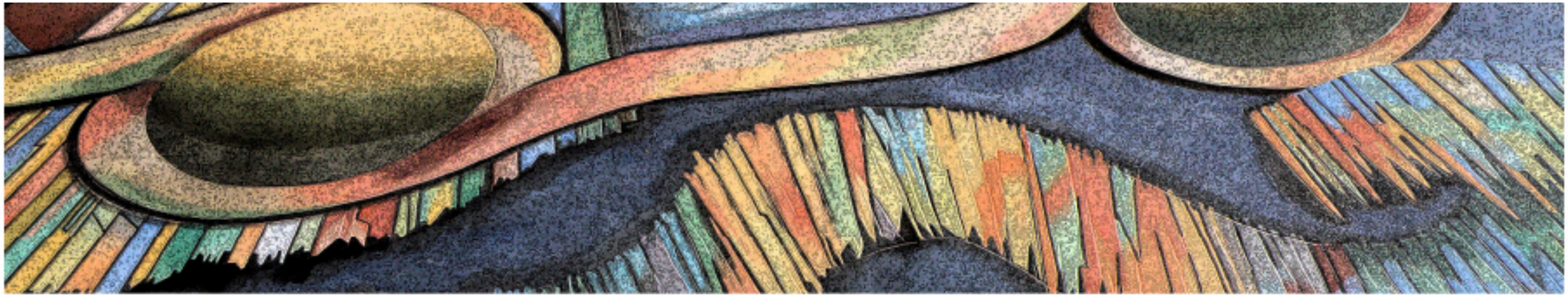


UiO : Department of Physics
University of Oslo

Measurements of the* Higgs boson

Alex Read (U.Oslo)

Nobel Symposium on LHC results, 13-17.05.2013

* The one announced at CERN 04.07.2012

The Research Council of Norway

Outline

- Recap SM, Higgs boson production @ LHC, ATLAS and CMS experiments, discovery of a Higgs boson
- Summarize enormous set of measurements:

Higgs Results for Winter 2013 Conferences NEW

Channel	Conference note	L	Date
Spin Combination	Almost new	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) BSM	...AS-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) BSM	...A-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

SM H to tautau	ATLAS-CONF-2012-160	4.7+13.0
SM VH, H to bb	ATLAS-CONF-2012-161	4.7+13.0
SM ttH, H to bb	ATLAS-CONF-2012-135	4.7

Recent Results (Preliminary) CMS

High mass (BSM)

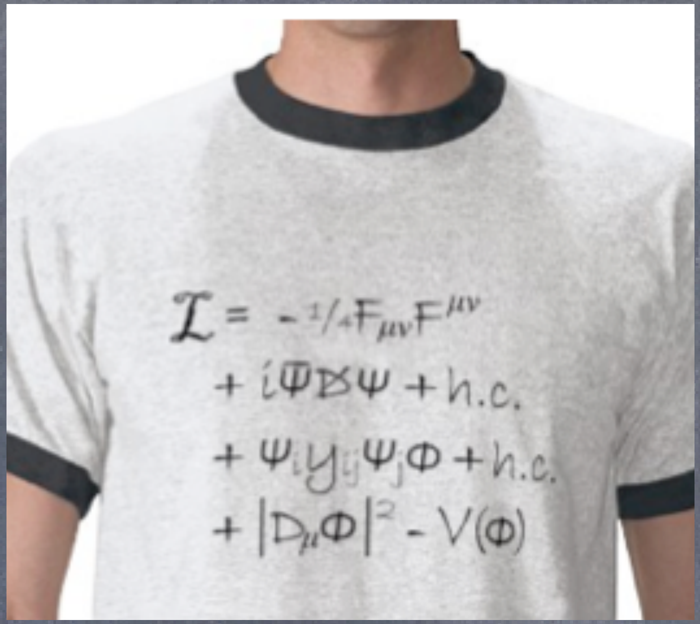
May-2013	Full 8 TeV dataset: H -> ...	TWiki, PAS
May-2013	Full 7+8 TeV dataset: H -> ZZ -> 2l2nu	TWiki, PAS
Apr-2013	Moriond Higgs Combination	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> gamma gamma	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> ZZ -> 4l	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> 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

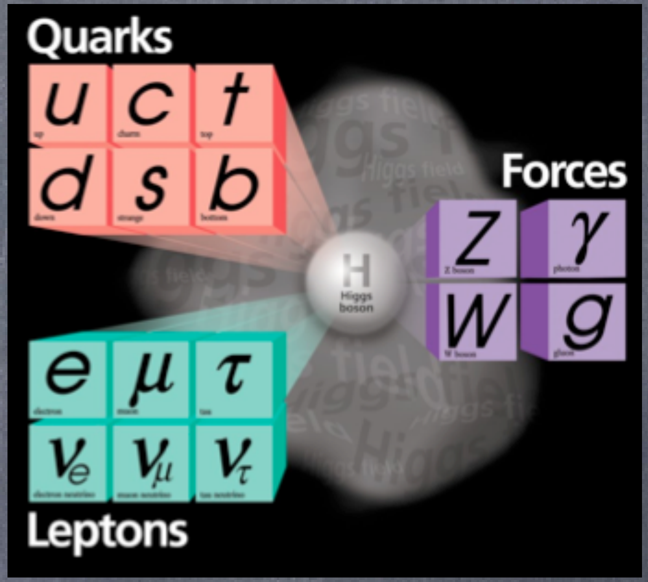
CMS New: VH->Vbb, VBF H->bb

Measurements of Higgs Boson Couplings and Properties *at the Tevatron*

The Higgs boson....
...an integral part of the SM

- Renormalizable relativistic QFT with local gauge invariance $U(1)_Y \times SU(2)_L \times SU(3)_C$
- Success of QED, high-energy behavior of 4-fermion weak interactions, drives electroweak unification to propose massive gauge bosons (not to mention exp. results at CERN in 1980's)
- Higgs/BEH/GABEGHHK'tH-mechanism breaks gauge symmetry in the vacuum state - W-S incorporated it in EW (G) model





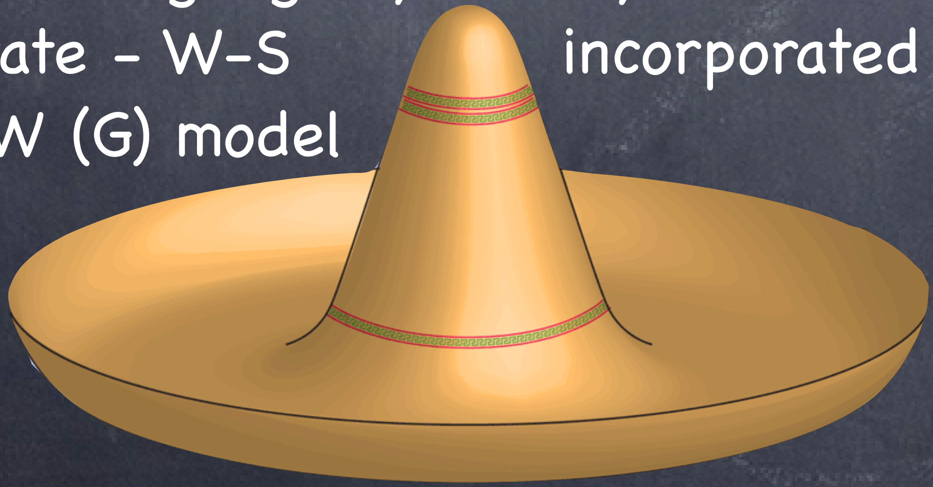
$$V(\phi^\dagger\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$

$$v = \sqrt{\frac{-\mu^2}{\lambda}}$$

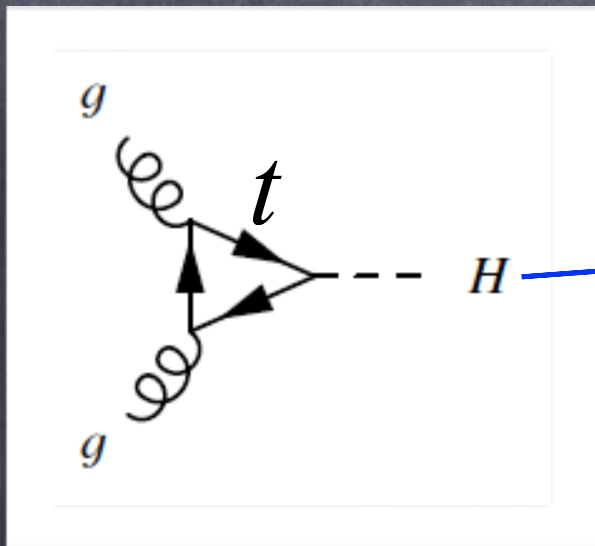
$$g = \frac{e}{\sin\theta_w}, \; m_W = \frac{gv}{\sqrt{2}}, \; m_Z = \frac{m_W}{\cos\theta_W}$$

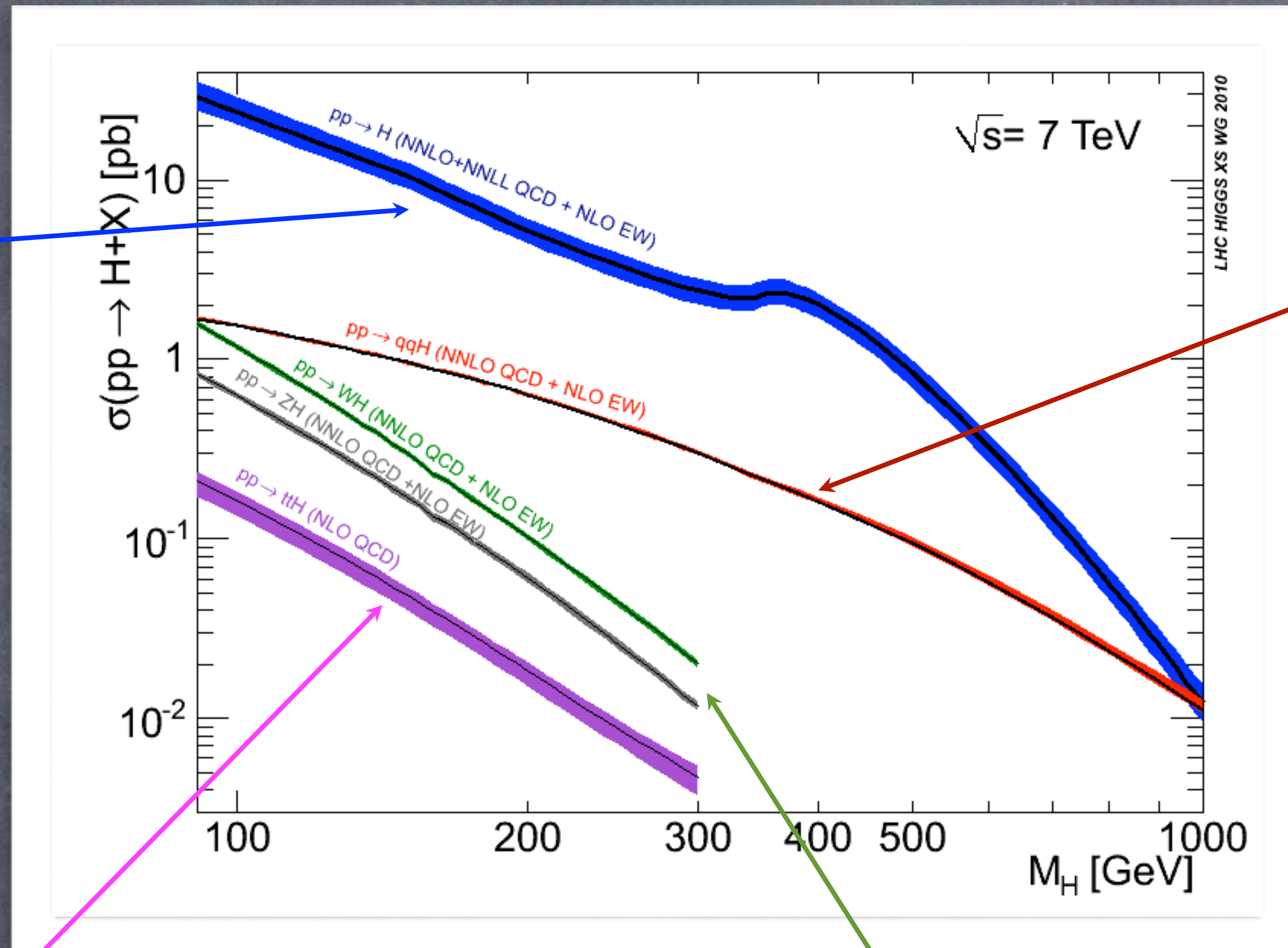
$$m_H^2 = -2\mu^2$$

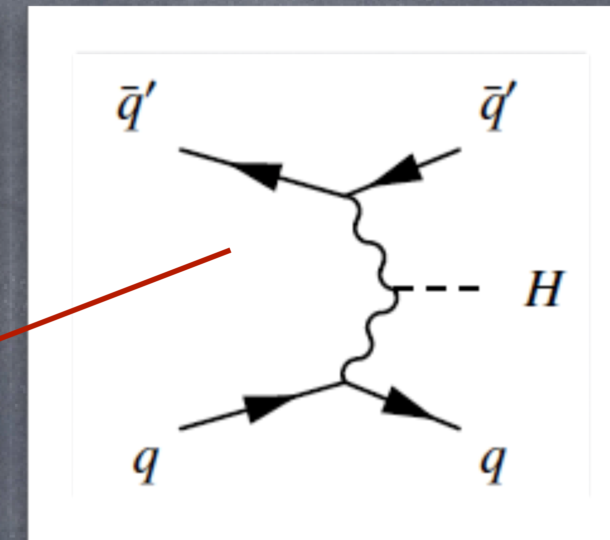
$$m_f = \frac{vg_f}{\sqrt{2}}, \Gamma_f \sim m_f^2 * n_c$$



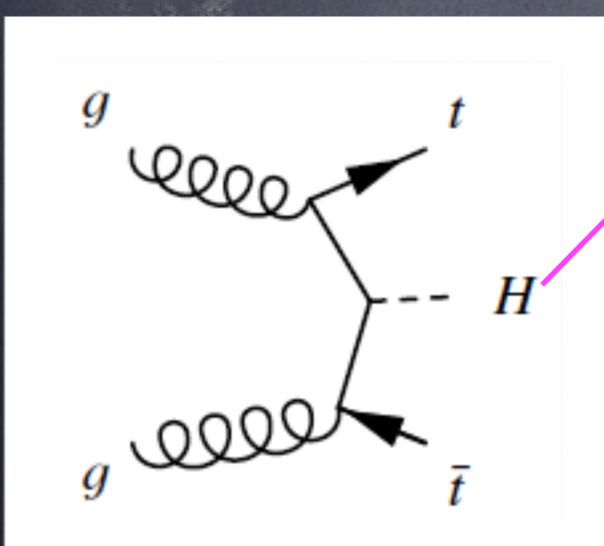
Higgs production @ LHC



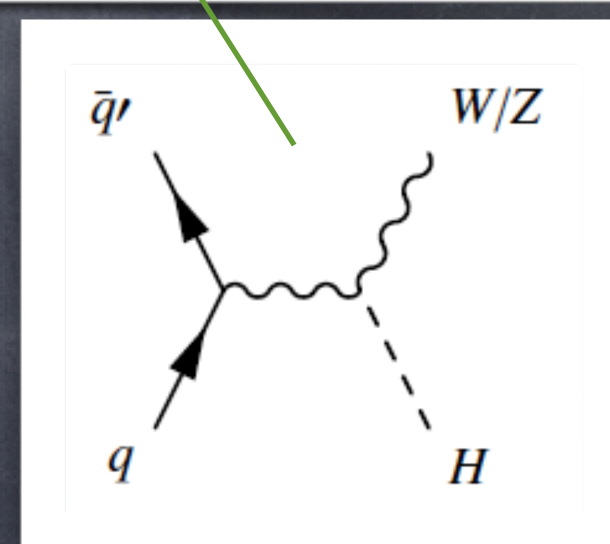




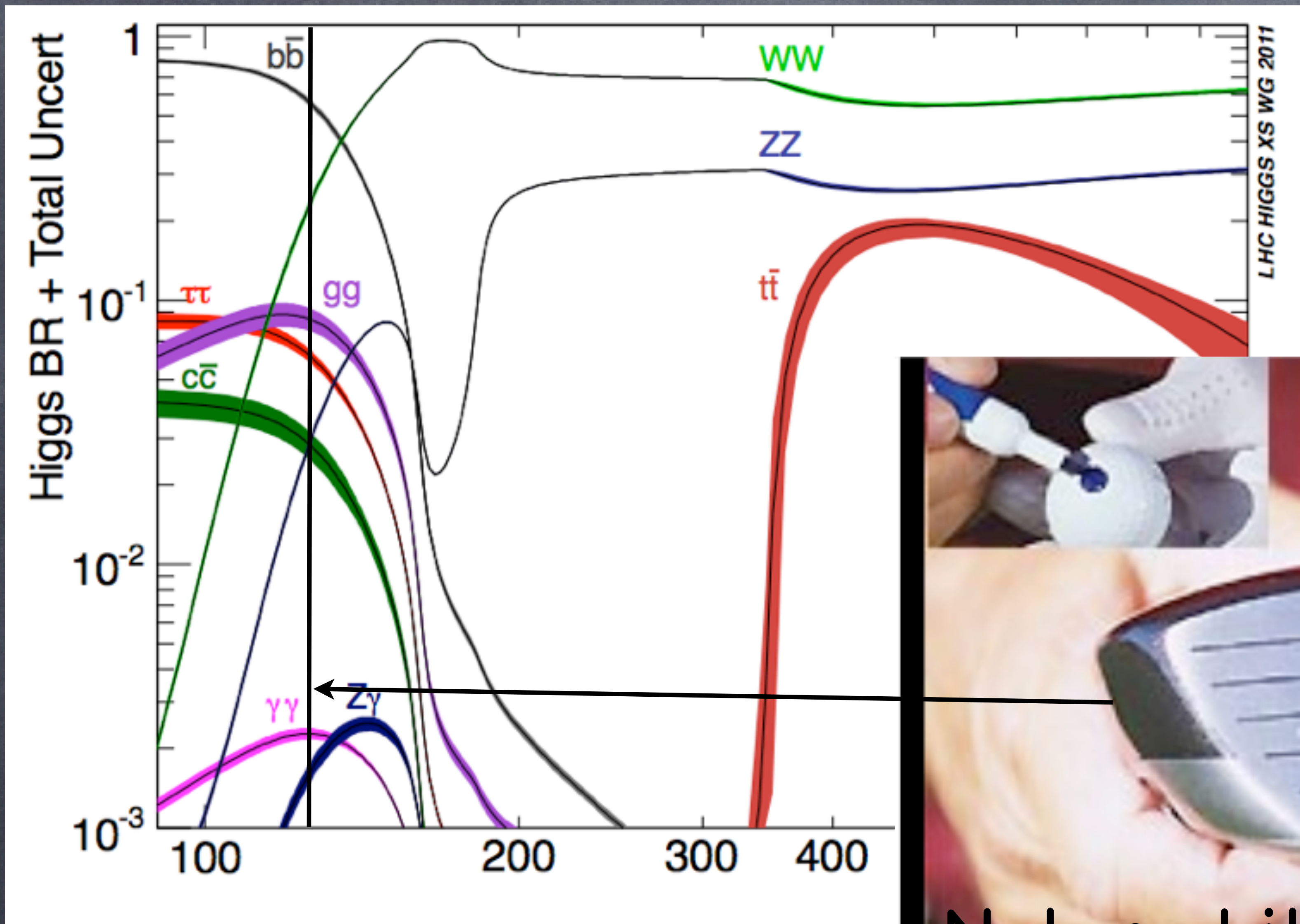
VBF



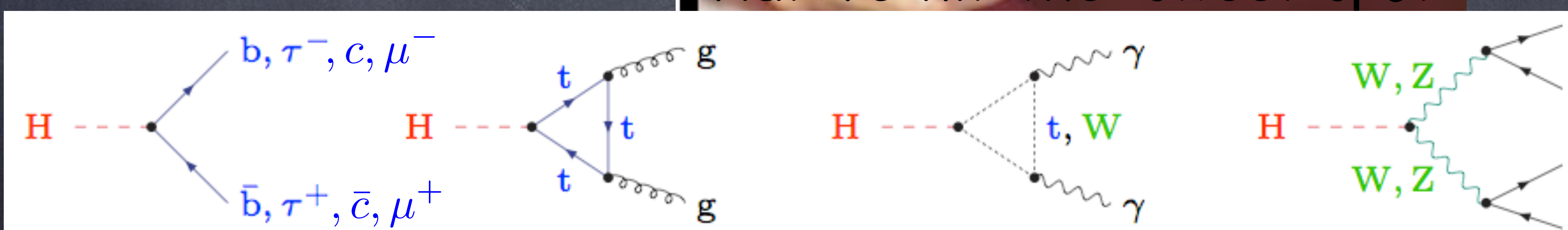
Compiled by LHCXSWG



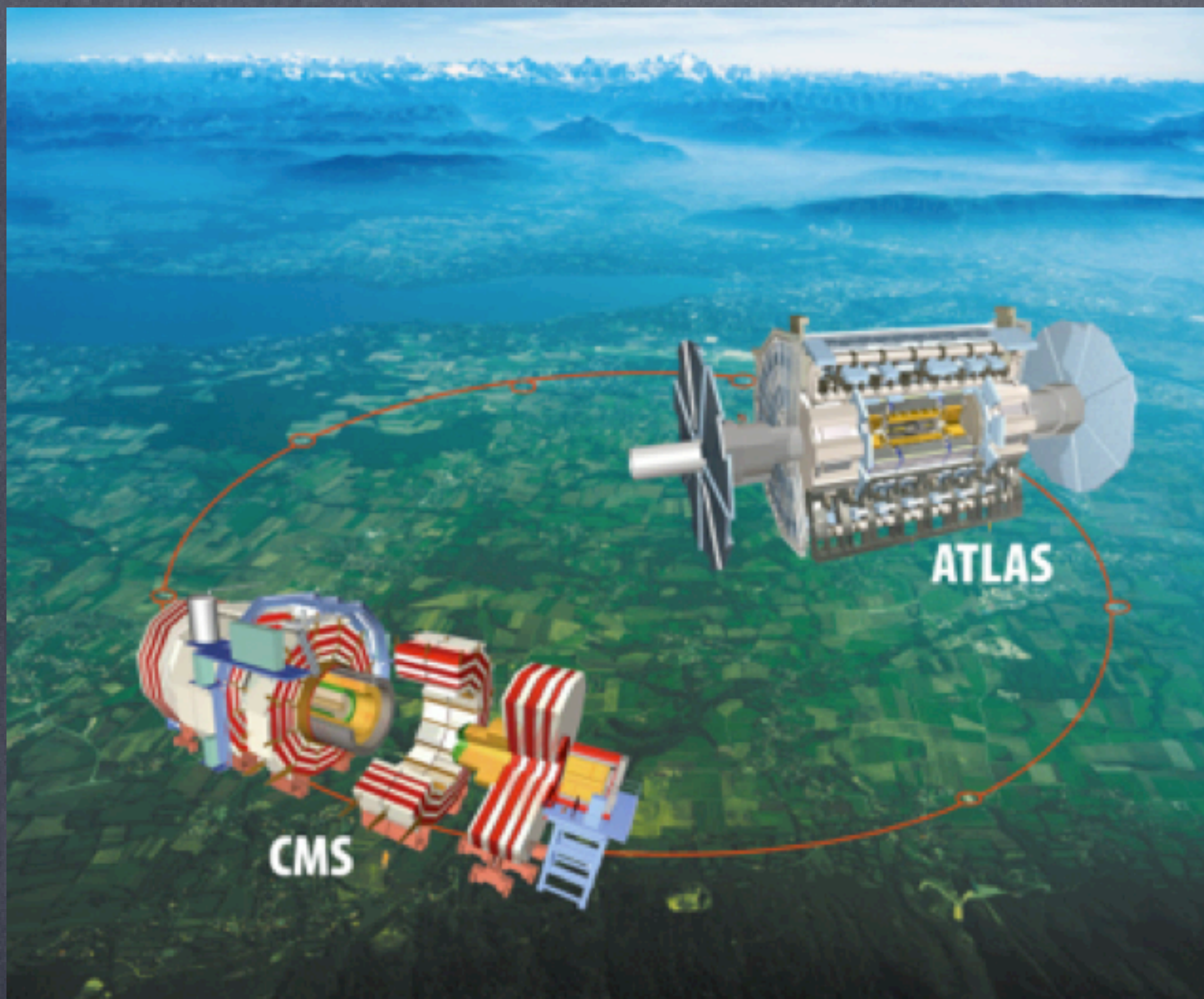
From m_H to branching fractions



- Assumes no invisible (BSM) width

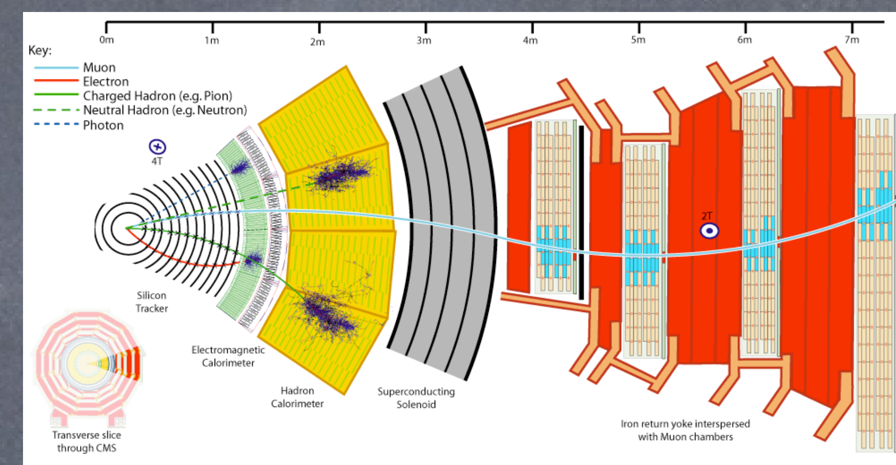


CMS, ATLAS experiments

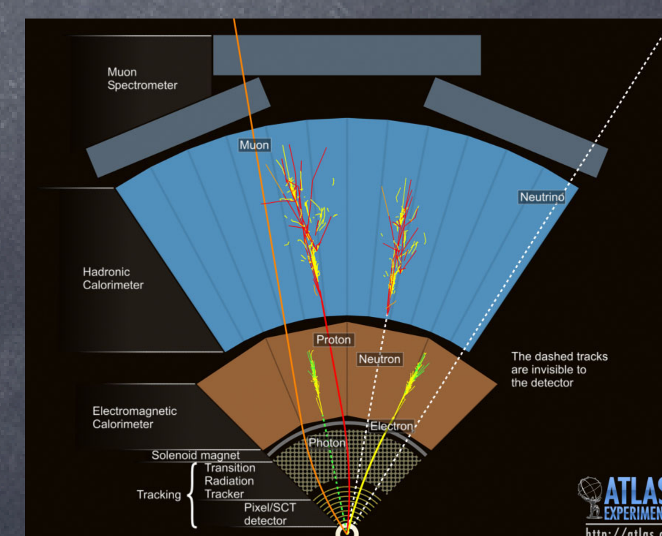


CMS	ATLAS
14 ktons	7 ktons
B=3.8 T	B=2 T
15x29 m	22x45 m

- CMS: Compact, high sol. field, all-Si tracker, crystal ECAL

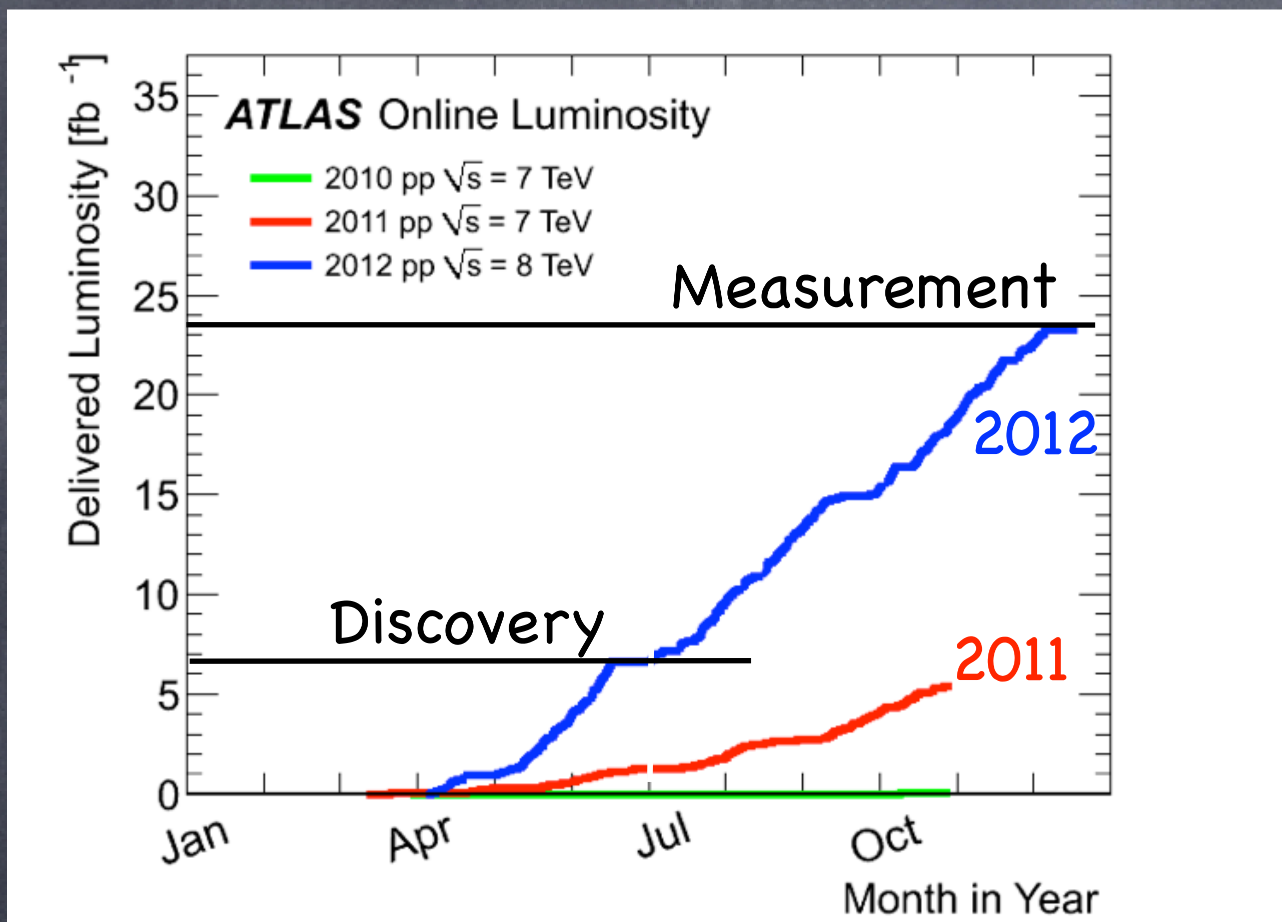


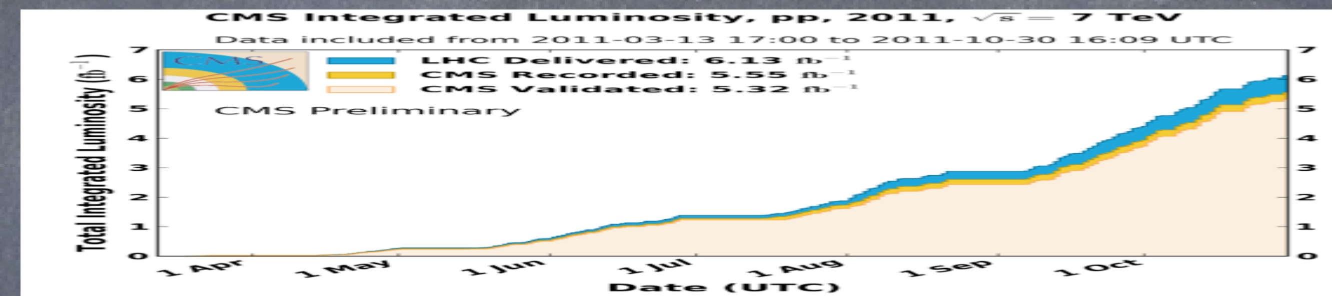
- ATLAS: Air-core toriod, accordian LAr ECAL

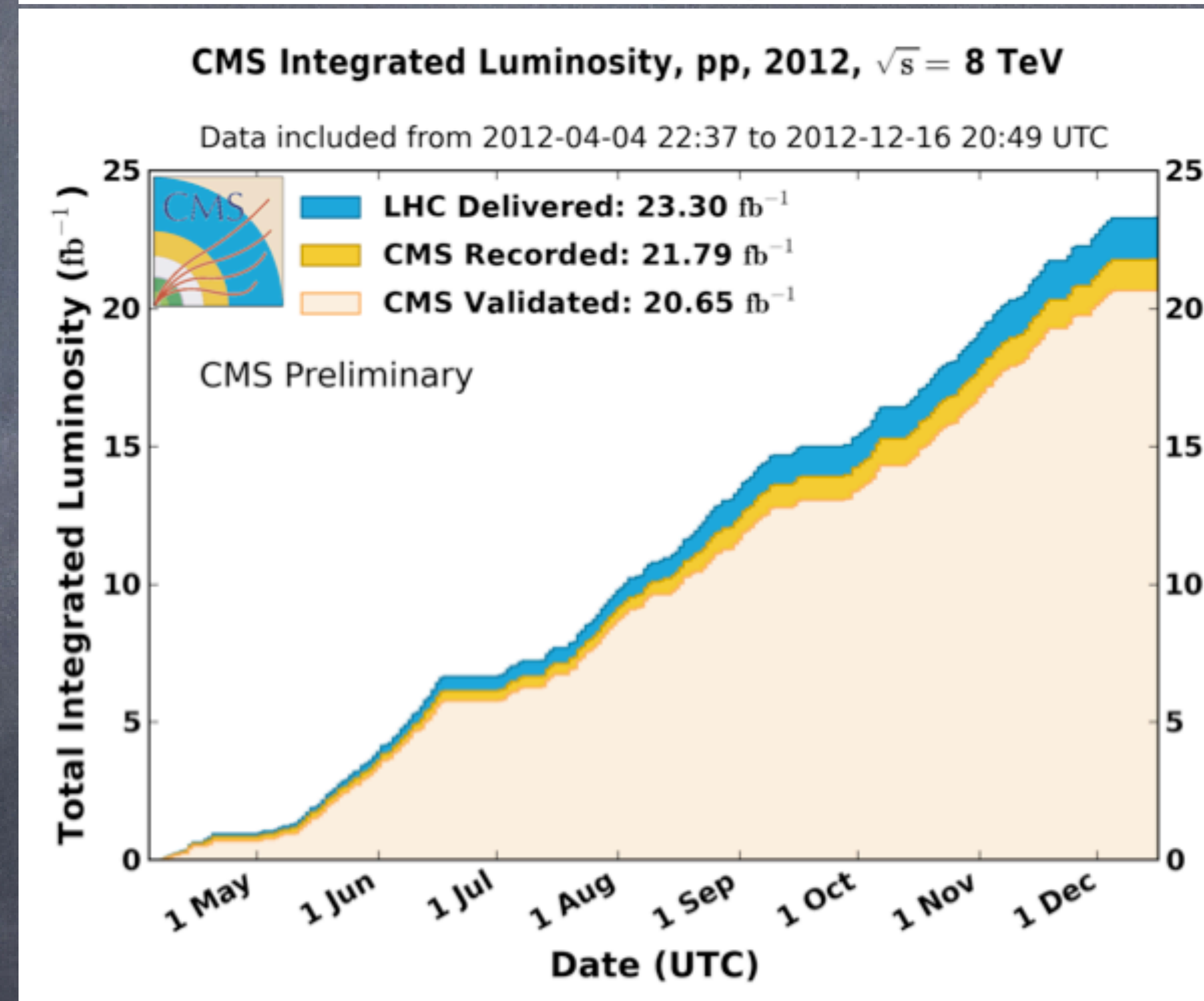


ATLAS, CMS collaborations

LHC data samples





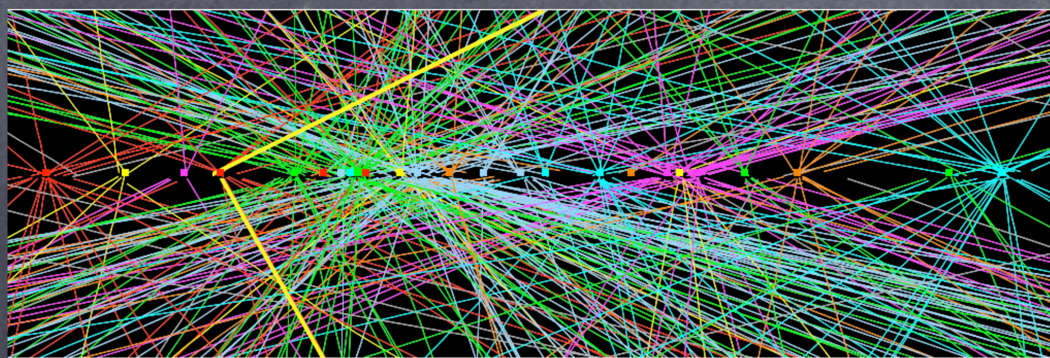


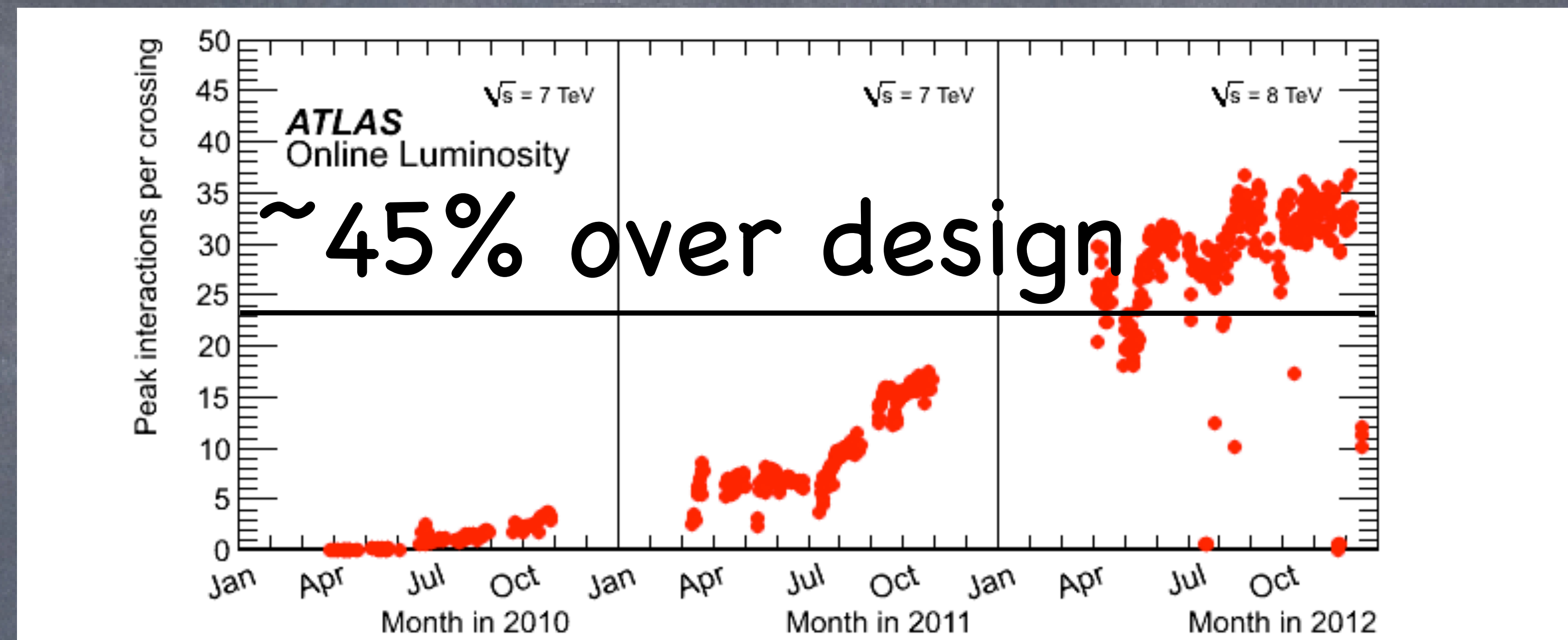
Results from both expt.s

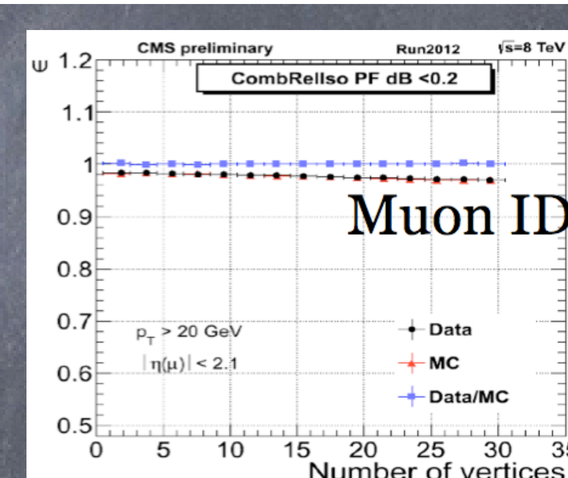
7 TeV: <~ 5/fb

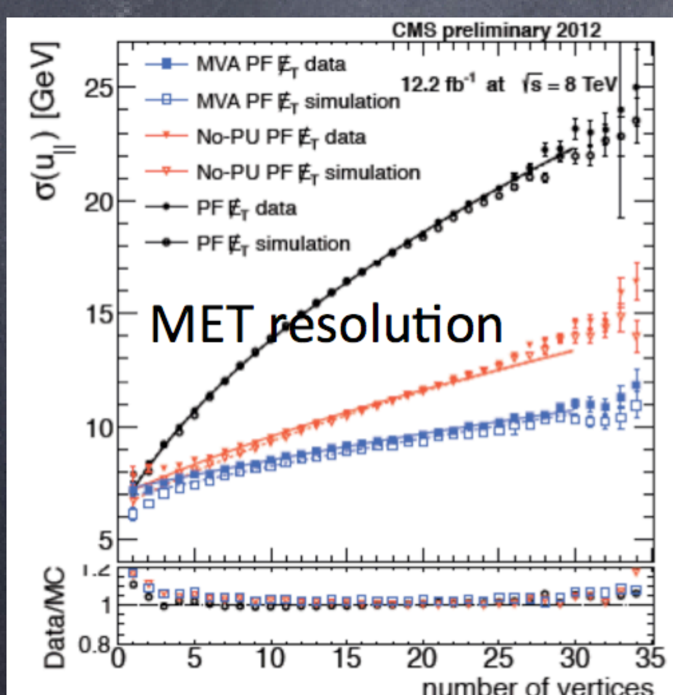
8 TeV: <~20/fb

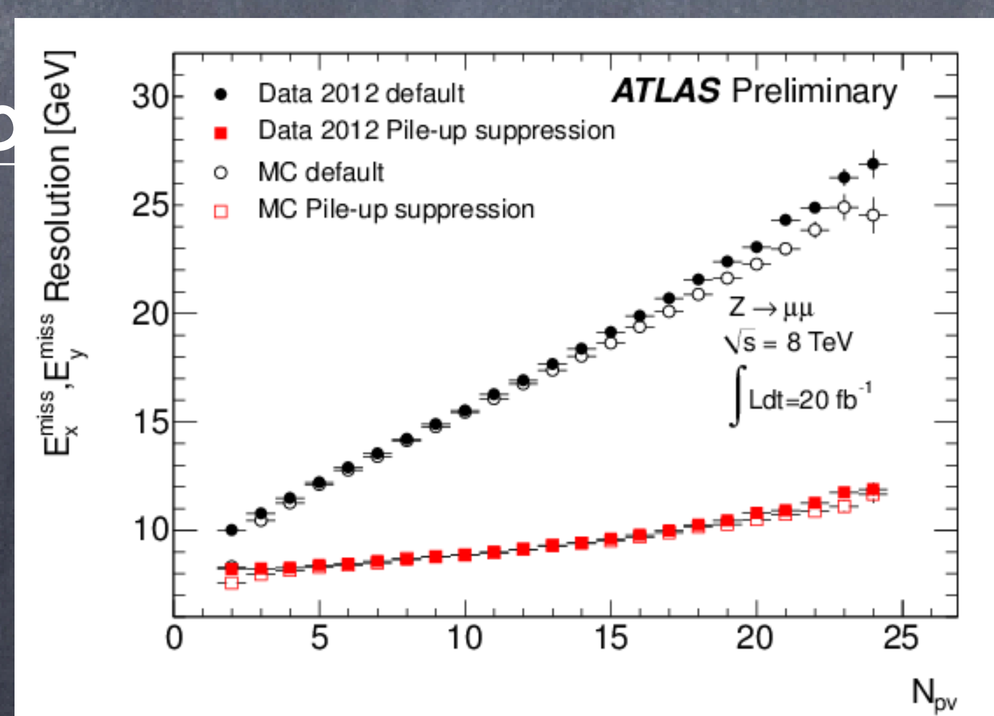
Pile-up challenge

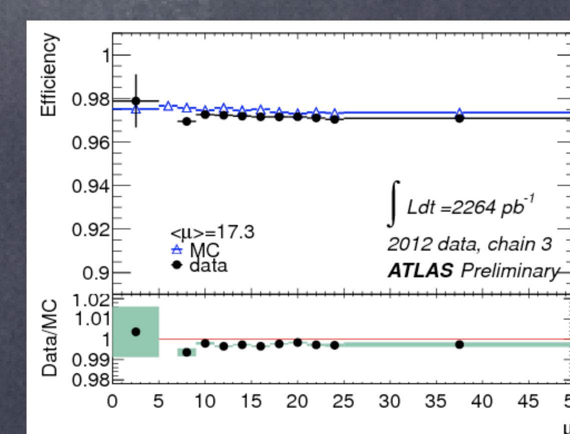




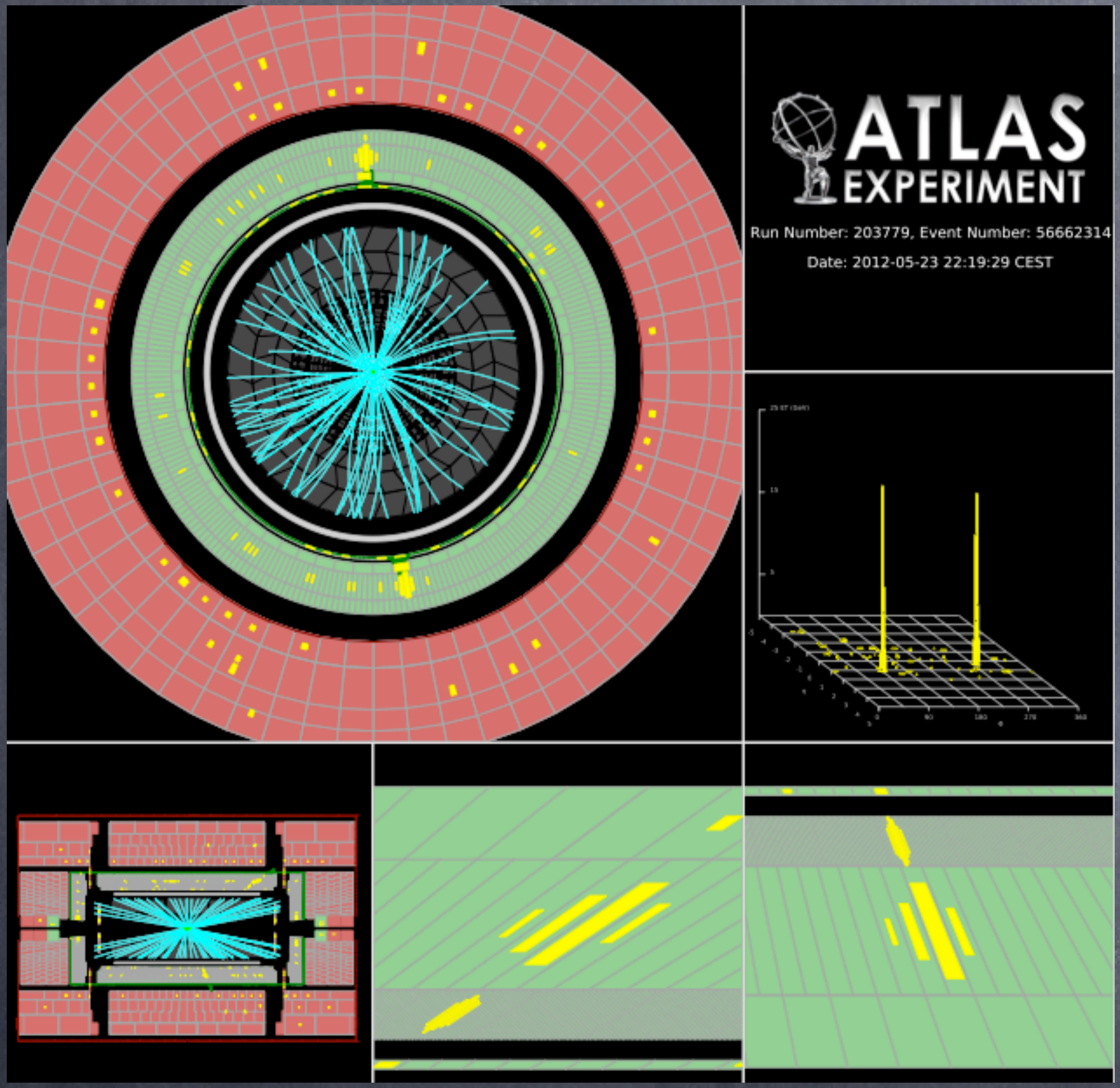


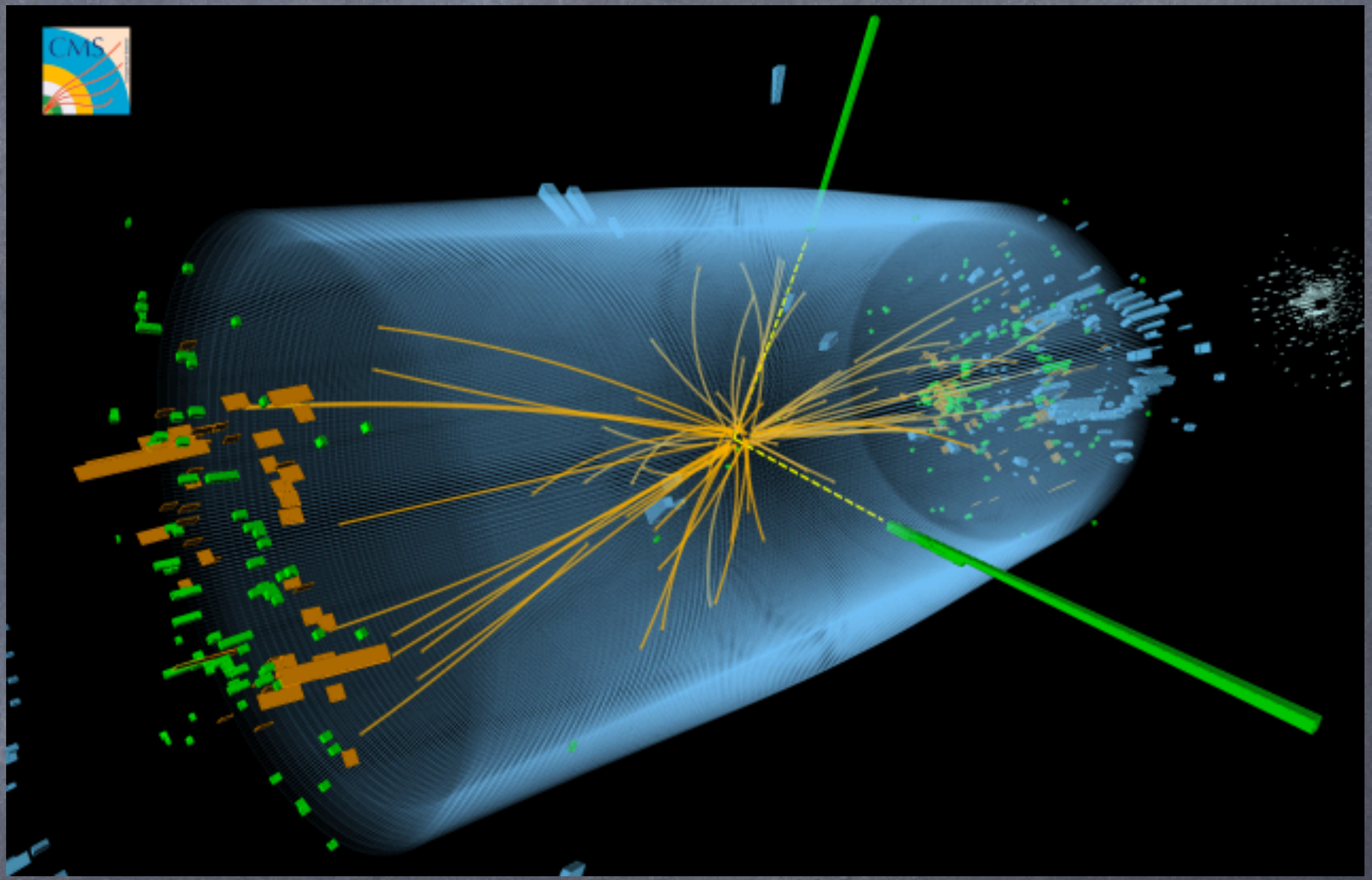






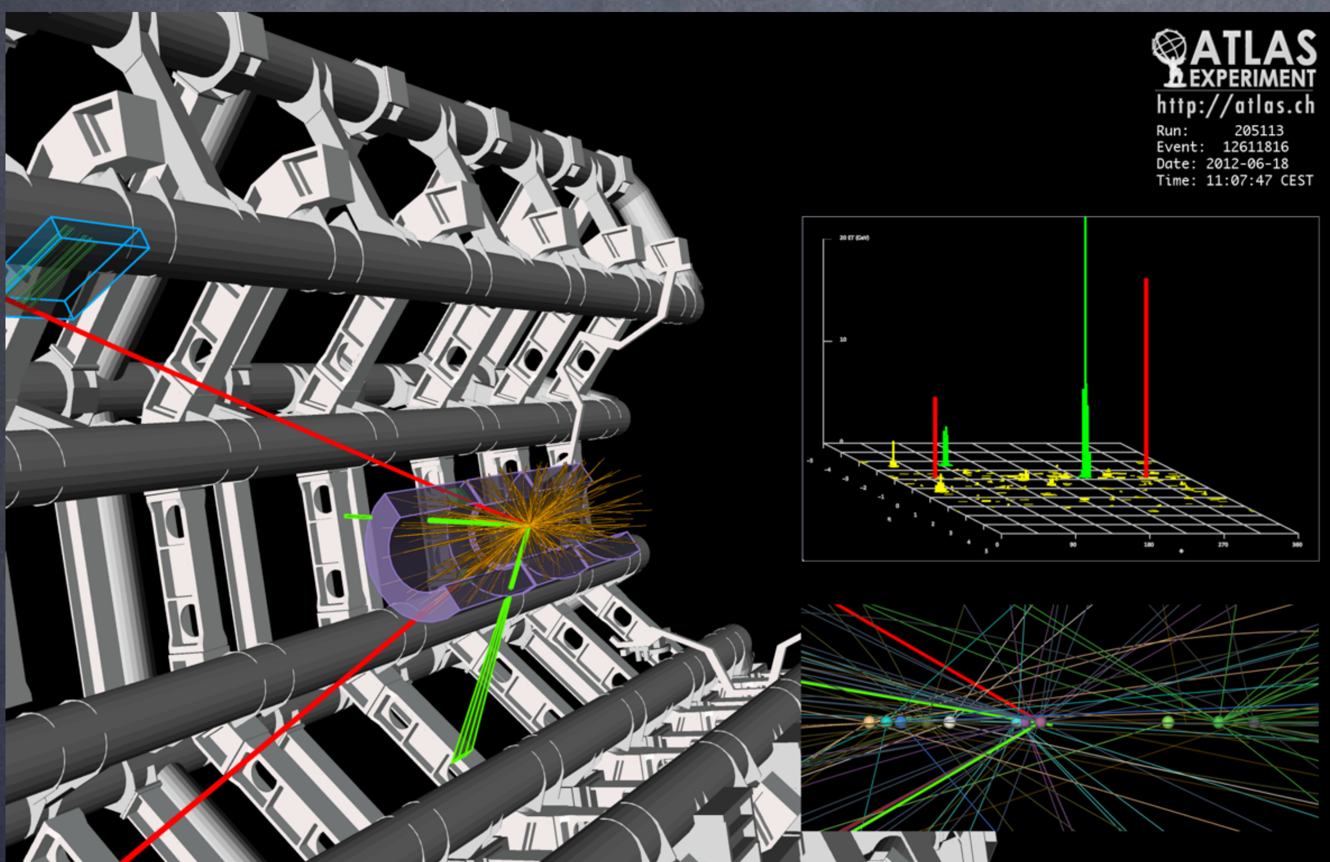
Candidate $H \to \gamma\gamma$

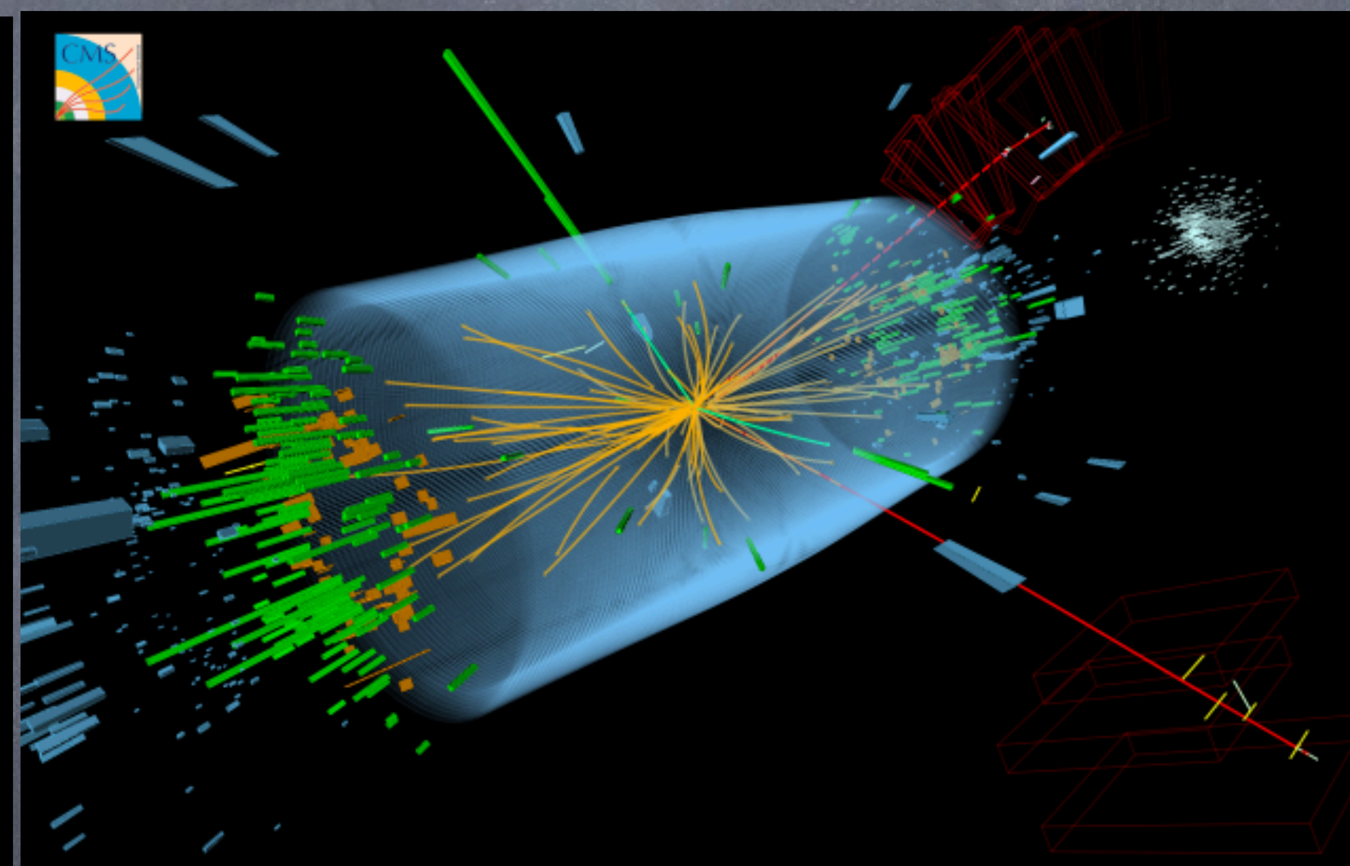




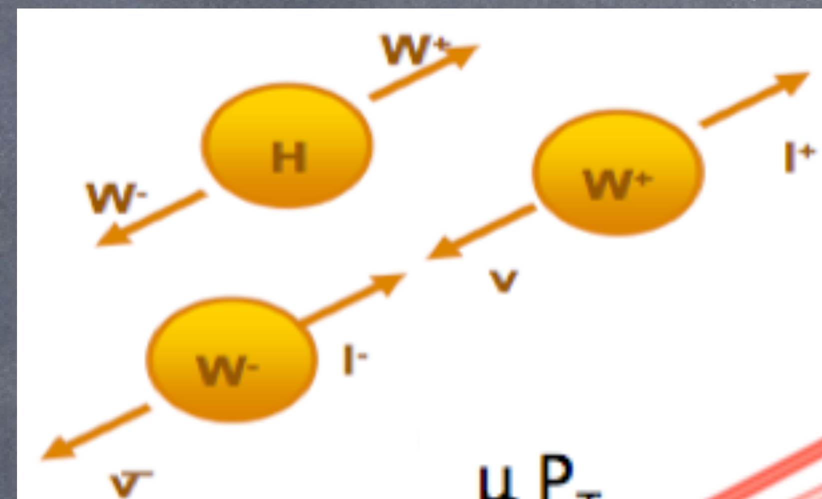
Candidate

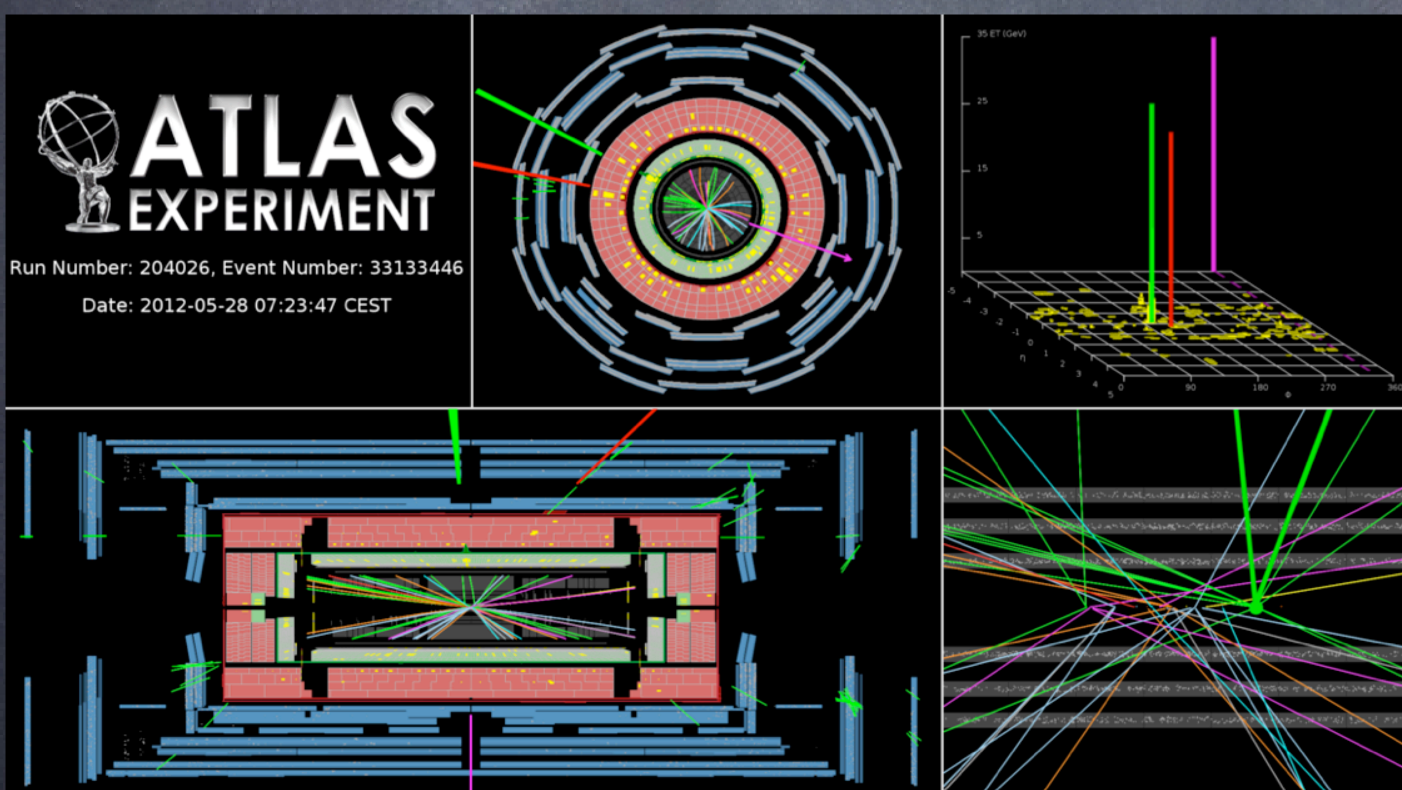
$$H \to ZZ^* \to (e^+e^-)(\mu^+\mu^-)$$

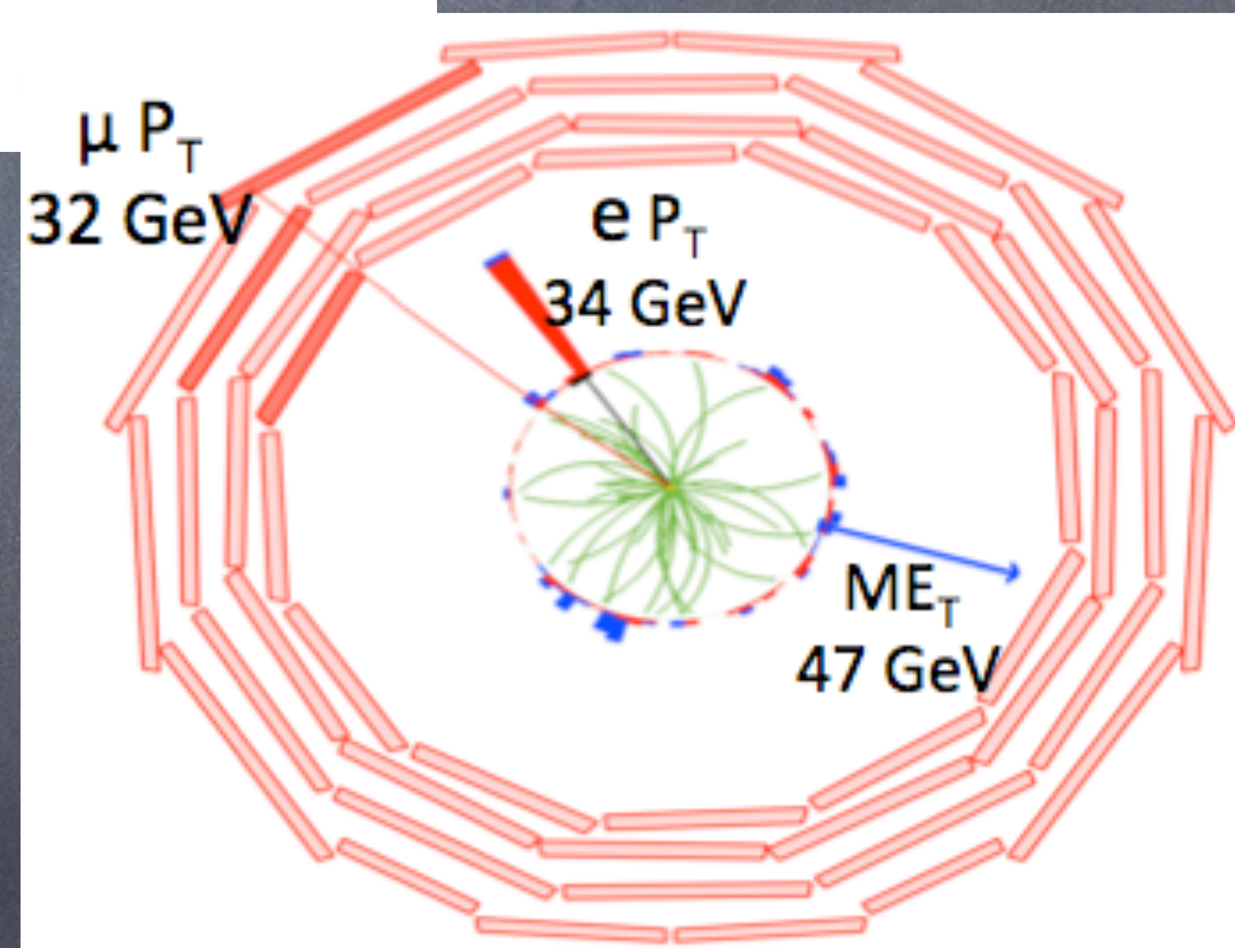




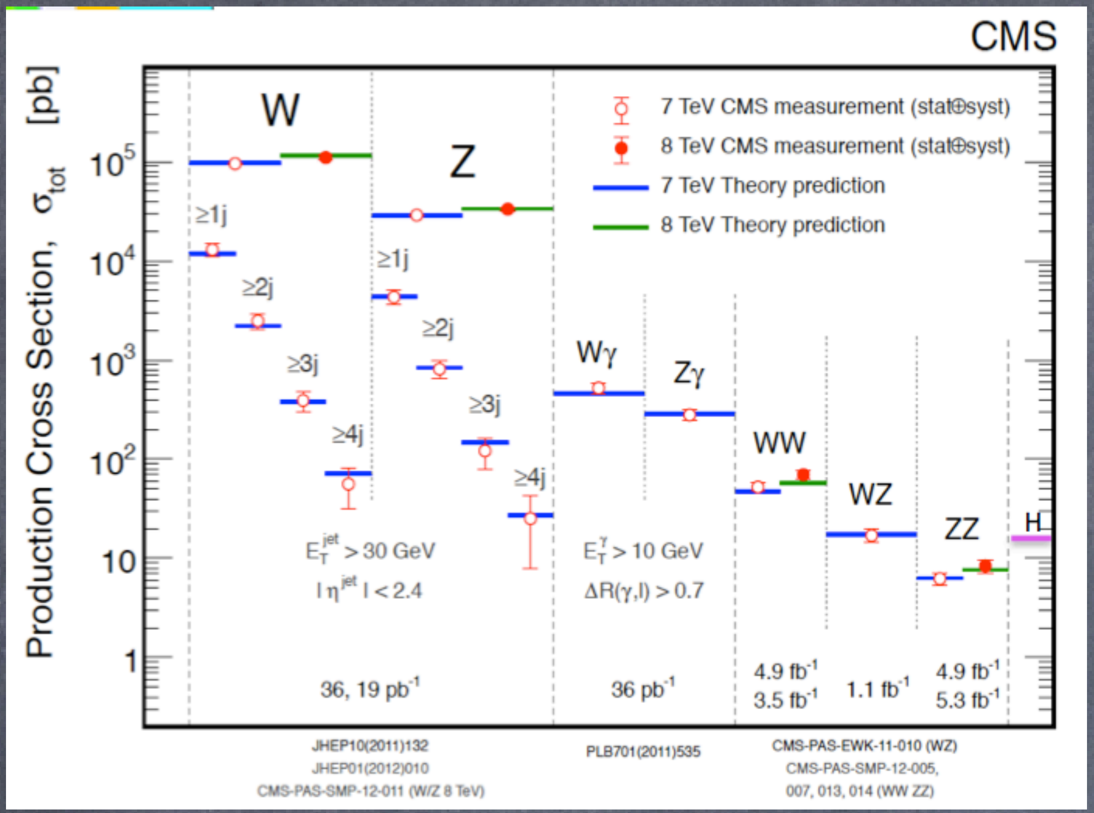
Candidate $H \to W^+W^{-(*)} \to e^+\nu_e\mu^-\nu_\mu$

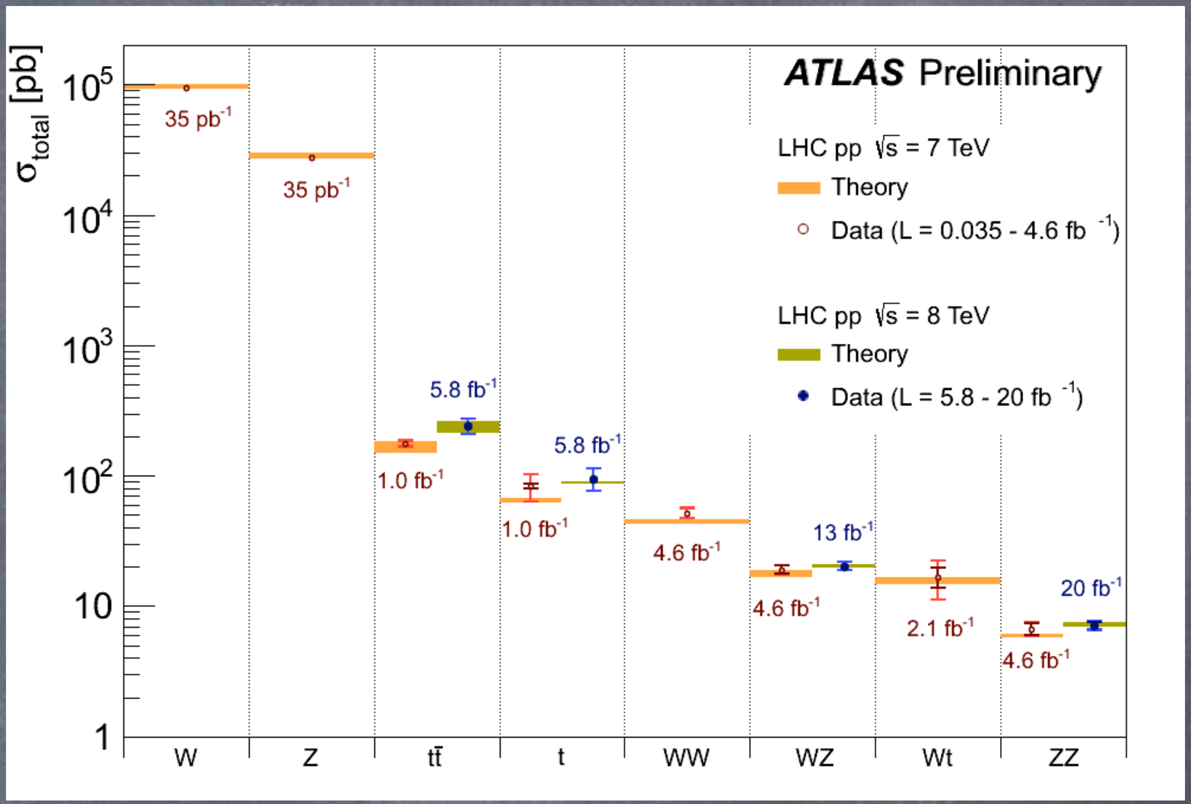


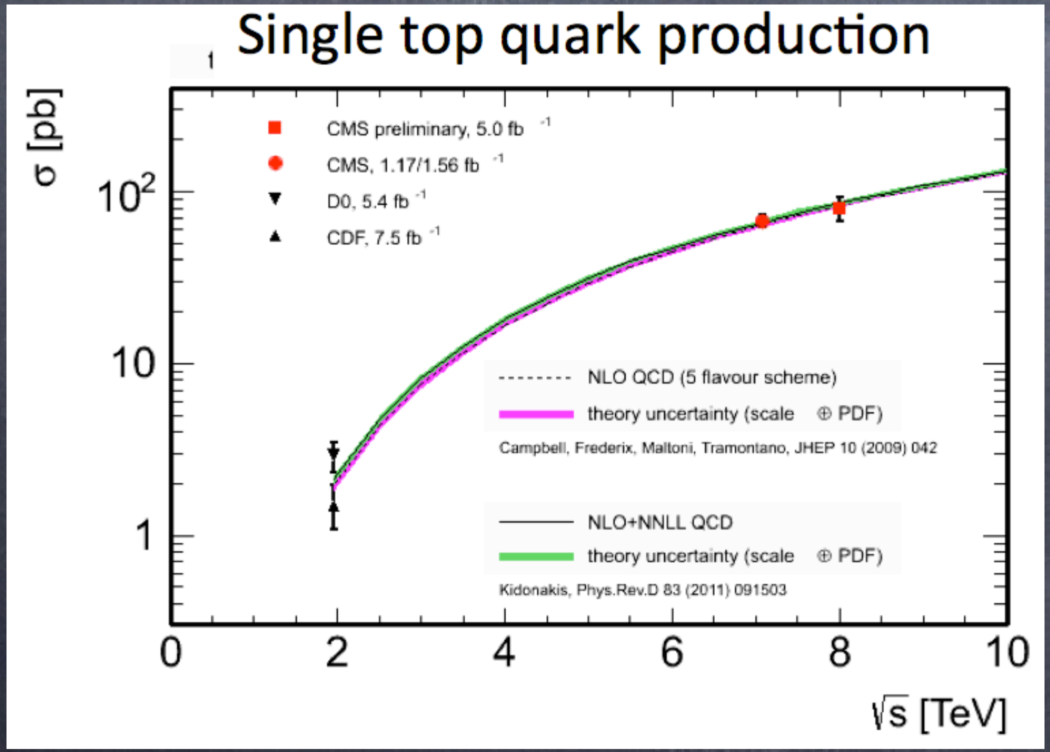


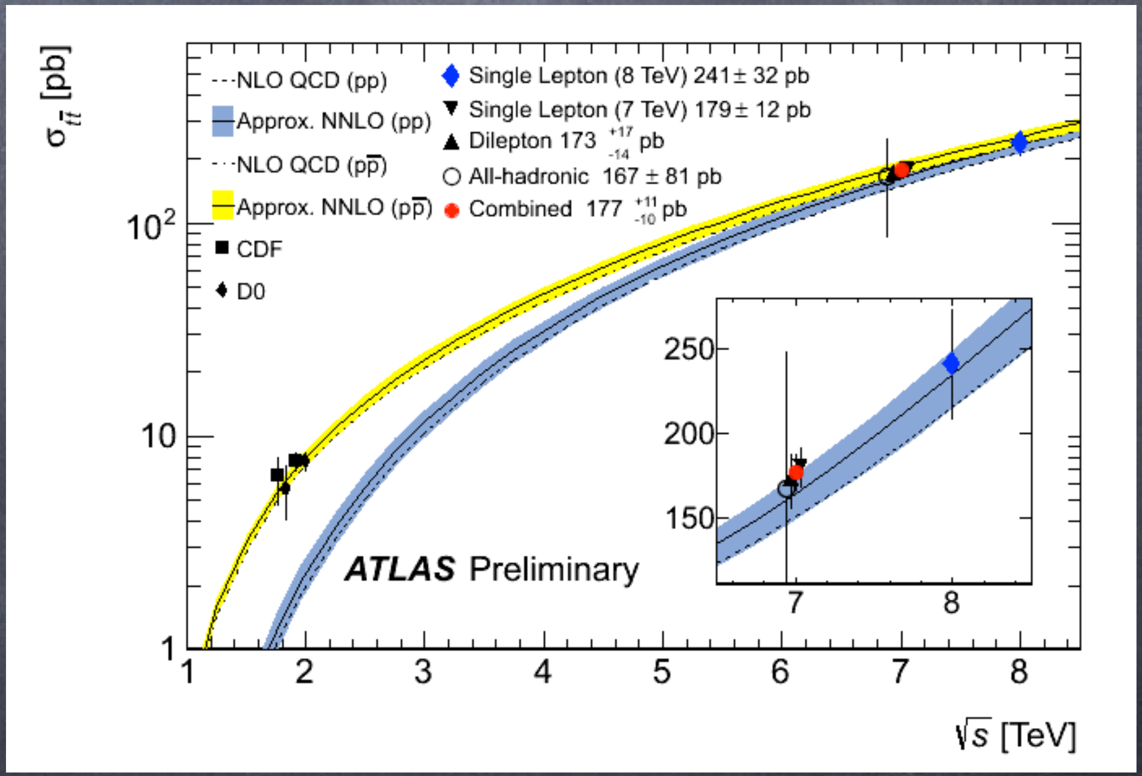


Standard "candles" ✓

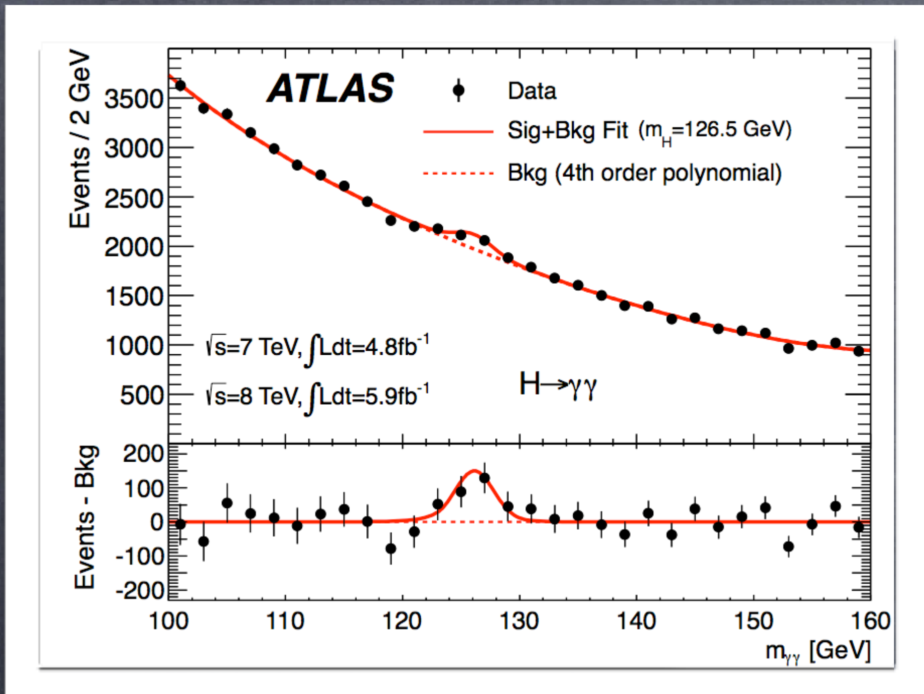




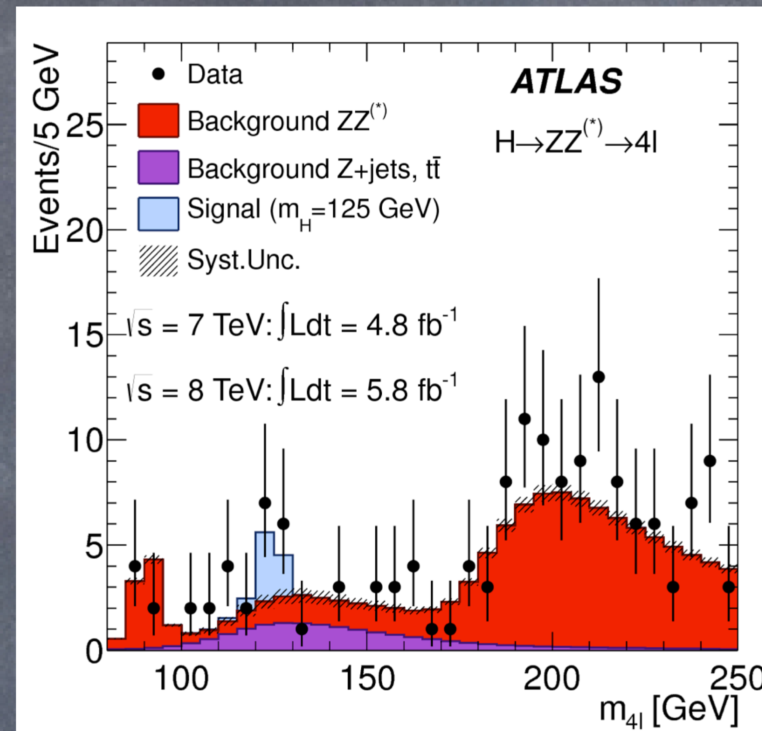




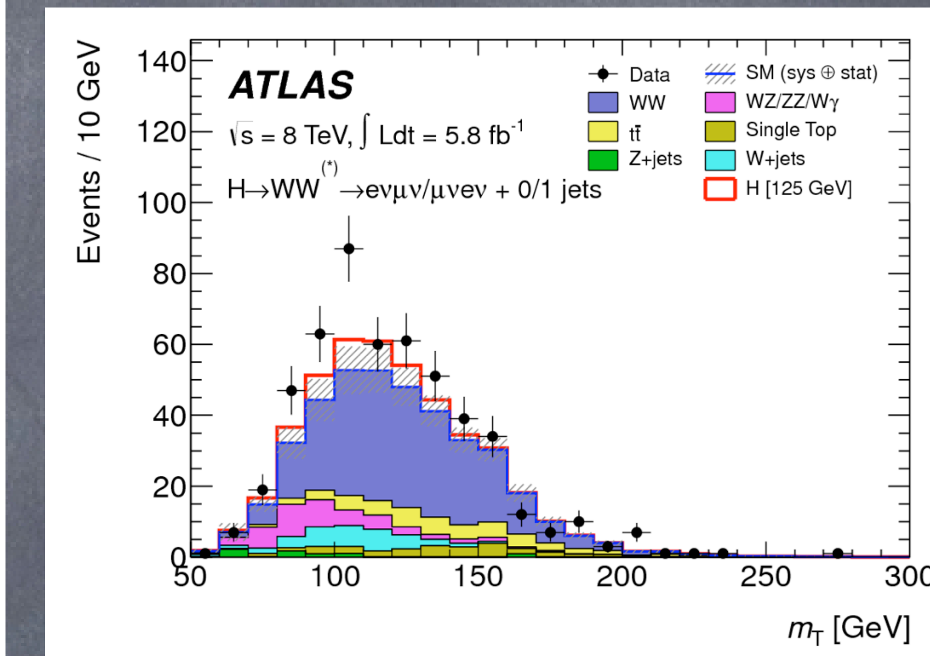
July, 2012



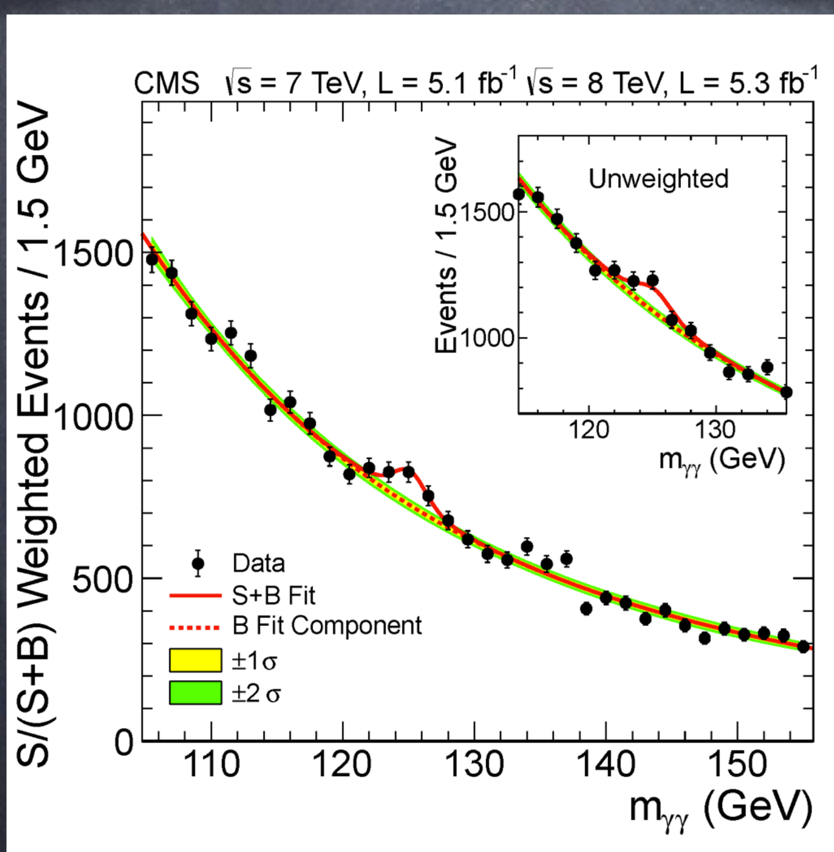
ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
$\sqrt{s}$=7 TeV, $\int Ldt$=4.8fb^{-1}
$\sqrt{s}$=8 TeV, $\int Ldt$=5.9fb^{-1}
$H\rightarrow\gamma\gamma$
Events / 2 GeV
Events - Bkg
$m_{\gamma\gamma}$ [GeV]



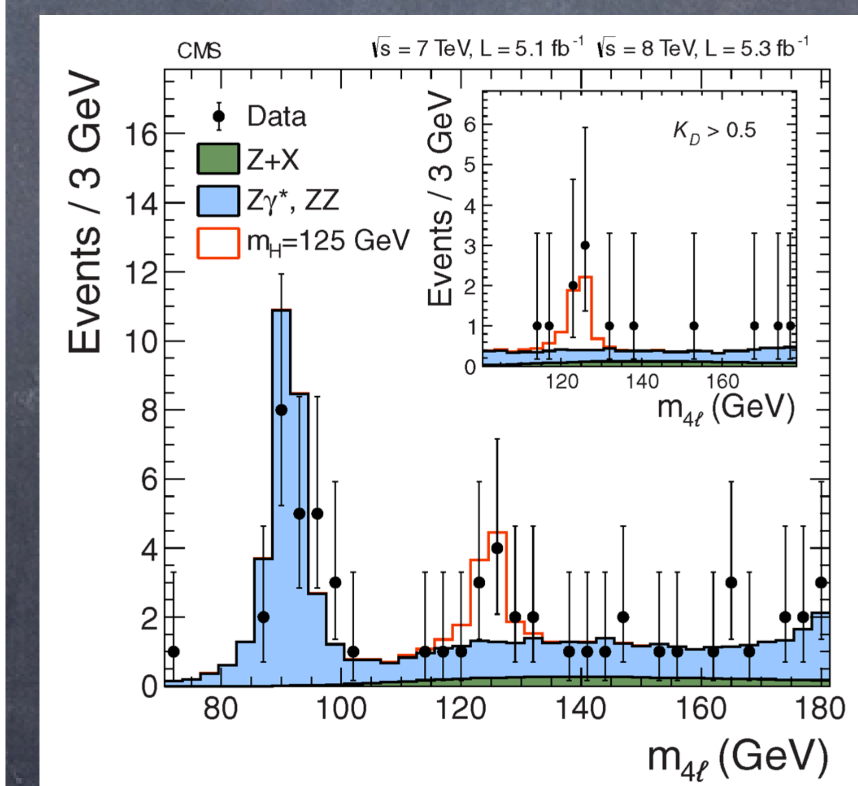
ATLAS
Data
Background ZZ$^{(*)}$
Background Z+jets, $t\bar{t}$
Signal (m_H=125 GeV)
Syst.Unc.
$H\rightarrow ZZ^{(*)}\rightarrow 4l$
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8 fb^{-1}
Events/5 GeV
m_{4l} [GeV]



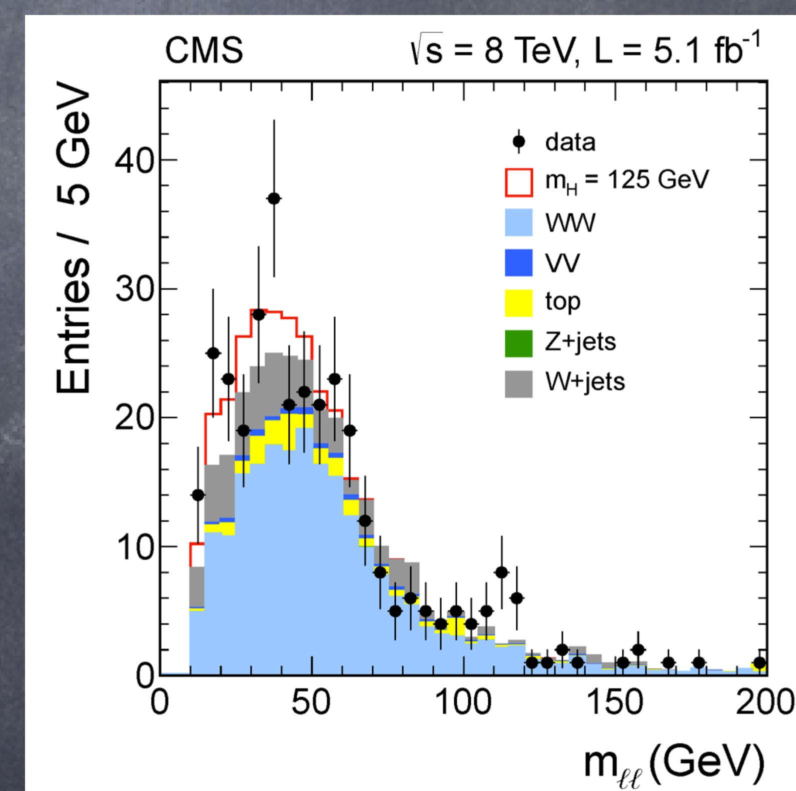
ATLAS
$\sqrt{s}$ = 8 TeV, $\int Ldt$ = 5.8 fb^{-1}
$H\rightarrow WW^{(*)}\rightarrow e\nu\mu\nu/\mu\nu e\nu$ + 0/1 jets
Data
SM (sys ⊕ stat)
WW
WZ/ZZ/Wγ
$t\bar{t}$
Single Top
Z+jets
W+jets
H [125 GeV]
Events / 10 GeV
m_T [GeV]



CMS $\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}
Unweighted
Data
S+B Fit
B Fit Component
±1σ
±2 σ
S/(S+B) Weighted Events / 1.5 GeV
Events / 1.5 GeV
$m_{\gamma\gamma}$ (GeV)

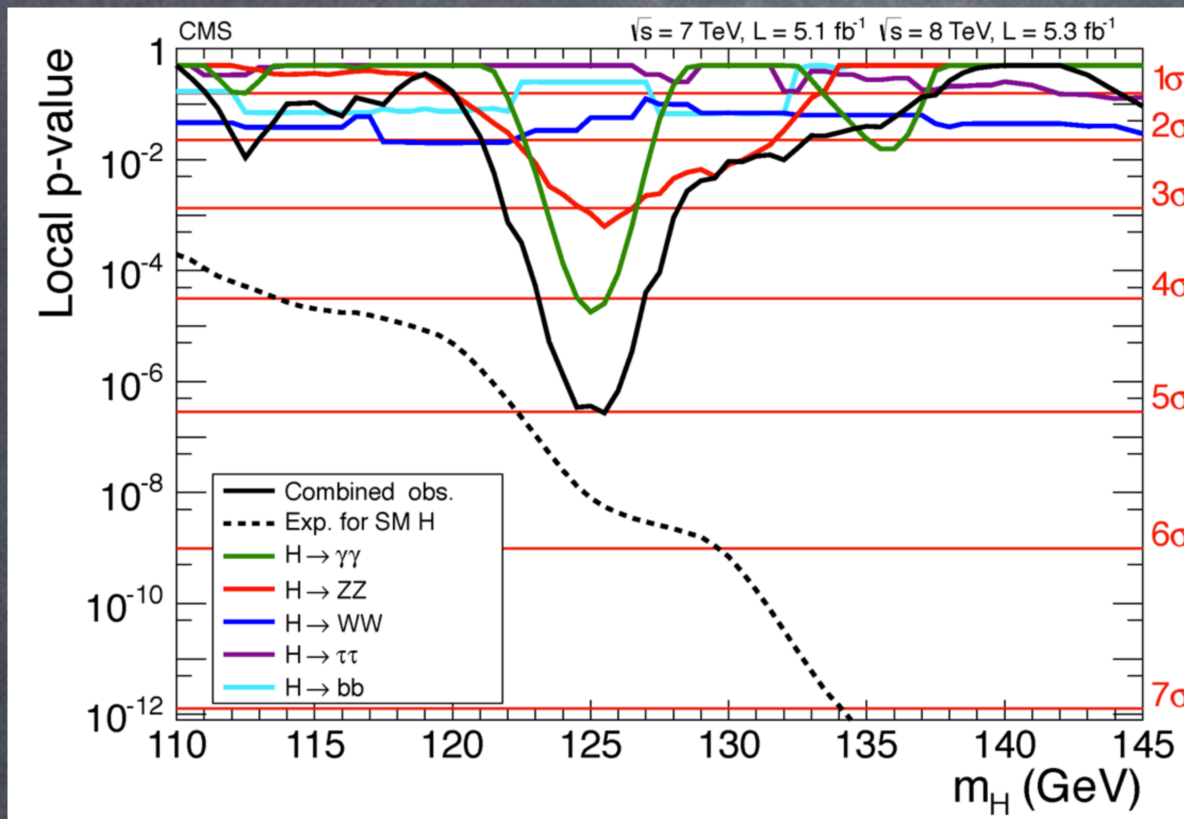


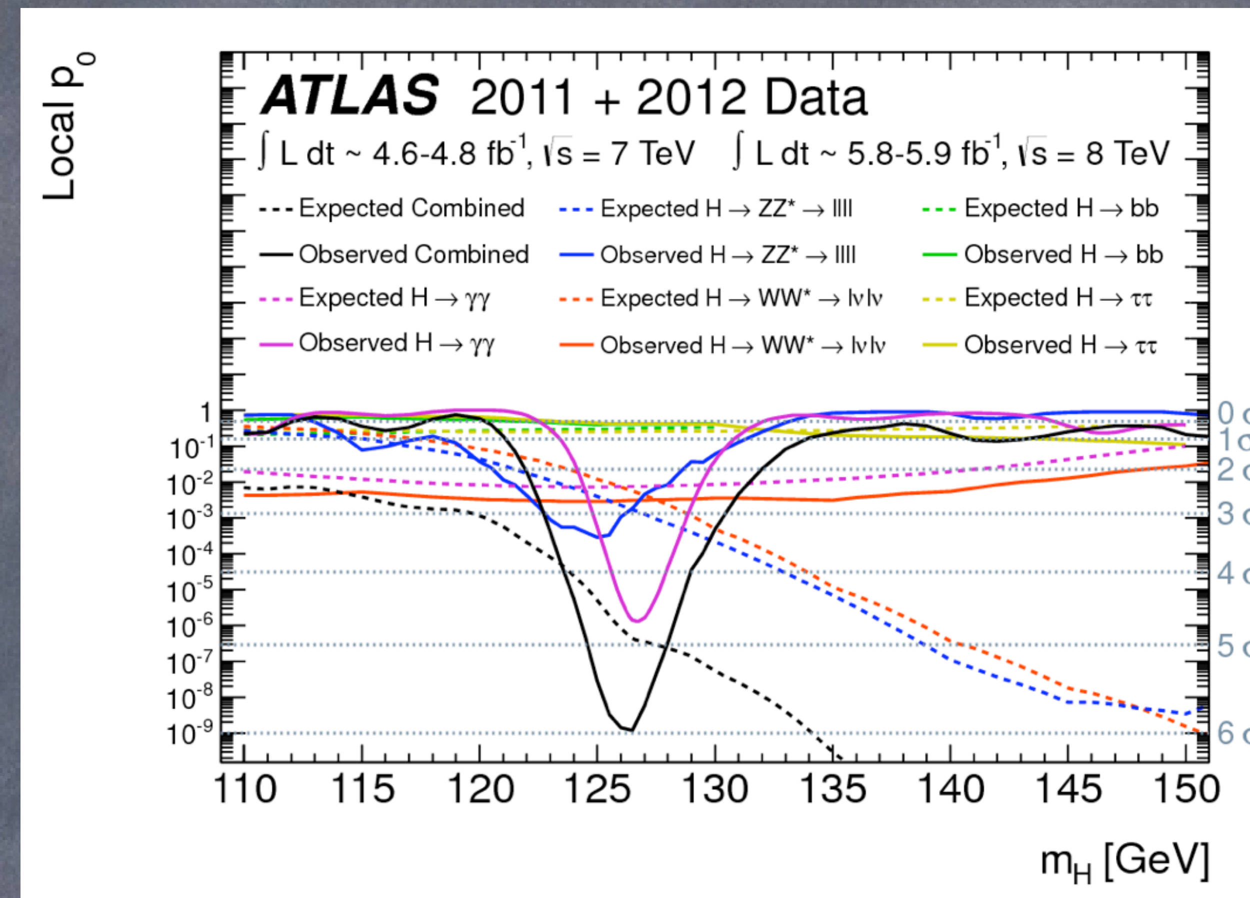
CMS $\sqrt{s}$ = 7 TeV, L = 5.1 fb^{-1} $\sqrt{s}$ = 8 TeV, L = 5.3 fb^{-1}
Data
Z+X
Zγ*, ZZ
m_H=125 GeV
K_D > 0.5
Events / 3 GeV
$m_{4\ell}$ (GeV)

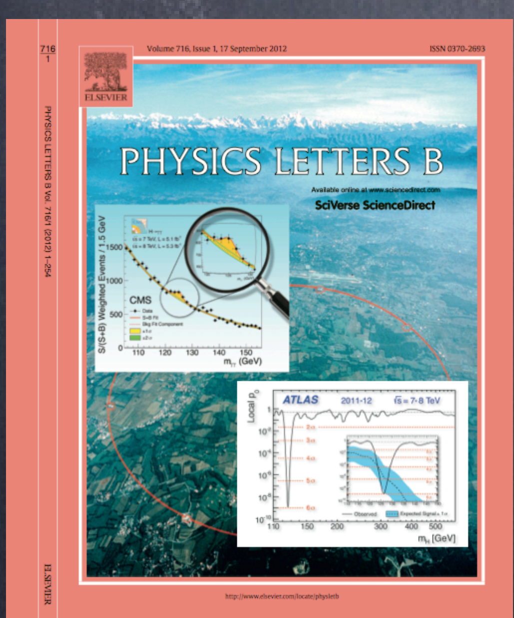


CMS $\sqrt{s}$ = 8 TeV, L = 5.1 fb^{-1}
data
m_H = 125 GeV
WW
VV
top
Z+jets
W+jets
Entries / 5 GeV
$m_{\ell\ell}$ (GeV)

A new boson, “Higgs-like”







- Combination of all channels and data available at the time
- 2 experiments with 5 σ at ~same mass
- The most sensitive channels making the impact

Since July 2012:
From "a Higgs-like boson"
to
"a Higgs boson"

Statistics miniworkshop

chaired by Louis Lyons (Imperial College-Unknown-Unknown)

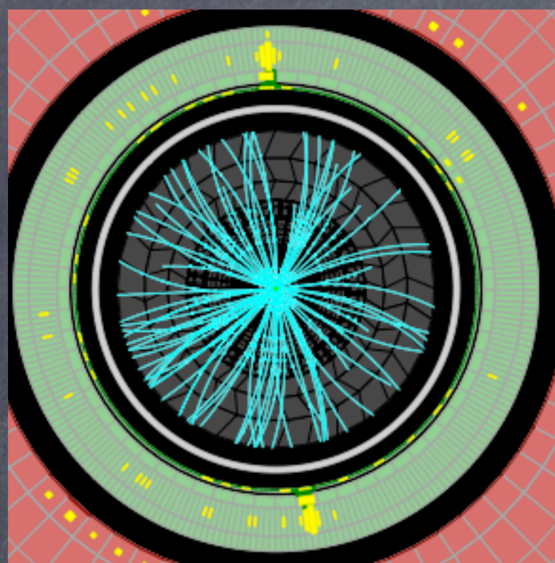
from Wednesday, 13 February 2013 at **08:00** to Thursday, 14 February 2013 at **18:00** (Europe/Zurich)
at **CERN**

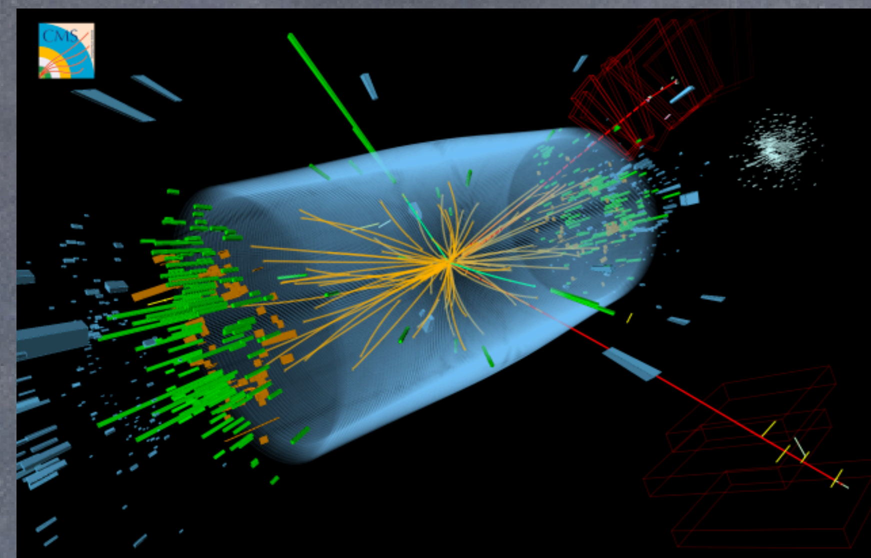
Description WHAT WE HAVE LEARNT FROM THE LHC HIGGS SEARCH?

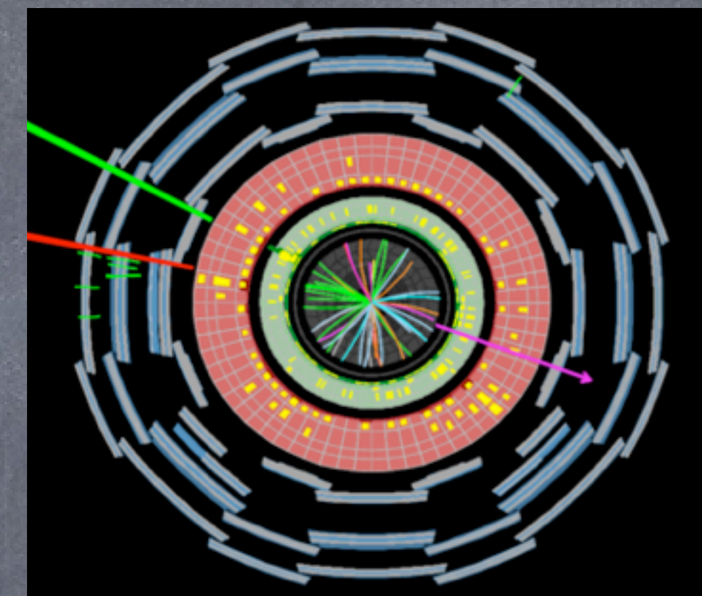
BASIC IDEA OF MEETING:
Now that we have actually searched for and found a Higgs-like boson, we should have a small meeting to try to decide what we have learnt about the statistical issues involved, and to consolidate our experience.

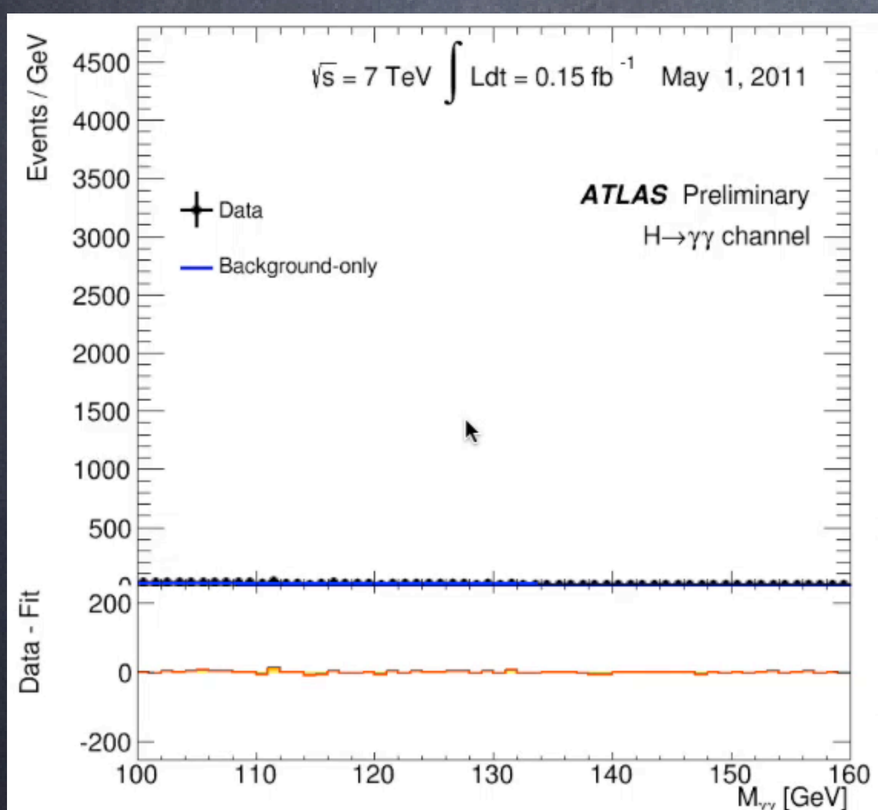
- While van Dyk asserted that he would advocate a different quantification of the evidence for a Higgs boson, he acknowledged that the ATLAS and CMS analyses must be among the most rigorous statistical treatments of a complex scientific data set "on the planet".
- Profile-likelihood ratio machinery (RooStats/RooFit/MINUIT) put us in position to rapidly (!!) advance from limits and discovery to measurements!

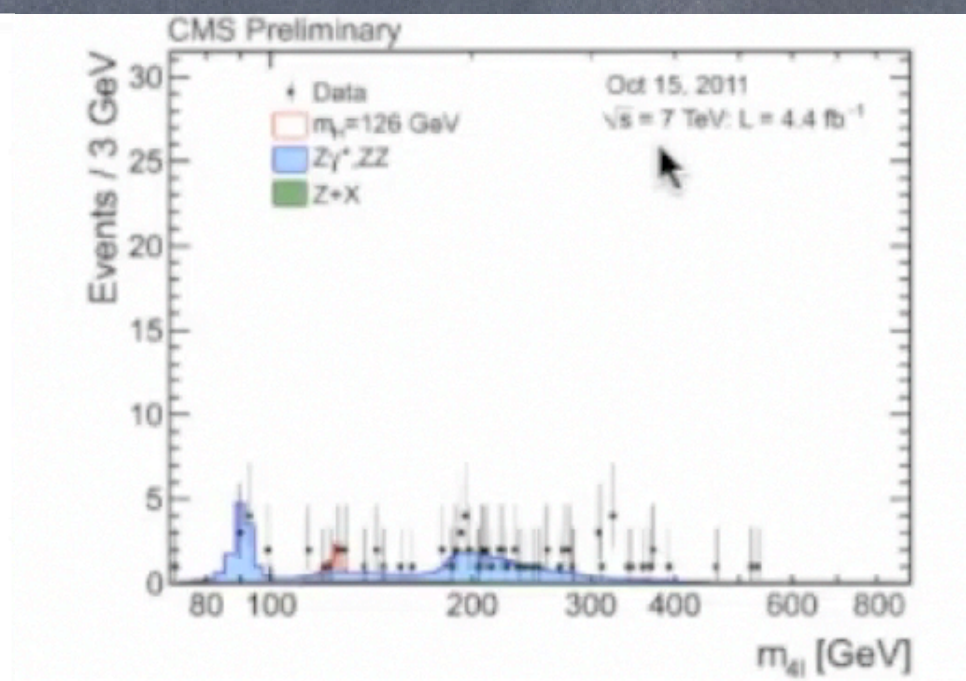
Rest of 2012: The signals grew…

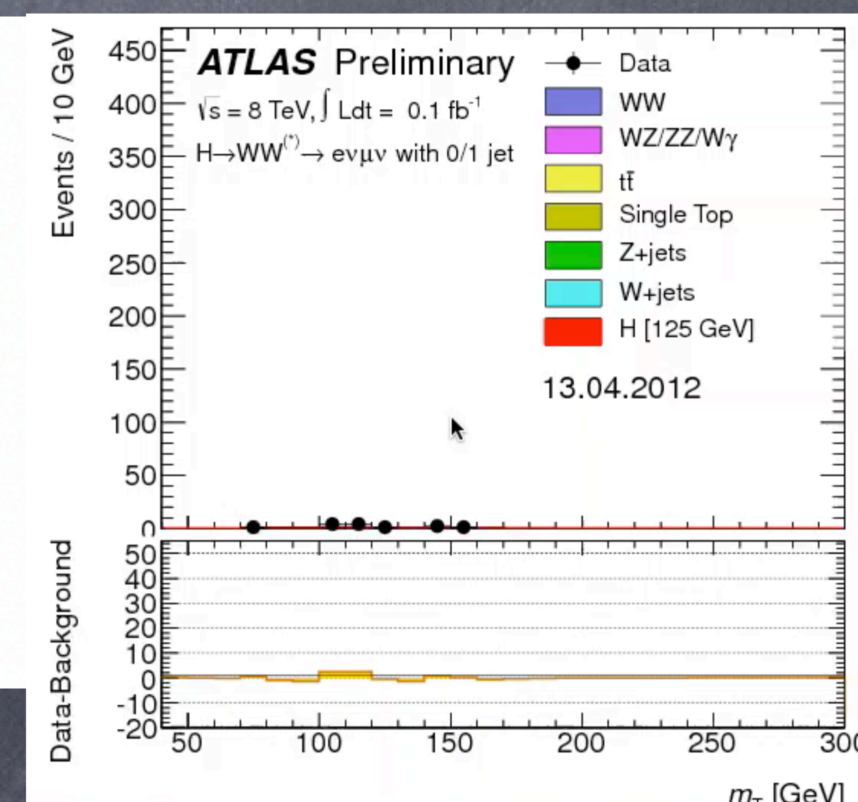




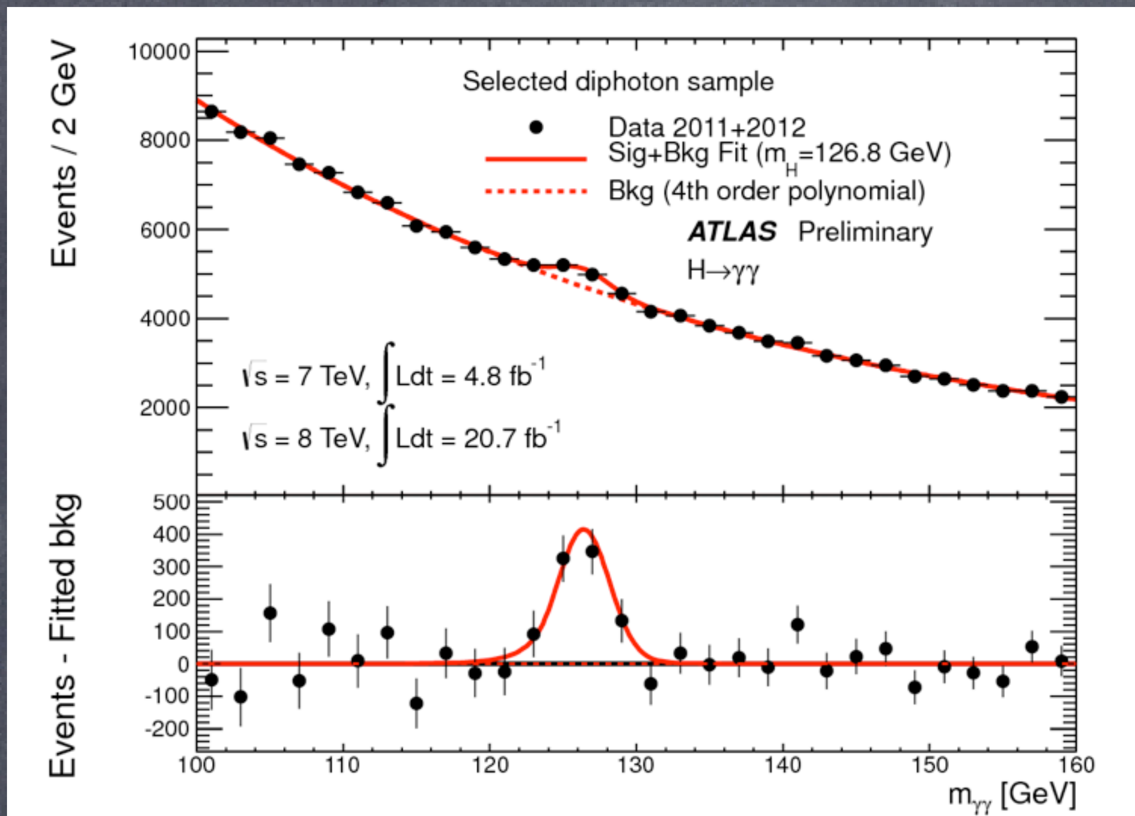


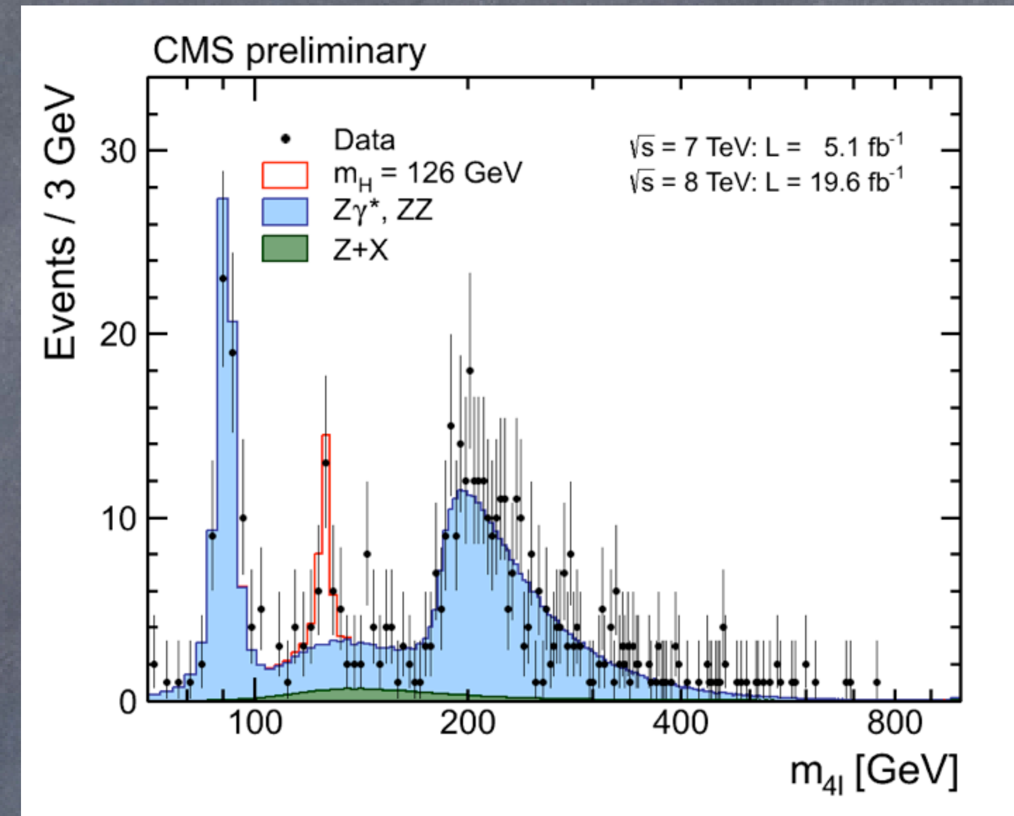


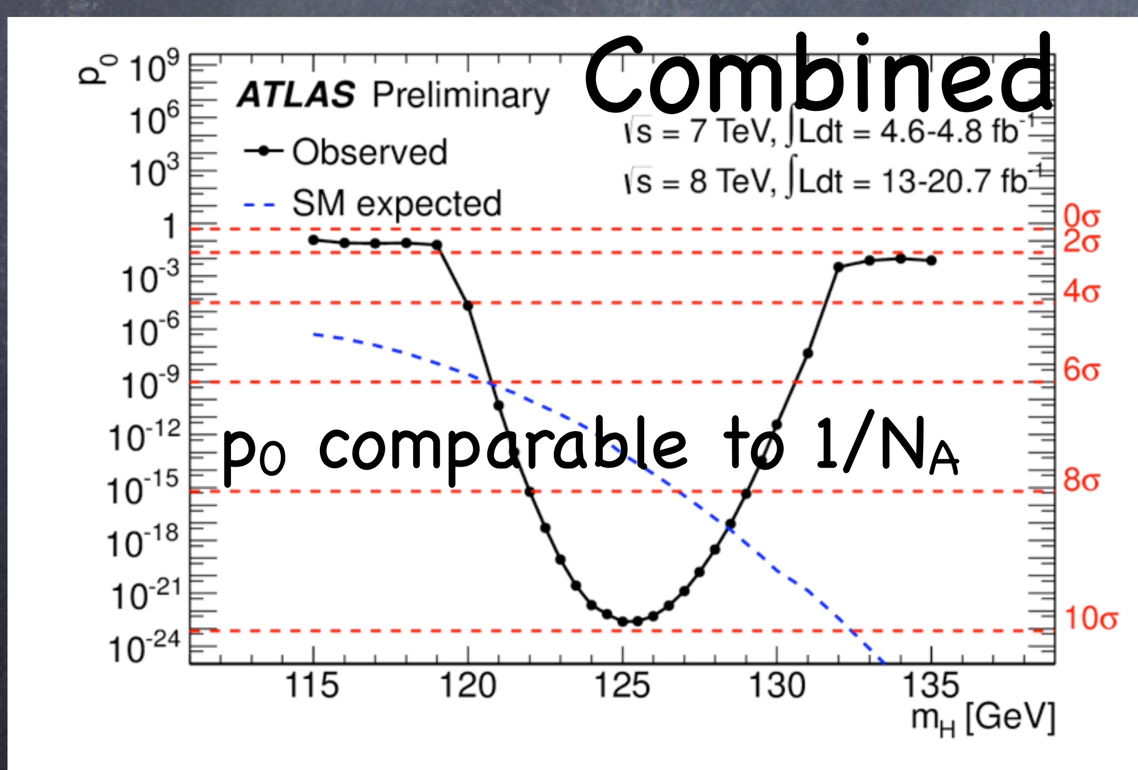


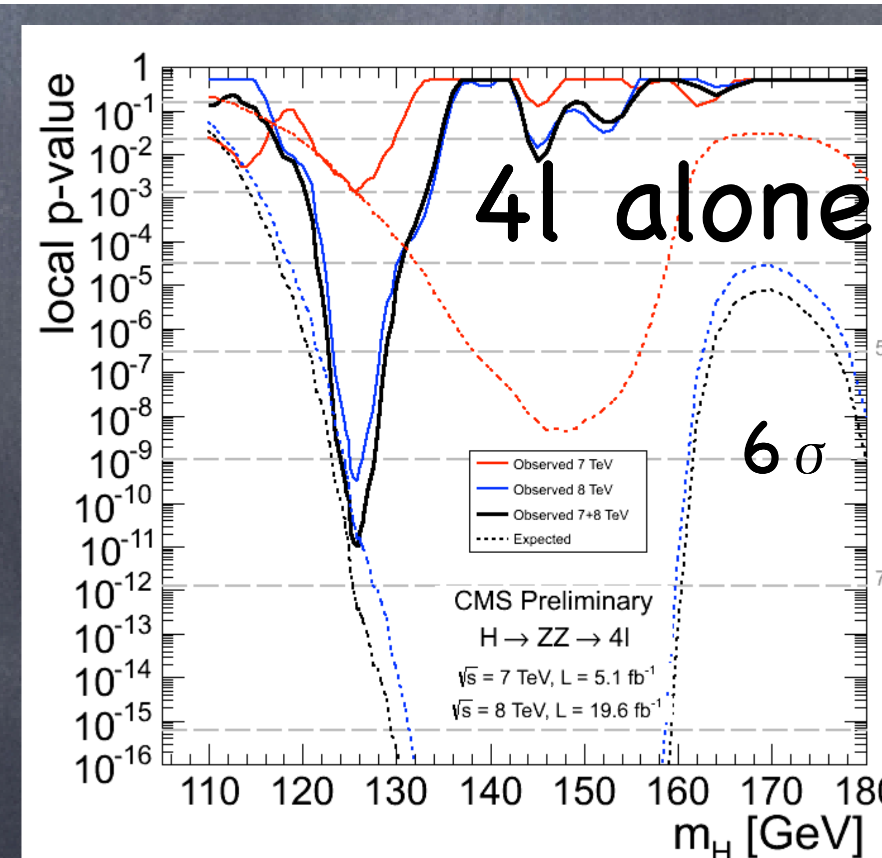


Rest of 2012: The signals grew...

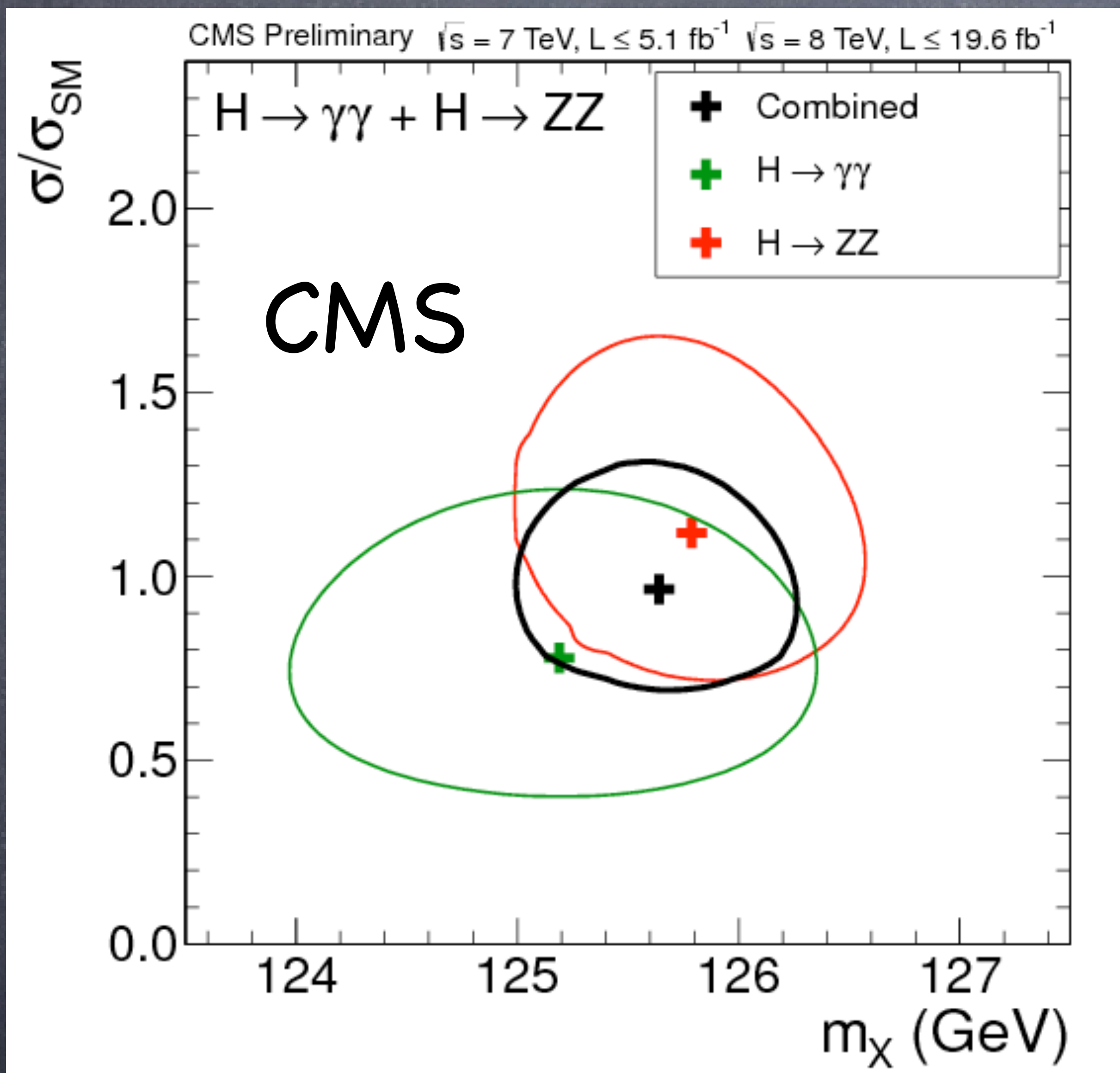


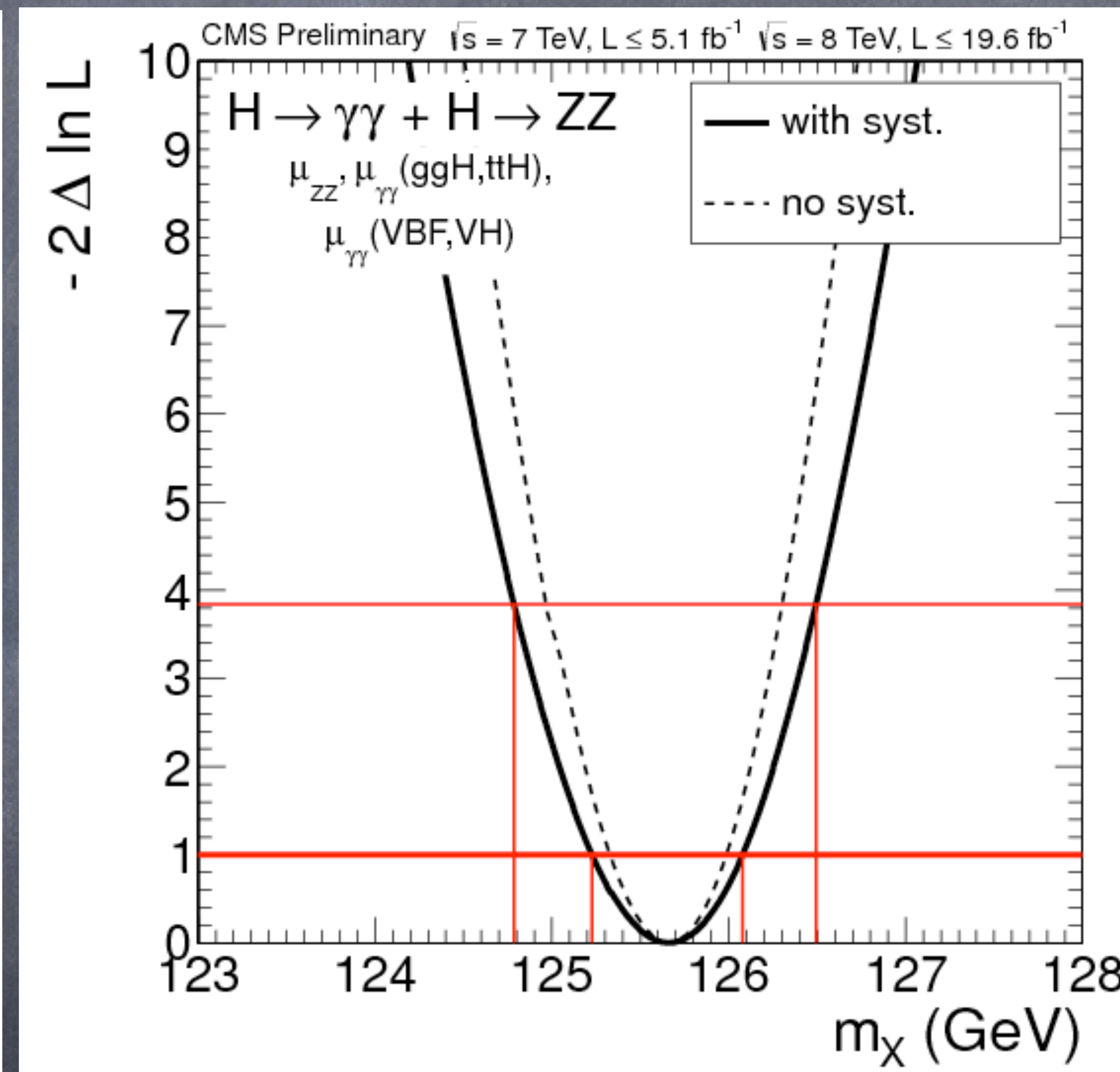




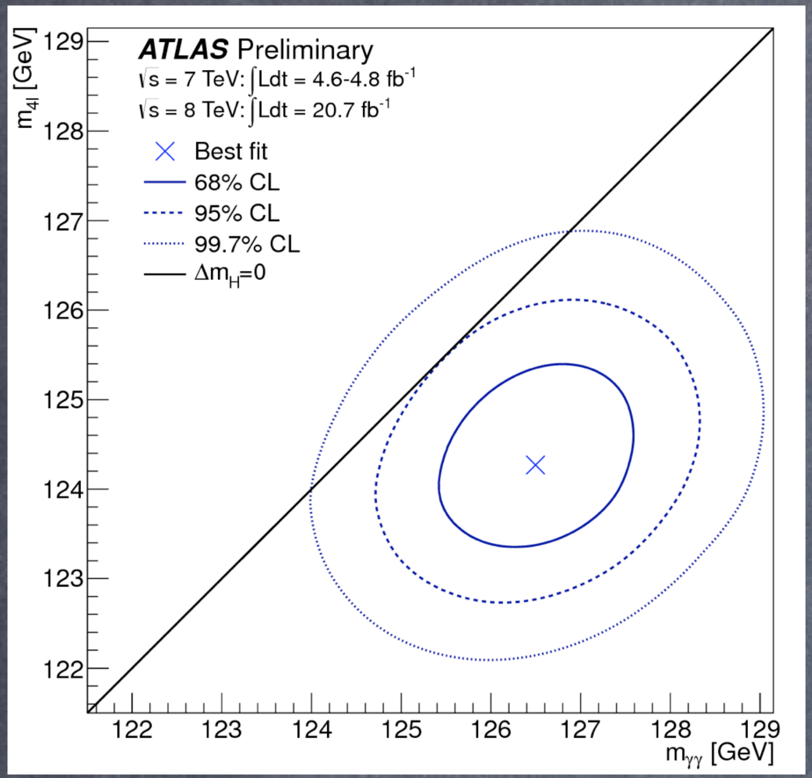


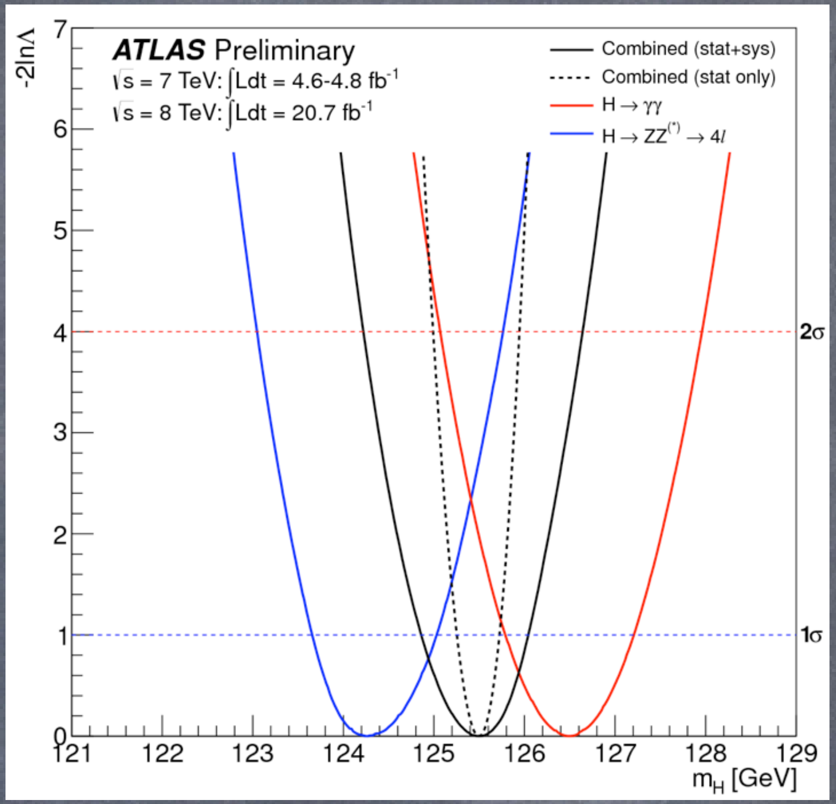
Mass of the Higgs boson

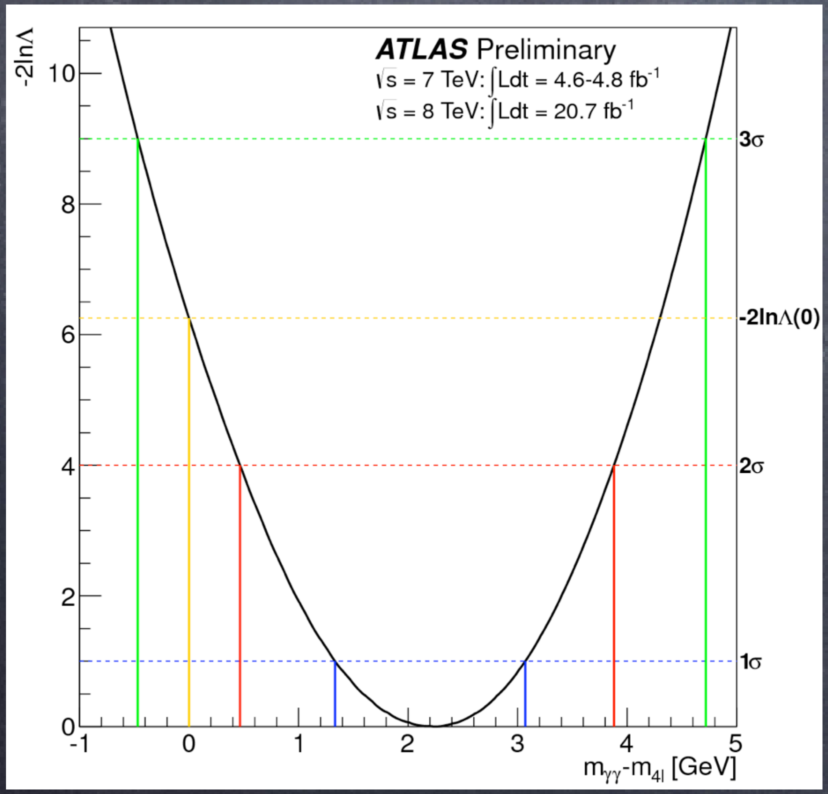




Mass of the Higgs boson







$$\Delta m = 2.3 \pm^{0.6}_{0.7} \,(\mathrm{stat}) \pm 0.6(\mathrm{sys})\ \mathrm{GeV}$$

- Significance of difference: 2.4 σ (p=1.5%)
- More conservative energy scale systematics: 1.8 σ (p=8%)

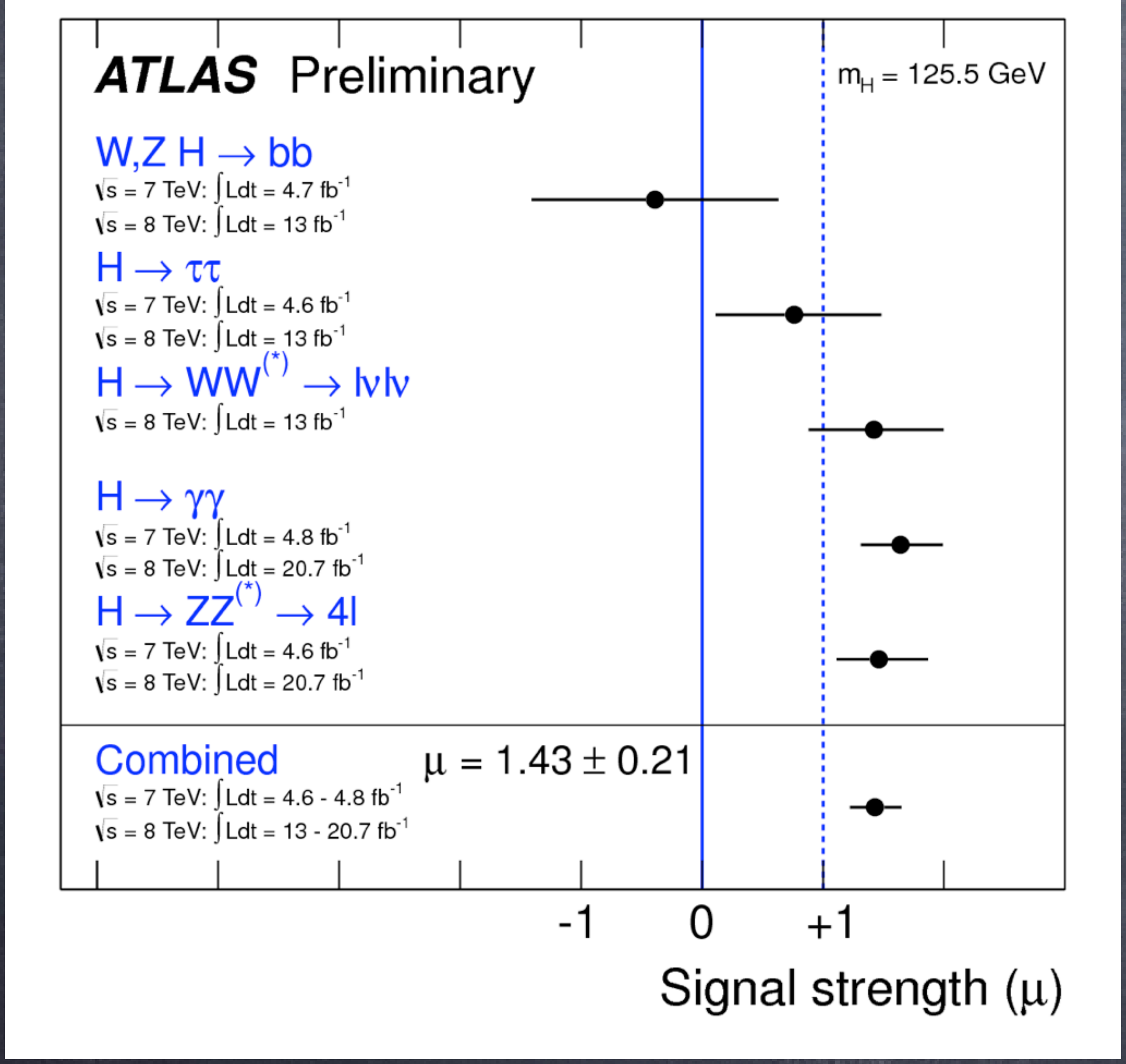
Mass of the Higgs boson

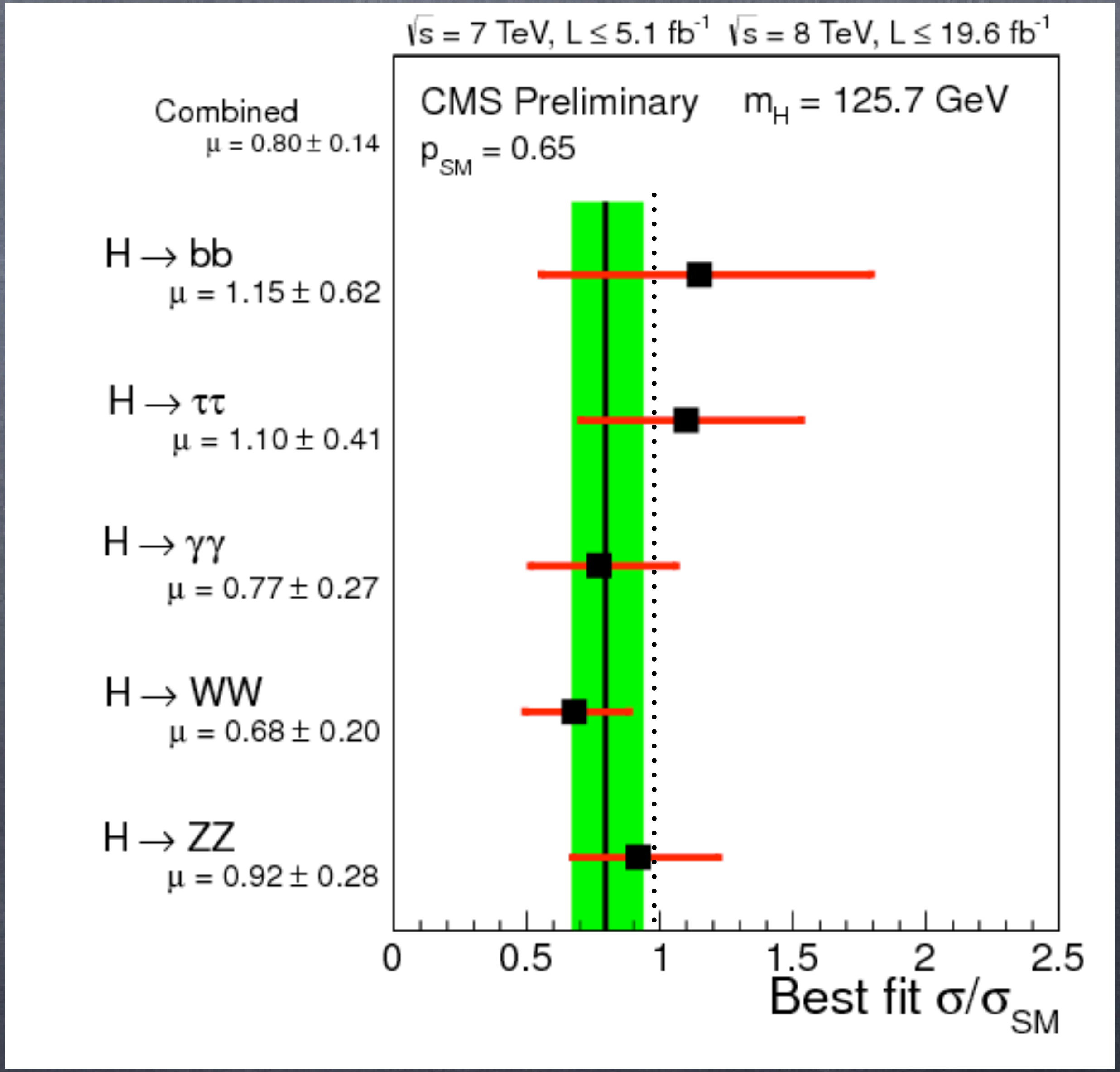
Expt.	Chan.	m_H	stat	syst
ATLAS	$\gamma\gamma$	126.8	0.2	0.7
CMS	$\gamma\gamma$	125.4	0.5	0.6
ATLAS	4l	124.3	0.6/0.5	0.5/0.3
CMS	4l	125.8	0.5	0.2
ATLAS	Comb	125.5	0.2	0.5/0.6
CMS	Comb	125.7	0.3	0.3

(Optimistic back of the envelope 125.6±0.3)

Signal strengths - μ

- (variations of μ represent no particular model)





SM Higgs frontiers

- Boson decays > 5 σ individually
- Several VBF-dominated channels > 2 σ
- Establish decays to leptons, e.g. $\tau^+\tau^-$
- Establish decays to down-type quarks, e.g. $b\bar{b}$
- So far consistent with top in production loop as well as decay loop, but would be good to show direct coupling as well.

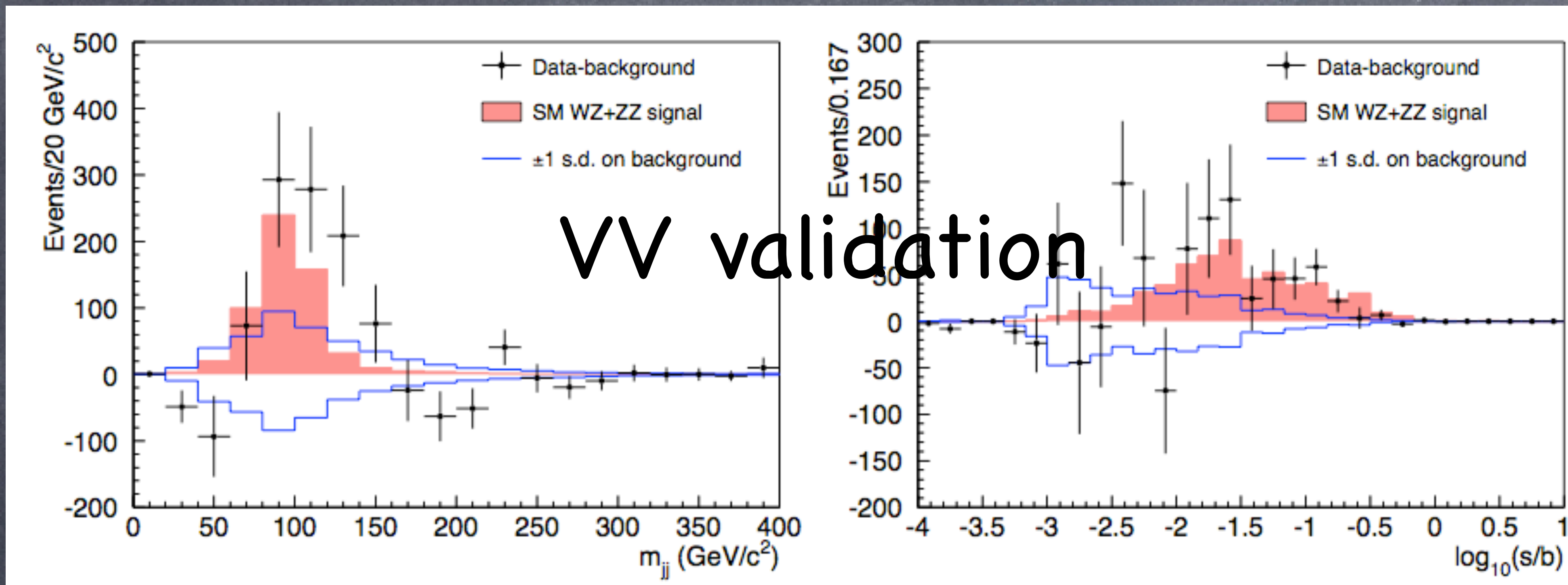
CMS @125.7

Decay mode	Expected (σ)	Observed (σ)
ZZ	7.1	6.7
$\gamma\gamma$	3.9	3.2
WW	5.3	3.9
bb	2.2	2.0
$\tau\tau$	2.6	2.8

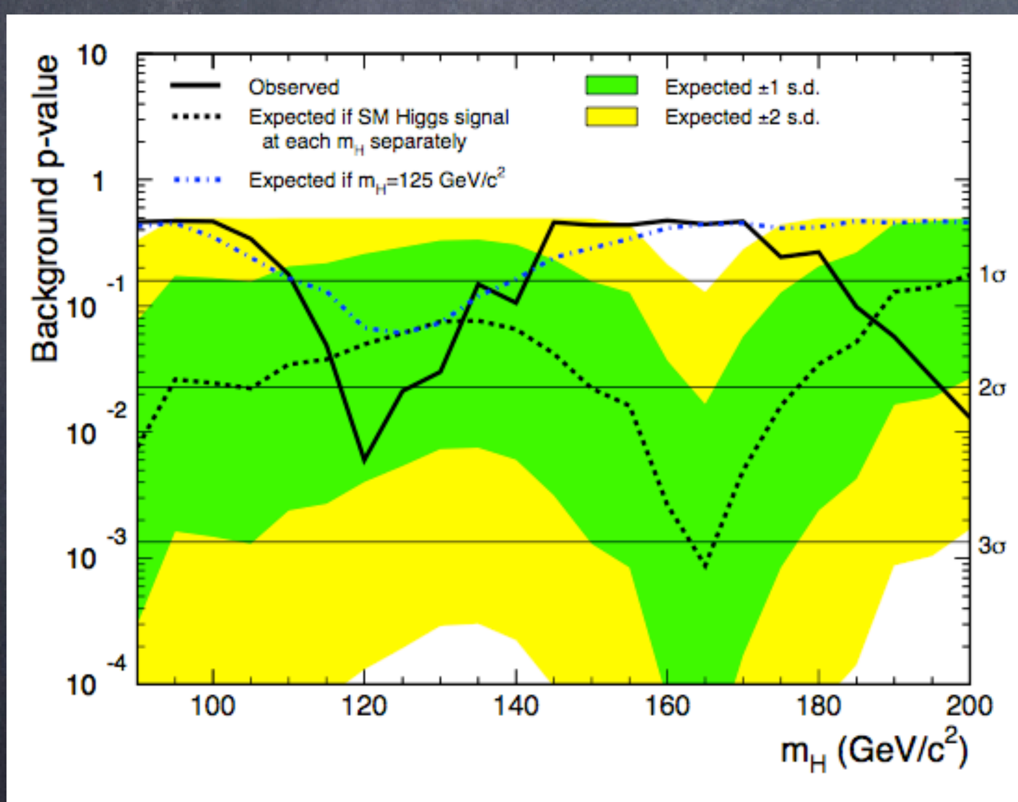
ATLAS

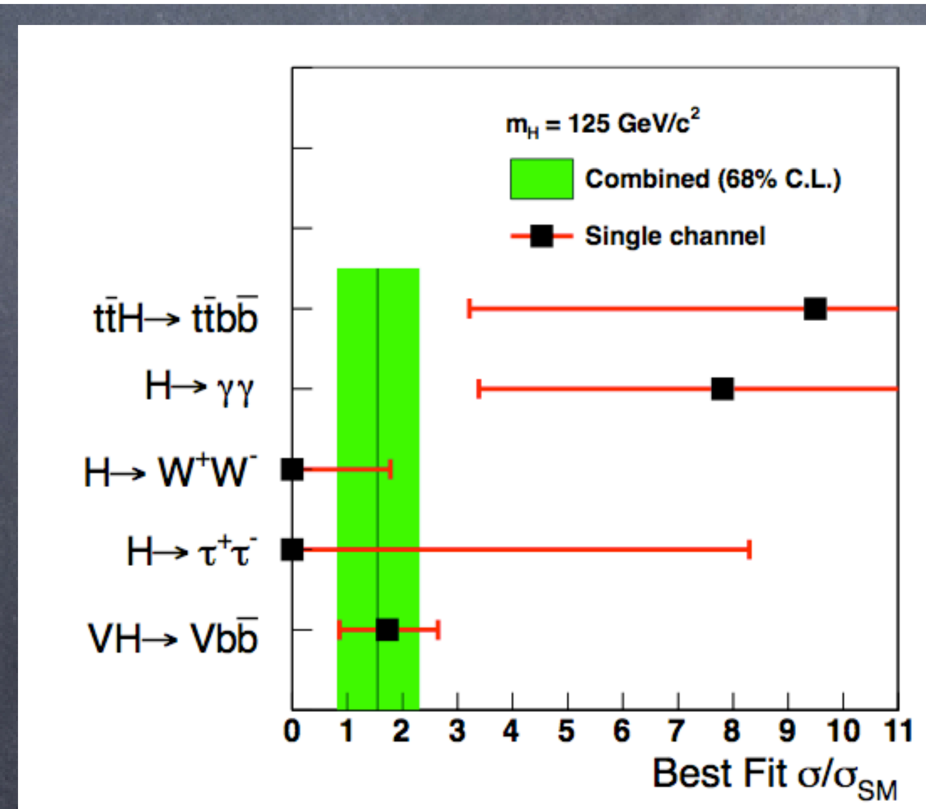
Chan	Obs (σ)	Exp (σ)	m (GeV)
4l	6.6	4.4	124.3
$\gamma\gamma$	7.4	4.1	126.8
$\gamma\gamma + \mathrm{VBF}$	2.0	1.3	"
WW	3.8	3.7	125
WW+VBF	2.5	1.6	"
$b\bar{b}$	-0.4	1.0	"
$\tau^+\tau^-$	1.1	1.7	"

CDF final results



VV validation

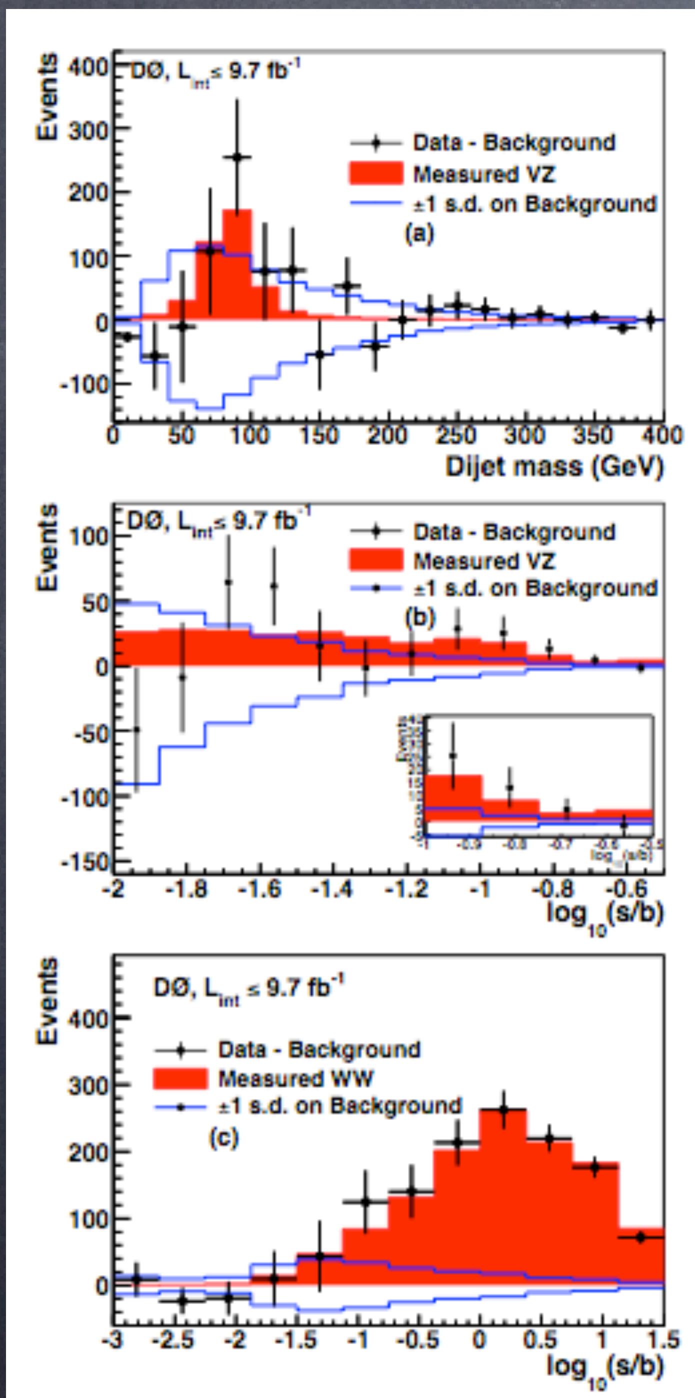


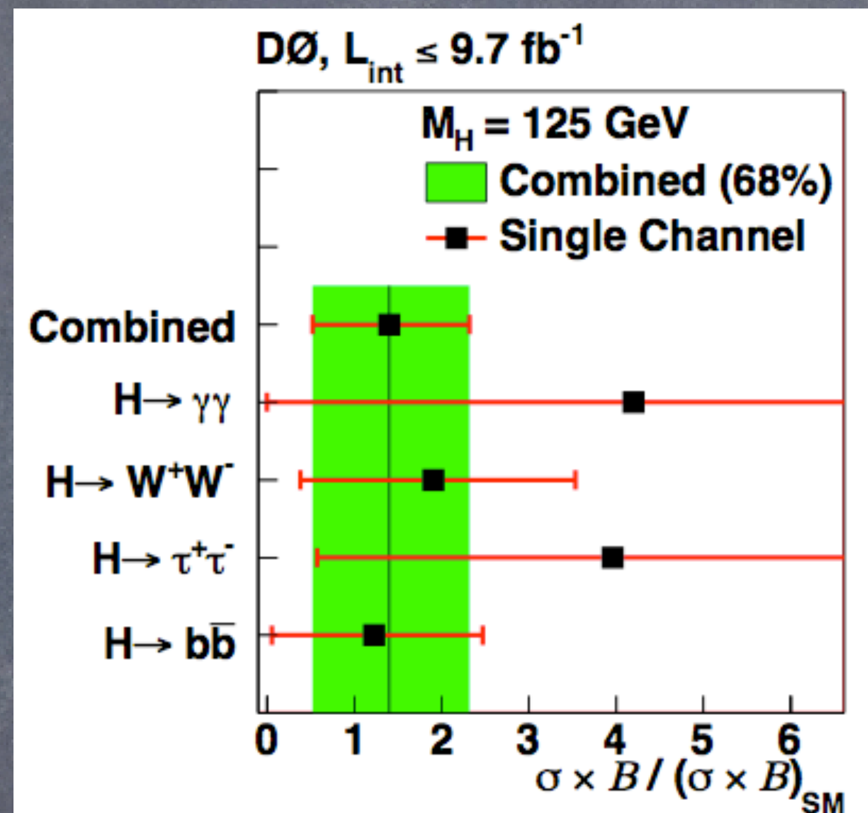


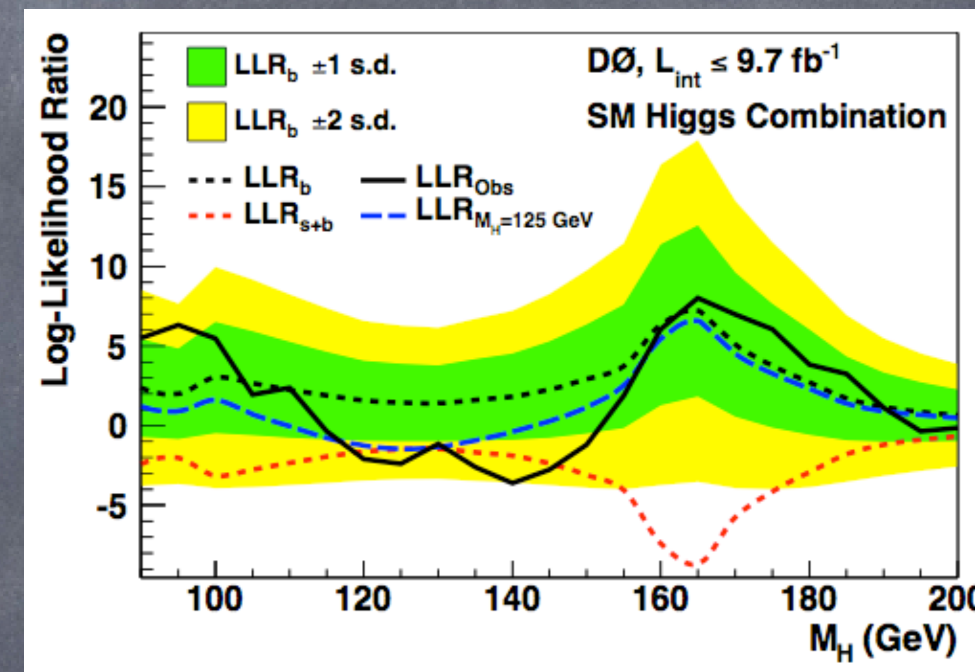
- WH->Wbb, H->WW expected 95% CL limits 1.8, 3.3
- 2 σ excess @ 125 GeV

D0 final results

VV validation

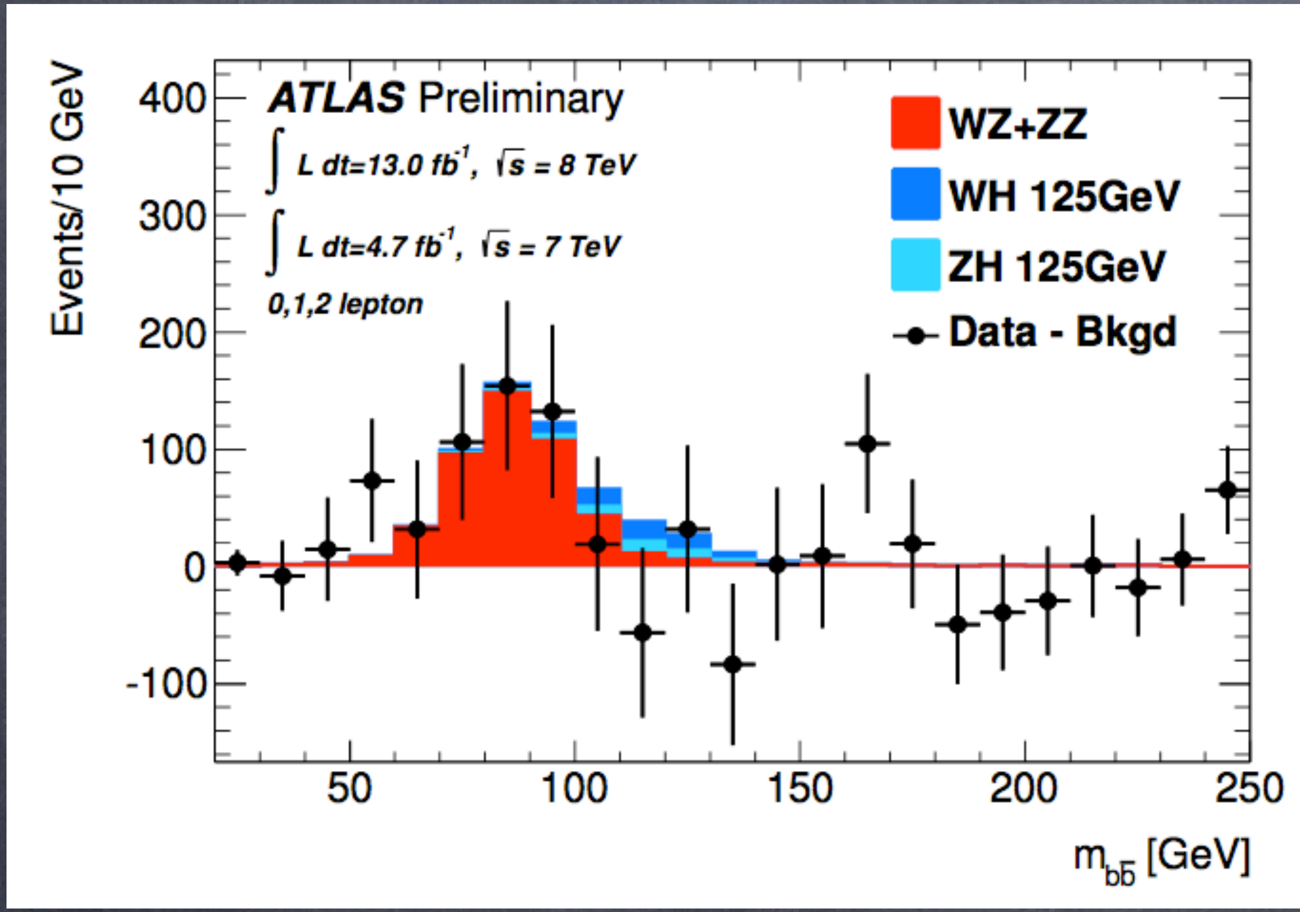






- 1.7 σ excess @ m_H=125 GeV

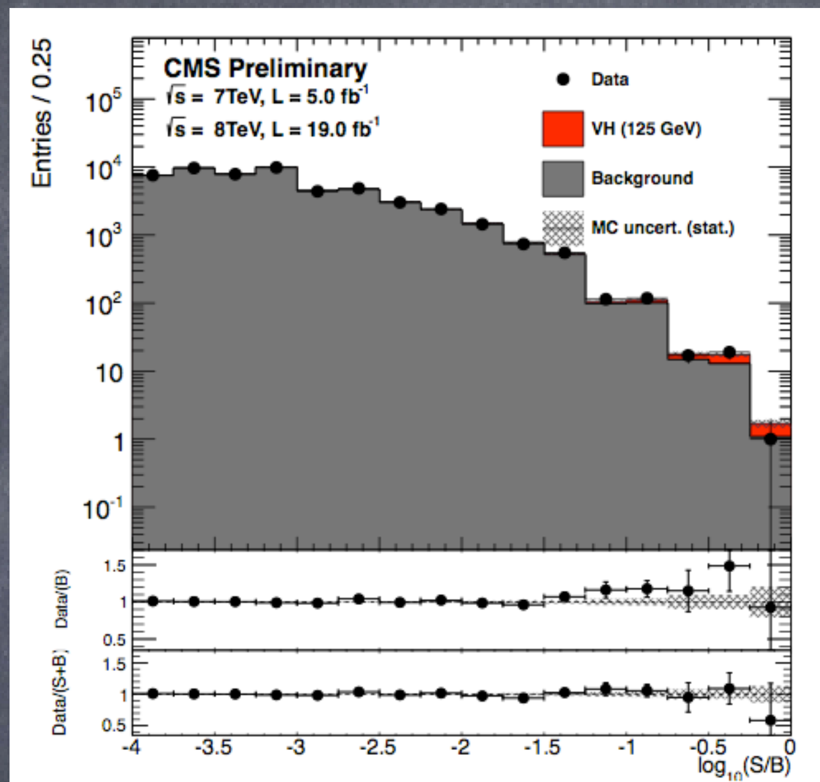
ATLAS VH->Vbb



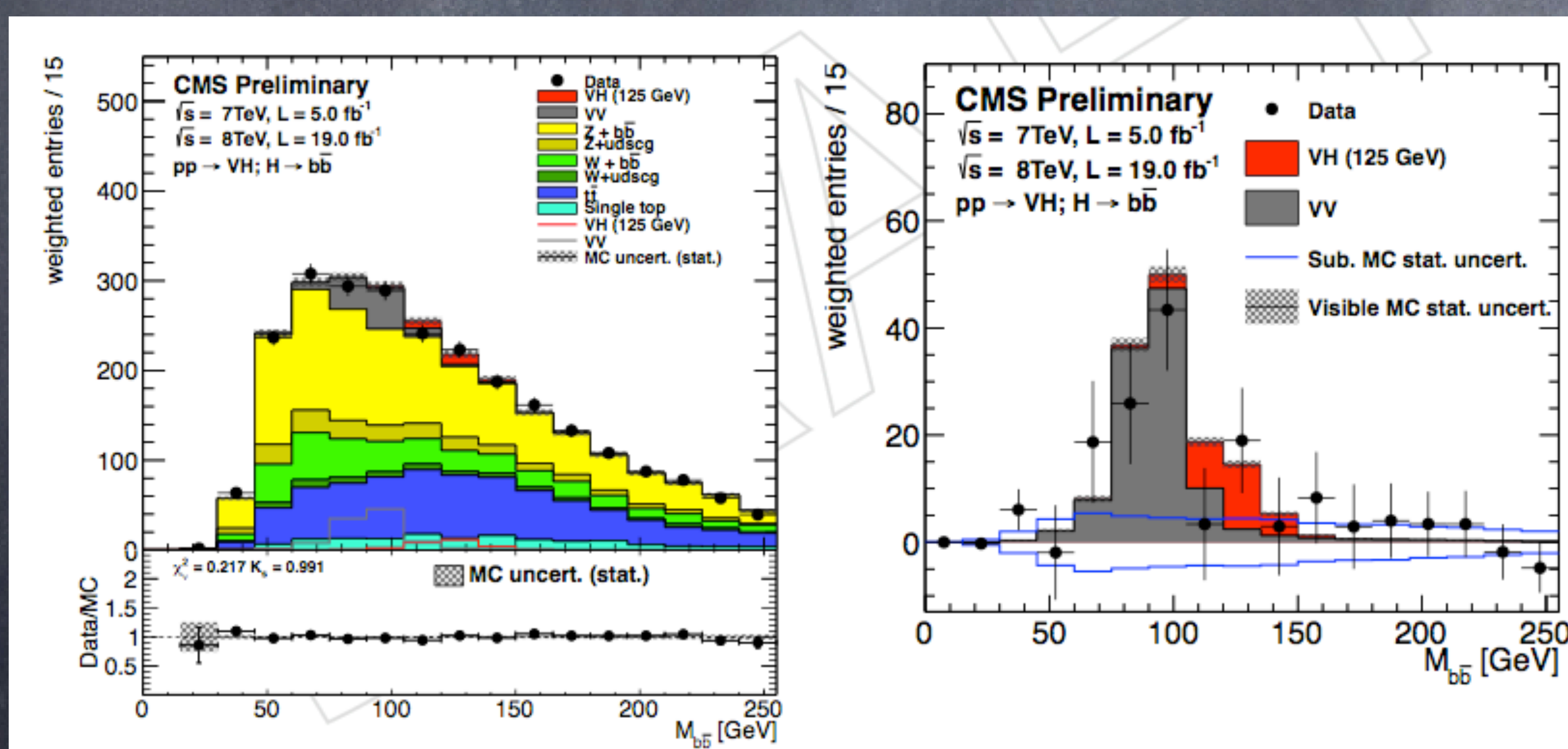
- 4 σ VZ->Vbb
- p_0=0.64
  (SMH 0.15 expected)
- μ=-0.4±1.1

CMS VH->Vbb

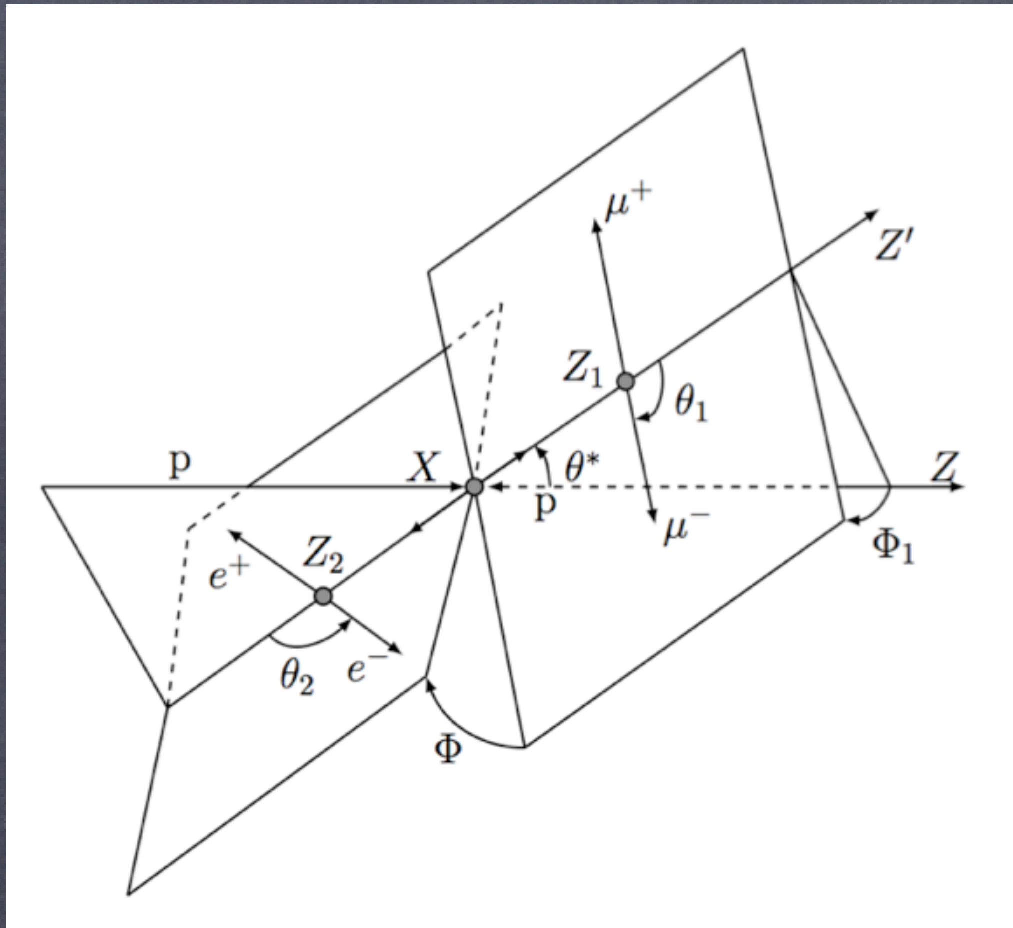
New 13.05.13!!



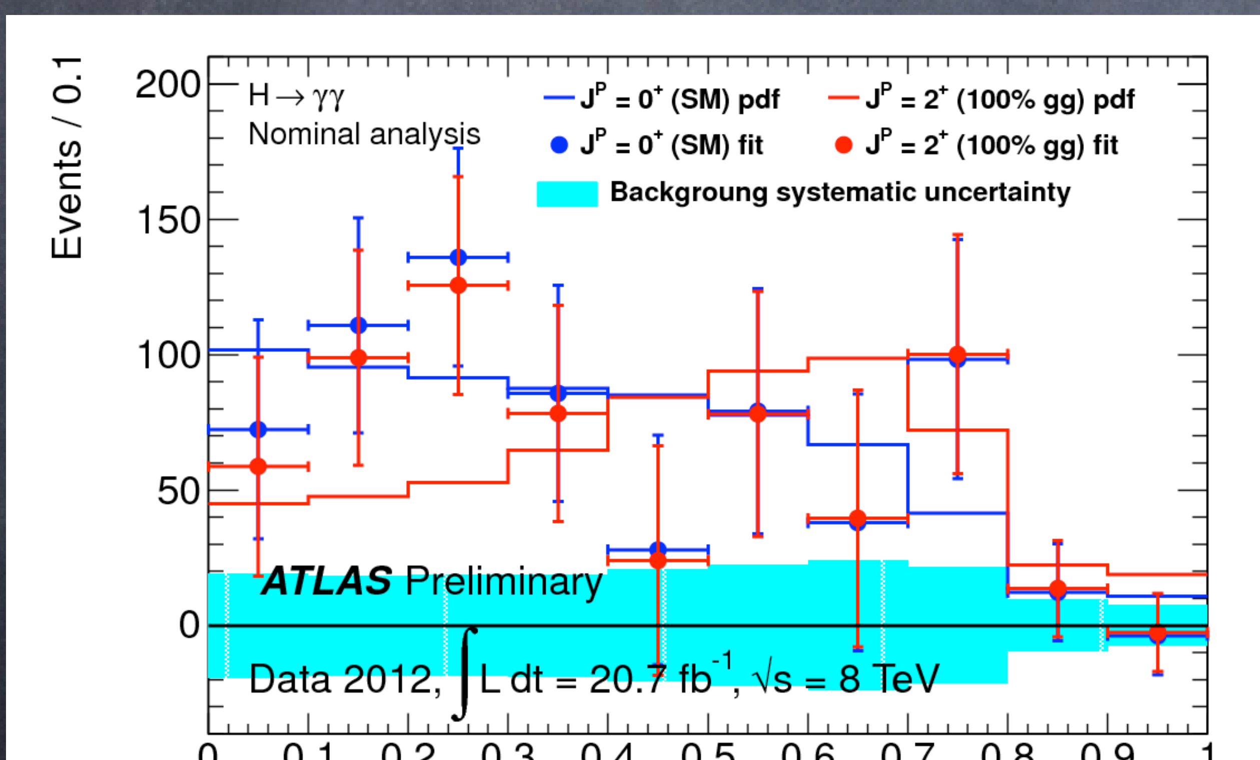
- 2.1 σ excess
- μ =1±0.5



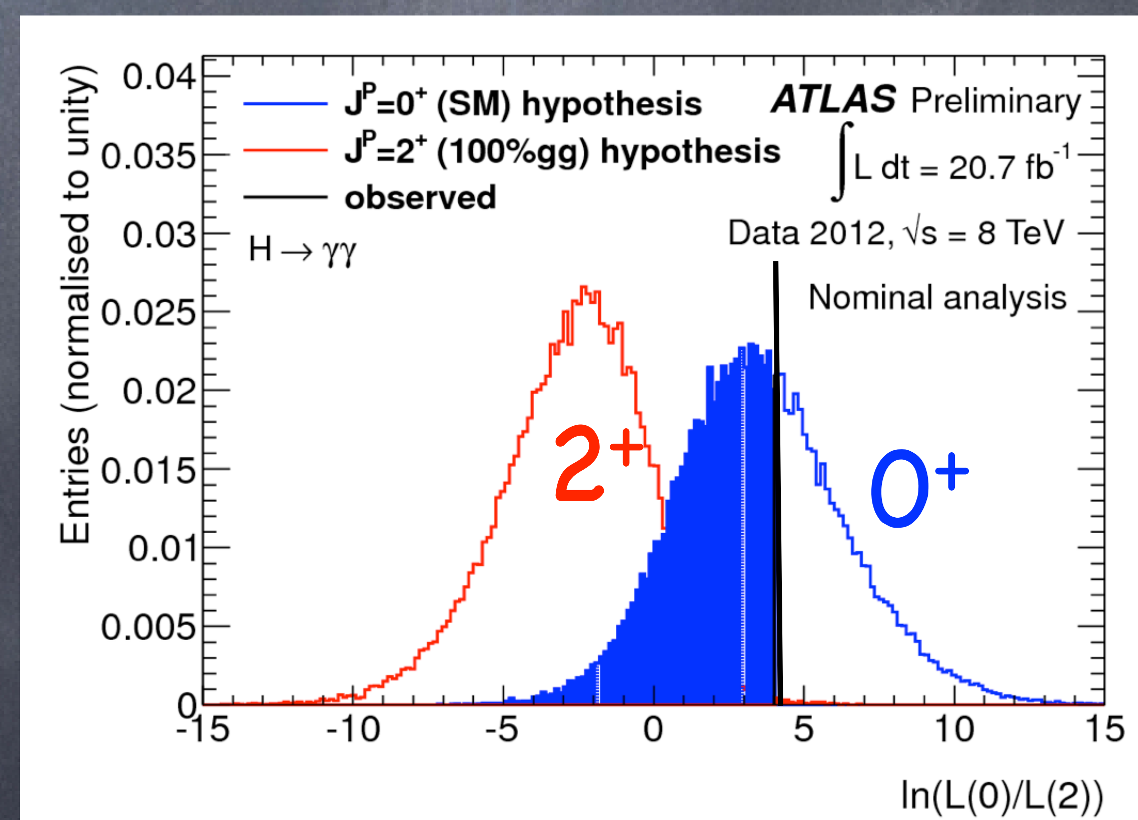
J^P



- 5 angle discriminant
- Only θ^* for $\gamma\gamma$
- Pairwise hypothesis tests of J^P - see if all but one rejected



Background from $m_{\gamma\gamma}$ sidebands

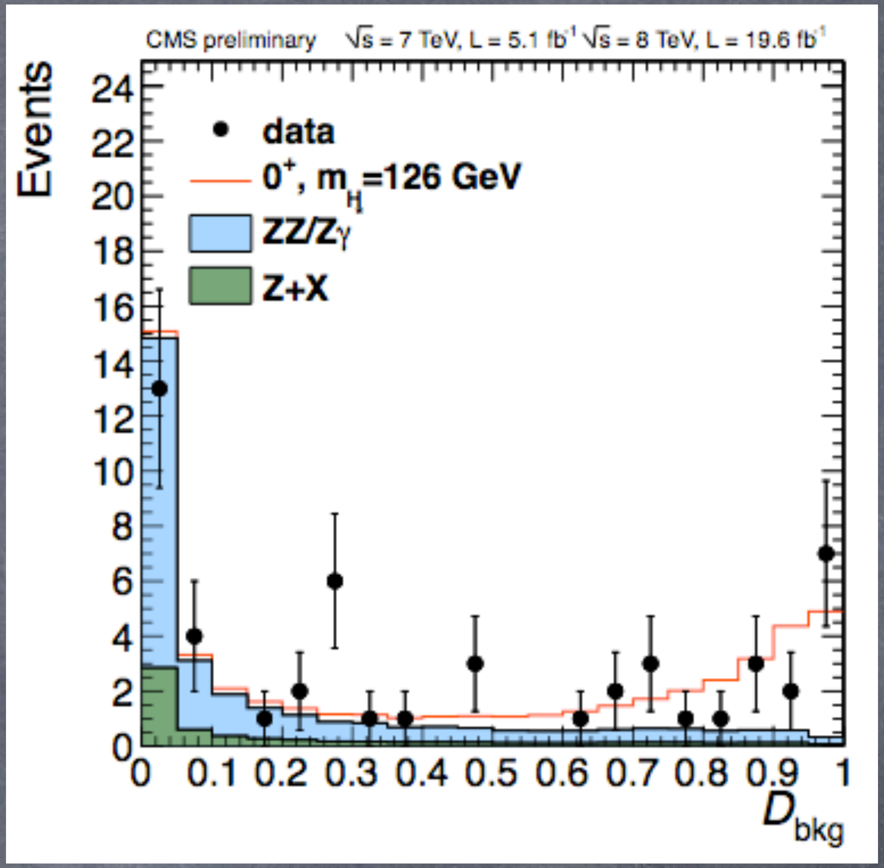


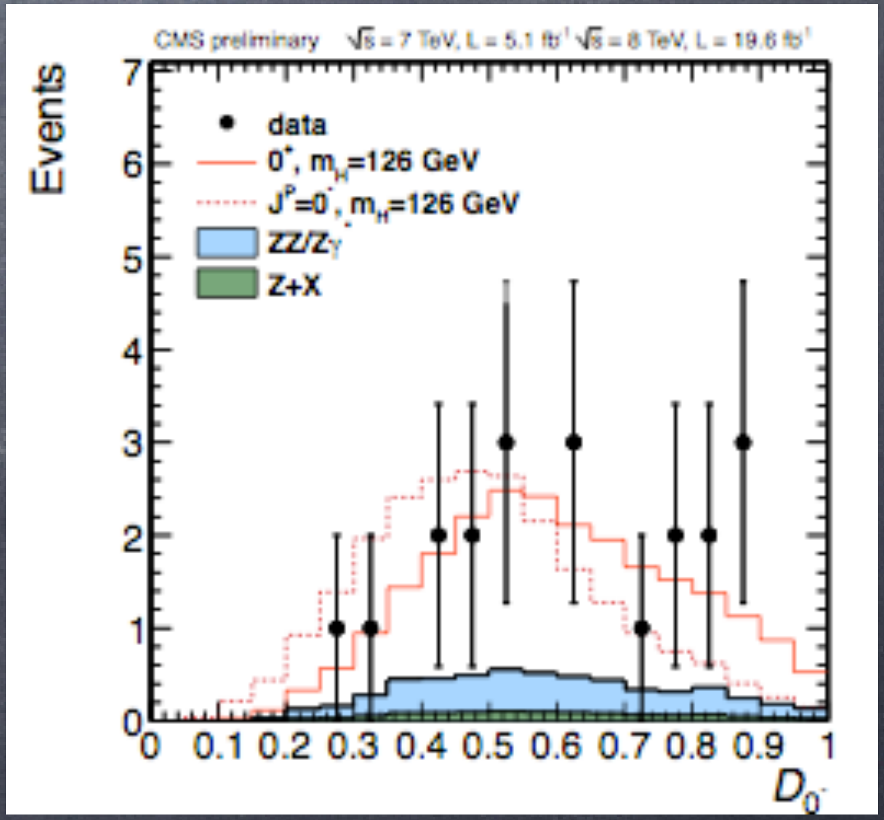
J^P from 4l

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

$$\mathcal{D}_{\rm bkg} = \mathcal{P}_{\rm sig} / (\mathcal{P}_{\rm sig} + \mathcal{P}_{\rm bkg})$$

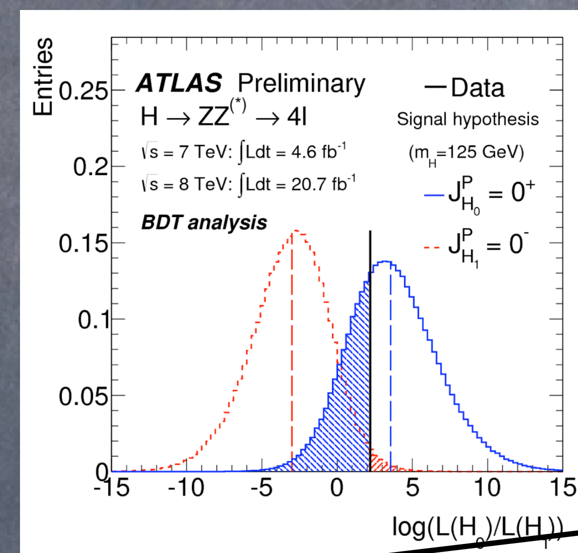
- for 4l: 5 angles and 2 Z masses
- 2-d analysis of (D_{bkg},D_{J^P})
- ATLAS trains MVA (BDT, MELA) per hypothesis
- CMS says BDT and Bayes NN give similar results for baseline analysis

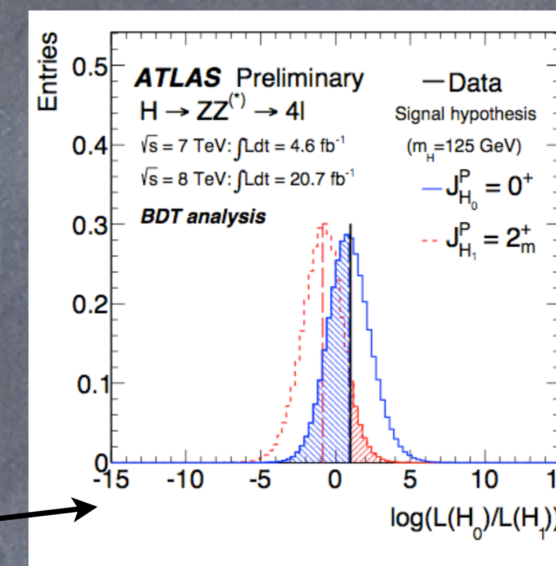


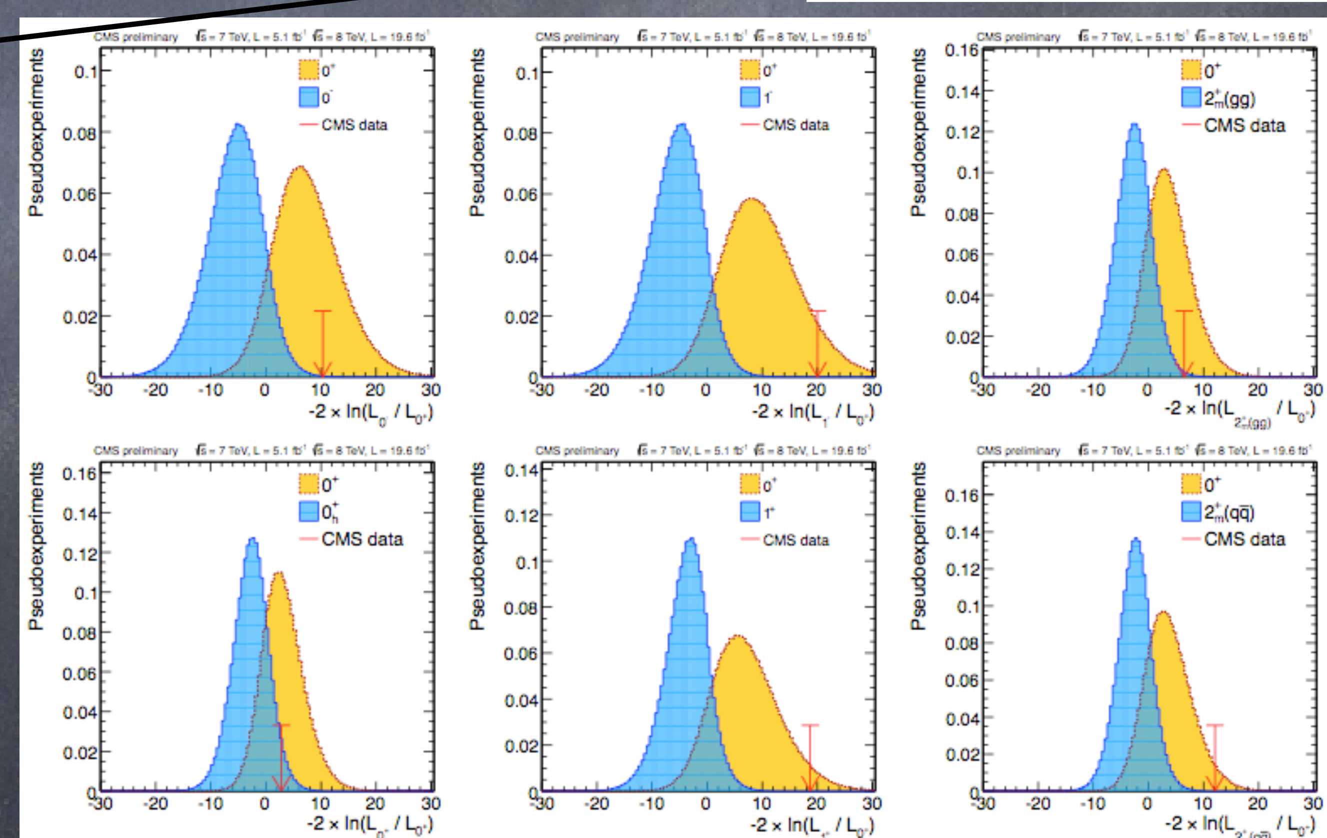


J^P from 4l

J^P	CL_s (CMS)	CL_s (ATLAS)
0^-	0.0016	0.022
0_h^+	0.081	–
2_{mqq}^+	0.015	0.168
2_{mqq}^+	<0.001	–
1^-	<0.001	0.060
1^+	<0.001	0.002
2^-	–	0.258







The couplings

They can be extracted from the different final states at the LO EW and NLO QCD approximation:

$$\sigma(H) \times BR(ii \rightarrow H \rightarrow xx) = \sigma_{ii} \times \Gamma_{xx} / \Gamma_H$$

We can measure deviations from the SM couplings, by measuring ratios w.r.t. to the SM prediction.

As an example for the gg→ H → γγ process:

$$(\sigma \times BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H)\, BR(H \rightarrow \gamma\gamma) \bullet \kappa_g^2\ \kappa_\gamma^2 / \kappa_H^2$$

- LHC XS WG benchmark models (arxiv:1209.0040):
  - Fermionic vs bosonic couplings: $\kappa_V\, \kappa_f$
  - Search for asymmetries: λ_{WZ}, λ_{du}, λ_{lq}
  - Search for new physics in loops: $\kappa_g\, \kappa_\gamma\, BR_{BSM}$

Chiara Mariotti

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Interim coupling framework

Example:

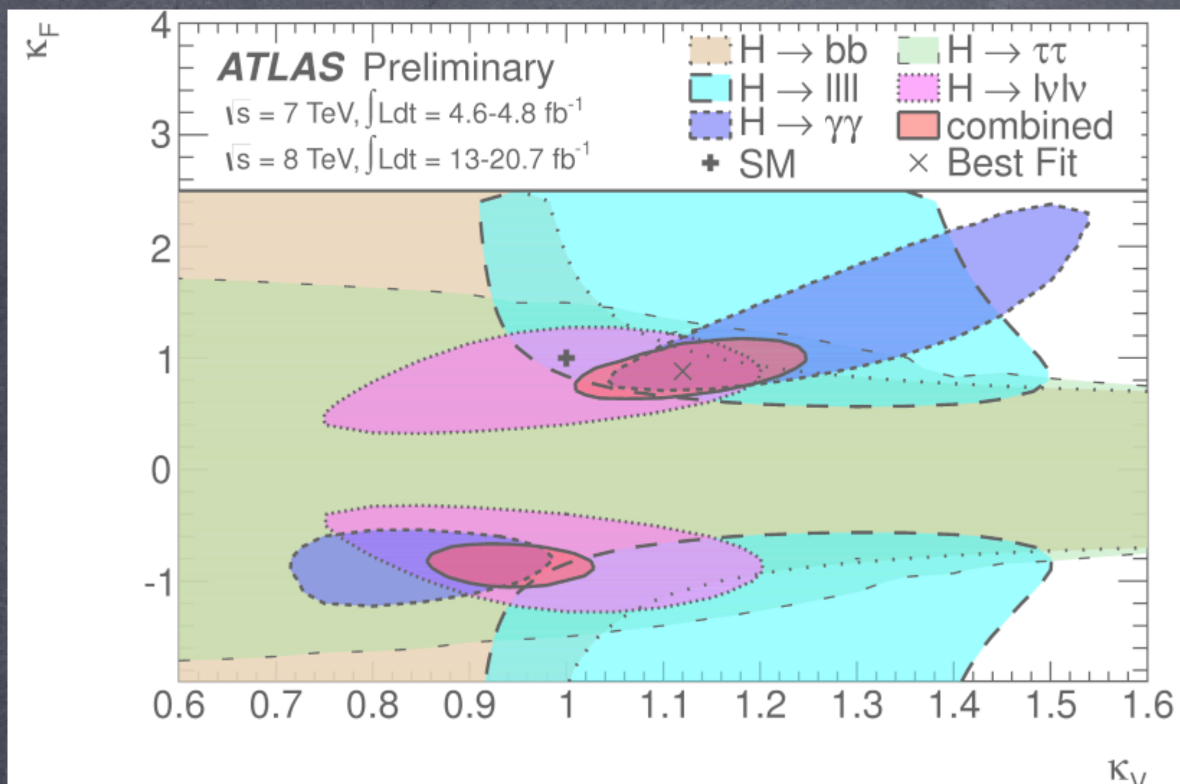
Probing custodial symmetry assuming no invisible or undetectable widths

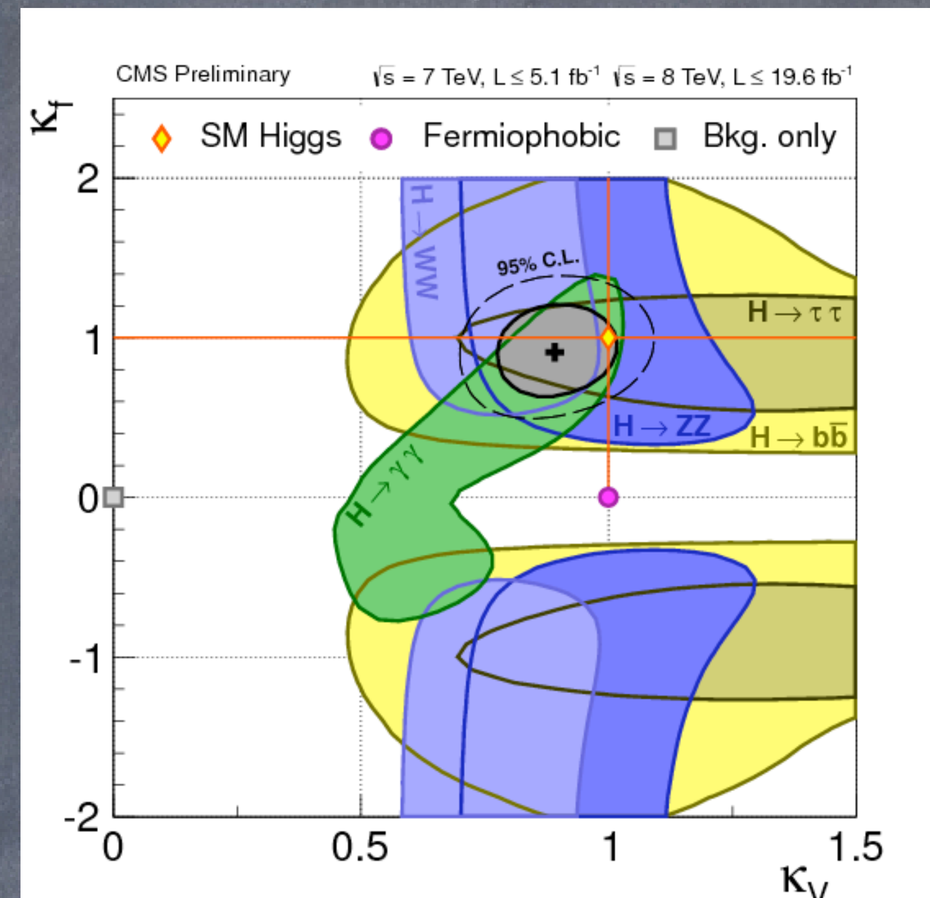
Free parameters: $\kappa_Z, \lambda_{WZ}(=\kappa_W/\kappa_Z), \kappa_f(=\kappa_t=\kappa_b=\kappa_\tau)$.

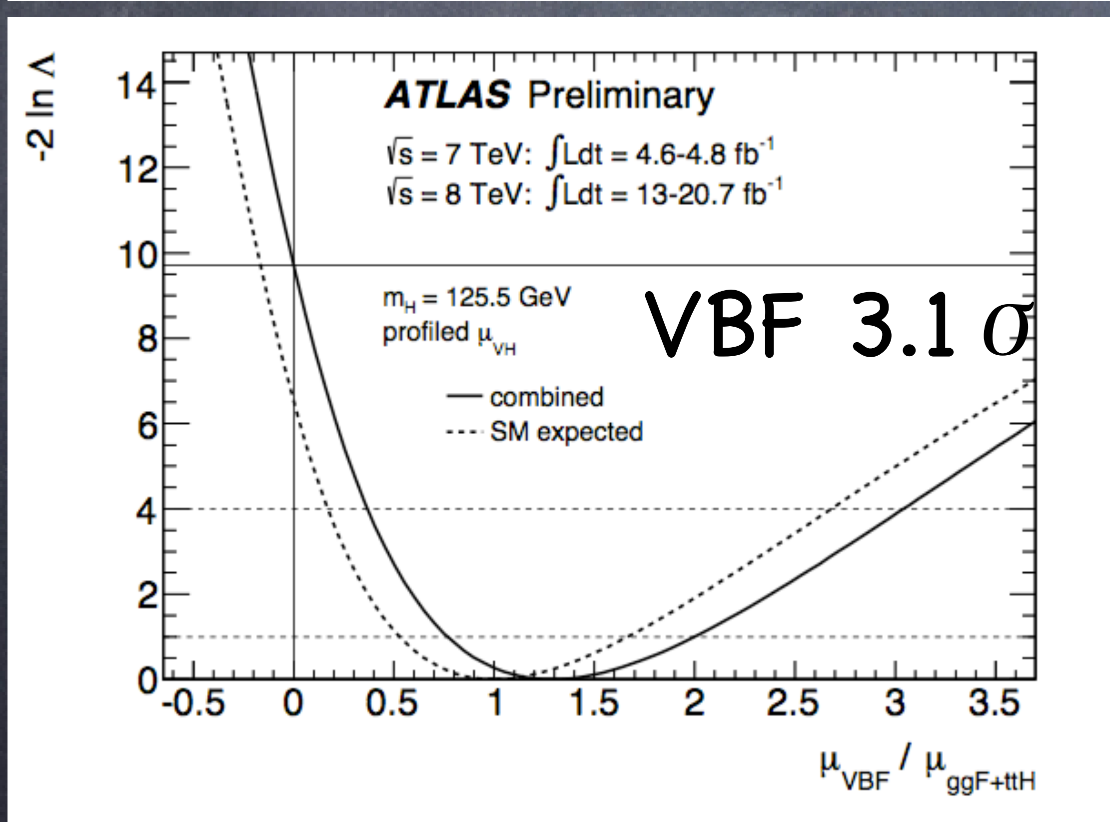
	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2\cdot\kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot\kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2\cdot(\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$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

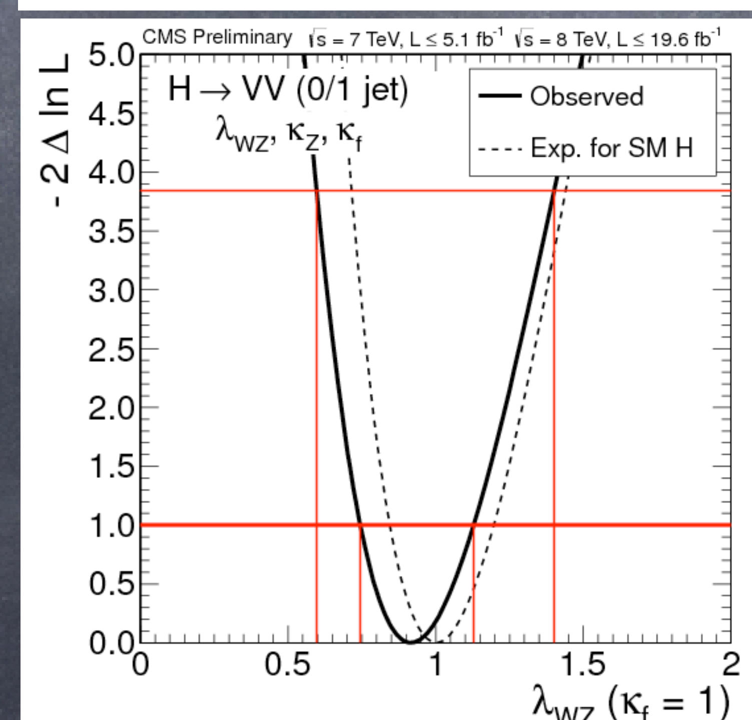
- Advantage: Don't test specific models one at a time
- Disadvantages:
  - Higher order corrections no longer necessarily correct (but NLO QCD factorizes so OK). [Gauge symmetry is explicitly broken.]
  - No obvious interpretation of deviation in a model (e.g. MSSM)
  - Anomolous couplings (add. terms in the lagrangian) would modify more than scaling factors

Couplings



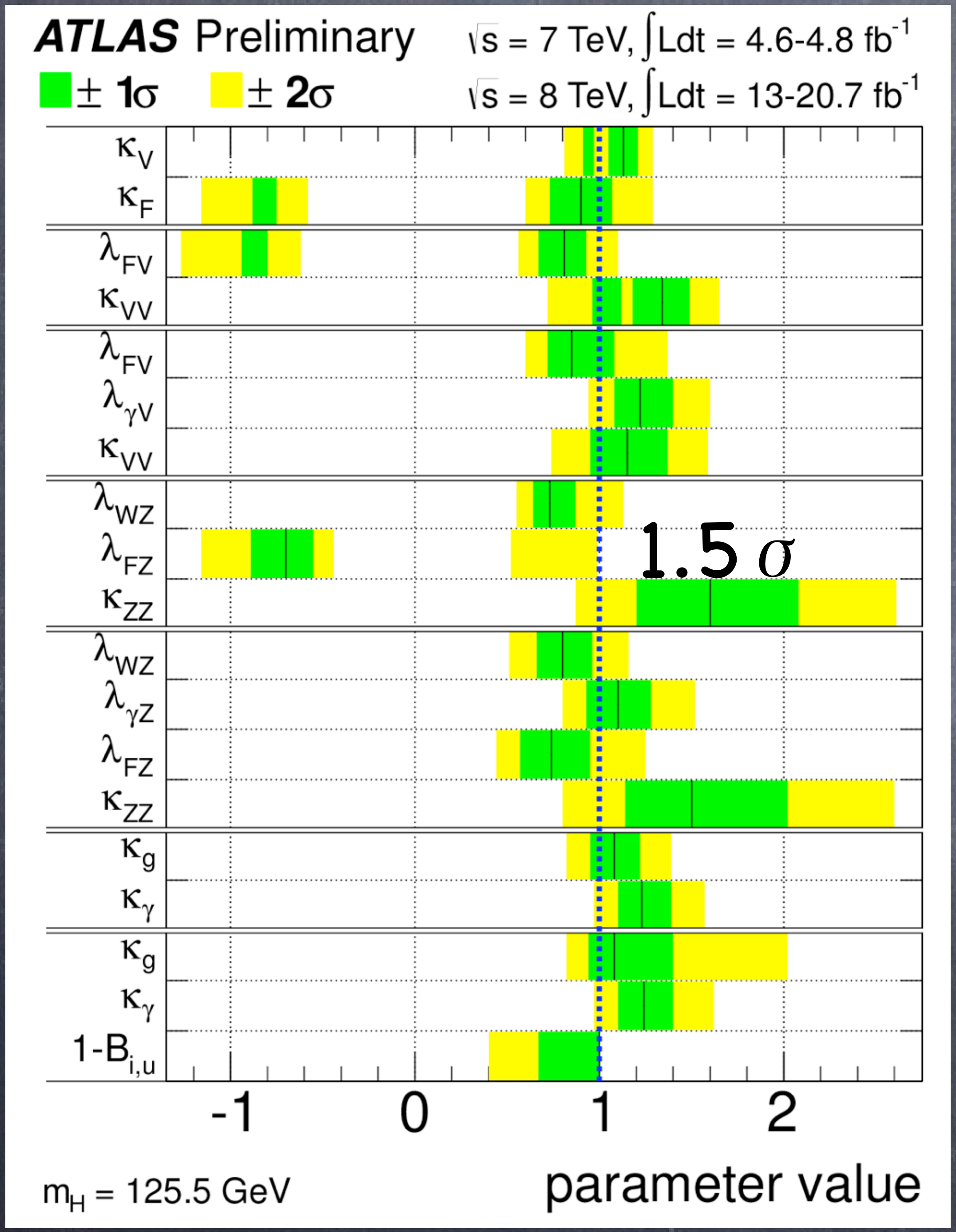


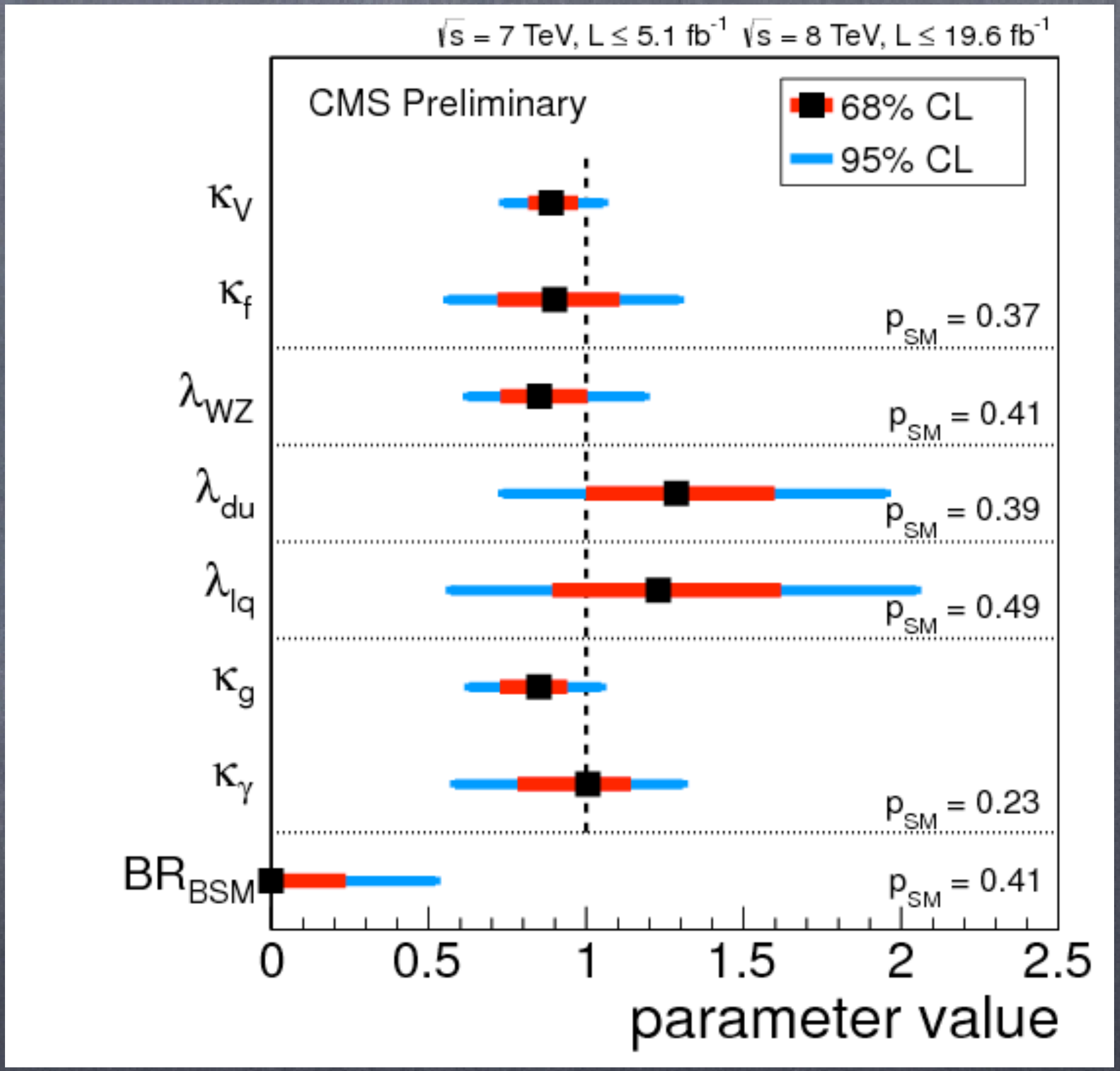




Custodial SU(2) symmetry

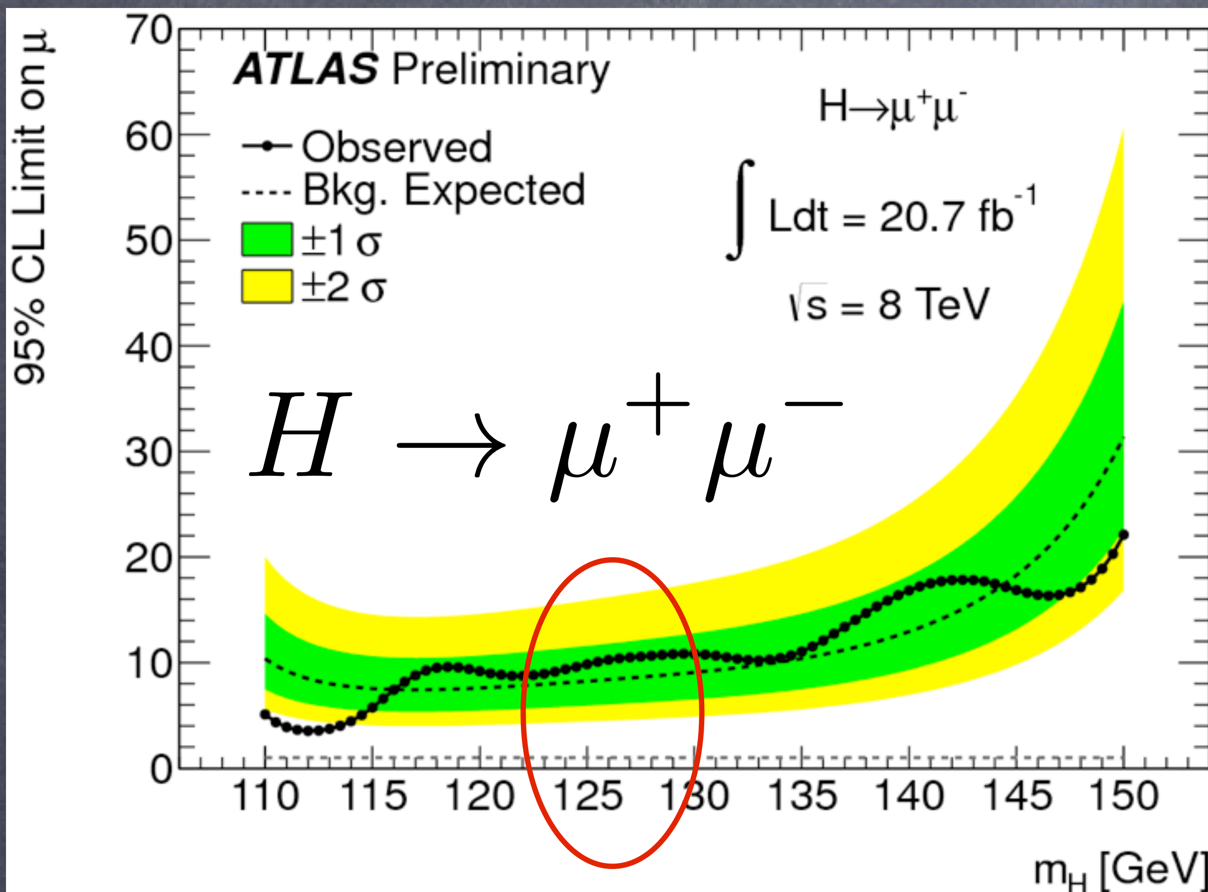
Coupling summary

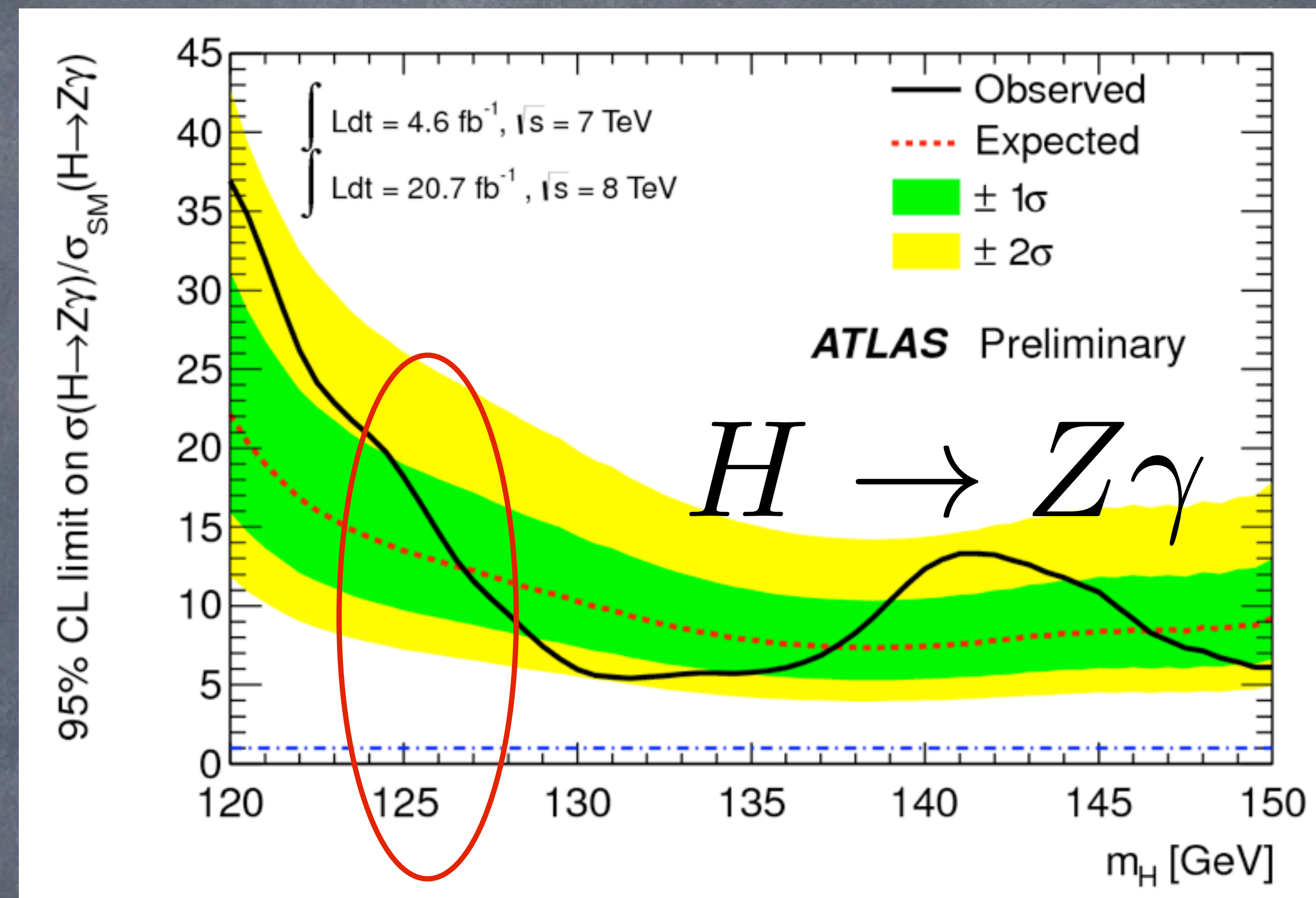


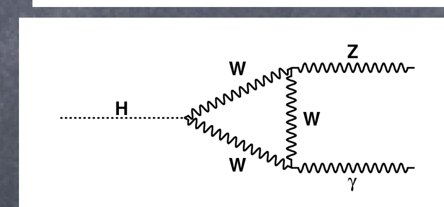


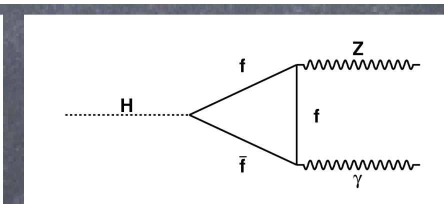
No sign of anomalies

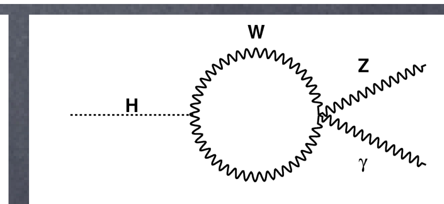
Decay modes we should see only later...







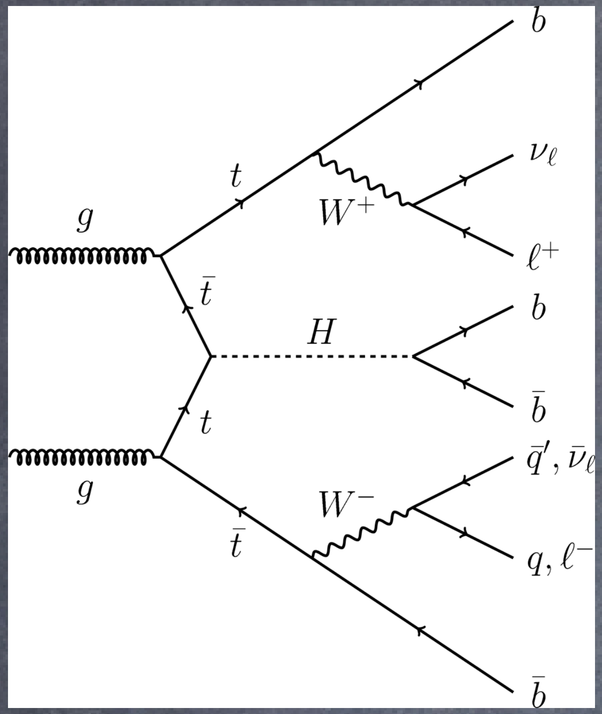




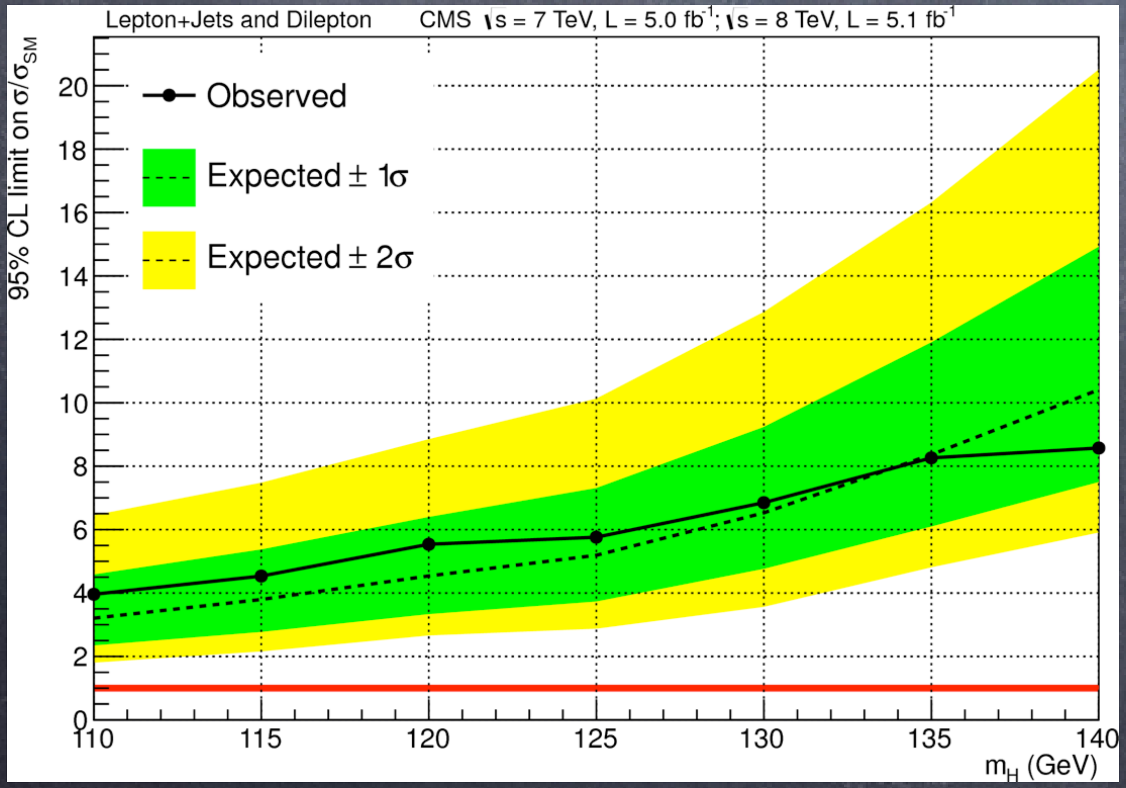
- With O(100) times more data ATLAS+CMS can test these rare decays as well

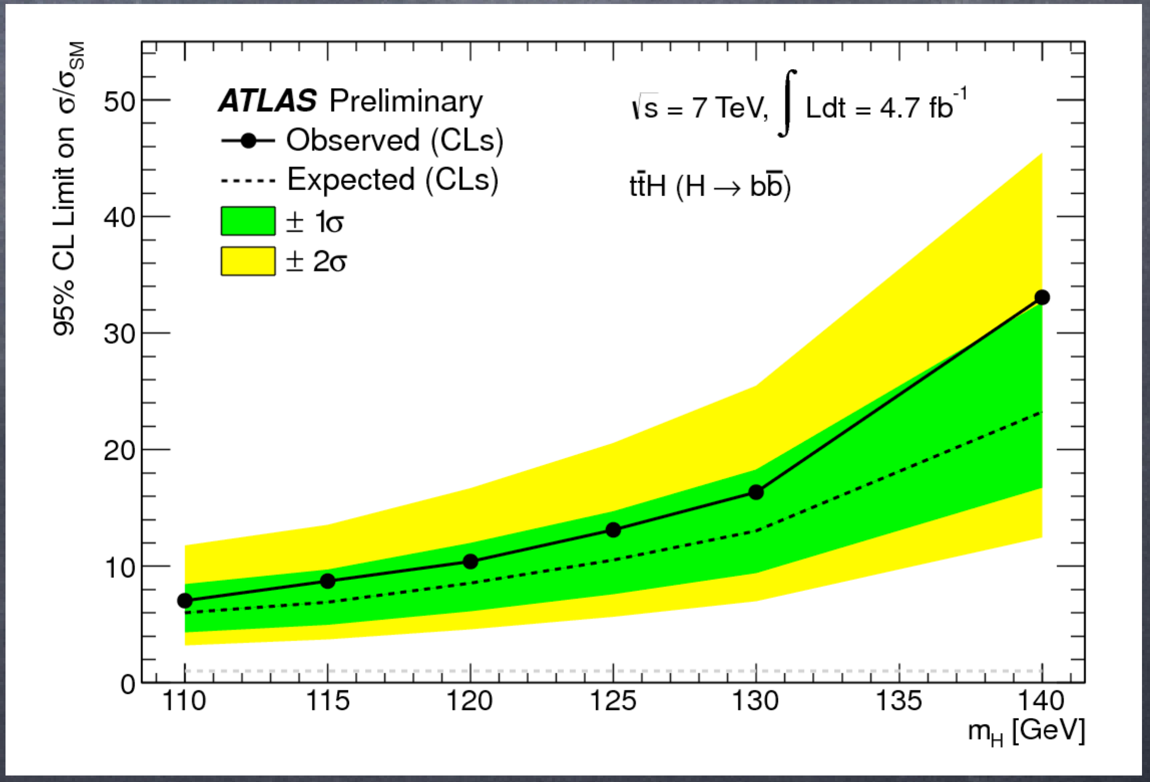
(Forward look on Friday)

ttH (only part of data)

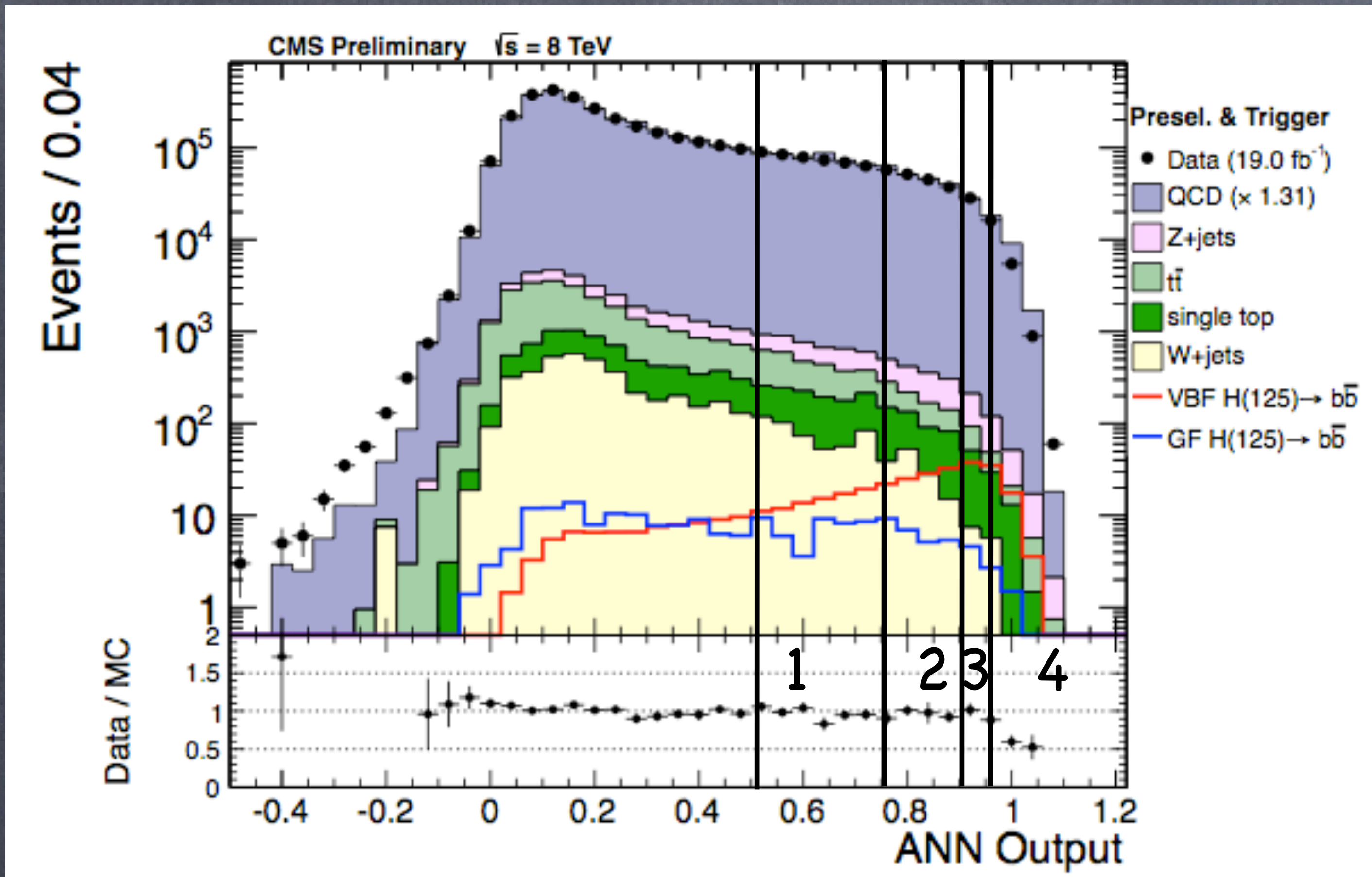


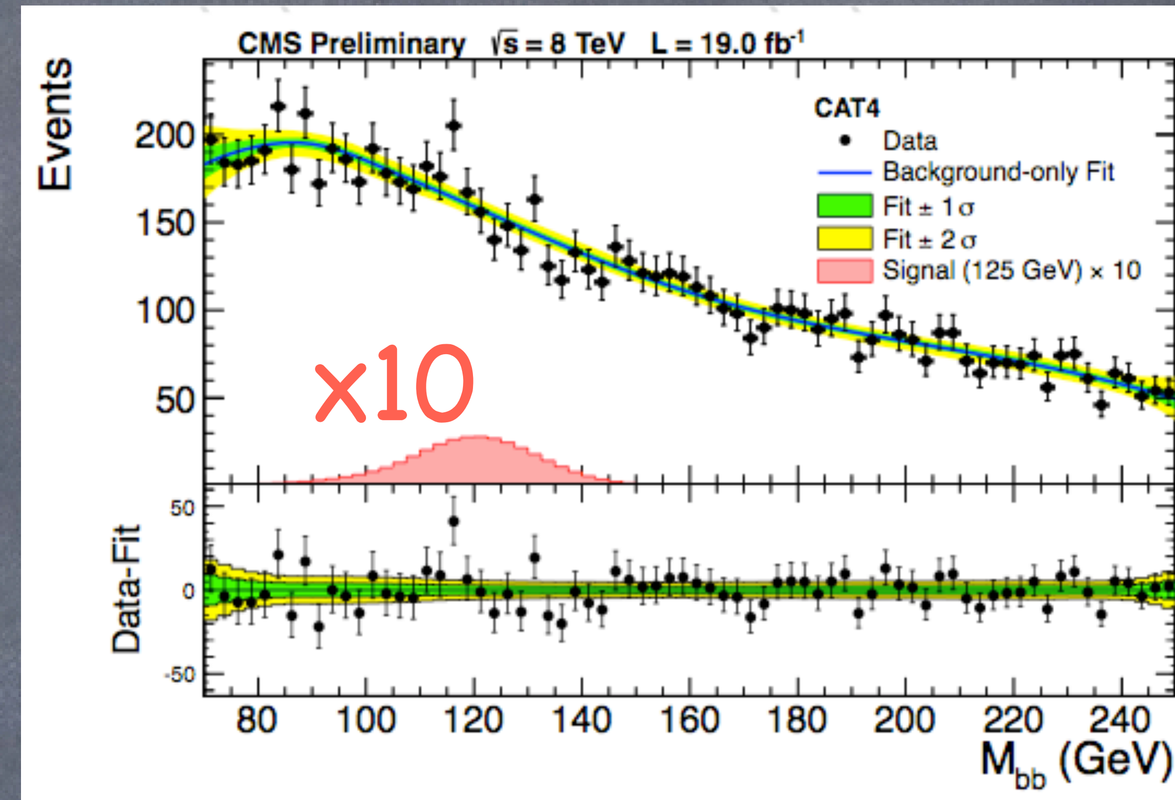
- leptons and jets, no explicit bb-recon.
- CMS: 9 ANN's, l+l (≧4j,≧2b), l+j (≧2j, ≧2b), 5+5/fb
- ATLAS: 1 lepton + 9 categories of 4,5,≧6 j and 0-4 b, 4.7/fb

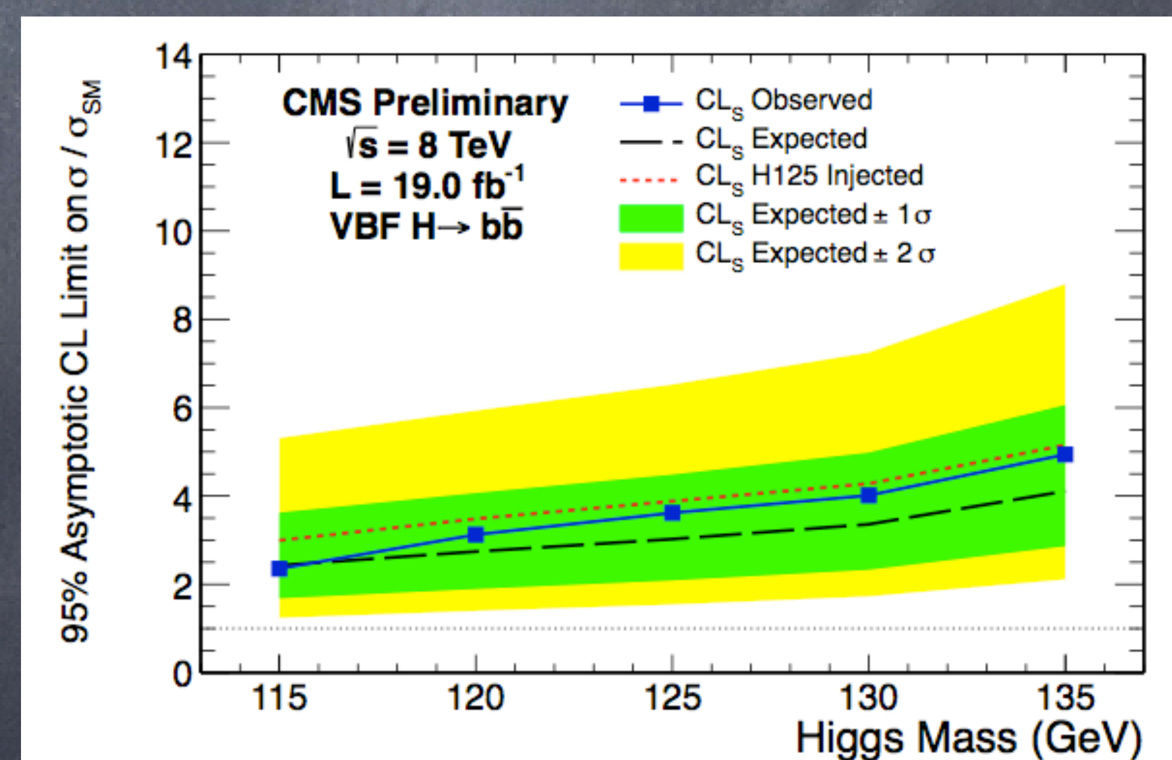




CMS VBF H->bb (New)







- Need more data (ditto for WH->3l3ν)

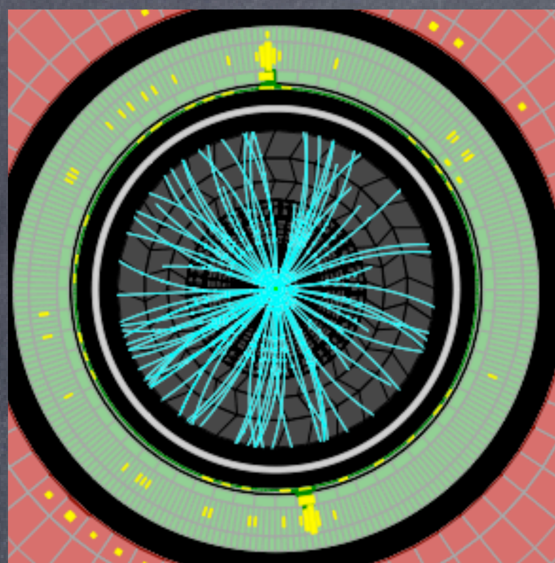
Conclusions

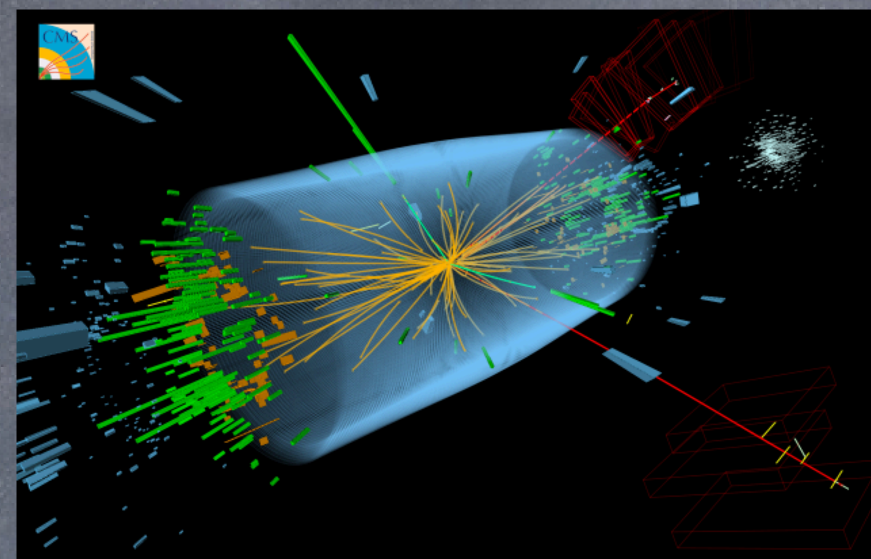
- Beyond any reasonable doubt we have started to measure and test in detail the properties of a Higgs boson, which in every way is so far consistent with the minimal SM ($J^P=0^+$, SM couplings)
- We have seen what we expect from SM for m_H~125 GeV
  - But $\tau^+\tau^-$ and $b\bar{b}$ not yet not well-established
- We have not seen what we don't yet expect to have sensitivity to (e.g. $Z\gamma$, $\mu^+\mu^-$, ttH)

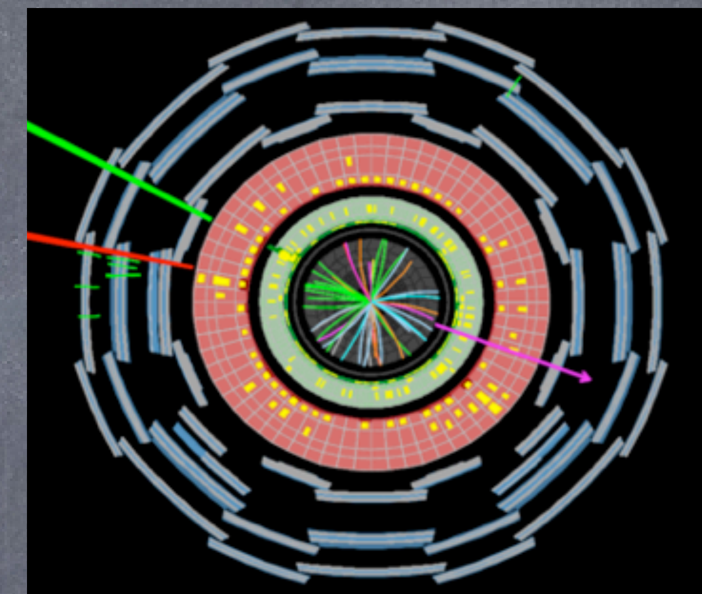
Questions

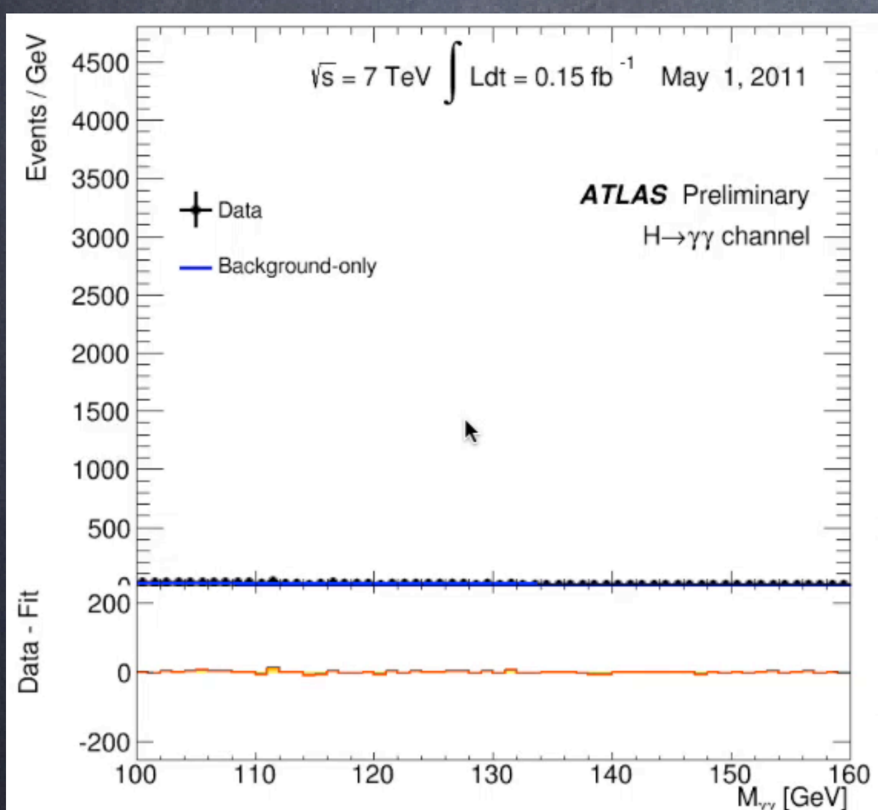
- Can we describe deviations from the SM (including the Higgs boson) which do not ruin the renormalizability (gauge invariance) of the Model we have worked so hard to establish?
- Are there complementary measurements we can make to reduce the O(10%) theoretical uncertainties (PDF's and scale uncertainty in truncated perturbation series) on the Higgs boson production cross-sections with loop diagrams?
- The thorough statistical models of ATLAS and CMS use many nuisance parameters. Given that the likelihoods are more and more parabolic around the minimum, can we perform accurate ATLAS-CMS combinations of mass, spin-parity hypothesis tests (parity violation), effective couplings with a greatly reduced number of effective nuisance parameters and effective observations? Could it save time?
- The observation and measurement of the self-interaction of the Higgs boson, and thus a direct test of the form of the scalar field potential, is far off in the future after many years of LHC running and perhaps even a new accelerator. Will we accept 3 sigma as evidence or is 5 sigma demanded for this last critical test of the BEH mechanism? (Shouldn't we look now although we don't expect to find?)
- Inspired by an earlier talk: What other decay channels should we search for at 125 GeV?

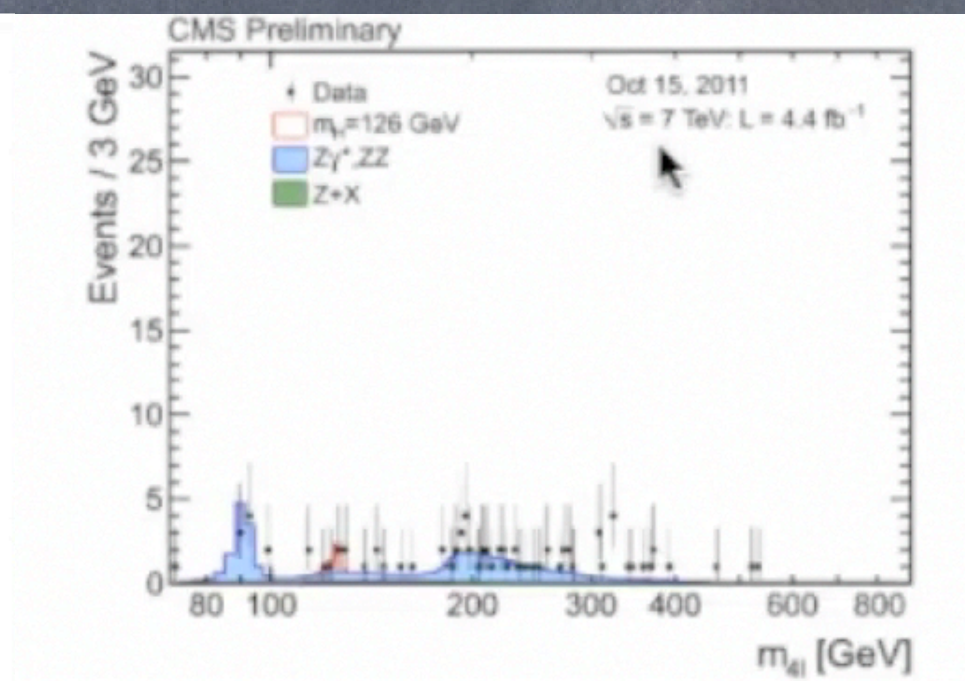
Rest of 2012: The signals grew…

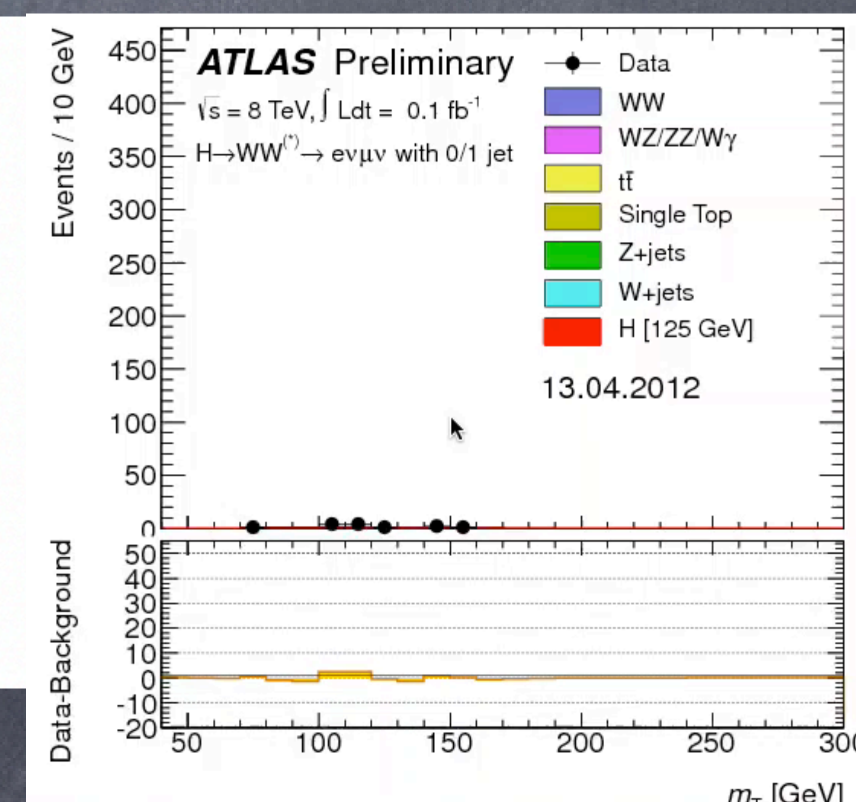




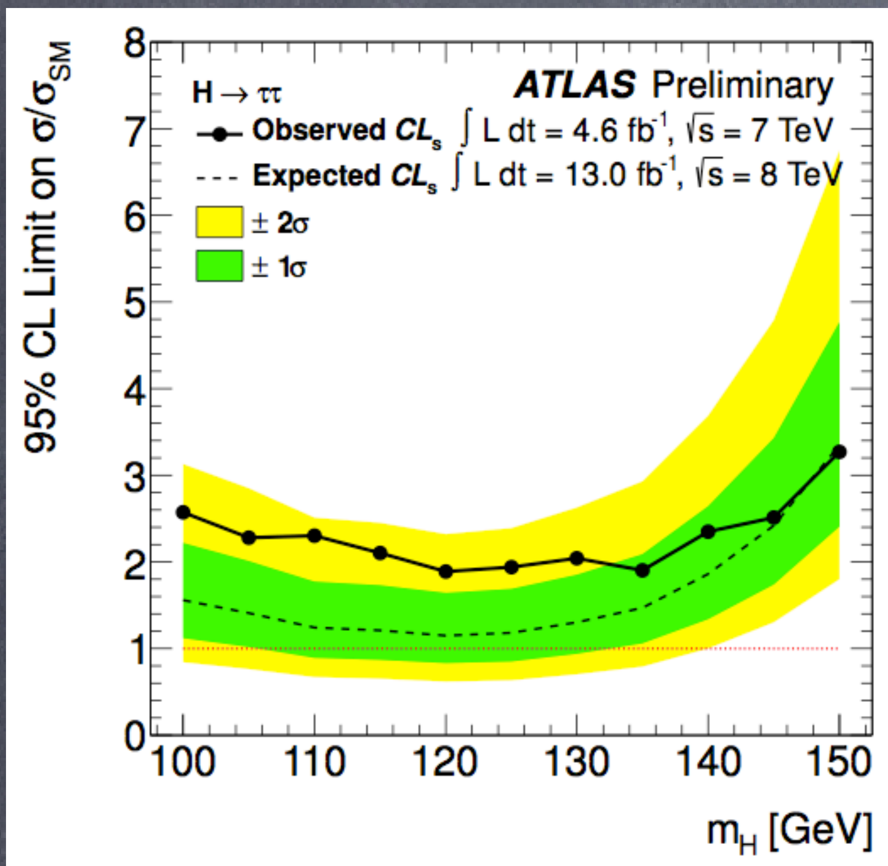








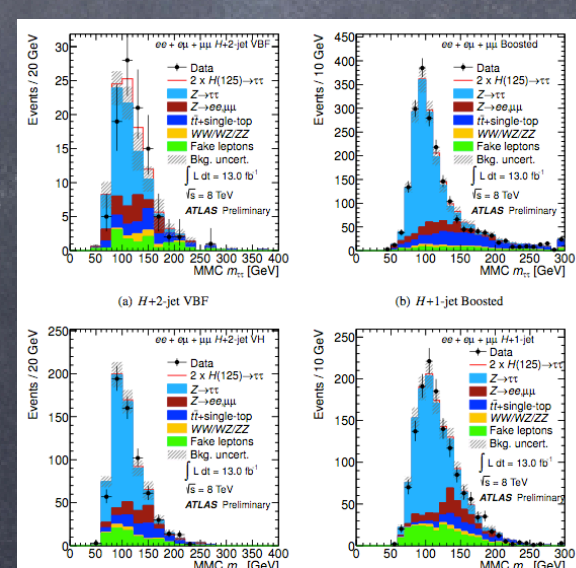
Higgs frontier - [illegible]

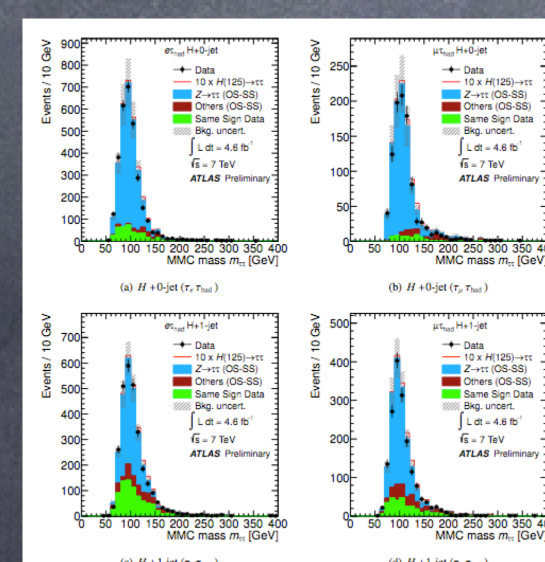


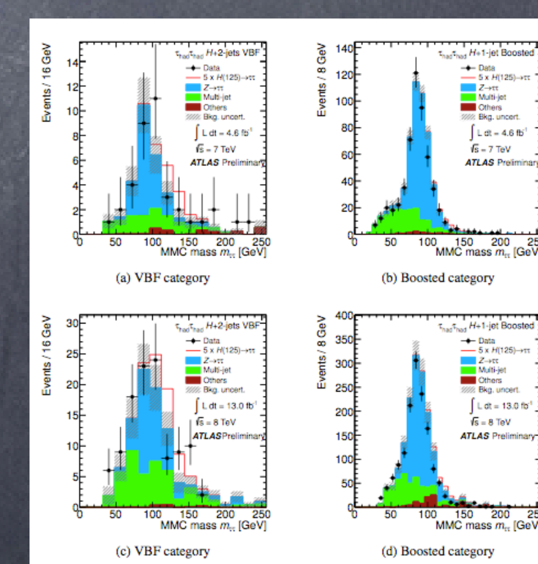
hh	VBF	boosted			
lh	VBF	boosted		1j	0j
ll	VBF	boosted	2j VH	1j	0j

7, 8 TeV separated

~1 σ excess







Higgs frontier –

CMS

- (eμ, $\mu\mu$, lh, hh) *(VBF, 1j, 0j)
  - 0j used to constrain bg, eff, E
- CMS: 2.9 σ (m_H=120-125 GeV)