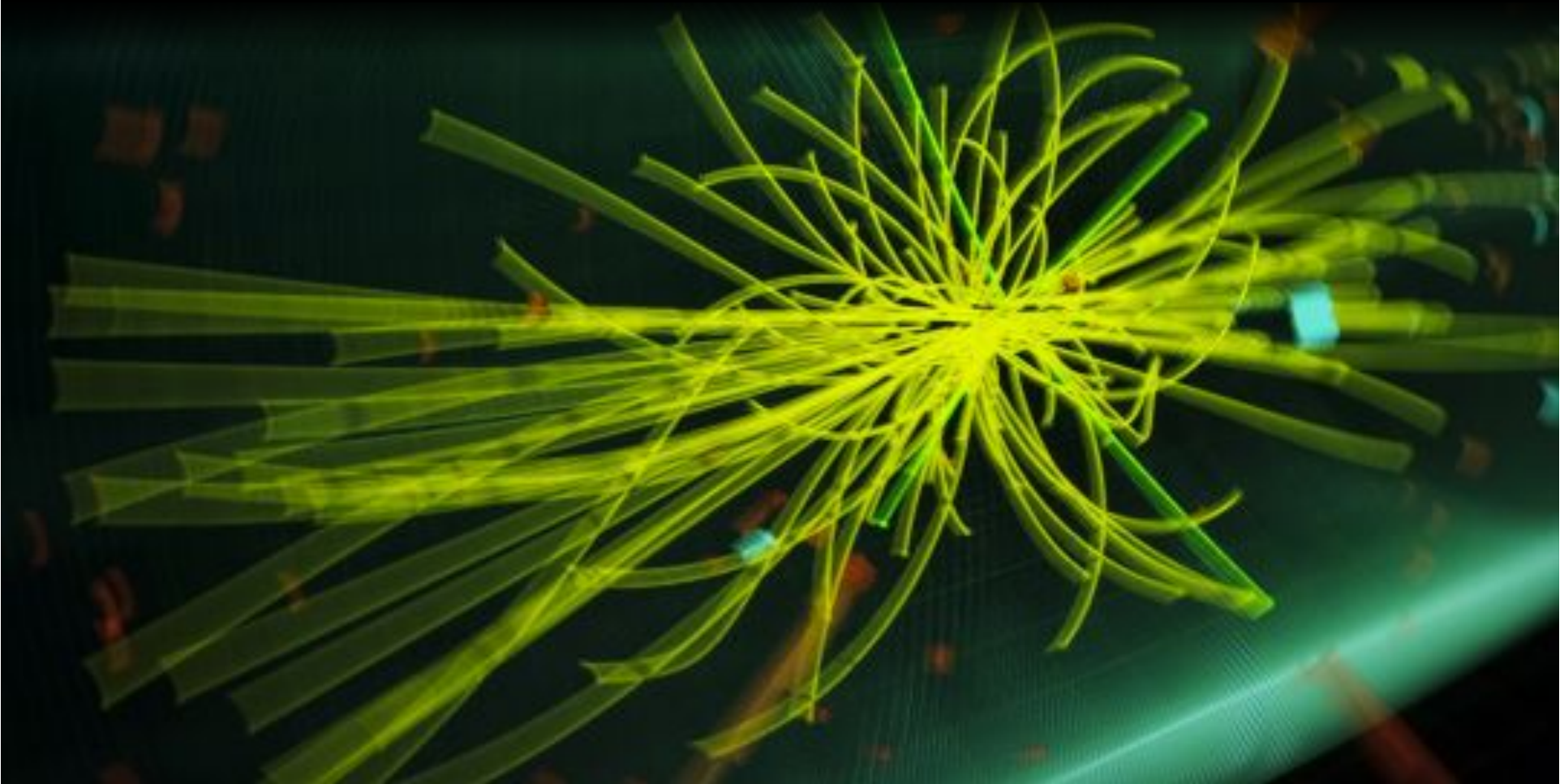


# Higgs Searches at LHC

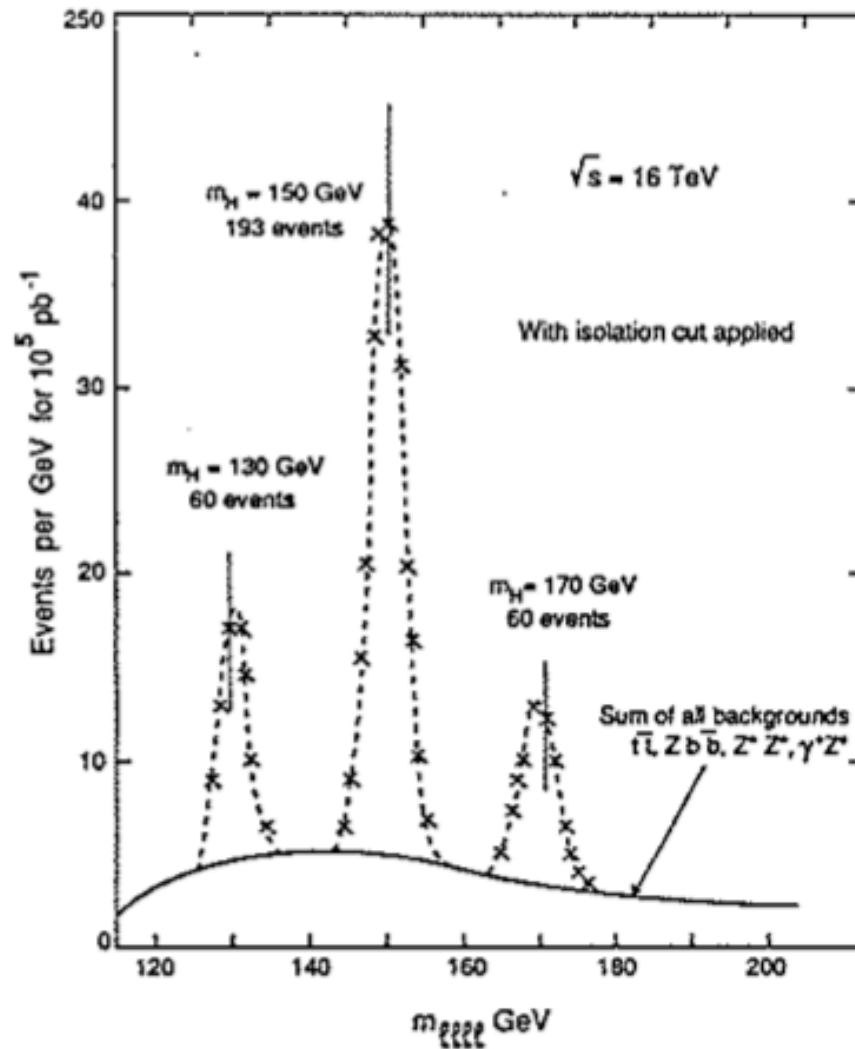


Marumi Kado

Laboratoire de l'Accélérateur Linéaire (LAL)  
IN2P3, CNRS

# Half a Century of Higgs Hunt...

...almost half of which preparing the searches at LHC

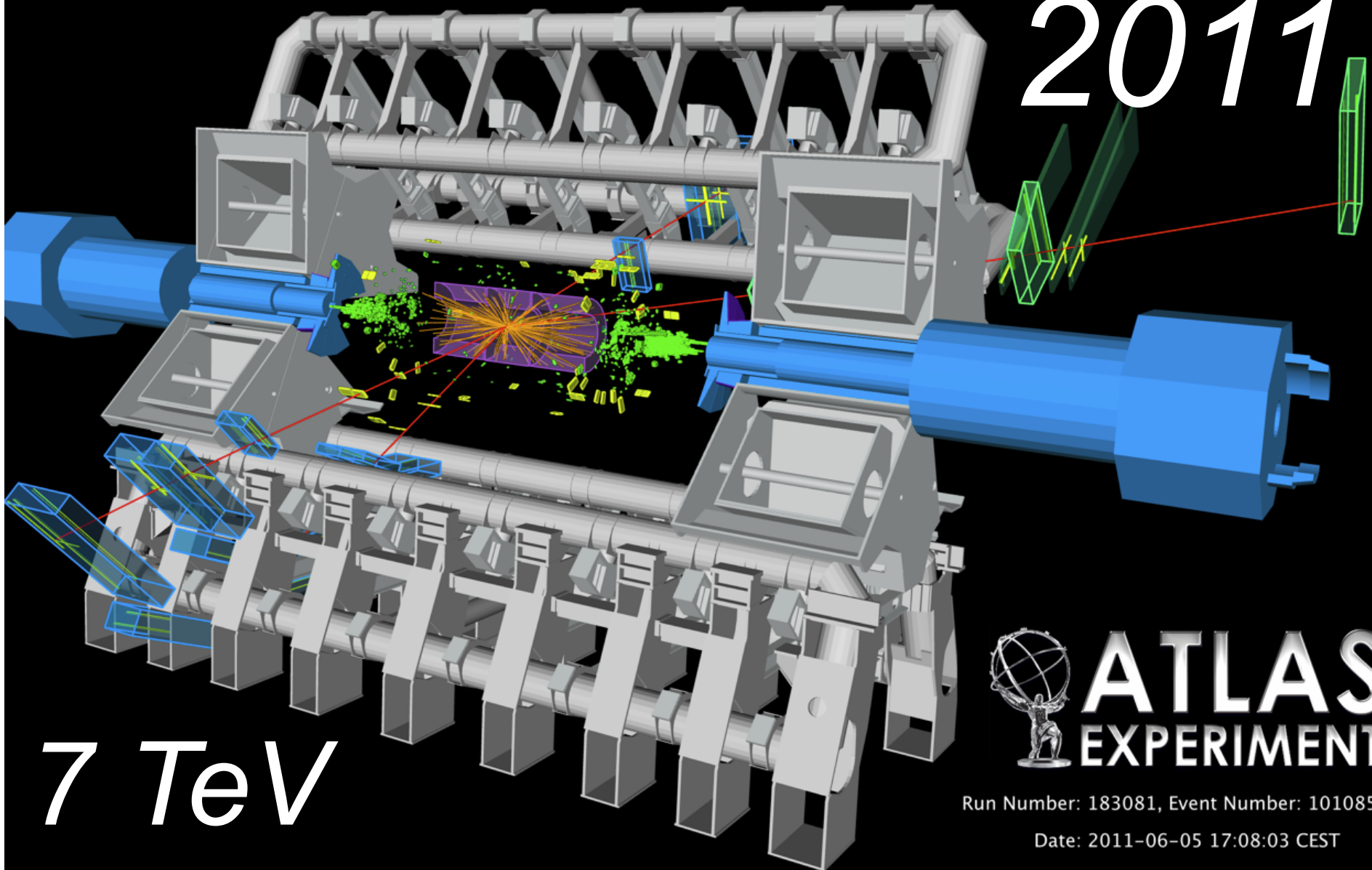


# 1990

Proceedings of LHC Workshop  
(Aachen, 1990):  $\sqrt{s} = 16 \text{ TeV}, 100 \text{ fb}^{-1}$

4  $\mu$  event ... *Standard EW only or Higgs?*

2011



7 TeV



**ATLAS**  
EXPERIMENT

Run Number: 183081, Event Number: 10108572

Date: 2011-06-05 17:08:03 CEST





Center-of-Mass Energy (Nominal)  
14 TeV

The image shows an aerial view of the LHC tunnel, which is a large red oval. The tunnel is surrounded by a landscape of green fields and small towns. In the background, there are mountains with snow-capped peaks under a clear blue sky. The LHCb detector is located at the top of the tunnel, and the CMS, ATLAS, and ALICE detectors are located at the bottom. The text 'Center-of-Mass Energy (Nominal) 14 TeV' is centered above the tunnel, and 'Center-of-Mass Energy (2010-2011) 7 TeV' is centered below it. The detector names are written in red and white text around the tunnel.

*LHCb*

***ATLAS***

Center-of-Mass Energy (2010-2011)  
7 TeV

***CMS***

*ALICE*



# CMS

Total weight 12500 t  
Overall diameter 15 m  
Overall length 21.6 m

**ECAL** 76k scintillating  
PbWO<sub>4</sub> crystals

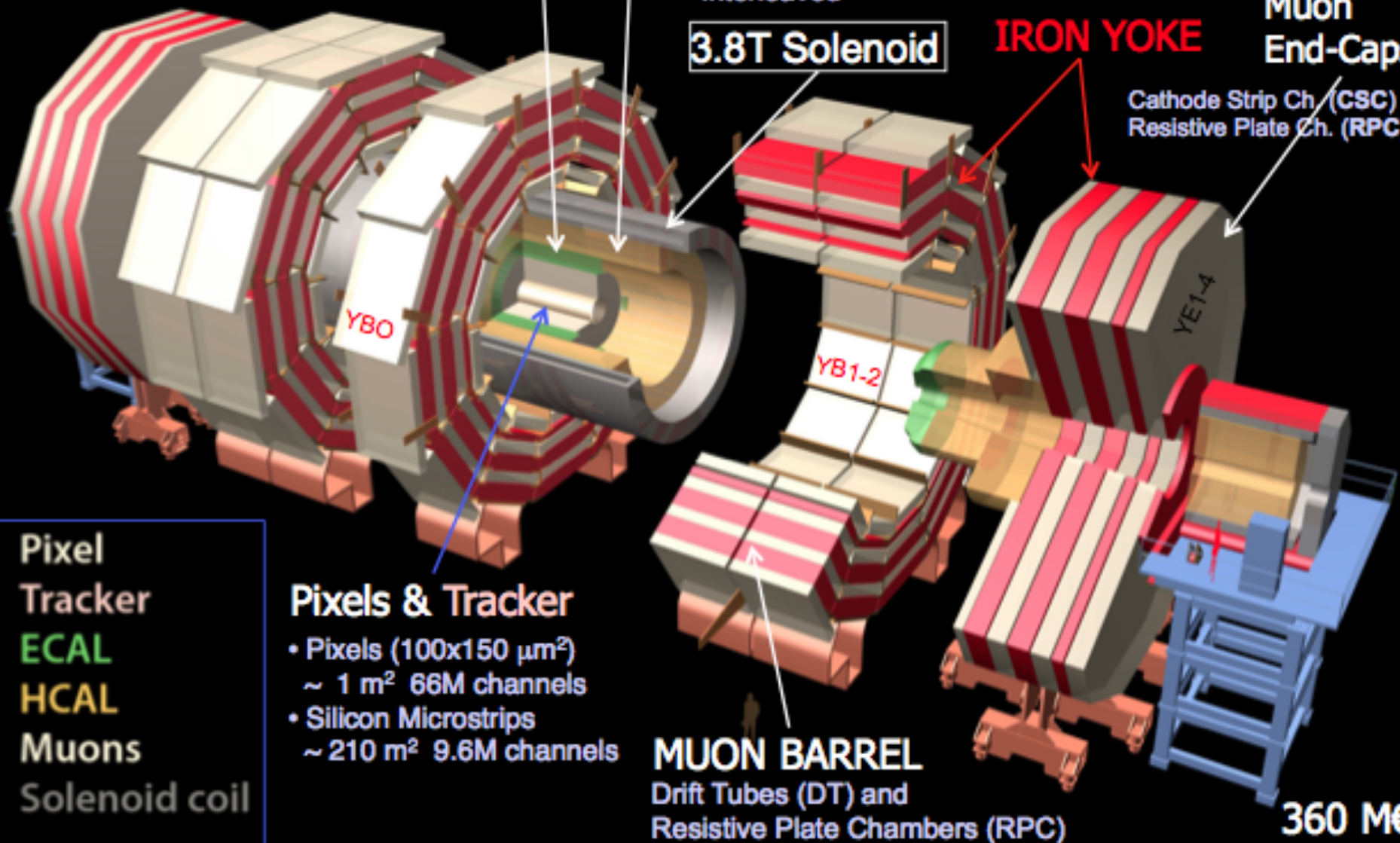
**HCAL** Scintillator/brass  
interleaved

**3.8T Solenoid**

**IRON YOKE**

**Muon  
End-Caps**

Cathode Strip Ch. (CSC)  
Resistive Plate Ch. (RPC)



Pixel  
Tracker

**ECAL**

**HCAL**

Muons

Solenoid coil

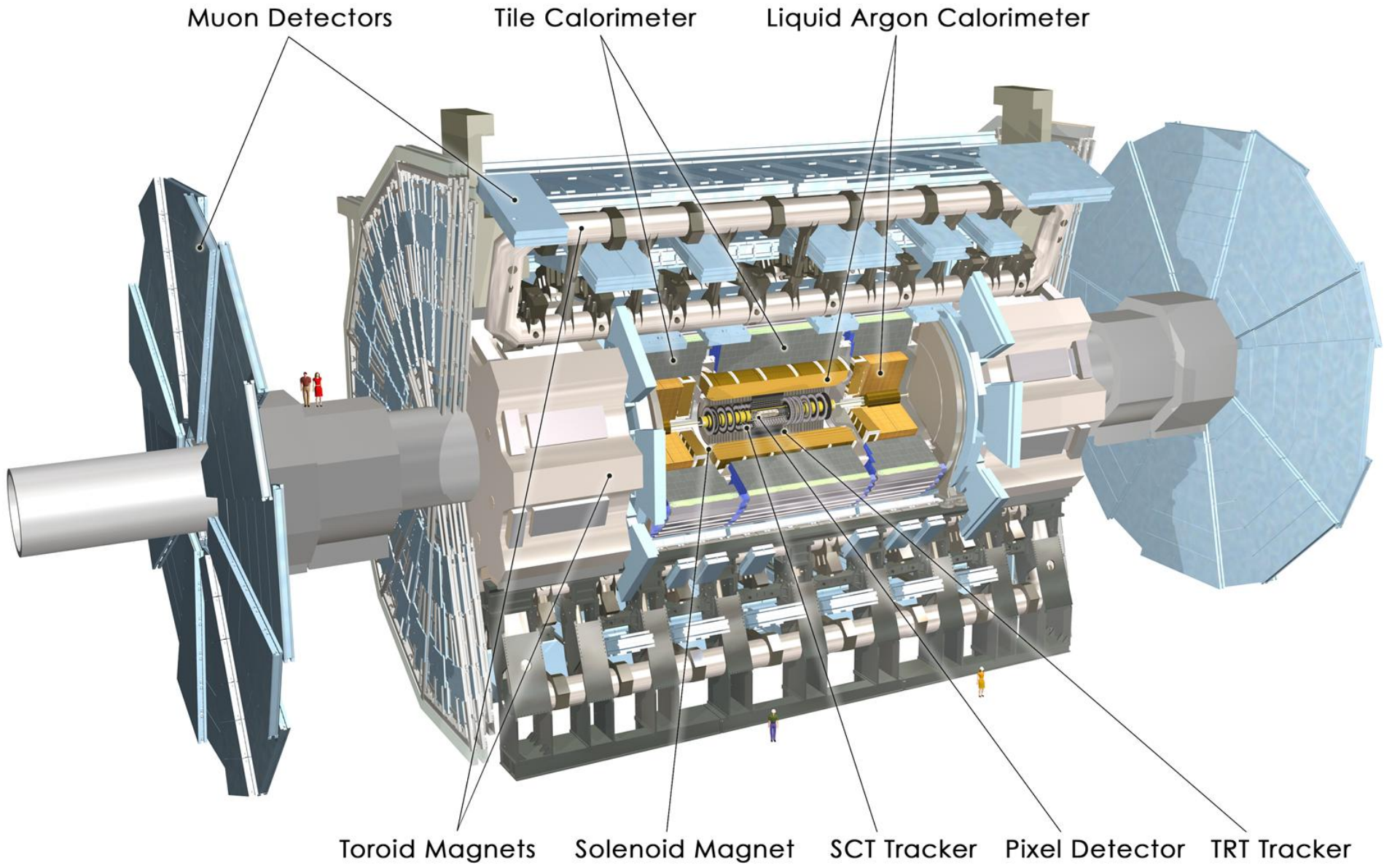
**Pixels & Tracker**

- Pixels (100x150  $\mu\text{m}^2$ )  
~ 1 m<sup>2</sup> 66M channels
- Silicon Microstrips  
~ 210 m<sup>2</sup> 9.6M channels

**MUON BARREL**

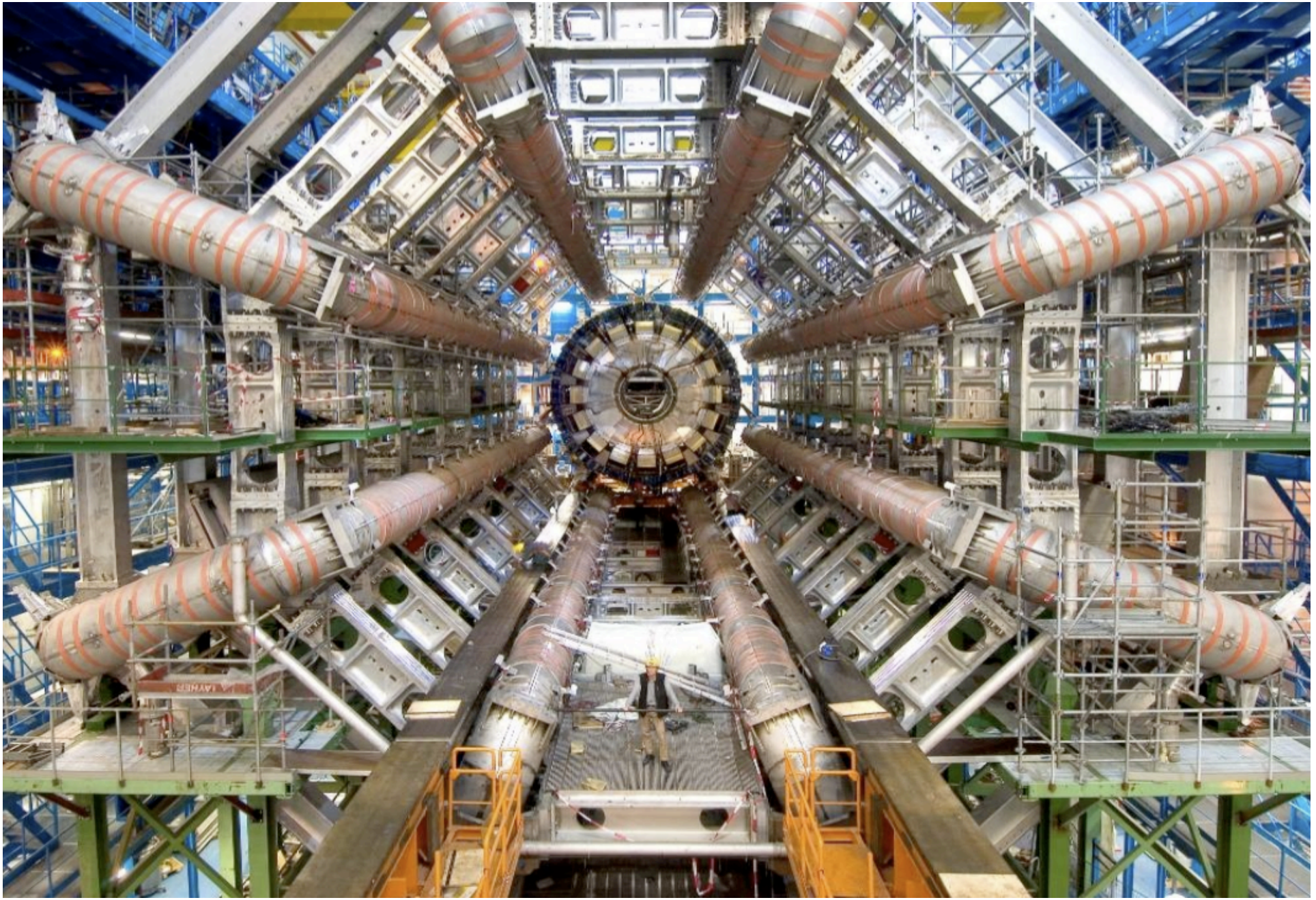
Drift Tubes (DT) and  
Resistive Plate Chambers (RPC)

**360 M€**



# ATLAS

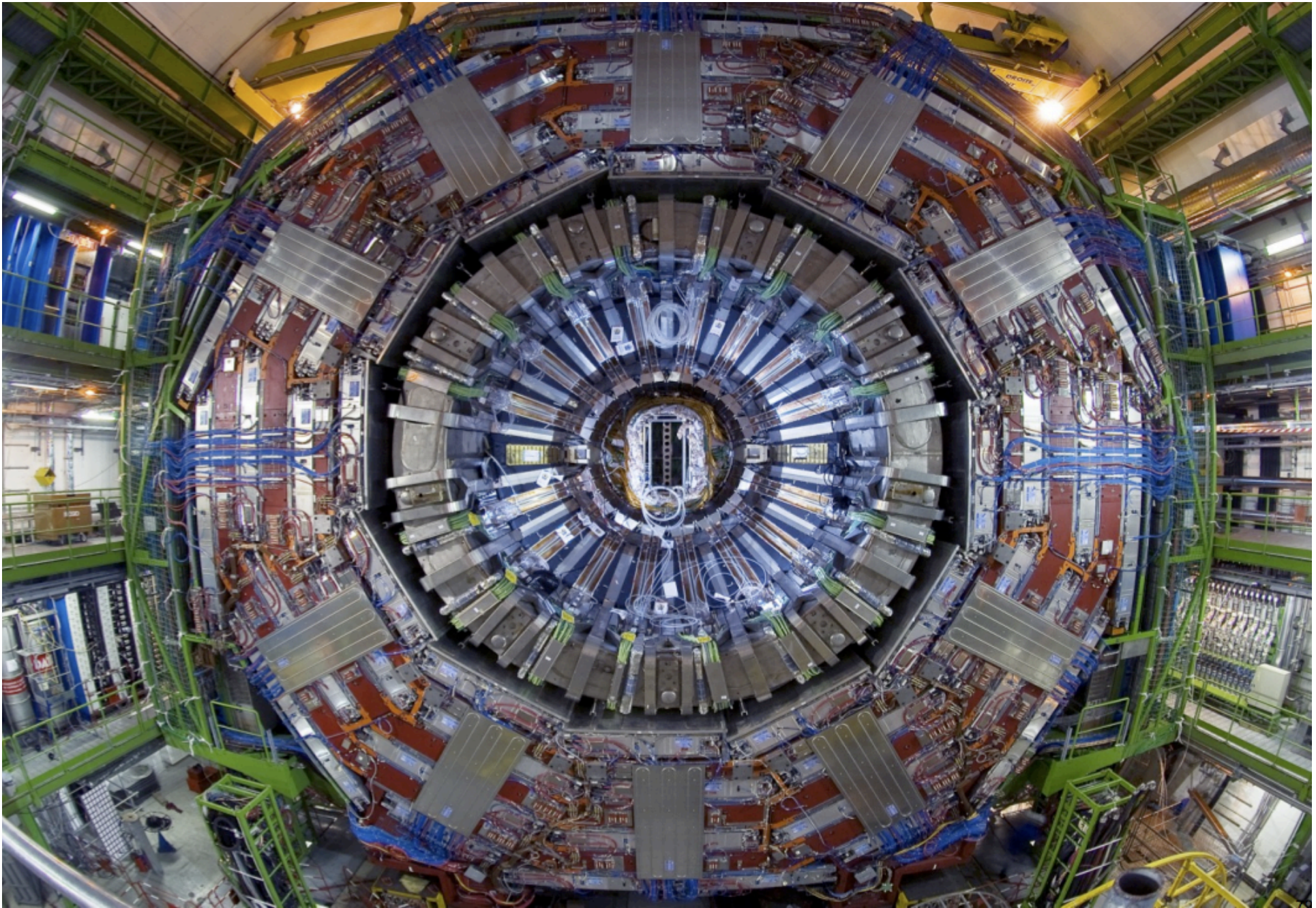




# ATLAS

FCPPL Workshop 21/03/2012





CMS

FCPPL Workshop 21/03/2012



# Luminosity and Beam cross section

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Reduction factor W/ Beam crossing angle  $O(0.9)$

Parameter	2010	2011	Nominal
N( $10^{11}$ p/bunch)	1.2	1.35	1.15
k (N bunches)	368	1380	2808
Bunch spacing	150	50	25
$\epsilon$ ( $\mu\text{m rad}$ )	2.4-4	1.9-2.3	3.75
$\beta^*$ (m)	3.5	1.5-1	0.55
L ( $\text{cm}^{-2}\text{s}^{-1}$ )	$2 \times 10^{32}$	$3.3 \times 10^{33}$	$10^{34}$

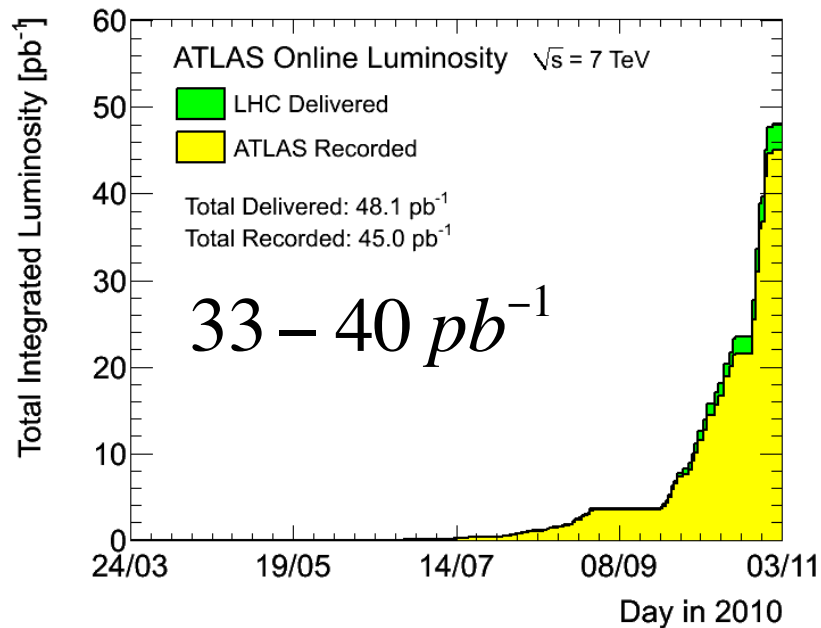
Beam parameters close to nominal in terms of luminosity

# Two Years of Remarkable LHC operations

Glimpse at the Luminosity

2010

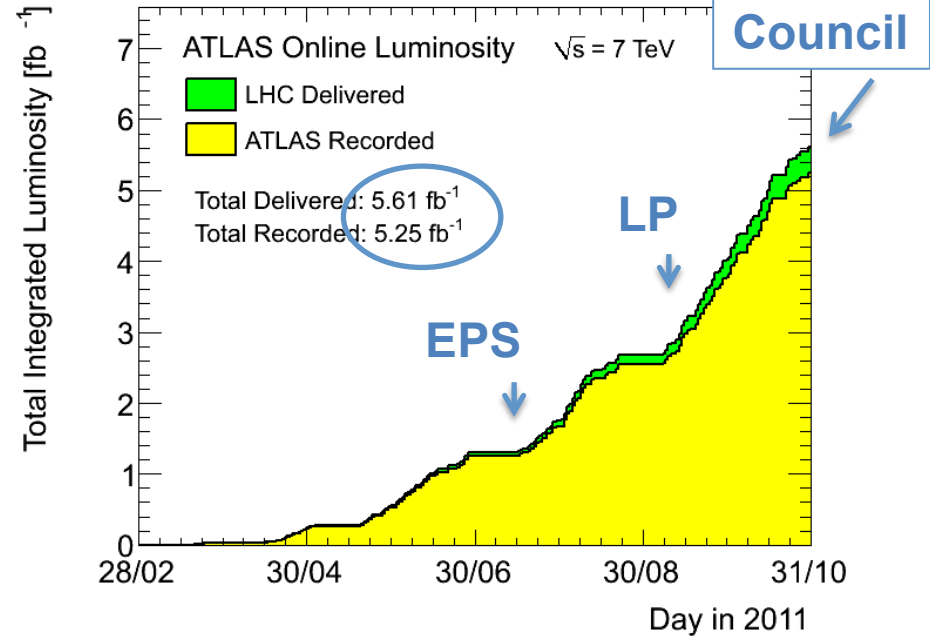
Re-discovery of the SM at LHC



Measurement of rather detailed properties of the W and Z boson production

2011

Closing in on the Higgs search



Measurement of di-boson production and Higgs searches



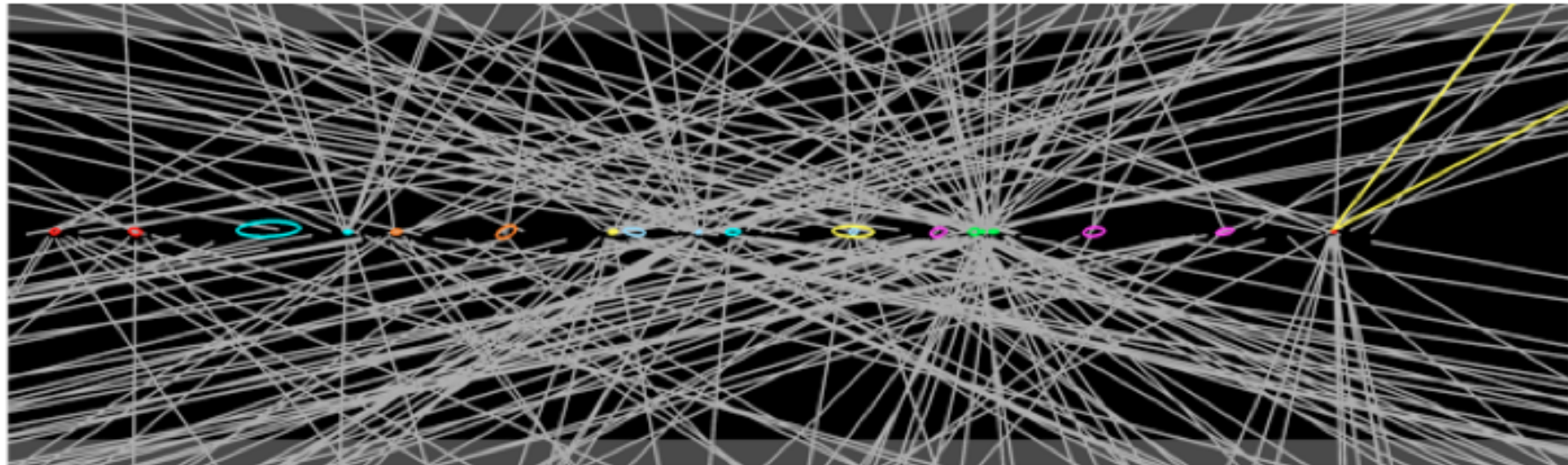
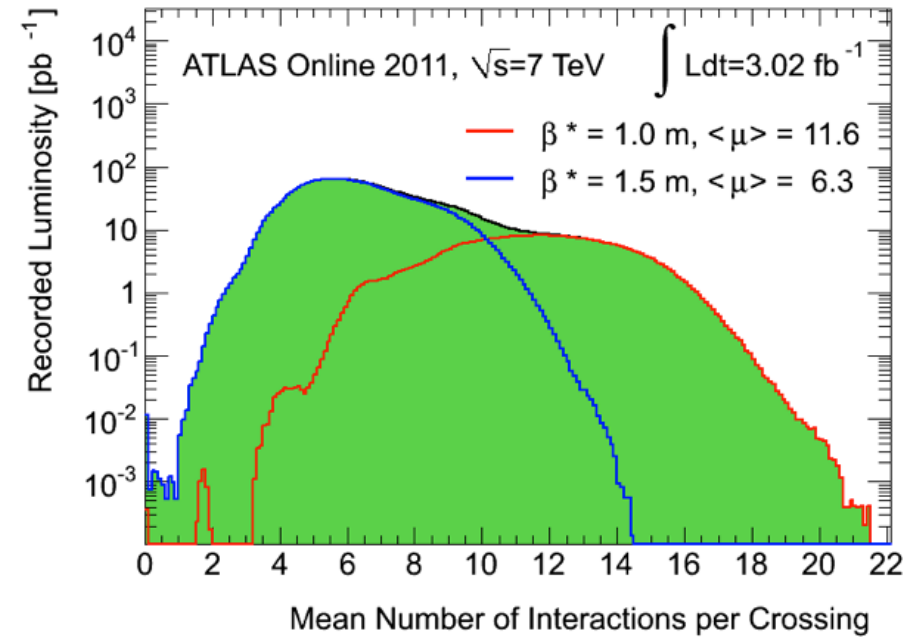
# The 2011 Dataset

2011 (Fall)

$$\sim 5 \text{ fb}^{-1}$$

Much higher PU!

Recent event with 15 Vertices



# Preamble : Breakthroughs in Phenomenology

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 and POWHEG.
- NLO+NLL or NNLL, CAESAR, ResBos, HqT
- NNLO, FEHIP, FEWZ, HNNLO, DYNNLO
- ...

## - NNLO PDFs sets

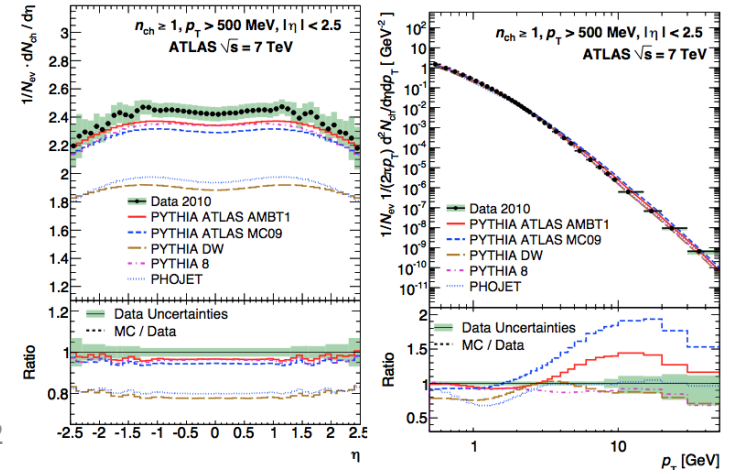
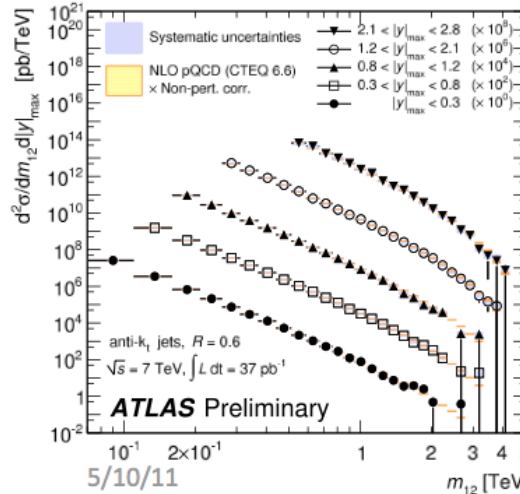
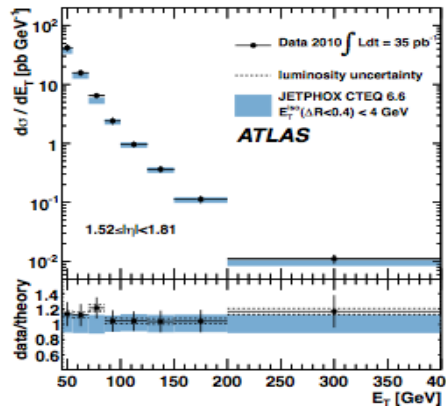
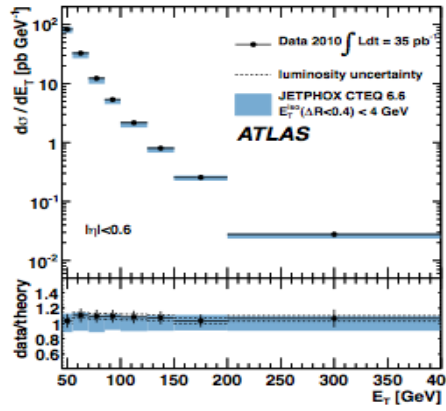
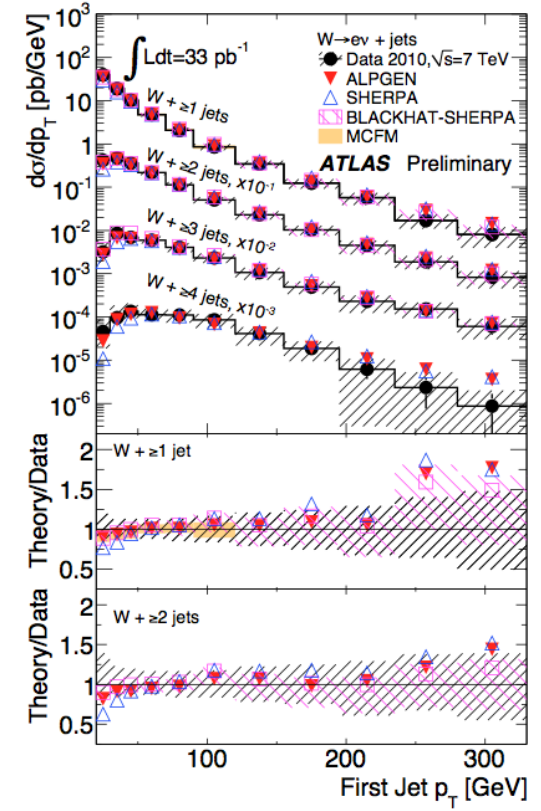
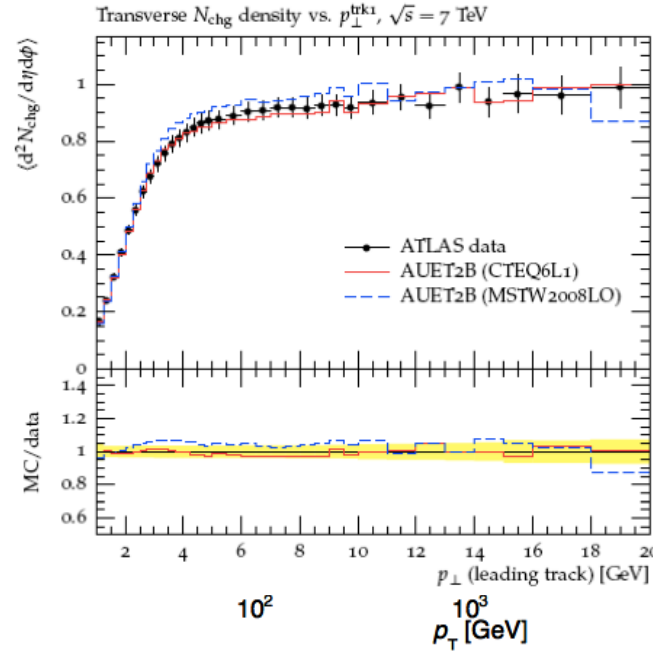
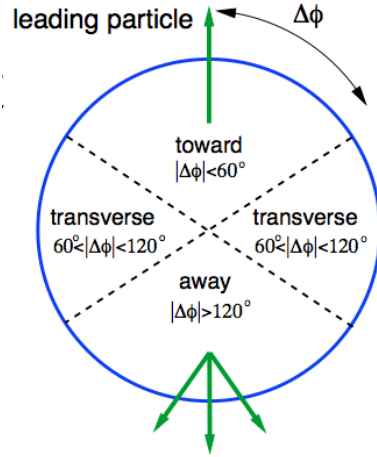
## - Parton Shower (and Matrix Element matching) improvements :

Pythia (8.1), Herwig++, Sherpa and CKKW (1.3) and MadGraph (5.0) performing very well (Including description of the Pile Up and the underlying event).

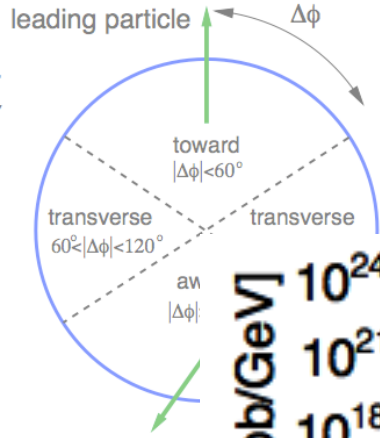
## - The Jet revolution (Fast Jet) : Allowing to compute in reasonable time infra-red safe $k_T$ jets.



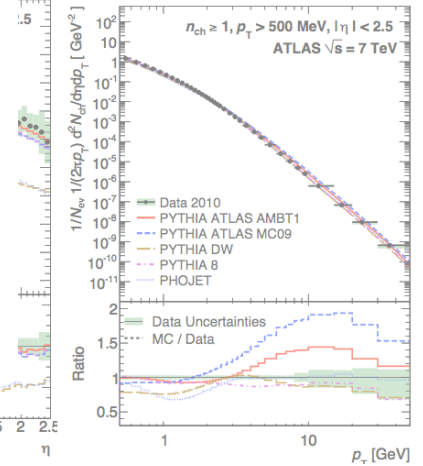
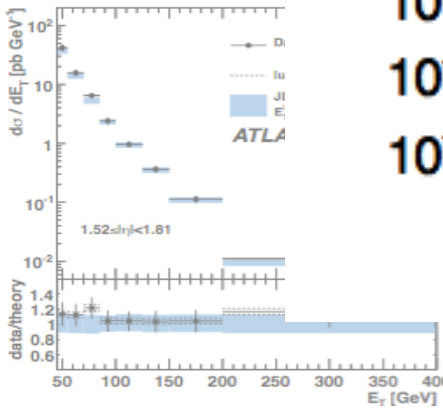
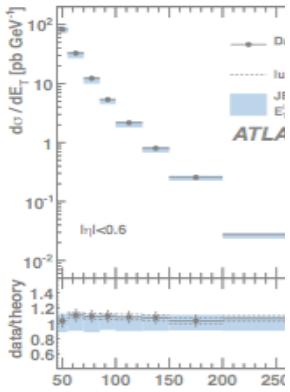
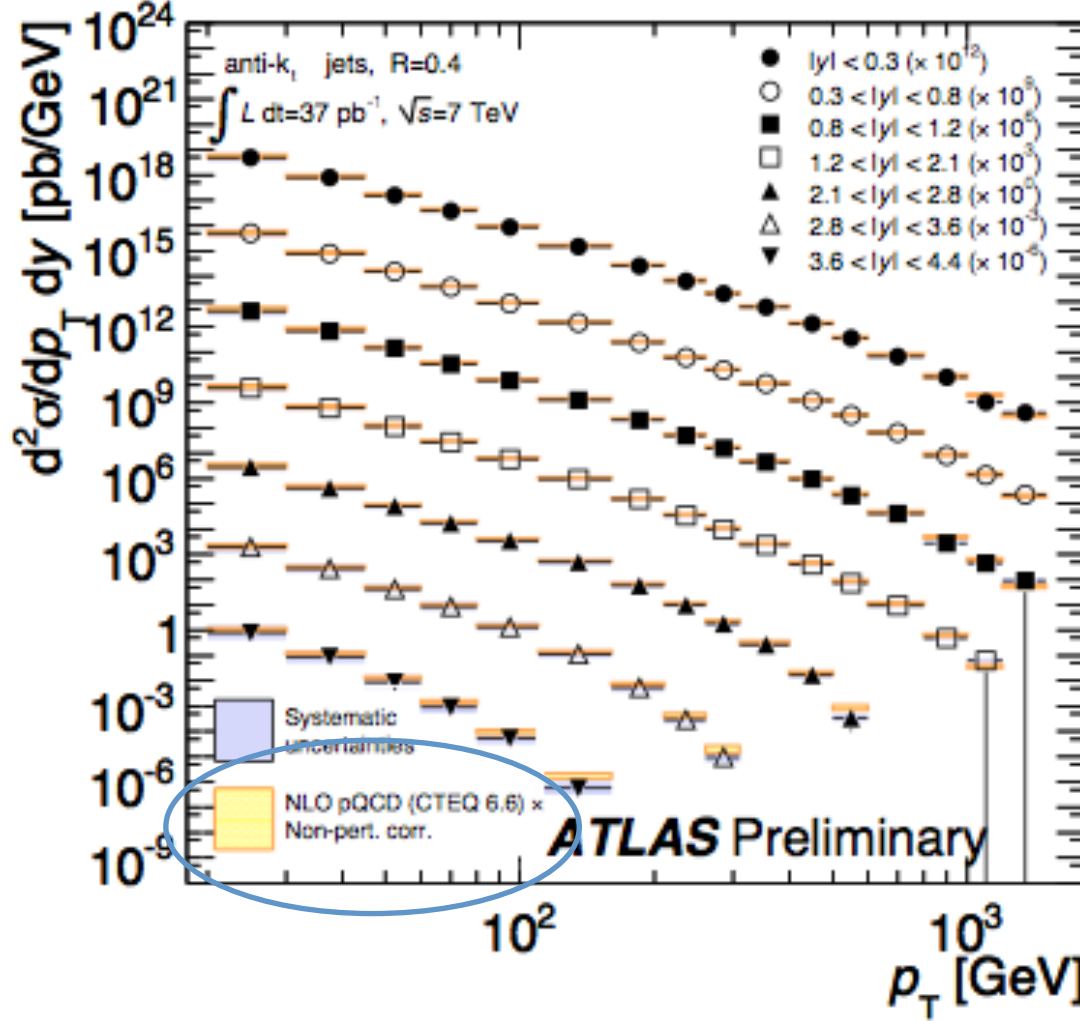
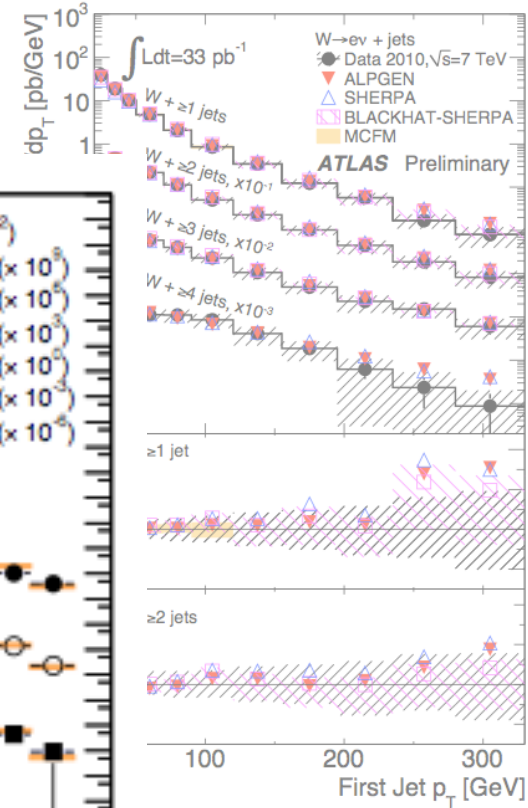
# QCD



# QCD

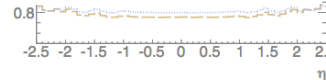


Transverse  $N_{ch}$  density vs.  $p_{\perp}^{trk1}$ ,  $\sqrt{s} = 7$  TeV



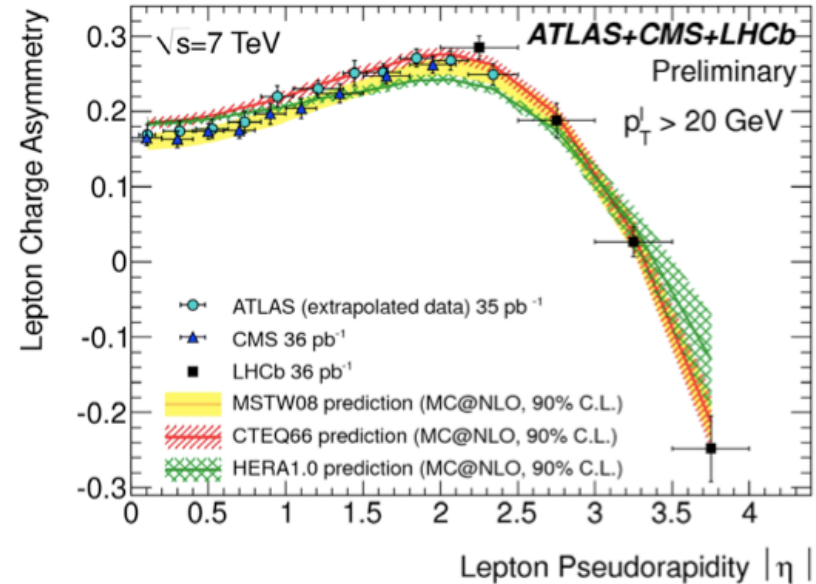
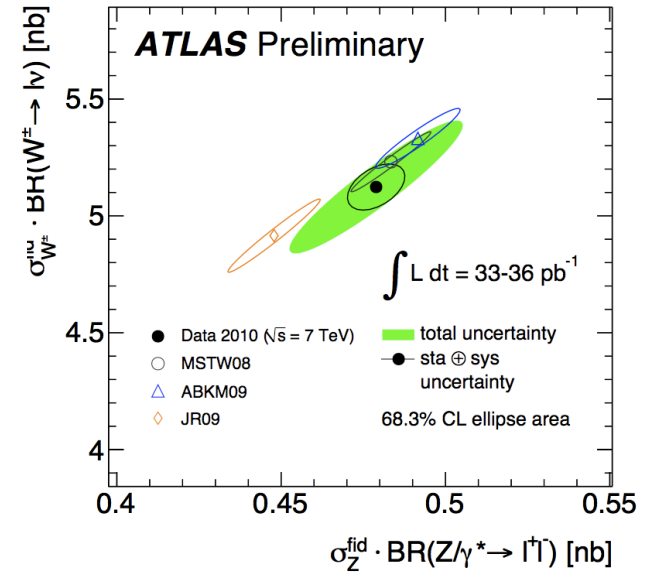
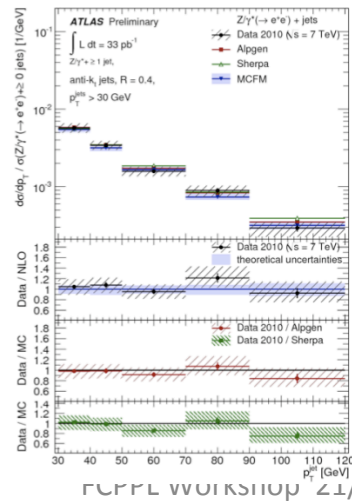
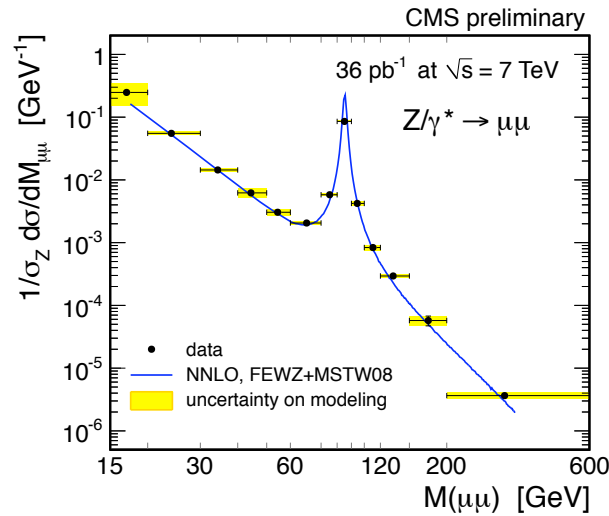
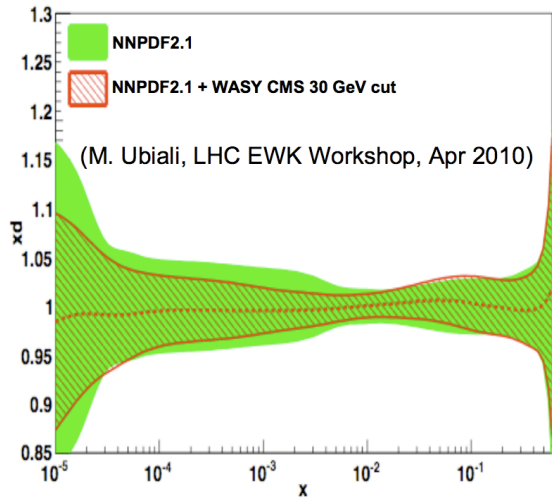
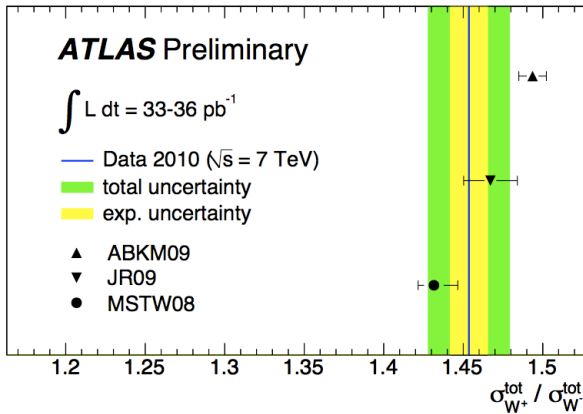
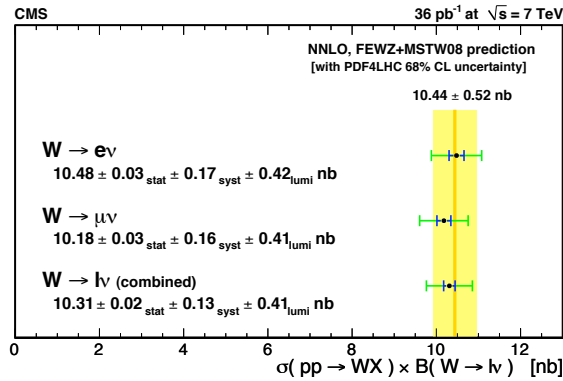
5/10/11

FCPPL Workshop  $m_{12}$  [TeV] 21/03/2012





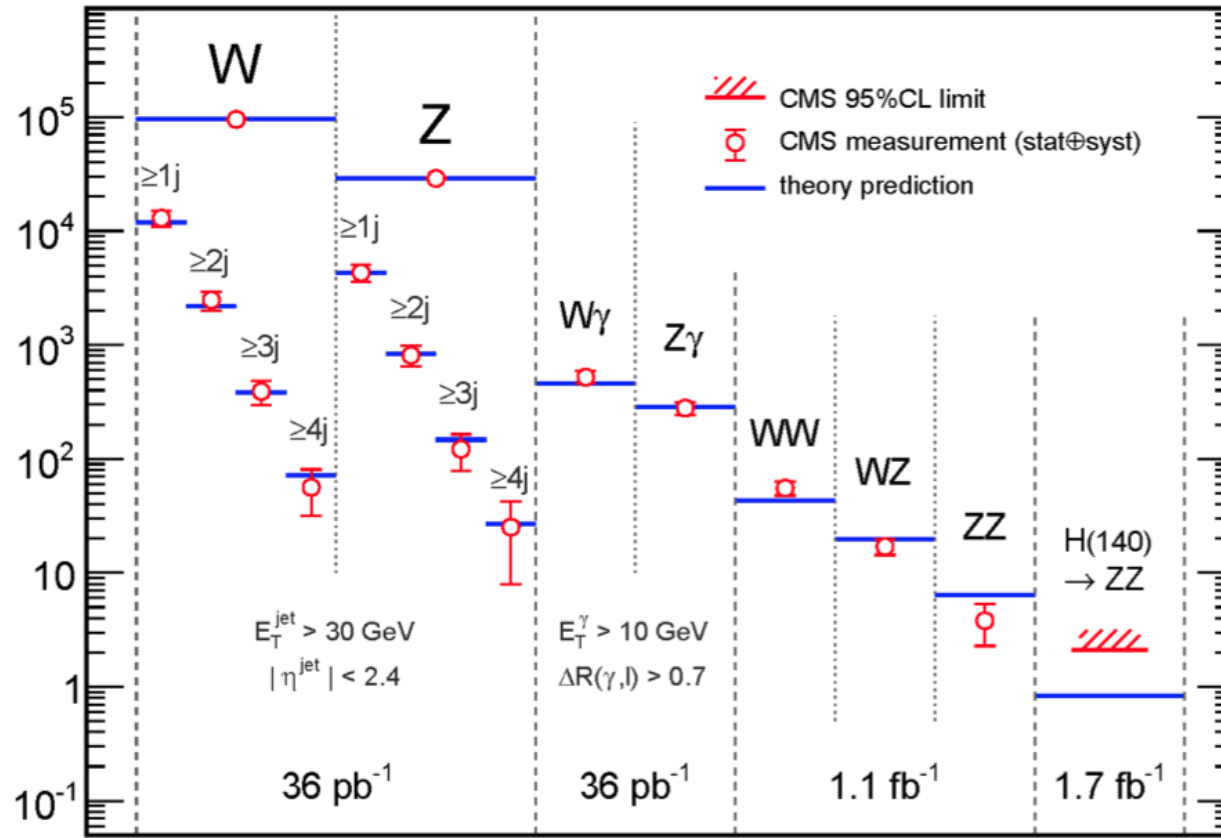
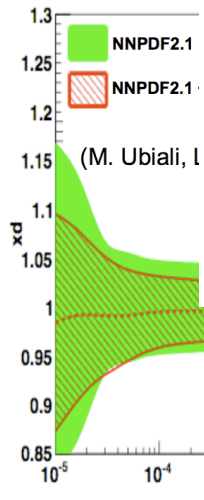
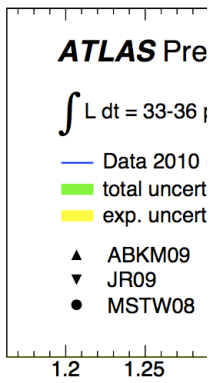
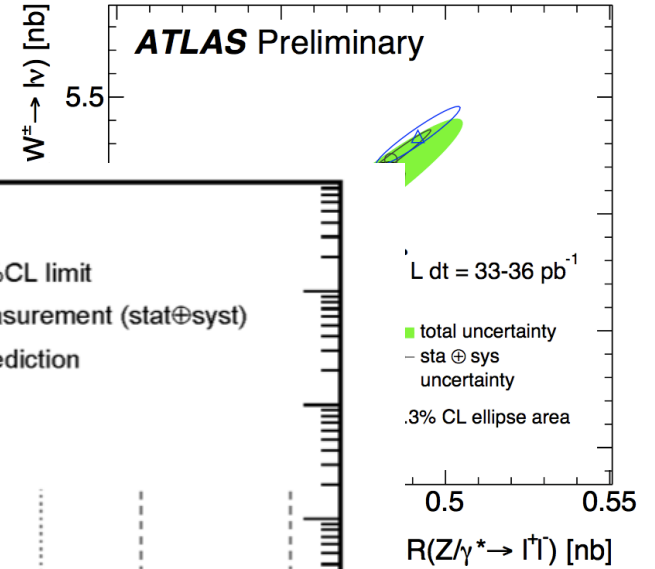
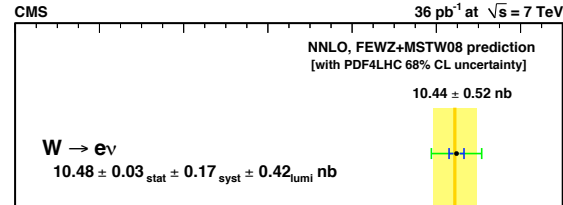
# EW







# EW

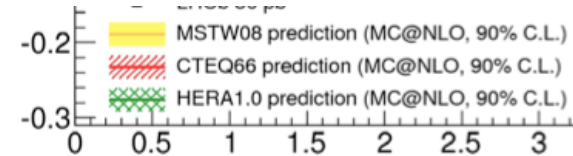
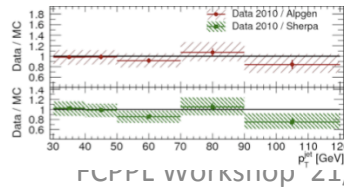


JHEP10(2011)132  
CMS-PAS-EWK-10-012

PLB701(2011)535

CMS-PAS-EWK-11-010

CMS-PAS-HIG-11-015

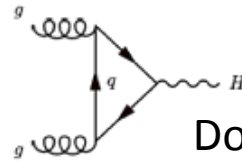
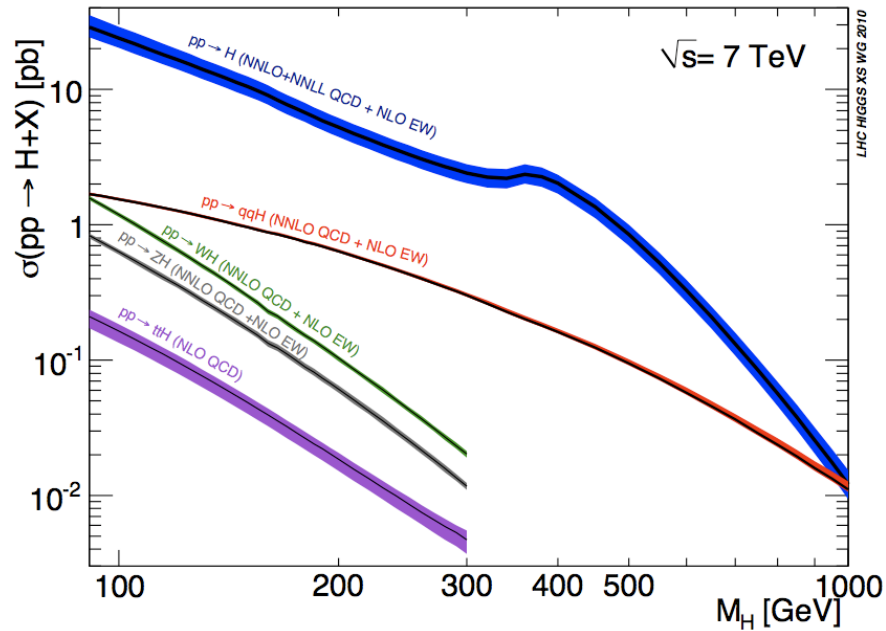


Lepton Pseudorapidity  $|\eta|$

**S+CMS+LHCb**  
Preliminary  
 $p_T^l > 20 \text{ GeV}$

# The Main Production Modes

Data driven background estimates legitimate use of NNLO cross sections!



- Gluon fusion process :

Dominant process known at NNnLO

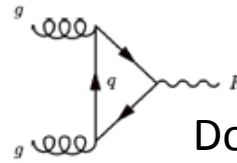
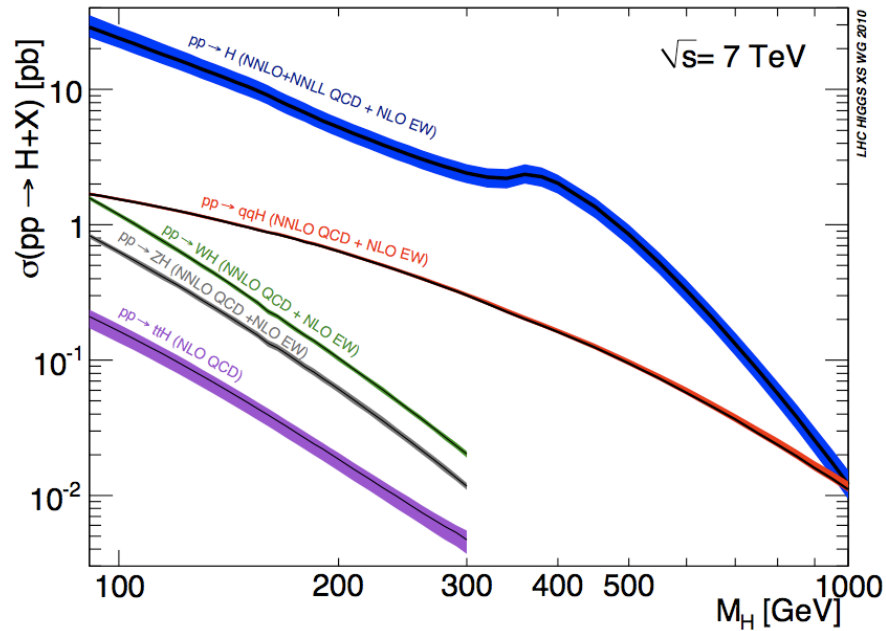
However rather large TH uncertainty\*  $\sim O(15\%)$  due to the large corrections for gluon initiated process

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



# The Main Production Modes

Data driven background estimates legitimate use of NNLO cross sections!



- Gluon fusion process :

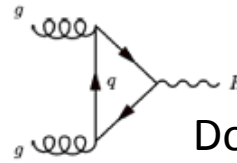
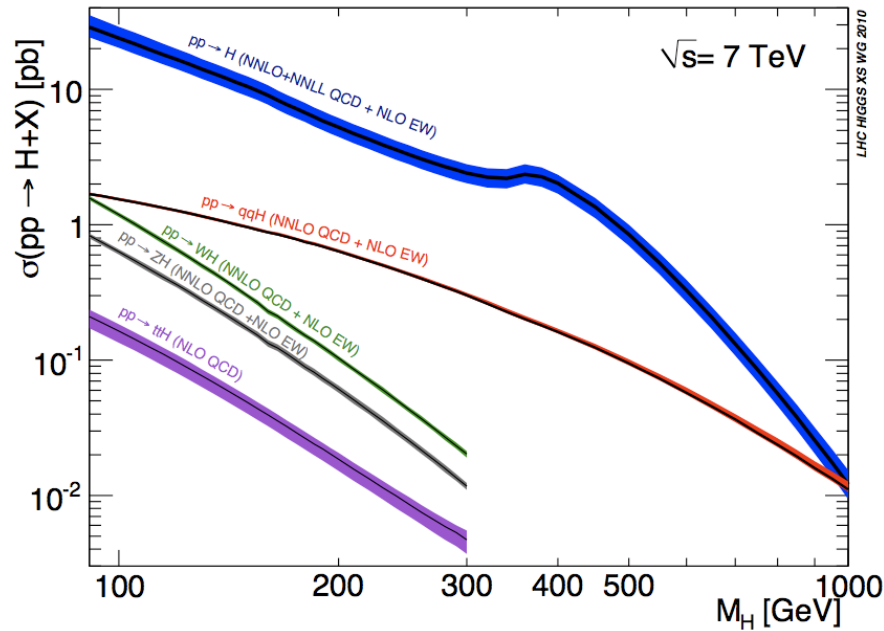
Dominant process known at NNnLO

**~100 kEvts produced at 120 GeV**

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

# The Main Production Modes

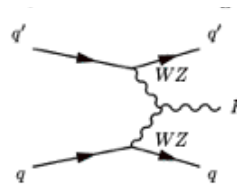
Data driven background estimates legitimate use of NNLO cross sections!



- Gluon fusion process :

Dominant process known at NNnLO

**~100 kEvs produced at 120 GeV**



- Vector Boson Fusion :

known at NLO TH uncertainty  $\sim 0(5\%)$

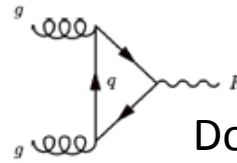
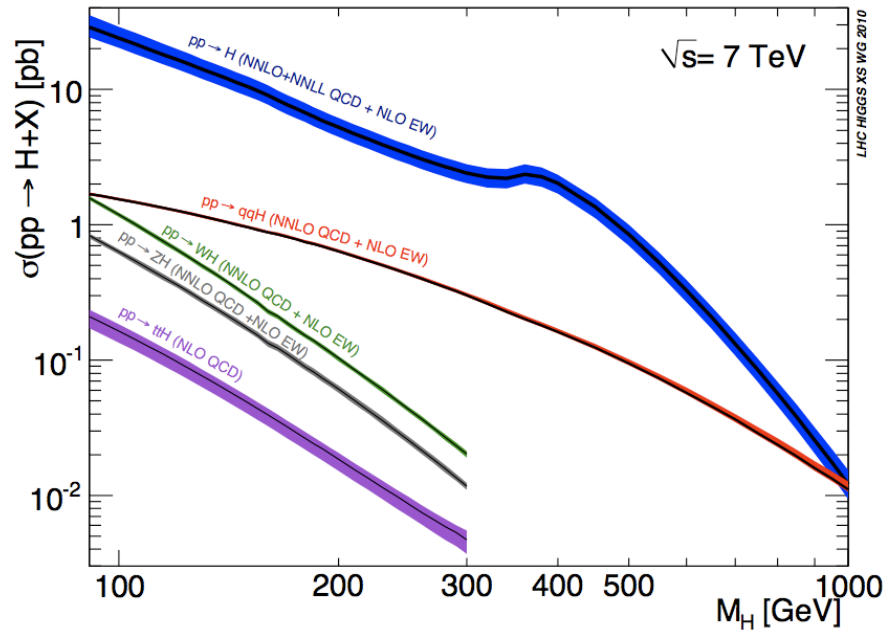
Rather distinctive features w/ two conspicuous forward jets and a rapidity gap

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



# The Main Production Modes

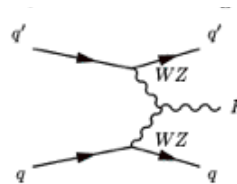
Data driven background estimates legitimate use of NNLO cross sections!



- Gluon fusion process :

Dominant process known at NNnLO

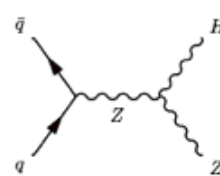
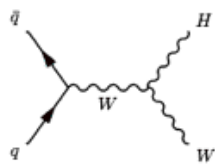
**~100 kEvts produced at 120 GeV**



- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

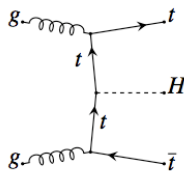
Rather distinctive features w/ two conspicuous forward jets and a rapidity gap



- Associated Production with W and Z :

known at NNLO TH uncertainty ~O(5%)

Very distinctive feature with a Z or W decaying leptonically



- Associated Production with top pair :

known at NLO TH uncertainty ~O(15%)

Quite distinctive but also quite crowded

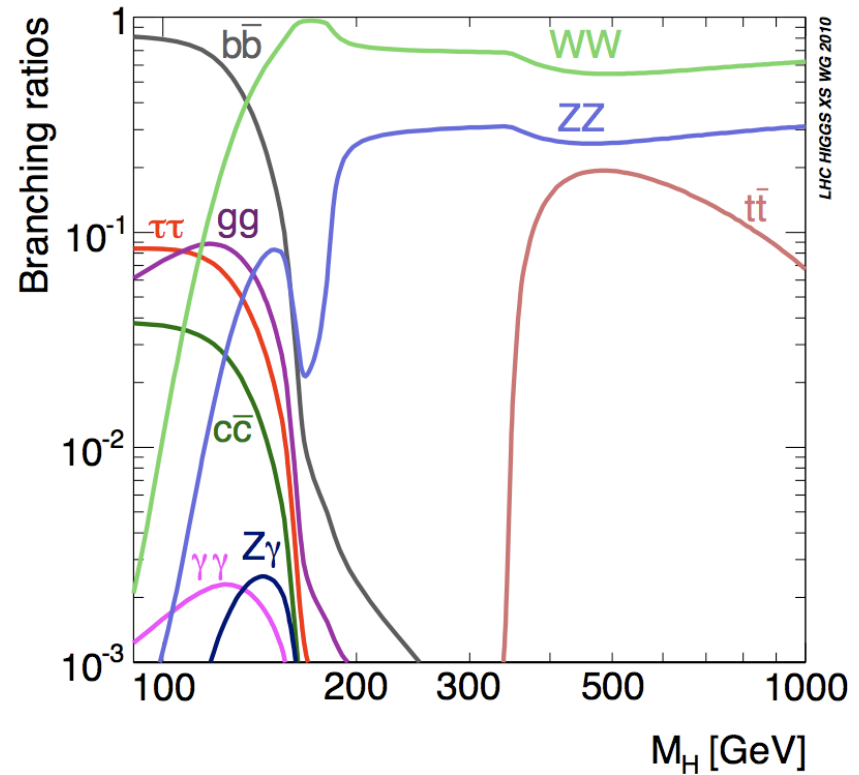
\* TH uncertainty mostly from scale variation and PDFs,  $\delta\sigma_{\text{PDF-}\alpha_s} \sim 8\text{-}10\%$  and  $\delta\sigma_{\text{Scale}} \sim 7\text{-}8\%$

# Decay Modes

Pure Branching Fractions

- The dominant b-decay channel

Huge backgrounds, needs distinctive features at production level and beyond... Associate production W,Z H and Boost!





# Decay Modes

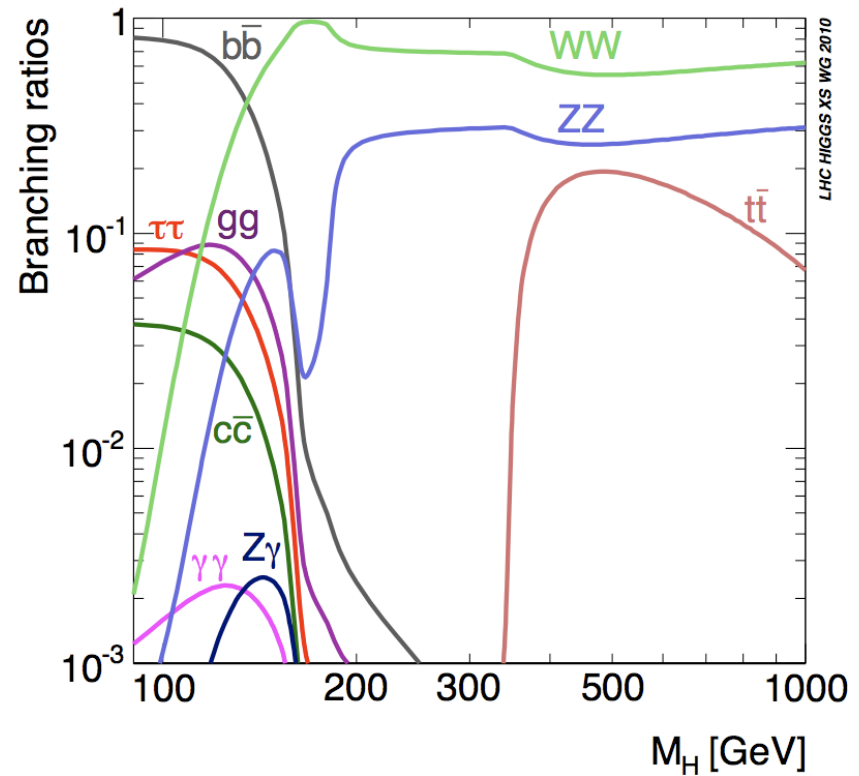
Pure Branching Fractions

## - The dominant b-decay channel

Huge backgrounds, needs distinctive features at production level and beyond... Associate production W,Z H and Boost!

## - The $\tau\tau$ channel

Also needs distinctive production features, typically VBF or VH. Hopes from NEW MASS RECONSTRUCTION techniques



# Decay Modes

## Exclusive Modes Cross Sections

### - The dominant b-decay channel

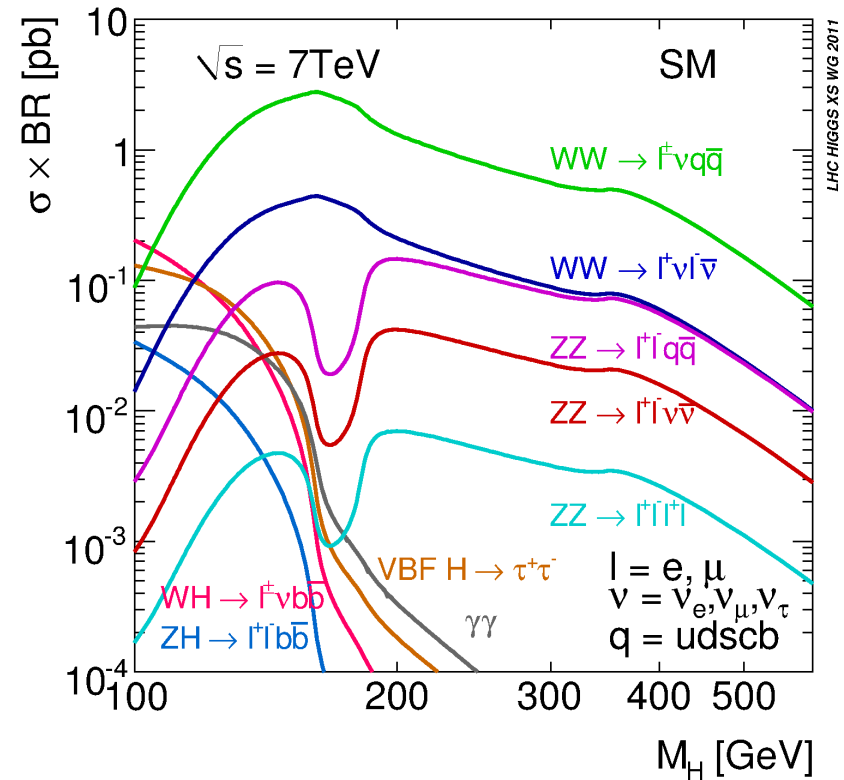
Huge backgrounds, needs distinctive features at production level and beyond... Associate production W,Z H and Boost!

### - The $\tau\tau$ channel

Also needs distinctive production features, typically VBF or VH. Hopes from NEW MASS RECONSTRUCTION techniques

### - The $\gamma\gamma$ channel

Dominant Channel in the very low mass range. Small branching but **sizable yield**. Very distinctive signature on its own.



# Decay Modes

## Exclusive Modes Cross Sections

### - The dominant b-decay channel

Huge backgrounds, needs distinctive features at production level and beyond... Associate production W,Z H and Boost!

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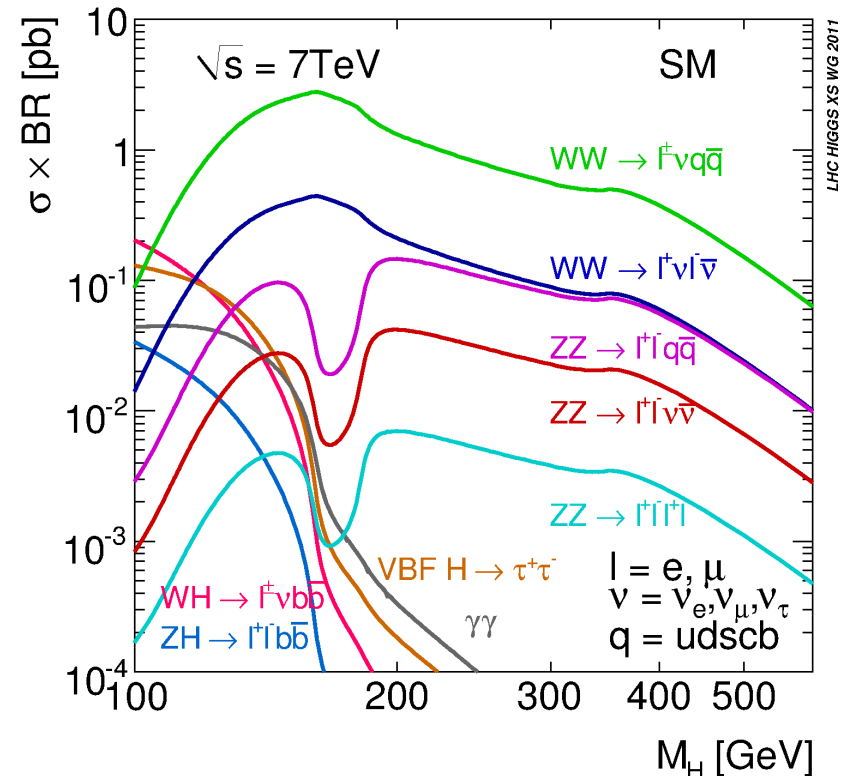
Also needs distinctive production features, typically VBF or VH. Hopes from NEW MASS RECONSTRUCTION techniques

### - The $\gamma\gamma$ channel

Dominant Channel in the very low mass range. Small branching but **sizable yield**. Very distinctive signature on its own.

### - The WW Channels

- Dilepton (lnln) channel is dominant in the low mass (very poor mass resolution, essentially counting experiment)
- Semi leptonic (lnqq) largest event yield effective at large mass where the background is smaller.





# Decay Modes

## Exclusive Modes Cross Sections

### - The dominant b-decay channel

Huge backgrounds, needs distinctive features at production level and beyond... Associate production W,Z H and Boost!

### - The $\tau\tau$ channel

Also needs distinctive production features, typically VBF or VH. Hopes from NEW MASS RECONSTRUCTION techniques

### - The $\gamma\gamma$ channel

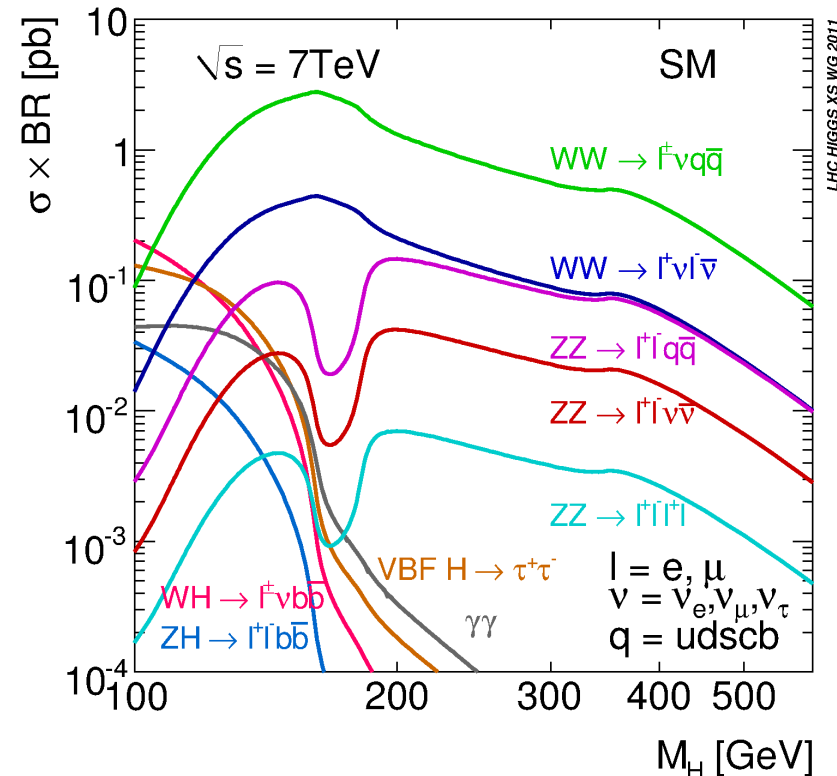
Dominant Channel in the very low mass range. Small branching but **sizable yield**. Very distinctive signature on its own.

### - The WW Channels

- Dilepton ( $l\nu l\nu$ ) channel is dominant in the low mass (very poor mass resolution, essentially counting experiment)
- Semi leptonic ( $l\nu q\bar{q}$ ) largest event yield effective at large mass where the background is smaller.

### - The ZZ Channels

- 4-leptons : "Golden mode" smallest event yield but large s/b ratio
- semi-leptonic ( $llq\bar{q}$ ) larger event yield but also much larger background (make use of the large branching Z in  $b\bar{b}$ )
- 2-leptons 2-neutrinos ( $ll\nu\nu$ ) : Best compromise yield/purity. Dominant channel at high mass



# Production Modes and Decay Channels

Channel		ggF	VBF	W,Z H	ttH	Range (GeV)
$\gamma\gamma$		✓	✓	✓	✓	110-150
$\tau\tau$		✓	✓			110-140
W,Z H (bb)				✓		110-130
ZZ (llll)		✓	✓			110-130
WW (lvlv)	0-jet	✓				110-600
	1-jet	✓	✓			110-600
	VBF	✓	✓			110-600
	WH*	✓		✓		110-200
WW** (lvqq)	0-jet	✓	✓			300-600
	1-jet	✓	✓			300-600
	VBF		✓			300-600
ZZ (llvv)		✓	✓			110-600
ZZ (ll $\tau\tau$ )*		✓	✓			200-600
ZZ (llqq)		✓	✓			130*-600

Low Mass :  
Challenging Range

110 - 150 GeV/c<sup>2</sup>

Intermediate :  
Wide Range

110 - 600 GeV/c<sup>2</sup>

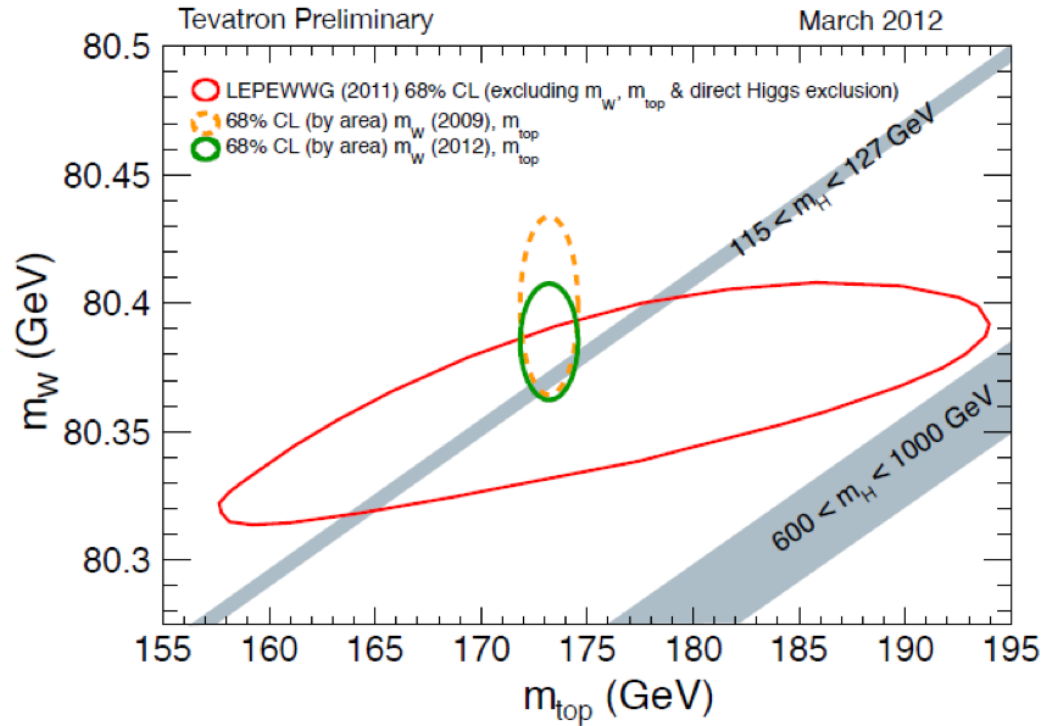
High Mass : Larger  
contribution from VBF

200 - 600 GeV/c<sup>2</sup>

Not theory difficulties above  
500 GeV/c<sup>2</sup>

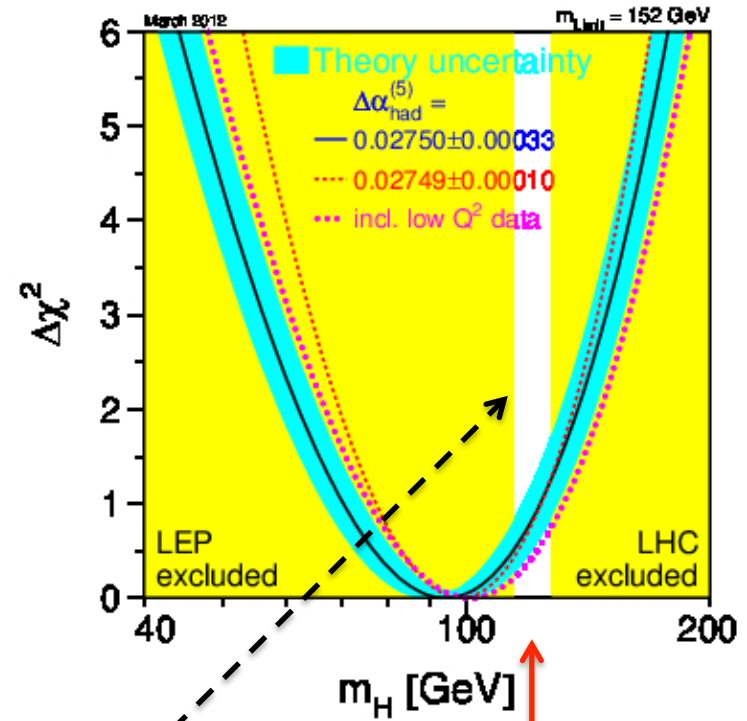
\* CMS only / \*\* ATLAS only

# Indirect Constraints



With  $M_W = 80385 \pm 15$  MeV

$M_H = 94^{+29}_{-24}$  GeV  
 $M_H < 152$  GeV @95% CL



LEP exclusion 114 GeV

Will concentrate on the low Higgs mass range [110-150] GeV



# Selected Topics

## Low mass channels only

Channel	ggF	VBF	W,Z H	ttH	Range (GeV)
$\gamma\gamma$	✓	✓	✓	✓	110-150
$\tau\tau$	✓	✓			110-140
W,Z H (bb)			✓		110-130
ZZ (llll)	✓	✓			110-130
WW (lνlν)	0-jet	✓			110-600
	1-jet	✓	✓		110-600
	VBF	✓	✓		110-600
	WH*	✓		✓	110-200
ZZ (llqq)	✓	✓			130*-600

\* CMS only

Will only cover  
**SM Higgs**  
 searches and  
 interpretation

← Lower Sensitivity at very low mass but very interesting (see backup)

← Very low sensitivity and does not cover vaery low masses (see backup)

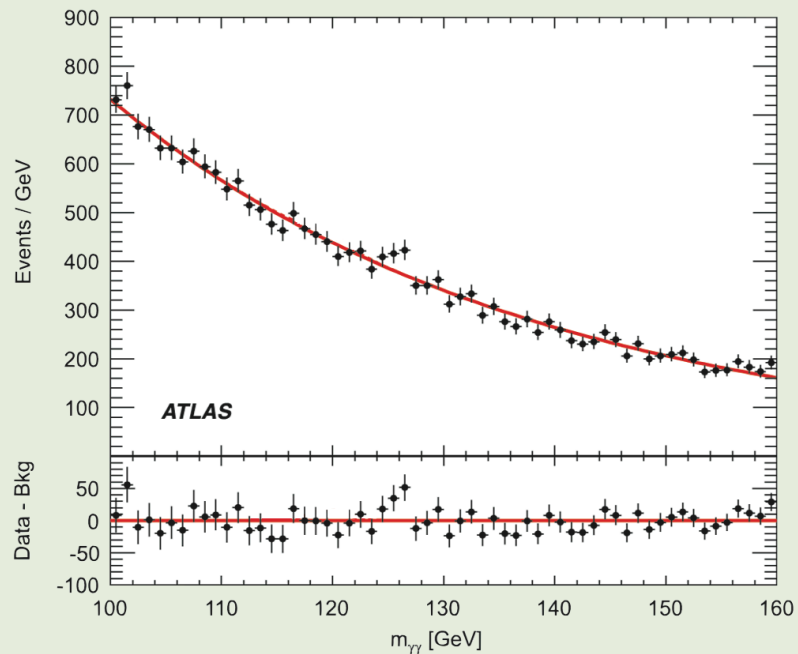
# *Statistical Interpretation*

How to read Higgs Search Plots

# PHYSICAL REVIEW LETTERS

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Articles published week ending 16 MARCH 2012



How to read Higgs Search Plots...

## Starting from PRL Cover Plot

Published by  
American Physical Society™

APS  
physics

Volume 108, Number 11



# Statistical Interpretation

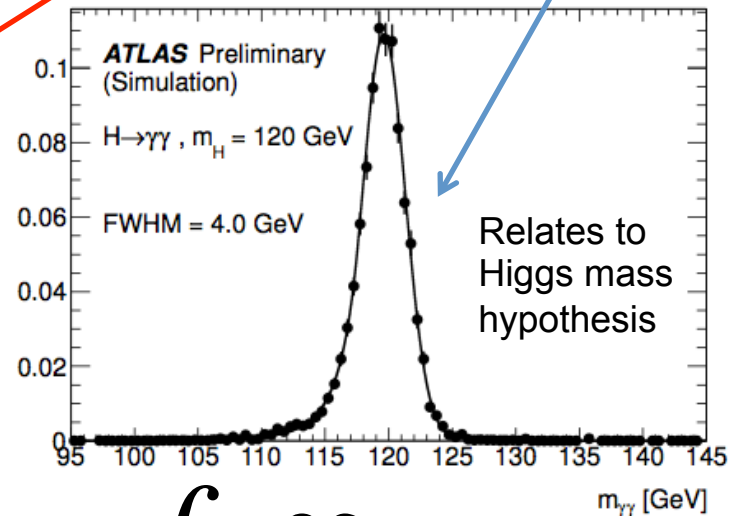
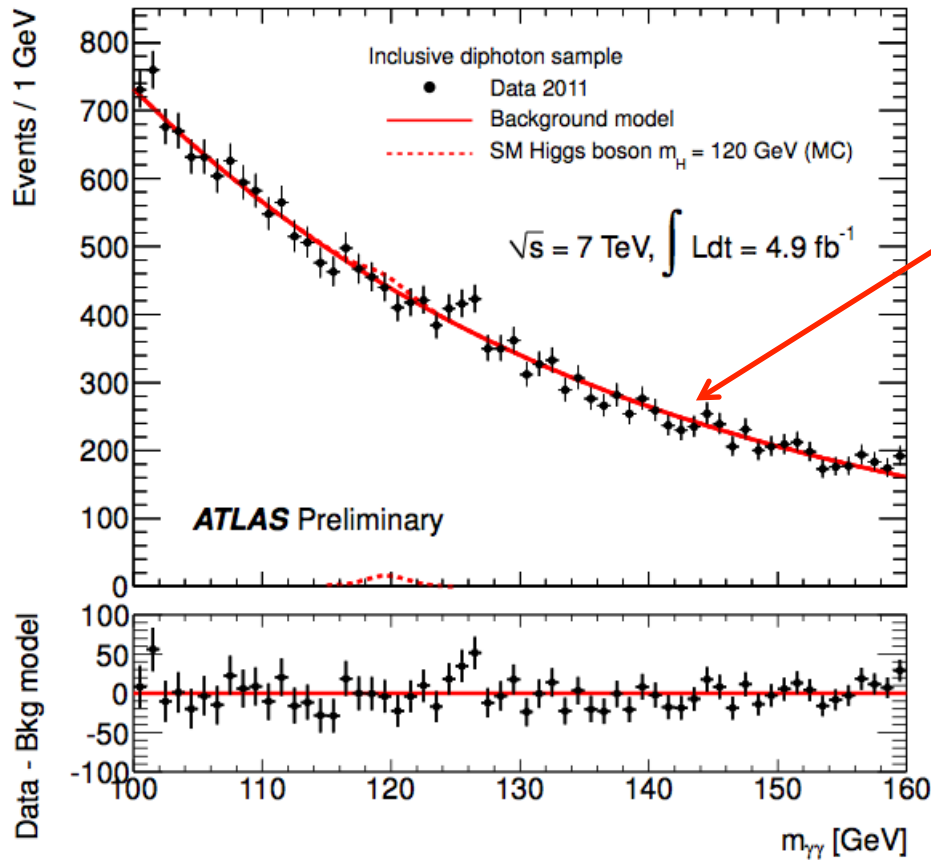
## How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio...

Likelihood Definition:

Simplified

$$L(\mu, \theta) = f_b \psi_b(M_{\gamma\gamma}) + f_s \psi_s(M_{\gamma\gamma})$$



$$f_s \propto \mu$$

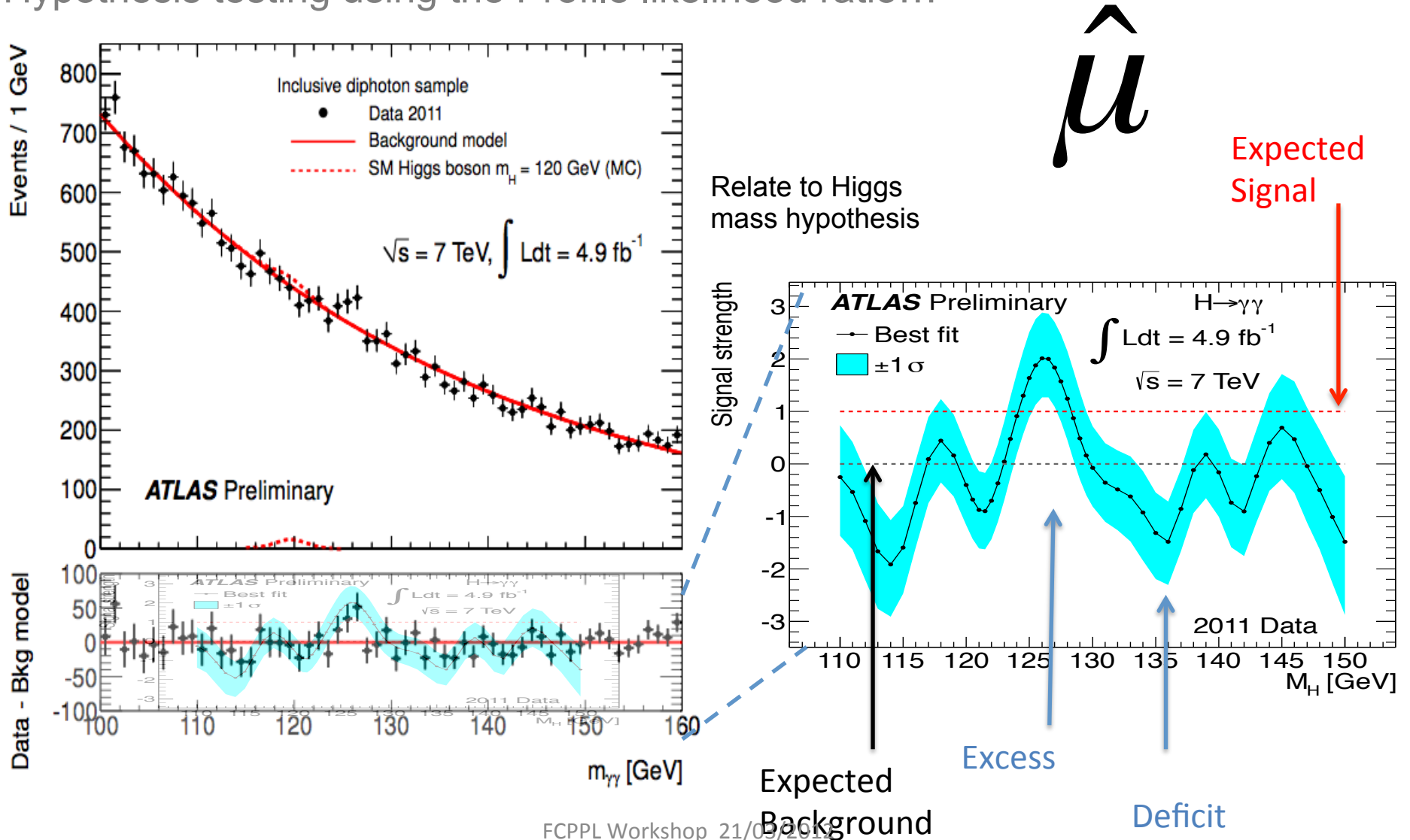
Global coherent factor

$$n_s = \mu \sigma Br L \epsilon$$

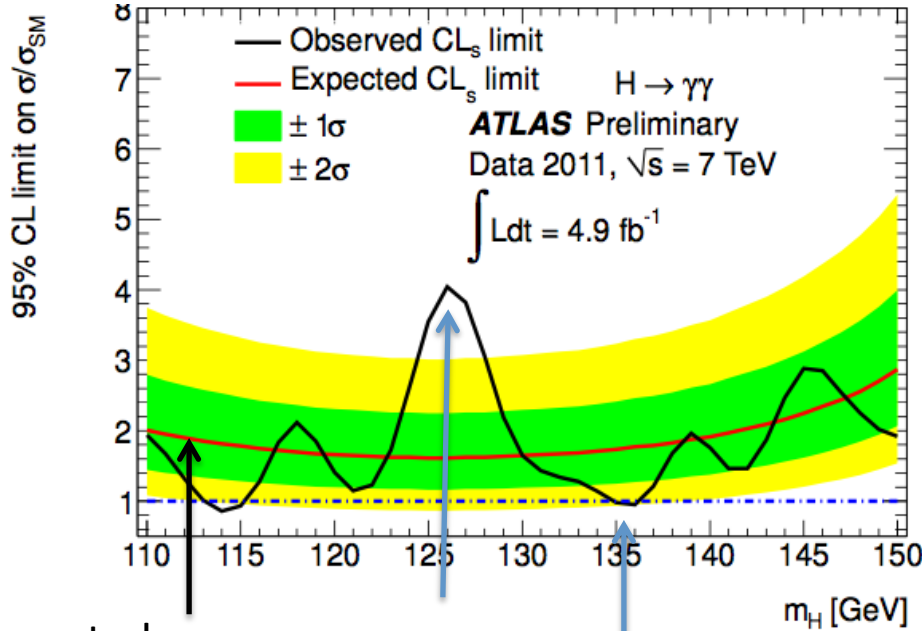
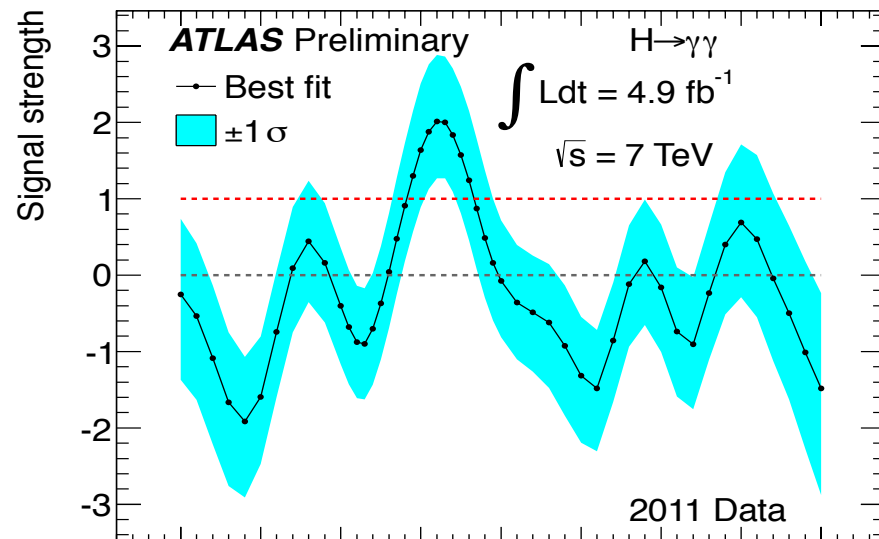
# Statistical Interpretation

## How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio...



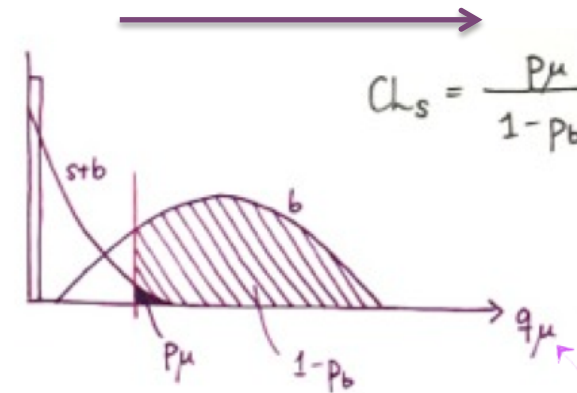
# How to Read Higgs Exclusion Limits Plots



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

$$q_\mu = -2 \ln \lambda_\mu$$

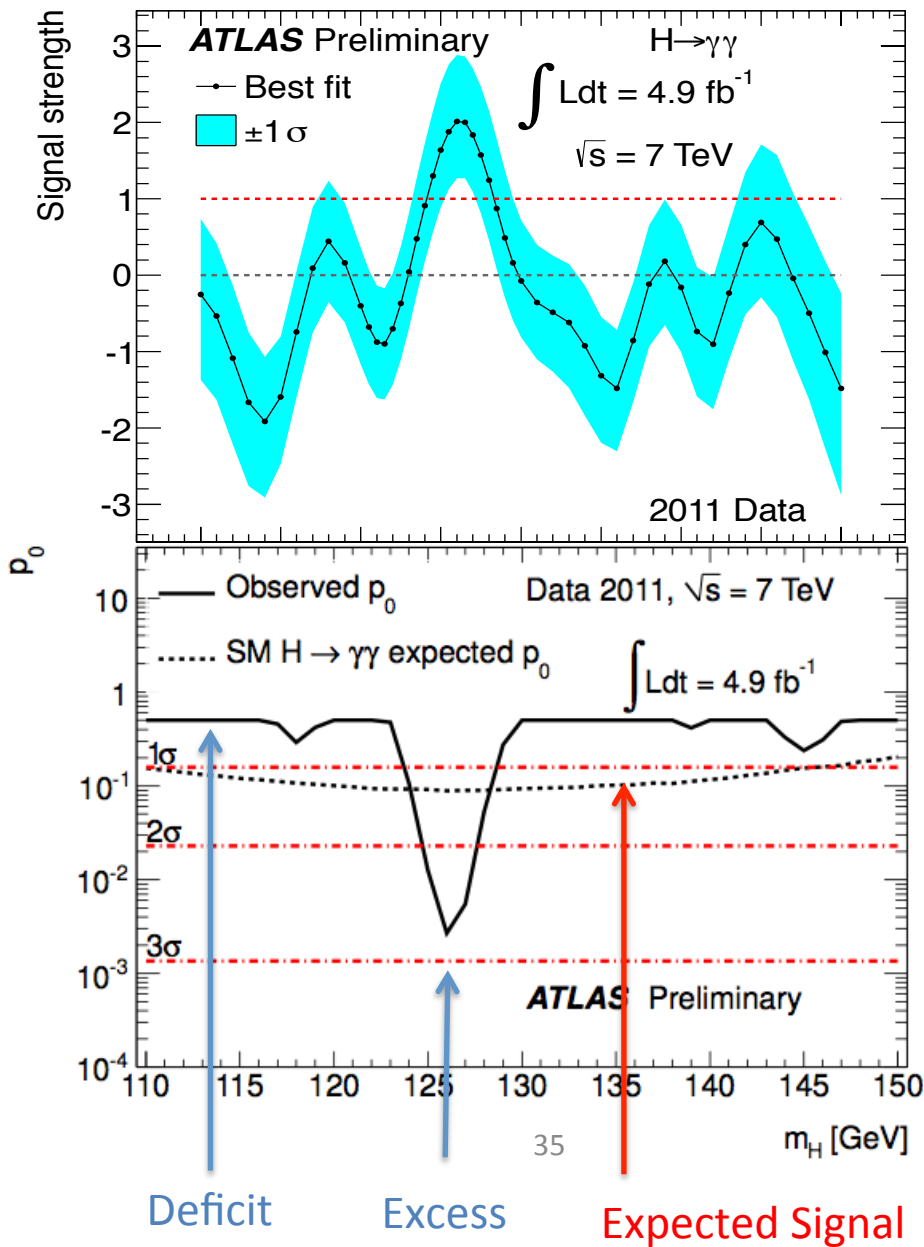
Background likeliness



$CL_{s+b}$  Probability that a signal-plus-background experiment be more background-like than observed

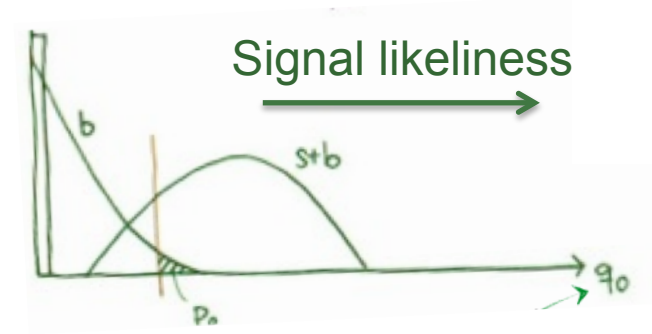


# How to Read Higgs Observation Estimates



$$\lambda_0 = \lambda(0, \theta) = \frac{L(0, \hat{\theta}(0))}{L(\hat{\mu}, \hat{\theta})}$$

$$q_0 = -2 \ln \lambda_0$$



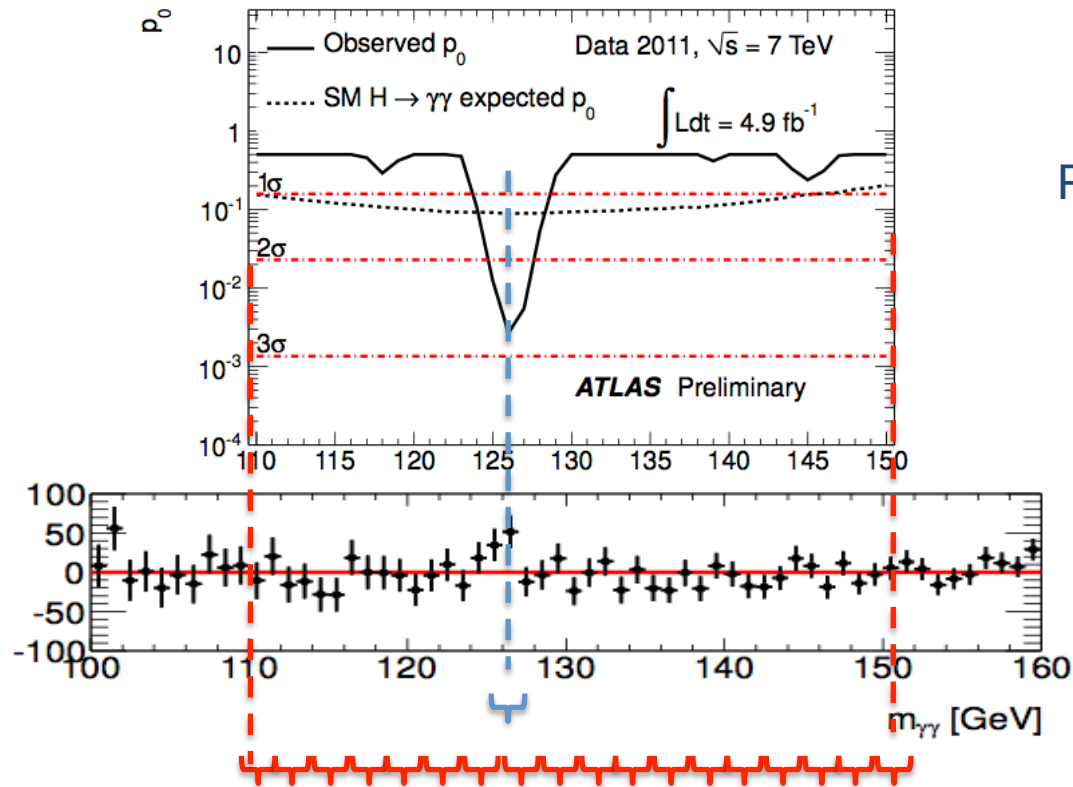
$p_0$  Probability that a background only experiment be more signal like than observed

Not a measurement of mass  
 Not a measurement of cross section

# Local vs. Global Probability

Look Elsewhere Effect

(over)Simplified View



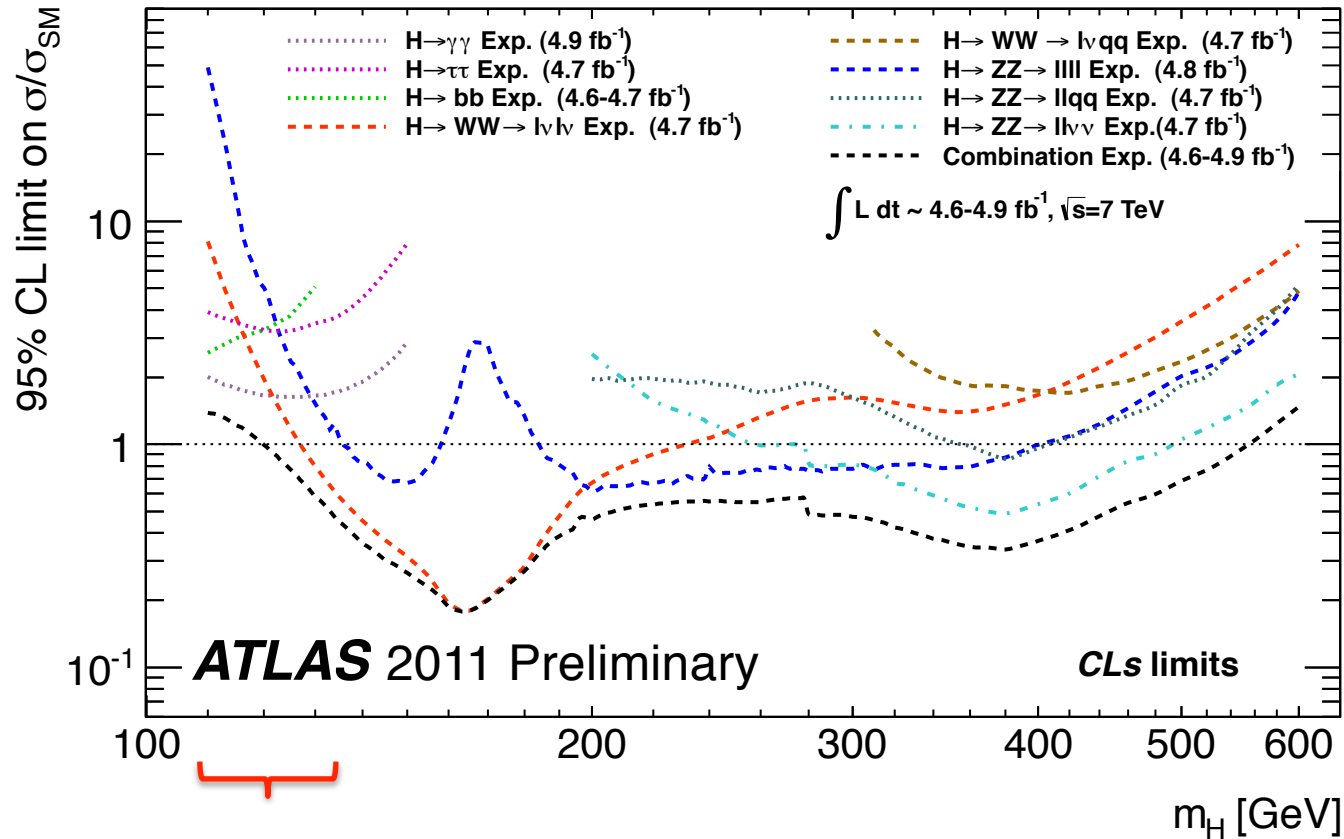
Probability of observing an excess at one specific mass (in absence of signal)...

What is the probability of observing an excess at least as large as observed within a mass range ?

**Trial factor** ~ Number of possible independent outcomes within a mass range... (dependence on the significance)

# Channels Overview

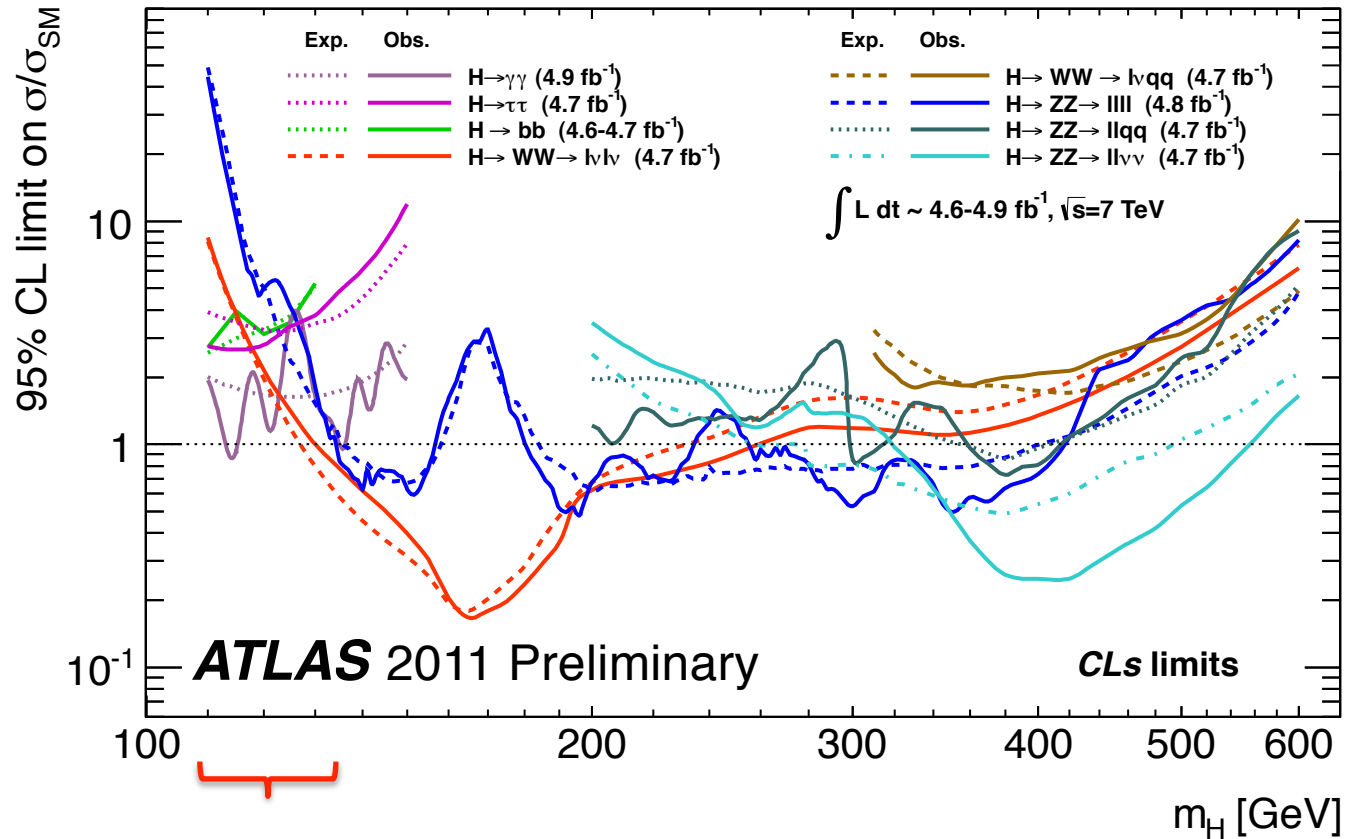
The Complete ATLAS Picture



Combination is Necessary to give a more quantitative result...  
 ... but (caution) does not give the entire picture

# Channels Overview

The Complete ATLAS Picture

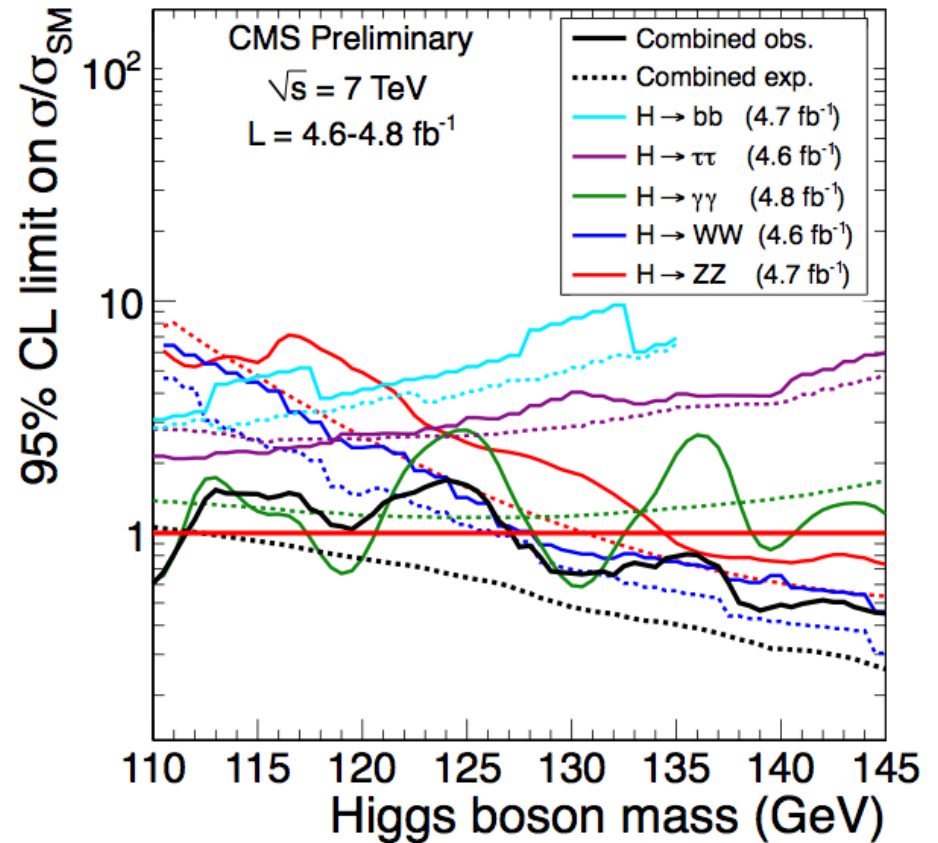
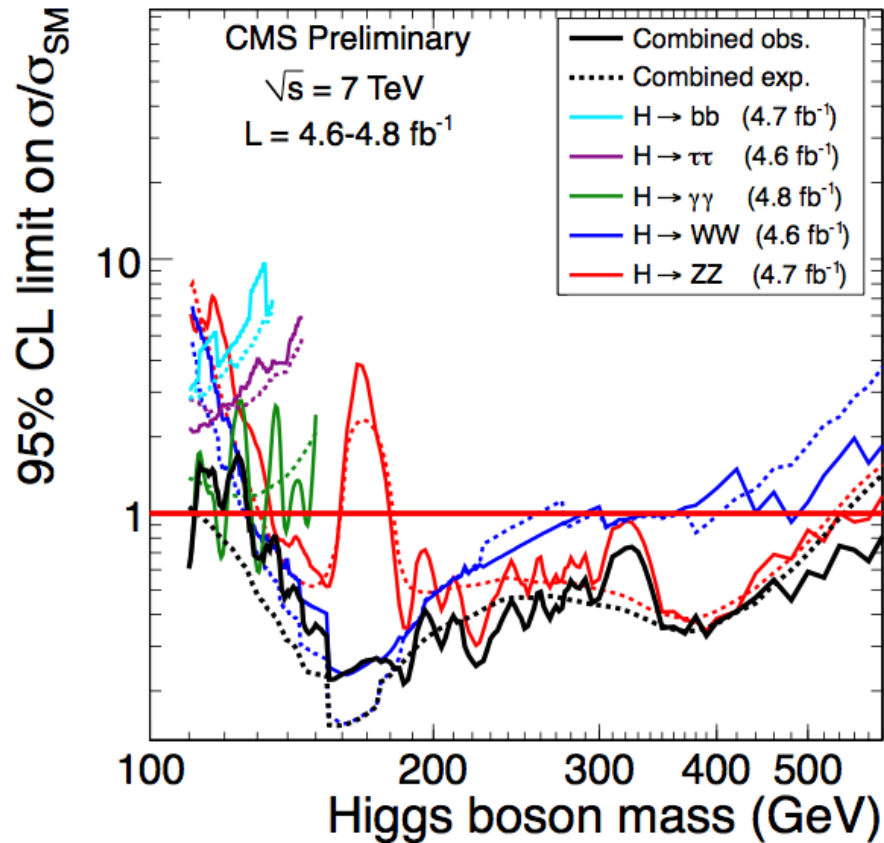


Combination is Necessary to give a more quantitative result...  
 ... but (caution) does not give the entire picture



# Channels Overview

The Complete CMS Picture



$$H \rightarrow \gamma\gamma$$

Most sensitive Channel in [115-125] GeV Mass range

ATLAS 4.9 fb<sup>-1</sup>

CMS 4.8 fb<sup>-1</sup>

Signal yield after cuts (low mass) ~O(80)

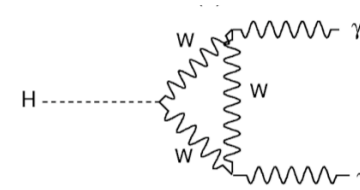
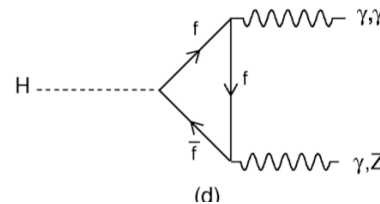
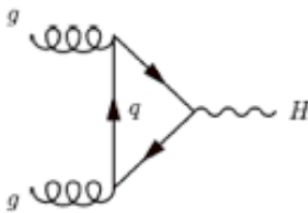
s/b ~ 1.5% to O(15)% depending on category

More Details in talks by [Liwen Gao](#) and [Giovanni Marchiori](#)

# DiPhoton Channel

## Common Misconceptions and Basic Facts

- Small branching... but amongst largest yields (Dominant Channel in the very low mass range 110-125 GeV)
- Main production and decay processes occur through loops :



*A priori potentially large enhancement...*

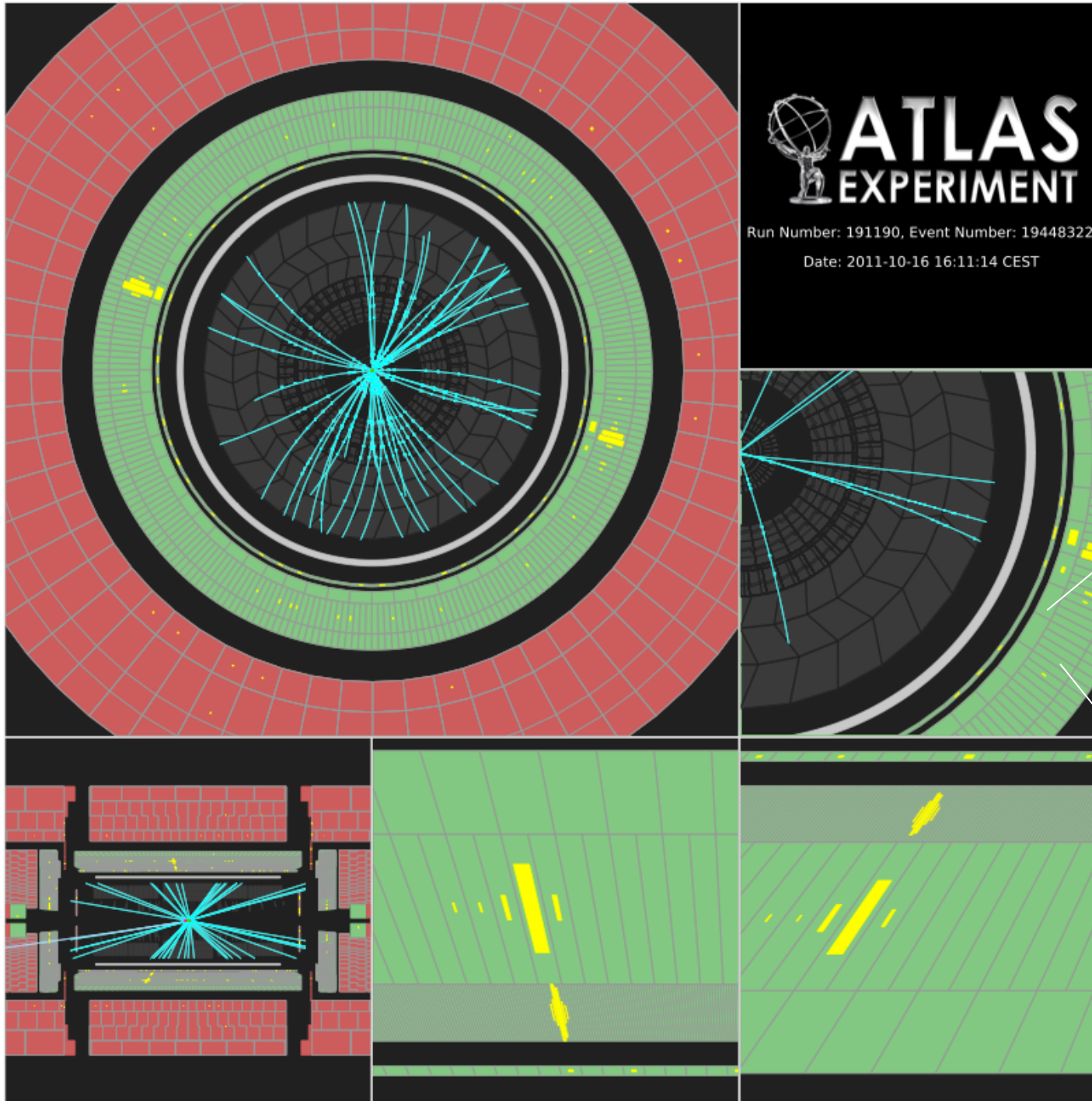
*... Not so obviously enhanced (e.g. SUSY, SM4)*

*Still e.g. NMMSSM (U. Ellwanger Phys.Lett. **B 698**, 293-296,2011) up to x6 at low masses, Fermiophobia...*

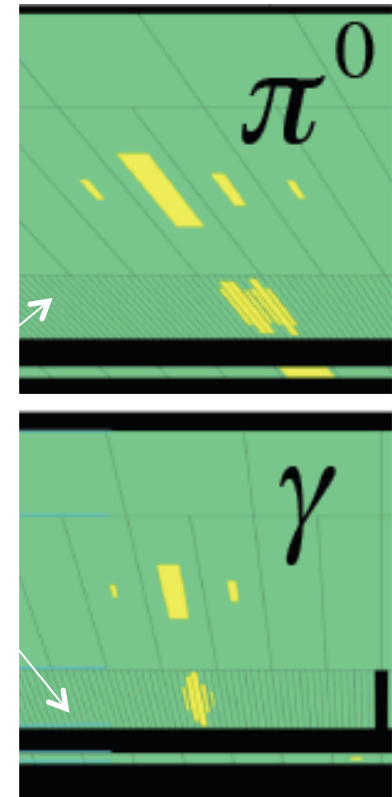
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem

L. Landau, Dokl. Akad. Nauk. , USSR **60**, 207 (1948) and C. N. Yang, Phys. Rev. **77**, 242 (1950).

- Extremely simple event selection : two photons 25/40 GeV (ATLAS) and 30/40 GeV (CMS)

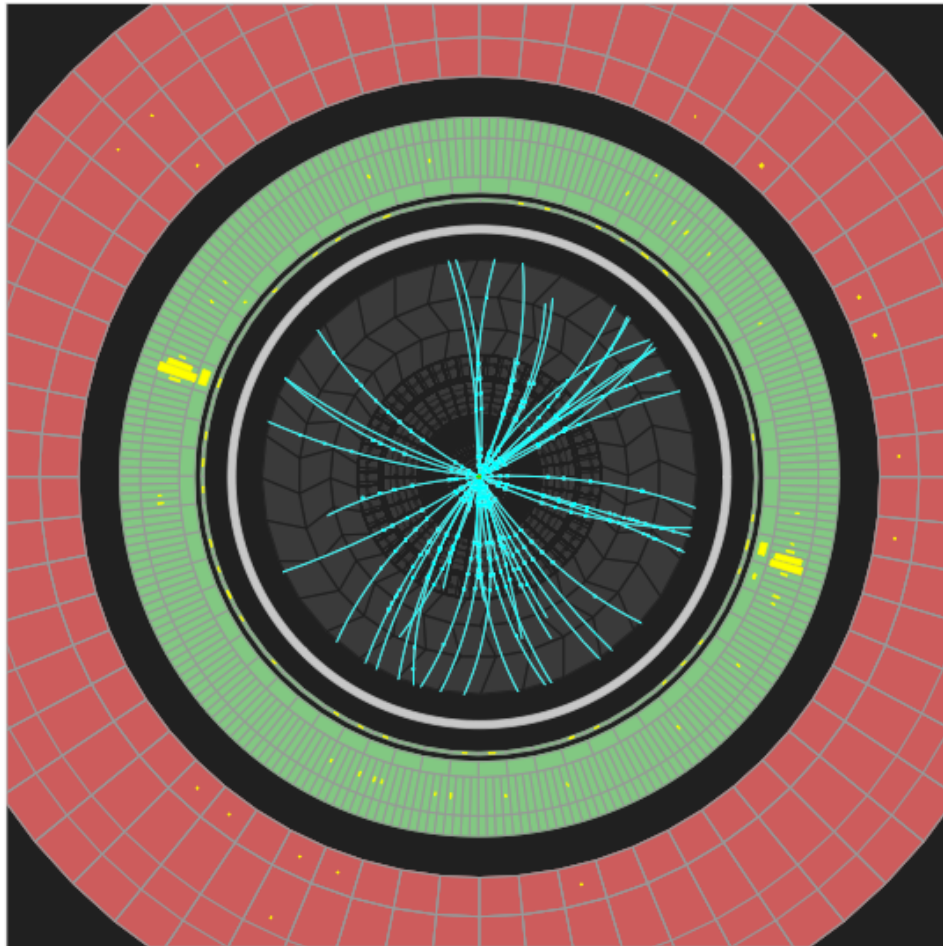


Background  
From jets



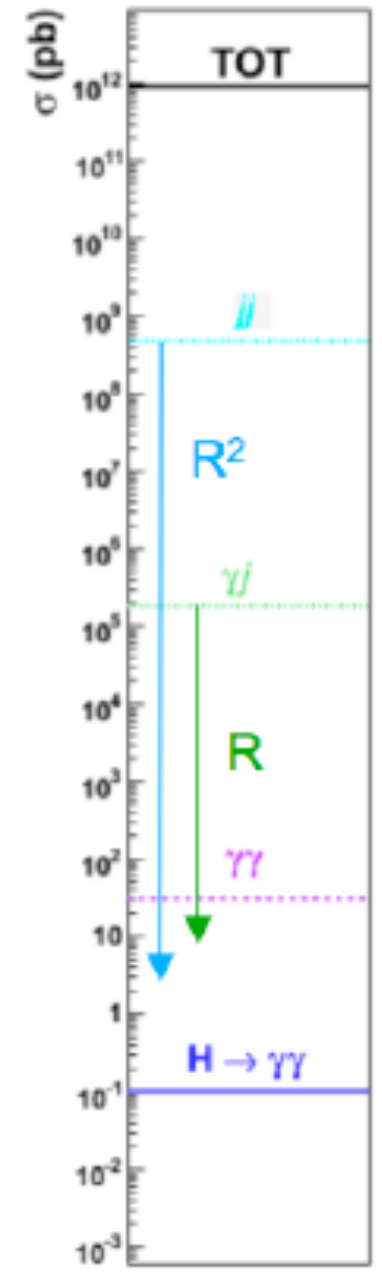
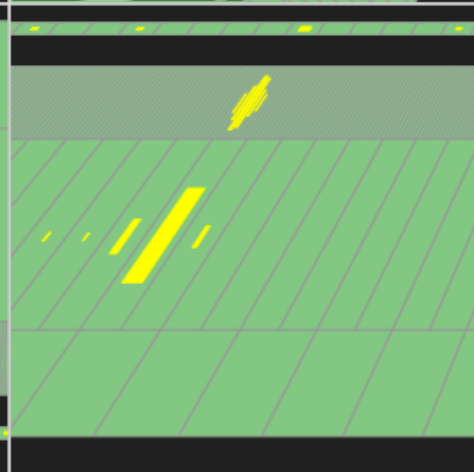
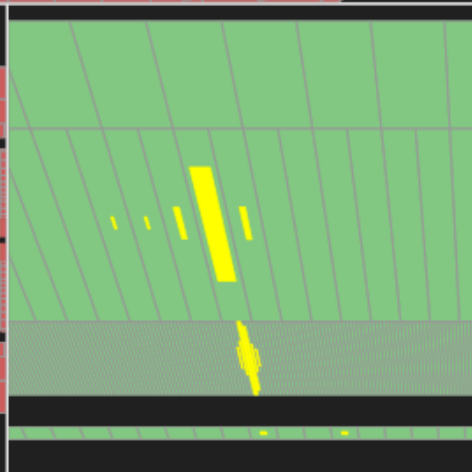
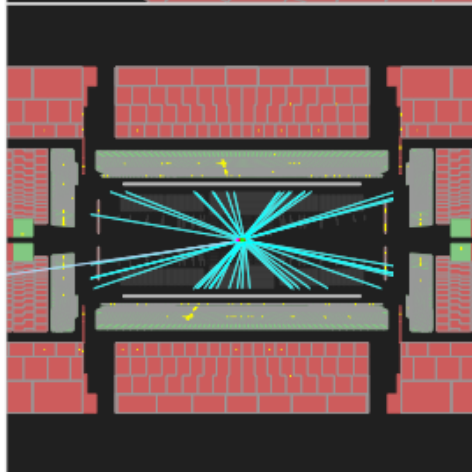
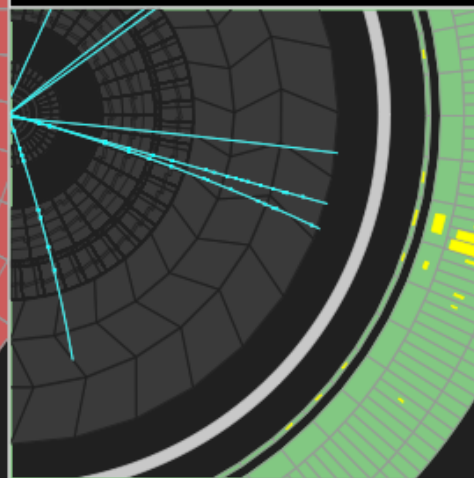
Signal





# ATLAS EXPERIMENT

Run Number: 191190, Event Number: 19448322  
 Date: 2011-10-16 16:11:14 CEST



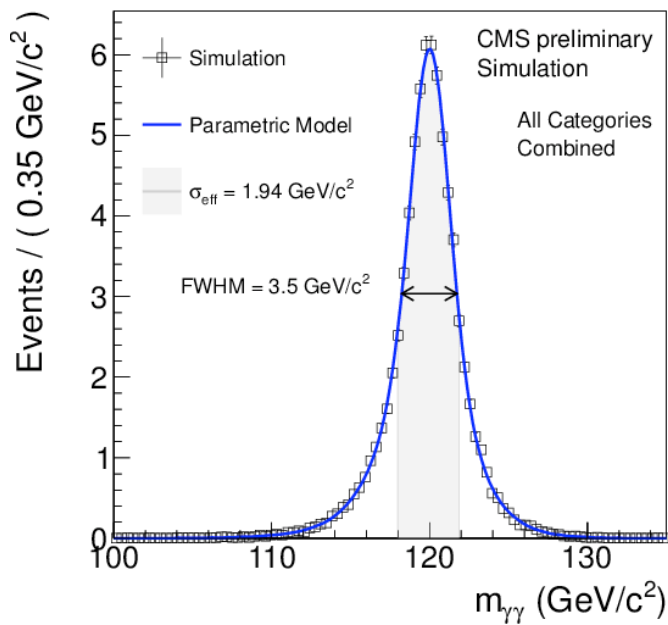
$R \sim O(8000)$

Key features :

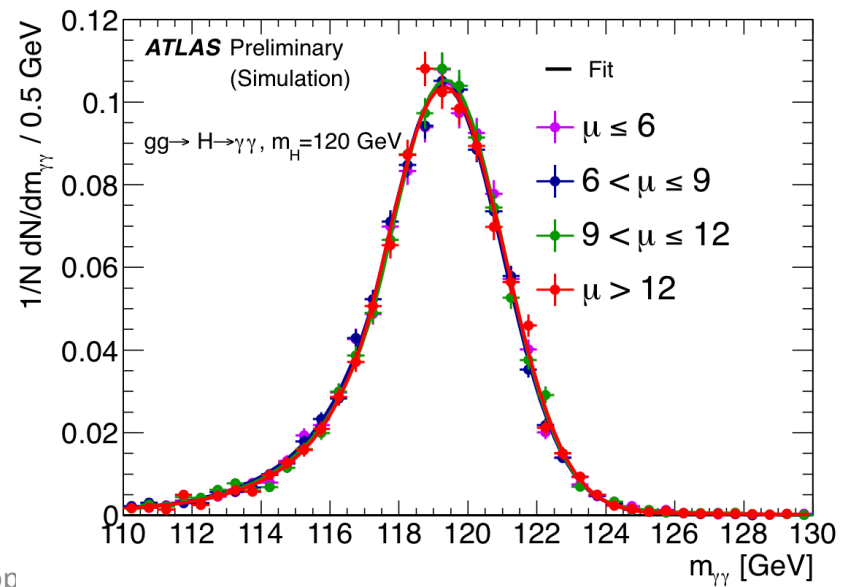
- Background rejection... but also...
- Invariant mass resolution
  - Energy response
  - Interaction vertex position

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

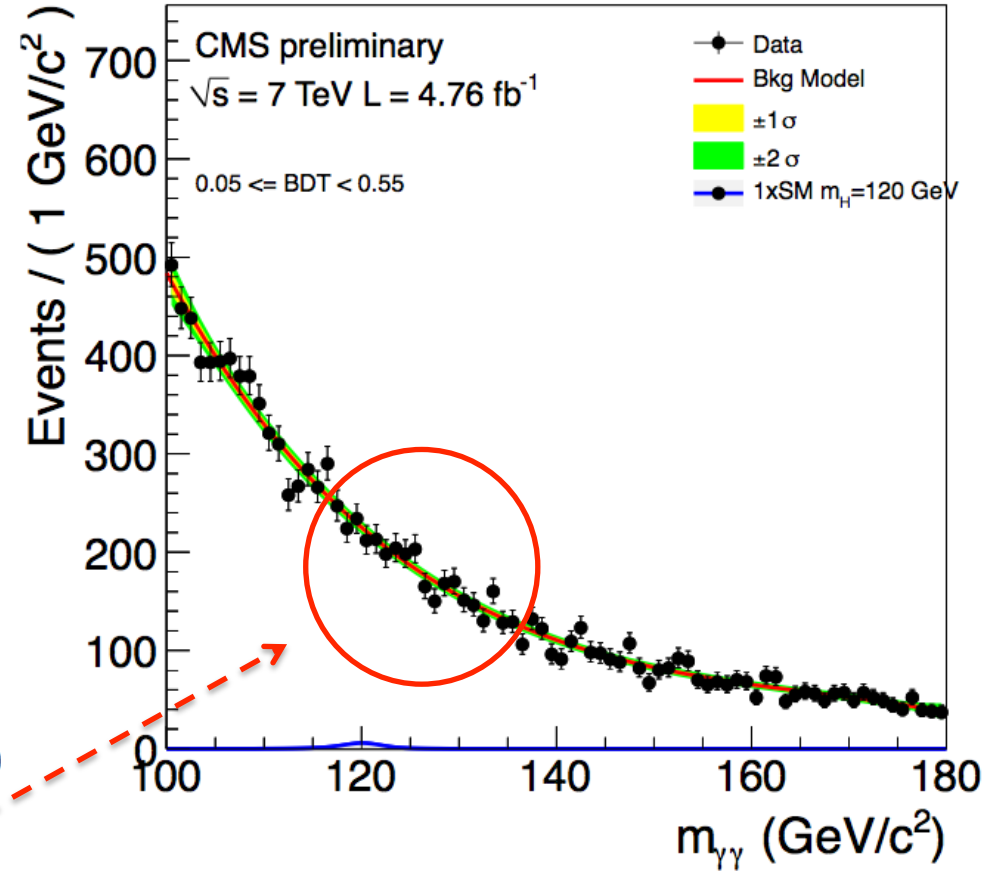
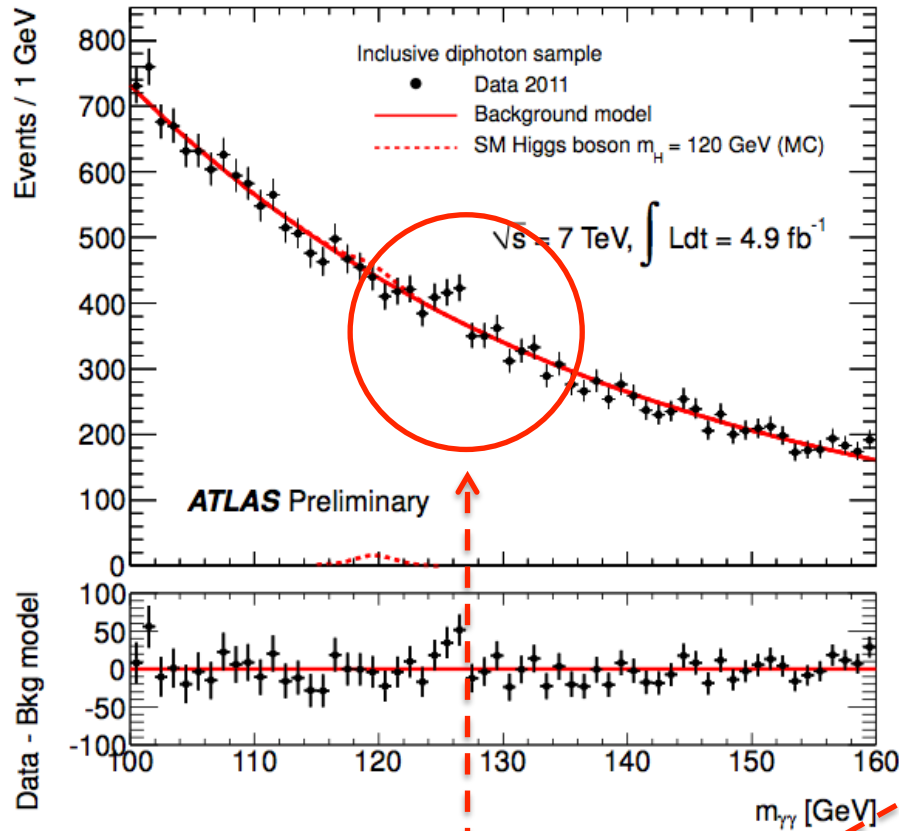
*FWHM* ~ 3.5 GeV



*FWHM* ~ 4.0 GeV



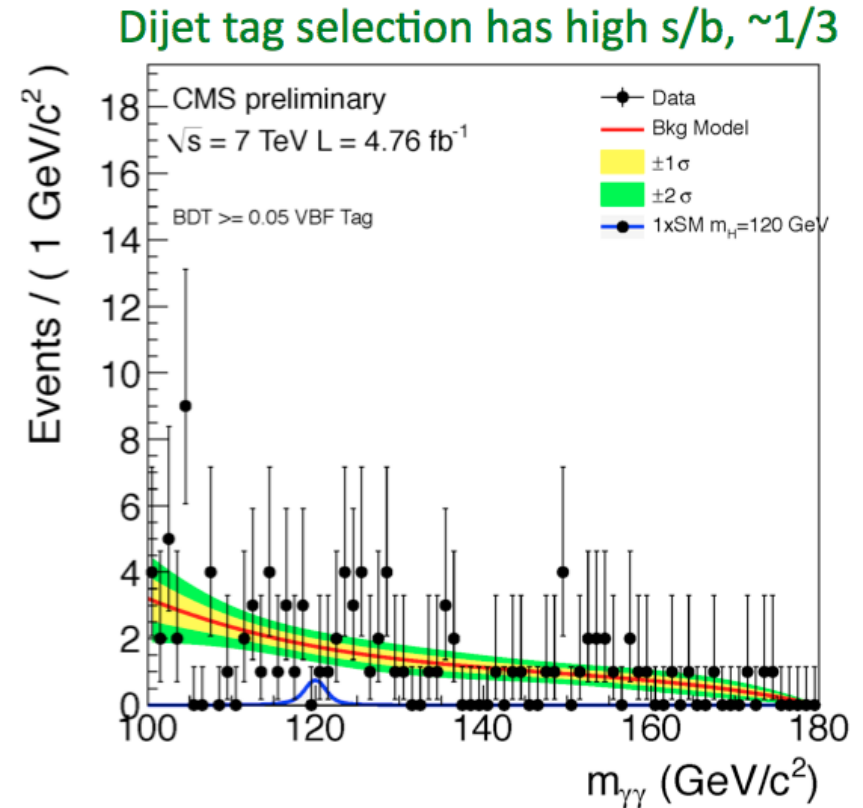
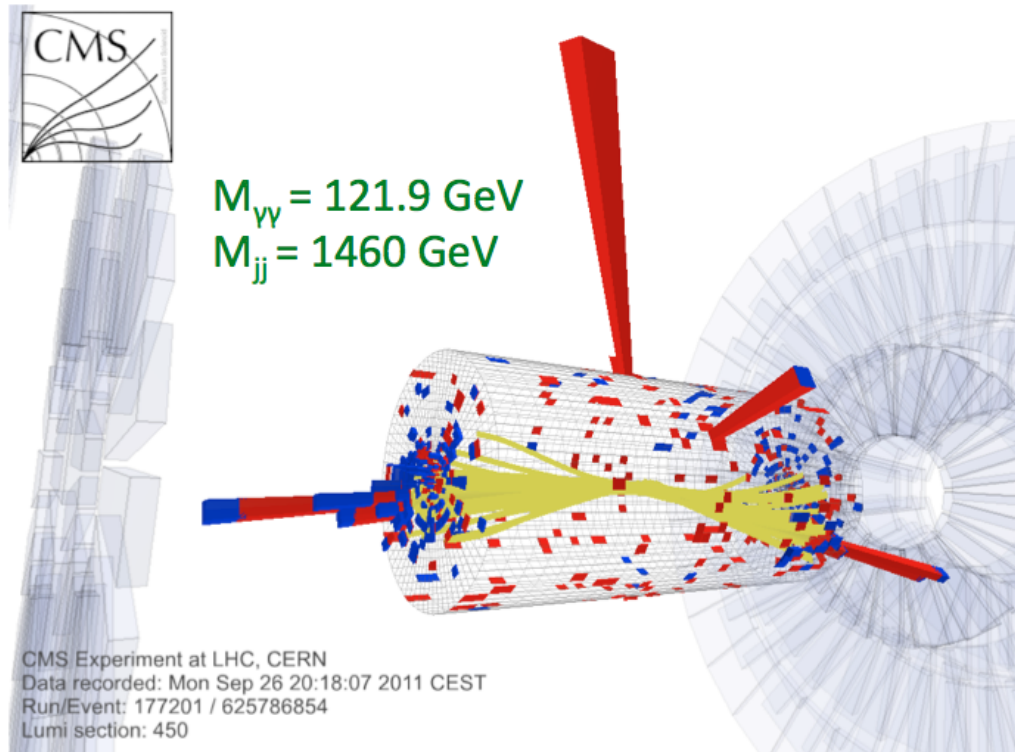
# Inclusive Mass Spectra



CMS has a slightly wider fit range

Excesses visible in the inclusive mass spectra

# Event Categorization to fully profit from distinctive features



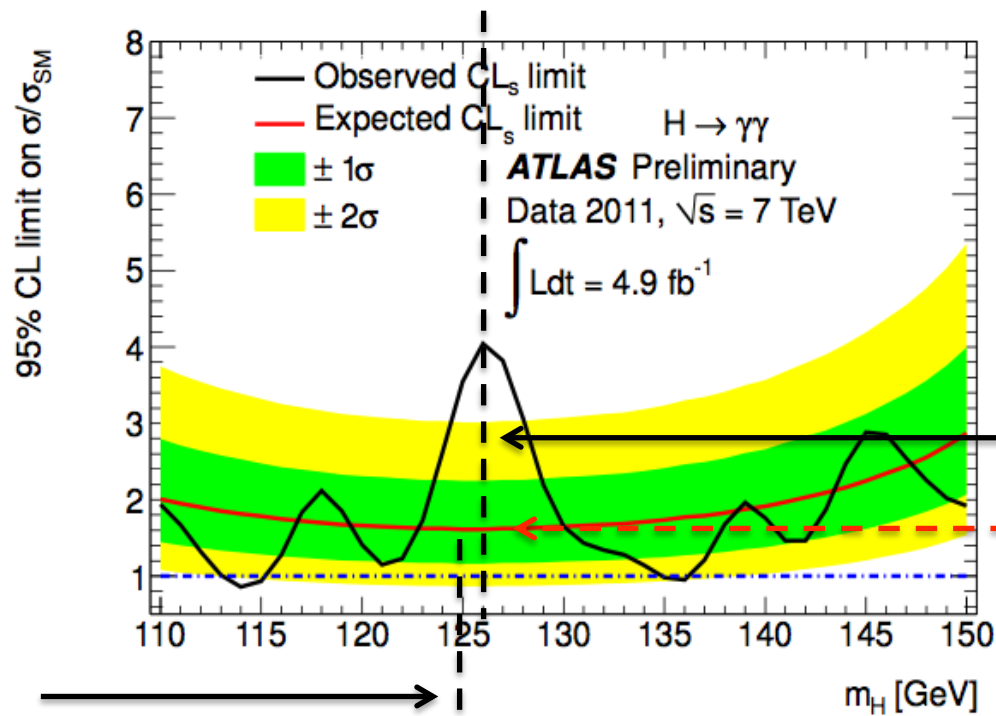
## ATLAS (9 Categories) :

- Pseudo-rapidity
- Conversion status (tracks)
- Transverse momentum w.r.t. thrust axis

## CMS (4 Categories) :

- MVA Analysis (4)
  - Kinematics
  - Conversion status
  - Resolution
- VBF (1)

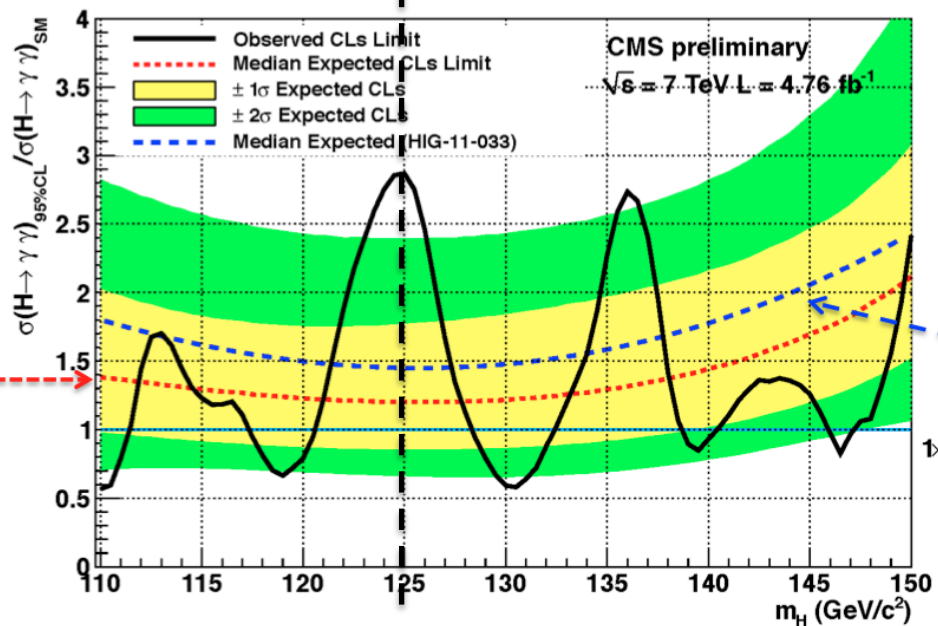




126 GeV

Limit  $\sim 1.6 \times SM$

125 GeV



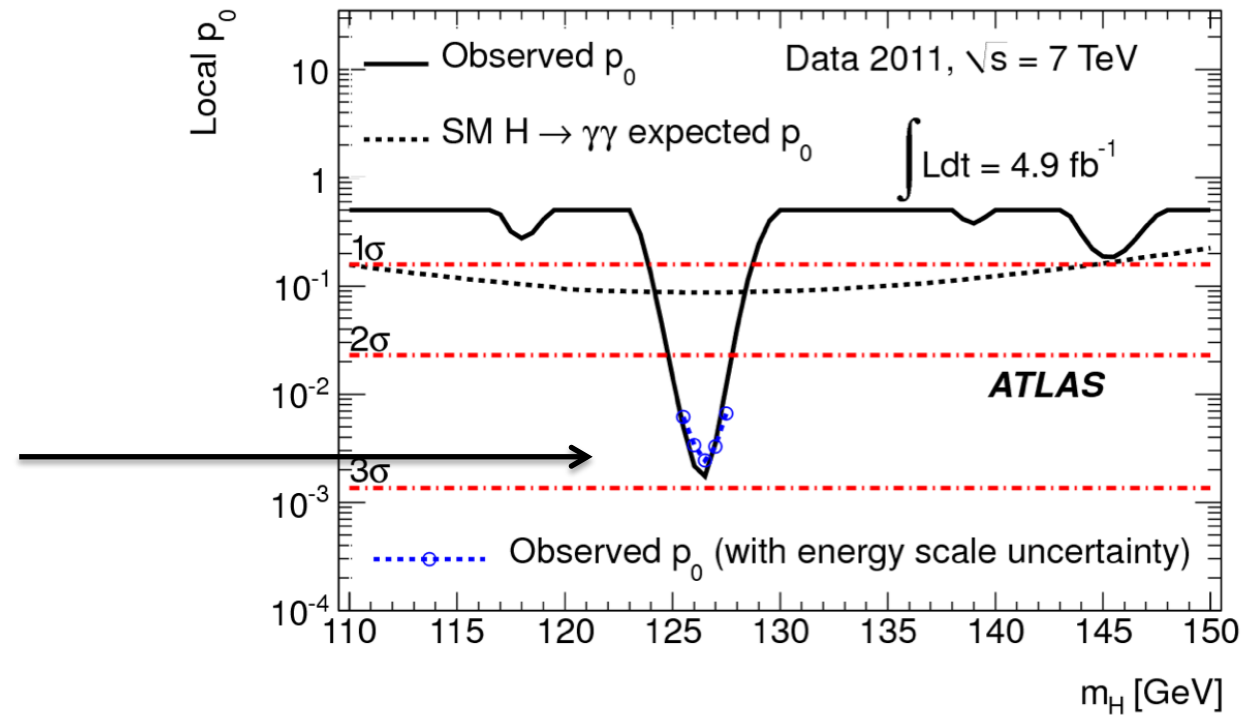
CMS document  
HIG-12-001

Expected from  
cut based  
analysis

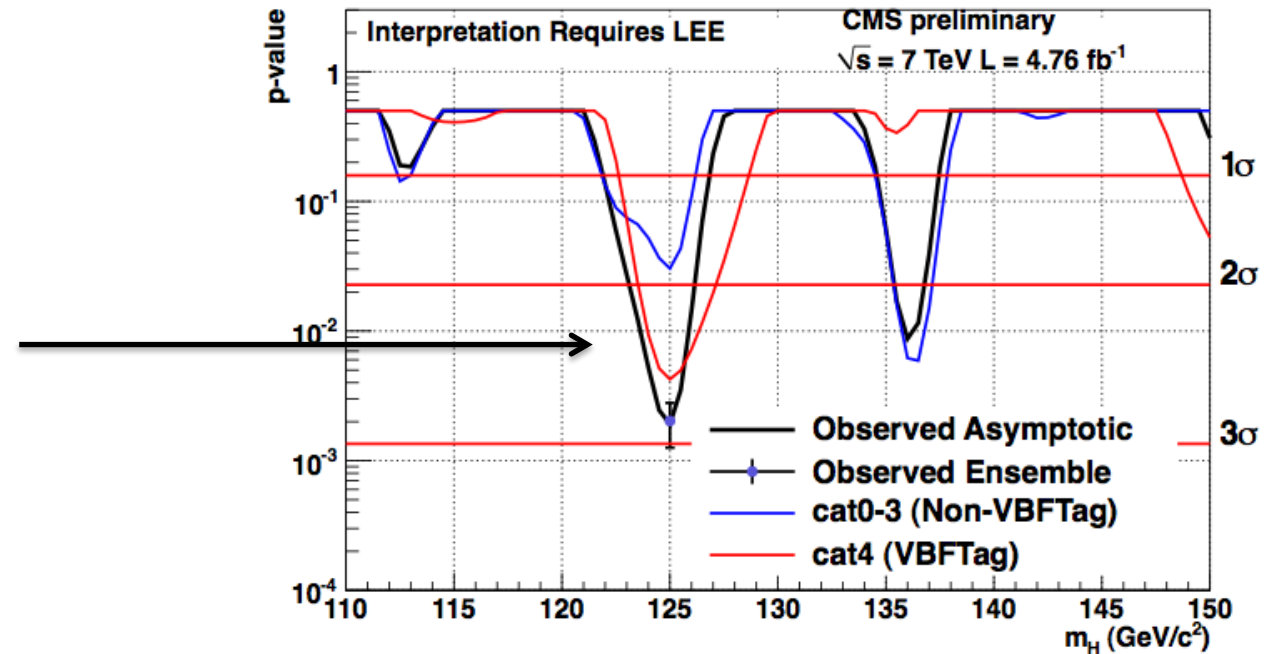
Expected from  
MVA analysis  
Improvement  
 $\sim 20\%$

Limit  $\sim 1.2 \times SM$

**ATLAS**  
 Excess of  
 $2.8\sigma$   
 Global of  $1.5\sigma$



**CMS**  
 Excess of  
 $2.9\sigma$   
 Global of  $1.6\sigma$



$$H \rightarrow ZZ \rightarrow llll$$

The « Golden » Channel

Most sensitive Channel in [180-250] GeV Mass range

ATLAS 4.9 fb<sup>-1</sup>

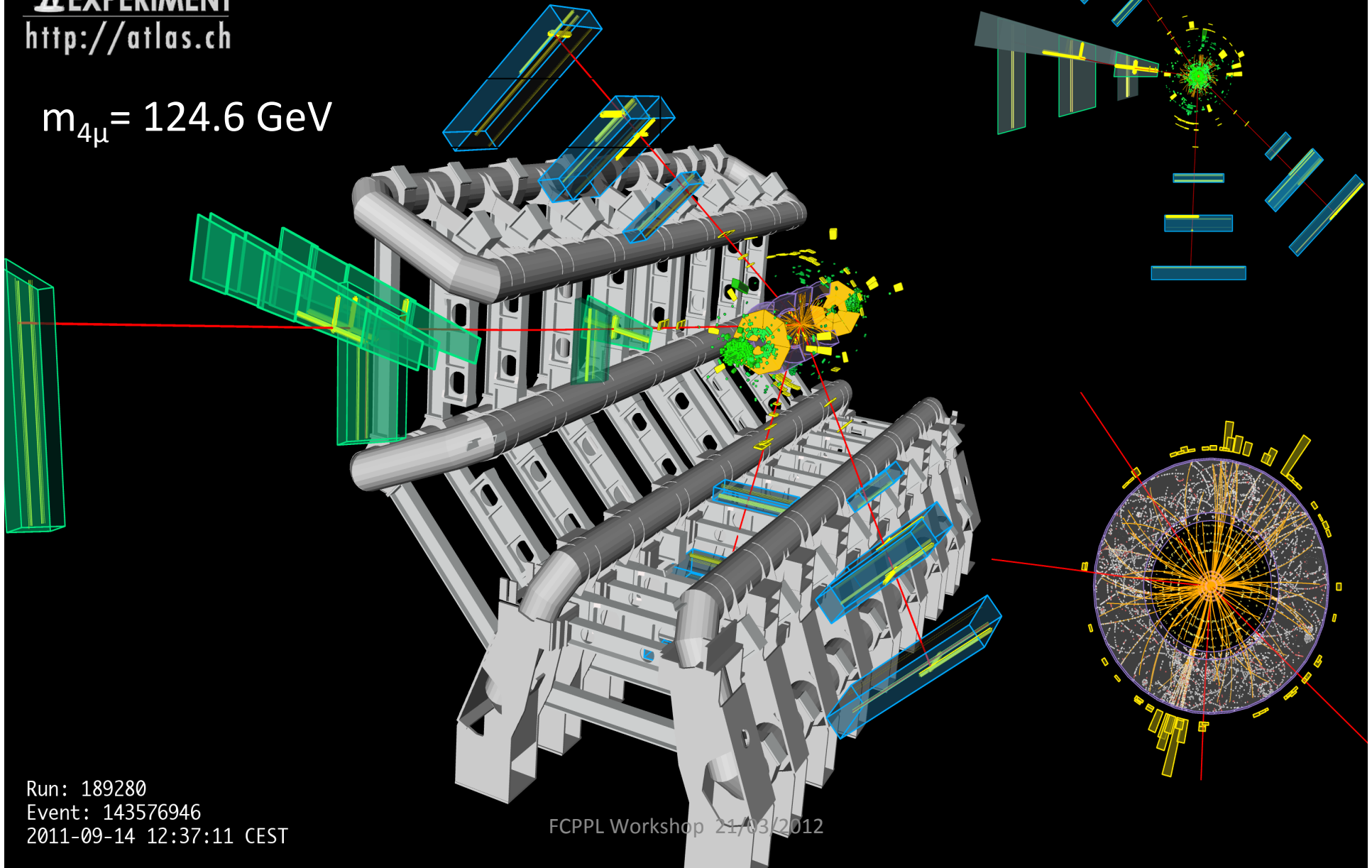
CMS 4.7 fb<sup>-1</sup>

Signal yield after cuts (low mass) ~ O(5)

s/b ~ O(1) locally at 125 GeV

$p_T (\mu^-, \mu^+, \mu^+, \mu^-) = 61.2, 33.1, 17.8, 11.6 \text{ GeV}$   
 $m_{12} = 89.7 \text{ GeV}, m_{34} = 24.6 \text{ GeV}$

$m_{4\mu} = 124.6 \text{ GeV}$



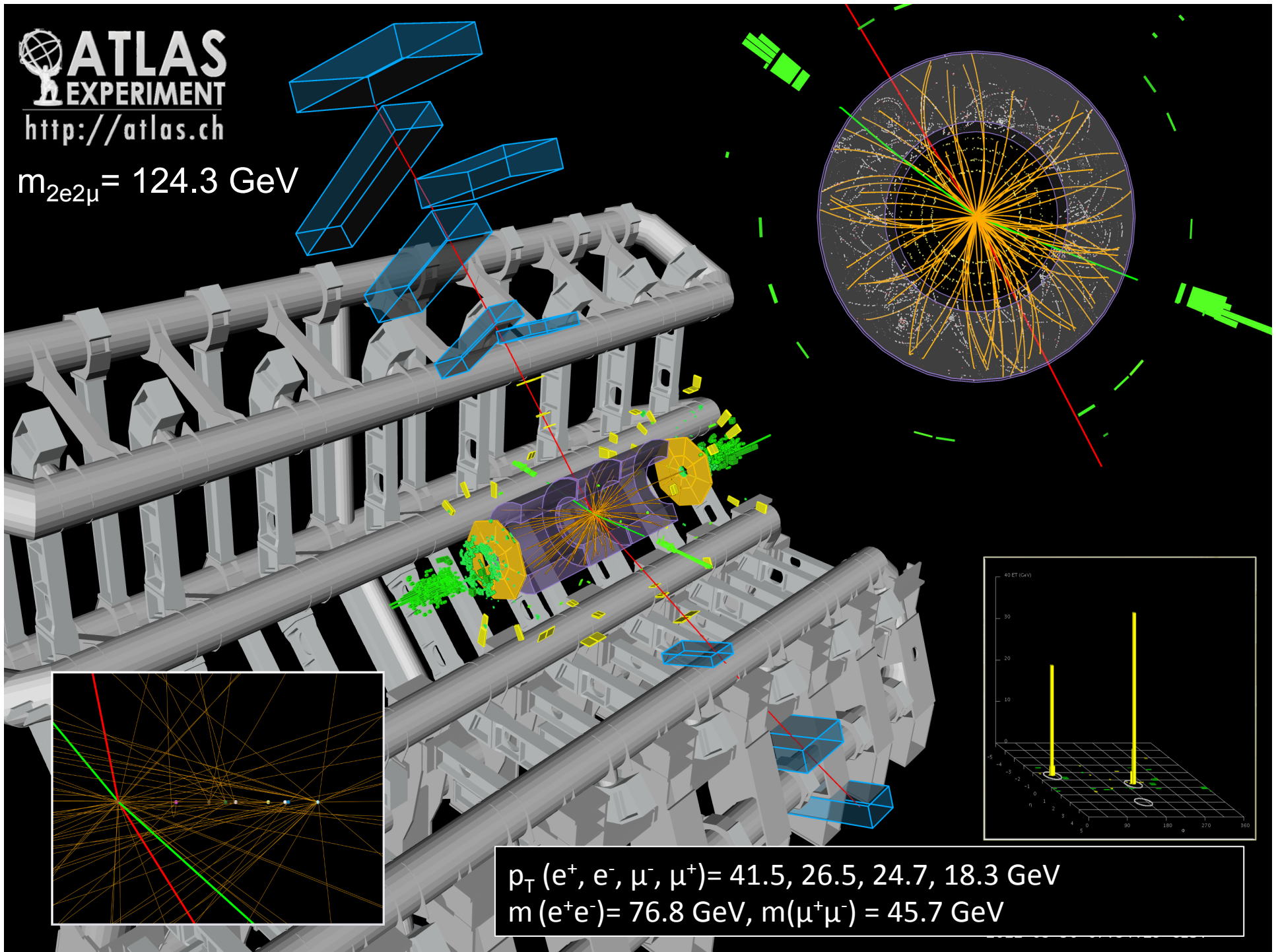
Run: 189280  
Event: 143576946  
2011-09-14 12:37:11 CEST



ATLAS  
EXPERIMENT

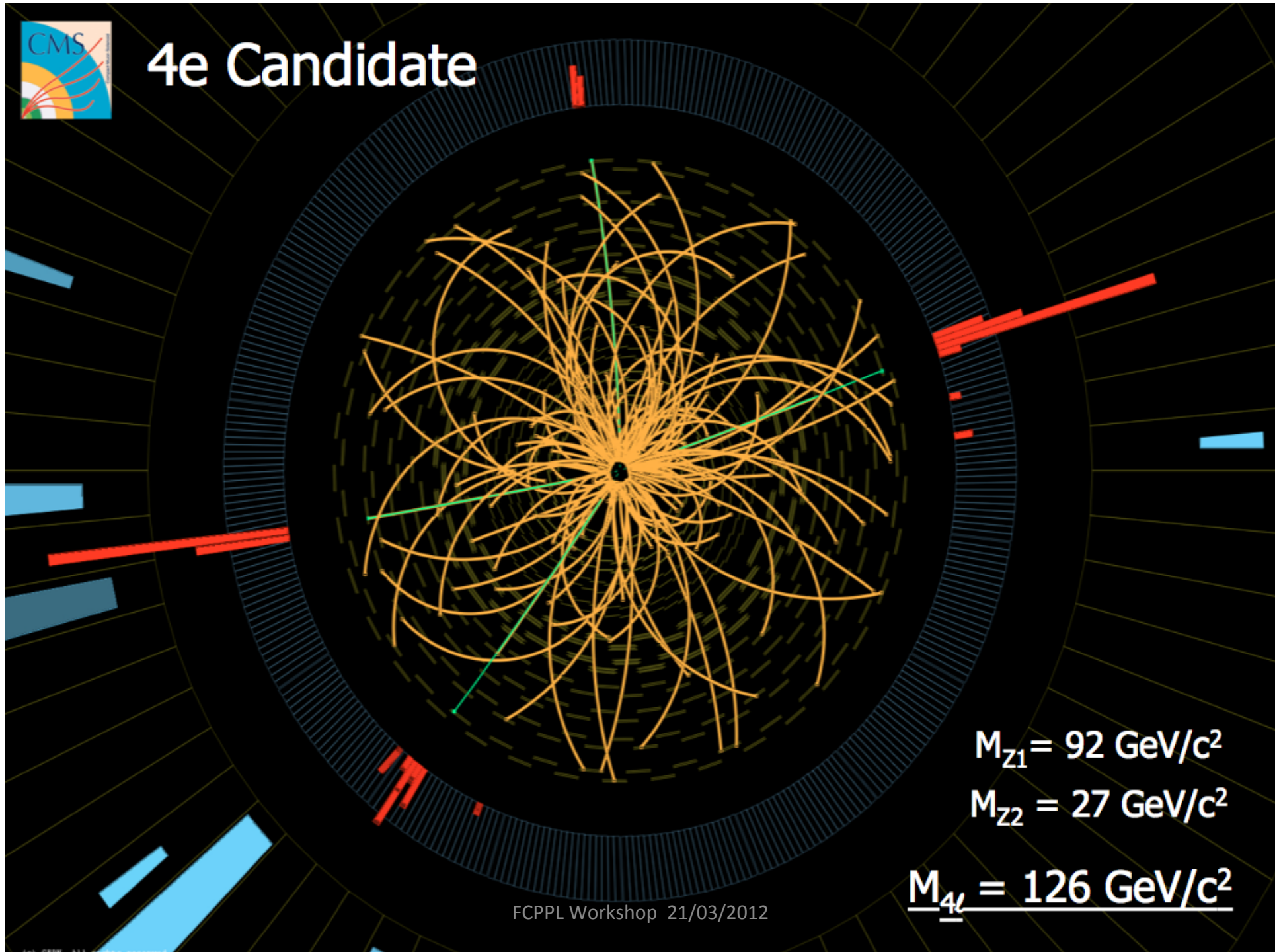
<http://atlas.ch>

$m_{2e2\mu} = 124.3 \text{ GeV}$





# 4e Candidate



$$M_{Z1} = 92 \text{ GeV}/c^2$$

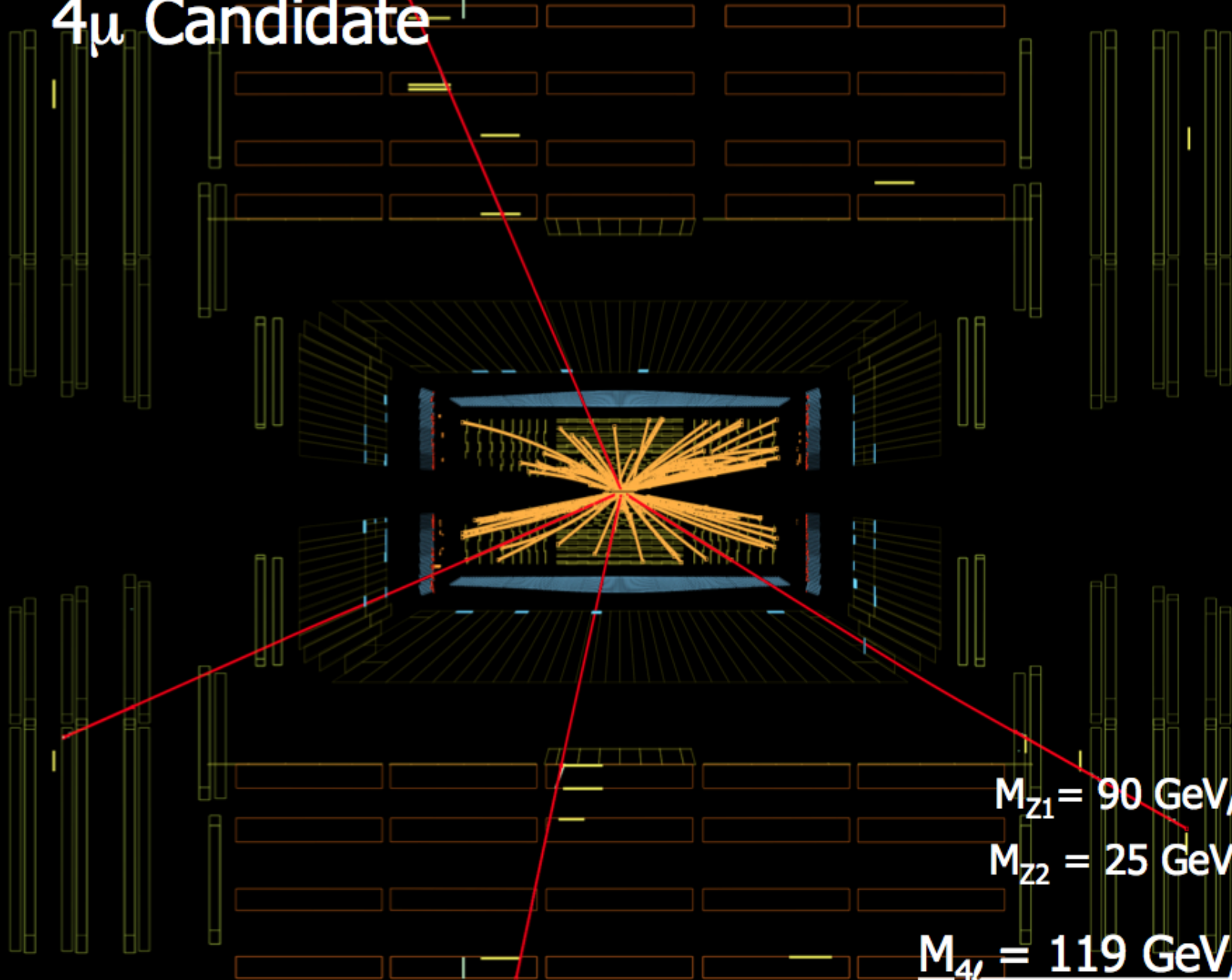
$$M_{Z2} = 27 \text{ GeV}/c^2$$

$$\underline{M_{4e}} = 126 \text{ GeV}/c^2$$

FCPPL Workshop 21/03/2012



# 4 $\mu$ Candidate



$$M_{Z1} = 90 \text{ GeV}/c^2$$

$$M_{Z2} = 25 \text{ GeV}/c^2$$

$$M_{4\mu} = 119 \text{ GeV}/c^2$$

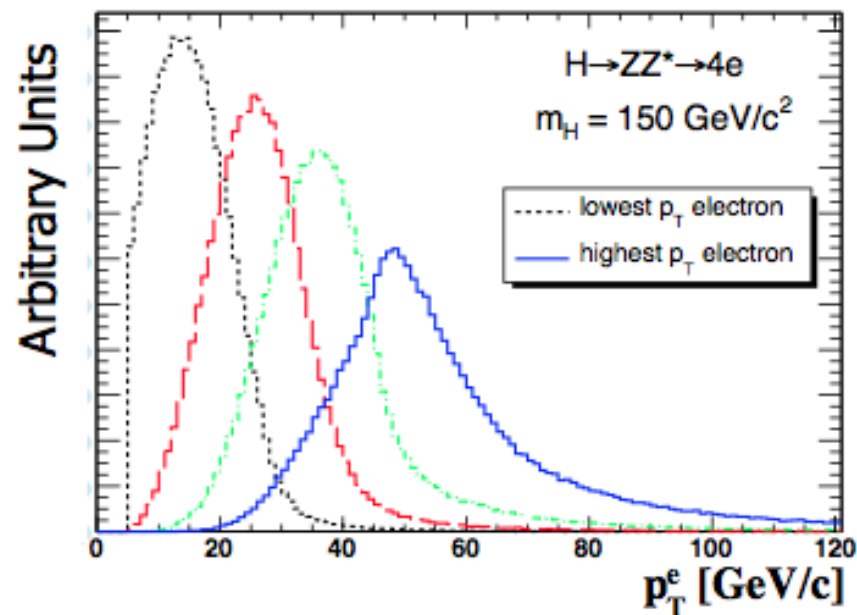
FCPPL Workshop 21/03/2012

# Higgs Boson Search in the $ZZ^{(*)}\rightarrow 4l$

## Key features

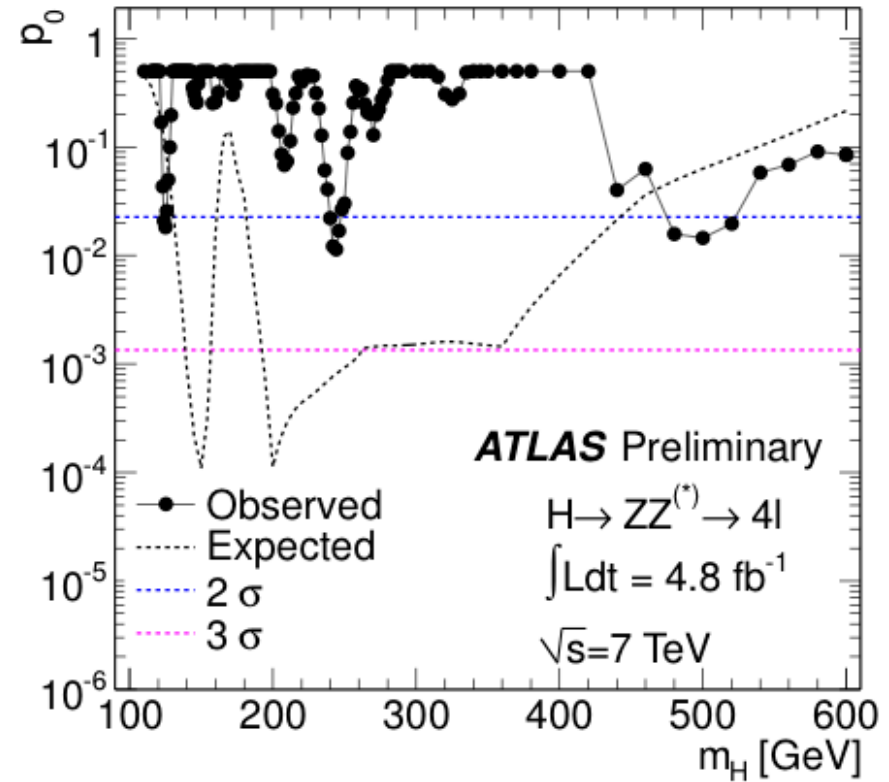
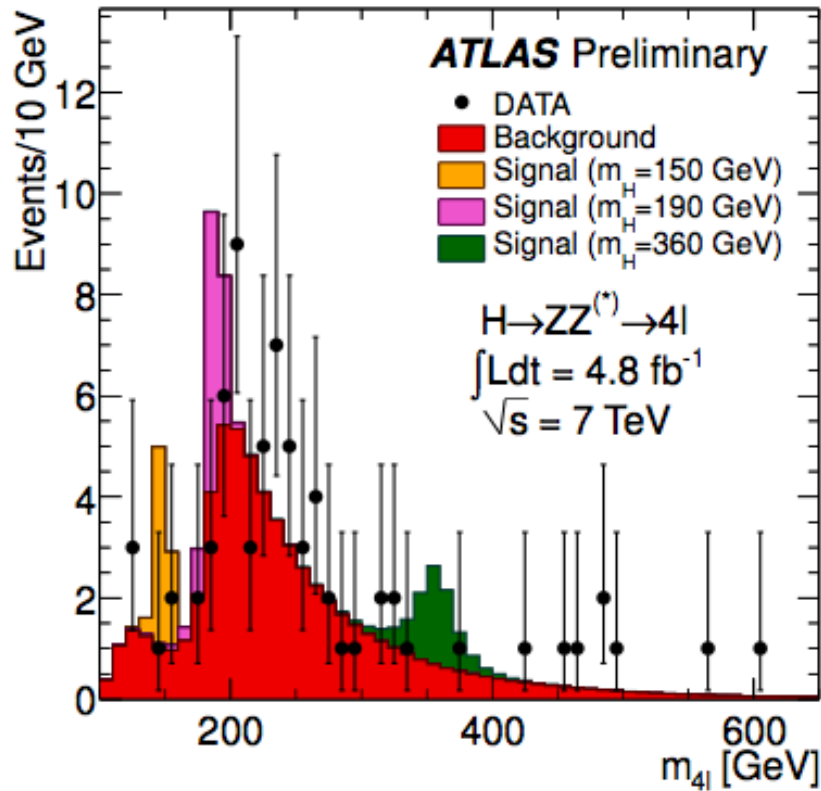
- One Z allowed to be off-mass shell ( $m_H < 180$  GeV)
- low  $p_T$  lepton reconstruction very important
- Invariant mass selections also important to optimize low mass selection

- Low Background {
- Main Background ZZ from Monte Carlo (ATLAS) and derived from Z (CMS)
  - Other backgrounds (Zbb and top) data driven (but small)





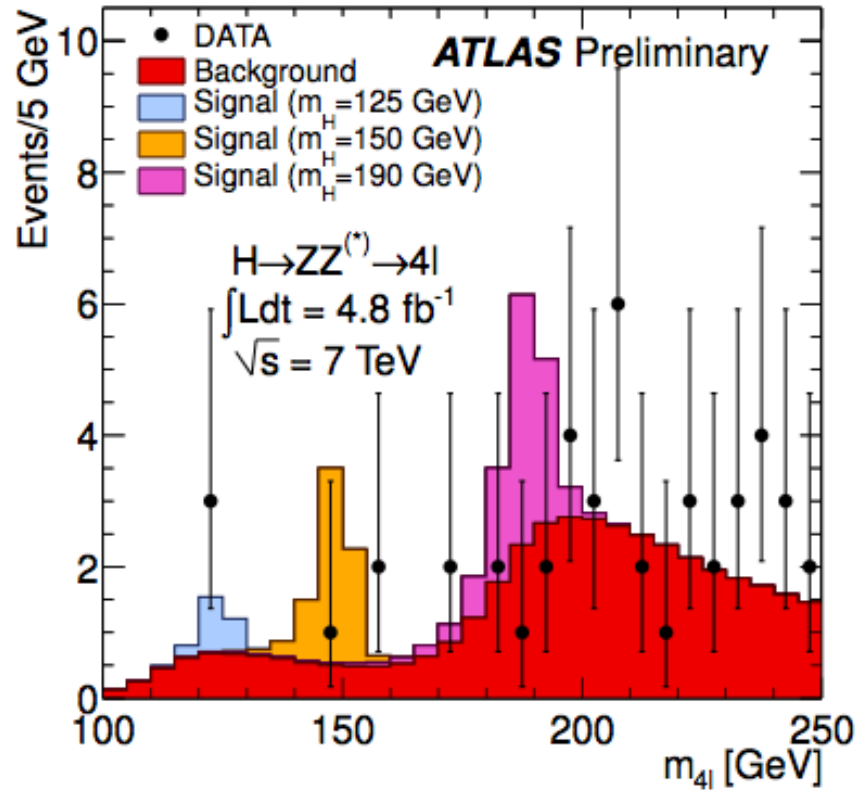
# ATLAS $ZZ^{(*)} \rightarrow 4l$ (Low Mass)



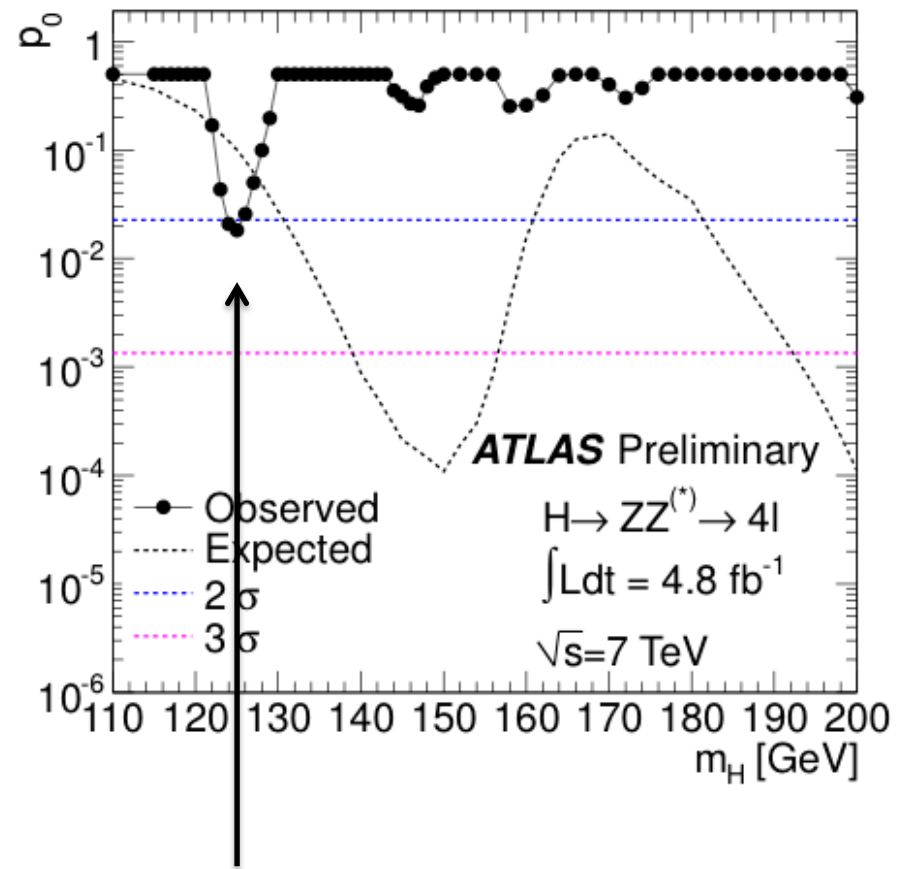
	$m_H$ (GeV)	Local (global) $p_0$	Local significance	Expected from SM Higgs
Excluded at 95% C.L. <span style="color: red; font-size: 2em;">→</span>	125	1.8% (~50%)	2.1 $\sigma$	1.4 $\sigma$
	244	1.1% (~50%)	2.3 $\sigma$	3.2 $\sigma$
	500	1.4% (~50%)	2.2 $\sigma$	1.5 $\sigma$



# ATLAS $ZZ^{(*)} \rightarrow 4l$ (Low Mass)

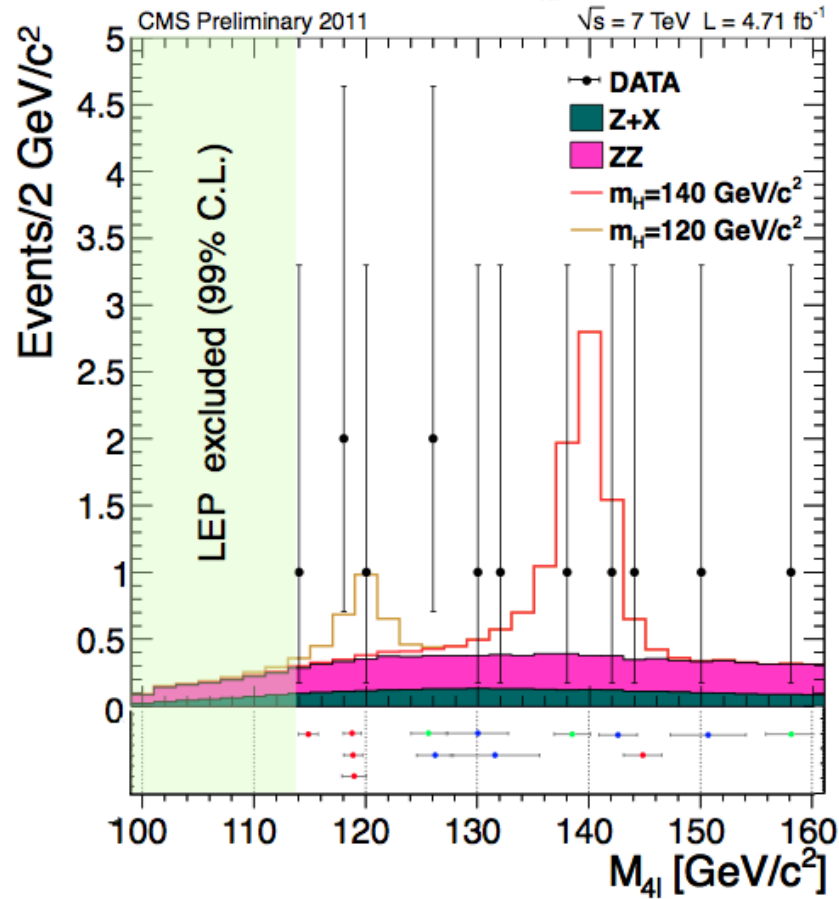


Globally not significant  
 but at 125 GeV



**ATLAS**  
 Excess of  
 2.1 $\sigma$

# CMS $ZZ^{(*)} \rightarrow 4l$ (Low Mass)



## Baseline Selection

$$50 < M_{Z1} < 120 \text{ GeV}/c^2$$

$$12 < M_{Z2} < 120 \text{ GeV}/c^2$$

$$\epsilon(M_H \sim 120) \sim 20\% (4e), 40\% (4\mu), 25\% (2e2\mu)$$

$$\epsilon(M_H \sim 160) \sim 42\% (4e), 75\% (4\mu), 55\% (2e2\mu)$$

## Event Yields:

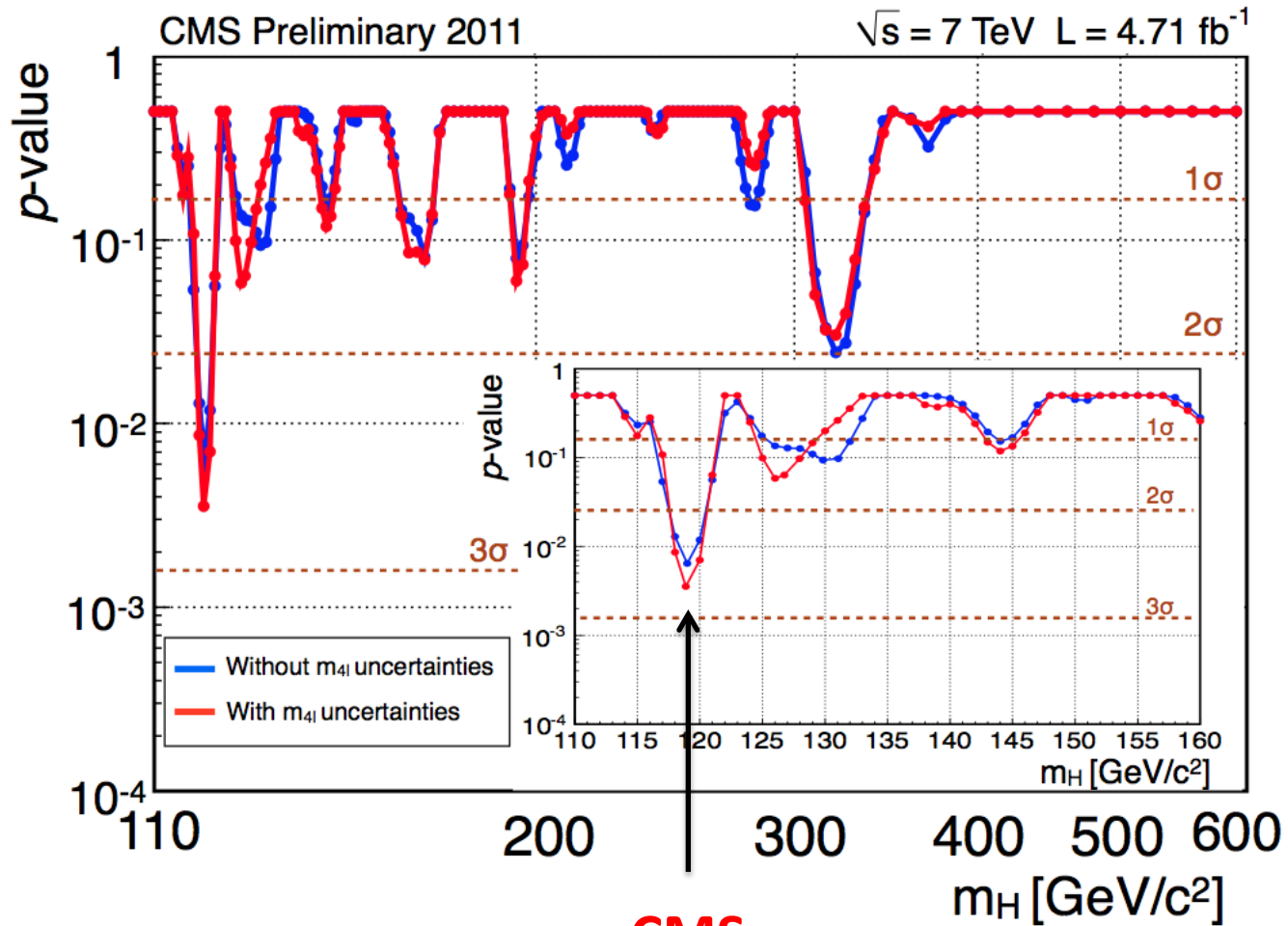
Final state:  $4e$   $4\mu$   $2e2\mu$

Obs. events:  $3$   $5$   $5$

Exp. events:  $1.7$   $3.3$   $4.5$

$100 < M_{4l} < 160 \text{ GeV}/c^2$  **Observed: 13** **Expected:  $9.5 \pm 1.3$  events**

# CMS $ZZ^{(*)} \rightarrow 4l$ (Low Mass)



Globally not significant  
and at 119 GeV

**CMS**  
Excess of  
**2.5σ**

$$H \rightarrow W^+ W^- \rightarrow l \nu l \nu$$

Most sensitive Channel in [125-180] GeV Mass range

ATLAS 4.7 fb<sup>-1</sup>

CMS 4.6 fb<sup>-1</sup>

Signal yield after cuts (low mass) ~O(30)

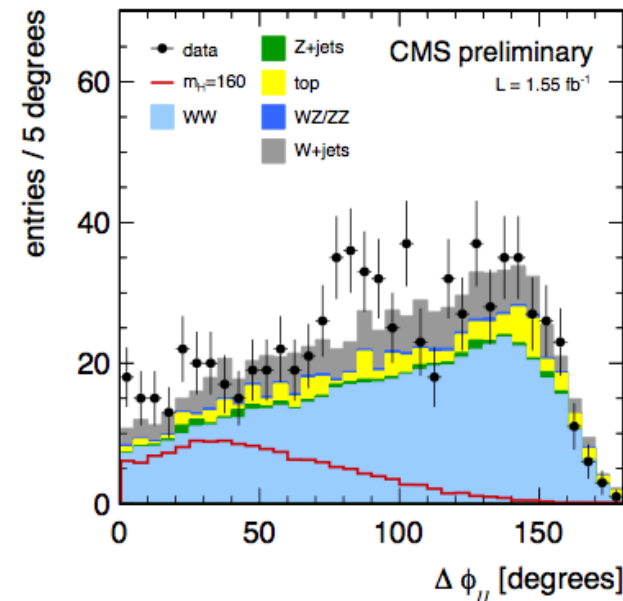
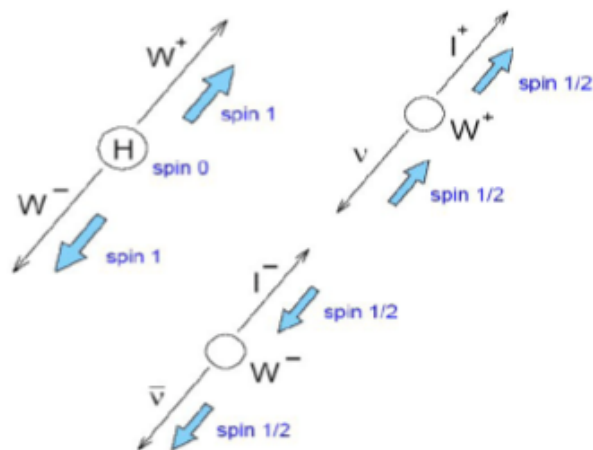
s/b ~ O(15)%

More Details in talk by [Xifeng Ruan](#)

# Higgs Boson Search in the $WW \rightarrow l\nu l\nu$

Key features :

- Poor resolution in mass (requires in particular a good control of MET)
- Search carried out in 0, 1-jet and VBF topologies
- ATLAS cut based only / CMS cut based and MVA
- Good control of the  $WW$  and top backgrounds is essential!
- Use of spin correlations is essential for the analysis and to define control regions... CMS also use a BDT (kinematic variables)

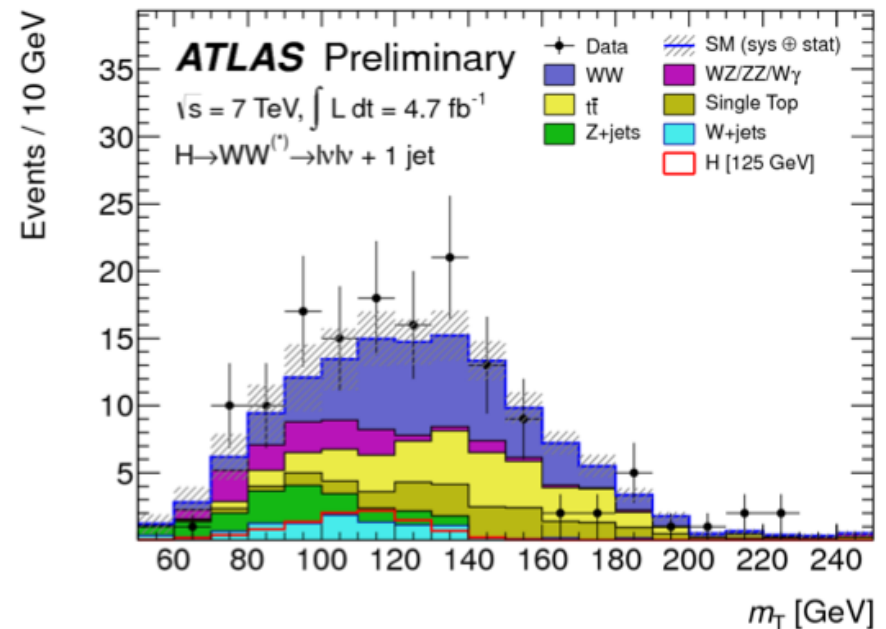
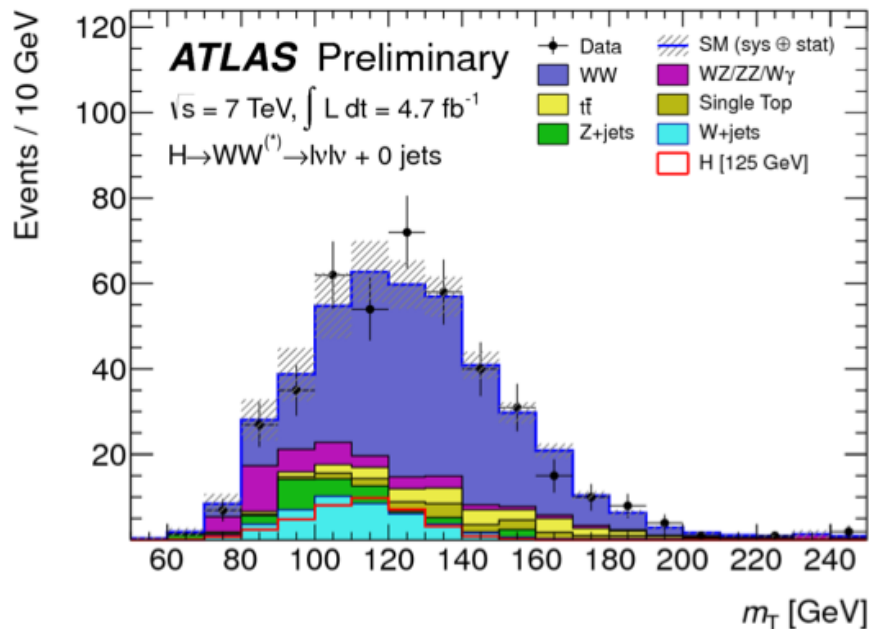




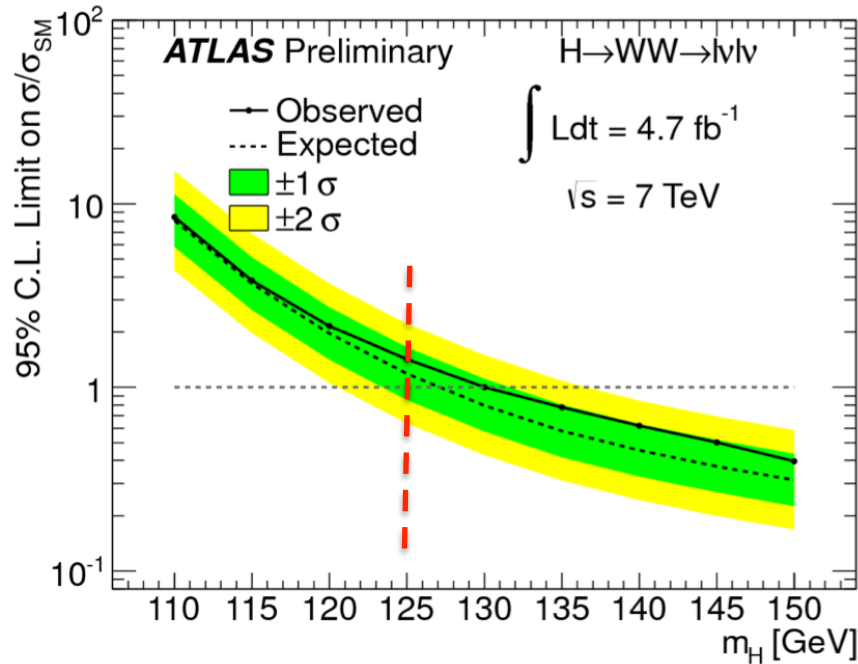
# Higgs Boson Search in the $WW \rightarrow l\nu l\nu$

Key features :

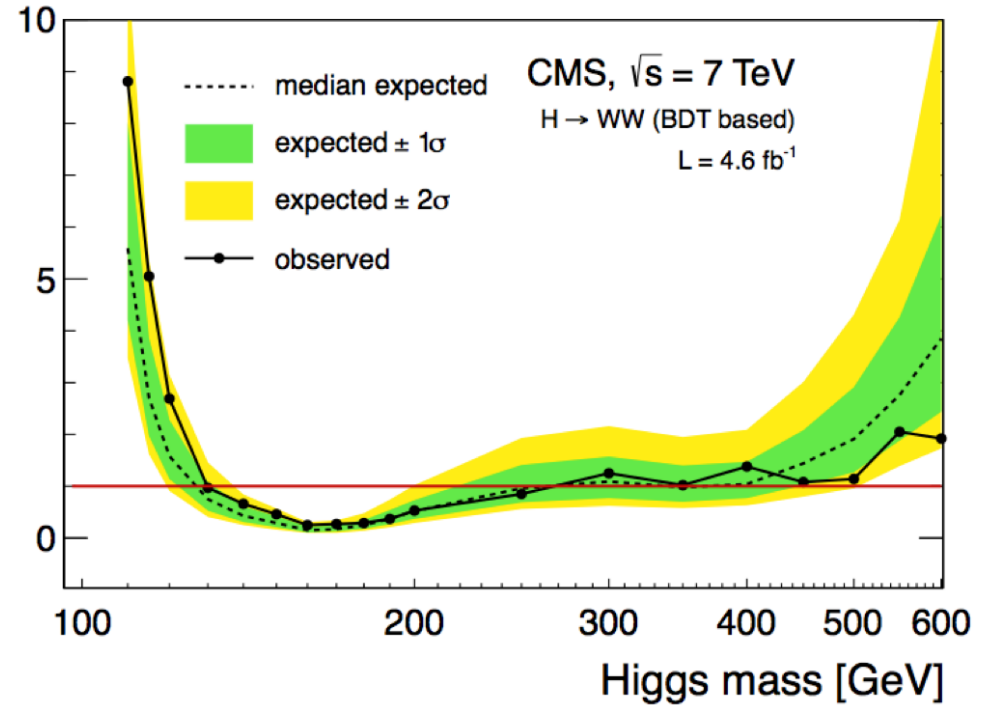
- Neutrinos : poor resolution in mass (requires in particular a good control of MET)
- Search carried out in 0, 1-jet and VBF topologies
- ATLAS cut based only / CMS cut based and MVA
- Good control of the WW and top backgrounds is essential!
- Use of spin correlations is essential for the analysis and to define control regions... CMS also use a BDT (kinematic variables)



# Higgs Boson Search in the $WW \rightarrow l\nu l\nu$



No excess in ATLAS...  
 ( $l\nu l\nu$  alone is sensitive to 125 GeV but does not exclude it)



Slight excess in CMS...

ATLAS and CMS (@125 GeV) Exp. Lim.  $\sim 1$

No Significant Excesses Observed

Single most sensitive analysis for a 125 GeV Higgs

(and small trial factor)

$$W(Z)H \rightarrow \ell\nu(\ell\ell, \nu\nu)b\bar{b}$$

ATLAS 4.7 fb<sup>-1</sup>

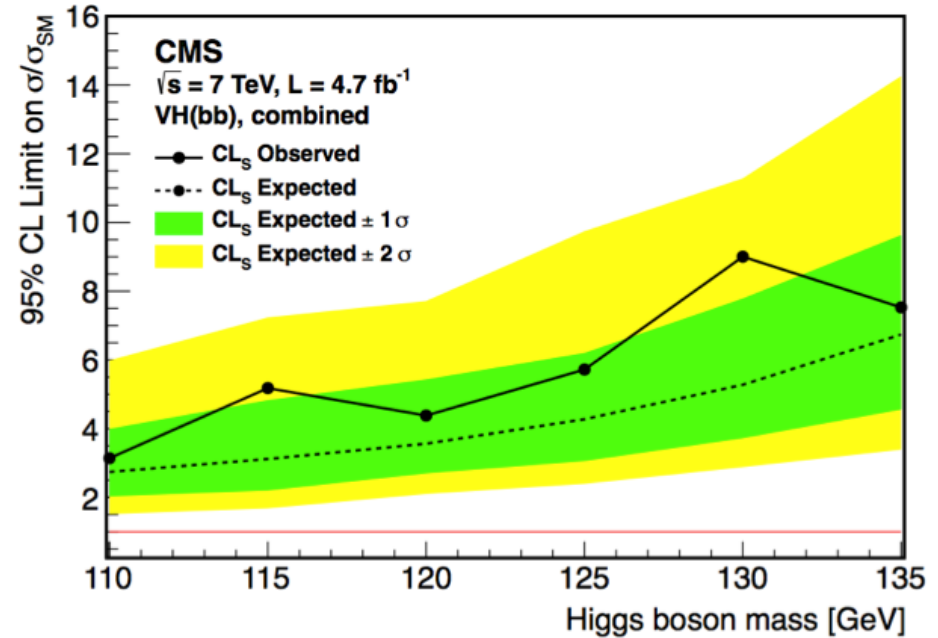
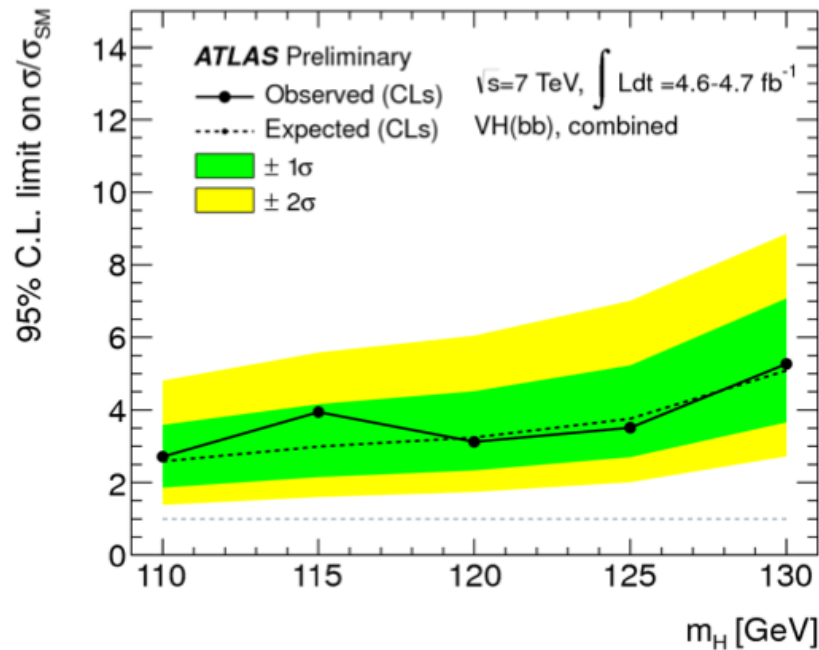
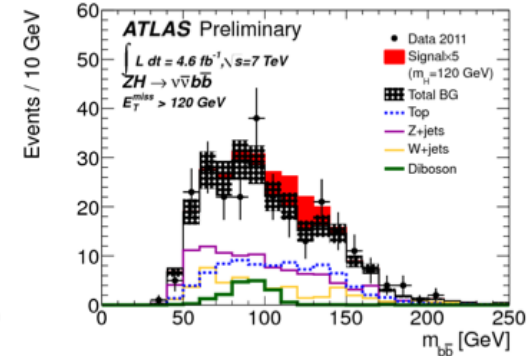
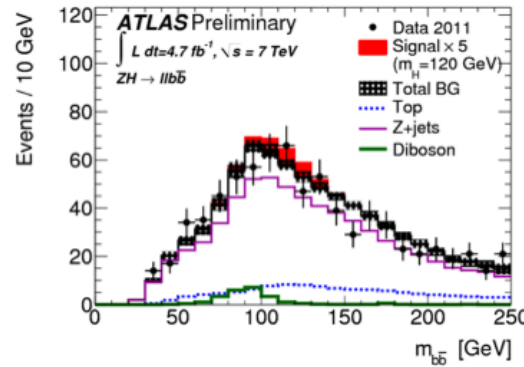
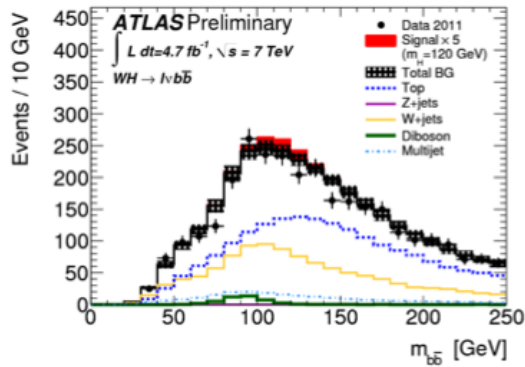
CMS 4.6 fb<sup>-1</sup>

Signal yield after cuts (low mass, Highest boost)  $\sim O(3-5)$

s/b  $\sim 10-15\%$

Key features :

- Search carried out in three channels (ll,lv and vv) bb (Associated prod.)
- Higgs system boosted in the transverse plane (but no substructure)



ATLAS and CMS (@125 GeV) Exp. Lim. ~4

No Significant Excess Observed

$$(VBF)H \rightarrow \tau^+ \tau^-$$

ATLAS 4.7 fb<sup>-1</sup>

CMS 4.6 fb<sup>-1</sup>

Signal yield after cuts (low mass and VBF) ATLAS ~O(3) / CMS~O(0.5)

ATLAS s/b ~ 2% / CMS s/b ~ 5%

ATLAS and CMS different working points

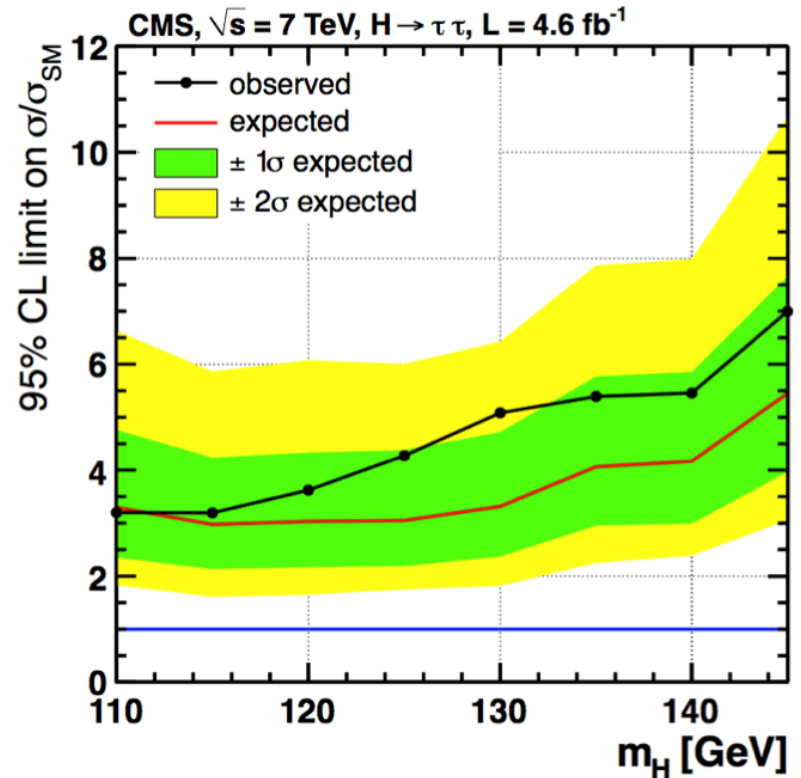
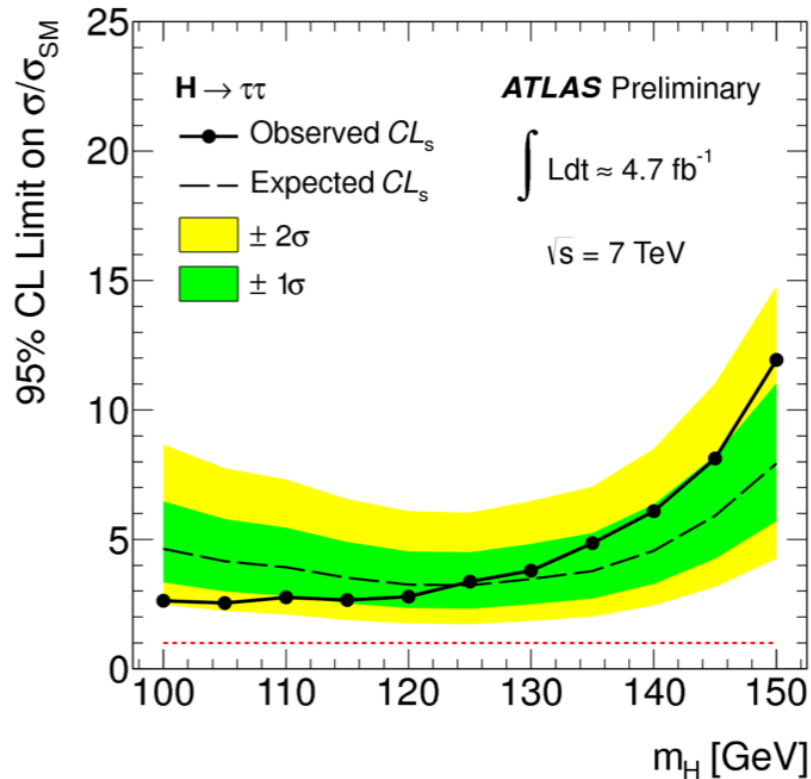
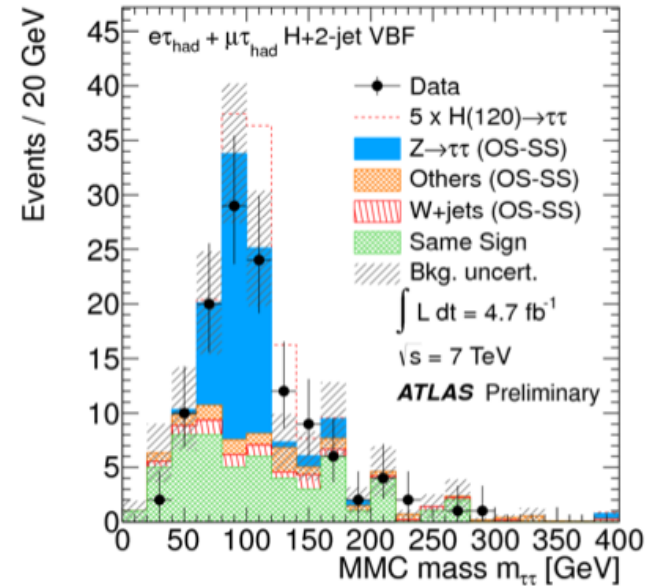


Key features :

- Search carried out in  $ll$ ,  $lh$  and  $hh$  channels
- Important use of VBF
- New Mass Reconstruction Techniques

ATLAS and CMS (@125 GeV) Exp. Lim.  $\sim 3$

No Significant Excess Observed

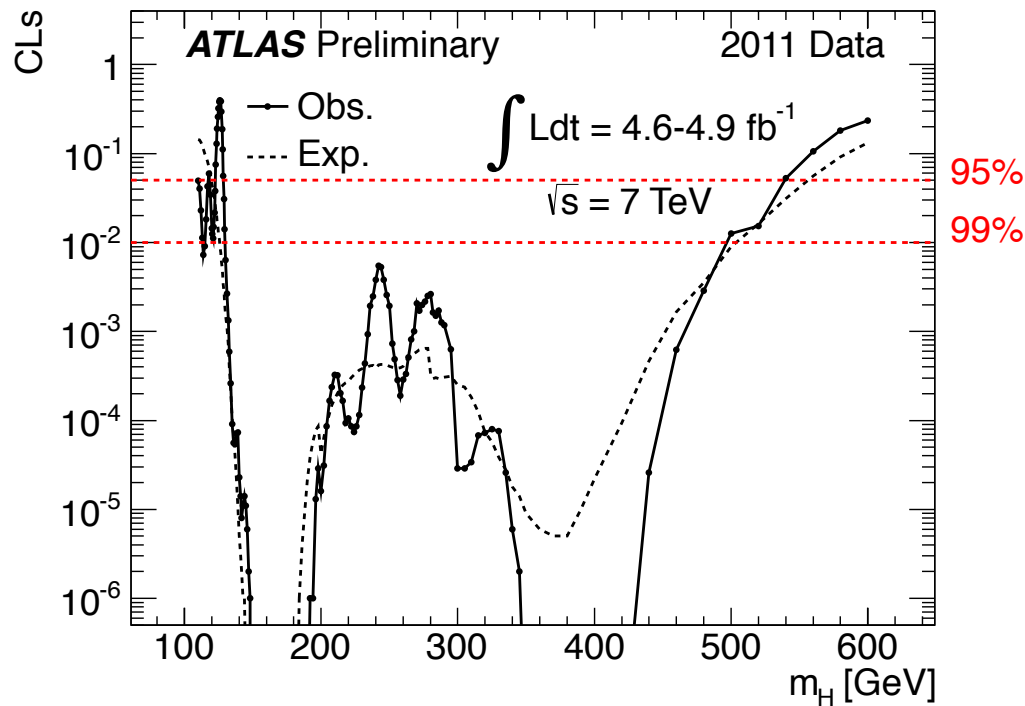


# *Combination(s)*

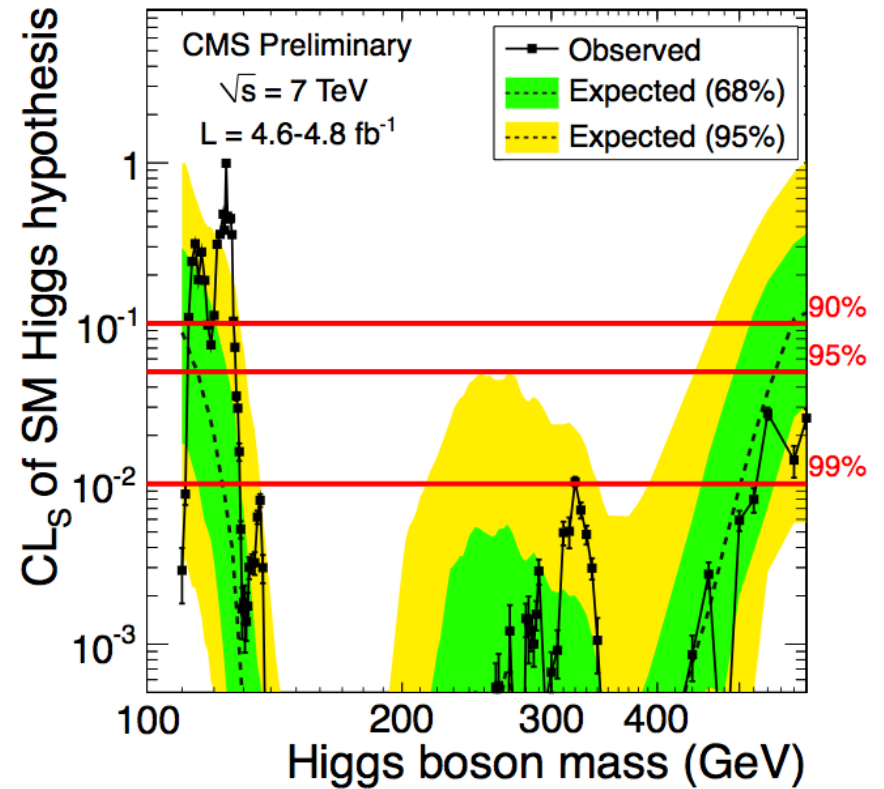
*The Overall Picture*

# Combination of All Channels

The ATLAS and CMS Combinations



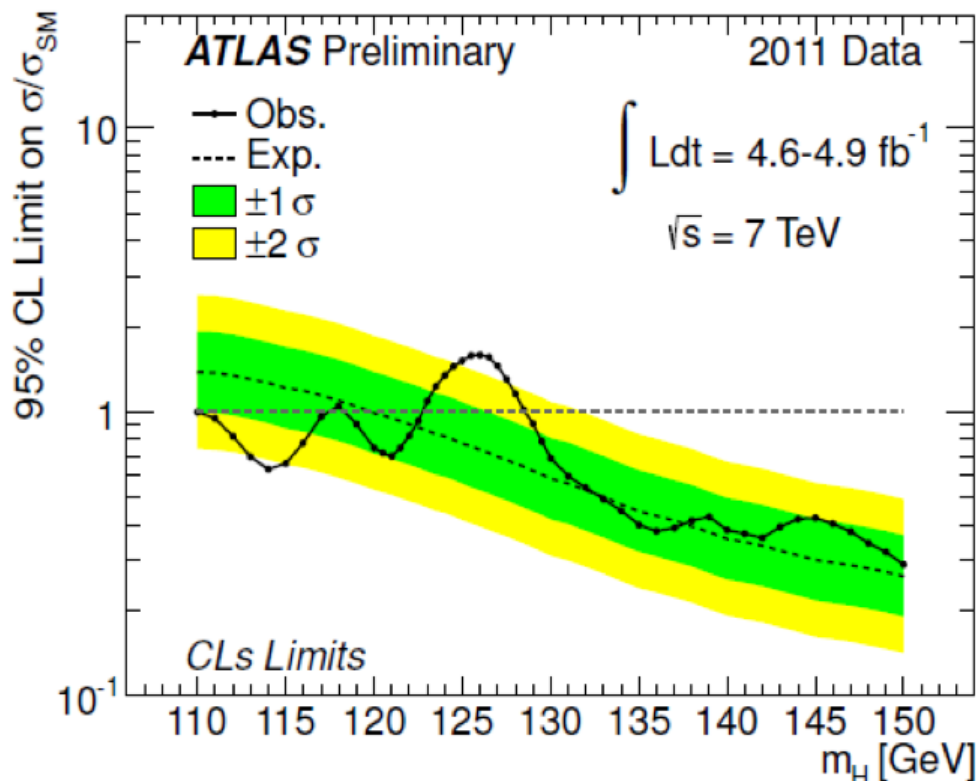
Expected (95% CL) : 120 – 555 GeV  
 Observed (95% CL) : 110-117, 117-122,  
 129-540 GeV  
 Expected (99% CL) : 126 – 500 GeV  
 Observed (99% CL) : 130-480 GeV



Expected (95% CL) : 114 – 540 GeV  
 Observed (95% CL) : 128 - 600 GeV  
 Observed (99% CL) : 129 – 520 GeV

# Combination of All Channels

The ATLAS and CMS Combinations



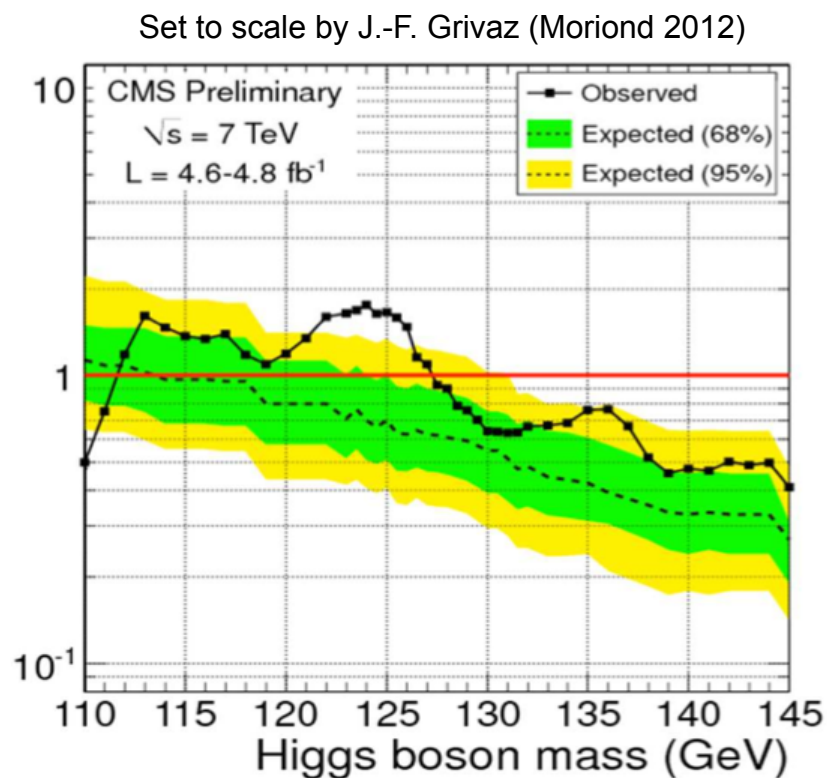
Expected (95% CL) : 120 – 555 GeV

Observed (95% CL) : 110-117, 117-122,

129-540 GeV

Expected (99% CL) : 126 – 500 GeV

Observed (99% CL) : 130-480 GeV

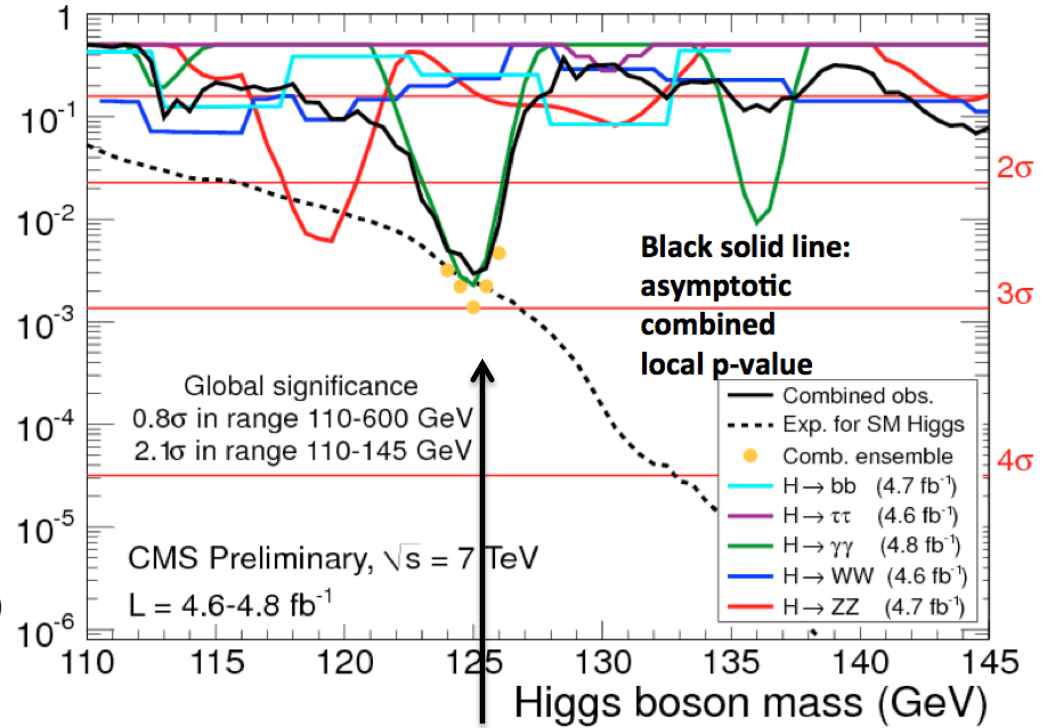
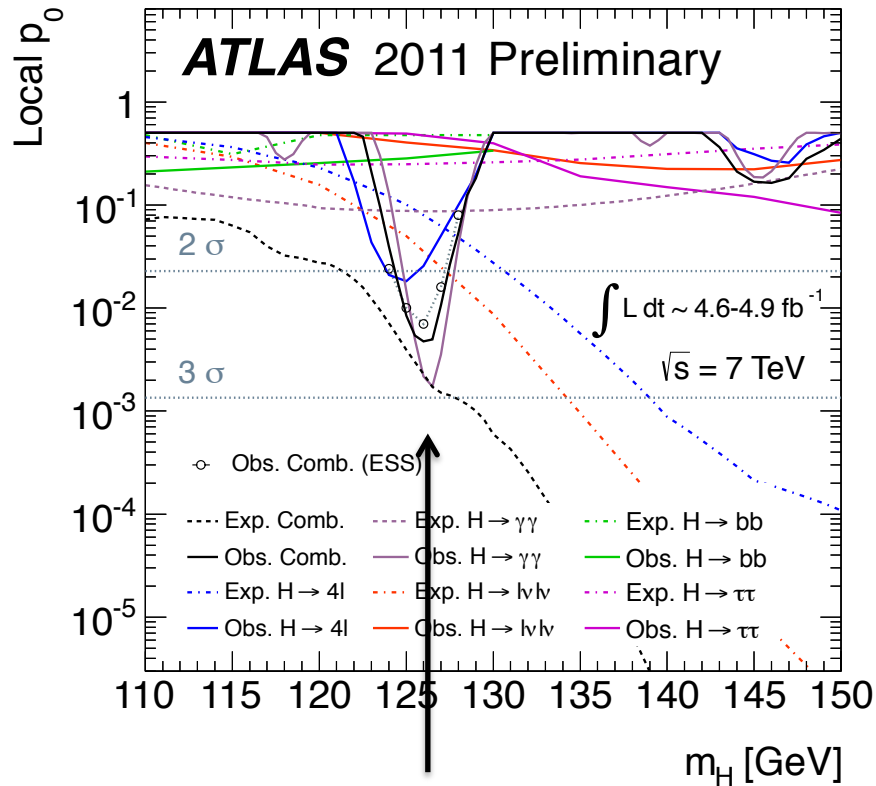


Expected (95% CL) : 114 – 540 GeV

Observed (95% CL) : 128 - 600 GeV

Observed (99% CL) : 129 – 520 GeV

# Are there Hints of a Signal ?



**ATLAS**

Excess of  
 **$2.5\sigma$**

- Excess mostly in  $\gamma\gamma$
- Slight excess in  $4l$
- No excess in  $l\nu l\nu$

Global of  $1.5\sigma$   
Exp. local  $2.9\sigma$

**CMS**

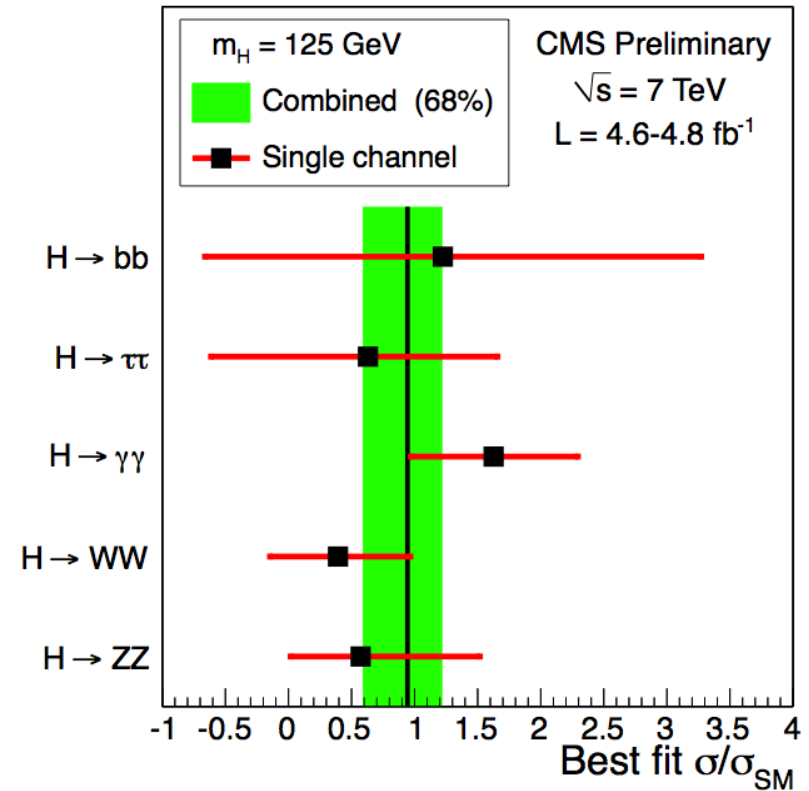
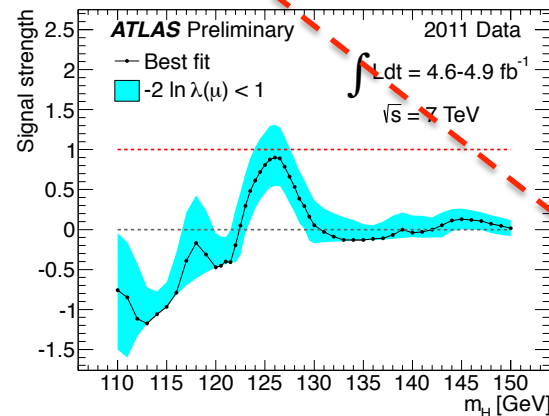
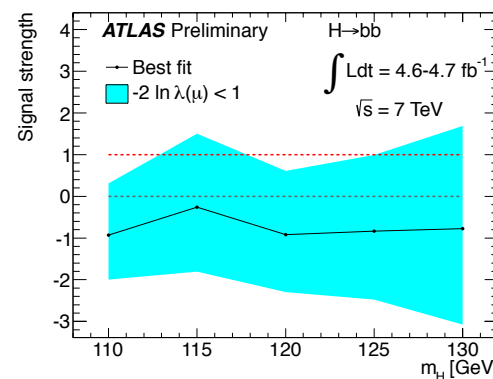
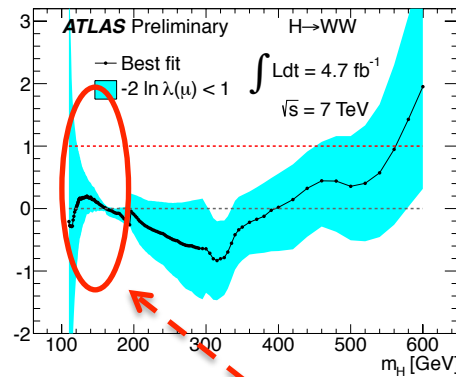
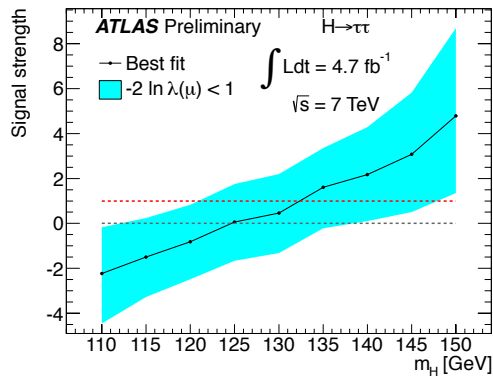
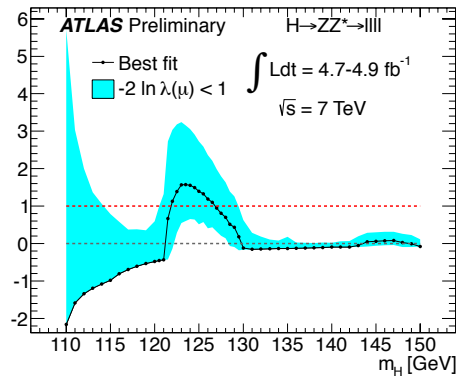
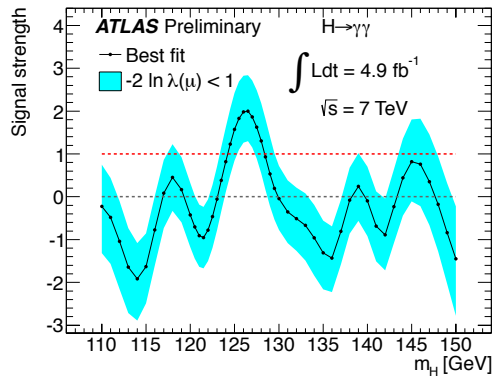
Excess of  
 **$2.8\sigma$**

- Excess mostly in  $\gamma\gamma$
- Various small excesses

Global of  $1.6\sigma$   
Exp. Local  $2.8\sigma$



# Individual Channels Consistency

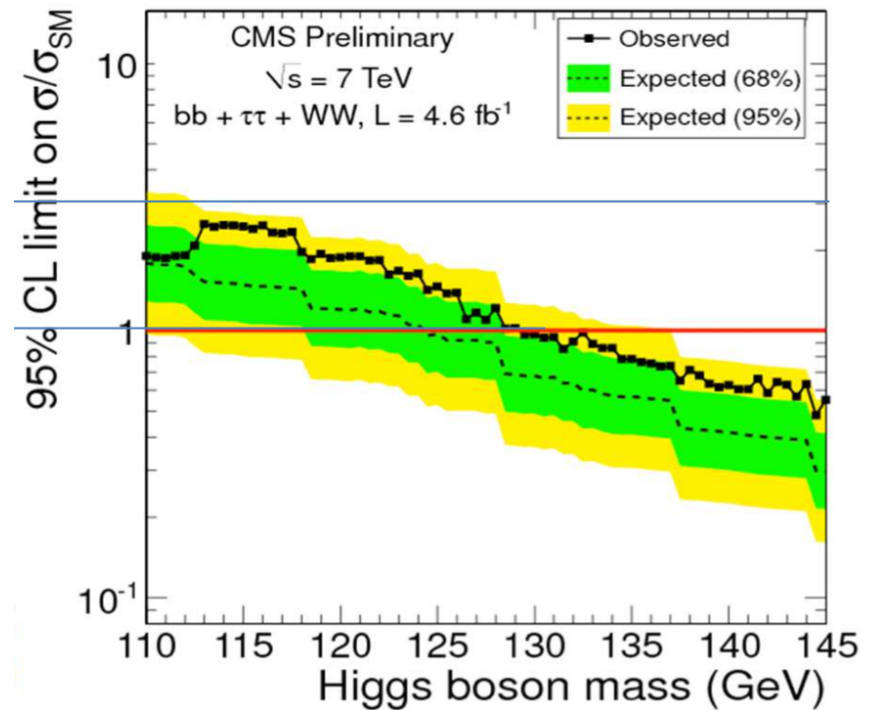
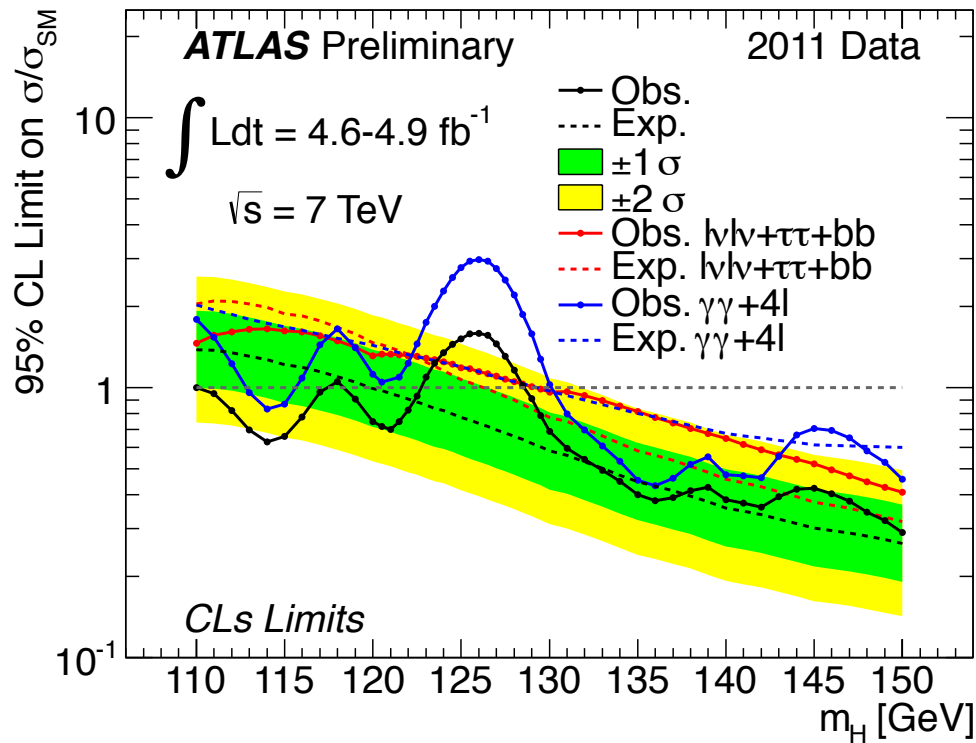


All channels compatible with SM signal hypothesis...

The specific case ATLAS  $l\nu l\nu$ ...

# Sub-combinations Consistency

- Seen that High resolution channels are consistent
- Low resolution channels do not exclude the excess observed



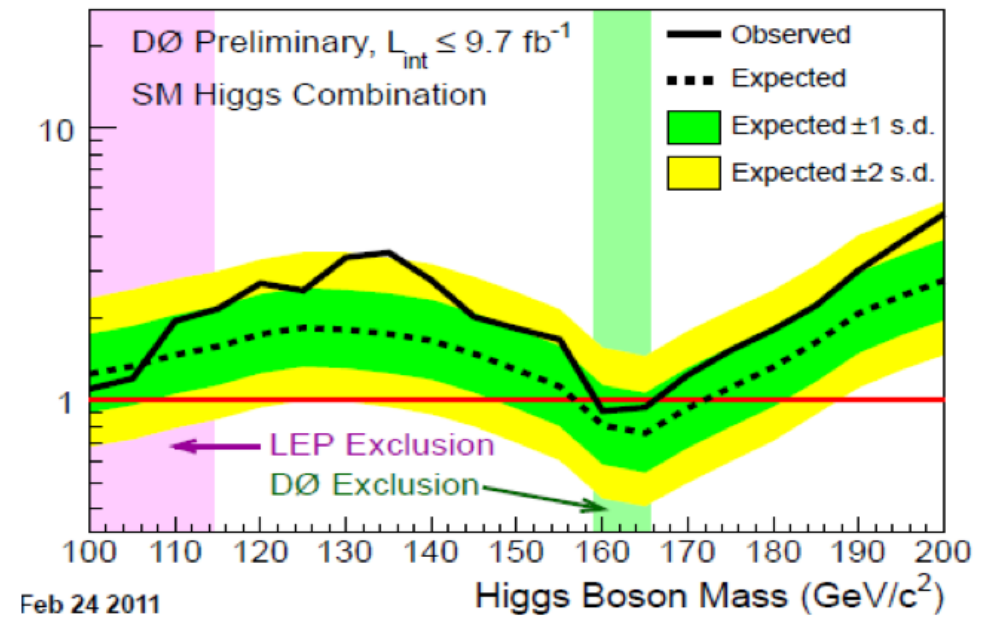
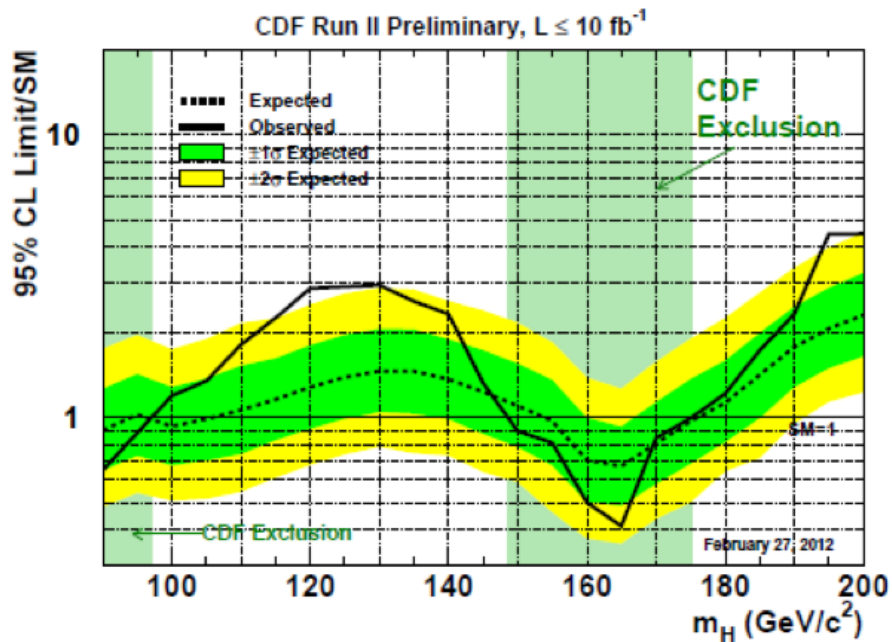
The sub-combinations do not contradict (not exclude at 95% CL) the excess observed

# Including the Latest (updated) Tevatron Results in the Overall Picture



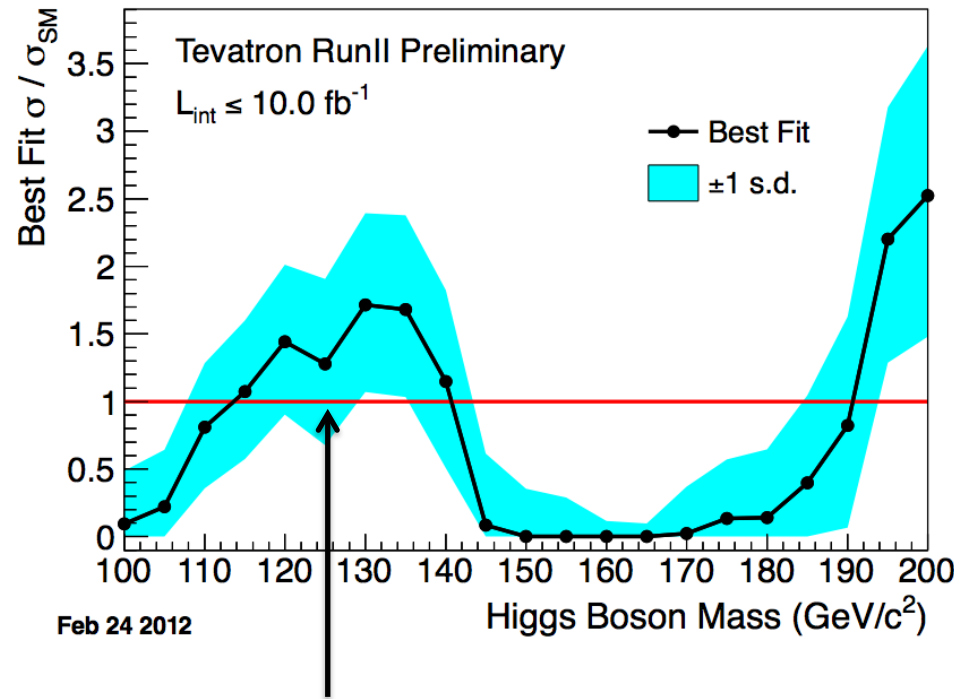
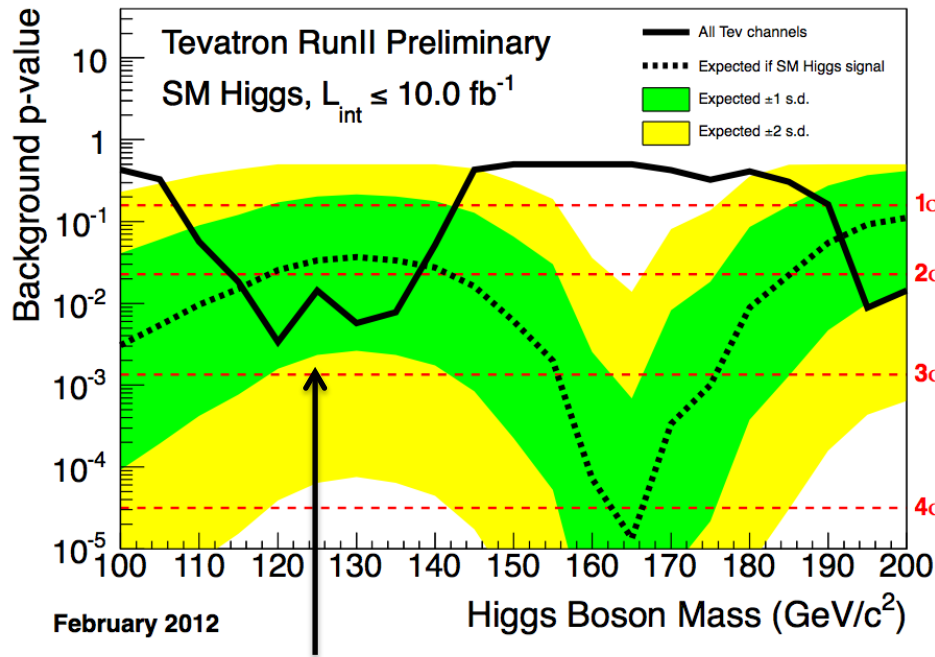
The Tevatron ended its operations Fall 2011

# Including the Latest (updated) TeVatron Results in the Overall Picture



Consistent picture in both CDF and DØ

# Including the Latest (updated) TeVatron Results in the Overall Picture



**TeVatron**

Excess of  
 $\sim 2.7\sigma$

Global of  $2.2\sigma$

Exp. local  $\sim 1.8\sigma$

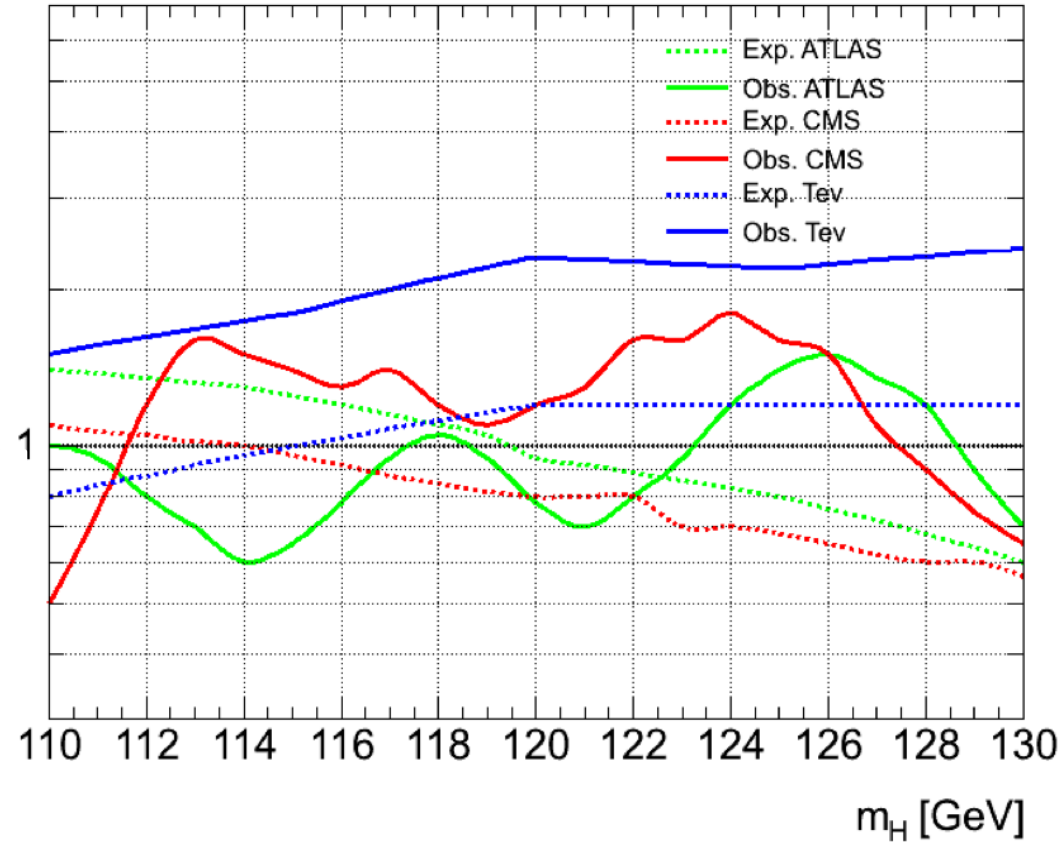
- Excess largest in bb (Mostly CDF)
- Excess also in  $l\nu l\nu$  (Both CDF and D0)

Excess compatible with SM signal



# The Full Picture

Courtesy of Bill Murray

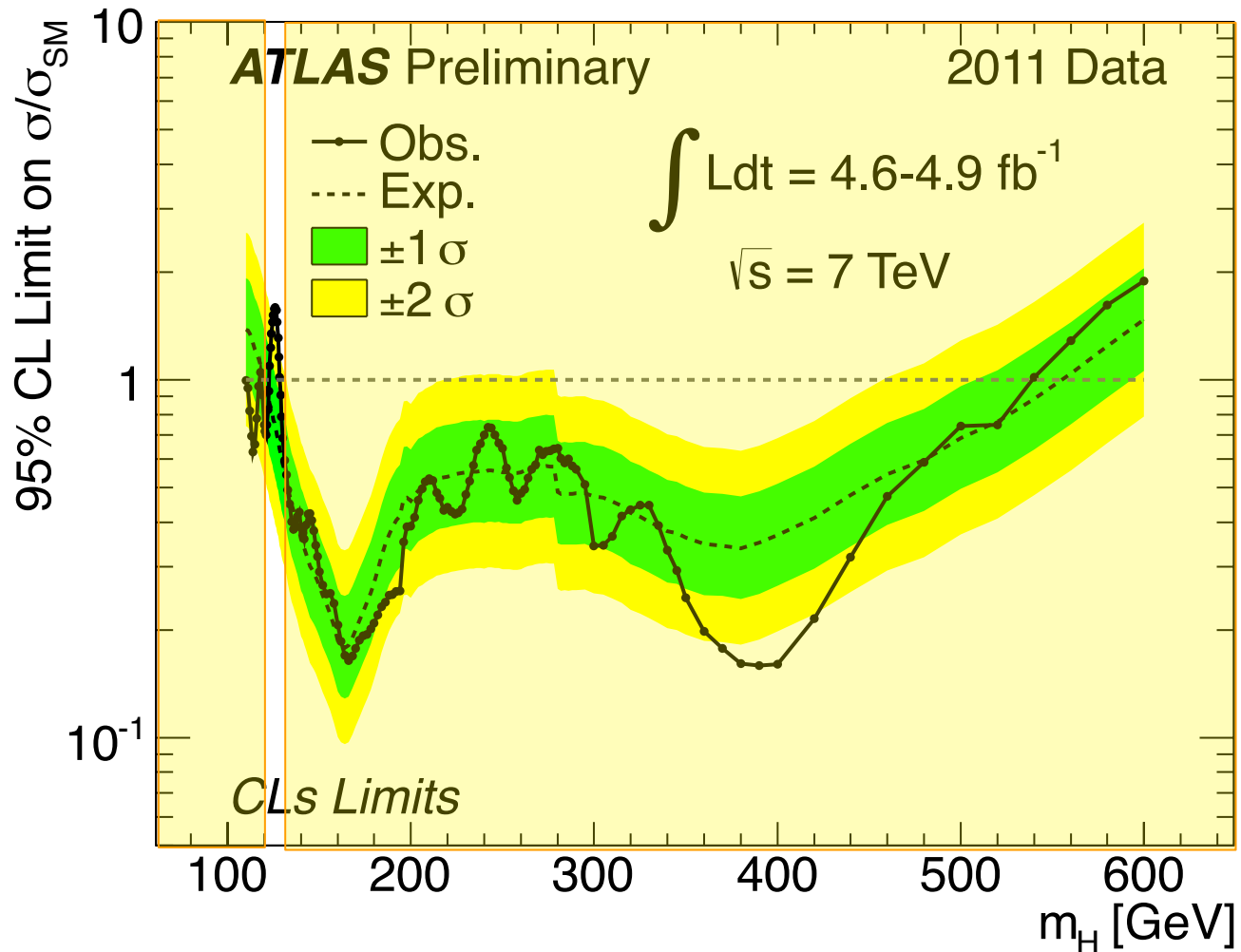


Impressively consistent picture :

- ATLAS, CMS and Tevatron consistently see excesses in a variety of channels
- ATLAS and CMS similar performance, Tevatron not so far lower

# *Conclusions and Outlook*

# New Landscape of Higgs Searches



Only a small window of opportunity left for the SM Higgs boson **~122-128 GeV**

In this mass window...

# Tantalizing Hints around 125 GeV...

- ATLAS and CMS observe  $2.5\sigma$  and  $2.8\sigma$  (respectively)
- Agreement with the  $2.9\sigma$  and  $2.8\sigma$  expected
- Observation of the excess mostly in  $\gamma\gamma$  for both channels but consistent with the observation of other channels
  
- TeVatron observes  $2.7\sigma$
- Agreement with expectation of  $1.8\sigma$
- Observation mostly in  $bb$  but also in  $l\nu l\nu$
  
- Taken individually none of these observations are globally very significant
- Need more data for a definitive answer...

... However excellent mass domain experimentally

# What Next?

# 8 TeV

~ 10% improvement in sensitivity

Parameter	2010	2011	2012	Nominal
k (N bunches)	368	1380	1380	2808
Bunch spacing	150	50	50	25
$\epsilon$ ( $\mu\text{m rad}$ )	2.4-4	1.9-2.3	2.5	3.75
$\beta^*$ (m)	3.5	1.5-1	0.6	0.55
L ( $\text{cm}^{-2}\text{s}^{-1}$ )	$2 \times 10^{32}$	$3.3 \times 10^{33}$	$\sim 7 \times 10^{33}$	$10^{34}$

More O(30) PU events!

- In 2012  $\sim 20 \text{ fb}^{-1}$  : Foresee O(7)  $\text{fb}^{-1}$  for ICHEP
  - Confirm ( $5\sigma$  sensitivity)
  - Infirm (exclude at 95% CL with such a large excess)
- Next LS1 preparing for higher energies  $>12 \text{ TeV}$

2012 Should bring a definite answer to the search of the SM Higgs boson



First beams in the LHC last Wednesday evening; first (both) beam(s) at 4 TeV

## BEAM SETUP: SQUEEZE

<b>Energy:</b>	<b>4000 GeV</b>	<b>I(B1):</b>	1.05e+10	<b>I(B2):</b>	4.03e+08
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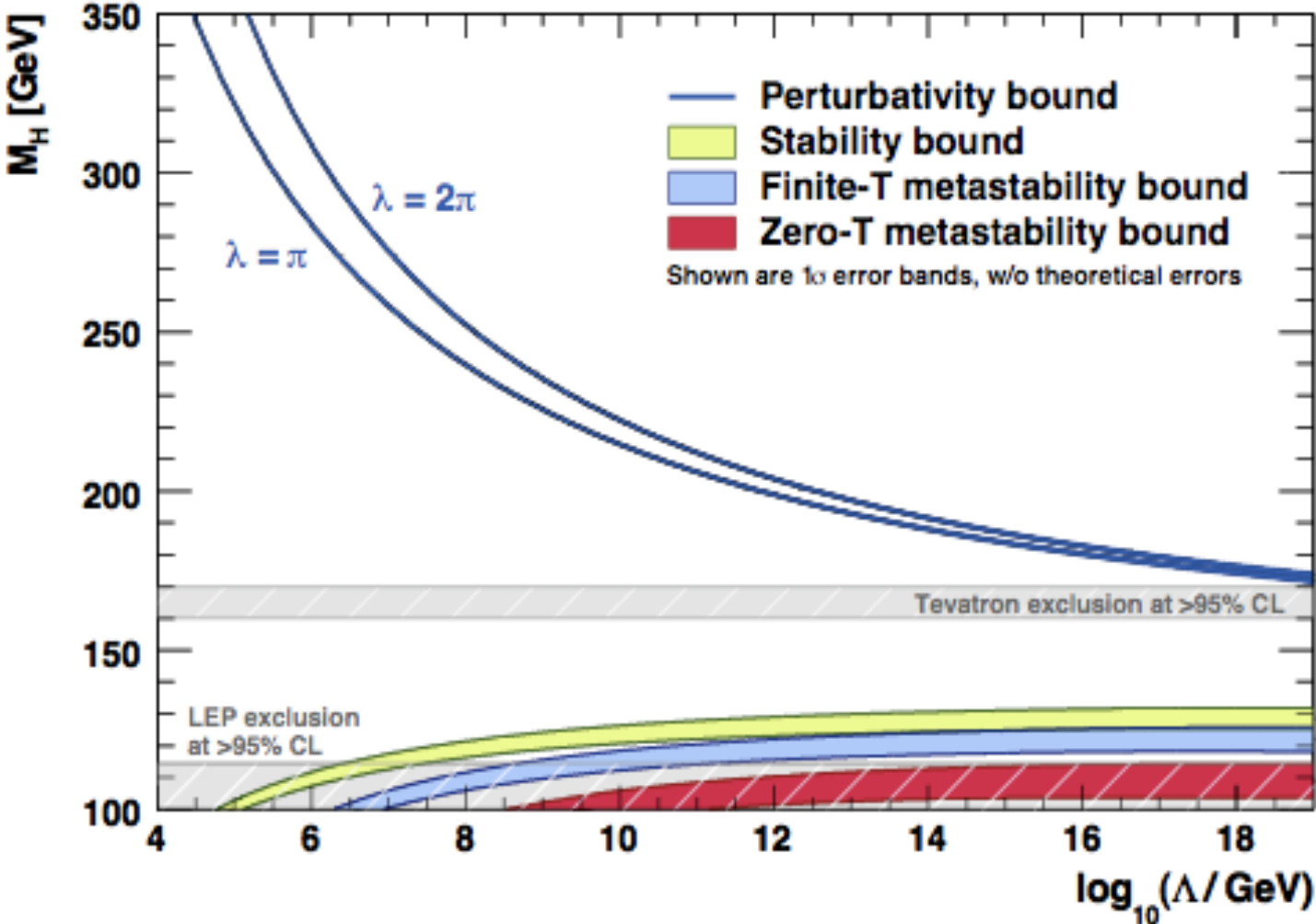
FBCT Intensity and Beam Energy Updated: 17:05:53

$\beta^* = 0.6 \text{ m}$

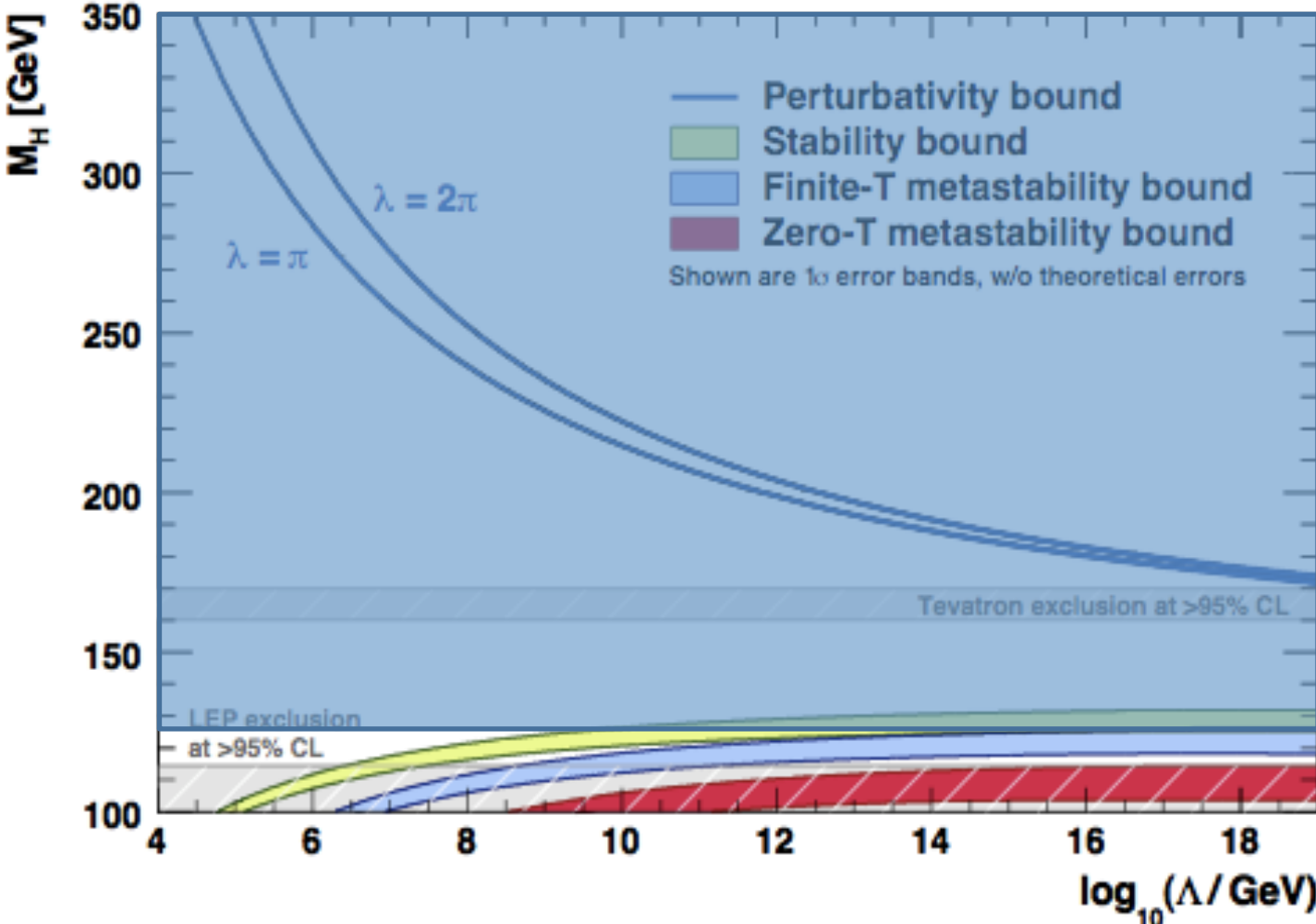
<b>Comments 17-03-2012 16:36:43 :</b>	<b>BIS status and SMP flags</b>			
No beam 2 from SPS 4 TeV  Beta* = 0.6 m !!!!	Link Status of Beam Permits	false	false	
	Global Beam Permit	true	false	
	Setup Beam	true	true	
	Beam Presence	true	false	
	Moveable Devices Allowed In	false	false	
	Stable Beams	false	false	
<b>AFS: alternating b1 buck1 + b2 buck 2001</b>	PM Status B1	ENABLED	PM Status B2	ENABLED

# *Backup*

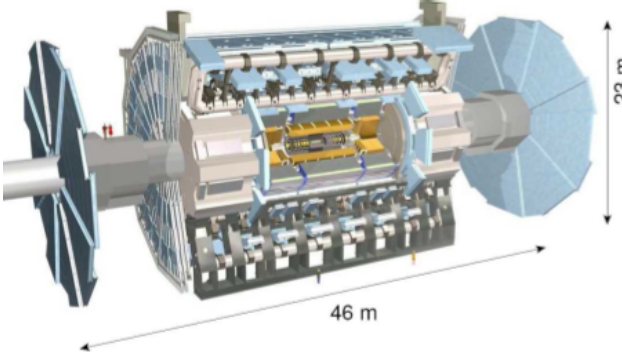
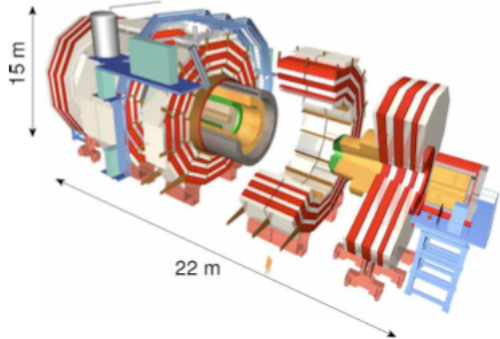
# What do we learn?



# What do we learn?



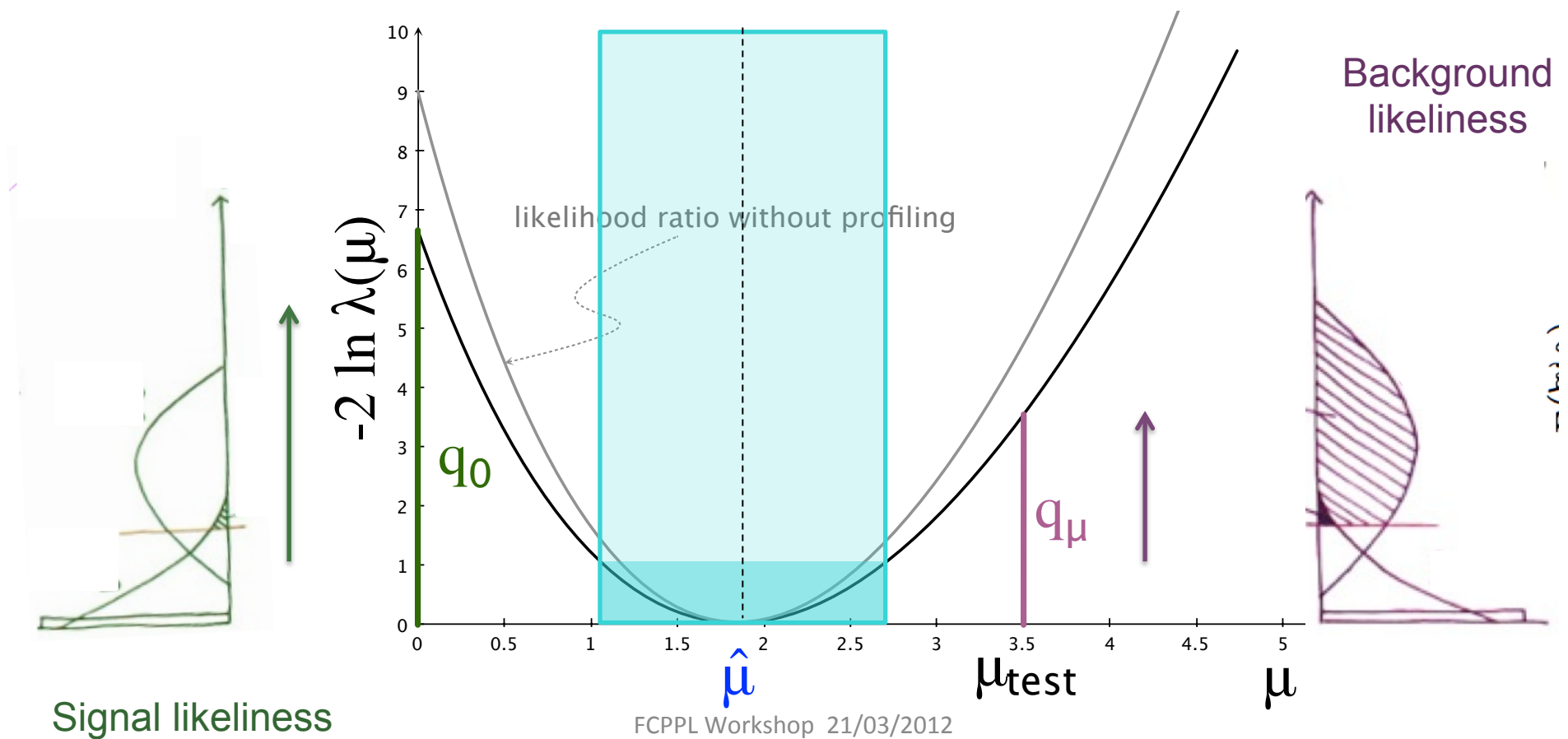
# The ATLAS and CMS Detectors In a Nutshell

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)



# How to Read Higgs Exclusion Limits Plots

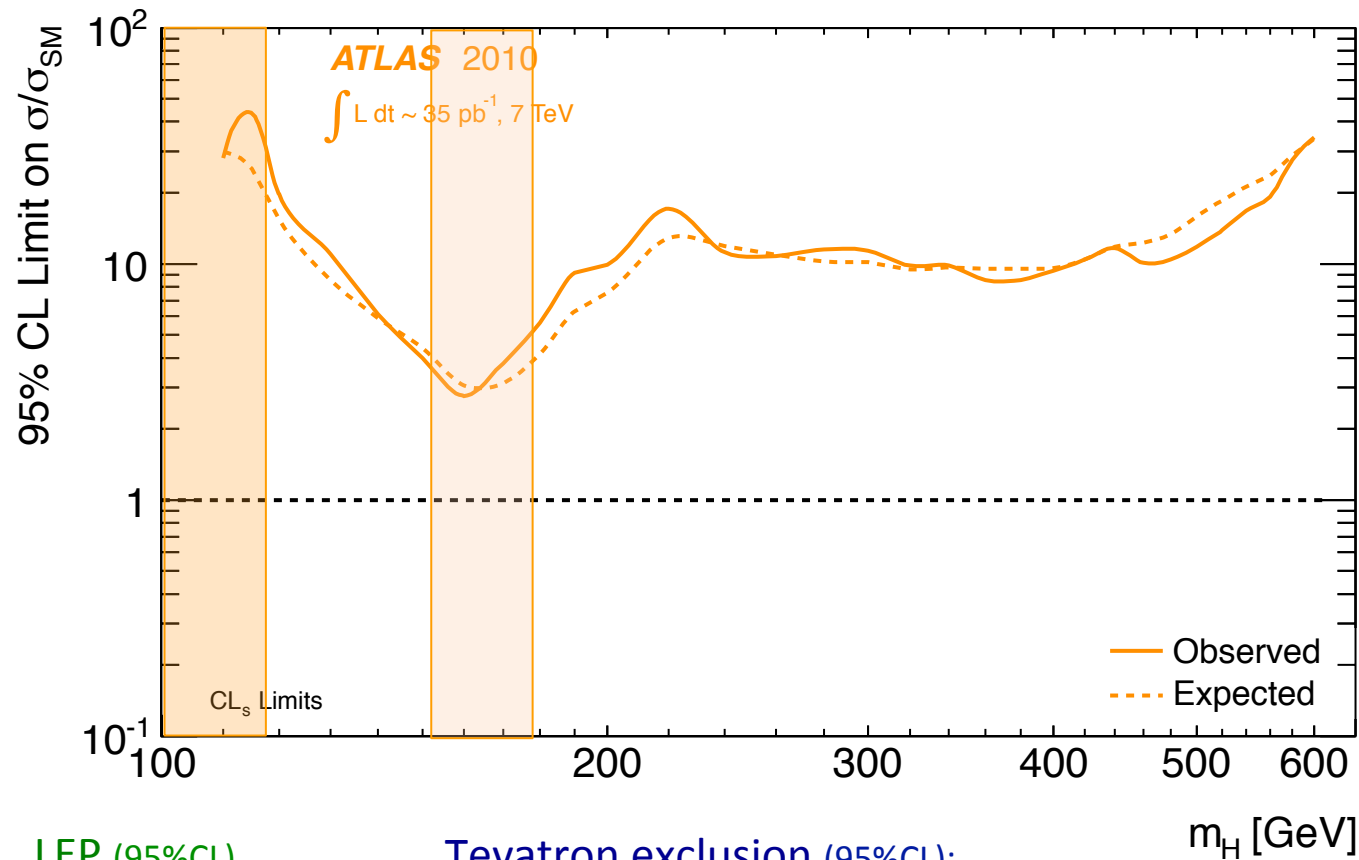
$$\lambda_\mu = \lambda(\mu, \theta) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} \quad q_\mu = -2 \ln \lambda_\mu$$



# Fast Forward Evolution Since Moriond 2011

...in ATLAS...

Moriond 2011 (2010 Data)



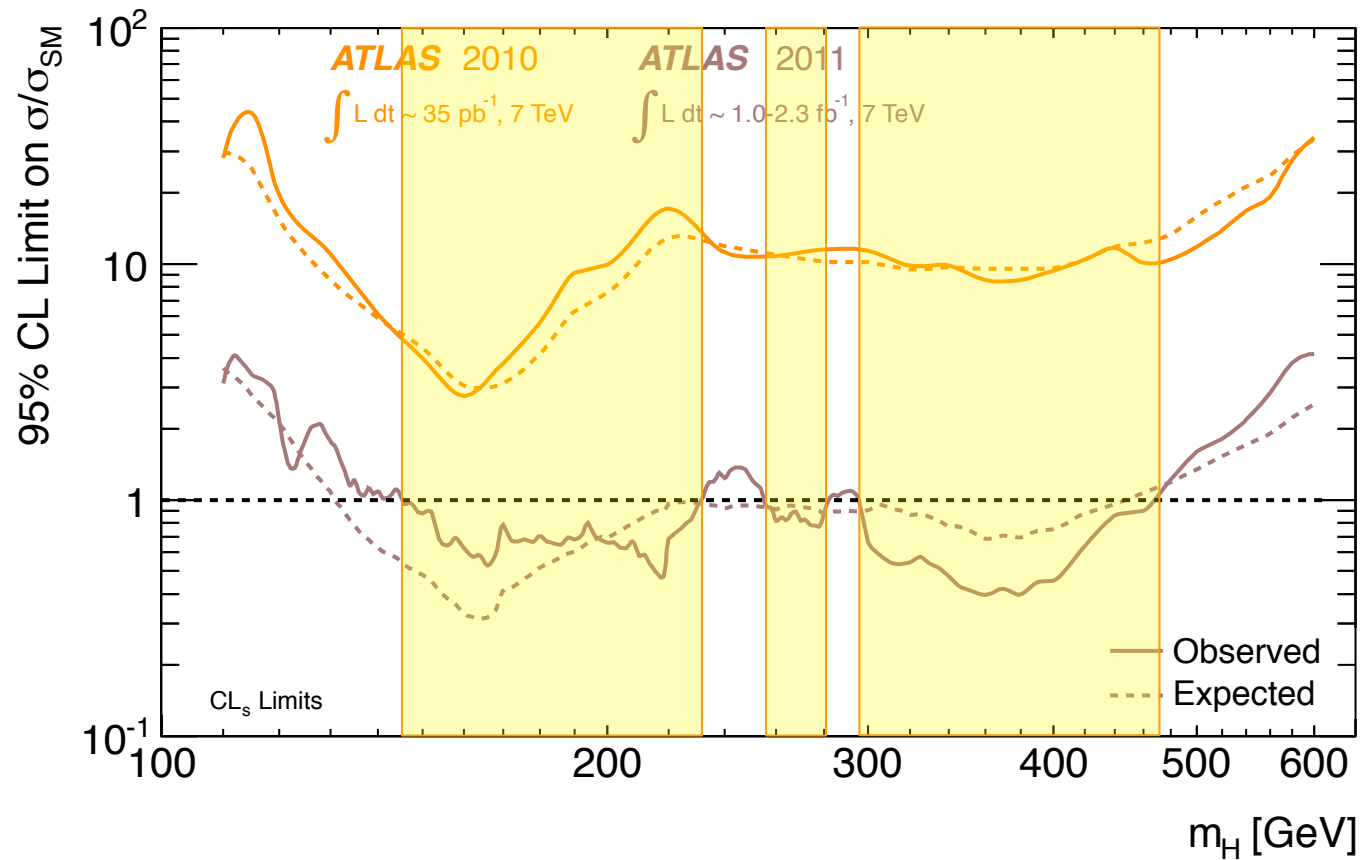
LEP (95%CL)  
 $m_H > 114 \text{ GeV}$

Tevatron exclusion (95%CL):  
 $100 < m_H < 109 \text{ GeV}$   
 $156 < m_H < 177 \text{ GeV}$

# Fast Forward Evolution Since Moriond 2011

...in ATLAS...

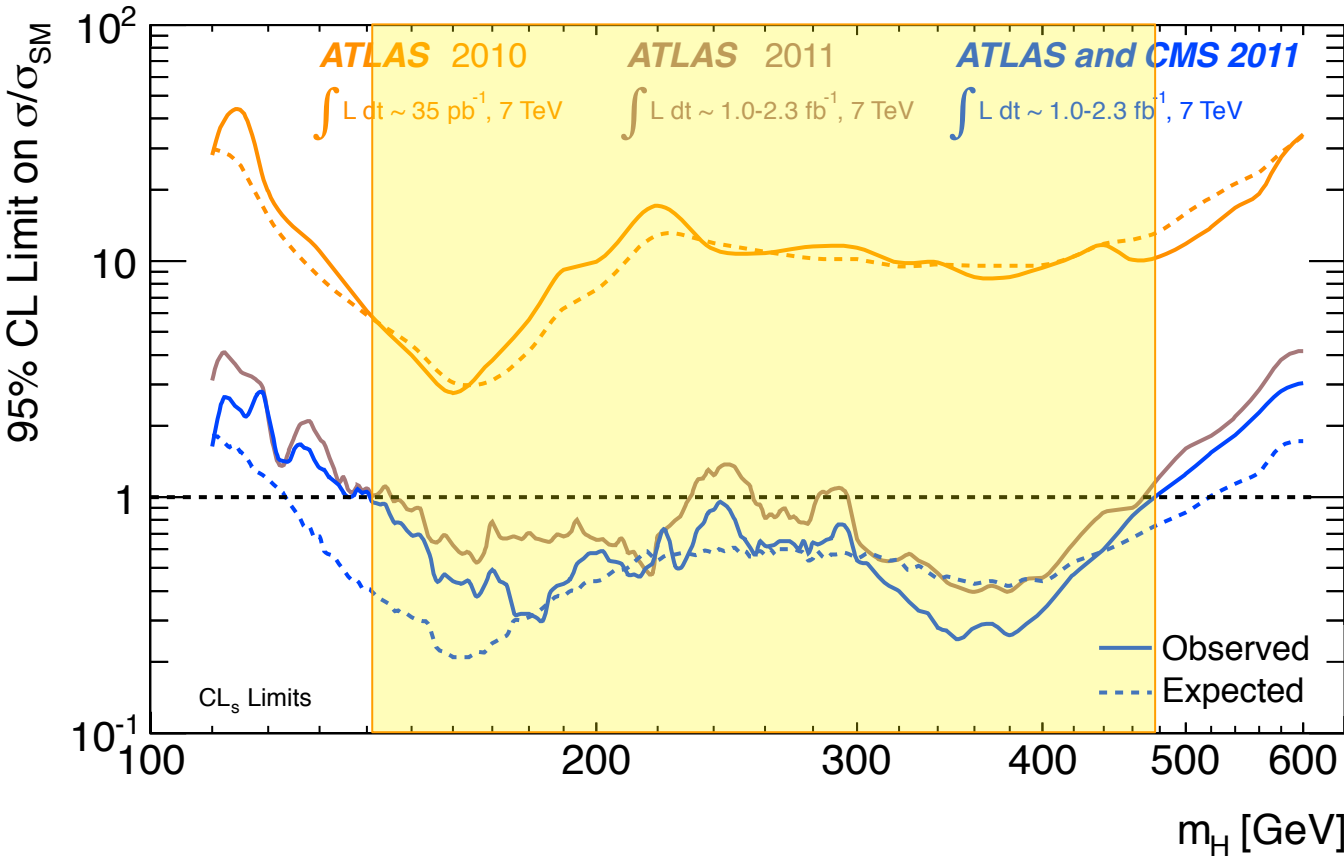
EPS 2011



# Fast Forward Evolution Since Moriond 2011

...in ATLAS...

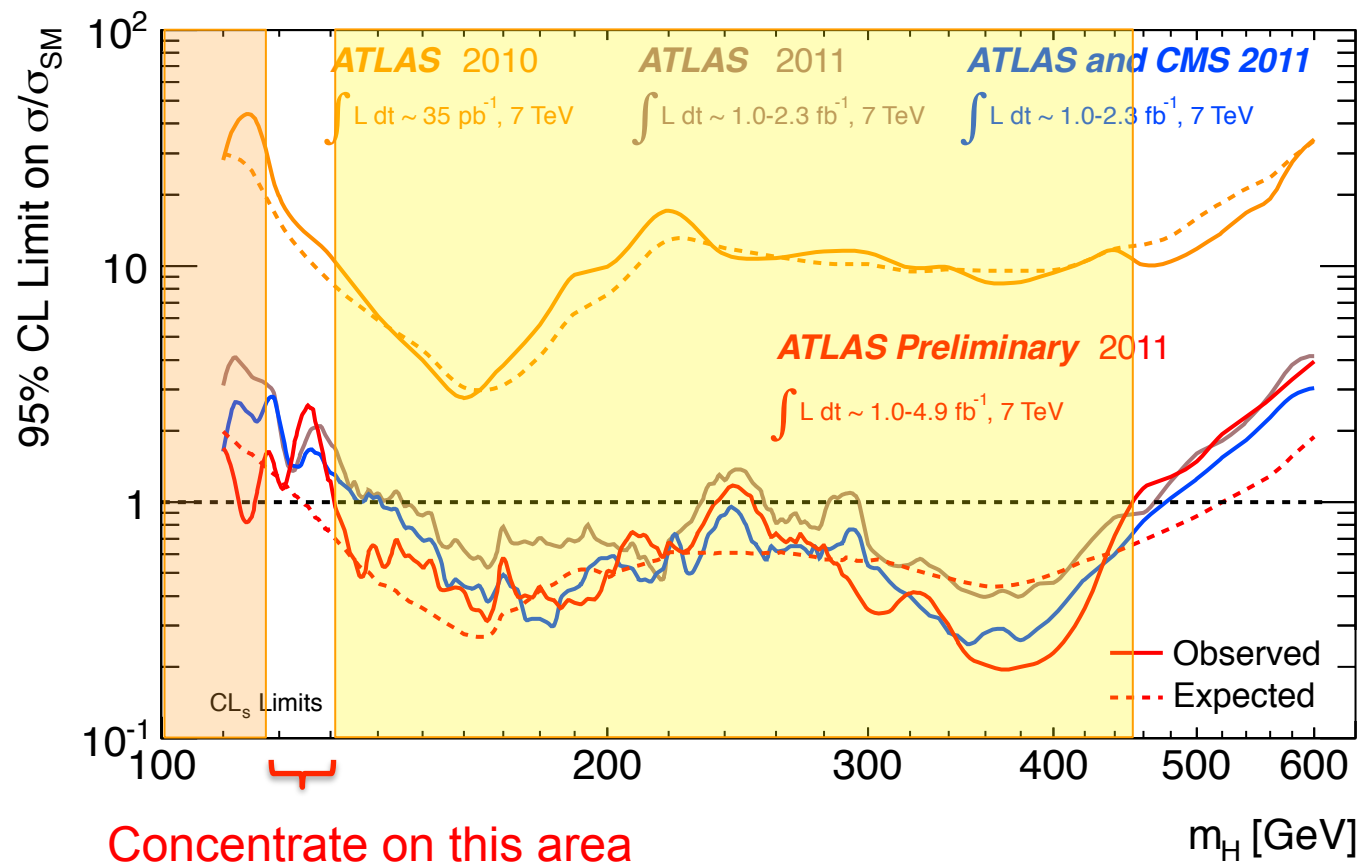
Combination HCP 2011



# Fast Forward Evolution Since Moriond 2011

...in ATLAS...

Council 2011



# In the News Three Days Ago...

la Repubblica.it

Scienze

*Half a Century of Higgs hunt...*

*the final dash?*

FISICA

## Bosone di Higgs, sprint finale verso il Nobel cambia nome

I prossimi mesi di esperimenti all'Lhc, l'acceleratore di particelle del Cern di Ginevra, saranno decisivi per la conferma dell'esistenza della 'particella di Dio', che potrebbe chiamarsi Beh (da Brout-Englert-Higgs). Si moltiplicano i libri di divulgazione e i convegni, in preparazione del premio più ambito di ELENA DUSI

Lo leggo dopo



Il Large Hadron Collider

È PRONTO a ripartire. Lhc, l'acceleratore di particelle del Cern di Ginevra, dopo la pausa invernale tornerà mercoledì a far scontrare protoni a velocità che lambiscono quella della luce. Con una lunga cavalcata fino a dicembre 2012, il più grande apparecchio scientifico del mondo darà probabilmente la zampata finale a quel bosone di Higgs che i fisici cercano da quasi 50 anni.

L'unica particella mancante fra le 17 che compongono la materia a noi nota, soprannominata "particella di Dio", è ormai nel mirino degli scienziati dell'Organizzazione europea per la ricerca nucleare. Ma servono più dati per confermare che il frammento di

materia generato nelle collisioni ad altissima energia di Lhc, e osservato negli ultimi mesi dell'anno scorso, sia davvero quello teorizzato dal fisico inglese Peter Higgs.

"La partita - ha più volte assicurato il direttore del Cern Rolf Heuer - sarà chiusa entro il 2012. Se il bosone di Higgs esiste, saremo in grado di trovarlo".

La statistica invita a una cautela più che altro formale. I dati ottenuti da Lhc l'anno scorso danno una probabilità del 99,5% che la particella osservata a Ginevra sia l'ultimo tassello mancante del modello standard: il quadro della realtà più preciso che la fisica è riuscita a disegnare finora.

Definitive answer to the quest for the Standard Model Higgs boson in 2012



# In the News December 2011...

*Le Cern aurait capté des "signaux" du boson de Higgs.*

**Le Monde**

*Science: les physiciens pensent avoir approché le mystérieux boson de Higgs.*

**Libération**

*Data Hints at Elusive Particle, but the Wait Continues*

**The New York Times**

*Higgs boson hunters scent their elusive quarry at the LHC.*

**theguardian**

# ... in the CERN Press Release

## Excerpts

Taken individually, none of these excesses is any more statistically significant than rolling a die and coming up with two sixes in a row ( $\sim 3\%$ ).

What is interesting is that there are multiple independent measurements pointing to the region of 124 to 126 GeV.