The Higgs Particle

CERN Academic Training

Lecture II

An (Early) Experimental Profile of the Higgs Boson

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and CERN

Outline

I.- The roadmap to the discovery (Lecture I)

From theoretical foundations to the discovery

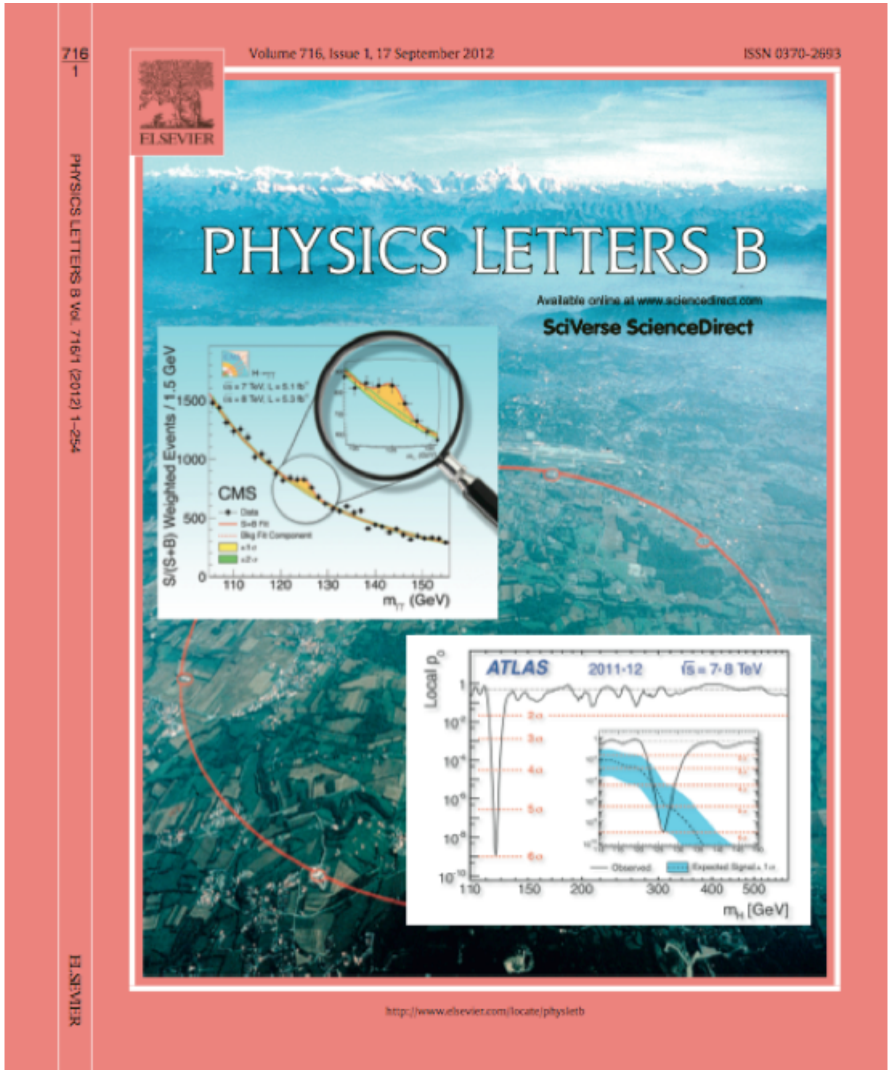
II.- An (early) experimental profile of the Higgs boson (Lecture II)

1.- Comments on Statistical Methods (Part II)
2.- Overview of the analyses
3.- Measurements of coupling properties of the Higgs boson
4.- Measurement of spin/CP properties of the discovered state

III.- Implications and future projects (Lecture III)

- Rare and invisible decays
- Implications of the discovered state
- Search for BSM Higgs and extended sectors
- Future Higgs programs

Picking up where we left yesterday…



- Discovery of a narrow bosonic Higgs-like resonance
- Compatible in all investigated aspects with the Higgs boson of the Standard Model
- Today: How the « Like » was removed… and…

… in 2013 Entrance of the H^0 in the PDG!

Higgs Bosons — H^0 and $H^\pm$

A REVIEW GOES HERE – Check our WWW List of Reviews

NODE=S055
NODE=S055

CONTENTS:

NODE=S055CNT
NODE=S055CNT

NODE=S055CNT

H^0 (Higgs Boson)

NODE=S055210

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

NODE=S055210

H^0 MASS

NODE=S055HBM
NODE=S055HBM

VALUE (GeV)	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	OCCUR=2
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. NODE=S055HBM;LINKAGE=CA

[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. NODE=S055HBM;LINKAGE=AA

[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. NODE=S055HBM;LINKAGE=CT

[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. NODE=S055HBM;LINKAGE=CH

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

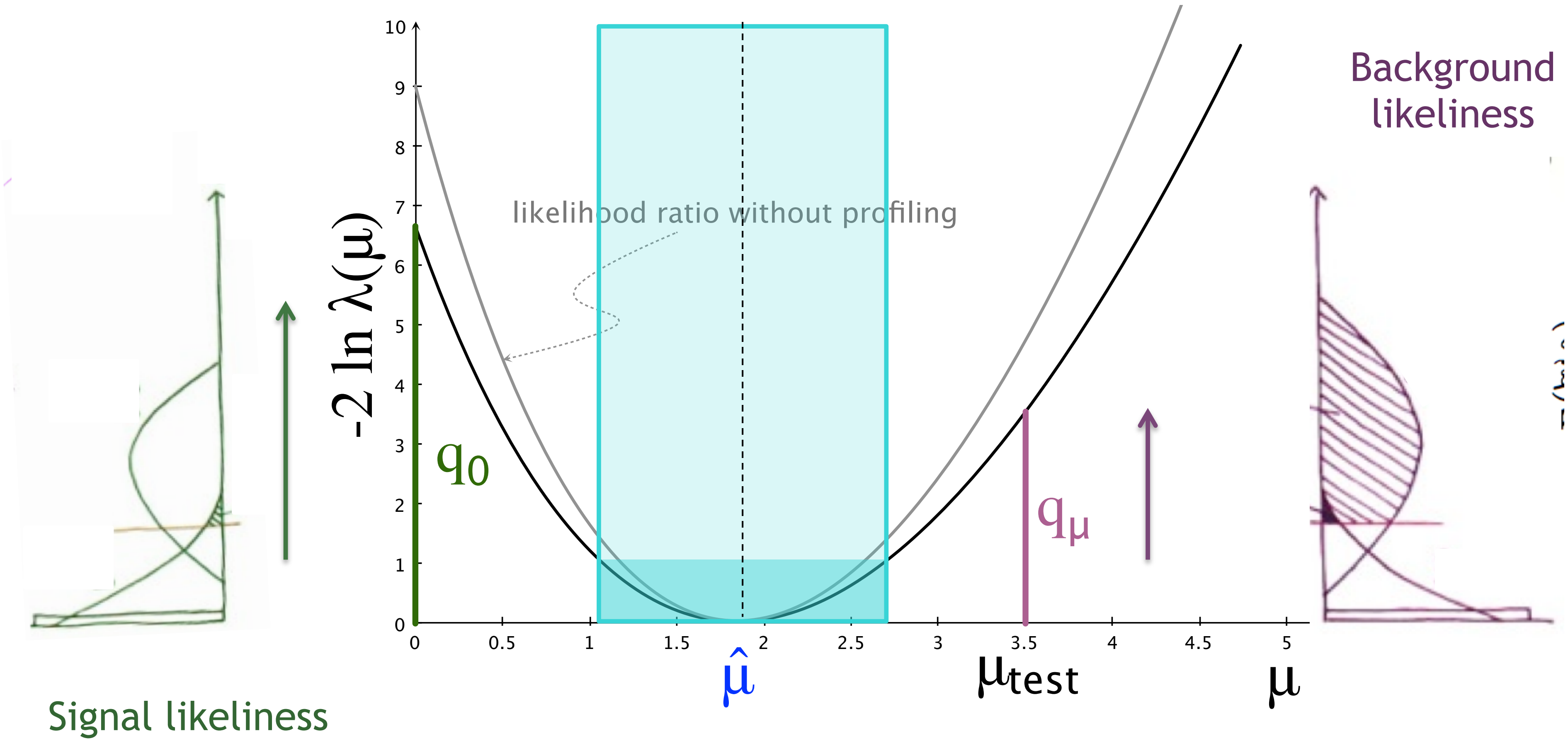
(not anymore as an hypothetical particle)

$$H^0$$

Comment on Statistical Methods
(Part II)

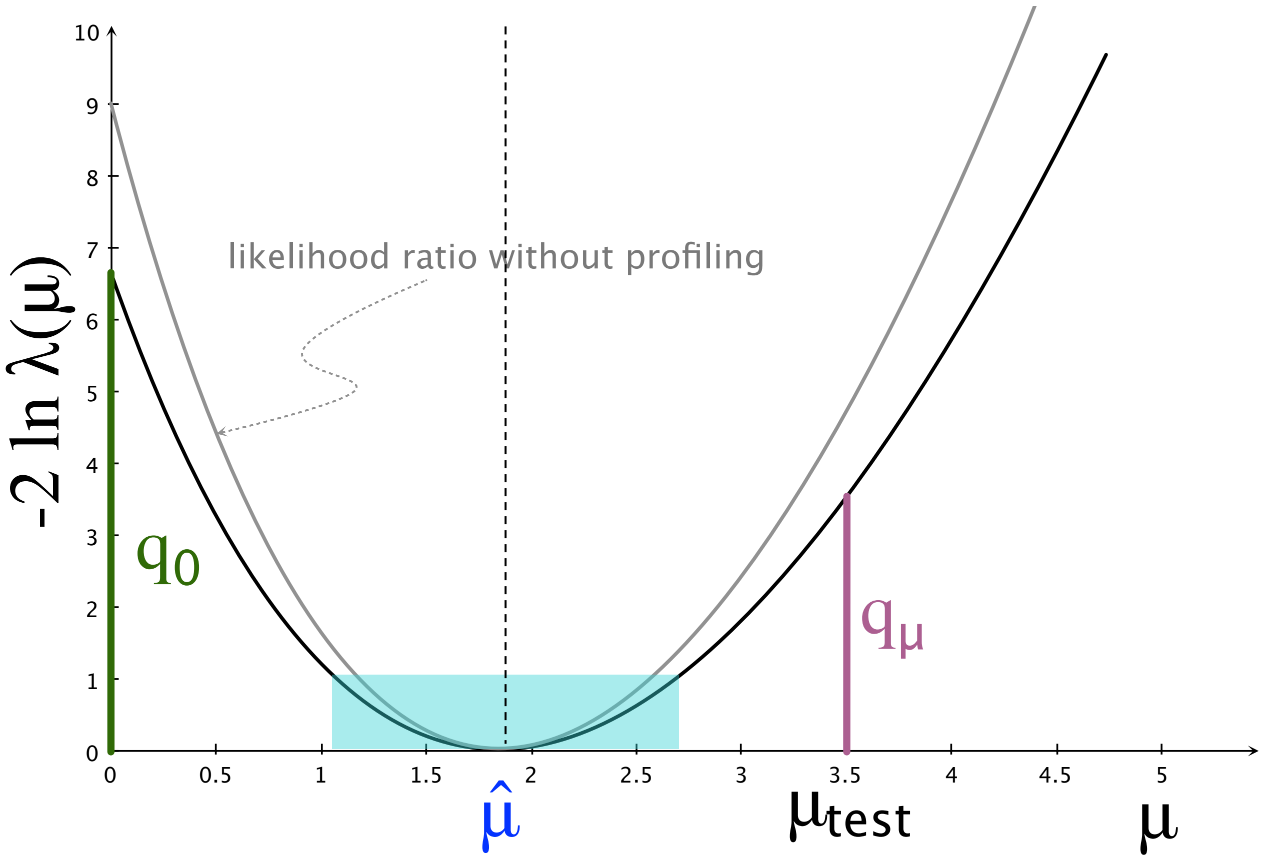
The Profiling Paradigm

$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad q_\mu = -2\ln\lambda_\mu$$



The Profiling Paradigm

$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad n_s = \mu\sigma B r L \varepsilon$$

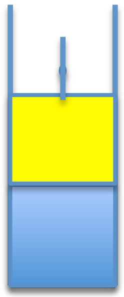


Simple Example

N

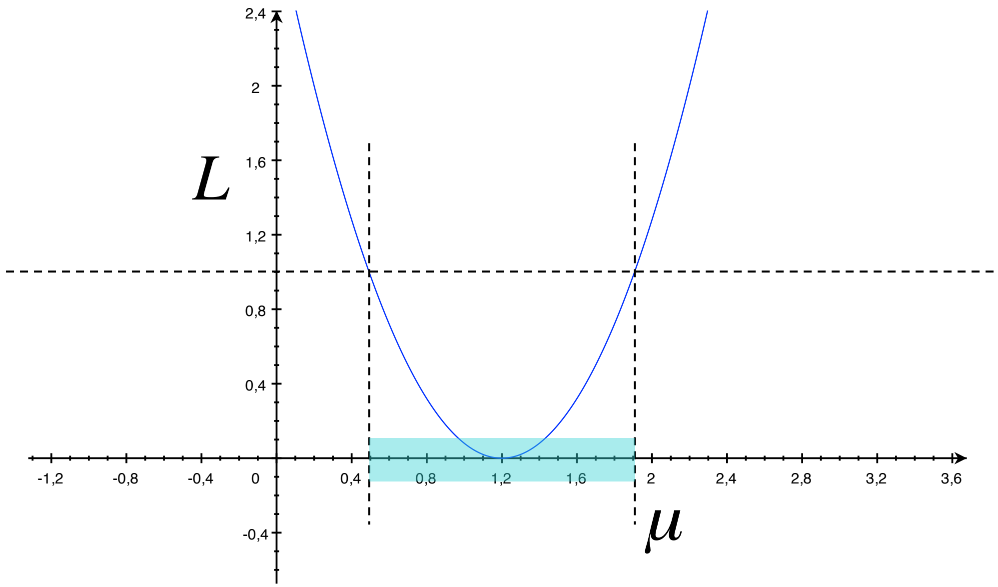
$n_s = \mu s$

n_b



SR

$$L(\mu) = \frac{(\mu s + n_b)^N}{N!} e^{-(\mu s + n_b)}$$

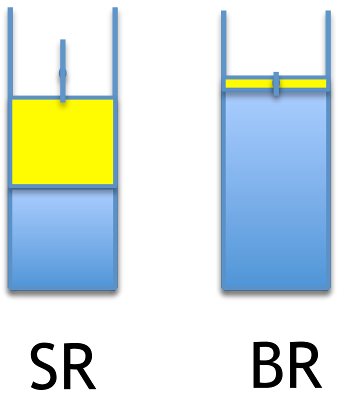


Simple example with control region

N^{SR}

$n_s = \mu s$

$n_b^{SR} = \alpha n_b^{CR}$

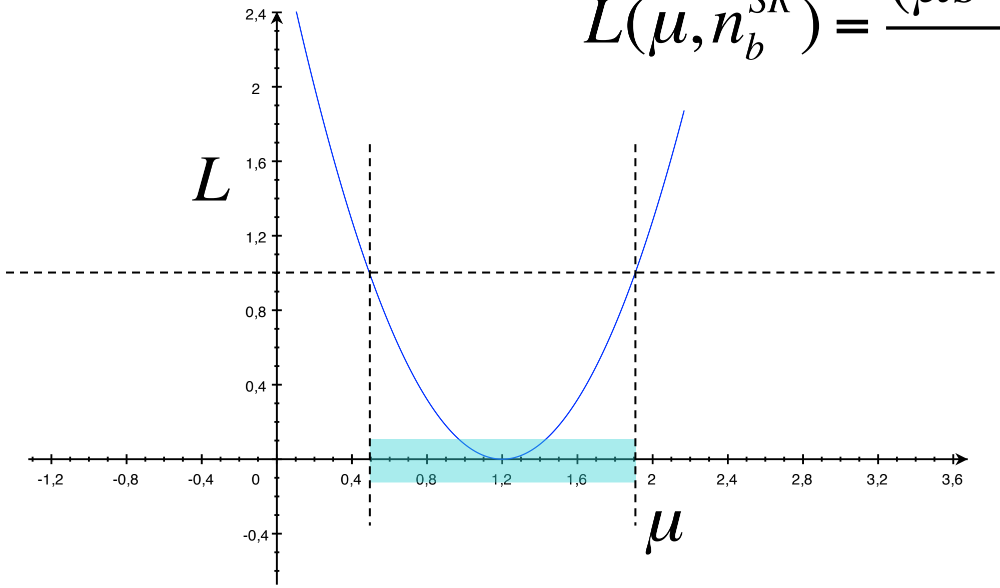


N^{CR}

$n_s \sim 0$

n_b^{CR}

$$L(\mu, n_b^{SR}) = \frac{(\mu s + \alpha n_b^{CR})^{N^{SR}}}{N^{SR}\,!} e^{-(\mu s + \alpha n_b)} \times \frac{(n_b^{CR})}{N^{CR}\,!} e^{-(n_b^{CR})}$$



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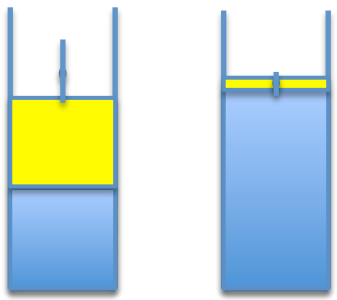

SR BR

N^{CR}

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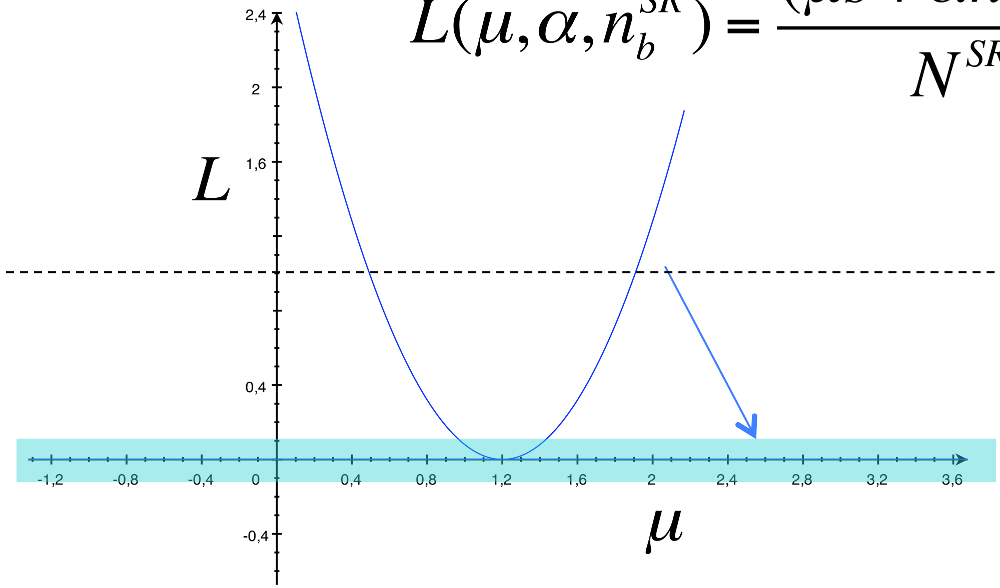

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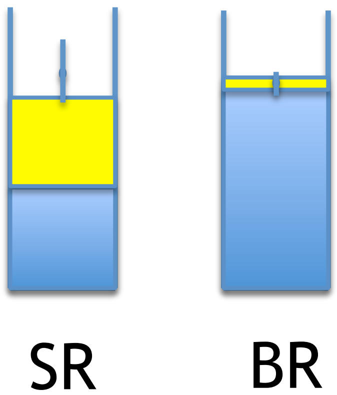

N^{CR}

$n_s \sim 0$

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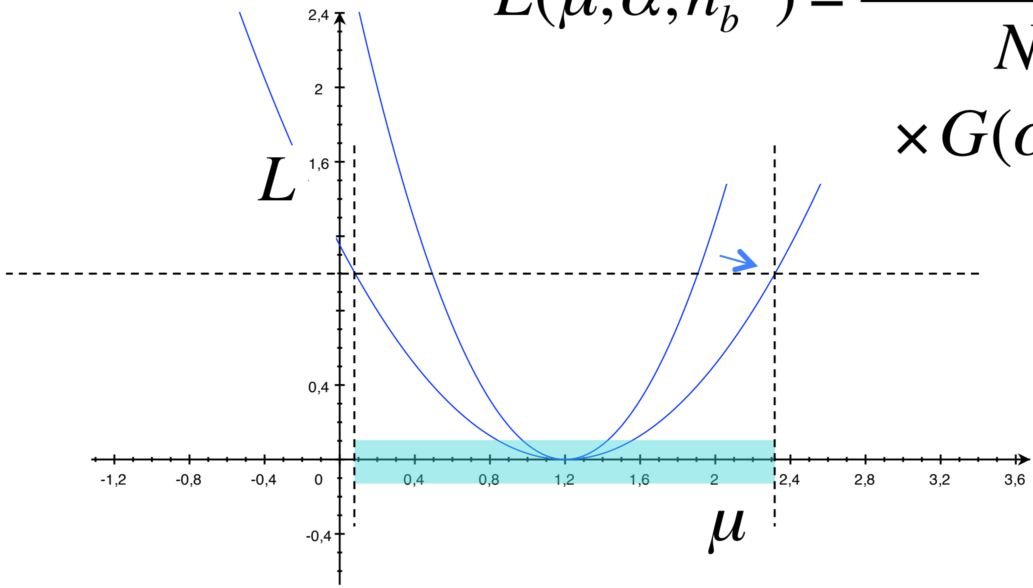
$$L(\mu,\alpha,n_b^{SR}) = \frac{(\mu s + \alpha n_b^{CR})^{N^{SR}}}{N^{SR}!} e^{-(\mu s + \alpha n_b)} \times \frac{(n_b^{CR})^{N^{CR}}}{N^{CR}!} e^{-(n_b^{CR})}$$

$$\times G(\alpha \mid \alpha_0, \delta_0)$$



Simple example with control region

N^{SR}

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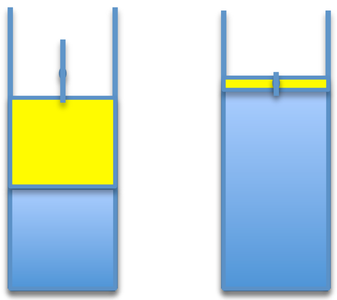


N^{CR}

$n_s \sim 0$

n_b^{CR}

$$n_b^{SR} = \sigma_{bSR} BrL\varepsilon$$

$$n_b^{CR} = \sigma_{bCR} BrL\varepsilon$$

$$L(\mu,\varepsilon,n_b^{SR}) = \frac{(\mu s + n_b^{SR}(\varepsilon))^{N^{SR}}}{N^{SR}!} e^{-(\mu s+\alpha n_b(\varepsilon))} \times \frac{(n_b^{CR}(\varepsilon))}{N^{CR}!} e^{-(n_b^{CR}(\varepsilon))}$$

$$\times G(\varepsilon \mid \varepsilon_0, \delta_0)$$

- Do we know that constraint term should be a Gaussian?
- Needs caution as in this case ε can change from its initial value and its post-fit variance can be smaller than δ_0 resulting from the data constraint
- Potentially dangerous (if not modeled correctly) when the parameter is correlated between background and signal

The Profiling Paradigm

- Allowed to take into account systematic uncertainties in our statistical methods (p_0 and limits).

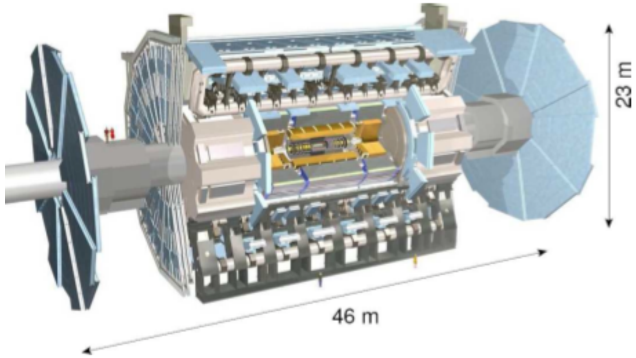
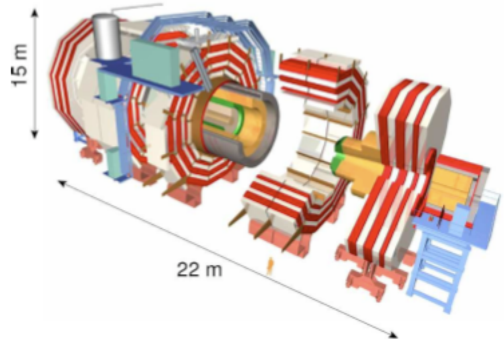
- It now serves as paradigm to model systematic uncertainties also in our measurements.

- Relies on modeling of prior probability of the systematic uncertainty (in many cases unknown).

- Often implies a re-measurement of model physical observable which should be handled with great care.

Overview of Main Current Analyses

Preamble I: The ATLAS and CMS Detectors In a Nutshell

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5\times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5\times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

Preamble II : Theoretical Breakthroughs

Several breakthroughs in the past decade have drastically changed the theory prospective to the hadron collider processes.

- The "Next-to…" revolution :
  - Breakthrough ideas in computation of loops (sewing together tree level amplitudes).
  - NLO generators, blackhat, NLOjet++, Phox, MCFM, etc…
  - NLO generators w/ PS, MC@NLO, aMC@NLO and POWHEG.
  - NLO+NLL or NNLL, CAESAR, ResBos, HqT
  - NNLO, FEHIP, FEWZ, HNNLO, DYNNLO
  - …
- NNLO PDFs sets
- Parton Shower (and Matrix Element matching) improvements :
  - Pythia (8.1), Herwig++, Sherpa and CKKW (1.3) and MadGraph (5.0)
  - MEPS@NLO, etc…
- The Jet revolution (Fast Jet) : Allowing to compute in reasonable time infra-red safe k_T jets.

Decay Modes

- Dominant decay mode b (57%)

Very large backgrounds, associated production W,Z H and Boost!

- The ττ channel (6.3%)

VBF, VH, but also ggF with new mass reconstruction techniques

- The γγ channel (0.2%)

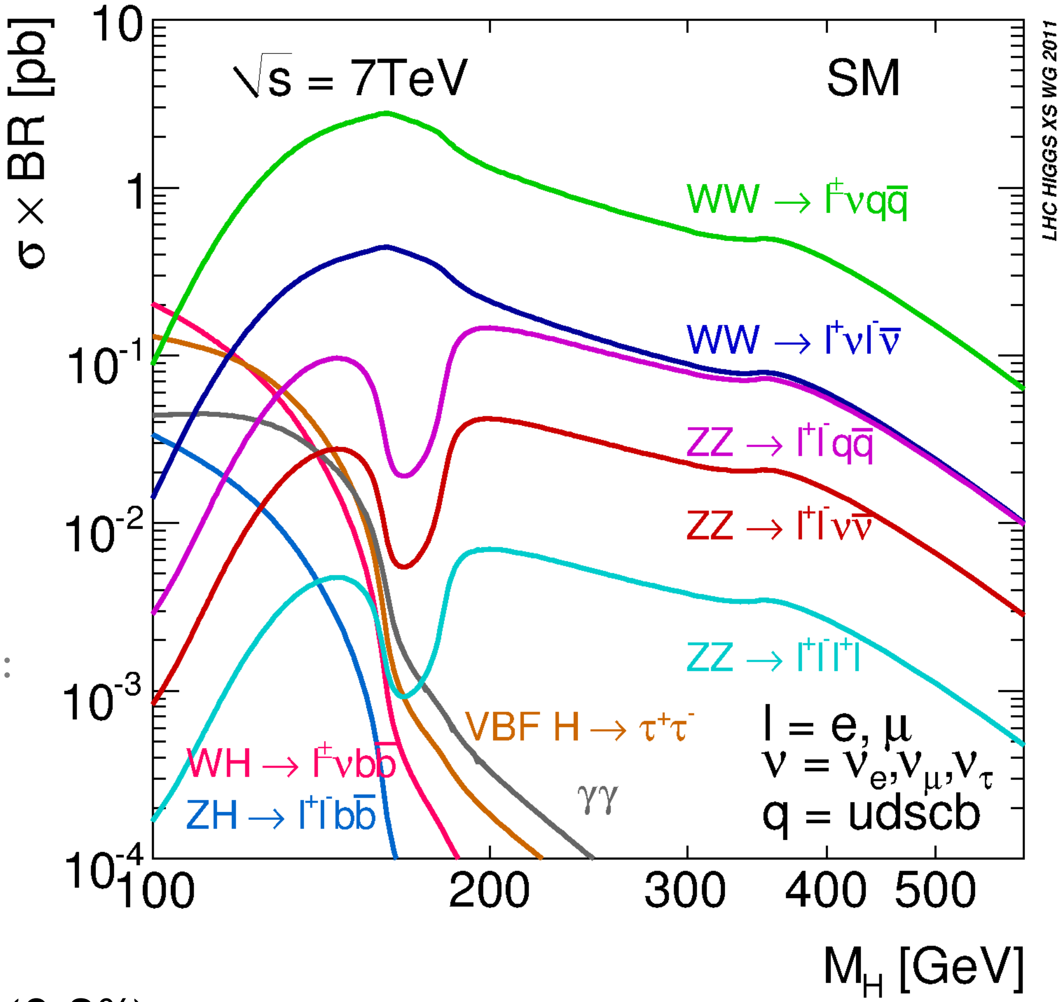
Discovery channel, high mass resolution (High stat, and backgrounds)

- The ZZ Channel (3%)

- Subsequent all leptons decays (low statistics): golden channel
- llqq and llvv sensitive mostly at high mass

- The WW Channel (22%)

- Subsequent lvlv very sensitive channel
- lvqq sensitive mostly at high mass



- The μμ channel (0.02%) and Zγ (0.2%)

Low statistics from the low branching in μμ or both the low branching and subsequent decay in leptons (Zγ)

- The cc channel (3%) Very difficult

Decay Modes

- Dominant decay mode b (57%)

Very large backgrounds, associated production W,Z H and Boost!

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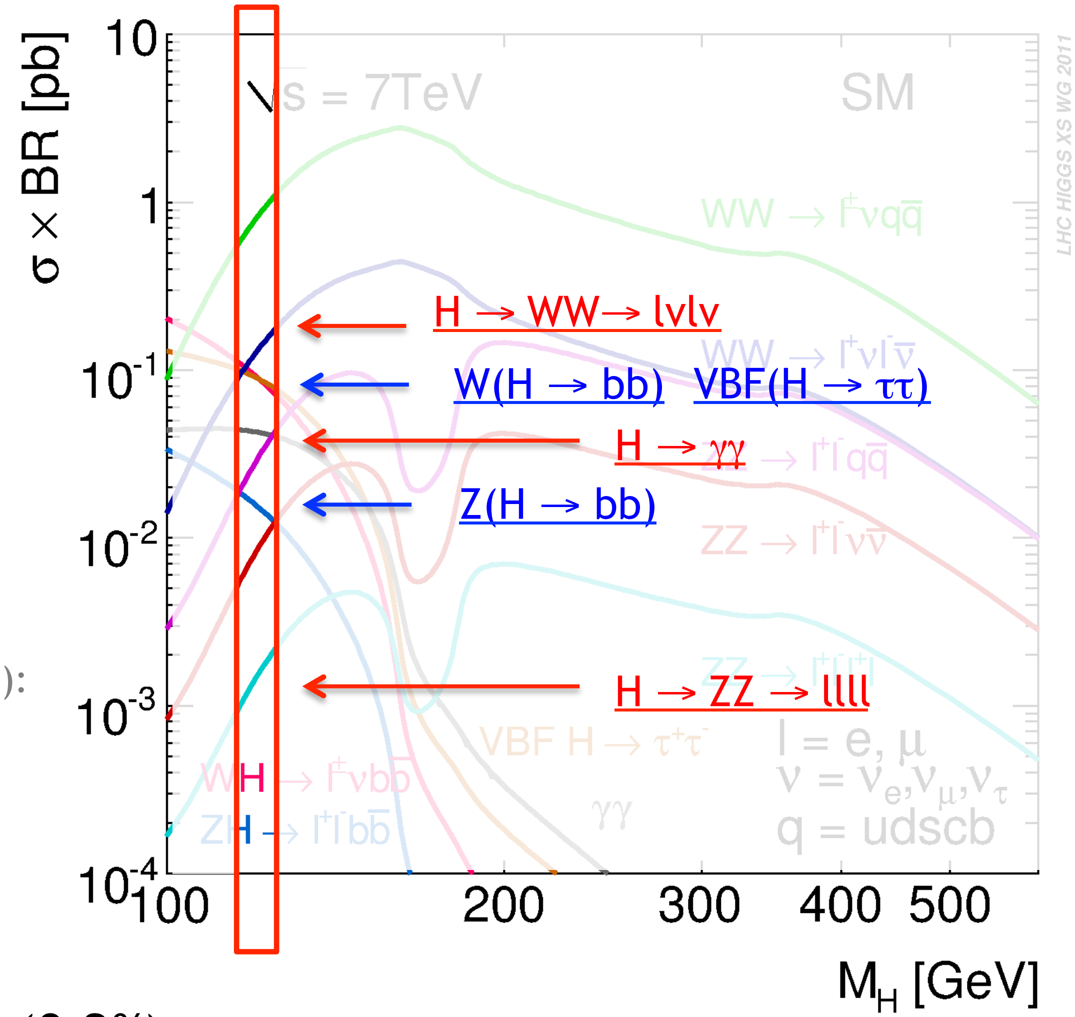

- The $\mu\mu$ channel (0.02%) and $Z\gamma$ (0.2%)

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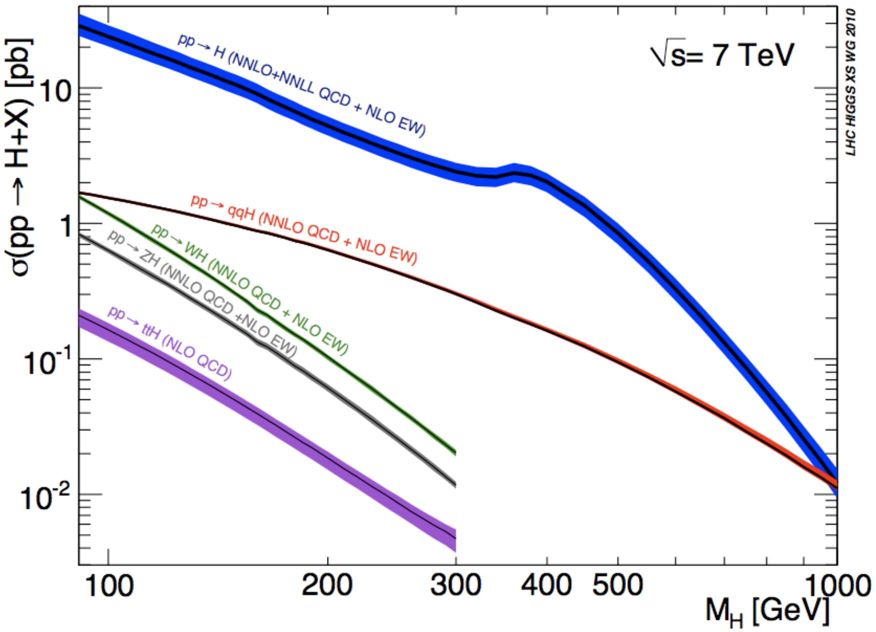
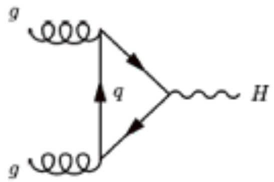
- The cc channel (3%) Very difficult

The Main Production Modes at the LHC

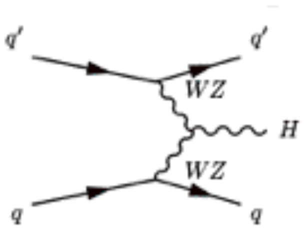




- Gluon fusion process :

Dominant process known at NNnLO TH uncertainty ~O(10%)

~0.5 M events produced!

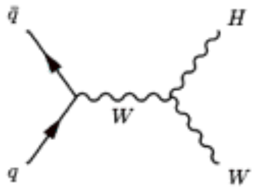


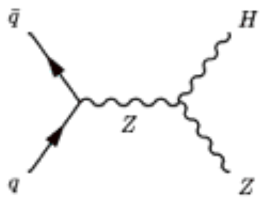
- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

Distinctive features with two forward jets and a large rapidity gap

~40 k events produced!



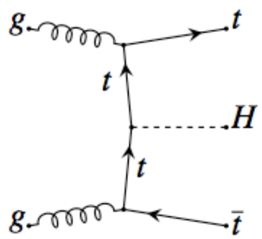


- W and Z Associated Production :

known at NNLO TH uncertainty ~O(5%)

Very distinctive feature with a Z or W decaying leptonically

~20 k events produced!



- Top Associated Production :

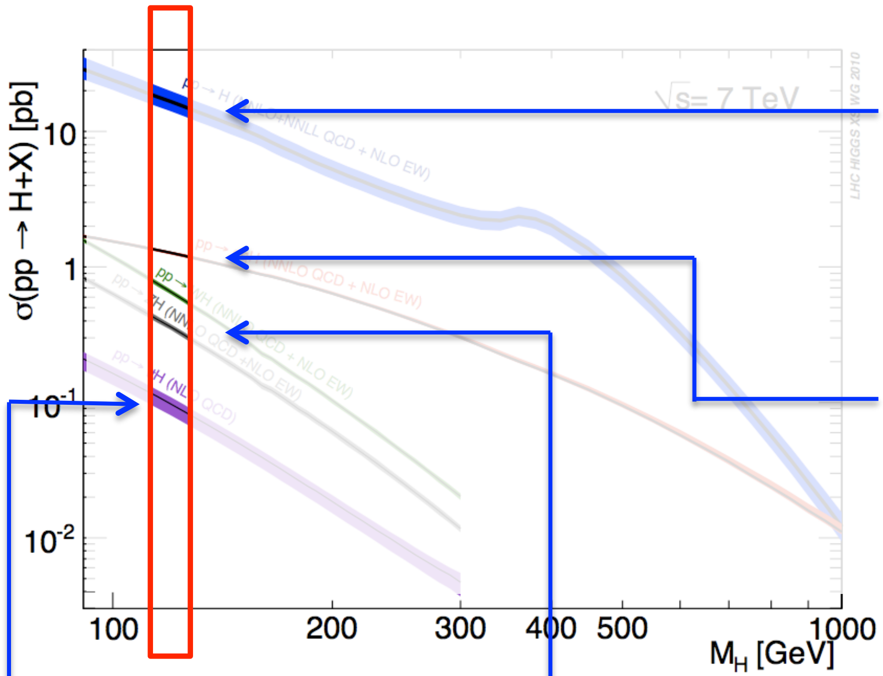
known at NLO TH uncertainty ~O(15%)

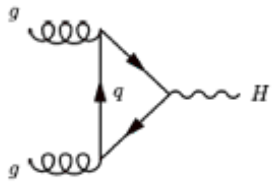
Quite distinctive but also quite crowded

~3 k events produced!

* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{PDF-\alpha s}$~8-10% and $\delta\sigma_{Scale}$~ 7-8%

The Main Production Modes at the LHC





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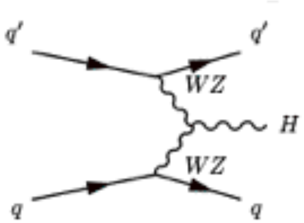
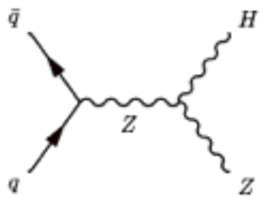


- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

Distinctive features with two forward jets and a large rapidity gap

~40 k events produced!



- W and Z Associated Production :

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Very distinctive feature with a Z or W decaying leptonically

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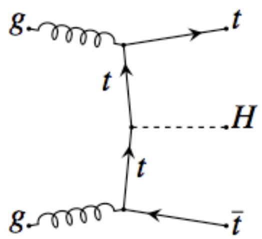

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Quite distinctive but also quite crowded

~3 k events produced!

* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{PDF\text{-}\alpha s}$~8-10% and $\delta\sigma_{Scale}$~ 7-8%

Channels investigated

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	(✓)		✓			✓	✓			

Overview of Current Main Analyses

Highlighting one example

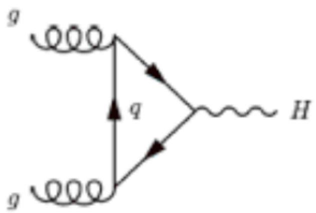
$$H \rightarrow \gamma\gamma$$

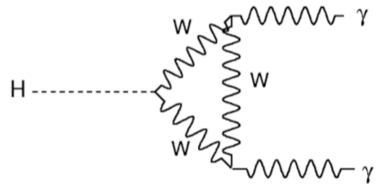
Somewhat detailing one example
(rather important one)

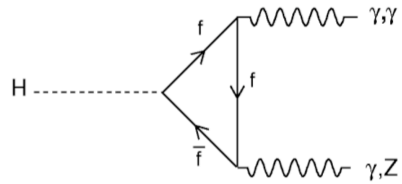
Interesting Facts about the γγ Channel

- Main production and decay processes occur through loops : Excellent probe for new physics !

known at NNnLO, still rather large uncertainty O(10%)







A priori potentially large possible enhancement…

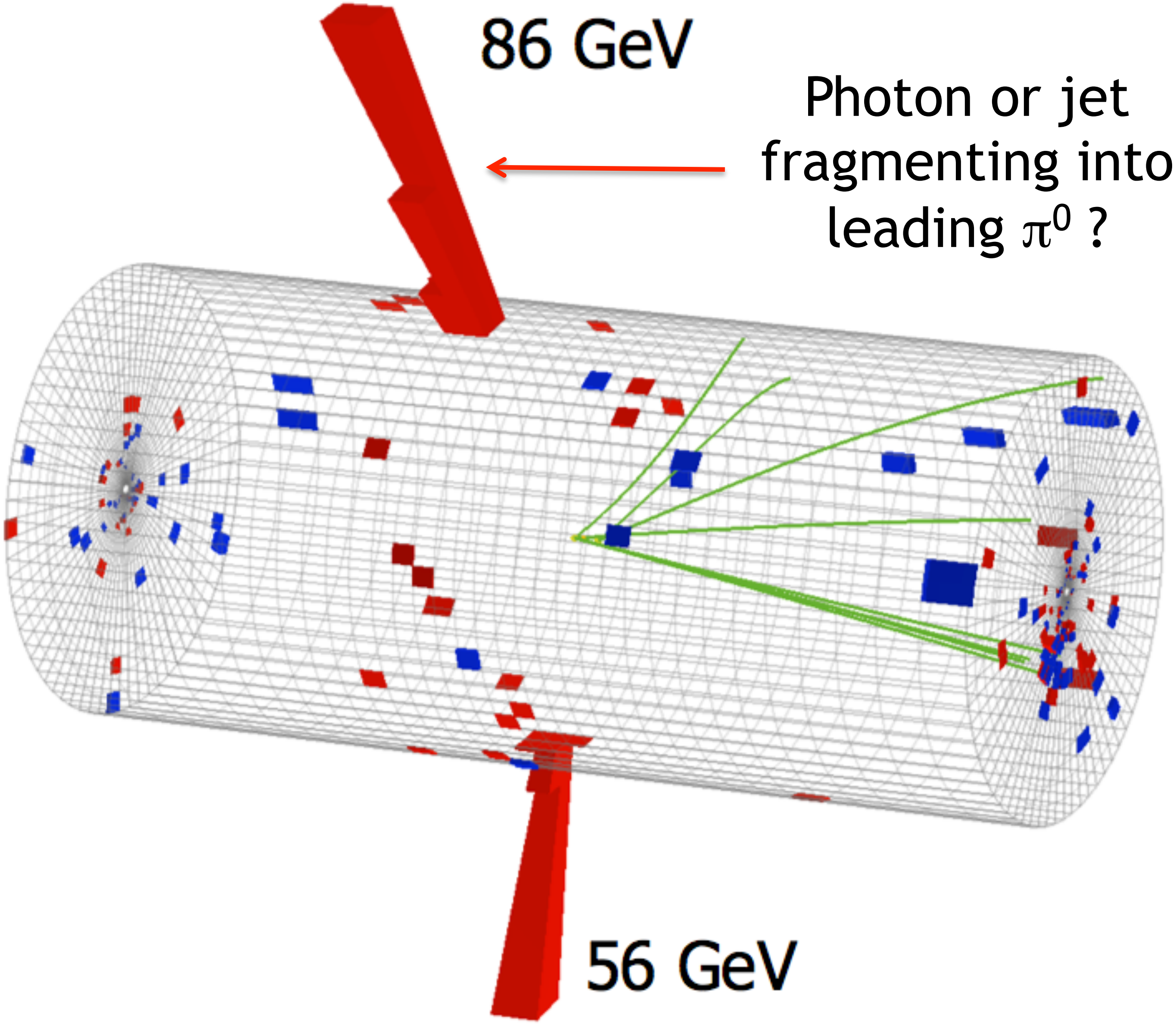
$$1.6 \times A_W^2 - 0.7 \times A_t A_W + 0.1 \times A_t^2$$

… Not so obviously enhanced (e.g. SM4)

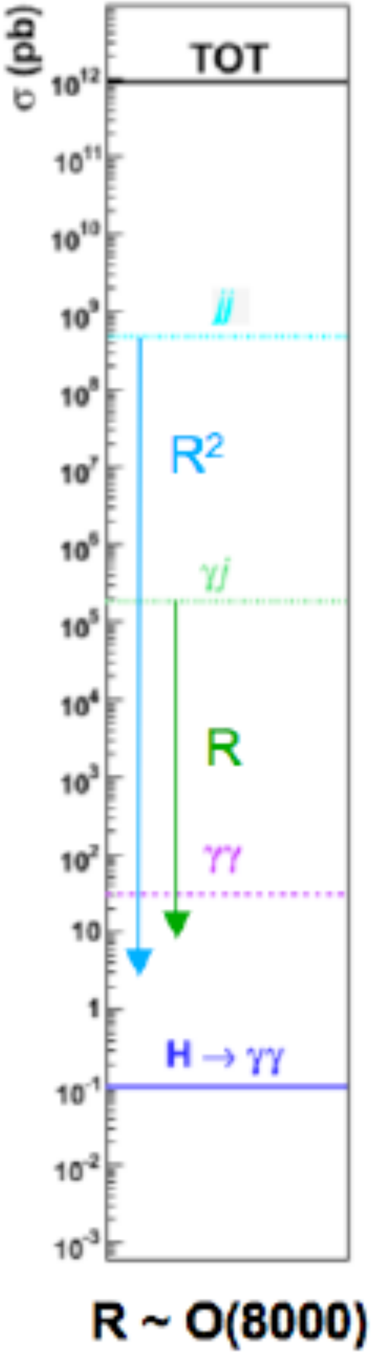
Seldom larger yields : e.g. NMSSM (U. Ellwanger et al.) up to x6, large stau mixing (M. Carena et al.), Fermiophobia…

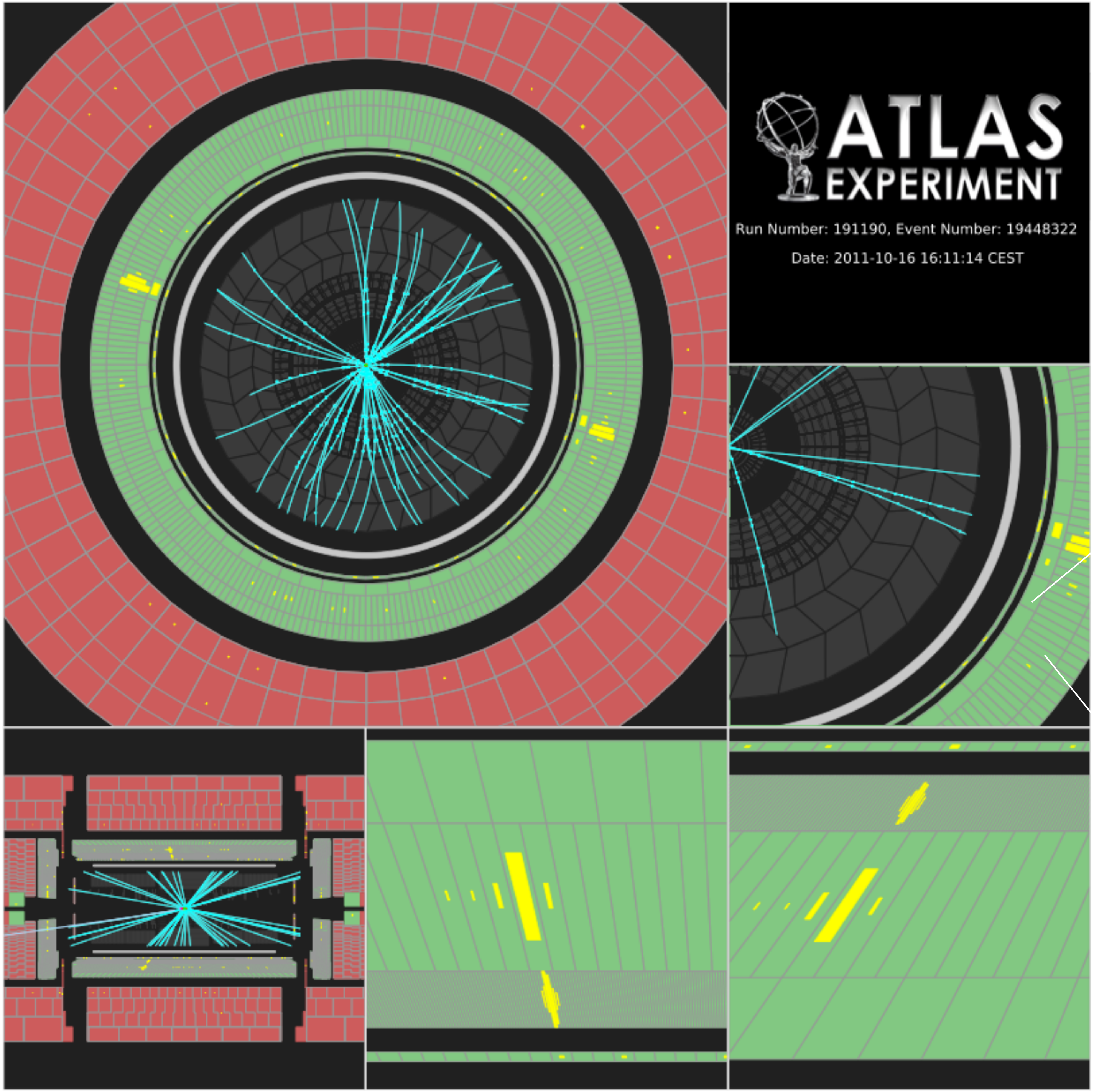
- High mass resolution channel
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem
- If observed implies that its Charge Conjugation is +1

Backgrounds

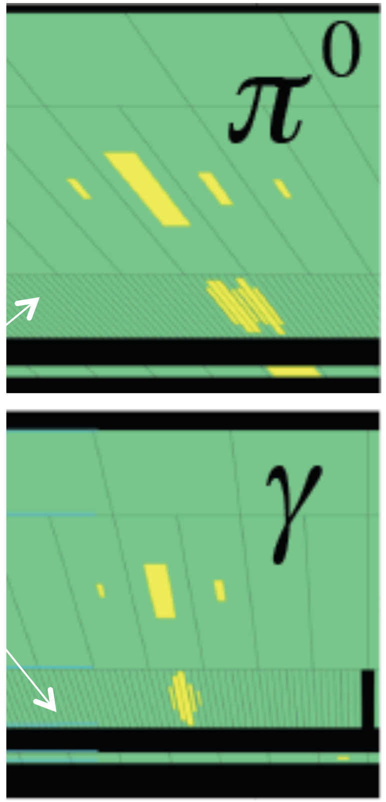


Photon or jet fragmenting into leading π^0 ?





Background
From jets



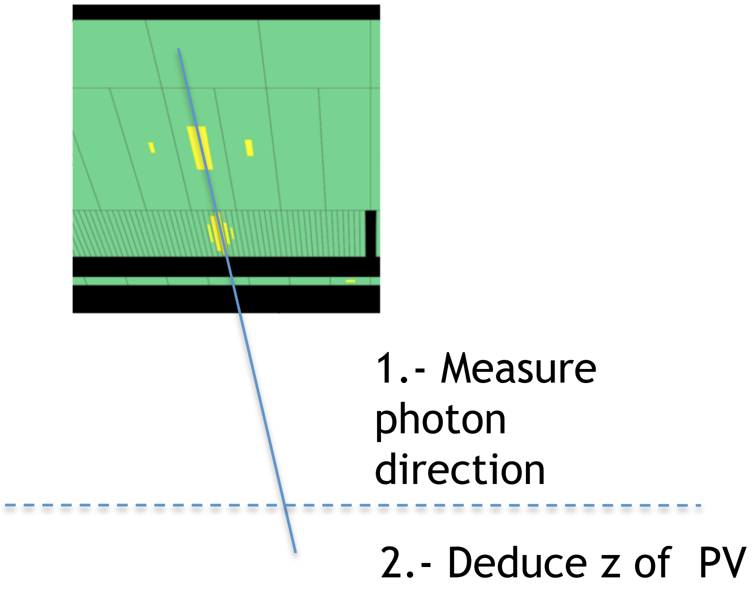
Signal

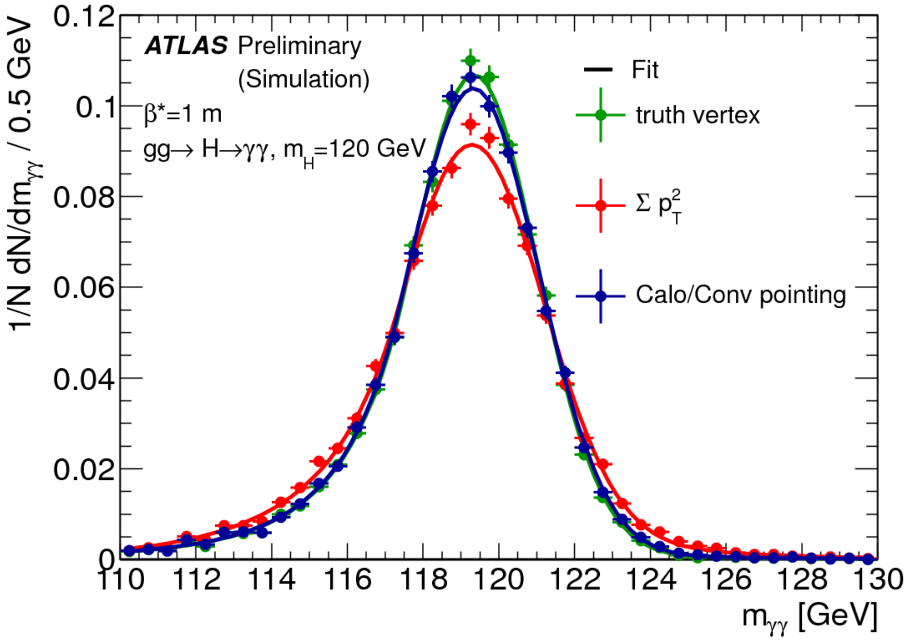
Reconstruction of the Angle in Space

- IP spread of 5.6 cm : assuming (0,0,0) adds ~1.4 GeV in mass resolution

(equiv. to the calo. $M_{\gamma\gamma}$ resolution itself).

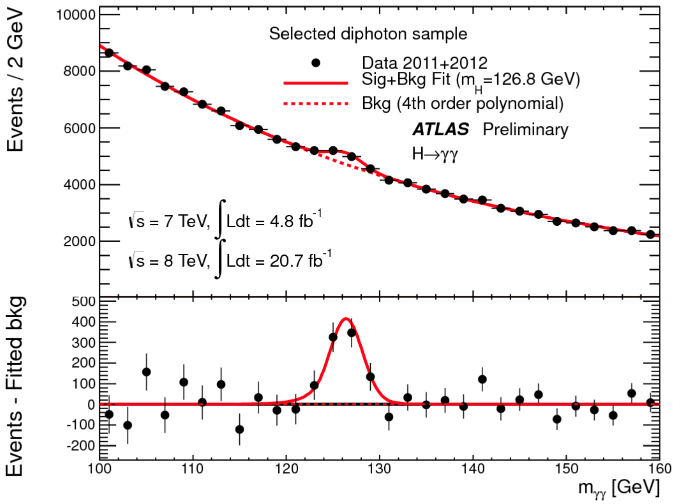
- Can use conversion as well
- Recoil tracks (less effective with large PU)

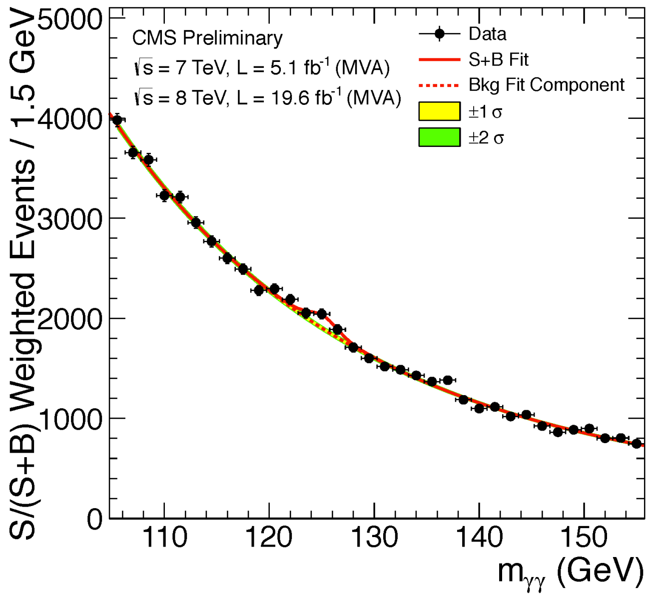




- Resolution with pointing ~1.6 cm
- Effective gain with O(10) PU events ~10%

$H \rightarrow \gamma\gamma$





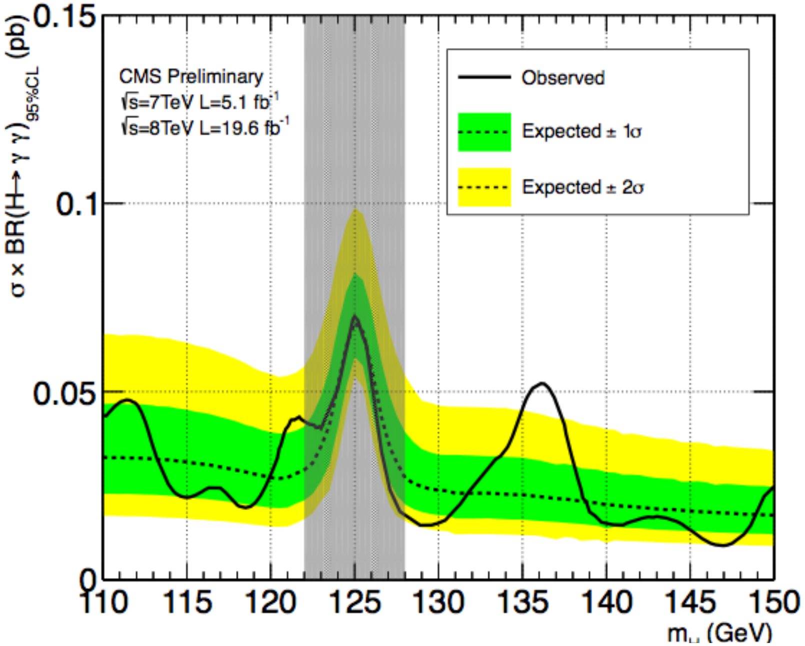
Analysis strategy:

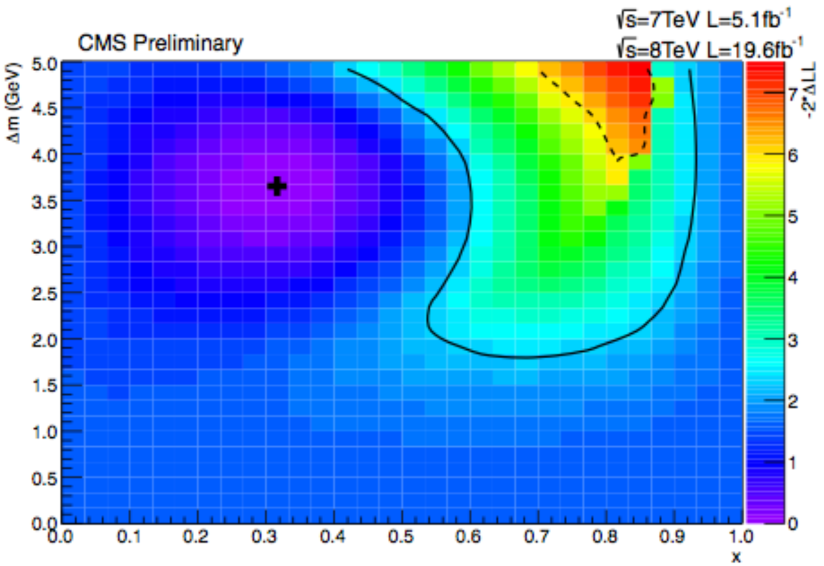
- **Di-photon mass** is the key observable
- two isolated high-p_T photons
  - vertex
    - CMS: from recoiling charged particles
    - ATLAS: from photon pointing (longitudinal ECAL segmentation)
  - split events into exclusive categories:
    - untagged, and further divided into 4/9 classes based on
      - 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%

$H \to \gamma\gamma$





- CMS estimate of the potential presence of two nearly degenerate states (CMS-PAS-HIG-13-016)

- CMS obs. (exp.) limit on natural width 6.9 (5.9) GeV

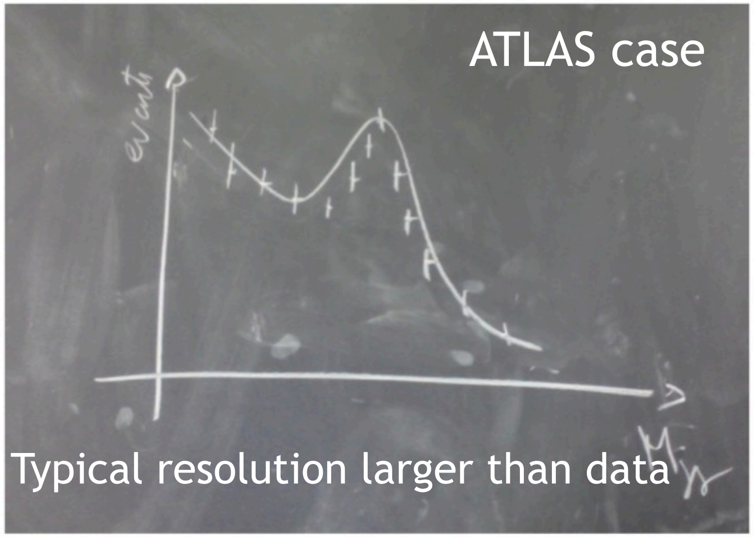
- CMS limit on higher mass states (an excess at around 136 GeV <2 s.d. with LEE)

The long standing ATLAS "excess" in diphoton rate

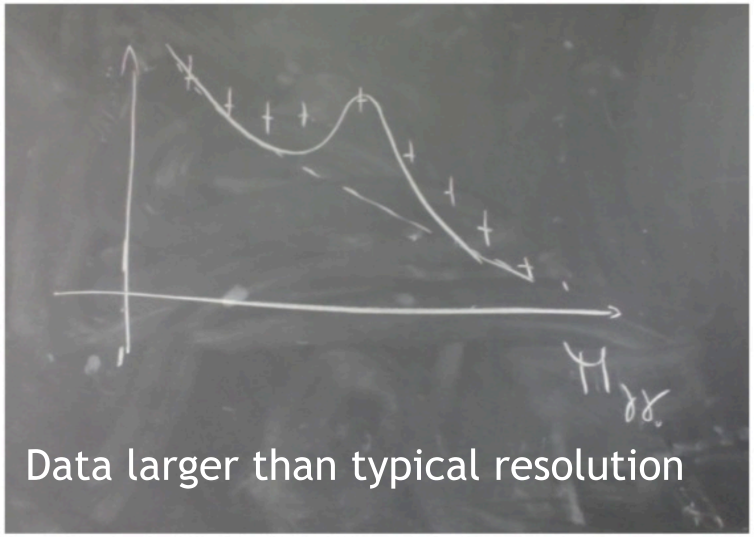
The compatibility in the signal strength parameter between the data and the SM Higgs boson signal plus background hypothesis is estimated with the test statistic $\lambda(\mu)$ with $\mu = 1$ [4], and is found to be at the 2.3 σ level.

The results reported above are extracted from a fit in which the mass resolution uncertainty, which is ~20%, is treated as a nuisance parameter with a Gaussian constraint. As a check, the fit was repeated with no constraint on the mass resolution parameter, giving $\mu = 1.49 \pm 0.33$ (1.8 σ compatibility with the SM Higgs boson signal hypothesis). This fit prefers a narrower mass resolution than the nominal one by 1.8 σ, which is better than the resolution corresponding to a perfectly uniform calorimeter. Dedicated studies revealed no indication that the systematic uncertainty on the resolution is underestimated; the large pull in this test fit can also be a statistical effect arising from background fluctuations.

Higher prob. to overestimate μ

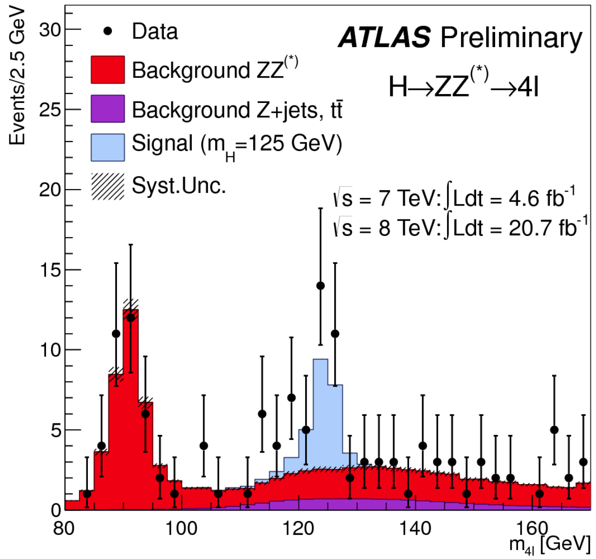


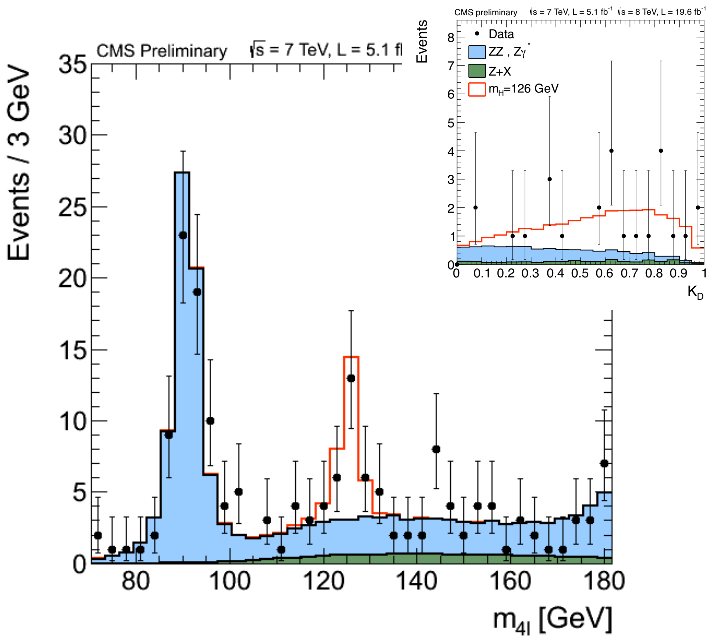
Higher prob. To underestimate μ



(Conditionnal) Probability for a fluctuation in the mass also higher

$$H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$$





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: **$V_D(m_{jj}, \Delta\eta_{jj})$**)

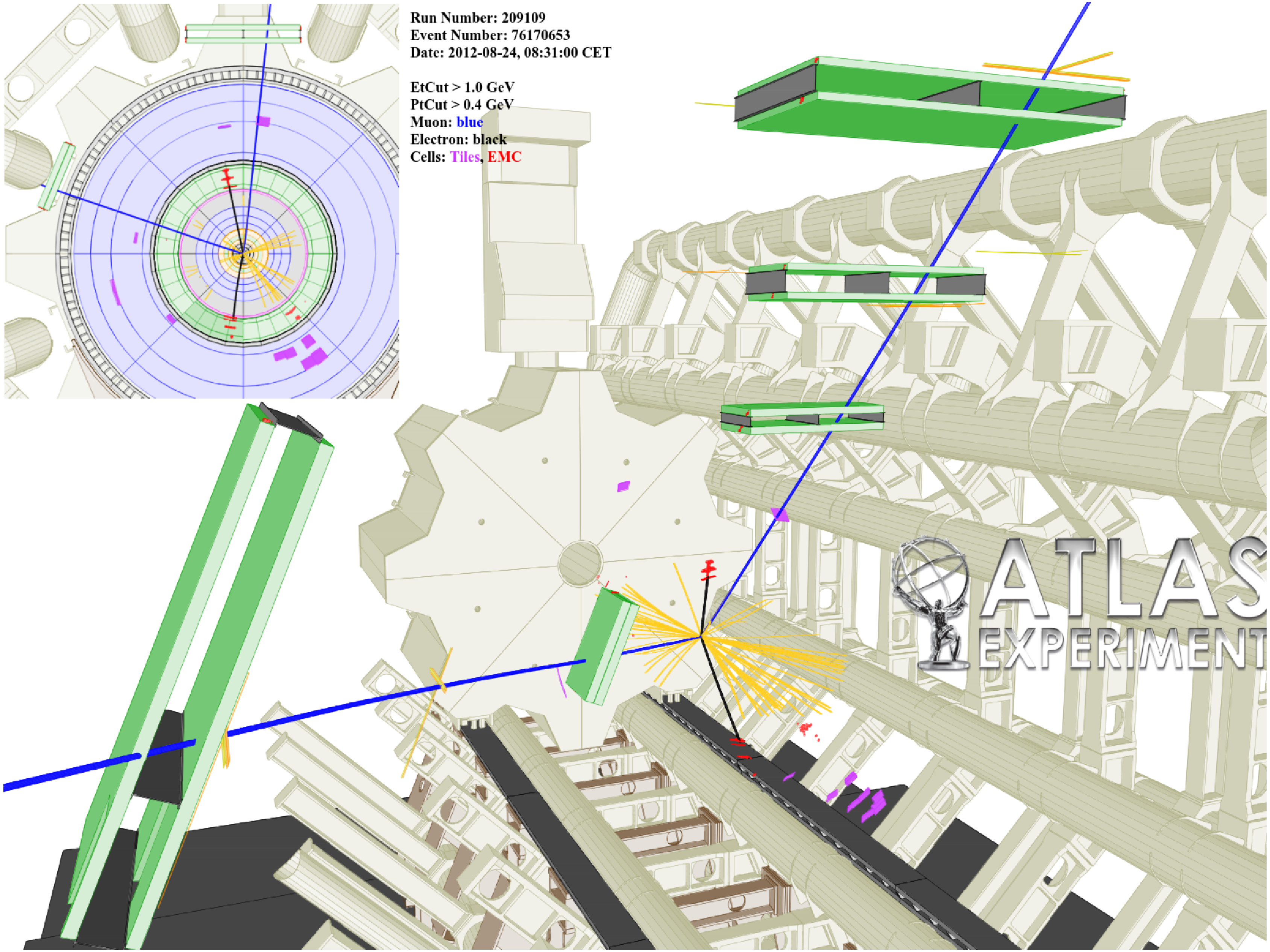
Analysis key features:

High S/B-ratio,

But small event yield

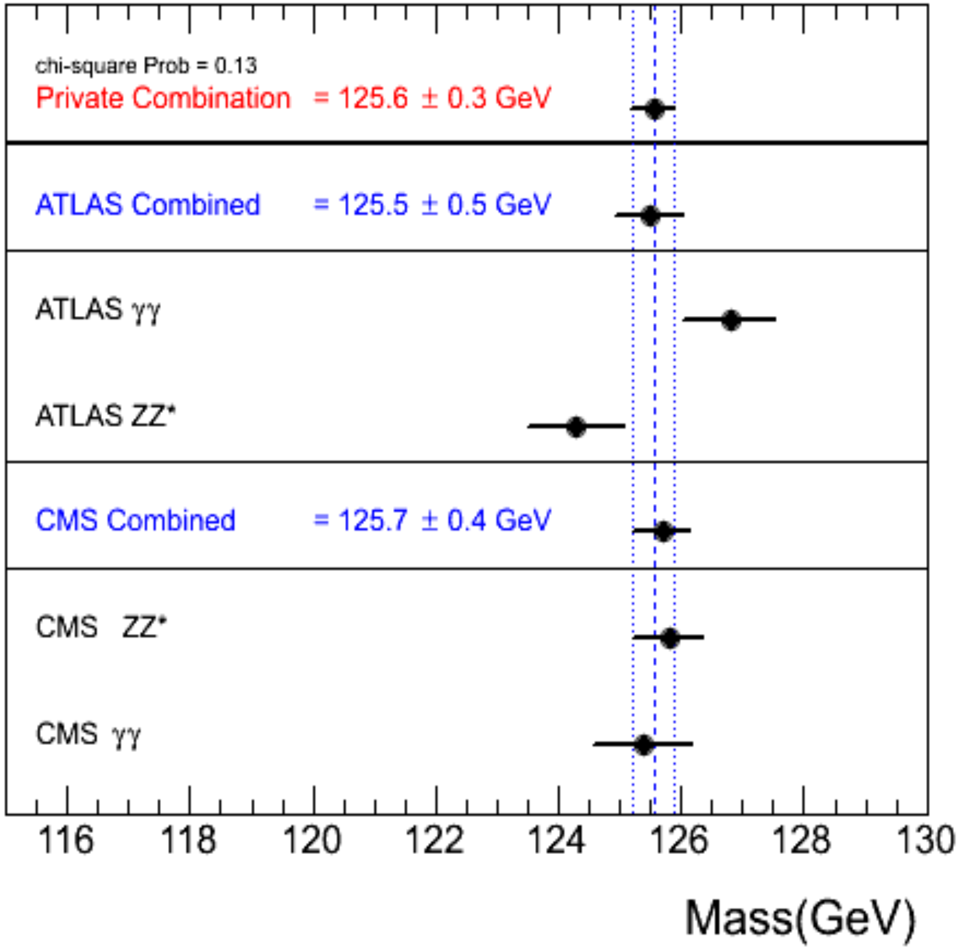
mass resolution = 1-2%

$H \rightarrow 4l$ Single Highest Purity Candidate Event ($2e2\mu$)



The Mass of the Higgs Particle

Review of mass measurements across channels and experiments



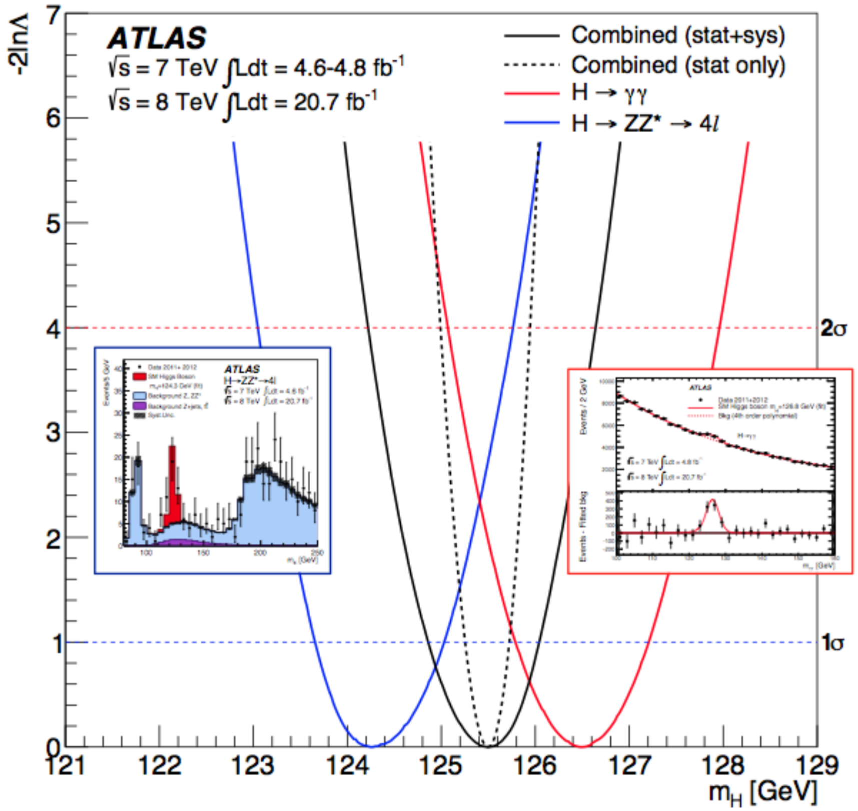
Unofficial combination

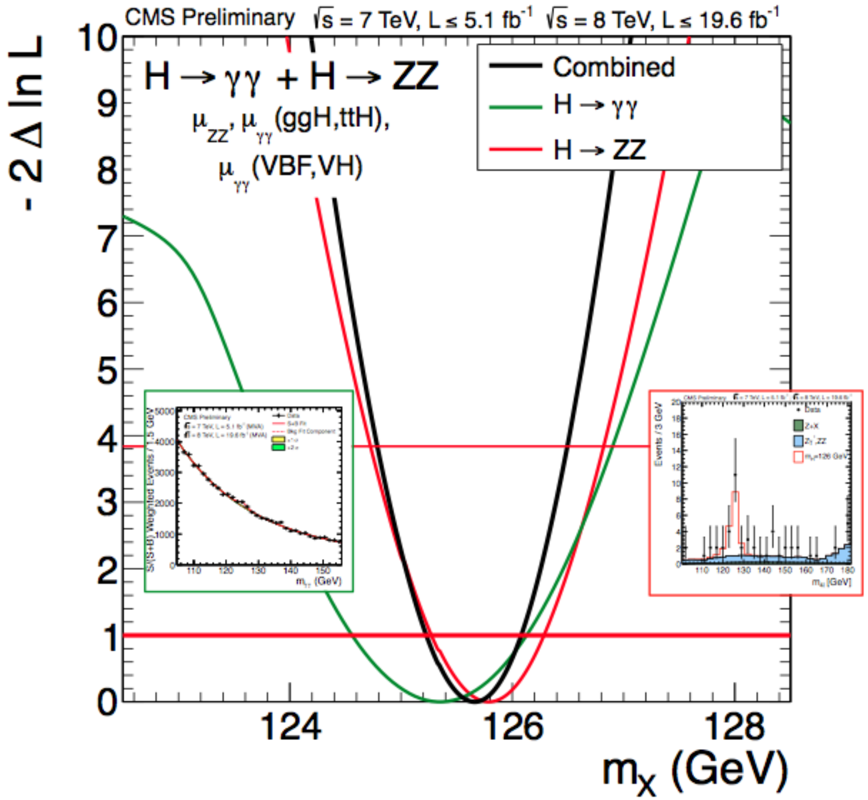
χ^2 Probability of 13%

Final word on mass and μ from both ATLAS and CMS will require final Run I calibration

The Mass of the Higgs Particle

(F. Cerutti @ EPS 2013)





ATLAS: $M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{sys}$ GeV

CMS: $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{sys}$ GeV

Diphoton : 126.8±0.2±0.7

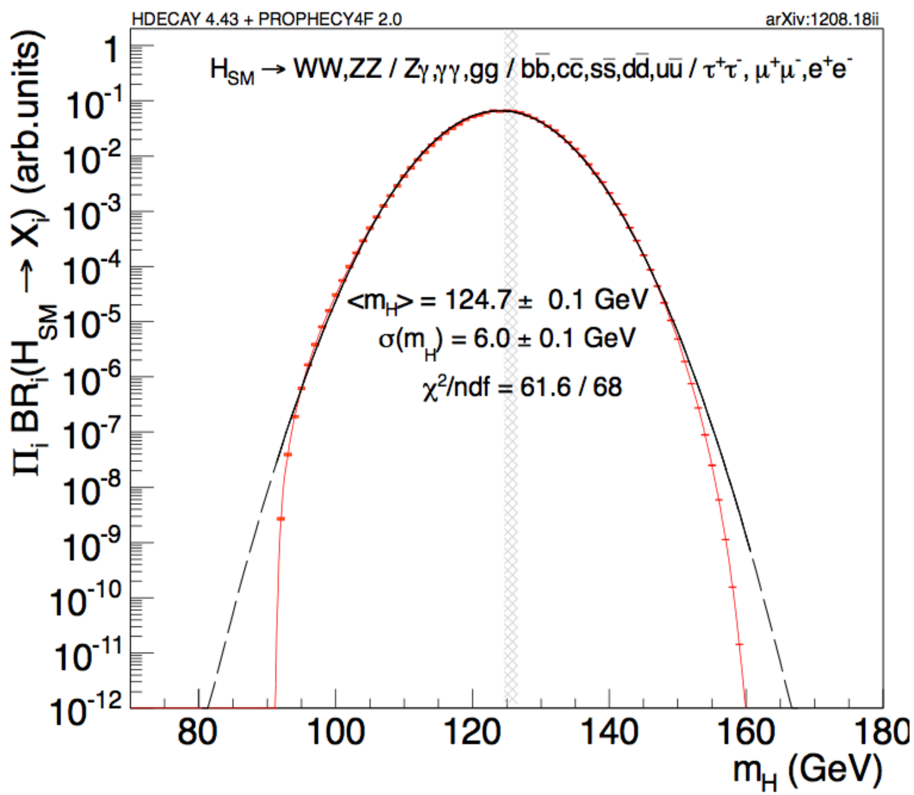
Four leptons : 124.3±0.5±0.5

Intriguing/Amusing Coincidences (?)

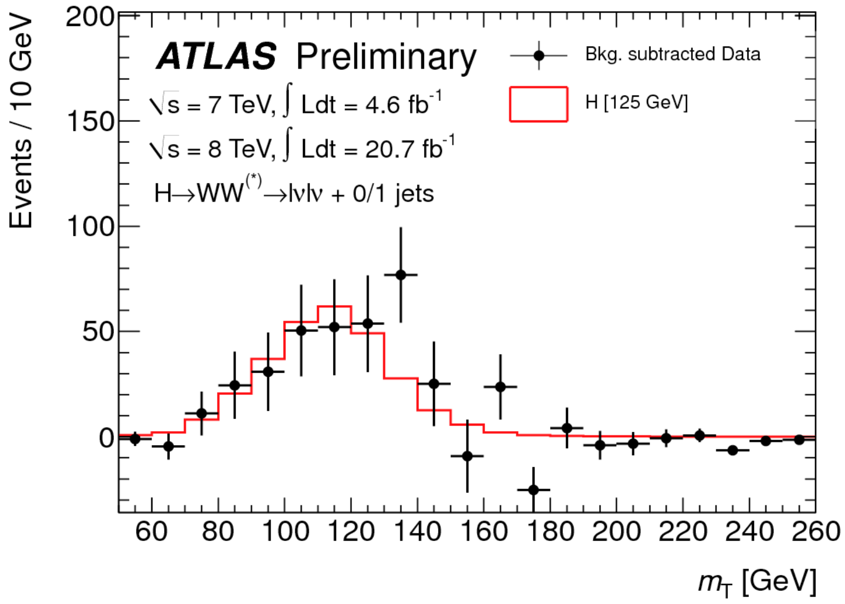
- $m_H = (m_W + m_W + m_Z)/2 = 126.0$ GeV (http://arxiv.org/abs/0912.5189)

- $m_H^2 = m_Z \times m_t \Rightarrow m_H = 125.8$ GeV (http://arxiv.org/pdf/1209.0474.pdf)

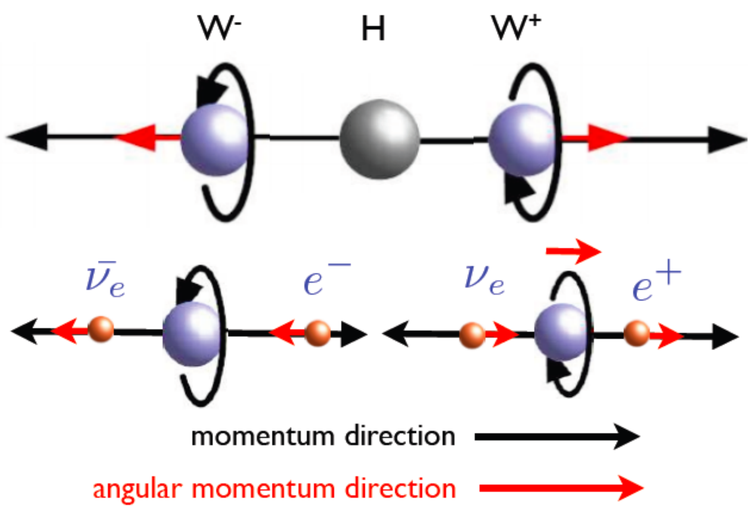
- Π BR peak at mH =124.7 GeV (http://arxiv.org/pdf/1208.1993.pdf)



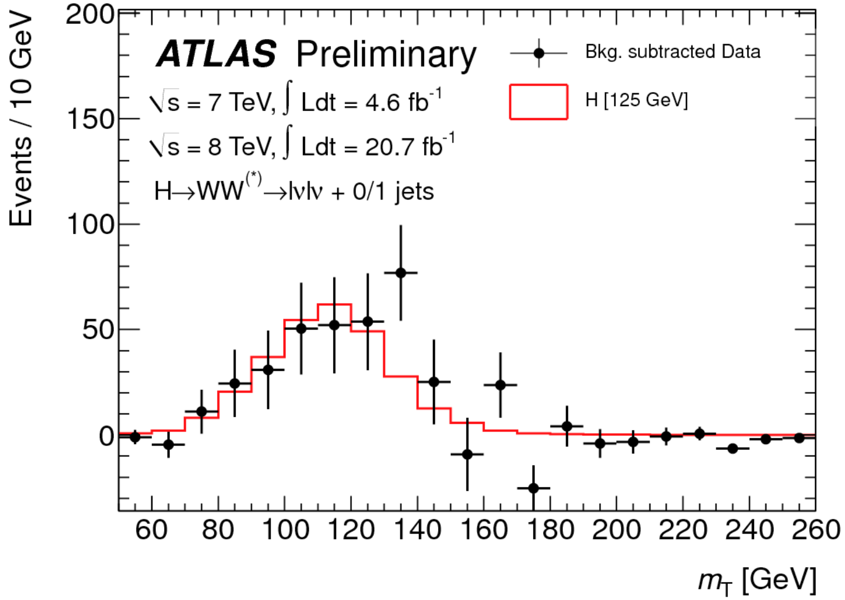
$H \to WW^* \to \ell^+ \upsilon \ell^- \upsilon$

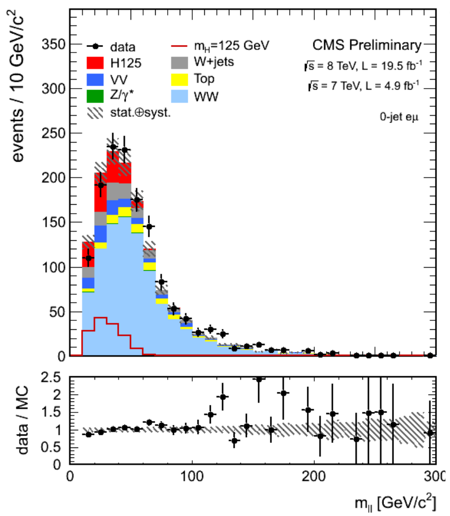


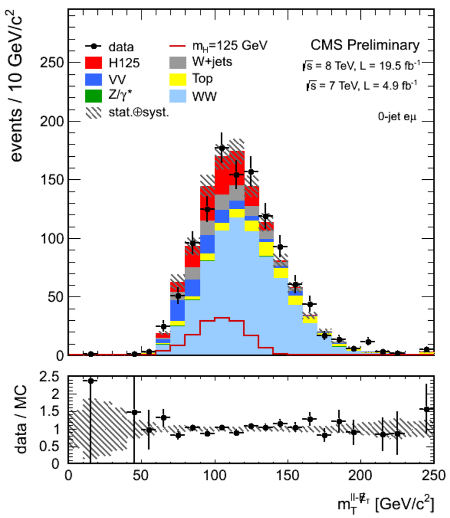
- Analysis strategy:
  - two prompt high-p_T leptons
  - Use spin-0 and V-A structure of W decay
  - MET
  - split events into ee, μμ, eμ channels:
    - different S/B rates: Drell-Yan in ee/μμ !
  - split events further into 0/1-jet:
    - different S/B rates: ttbar in 1-jet !



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





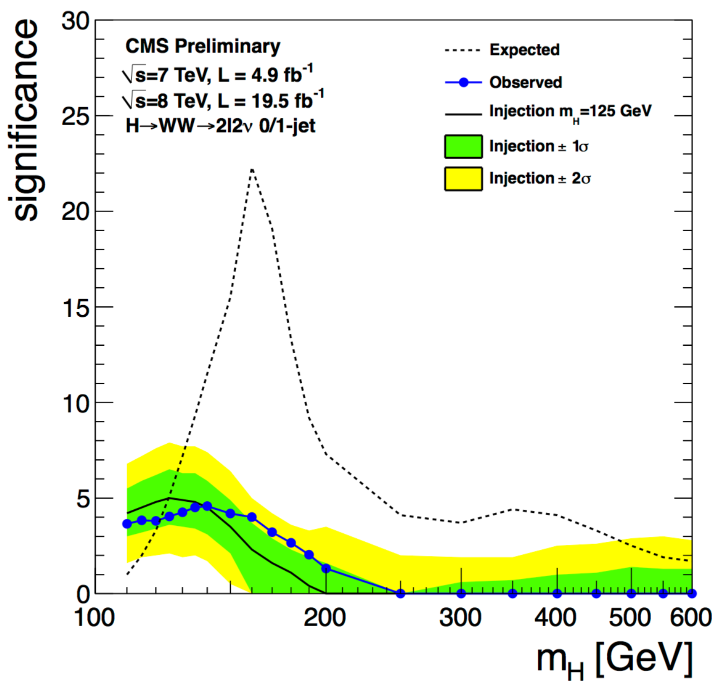


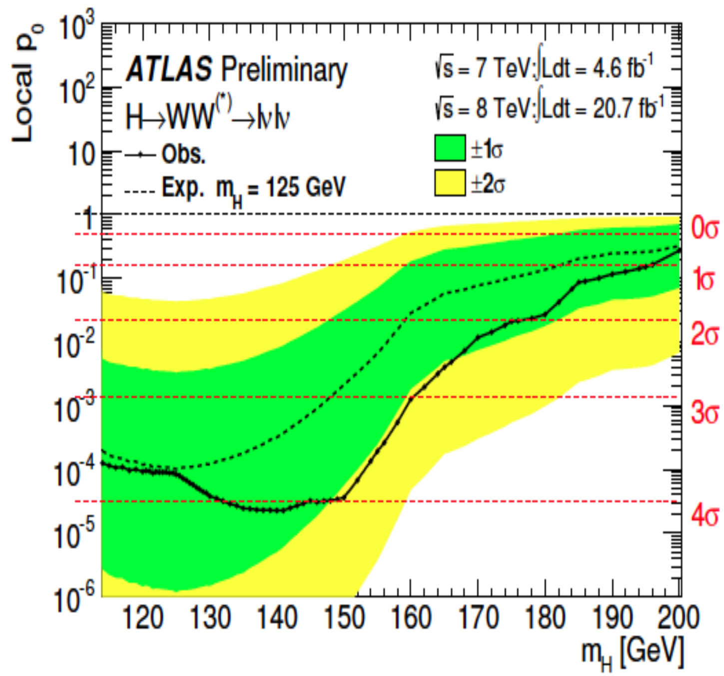
- Analysis strategy:
  - two prompt high-p_T leptons
  - Use spin-0 and V-A structure of W decay
  - MET
  - split events into ee, μμ, eμ channels:
    - different S/B rates: Drell-Yan in ee/μμ !
  - split events further into 0/1-jet:
    - different S/B rates: ttbar in 1-jet !
  - **ATLAS: m_T-distribution**
  - **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%

Background Uncertainties

TH uncertainty on the WW kinematics

$$\mu_{obs} = 1.01 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{theo. syst.}) \pm 0.12\,(\text{expt. syst.}) \pm 0.04\,(\text{lumi.})$$
$$= 1.01 \pm 0.31.$$

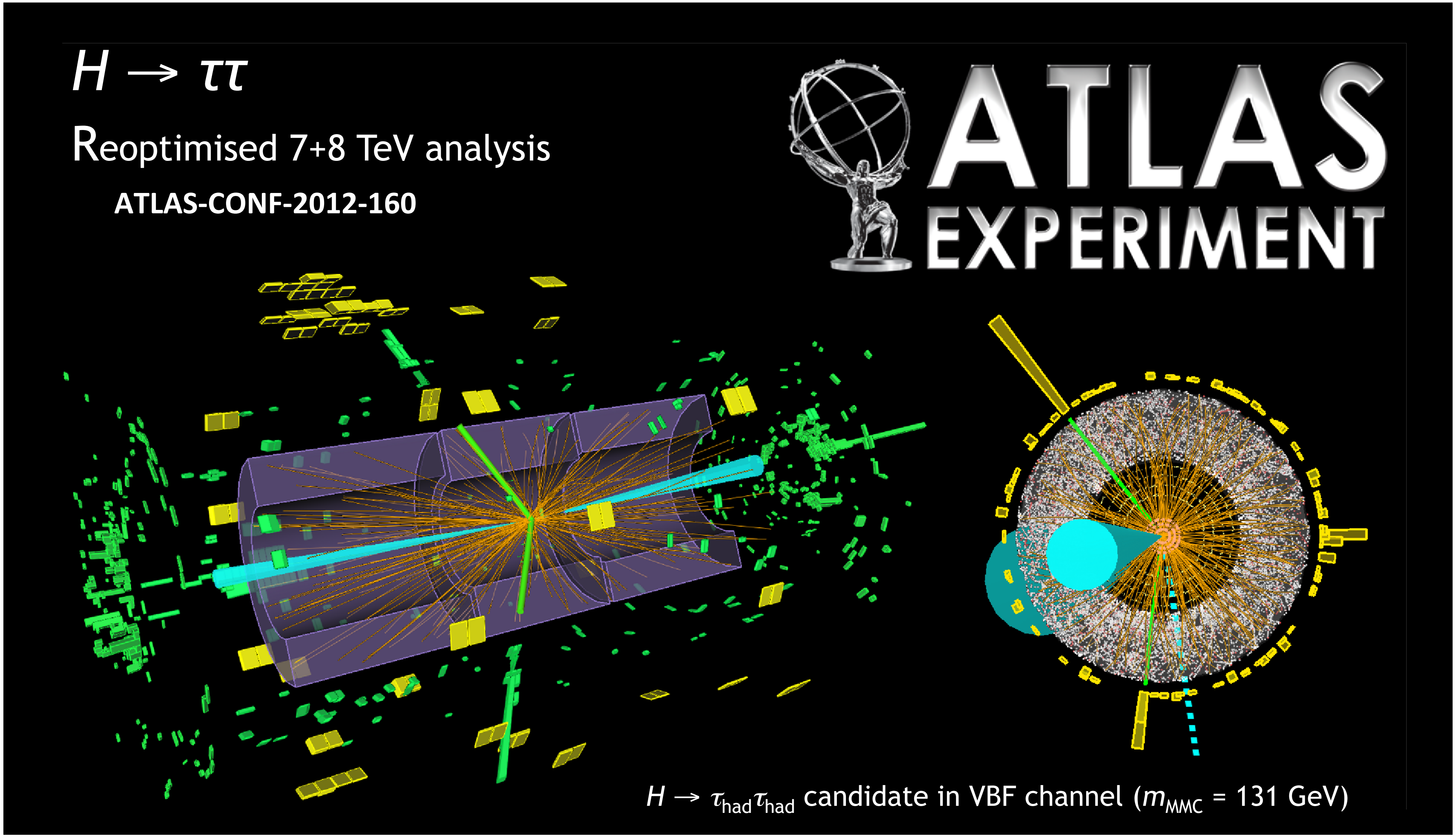




NNLO calculation underway!!!

(m = 125) **Z_{obs} = 4.0 σ**
Z_{exp} = 5.0 σ

(m = 125) **Z_{obs} = 3.8 σ**
Z_{exp} = 3.7 σ

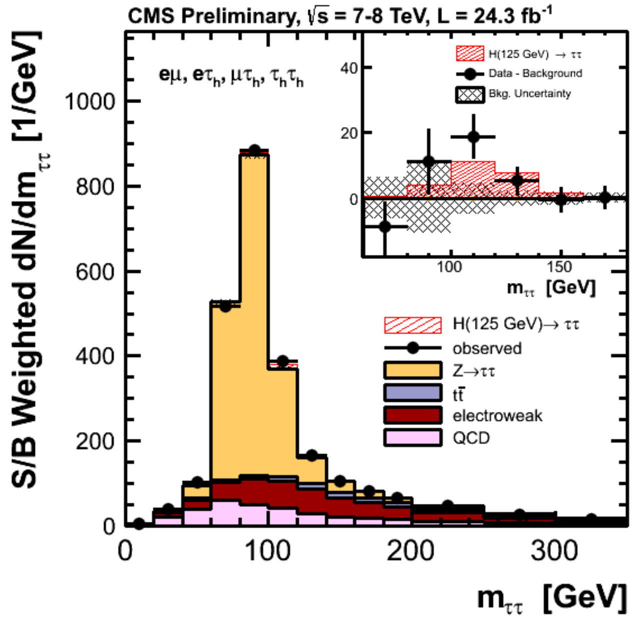


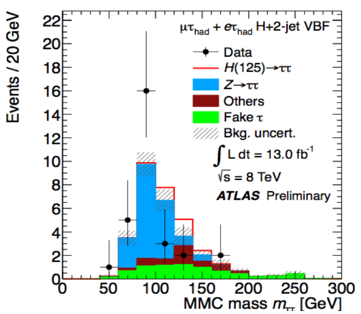
ττ channel basic facts sheet :

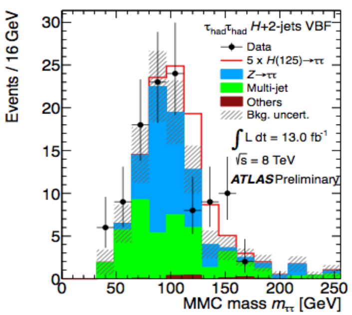
ττ channel basic facts :

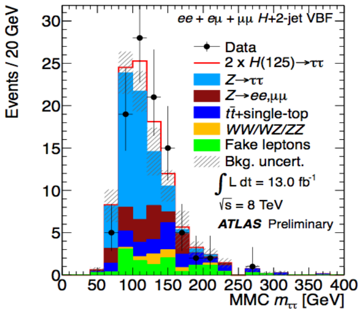
- Ns ~ O(500) per experiment
- Signal purity ~ 0.3% - ~O(50%)

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









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:

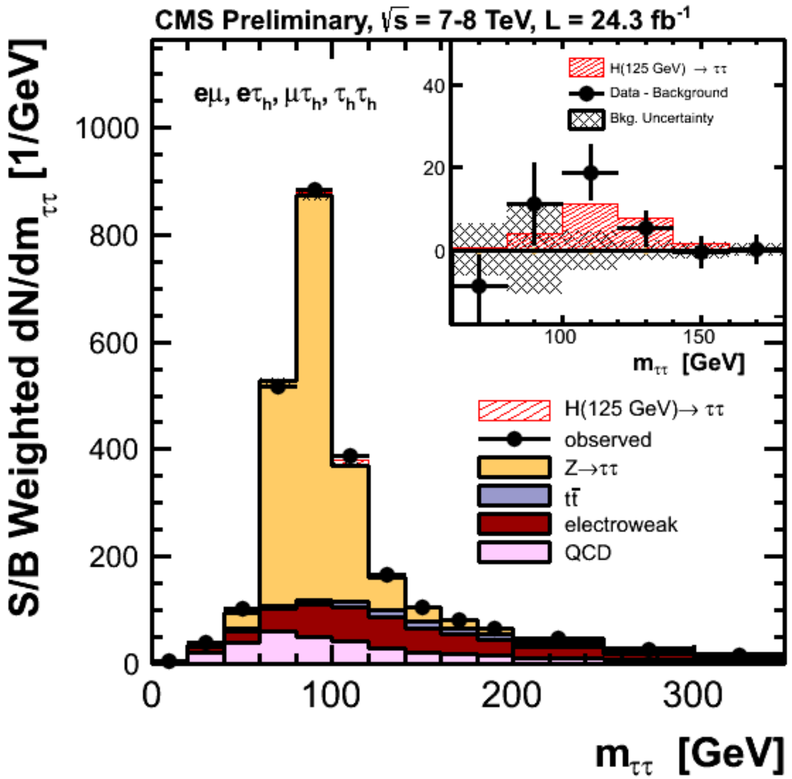
- **2-jets (VBF-tag)**: best S/B-ratio
- **2-jets (VH-tag)**: best S/B-ratio
- **VH Lepton tag**
- **1-jet (ggF, VH)**: acceptable S/B-ratio
- untagged: control region (S/B≅0)

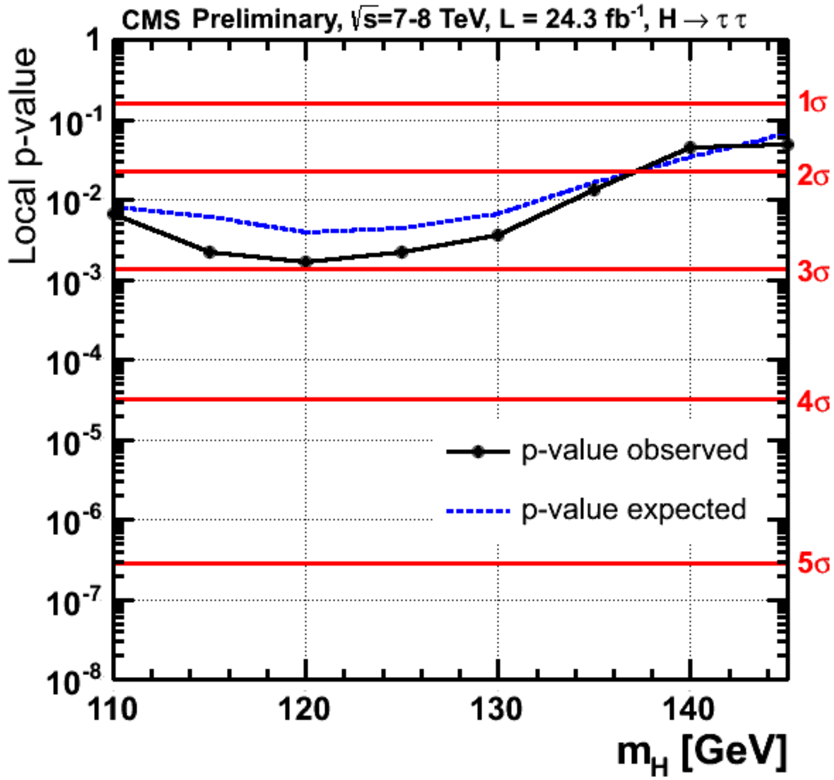
- Split 1-jet events further high/low p_T tau
  - different S/B rates
- Backgrounds:
  - Z→ττ: Z→μμ (data) with embedding
  - Z→ee, W+jets, ttbar: MC for shapes, data for normalization
  - QCD: from control regions

Key Analysis features:

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

$H \to \tau^+\tau^-$

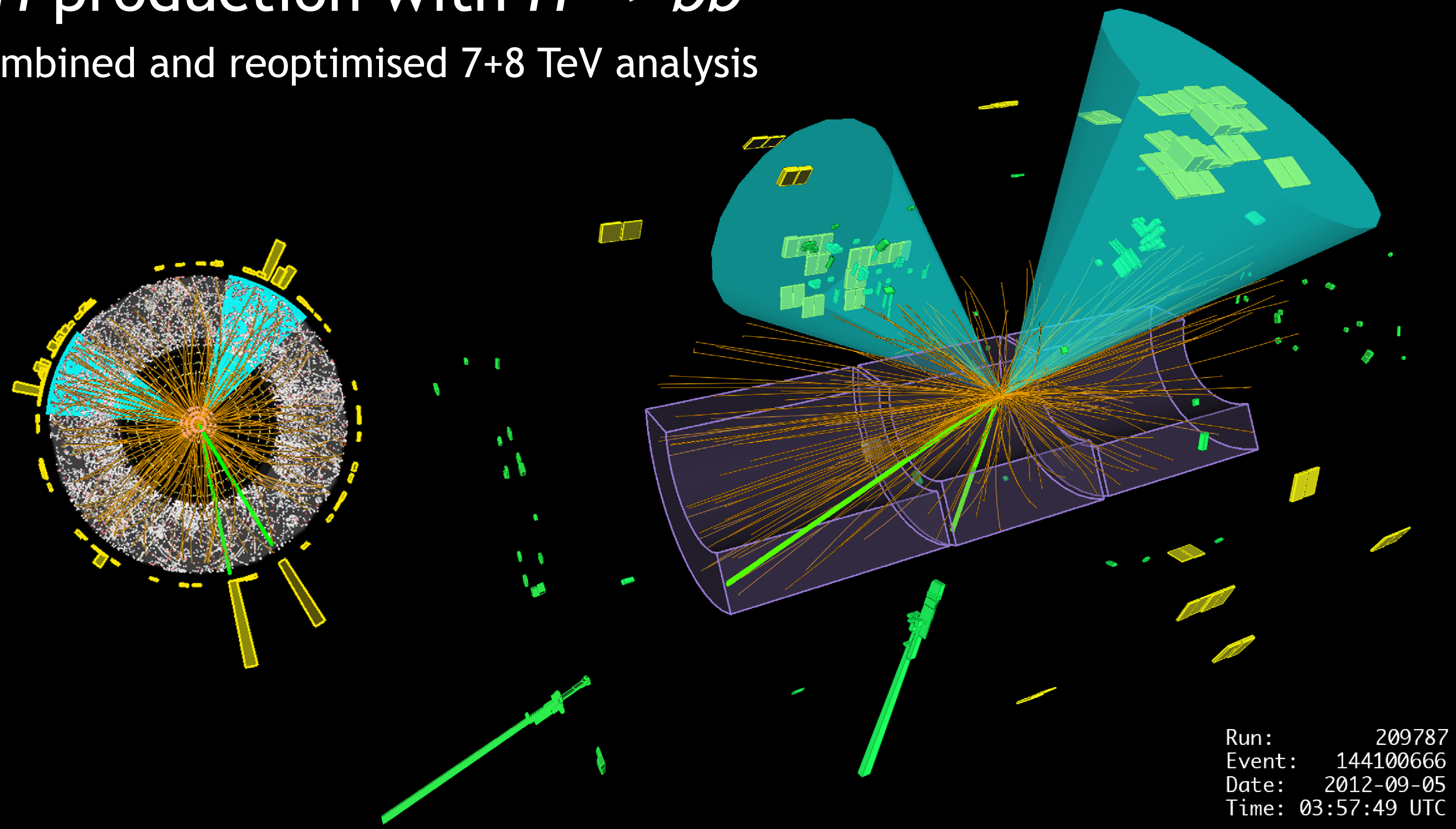




Excess with a significance of 2.8σ observed and 2.6σ expected

VH production with $H \rightarrow bb$

Combined and reoptimised 7+8 TeV analysis

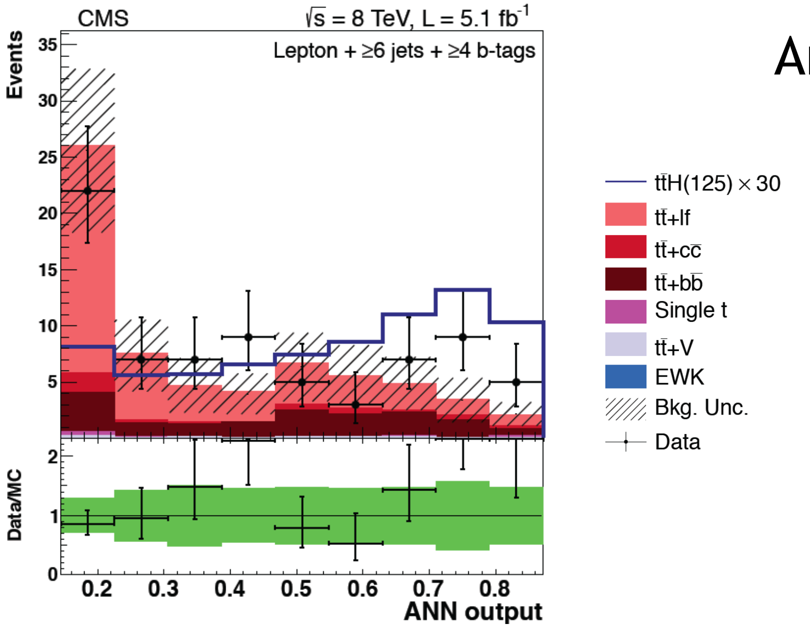


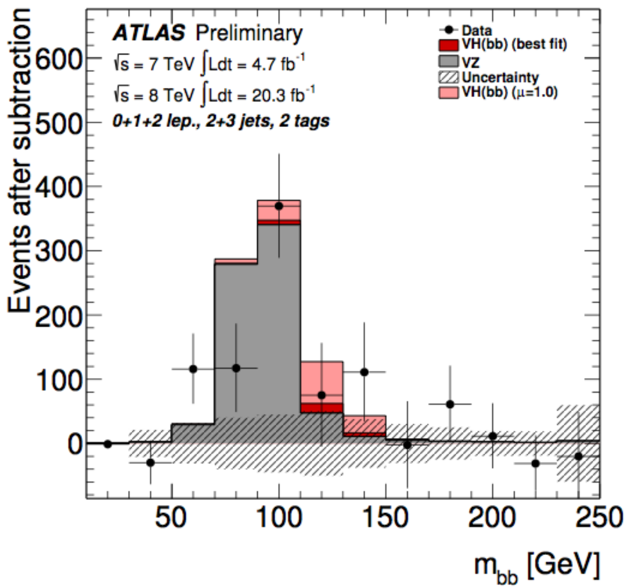
VH(bb) channel basic facts sheet :

VH(bb) channel basic facts :

- Ns ~ O(100) per experiment
- Signal purity ~ 1% - 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

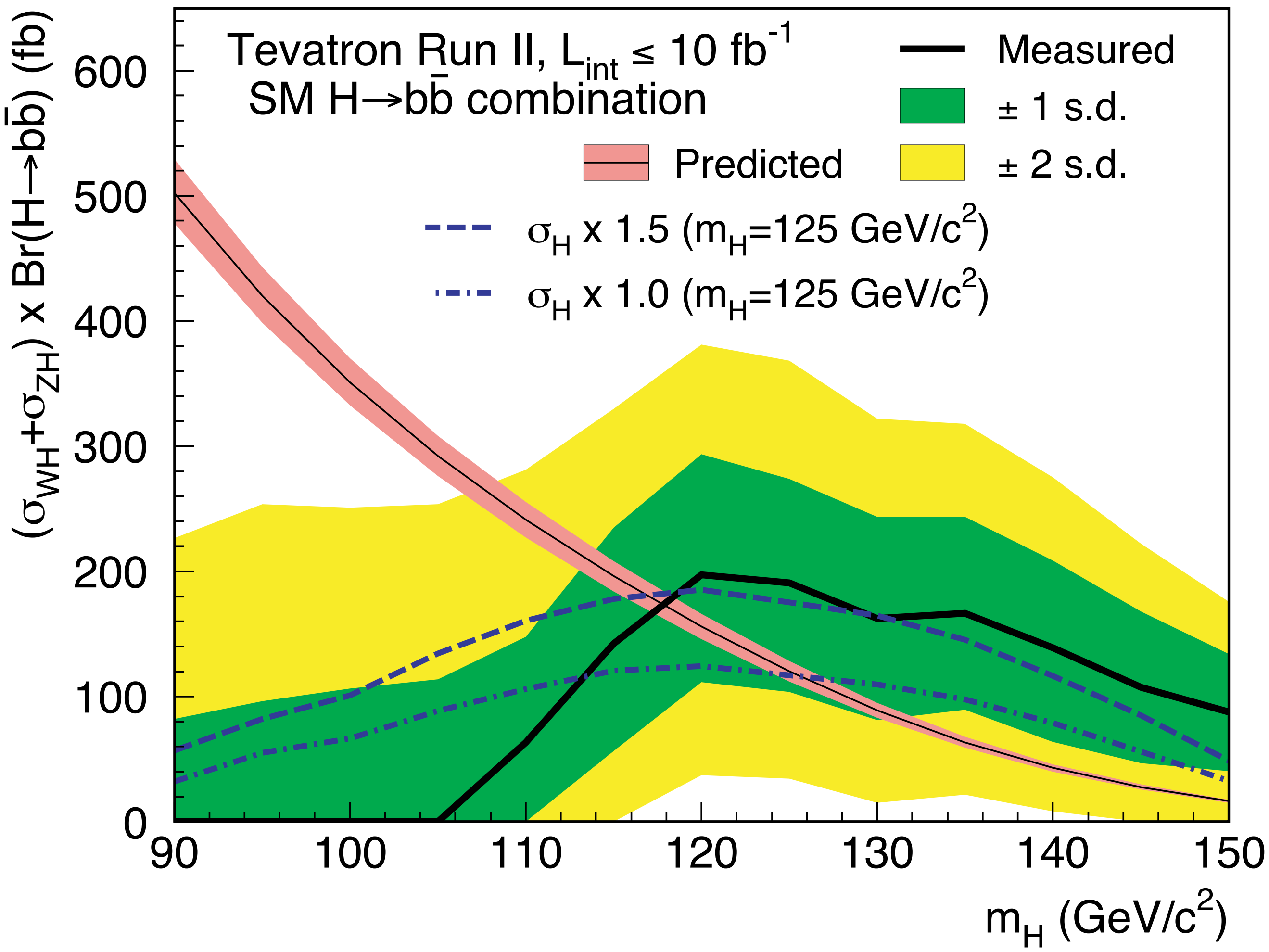
- Main Backgrounds:
  - V+bb and top
  - Uses mainly control regions except

Key Analysis features:

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

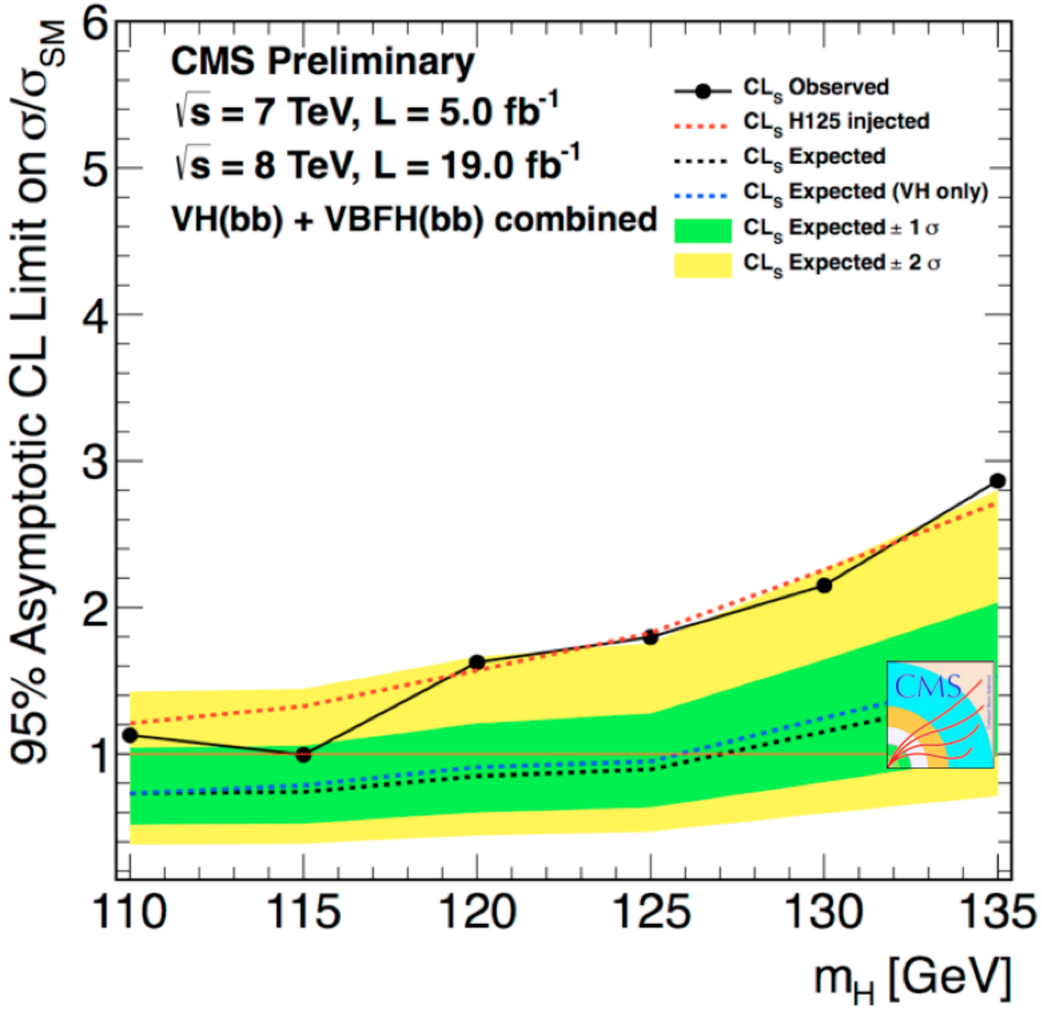
$VH \to Vbb$

VH(bb) at the Tevatron



$$\not{VH \to V} \quad (H \to bb)$$

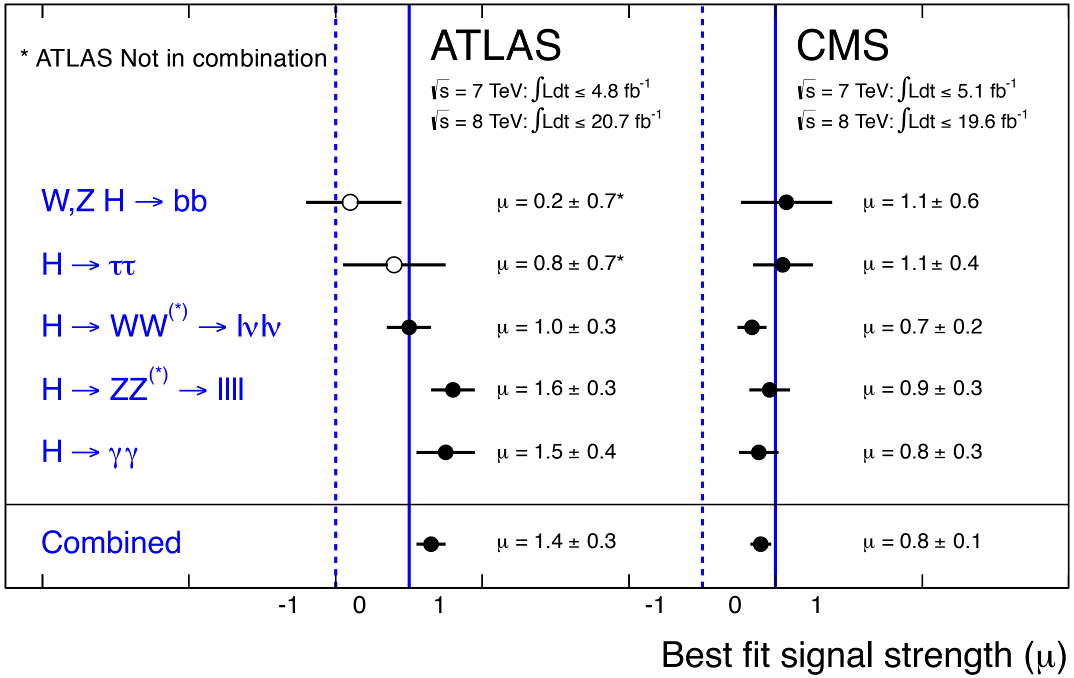
CMS with VBF analysis combined



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	1.5±0.4	4.1	7.4	126.8±0.2±0.7	0.8±0.3	3.9	3.2	125.4±0.5±0.4
ZZ (llll)	1.6±0.3	4.4	6.6	124.3±0.5±0.5	0.9±0.3	7.1	6.7	125.8±0.5±0.2
WW (lnln)	1.0±0.3	3.8	3.8	-	0.7±0.2	5.3	3.9	-
ττ	0.8±0.7	1.6	1.1	-	1.1±0.4	2.6	2.8	120^{+9}_{-7}
W,Z H (bb)	0.2±0.7	1.4	0.3	-	1.1±0.6	2.2	2.0	-
Combination	1.30±0.20	7.3	10	125.5±0.2±0.6	0.80±0.14	-	-	125.7±0.3±0.3

Channel categories	Tevatron
	μ (at 125 GeV)
γγ	$6.0^{+3.4}_{-3.1}$
ZZ (llll)	-
WW (lnln)	1.6±1.2
ττ	$1.7^{+2.3}_{-1.7}$
W,Z H (bb)	1.6±0.7
Combination	1.4±0.6



Measurement of Coupling Properties

The Complete Model*

$$\lambda_\mu = \lambda(\mu,\theta) = \prod_{Channels\ i} \frac{L_i(\mu,\hat{\hat{\theta}}(\mu))}{L_i(\hat{\mu},\hat{\theta})} \times CT$$

$$n_s^i = \mu \sum_{\text{Production mode k}} \sigma_{SM}^k \times Br^i \times Lumi^i \times A^{ki} \times \varepsilon^{ki}$$

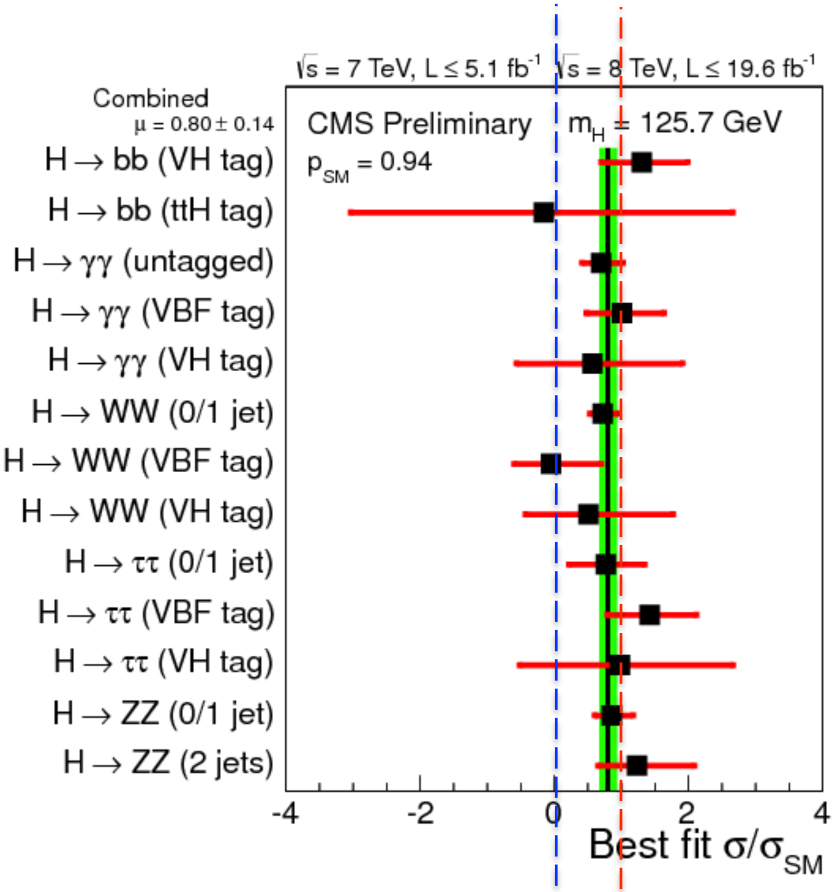
Measures the agreement between an hypothesis μ and the value most favored by the data $\hat{\mu}$

* O(500) Nuisance Parameters to describe systematic uncertainties and background models

How the fit works

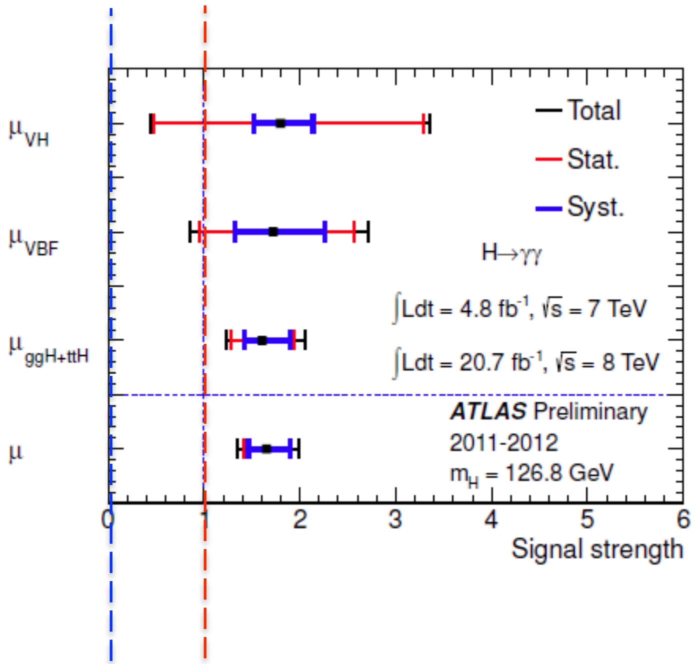
$$n_s^c = \left(\sum_{i \in \{ggF, VBF, VH, ttH\}} \mu^i \sigma_{SM}^i \times A^{ic} \times \varepsilon^{ic} \right) \times \mu^f Br^f \times L^c$$

Sub-channel signal strengths



μ=0 μ=1

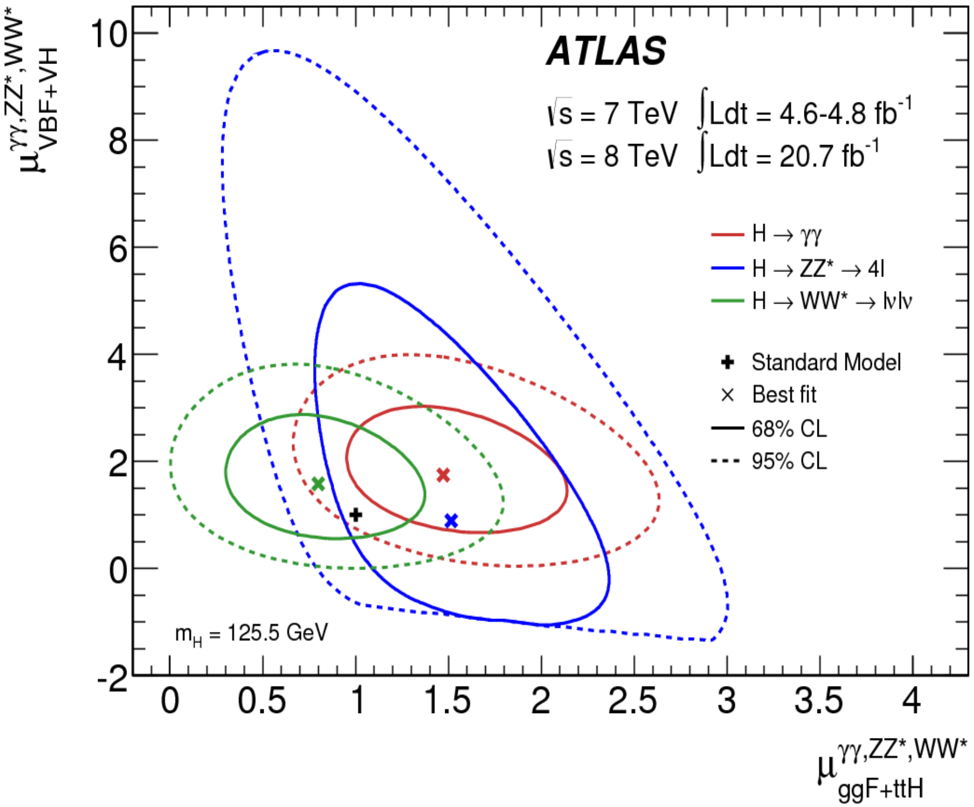
Production mode signal strengths (per channel)

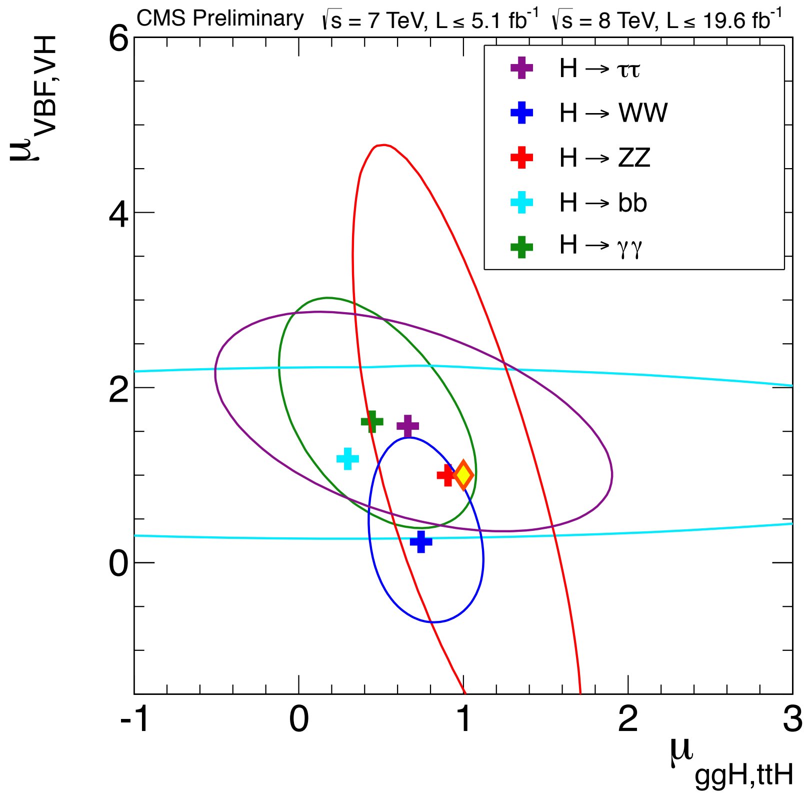


μ=0 μ=1

Production Signal Strengths

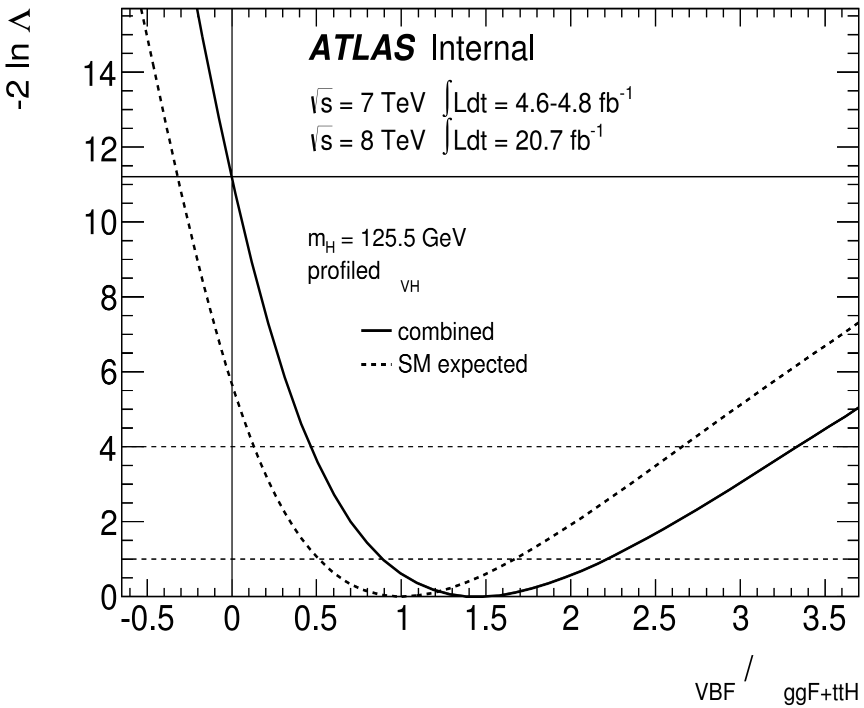
For individual channels



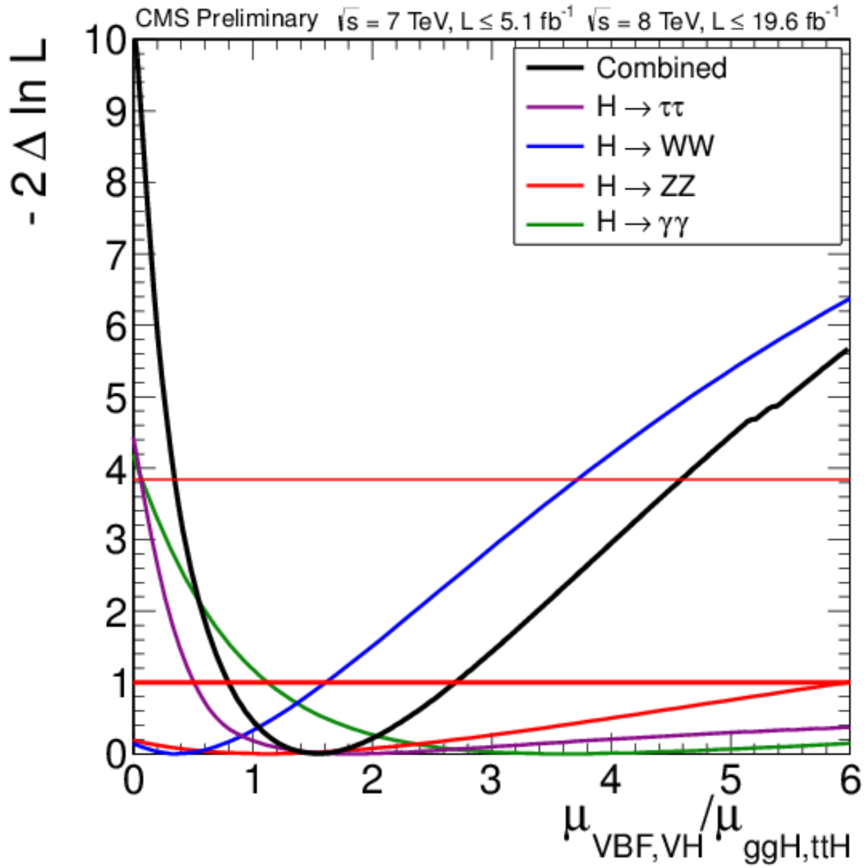


Evidence for VBF production

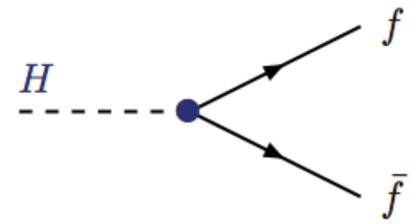
From the ratio of individual production signal strengths



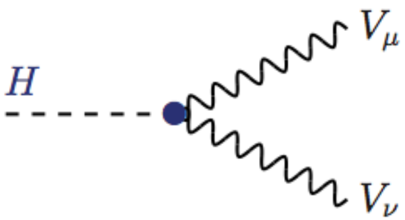
Evidence for VBF(,VH) production



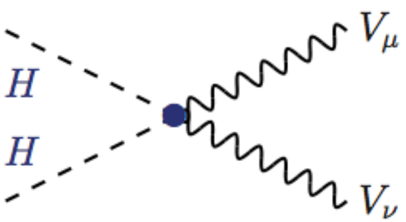
Measuring the Coupling Properties of the Observed State



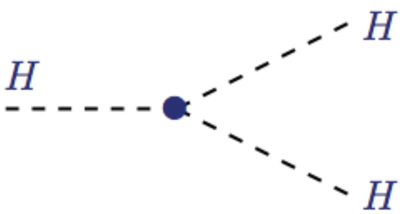
$$g_{Hff} = m_f/v$$



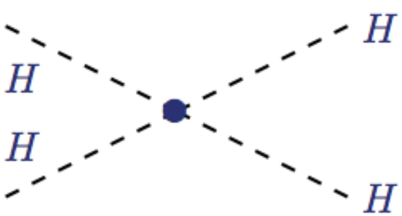
$$g_{HVV} = 2M_V^2/v$$



$$g_{HHVV} = 2M_V^2/v^2$$



$$g_{HHH} = 3M_H^2/v$$



$$g_{HHHH} = 3M_H^2/v^2$$

For the time being only test the bosonic and fermionic sector

Coupling Properties (Deviations) Measuremens

Further re-parameterization of the n_s^c yields per categories

- Assuming narrow width approximation
- Assume the same tensor structure of the SM Higgs boson : $J^{CP} = 0^{++}$
- Link to an effective Lagrangian and use scale factors

$$\mathcal{L} = \kappa_W \frac{2m_{\mathrm{W}}^2}{v} \mathrm{W}_\mu^+ \mathrm{W}_\mu^- \mathrm{H} + \kappa_Z \frac{m_{\mathrm{Z}}^2}{v} \mathrm{Z}_\mu \mathrm{Z}_\mu \mathrm{H} - \sum_f \kappa_f \frac{m_f}{v} \mathrm{f}\bar{\mathrm{f}}\mathrm{H}$$
$$+ c_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G_{\mu\nu}^a \mathrm{H} + c_\gamma \frac{\alpha}{\pi v} A_{\mu\nu} A_{\mu\nu} \mathrm{H}$$

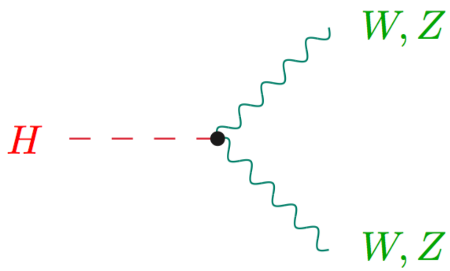
Parametrize μ_i and μ_f as a function of κ's

For example, the main contribution (ggF) to the gg channel can be written as:

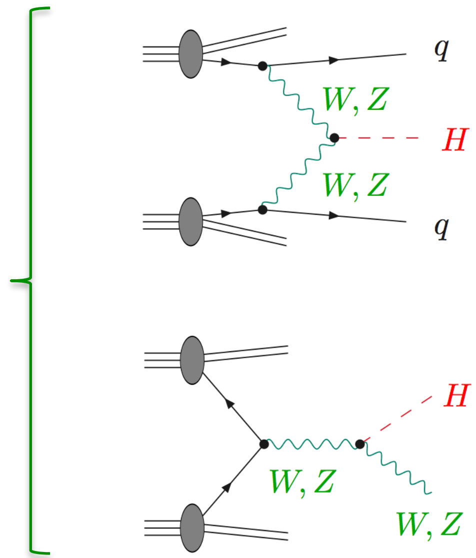
$$\sigma \cdot \mathrm{BR}\,(gg \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

Relating Couplings and Event Yields

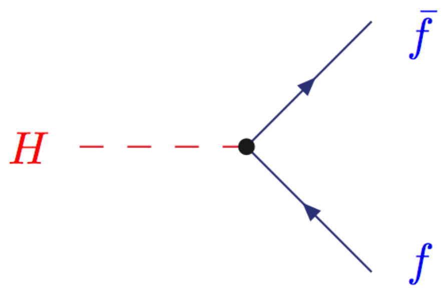
(I) Tree Level Couplings scale factors w.r.t. SM



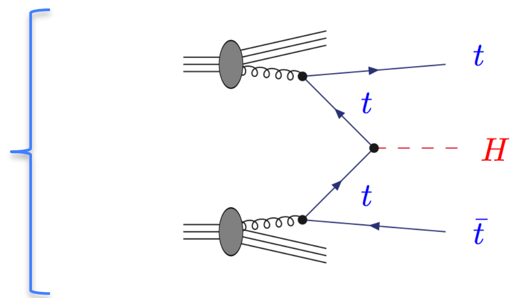
$\propto \kappa_V$



Affecting decay and production modes

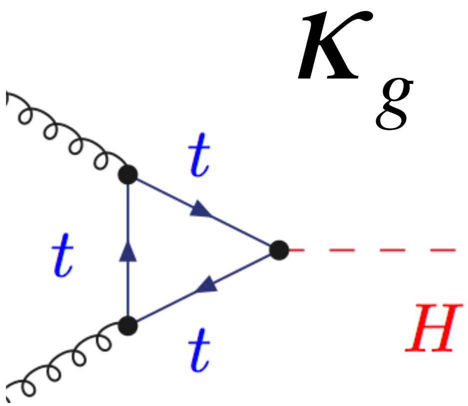


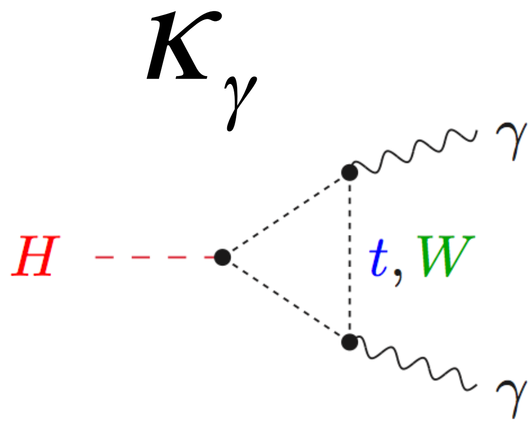
$\propto \kappa_F$



Relating Couplings and Event Yields

(II) Scale factors of loop induced couplings w.r.t. SM





- Loop expression ambiguity :
  - Can be expressed in terms of k_F and k_V (Assuming the SM field content)
  - Or treated effectively (Allowing for possible additional particles)

$$\kappa_g^2(\kappa_b, \kappa_t, m_H) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt}(m_H) + \kappa_b^2 \cdot \sigma_{ggH}^{bb}(m_H) + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}(m_H)}{\sigma_{ggH}^{tt}(m_H) + \sigma_{ggH}^{bb}(m_H) + \sigma_{ggH}^{tb}(m_H)}$$

$$\kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) = \frac{\sum_{i,j} \kappa_i \kappa_j \cdot \Gamma_{\gamma\gamma}^{ij}(m_H)}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}(m_H)}$$

Model I : Couplings to Fermions and Vector Bosons

Single scale factor for all fermion couplings κ_F and vector boson κ_V couplings

$Br_{\gamma\gamma, etc...}$

$\sigma_{ggH, VBF, etc...}$

Boson and fermion scaling without 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	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

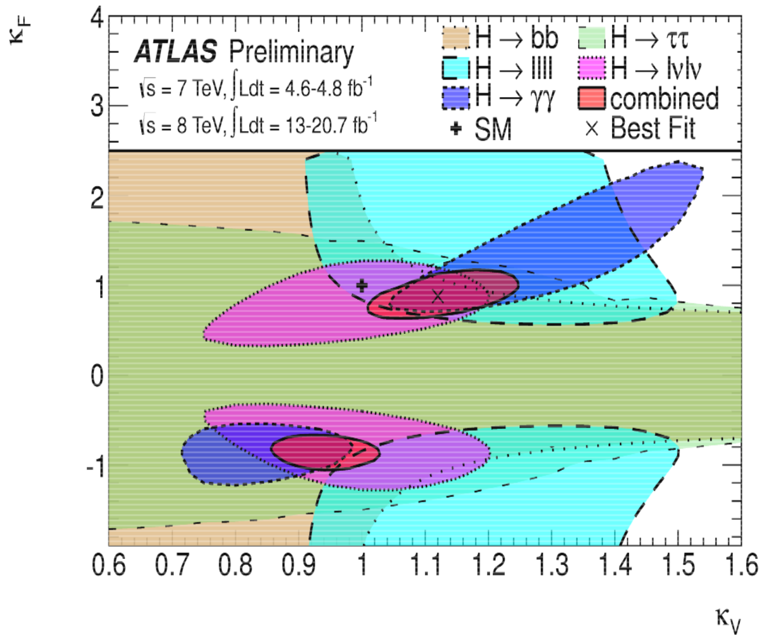
Boson and fermion scaling without assumptions on the total width

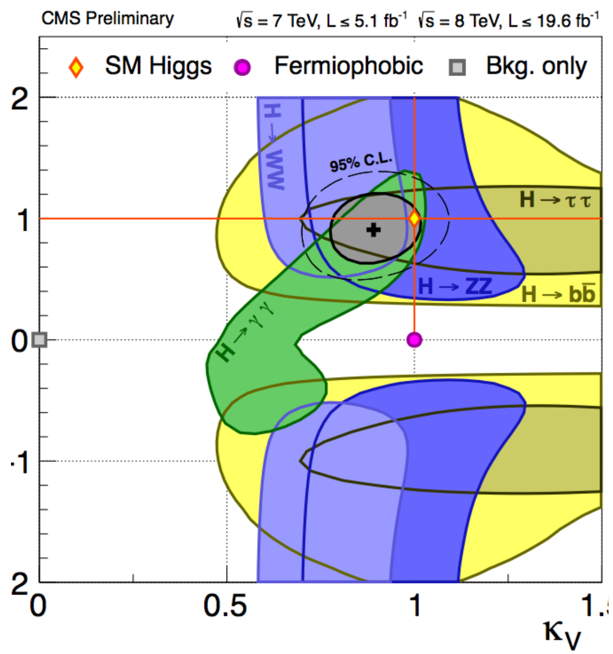
Free parameters: $\kappa_{VV} (= \kappa_V \cdot \kappa_V / \kappa_H)$, $\lambda_{fV} (= \kappa_f / \kappa_V)$.

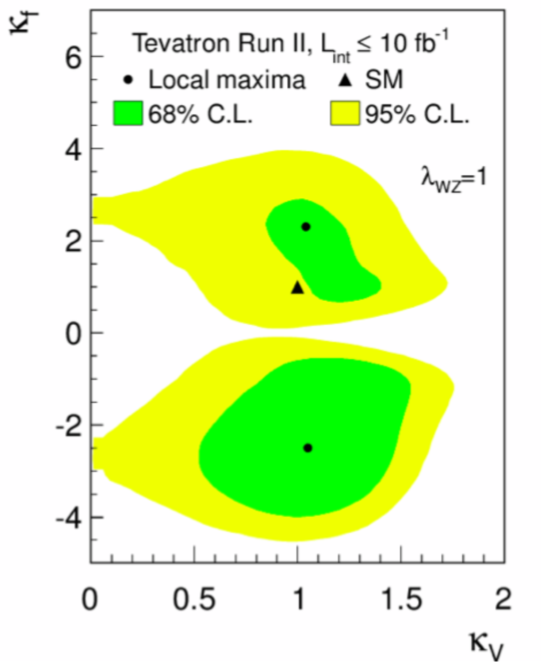
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH, $t\bar{t}H$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	$\kappa_{VV}^2 \cdot \lambda_{fV}^2$		$\kappa_{VV}^2 \cdot \lambda_{fV}^2 \cdot \lambda_{fV}^2$	
VBF, WH, ZH	$\kappa_{VV}^2 \cdot \kappa_\gamma^2(\lambda_{fV}, \lambda_{fV}, \lambda_{fV}, 1)$	κ_{VV}^2		$\kappa_{VV}^2 \cdot \lambda_{fV}^2$	

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

Main results I : Probing the coupling to SM particles





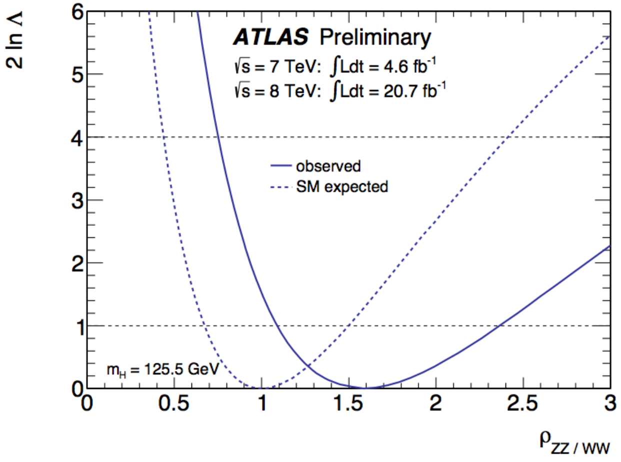


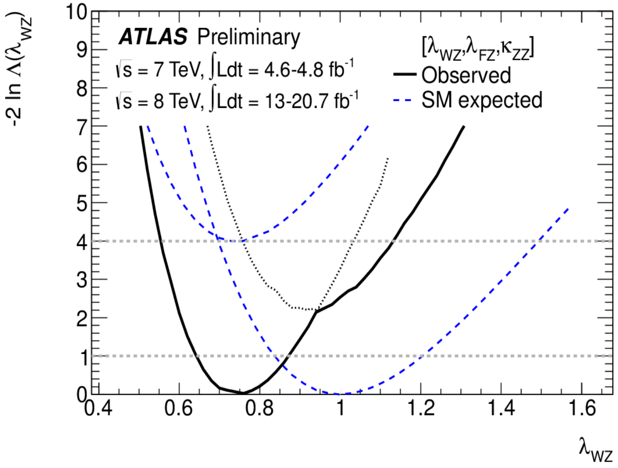
- By convention sign on the fermion yukawa strength multiplier (relying on the $\gamma\gamma$ strength primarily)… ambiguity inspired tH analyses

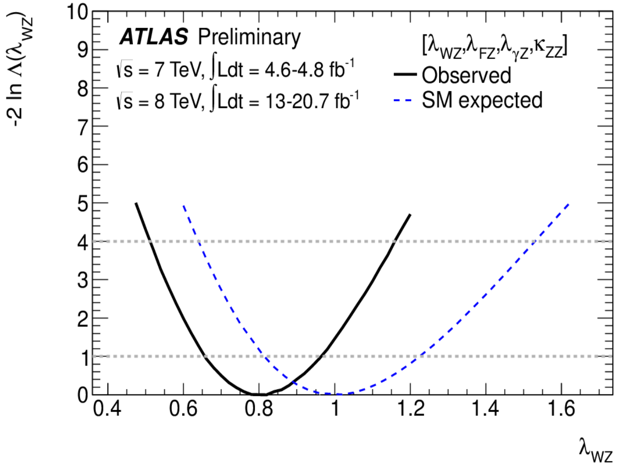
- Checking the direct and indirect couplings to fermions

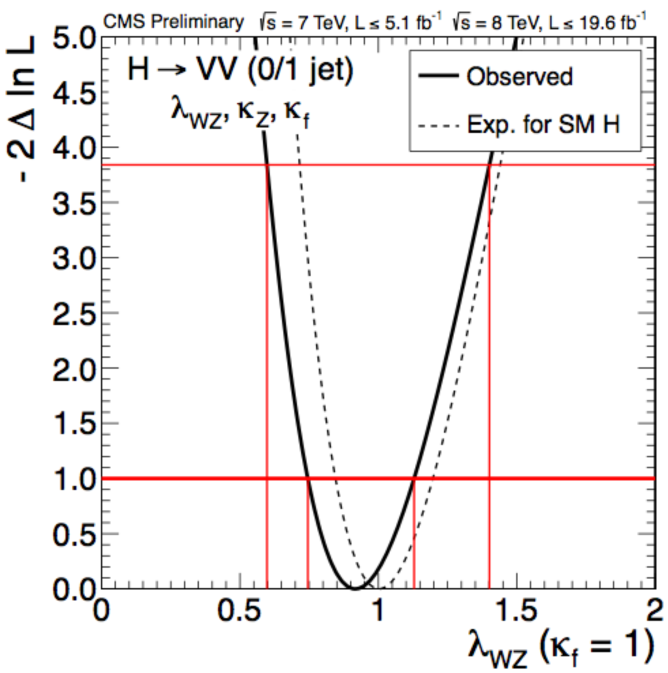
- Checks of specific composite models

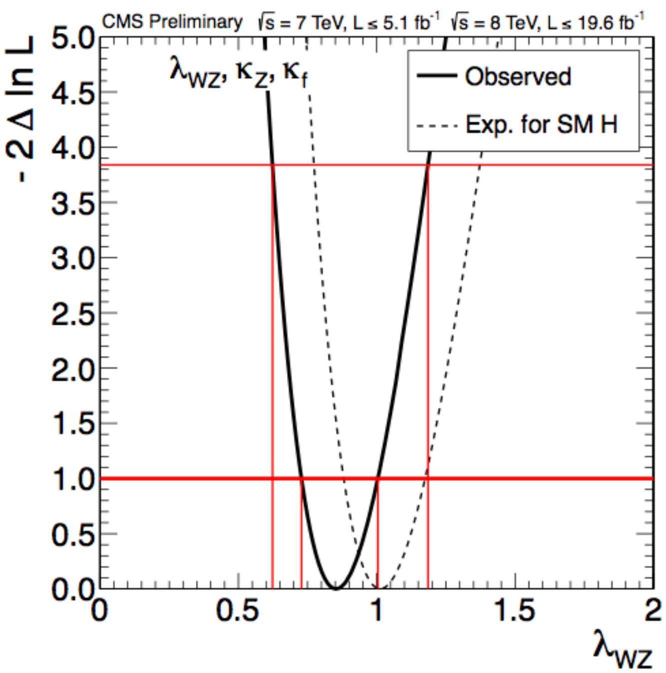
Main results II : Probing the W to Z ratio (custodial symmetry)





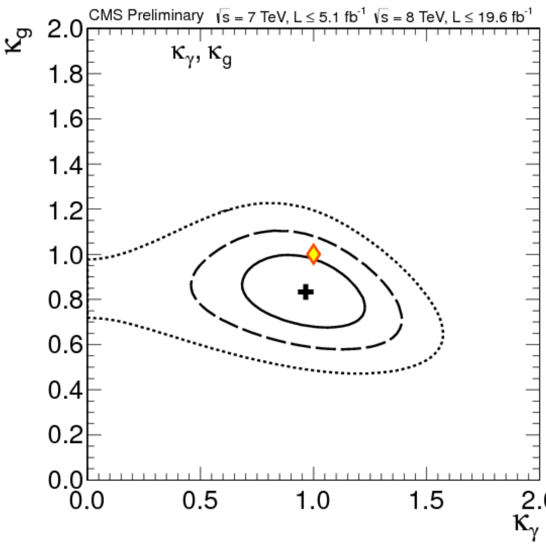


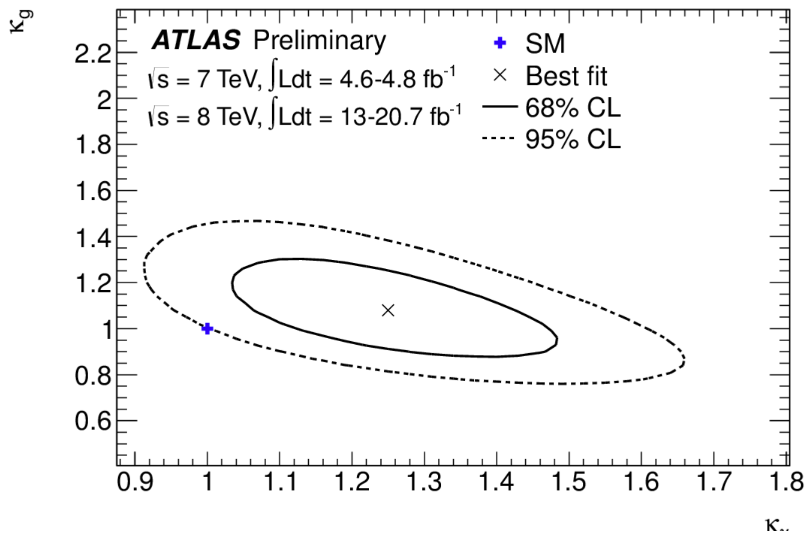




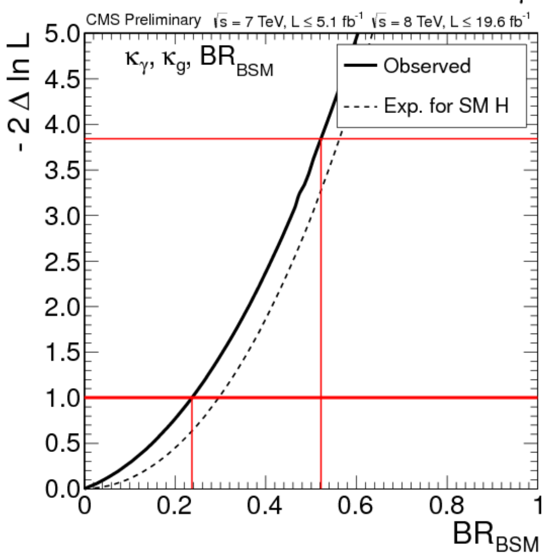
Main results III : Probing physics beyond the Standard Model

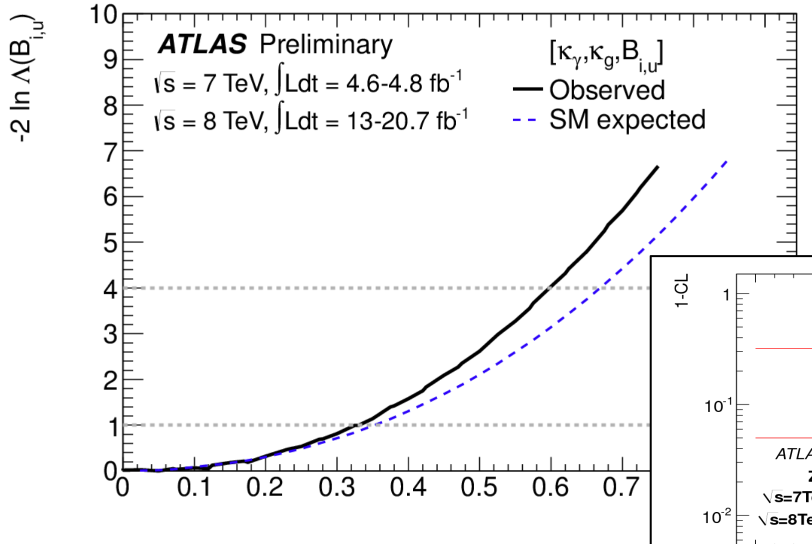
(In the decays and/or in the loops)

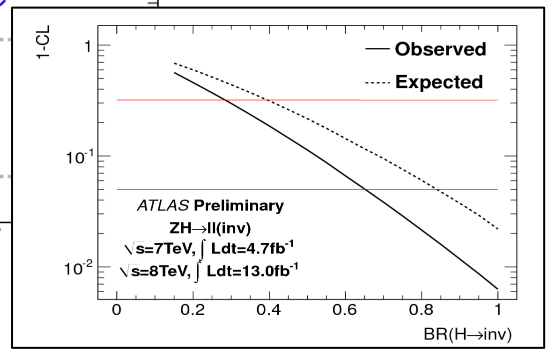


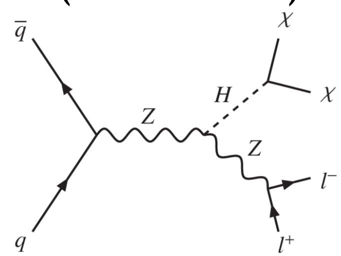


Also direct invisible only search (Tomorrow)

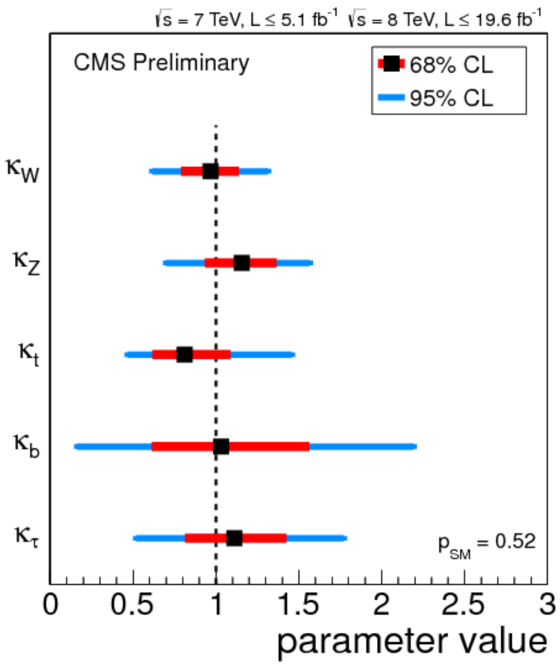


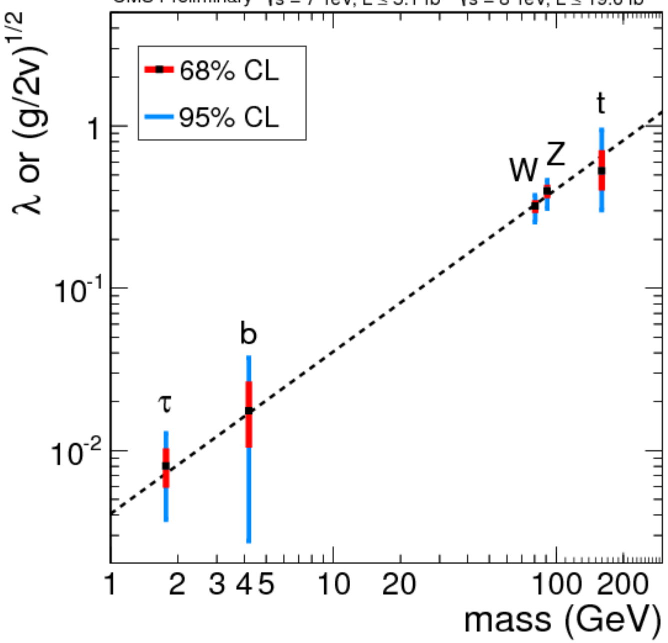


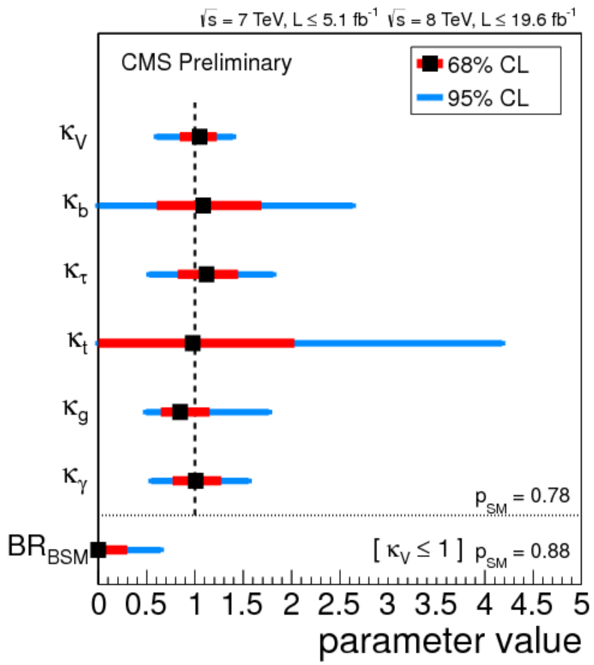




Main results IV : Other Relevant Models



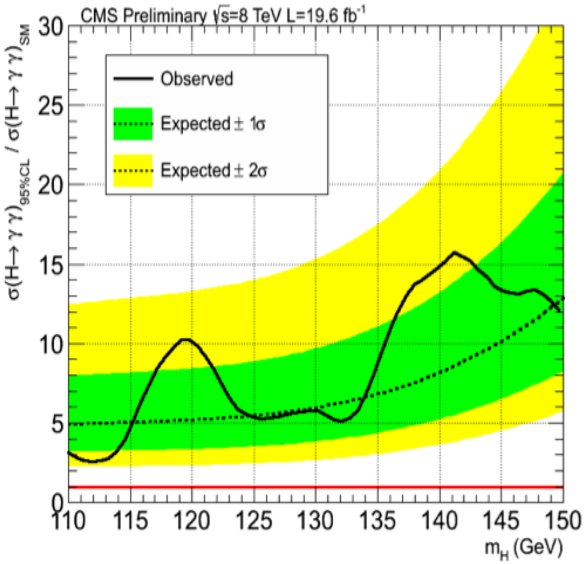




- Test of the predicted Yukawa structure of the couplings
- 3 coupling strength parameter fits κu, κd and κV for MSSM and 2HDM limits

ttH

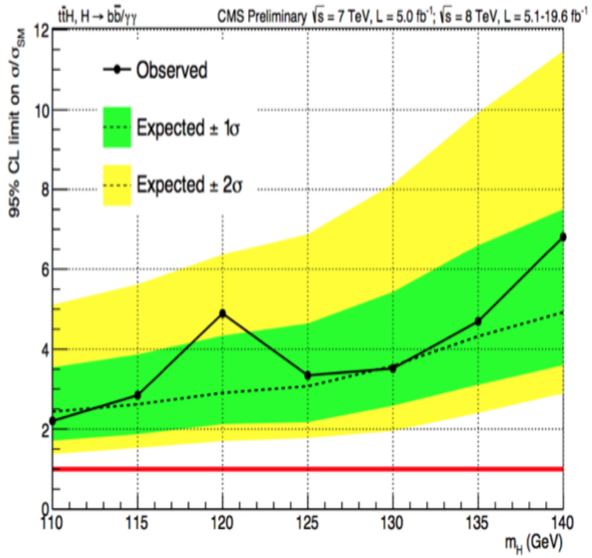
$H \rightarrow \gamma\gamma$



Key Features:

- Robust channel
- Will require (very) large statistics

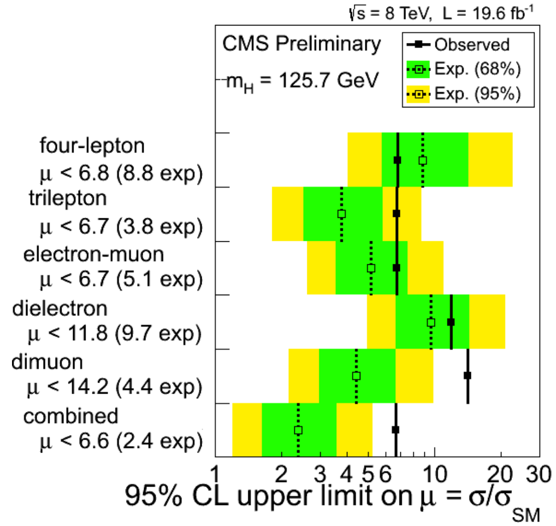
$H \rightarrow bb$



Key Features:

- Will it ever be possible be sensitive?
- Relies on the control of the tt+HF background

$H \rightarrow WW, \tau\tau$

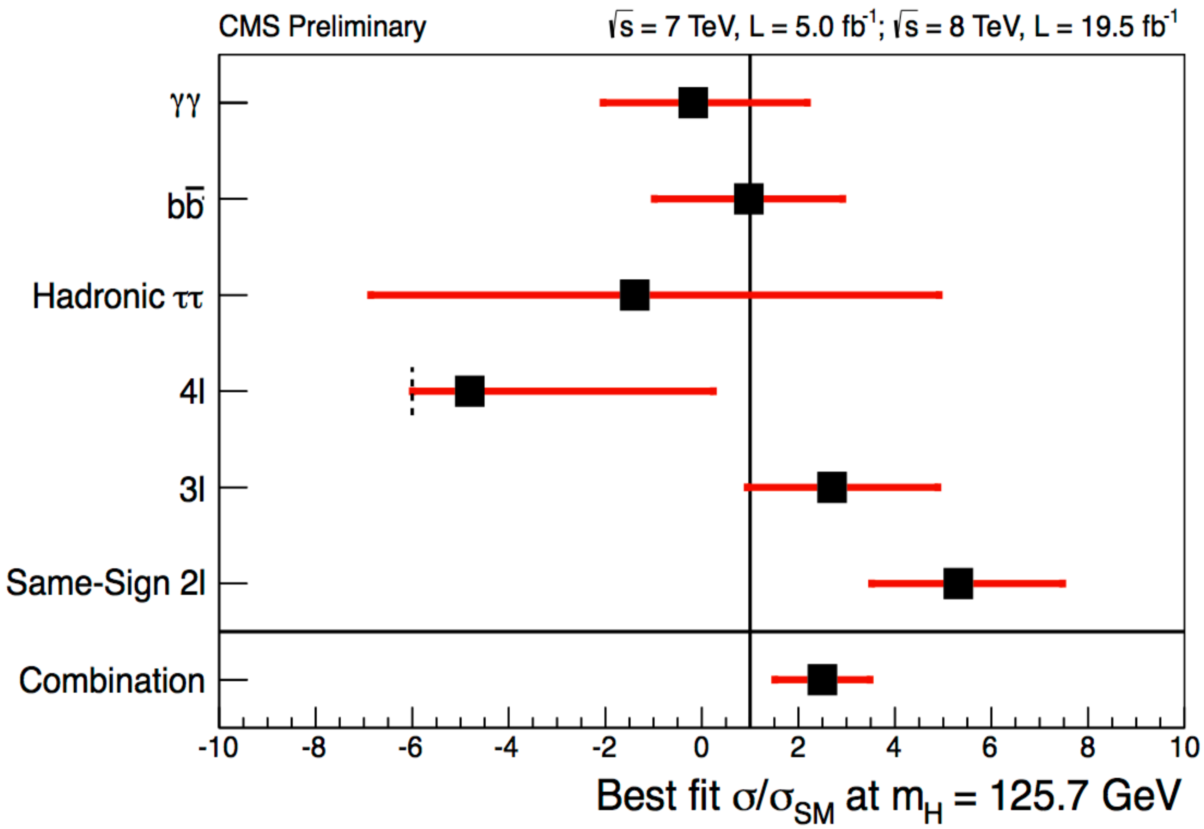


Key Features:

Inclusive multi-signatures

ttH

Summary and combination :



Beyond any reasonable doubt…

The consistency of rates of the three discovery channels and the supporting evidence from the additional channels leaves little doubt about the nature of the particle.

For it NOT to be a Higgs boson would require a very savvy conspiring impostor

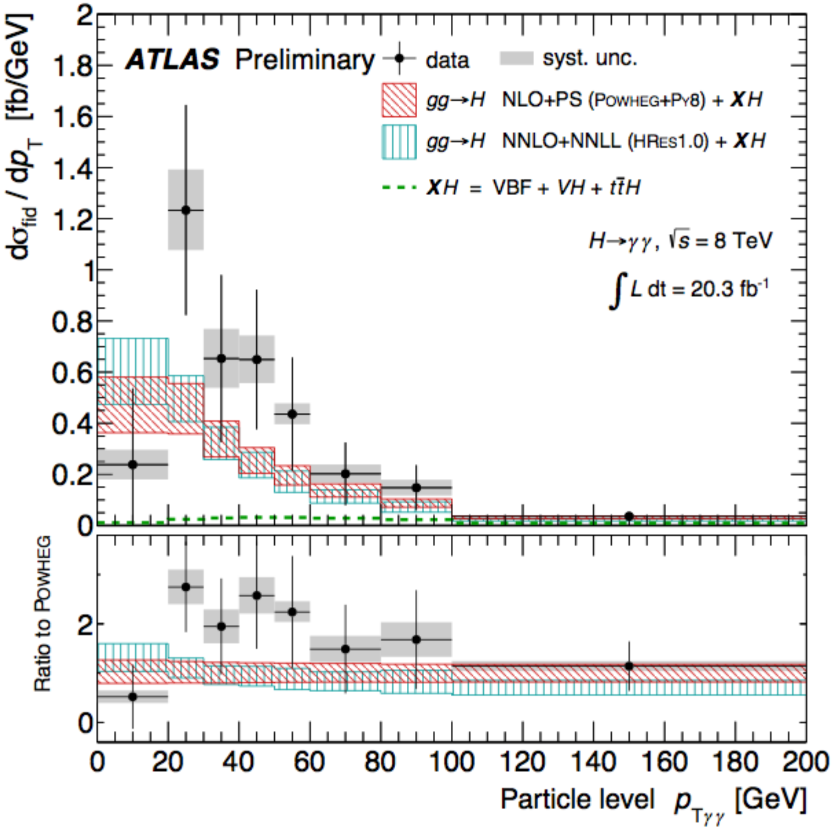
- Observation in the diphoton channel implies $C = 1$
- Observation in the diphoton channel (Landau-Yang theorem) implies $J \neq 1$
- Observation in WW channel favors $J=0$
- Observation in the ZZ and WW channels disfavors $P=-1$

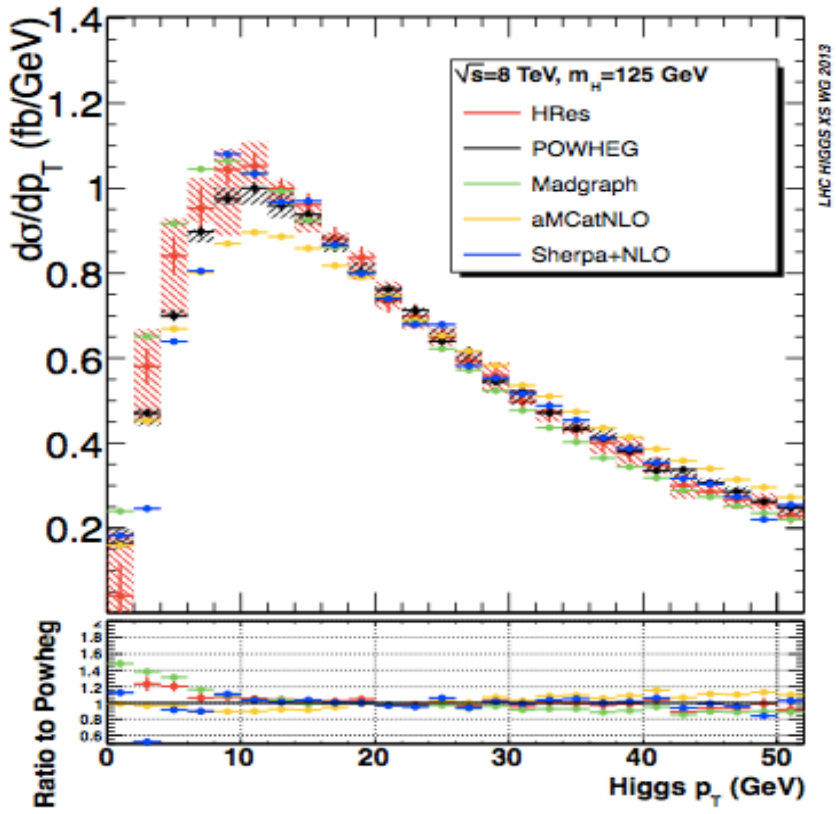
This being said we still perform analyses to test the main quantum numbers directly from model independent observables.

Measurement of Differential Cross Sections

Differential Cross Sections

(Differential and fiducial cross sections in the Diphoton channel)





Possibly learn about the loop content of gluon fusion

Differential Cross Sections

(Differential and fiducial cross sections in dijet - Diphoton channel)