Higgs Review

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More importantly…

H^0 (Higgs Boson)

H^0 MASS

VALUE	DOCUMENT ID		TECN	COMMENT
125.9±0.4 OUR AVERAGE				
125.8±0.4±0.4	[1] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
126.0±0.4±0.4	[2] AAD	12AI	ATLS	pp, 7 and 8 TeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
126.2±0.6±0.2	[3] CHATRCHYAN	13J	CMS	pp, 7 and 8 TeV
125.3±0.4±0.5	[4] CHATRCHYAN	12N	CMS	pp, 7 and 8 TeV

[1] Combined value from ZZ and $\gamma\gamma$ final states.

[2] AAD 12AI obtain results based on 4.6–4.8 fb^{-1} of pp collisions at $E_{cm} = 7$ TeV and 5.8–5.9 fb^{-1} at $E_{cm} = 8$ TeV. An excess of events over background with a local significance of 5.9 σ is observed at $m_{H^0} = 126$ GeV. See also AAD 12DA.

[3] Result based on $ZZ \to 4\ell$ final states in 5.1 fb^{-1} of pp collisions at $E_{cm} = 7$ TeV and 12.2 fb^{-1} at $E_{cm} = 8$ TeV.

[4] CHATRCHYAN 12N obtain results based on 4.9–5.1 fb^{-1} of pp collisions at $E_{cm} = 7$ TeV and 5.1–5.3 fb^{-1} at $E_{cm} = 8$ TeV. An excess of events over background with a local significance of 5.0 σ is observed at about $m_{H^0} = 125$ GeV. See also CHATRCHYAN 12BY.

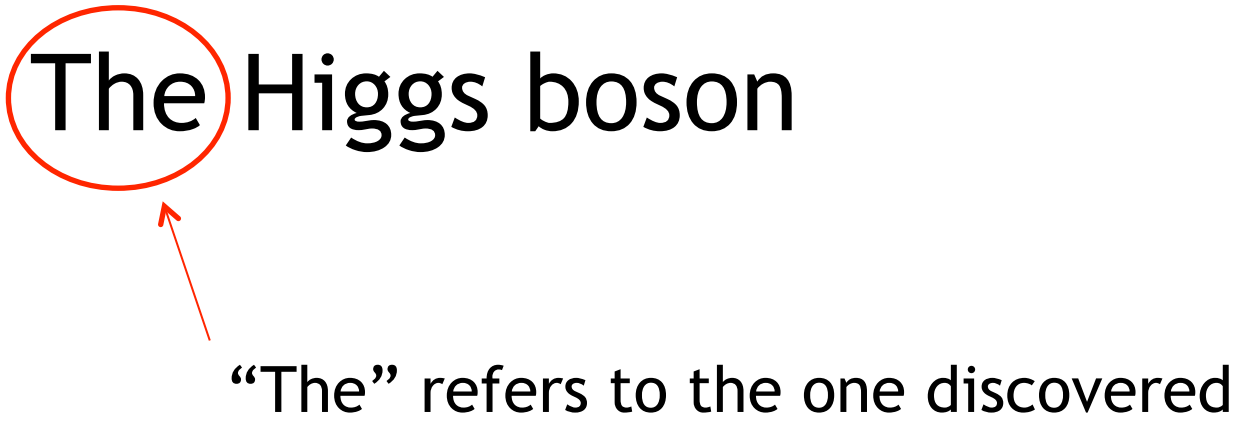
H^0 SPIN

H^0 DECAY WIDTH

Inaugural entrance of the Higgs boson in the PDG particle listing !

Not anymore as a hypothetical particle!

Disclaimer



Next Major Conference Updates

Timeline

1.- Tomorrow SFO: The Lepton-Photon Conference (June 24, 2013)

2.- EPS conference in Stockholm (July 18, 2013)

PDG Review

3.- Moriond 2014 (March 2014)

Two Outstanding Format Questions

1.- Two reviews? TH and EXP or only one?

(Potentially painful integration process for 2 reviews)

2.- Length?

3.- Hypothetical particles or Standard Model (which has e.g. GUT)?

Draft Outline(s) Proposal

Machines concise description: TeVatron, LEP and LHC? ?

1.- Discovery of a Higgs boson
- a.- The discovery channels gg and 4l.
- b.- The discovery of a Higgs boson.
- c.- Measurement of the mass (and width).
- d.- Supporting evidence in the lvlv channel.

Ultra light prospects mini section? ?

2.- Coupling Properties measurements
- a.- The fermionic channels (Tevatron and LHC).
  - - VH(bb) At tevatron
  - - VH and ttH(bb) at LHC
  - - tau tau at LHC
- b.- Rare decay channels (mumu, Zgamma).
- c.- Couplings fits (Testing couplings to SM particles).
- d.- Couplings fits (Assuming SM couplings to SM but not in the loops and decay).

Statistics ?

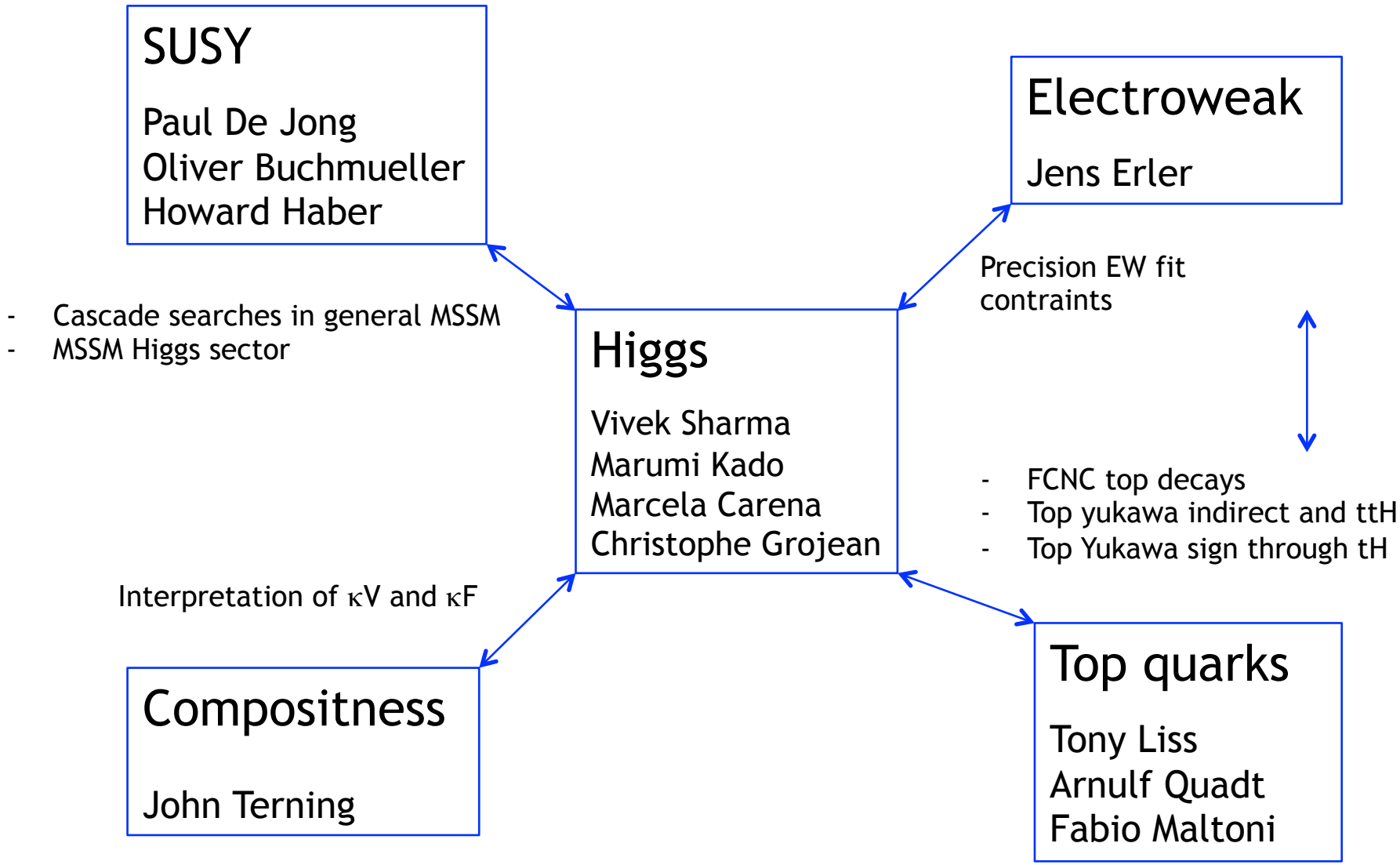
?

3.- Spin and CP properties measurements

4.- Using the newly discovered state for BSM searches
- a.- Invisible decays.
- b.- Decays to hidden valley pions.
- c.- FCNC top decays…

5.- Search for additional states of the EWSB sector
- a.- Overview of searches in the low mass region before LHC. (LEP etc)
- b.- Simple singlet case (with unitarity).
- c.- 2HDM models.
- d.- MSSM , nMSSM(a -> mu mu etc) at LEP, TEV, BaBar etc
- e.- Triplet models and doubly charged Higgs.

(Potential) Connections

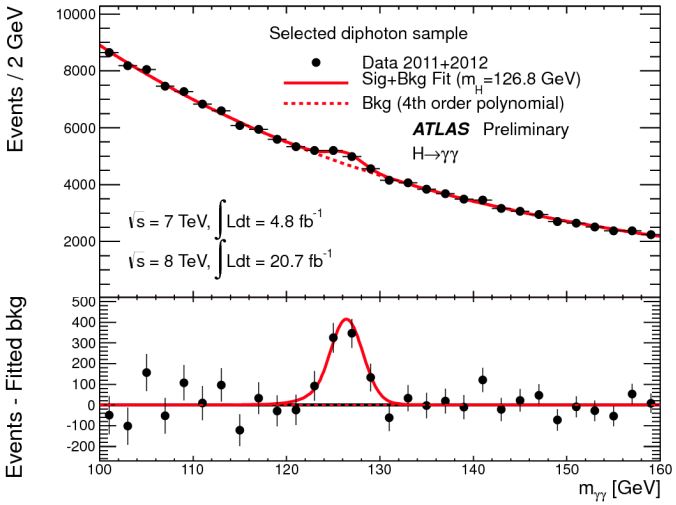


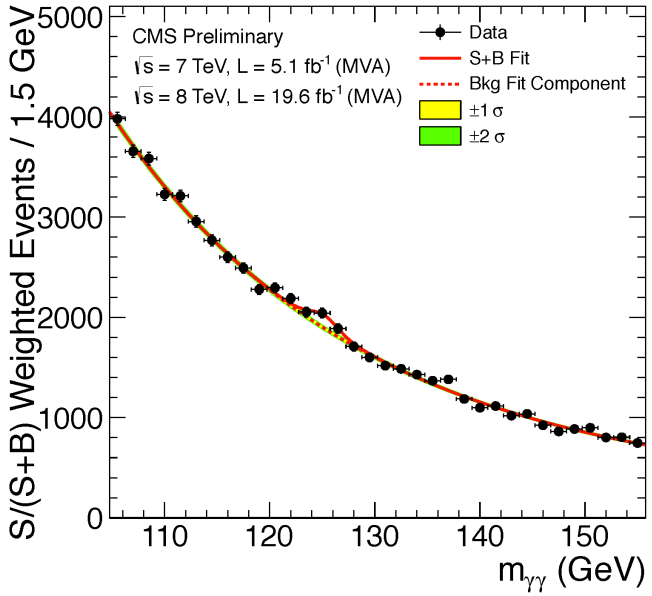
Channels Mini Review

- Discuss the level of detail necessary in the review

- Other channels will be described in the review with less details (only outstanding features)

$H \rightarrow \gamma\gamma$





Analysis strategy:

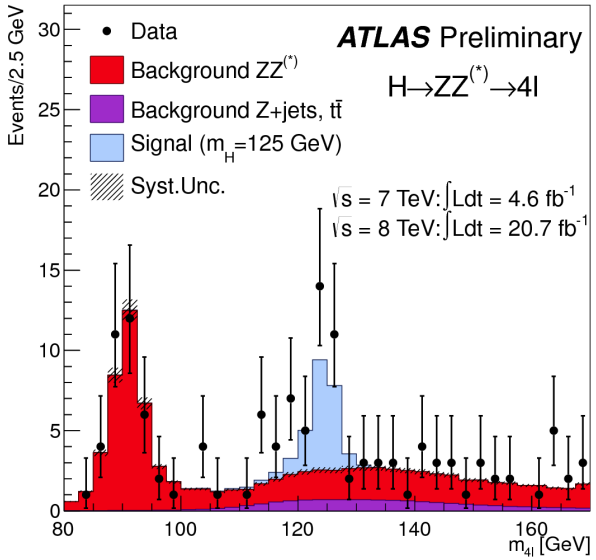
- Di-photon mass is the key observable

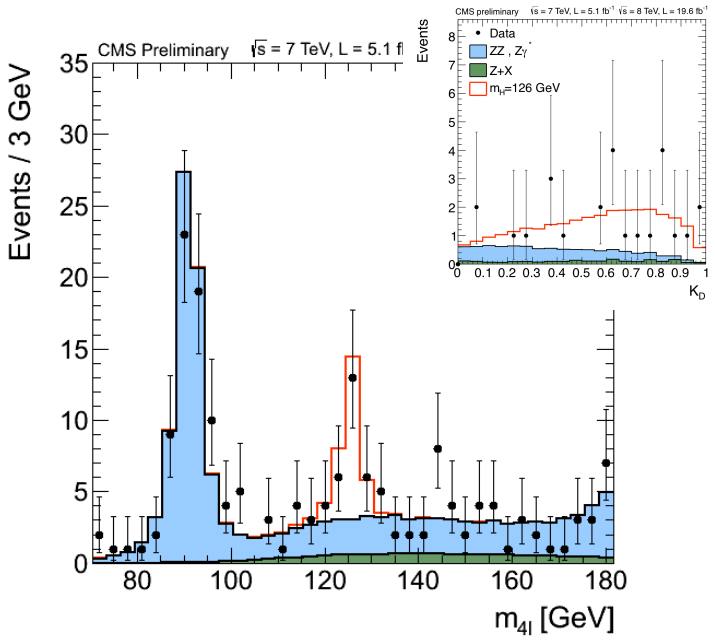
- two isolated high-p_T photons
  - vertex
    - CMS: from recoiling charged particles
    - ATLAS: from photon pointing (longitudinal ECAL segmentation)
  - split events into exclusive categories:
    - untagged, and further divided into 4/9 classes based on
      - expected mass resolution
      - expected S/B-ratio
    - di-jet tagged (VBF), and further divided into 2 classes based on
      - expected S/B-ratio
    - ATLAS: low mass di-jet tag (VH)
    - MET-tagged (VH)
    - lepton-tagged (VH)
  - background: from $m_{\gamma\gamma}$ distribution (in the sidebands)

Key Analysis Features to note:

- Small S/B-ratio,
- High event yield
- di-photon mass resolution = 1-2%

$$H \rightarrow ZZ^{*} \rightarrow \ell^{+}\ell^{-}\ell^{+}\ell^{-}$$





Analysis strategy:

four prompt leptons (low p_T is important!)

four-lepton mass is the key observable

split events into 4e, 4μ, 2e2μ channels:

Different resolutions and S/B rates

CMS specificities:

- **ME-based discriminant K_D**
- Per event (mass) errors

split events further into exclusive categories:

untagged (CMS: add a 3rd observable: **four-lepton p_T/m**)

di-jet tagged (CMS: add a 3rd observable: **$V_D(m_{jj}, \Delta\eta_{jj})$**)

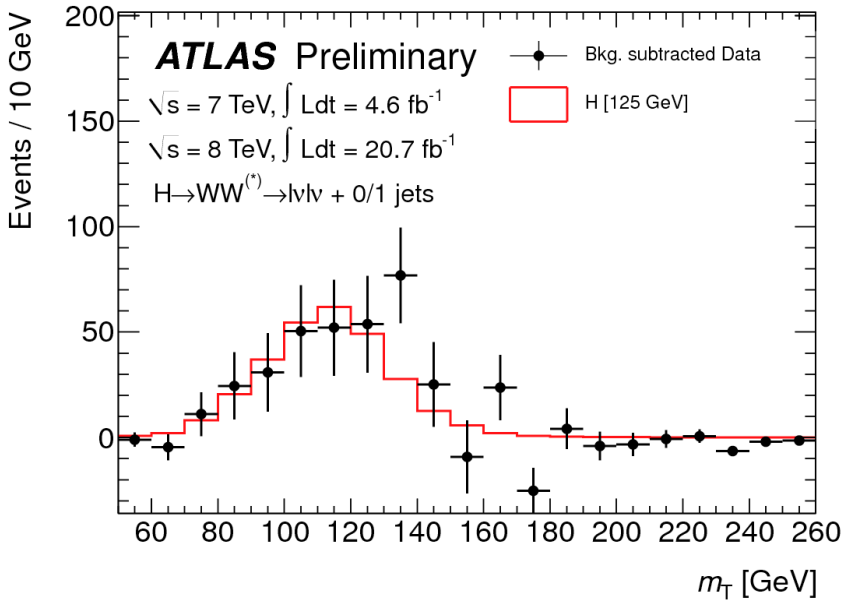
Analysis key features:

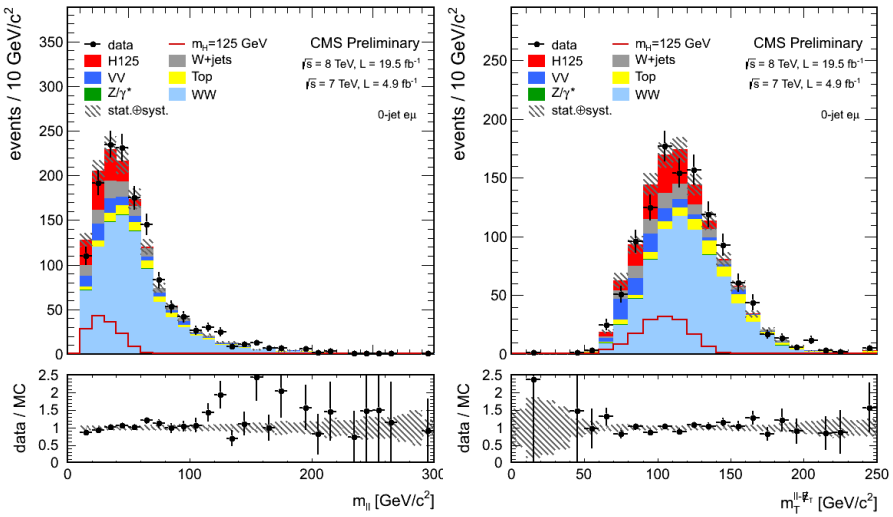
High S/B-ratio,

But small event yield

mass resolution = 1-2%

$H \rightarrow WW^{*} \rightarrow \ell^{+}\upsilon\ell^{-}\upsilon$

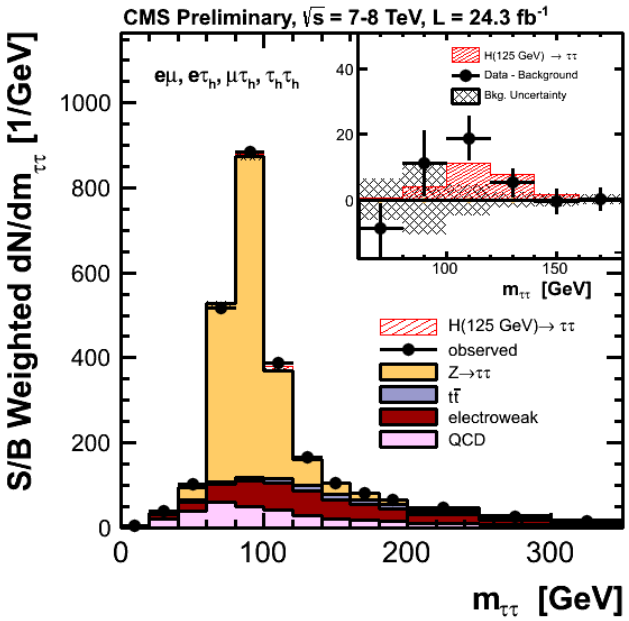


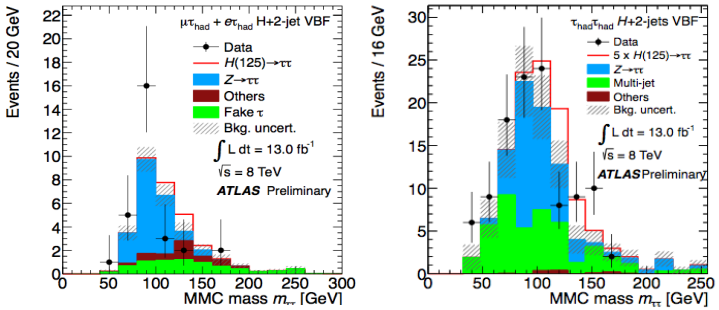


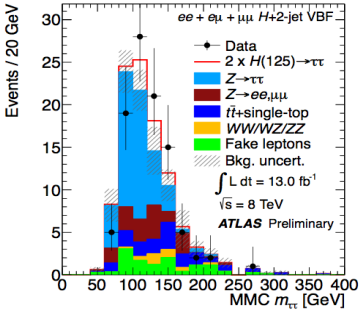
- Analysis strategy:
  - two prompt high-p_T leptons
  - MET
  - split events into ee, μμ, eμ channels:
    - different S/B rates: Drell-Yan in ee/μμ !
  - split events further into 0/1-jet:
    - different S/B rates: ttbar in 1-jet !
  - **ATLAS: m_T-distribution**
  - **CMS:**
    - Different-flavor: **2D distribution N(m_{ll},m_T)**
    - Same-flavor dileptons: **cut-based analysis**
  - Backgrounds (for low mass Higgs):
    - WW, tt, W+jets, DY+jets, Wγ: from control regions
    - ZW, ZZ: from MC (very small contribution)

- Analysis features to note (m_H=125):
  - Fair S/B
  - Fair signal event yield (200 events)
  - Poor mass resolution ≈20%

$H \rightarrow \tau^{+}\tau^{-}$







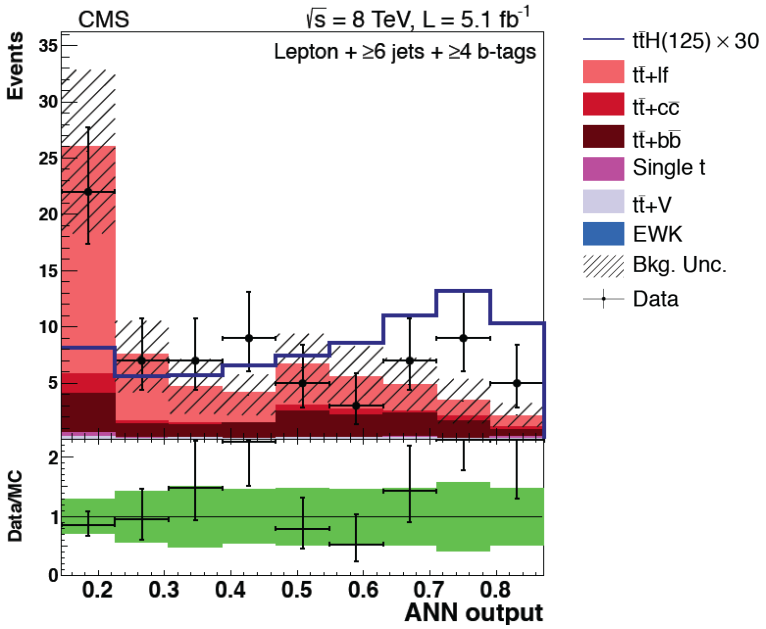
Analysis strategy:

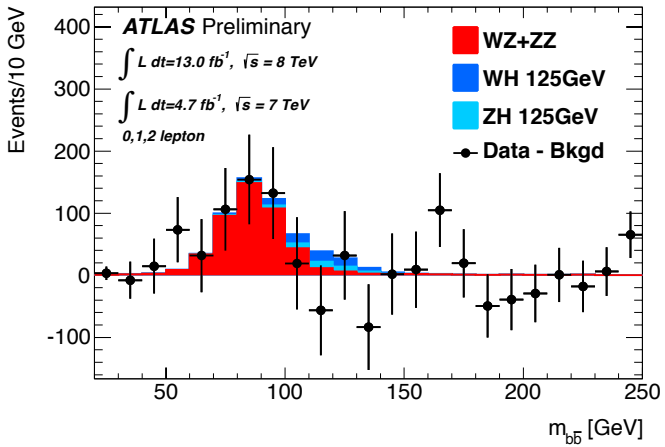
- di-tau candidates: $e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- MET
- **DiTau mass (including MET)**: key distribution split events into jet categories:
  - **2-jets (VBF-tag)**: best S/B-ratio
  - **2-jets (VH-tag)**: best S/B-ratio
  - **VH Lepton tag**
  - **1-jet (ggF, VH)**: acceptable S/B-ratio
  - untagged: control region (S/B≅0)
- Split 1-jet events further high/low p_T tau
  - different S/B rates
- Backgrounds:
  - Z→ττ: Z→μμ (data) with embedding
  - Z→ee, W+jets, ttbar: MC for shapes, data for normalization
  - QCD: from control regions

Key Analysis features:

- poor S/B-ratio
- small signal event yield
- Higgs is on falling slope of Z-decays
- poor mass resolution ≈15%

$VH \rightarrow Vbb$





Analysis strategy:

- Channels separated in 0 (MET), 1 (MET) and 2 leptons
- With two b-tagged jets (using 0 and 1 for control)
- Further categorize in pT of the V
- Mass reconstruction is Key
- Simulation ISR and gluon splitting is also Key
- Diboson reconstruction also important element

- Main Backgrounds:
  - V+bb and top
  - Uses mainly control regions except

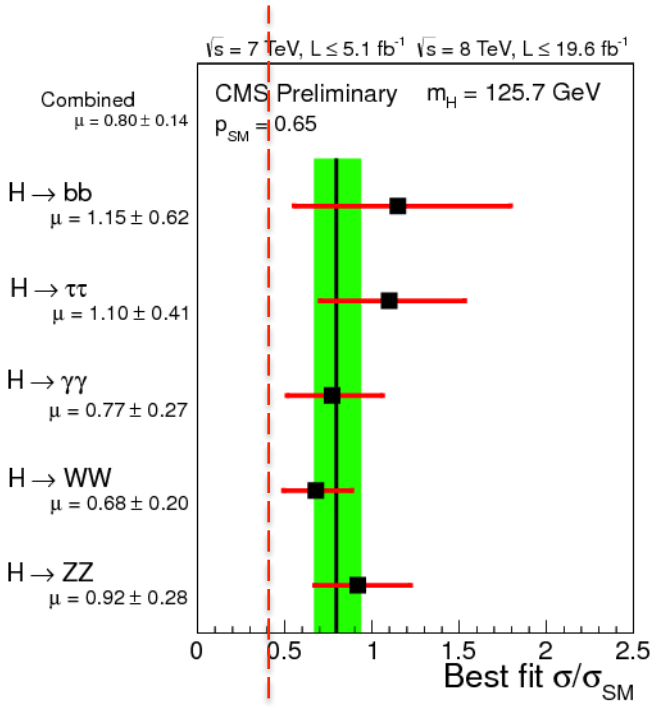
Key Analysis features:

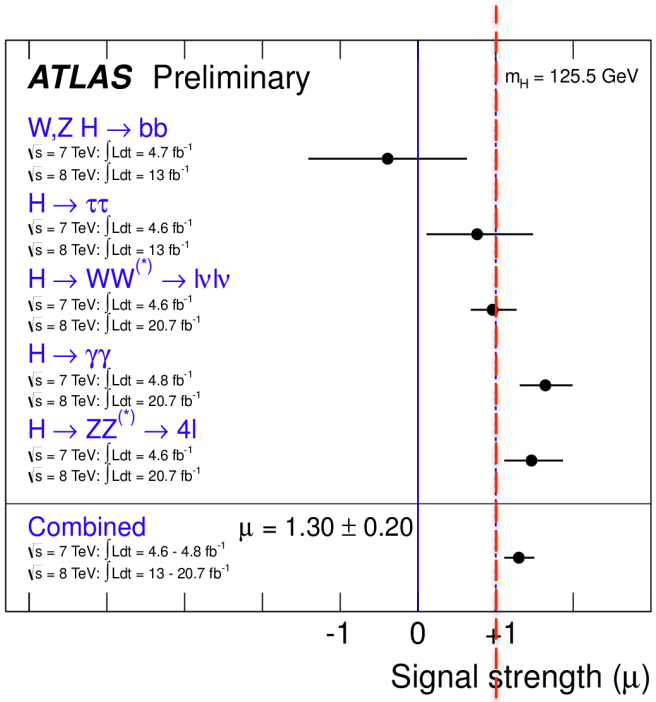
- Rather low S/B-ratio
- small signal event yield
- Higgs is on falling slope of Z-decays
- poor mass resolution ≈15%

H_{125} Summary

H^0 DECAY MODES

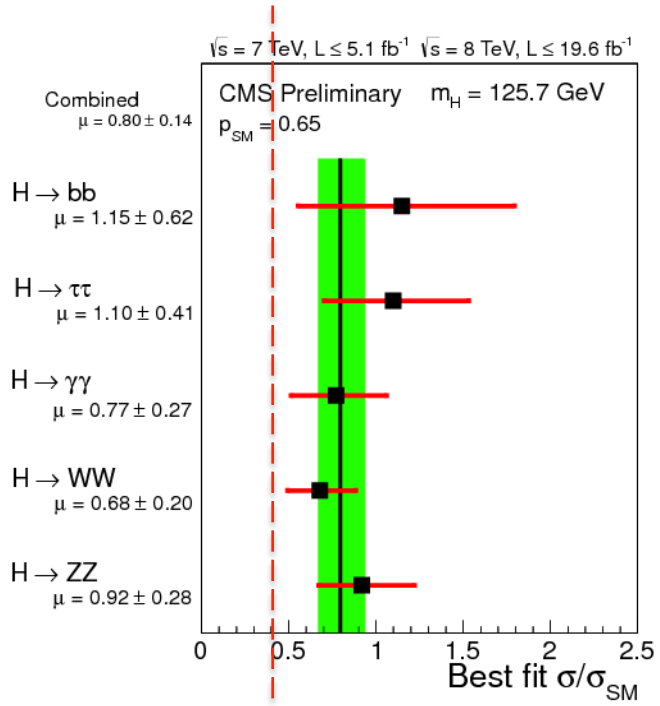
	Mode	Fraction (Γ_i/Γ)
Γ_1	W^+W^-	seen
Γ_2	ZZ^*	seen
Γ_3	$\gamma\gamma$	seen
Γ_4	$b\bar{b}$	possibly seen
Γ_5	$\tau^+\tau^-$	possibly seen

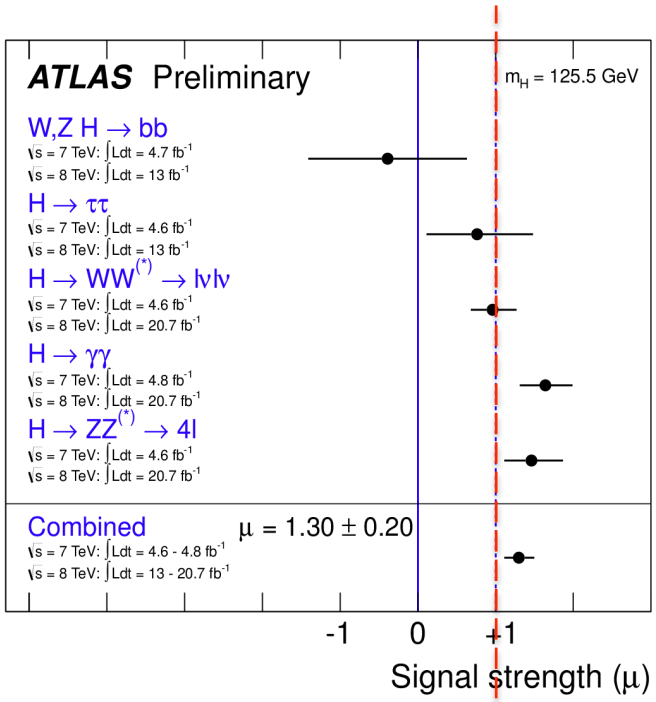




H_{125} Summary

Channel categories	ATLAS				CMS			
	μ (at 125.5 GeV)	Z exp	Z obs	M (GeV)	μ	Z exp	Z obs	M (GeV)
γγ	1.6±0.3	4.1	7.4	126.8±0.2±0.7	0.8±0.3	3.9	6.7	125.4±0.5±0.4
ZZ (llll)	1.5±0.4	4.4	6.6	124.3±0.5±0.5	0.9±0.3	7.1	3.2	125.8±0.5±0.2
WW (lnln)	1.0±0.3	3.8	3.8	-		5.3	3.9	-
ττ	0.8±0.7	1.6	1.1	-	1.1±0.4	2.6	2.8	$125\ ^{+9}_{-7}$
W,Z H (bb)	-0.4±1.0	1.0	0.0	-		2.1	2.1	-
Combination	1.30±0.20	7.3	10	125.5±0.2±0.6	0.80±0.14	-	-	125.7±0.3±0.3





Main Quantum Numbers J^{PC}

A large number of options to probe the spin directly from angular (or threshold behavior) distributions.

- From the associated production modes (VH, VBF or ggF+jets)
- From the production angle cos θ^* distribution
- From the decay angles and the spin correlation when applicable

The philosophy of the LHC approach

- Measure the compatibility with the 0^+ hypothesis in specific framework
- Probe alternative hypotheses simulated using an effective Lagrangian including higher order couplings.

Overview of Spin and Parity Results

J^P CL_S	ATLAS				CMS		
	$ZZ^*(4l)$	$\gamma\gamma$	$WW^*(lvlv)$	Combination	$ZZ^*(4l)$	WW^*	Comb.
0^-	2.2%	-	-	-	0.16%		0.16%
0^-_h	-	-	-	-	8.1%		8.1%
1^-	6.0%	-	-	-			
1^+	0.2%	-	-	-			
2^+_m (gg)	16.9%	0.7%	5%	<0.1%	1.5%	14%	0.5%
2^+_m (qq)	<0.1%	2%	1%	<0.1%	<0.1%		<0.1%
2^-	<0.1%	-	-	-	<0.1%		<0.1%

- Also discussion of f_{CP} results (CMS only for the time being)
- What is the right level of detail necessary here?
- Typically important input from TH to explain the already clear indication from the rates.
- Should include the VH(bb) threshold analysis of TeVatron?

Coupling Properties Analyses

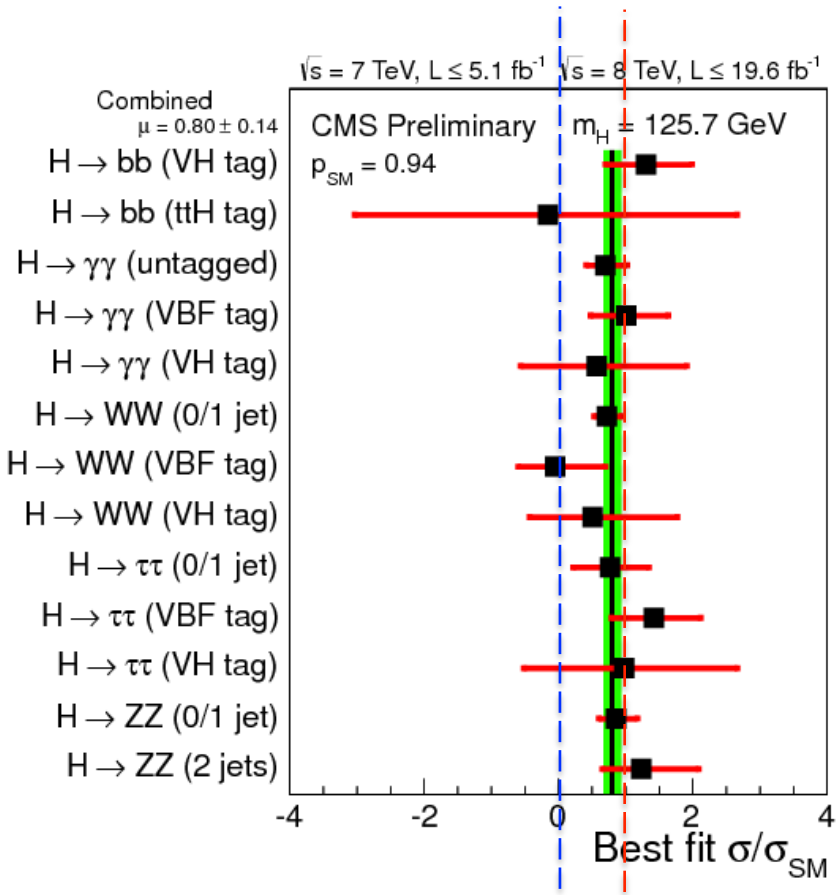
Channel categories	ATLAS				CMS				TeVatron	
	ggF	VBF	VH	ttH	ggF	VBF	VH	ttH	VH	ggF
γγ	✓	✓	✓		✓	✓	✓	✓	(inclusive) ✓	
ZZ (llll)	✓	✓			✓	✓			✓	
WW (lνlν)	✓	✓	✓		✓	✓	✓		✓	✓
ττ	✓	✓	✓		✓	✓	✓		✓	
H (bb)			✓	✓		✓	✓	✓	✓	
Zγ	(inclusive) ✓				✓					
μμ	(inclusive) ✓									
Invisible			✓							

- Long standing question: what about ATLAS and CMS combination?
- New channels will soon be included
- Qualitative interpretation(s) between indirect constraints and direct searches
  - Fermiophobic Higgs
  - SM4
  - Invisible decays

Information Format

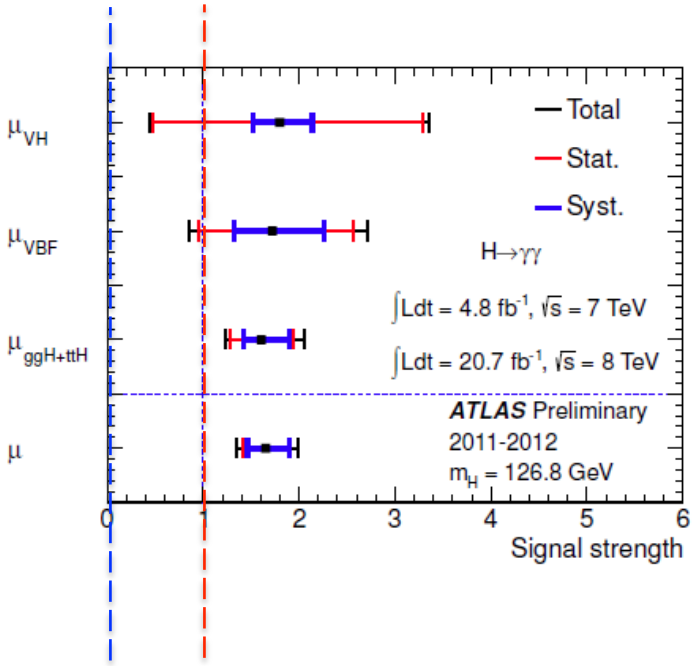
$$n_s^c = \left(\sum_{i \in \{ggF, VBF, VH, ttH\}} \mu^i \sigma_{SM}^i \times \mathrm{A}^{ic} \times \varepsilon^{ic} \right) \times \mu^f Br^f \times L^c$$

Sub-channel signal strengths



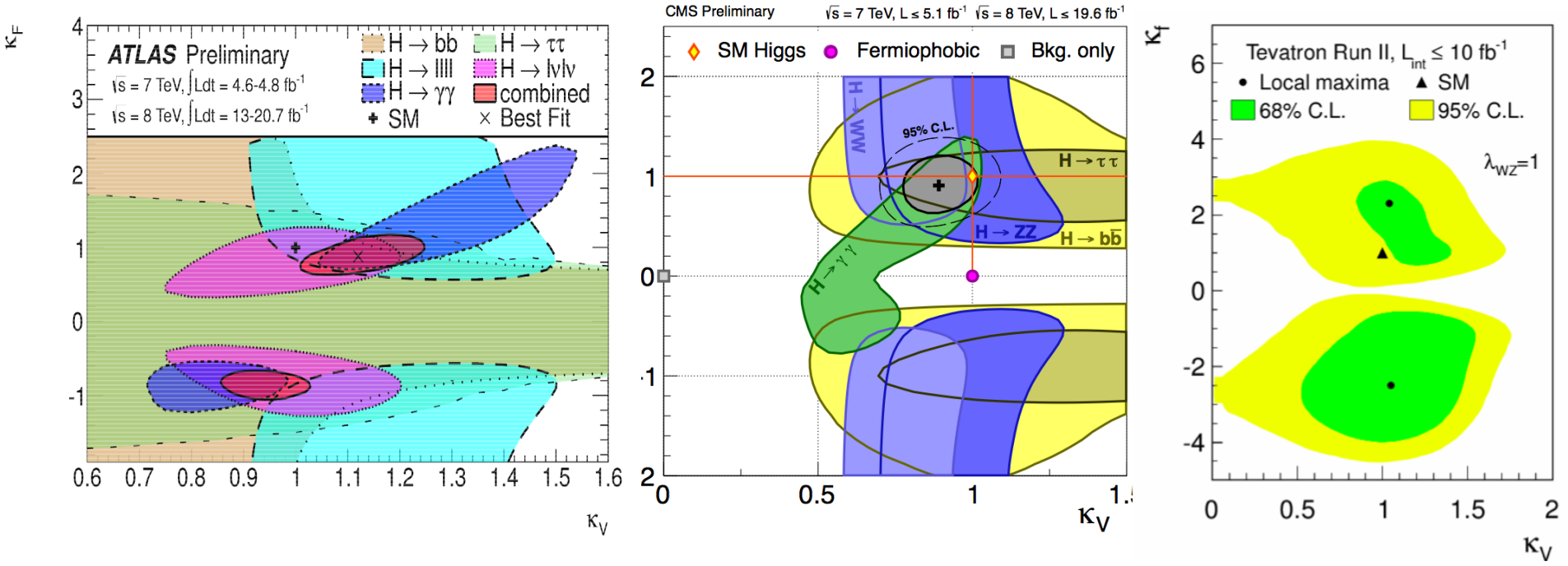
μ=0 μ=1

Production mode signal strengths (per channel)



μ=0 μ=1

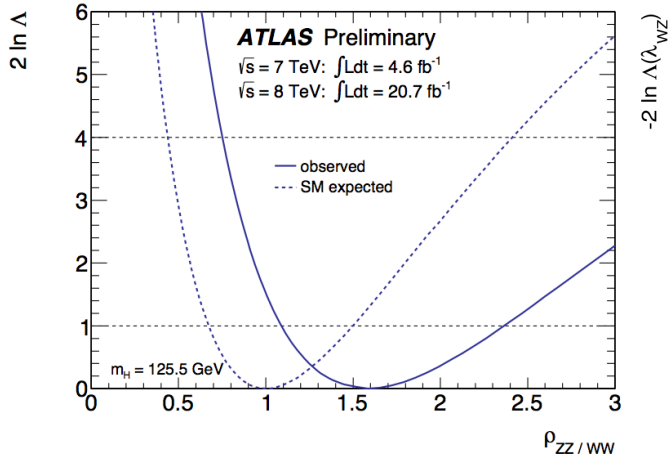
Main results I : Probing the coupling to SM particles

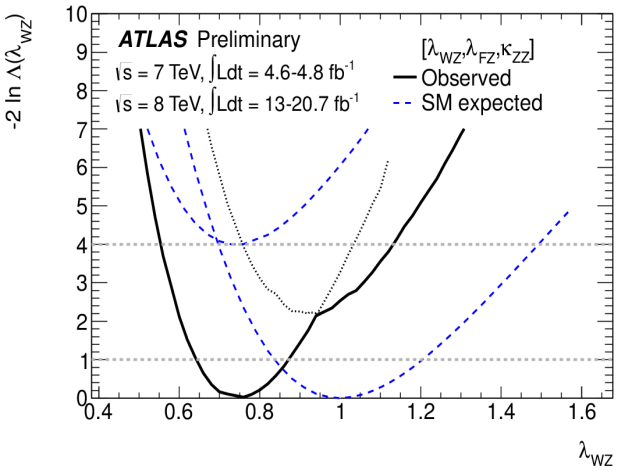


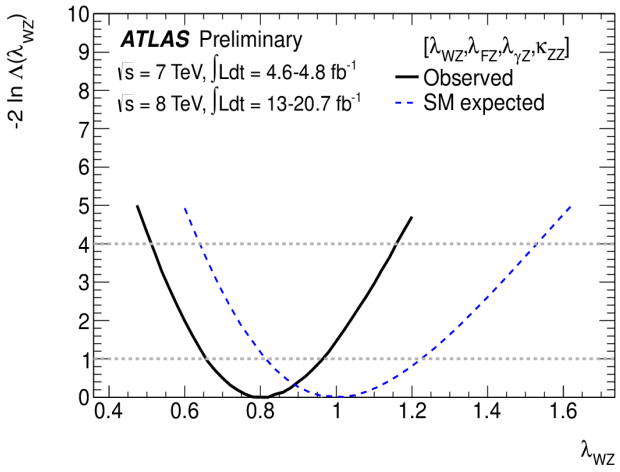
- Clarity: nice to have same style plots (delicate discussion with collaborations)

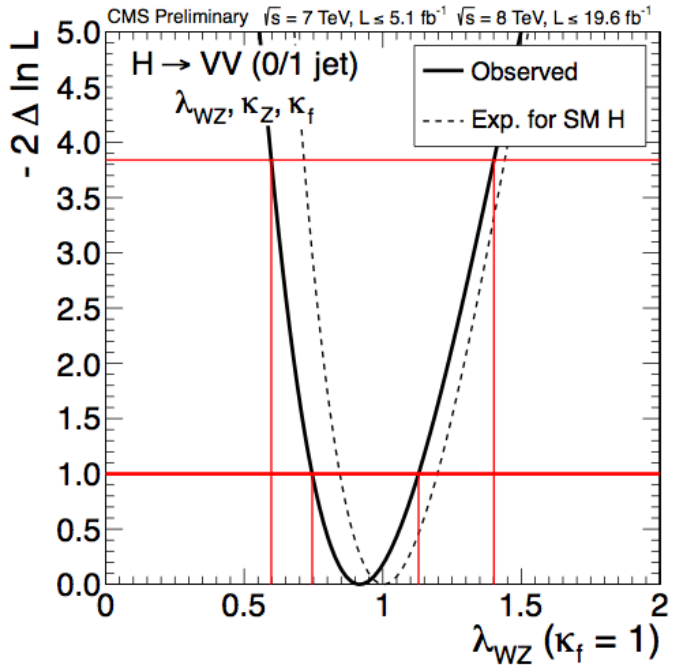
- Should MCHM4-5 be illustrated in this plot(s)?

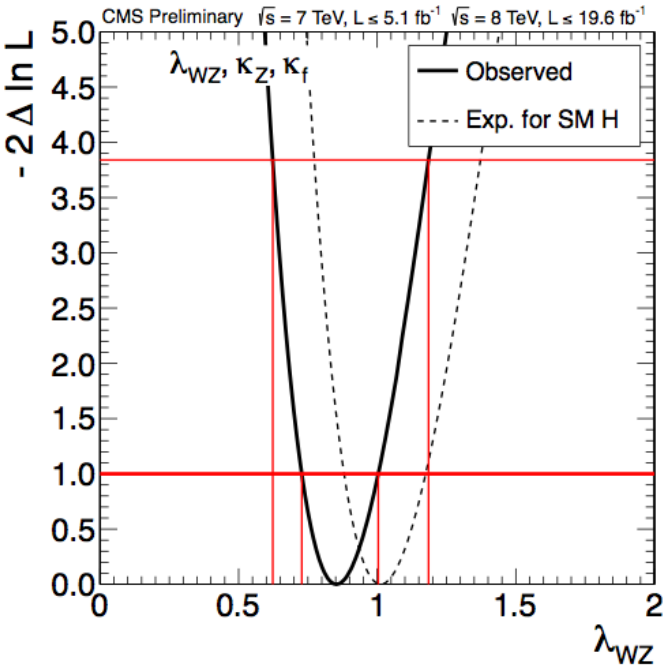
Main results II : Probing the W to Z ratio (custodial symmetry)





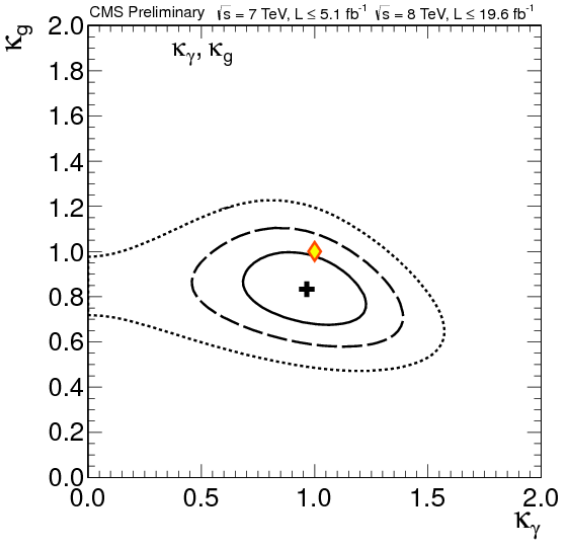


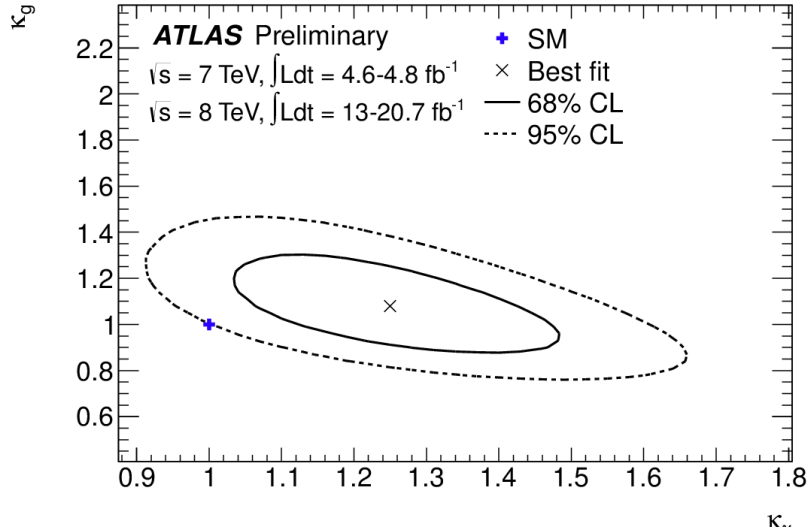


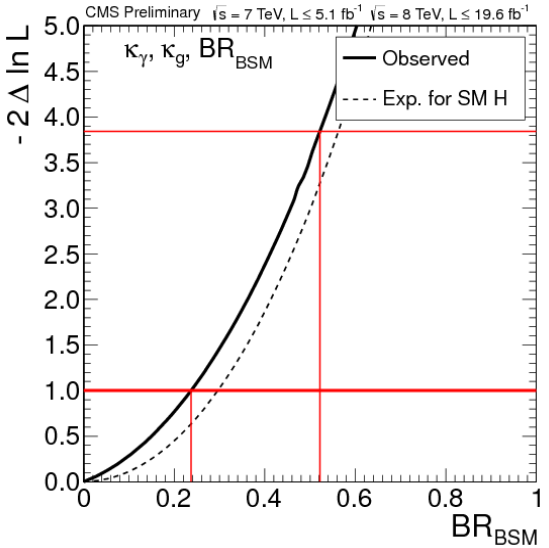


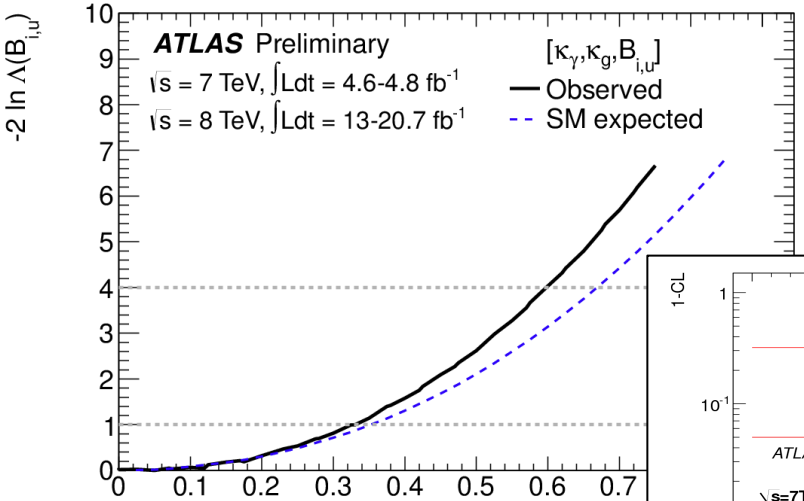
Main results III : Probing physics beyond the Standard Model

(In the decays and/or in the loops)

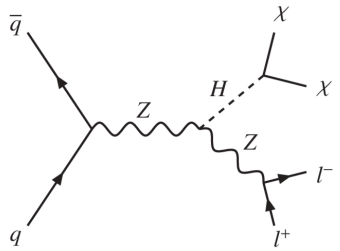


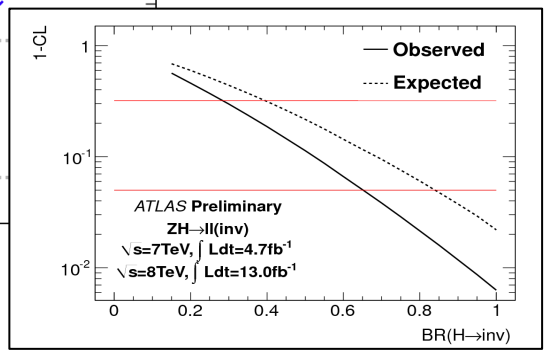






Also direct invisible only search

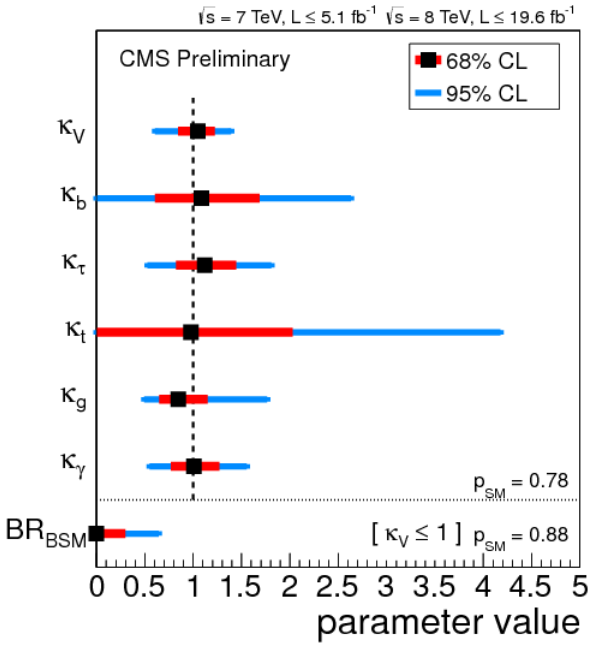


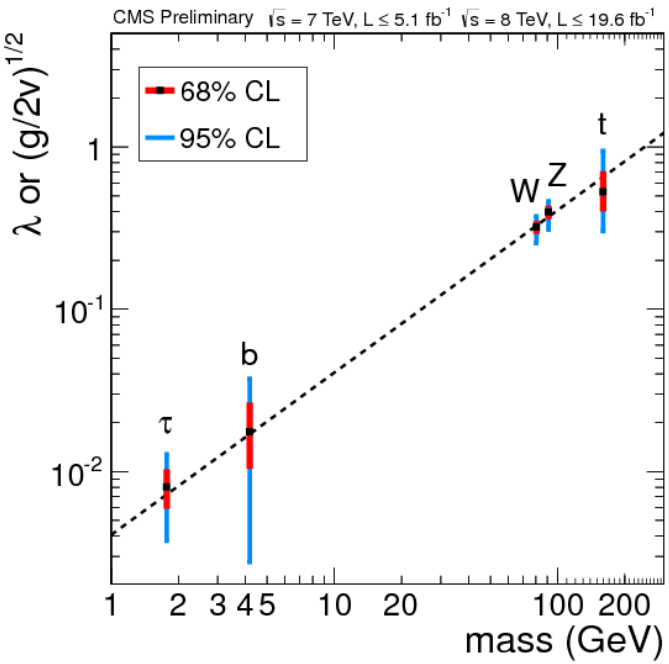


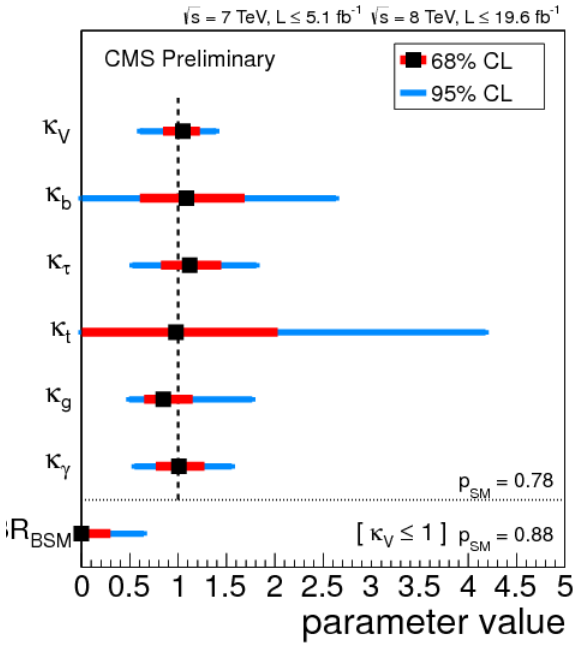
Main results III : Evidence for VBF production

Should the implications of such a measurement be discussed?

Main results IV : Other Relevant Models





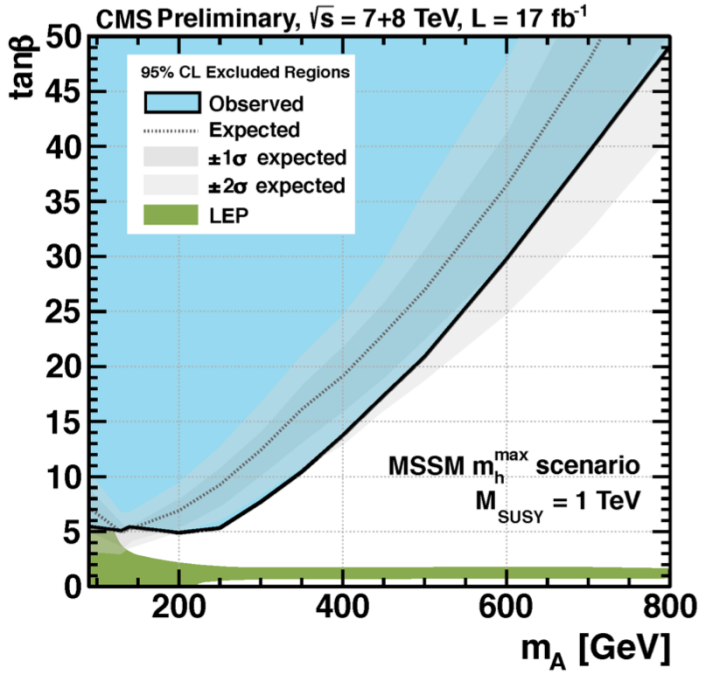


- Illustrating the mass dependence (also Ellis and You *vev* and critical coef.)
- 3 coupling strength parameter fits κu, κd and κV for MSSM limits

Overview of BSM Current Channels at (mostly) LHC (I)

- Interpretation of the observed H_{125} state

- Charged Higgs in the following channels:
  - Main current analysis $H^{\pm}$ to tn
  - $H^{\pm}$ to cs
  - High mass specific $H^{\pm}$ to AW
  - High mass specific $H^{\pm}$ to tb

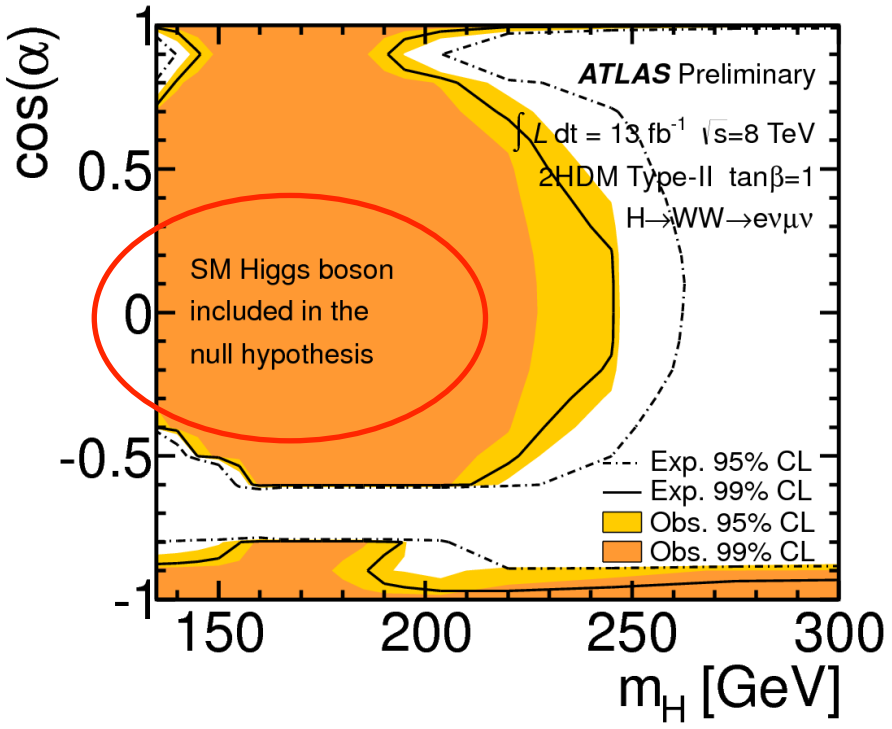


- MSSM h, H, and A
  - Main current analysis tt
  - Also searched for in mm
  - Also searched for in bb(b)
  - New open channel in the intermediate-high mass: hh

- NMSSM a
  - Main search at LHC μμ
  - Exotic cascades h to aa to four photons (ATLAS), or four taus (ALEPH)

Overview of BSM Current Channels at (mostly) LHC (II)

- Singlet interpretation with unitarity constraint (High mass analyses)
  - ZZ to llnn channel (most powerfull, overlap with invisible search)
  - ZZ to llqq channel (potentially interesting lower mass reach)
  - ZZ to llll: Interesting to fit all h and H simultaneously
  - WW to lvlv can also fit h and H simultaneously
  - WW to lvqq high mass only
  - γγ
- 2HDM Interpretation
  - ZZ to llll simultaneous fit
  - WW to lnln simultaneous fit
  - γγ simultaneous fit
  - With all the above
- Doubly charged Higgs specifc triplet models



Other Higgs Programs

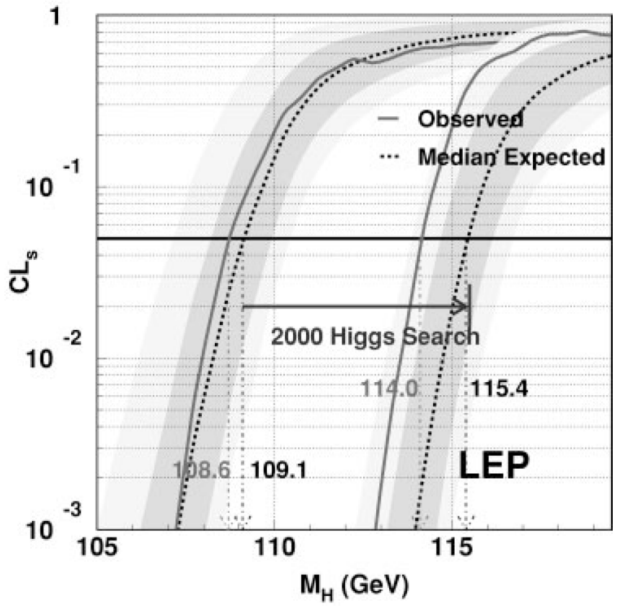
- LEP limits m_H > 114 GeV covering down to 32 MEV

- In general reinterpretation of low mass searches

- PreLEP era
  - Absence of Higgs related effects in Nuclear Physics, neutron stars and neutron scattering experiments m_H>20 MeV
  - Kaon abd B-Meson decays limits m_H>5 GeV

- LHCb
  - Standard Model H in bb
  - Higgs decays to long lived partices
  - (MSSM) Higgs to $\tau\tau$

- BaBar and Belle search for NMSSM a



Prospects

- Short Term at LHC
  - Analysis at 13-14 TeV (e.g. Boosted, analyses in high PU environment)
  - The diffractive program
- Long Term HL-LHC
- Long Term Higgs factory (e^+e^- collider)
  - Linear (energy?)
  - Circular (a priori limited to tt threshold)
- Long Term (V)HE-LHC
- VL Term muon collider

Statistics

From PDG (Glen's Review of Statistics)

Here Φ is the cumulative distribution of the Standard Gaussian, and Φ^{-1} is its inverse (quantile) function. Often in HEP, the level of significance where an effect is said to qualify as a discovery is $Z = 5$, *i.e.*, a 5σ effect, corresponding to a p-value of 2.87×10^{-7}. One's actual degree of belief that a new process is present, however, will depend in general on other factors as well, such as the plausibility of the new signal hypothesis and the degree to which it can describe the data, one's confidence in the model that led to the observed p-value, and possible corrections for multiple observations out of which one focuses on the smallest p-value obtained (the "look-elsewhere effect"). For a review of how to incorporate systematic uncertainties into p-values see, *e.g.*, Ref. 17; a computationally fast method that provides an approximate correction for the look-elsewhere effect is described in Ref. 18.

New Paradigm in measurements: Profiling

$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})}$$

Systematic uncertainties are (typically) treated statistically