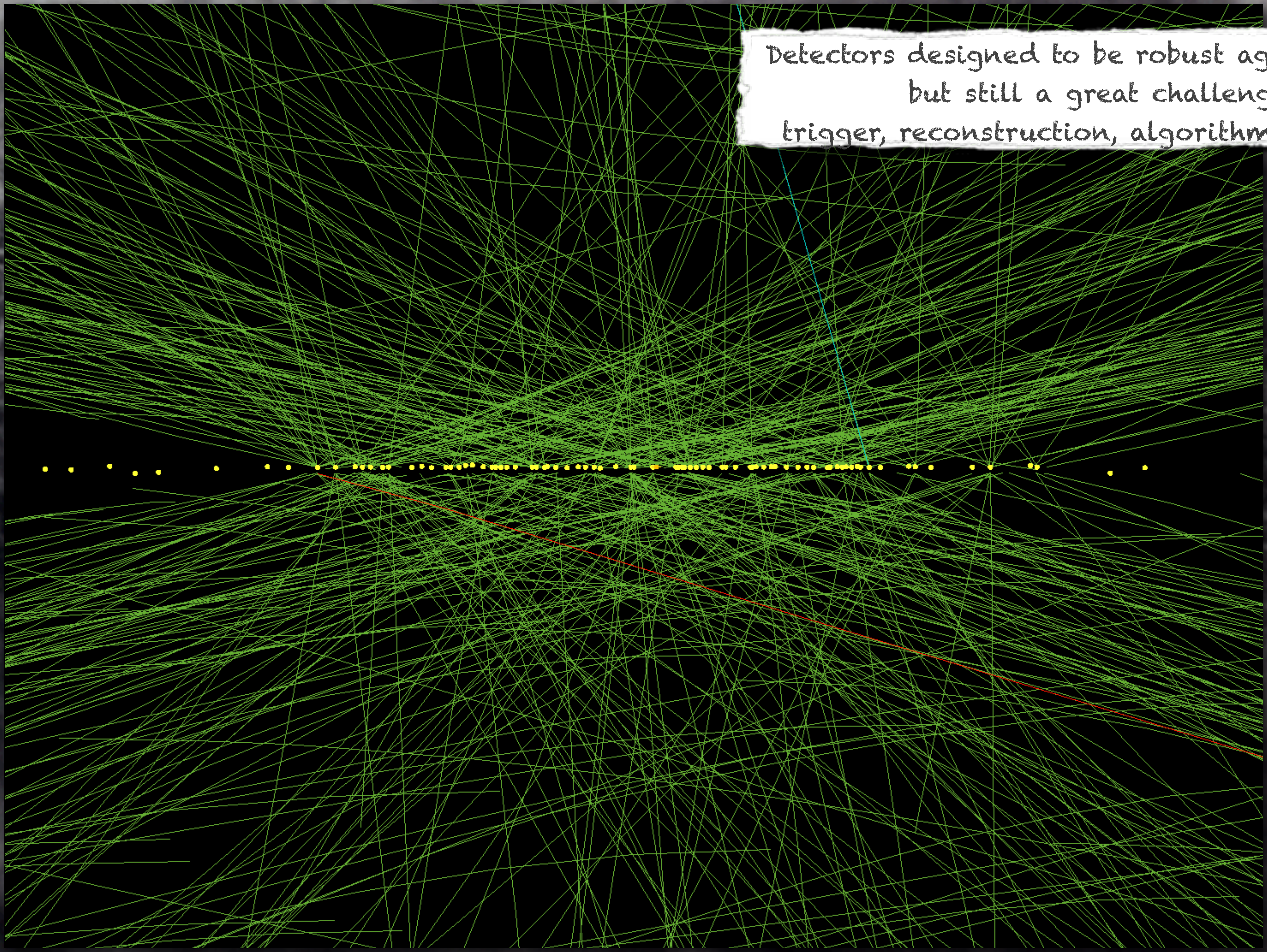


"pileup"



Not without challenges

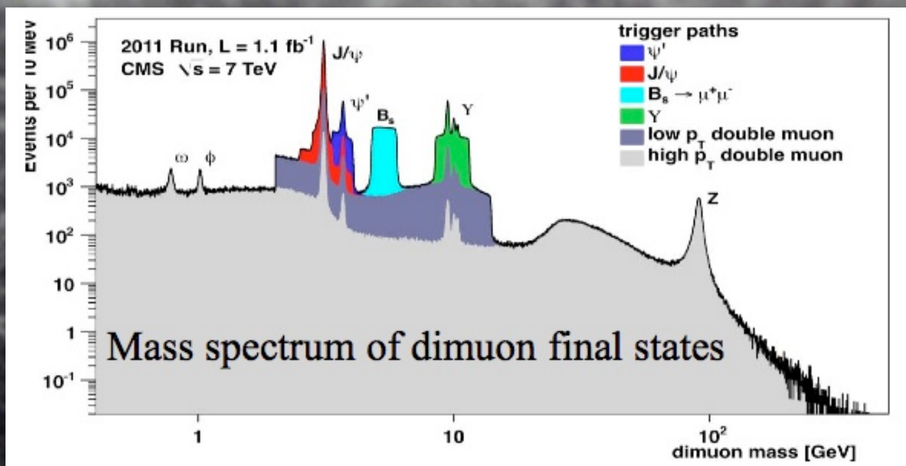


Detectors designed to be robust against pileup but still a great challenge: trigger, reconstruction, algorithms, analyses

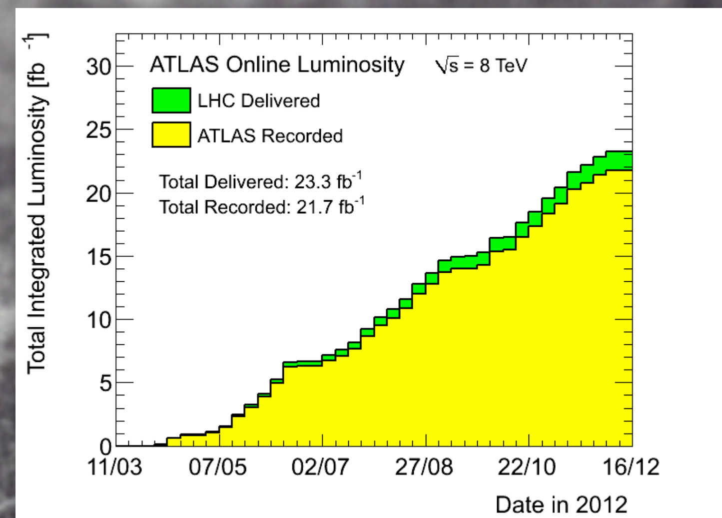
78 reconstructed collision vertices in one bunch crossing @ CMS

Detectors performance

CMS muons



ATLAS data recorded



ATLAS % live channels

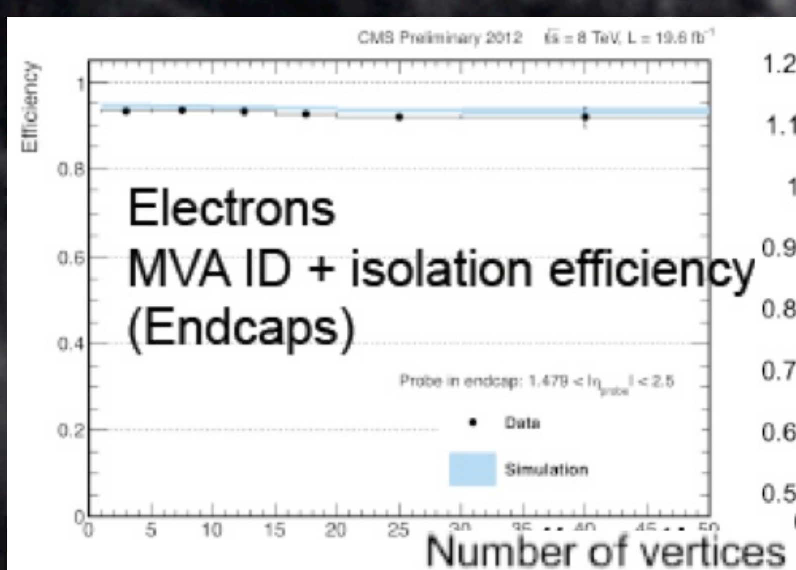
ATLAS p-p run: April-December 2012

Inner Tracker			Calorimeters		Muon Spectrometer				Magnets	
Pixel	SCT	TRT	LAr	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.9	99.4	99.8	99.1	99.6	99.6	99.8	100.	99.6	99.8	99.5

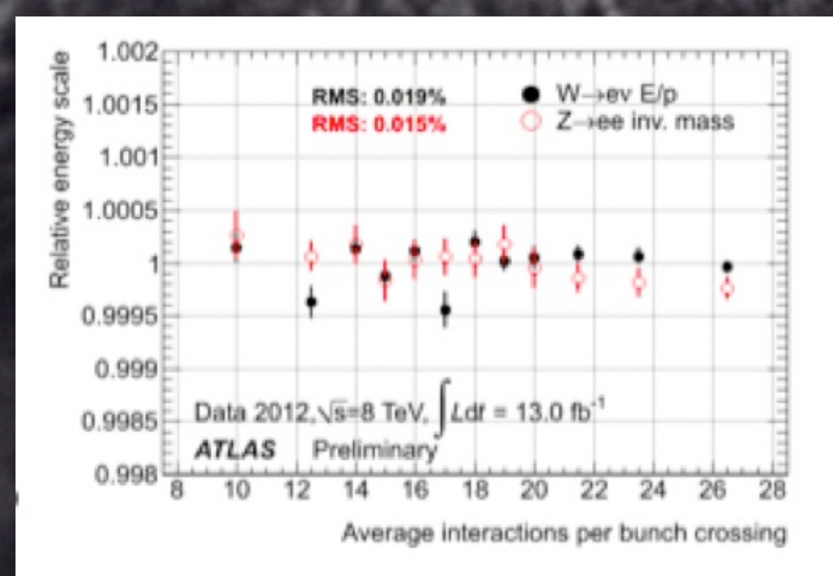
All good for physics: 95.8%

Luminosity weighted relative detector uptime and good quality data delivery during 2012 stable beams in pp collisions at √s=8 TeV between April 4th and December 6th (in %) – corresponding to 21.6 fb^{-1} of recorded data.

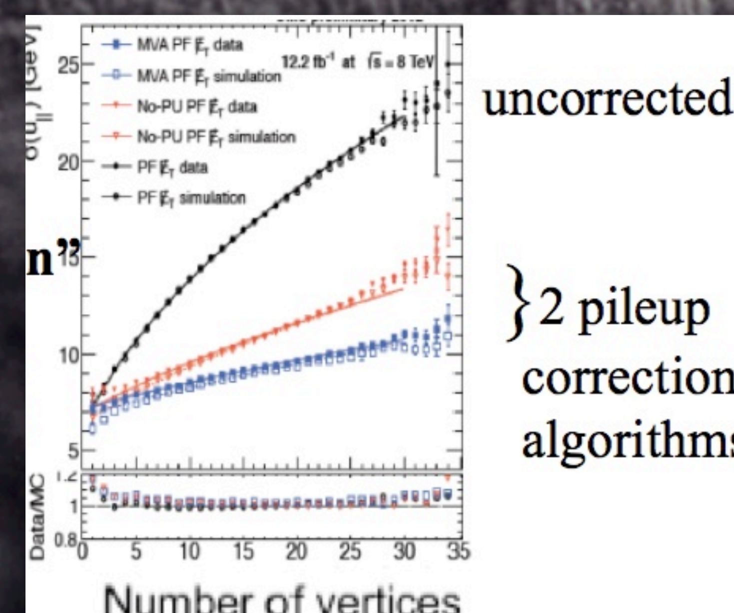
CMS electrons



ATLAS calorimeter



CMS missing E_T res.

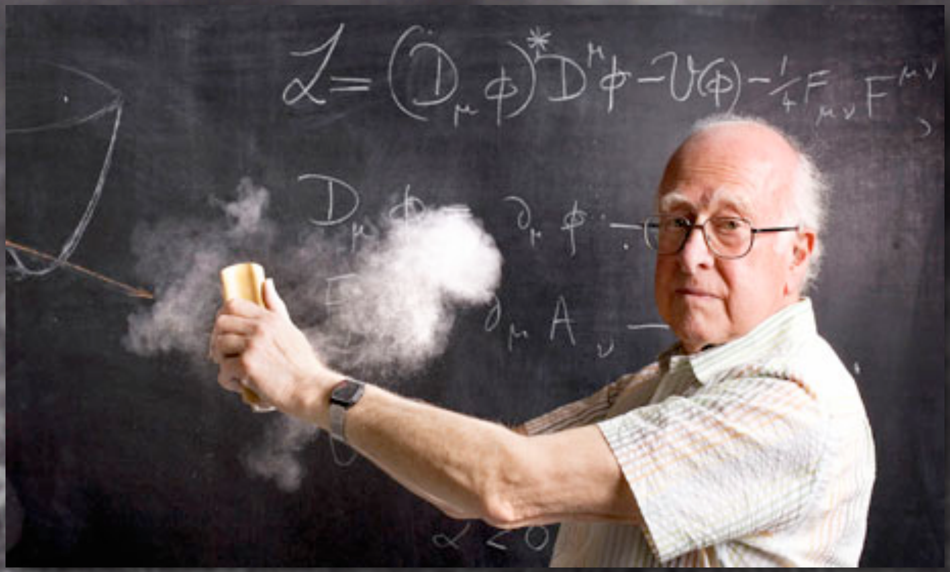


The Big Question

How compatible is H_{125} with the SM Higgs ?

What we've learned so far

- **Highlights up to ~LHCP-2013**
  - **Landscape**
    - **Main channels studied**
  - **Compatibility with SM Higgs**
    - **Production mechanisms**
    - **Intrinsic properties**
    - **Interactions w/ others**

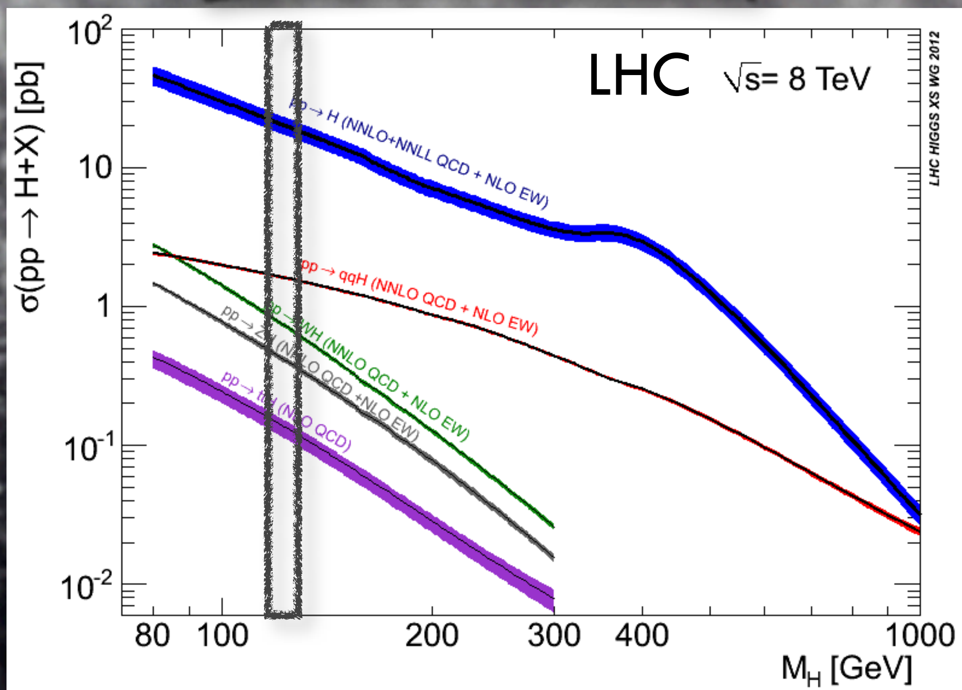


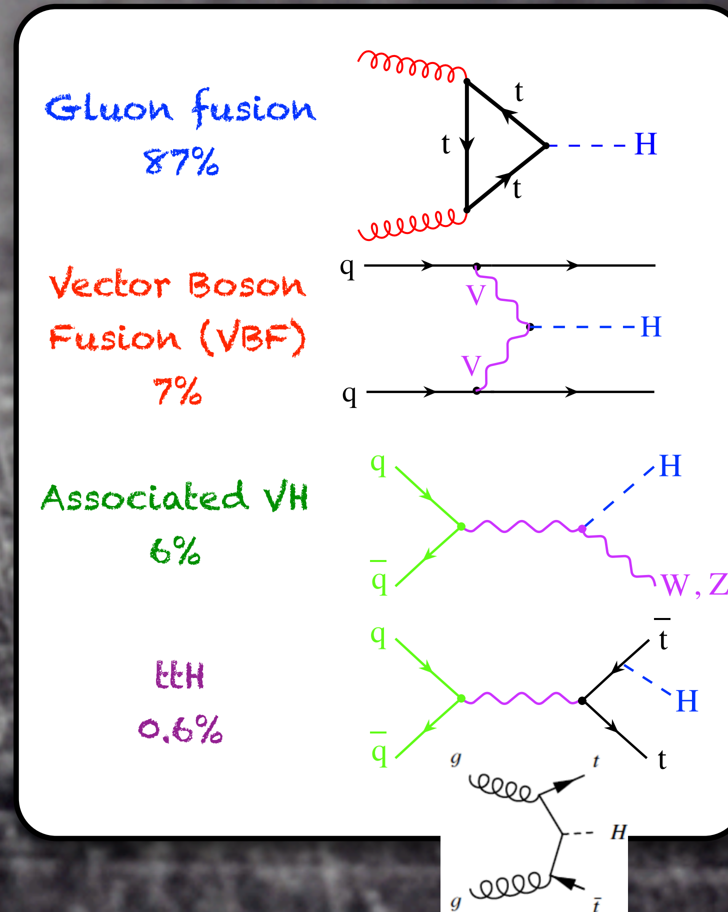
i.e. the road from "Higgs-like" to "a Higgs" to ... ?

Predicted production and decay

Predicted production and decay

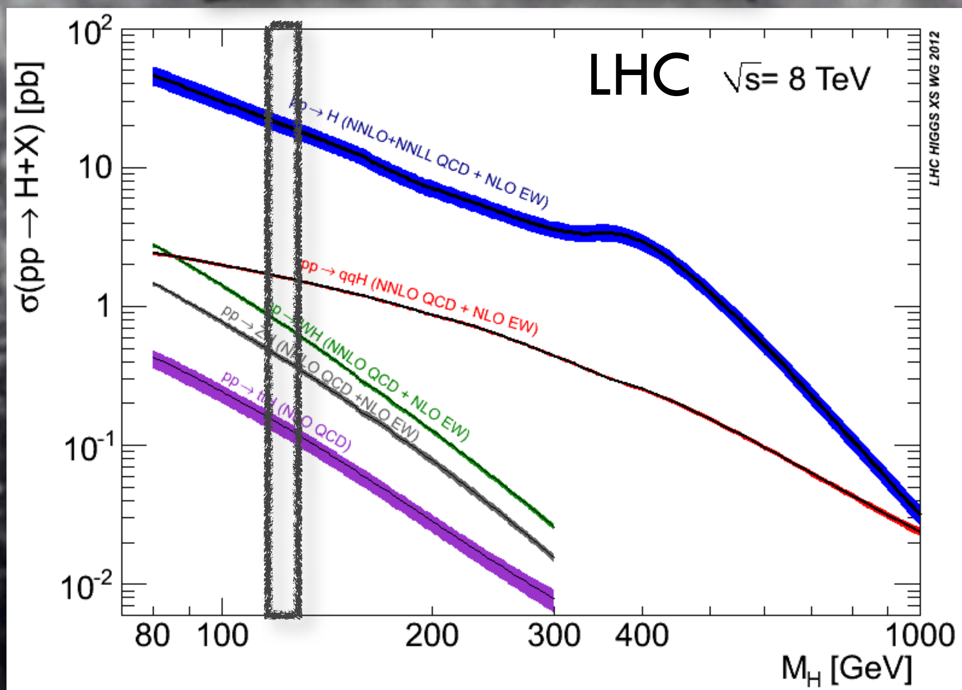
Production





Predicted production and decay

Production

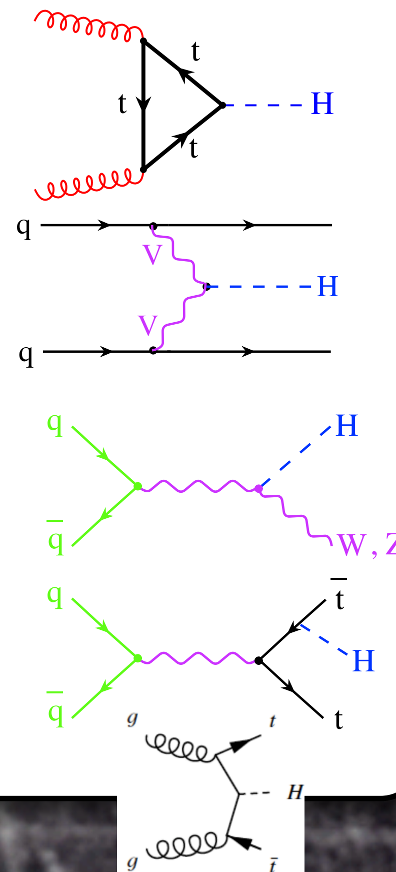


Gluon fusion
87%

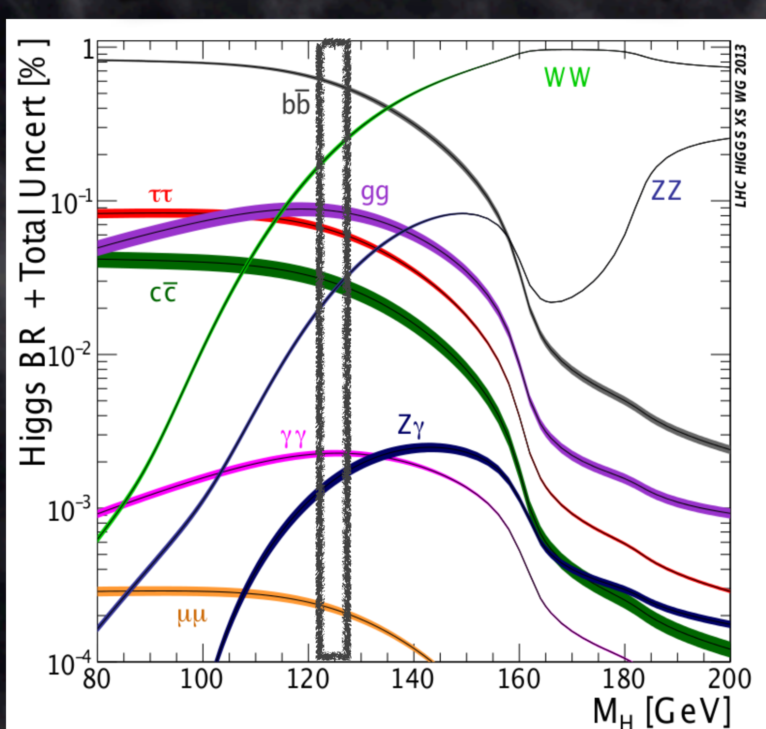
Vector Boson Fusion (VBF)
7%

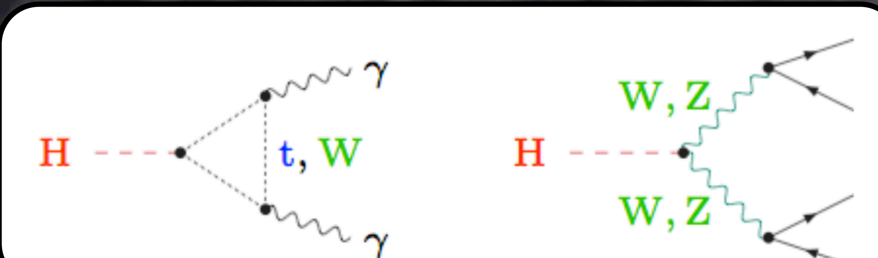
Associated VH
6%

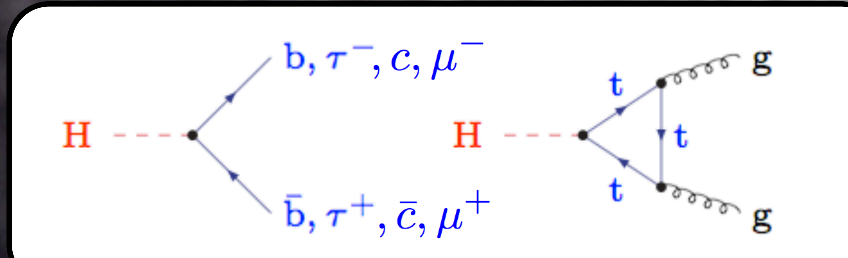
ttH
0.6%



Decay







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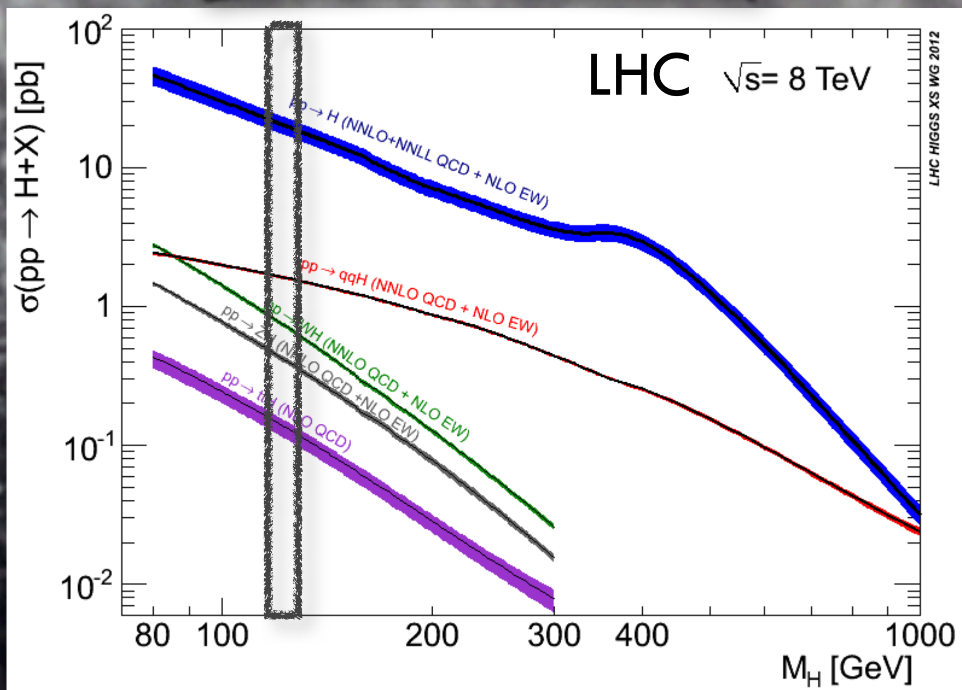

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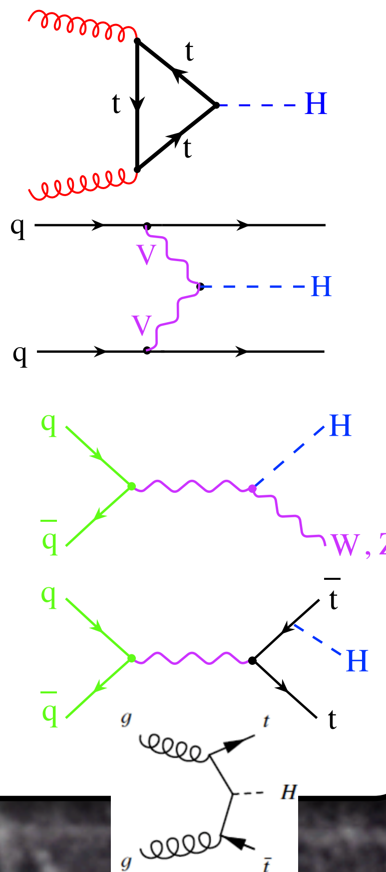
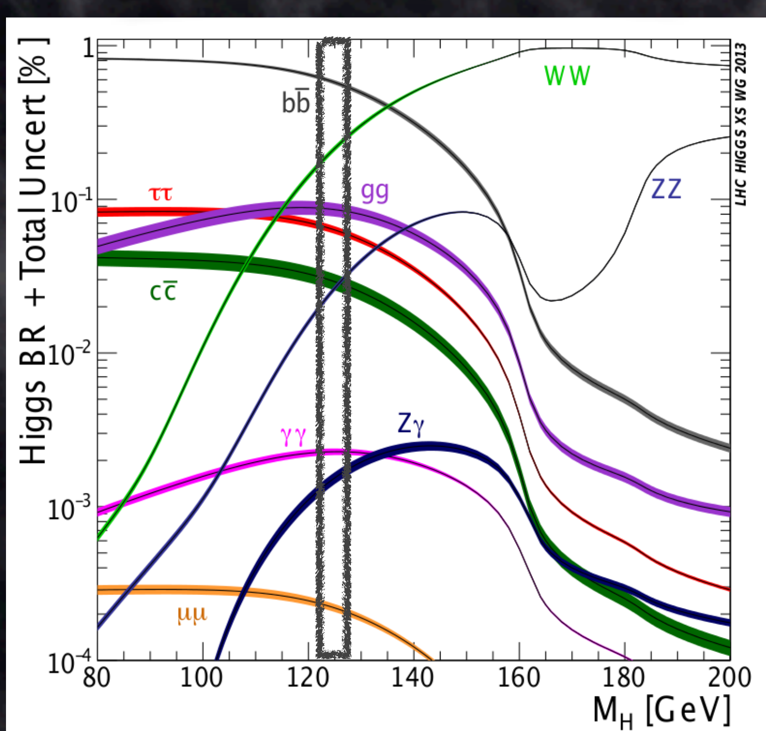
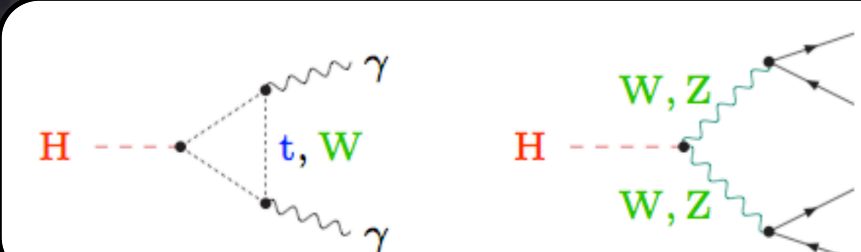


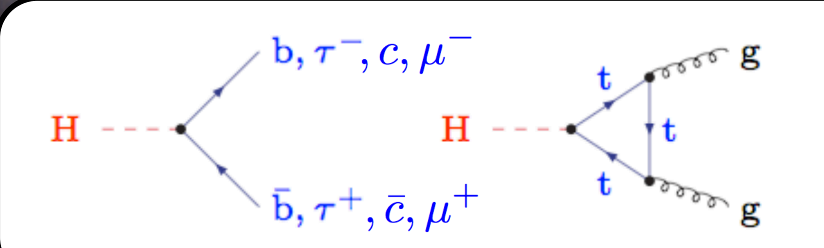
Lucky !

@ M$_H$~125 GeV
We have access to a plethora of production x decay modes that have allowed a very quick and rich exploration of [yes!] the Higgs Sector

Decay







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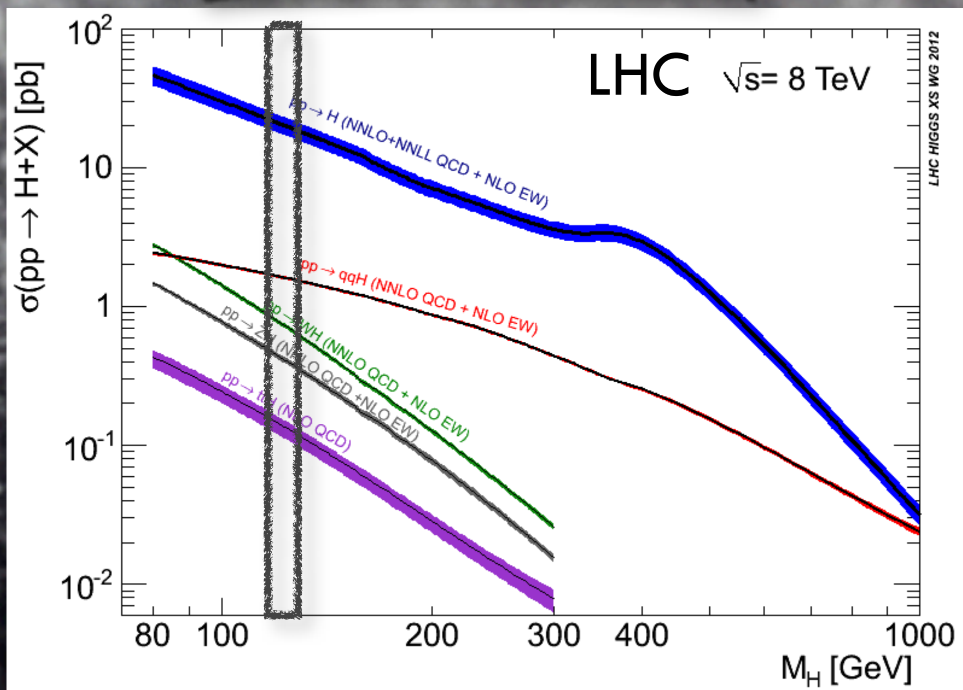

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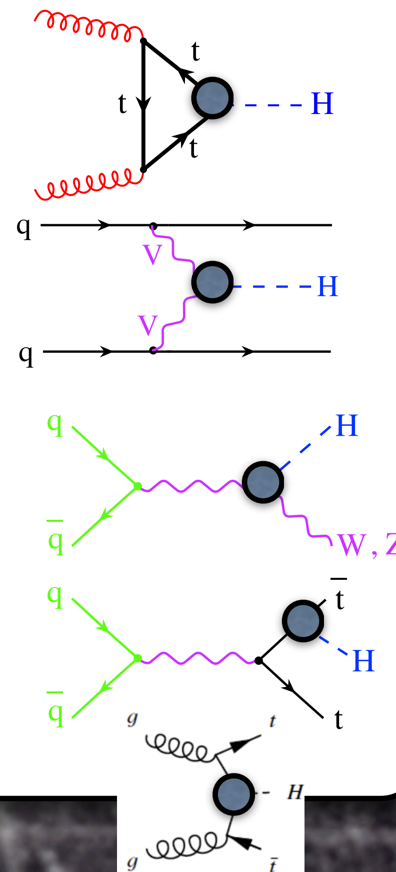

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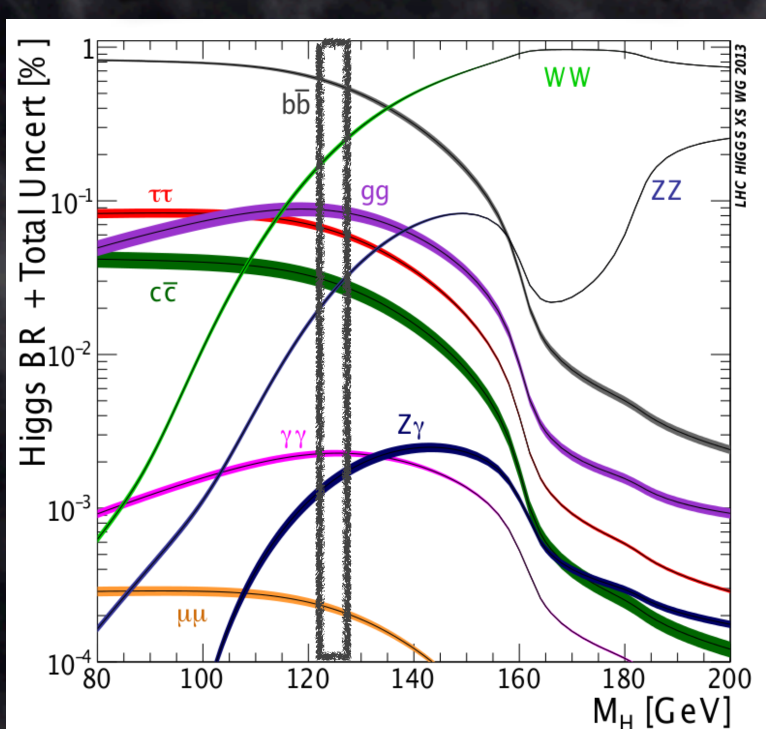

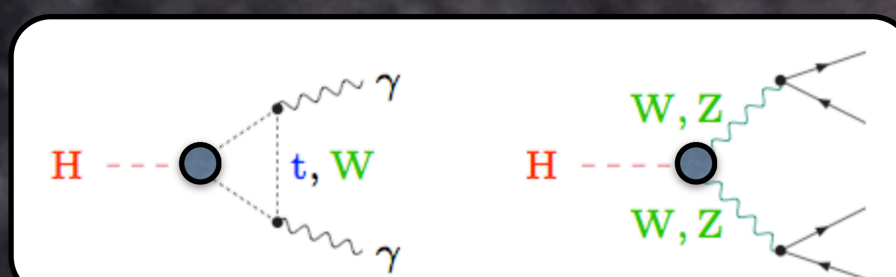

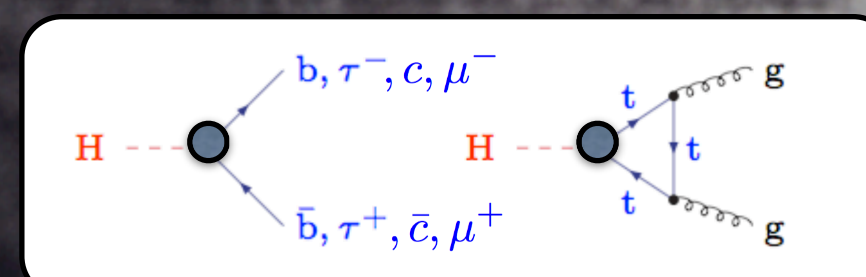

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Predicted production and decay

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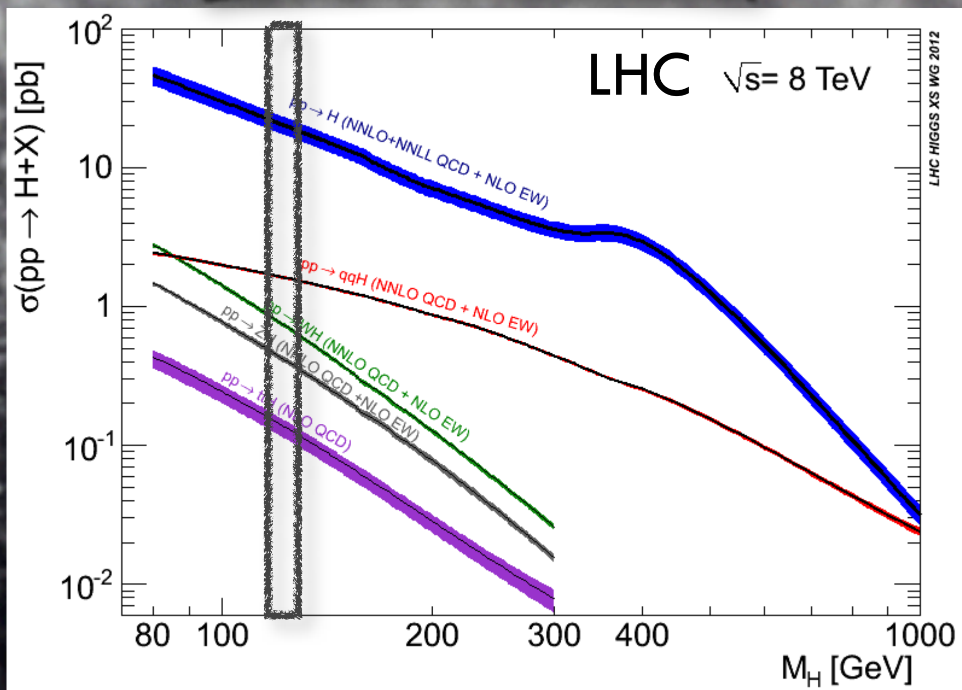

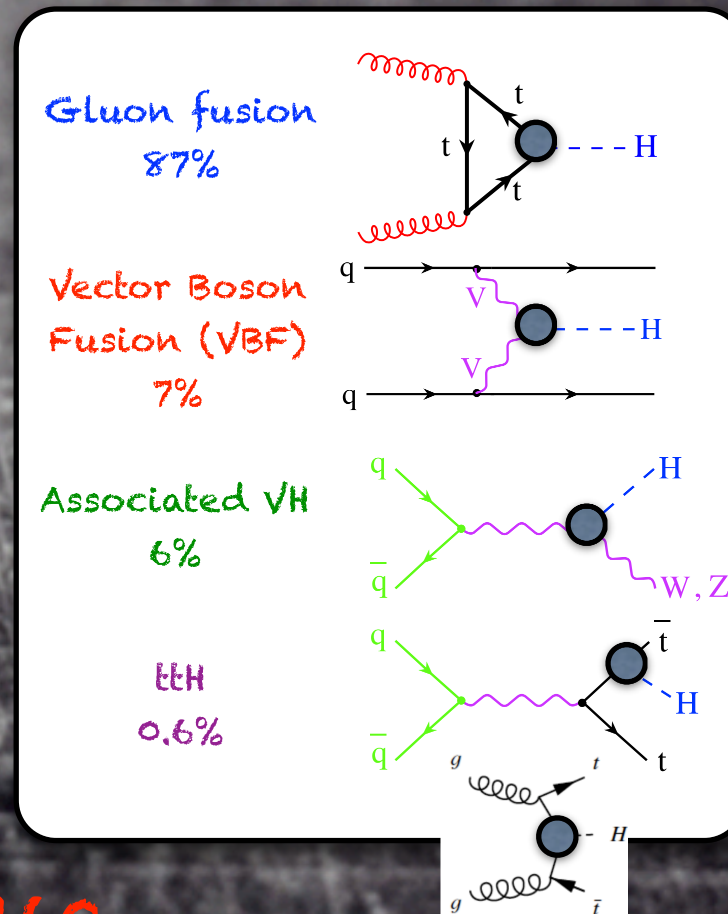

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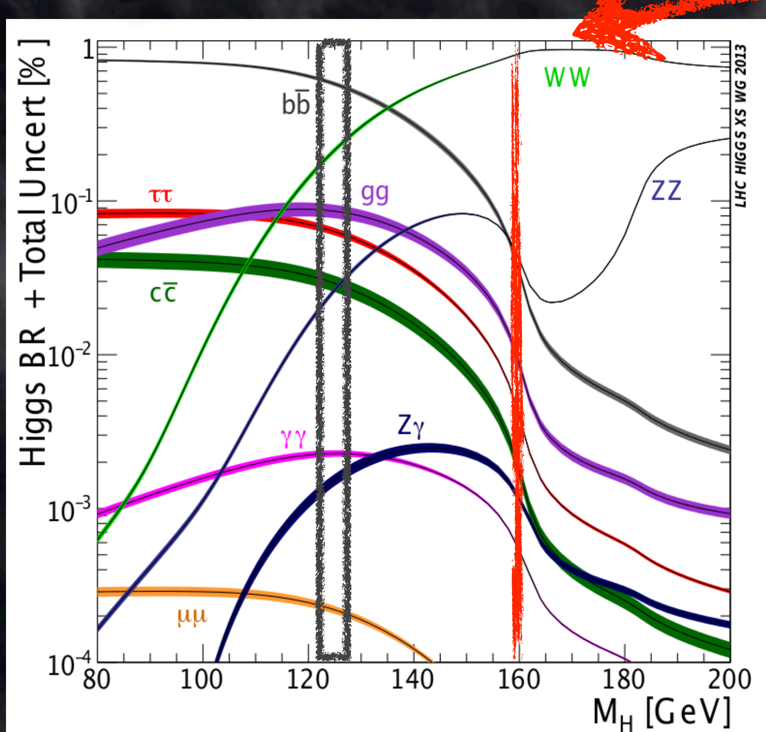
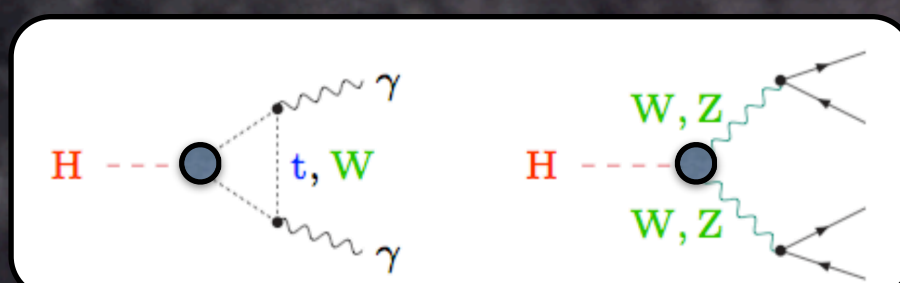
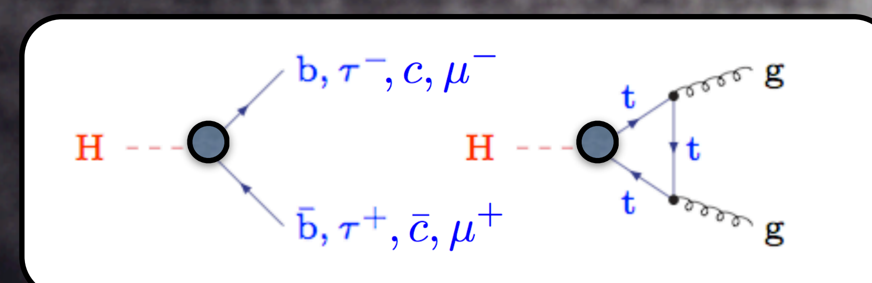
Decay

had M_H~160 ...







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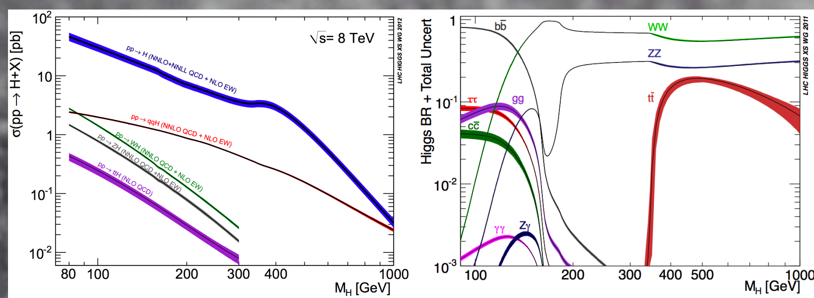
Channels studied



CMS

7 TeV, 5 fb^{-1}
8 TeV, 5 fb^{-1}
8 TeV, 12 fb^{-1}
8 TeV, 20 fb^{-1}

ATLAS

7 TeV, 5 fb^{-1}
8 TeV, 5 fb^{-1}
8 TeV, 13 fb^{-1}
8 TeV, 21 fb^{-1}

decay/prod.	untagged	VBF-tag	VH-tag	ttH-tag
WW				
ZZ				
bb				
ττ				
μμ				
γγ				
Zγ				

Note: "Tags" refer to what else, other than the Higgs, is identified explicitly in the event

BEWARE: Tags are never pure; e.g. VBF-tags have 20%-80% of ggF, depending on analysis

In more detail

- Main channels

H decay	Analyses: Prod. tag	Analyses: Exclusive final states	No. of channels
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	$4+4$
	VBF-tag	$\gamma\gamma + (jj)_{\mathrm{VBF}}$ (two dijet classes for 8 TeV)	$1+2$
	VH-tag	$\gamma\gamma + (\mathrm{e}, \mu, \mathrm{MET})$	3
$ZZ \to 4\ell$	$N_{\mathrm{jet}} < 2$	4e, 4μ, $2e2\mu$	$3+3$
	$N_{\mathrm{jet}} \geq 2$		$3+3$
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	$4+4$
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\mathrm{VBF}}$ (DF or SF dileptons for 8 TeV)	$1+2$
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	$2+2$
$\tau\tau$	0/1-jet	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu) \times$ (low or high p_T^τ)	$16+16$
	1-jet	$\tau_h\tau_h$	$1+1$
	VBF-tag	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\mathrm{VBF}}$	$5+5$
	ZH-tag	$(\mathrm{ee}, \mu\mu) \times (\tau_h\tau_h, \mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu)$	$8+8$
	WH-tag	$\tau_h\mu\mu, \tau_h\mathrm{e}\mu, \mathrm{e}\tau_h\tau_h, \mu\tau_h\tau_h$	$4+4$
bb	VH-tag	$(\nu\nu$, ee, $\mu\mu$, eν, $\mu\nu$ with 2 b-jets) $\times$ (low or high $p_{\mathrm{T}}(\mathrm{V})$ or loose b-tag)	$10+13$
	ttH-tag +VBF-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	$6+6$
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	$3+3$

Example CMS [similar for ATLAS]

In more detail

- Main channels

H decay	Prod. tag	Analyses Exclusive final states	No. of channels
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	$4+4$
	VBF-tag	$\gamma\gamma + (jj)_{\mathrm{VBF}}$ (two dijet classes for 8 TeV)	$1+2$
	VH-tag	$\gamma\gamma + (\mathrm{e}, \mu, \mathrm{MET})$	3
$\mathrm{ZZ} \to 4\ell$	$N_{\mathrm{jet}} < 2$	4e, 4μ, $2e2\mu$	$3+3$
	$N_{\mathrm{jet}} \geq 2$		$3+3$
$\mathrm{WW} \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	$4+4$
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\mathrm{VBF}}$ (DF or SF dileptons for 8 TeV)	$1+2$
	WH-tag	$3\ell 3\nu$ (same-sign SF and otherwise)	$2+2$
$\tau\tau$	0/1-jet	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu) \times$ (low or high p_T^τ)	$16+16$
	1-jet	$\tau_h\tau_h$	$1+1$
	VBF-tag	$(\mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\mathrm{VBF}}$	$5+5$
	ZH-tag	$(\mathrm{ee}, \mu\mu) \times (\tau_h\tau_h, \mathrm{e}\tau_h, \mu\tau_h, \mathrm{e}\mu)$	$8+8$
	WH-tag	$\tau_h\mu\mu, \tau_h\mathrm{e}\mu, \mathrm{e}\tau_h\tau_h, \mu\tau_h\tau_h$	$4+4$
bb	VH-tag	$(\nu\nu$, ee, $\mu\mu$, eν, $\mu\nu$ with 2 b-jets$) \times$ (low or high $p_{\mathrm{T}}(\mathrm{V})$ or loose b-tag)	$10+13$
	ttH-tag +VBF-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	$6+6$
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	$3+3$

Example CMS [similar for ATLAS]

Many teams, lots of people...

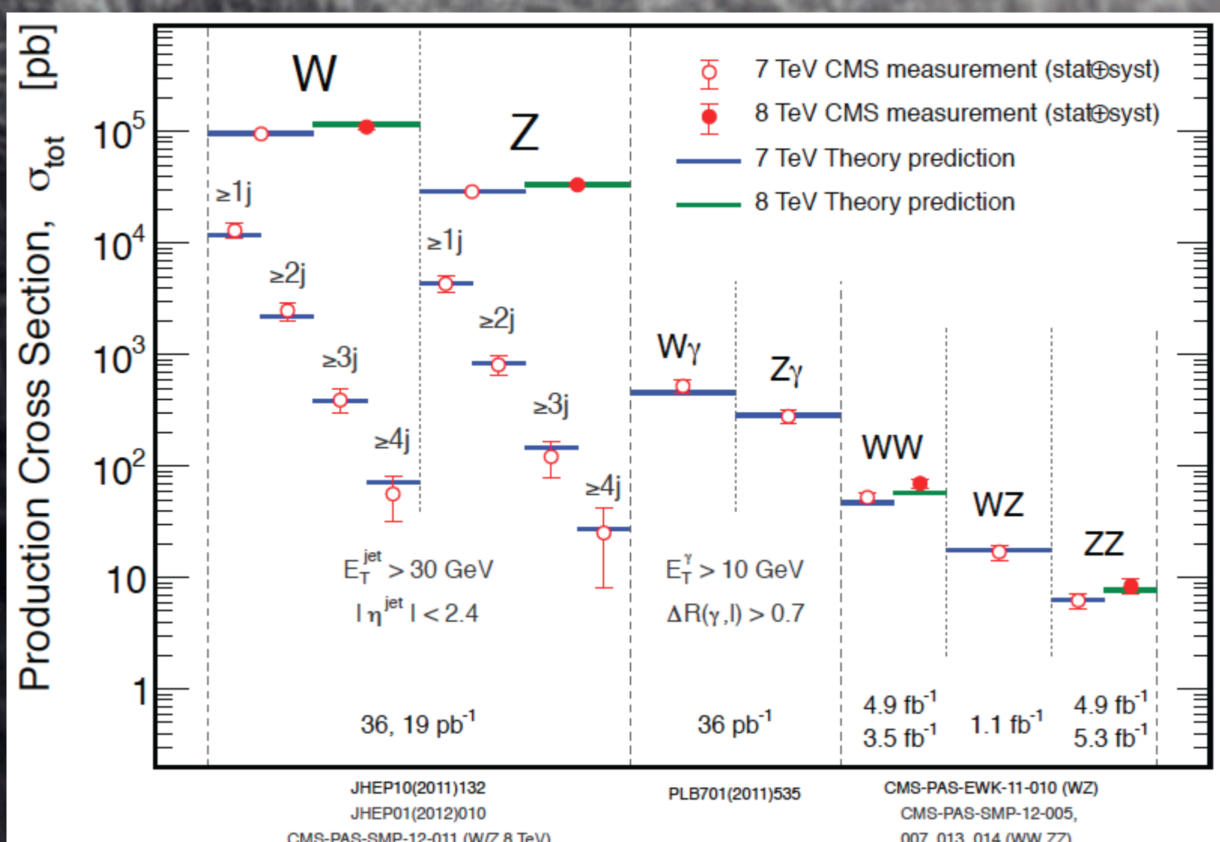
CMS Compact Muon Solenoid

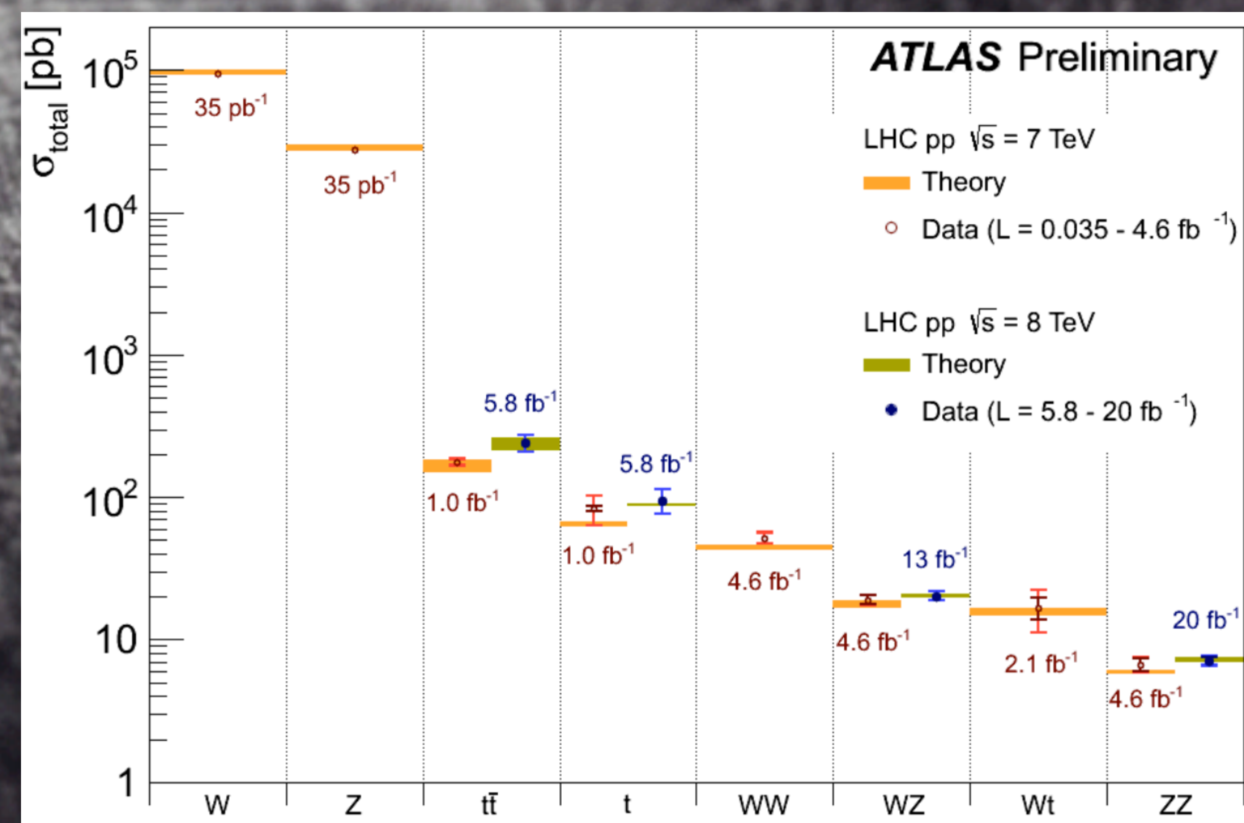
ATLAS

Key: understand SM well

See earlier presentation by J. G. da Costa

- Amazing results





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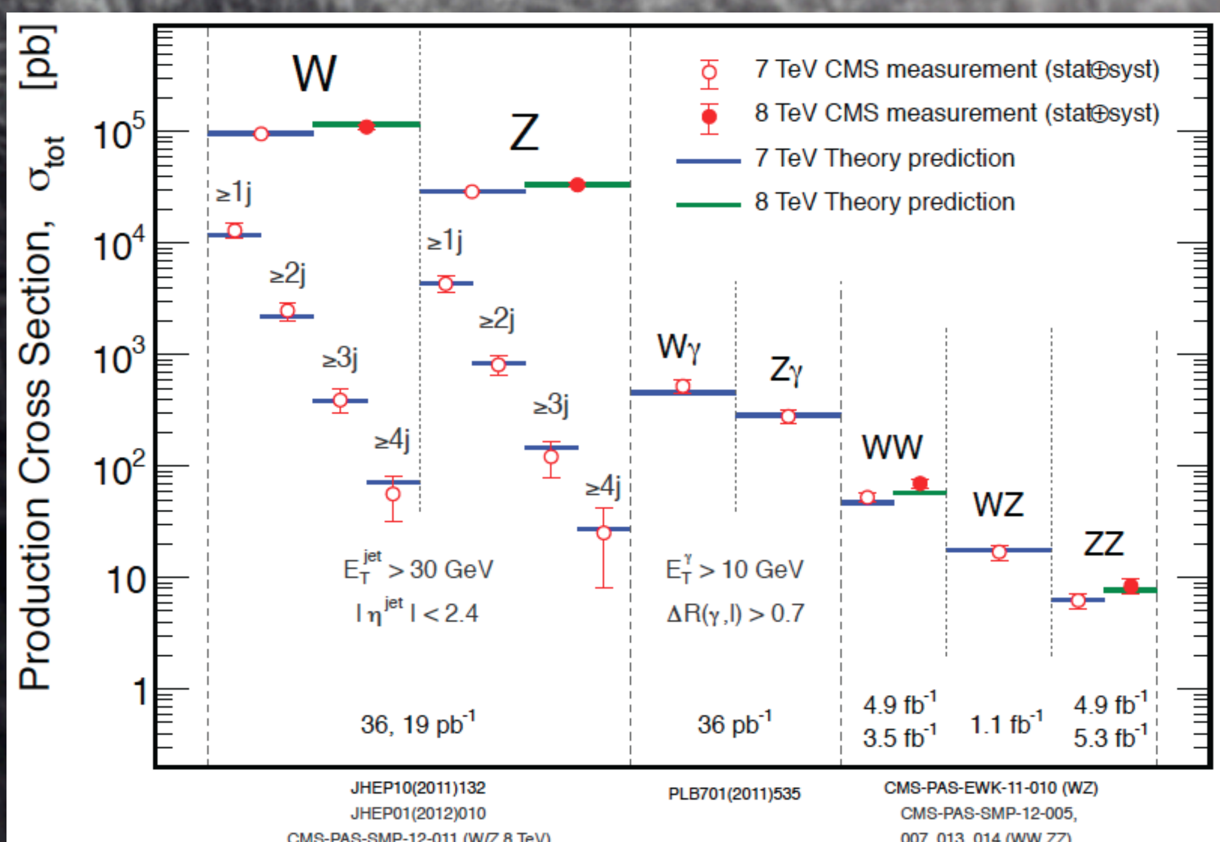
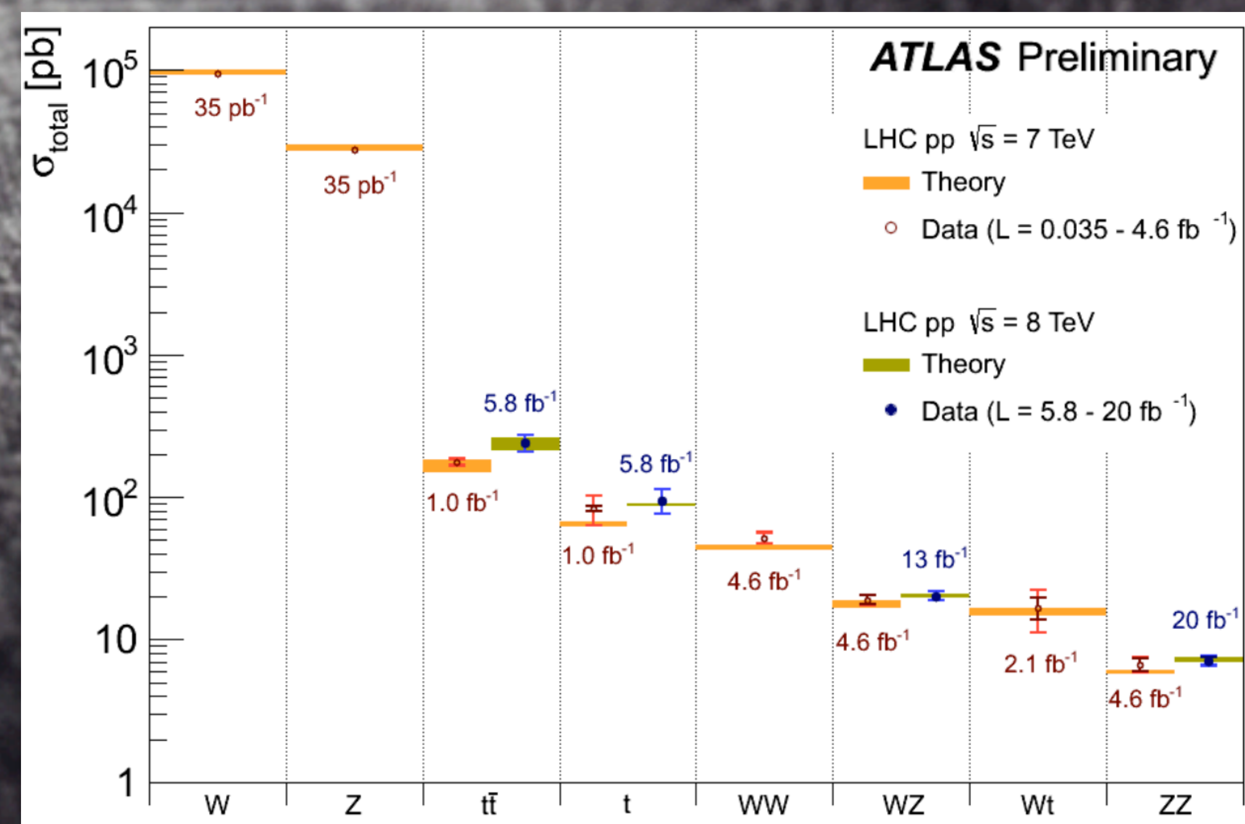


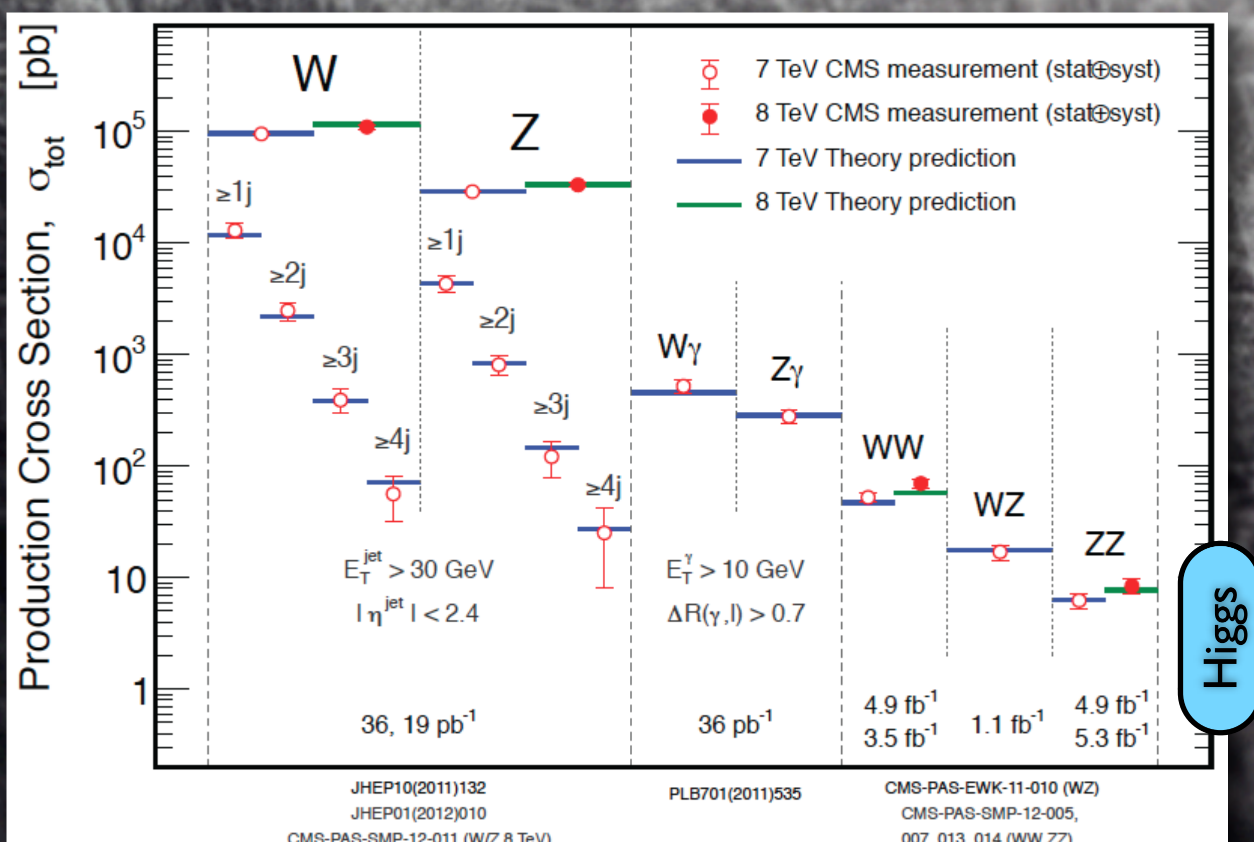


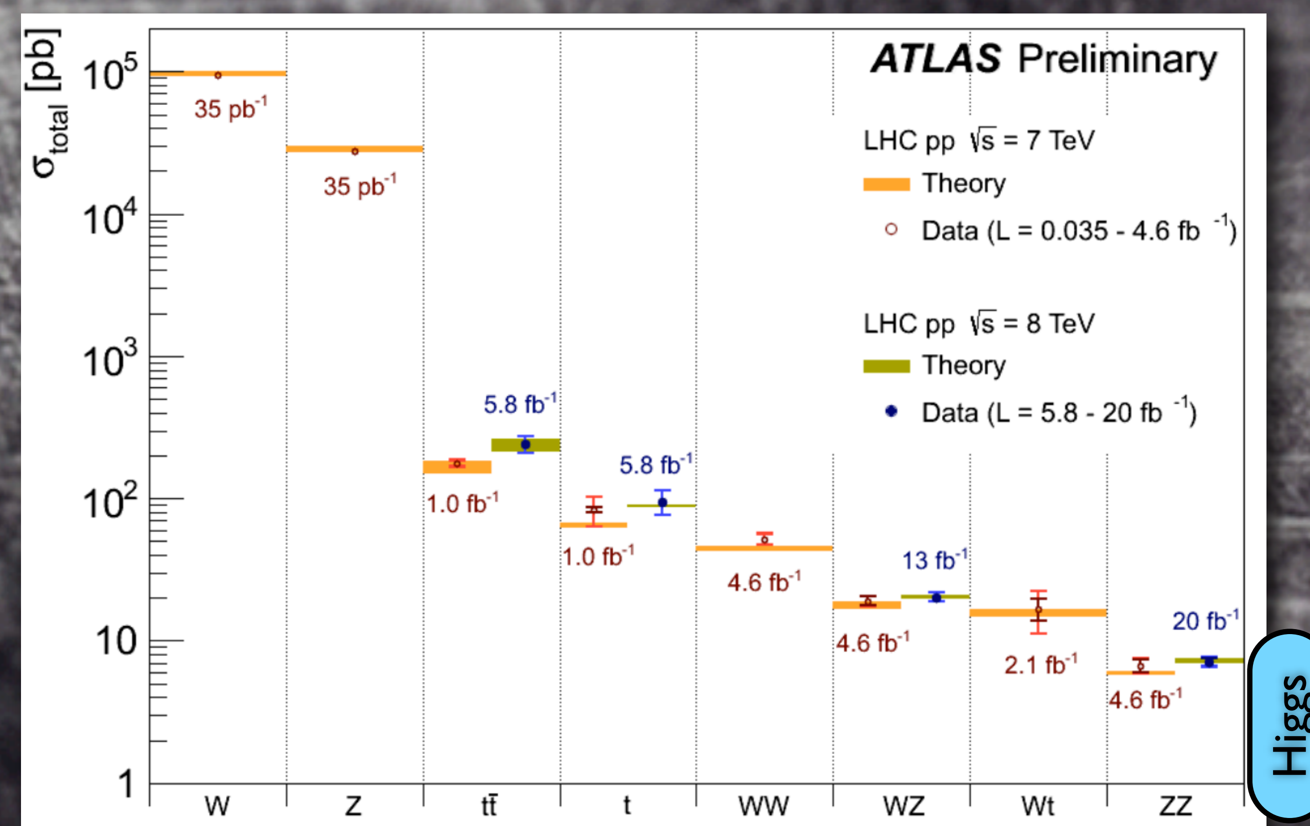
➡ Many teams, lots of people…

Key: understand SM well

See earlier presentation by J. G. da Costa

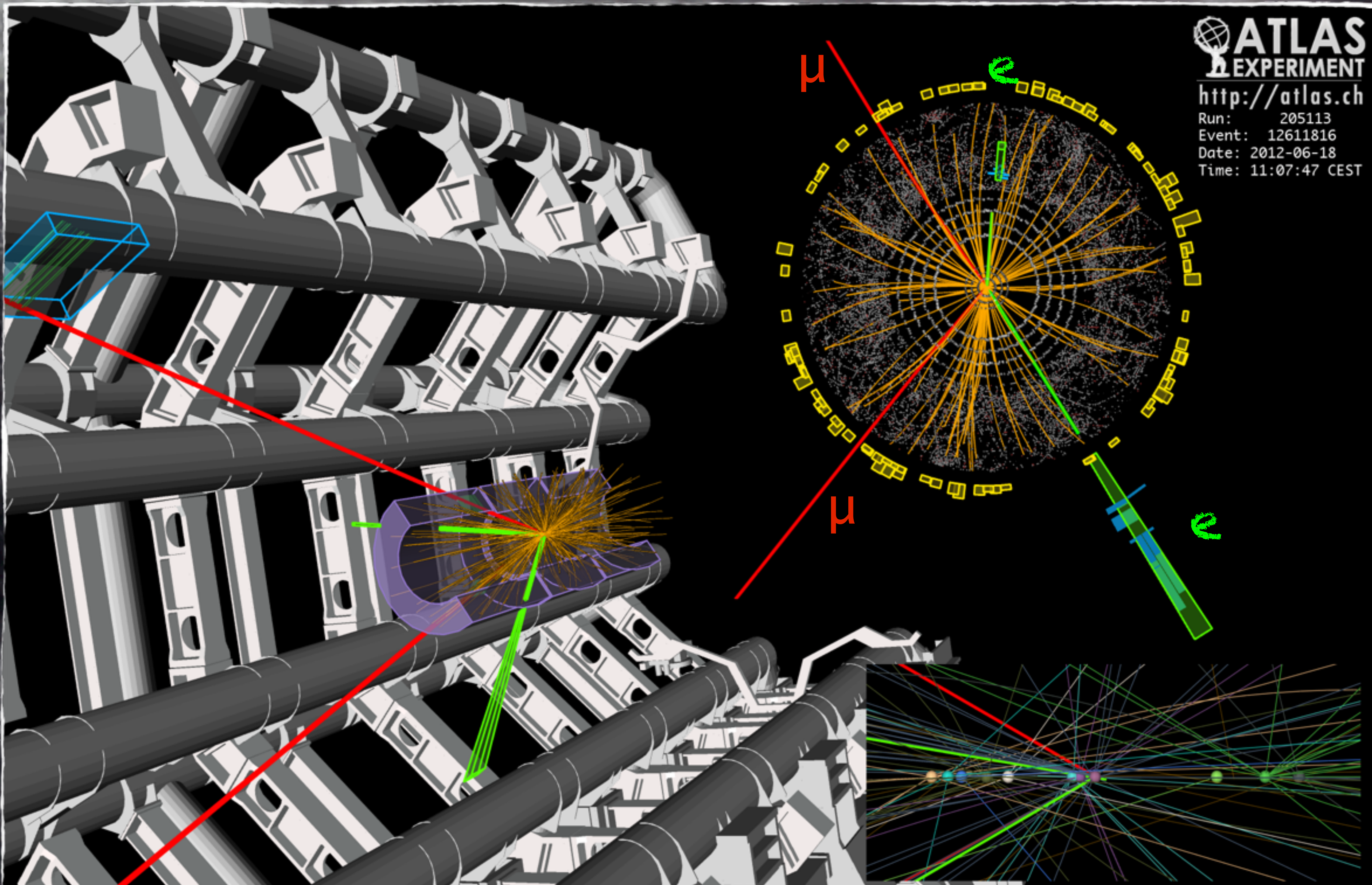
- Amazing results
  - It is also all Higgs background...





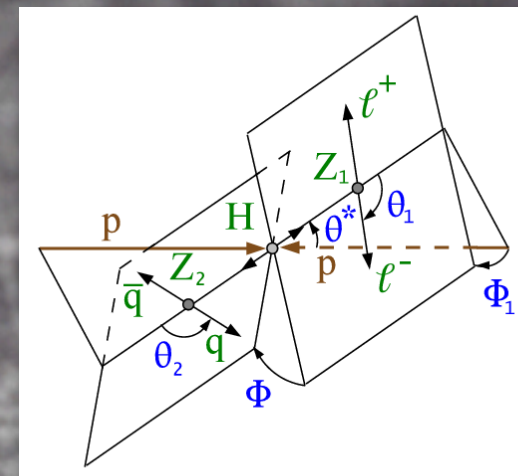
➡ Many teams, lots of people...

H => Z*Z => 4l


μ
e
μ
e
ATLAS
EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST

H => Z*Z => 4l

- **Main signature**
  - H=>Z*Z=>4l (e,mu)
  - Allow Z* for more acceptance
- **Advantages**
  - Fully reconstructed final state
    - Great m_{4l} resolution (1-2 %)
    - Higgs spin/parity measurements
  - Great S/B
  - In situ candle: Z=>4l
- **Challenge**
  - Small S
  - Keep high lepton efficiency
- **Key in analysis**
  - Inclusive & dijet tag split
- **Backgrounds**
  - ZZ (dominant)
  - fake leptons

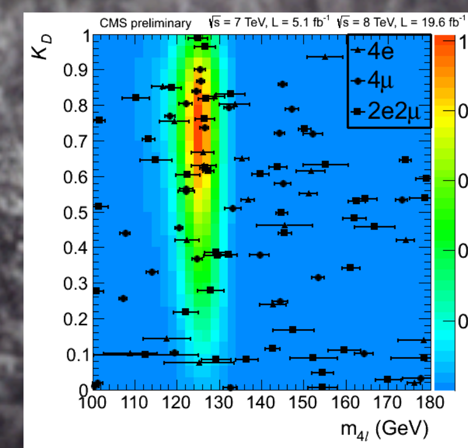


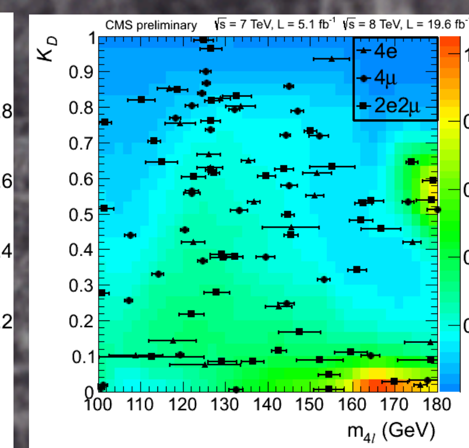
K_D = J^P kinematic discriminant

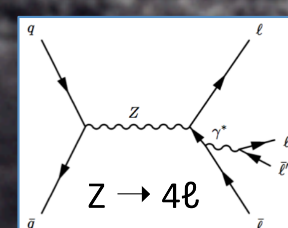
$K_D = P_S \,/\, (P_S + P_B)$

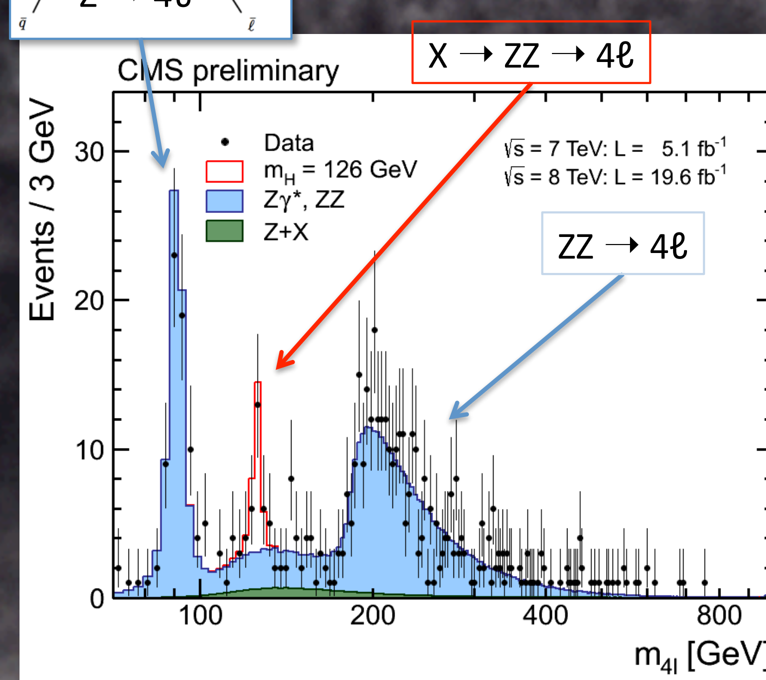
where $P_{S,B} = f(m_1, m_2, \theta_1, \theta_2, \Phi_1, \theta^*, \Phi^* \,|\, m_{4\ell})$

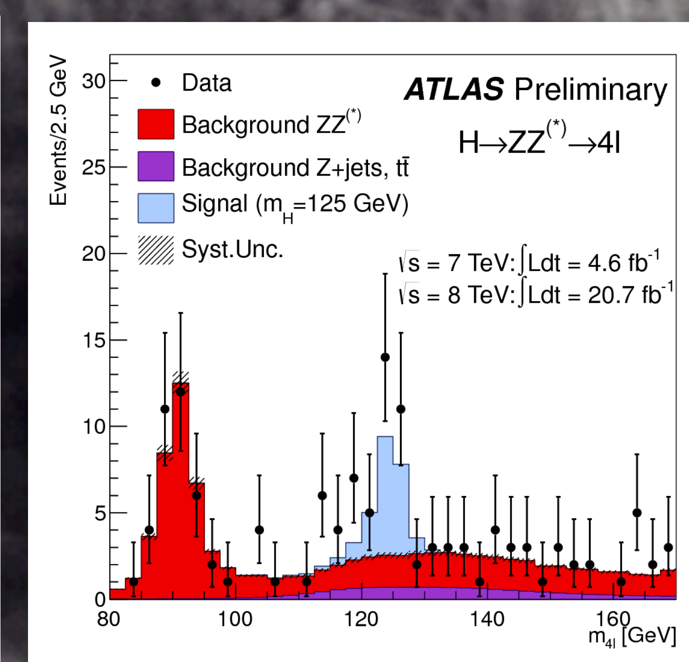
calculated from production and decay kinematics in the Z's and H rest frames.











H => Z*Z => 4l

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- **Advantages**
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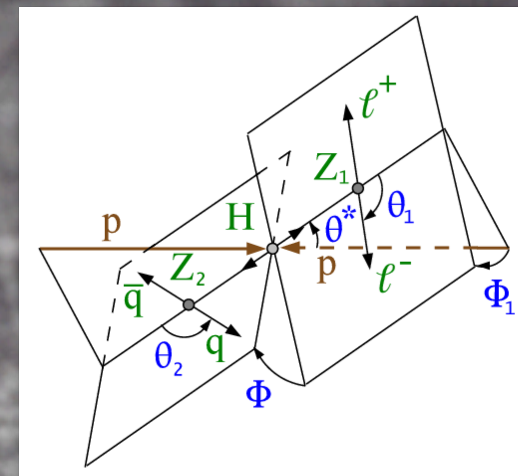
  - Inclusive & dijet tag split
- **Backgrounds**
  - ZZ (dominant)
  - fake leptons



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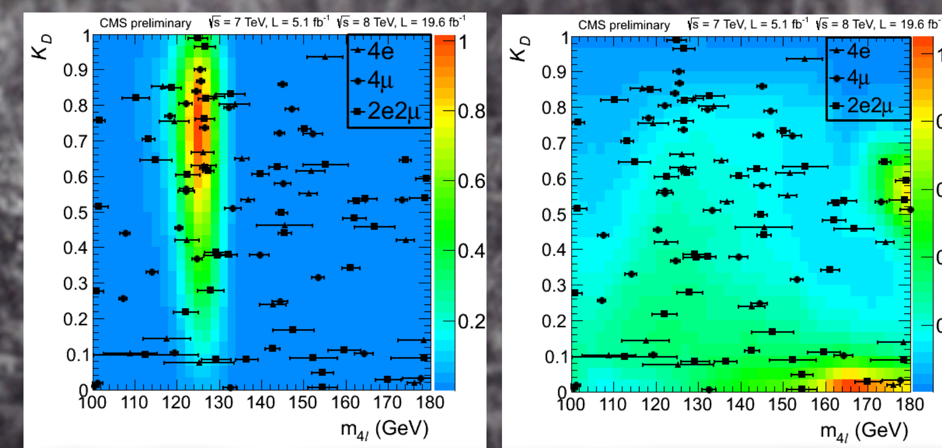
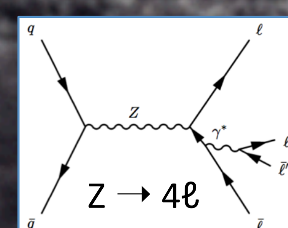
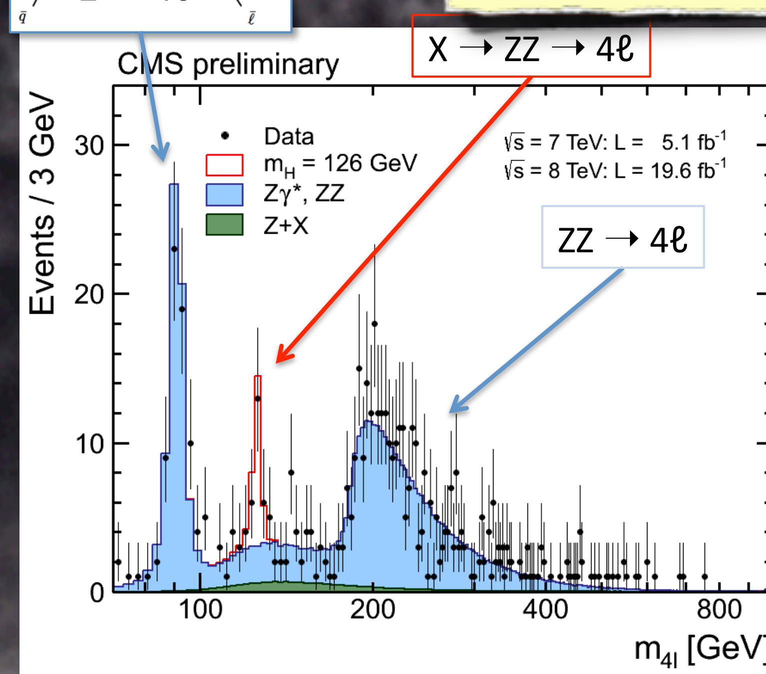
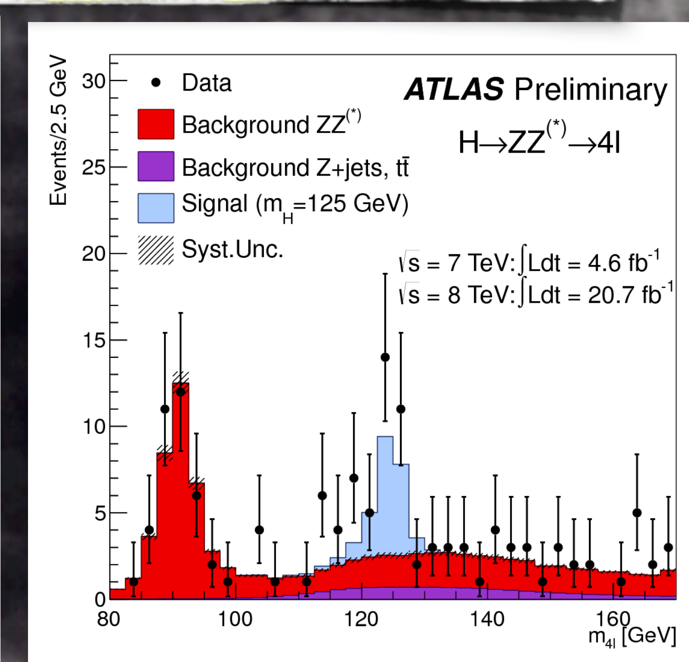


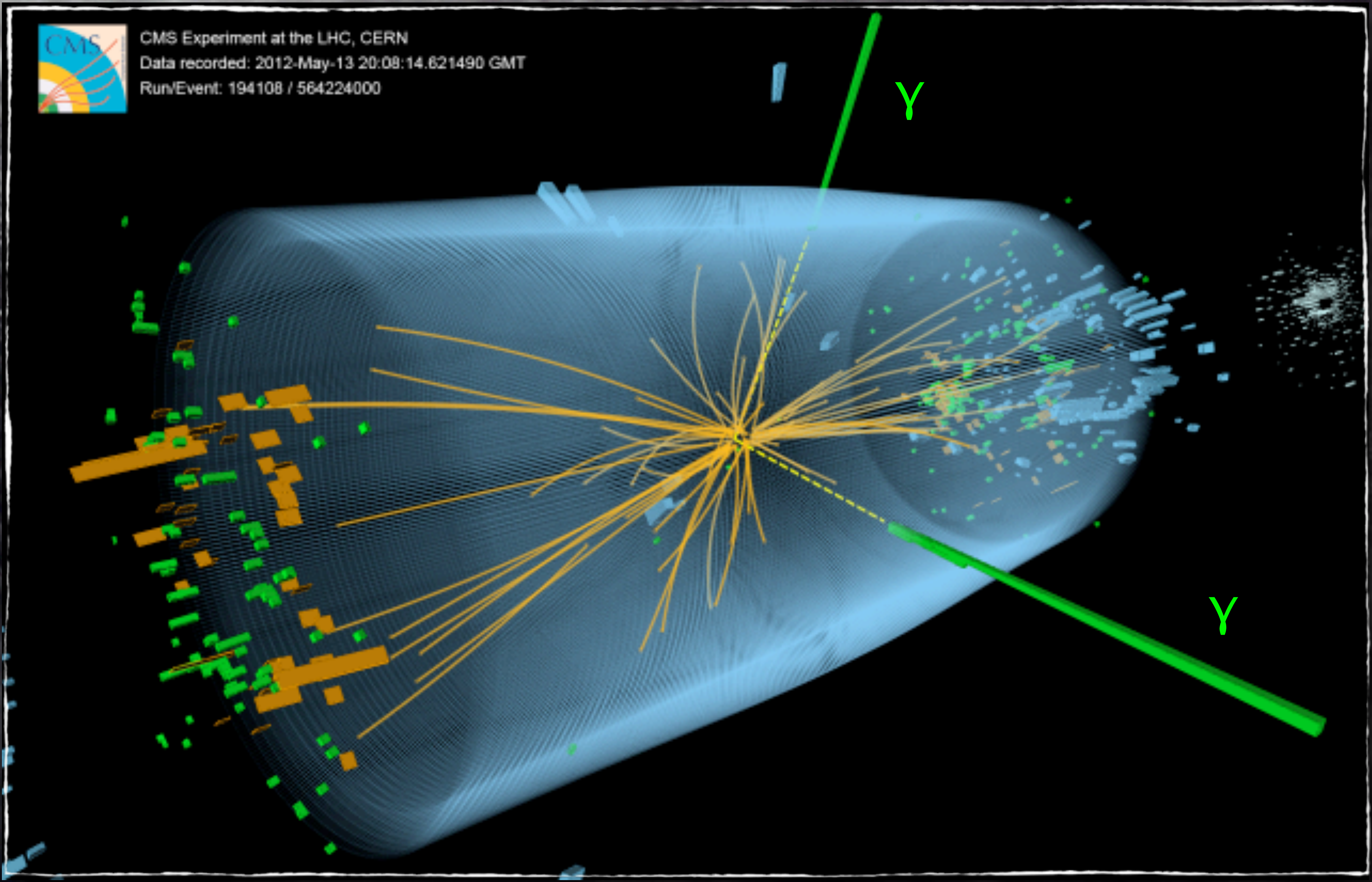
ATLAS 6.6 σ / CMS 6.7 σ





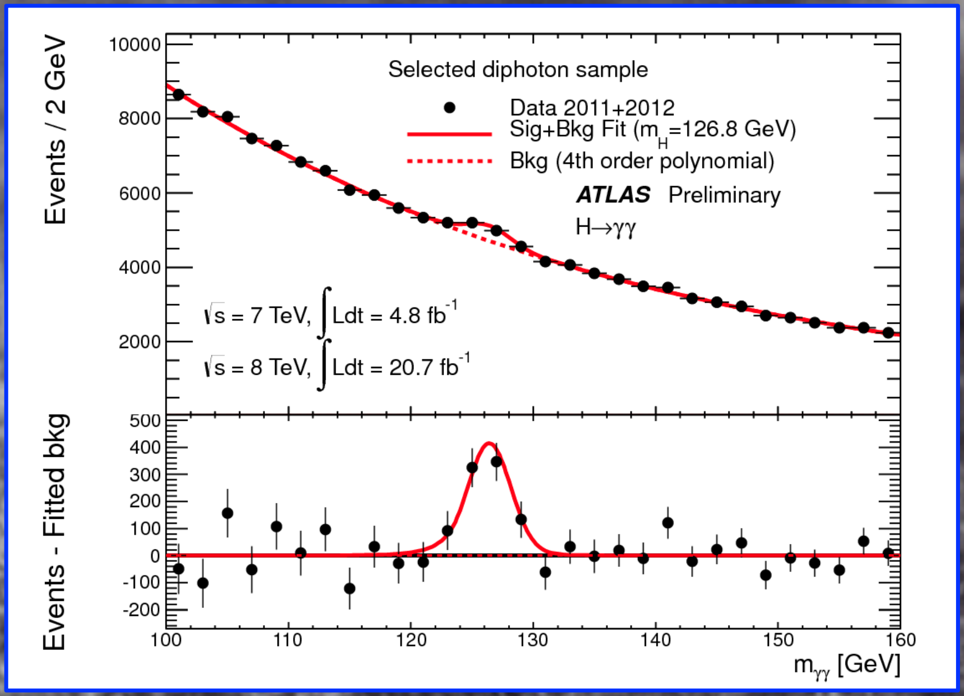


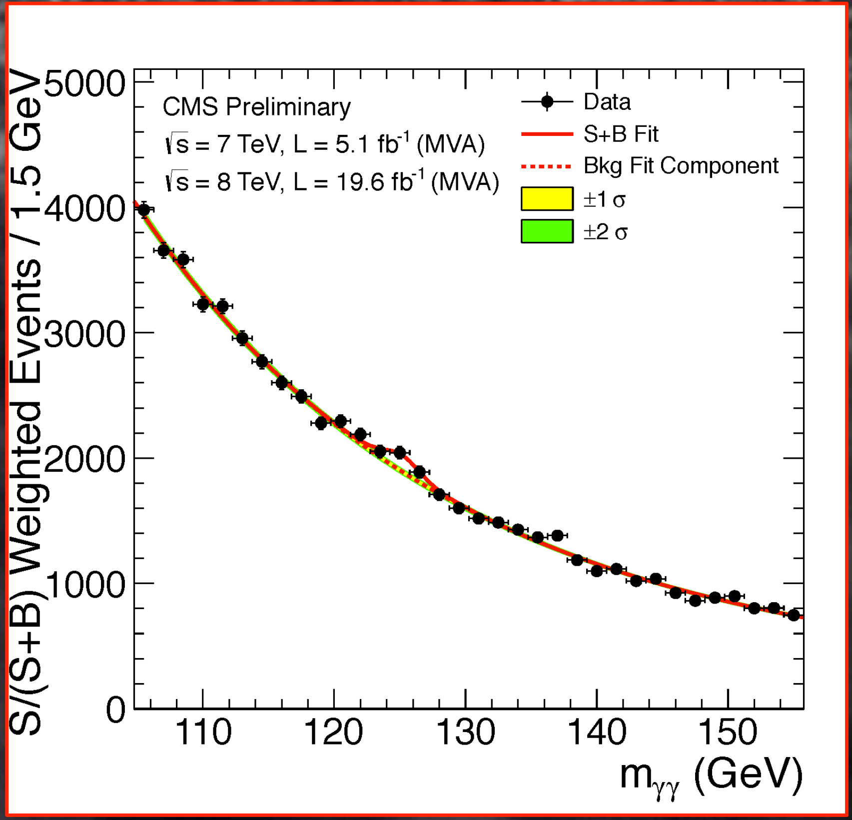
H => γγ


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
γ
γ

H => γγ

- **Main signature**
  - **Two isolated photons**
  - **Hard p_T spectrum**
- **Advantages**
  - **Fully reconstructed final state**
    - **Great $m_{\gamma\gamma}$ resolution (1-2%)**
  - **Large S (~500 evts vs ~20 ZZ)**
- **Challenge**
  - **Small S/B**
  - **Collision vertex assignment**
  - **Modeling background**
  - **Photon calibration**
- **Key in analysis**
  - **Split in tag categories**
  - **Split in resolution and S/B categories**





H => γγ

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  - Two isolated photons
  - Hard p_T spectrum
- **Advantages**
  - Fully reconstructed final state
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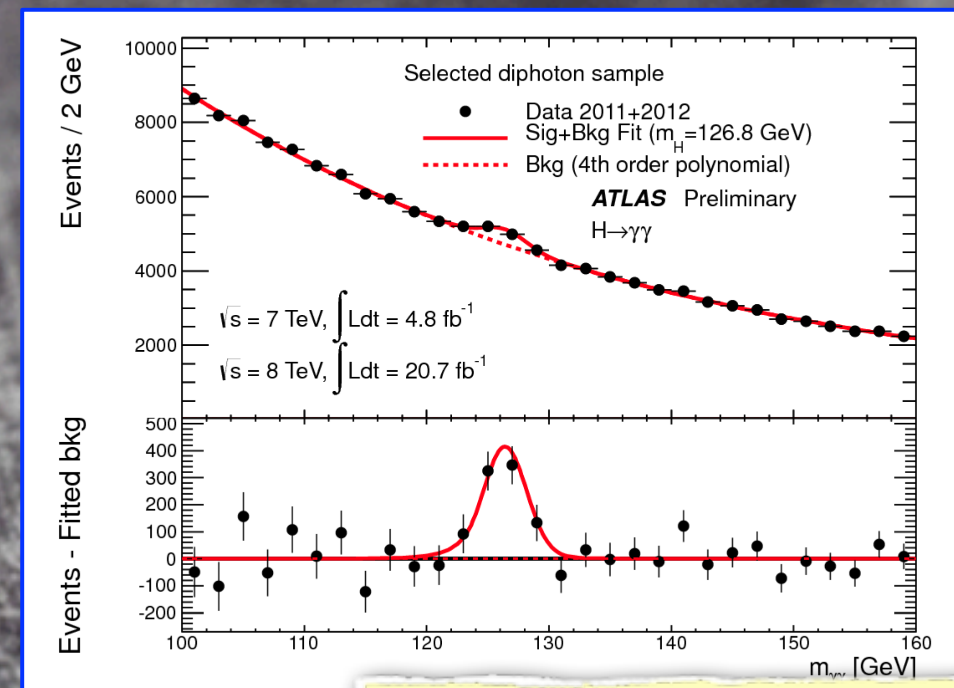
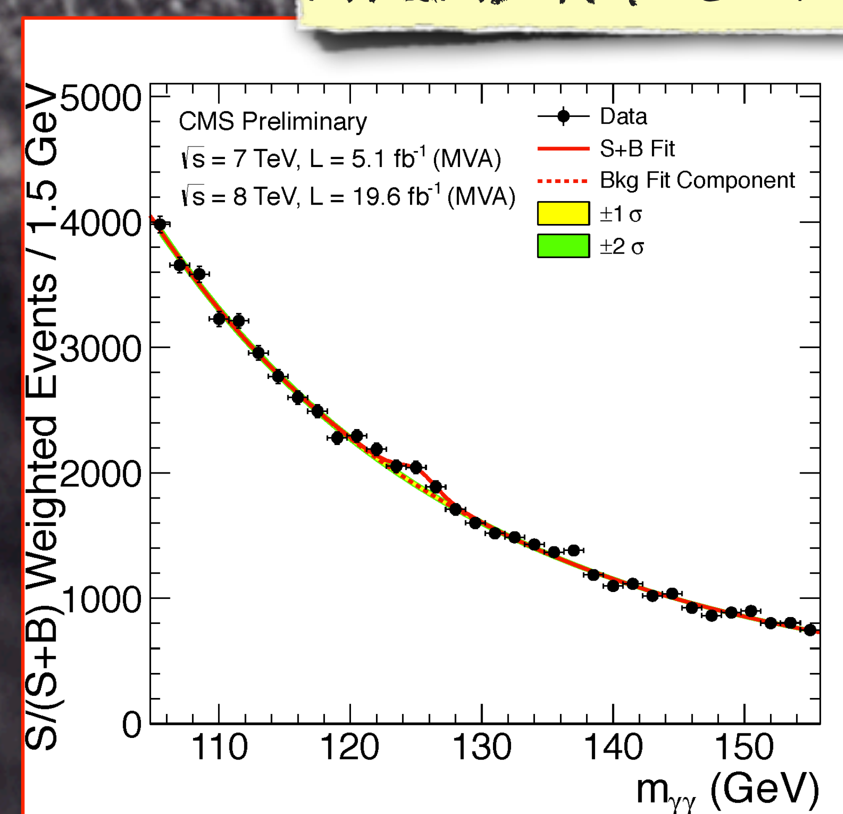
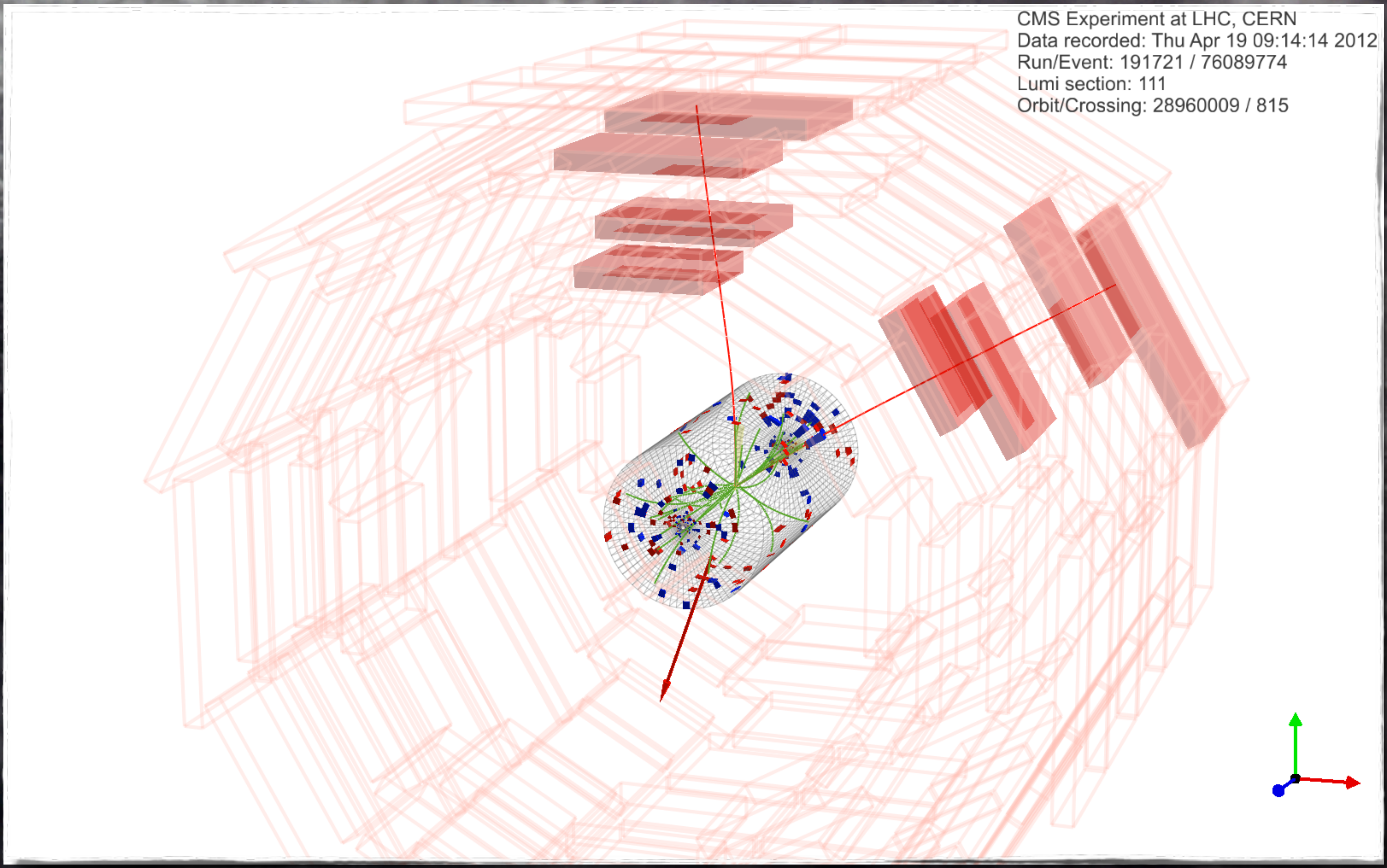
  - Large S (~500 evts vs ~20 ZZ)
- **Challenge**
  - Small S/B
  - Collision vertex assignment
  - Modeling background
  - Photon calibration
- **Key in analysis**
  - Split in tag categories
  - Split in resolution and S/B categories



ATLAS 7.4 σ / CMS 3.9 σ

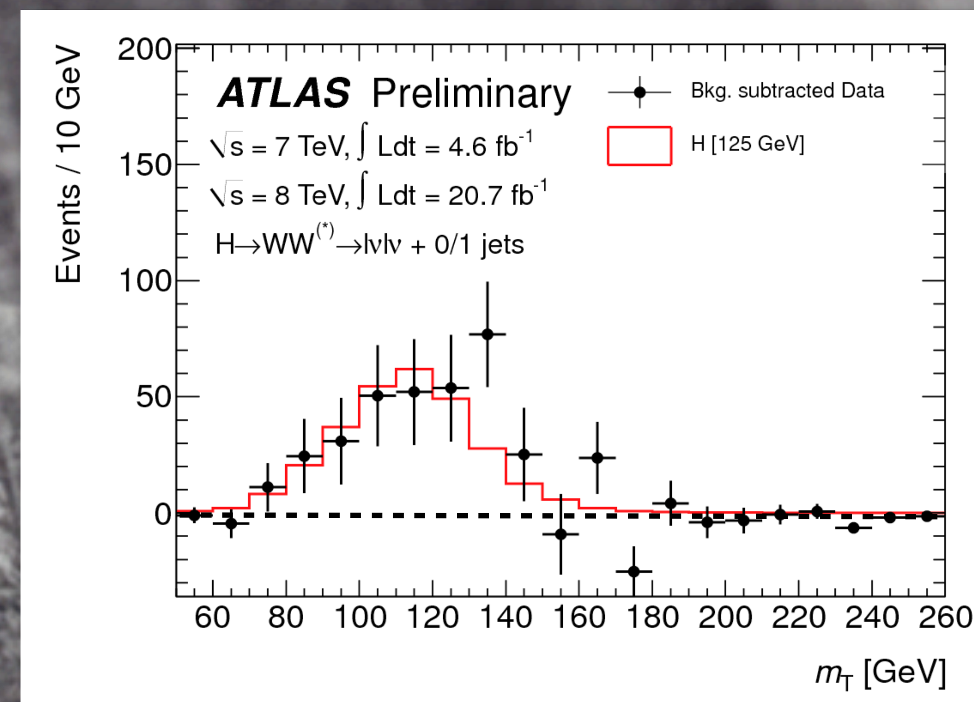


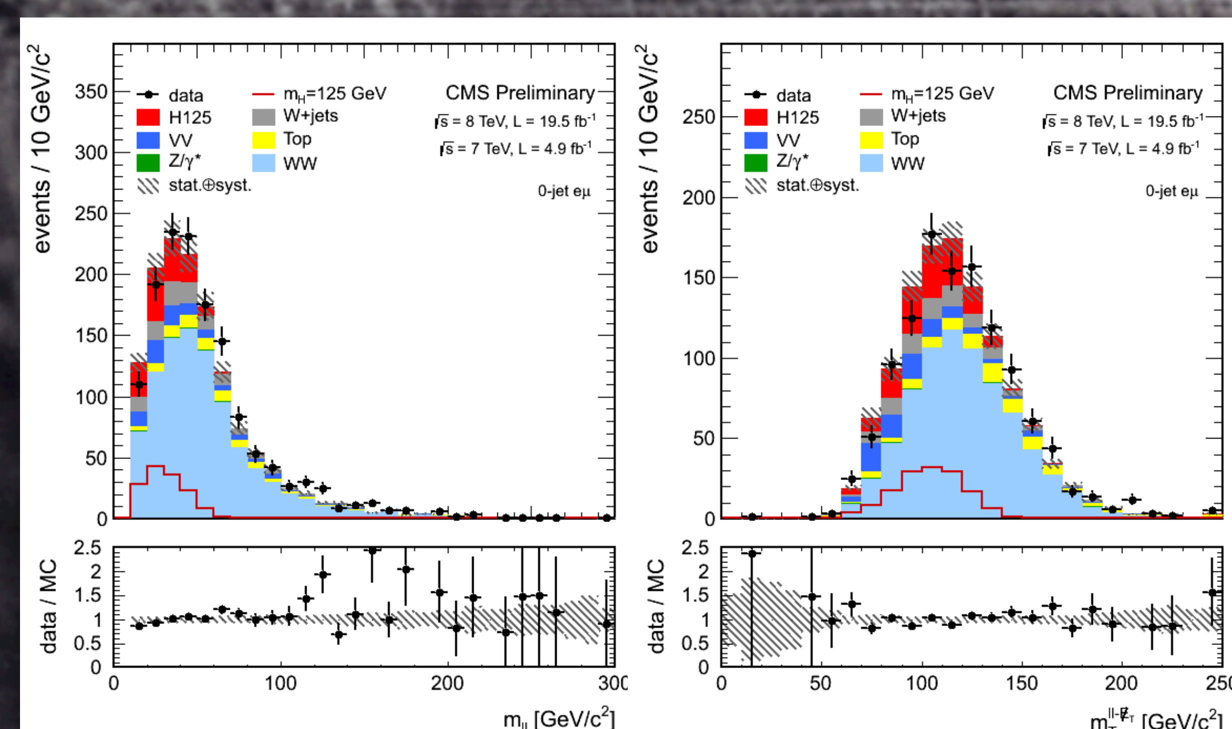
H => WW => lnu,lnu


CMS Experiment at LHC, CERN
Data recorded: Thu Apr 19 09:14:14 2012
Run/Event: 191721 / 76089774
Lumi section: 111
Orbit/Crossing: 28960009 / 815

H => WW => lnu,lnu

- **Main signature**
  - Two high p_T isolated leptons
  - Missing transverse energy: MET
- **Advantages**
  - OK S
  - OK S/B
  - Kinematical handles (M_{ll}, M_T)
- **Challenge**
  - No sharp mass peak (MET)
  - Some 20% resolution on M_T
- **Key in analysis**
  - Split in jet categories
  - Split in lepton flavors
- **Backgrounds**
  - WW, tt, W+jets, DY+jets, dibosons



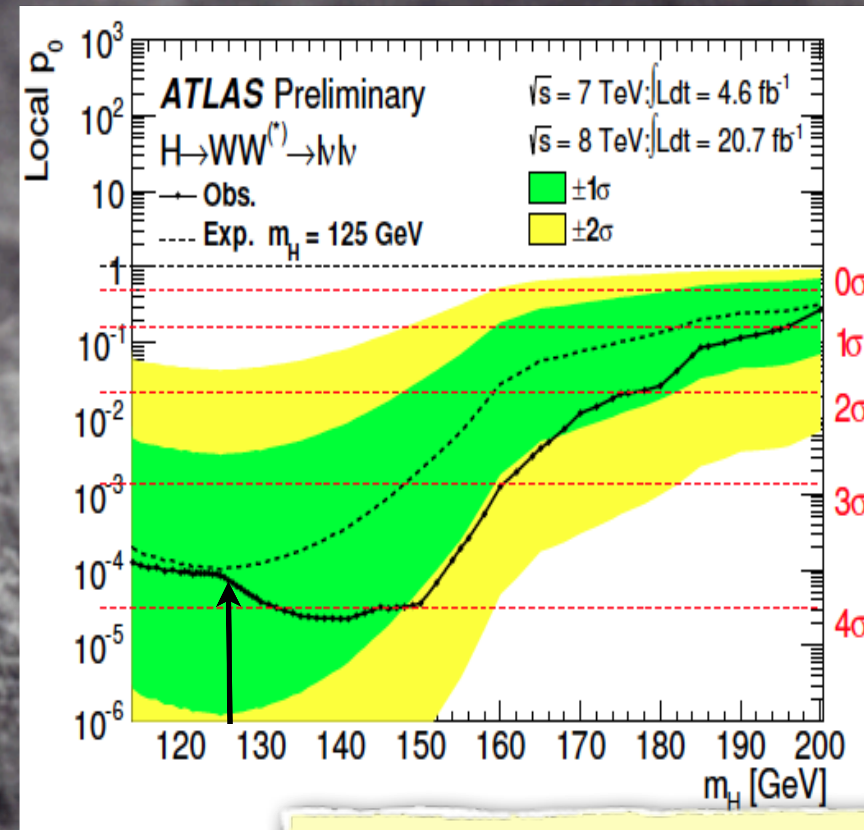


Mll

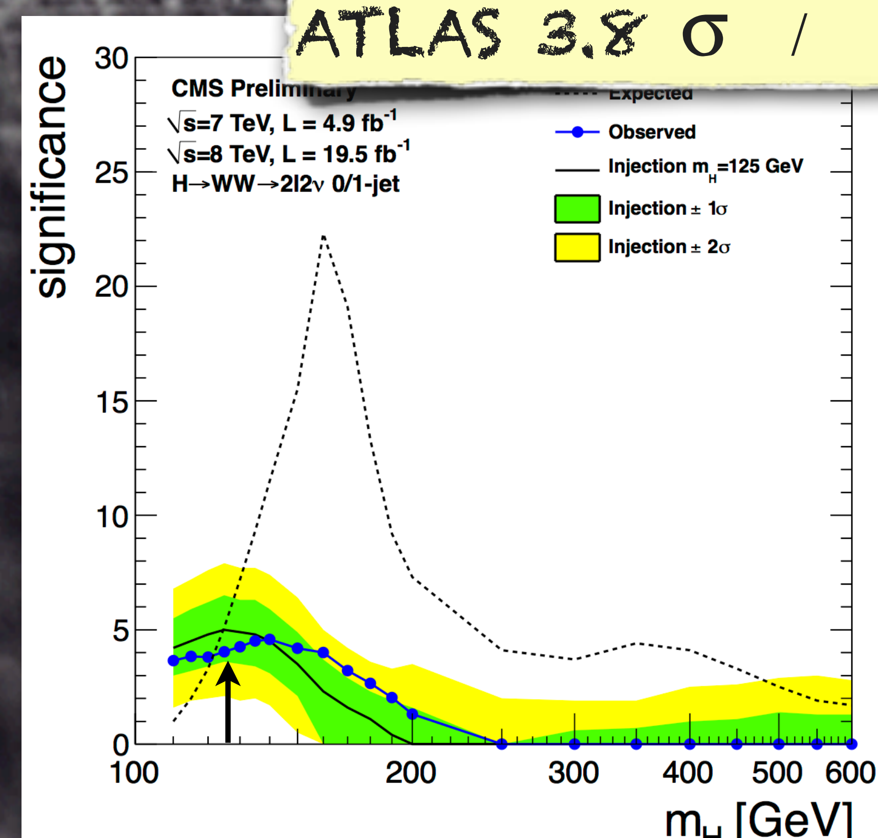
MT

H => WW => lnu,lnu

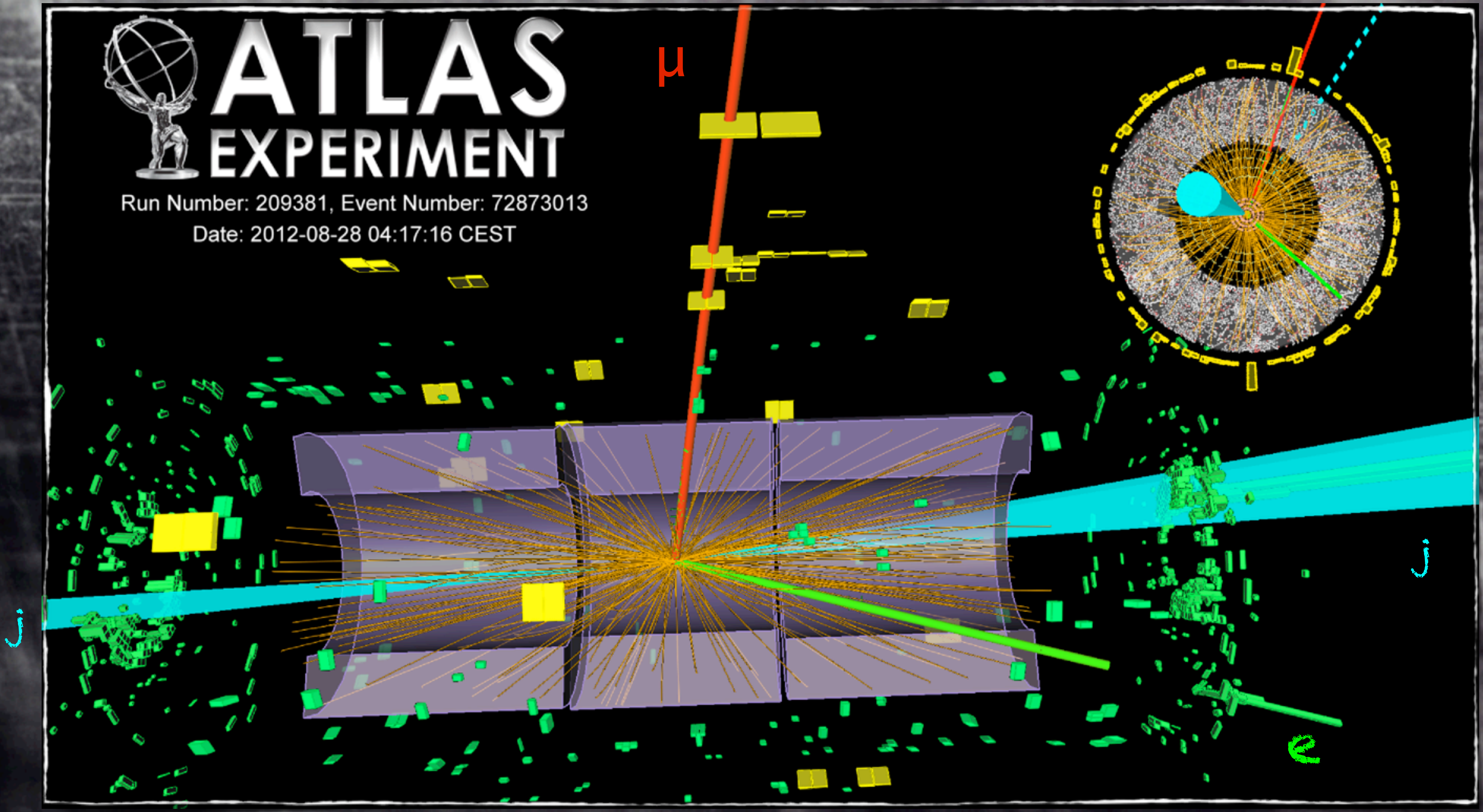
- **Main signature**
  - Two high p_T isolated leptons
  - Missing transverse energy: MET
- **Advantages**
  - Large SxBR
  - OK S/B
  - Kinematical handles (M_{ll}, M_T)
- **Challenge**
  - No sharp mass peak (MET)
  - Some 20% resolution on M_T
- **Key in analysis**
  - Split in jet categories
  - Split in lepton flavors
- **Backgrounds**
  - WW, tt, W+jets, DY+jets, dibosons



ATLAS 3.8 σ / CMS 3.9 σ



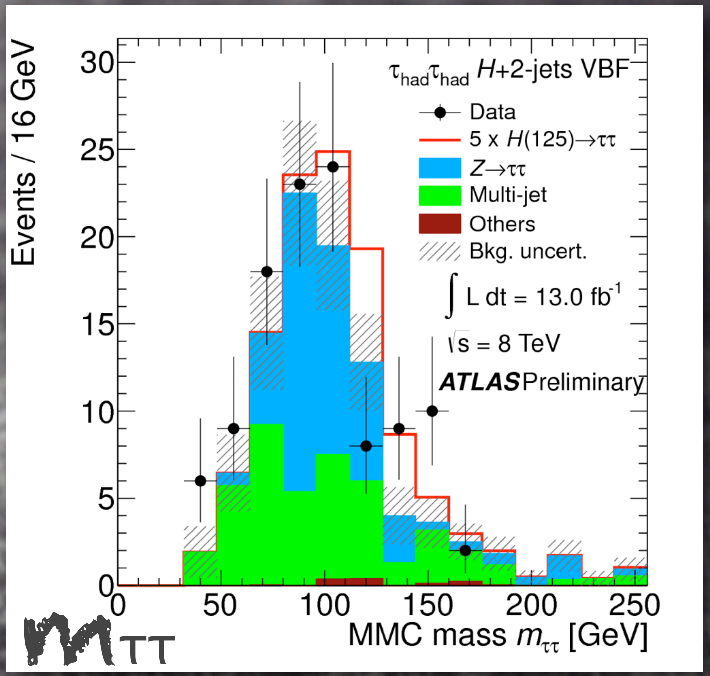
H => ττ

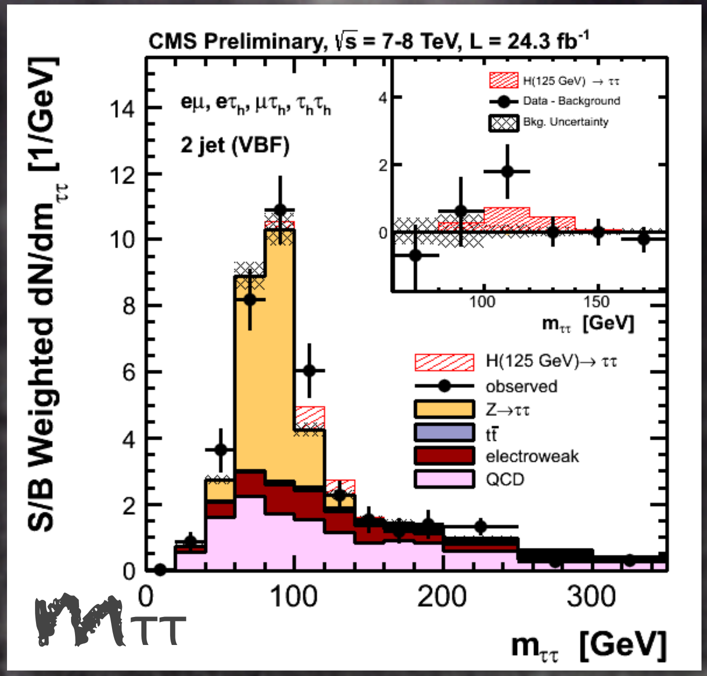


VBF candidate with H=>τ(e)τ(μ)

H => ττ

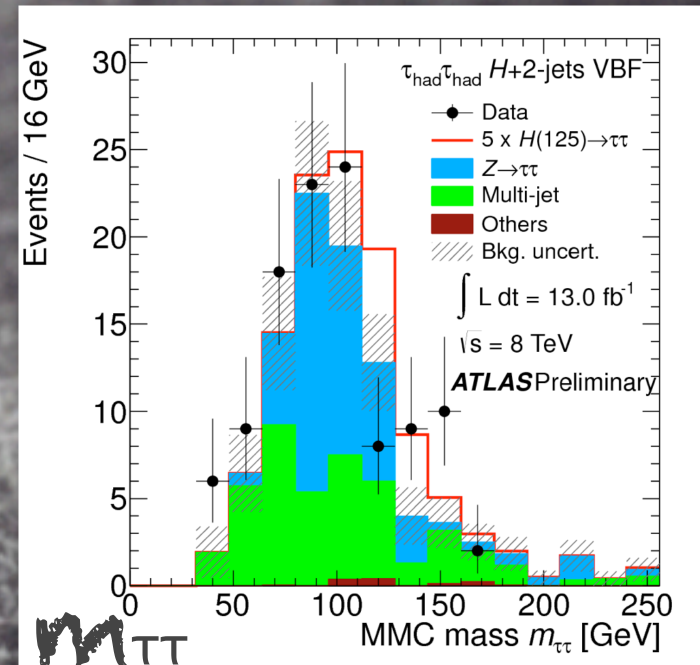
- Main signature
  - H=>ττ (with τ_h and leptonic decays)
- Advantages
  - Test down-type f couplings w/ H=>bb
  - Only direct H=>leptons probe
- Challenge
  - Very small S
  - Control τ_h ID
  - Reconstruct ττ mass
- Key in analysis
  - Can calibrate with Z=>ττ
  - Split by Nj, p_T(j) and VBF
- Backgrounds
  - Z=>ττ, QCD

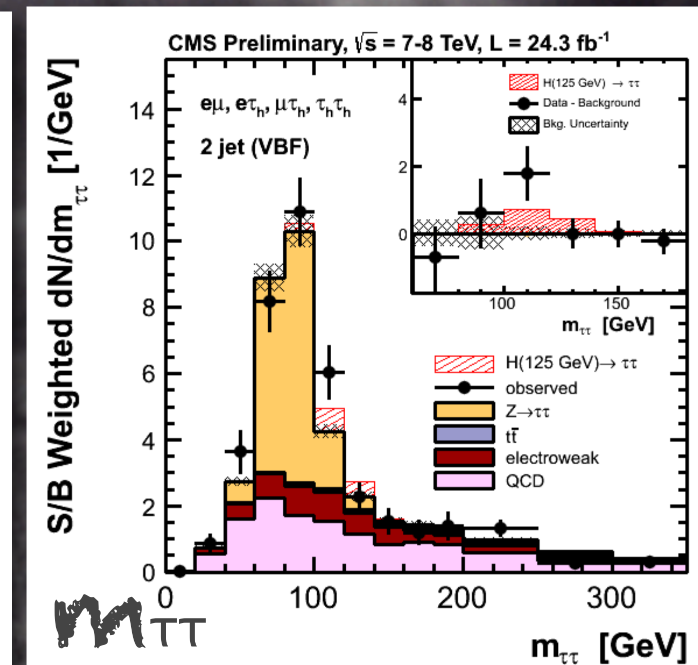


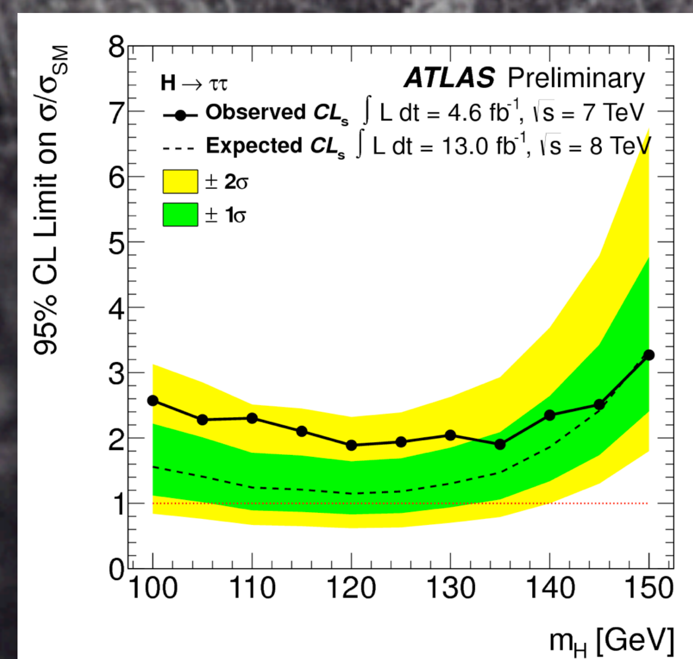


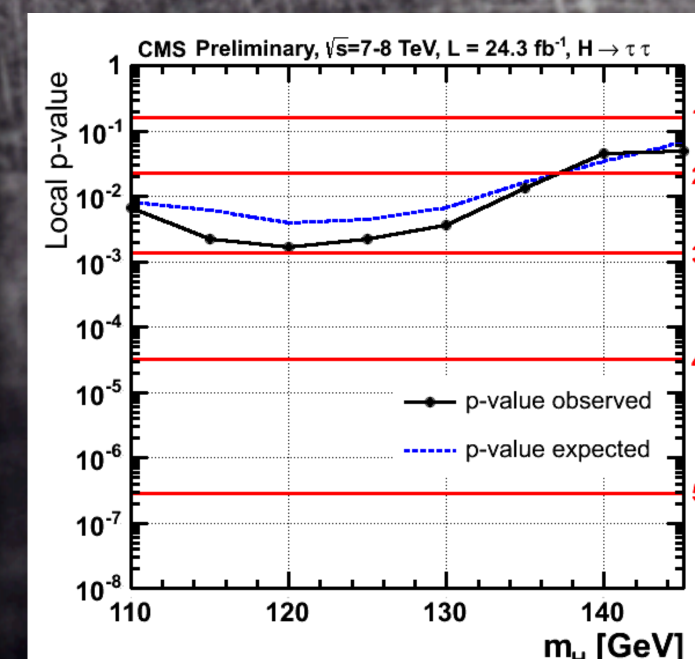
H => ττ

- Main signature
  - H=>ττ (with τ_h and leptonic decays)
- Advantages
  - Test down-type f couplings w/ H=>bb
  - Only direct H=>leptons probe
- Challenge
  - Very small S
  - Control τ_h ID
  - Reconstruct ττ mass
- Key in analysis
  - Can calibrate with Z=>ττ
  - Split by Nj, p_T(j) and VBF
- Backgrounds
  - Z=>ττ, QCD



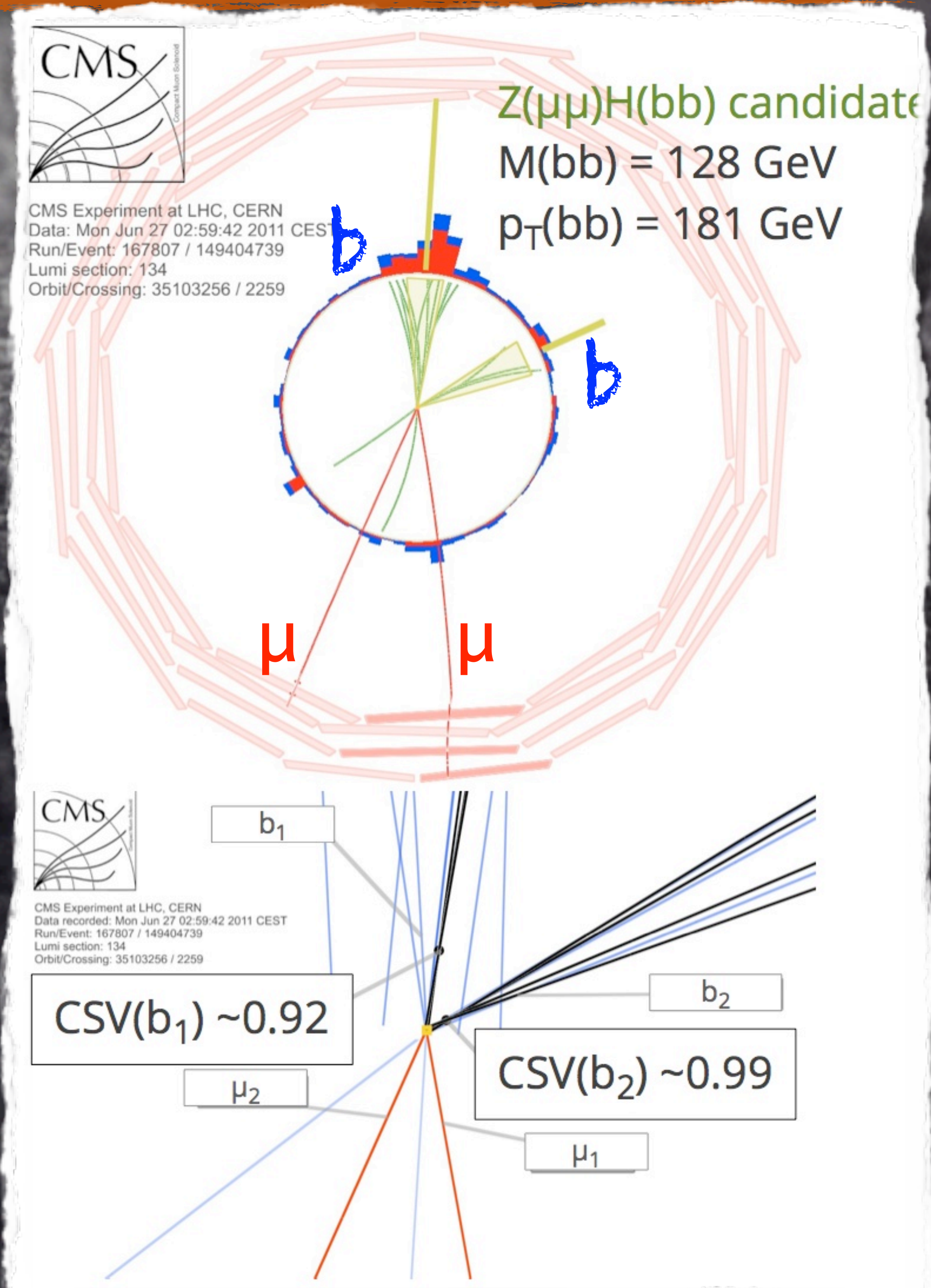






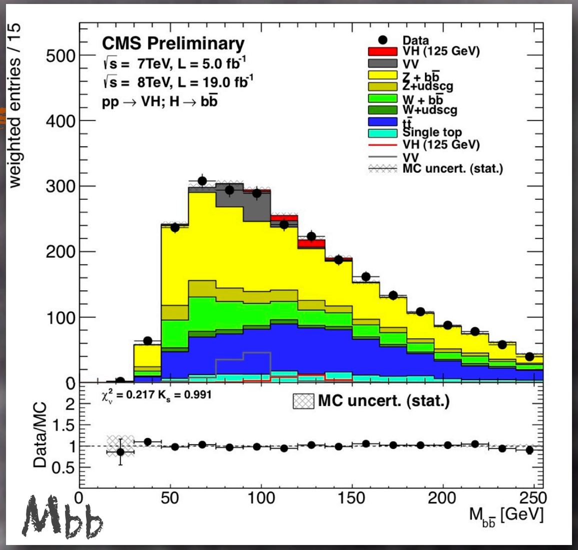
ATLAS 1.1 σ / CMS 2.8 σ

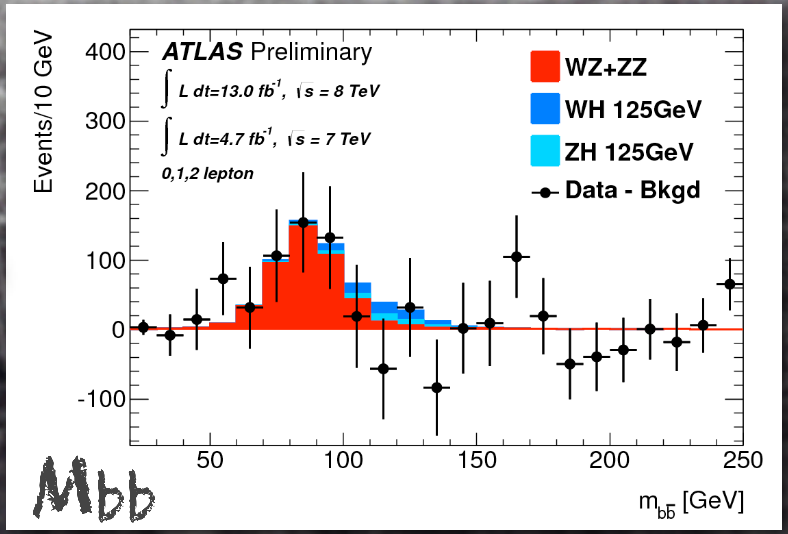
H => bb

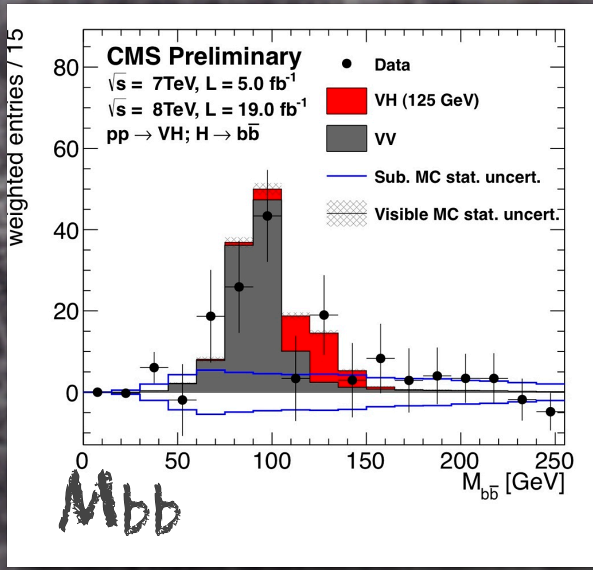

CMS
CMS Experiment at LHC, CERN
Data: Mon Jun 27 02:59:42 2011 CEST
Run/Event: 167807 / 149404739
Lumi section: 134
Orbit/Crossing: 35103256 / 2259
Z(μμ)H(bb) candidate
M(bb) = 128 GeV
pT(bb) = 181 GeV
b
b
μ
μ
CMS
CMS Experiment at LHC, CERN
Data recorded: Mon Jun 27 02:59:42 2011 CEST
Run/Event: 167807 / 149404739
Lumi section: 134
Orbit/Crossing: 35103256 / 2259
b1
b2
CSV(b1) ~0.92
CSV(b2) ~0.99
μ2
μ1

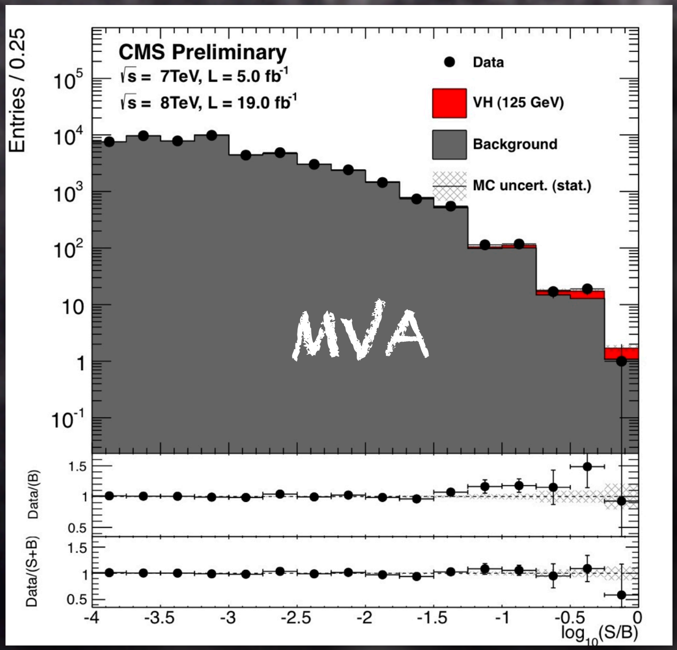
H => bb

- **Main signature**
  - ZH/WH with Z(ll,νν)/W(lν)
    - ttH(bb) and VBF H(hh) also!
- **Advantages**
  - Largest Higgs BR
  - Direct coupling to down quark sector
  - Measure VZ(bb) !
- **Challenge**
  - Poor S/B
- **Key in analysis**
  - Sensitivity through boosted H/V
  - B-tagging
  - Improve bb mass resolution (~10%)
  - Multi-variate analysis
- **Backgrounds**
  - top, V+jets, V+HF, dibosons, QCD









H => bb

- **Main signature**
  - ZH/WH with Z(ll,νν)/W(lν)
    - ttH(bb) and VBF H(hh) also!
- **Advantages**
  - Largest Higgs BR
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  - Improve bb mass resolution (~10%)
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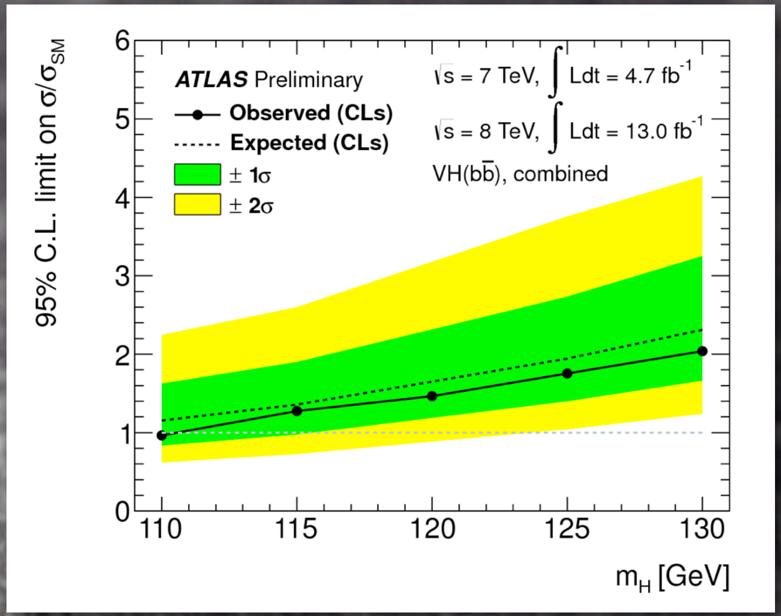
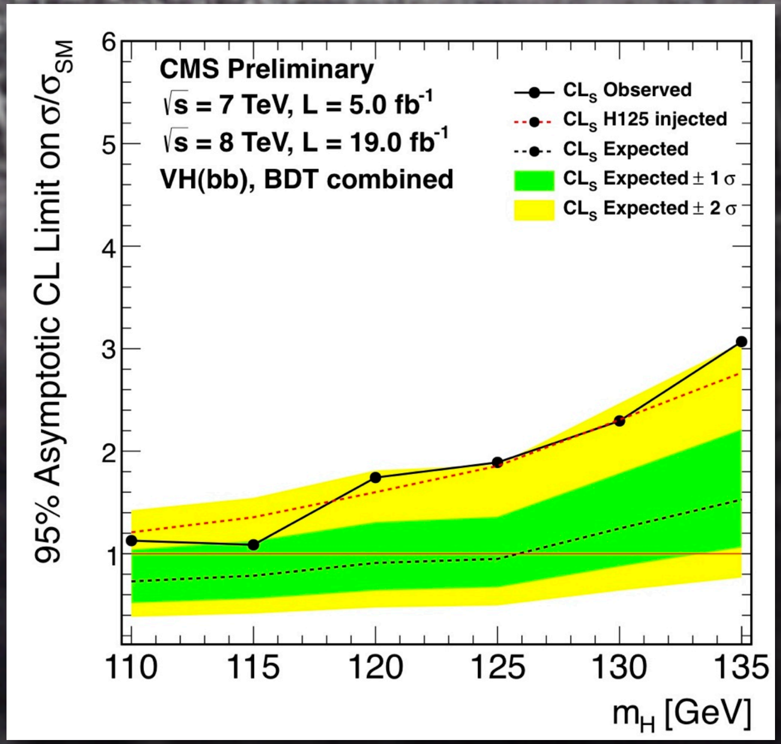
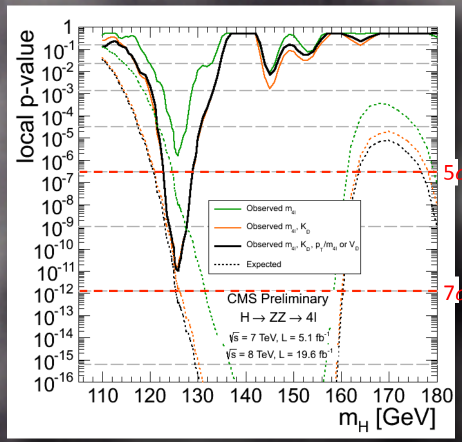
  - Measure VZ(bb) !
- **Backgrounds**
  - top, V+jets, V+HF, dibosons, QCD





ATLAS -0.4 σ / CMS 2.1 σ

Significance summary

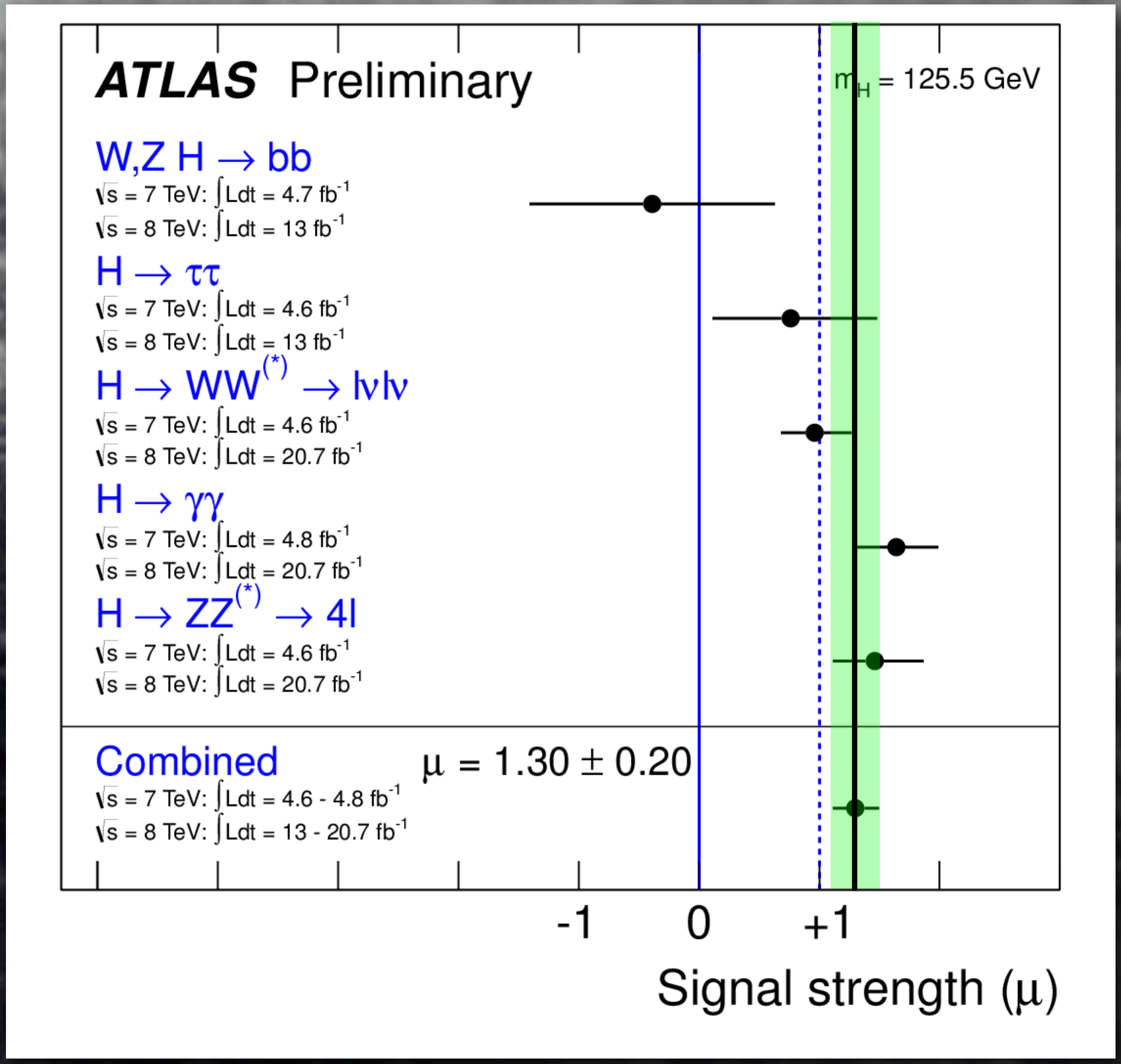


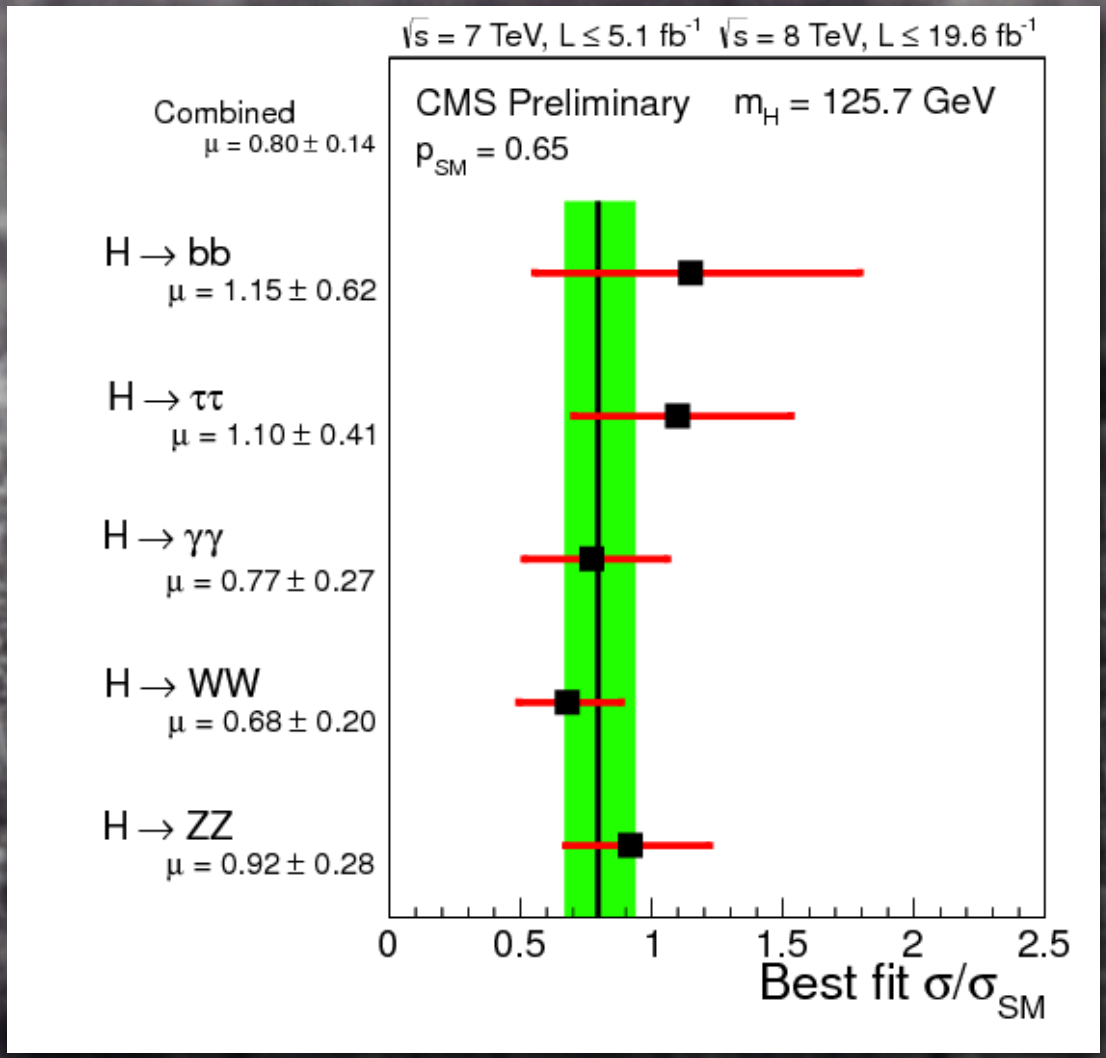
	bosonic decays			fermionic decays	
Significance Obs. (pre-fit exp.)	**H⟶ZZ**	**H⟶$\gamma\gamma$**	**H⟶WW**	**H⟶$b\bar{b}$**	**H⟶$\tau\tau$**
ATLAS	**6.6 σ** (4.4 σ)	**7.4 σ** (4.1 σ)	**3.8 σ** (3.7 σ)	-0.4 σ (**1.0** σ)	1.1 σ (**1.7** σ)
	124.3 GeV	*126.8 GeV*		*125 GeV*	
CMS	6.7 σ (**7.1** σ)	3.9 σ (**4.2** σ)	3.9 σ (**5.6** σ)	2.1 σ (**2.1** σ)	**2.8 σ** (2.7 σ)
			125.7 GeV		

a.david@cern.ch

- Higgs decays to bosons are the smoking gun
- The fermionic decays start to show up

Signal strength (μ) summary





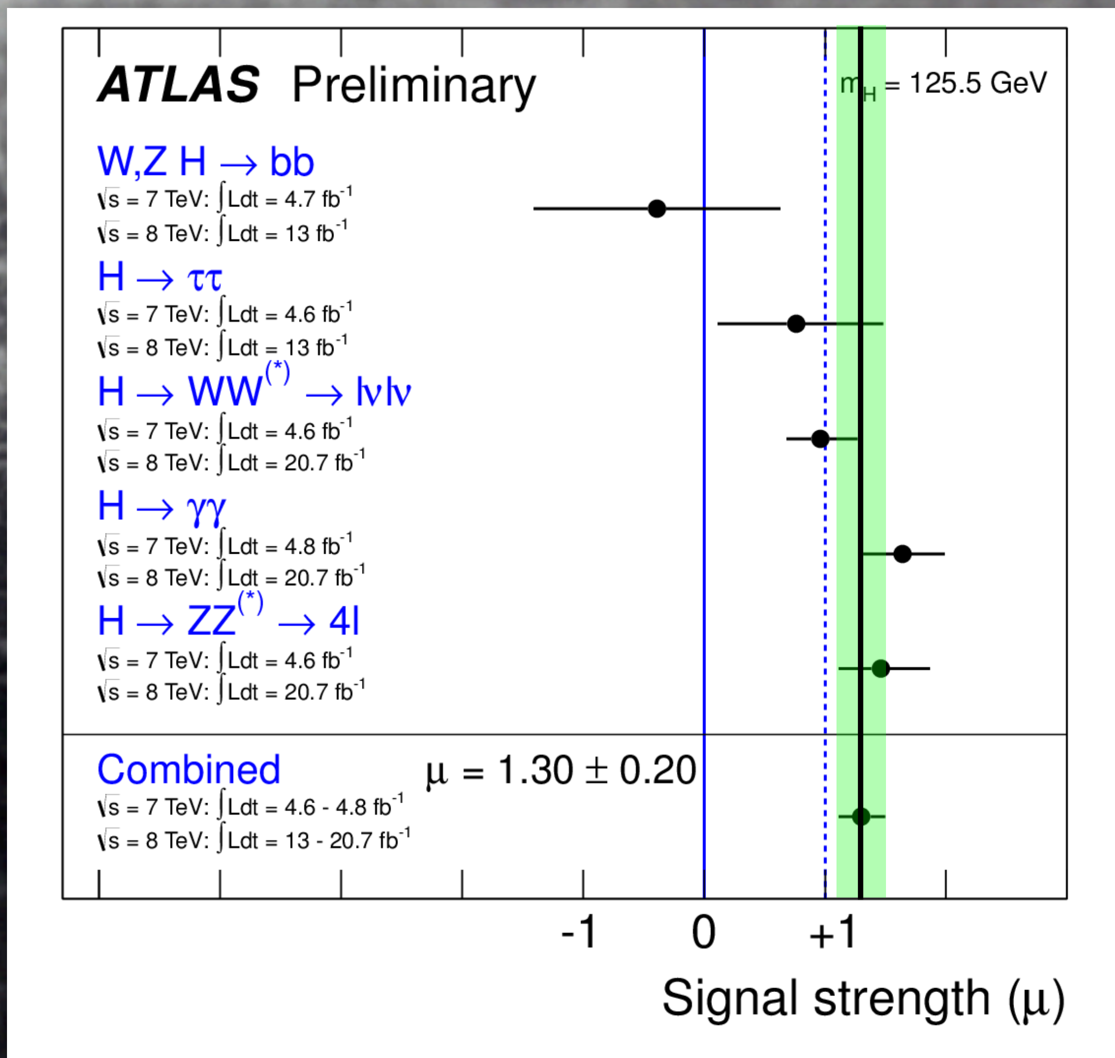
$\mu = 1.30 \pm 0.20$

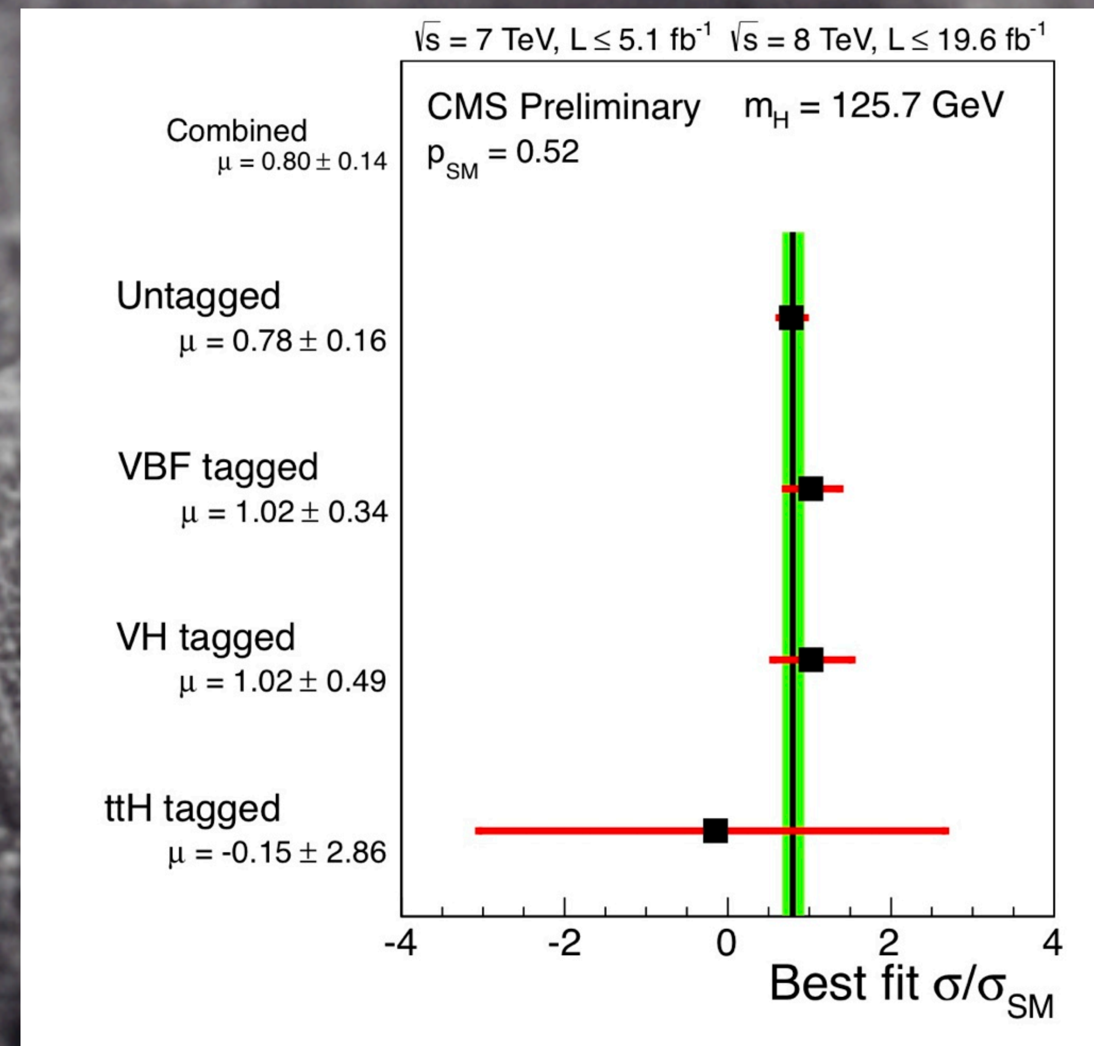
$\mu = 0.8 \pm 0.14$

Consistency across decay modes, within uncertainties

Note: μ is the measured process rate relative to SM prediction

Signal strength (μ) summary





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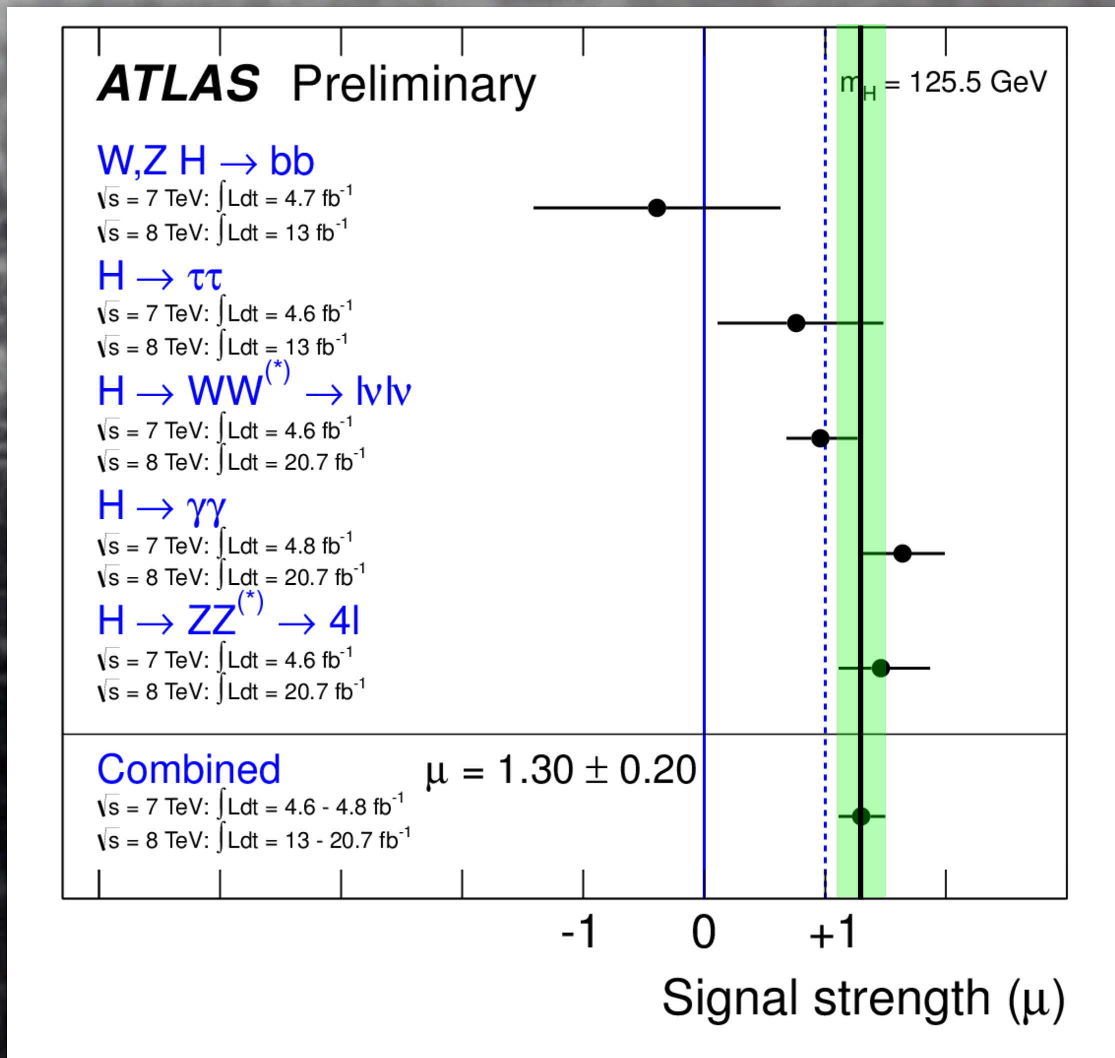
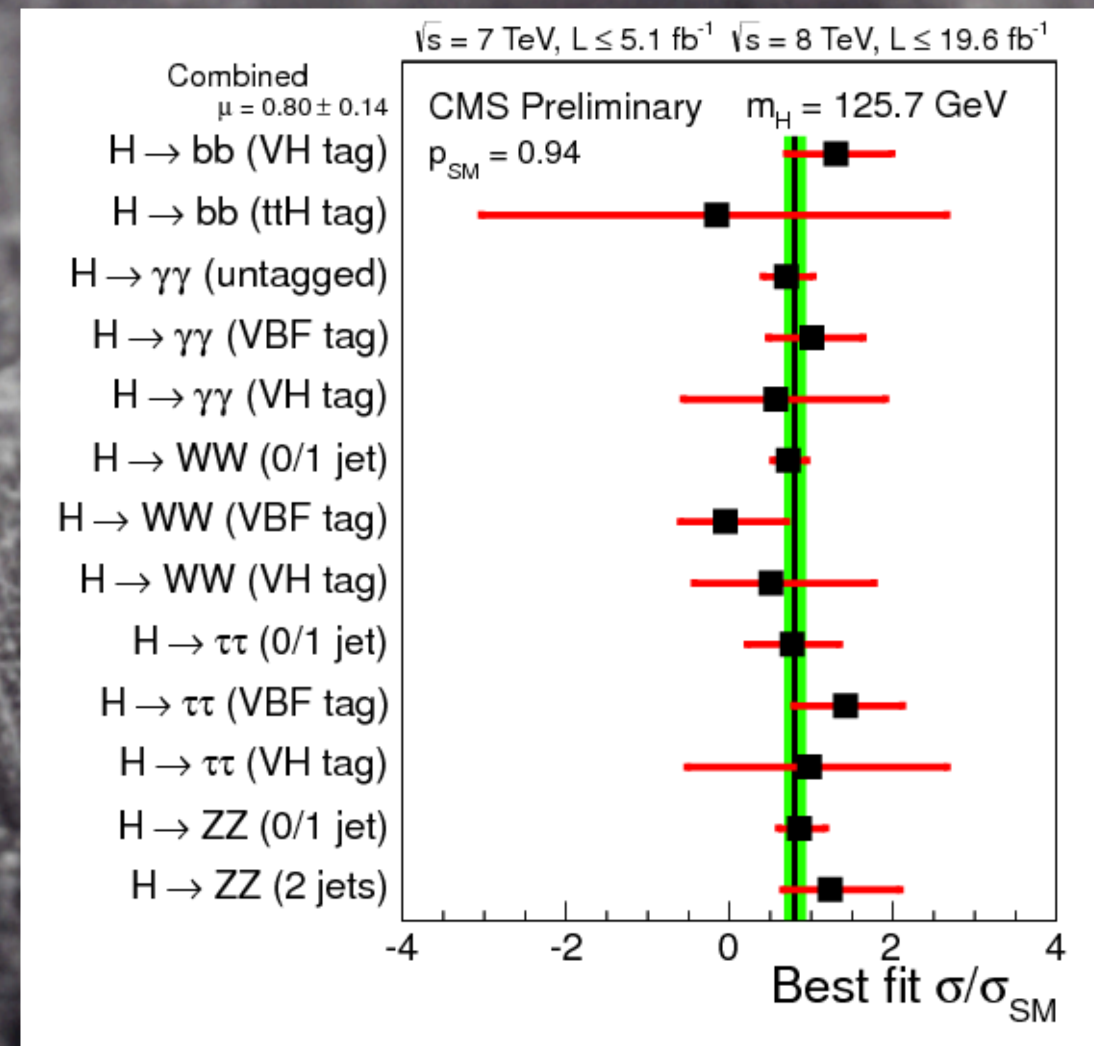
Signal strength (μ) summary





μ = 1.30 ±0.20

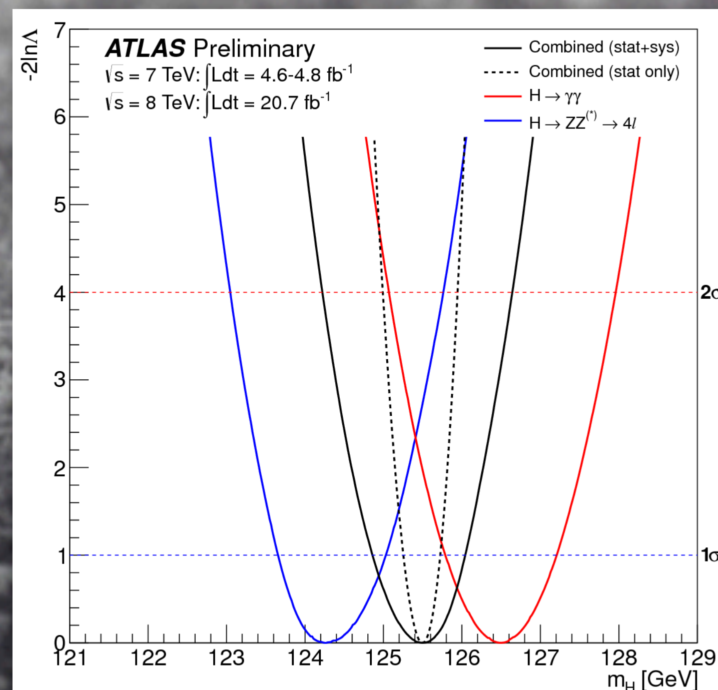
μ = 0.8 ±0.14

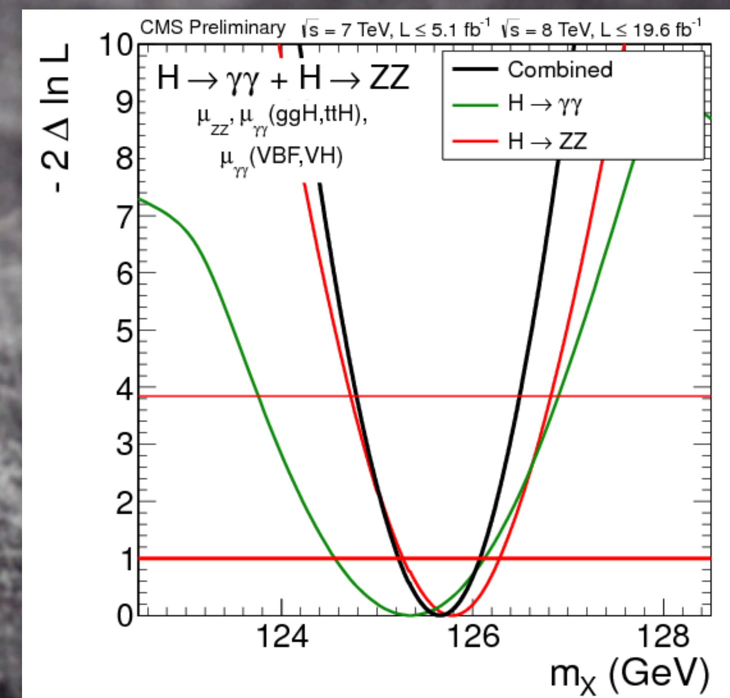
Consistency across decay modes, within uncertainties

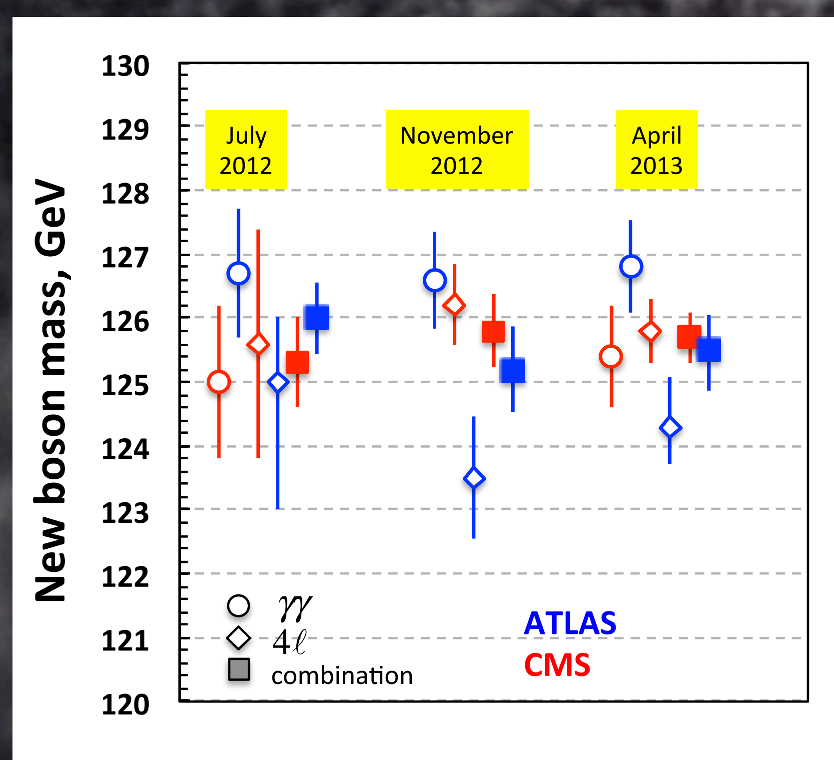
Note: μ is the measured process rate relative to SM prediction

Mass measurements

Precision measurements from H=>γγ and H=>ZZ=>4l







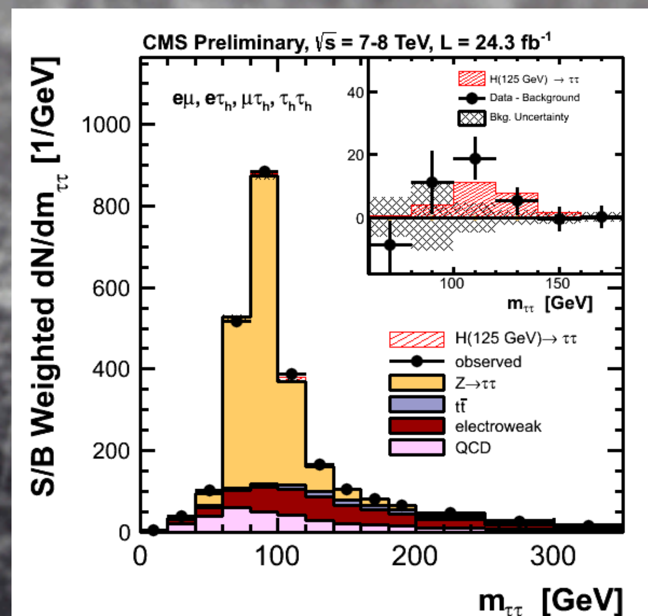
CMS: 125.7 ± 0.4 GeV
ATLAS: 125.5 ± 0.6 GeV

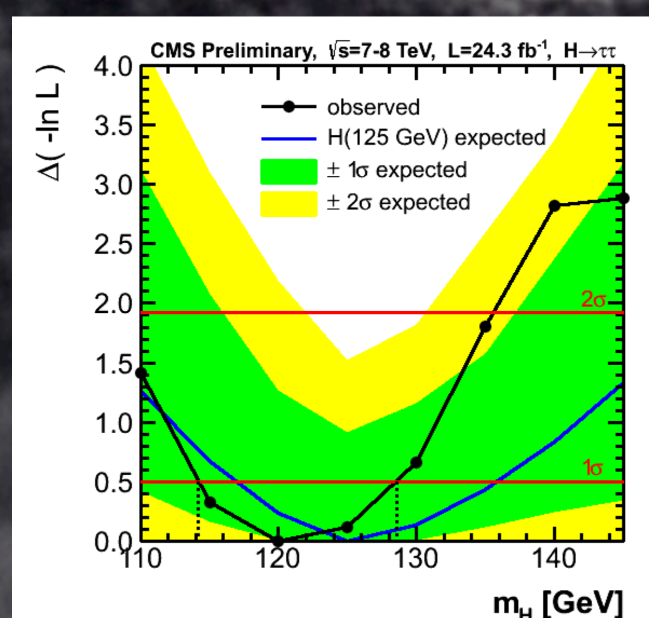
Precision to 0.3-0.5 %

Más mass

From the CMS fermionic channels

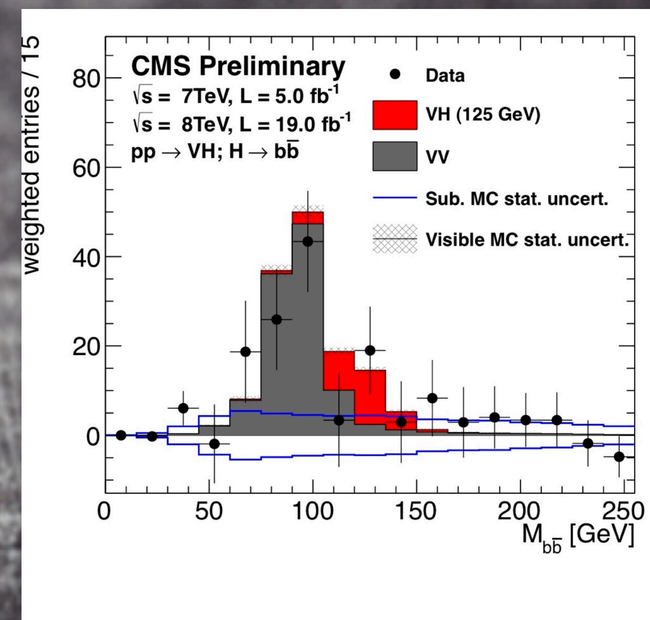
H=>ττ

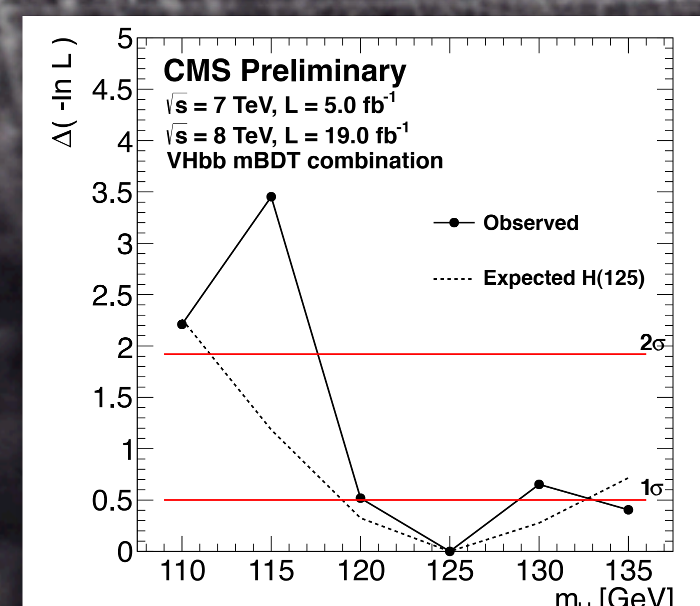




$m_X = 120^{+9}_{-7}$ GeV

VH(bb)





Most likely $m_X \sim 125$ GeV

Test of SM couplings

- Production x decay:
  - Can be described by 8 independent parameters

$$\sigma(xx \to H) \cdot BR(H \to yy) \propto \frac{\Gamma_{xx} \cdot \Gamma_{yy}}{\Gamma_{TOT}}$$

- Γ_{WW}
- Γ_{ZZ}
- Γ_{bb}
- $\Gamma_{\tau\tau}$
- $\Gamma_{\gamma\gamma}$ (loop induced)
- Γ_{gg} (loop induced)
- Γ_{tt}
- Γ_{TOT} (including H → "invisible")
- Zγ and μμ still have too little sensitivity to affect anything in the combination

modes contributing to coupling tests

	untagged	VBF-tag	VH-tag	ttH-tag
WW	✔	✔	✔	
ZZ	✔	✔		
bb			✔	✔
ττ	✔	✔	✔	
γγ	✔	✔	✔	

Define scale factors K as the ratio with respect to SM couplings:

e.g. $$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = (K_Z)^2$$

Framework

- **LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle:** arXiv:1209.0040

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa_\tau^2$$

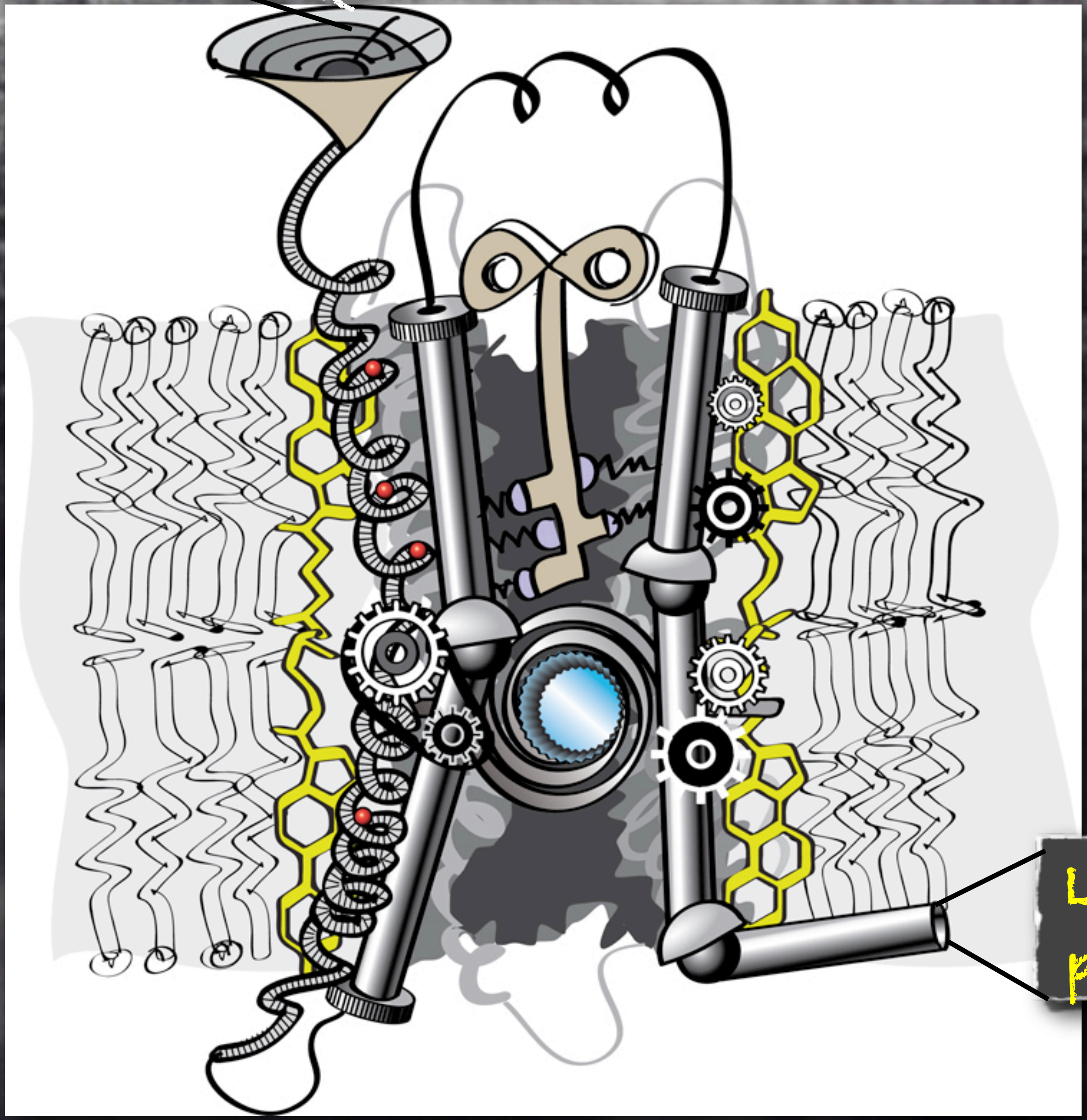
Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

The "combine" machine

S & B yields/shapes, uncertainties, correlations, assumptions, constraints

Run it all through the machine

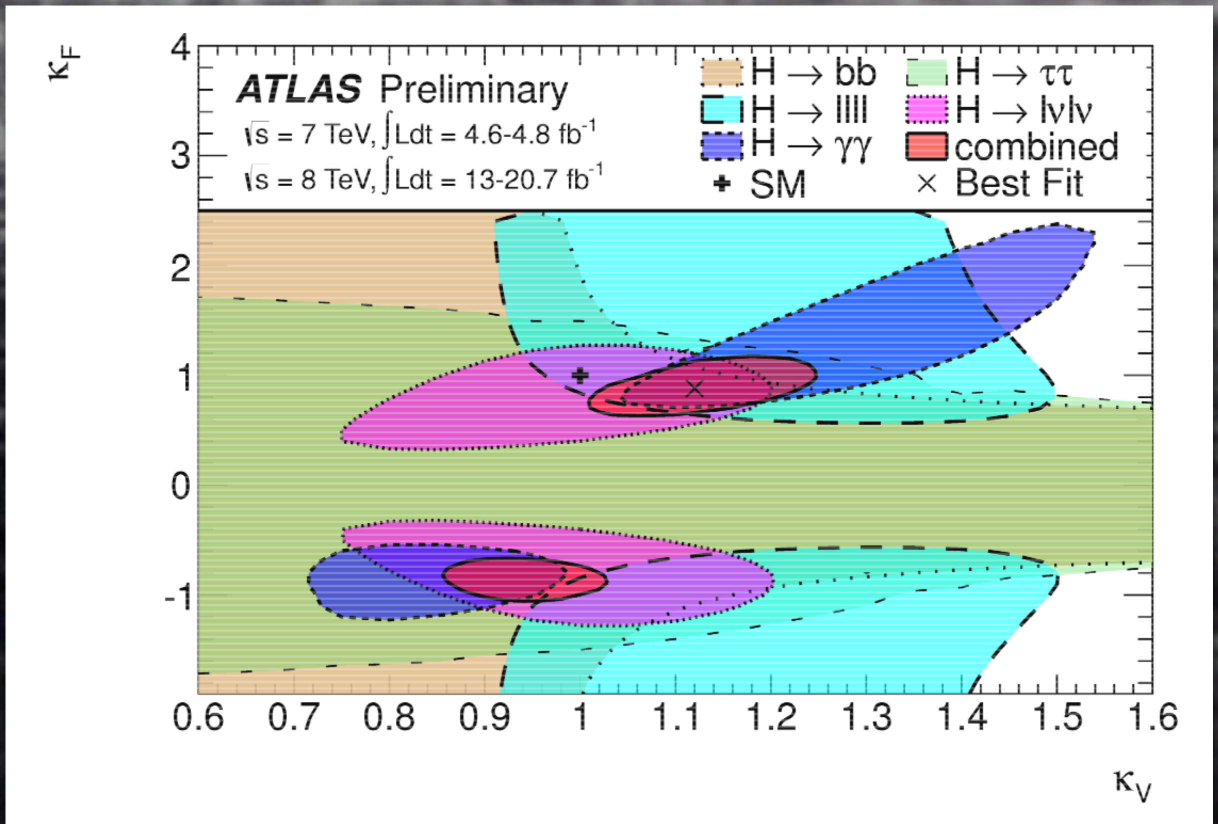


The size of the current dataset is insufficient to quantify meaningfully all 8 phenomenological parameters. A set of combinations with more limited # of d.o.f is presented. Other d.o.f are either constrained or profiled in the likelihood scans

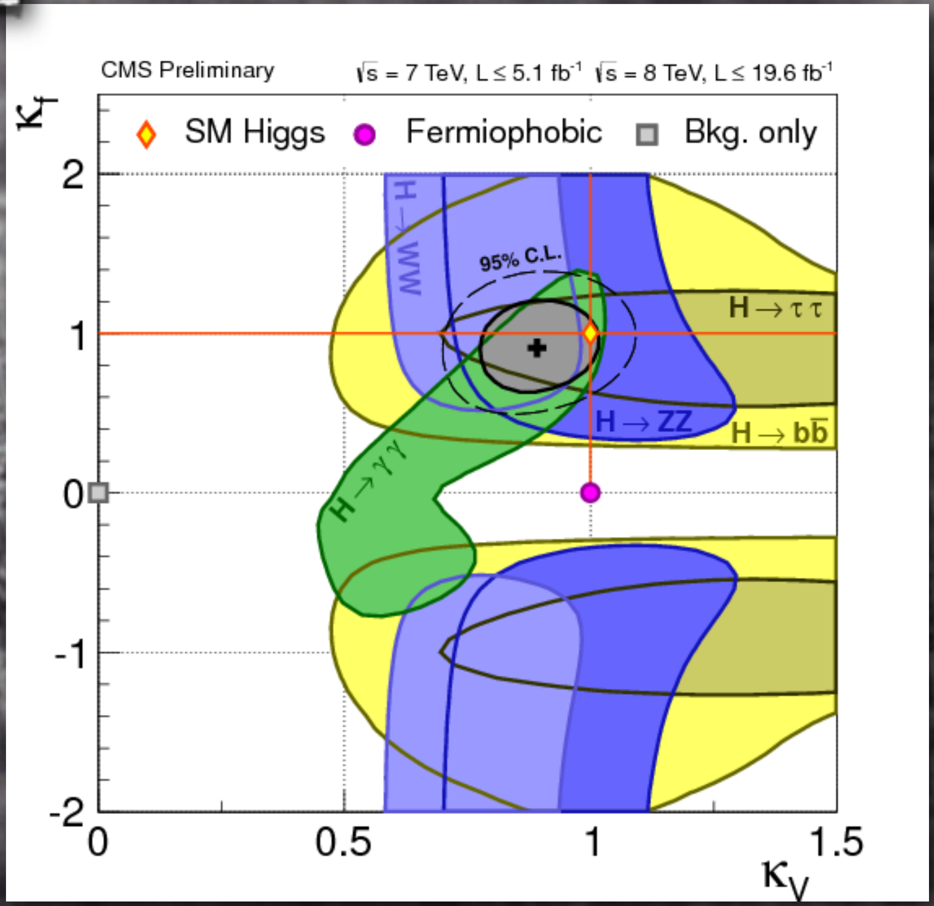
Look at different parameter subsets

Boson and fermion couplings

κ_V vs. κ_f



P(SM) ~ 8% for ATLAS

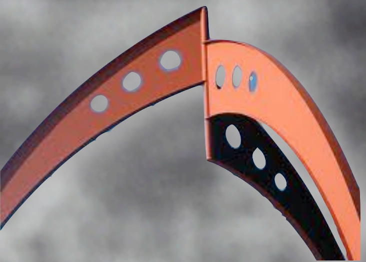


P(SM) < 1σ for CMS

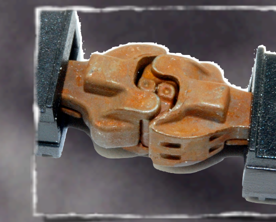
Boson and fermion scaling assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_W = \kappa_Z), \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

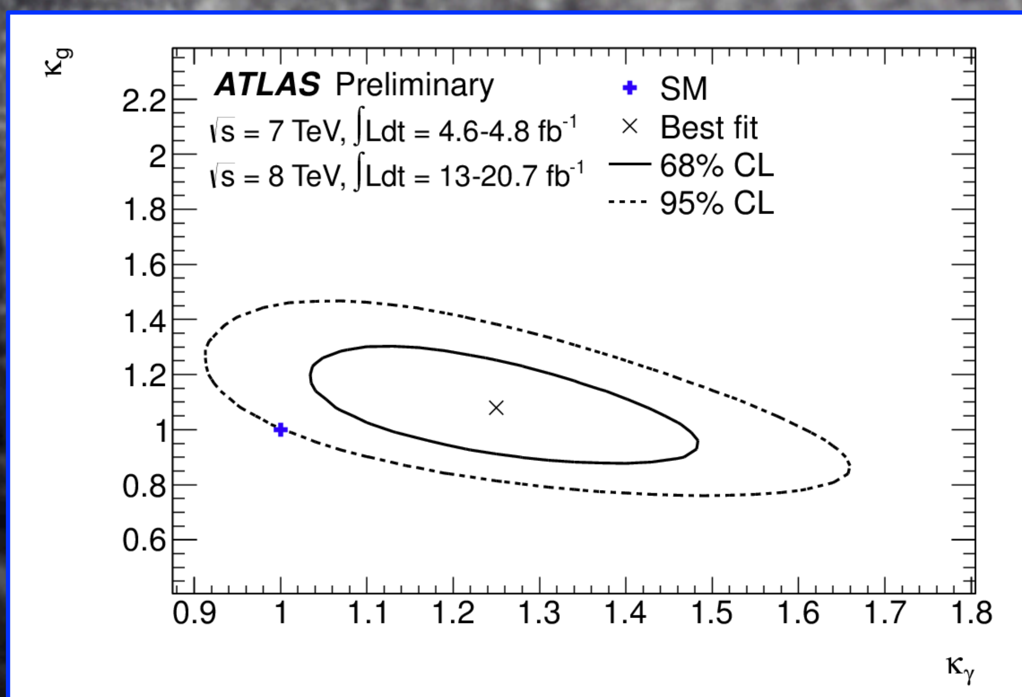
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

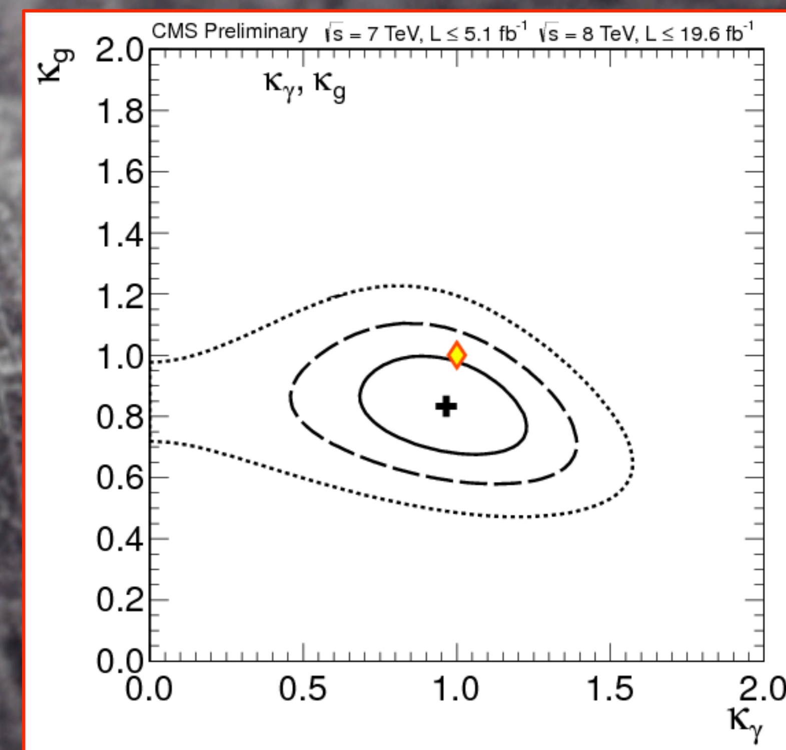


Look for new physics in loops



κ_g vs. κ_γ





So far ~consistency with $\kappa_g = \kappa_\gamma = 1$

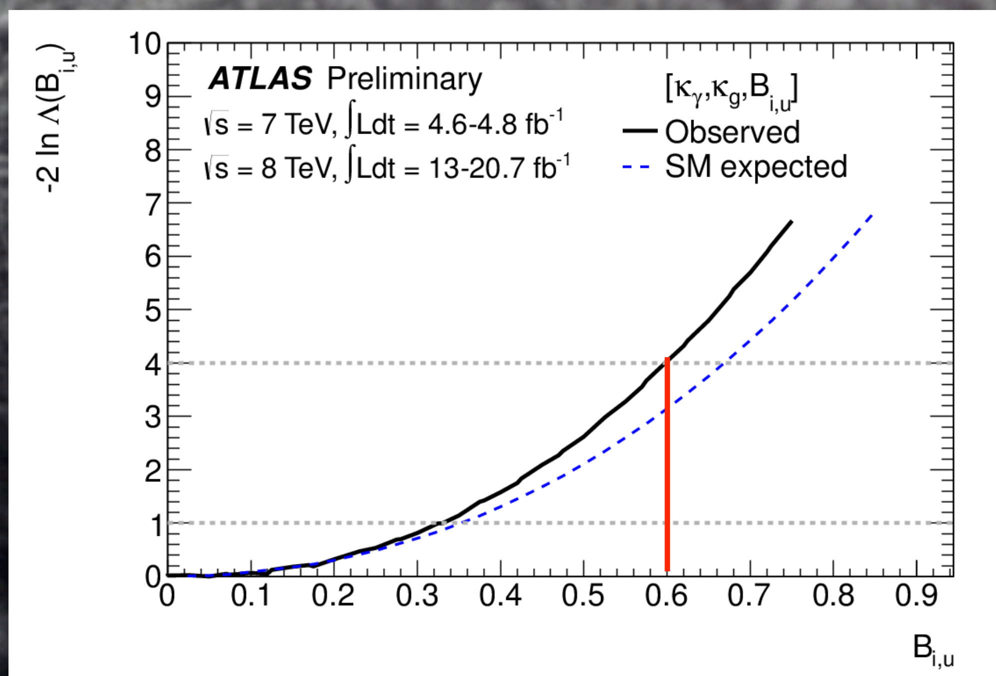
Probing loop structure assuming no invisible or undetectable widths

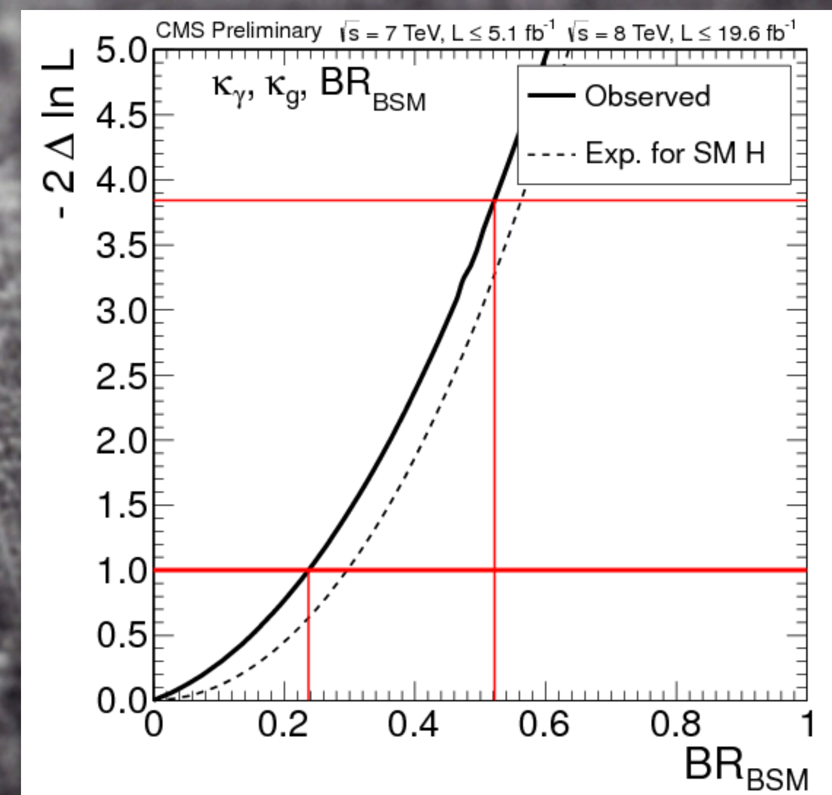
Free parameters: κ_g, κ_γ.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)}$			
$t\bar{t}H$, VBF, WH, ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{1}{\kappa_H^2(\kappa_i)}$			

BR to undetected particles

H => [   ]





BS(BSM) < 0.60 (95% CL)

BR(BSM) < 0.52 (95% CL)

Probing loop structure allowing for invisible or undetectable widths

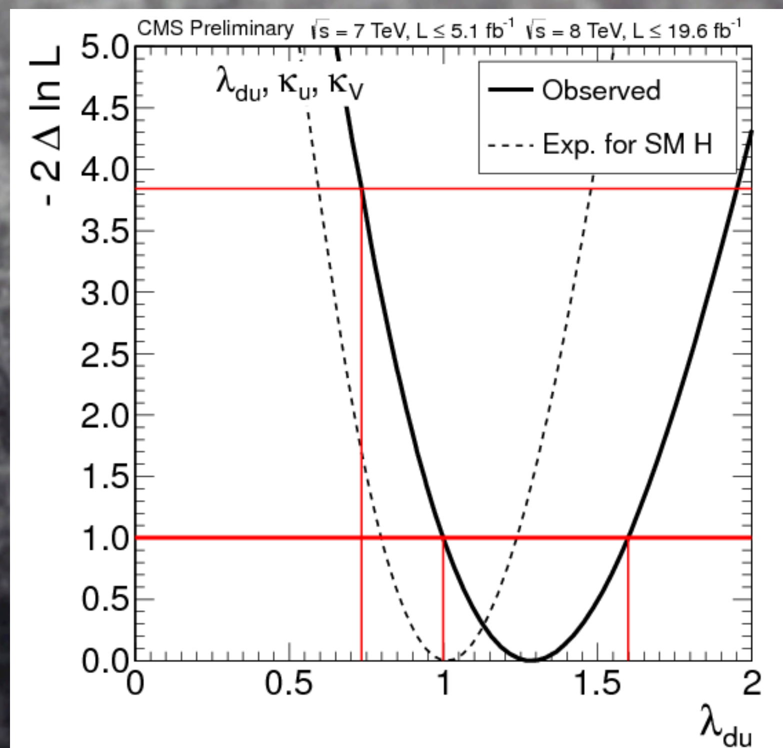
Free parameters: κ_g, κ_γ, $BR_{inv.,undet.}$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$	$\frac{1}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$			

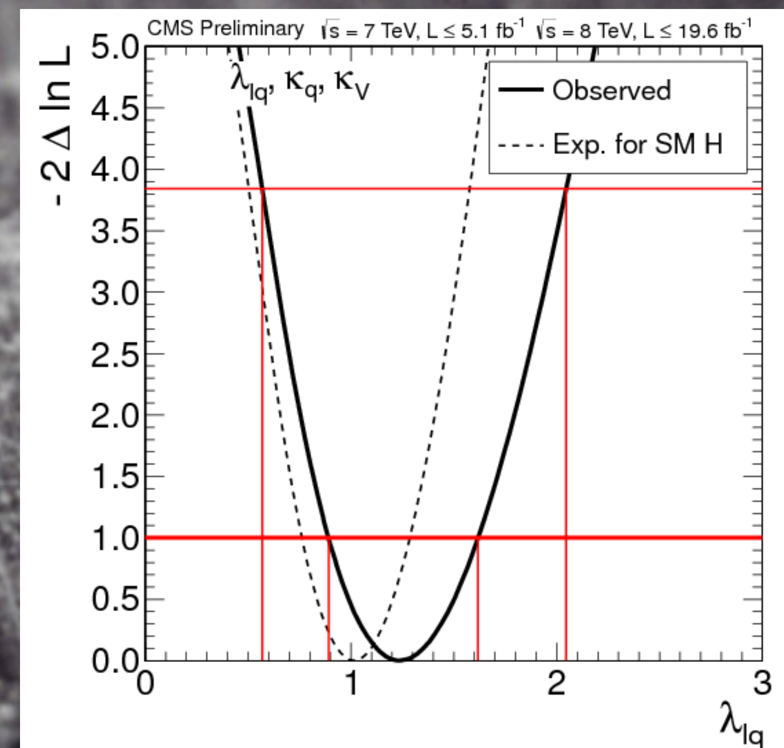
$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$

Tests on the fermion sector

up-type / down-type



quark / lepton



CMS

$\lambda_{du} = (\kappa_d/\kappa_u)$ => [0.74, 1.95] (95% CL)

$\lambda_{lq} = (\kappa_l/\kappa_q)$ => [0.57, 2.05] (95% CL)

Probing up-type and down-type fermion symmetry assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_Z = \kappa_W)$, $\lambda_{du} (= \kappa_d/\kappa_u)$, $\kappa_u (= \kappa_t)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_g^2(\kappa_u\lambda_{du},\kappa_u)\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	
$t\bar{t}H$	$\frac{\kappa_u^2\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_u^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_u^2\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2\cdot\kappa_\gamma^2(\kappa_u\lambda_{du},\kappa_u,\kappa_u\lambda_{du},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2\cdot(\kappa_u\lambda_{du})^2}{\kappa_H^2(\kappa_i)}$	

Probing quark and lepton fermion symmetry assuming no invisible or undetectable widths

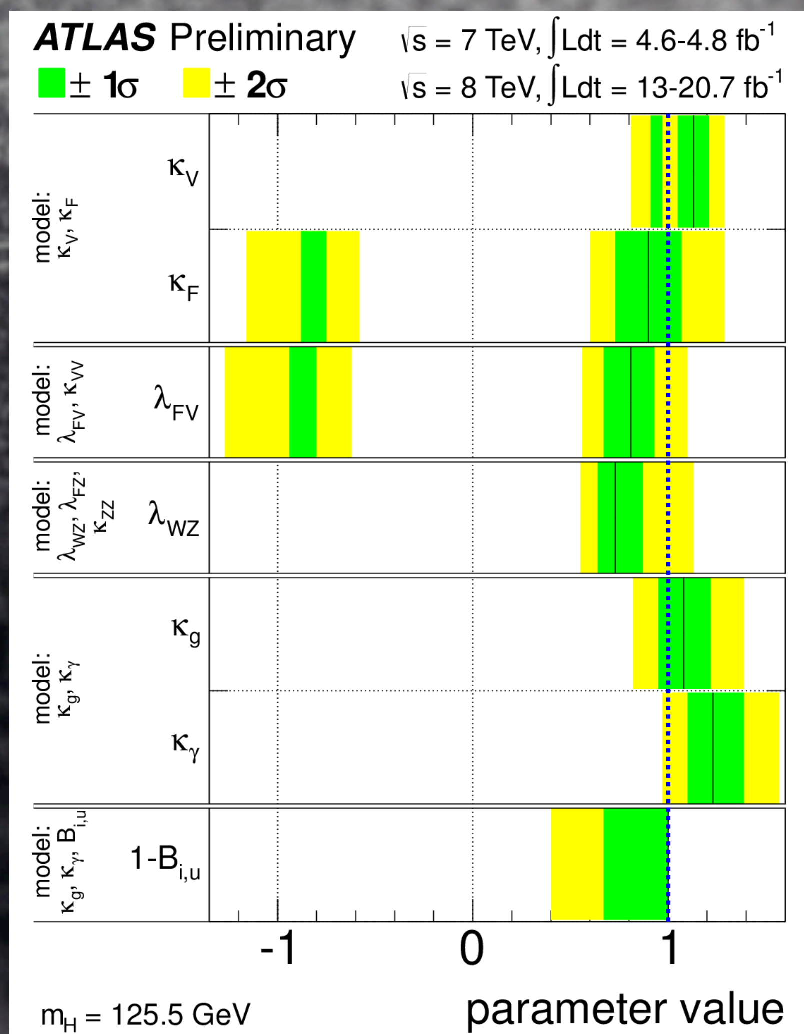
Free parameters: $\kappa_V (= \kappa_Z = \kappa_W)$, $\lambda_{lq} (= \kappa_l/\kappa_q)$, $\kappa_q (= \kappa_t = \kappa_b)$.

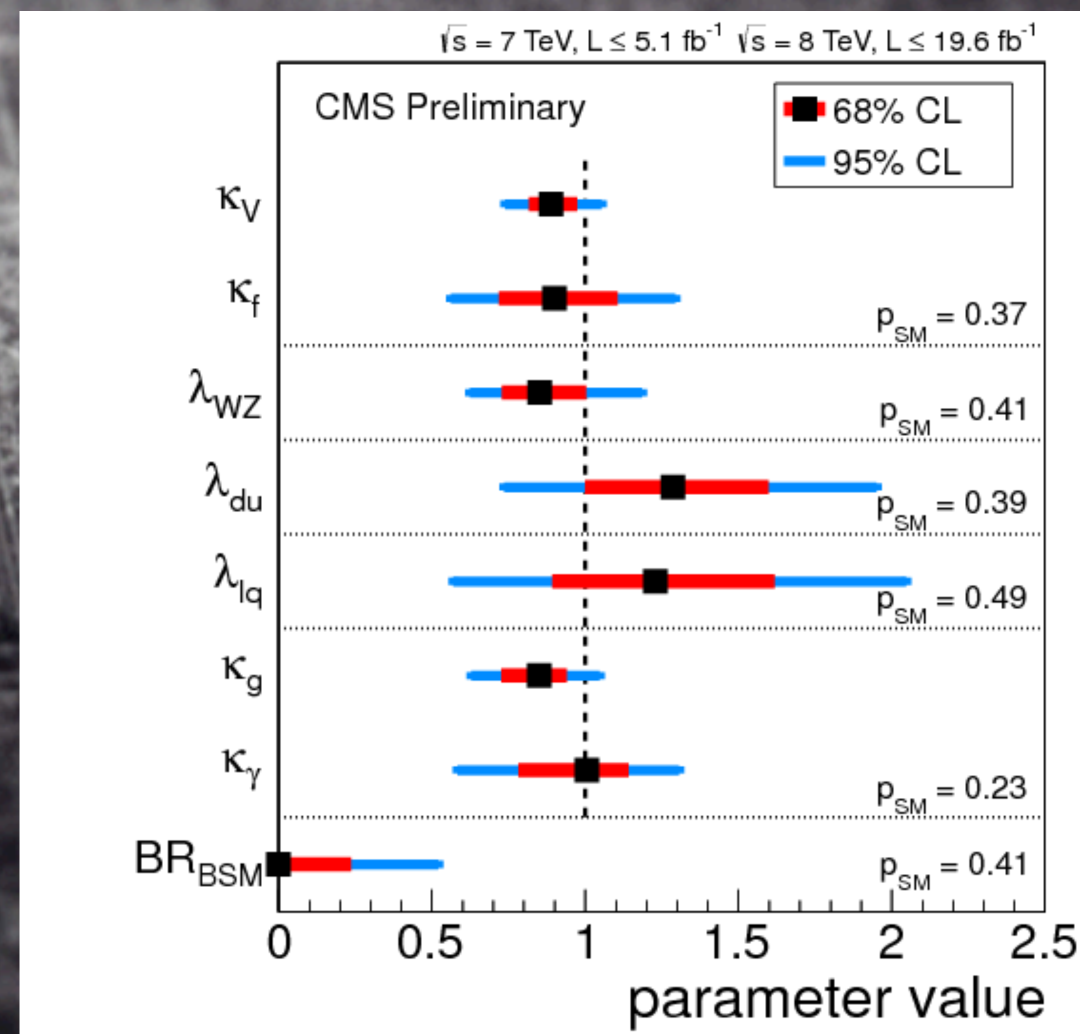
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_q^2\cdot\kappa_\gamma^2(\kappa_q,\kappa_q,\kappa_q\lambda_{lq},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_q^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_q^2\cdot\kappa_q^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_q^2\cdot(\kappa_q\lambda_{lq})^2}{\kappa_H^2(\kappa_i)}$
VBF WH ZH	$\frac{\kappa_V^2\cdot\kappa_\gamma^2(\kappa_q,\kappa_q,\kappa_q\lambda_{lq},\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot\kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2\cdot\kappa_q^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2\cdot(\kappa_q\lambda_{lq})^2}{\kappa_H^2(\kappa_i)}$

Summary of coupling tests

CMS-PAS-HIG-13-005

ATLAS-CONF-2013-034

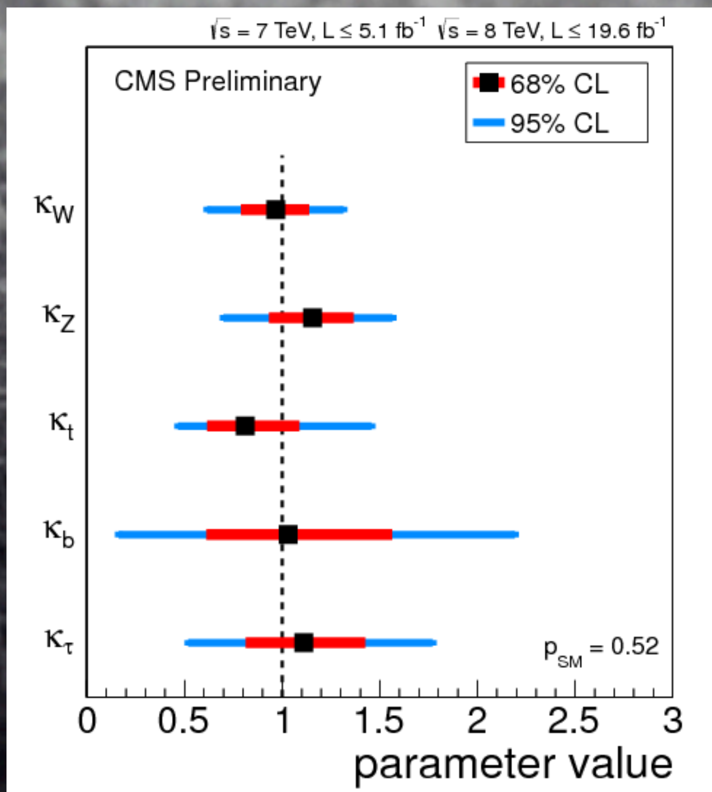




It couples to bosons, couples to fermions, couples the same to W &Z, to up & down families, to leptons and quarks, no [much] new physics in loops, and no large invisible decays

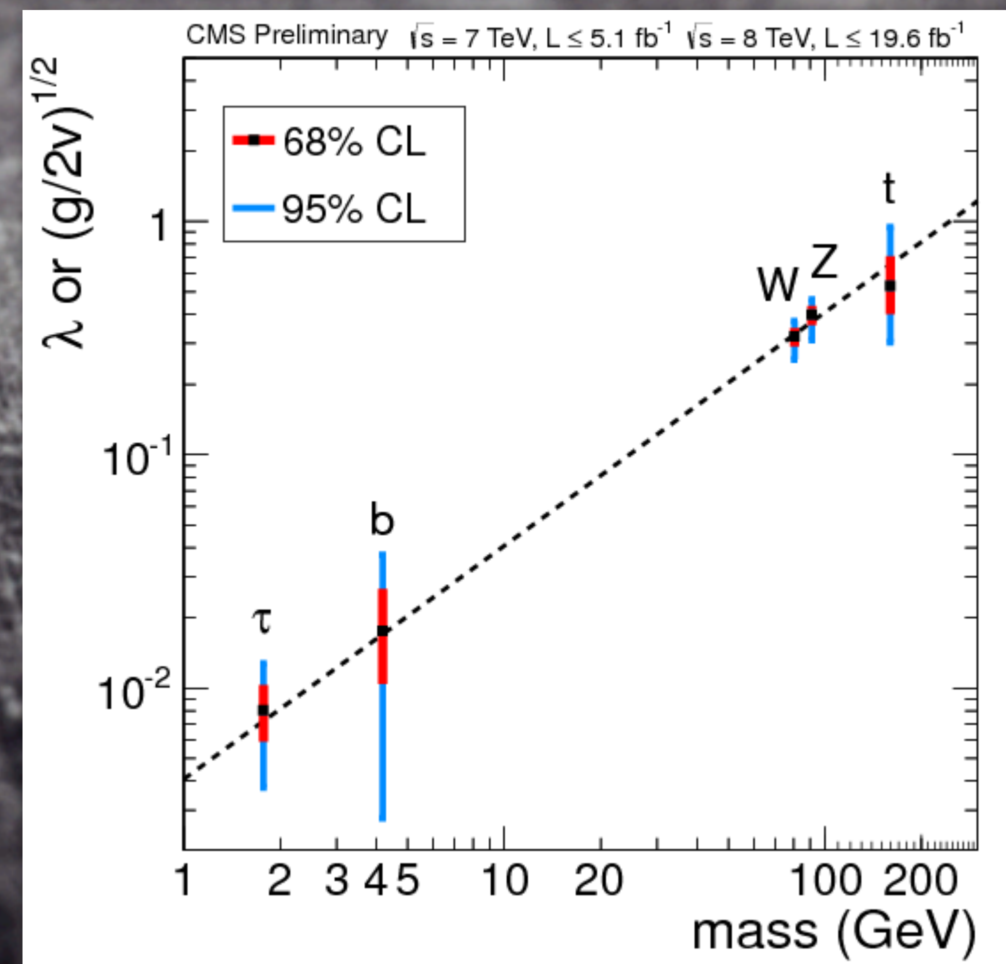
all as expected - within the measured uncertainties -

Couplings vs mass ?



$(g_V/2vev)^{1/2} = K_V^{1/2}\,(m_V/vev)$

$\lambda_f = K_f\,(m_f/vev)$



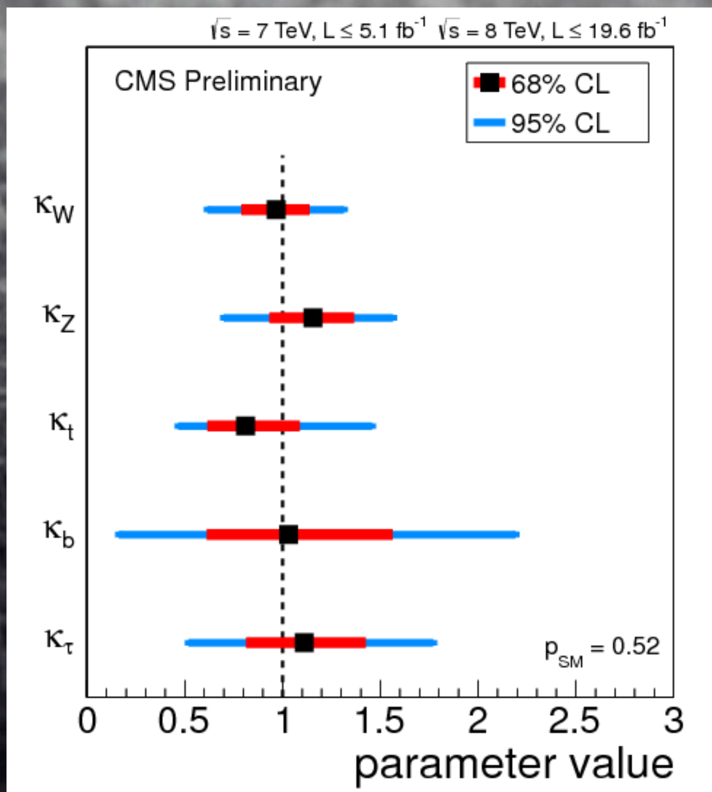
8 independent parameters to describe all currently relevant decays and production mechanisms:

- Γ_{WW} → κ_W
- Γ_{ZZ} → κ_Z
- Γ_{tt} → κ_t
- Γ_{bb} → κ_b
- $\Gamma_{\tau\tau}$ → κ_τ
- $\Gamma_{\gamma\gamma}$ (loop is resolved) → κ_W, κ_t
- Γ_{gg} (loop is resolved) → κ_t, κ_b
- assume **BR(BSM)=0**
- Assume couplings to the 1st, 2nd, 3rd generations are modified the same way

=> C5 model

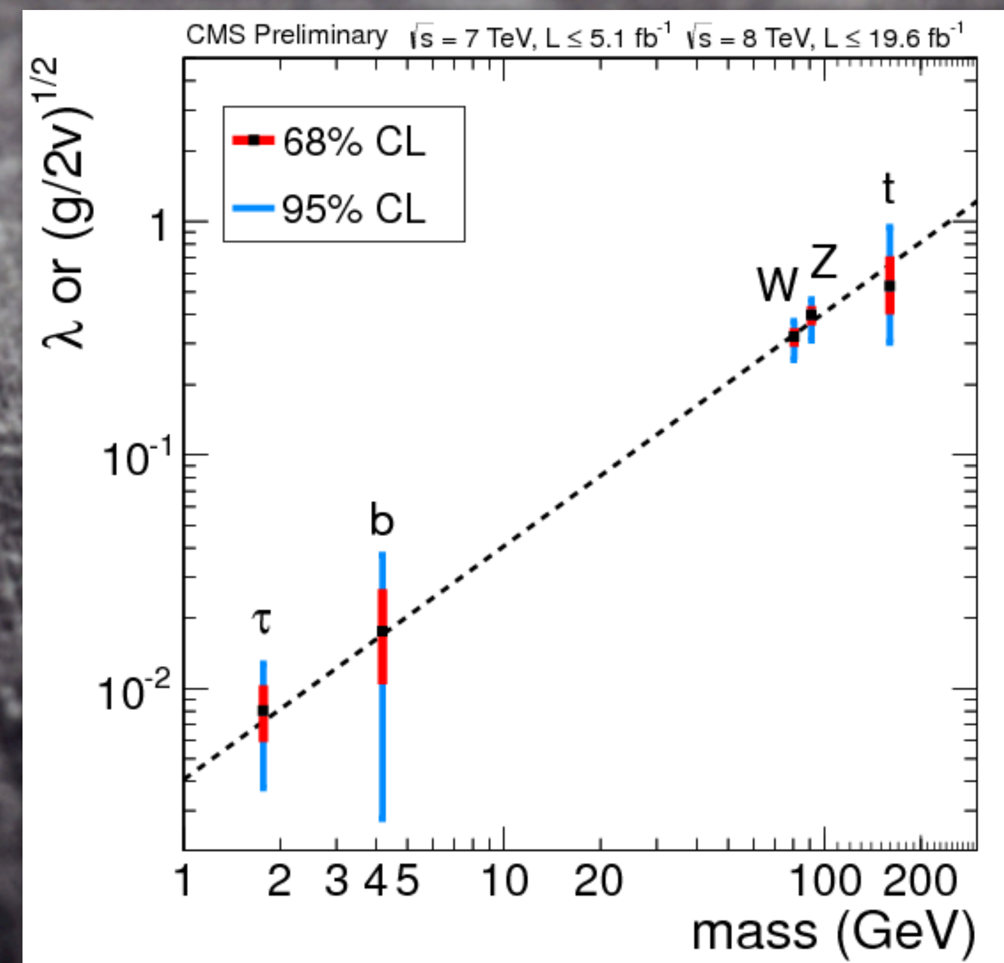
Scale SM couplings by measured K
plot reformulated couplings vs mass

Couplings vs mass ?



$$(g_V/2vev)^{1/2} = K_V^{1/2}\,(m_V/vev)$$

$$\lambda_f = K_f\,(m_f/vev)$$



8 independent parameters to describe all currently relevant decays and production mechanisms:

- Γ_{WW} → κ_W
- Γ_{ZZ} → κ_Z
- Γ_{tt} → κ_t
- Γ_{bb} → κ_b
- $\Gamma_{\tau\tau}$ → κ_τ
- $\Gamma_{\gamma\gamma}$ (loop is resolved) → **κ_W, κ_t**
- Γ_{gg} (loop is resolved) → **κ_t, κ_b**
- assume **BR(BSM)=0**
- Assume couplings to the 1st, 2nd, 3rd generations are modified the same way

=> C5 model

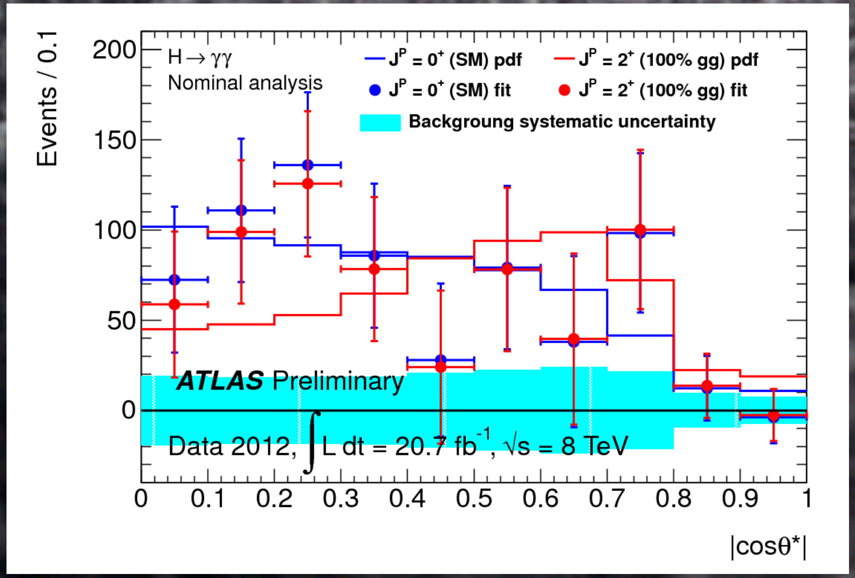
Scale SM couplings by measured K
plot reformulated couplings vs mass

Quite a Higgs-like statement...

Spin & parity

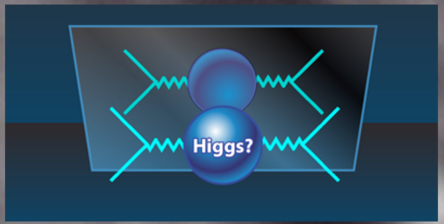
- SM prediction is $J^P = 0^+$
  - Can be tested in different ways with ZZ, γγ, WW
    - Reconstruct angles and inv. masses where possible

for example, J=0 vs J=2 in γγ



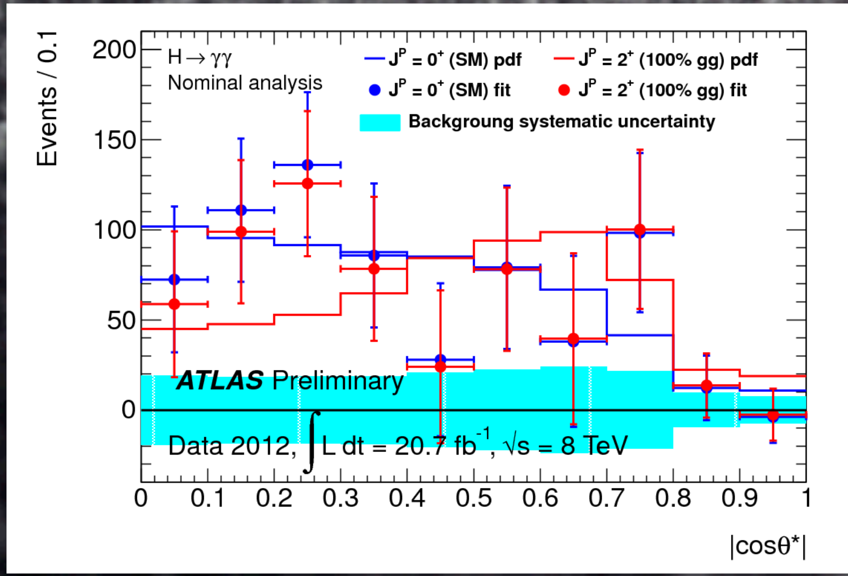
spin = 0 is favored

Spin & parity



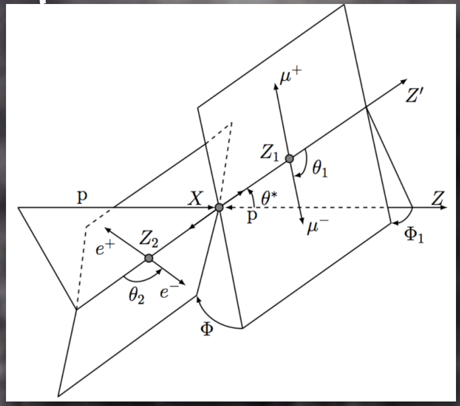
- SM prediction is $J^P = 0^+$
  - Can be tested in different ways with ZZ, γγ, WW
    - Reconstruct angles and inv. masses where possible

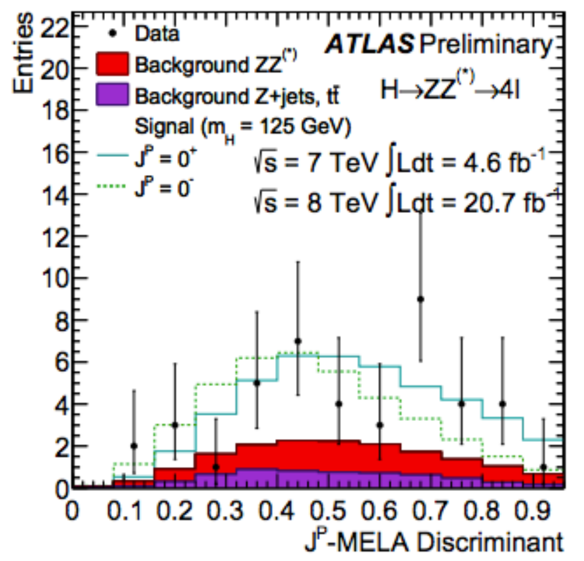
for example, J=0 vs J=2 in γγ

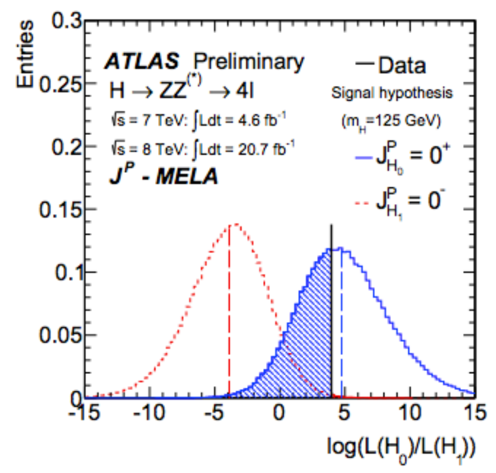


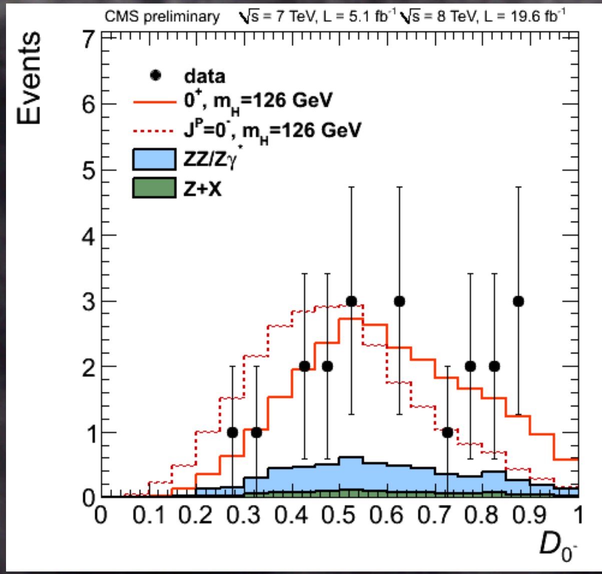
spin = 0 is favored

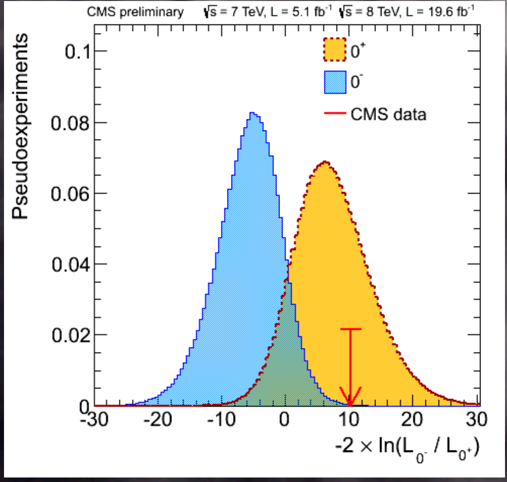
example 0⁺ vs 0⁻ in ZZ







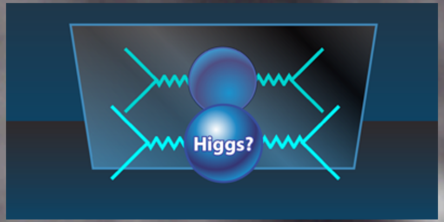




	ATLAS	CMS
CL_s	0.37%	0.16%
P(obs.|0⁺)	0.40	-0.5 σ
P(obs.|0⁻)	0.0022	3.3 σ

P(0⁺)
P(0⁻)

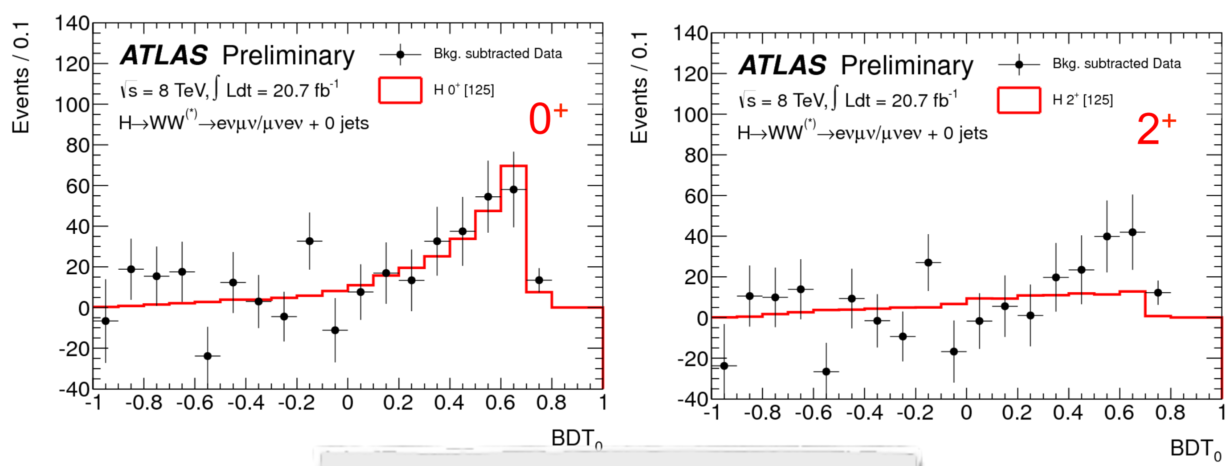
Spin & parity



0^+ vs 2^+

Spin from H→WW

- Combine several variables in a multivariate discriminant (boosted decision tree)
- Variables used: m_{ll}, P_T^{ll}, $\Delta\varphi_{ll}$, m_T



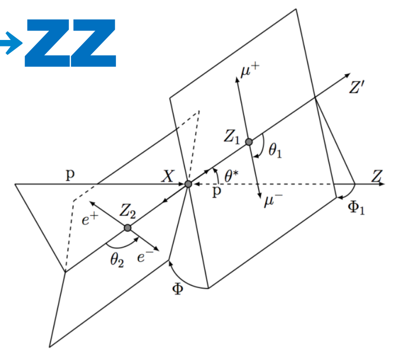
spin = 0 is favored

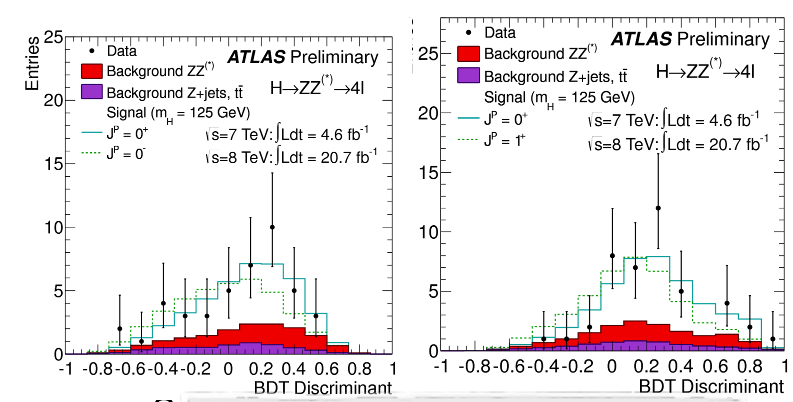
0^+ vs. 0^- / 1^+

Spin from H→ZZ and parity

Combine several variables using a boosted decision tree

Variables used: Φ, θ_1, θ_2, m_{12}, m_{34}, θ^*, Φ_1





Se… voured.

$J^P = 0^+$ is favored

Spin & parity summary

CL_s values for testing J^{CP} state hypotheses vs SM-like Higgs boson (0^+_m)

- (light orange) $CL_s < 0.05$
- (red) $CL_s < 0.01$

	CMS				ATLAS			
	γγ	ZZ	WW	ZZ+WW	γγ	ZZ	WW	comb
0^-		0.0016				0.004		
0^+_h		0.081						
1^-	excluded	<0.001			excluded	0.031		
1^+	excluded	<0.001			excluded	0.002		
$gg \to 2^+_m$		0.015	0.04	0.006	0.007	0.182	0.05	<0.001
$qq \to 2^+_m$		<0.001			0.12	~3σ (?)	0.01	<0.001
$gg \to 2^-$						0.116		

Andrey Korytov (UF)

It also prefers to be $J^P = 0^+$

“A Higgs”

Birth of a Higgs boson

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as ‘a Higgs boson’.

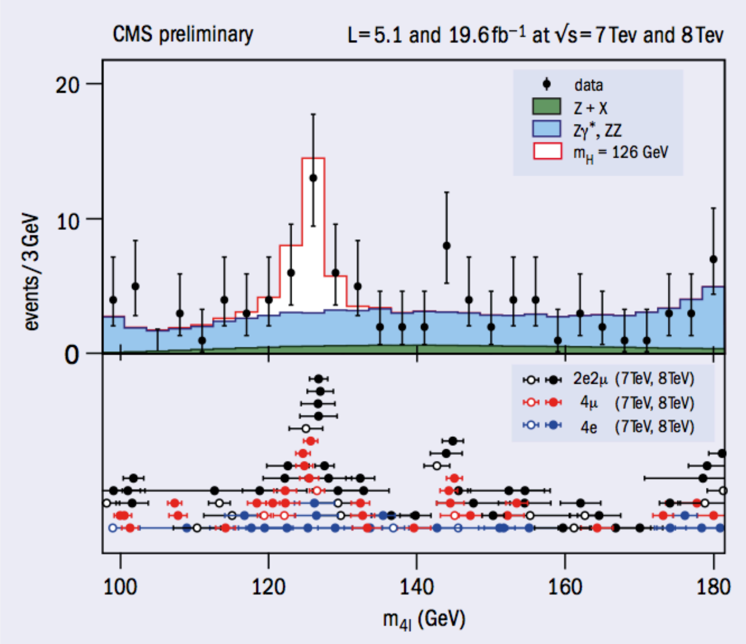
In the history of particle physics, July 2012 will feature prominently as the date when the ATLAS and CMS collaborations announced that they had discovered a new particle with a mass near 125 GeV in studies of proton–proton collisions at the LHC. The discovery followed just over a year of dedicated searches for the Higgs boson, the particle linked to the Brout-Englert-Higgs mechanism that endows elementary particles with mass. At this early stage, the phrase “Higgs-like boson” was the recognized shorthand for a boson whose properties were yet to be fully investigated (*CERN Courier* September 2012 p43 and p49). The outstanding performance of the LHC in the second half of 2012 delivered four times as much data at 8 TeV in the centre of mass as were used in the “discovery” analyses. Thus equipped, the experiments were able to present new results at the 2013 Rencontres de Moriond in March, giving the particle-physics community enough evidence to name this new boson “a Higgs boson”.

At the Moriond meeting, in addition to a suite of final results from the experiments at Fermilab’s Tevatron on the same subject, the ATLAS and CMS collaborations presented preliminary new results that further elucidate the nature of the particle discovered just eight months earlier. The collaborations find that the new particle is looking more and more like a Higgs boson. However, it remains an open question whether this is *the* Higgs boson of the Standard Model of particle physics, or one of several such bosons predicted in theories that go beyond the Standard Model. Finding the answer to this question will require more time and data.

This brief summary provides an update of the measurements

Observed CL_s compared with $J^P=0^+$		0^- (gg) pseudo-scalar	2^+_m (gg) minimal couplings	2^+_m ($q\bar{q}$) minimal couplings	1^- ($q\bar{q}$) exotic vector	1^+ ($q\bar{q}$) exotic pseudo-vector
$ZZ^{(*)}$	ATLAS	2.2%	6.8%	16.8%	6.0%	0.2%
	CMS	0.16%	1.5%	<0.1%	<0.1%	<0.1%
$WW^{(*)}$	ATLAS	–	5.1%	1.1%	–	–
	CMS	–	14%	–	–	–
$\gamma\gamma$	ATLAS	–	0.7%	12.4%	–	–

Table 1. Summary of preliminary results of the hypothesis tests compared with the Standard Model hypothesis of no spin, positive parity ($J^P=0^+$). All alternatives are disfavoured using the CL_s ratio of probabilities that takes into account how the observation relates to both the Standard Model and the alternative hypotheses.



"A Higgs"

LHC discovery

Birth of a Higgs boson

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as 'a Higgs boson'.

In the history of particle physics, July 2012 will feature prominently as the date when the ATLAS and CMS collaborations announced that they had discovered a new particle with a mass near 125 GeV in studies of proton–proton collisions at the LHC. The discovery followed just over a year of dedicated searches for the Higgs boson, the particle linked to the Brout-Englert-Higgs mechanism that endows elementary particles with mass. At this early stage, the phrase "Higgs-like boson" was the recognized shorthand for a boson whose properties were yet to be fully investigated (*CERN Courier* September 2012 p43 and p49). The outstanding performance of the LHC in the second half of 2012 delivered four times as much data at 8 TeV in the centre of mass as were used in the "discovery" analyses. Thus equipped, the experiments were able to present new results at the 2013 Rencontres de Moriond in March, giving the particle-physics community enough evidence to name this new boson "a Higgs boson".

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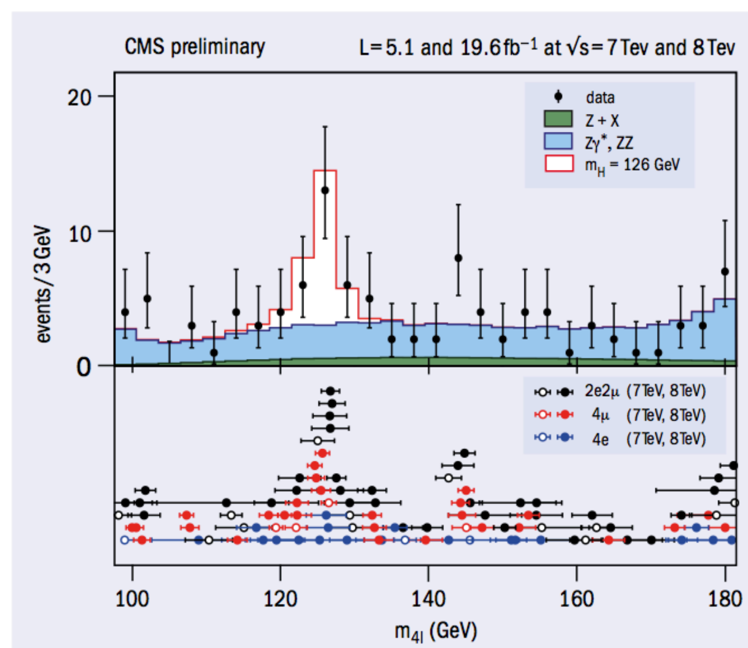
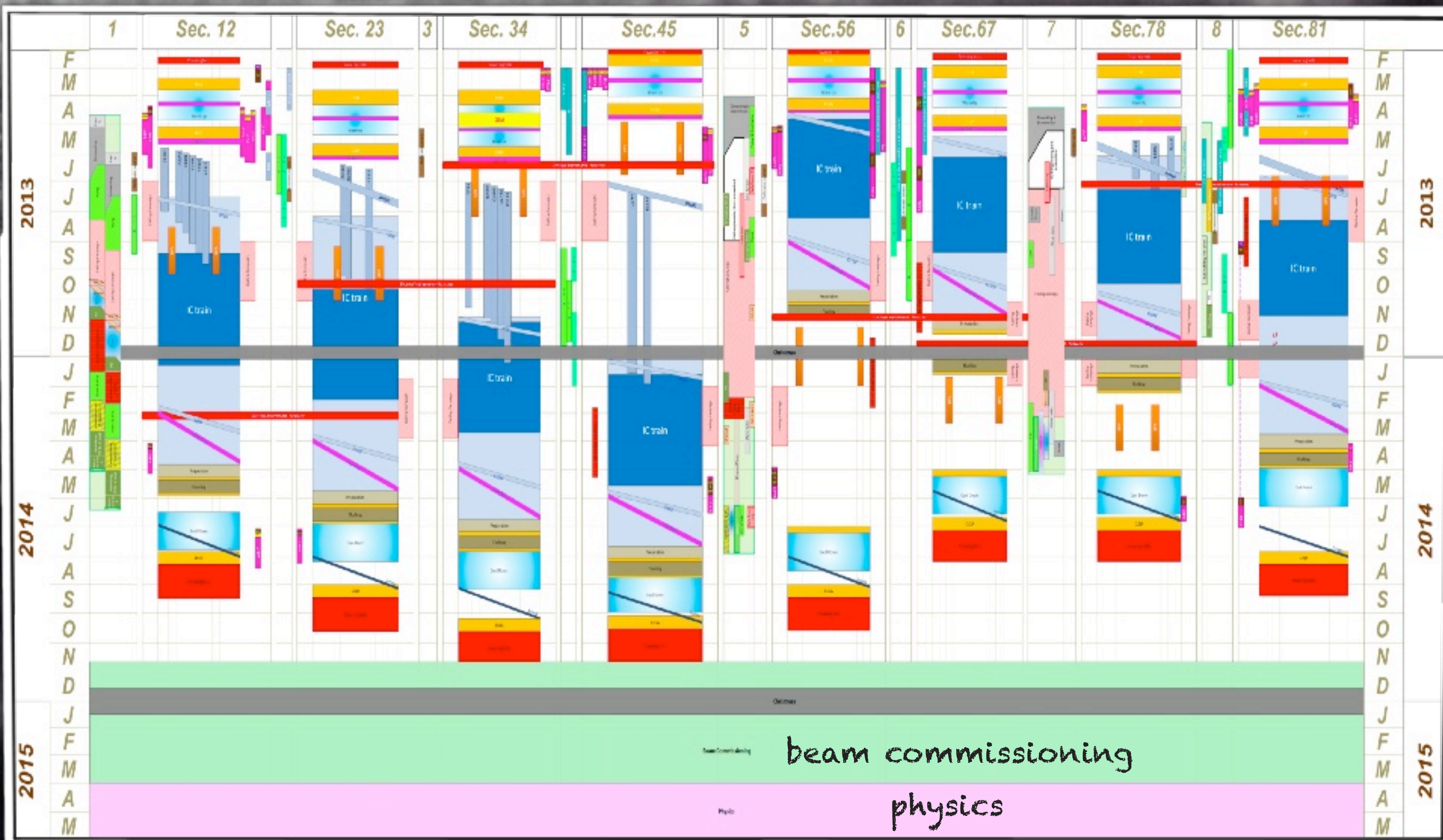


What's next

very briefly...

LHC schedule :)



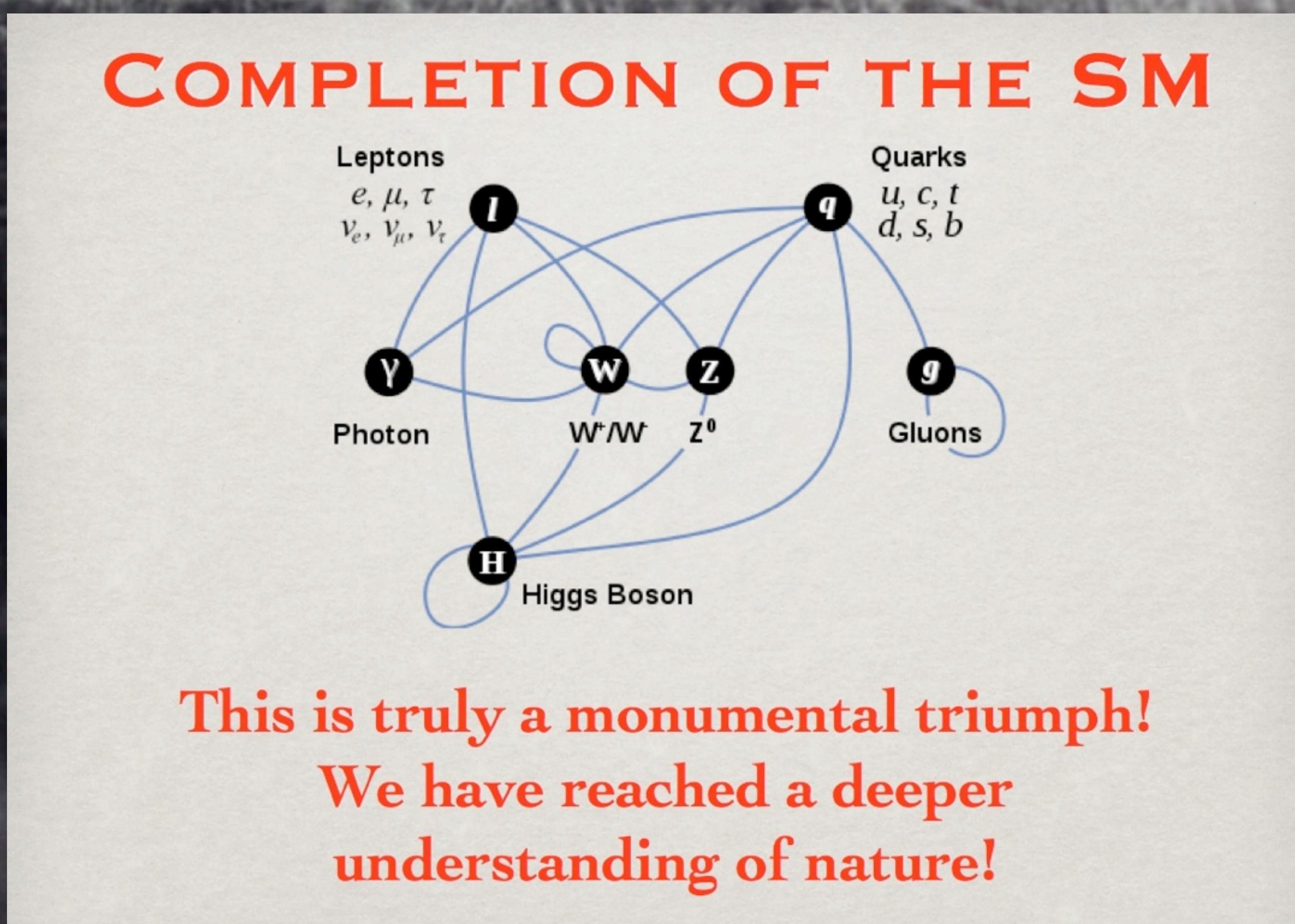
Meanwhile

- Measure/search everything possible:
  - More Higgses, companions to this one
  - Other production modes & decays
  - Connections to New Physics
- Prepare for 2015 run @ ~13 TeV

Conclusions

We reached a deeper understanding of Nature

A new research area opened up...



cant remember where this came from, sorry

C. Mariotti - CERN seminar

Acknowledgements

- Lots of material "borrowed" from recent presentations by:
  - Sergio Bertolucci, Sally Dawson, Pablo García-Abia, Andrew Mehta, Jim Olsen, Andrey Korytov, Chiara Mariotti, André David Mendes and others
    - @LHCP, Blois, CERN seminars & other venues

References

Channel	Conference note	L	Date
Spin Combination	ATLAS-CONF-2013-040	up to 25 fb-1	16/04/2013
Couplings Combination	ATLAS-CONF-2013-034	up to 25 fb-1	14/03/2013
Higgs to Diphoton spin	ATLAS-CONF-2013-029	21 fb-1	13/03/2013
Higgs to WW(lvlv) spin	ATLAS-CONF-2013-031	21 fb-1	11/03/2013
Higgs to WW(lvlv)	ATLAS-CONF-2013-030	25 fb-1	11/03/2013
2HDM WW(lvlv)	ATLAS-CONF-2013-027	13 fb-1	11/03/2013
Combined of Mass	ATLAS-CONF-2013-014	up to 25 fb-1	05/03/2013
Higgs to Diphoton	ATLAS-CONF-2013-012	25 fb-1	05/03/2013
Higgs to 4 leptons	ATLAS-CONF-2013-013	25 fb-1	05/03/2013
ZH (invisible decays)	ATLAS-CONF-2013-011	18 fb-1	05/03/2013
Higgs to dimuon	ATLAS-CONF-2013-010	21 fb-1	05/03/2013
Higgs to Zgamma	ATLAS-CONF-2013-009	25 fb-1	05/03/2013

May-2013	Full 8 TeV dataset: VBF H, H -> bb	TWiki, PAS
May-2013	Full 8 TeV dataset: ttH, H -> gamma gamma	TWiki, PAS
May-2013	Full 7+8 TeV dataset: VH, H -> bb	TWiki, PAS
May-2013	Full 8 TeV dataset: H -> WW -> lnuJ	TWiki, PAS
May-2013	Full 7+8 TeV dataset: H -> ZZ -> 2l2nu	TWiki, PAS
Apr-2013	Moriond Higgs Combination	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> gamma gamma	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> ZZ -> 4l	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> WW -> 2l2nu	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> tau tau	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> Z gamma	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> WWW -> 3l3nu	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: VH -> tau tau	TWiki, PAS

Backup

SM Higgs

1. The Higgs in the SM: EWSB

To generate particle masses in an SU(2)×U(1) gauge invariant way:

introduce a doublet of scalar fields $\Phi = \binom{\Phi^+}{\Phi^0}$ with $\langle 0|\Phi^0|0\rangle \neq 0$

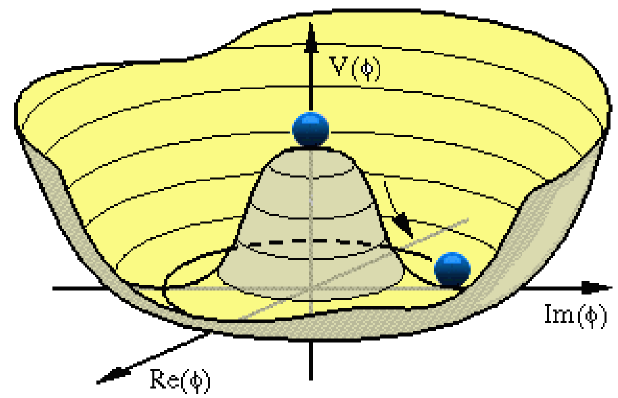
$$\mathcal{L}_S = D_\mu \Phi^\dagger D^\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2$$

$$v = (-\mu^2/\lambda)^{1/2} = 246 \text{ GeV}$$

$\Rightarrow$ three d.o.f. for $M_{W^\pm}$ and M_Z

For fermion masses, use same Φ:

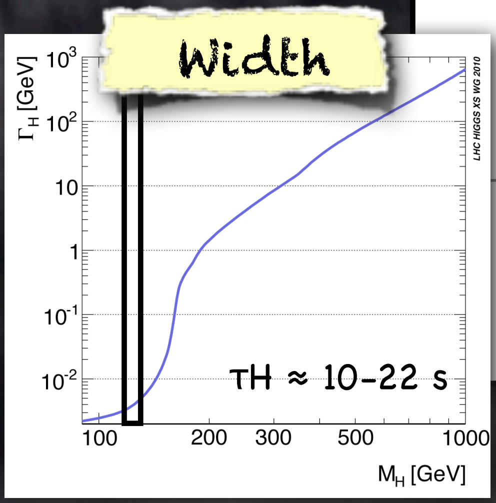
$$\mathcal{L}_{Yuk} = -f_e(\bar{e}, \bar{\nu})_L \Phi e_R + \ldots$$



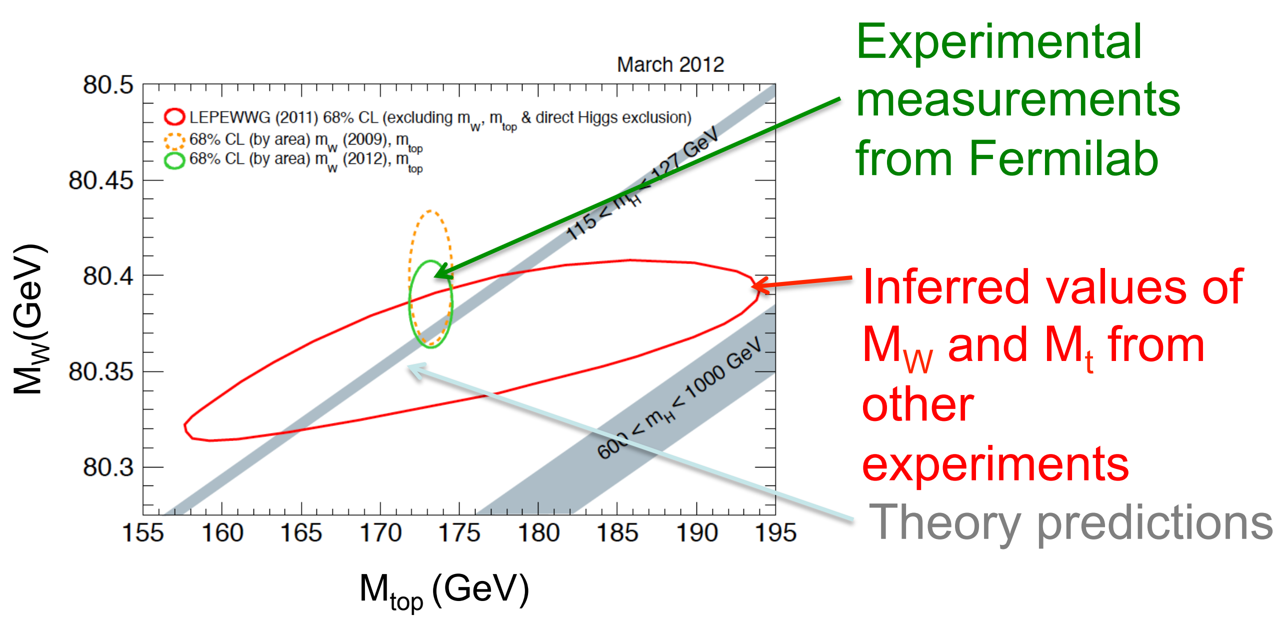
The residual degree corresponds to the spin–zero Higgs particle, H.

- The Higgs boson: $J^{PC} = 0^{++}$ quantum numbers.
- Masses and self–couplings from V : $M_H^2 = 2\lambda v^2$, $g_{H^3} = 3\frac{M_H^2}{v}, \ldots$
- Higgs couplings $\propto$ particle masses: $g_{Hff} = \frac{m_f}{v}$, $g_{HVV} = 2\frac{M_V^2}{v}$

Since v is known, the only free parameter in the SM is M_H (or λ).



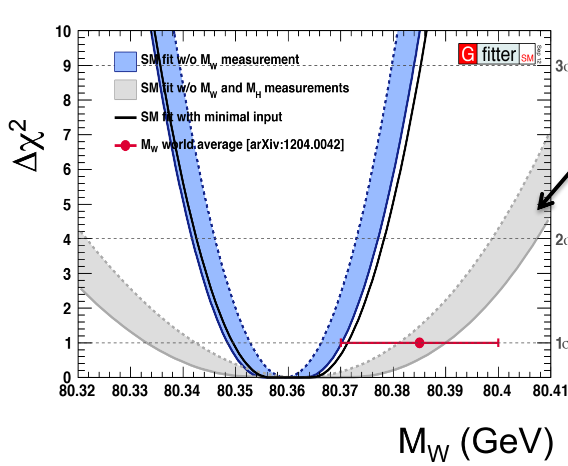
SM consistency

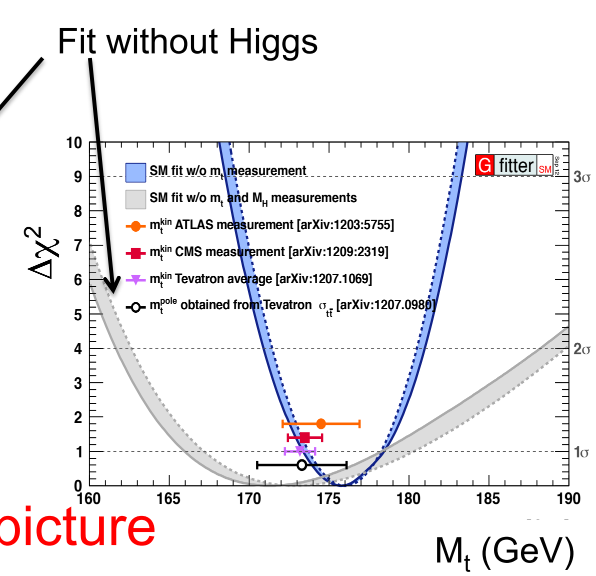


Self-consistency of the theory told us the Higgs couldn't be too heavy

S. Dawson 4

After Discovery



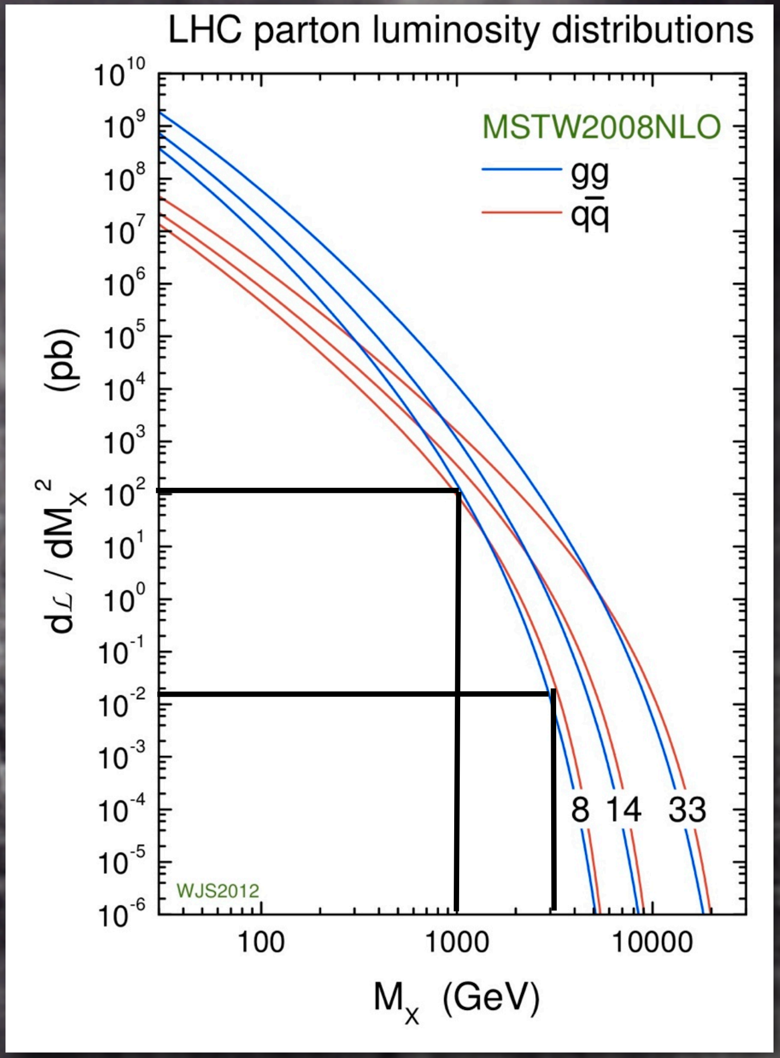


A consistent picture

Hadron colliders exploration

- An important point to keep in mind
  - Collisions at E_{cm} of the machine are very rare
  - Need vast amounts of data to exploit the tail of the high-energy parton collisions.
    That takes years
  - One cannot claim that there is nothing to be discovered until the edge of the E reach has been fully explored
    - At 8 TeV (with 20 fb^{-1}) we have barely covered up to 2-3 TeV

See presentation by P. Tang



  - So "just" integrating luminosity, is like having higher and higher E colliders in a pipeline --that kick in as time goes on... [already built !]

Less sensitive searches

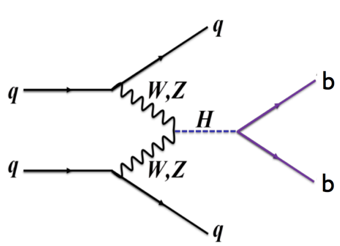
NEW

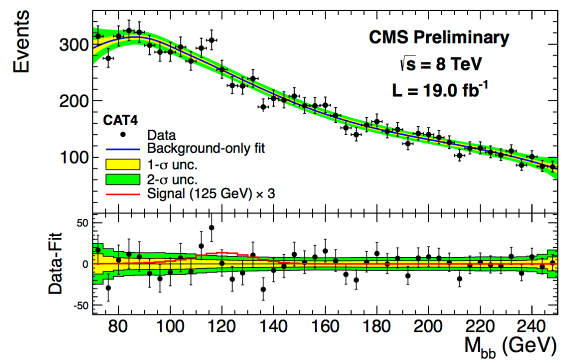
VBF H ➛ bb

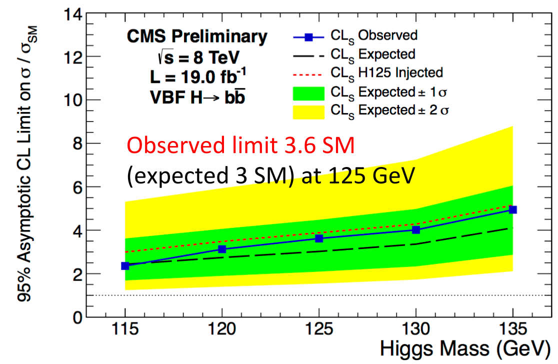
Fully hadronic final stat (b jets), dominated by QCD background.

Increase signal sensitivity splitting the sample in 4 categories (NN).

Use m_{bb} distribution to discriminate signal from background.

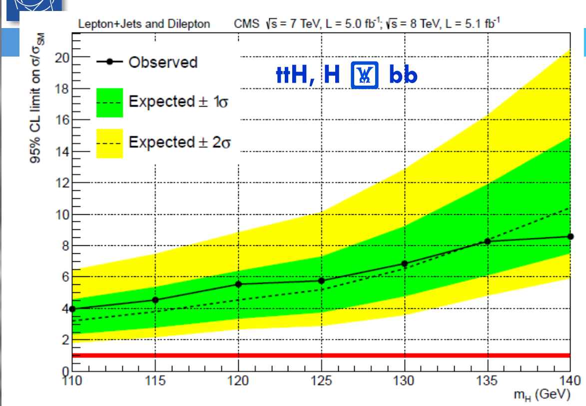






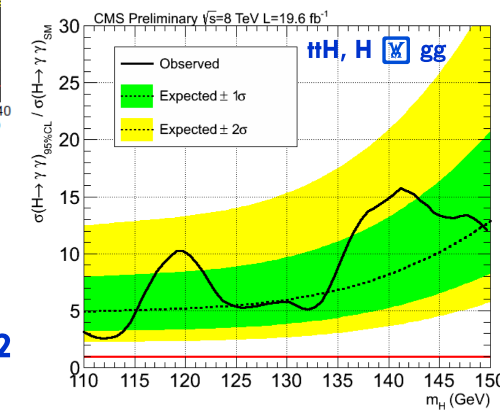
Pablo García-Abia,

ttH Results: bb and gg



Using 10/fb, bb achieves an expected limit of 5.2 x SM

Update on full dataset coming



With full 8 TeV data, ttH(gg) has similar sensitivity to bb (~5 x SM)

Combining additional channels and full dataset, should reach < 2 x SM for the combined ttH limit

Less sensitive searches

Pablo García-Abia, LHCP

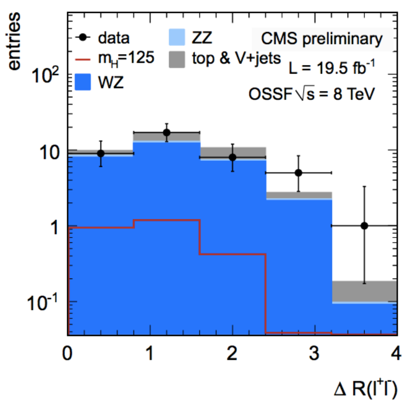
NEW

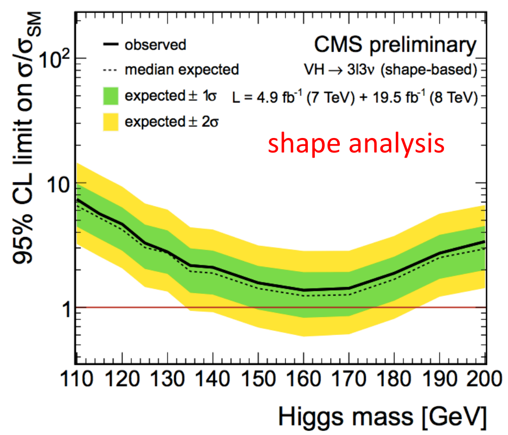
WH ➛ WWW ➛ 3ℓ 3n

Events with 3 high-p_T isolated leptons (e, μ), large missing energy, low hadronic activity.

Z veto and anti b-tagging to reject WZ and top events.

Cut- and shape-based analyses based on the smallest distance between opposite-charge leptons: $\Delta R_{\ell^+\ell^-}$



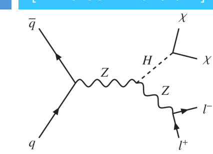


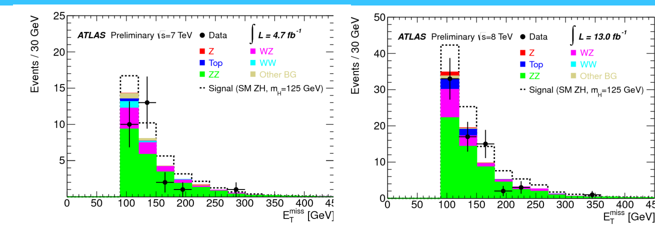
No significant excess of events. Observed (expected) upper limits on $\sigma(WH)/\sigma_{SM}$ at the 95% CL: 3.3 (3.0) for m_H = 125 GeV.

29

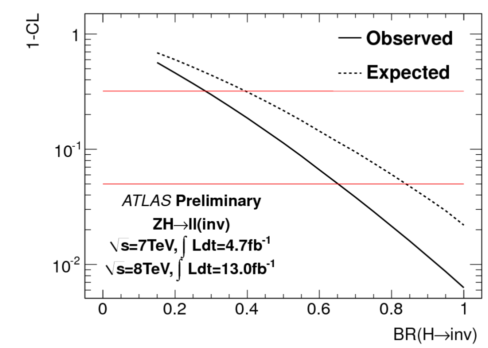
ZH⟶ℓℓ+invisible

40 [ATLAS-CONF-2013-011]





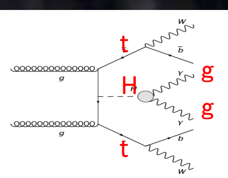
- MET > 90 GeV.
- 2D sideband on:
  - $|MET-p_T^{\ell\ell}|/p_T^{\ell\ell}$
  - $\Delta\phi(MET, \vec{p}_T^{\,miss.})$
- Not yet sensitive to standard candle: ZH⟶ZZZ⟶2ℓ4ν
- **At m_H=125 GeV, $BR_{inv.}$ < 0.65 (0.84)** (95%CL), obs.(exp.).



a.david@cern.ch Rencontres de Blois, May 2013

ttH, H ➛ gg

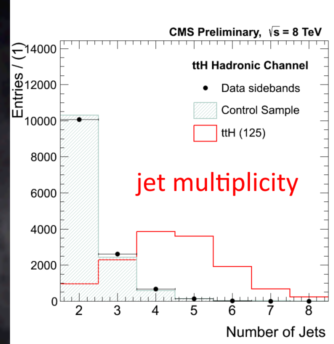
NEW

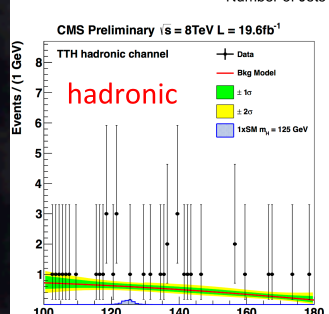


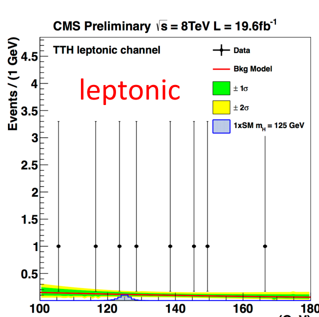
Small signal expected.

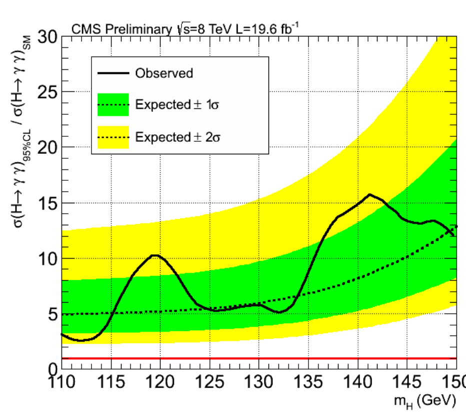
Preform two analyses to maximize sensitivity, optimized for leptonic and hadronic tt decays.

Not a significant excess observed, 95% CL upper limit on σ (ttH) × BR(H → γγ) = 5.4 × SM, 5.3 expected, at m_H = 125 GeV.



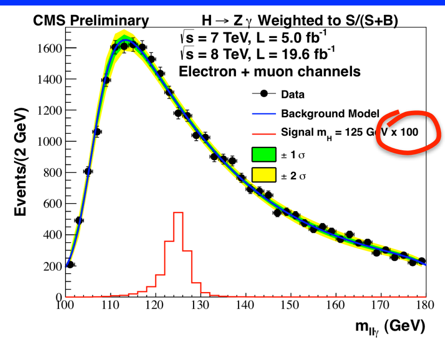


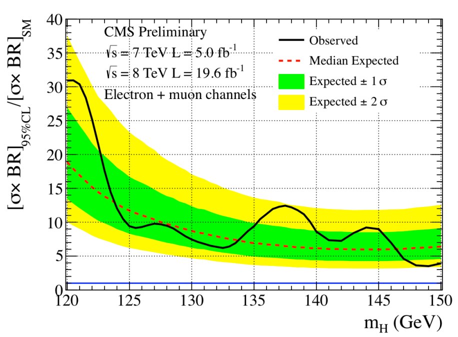




Less sensitive channels

H → Zγ





Analysis strategy:

- two prompt leptons: Z→ee, Z→μμ
- isolated photon
- **dilepton-photon mass** is the key observable
- split events further into classes, based on "geography" of leptons/photon and photon cluster quality
  - different mass resolutions
  - different S/B-ratios
- Background: fit using sidebands

Analysis features to note:

- very poor S/B-ratio
- very small event yield
- mass resolution = 1-2%

Results:

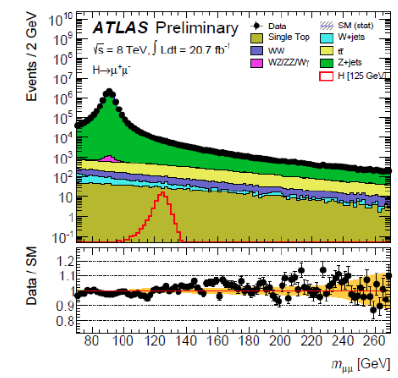
CMS (m_H=125): μ>10 is excluded at 95% CL
ATLAS (m_H=125): μ>18 is excluded at 95% CL

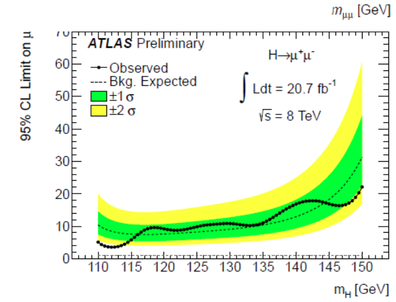
Points to note:

- **need 100 times more data** to reach 2σ-sensitivity

Andrey Korytov (UF) Tallahassee, 13 May 2013 16

H → μμ (ATLAS only)





Analysis strategy:

- two prompt muons: μμ
- **dimuon mass** is the key observable
- Background: fit using sidebands

Analysis features to note:

- very poor S/B-ratio
- very small event yield
- mass resolution = 2%

Results:

ATLAS (m_H=125): μ>10 is excluded at 95% CL

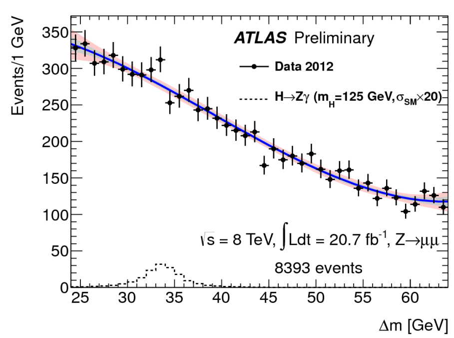
Points to note:

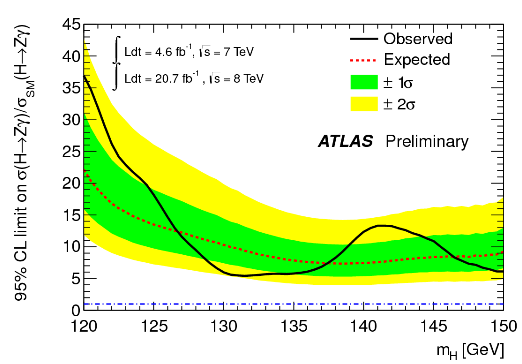
- **need 100 times more data** to reach 2σ-sensitivity

Andrey Korytov (UF) Tallahassee, 13 May 2013 17

Search for H→Zγ

- Reconstruct Z→ll and photon
- Take mass difference between H and Z





Observed limit at M_H=125 GeV is 18.2 × SM cross section (95% CL)

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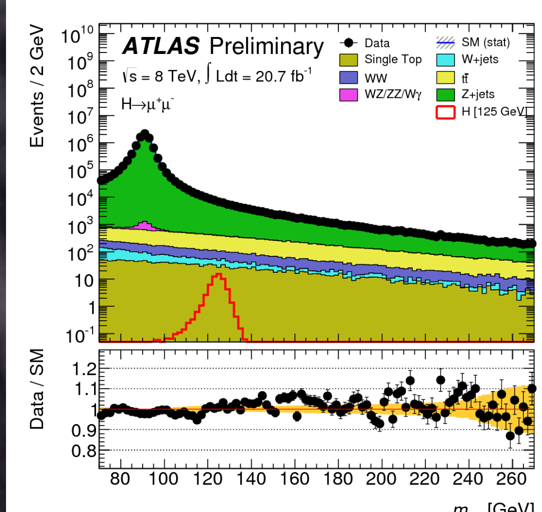
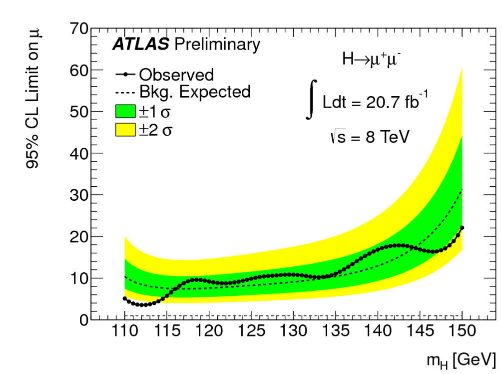
Search for H→μ μ

- Look for a peak in μμ mass spectrum





Observed limit at M_H=125 GeV is 9.8 × SM cross section (95% CL)

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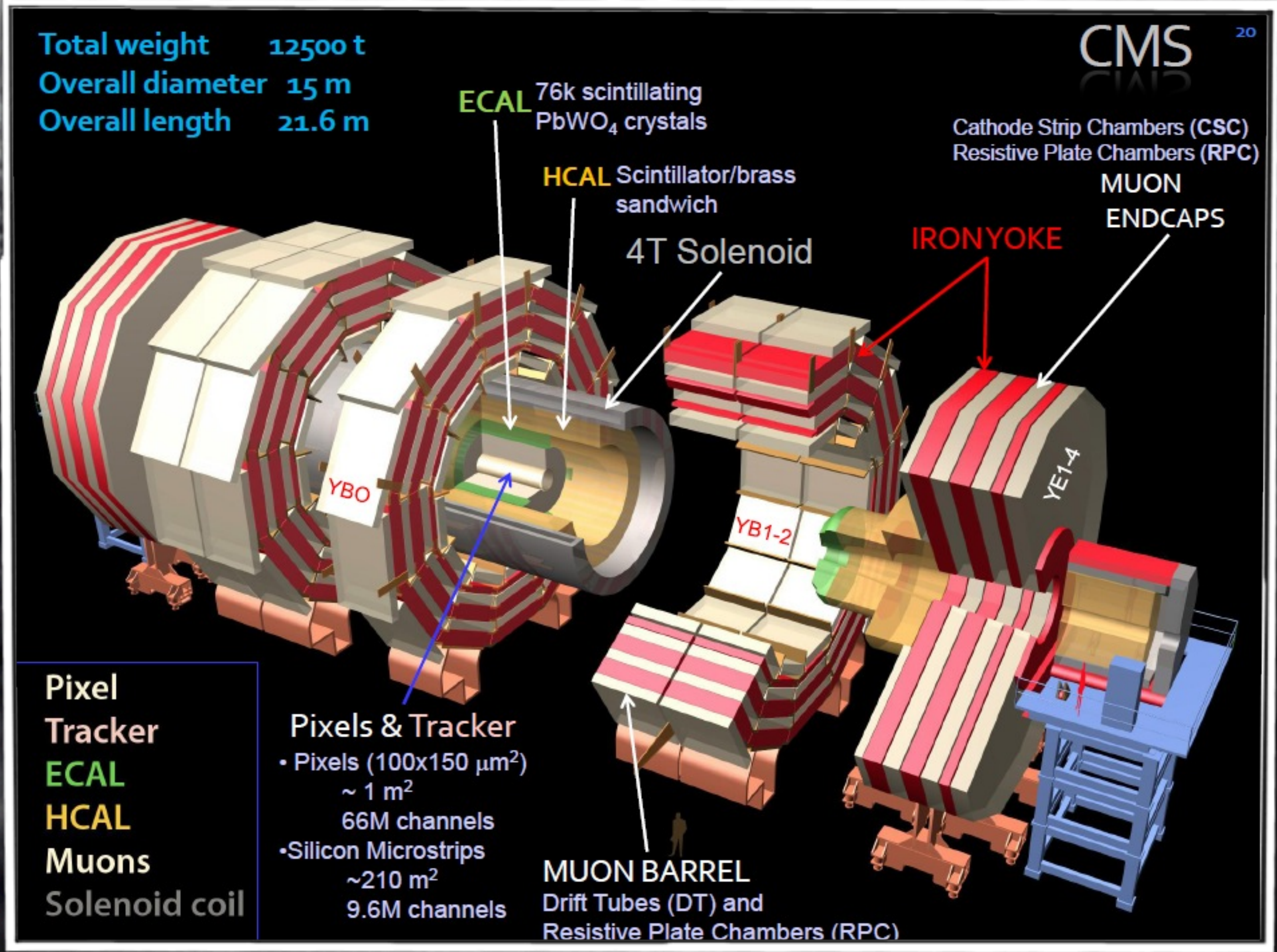
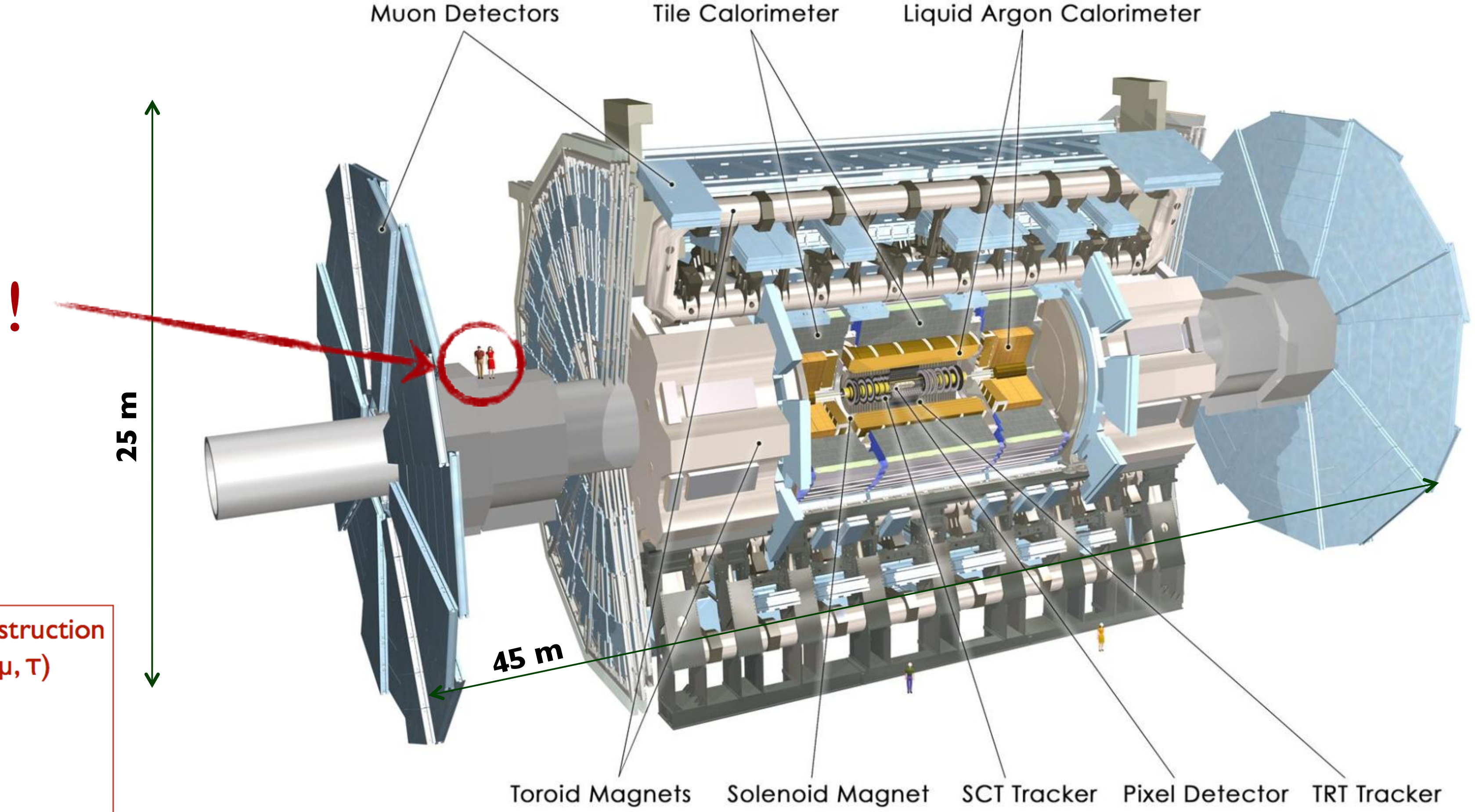
CMS


Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
CMS
20
ECAL 76k scintillating PbWO4 crystals
HCAL Scintillator/brass sandwich
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
IRON YOKE
4T Solenoid
YBO
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²)
~ 1 m²
66M channels
•Silicon Microstrips
~210 m²
9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)

ATLAS

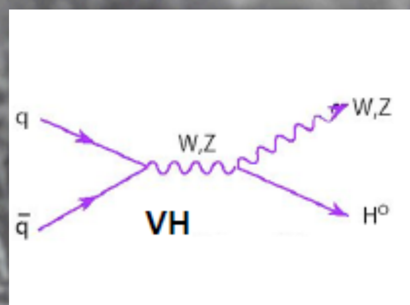
Detector Overview

Multi-purpose, high resolution and hermetic detector
Magnets: Central Solenoid + 3 Toroids
Tracking: Silicon, Transition Radiation Tracker
Calorimeter: EM (LAr), Had Cal
Muon: Trigger + Precision chambers

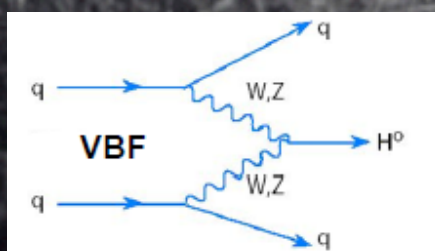


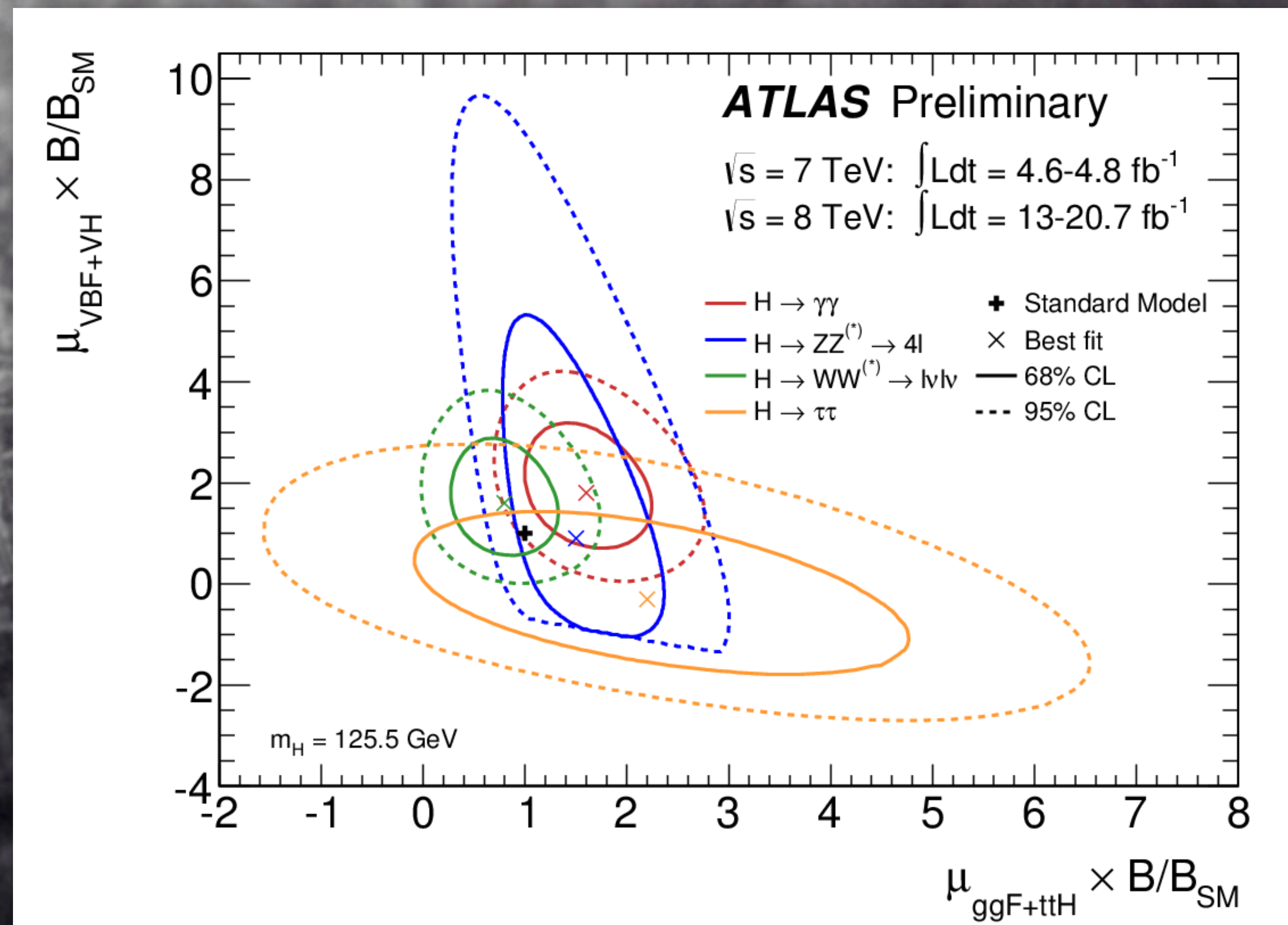
Object Reconstruction
- leptons (e, μ, τ)
- photons
- jets
- b-jets
- Etmiss

Compare production modes

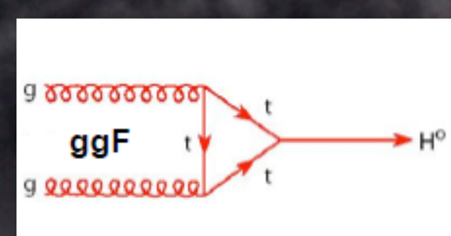


+





vs.



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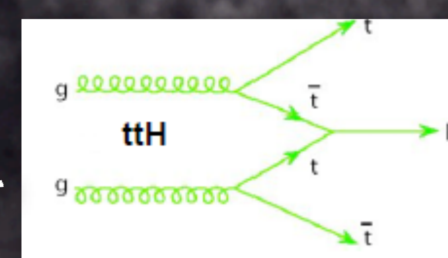


μ(VBF+VH) / μ(ggF+ttH) = 1.2 (+0.7,-0.5)

LHC in 2015

Potential performance

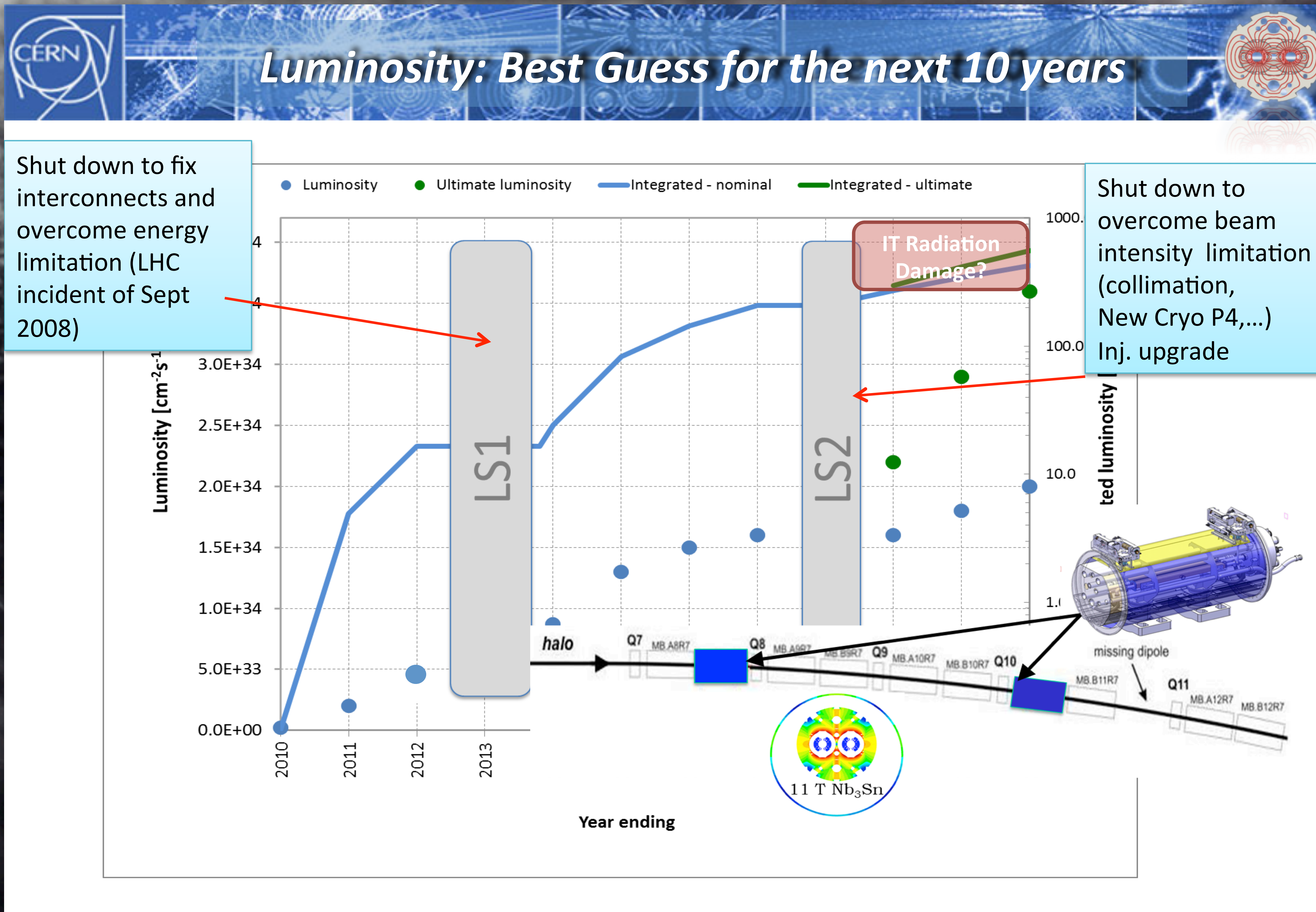
	Number of bunches	Ib LHC FT[1e11]	Collimator scenario	Emit LHC (SPS) [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi [fb^{-1}]
25 ns	2760	1.15	S1	3.5 (2.8)	9.2e33	21	24
25 ns low emit	2320	1.15	S4	1.9 (1.4)	1.6e34	43	42
50 ns	1380	1.6	S1	2.3 (1.7)	1.7e34 level 0.9e34	76 level 40	~45*
50 ns low emit	1260	1.6	S4	1.6 (1.2)	2.2e34	108	…

- 6.5 TeV
- 1.1 ns bunch length
- 150 days proton physics, HF = 0.2
- 70 mb visible cross-section
- * different operational model – caveat - unproven

All numbers approximate

LHCP 2013
Sergio Bertolucci CERN

LHC 10 yrs


CERN
Luminosity: Best Guess for the next 10 years
Shut down to fix interconnects and overcome energy limitation (LHC incident of Sept 2008)
Luminosity
Ultimate luminosity
Integrated - nominal
Integrated - ultimate
IT Radiation Damage?
Shut down to overcome beam intensity limitation (collimation, New Cryo P4,…) Inj. upgrade
Luminosity [cm-2s-1]
3.0E+34
2.5E+34
2.0E+34
1.5E+34
1.0E+34
5.0E+33
0.0E+00
1000.
100.0
10.0
LS1
LS2
2010
2011
2012
2013
Year ending
halo
Q7
Q8
Q9
Q10
Q11
MB.A8R7
MB.A10R7
MB.B10R7
MB.B11R7
MB.A12R7
MB.B12R7
missing dipole
11 T Nb3Sn

Early speculation

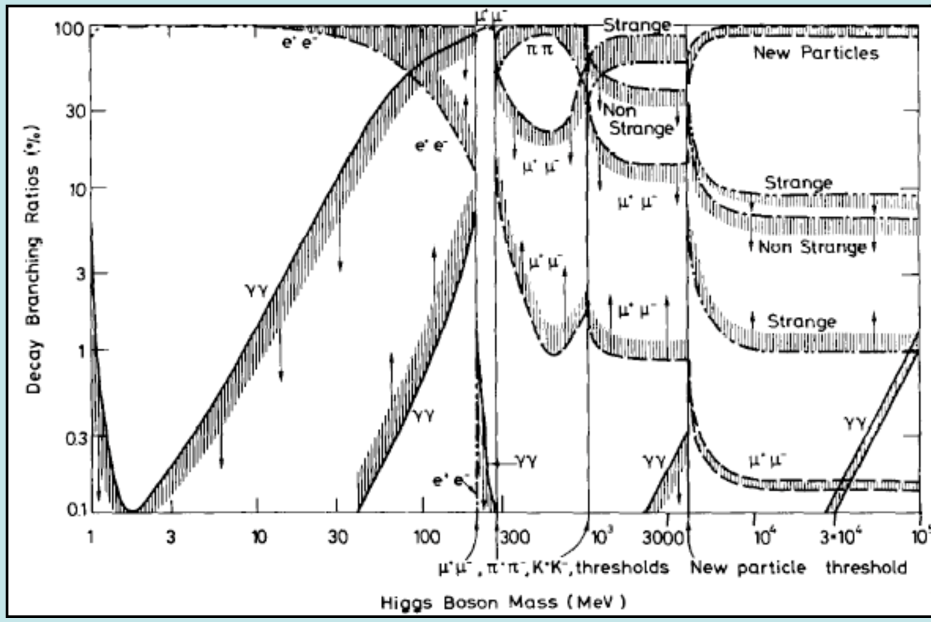
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

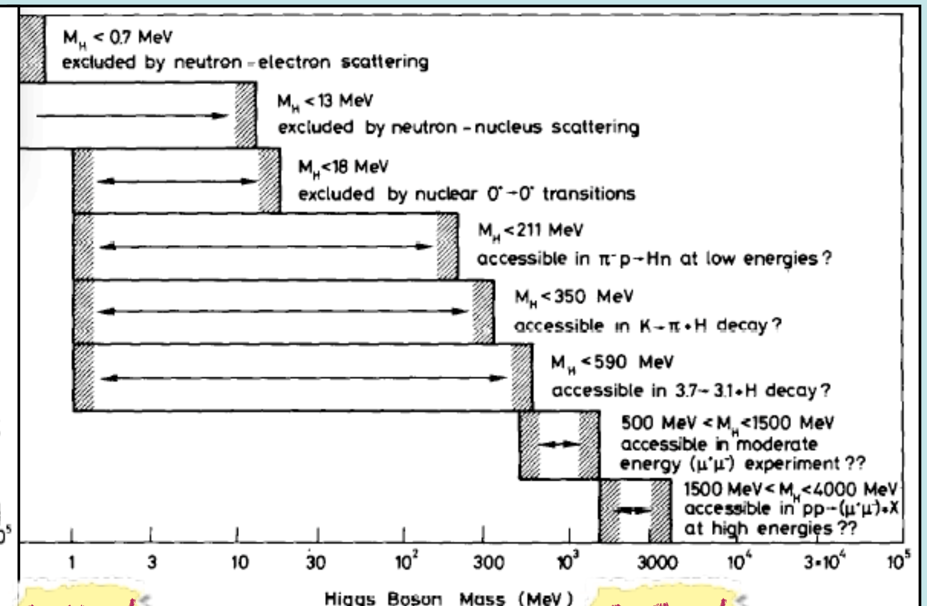
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

From J. Ellis @ 2011 Higgs Hunting Workshop

- Higgs decay modes and searches in 1975:





1 MeV

3 GeV

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

On Spin

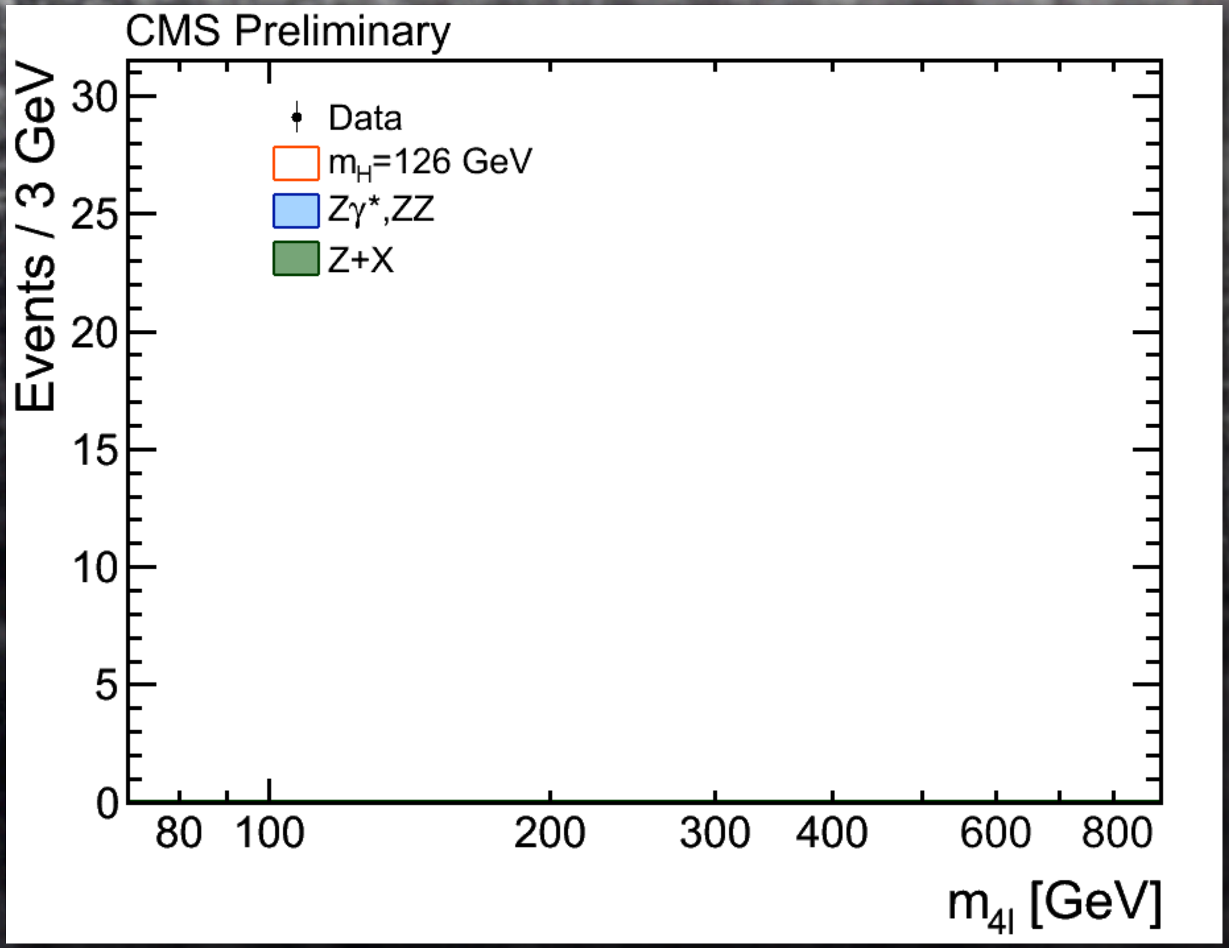
Determining Spin and CP Properties

- The determination of the spin and CP properties of the new boson relies on the study of angular (and invariant-mass) distributions from the $X \rightarrow ZZ^* \rightarrow 4l$, $X \rightarrow WW^* \rightarrow 2\ell 2\nu$, and $X \rightarrow 2\gamma$ decays.
  - For a SM Higgs boson (a scalar, JP = 0+), the decay angles are independent of the production mechanism
  - For a vector (JP = 1-) such as some exotic Z' or axial vector (JP = 1+) the differential cross sections depend in no-trivial ways on Z production angles
  - For a spin 2 tensor (JP = 2+) or pseudo-tensor (JP = 2-) many different models are possible (graviton-like or couplings to ZZ energy-momentum tensor with non-universal graviton-like coupling to avoid existing exclusion constraints) (see e.g. S. Bolognesi et al., Phys.Rev.D86 (2012) 095031)
  - The X production mechanism (e.g. fraction of gluon-gluon vs q-qbar induced production, etc.) can in general play a role (via initial state polarization scenarios for J=1,2; spin correlations, ...)
  - The new boson is of course not necessarily a pure spin-parity state ... there could be coupling mixture etc. ... or the couplings can conserve P and CP while the X is not ` point-like so that couplings to the Z are affected etc.
- Any deviation from the predicted quantum numbers or couplings of a SM Higgs would have deep ramifications for particle physics

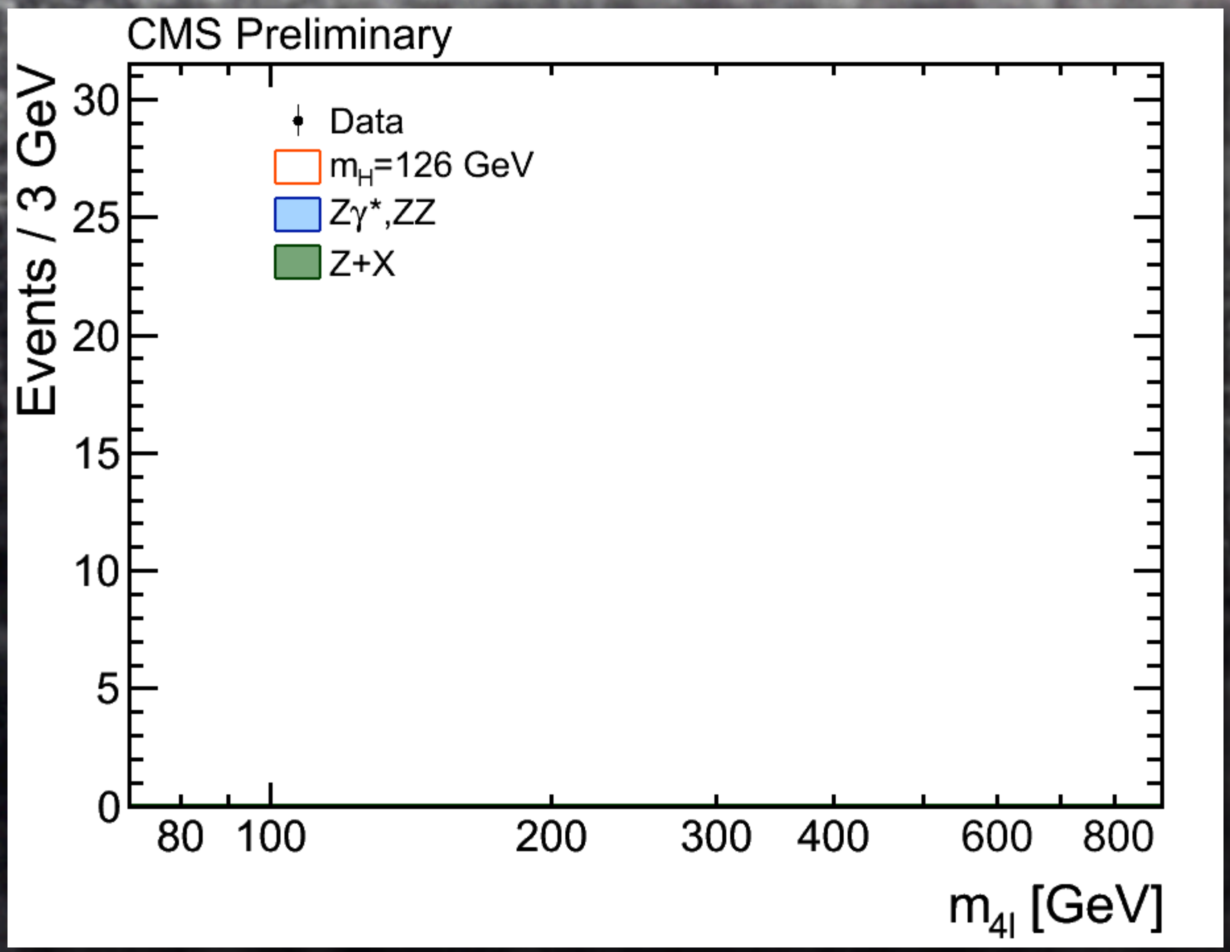
Y. Sirois - LLR Ecole Polytechnique & CNRS

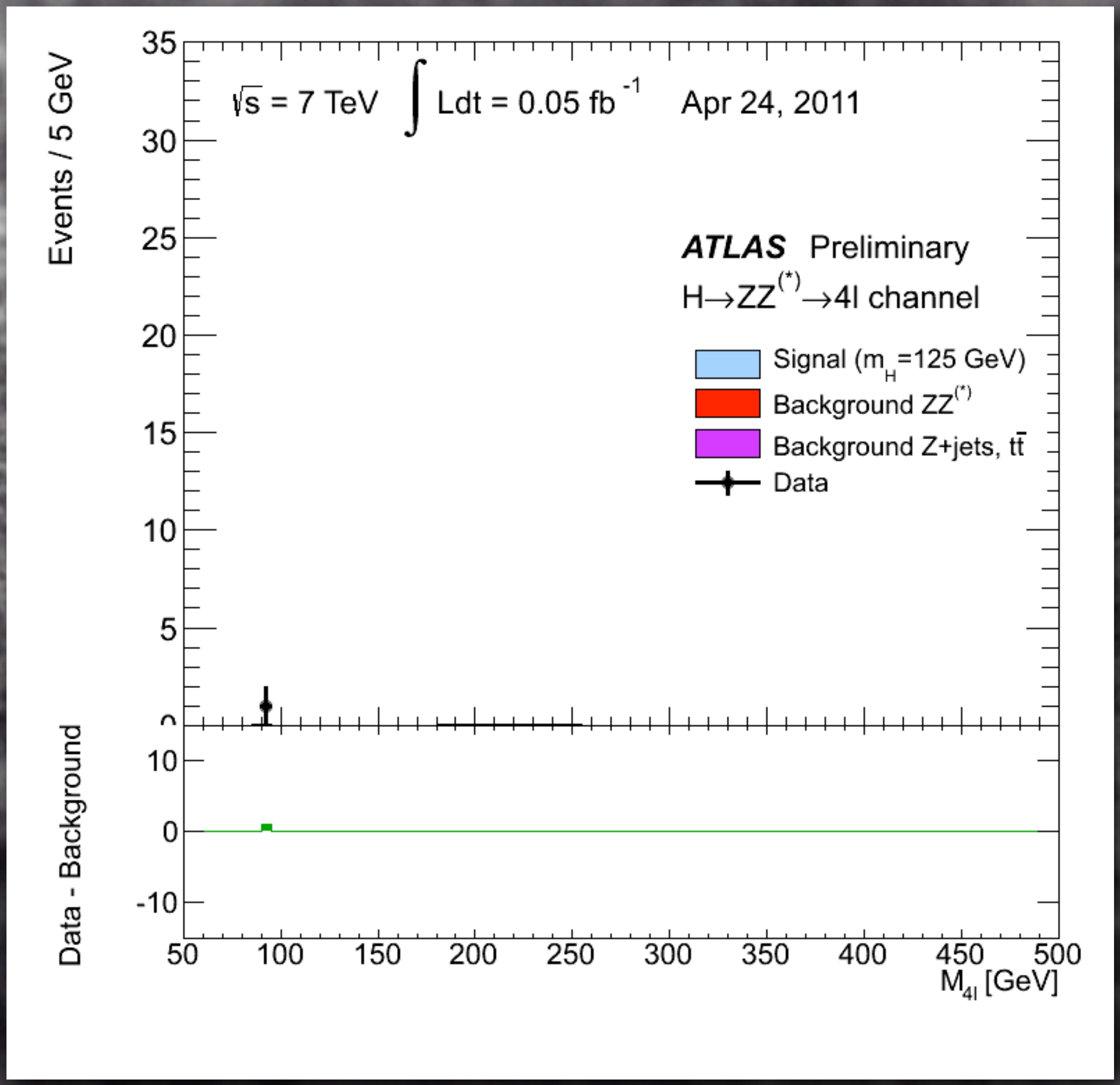
H => Z*Z => 4l - the movie

H => Z*Z => 4l - the movie



H => Z*Z => 4l - the movie





H => Z*Z => 4l - the movie