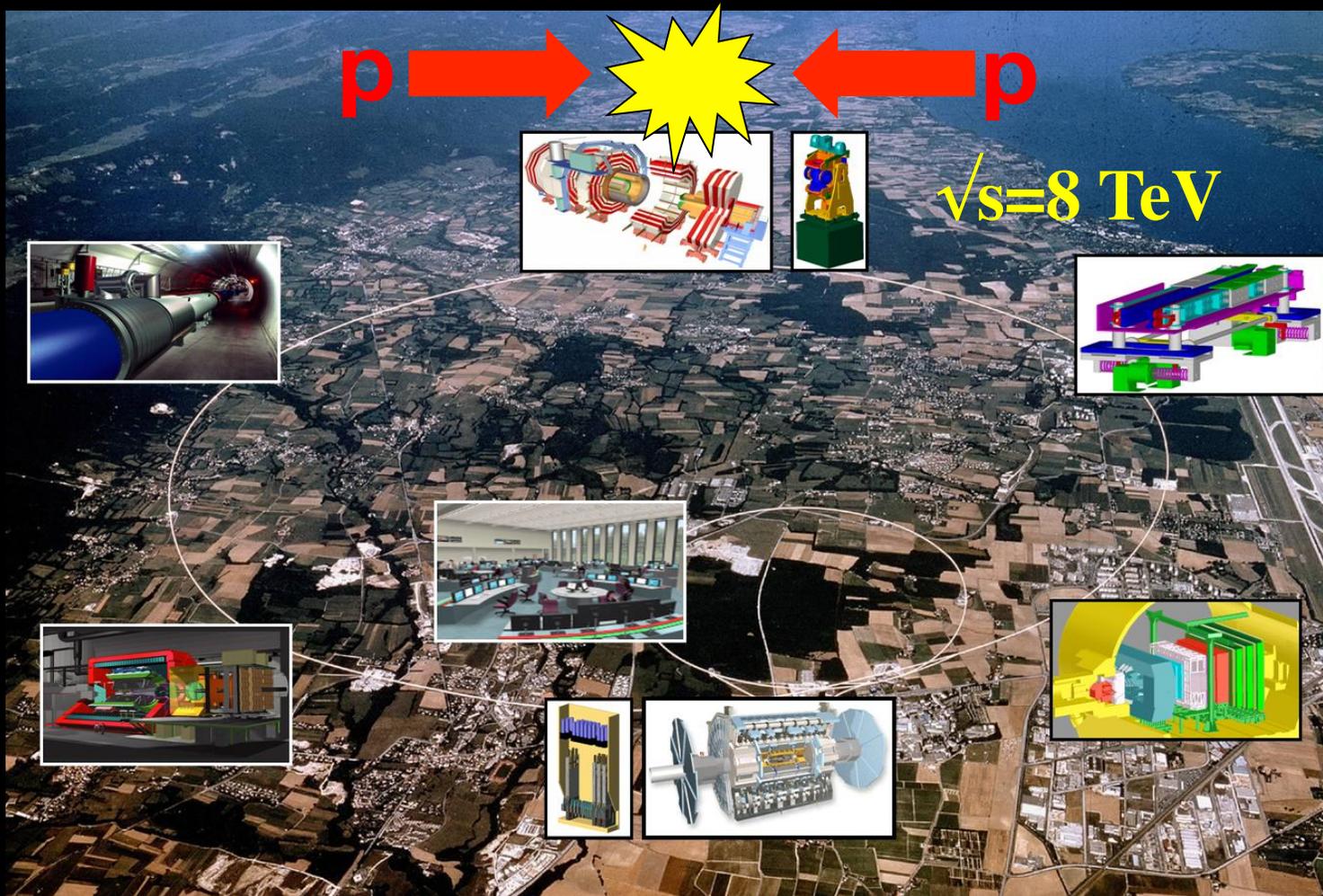


The Standard Model at the LHC

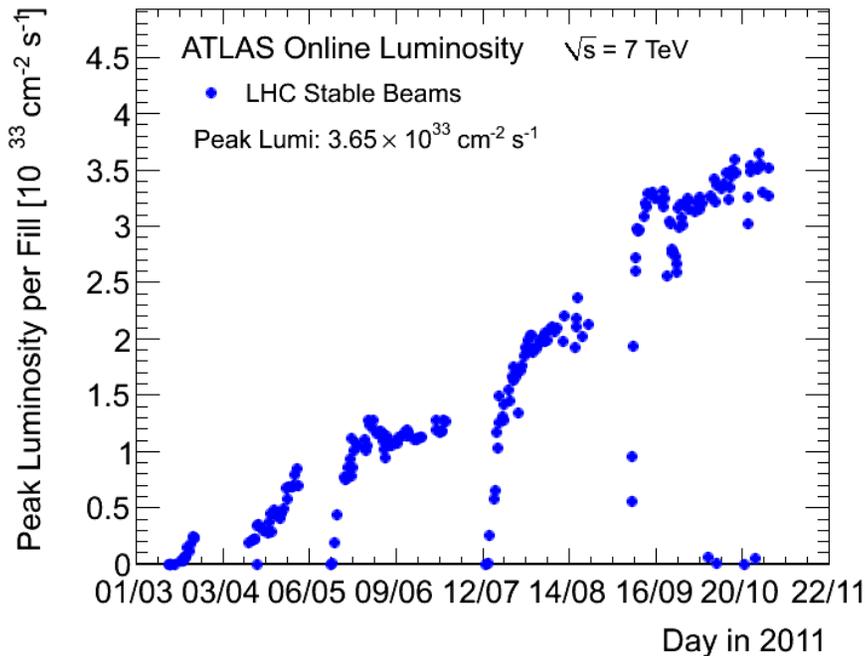
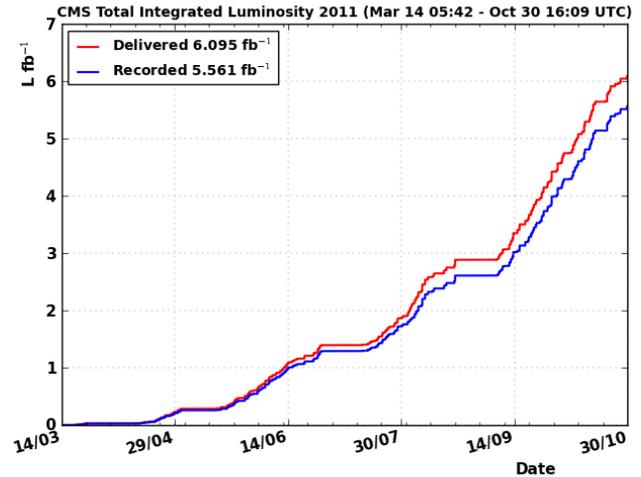


Beate Heinemann

University of California at Berkeley and Lawrence Berkeley National Laboratory

SavasFest, Stanford, May 2012

LHC and Luminosity



year	\sqrt{s} [TeV]	L [fb ⁻¹]
2009	0.9-2.36	10 ⁻¹¹
2010	7	0.05
2011	7	6
2012	8	15?

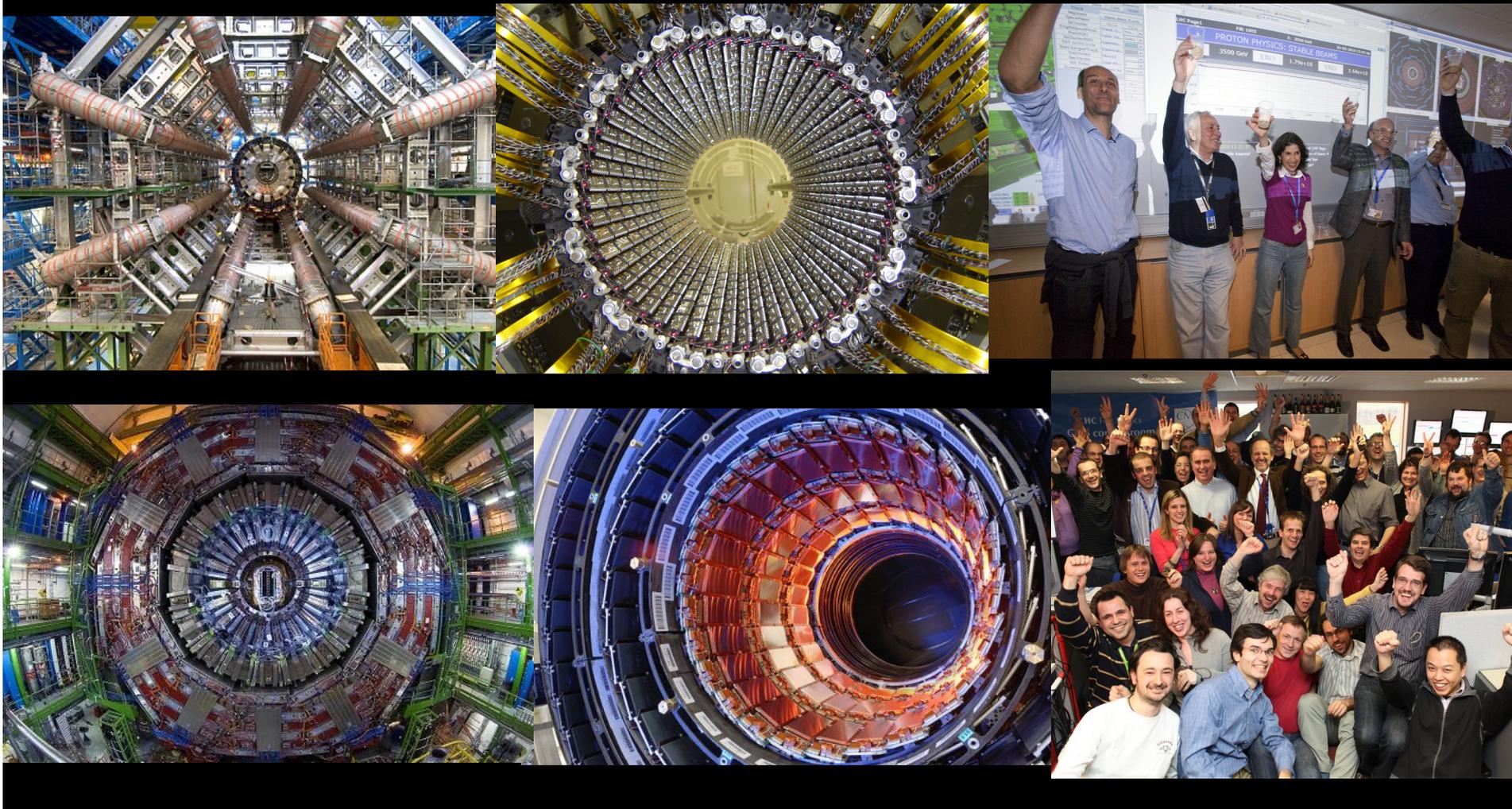
2011 peak luminosity $3.65 \text{ nb}^{-1}/\text{s}$: $\sim 37 \text{ W} \rightarrow \text{lv events/s}$

ATLAS and CMS Detectors

2005

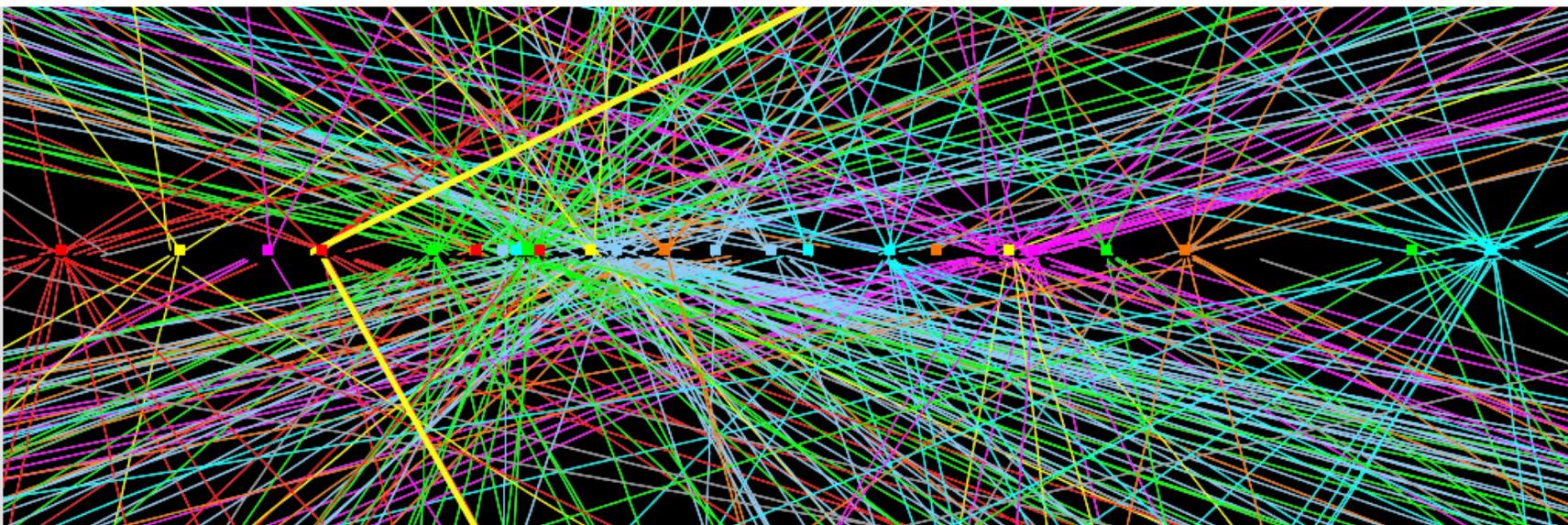
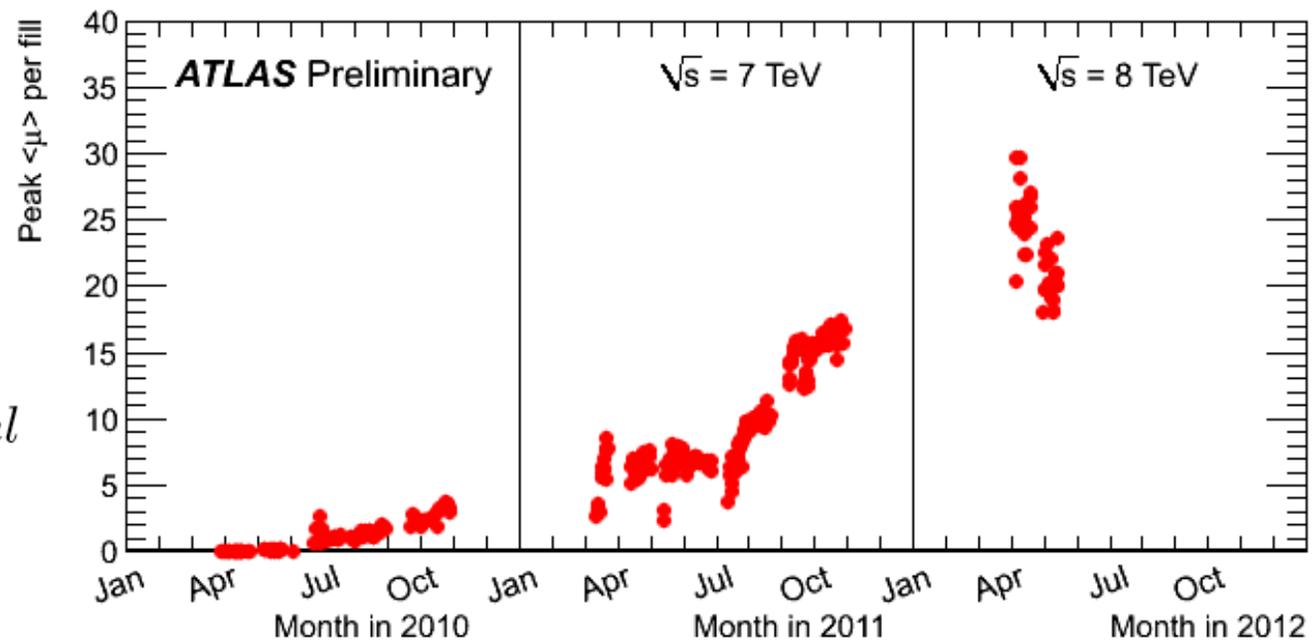
2007

2009



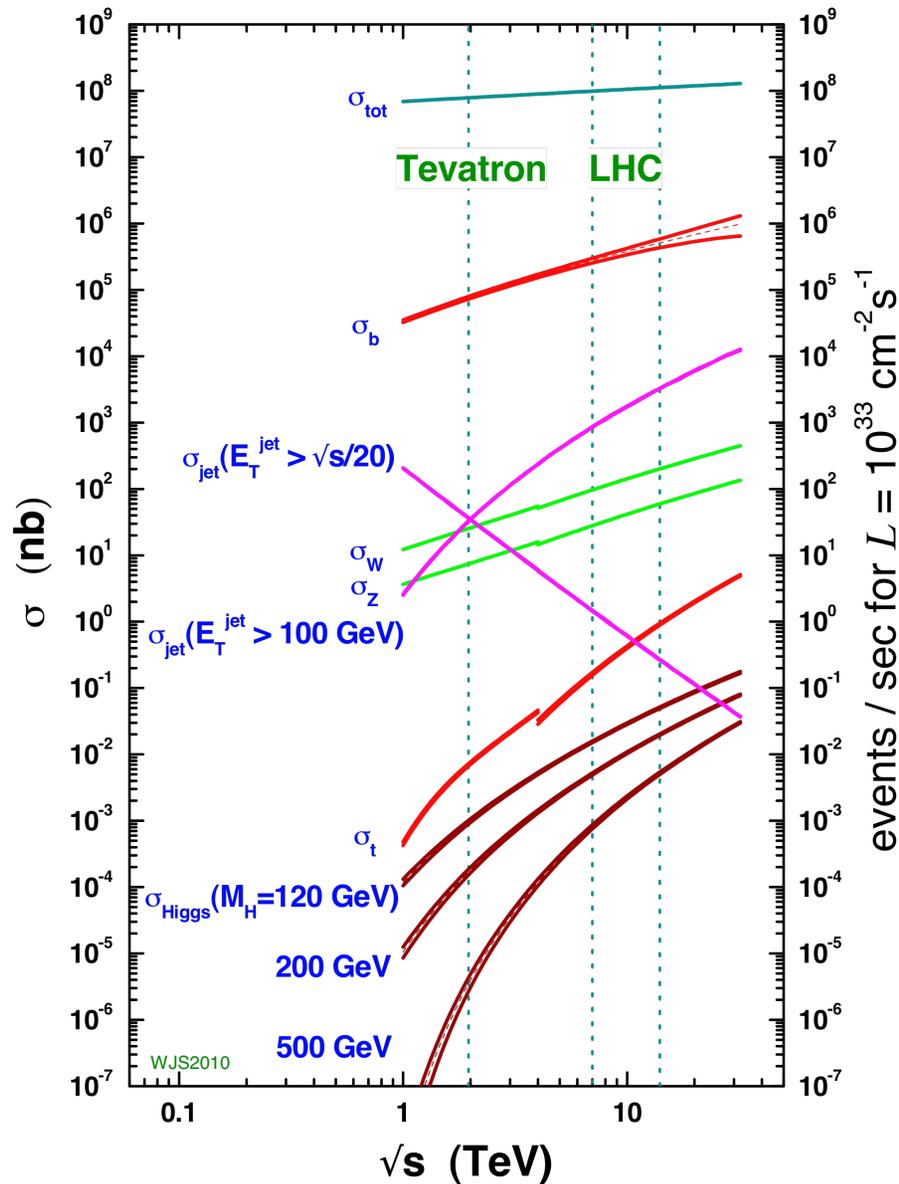
The Price for high Luminosity: Pileup

$$\mu = \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y} \sigma_{inel}$$



Outline

proton - (anti)proton cross sections



Inelastic interactions

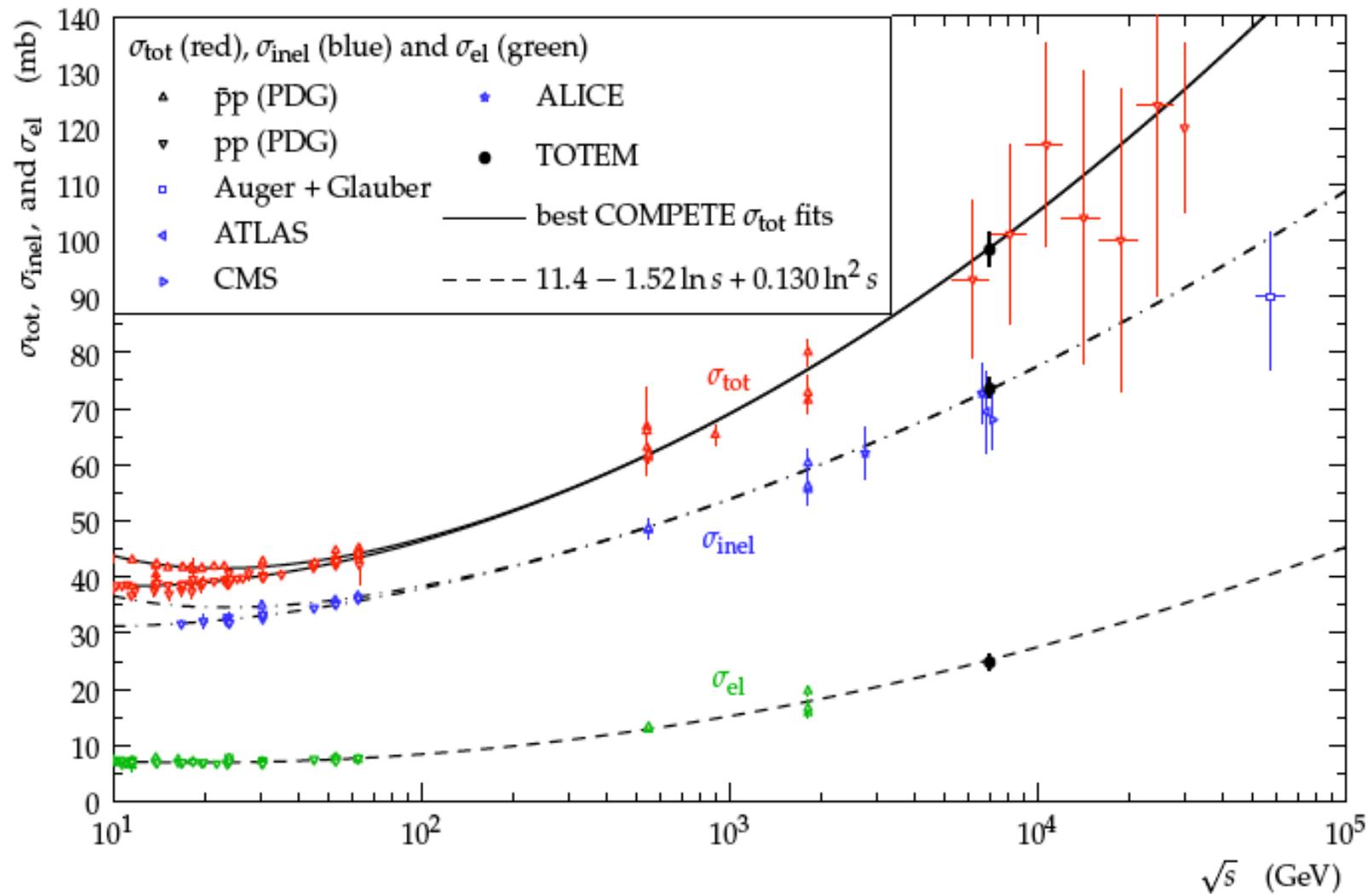
Jets

W and Z bosons

Top quark

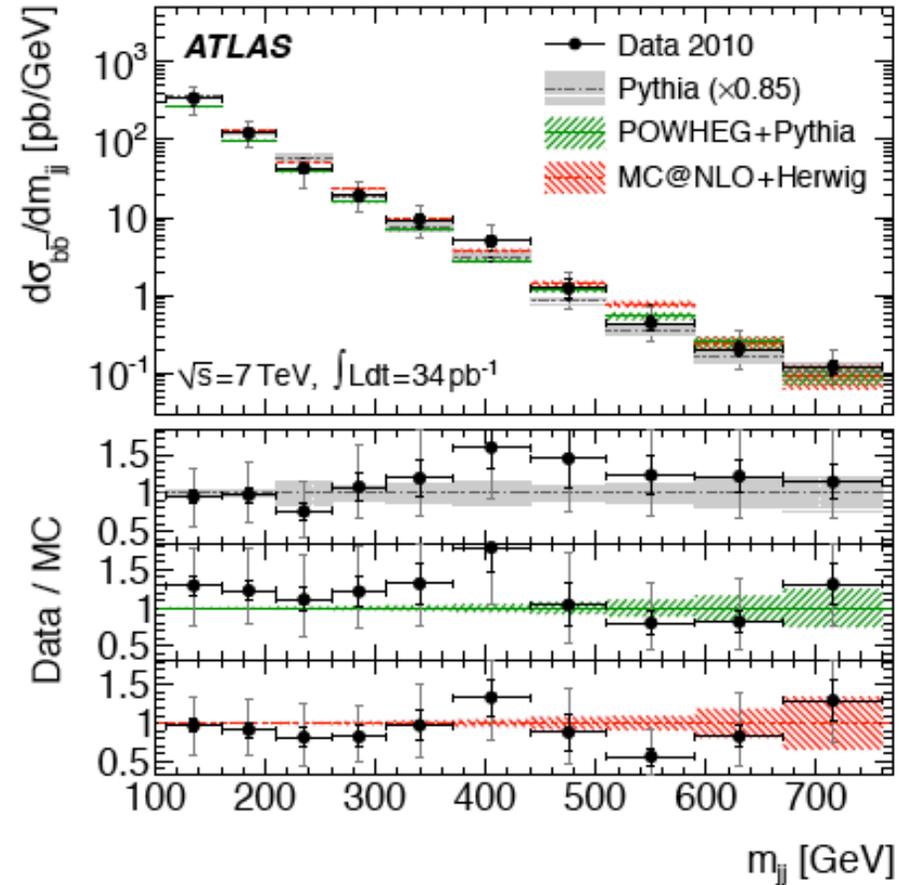
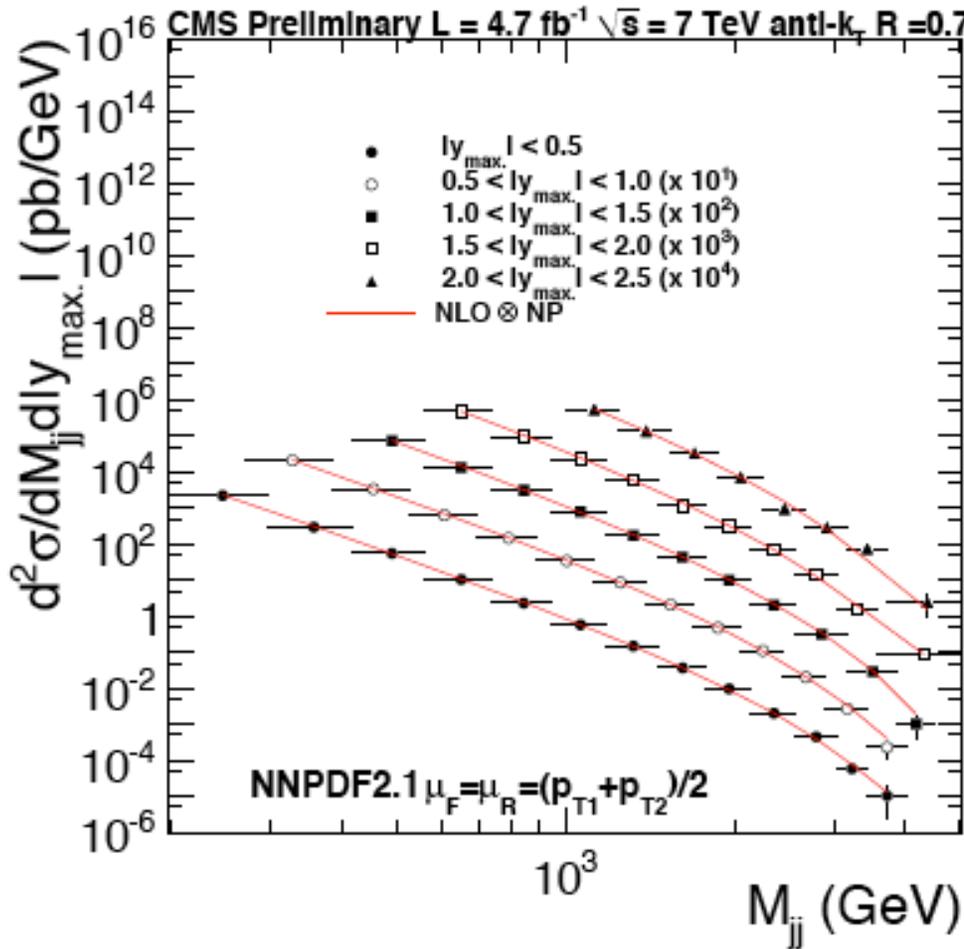
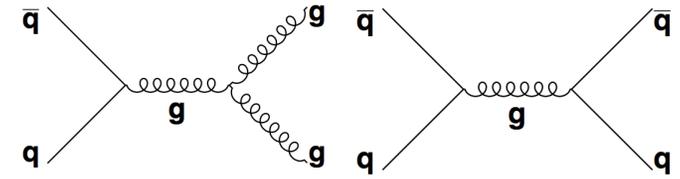
Higgs Boson

proton-proton cross section



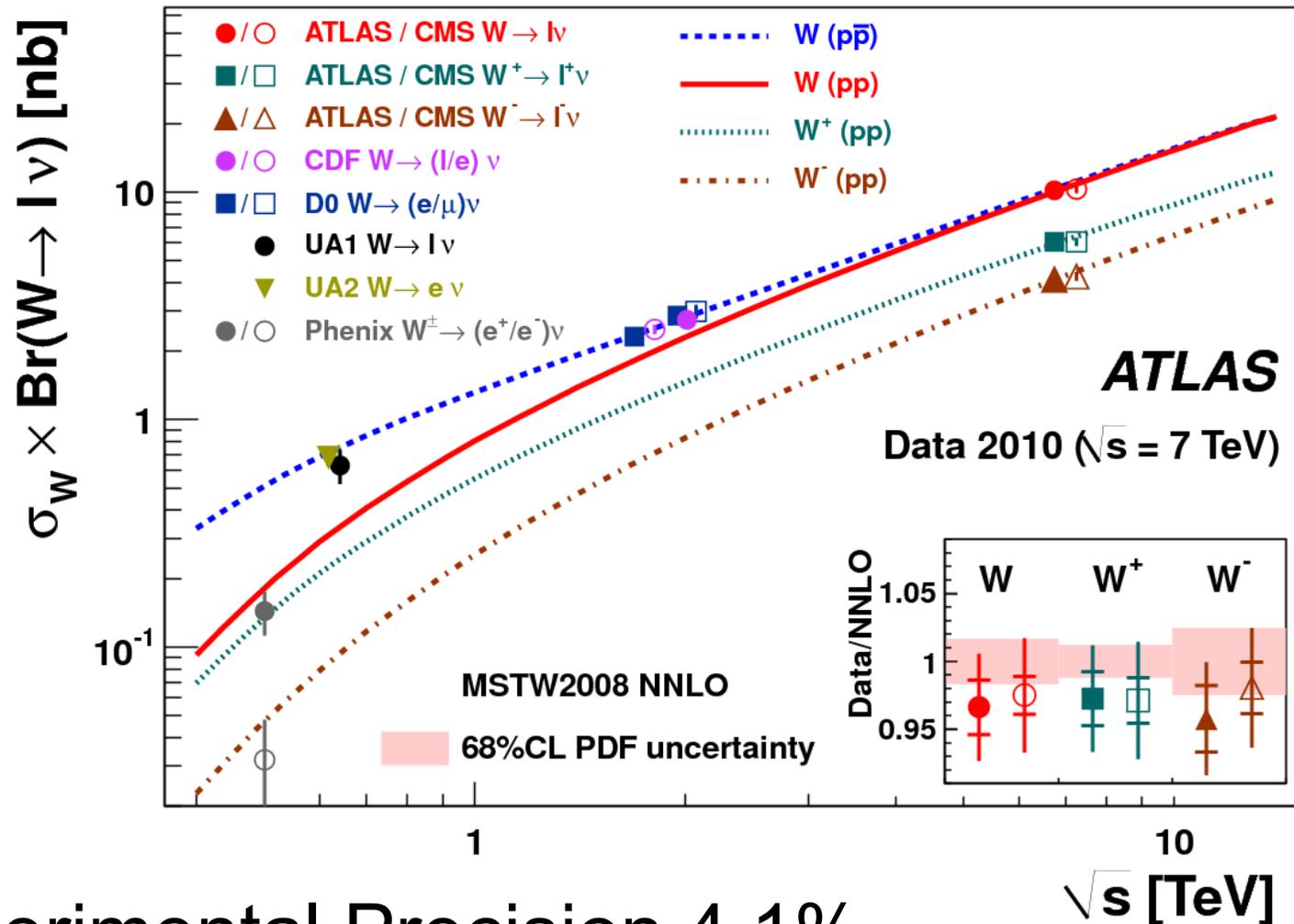
- Growth with energy as anticipated

Jet Cross Sections



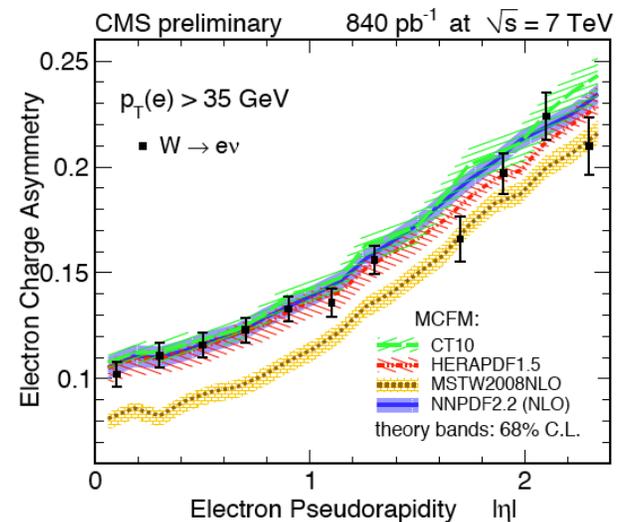
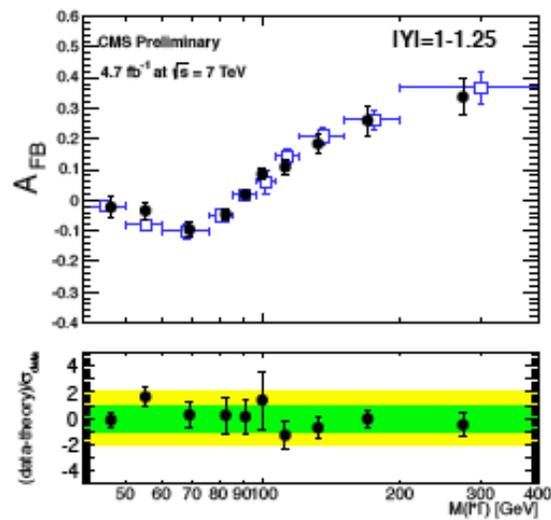
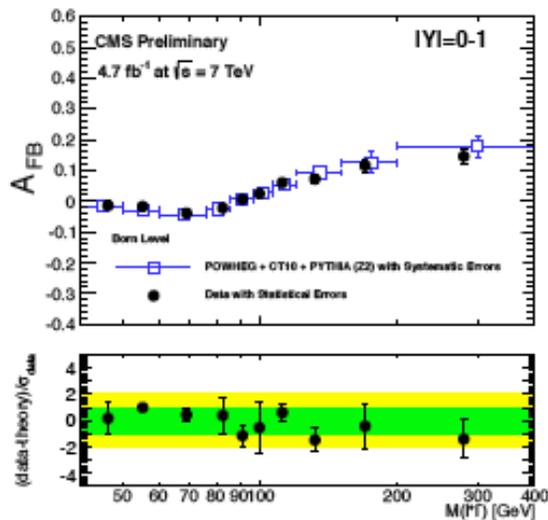
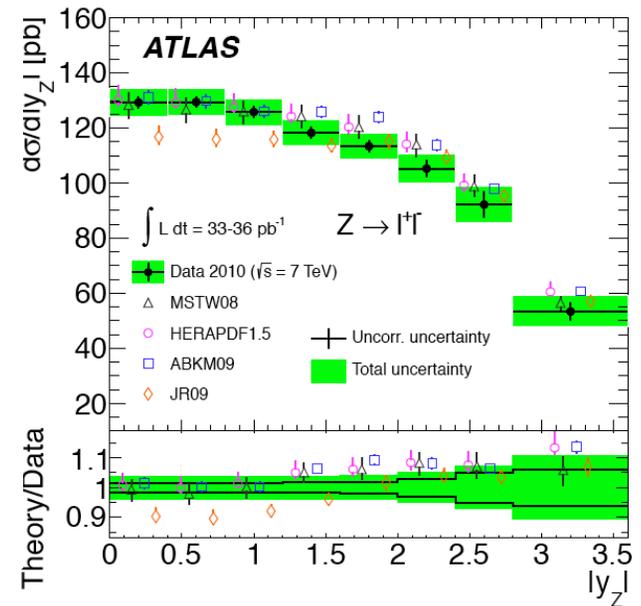
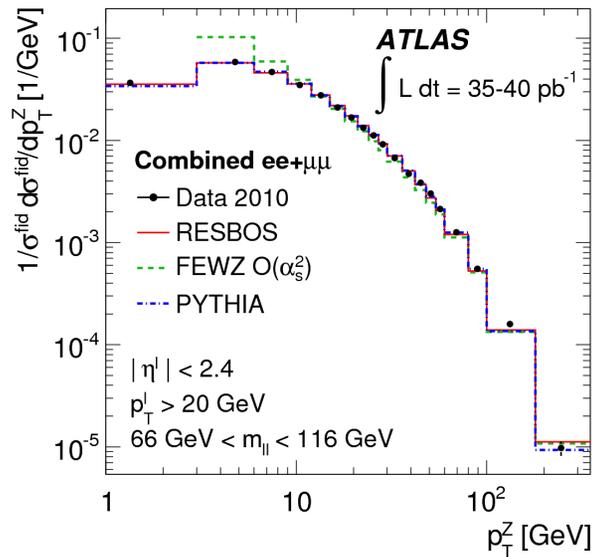
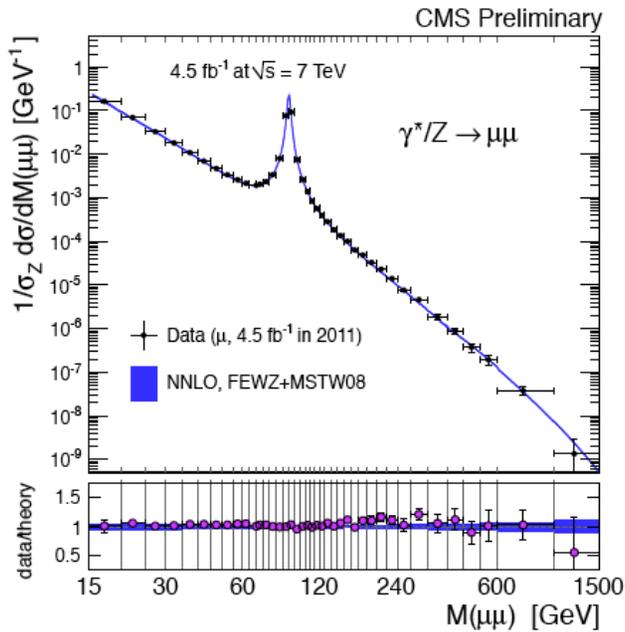
- Data well described by SM prediction both for light and heavy flavor jets

W and Z boson production

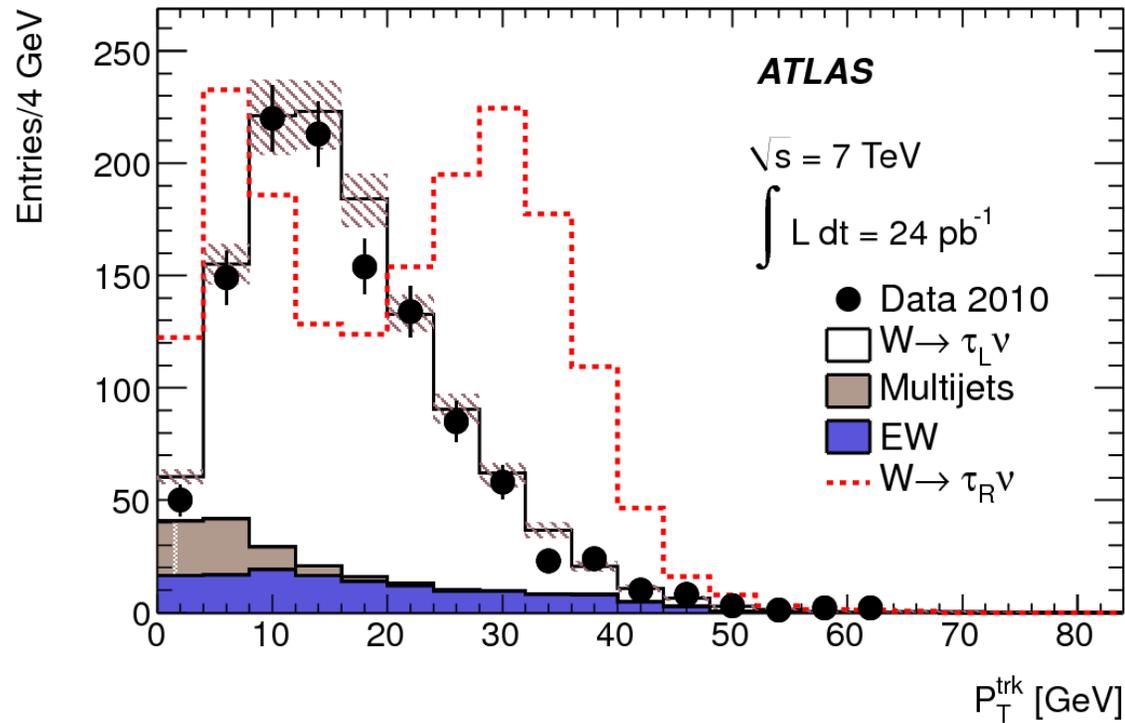


- Experimental Precision 4.1%
 - Luminosity: 3.4%, other: 2.2%

W and Z boson production



Tau polarisation in W decays



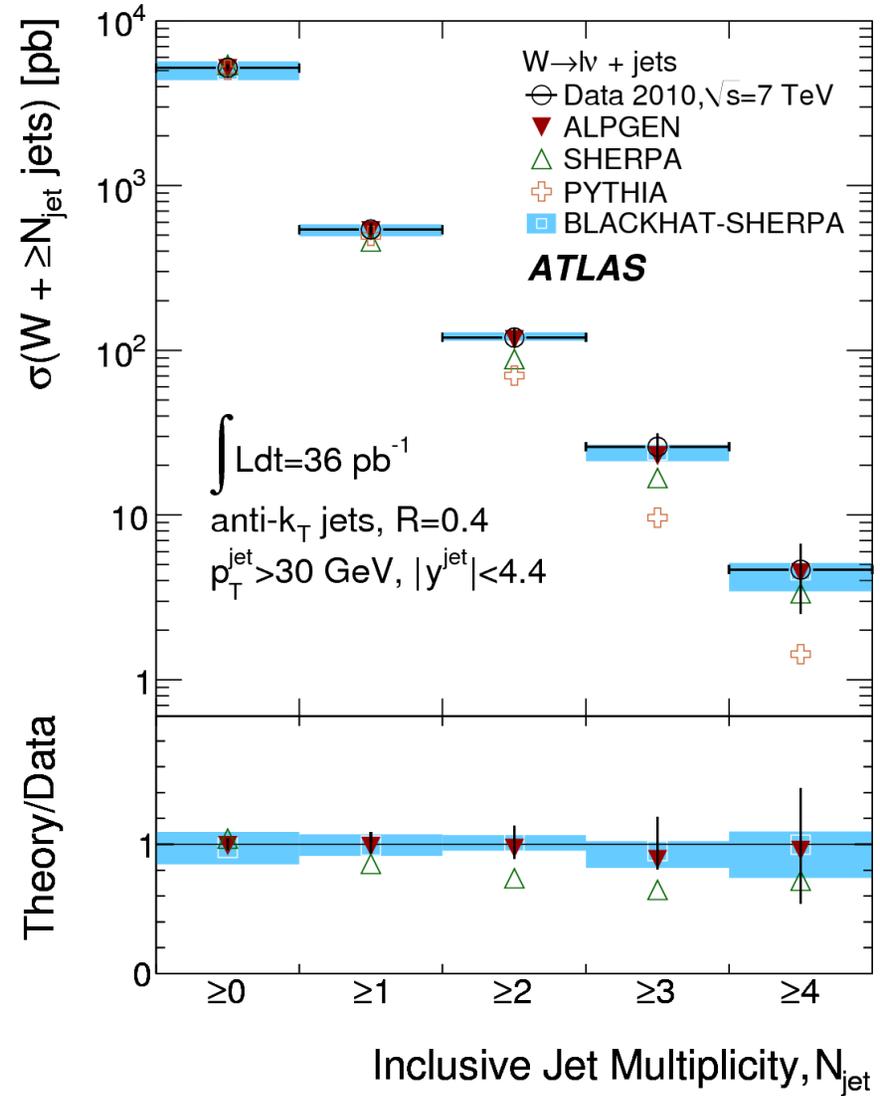
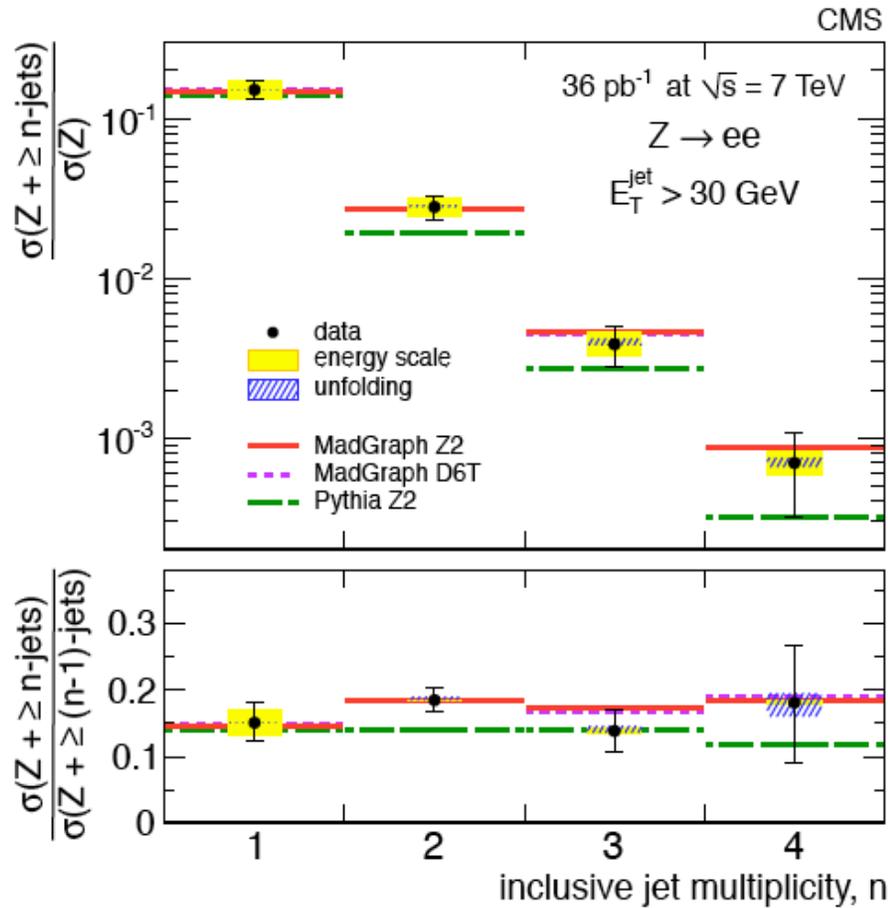
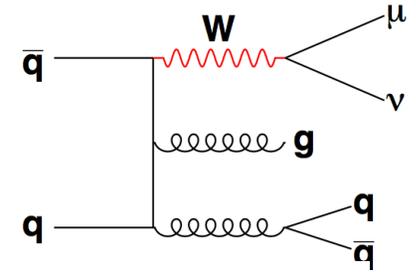
$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1.06 \pm 0.04 \text{ (stat)} \begin{matrix} +0.05 \\ -0.07 \end{matrix} \text{ (syst)}$$

- Interesting handle for new physics searches

W/Z + Jets Production

Z + n jets

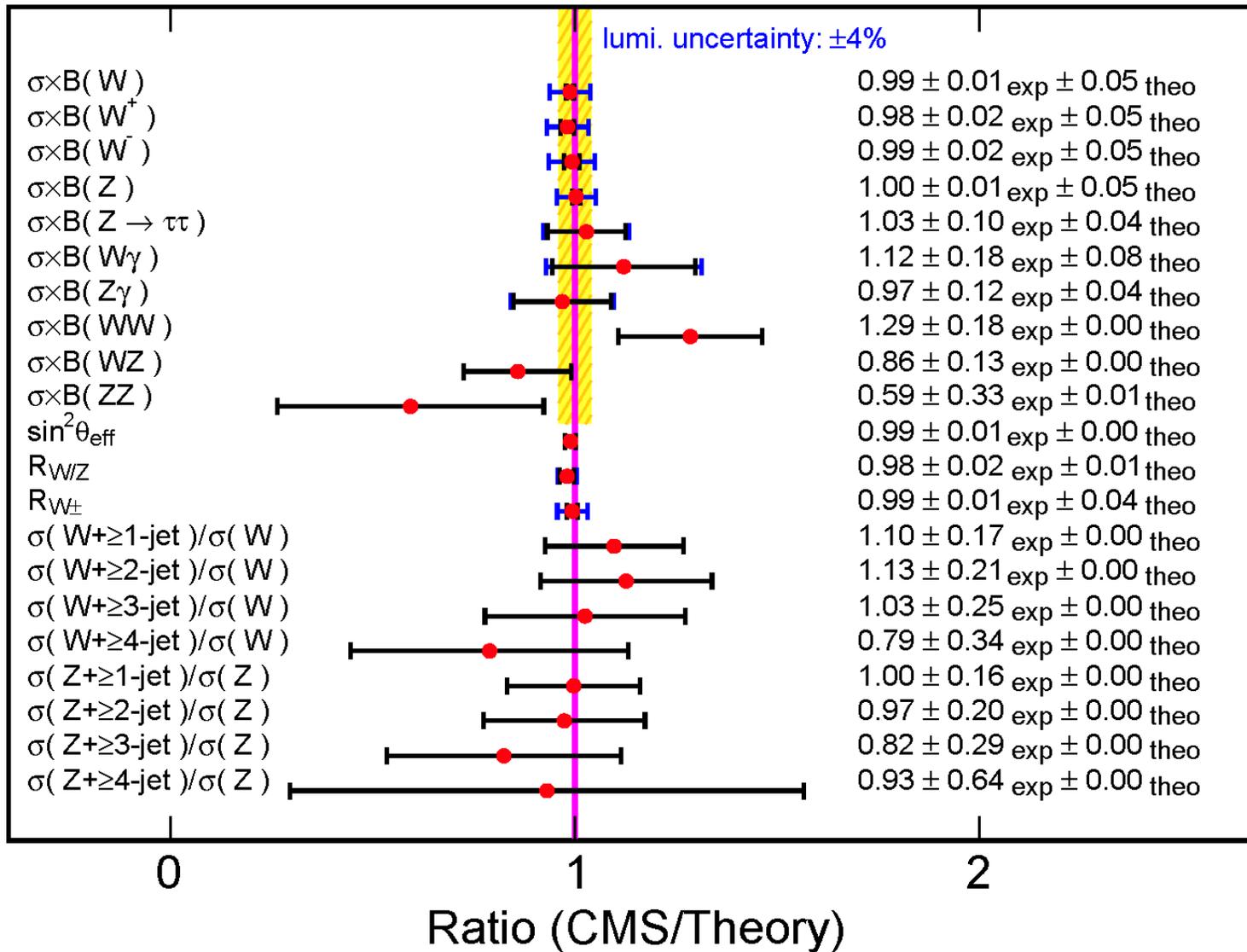
W + n jets



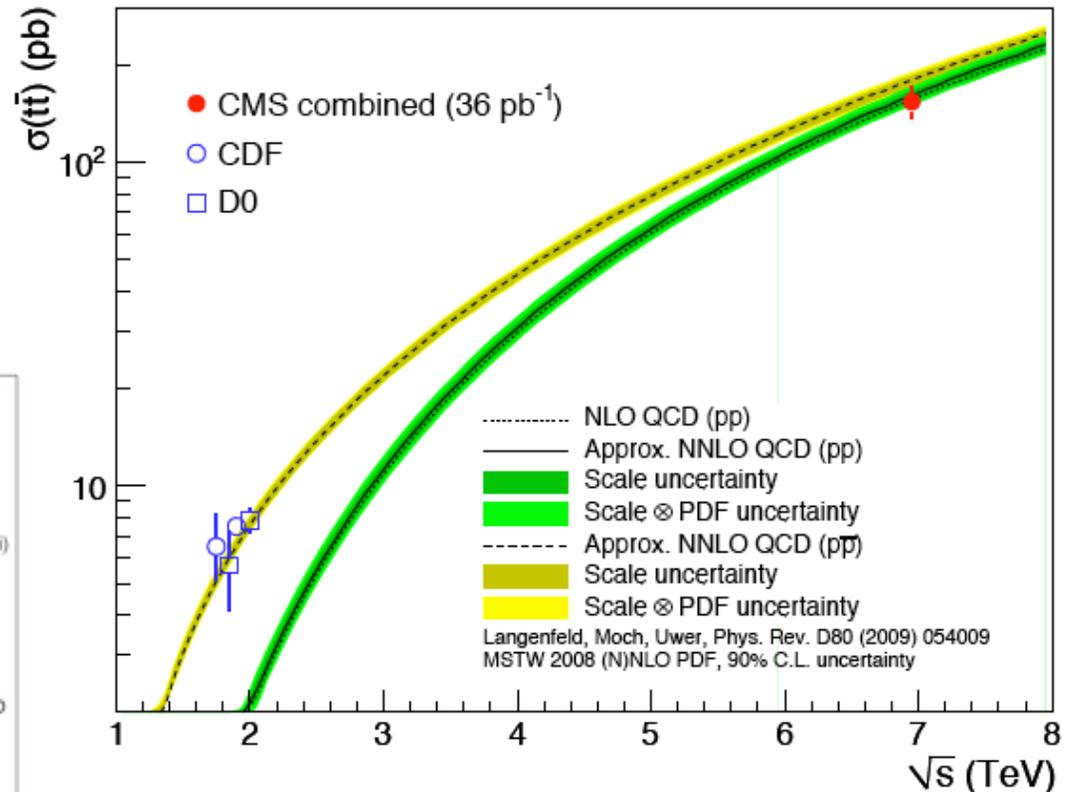
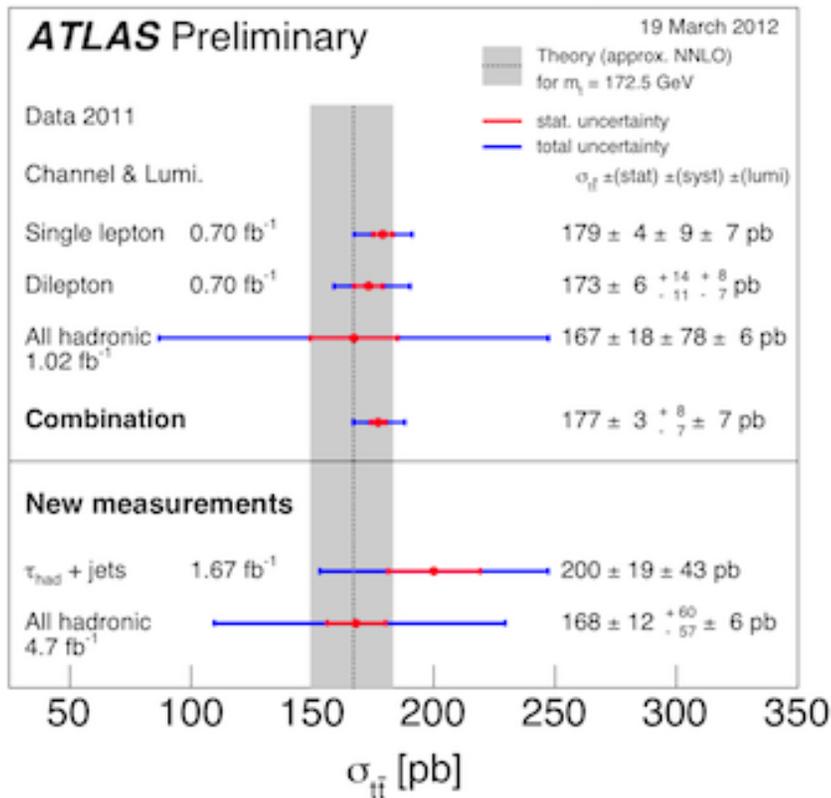
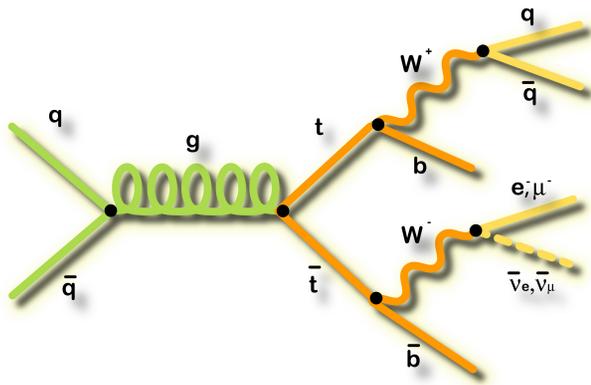
Summary: Data versus Theory

CMS

$\sqrt{s} = 7 \text{ TeV}$

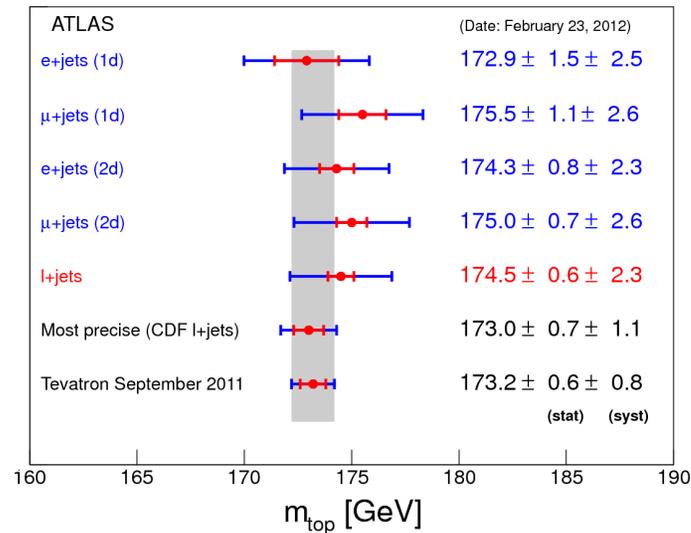
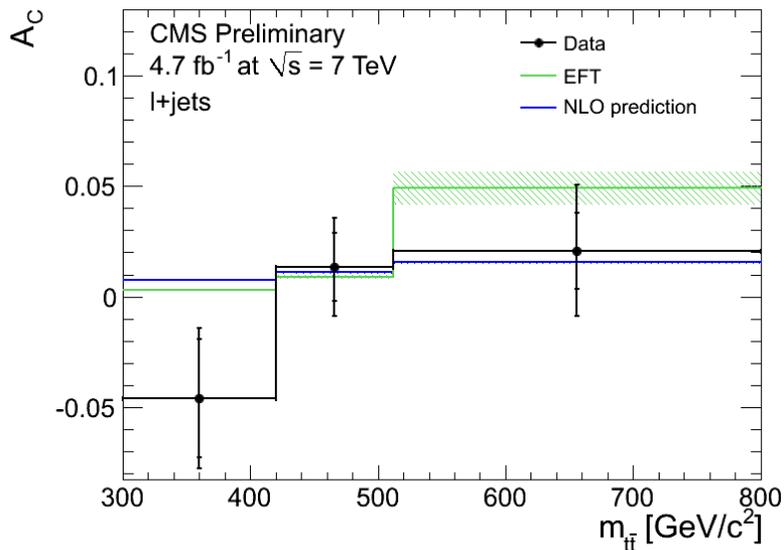
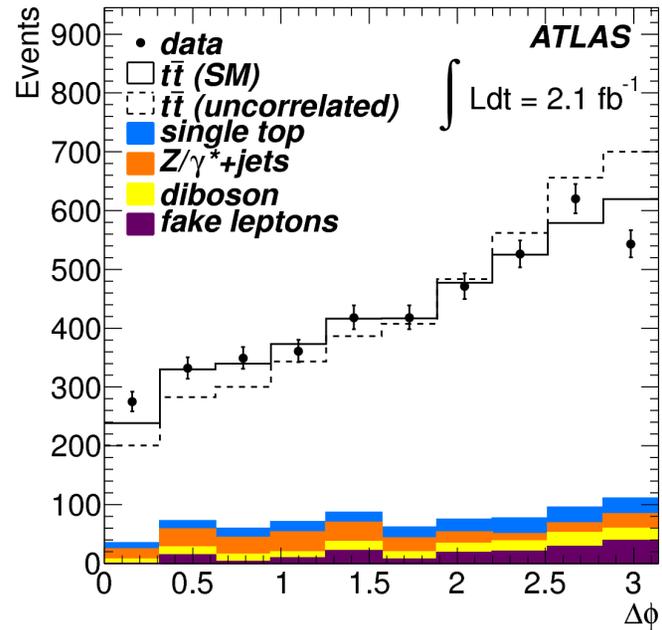
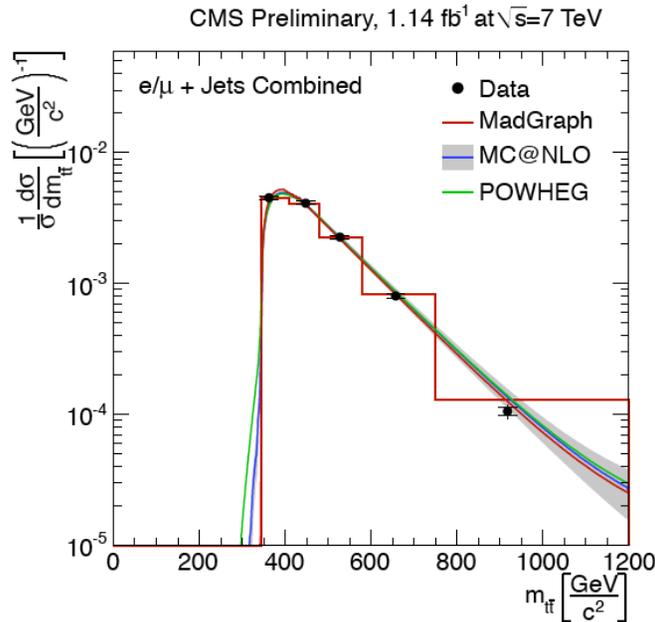


Top Quark: Inclusive Cross Section



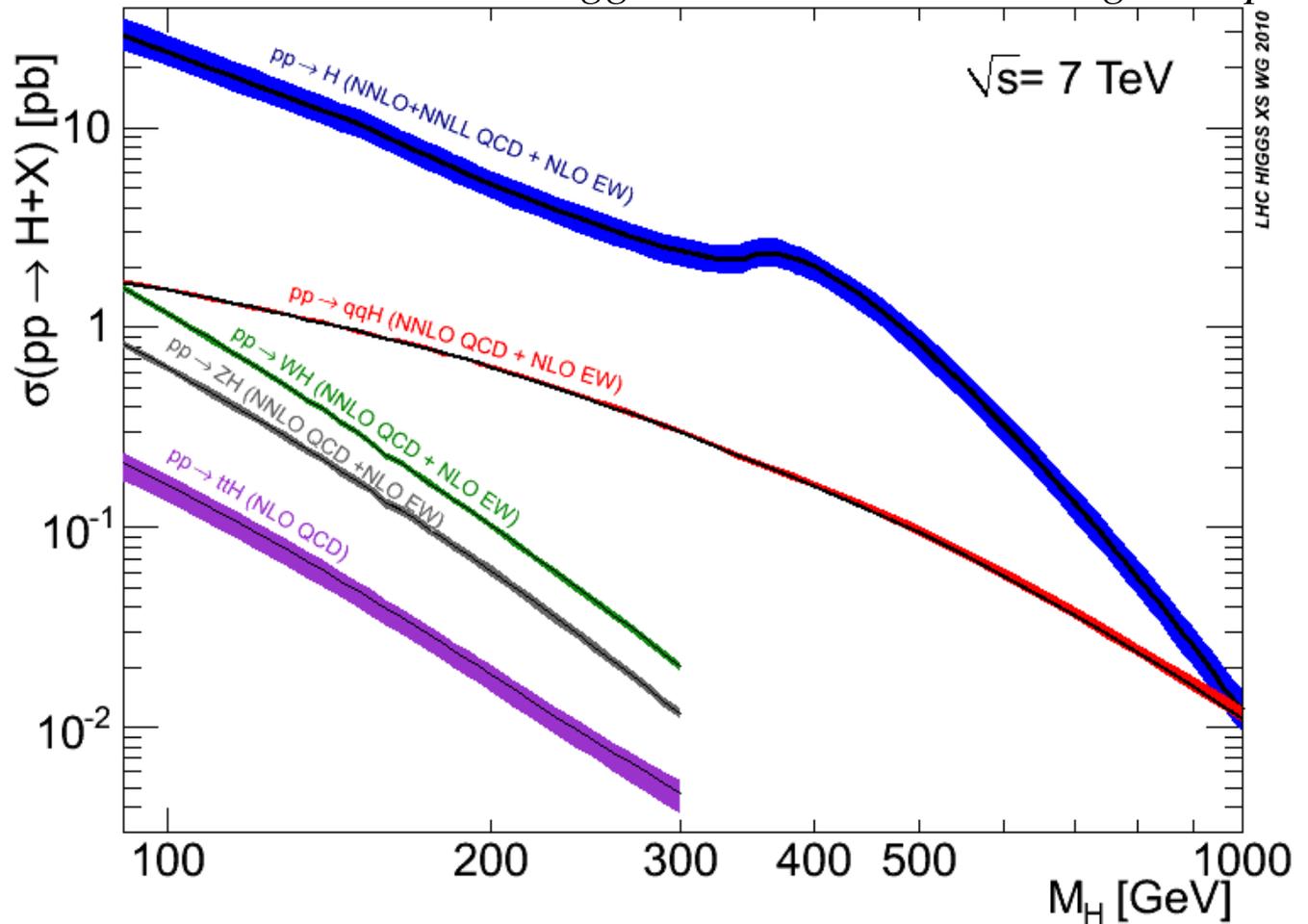
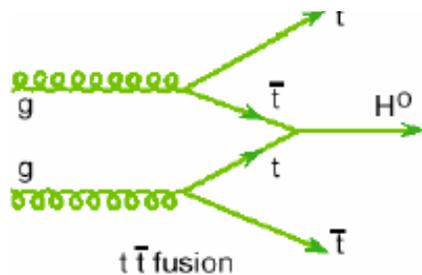
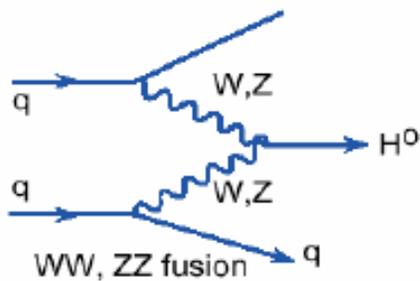
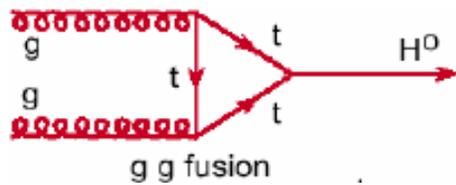
- Experimental precision 6%!

The top quark: a closer look



Higgs Production at the LHC

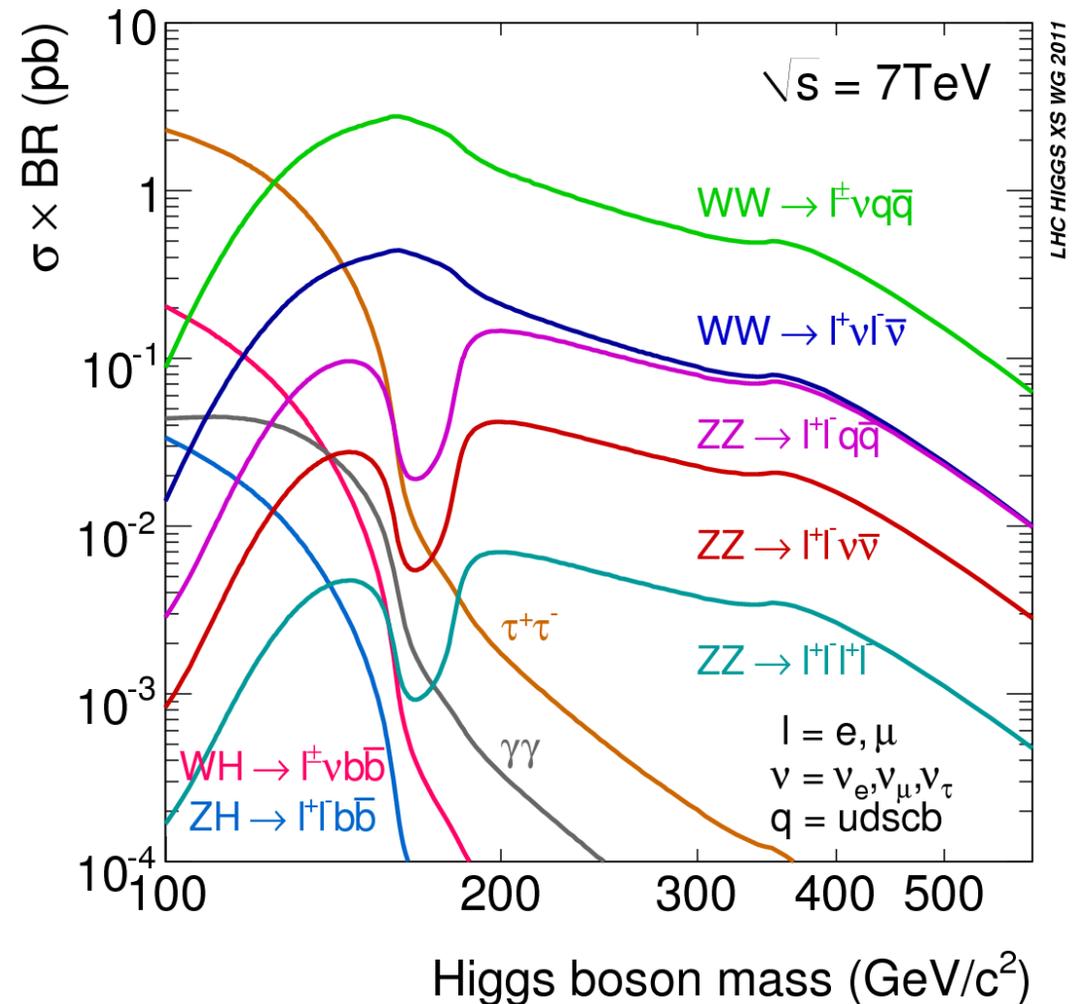
LHC Higgs Cross Section Working Group



LHC HIGGS XS WG 2010

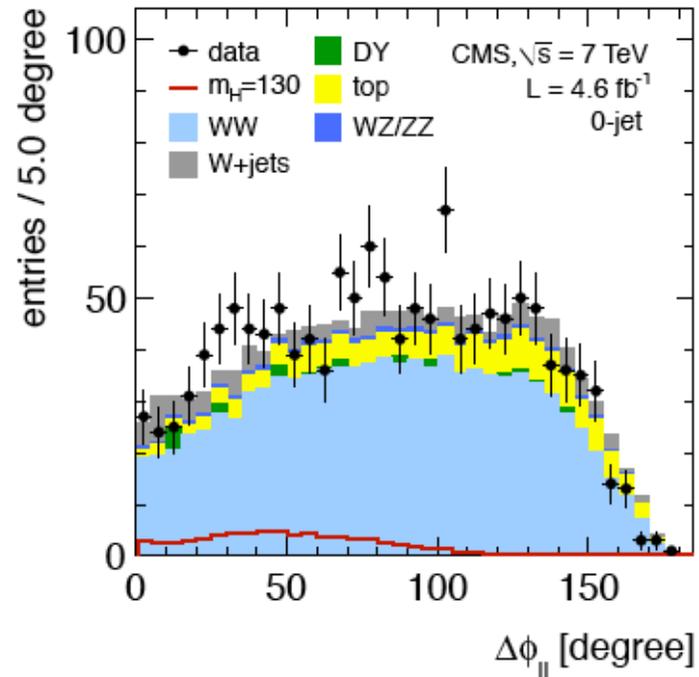
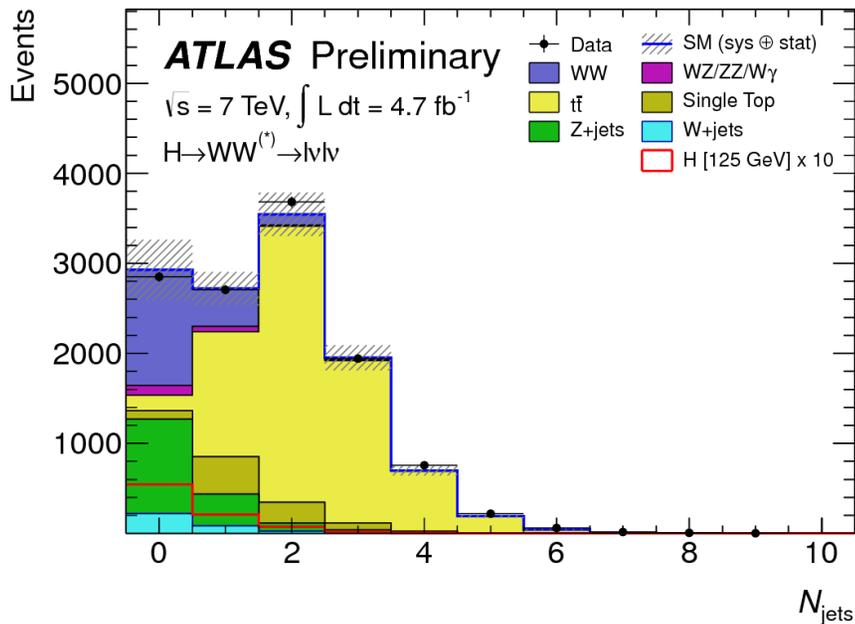
Cross Section x Branching Ratio

- Low mass region:
 - $ZZ^* \rightarrow 4$ leptons
 - $\gamma\gamma$
 - $WW \rightarrow l\nu l\nu$
 - $\tau\tau$
 - $WH \rightarrow Wbb$

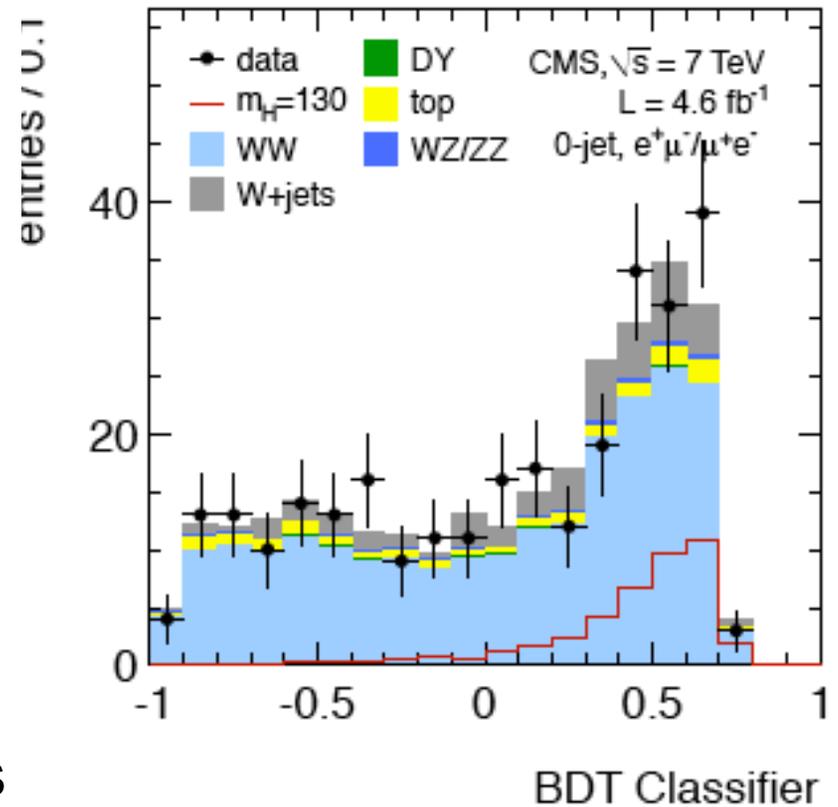
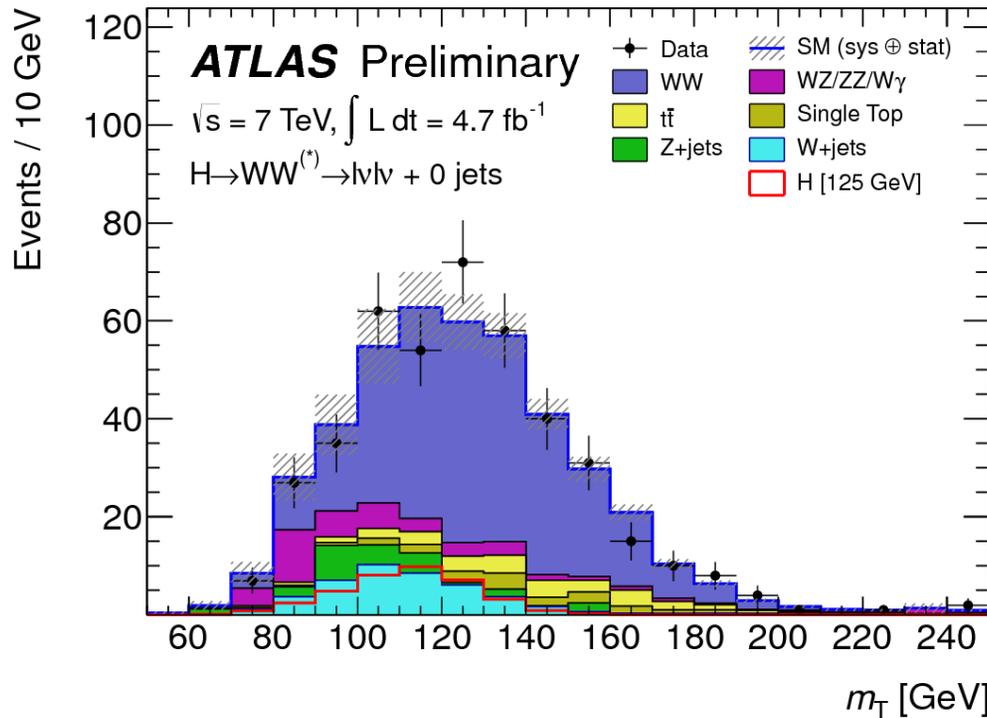


H→WW→lvlv Search

- For $m_H=130$ GeV: $\sigma \times \text{BR} = 170 \text{ fb} \Rightarrow 850 \text{ events} / 5 \text{ fb}^{-1}$
- Main backgrounds:
 - WW, ttbar and Drell-Yan production
 - Understanding of E_T^{miss} and low p_T jets critical
- Simple cut based analysis done by both ATLAS and CMS
 - CMS also does multivariate analysis

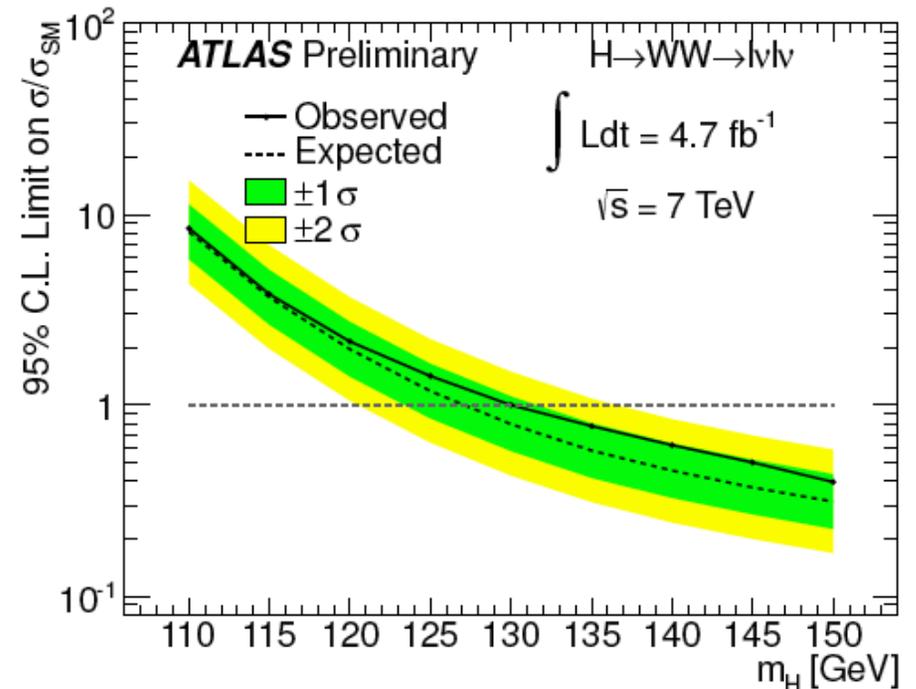
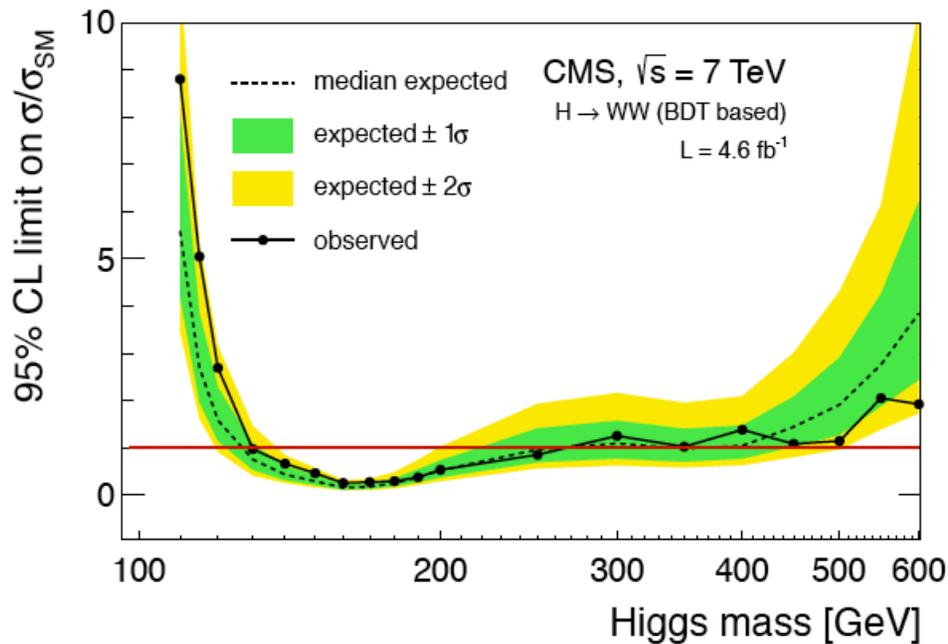


H→WW Search: Results



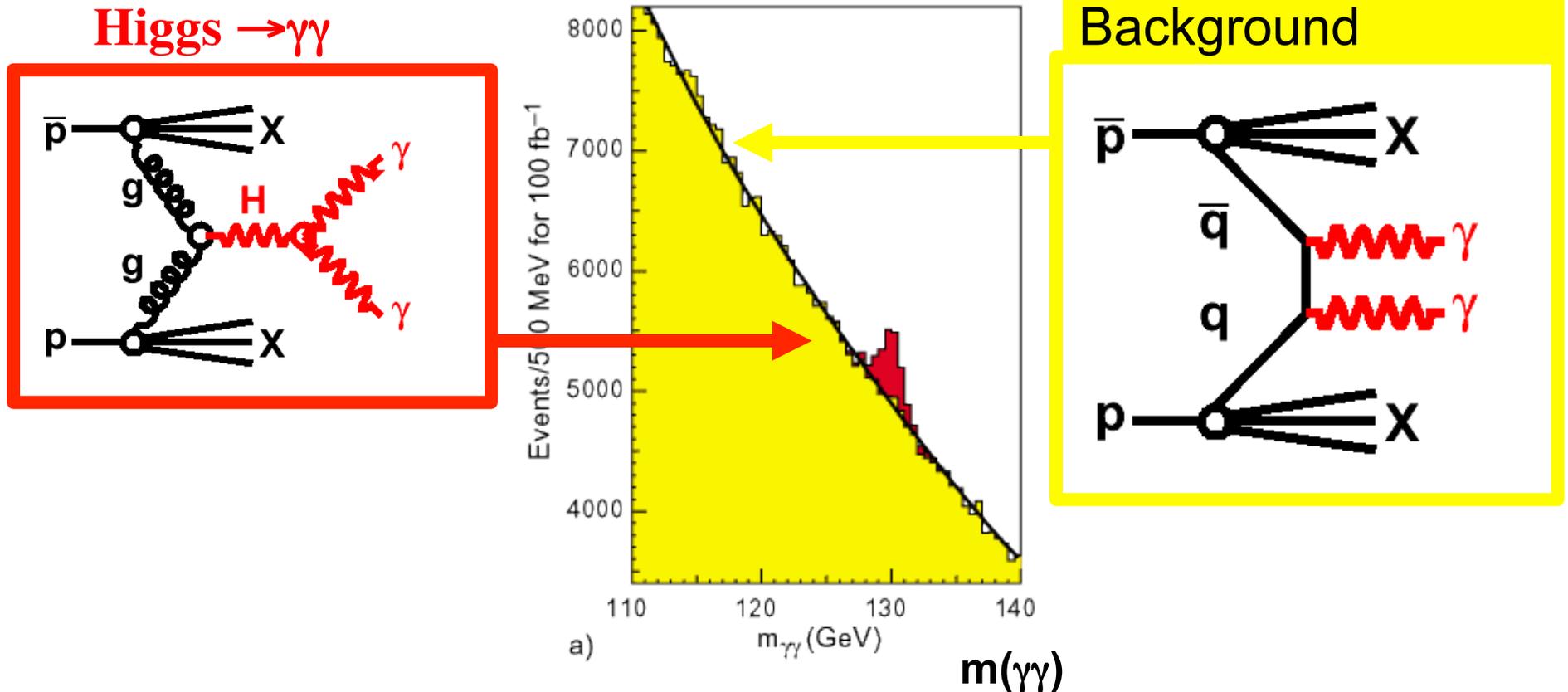
- Final discriminating variable is
 - ATLAS: transverse mass of leptons and E_t^{miss} : m_t
 - CMS has 2 analysis: m_t or Boosted Decision Tree Classifier
- Data agree with background expectation

H→WW Cross Section Exclusion



- CMS excludes **129 < m_H < 270 GeV**
 - Expected 127 < m_H < 270 GeV
- ATLAS excludes **130 < m_H < 260 GeV**
 - Expected 127 < m_H < 234 GeV

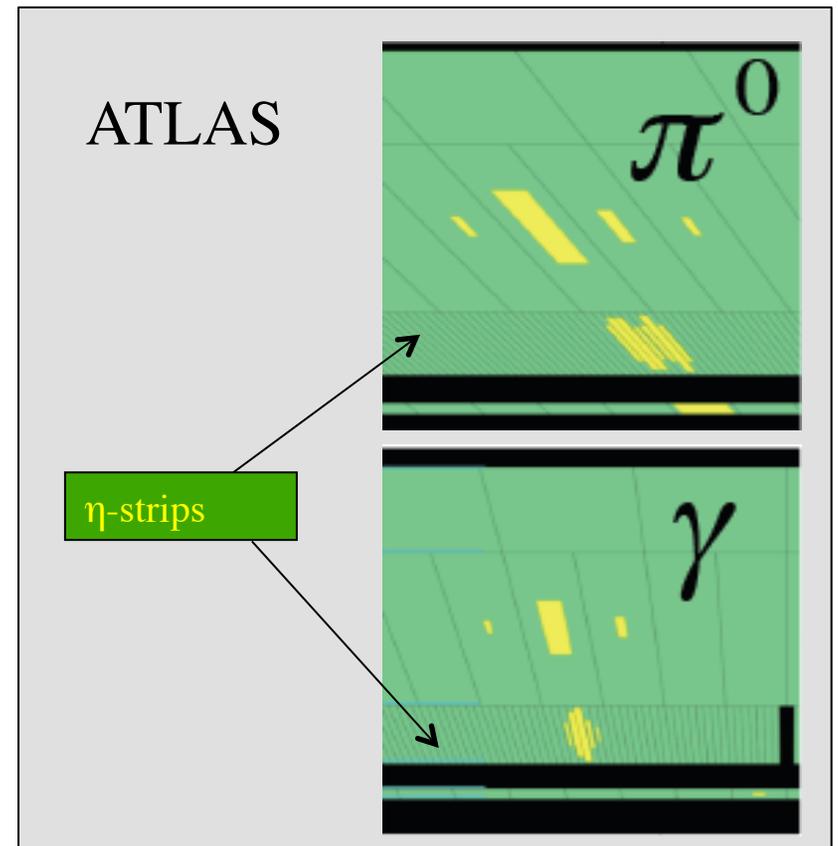
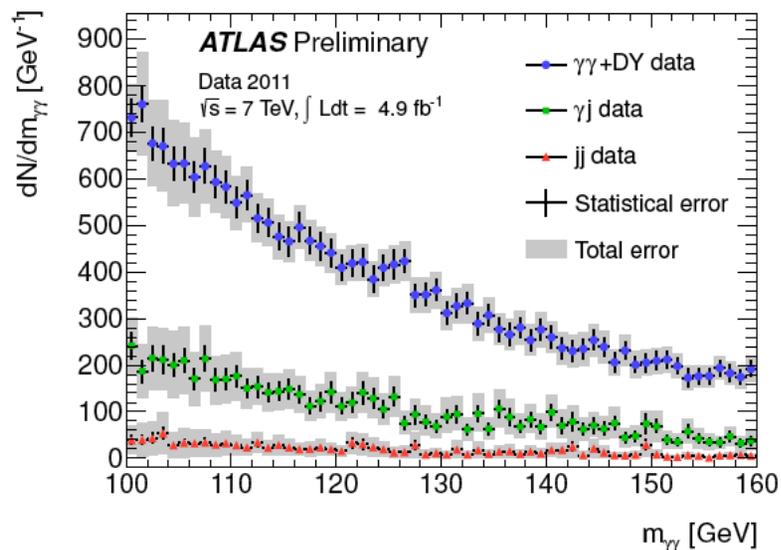
Higgs decaying to two photons



- $\sigma \times \text{BR} = 43 \text{ fb} \Rightarrow 215 \text{ evts}/5\text{fb}^{-1}$ for $m_H = 120 \text{ GeV}$
 - 70 events expected after reconstruction and event selection
- But large background from prompt diphoton events and from jets with leading π^0 's
 - Signal/Background $\sim 3\%$ ($\sim 70/2300$)

Rejection of $\pi^0 \rightarrow \gamma\gamma$ Background

- Fine segmentation of strip layer in LAr calorimeter in η -direction
 - Designed to reject precisely this background
 - Also used to estimate background composition



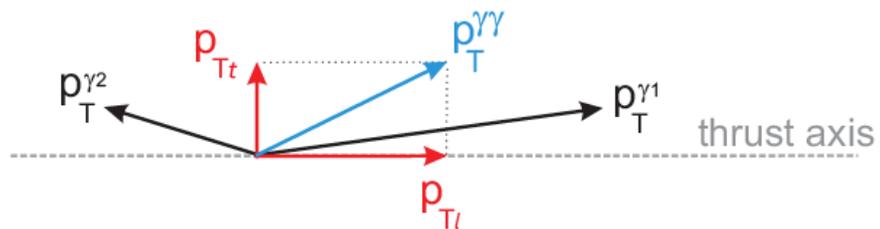
- **$71 \pm 5 \%$ of background from irreducible prompt diphoton production**

ATLAS Analysis Strategy

- Events with two isolated photon candidates selected:
 - $E_T(\gamma_1) > 40 \text{ GeV}$
 - $E_T(\gamma_2) > 25 \text{ GeV}$
- Isolation cut:
 - $E_T < 5 \text{ GeV}$ in 0.4 cone around photon
- Divide sample into 9 categories:
 - Converted versus unconverted
 - High $p_T(\gamma\gamma)$ versus low $p_T(\gamma\gamma)$
 - Different η regions

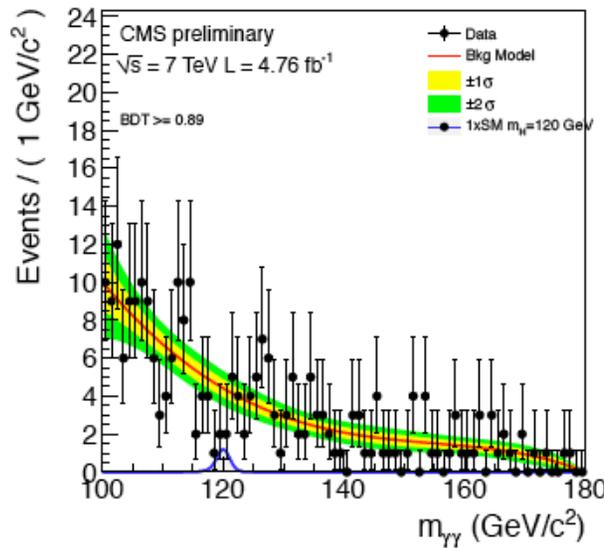
Examples of categories

category	FWHM (GeV)	Signal	S/BG
Unc. low pt central	3.4	7.3	0.051
Unc high pt central	3.3	3.3	0.117
Conv. Low pt central	3.9	4.7	0.038
Conv. transition	5.8	5.9	0.014
Unc. Low pt other	4.1	13.5	0.023
Conv. Low pt other	4.7	14.0	0.017

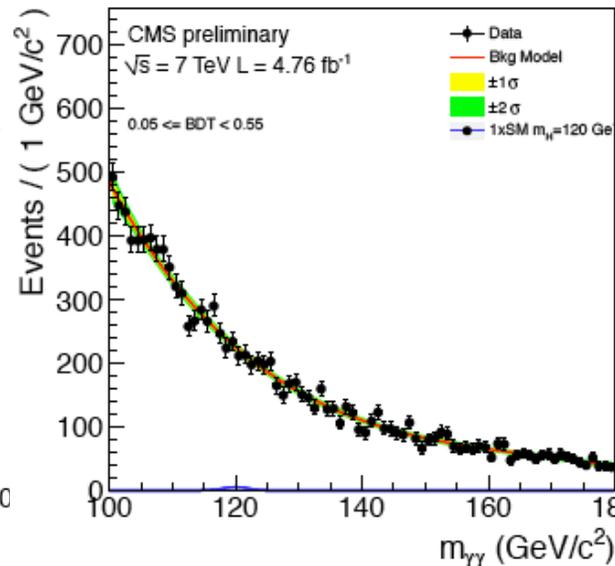


CMS Analysis Strategy

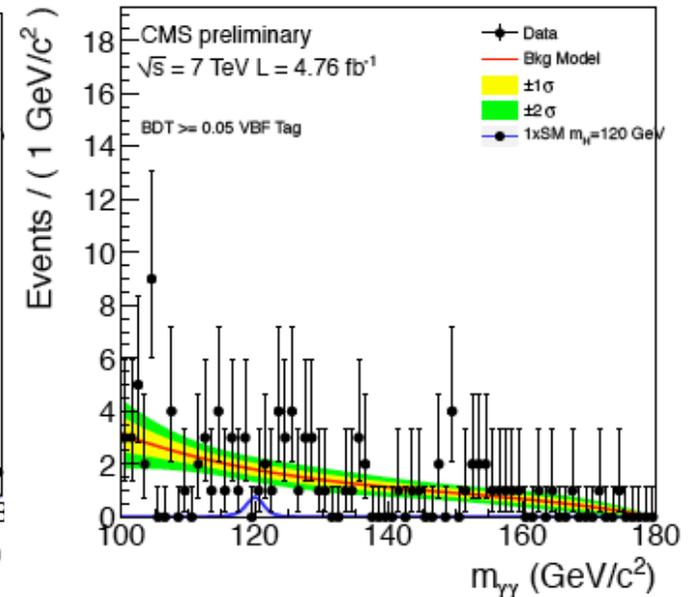
High S/B



Low S/B



VBF

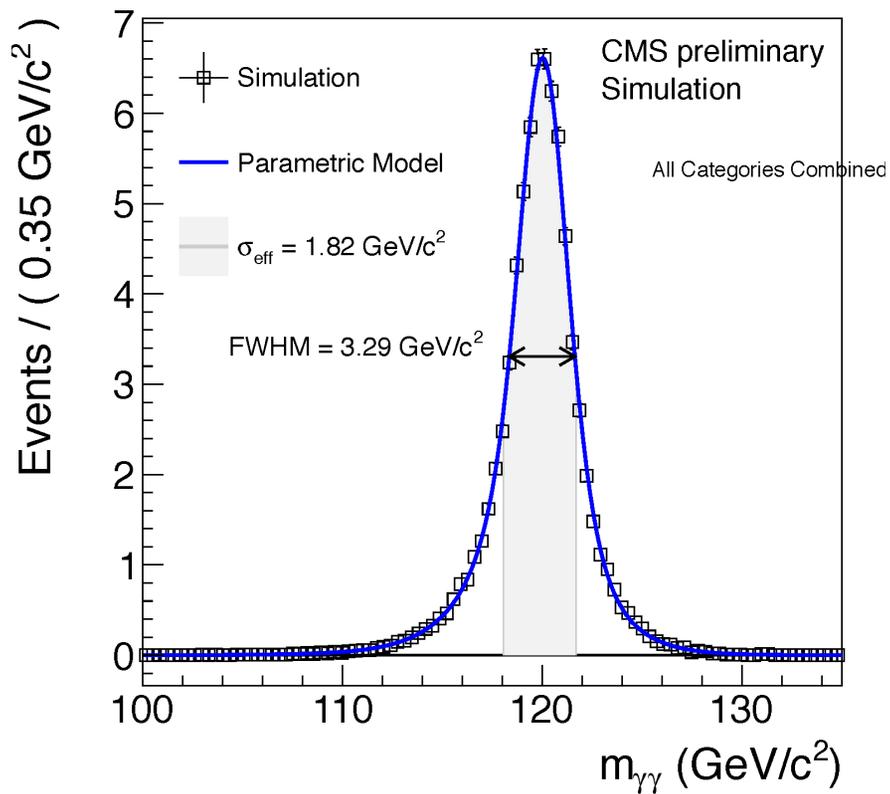


- Events with two isolated photons selected
- Events categorized by Boosted Decision Tree (BDT)
 - Each category has different signal/background and resolution
 - Vector-Boson-Fusion is separate category

Diphoton Mass Resolution

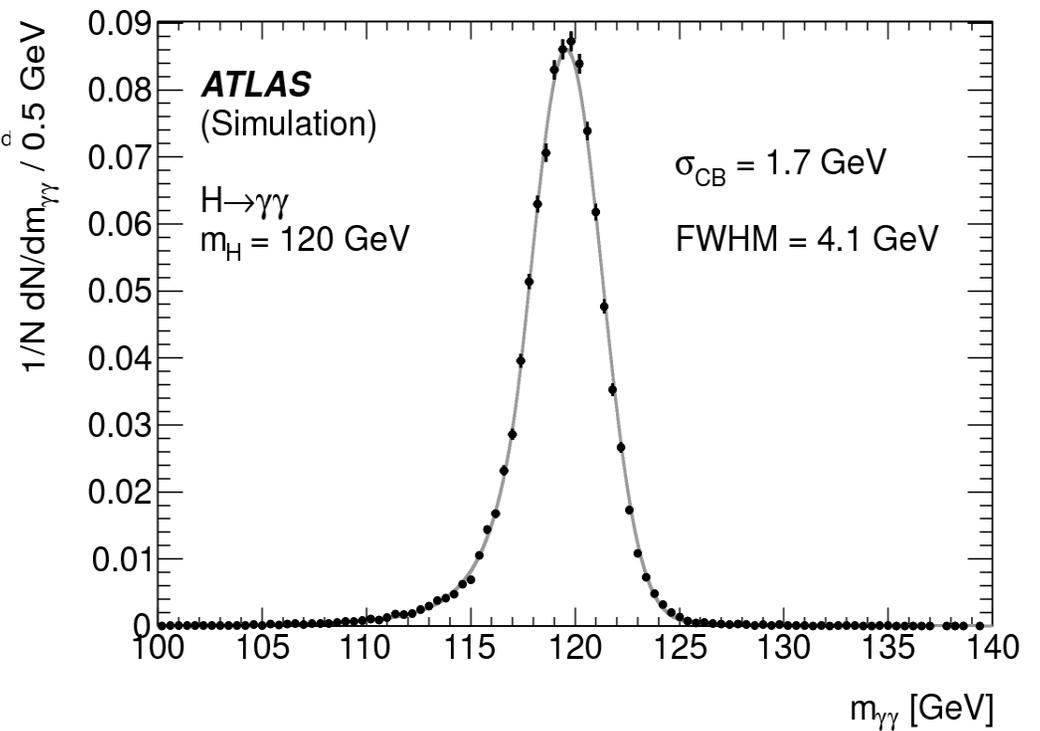
CMS

$\sigma(M)=1.2-2.5$ GeV

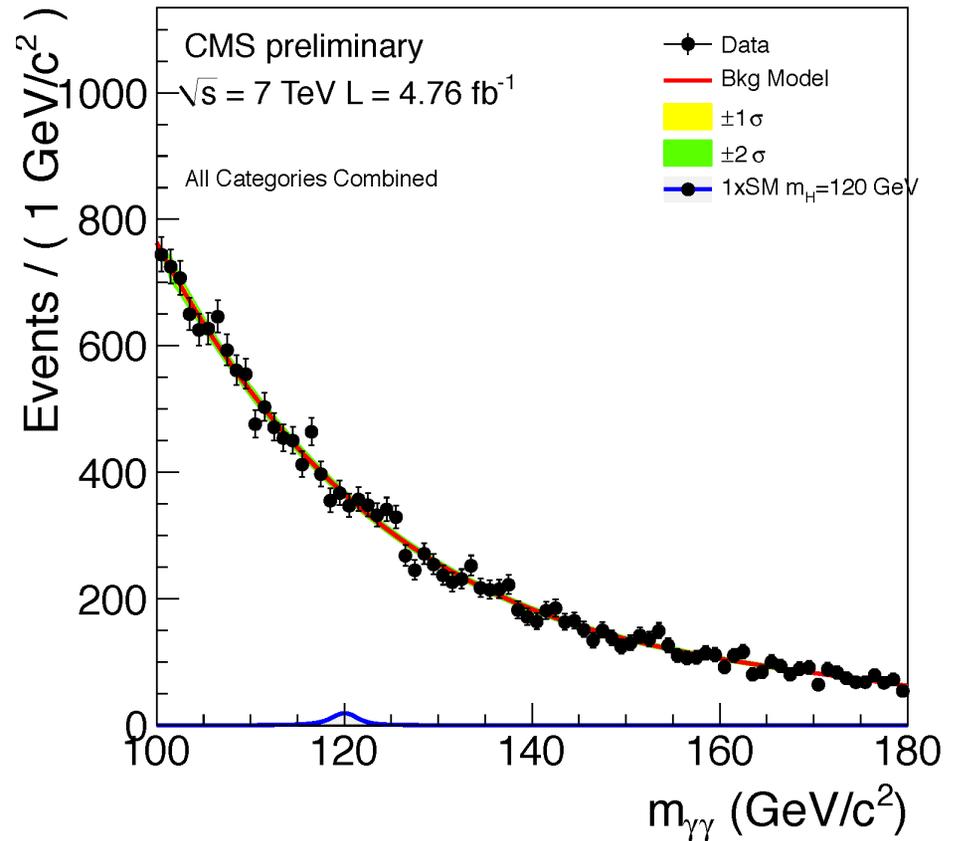
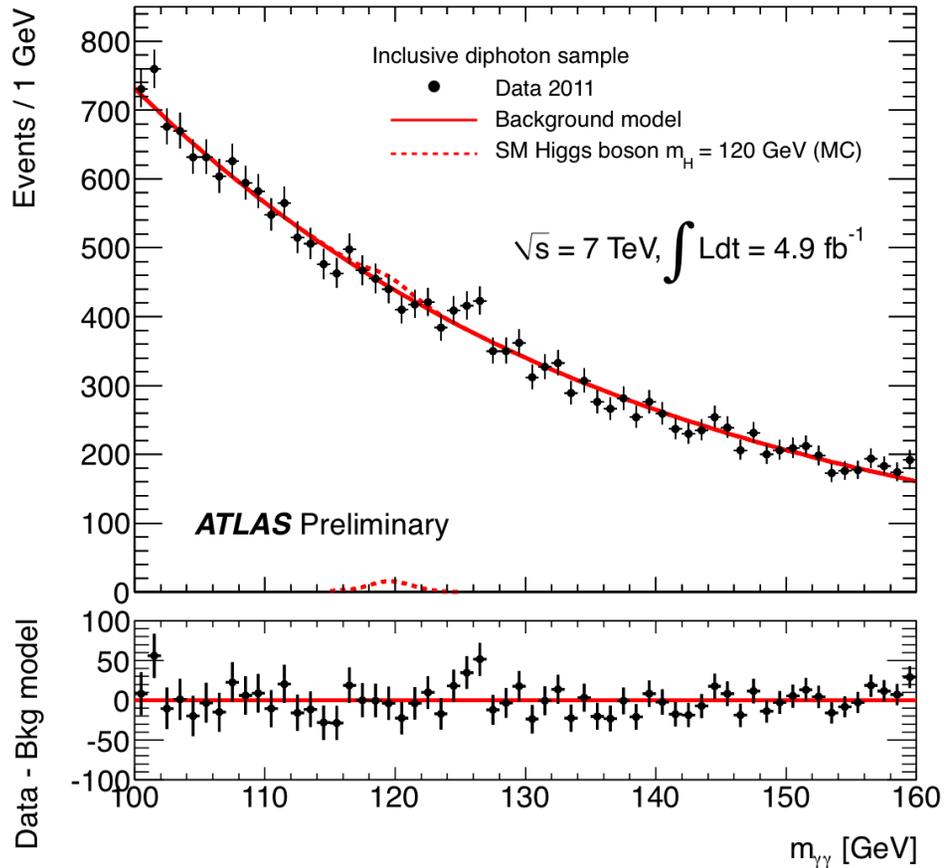


ATLAS

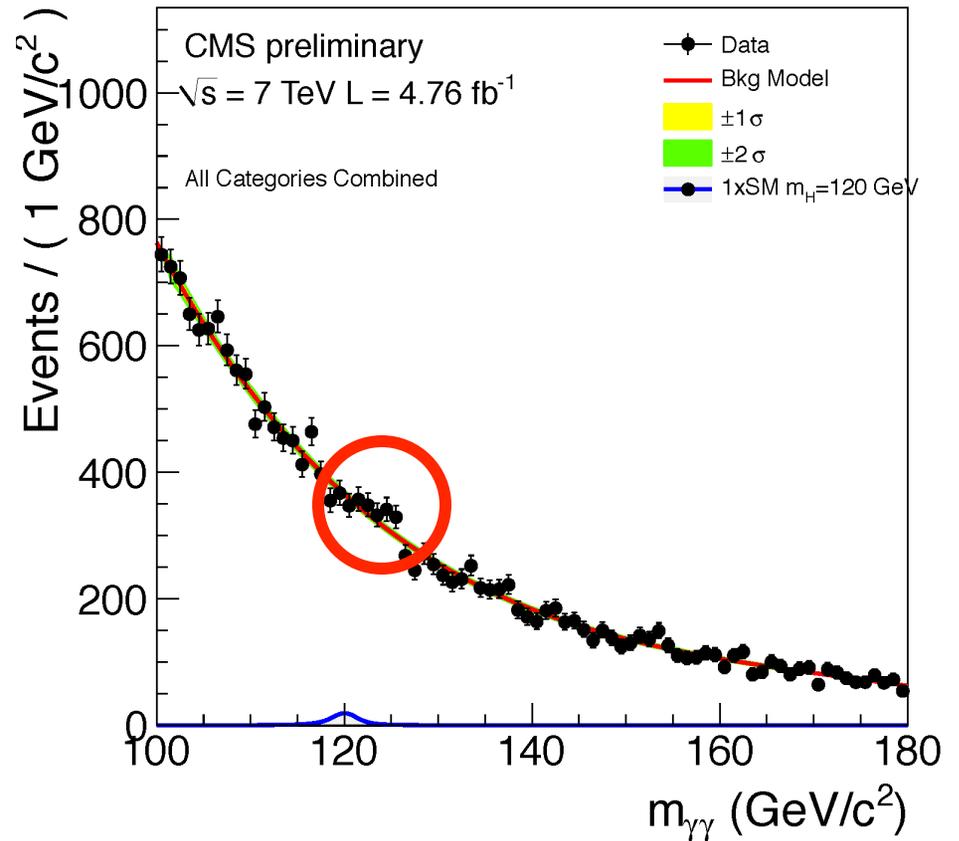
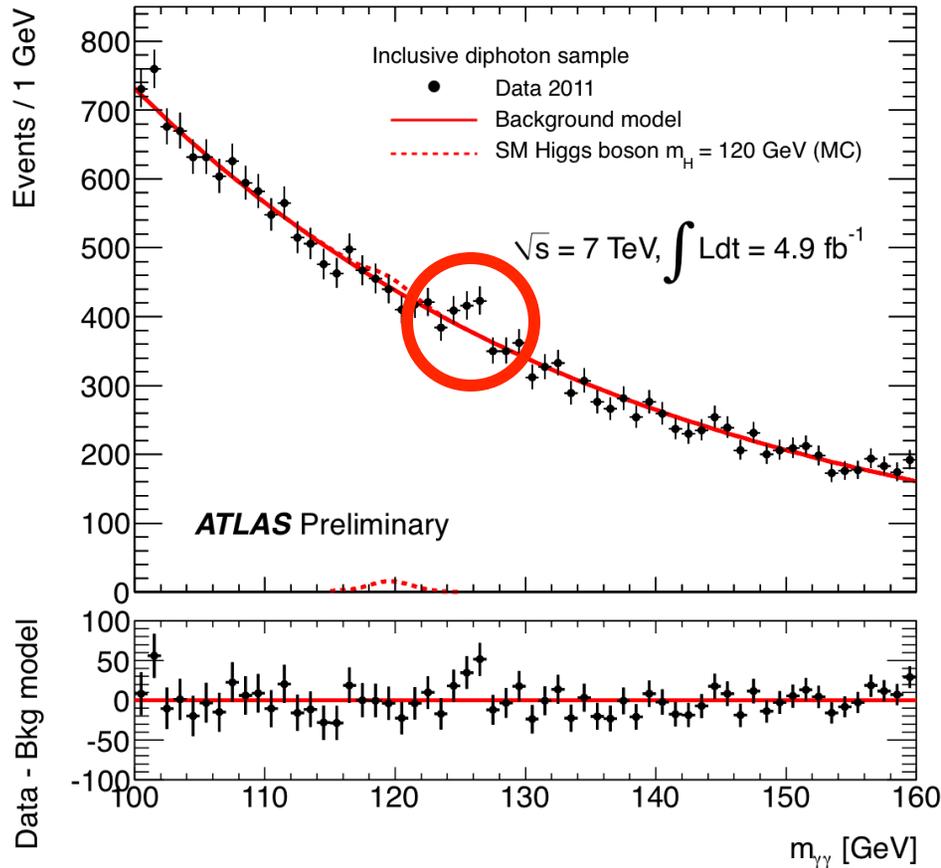
$\sigma(M)=1.4-2.3$ GeV



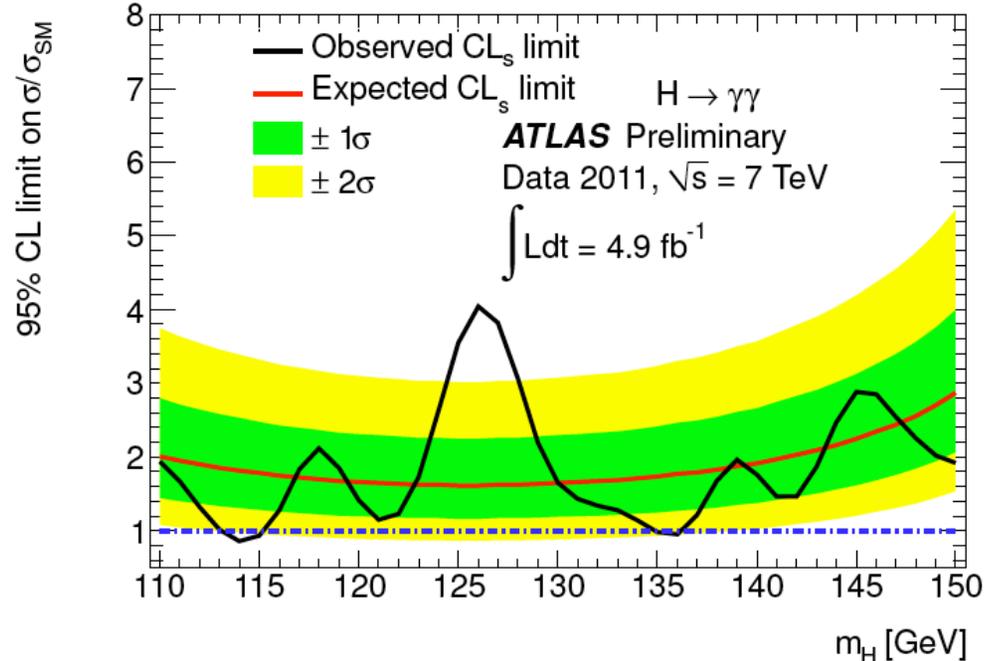
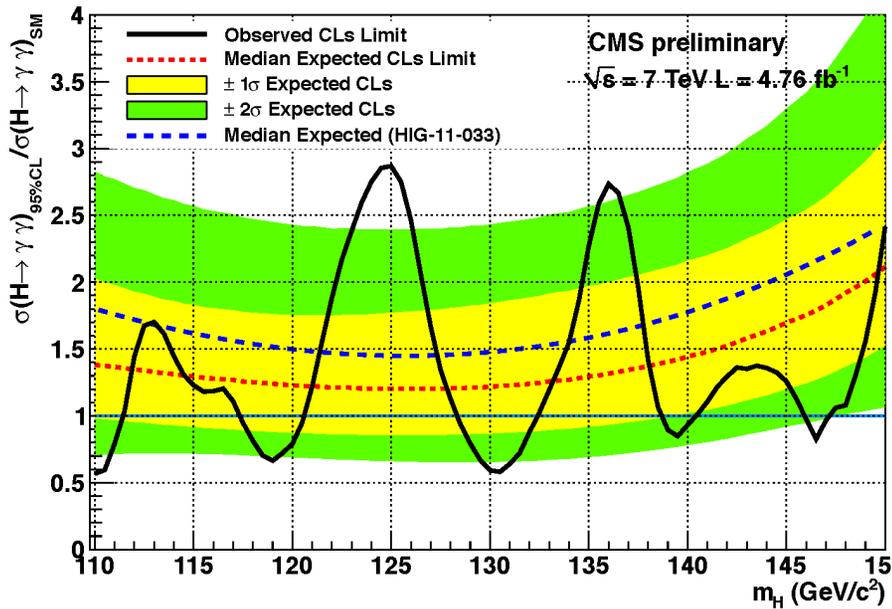
Overall Diphoton Mass Distribution



Overall Diphoton Mass Distribution



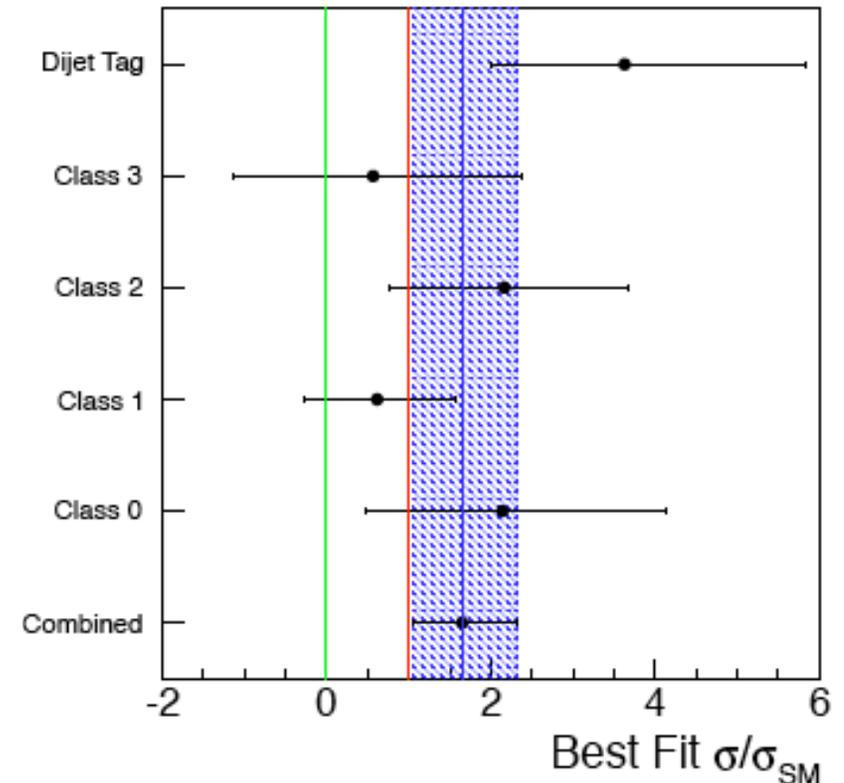
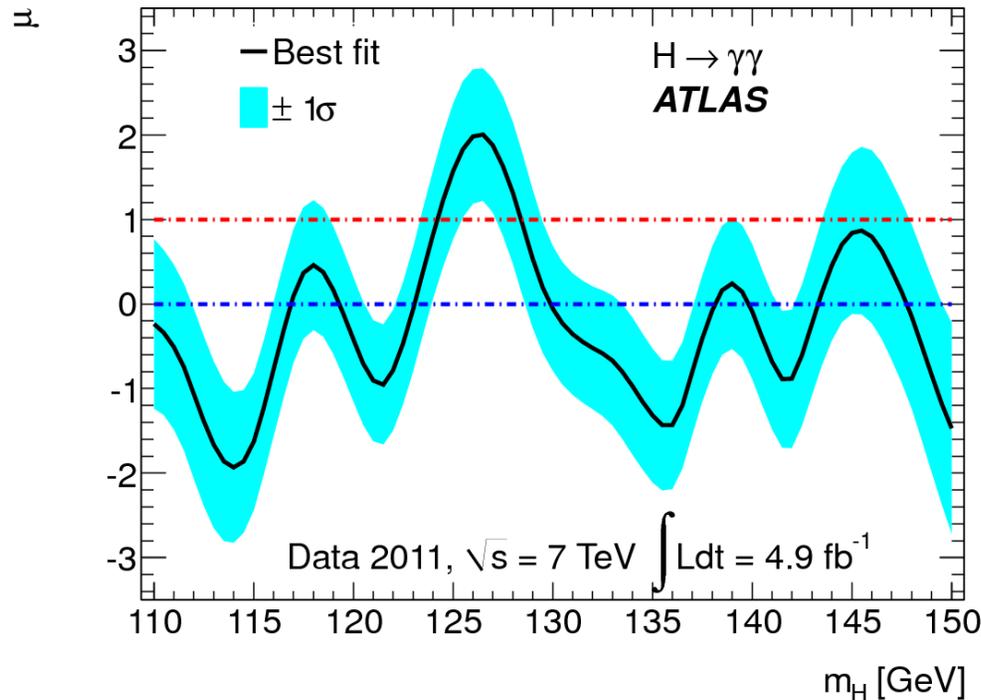
H $\rightarrow\gamma\gamma$ Cross Section Limits



- Most significant excess

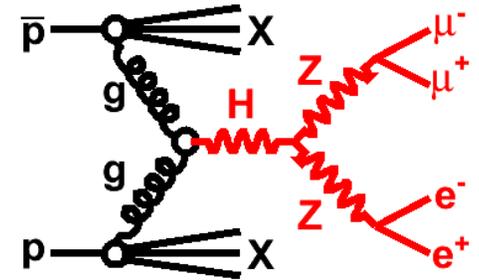
- CMS: $m_H = 125 \text{ GeV}$, global (local) significance 1.6σ (2.9σ)
- ATLAS: $m_H = 126 \text{ GeV}$, global (local) significance 1.5σ (2.8σ)

Is Signal Strength Consistent with SM?

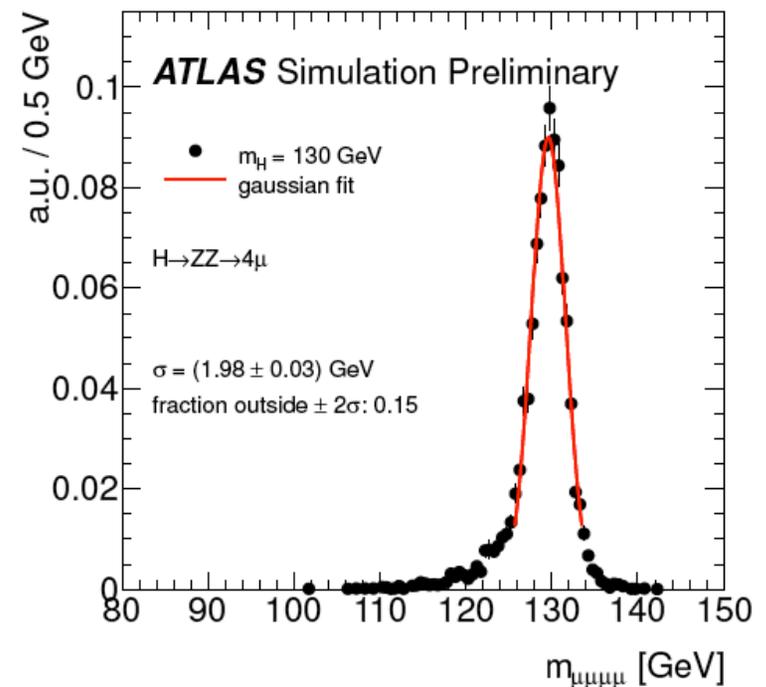


- Diphoton signal about 1σ stronger than SM expectation in both experiments

H \rightarrow Z*Z \rightarrow 4 leptons

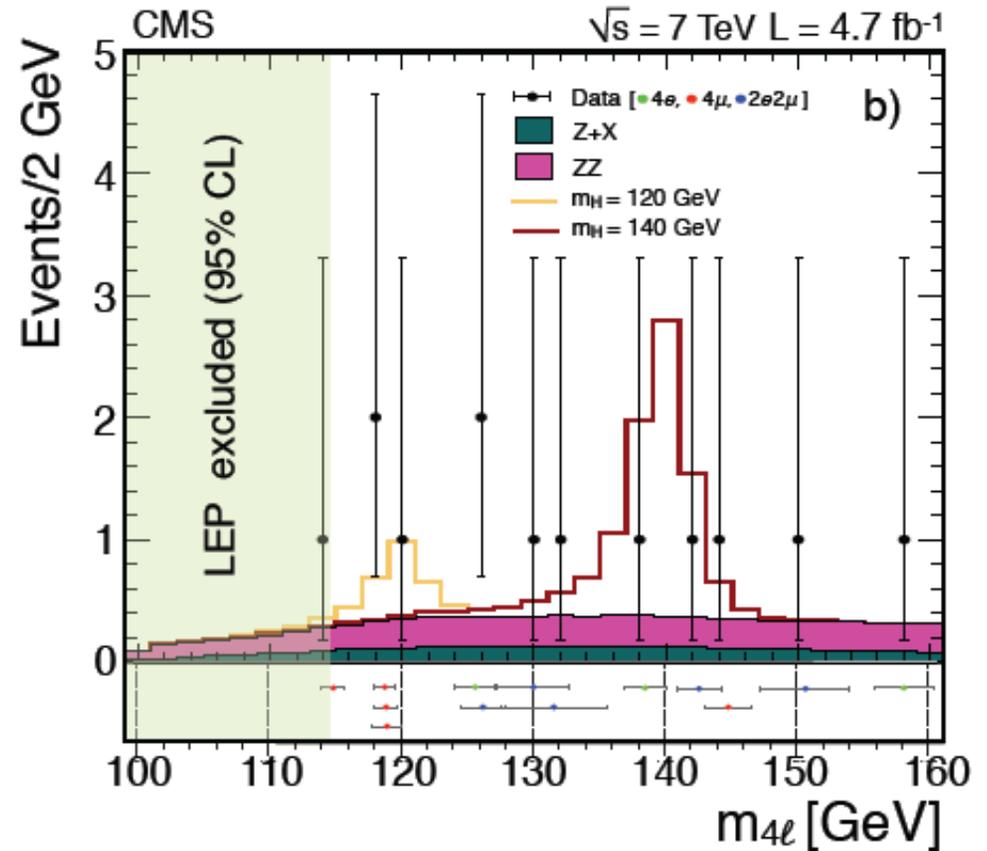
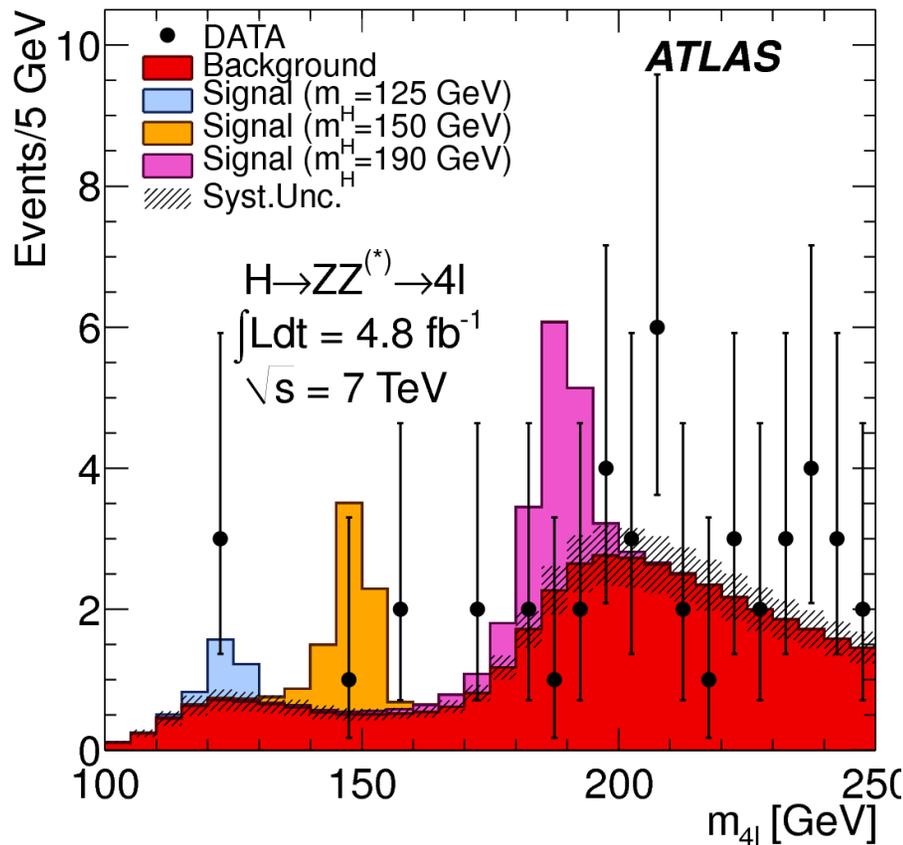


- 125 GeV Higgs: expect ~ 2 evts/5 fb $^{-1}$
- ATLAS Selection:
 - 4 leptons with $p_T > 7$ GeV
 - 2 leptons with $p_T > 20$ GeV
 - Leading dilepton mass:
 - $|m_{12} - m_Z| < 15$ GeV
 - Subleading mass from off-shell Z boson at low mass: $m_{34} > 15$ GeV
 - 4-lepton mass resolution:



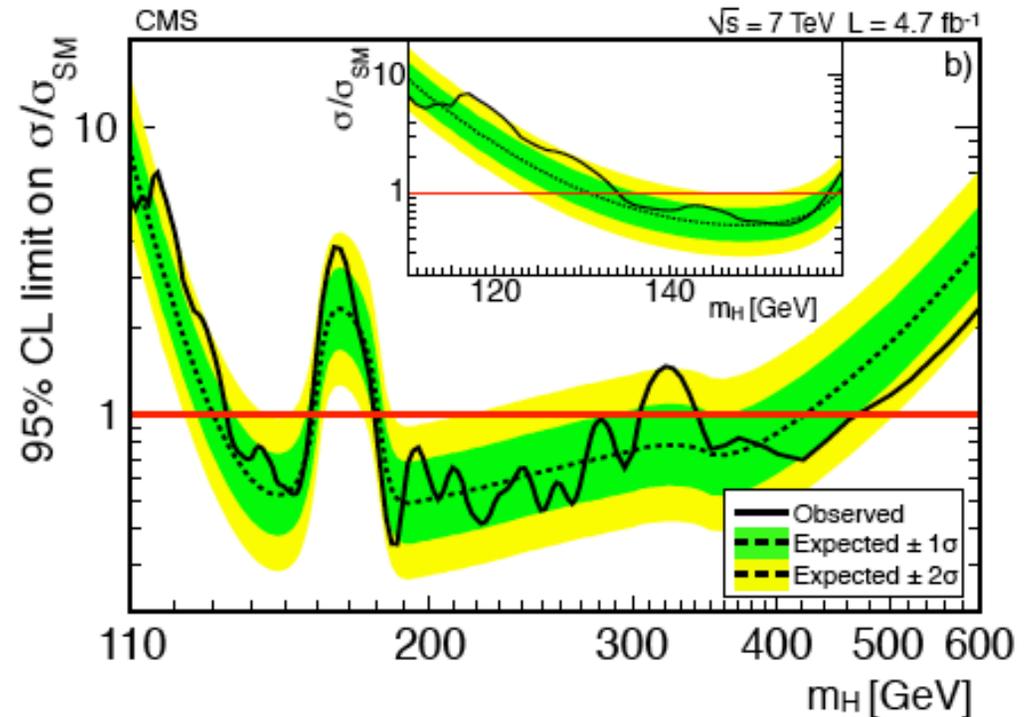
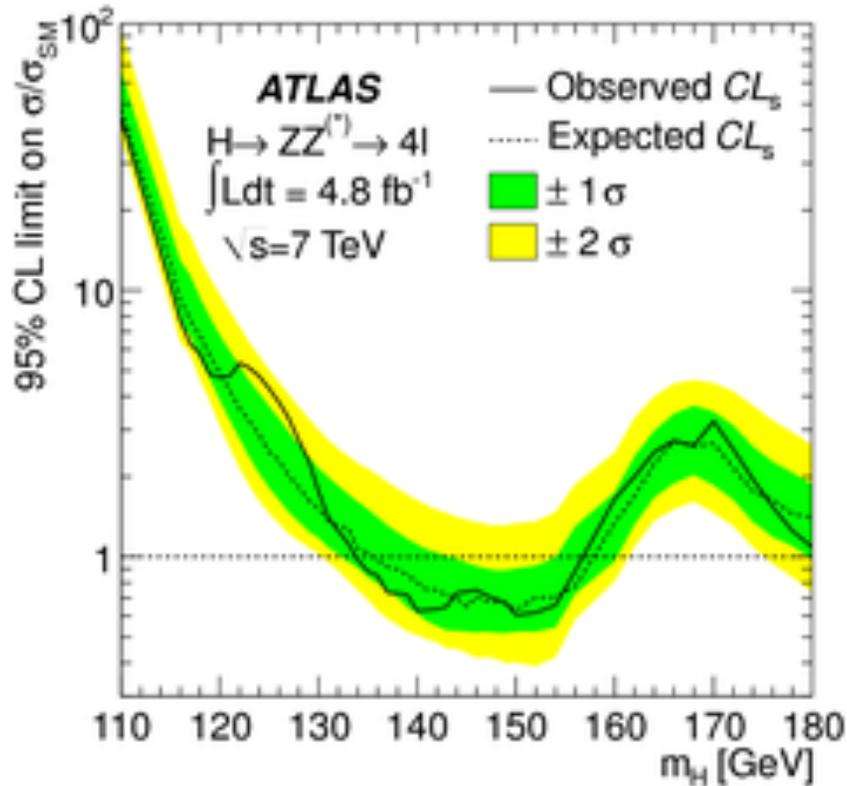
Experiment	4 μ	4e
ATLAS	1.5%	1.9%
CMS	1.1%	2.1%

Results of 4-lepton search



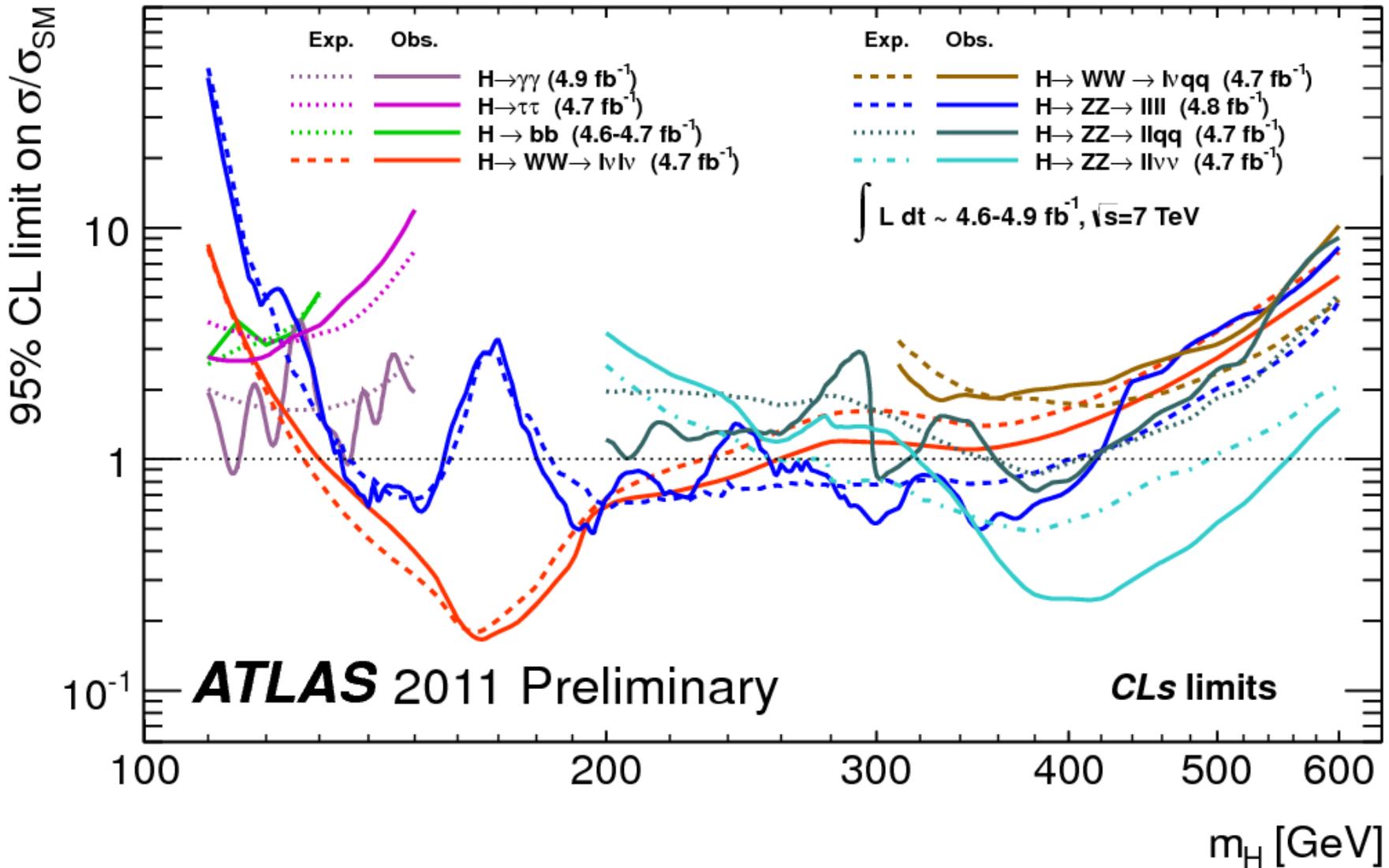
- High Signal to Background Ratio: ~ 1
- Will be very interesting to watch develop in 2012 data!
 - Expect ~ 8 events / 15 fb^{-1} per experiment for $m_H = 125 \text{ GeV}$

H→4 leptons: cross section limits

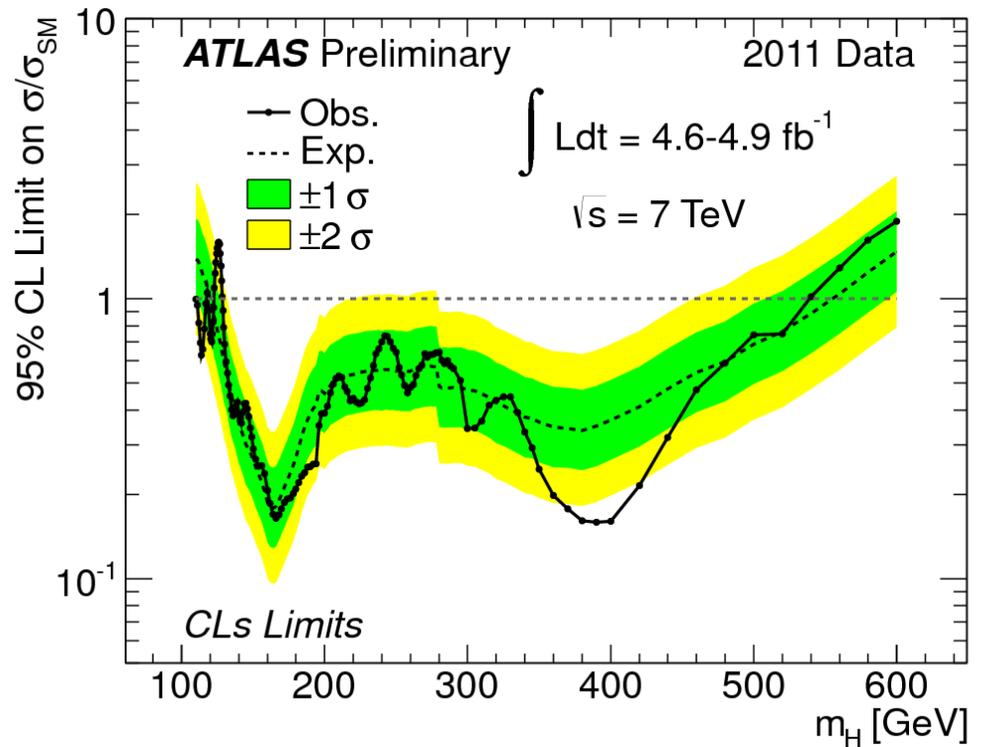
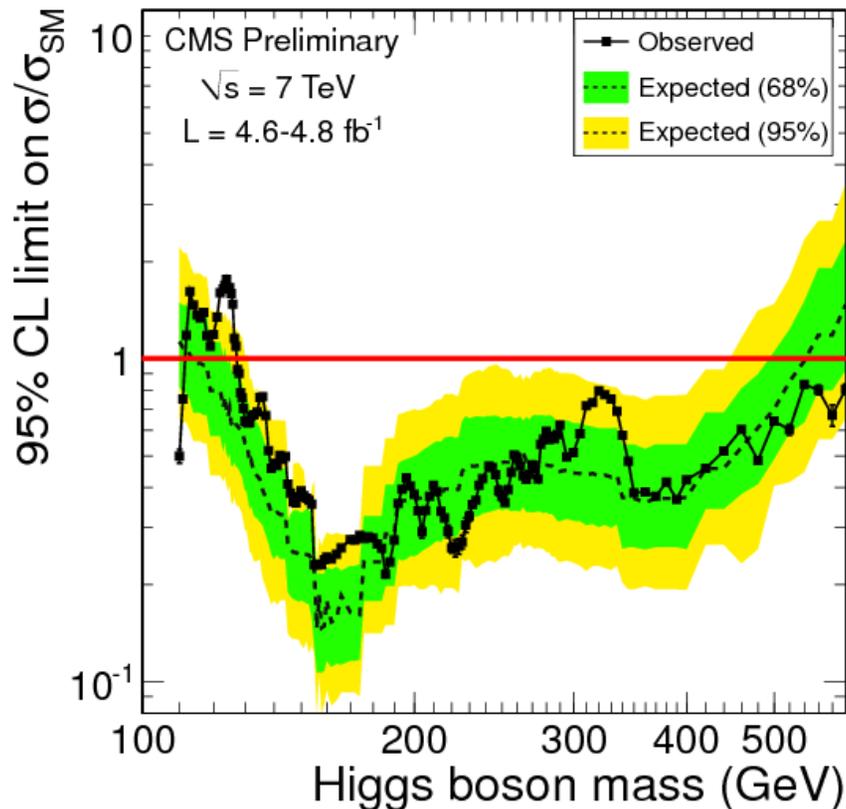


- Observed limit agrees with expected limit to within 2σ over full mass range

Combining the Higgs Search Channels



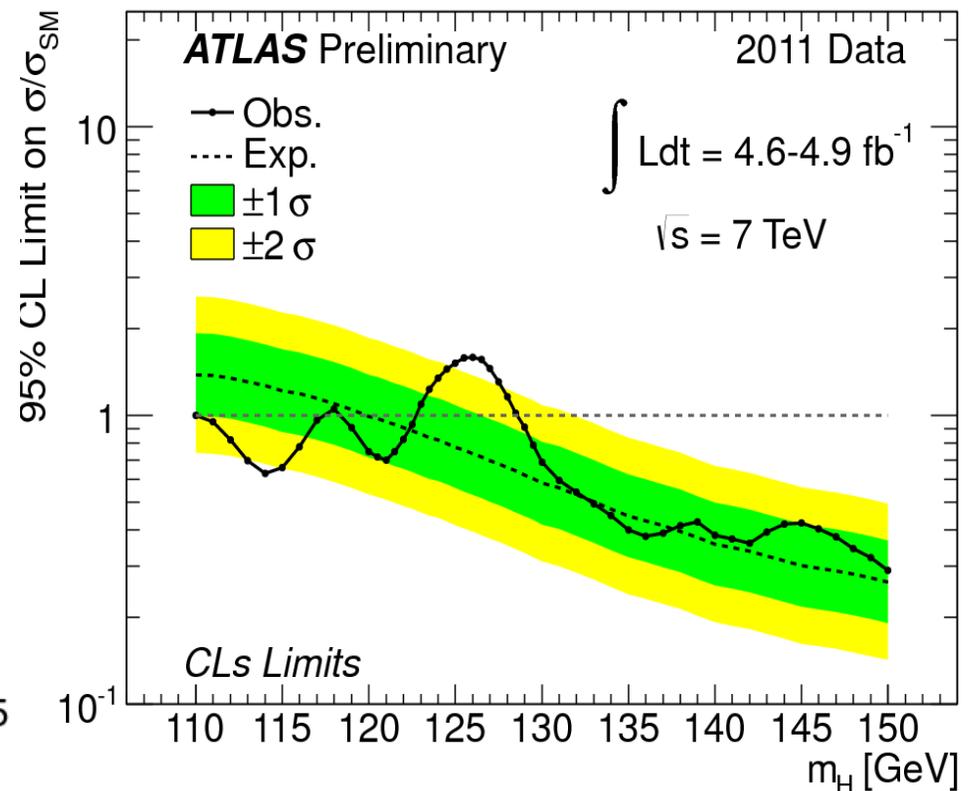
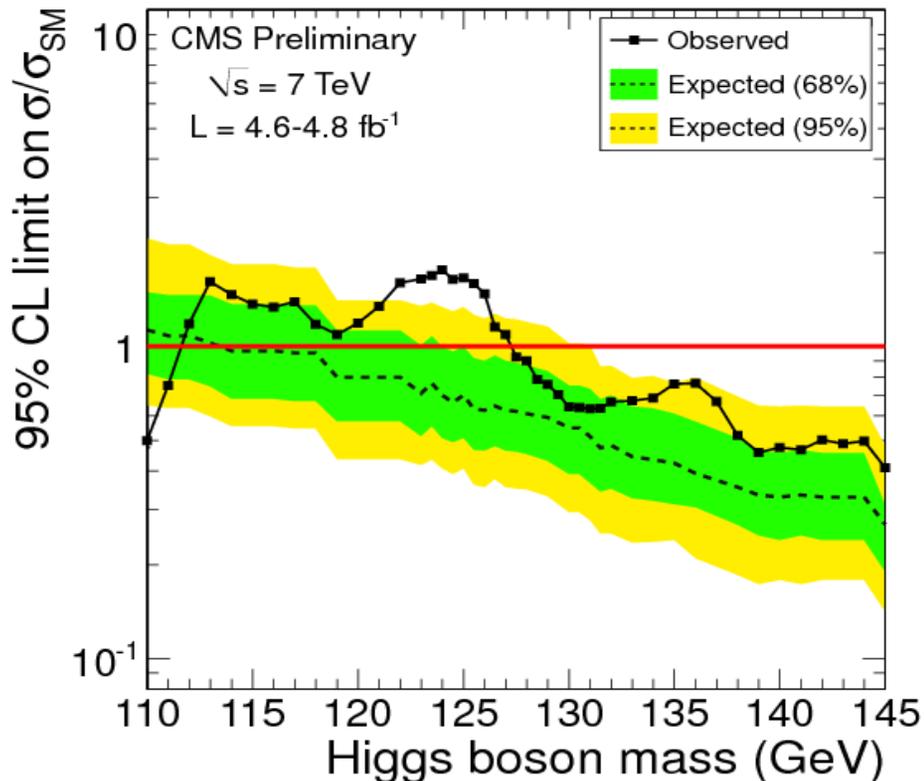
Combined result of Higgs Searches



■ At 95% CL:

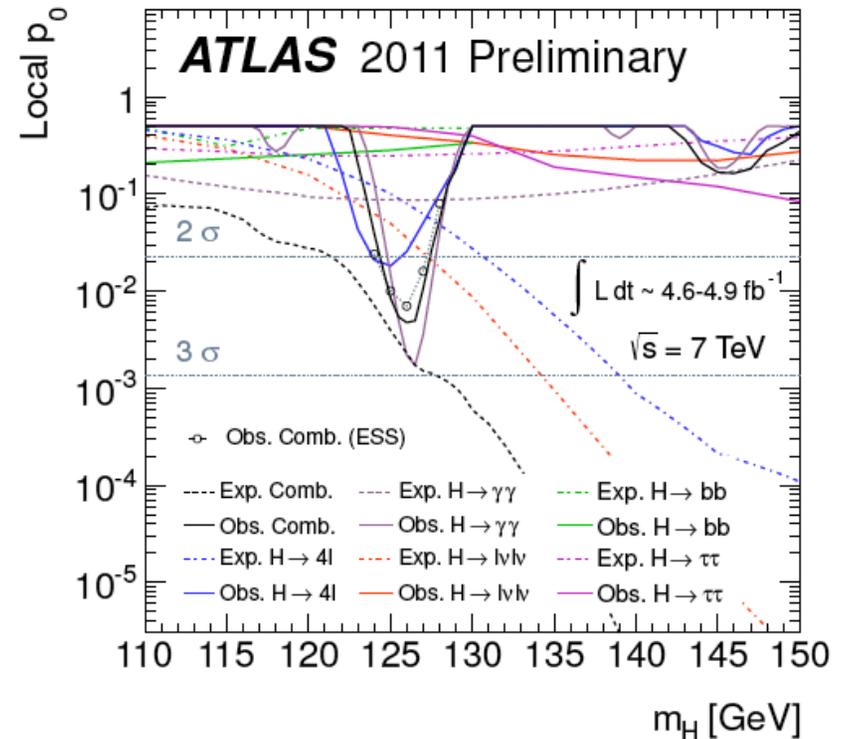
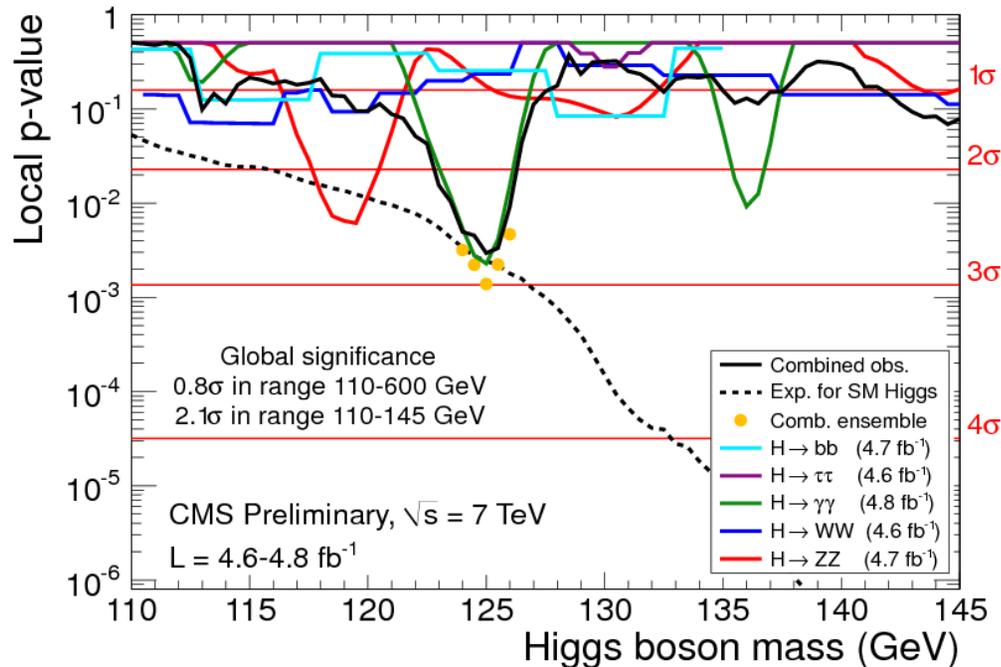
- CMS exclude $127.5 < m_H < 600 \text{ GeV}$
- ATLAS exclude $110-117.5 \text{ GeV}$, $118.5-122.5 \text{ GeV}$ and $129-539 \text{ GeV}$

Combined result of Higgs Searches



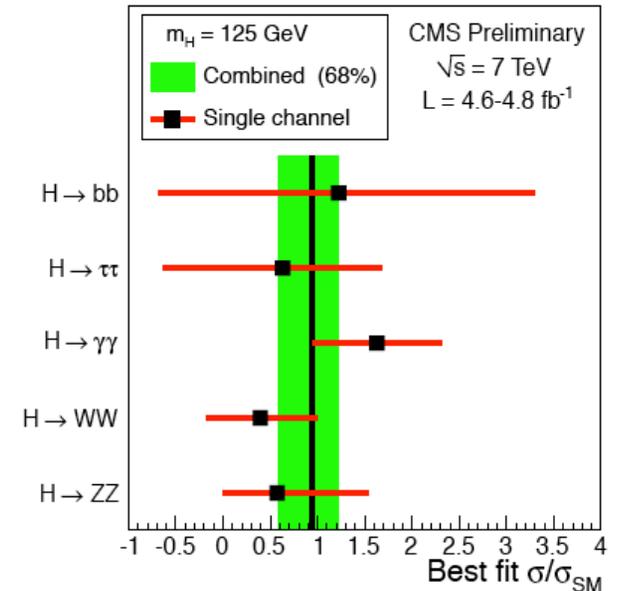
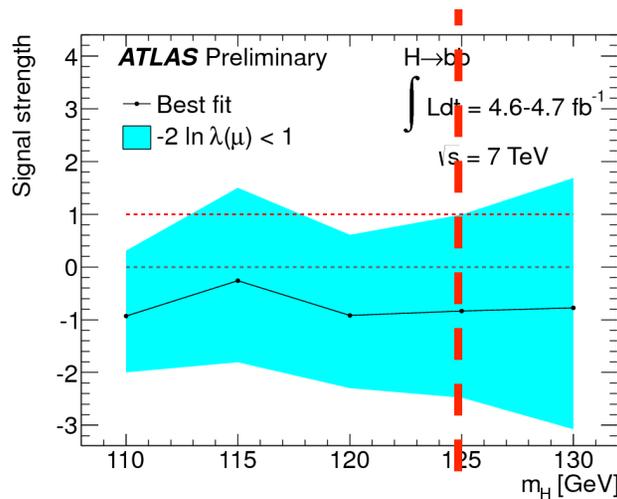
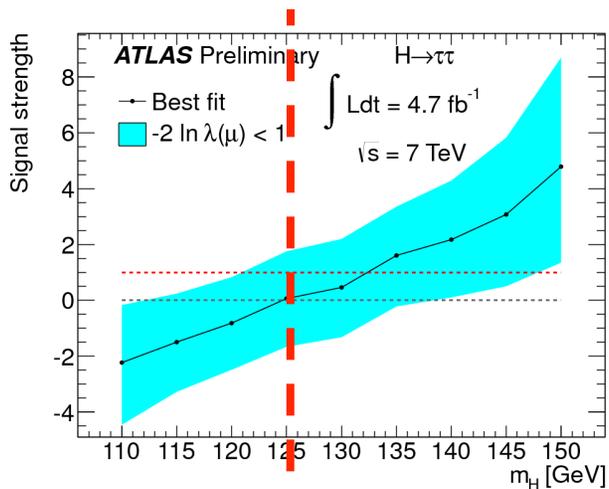
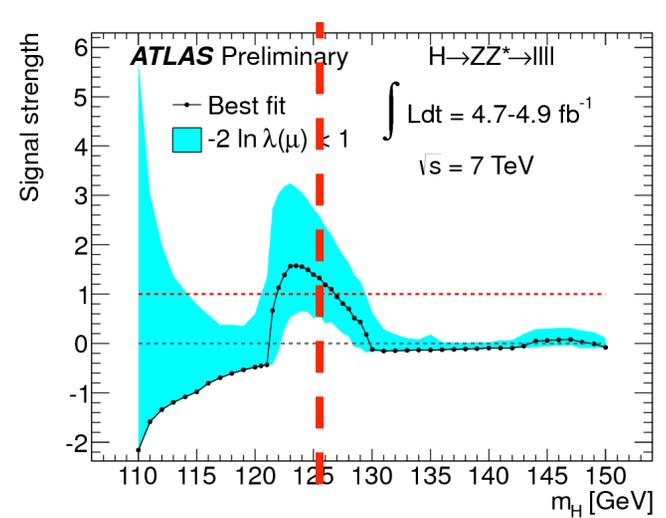
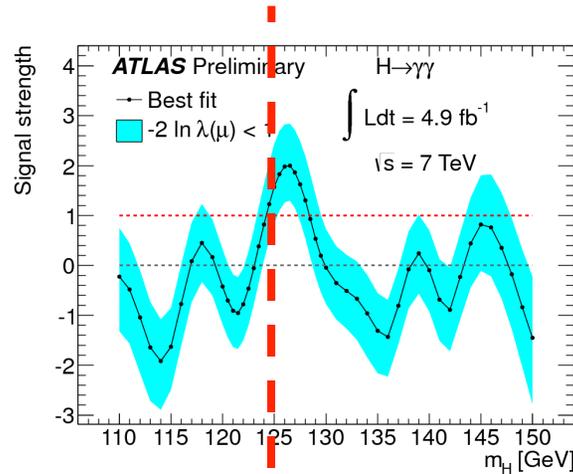
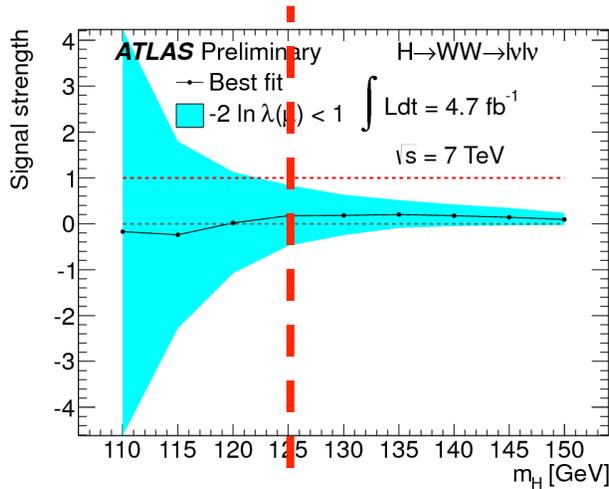
- Local significance of excess 2.5σ (ATLAS) and 2.8σ (CMS)
- Global significance for search window 110-145 GeV:
 - 10% (ATLAS) and 4% (CMS)

Contributions of individual channels



- CMS: excess driven by $\gamma\gamma$
- ATLAS: excess driven by $\gamma\gamma$ and ZZ^*
- Overall signal strength consistent with SM
 - But also with 50% difference!

Are the data compatible with SM Higgs boson?

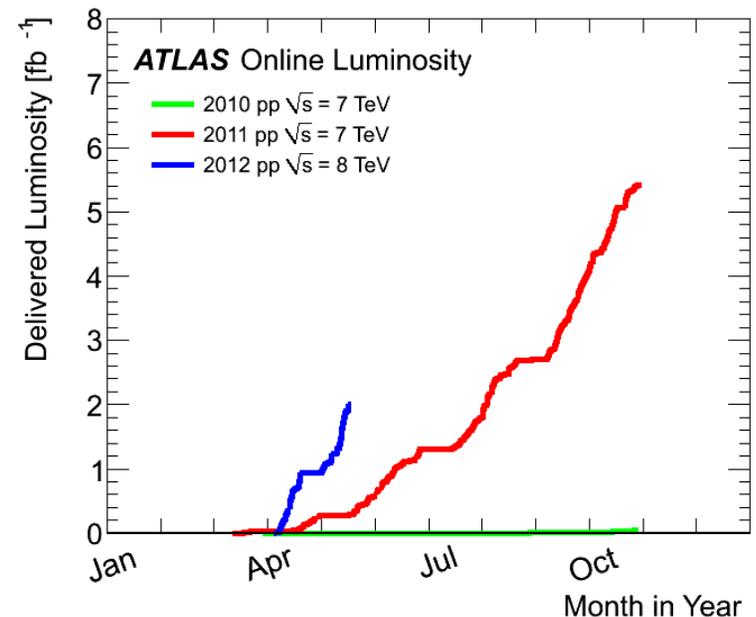


Conclusions and Outlook

- **ATLAS and CMS have made many measurements of SM processes**
 - All agree with SM expectation
 - Some of high precision => challenge theoretical calculations
- **The SM Higgs boson search has entered it's last round!**
 - *Nearly* entire range $m_H < 600$ GeV excluded at 95% CL
 - It's mass is either ~ 125.5 GeV or it does not exist with SM properties
 - Will find out by the end of this year with $\sim 15 \text{ fb}^{-1}$ at $\sqrt{s}=8$ TeV

2012:

Peak $L=5.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$



Happy Birthday Savas!

