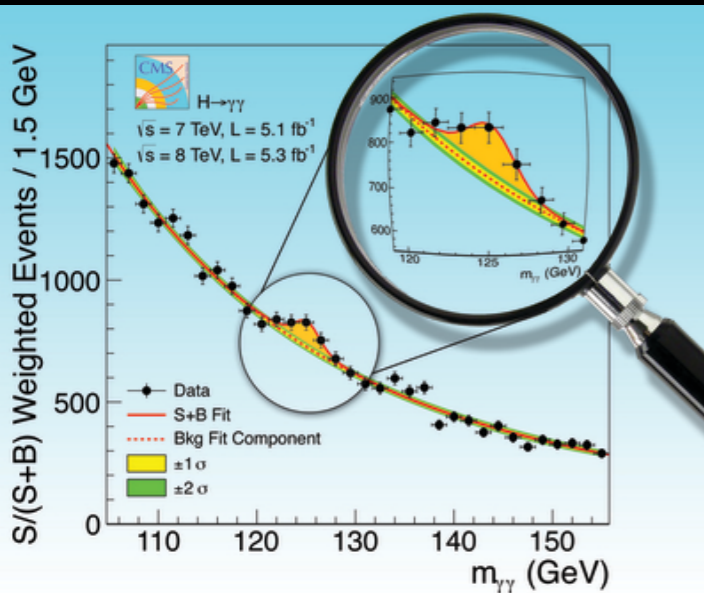
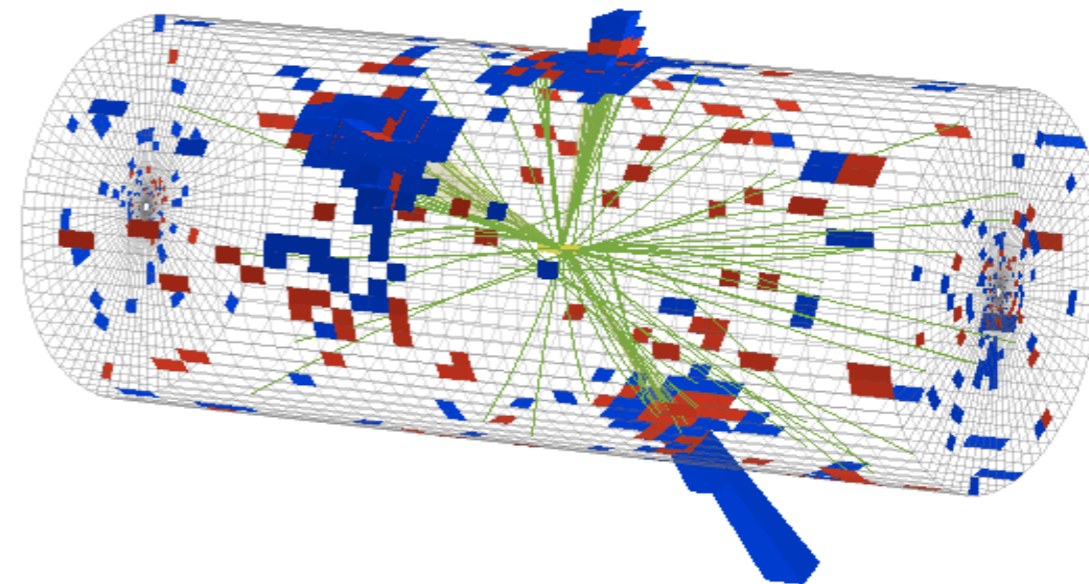


CMS Experiment at LHC, CERN  
 Data recorded: Sat May 26 13:25:29 2012 CEST  
 Run/Event: 195016 / 425646417  
 Lumi section: 384



# SM Higgs boson search at LHC: summary

**Victor T. Kim**

**Session of Scientific Council of High Energy Physics Division  
 PNPI NRC KI, Gatchina, December 24-27, 2012**



# Outline

- **Highlights of CMS & ATLAS results on search for SM Higgs boson:**

**CERN, July 4, 2012  
ICHEP, Melbourne**

- **Recent updates of CMS & ATLAS results on search for SM Higgs boson:**

**- Hadron Collider Physics Symposium (HCP-2012),  
November 15, 2012, Kyoto**

**- Hadron Collider Physics Symposium (HCP-2012),  
December 13, 2012, Kyoto**

# Search for SM Higgs boson at LHC : new particle at ATLAS & CMS (July4)!



## Evidence for a new state:

- **Excesses in both 7 (5 Fb-1) and 8 TeV (5.3 Fb-1) data**  
**ATLAS: local significance:  $5.9\sigma$       global:  $5.1\sigma$**   
**CMS:    local significance:  $5.0\sigma$       global:  $4.6\sigma$**
- **Signal strength**  
**ATLAS:  $(1.4 \pm 0.3) \times \sigma_{SMH}$**   
**CMS:     $(0.87 \pm 0.23) \times \sigma_{SMH}$**
- **Mass**  
**ATLAS:  $M = 126.0 \pm 0.4$  (stat.)  $\pm 0.4$  (syst.) GeV**  
**CMS:     $M = 125.3 \pm 0.4$  (stat.)  $\pm 0.5$  (syst.) GeV**
- **Compatible within limited precision with SM Higgs boson**

# CMS data taking 2011-2012: integrated luminosity



## CMS @ LHC

<b>2011: March 14 – October 30</b>	<b>5.3 Fb-1</b>	<b>7 TeV</b>
<b>2012: April 4 - present</b>	<b>20.3 Fb-1</b>	<b>8 TeV</b>

### July 4, 2012 (CERN-ICHEP):

<b>2011 data</b>	<b>5.1 Fb-1</b>
<b>2012 data until July</b>	<b>5.3 Fb-1</b>

### November 15, 2012 (HCP):

<b>2011 data</b>	<b>5.1 Fb-1</b>
<b>2012 data until October</b>	<b>~12.3 Fb-1</b>

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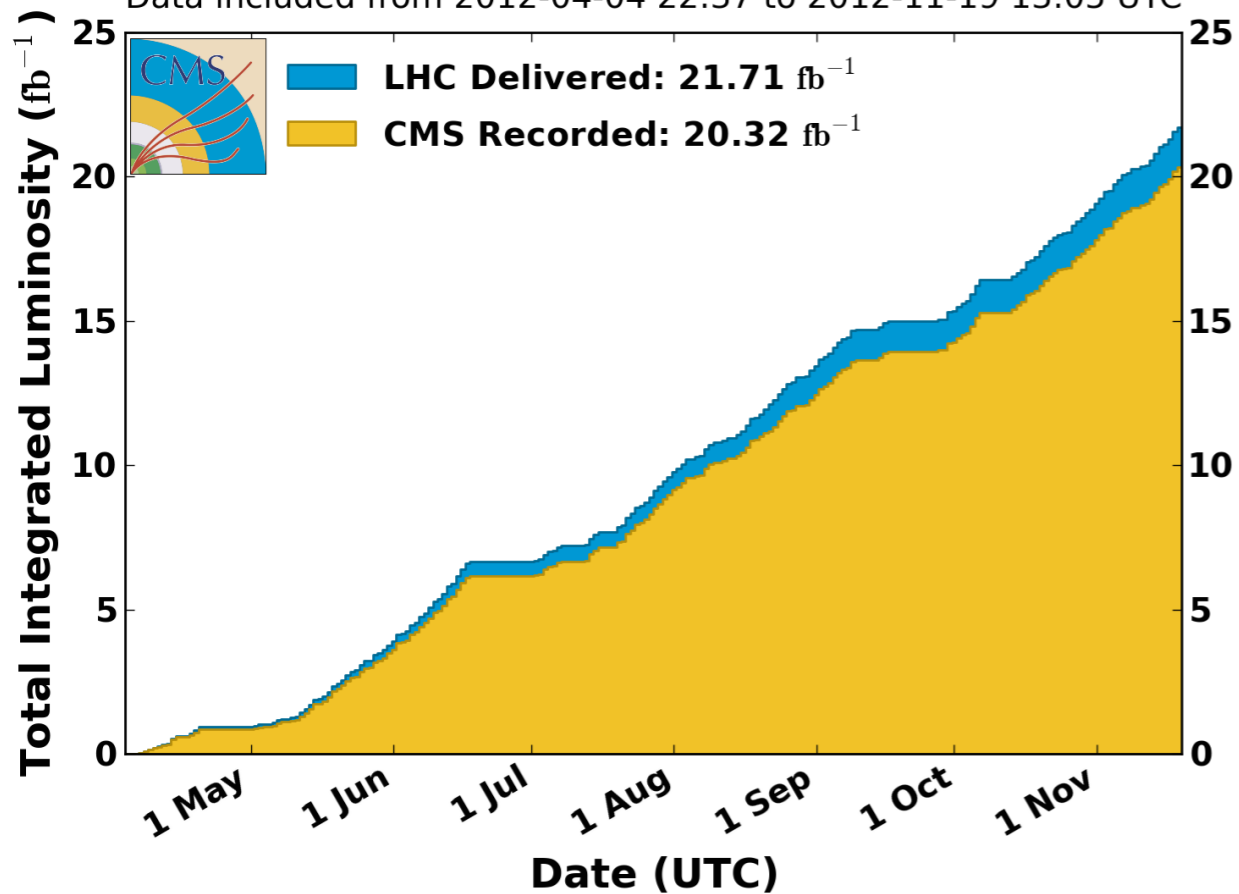
	<b>Peak luminosity:</b>	<b>Averaged pile-up:</b>
<b>2011</b>	<b><math>3.5 \times 10^{33} \text{ cm}^{-2} \text{ c}^{-1}</math></b>	<b>10</b>
<b>2012</b>	<b><math>7.5 \times 10^{33} \text{ cm}^{-2} \text{ c}^{-1}</math></b>	<b>21</b>

# CMS data taking 2012: integrated luminosity



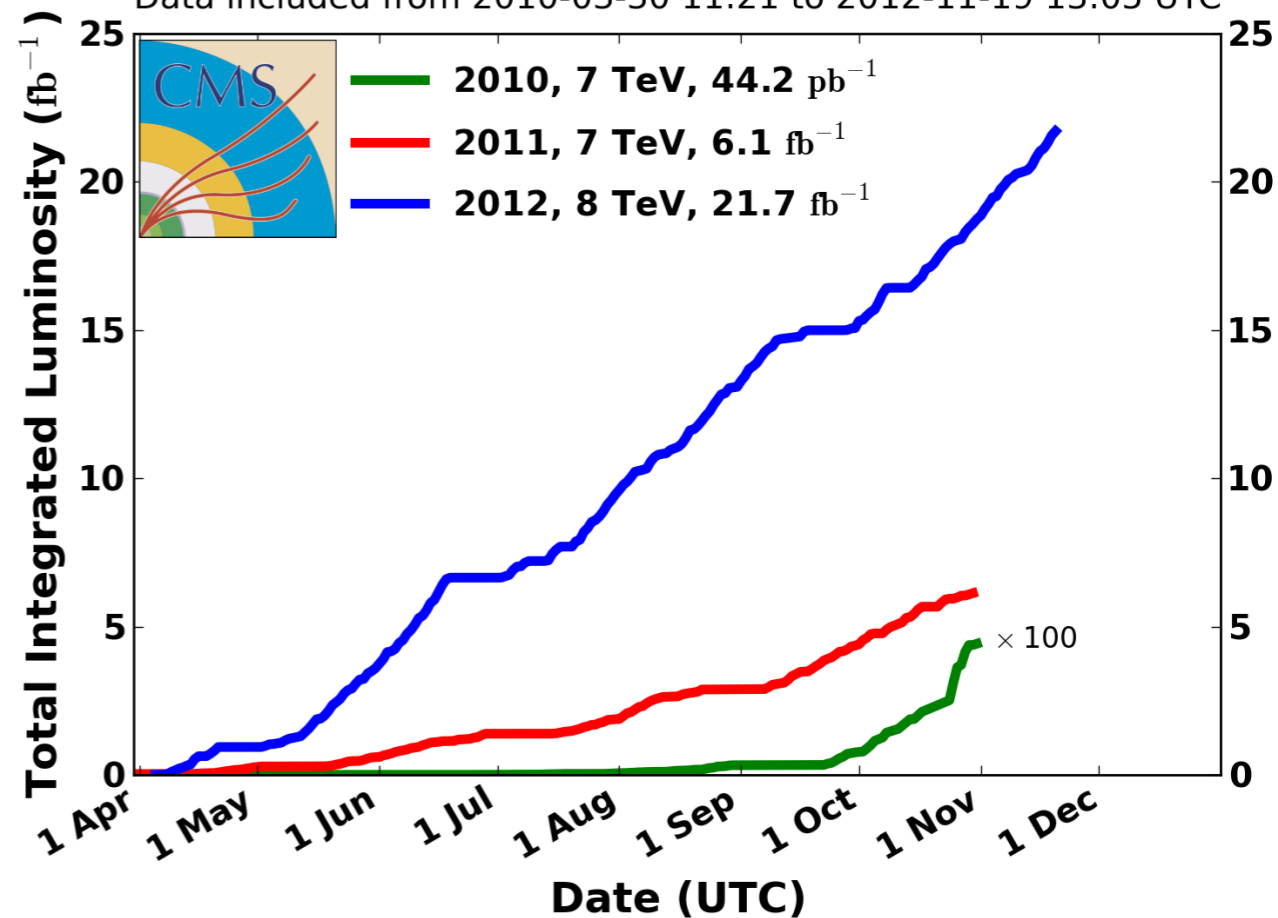
**CMS Integrated Luminosity, pp, 2012,  $\sqrt{s} = 8$  TeV**

Data included from 2012-04-04 22:37 to 2012-11-19 13:05 UTC



**CMS Integrated Luminosity, pp**

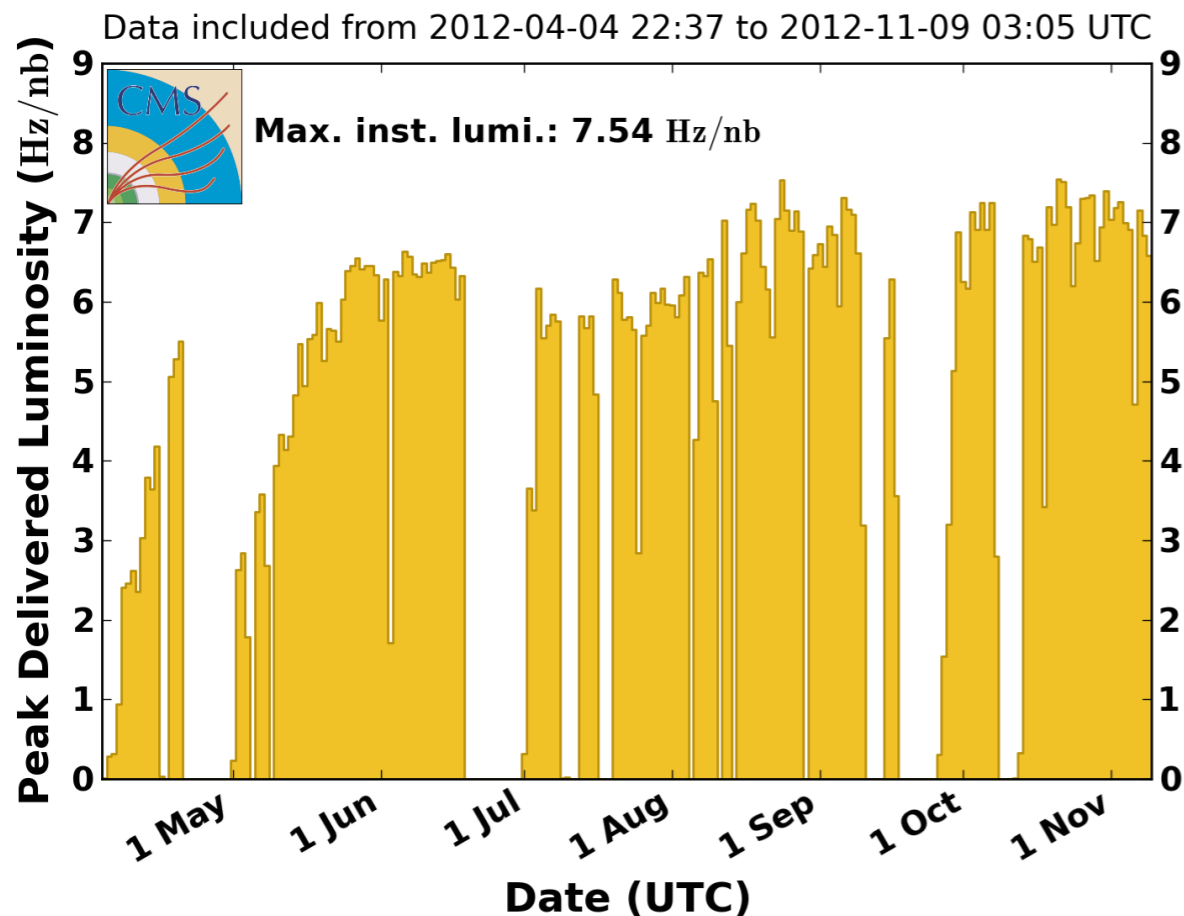
Data included from 2010-03-30 11:21 to 2012-11-19 13:05 UTC



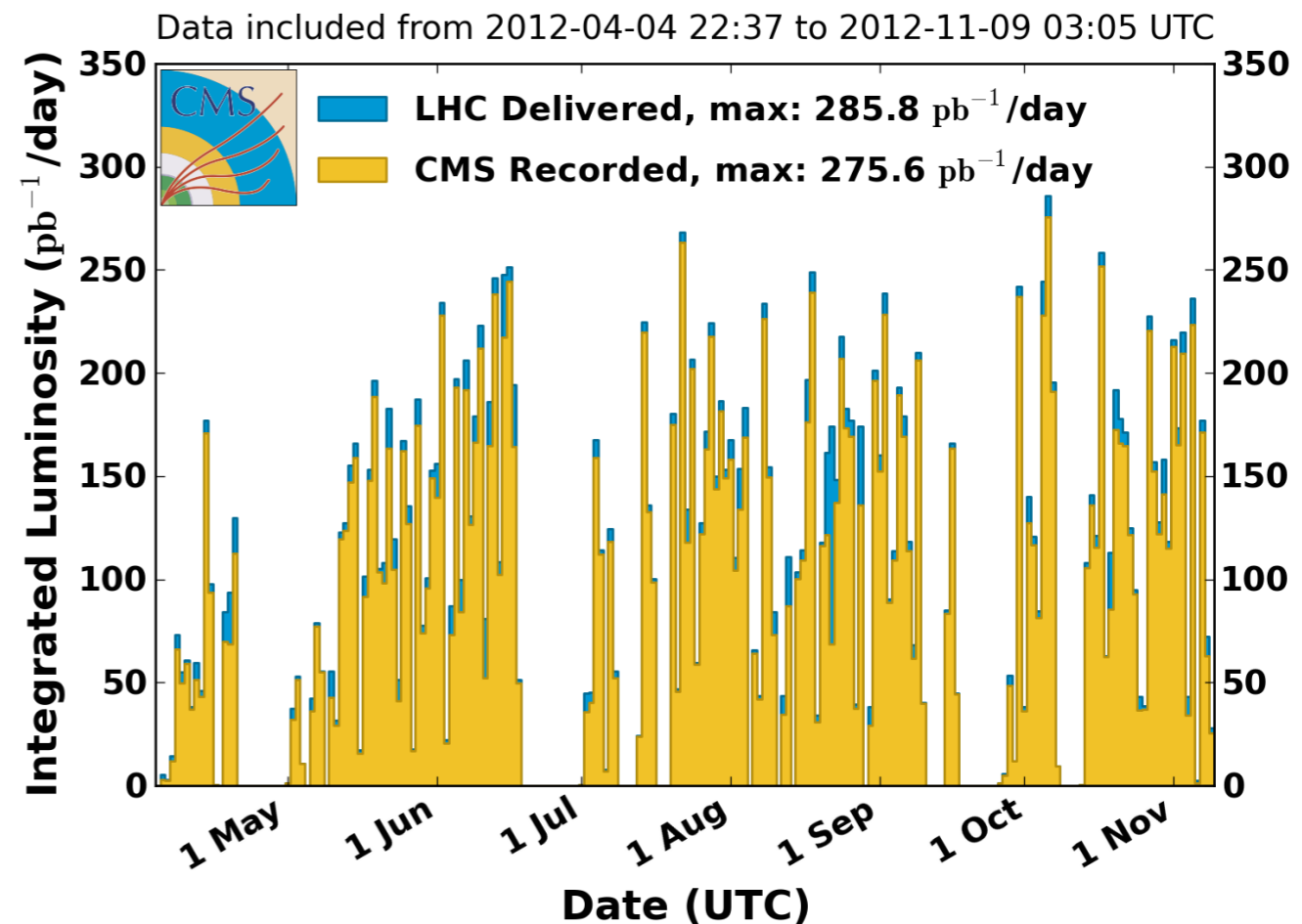
# CMS data taking 2012: luminosity per day



### CMS Peak Luminosity Per Day, pp, 2012, $\sqrt{s} = 8$ TeV



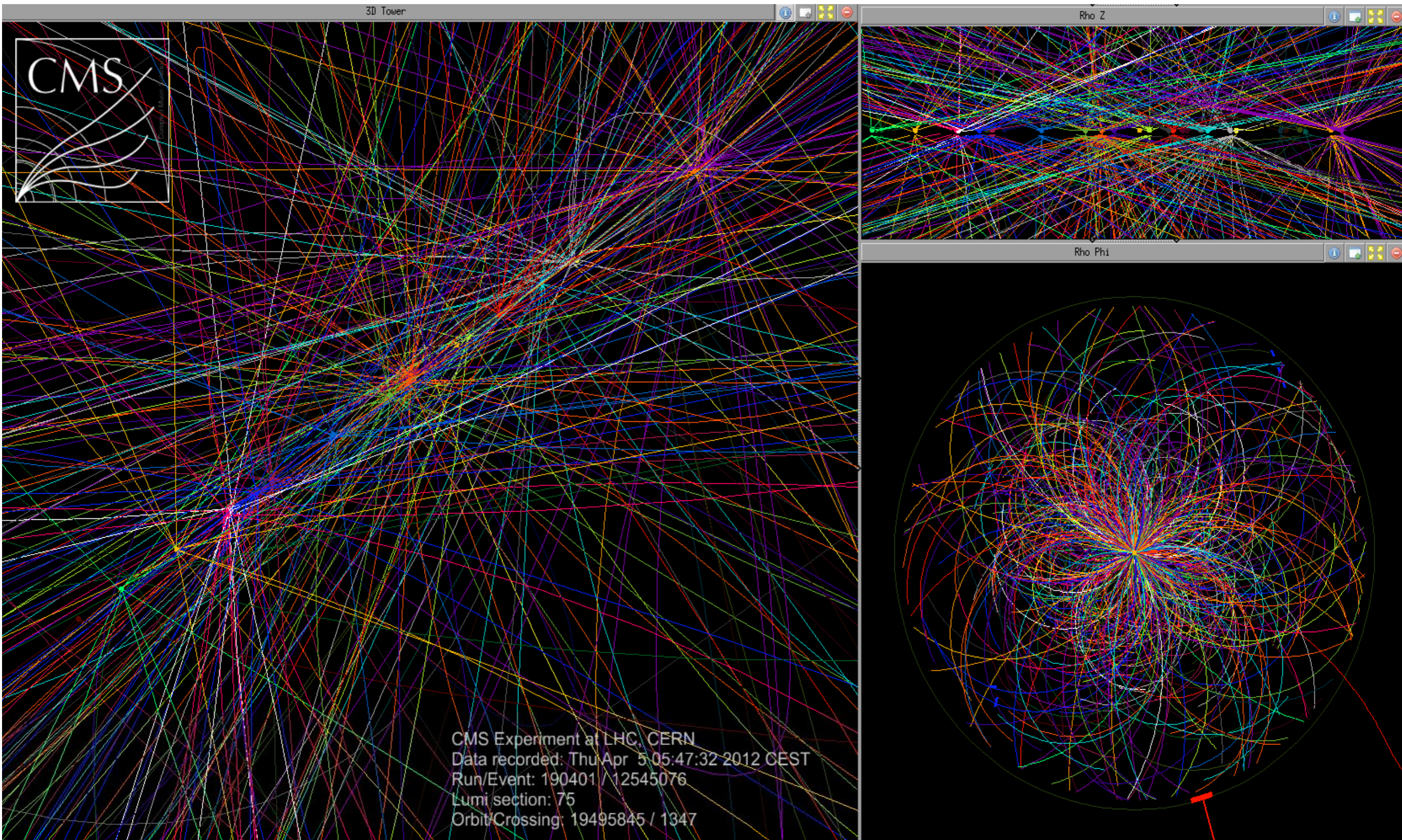
### CMS Integrated Luminosity Per Day, pp, 2012, $\sqrt{s} = 8$ TeV



# 2012 challenges at 8 TeV: high pile-up!



## Overlapping pp-collisions per bunch crossing





# 2012 challenges at 8 TeV: high pile-up!

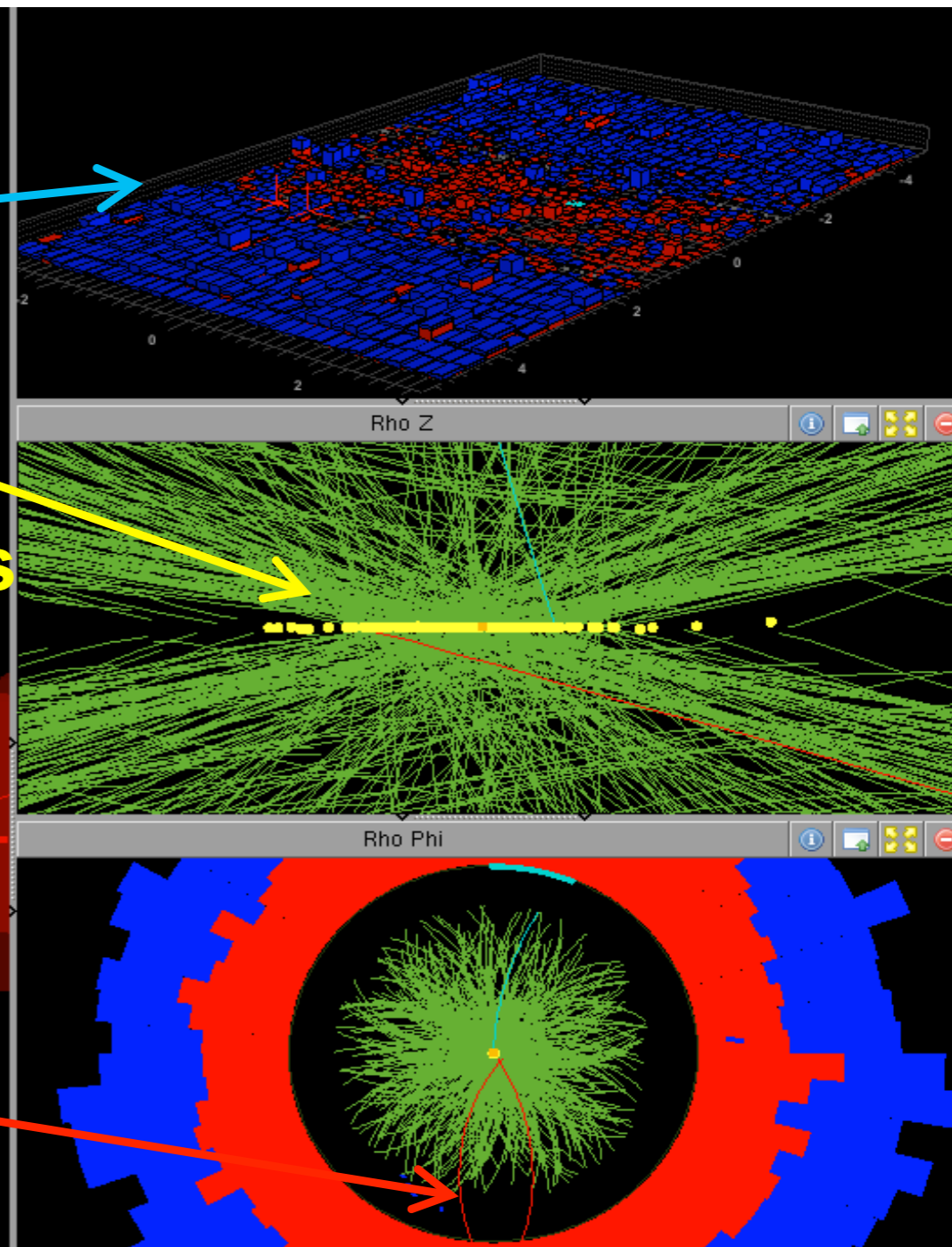
## Reconstructed 78-vertices dimuon event at CMS

Lots and lots of low energy deposits

Tracking worked

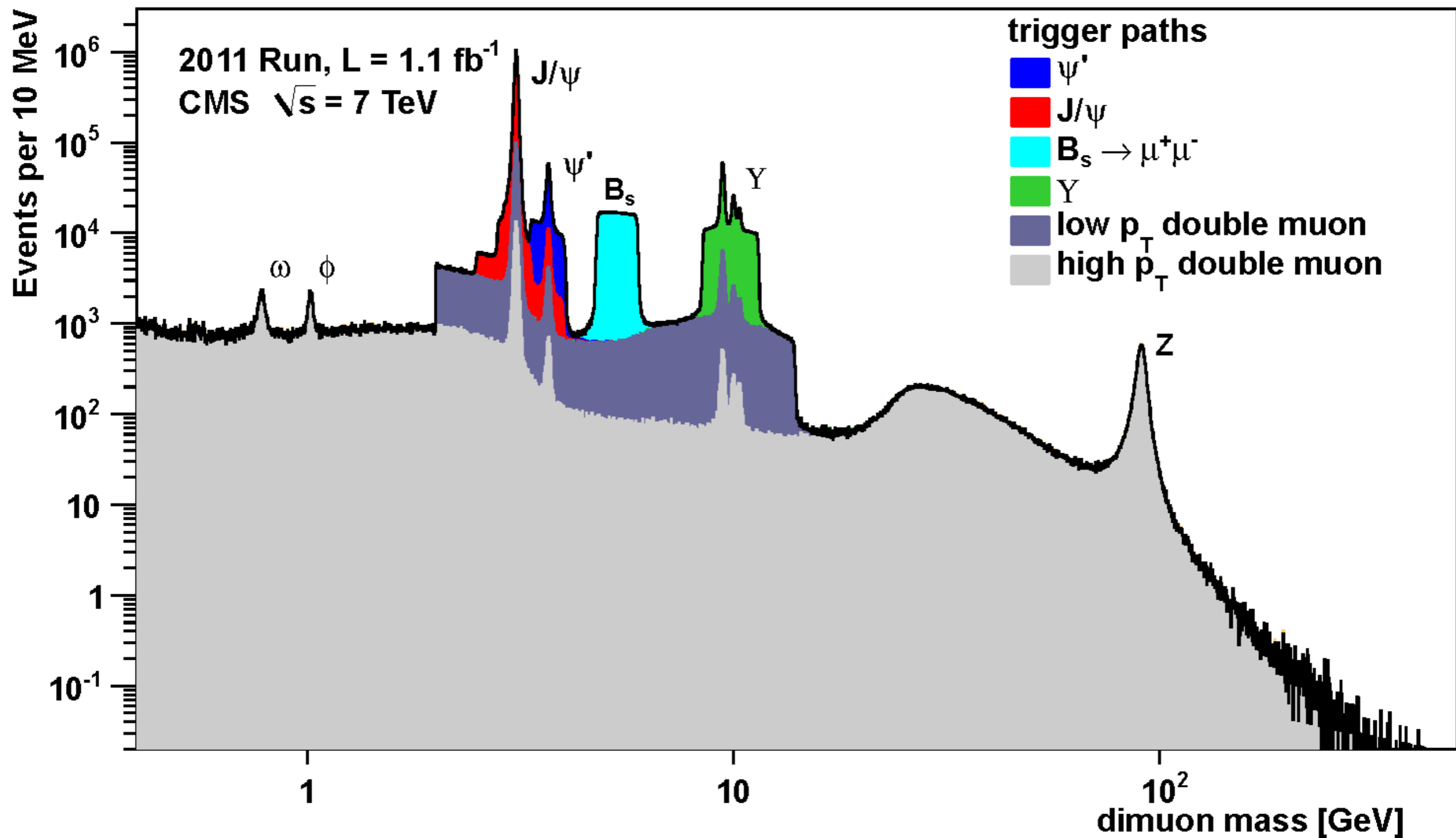
78 (!) vertices

2 muons



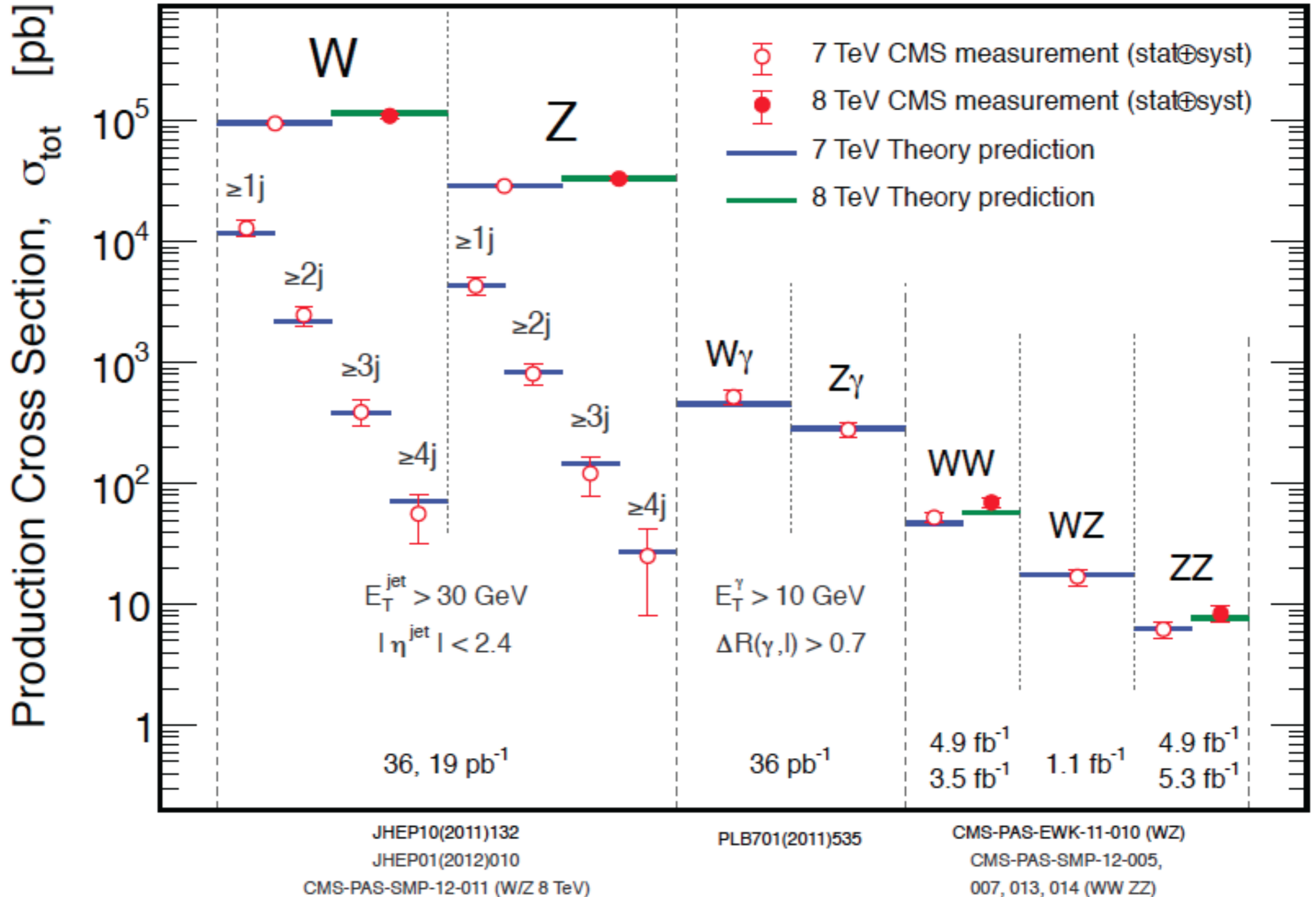


# SM resonances: dimuons



**CMS: a superb muon detector**

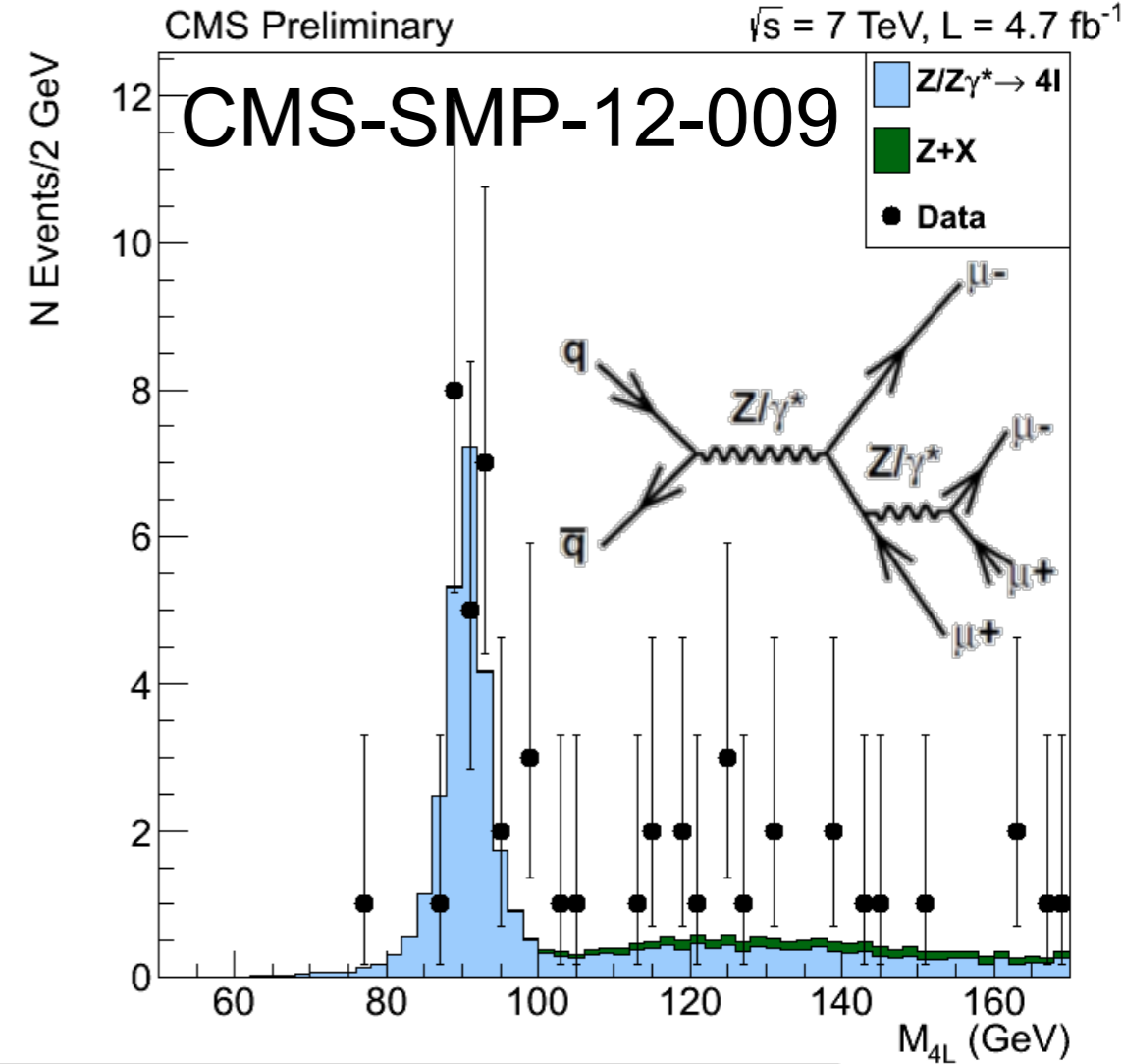
# EW highlights: vector boson production



# EW highlights: rare processes



**$Z \rightarrow 4\ell$**   
 **$BR = 4.4 \times 10^{-6}$**   
 **$\sigma \approx 125 \pm 26 \text{ Fb}$**



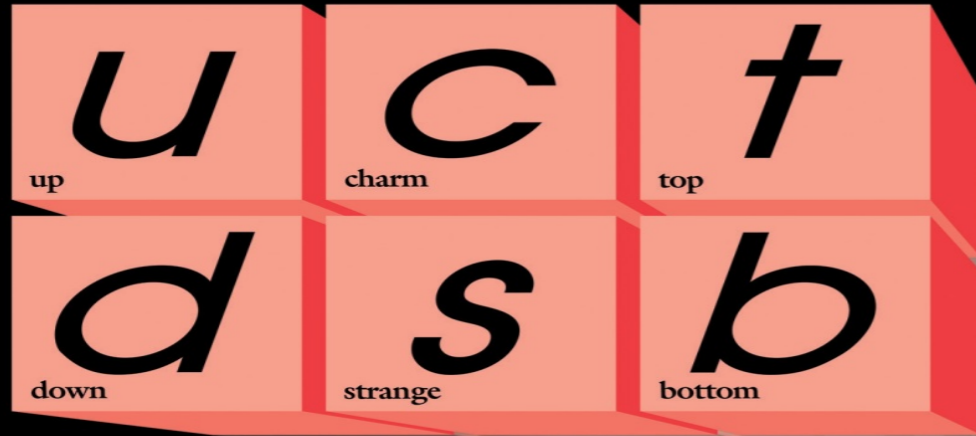
Final state channels	$4e$	$4\mu$	$2e2\mu$	$4\ell$
Irreducible background ( $pp \rightarrow Z\gamma^* \rightarrow 4\ell$ )	0.04	0.16	0.08	$0.3 \pm 0.03$
Other reducible backgrounds	0.01	0.01	0.05	$0.1 \pm 0.13$
Expected signal ( $pp \rightarrow Z \rightarrow 4\ell$ )	3.1	12.3	9.2	$24.6 \pm 2.2$
Total expected (MC)	3.2	12.5	9.3	$25.0 \pm 2.2$
Observed events	2	14	10	26
Rate from the fit of the observed mass distribution		13.6	9.7	25.4

# Search for SM Higgs boson

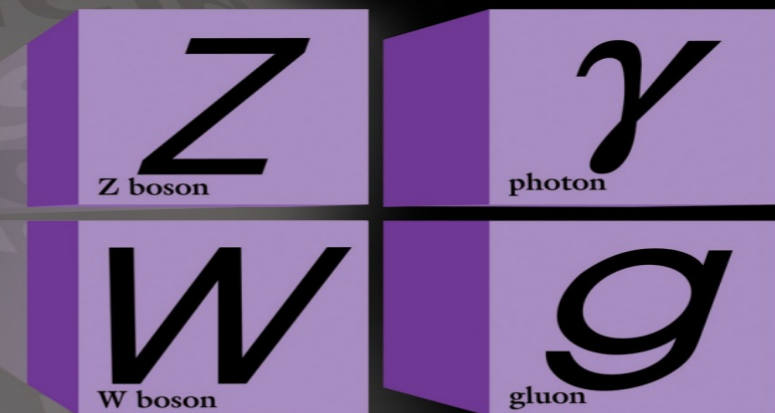


The last “brick” of SM building

## Quarks



## Forces

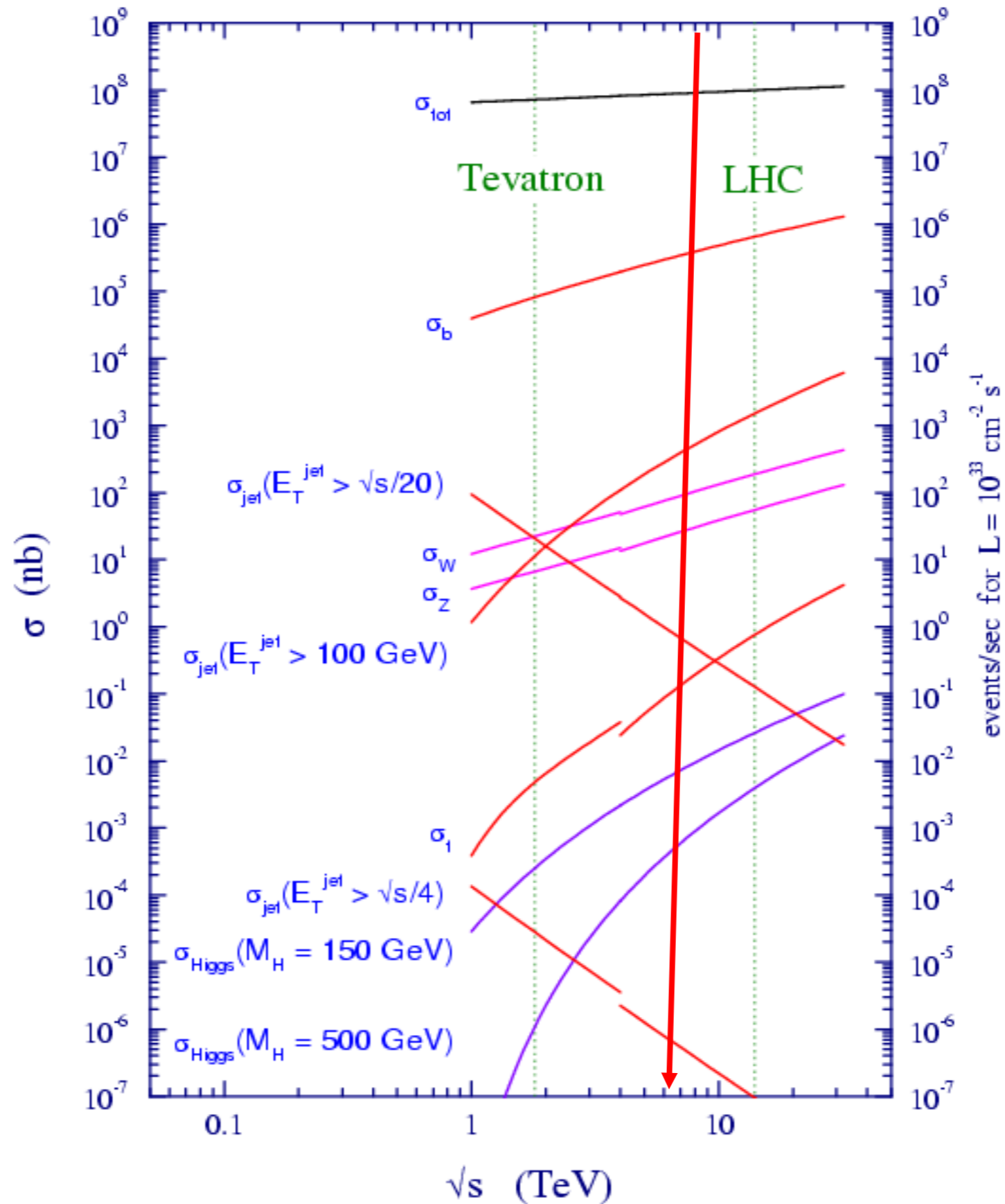


## Leptons

# Search for SM Higgs boson: cross sections

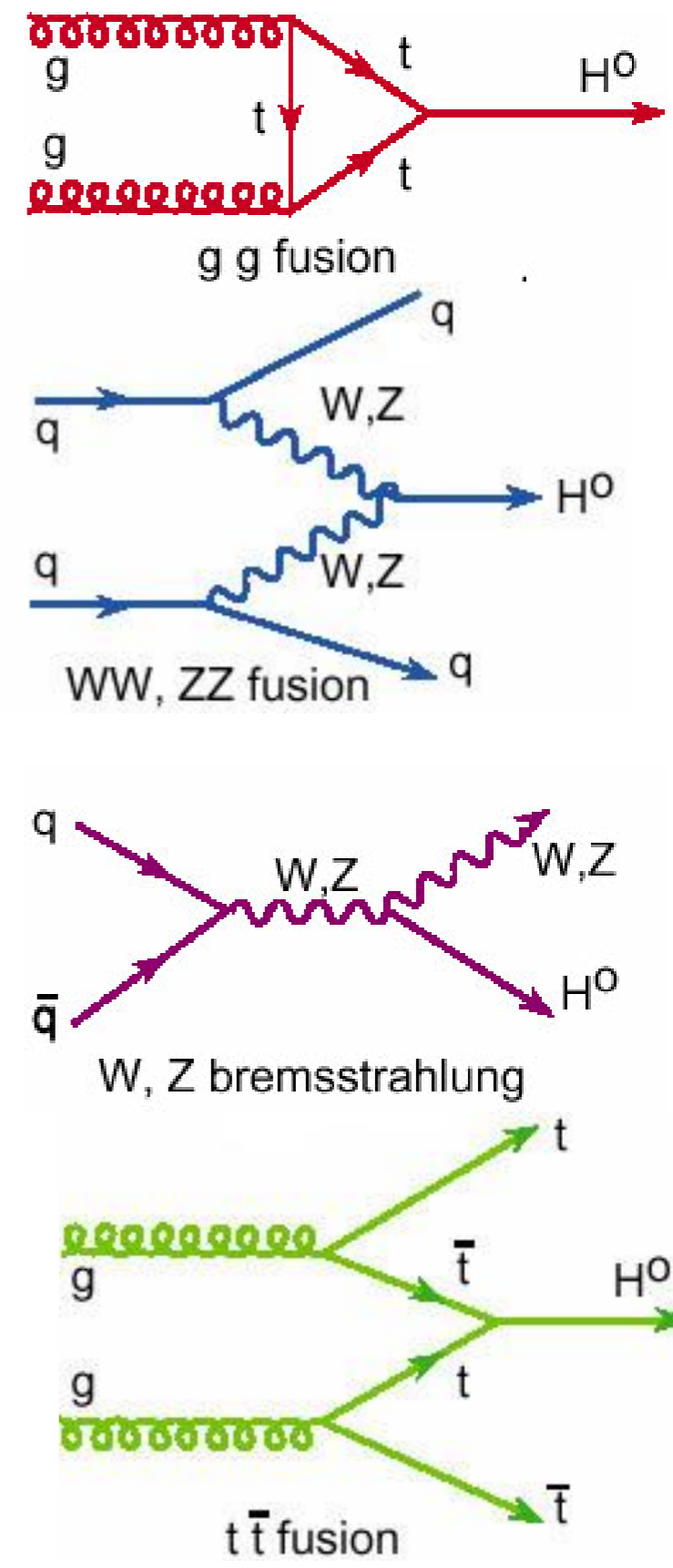
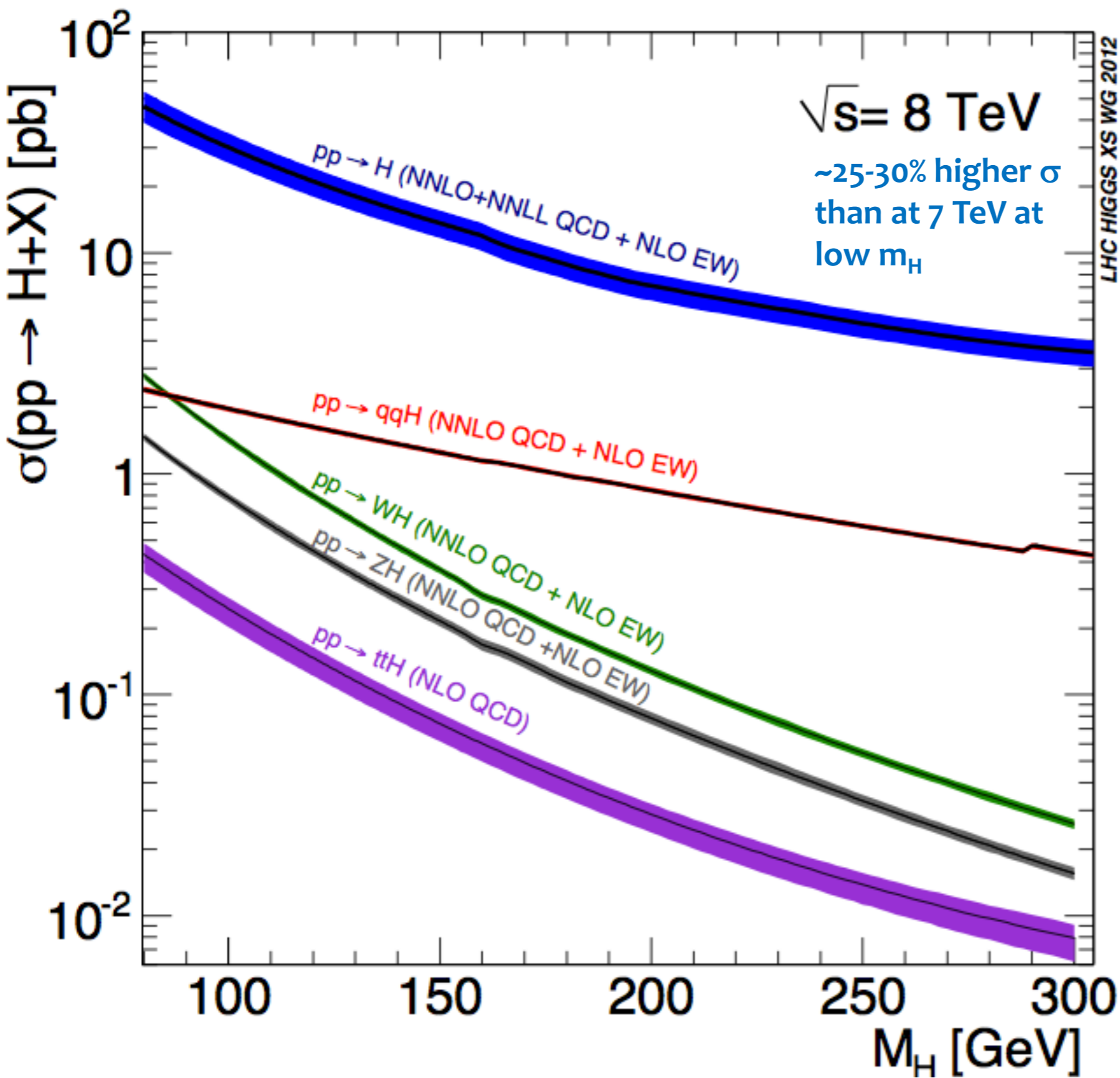


proton - (anti)proton cross sections





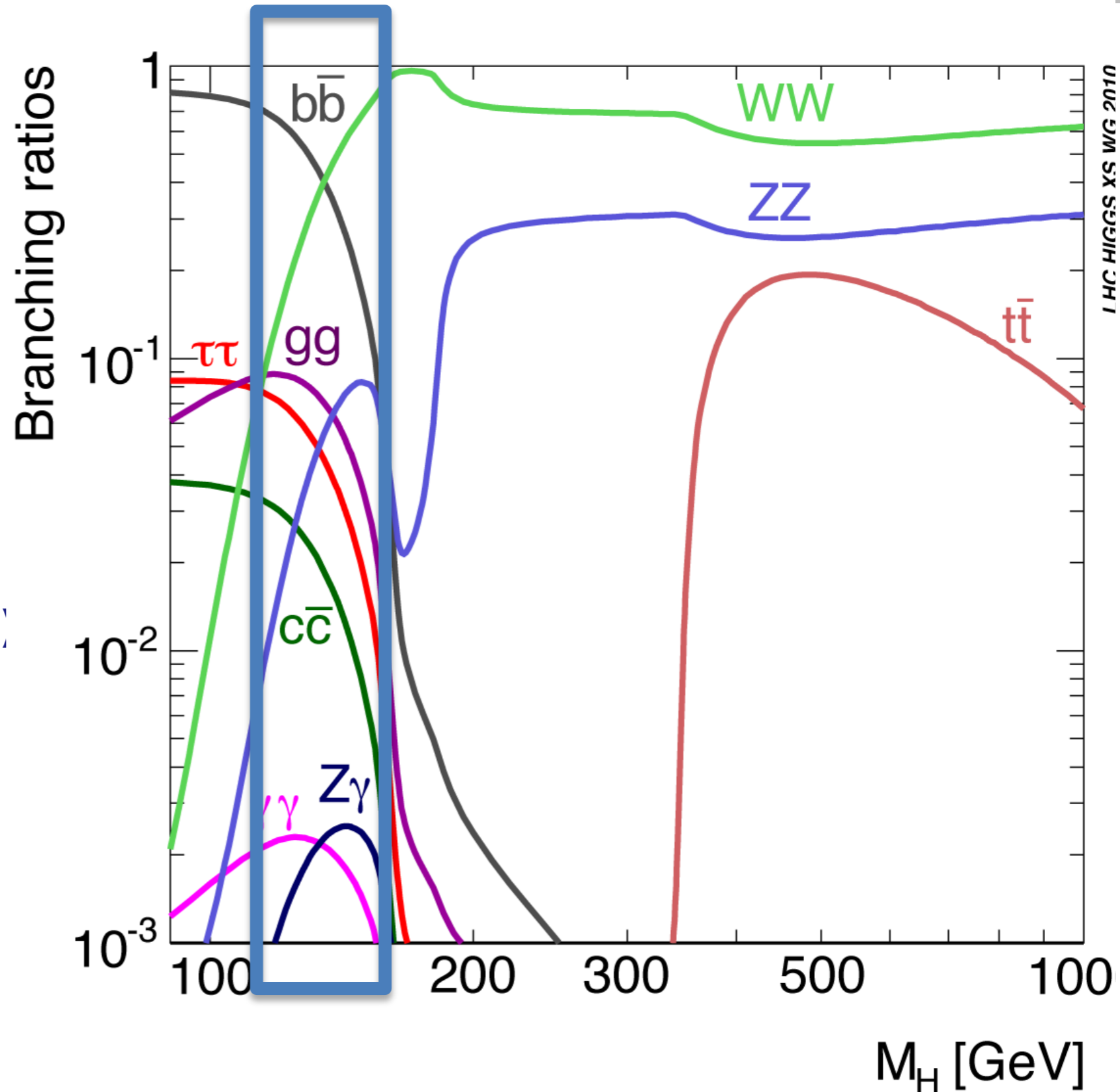
# Search for SM Higgs boson: production



# Search for SM Higgs boson: decay modes



- \* **SM Higgs decay modes**
  - high mass:  $WW$ -,  $ZZ$ -
  - low mass:  $\gamma\gamma$ -,  $\tau\tau$ -,  $bb$ -,  $ZZ^*$ -,  $WW^*$ -
- \* **Low mass challenges:**  
 $\tau\tau$ -,  $bb$ - huge background
- \* **High resolution mass ( $\sim 1\%$ ):**  
 $ZZ \rightarrow 4l$  and  $\gamma\gamma$ - modes
- \*  **$ZZ \rightarrow 4l$  low background**



LHC HIGGS XS WG 2010

# Search for SM Higgs boson: 5 main channels



**ICHEP, July 4: ~5 Fb-1 (7 TeV, 2011) + ~ 5 Fb-1 (8 TeV)**

Decay mode	Production tagging	No. of subchannels	$m_H$ range (GeV)	Int. Lum. ( $\text{fb}^{-1}$ )	
				7 TeV	8 TeV
$\gamma\gamma$	untagged	4	110–150	5.1	5.3
	dijet (VBF)	1 or 2			
ZZ	untagged	3	110–160	5.1	5.3
WW	untagged	4	110–160	4.9	5.1
	dijet (VBF)	1 or 2			
$\tau\tau$	untagged	16	110–145	4.9	5.1
	dijet (VBF)	4			
bb	lepton, $E_T^{\text{miss}}$ (VH)	10	110–135	5.0	5.1

**The other channels: only  $0.1\sigma$  improvement**



# Search for SM Higgs boson: recent update



**CERN-ICHEP, Melbourne, July 4, 2012:**

**CMS:  $\sim 5 \text{ Fb}^{-1}$  (7 TeV, 2011) +  $\sim 5 \text{ Fb}^{-1}$  (8 TeV)**

**ATLAS  $\sim$  CMS**

**New particle  $\sim 125 \text{ GeV}$ !**

**Hadron Collider Physics (HCP-2012) November 15, 2012:**

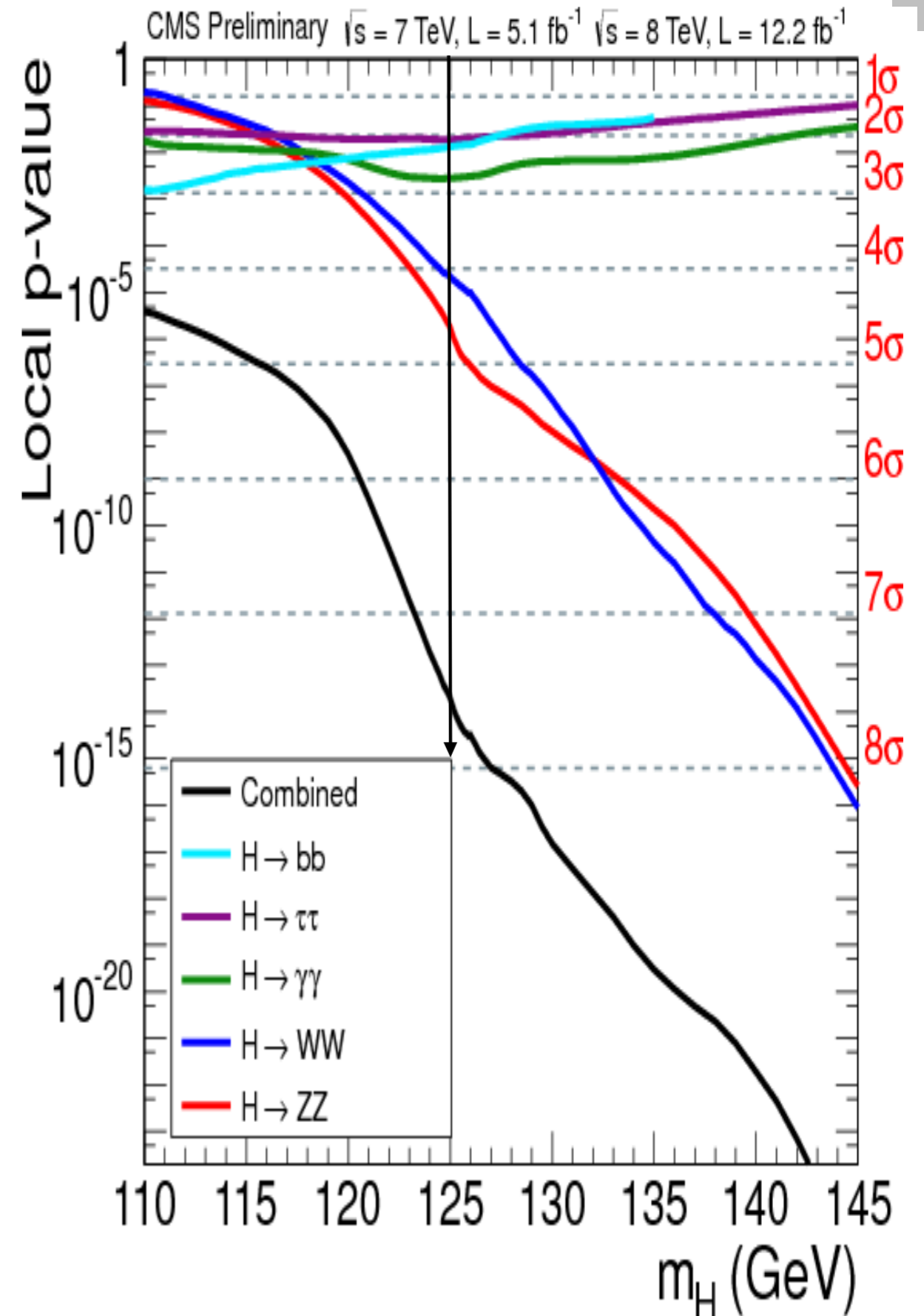
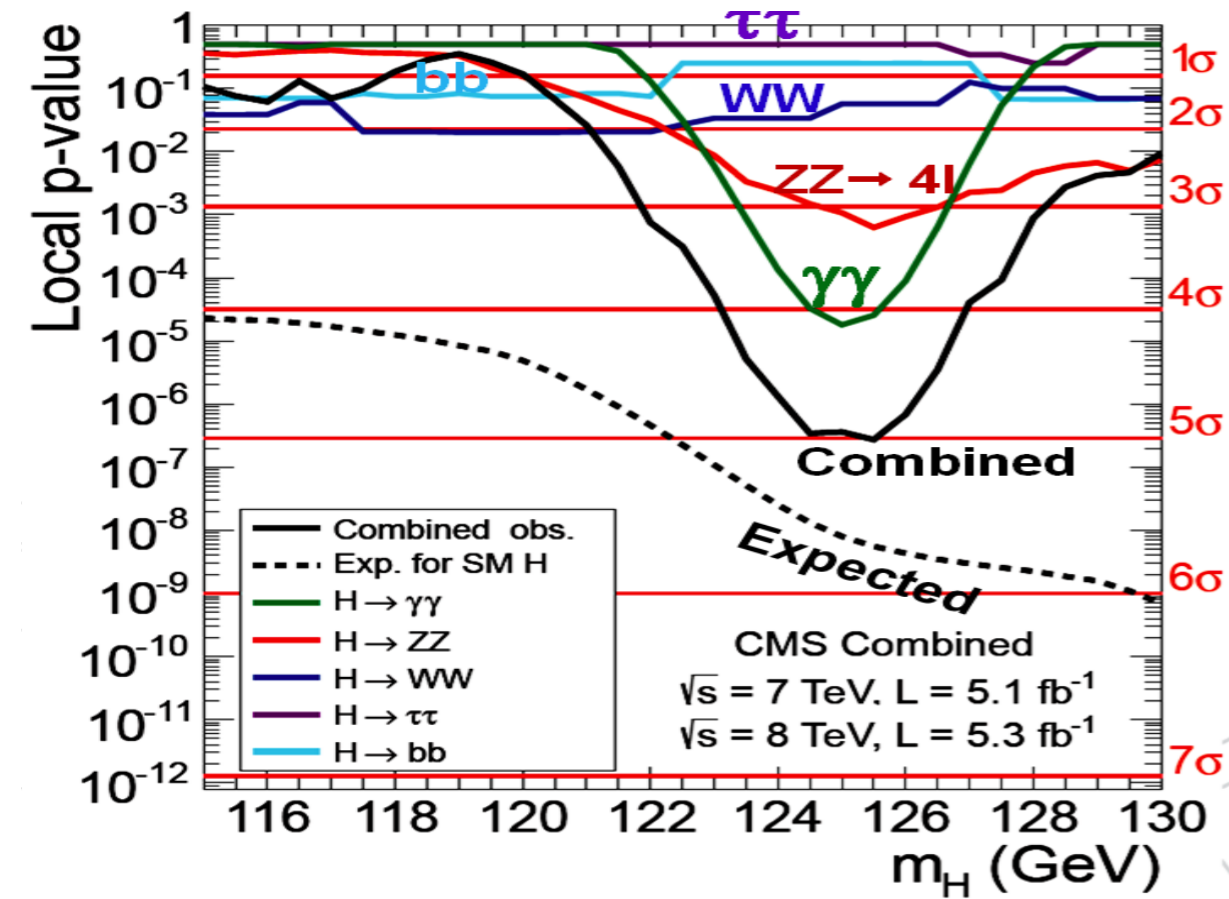
**CMS update:  $\sim 5 \text{ Fb}^{-1}$  (7 TeV, 2011) +  $\sim 12 \text{ Fb}^{-1}$  (8 TeV)**

**ATLAS presented only update on three channels**

**Current Luminosity Projection:**

**both CMS & ATLAS  $\sim 25 \text{ Fb}^{-1}$  at 8 TeV before Xmas**

# Search for SM Higgs: expected performance



## Sensitivity at 125 GeV:

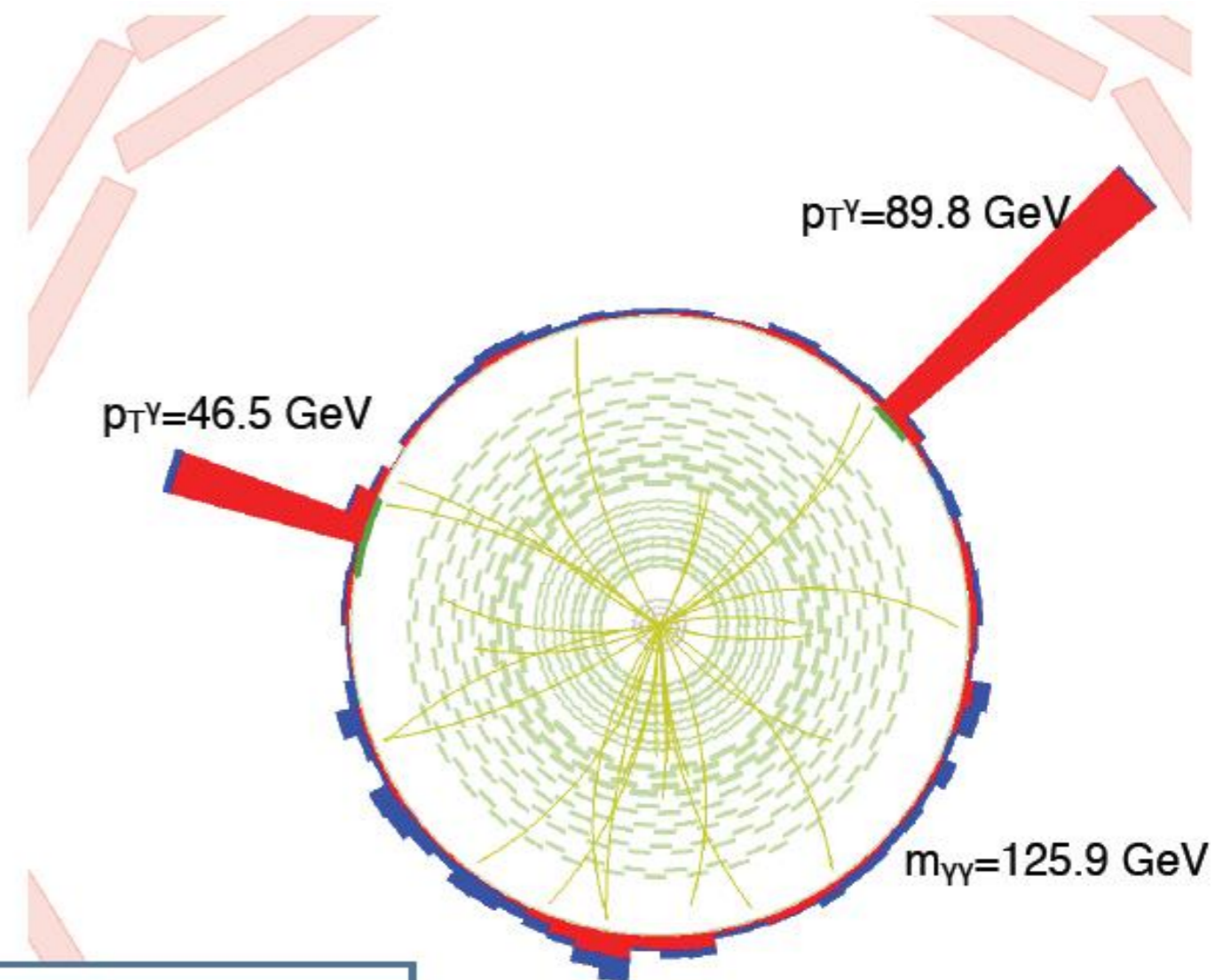
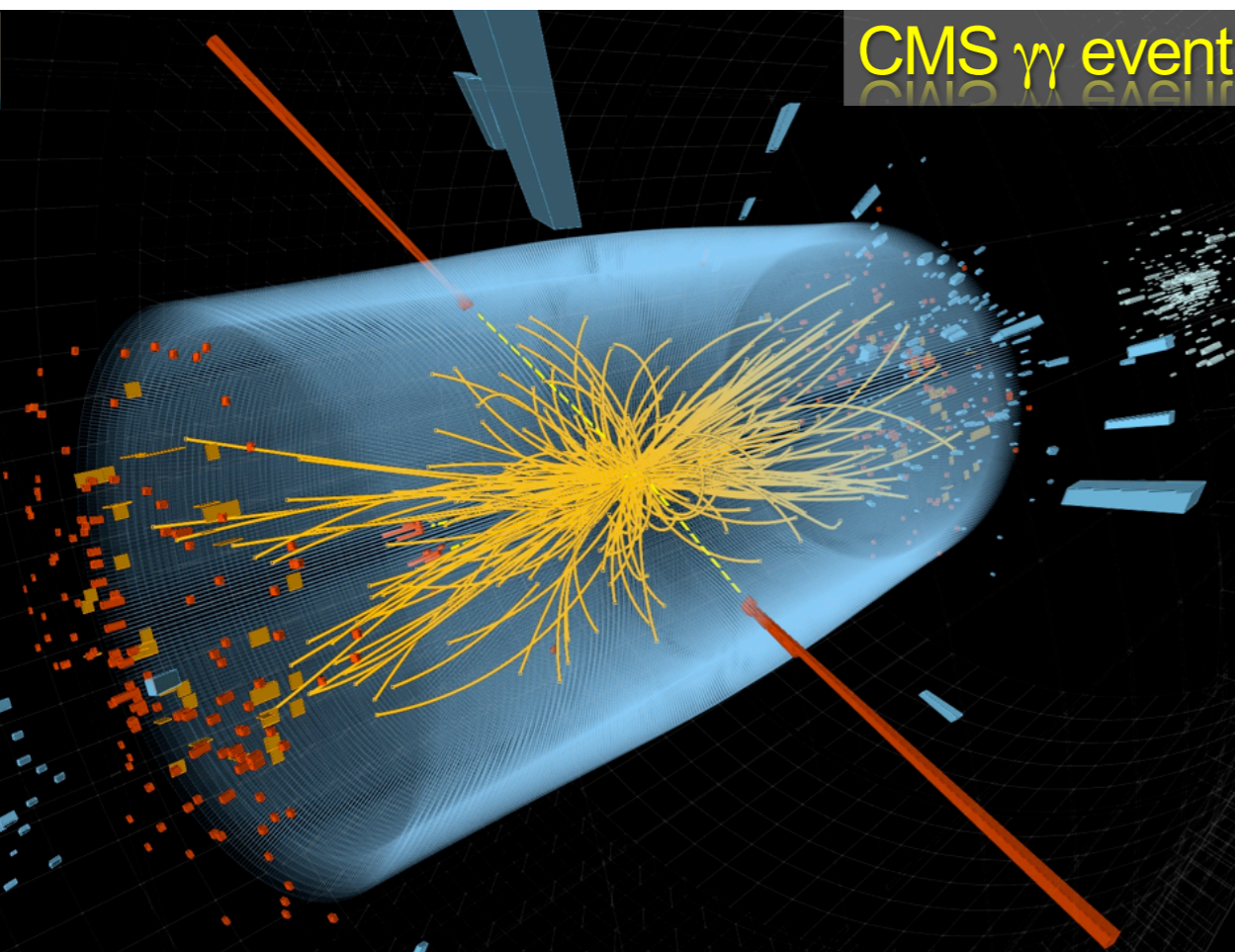
- **ICHEP -> 5.8 $\sigma$**
- **HCP -> 7.8 $\sigma$**

# Search for SM Higgs boson: $\gamma\gamma$ -decay mode



High resolution mass mode ( $\sim 1\%$ )

5 fb/1 at 7 TeV (2011) + 5 fb/1 at 8 TeV (2012)

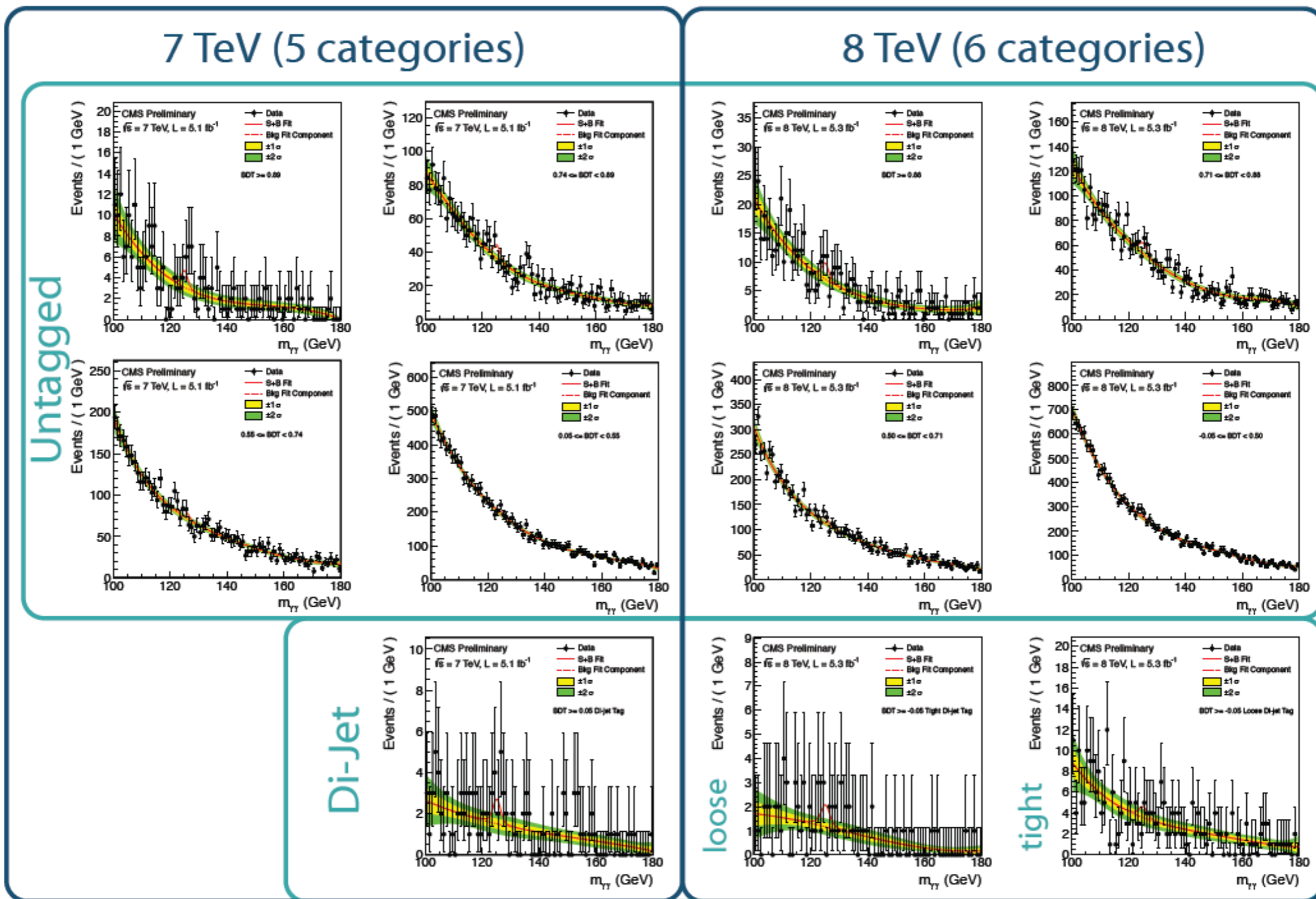


$H \rightarrow \gamma\gamma$   
candidate

# Search for SM Higgs boson: $\gamma\gamma$ events



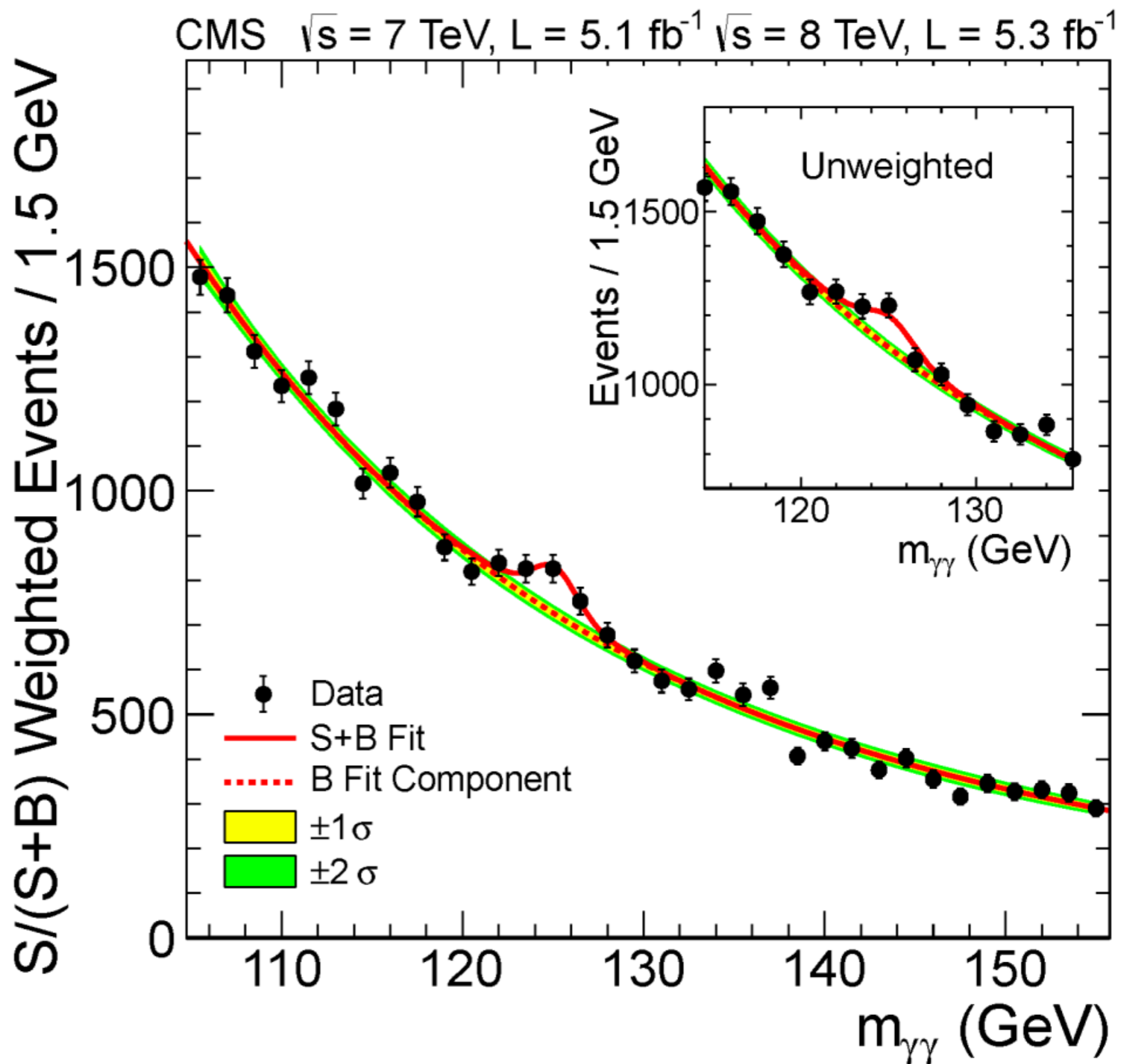
Categorized into non-overlapping event samples



# $\gamma\gamma$ -mode: weighted mass distribution



Sum of each event category with weight  $S/(S+B)$



# Search for SM Higgs boson: $\gamma\gamma$ -excess

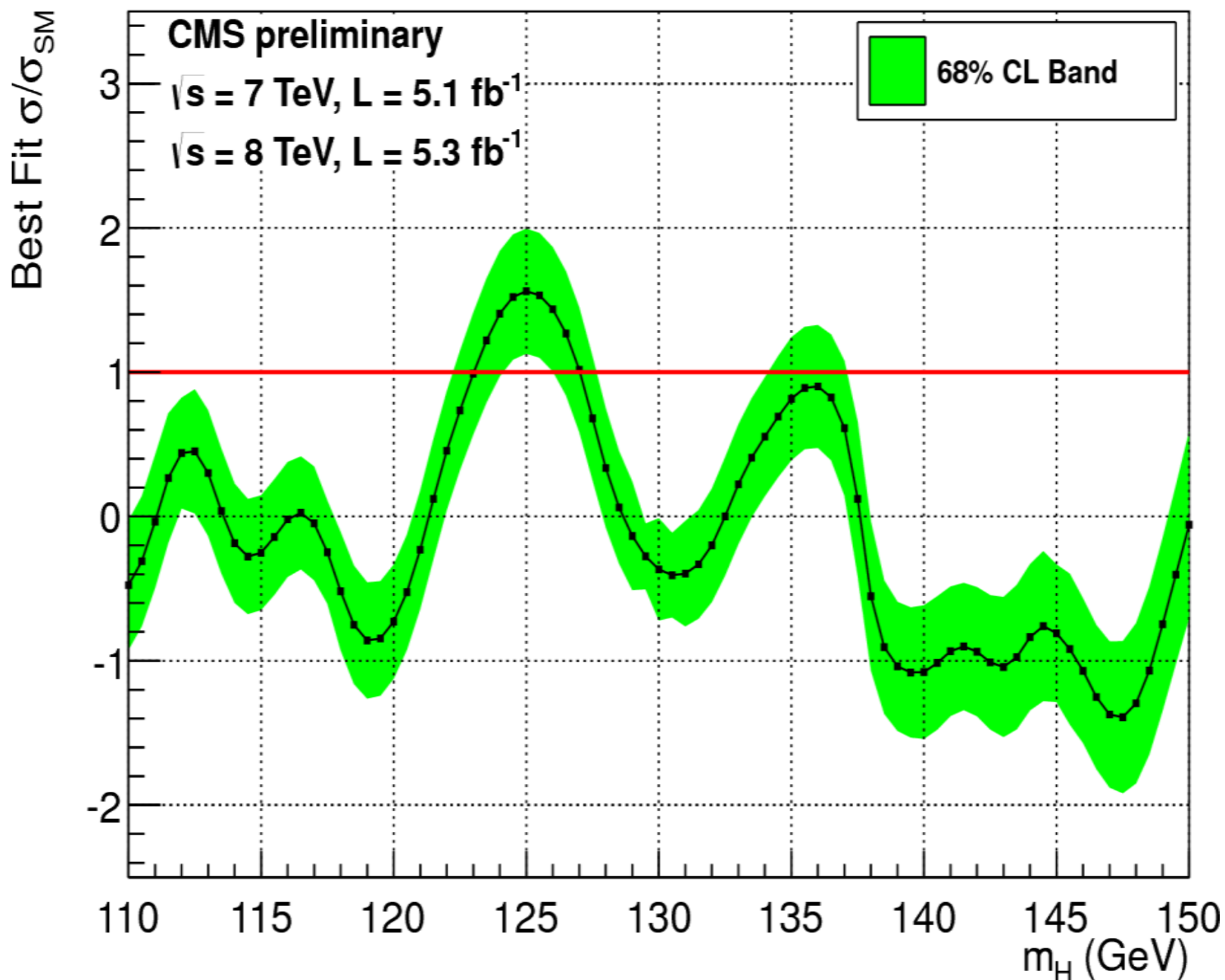


**CMS evidence for a new state (July 4, 2012):**

**excess in  $\gamma\gamma$ -mass in both 7 and 8 TeV data**

**local significance:  $4.1\sigma$**

**signal strength:  $(1.6 \pm 0.4) \times \sigma_{SMH}$**

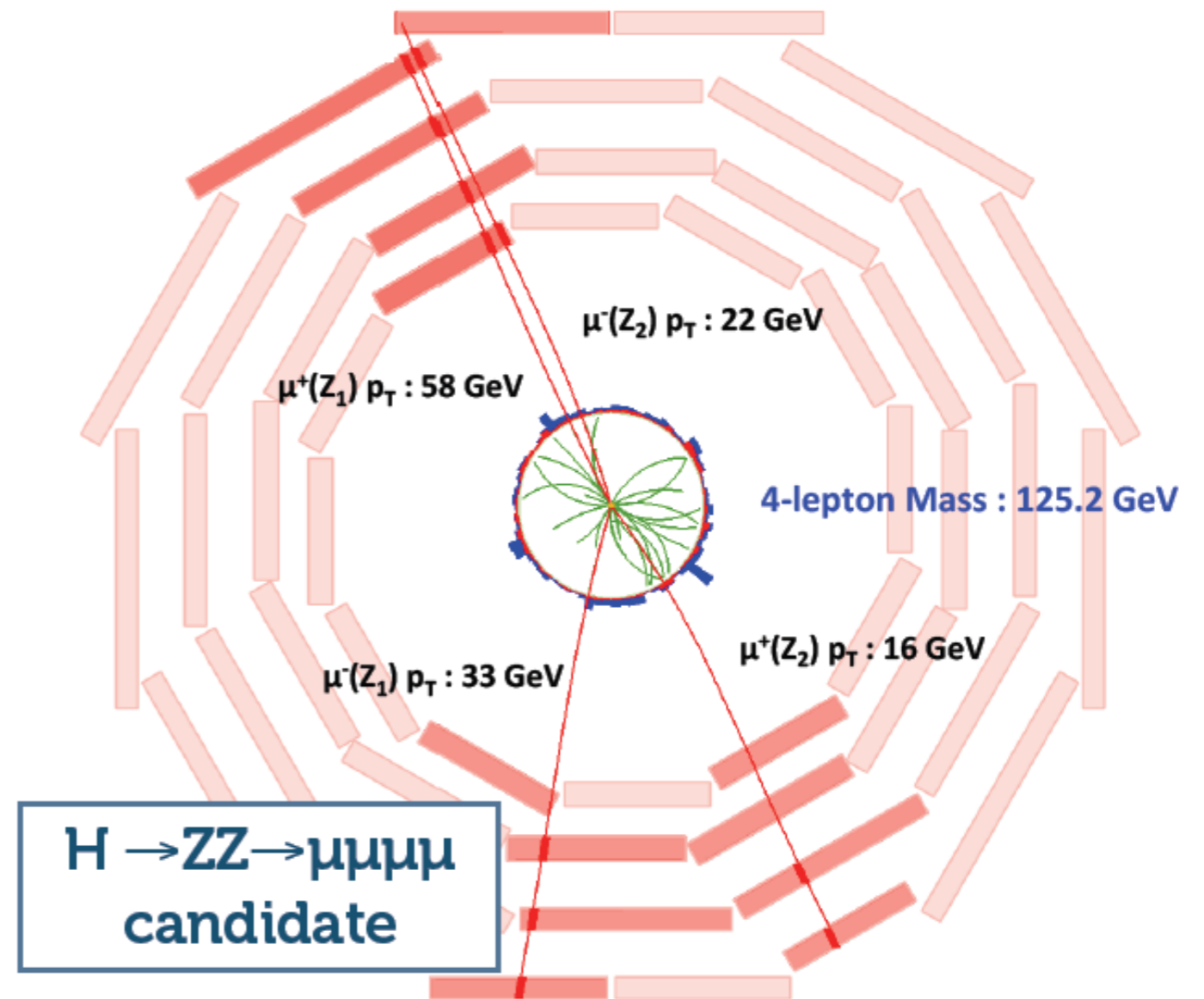


# Search for SM Higgs boson: 4 lepton mass



High resolution mass mode (~1-4%)

5 fb/1 at 7 TeV (2011) + 5 fb/1 at 8 TeV (2012)



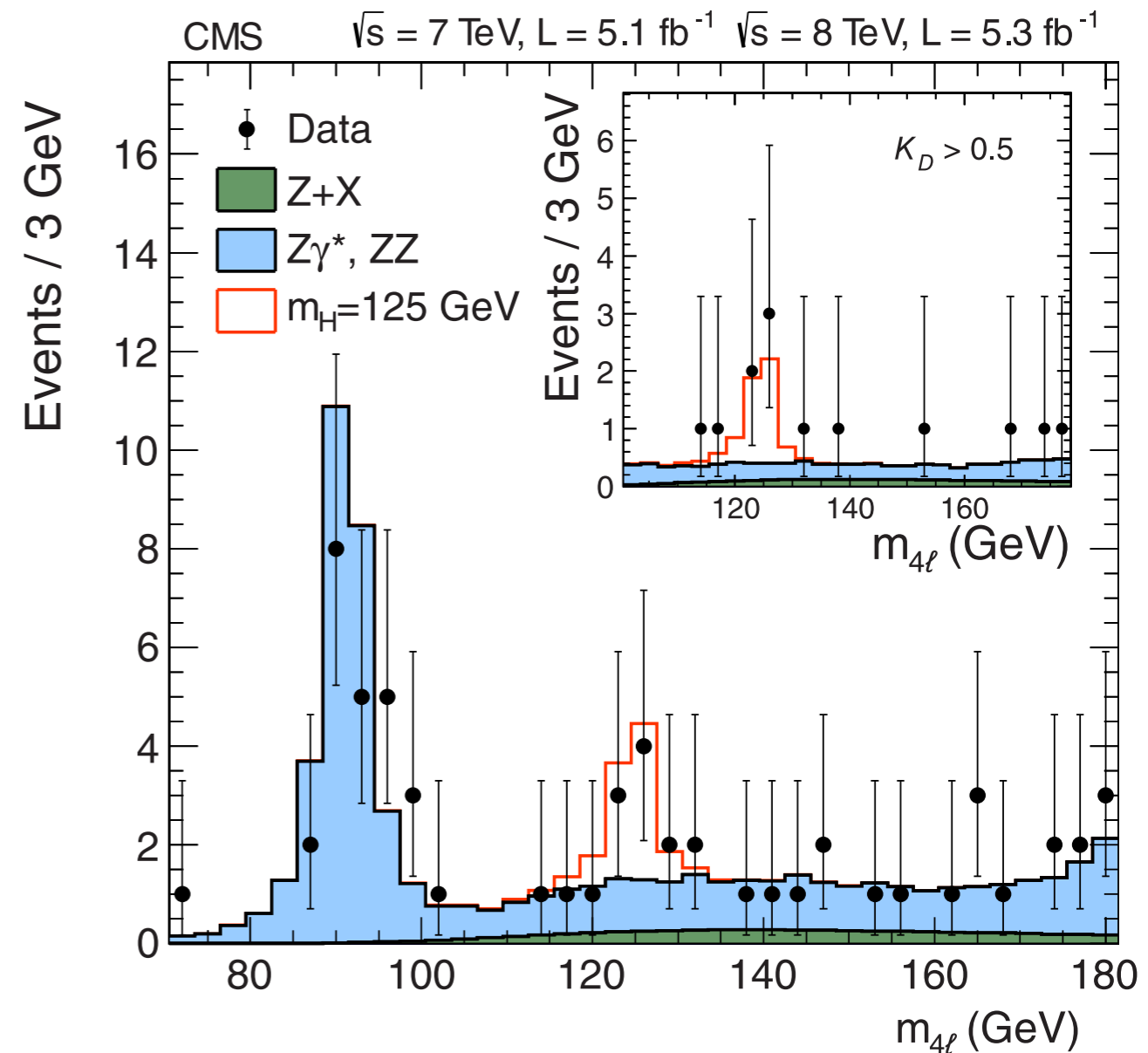
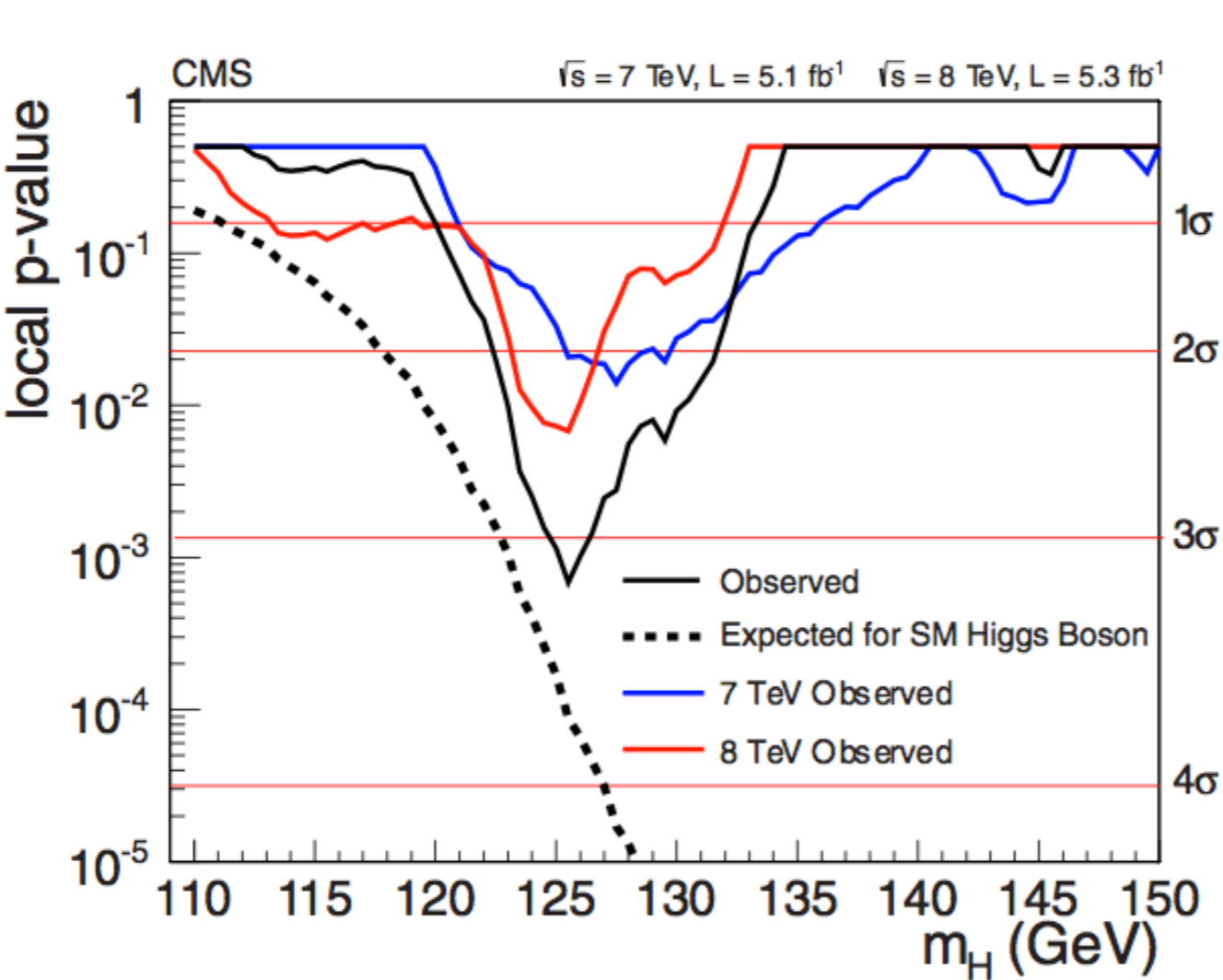
# Search for SM Higgs boson: 4 lepton mass



**Localized excess at ~126 GeV (July 4, 2012)**

**Local significance:  $3.2\sigma$**

**SM expectation:  $3.8\sigma$**





# SM Higgs boson $\rightarrow$ 4leptons: the golden mode



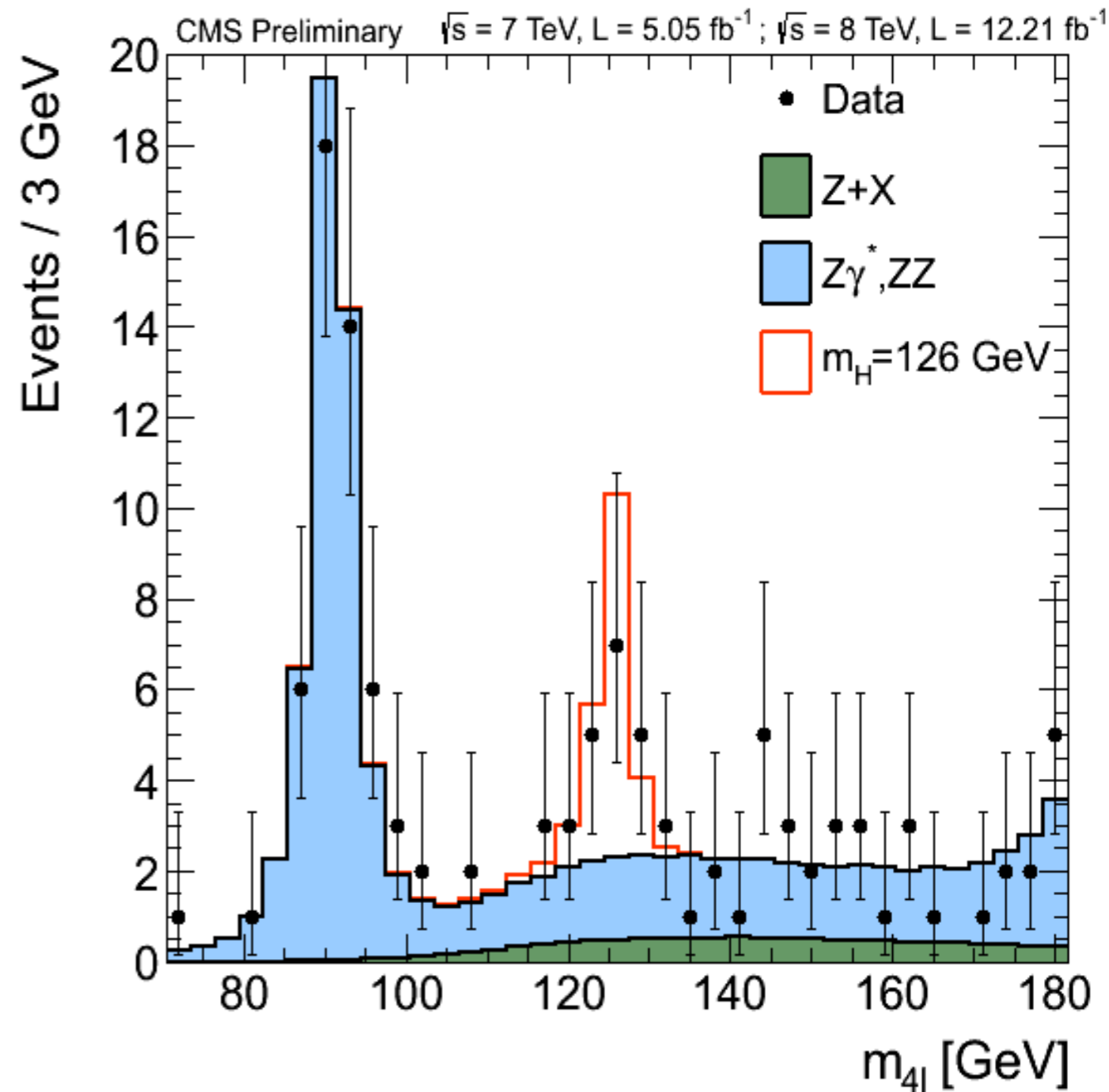
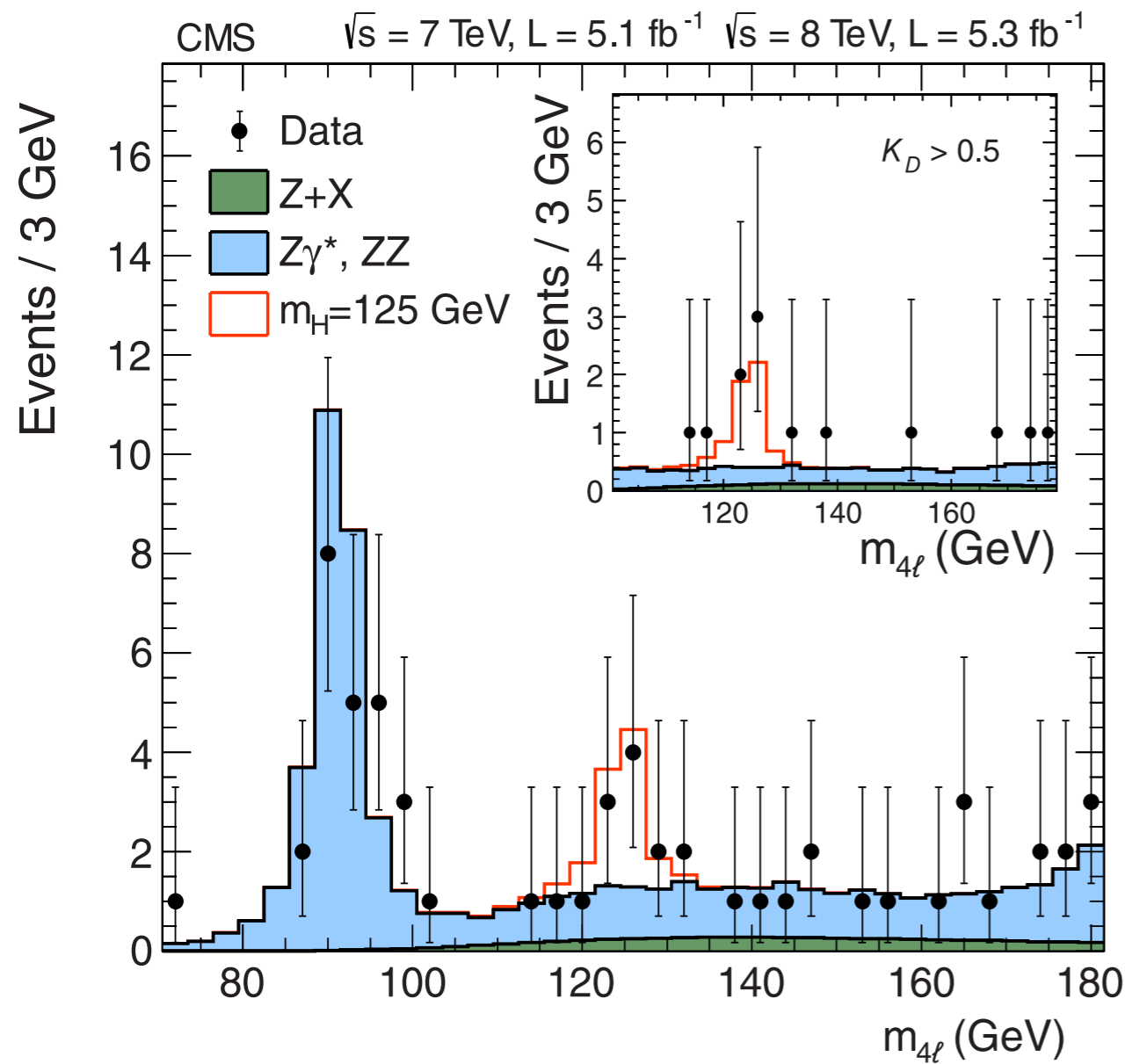
Localized excess at  $\sim 126$  GeV got more significant

July 4

Nov. 15

Local significance:  $3.2\sigma \rightarrow 4.4\sigma$

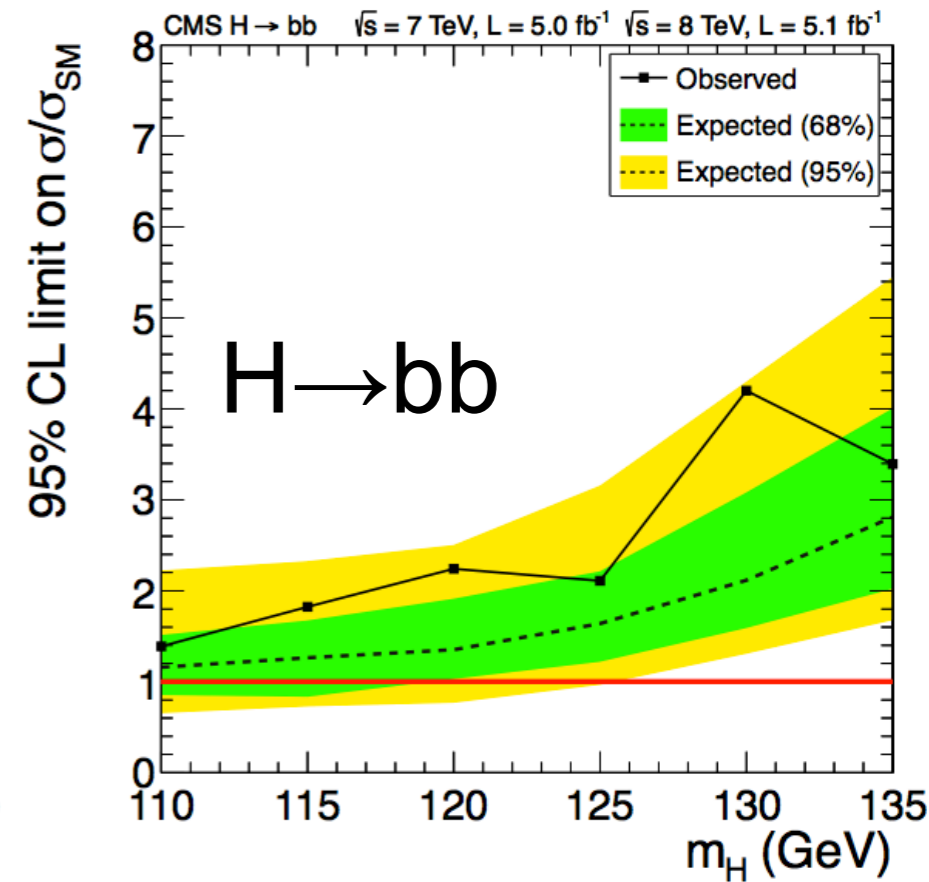
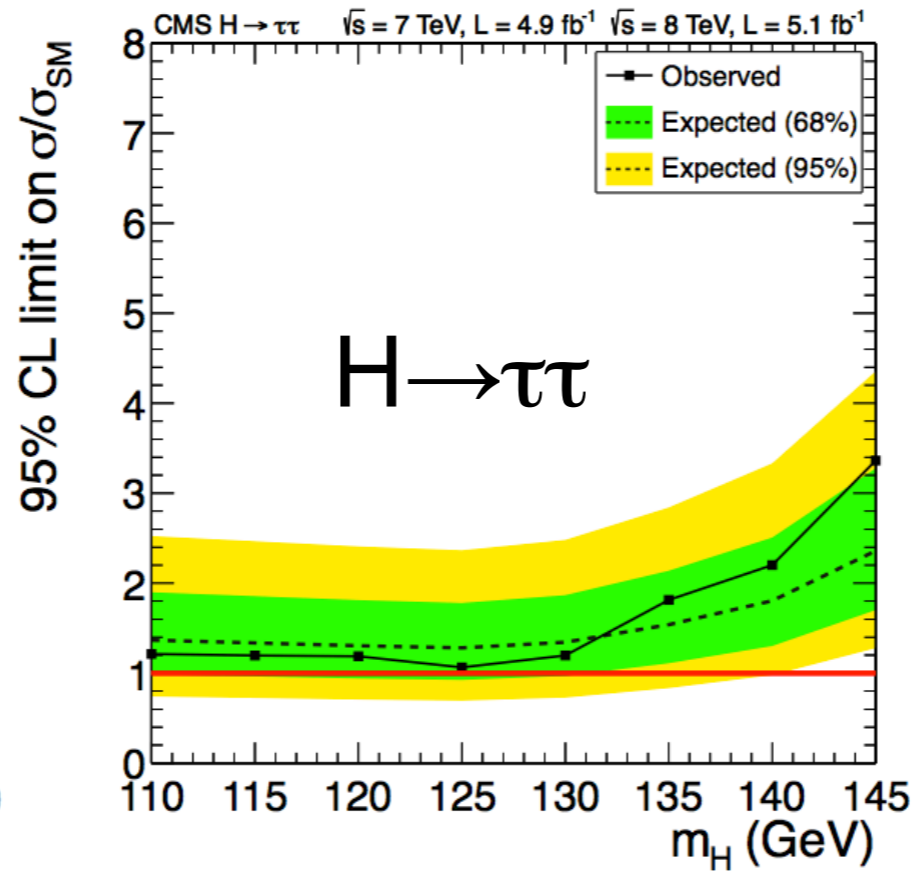
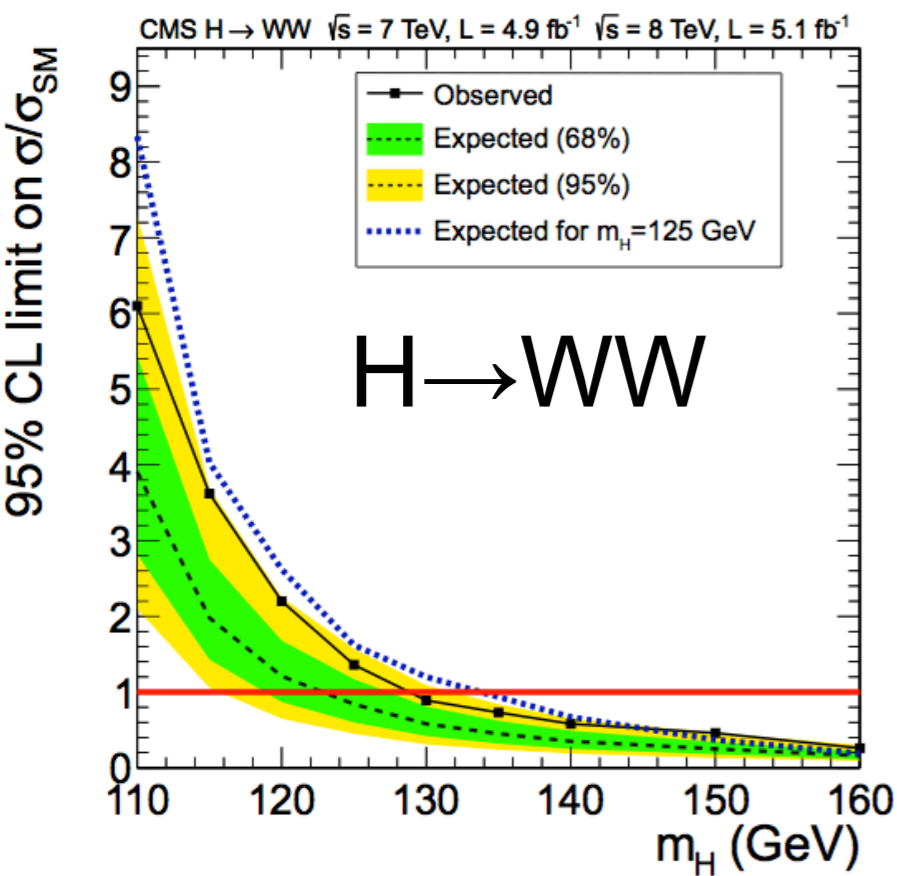
SM expectation:  $3.8\sigma \rightarrow 5.0\sigma$



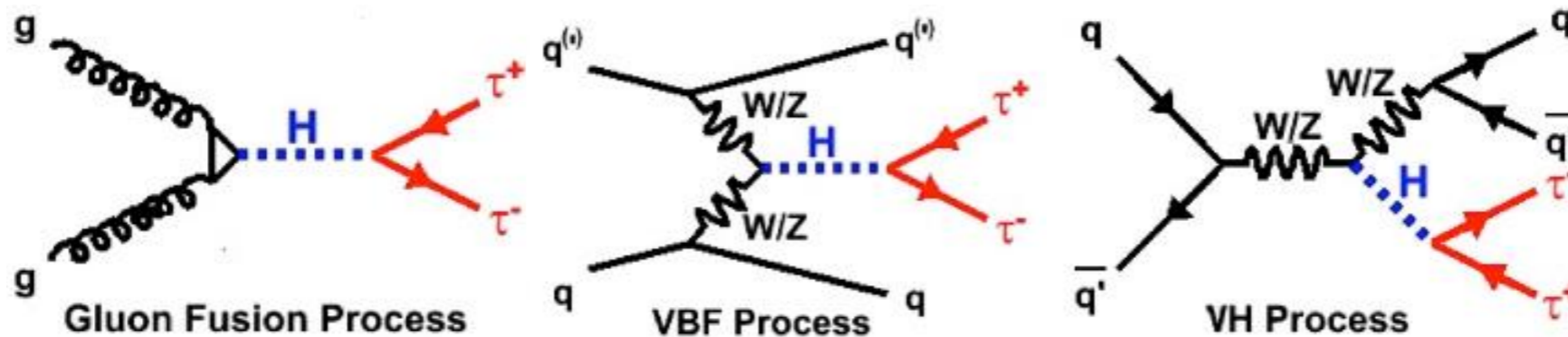
# Search for SM Higgs boson: low resolution mass channels



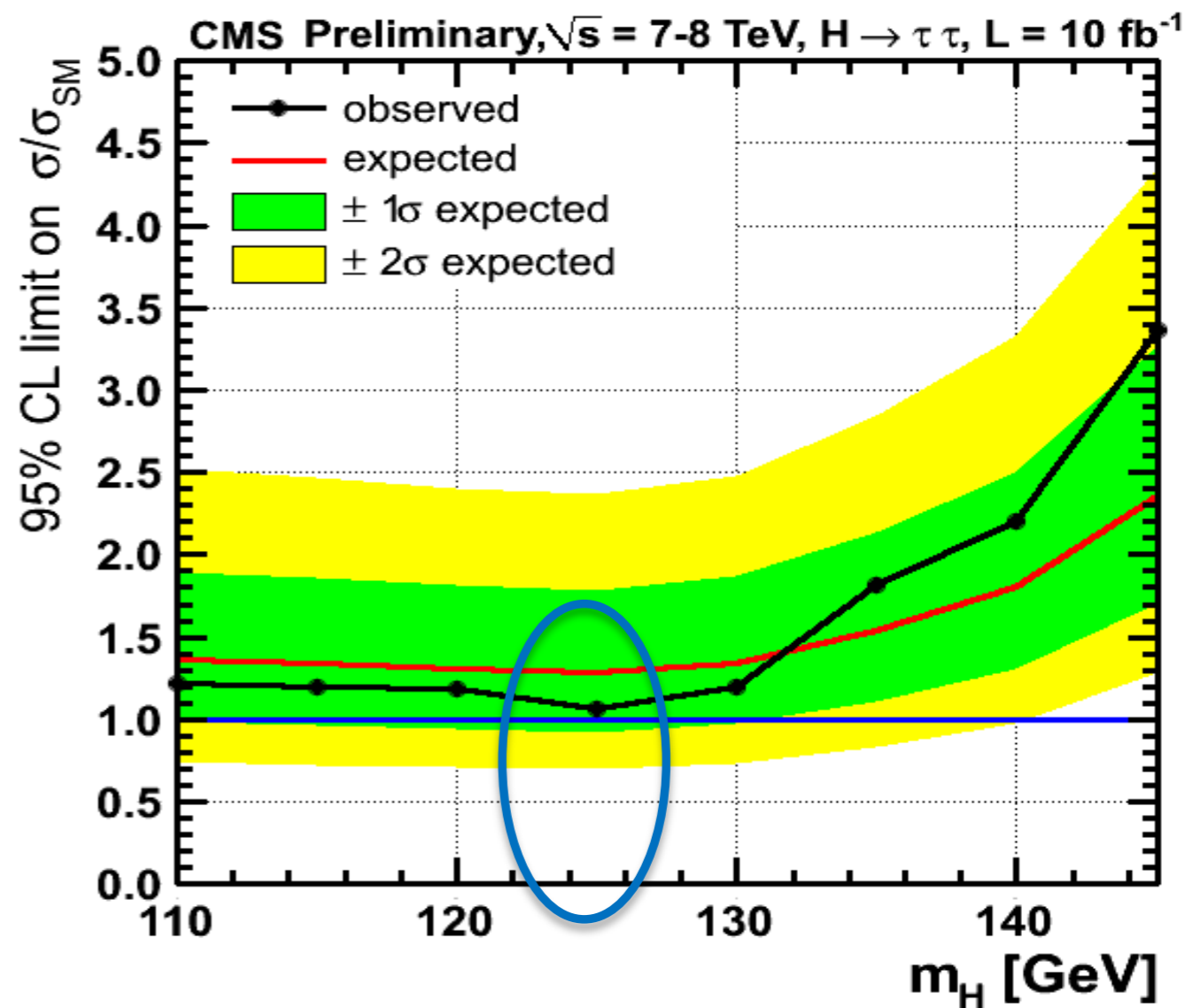
Decay mode	Production tagging	No. of subchannels	$m_H$ range (GeV)	Int. Lum. ( $\text{fb}^{-1}$ )	
				7 TeV	8 TeV
WW	untagged dijet (VBF)	4 1 or 2	110–600	4.9	5.1
$\tau\tau$	untagged dijet (VBF)	16 4	110–145	4.9	5.1
bb	lepton, $E_T^{\text{miss}}$ (VH)	10	110–135	5.0	5.1



# Search for SM Higgs boson: $\tau\tau$ -mode



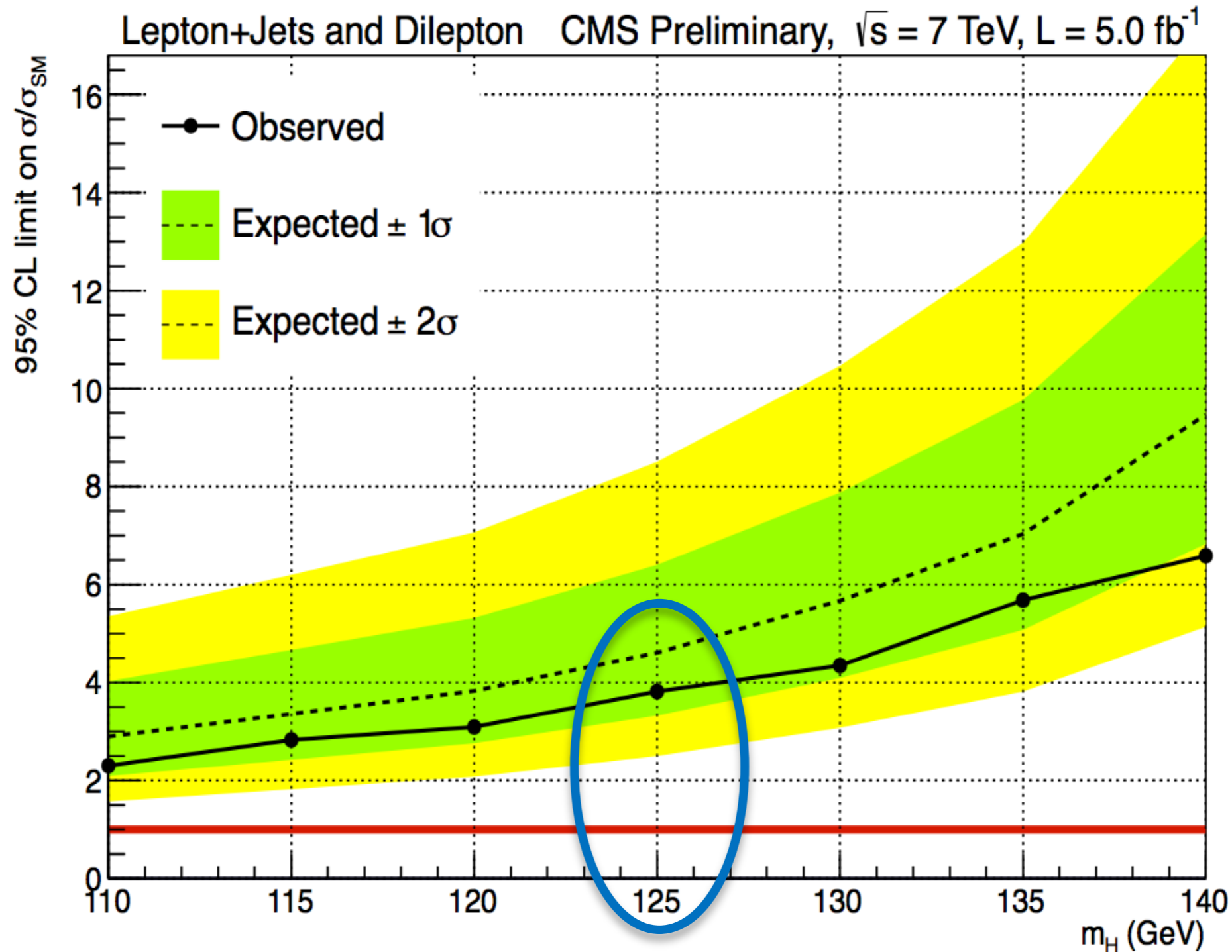
- No excess observed so far, reached sensitivity  $1 \times \sigma_{SM}$  already
- Bad luck? or non-SM Higgs boson?



# Search for SM Higgs boson: bb-mode



- At present only 2011 data analyzed
- No excess observed so far, but not sensitive to  $1\sigma_{SM}$  yet



# Search for SM Higgs: combined channels



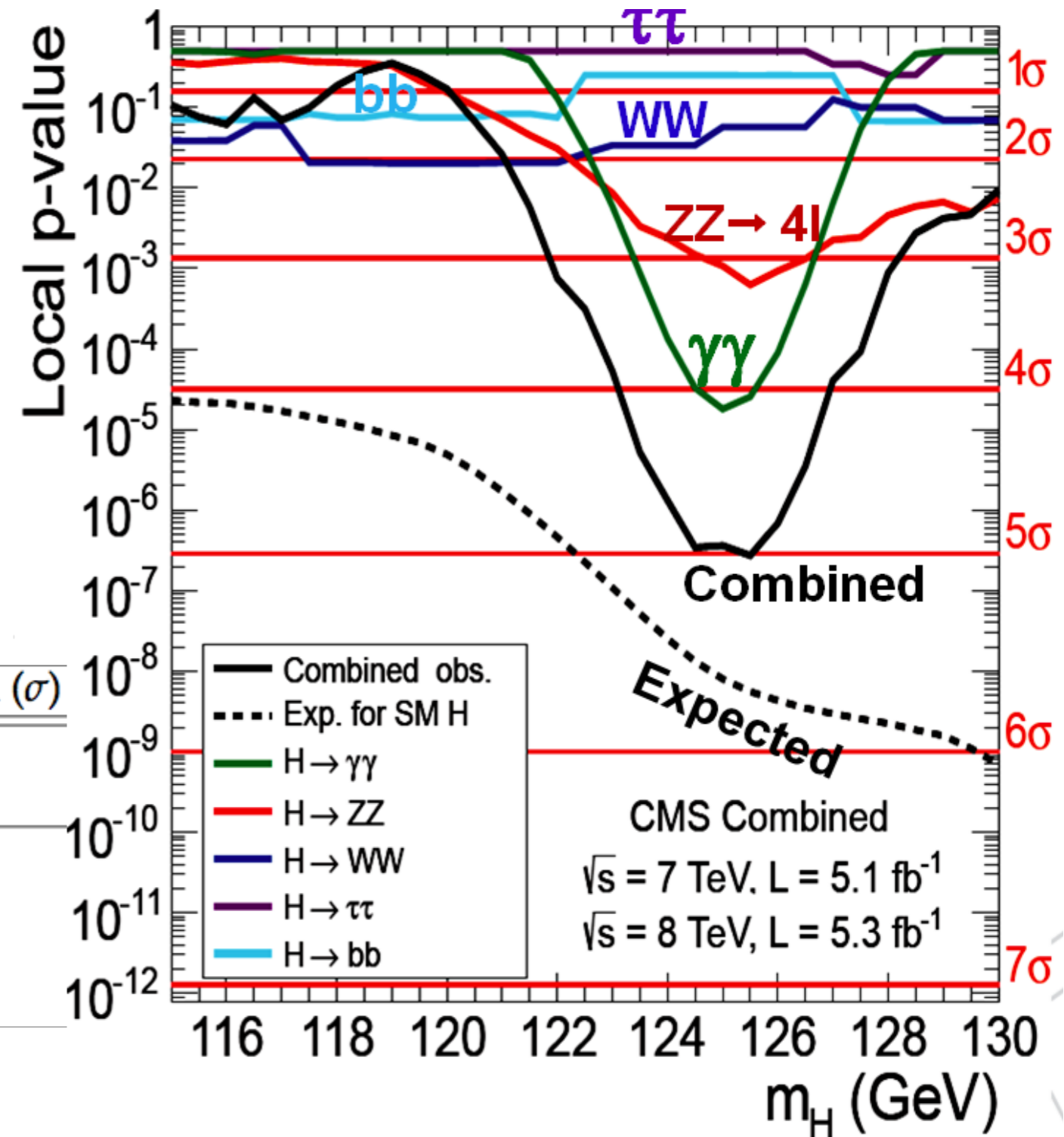
## Excess at 125 GeV:

- 7 TeV data  $3.2\sigma$
- 8 TeV data  $3.8\sigma$

## Most sensitive channels:

- $\gamma\gamma$
- $4l$

Decay mode/combination	Expected ( $\sigma$ )	Observed ( $\sigma$ )
$\gamma\gamma$	2.8	4.1
$ZZ$	3.6	3.1
$\tau\tau + bb$	2.4	0.4
$\gamma\gamma + ZZ$	4.7	5.0
$\gamma\gamma + ZZ + WW$	5.2	5.1
$\gamma\gamma + ZZ + WW + \tau\tau + bb$	5.8	5.0



# Search for SM Higgs: combined channels (July4)

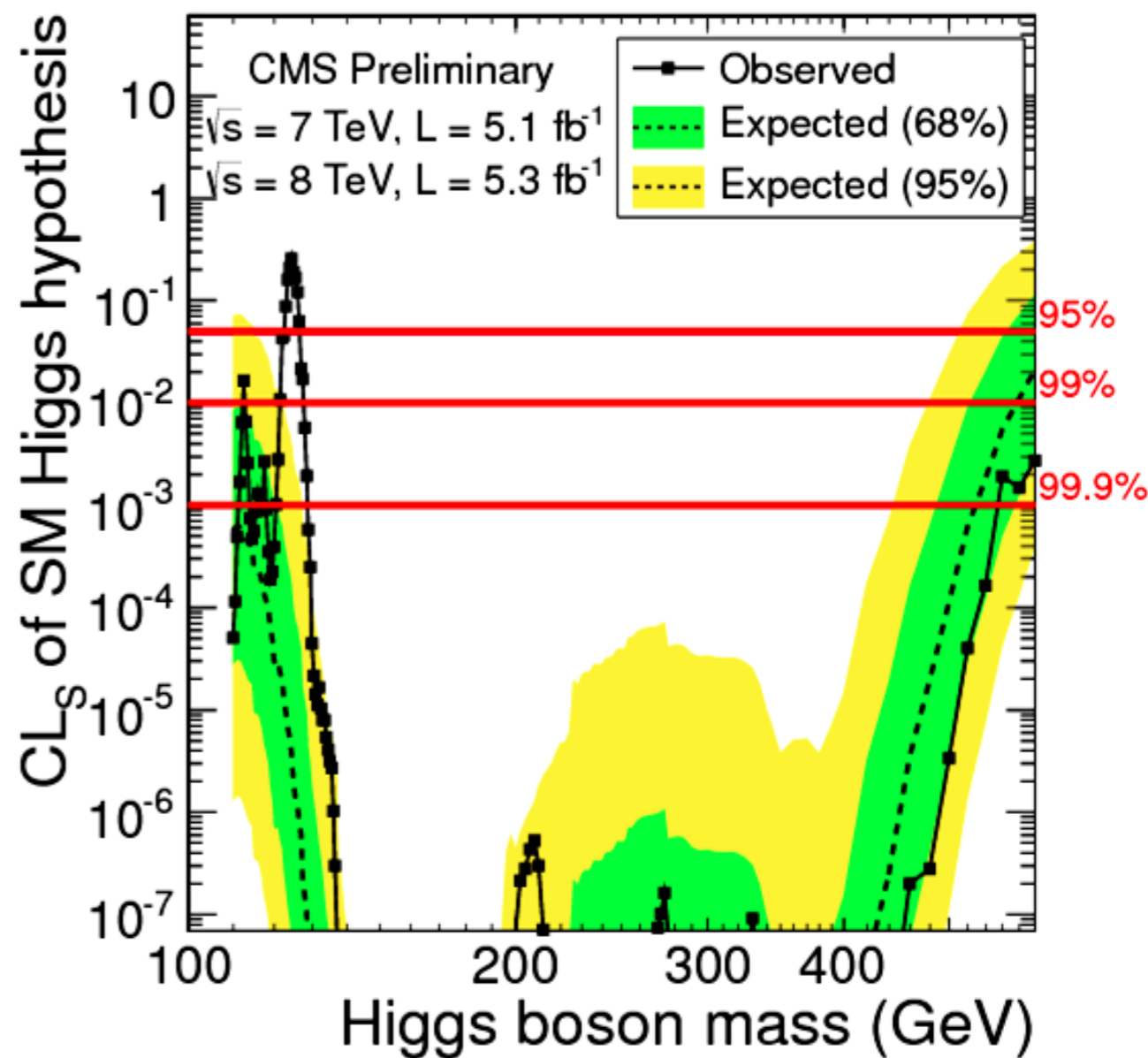
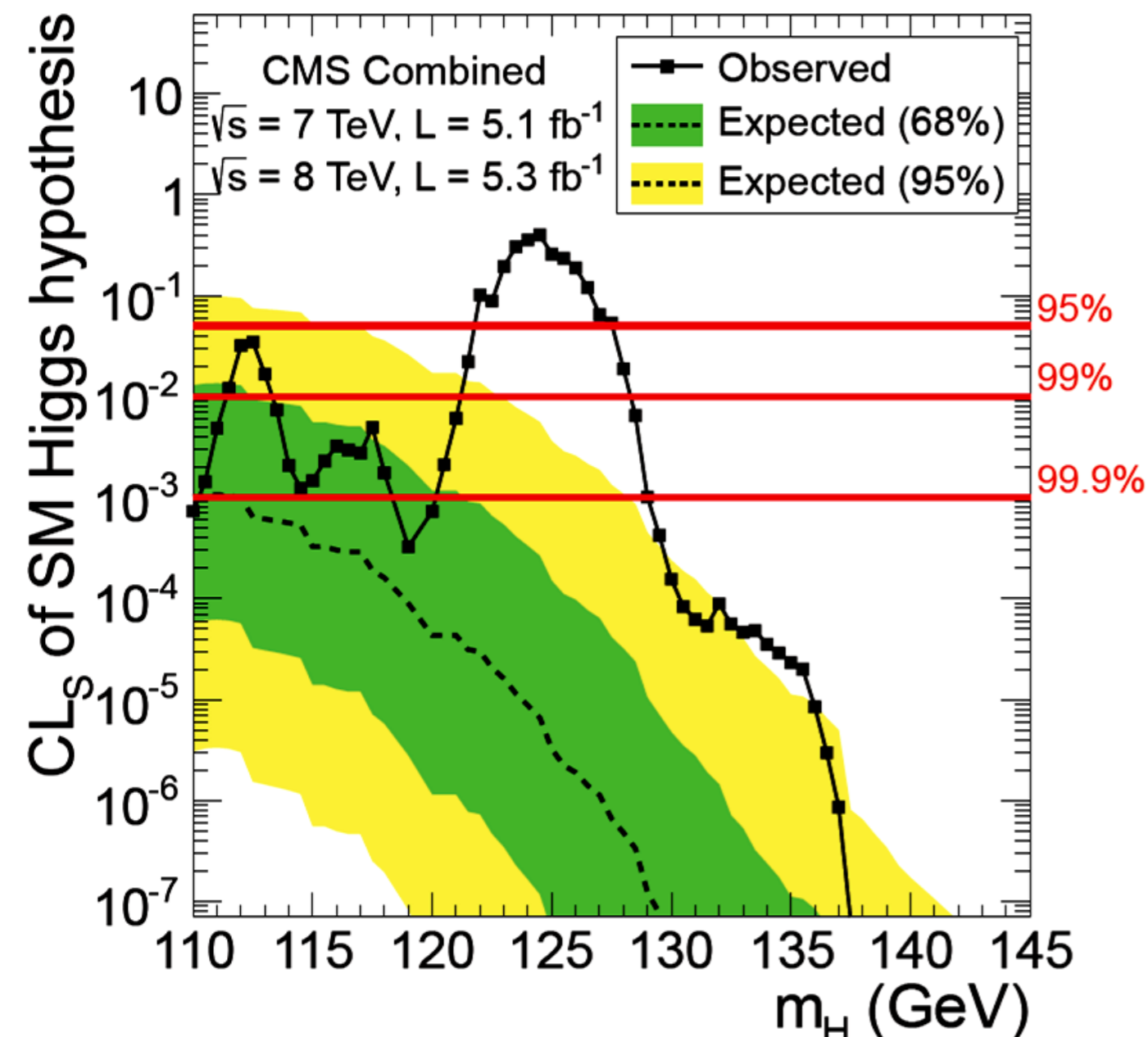


**CMS excess: ~ 125 GeV Evidence for a new state (July 4)**

**Exceses in both 7 and 8 TeV data**

**local significance:  $5.0\sigma$       global:  $4.6\sigma$**

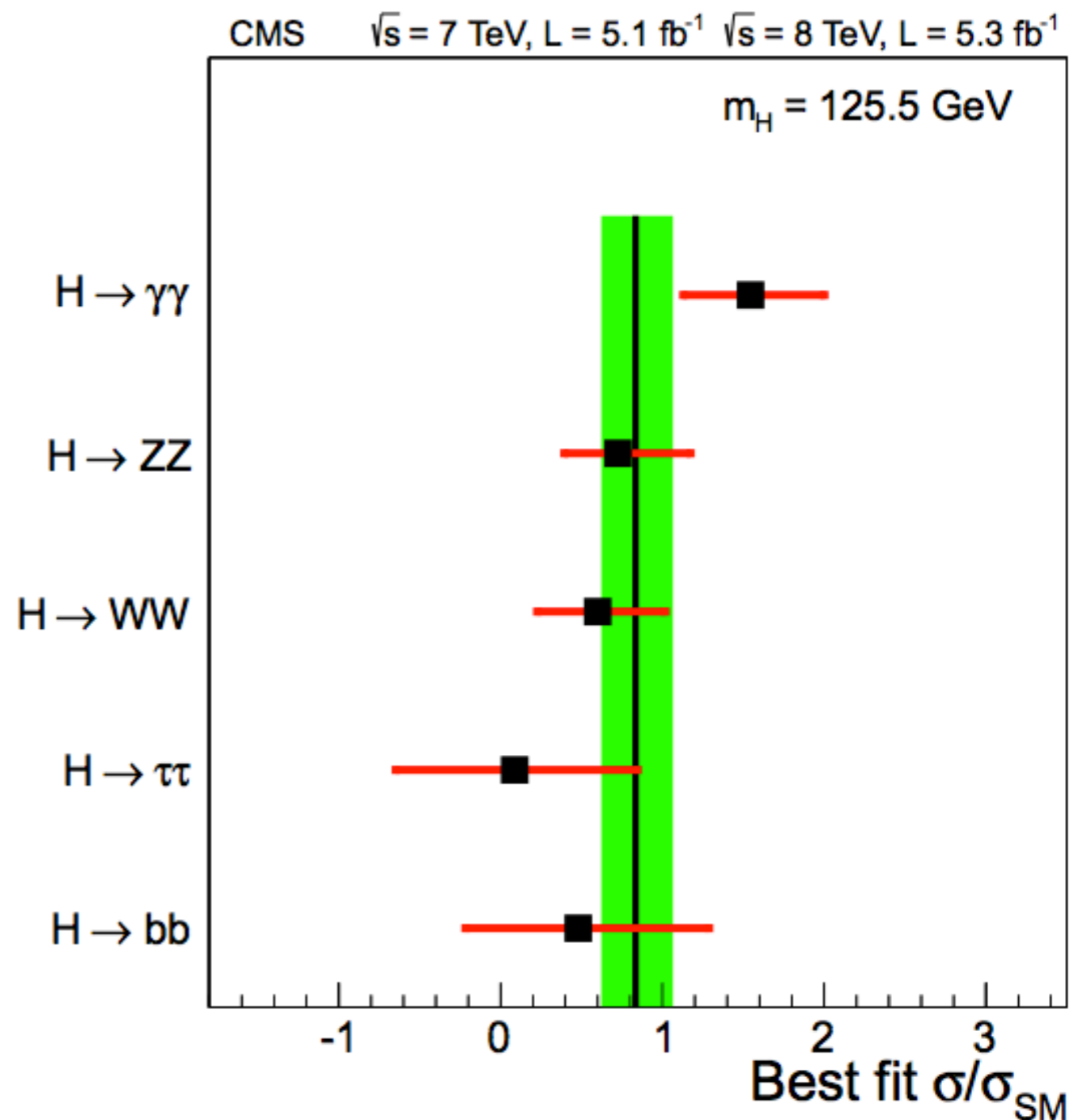
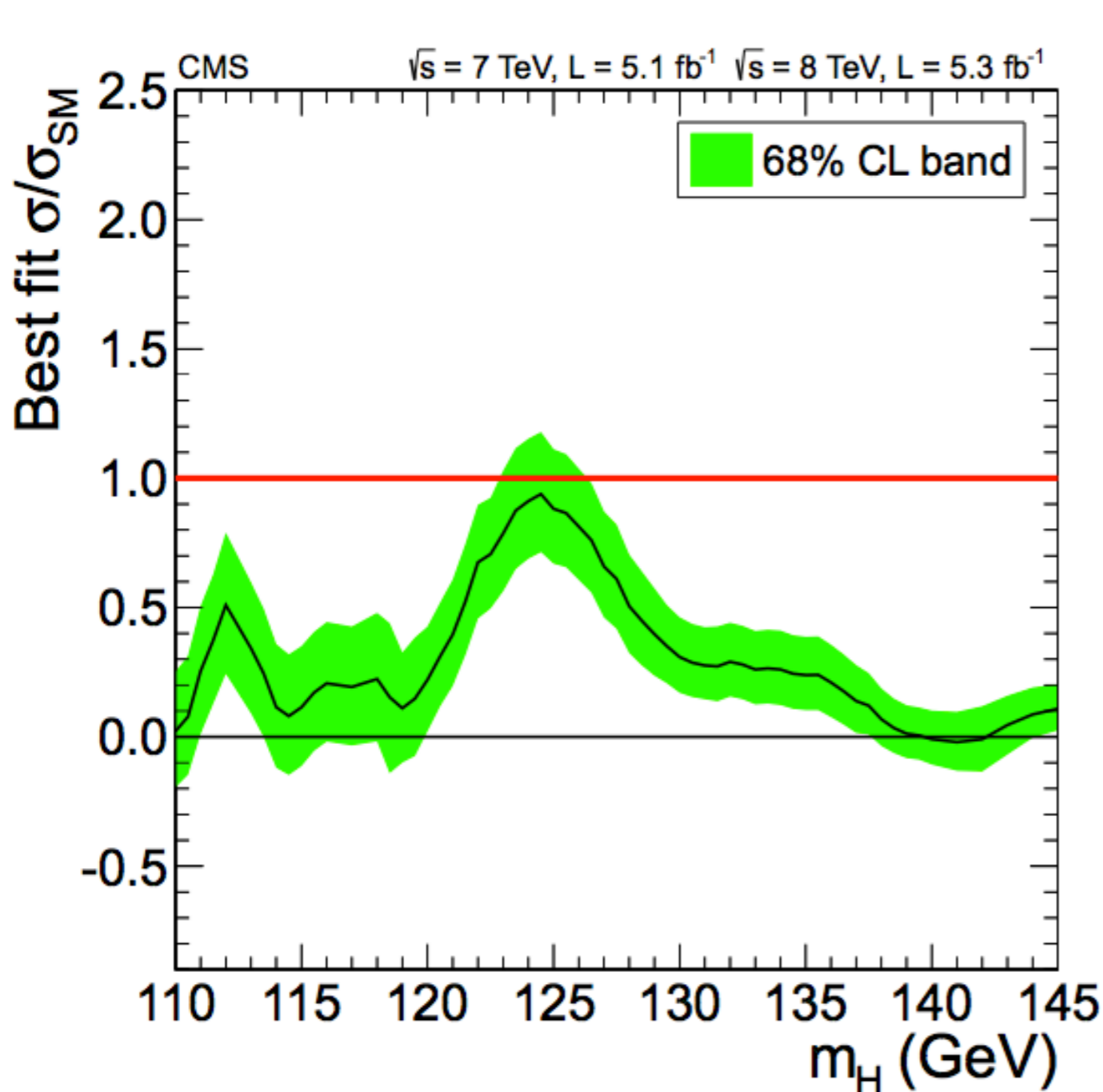
**signal strength:  $(0.87 \pm 0.23) \times \sigma_{SMH}$**



# Search for SM Higgs: combined channels



Overall strength:  $\sigma/\sigma_{\text{SM}} = 0.87 \pm 0.23$





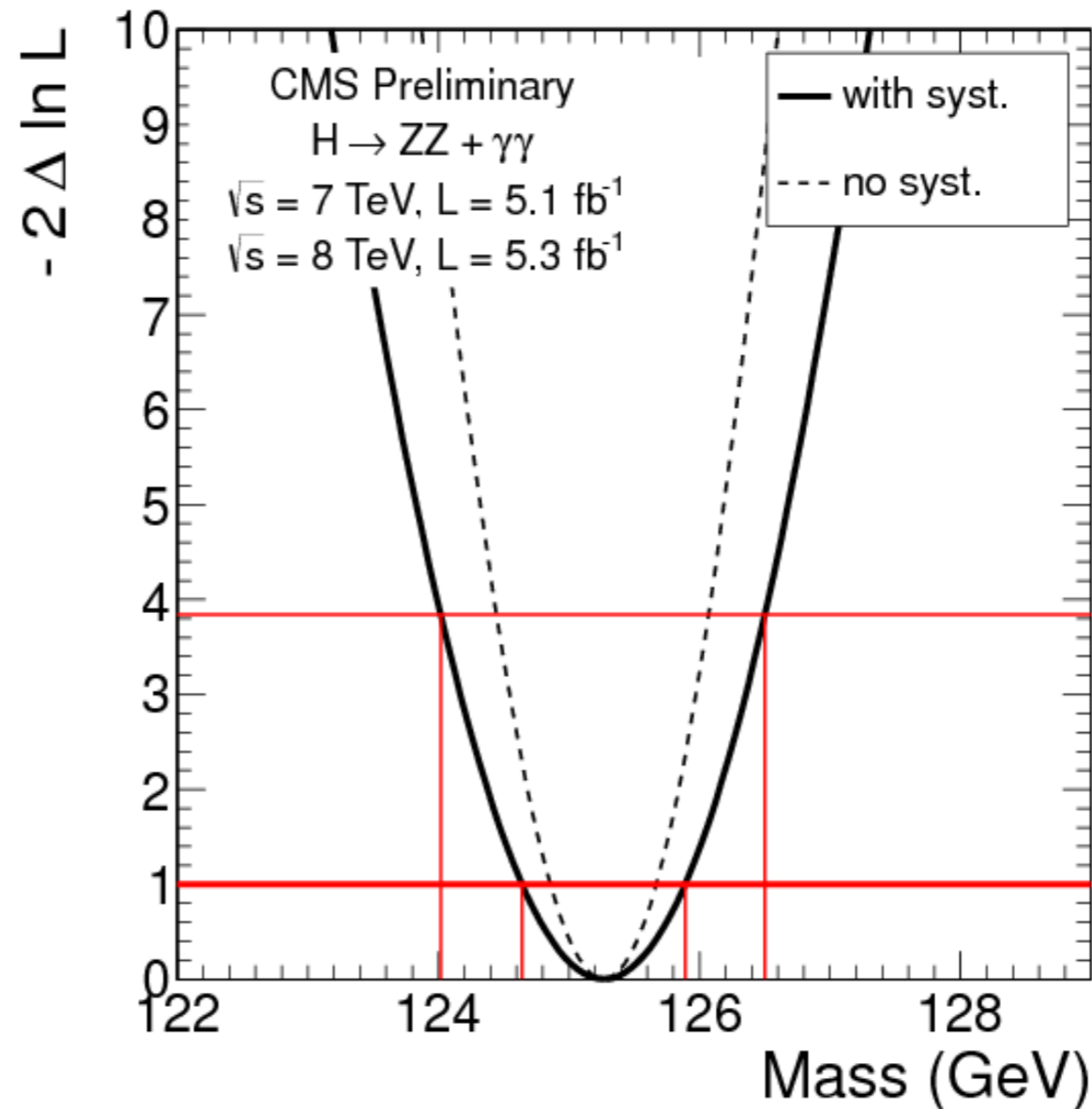
# CMS search for SM Higgs boson: new particle mass (July 4, 2012)

**Evidence for a new state: boson (because of  $\gamma\gamma$ -decay)**

**new particle mass at CMS (July 4, 2012):**

**$M = 125.3 \pm 0.4$  (stat.)  $\pm 0.5$  (syst.) GeV**

**$M = 125.3 \pm 0.6$  GeV**





# **Search for SM Higgs: new state evidence update at CMS!**



**HCP-2012, Kyoto, Japan, November 15, 2012**

**CMS:**

**Excess: ~ 125 GeV: Evidence update for a new state!**

**Excesses in both 7 (5.1 Fb-1) and 8 TeV (5.3 -> 12.3 Fb-1) data**

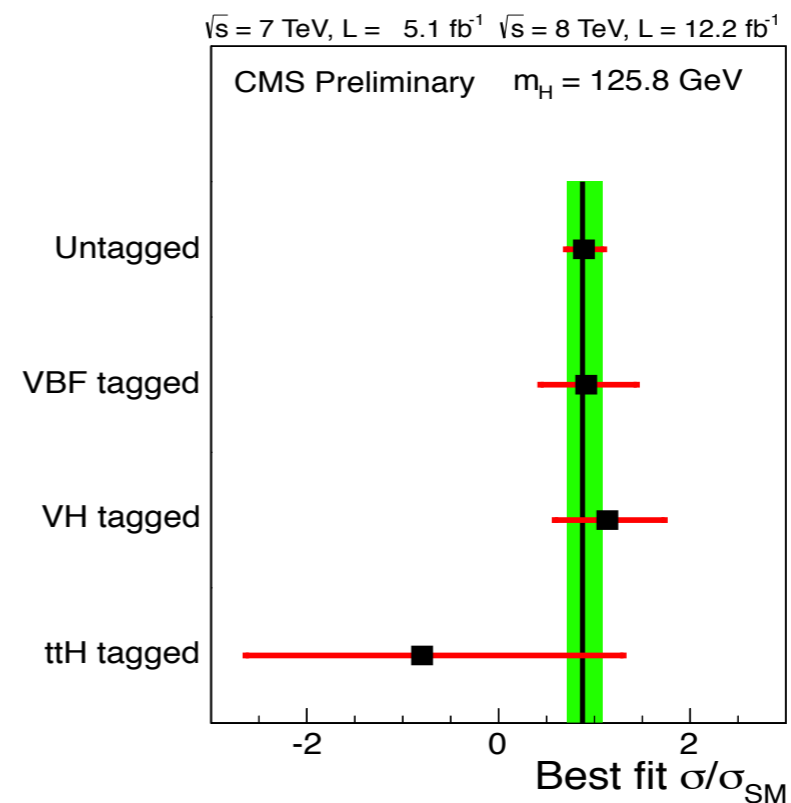
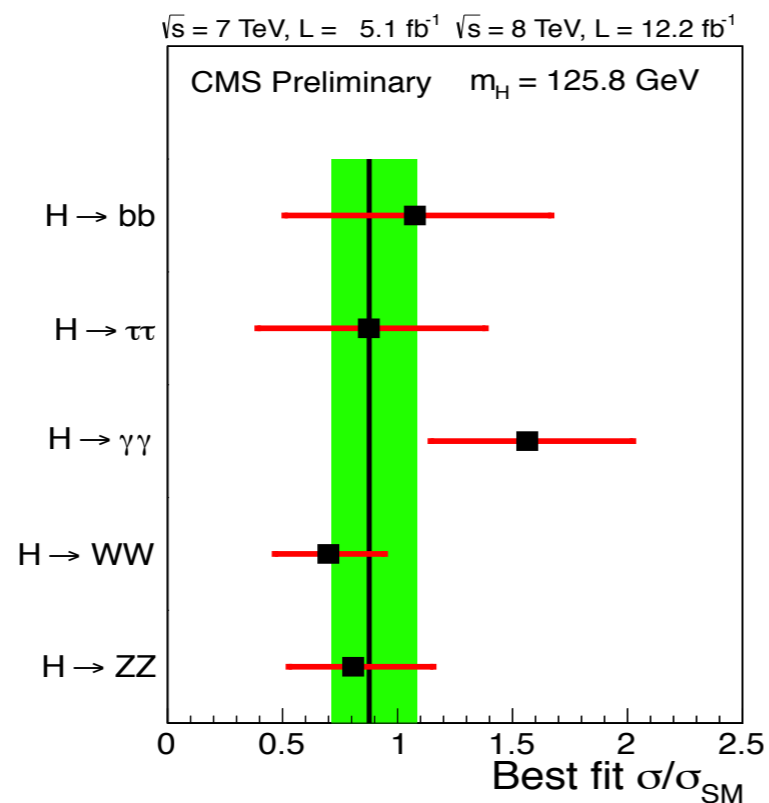
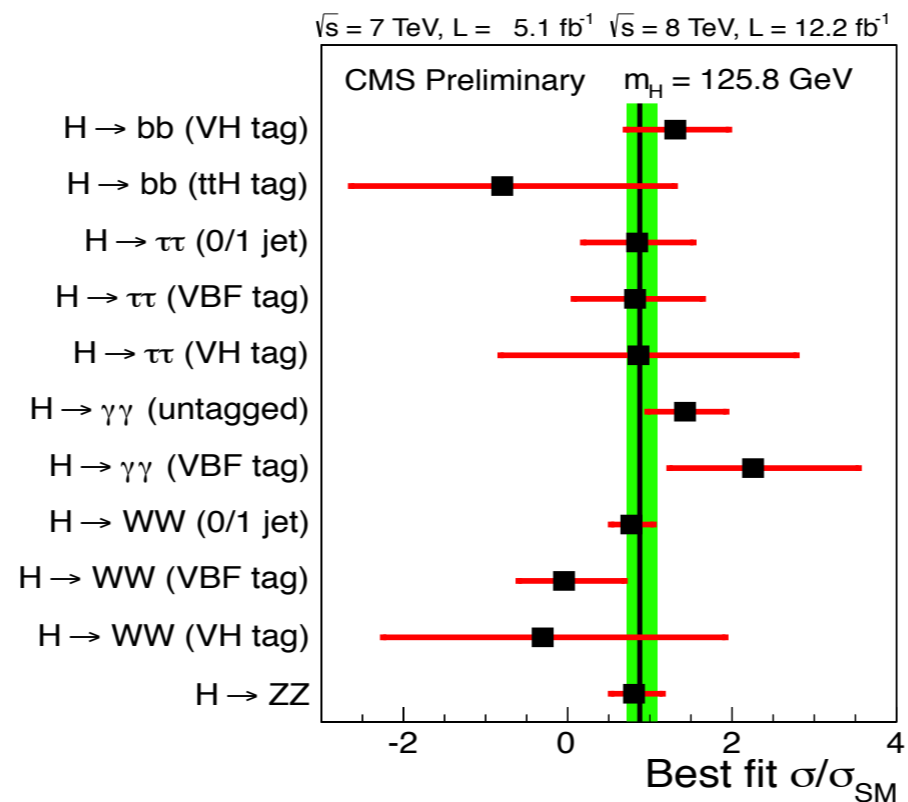
**local significance: 4.9 $\sigma$       expected: 5.8 $\sigma$       CERN, July 4**

**local significance: 6.9 $\sigma$       expected: 7.8 $\sigma$       HCP, Nov. 15**

# Search for SM Higgs boson: couplings



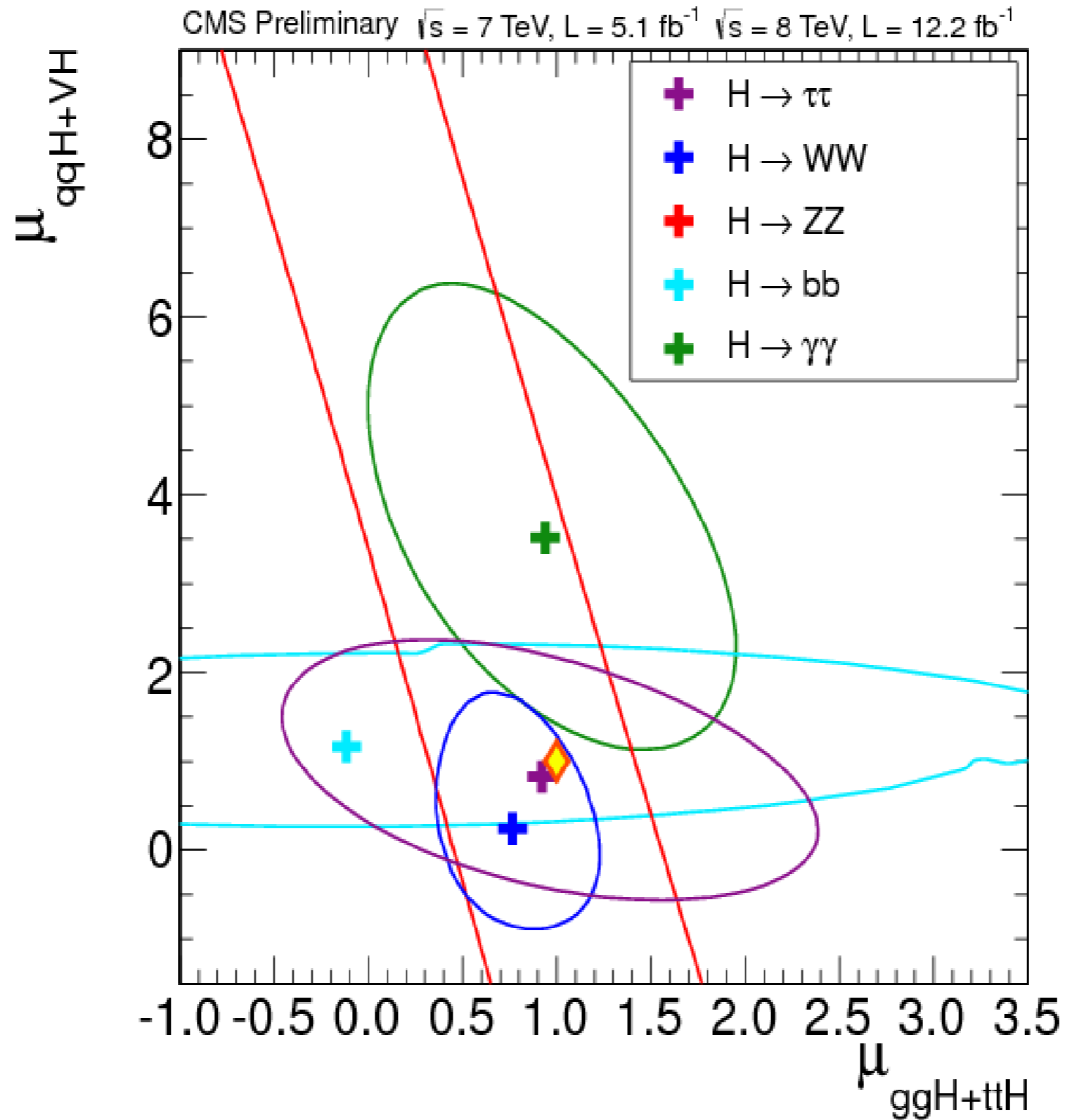
The CMC data: updated Nov. 15, 2012



# Search for SM Higgs boson: couplings



The CMC data: updated Nov. 15, 2012

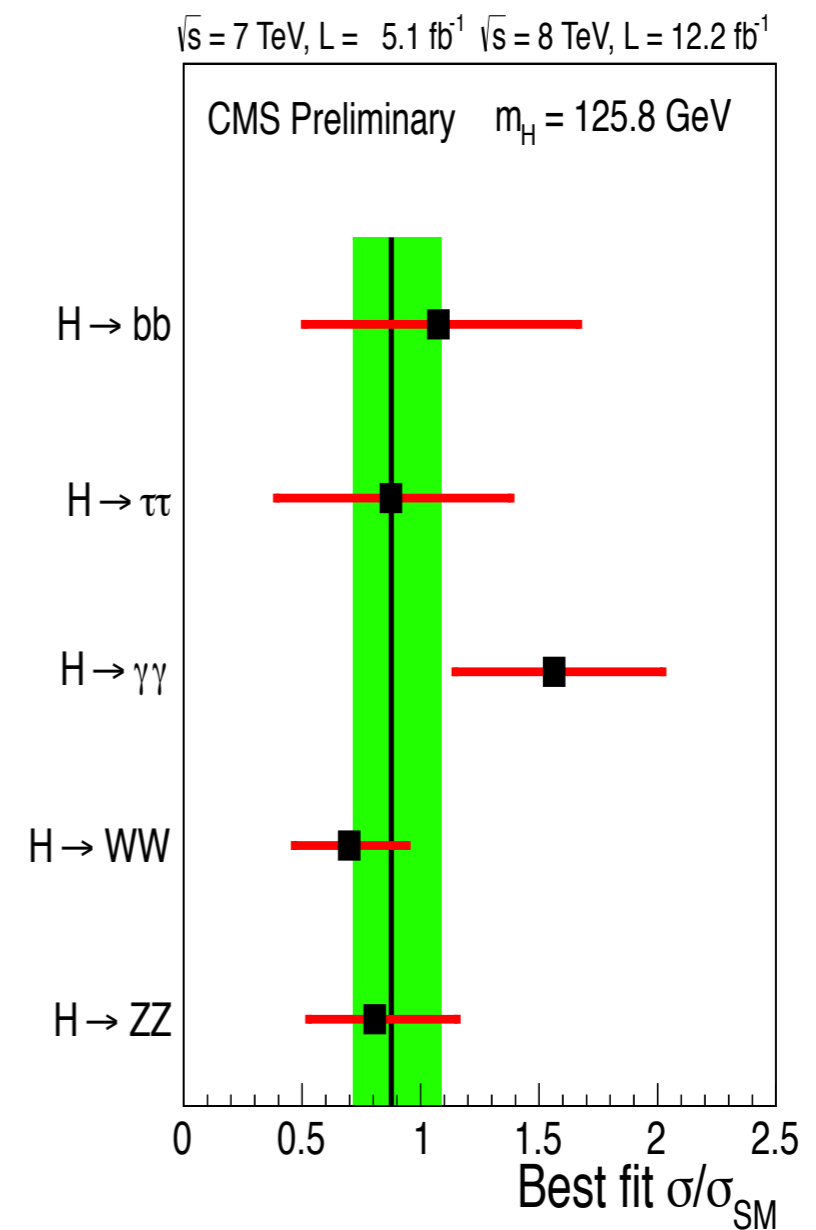
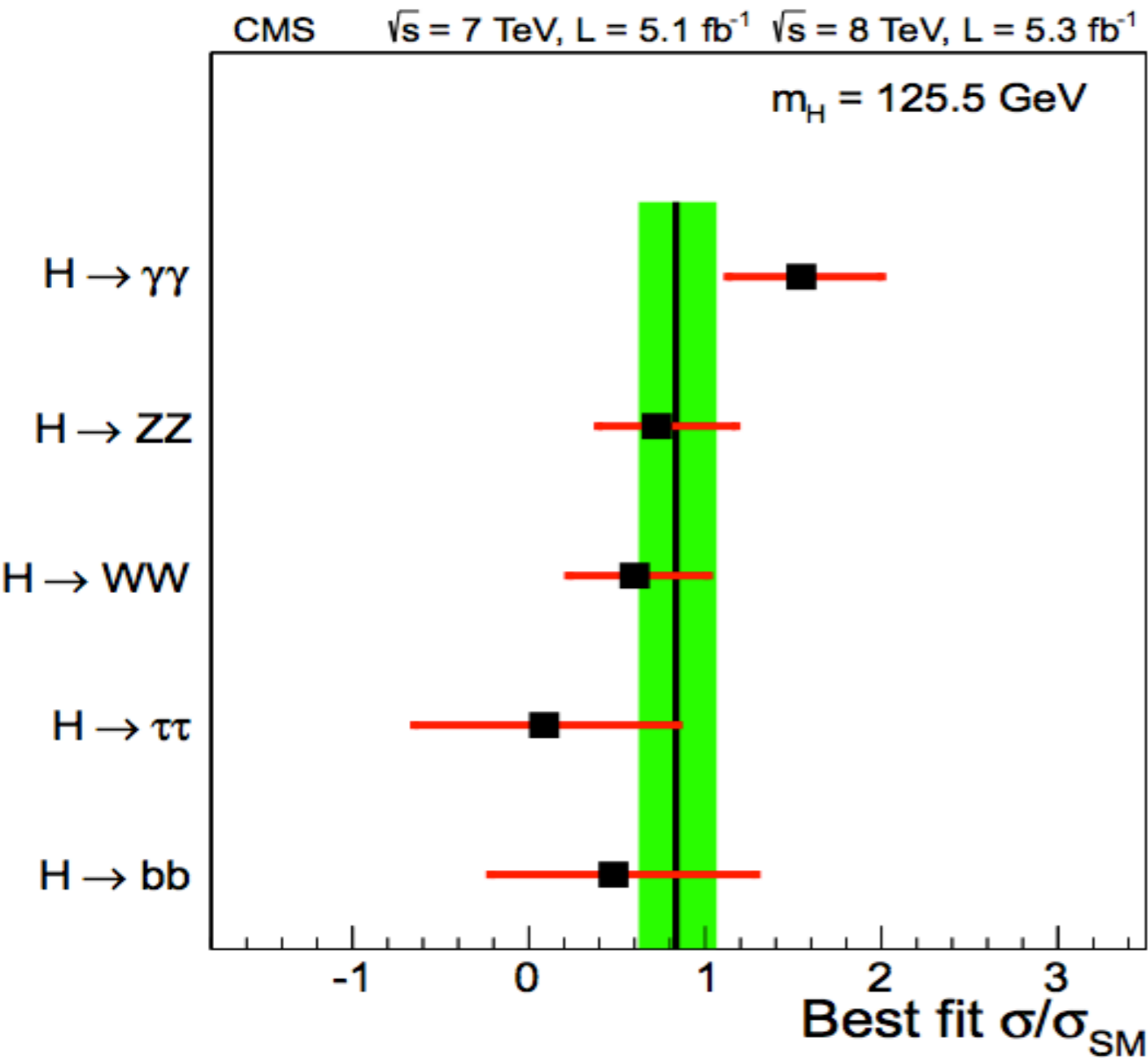




# Search for SM Higgs: CMS signal strength update (Nov. 15)

**ICHEP:  $\sigma/\sigma_{SM} = 0.87 \pm 0.23$**

**HCP:  $\sigma/\sigma_{SM} = 0.88 \pm 0.21$**



# Search for SM Higgs boson: mass resolution



Channel	$m_H$ range [GeV/c <sup>2</sup> ]	data set [fb <sup>-1</sup> ]	Data used CMS [fb <sup>-1</sup> ]	$m_H$ resolution
1) $H \rightarrow \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \rightarrow \text{tau tau}$	110-145	5+12/fb	2011+12	15%
3) $H \rightarrow bb$	110-135	5+12/fb	2011+12	10%
4) $H \rightarrow WW \rightarrow l\nu l\nu$	110-600	5+12/fb	2011+12	20%
5) $H \rightarrow ZZ \rightarrow 4l$	110-1000	5+12/fb	2011+12	1-2%

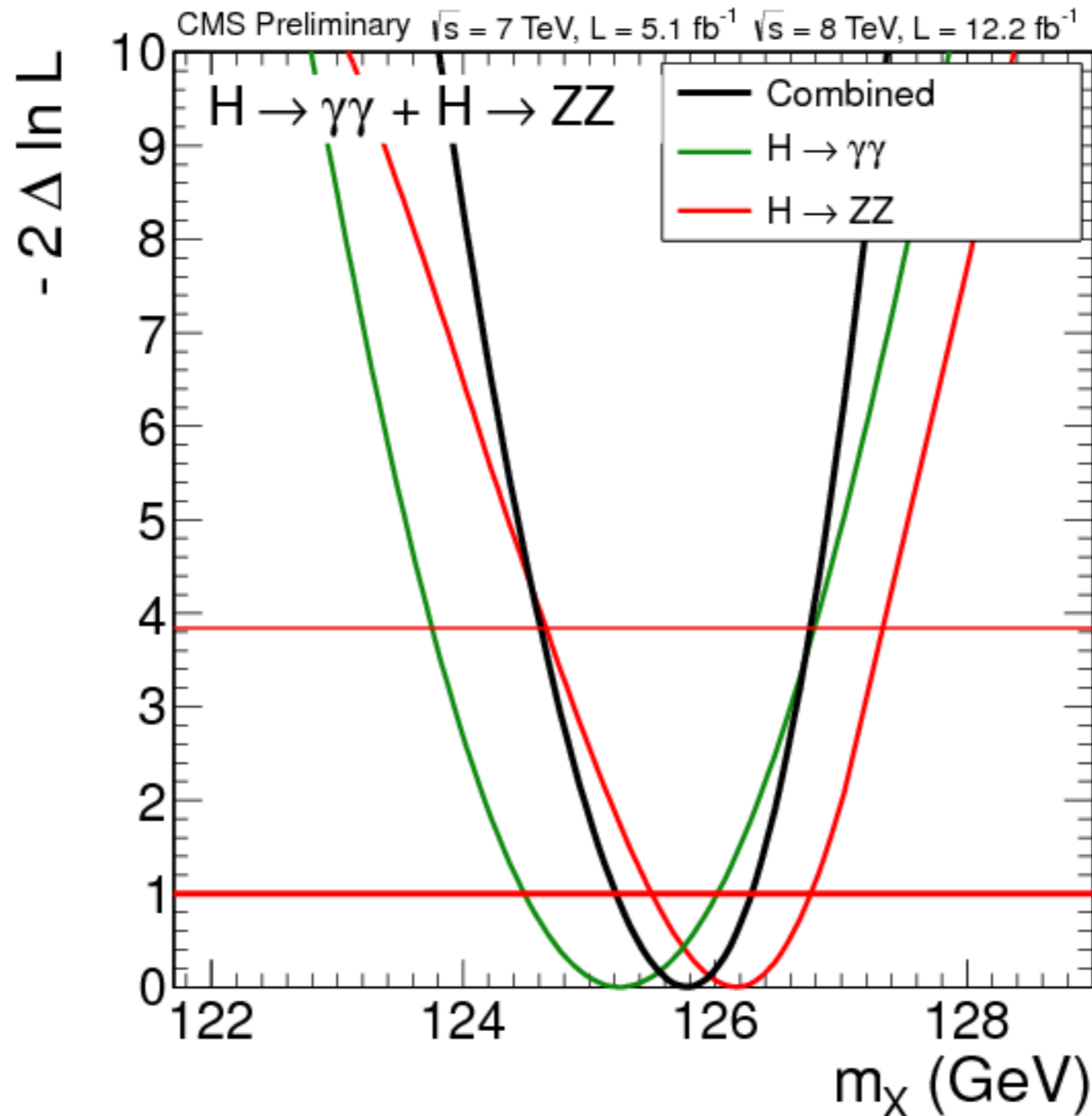
**The CMC detector: a superb lepton and photon detector!**

# Search for SM Higgs boson: mass



The CMC data: updated Nov. 15, 2012

Mass:  $125.8 \pm 0.4$  (stat.)  $\pm 0.4$  (syst.) GeV





# Search for SM Higgs: new state evidence update at CMS!

**Excess update:  $\sim 125.8 \pm 0.4$  (stat.)  $\pm 0.4$  (syst.) GeV !**

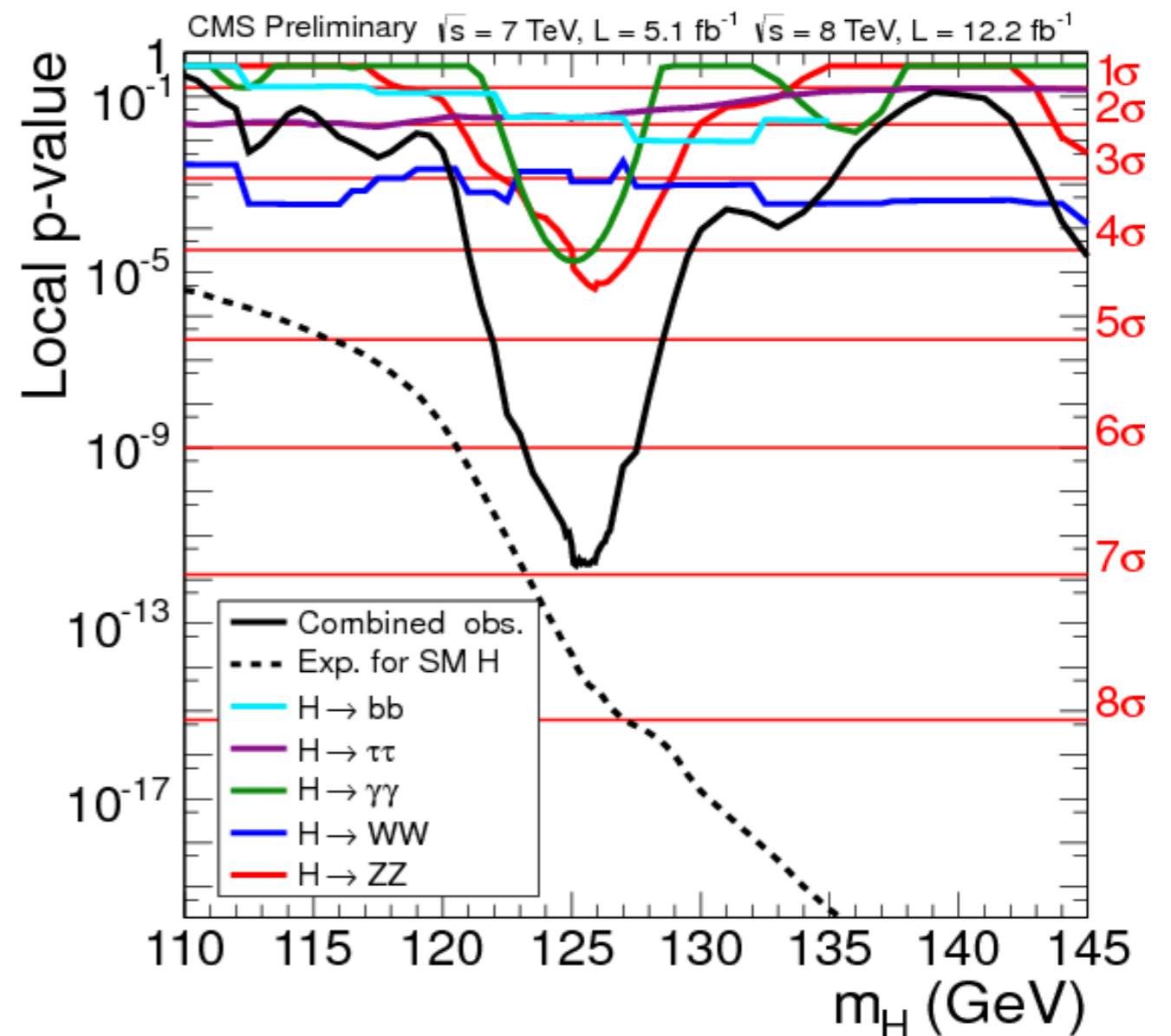
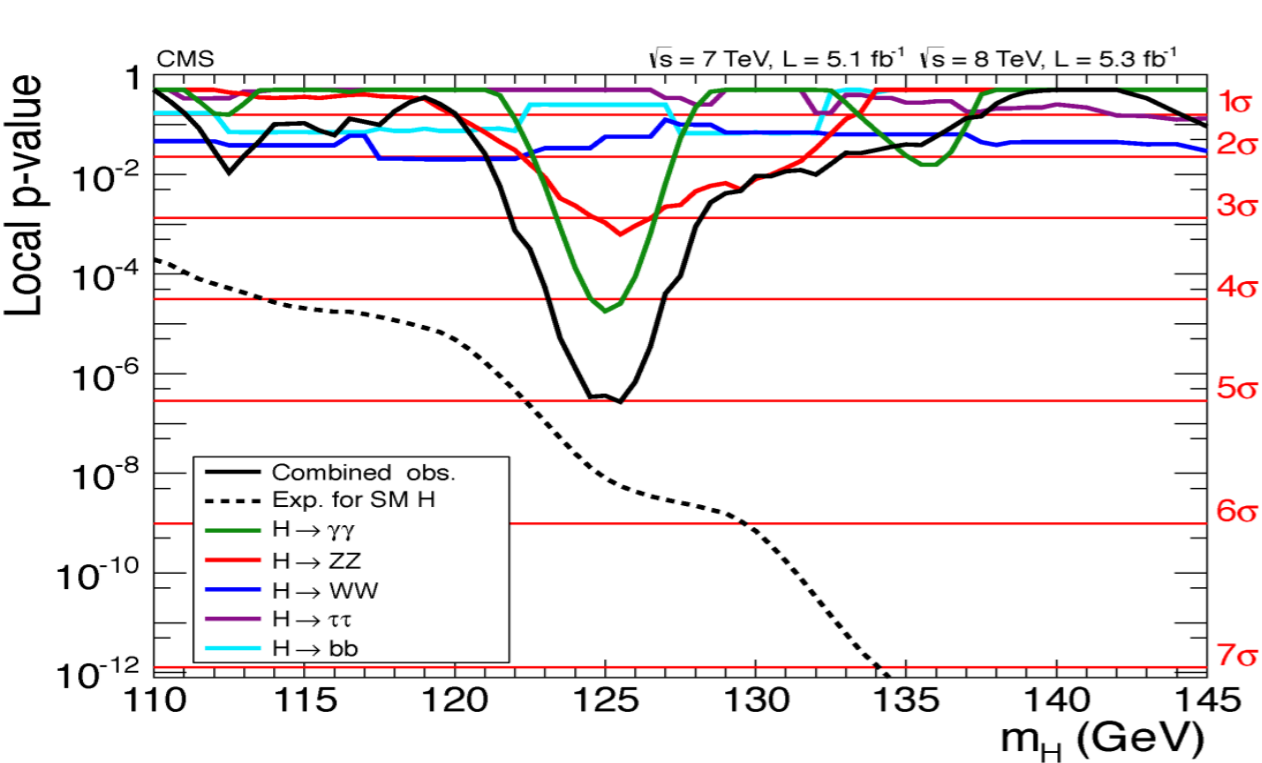
**Excesses in both 7 and 8 TeV data**

**local significance:  $4.9\sigma$**

**expected:  $5.8\sigma$  CERN, July 4**

**local significance:  $6.9\sigma$**

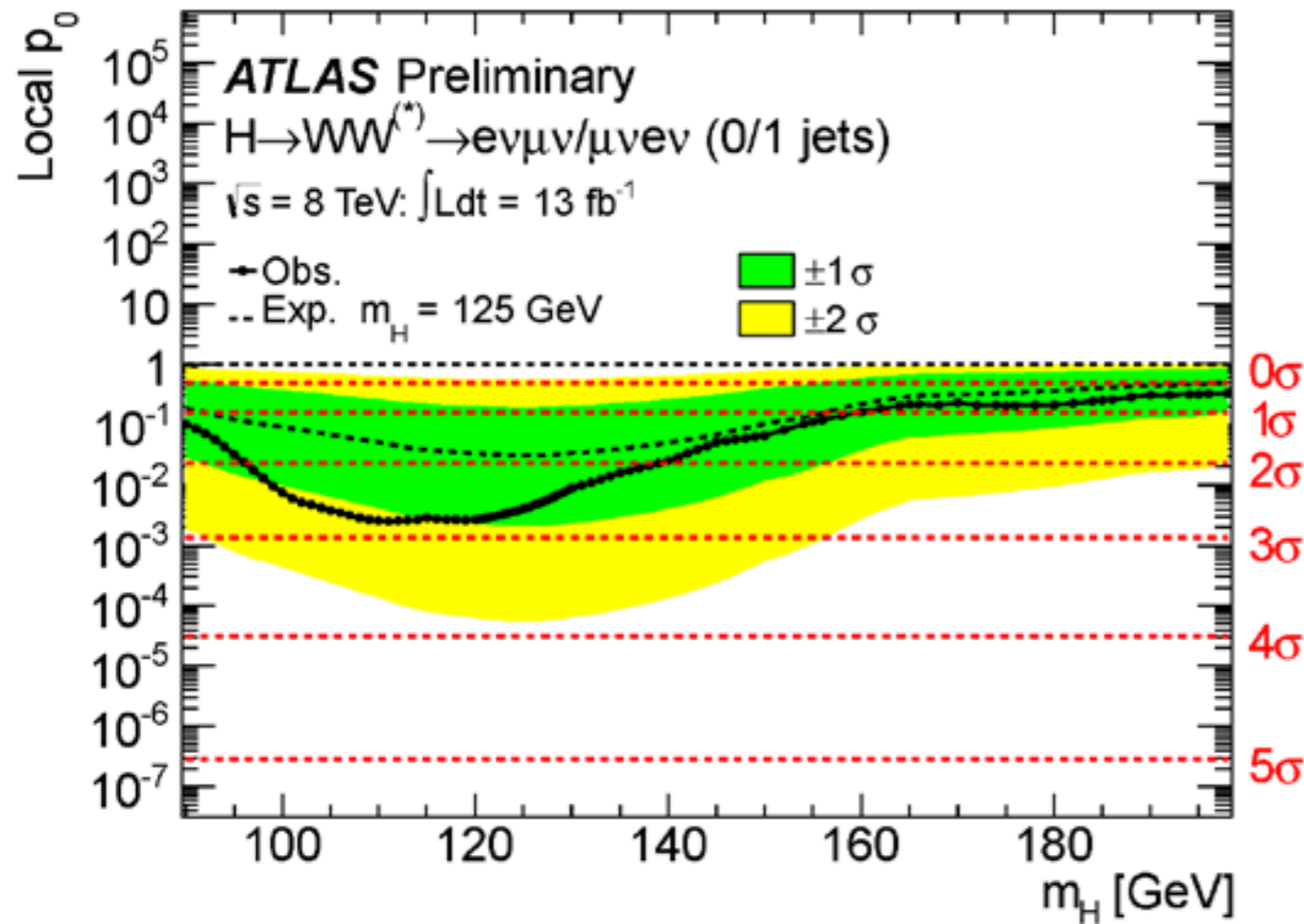
**expected:  $7.8\sigma$  HCP, Nov. 15**





# ATLAS: 3 channels update (Nov. 15)

## WW\*-mode



**WW\***  
**observed: 2.6 $\sigma$**   
**expected: 1.9 $\sigma$**

**HCP:  $\sigma/\sigma_{SM} = 1.5 \pm 0.6$**



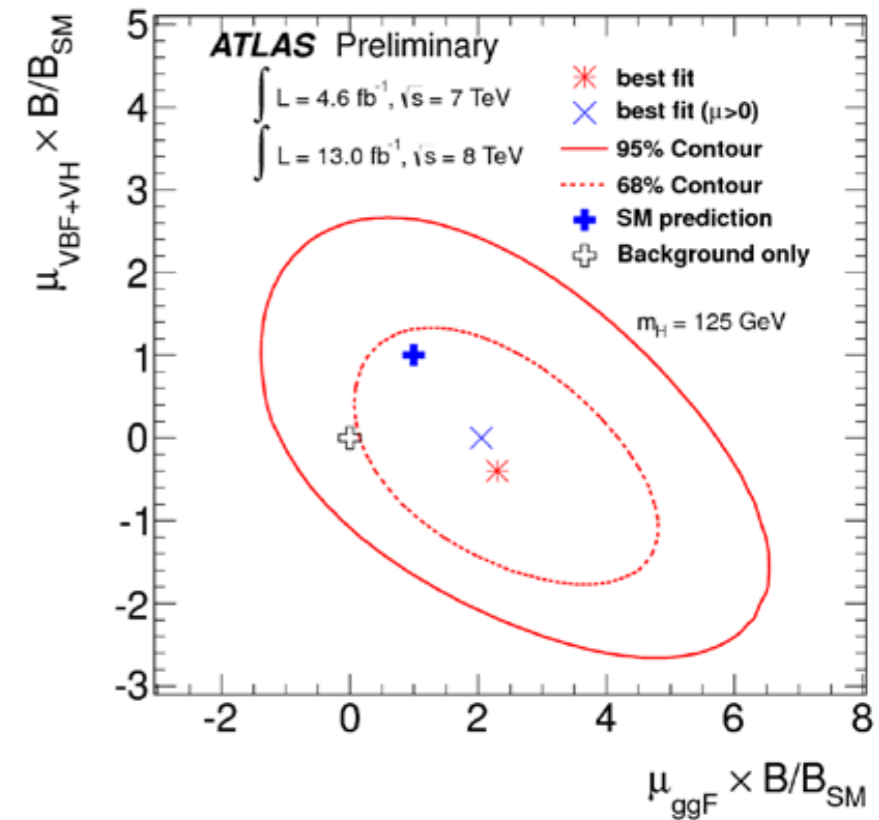
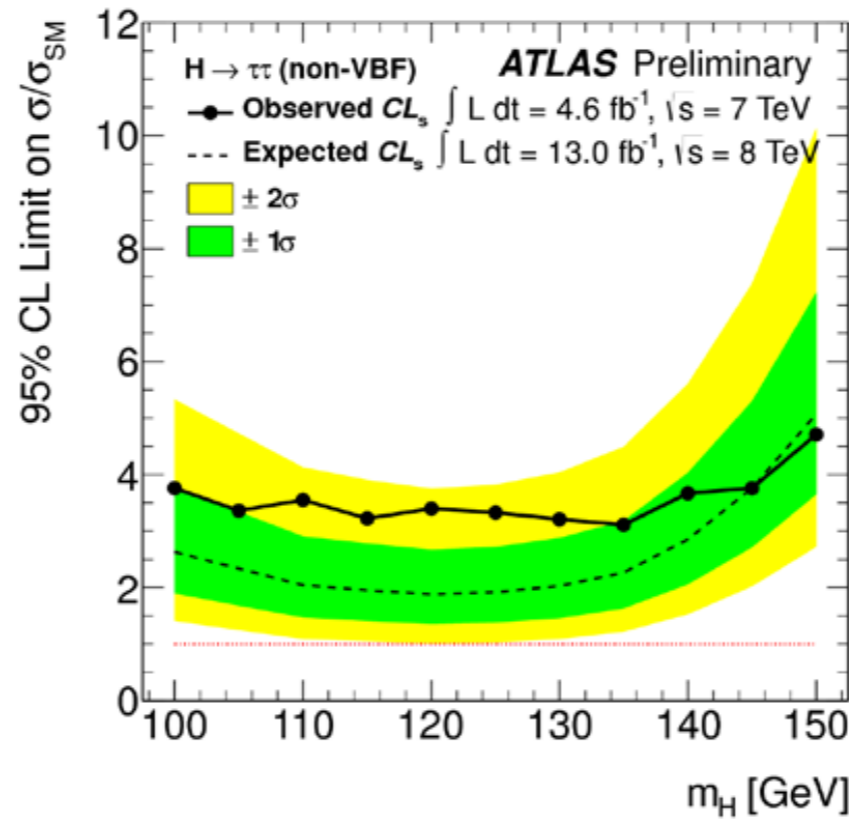
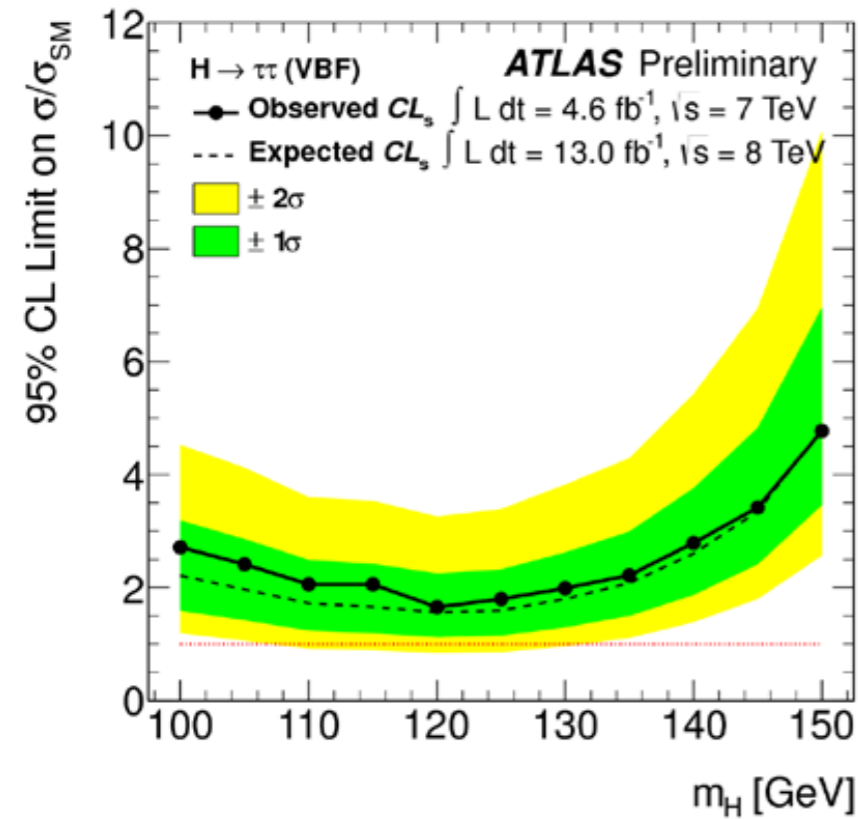
# ATLAS: 3 channels update (Nov. 15)

## $\tau\tau$ -mode



### VBF categories

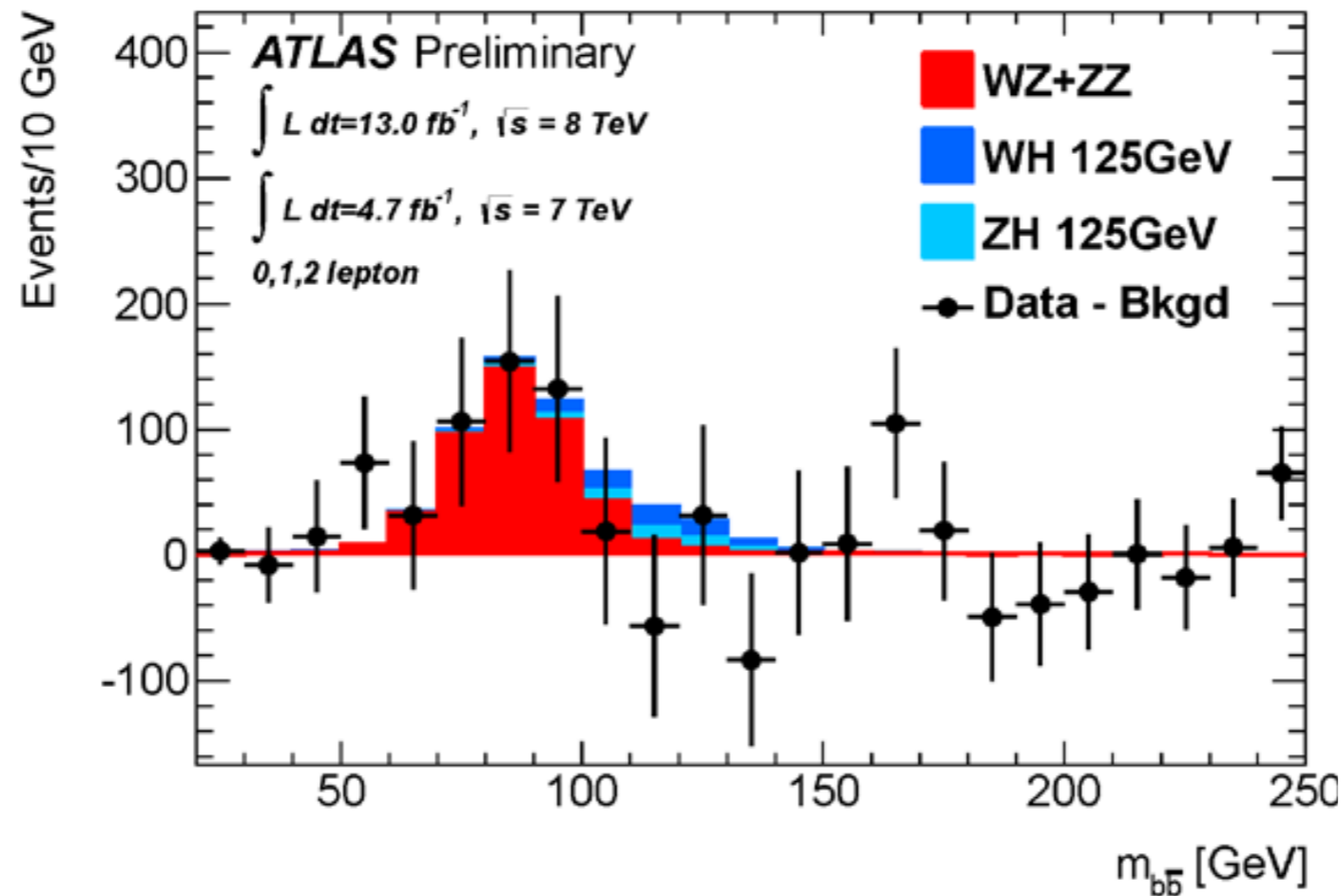
### Non-VBF categories





# ATLAS: 3 channels update (Nov. 15)

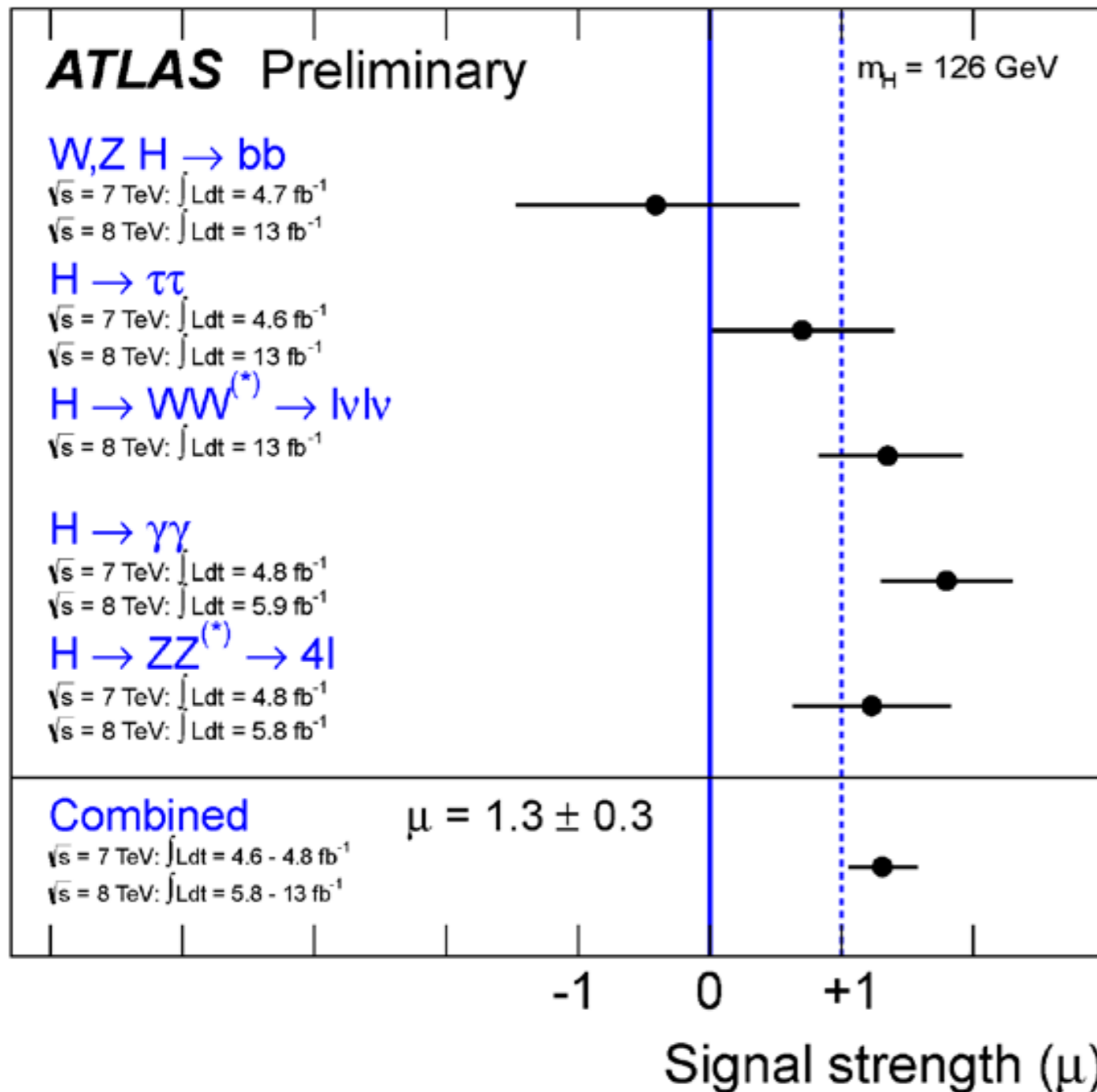
## bb-mode



**bb-mode**  
**observed limit:  $1.9\sigma$**   
**expected limit:  $1.8\sigma$**



# Search for SM Higgs: ATLAS signal strength update (Nov. 15)



**ICHEP:  $\sigma/\sigma_{SM} = 1.4 \pm 0.3$**   
**HCP:  $\sigma/\sigma_{SM} = 1.3 \pm 0.3$**

# Is it SM Higgs boson?

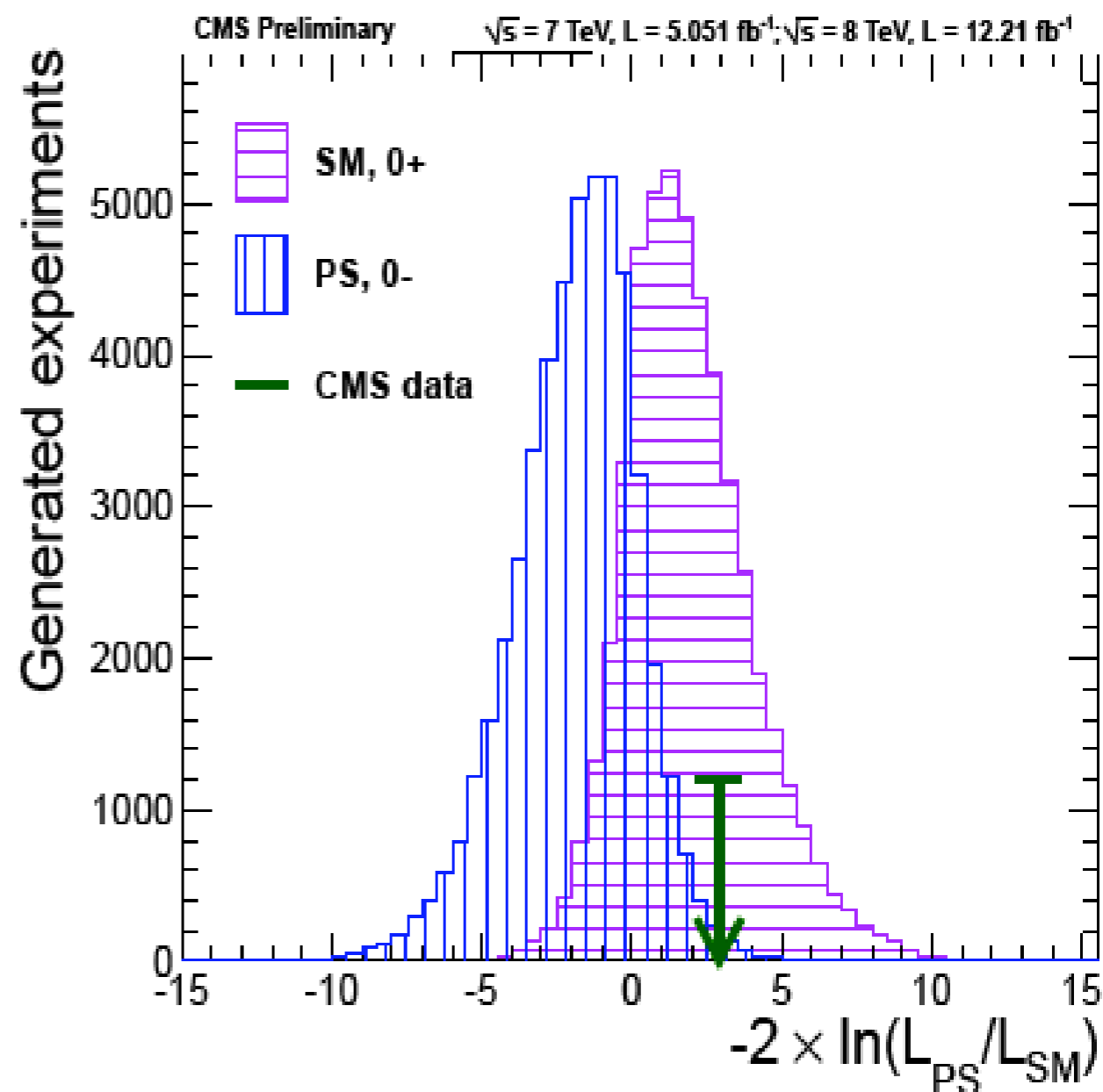


**H->ZZ->4 leptons: golden mode**

**CMS: Expected separation 0+ and 0- with 17 Fb-1:  $\sim 2\sigma$**

**0+: CMS data consistent within  $0.6\sigma$**

**0- : CMS data different by  $2.5\sigma$**



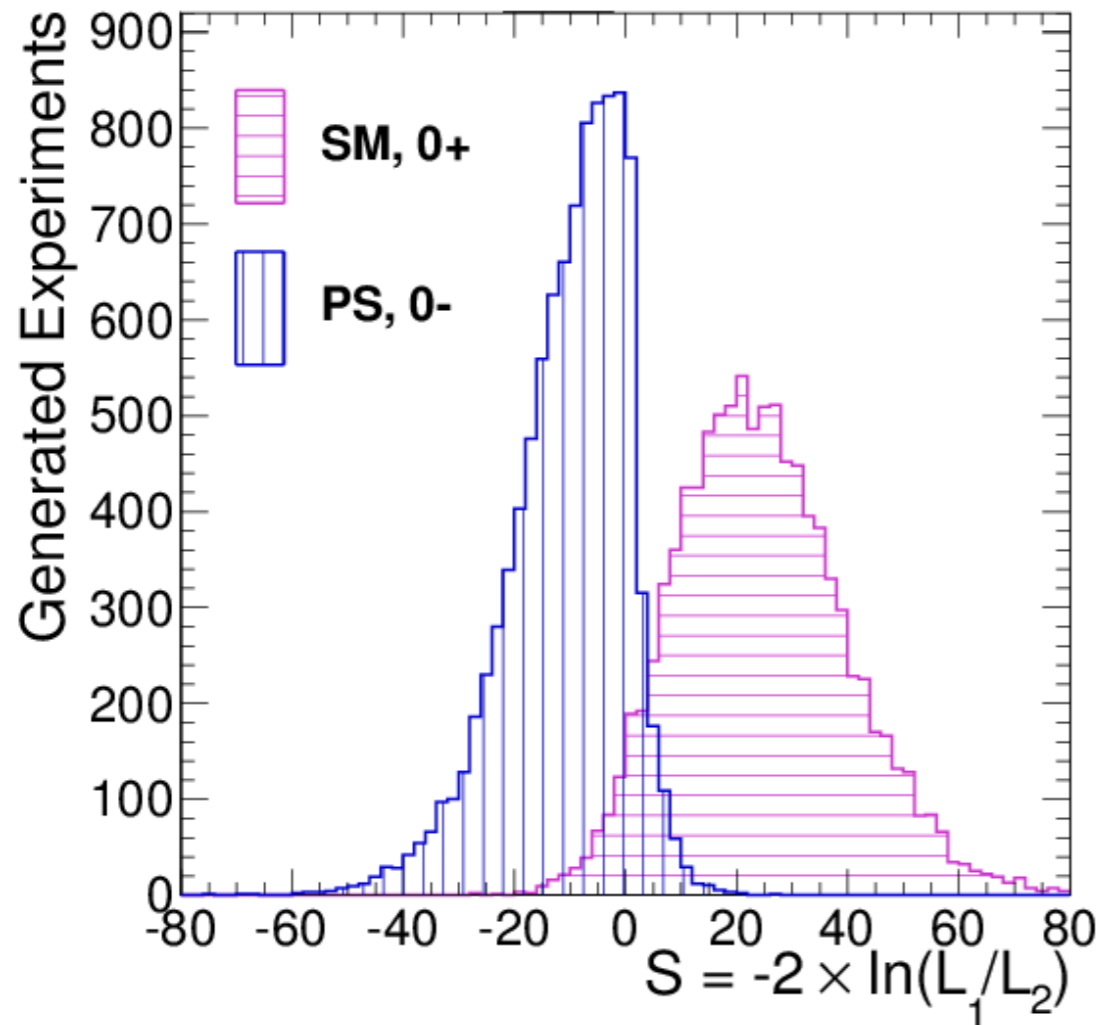


# New particle: SM Higgs boson?

**Expectation:  $\sim 3\sigma$  separation between scalar and pseudoscalar with full 2011-2012 data set**

$$H \rightarrow ZZ \rightarrow 4l$$

CMS Simulation  $L = 30 \text{ fb}^{-1}$ ,  $\sqrt{s} = 8 \text{ TeV}$



**Similarly for  $H \rightarrow WW \rightarrow 2l 2\nu$  for  $3\sigma$  separation between spin 0 and 2**

# SM Higgs boson search at LHC: ATLAS & CMS update, Nov. 15, 2012



## Update for a new particle (Nov. 15, 2012):

- **Excesses at 7 (5 Fb-1) and 8 TeV (5.3 Fb-1 & 12Fb-1)**  
**ATLAS: local significance:  $5.9\sigma$**   
**CMS: local significance:  $6.9\sigma$**
- **Signal strength**  
**ATLAS:  $(1.3 \pm 0.3) \times \sigma_{SMH}$**   
**CMS:  $(0.88 \pm 0.21) \times \sigma_{SMH}$**
- **Mass**  
**ATLAS:  $M = 126.0 \pm 0.4$  (stat.)  $\pm 0.4$  (syst.) GeV**  
**CMS:  $M = 125.8 \pm 0.4$  (stat.)  $\pm 0.4$  (syst.) GeV**
- **CMS: scalar boson  $2.5\sigma$**
- **Compatible within limited precision with SM Higgs boson**

# SM Higgs boson search at LHC: ATLAS update Dec. 13, 2012

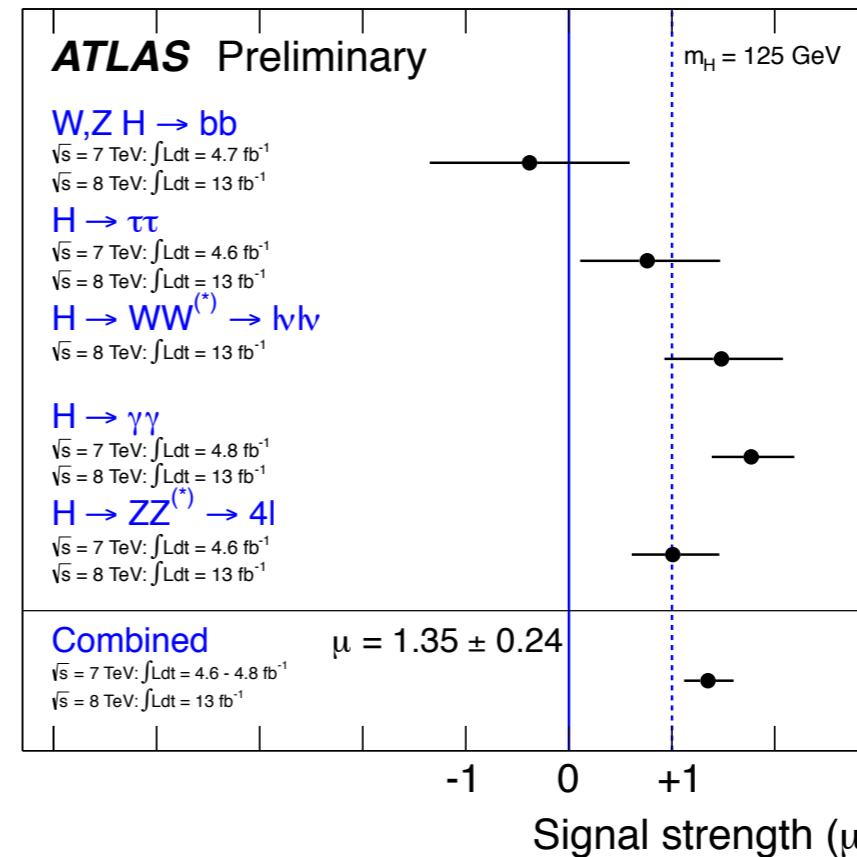
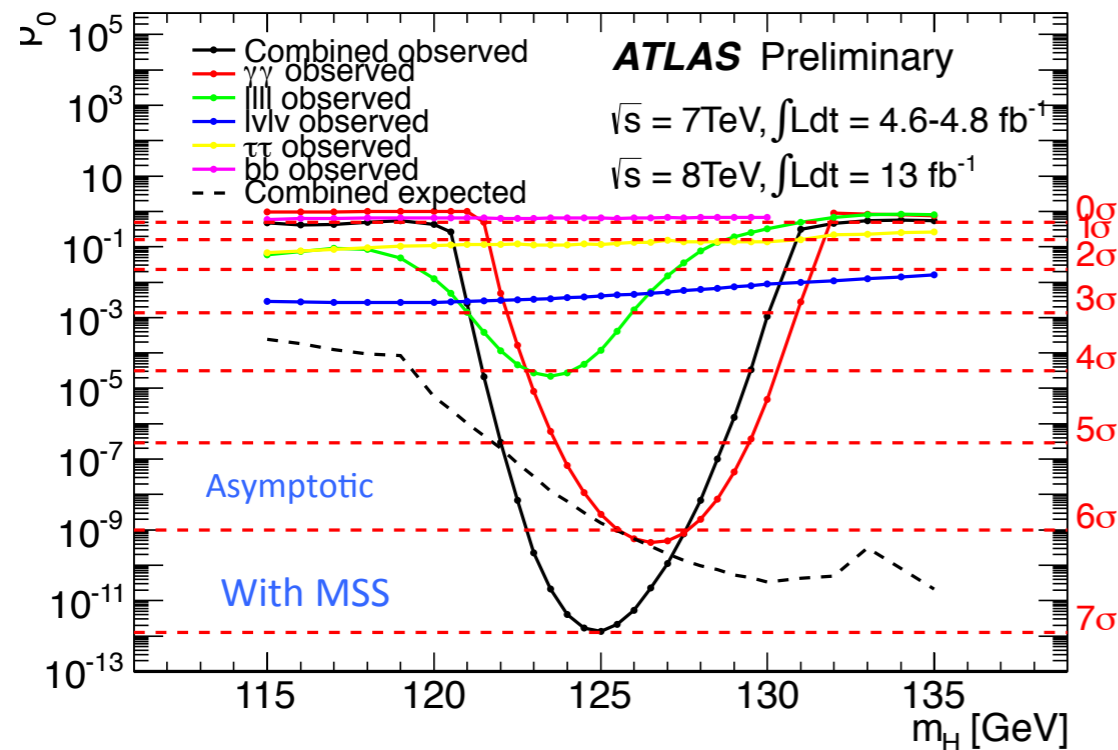


## Combination of All Channels

ATLAS-CONF-2012-170

Updated with 13 fb<sup>-1</sup> of 2012 8 TeV data

Summary of the signal strength in all SM Higgs search channels



$$\hat{\mu} = 1.35 \pm 0.19 \text{ (stat)} \pm 0.15 \text{ (syst)}$$

Overall agreement with the SM Higgs boson hypothesis

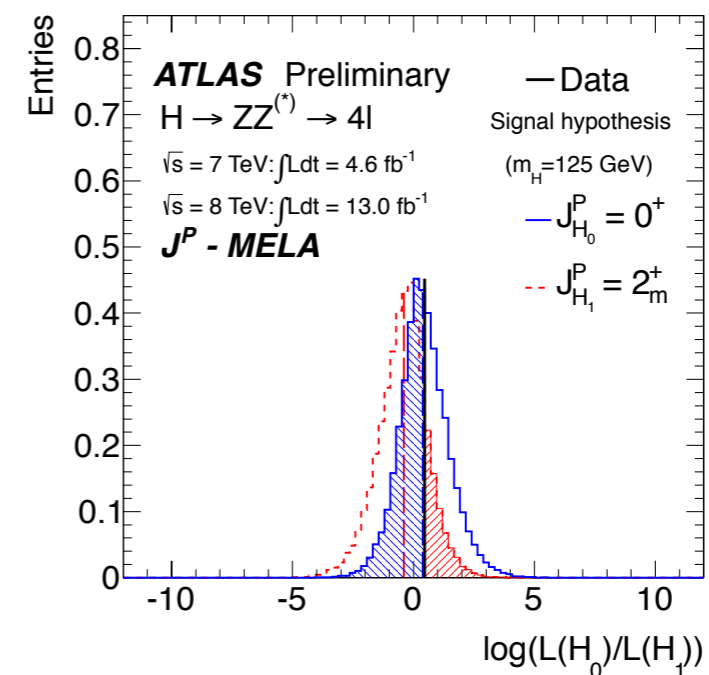
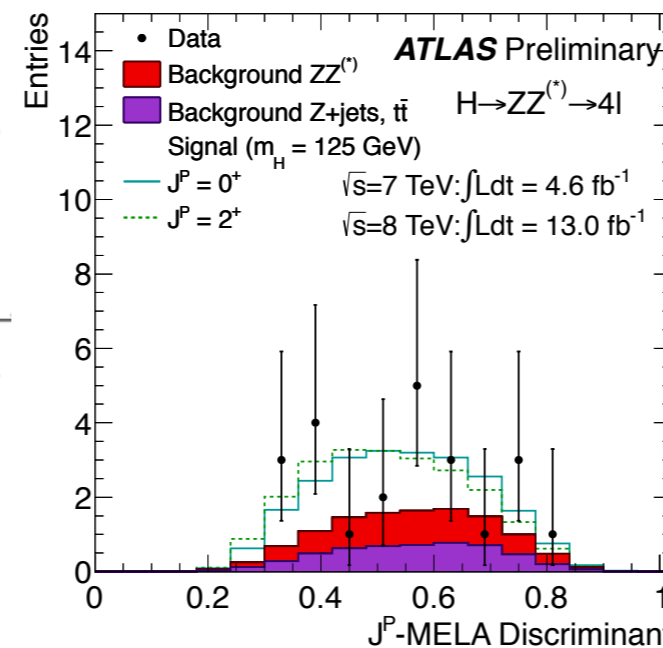
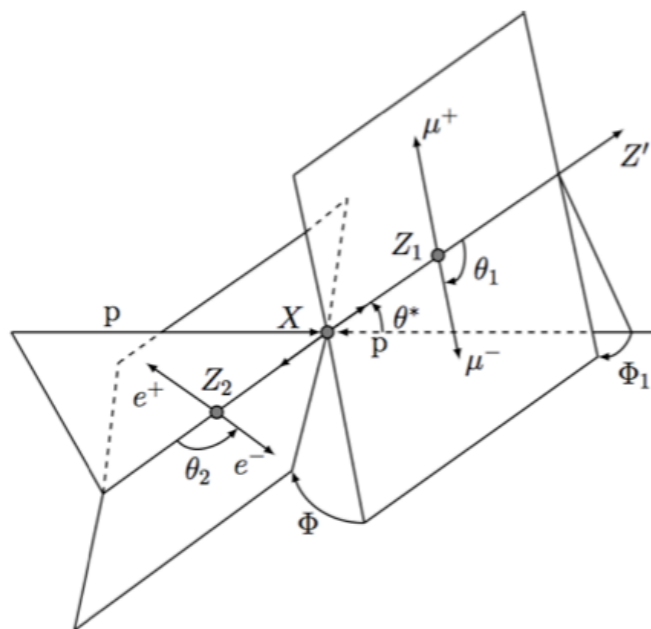
# SM Higgs boson search at LHC: ATLAS update Dec. 13, 2012



## Analysis of Spin in the $H \rightarrow 4l$ Channel

ATLAS-CONF-2012-169

Using the distributions of 5 production and decay angles combined in BDT or Matrix Element (MELA) discriminants



- $0^+$  vs  $2^+$ : (Low) Expected Exclusion of  $2^+$  at the 80% CL
- Observed exclusion of spin  $2^+$  at the 85% CL

Observation fully compatible with spin 0 (within  $0.18 \sigma$ )

35



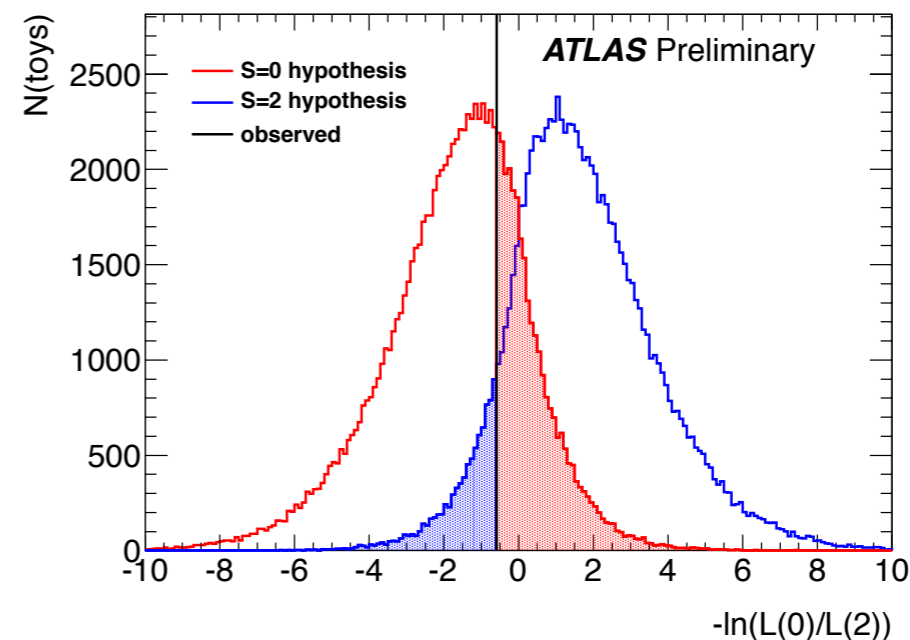
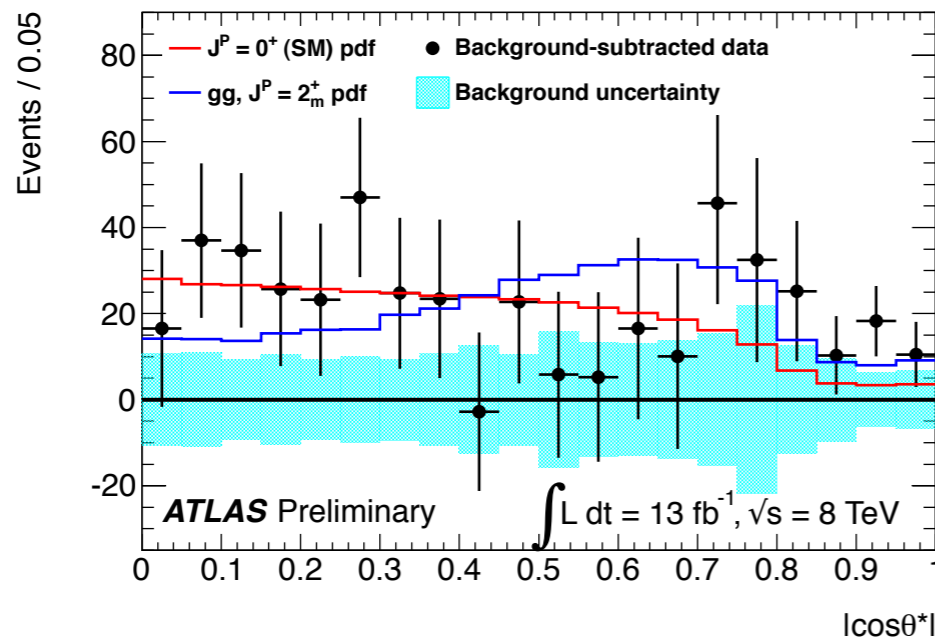
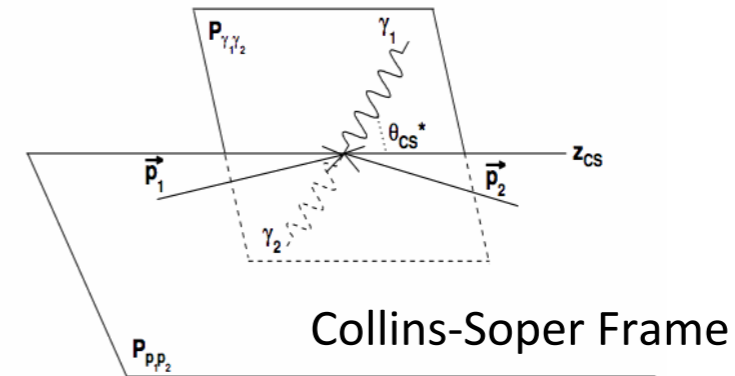
# SM Higgs boson search at LHC: ATLAS update Dec. 13, 2012



## First Analysis of Spin in the $H \rightarrow \gamma\gamma$ Channel

Using the inclusive analysis

- Sensitive variable is dihoton  $\cos \theta^*$  distribution
- Use events within  $1.5\sigma$  of the peak ( $m_H=126.5$  GeV)



- Expected sensitivity: exclusion of the spin  $2^+$  hypothesis at the 97% CL
- Observed exclusion of spin  $2^+$  hypothesis at the 91% CL

Observation compatible with spin 0 (within  $0.5\sigma$ )

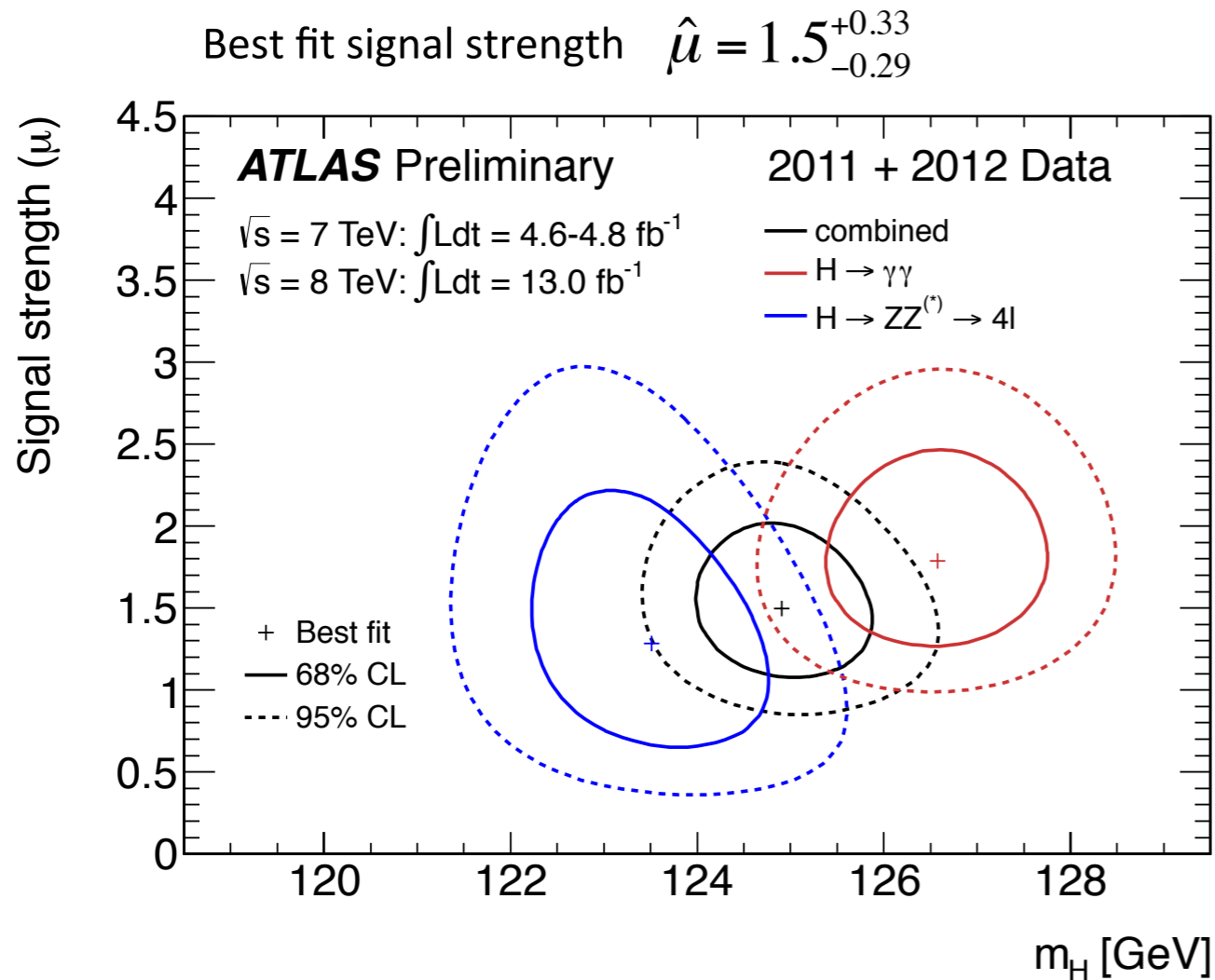
ATLAS-CONF-2012-168

# SM Higgs boson search at LHC: ATLAS update Dec. 13, 2012



ATLAS-CONF-2012-170

## $H \rightarrow \gamma\gamma$ and $H \rightarrow 4l$ Combination



Combined Mass Measurement :

$$m_H = 125.2 \pm 0.3 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ GeV}$$



# Search for SM Higgs boson: Summary

- \* **CERN, July 4 & ICHEP: a new particle!**
  - **5.9 $\sigma$  (ATLAS): particle  $126.0 \pm 0.4$  (stat.)  $\pm 0.4$  (syst.) GeV**
  - **4.9 $\sigma$  (CMS): boson  $125.3 \pm 0.4$  (stat.)  $\pm 0.5$  (syst.) GeV**
  
- \* **HCP, November 15 and December 13, 2012**
  - CMS: the new particle at 6.9 $\sigma$ :**  
**scalar boson  $125.8 \pm 0.4$  (stat.)  $\pm 0.4$  (syst.) GeV**
  
- \* **ATLAS Dec. 13, 2012**  
**scalar boson  $125.2 \pm 0.4$  (stat.)  $\pm 0.6$  (syst.) GeV**
  
- \* **within limited precision: compatible with SM Higgs boson**
  
- \* **Is the new particle the SM Higgs boson?**
  - **more data needed: spin-parity properties and couplings**
  
- \* **Upcoming major updates:**
  - **March 2013, Moriond**
  - **May 2013 LHCp (full 2011+2012 dataset)**



# **Search for SM Higgs boson: Discussion**



# **SM problems: Naturalness, fine tuning, hierarchy**

## **\* Non-naturalness of scalar fields**

**Fermions: Chiral symmetry  $m^2 = m_0^2 + C \text{Log}[\Lambda^2]$**

**K. Wilson (1970)**

**Susskind (1979), 't Hooft (1979)**

**Scalar: mass divergence:  $m^2 \sim m_0^2 + \Lambda^2$**

**Higgs mass  $\sim \Lambda^2$**

**in SM strong EW interaction at 2-4 TeV**

**Naturalness in SM extends up to 6-10 TeV**

**G. Pivovarov & V. Kim (2009)**