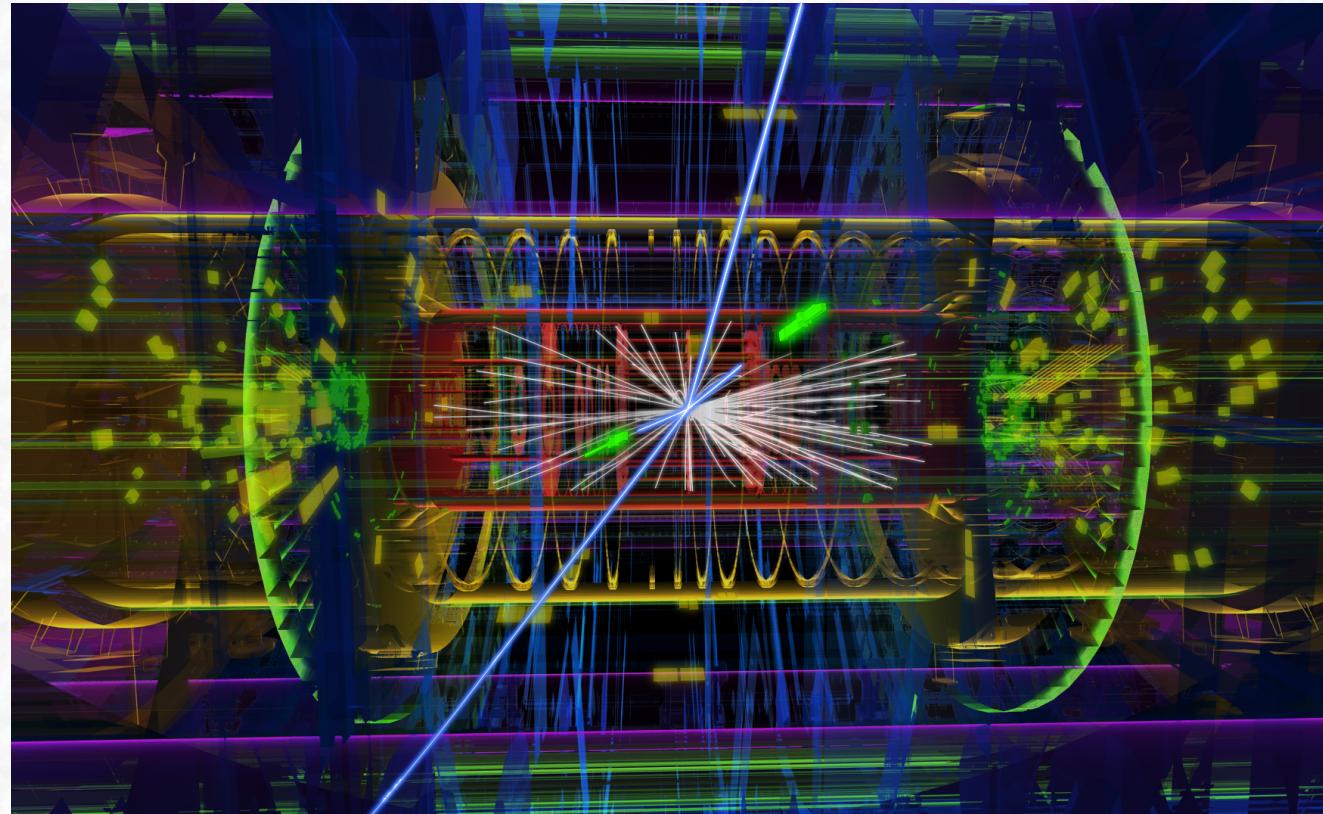


Higgs analyses at the LHC



Karl Jakobs
Physikalisches Institut
Universität Freiburg



From the editorial:

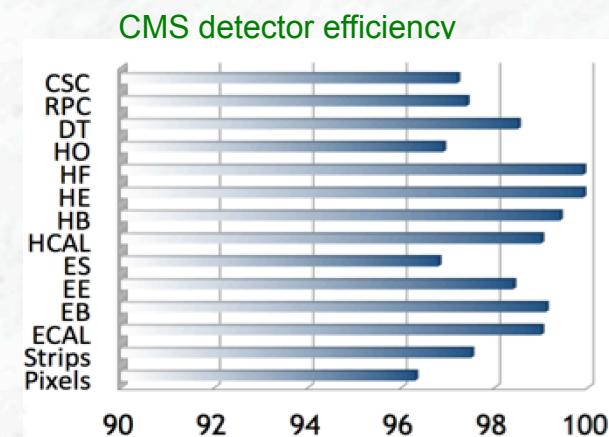
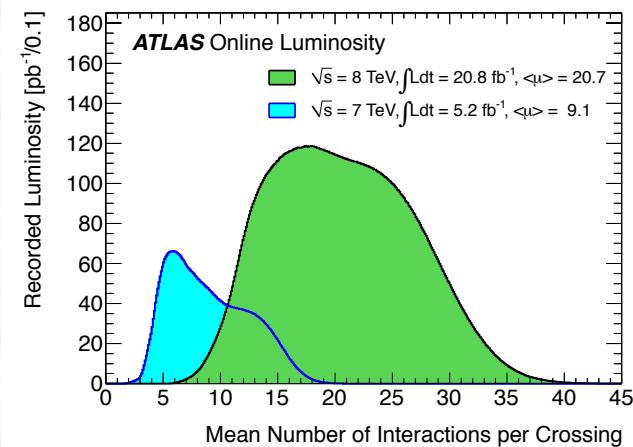
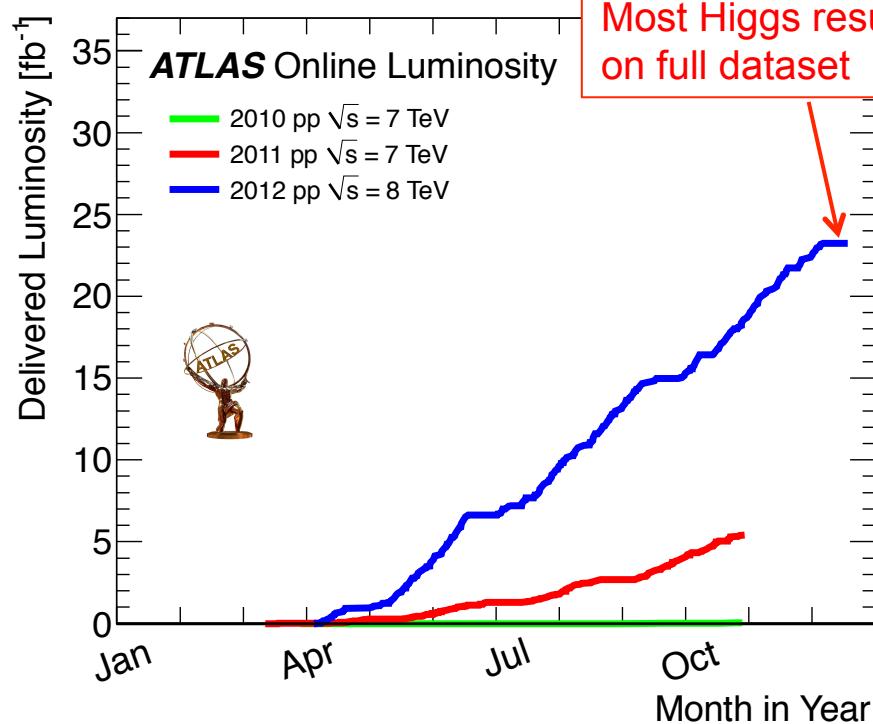
The top Breakthrough of the Year – the discovery of the Higgs boson – was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers

Outline

- **Lecture I:** Introduction and the “easy” decay modes
 - LHC running, the data set
 - Higgs boson production and decays
 - Higgs boson studies in the high resolution channels
 - $H \rightarrow \gamma\gamma$ (in some detail, incl. some detector performance issues)
 - $H \rightarrow ZZ^*$
- **Lecture II:** The more challenging decay modes
 - $H \rightarrow WW^*$
 - Decays into fermions?
- **Lecture III:** Higgs boson parameters
 - How to measure its properties
 - Couplings to fermions and boson
 - Spin / parity

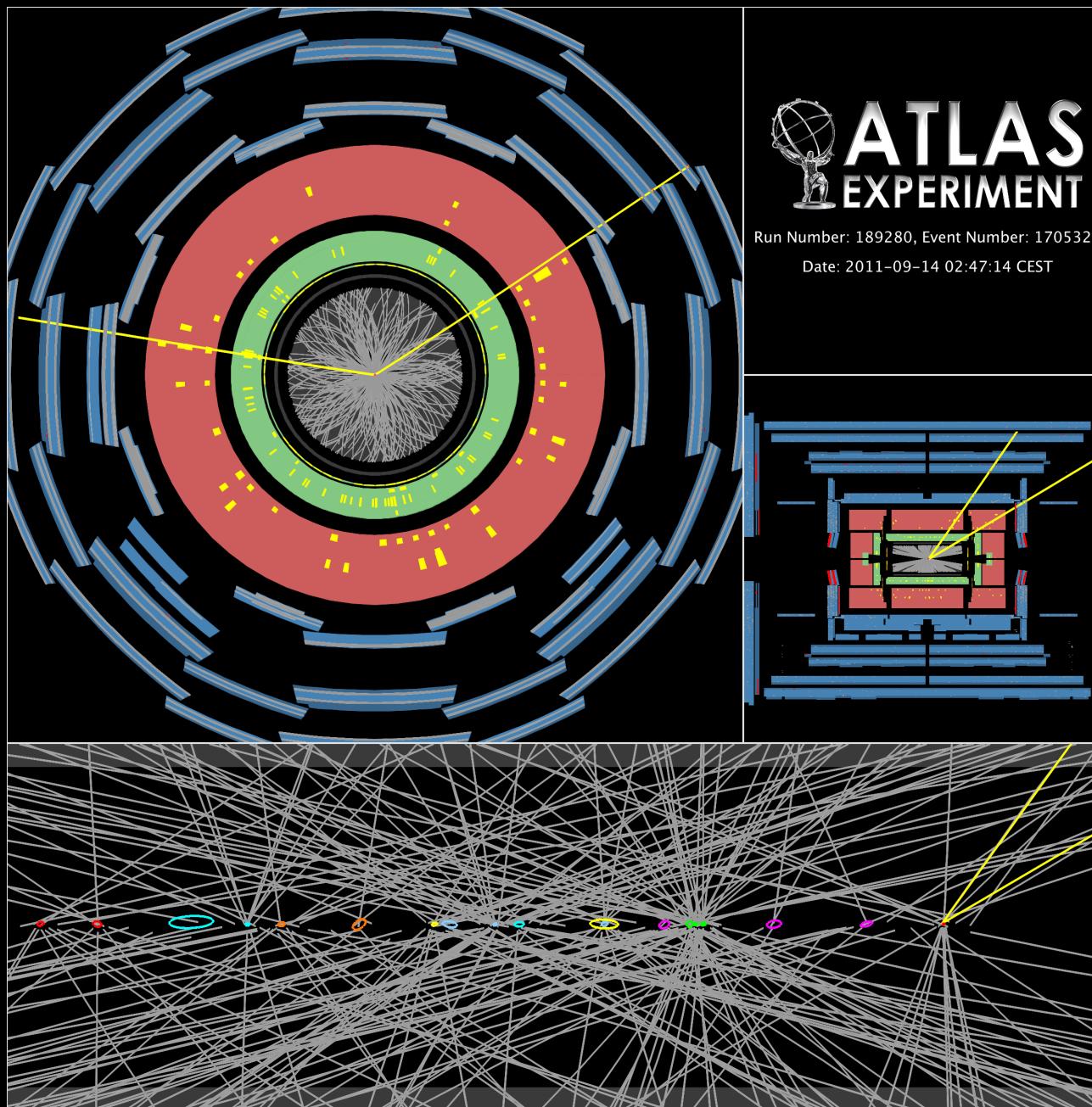
Disclaimer: I will try to discuss important analyses and measurements. The coverage is not complete, i.e. not all results available are presented; Results from both general purpose experiments, ATLAS and CMS, are shown, but there might still be a bias towards the experiment I am working on. This bias is not linked to the scientific quality of the results.

Summary of LHC and ATLAS/CMS performance

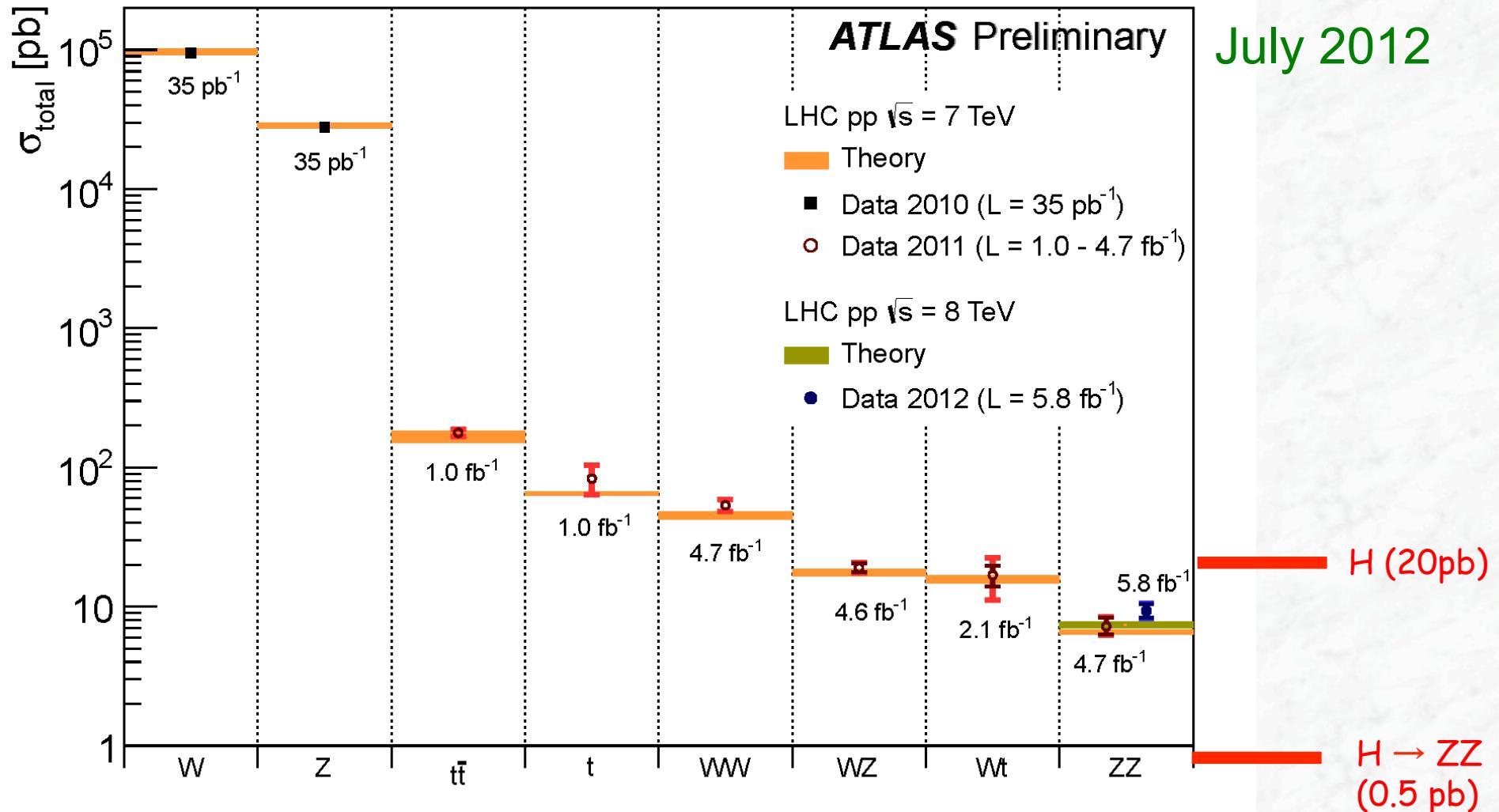


- Excellent LHC performance in 2011 and 2012
- Peak luminosities $> 7 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- High level of pileup: mean of ~ 21 interactions / beam crossing in 2012
- Excellent performance of the experiments: (Data recording efficiency: $\sim 93.5\%$ (ATLAS) working detector channels $> 99\%$ for most sub-detectors, high data quality, speed of the data analysis)

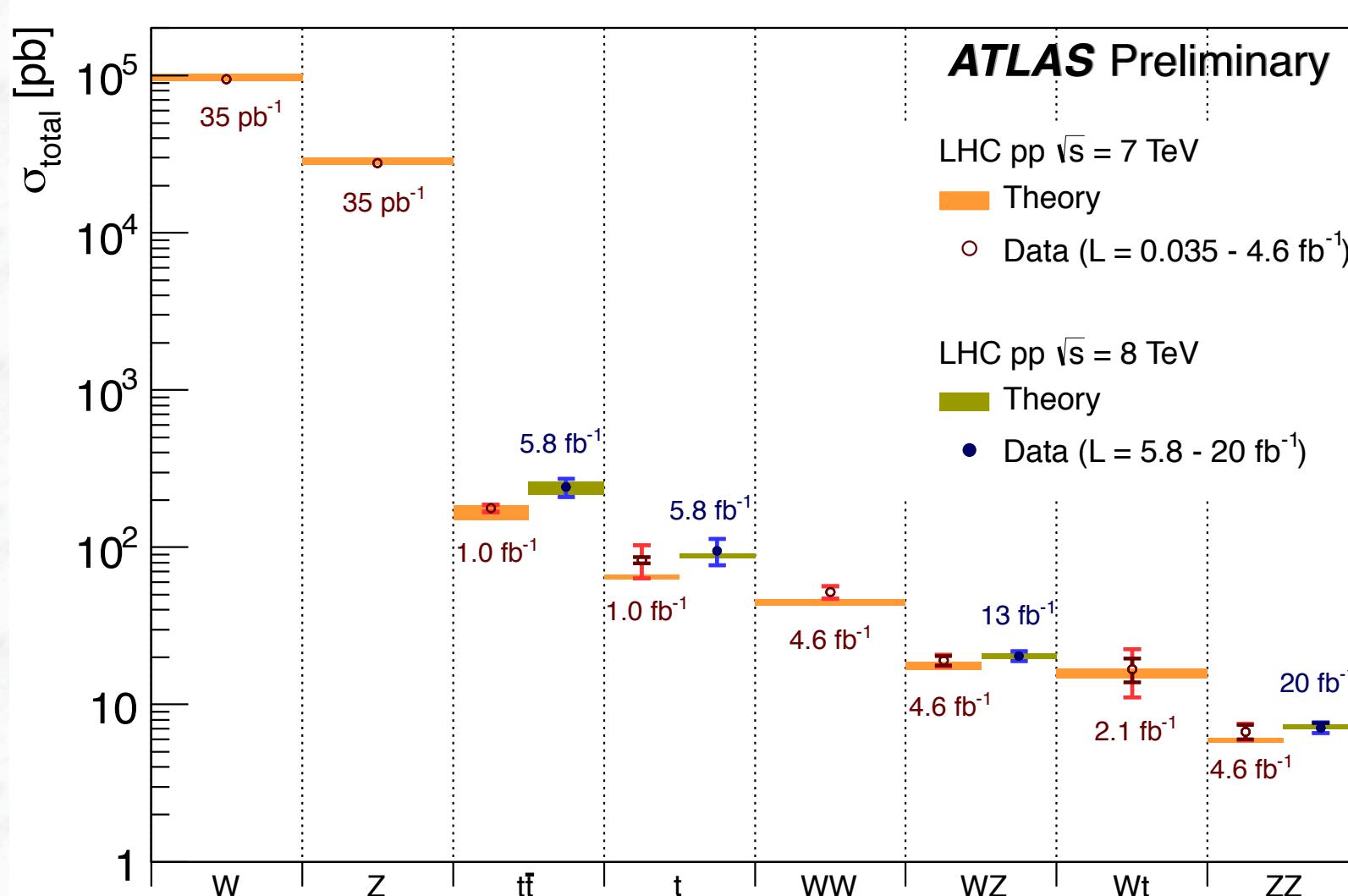
$Z \rightarrow \mu^+ \mu^-$ with 20 reconstructed pp vertices



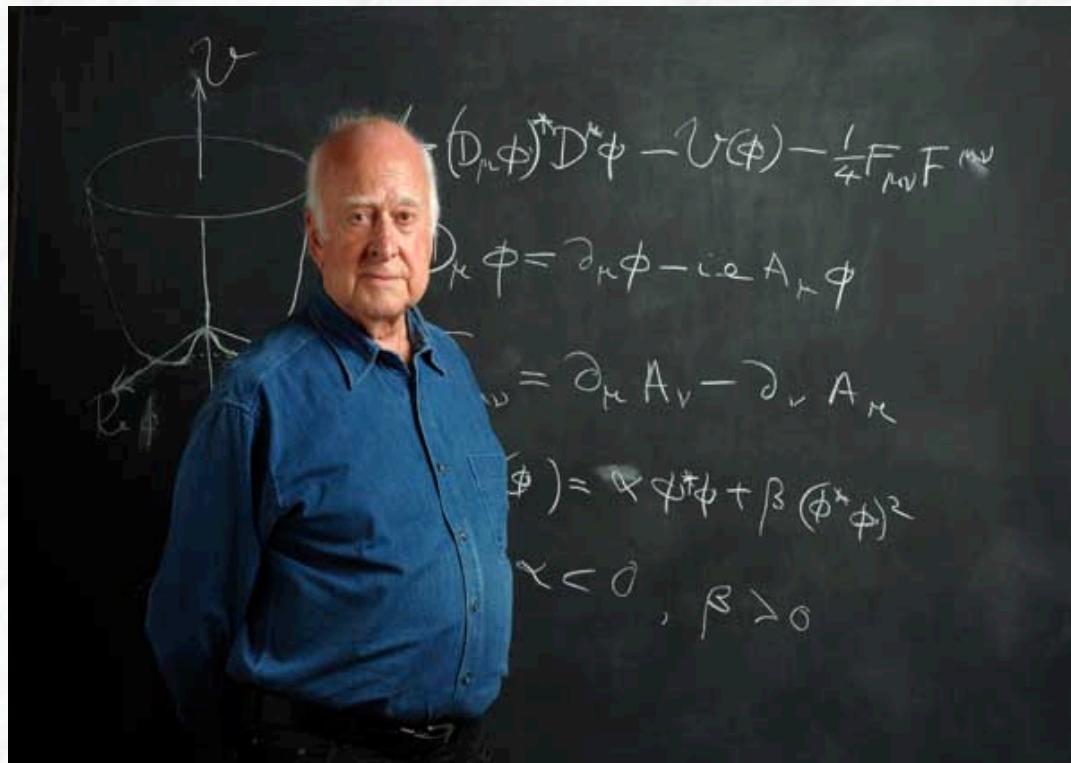
The Standard Model at the LHC



Standard Model processes at the LHC



The Brout-Englert-Higgs Mechanism



→ Lecture by M. Schmaltz

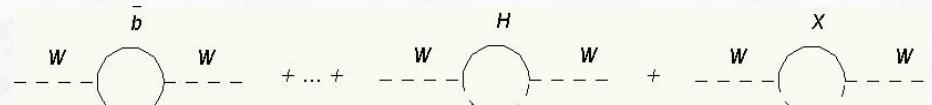
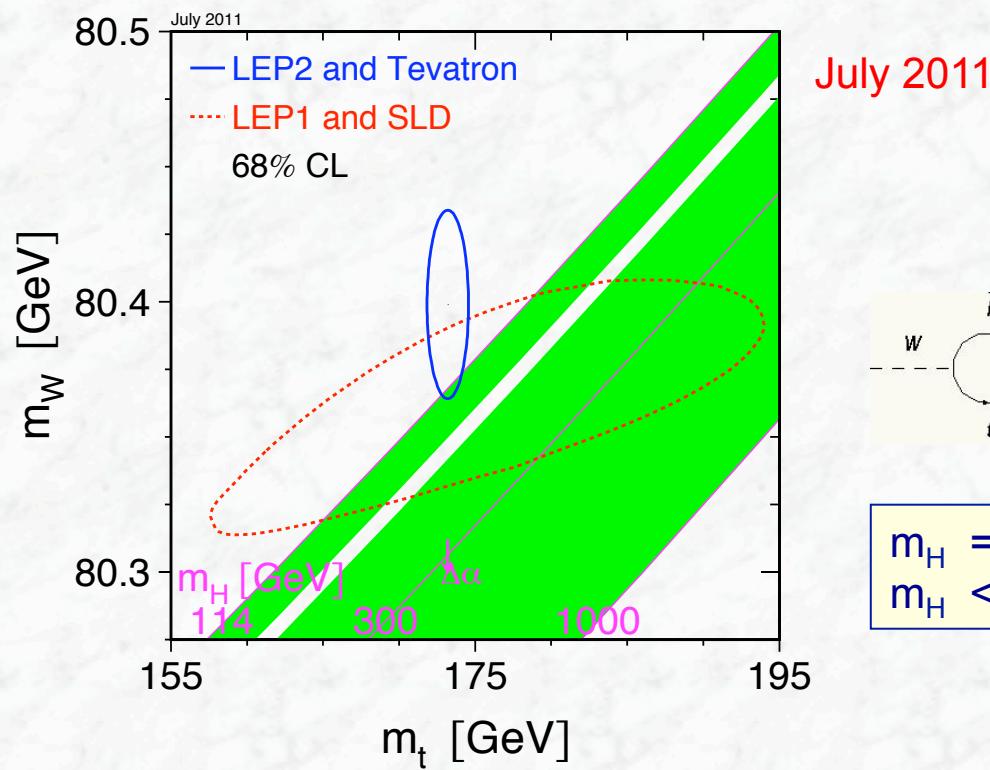
F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;

P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;

G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

Constraints on the Higgs boson mass (before LHC)

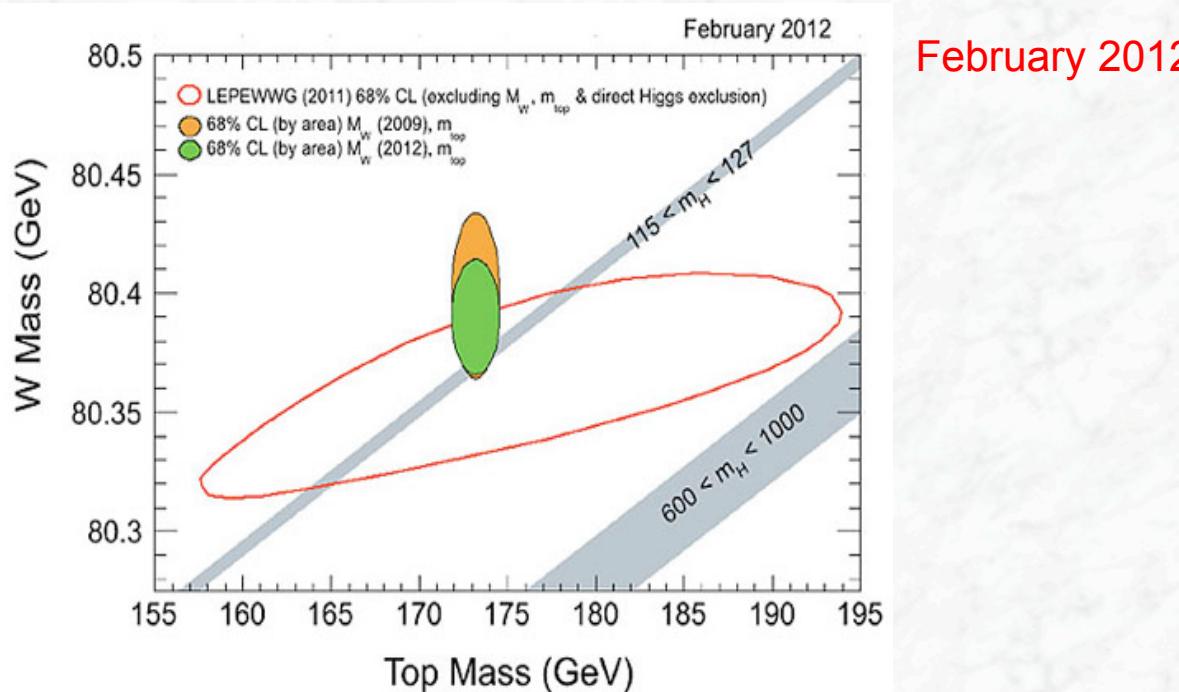
- $m_H > 114.4 \text{ GeV}/c^2$ from direct searches at LEP
- $m_H < 156 \text{ GeV}/c^2$ or $m_H > 177 \text{ GeV}/c^2$ from direct searches at the Tevatron



$m_H = 92^{+34}_{-26} \text{ GeV}/c^2$
 $m_H < 161 \text{ GeV}/c^2 \quad (95 \% \text{ C.L.})$

- Indirect constraints from precision measurements (quantum corrections)

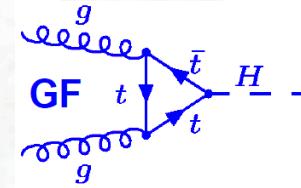
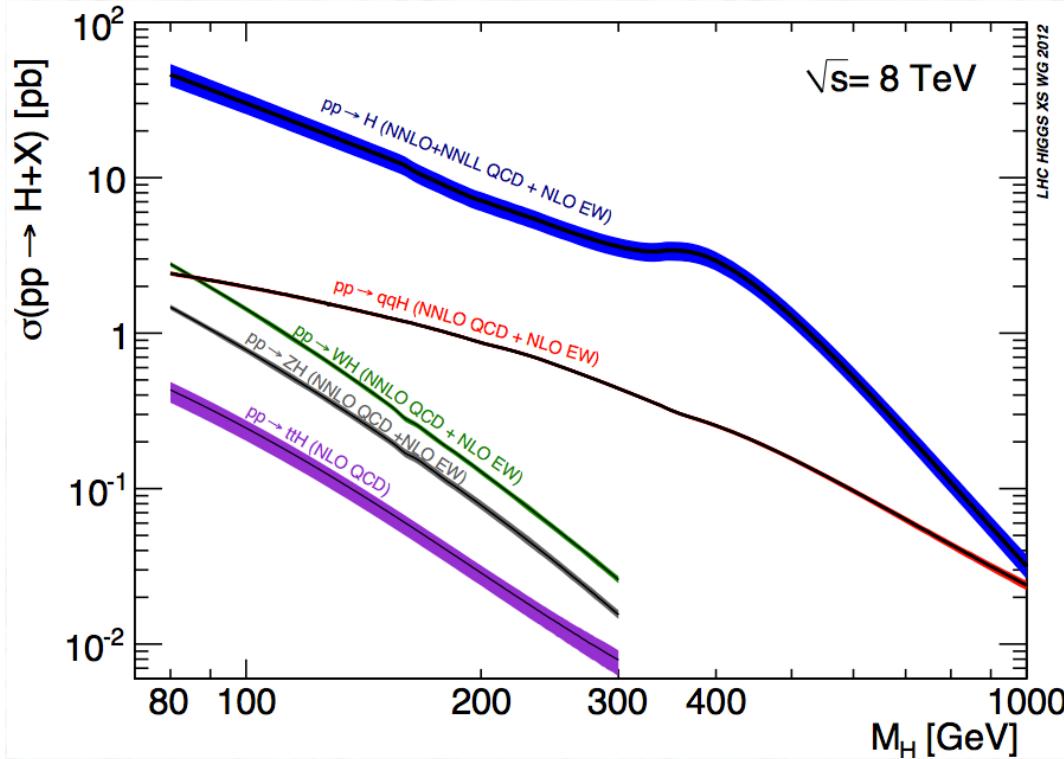
Constraints on the Higgs boson mass (Feb. 2012)



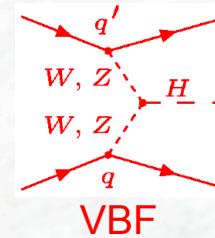
Two impressive results (2011/12):

- LHC has ruled out a huge mass range, after only ~2 years of data taking (only a narrow mass range left open at low mass)
- Impressive precision in m_W (and m_t) achieved at the Tevatron (might provide the basis for the ultimate test of the Standard Model)

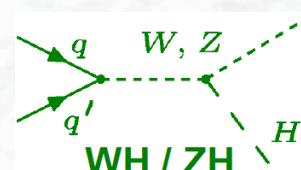
Higgs Boson Production



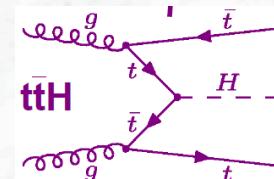
Gluon fusion



Vector boson
fusion



WH/ZH
associated
production



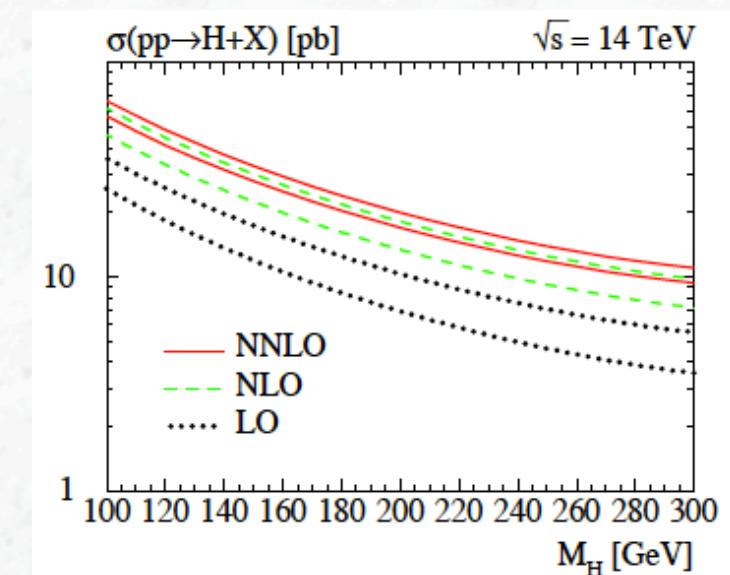
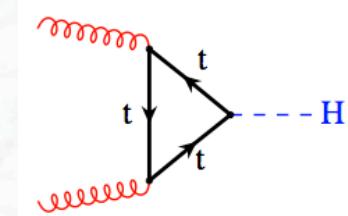
$t\bar{t}$ associated
production

*) LHC Higgs cross-section working group

- Large theory effort, huge progress in perturbative calculations during the past 20 years
- (N)NLO precision (QCD and el. weak) for nearly all production processes

Gluon fusion:

- Dominant production mode
- Sensitive to heavy particle spectrum ...
(e.g. 4th generation quarks)
...and the corresponding Yukawa couplings
(important for coupling measurements, top Yukawa coupling)
- Large K-factors (NLO, NNLO corrections)
 - Difficult to calculate, loop already at leading order
(calculation with infinite top mass is used as an approximation, however, this seems to be a good approximation)
 - Nicely converging perturbative series;
residual uncertainty estimated to be of order 15%.
(variation of renormalization and factorization scales)
- In addition, NNLL re-summation of soft QCD radiation
- NLO el.weak corrections available as well



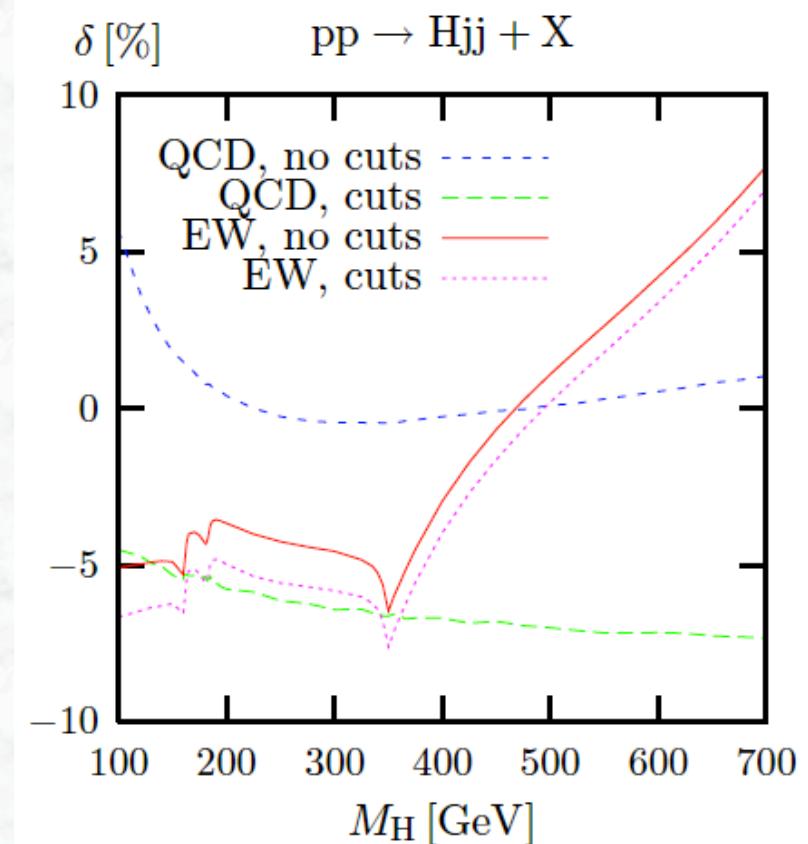
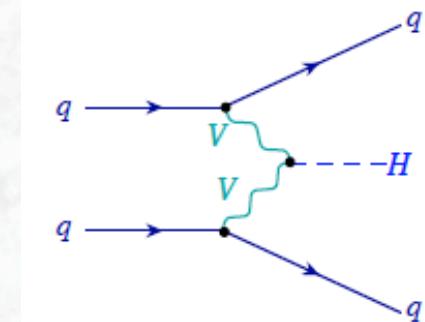
- Spira, Djouadi, Graudenz, Zerwas (1991)
- Dawson (1991)
- Harlander, Kilgore (2002)
- Anastasiou, Melnikov (2002)
- Ravindran, Smith, van Neerven (2003)
- Catani, De Florian, Grazzini, Nason (2003)
- Aglietti et al, (2004), Actis et al. (2008)

Vector boson fusion:

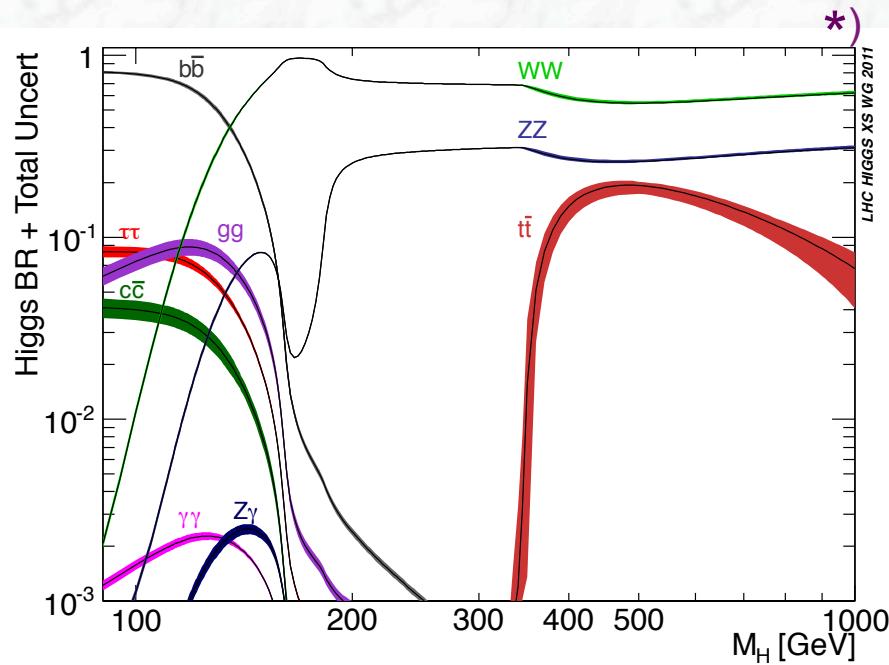
- Second largest production mode,
Distinctive signature
(forward jets, little jet activity in the central region)
- Sensitivity to W/Z couplings
- Both NLO QCD and el.weak corrections
have been calculated
(moderate K-factors)
Approx. NNLO QCD calculation available
(Bolzoni et al. 2010)
- Effective K-factor depends on
experimental cuts

Example: typical VBF cuts
 $P_T(\text{jet}) > 20 \text{ GeV}$
 $\eta < 4.5, \Delta\eta > 4, \eta_1 \cdot \eta_2 < 0$

Ciccolini, Denner, Dittmaier (2008)



Higgs Boson Decays



Useful decays at a hadron collider:

- Final states with leptons via WW and ZZ decays
- $\gamma\gamma$ final states (despite small branching ratio)
- $\tau\tau$ final states (more difficult)
- In addition: $H \rightarrow bb$ decays via associated lepton signatures (VBF, VH or ttH production)

SM predictions ($m_H = 125.5$ GeV):

$$BR(H \rightarrow WW) = 22.3\%$$

$$BR(H \rightarrow ZZ) = 2.8\%$$

$$BR(H \rightarrow \gamma\gamma) = 0.24\%$$

$$BR(H \rightarrow bb) = 56.9\%$$

$$BR(H \rightarrow \tau\tau) = 6.2\%$$

$$BR(H \rightarrow \mu\mu) = 0.022\%$$

→ at 125 GeV: only ~11% of decays not observable (gg, cc)

125 GeV is a perfect mass !

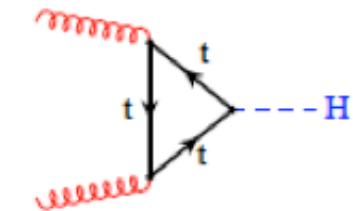
~89 % of Higgs boson decays accessible

*) LHC Higgs cross-section working group

The important Higgs boson search channels at the LHC

(i) The bosonic decay channels

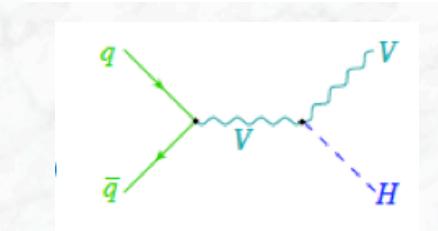
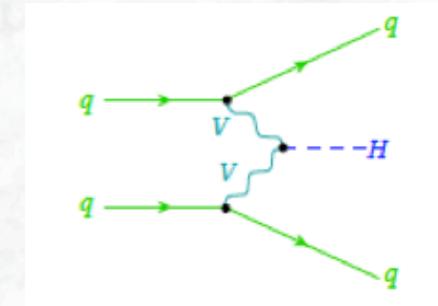
Important channels:

$$H \rightarrow \gamma\gamma$$
$$H \rightarrow ZZ \rightarrow l^+l^- l^+l^-$$
$$H \rightarrow WW \rightarrow l\nu l\nu$$


- dominated by gluon fusion
- valuable contributions from vector boson fusion

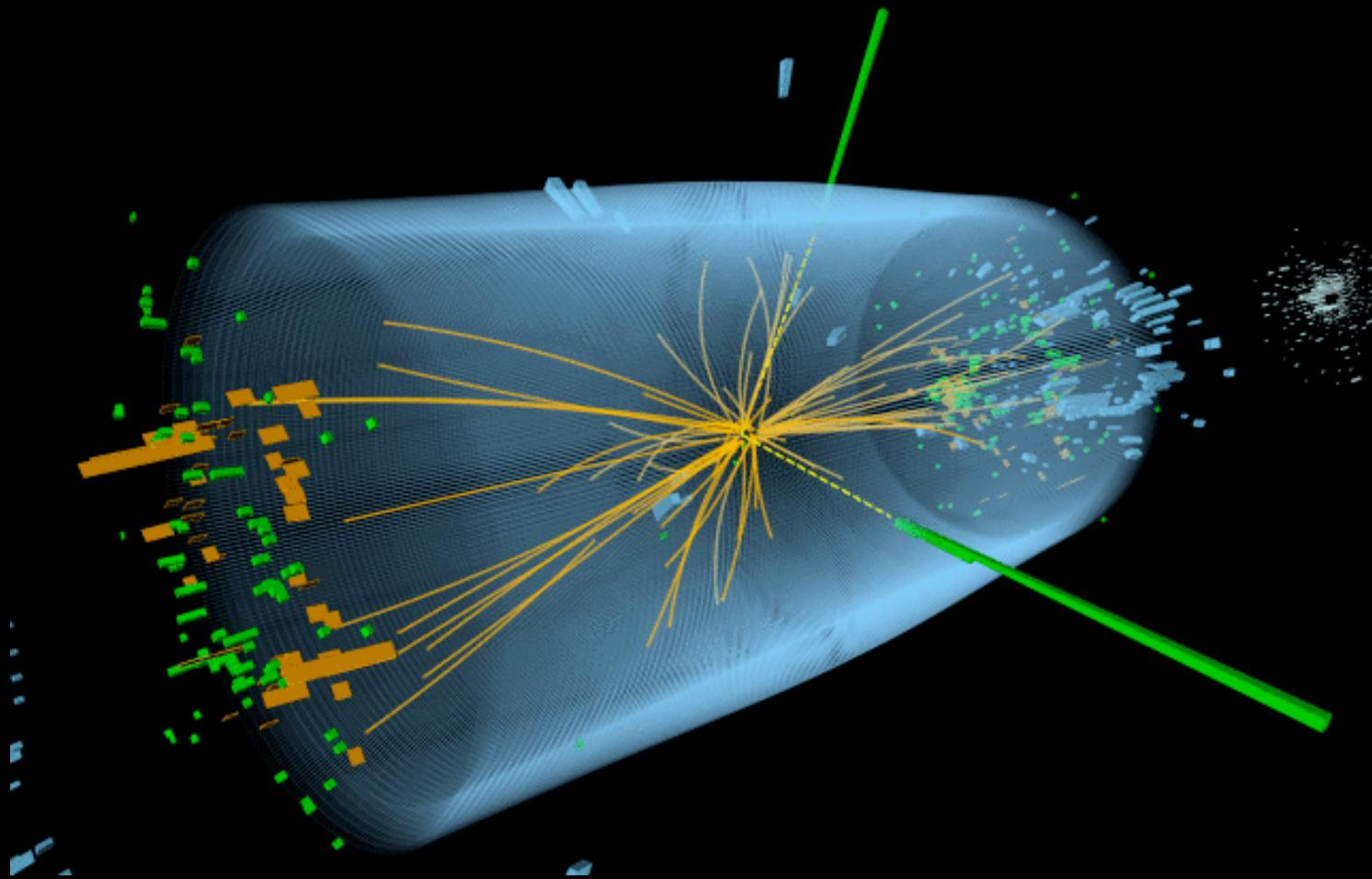
(ii) The fermionic decay channels

Important channels:

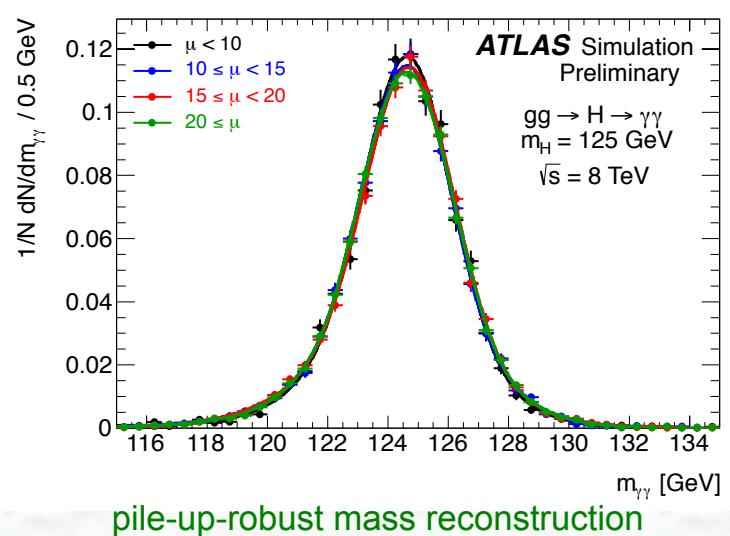
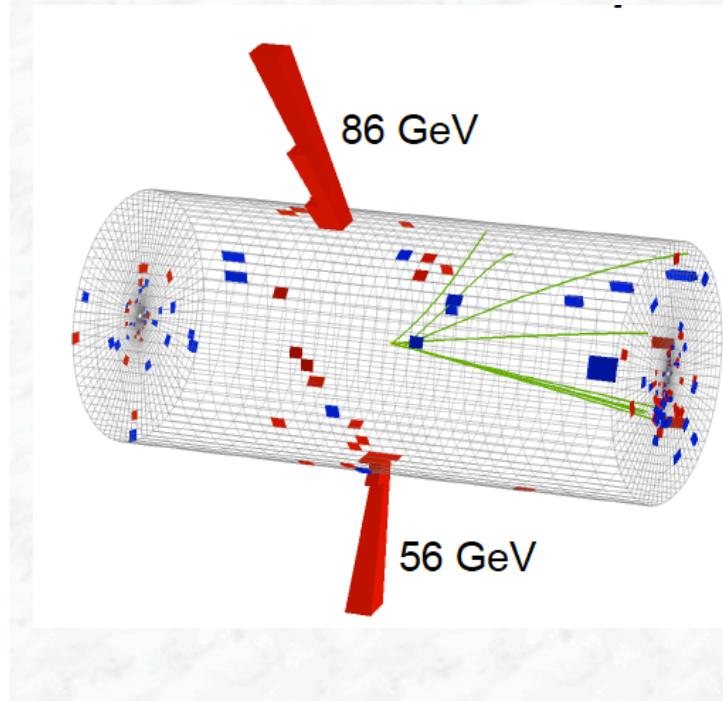
$$q\bar{q} H \rightarrow q\bar{q} \tau\tau$$
$$VH, V \rightarrow ll \quad (l=e,\mu,\nu) \quad H \rightarrow bb$$


- Associated production essential for bb decays
(suppression against overwhelming backgrounds from multijet production)
- exploit VBF topology (tag jets, no colour flow in central region)
high-p_T topologies

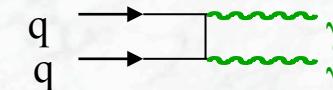
Search for the $H \rightarrow \gamma\gamma$ decay



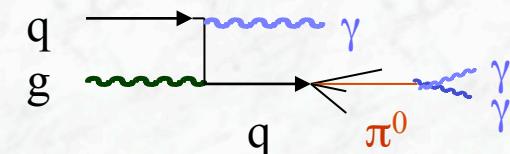
Result of the ATLAS search for $H \rightarrow \gamma\gamma$



- Two photons (isolated) with large transverse momentum ($P_T > 40, 30 \text{ GeV}$)
- Mass of the Higgs boson can be reconstructed $m_{\gamma\gamma}$
 Both experiments have a good mass resolution
 ATLAS: $\sim 1.7 \text{ GeV}/c^2$ for $m_H \sim 120 \text{ GeV}$
 Different calorimeters \rightarrow different γ -performance
- Challenge: signal-to-background ratio
 - irreducible $\gamma\gamma$ background



- reducible backgrounds from γj and jj
 (several orders of magnitude larger than the irreducible one, before selections / isolation)

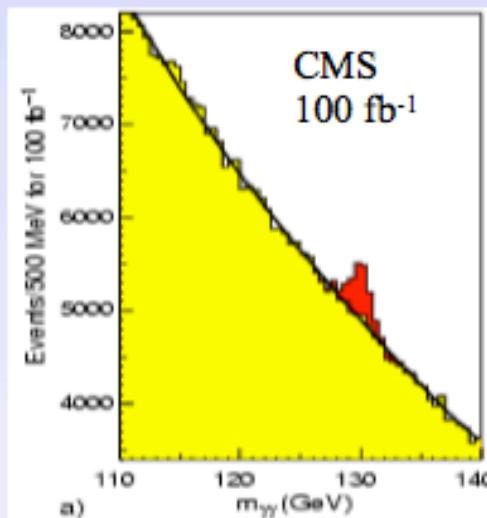
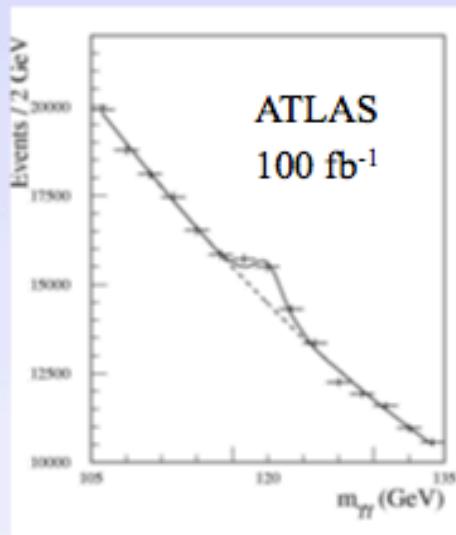


How does the expected signal look like ?

What is the signal-to-background situation

Result of simulation studies (ATLAS and CMS, ~1998)

H $\rightarrow \gamma\gamma$ (cont.)



Two isolated photons:
 $P_T(\gamma_1) > 40 \text{ GeV}$
 $P_T(\gamma_2) > 25 \text{ GeV}$
 $|\eta| < 2.5$

Mass resolution: $m_H = 100 \text{ GeV}/c^2$

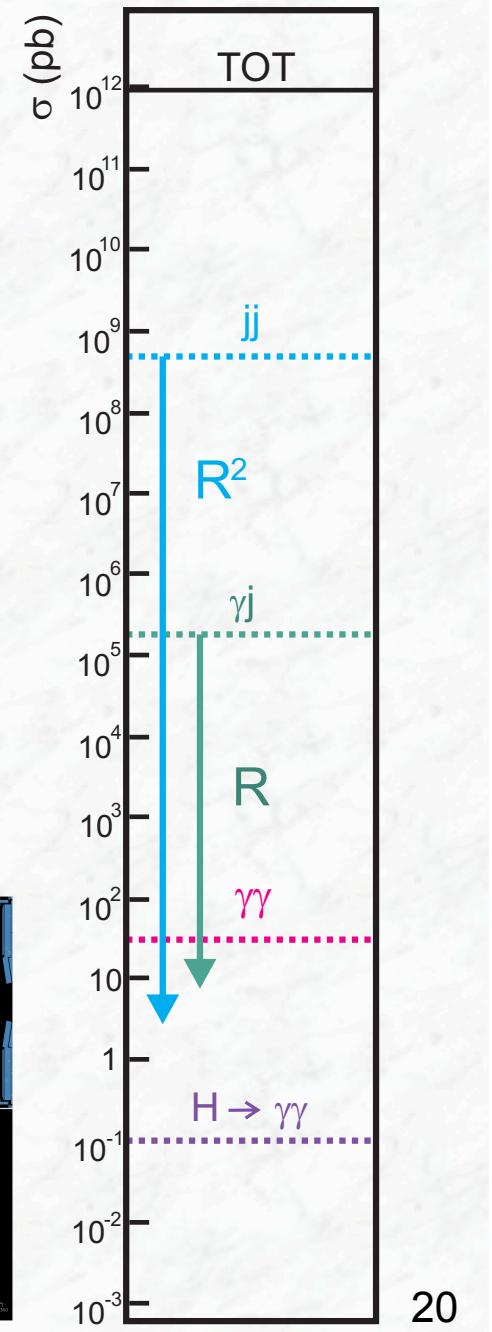
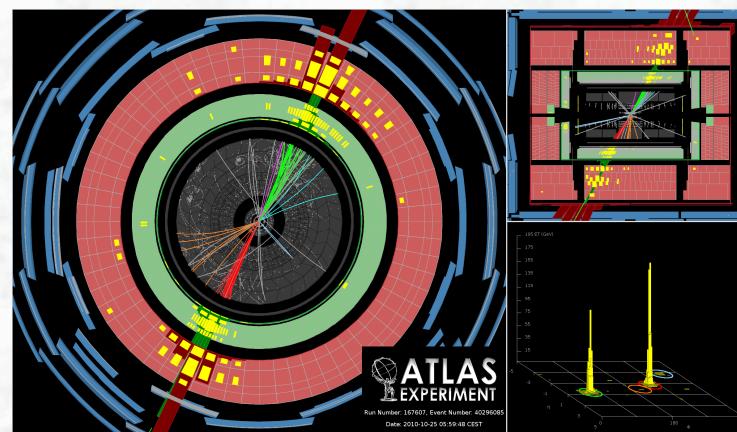
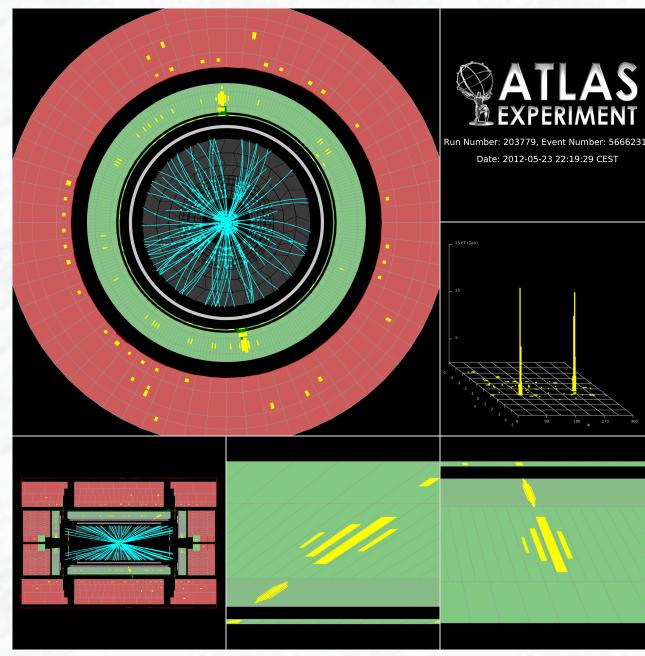
ATLAS : 1.1 GeV (LAr-Pb)
CMS : 0.6 GeV (crystals)

Signal / background $\sim 4\%$ (Sensitivity in mass range $100 - 140 \text{ GeV}/c^2$)
background (dominated by $\gamma\gamma$ events *) can be determined from side bands
important: $\gamma\gamma$ -mass resolution in the calorimeters, γ / jet separation

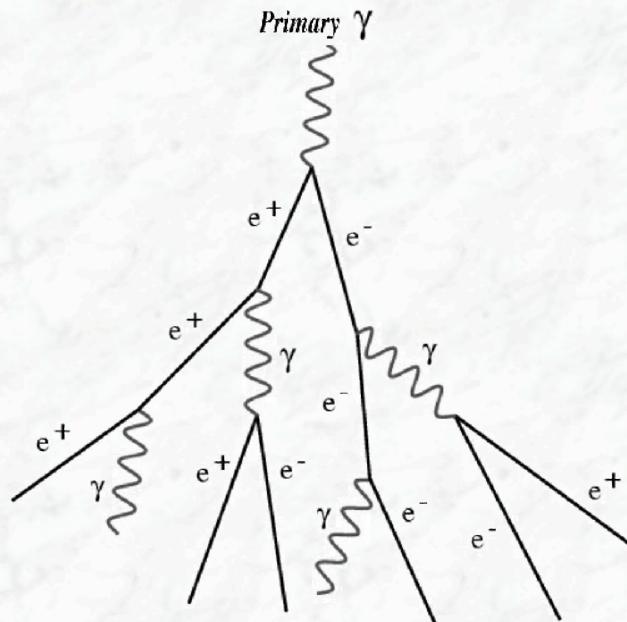
*) detailed simulations indicate that the γ -jet and jet-jet background can be suppressed to the level of 10-20% of the irreducible $\gamma\gamma$ -background

The key ingredients:

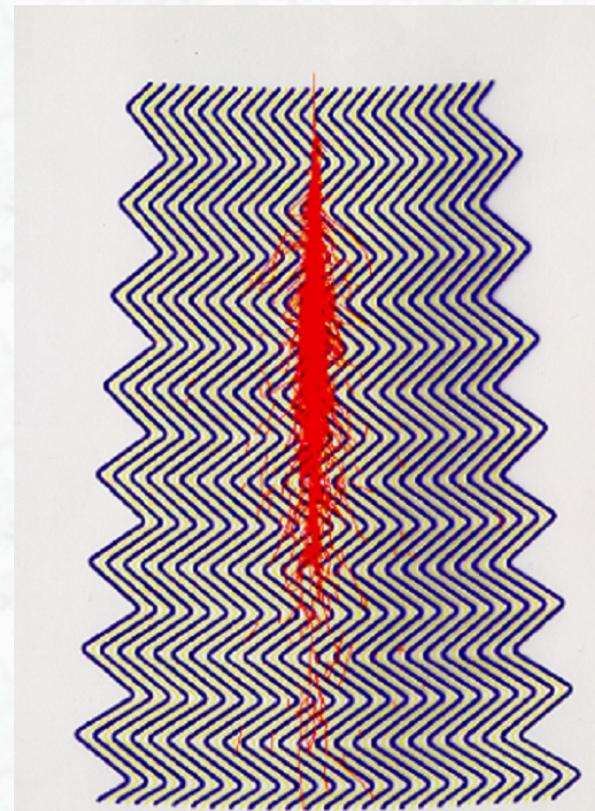
1. Good photon identification (γ /jet separation)
 2. Good mass resolution
- excellent electromagnetic calorimetry



Identifying Photons – Basics of Calorimeter Design



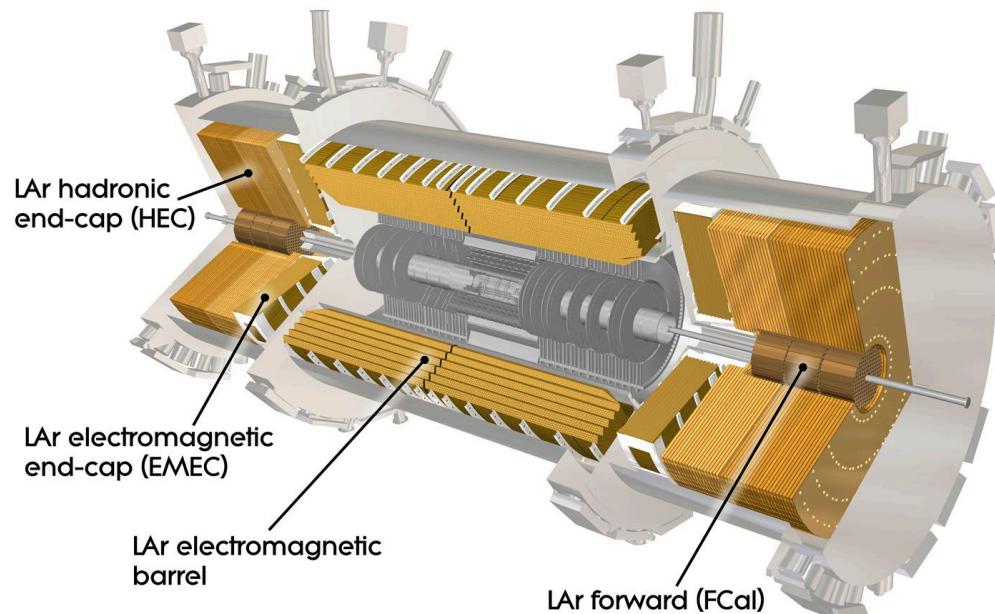
A schematic of an
electromagnetic shower



A GEANT simulation of an
electromagnetic shower

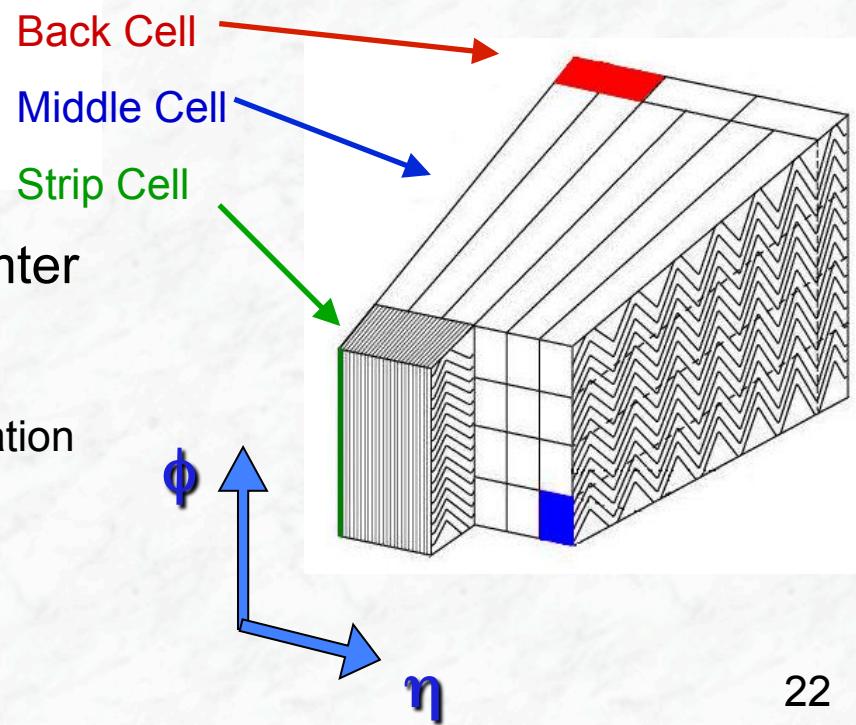
- } Not too much or too little energy here.
- } Exactly one photon
 - not 0 (a likely hadron) or 2 (likely π^0)
- } Not too wide here.
- } One photon and not two nearby ones (again, a likely π^0)
- } Not too much energy here.
- } Indicative of a hadronic shower: probably a neutron or K_L .

ATLAS Calorimetry

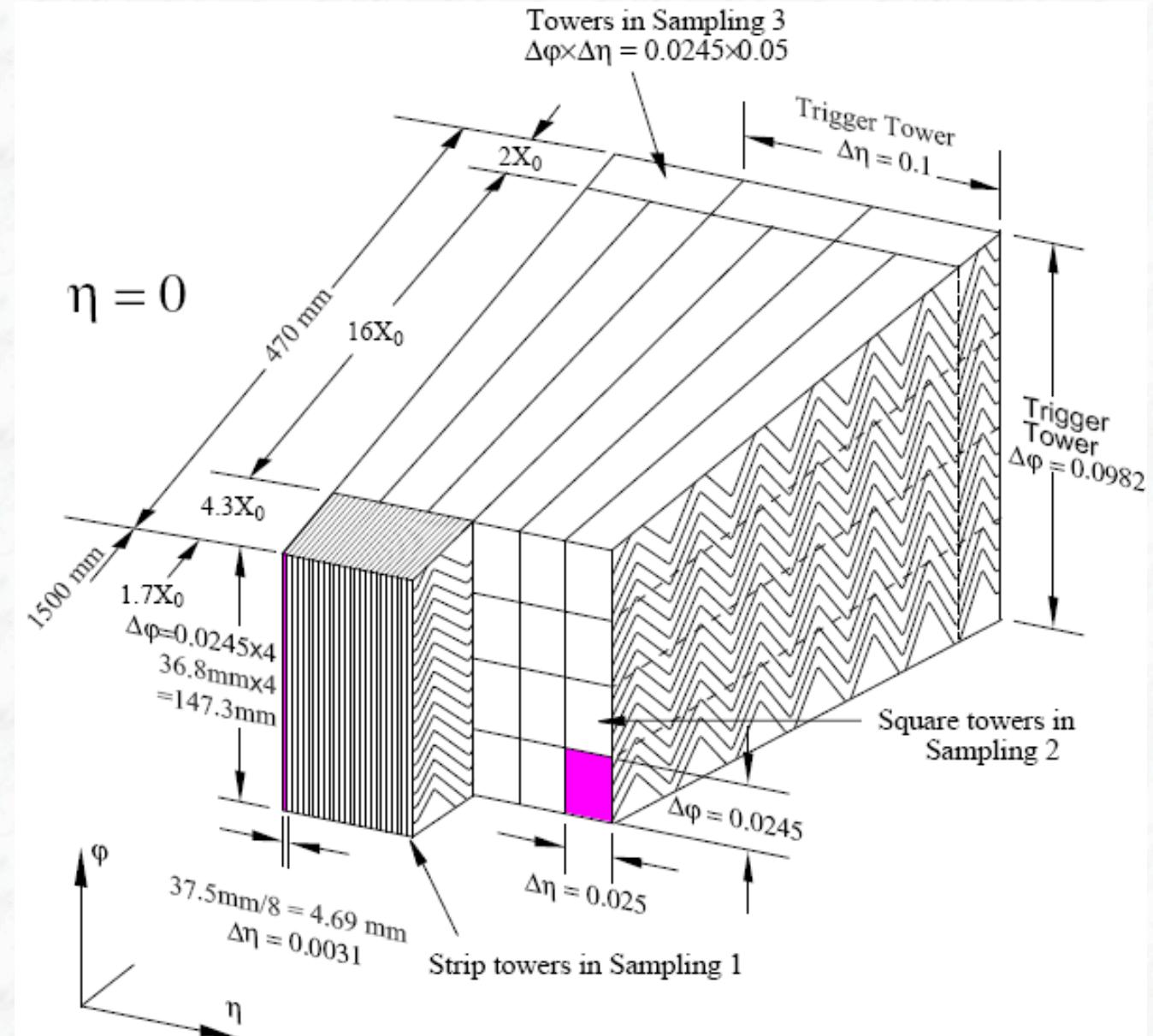


- Liquid argon sampling el.magn. calorimter
 - - Electrical signals, high stability
 - High granularity and longitudinal segmentation
 - Radiation resistant
 - Good energy resolution

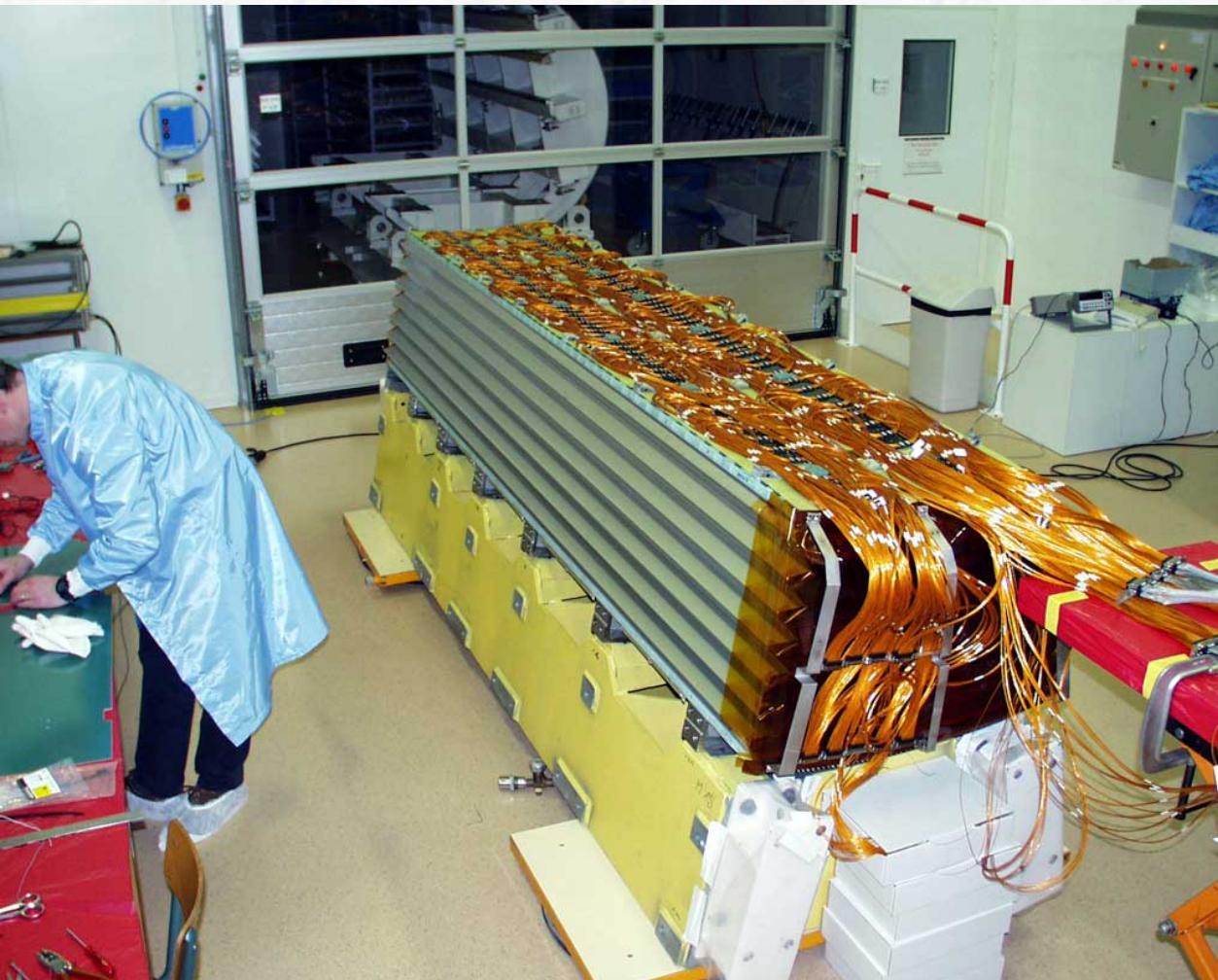
$$\frac{\Delta E}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\% \oplus \frac{0.2\text{ GeV}}{E}$$



Structure of the ATLAS el. magn. calorimeter



ATLAS Calorimeter in Real Life

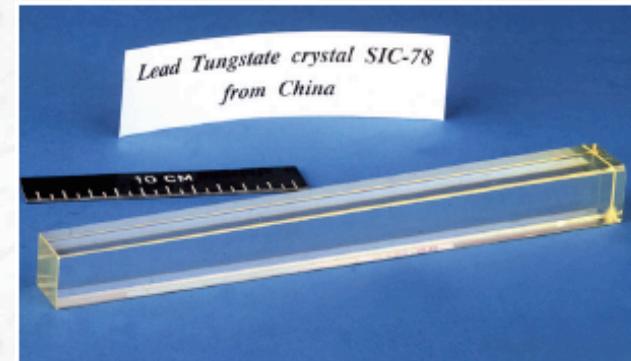


A slice of the ATLAS accordion barrel calorimeter, before installation;
It is now in a cryostat and impossible to see.

CMS el. magn. Calorimeter



- Lead Tungstate crystals
 - Scintillator: energy is converted to light (much faster than LARG signal)
 - **Exceptional** energy resolution, homogeneous calorimeter

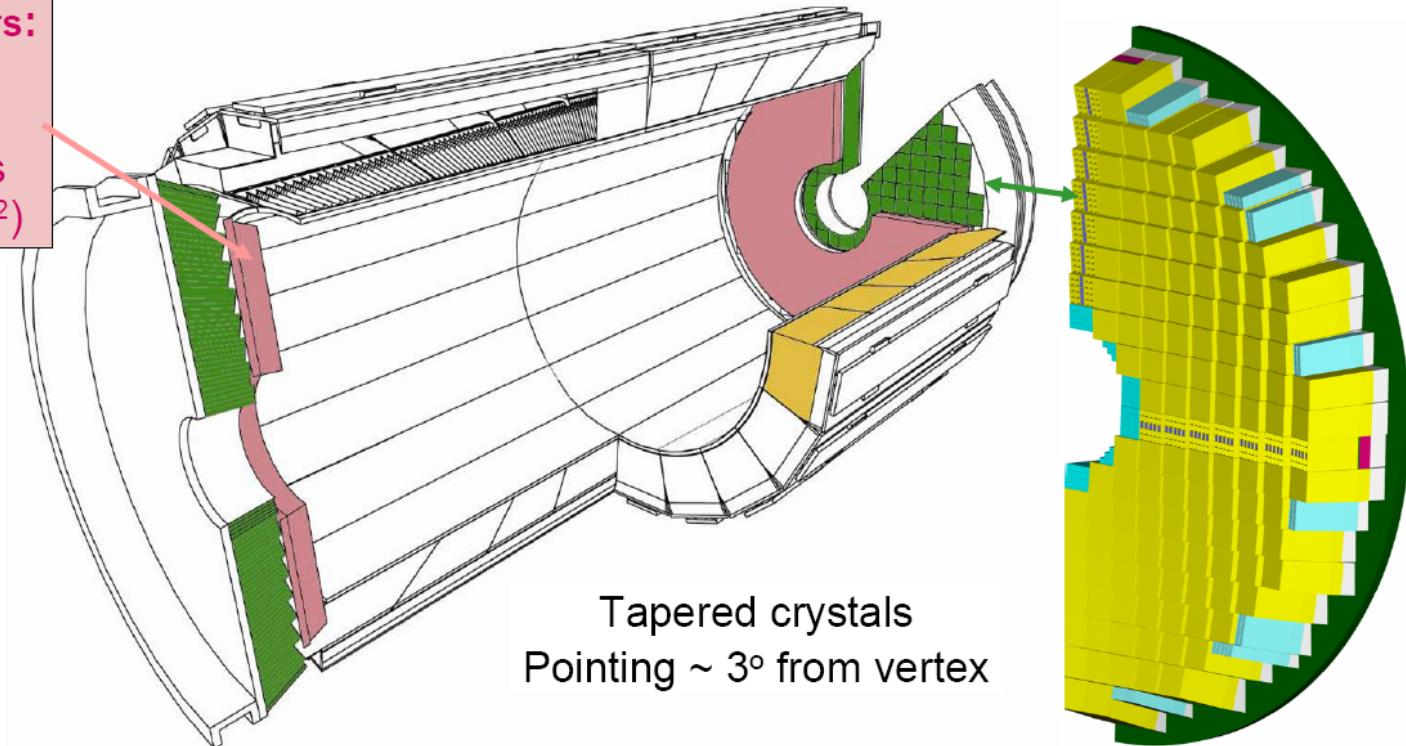


- Focus is to get the best possible energy resolution
- Low noise
- However, radiation and temperature sensitive

$$\frac{\Delta E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.16\text{GeV}}{E}$$

CMS el. magn. Calorimeter

Pb/Si Preshowers:
4 Dees
(2/endcap)
4300 Si strips
($\sim 63 \times 1.9 \text{ mm}^2$)



Barrel: 36 Supermodules (18 per half-barrel)
61200 Crystals (34 types) – total mass 67.4 t
Dimensions: $\sim 25 \times 25 \times 230 \text{ mm}^3$ ($25.8 X^0$)
 $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$

Endcaps: 4 Dees (2 per endcap)
14648 Crystals (1 type) – total mass 22.9 t
Dimensions: $\sim 30 \times 30 \times 220 \text{ mm}^3$ ($24.7 X^0$)
 $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175 \leftrightarrow 0.05 \times 0.05$

ATLAS photon identification

Graphical representation of shower shape variables used in the ATLAS photon identification:

Variables and Position

	Strips	2nd	Had.
Ratios	f_1, f_{side}	R_η^*, R_ϕ	$R_{\text{Had.}}^*$
Widths	$w_{s,3}, w_{s,\text{tot}}$	$w_{\eta,2}^*$	-
Shapes	$\Delta E, E_{\text{ratio}}$	* Used in PhotonLoose.	

Energy Ratios

$$R_\eta = \frac{E_{3 \times 7}^{S2}}{E_{7 \times 7}^{S2}}$$

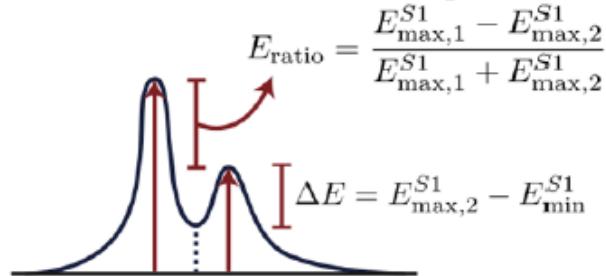
$$R_\phi = \frac{E_{3 \times 3}^{S2}}{E_{3 \times 7}^{S2}}$$

$$R_{\text{Had}} = \frac{E_T^{\text{Had}}}{E_T}$$

$$f_1 = \frac{E_{S1}}{E_{\text{Tot.}}}$$

$$f_{\text{side}} = \frac{E_7^{S1} - E_3^{S1}}{E_3^{S1}}$$

Shower Shapes



Widths

$$w_{\eta,2} = \sqrt{\frac{\sum E_i \eta_i^2}{\sum E_i} - \left(\frac{\sum E_i \eta_i}{\sum E_i} \right)^2}$$

Width in a 3×5 ($\Delta\eta \times \Delta\phi$) region of cells in the second layer.

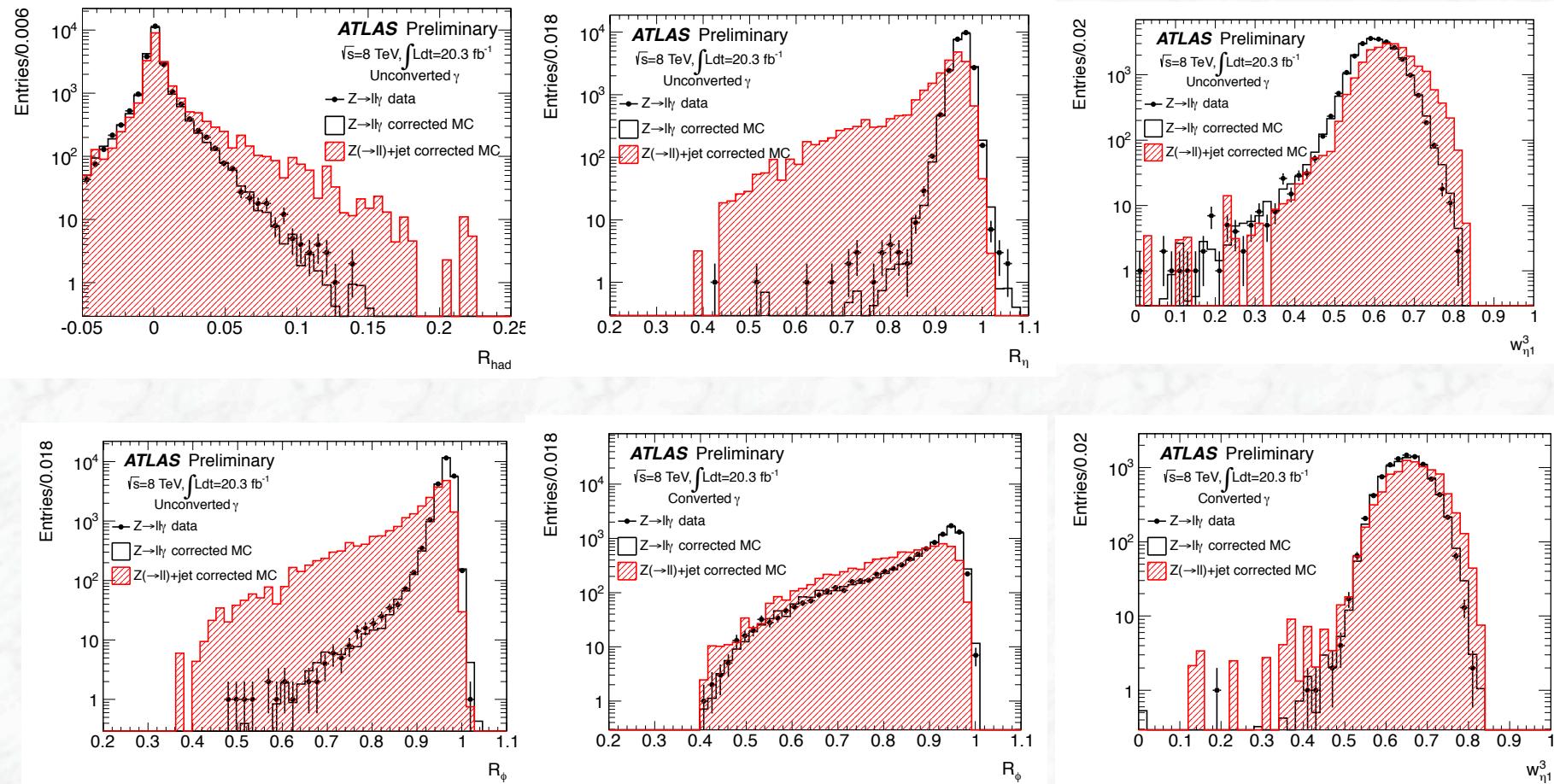
$$w_s = \sqrt{\frac{\sum E_i (i - i_{\max})^2}{\sum E_i}}$$

$w_{s3} = w_1$ uses 3 strips in η ;
 $w_{s\text{tot}}$ is defined similarly,
but uses 20 strips.

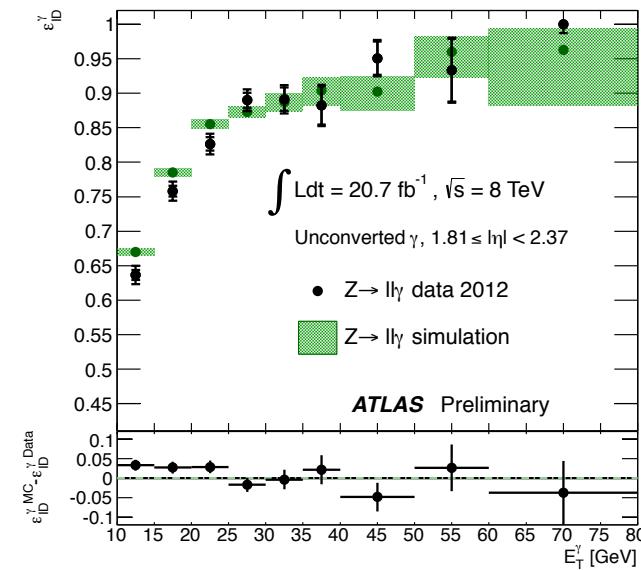
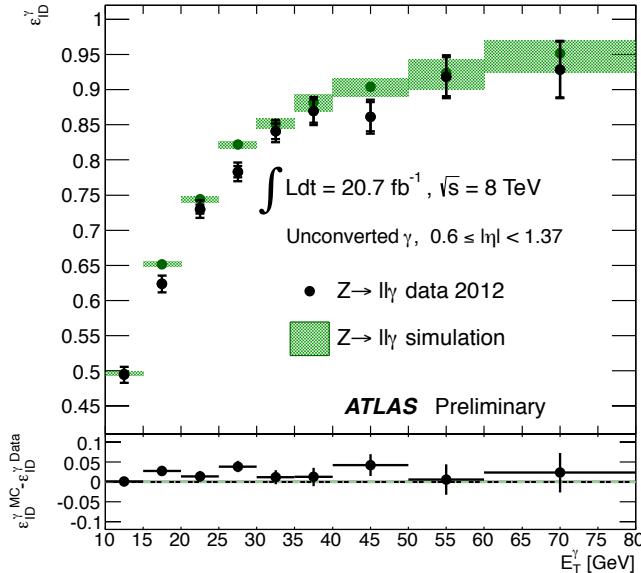
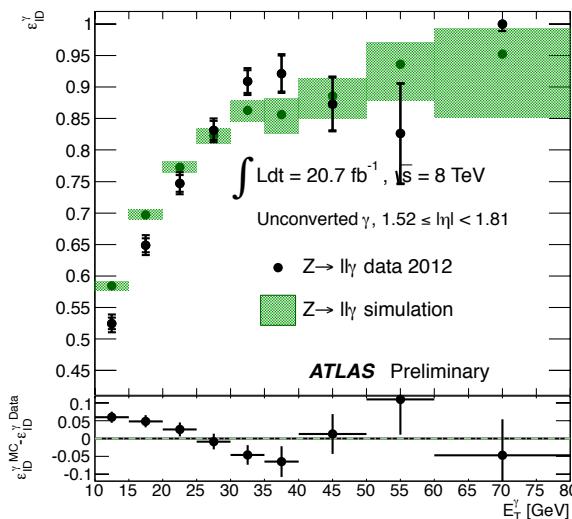
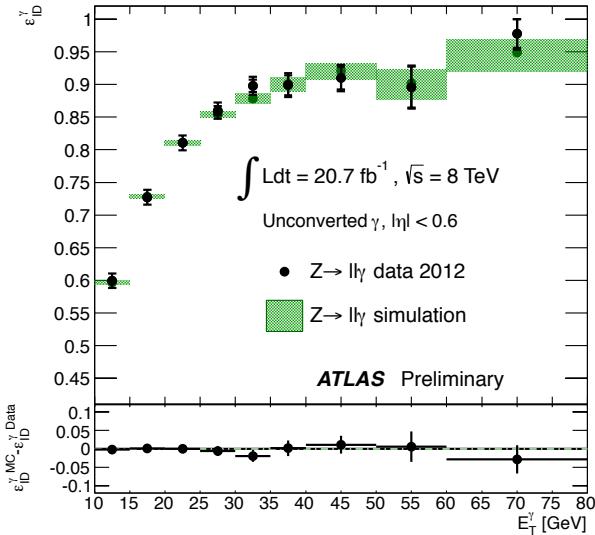
ATLAS photon identification at high pile-up (2012 data)

- Photon shower shape variables: (i) Data versus Monte Carlo agreement
(ii) Photon / jet separation

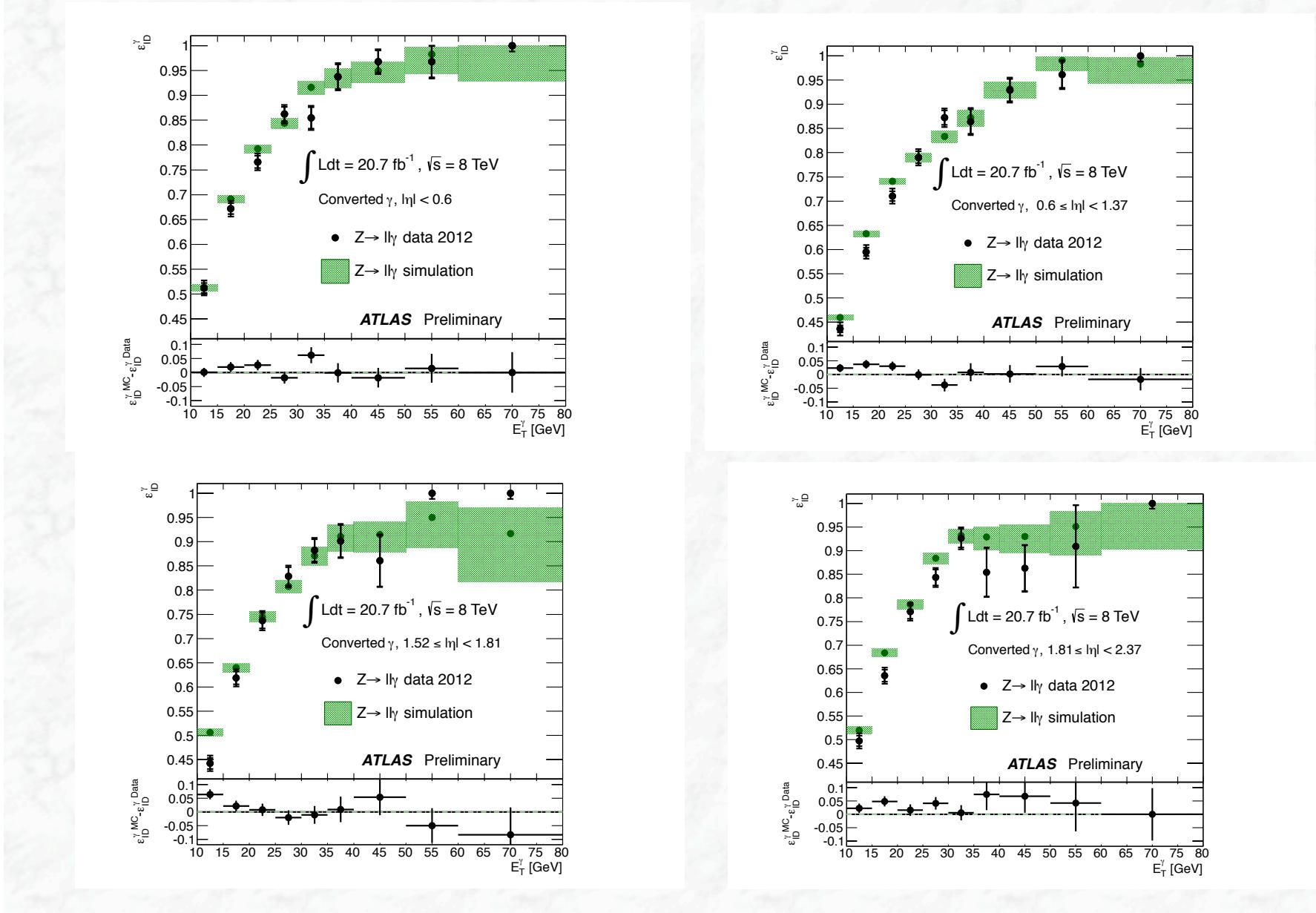
Extracted at high luminosity (2012 data, 20.3 fb^{-1}) from $Z \rightarrow ee\gamma$ and $Z \rightarrow \mu\mu\gamma$ events



ATLAS photon identification efficiency from $Z \rightarrow ll\gamma$ data -unconverted photons-



ATLAS photon identification efficiency from $Z \rightarrow ll\gamma$ data -converted photons-

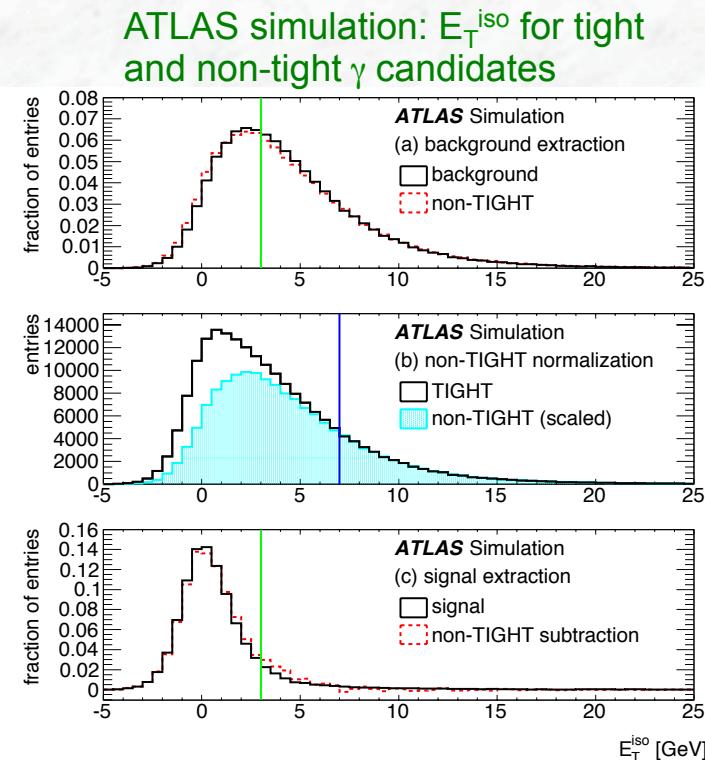


Di-photon Background

- Despite the fact that the background can be determined from sidebands, it is important to understand
 - (i) its composition and
 - (ii) how well the Monte Carlo simulation models it.
- Try to measure the $\gamma\gamma$ background first (cross section) and determine its fake contribution
- The **key variable** to separate true γ from jets is the **isolation energy**
e.g. calorimeter isolation:
 E_T^{iso} = transverse energy measured in the calorimeter in a cone of

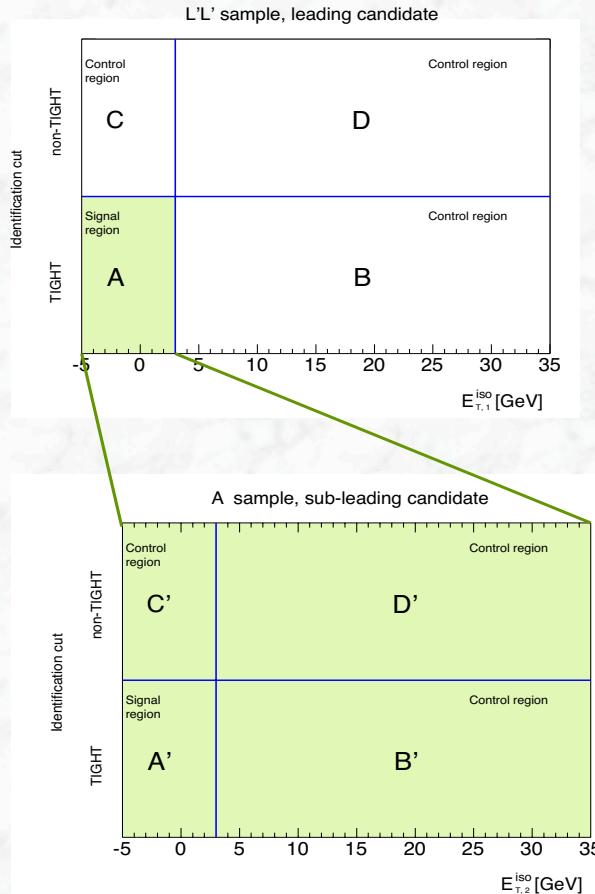
$$\Delta R = \sqrt{(\eta - \eta')^2 + (\phi - \phi')^2} < 0.4$$

For isolated photons: require $E_T^{\text{iso}} < 3 \text{ GeV}$



Di-photon Background (cont.)

- Several methods have been used to determine the fractions of true and fake photons in the selected samples
- One example: ABCD-method (use E_T^{iso} and γ -quality (tight, non-tight) and estimate the γ -signal contribution)



$$N_A^{\text{sig}} = N_A - \left[(N_B - c_1 N_A^{\text{sig}}) \frac{N_C - c_2 N_A^{\text{sig}}}{N_D - c_1 c_2 N_A^{\text{sig}}} \right] R^{\text{bkg}}$$

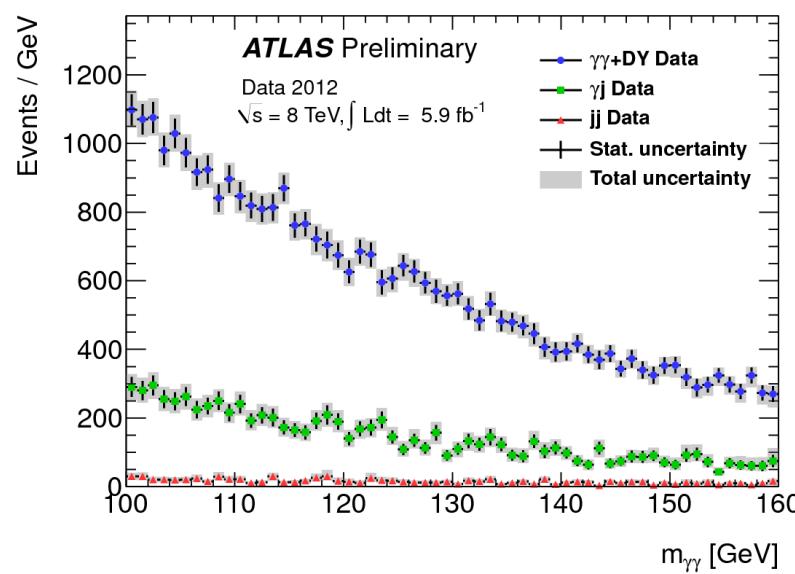
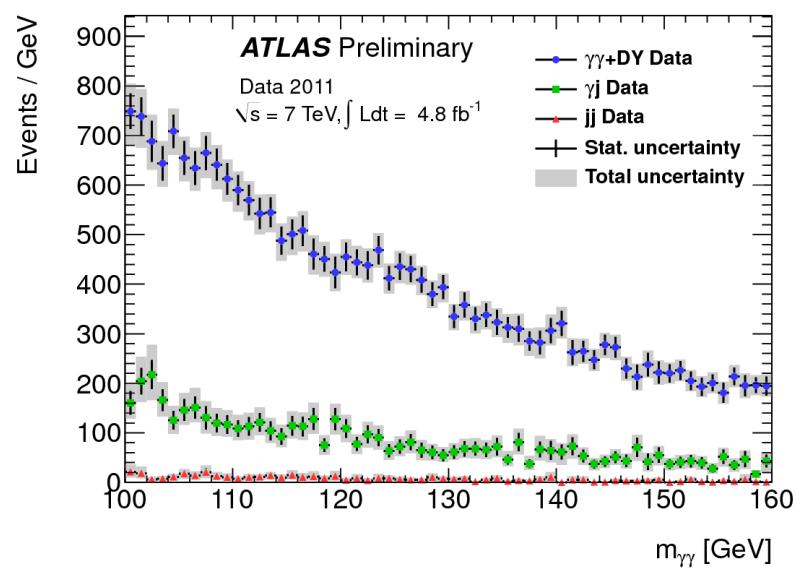
where: c_1 = signal fraction failing the isolation requirement
(from E_T^{iso} distribution)

c_2 = signal fraction failing the tight selection
(from Monte Carlo simulation)

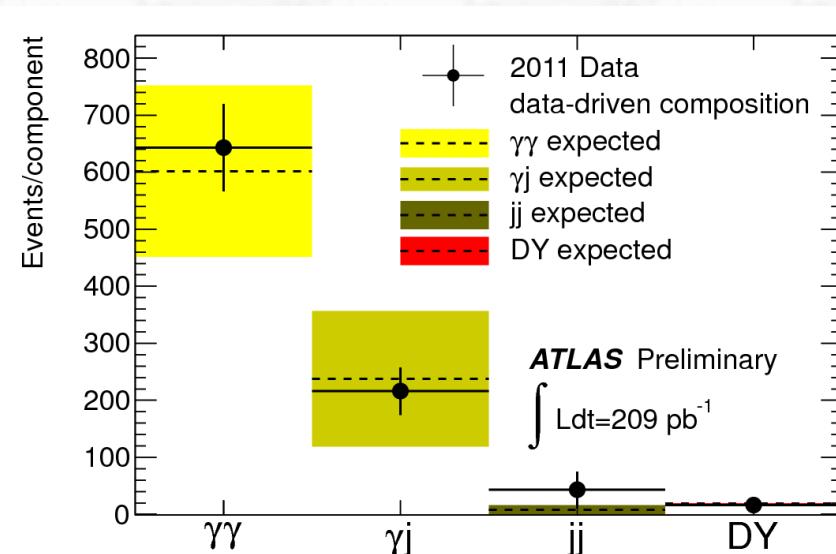
R^{bkg} = correction factor for correlations between the
isolation energy and the photon selection

- Extract genuine $\gamma\gamma$, γj , jj fractions bin-by-bin,
e.g. in the $\gamma\gamma$ mass distribution

Results on di-photon background



- The background is dominated by real di-photons (γj fraction $\sim 25\%$, jj fraction $\sim 7\%$)
- The 7 TeV and 8 TeV data look similar, but not identical
(have to be handled separately in the combination)
- And finally: good agreement between Monte Carlo simulation and data

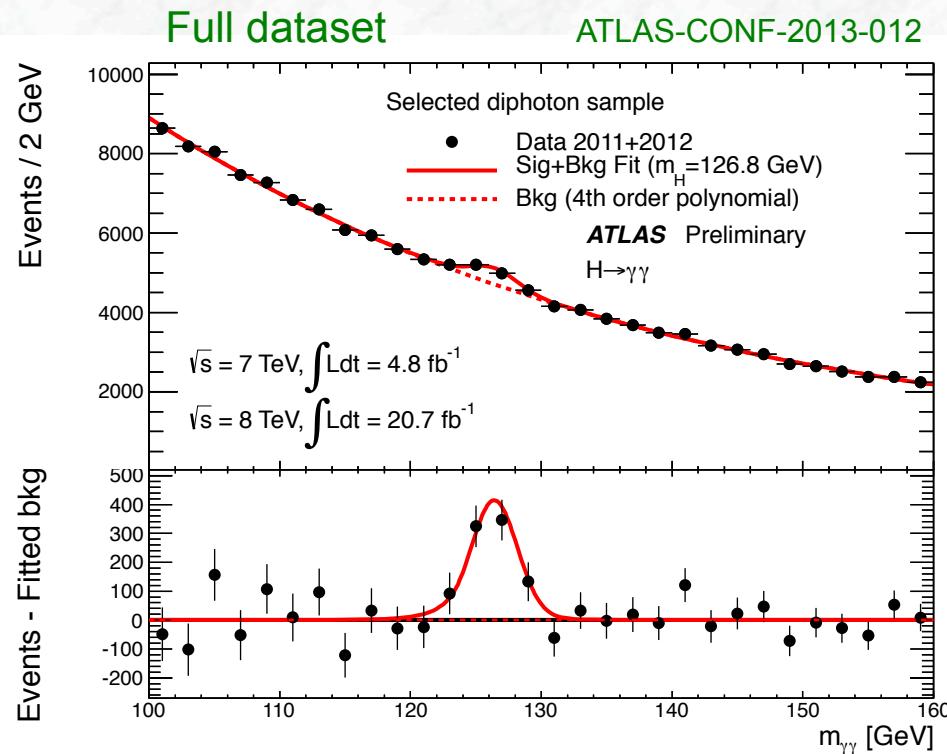


note: no absolute MC prediction necessary for Higgs analysis, but useful to extract functional form of the background



Result of the ATLAS search for $H \rightarrow \gamma\gamma$

- one of the famous plots-



$100 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}:$

$\sqrt{s} = 7 \text{ TeV}$ 23 788 events
 $\sqrt{s} = 8 \text{ TeV}$ 118 893 events

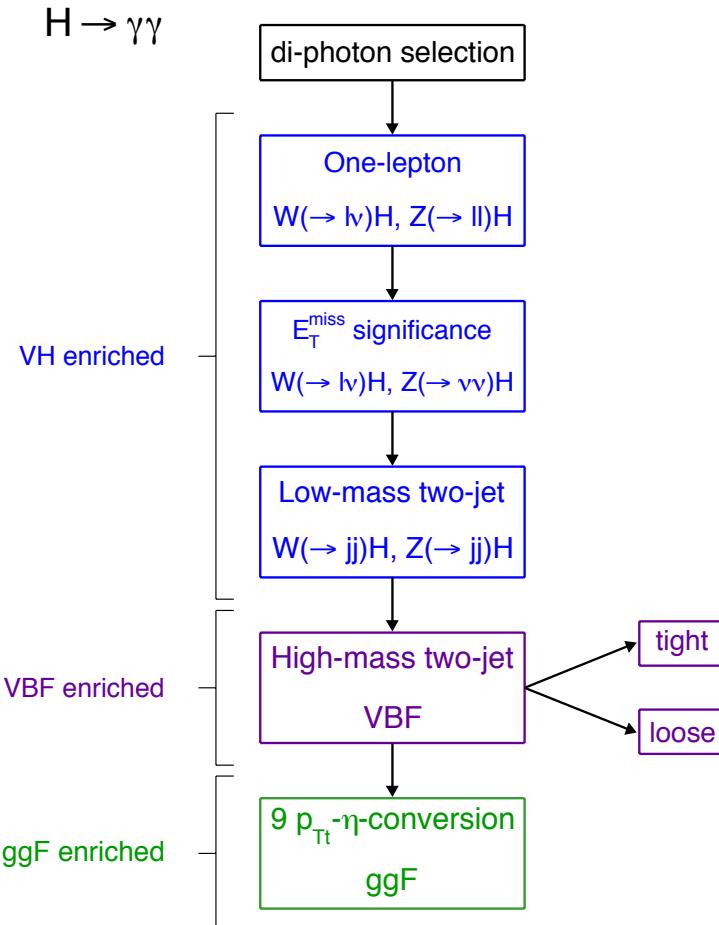
- Clear excess seen around $m_{\gamma\gamma} = 126$ GeV
- Background obtained from sidebands, interpolation in the region of the excess
- This plot, shown in many places, is actually not really used in the analysis.
Both experiments (ATLAS and CMS) split $\gamma\gamma$ sample in categories.



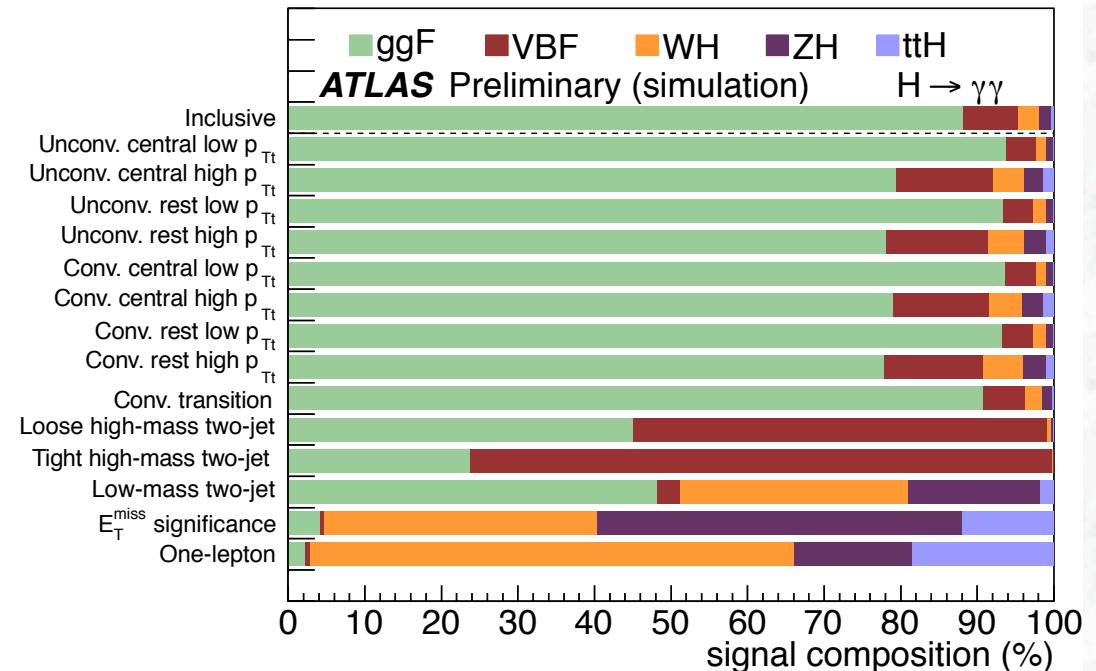
Categorisation of $H \rightarrow \gamma\gamma$ candidate events

ATLAS-CONF-2013-012

ATLAS Preliminary

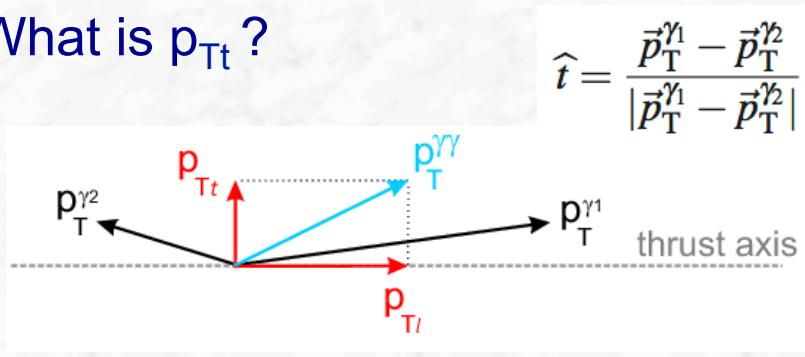


Categorisation: to increase overall sensitivity and sensitivity to different production modes (VBF, VH)

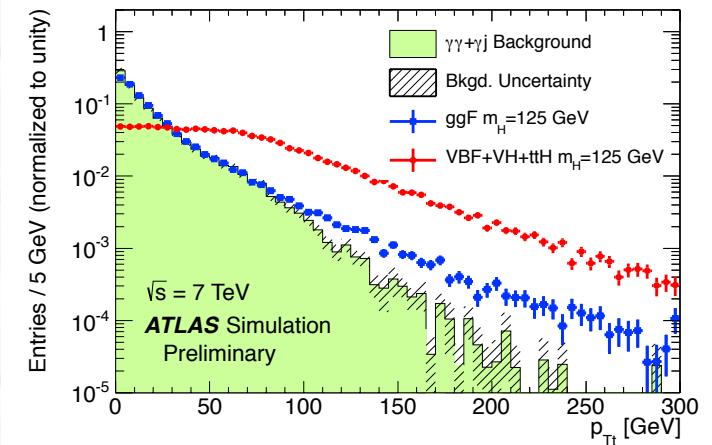


- VH enriched: one-lepton, E_T^{miss} , low-mass di-jets
- VBF enriched (tag-jet configuration, $\Delta\eta$, m_{jj})
- gluon fusion: 9 categories, exploit different mass resolution for different detector regions, $\gamma\gamma$ conversion status and p_{Tt}

- What is p_{Tt} ?

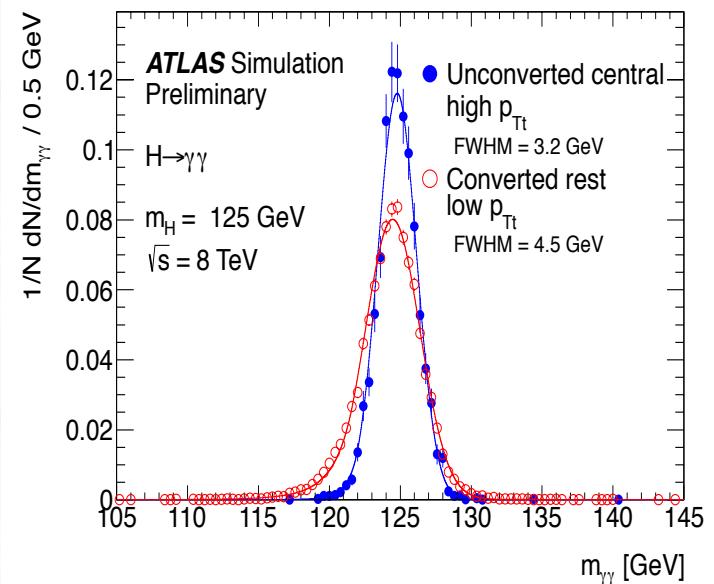


- Slightly better separation power than p_T .
- It leaves a smoother background than p_T .
- Split sample in two P_{Tt} bins (high/low), separation at 60 GeV.



Harder spectrum for Higgs boson signal (VBF, gluon fusion)

- Nine gluon-fusion enriched categories
 - Main argument: g performance (resolutions, jet rejection) in different detector regions
 - Signal-to-background (S/B) varies from 1 : 6.1 (unconverted, central, high p_{Tt}) to 1 : 72 (converted photons, transition region)



Mass resolution and S/B in various categories ($\sqrt{s} = 8$ TeV)

Table 2: Signal mass resolution (σ_{CB}), number of observed events, number of expected signal events (N_S), number of expected background events (N_B) and signal to background ratio (N_S/N_B) in a mass window around $m_H = 126.5$ GeV containing 90% of the expected signal for each of the 14 categories of the 8 TeV data analysis. The numbers of background events are obtained from the background + signal fit to the $m_{\gamma\gamma}$ data distribution.

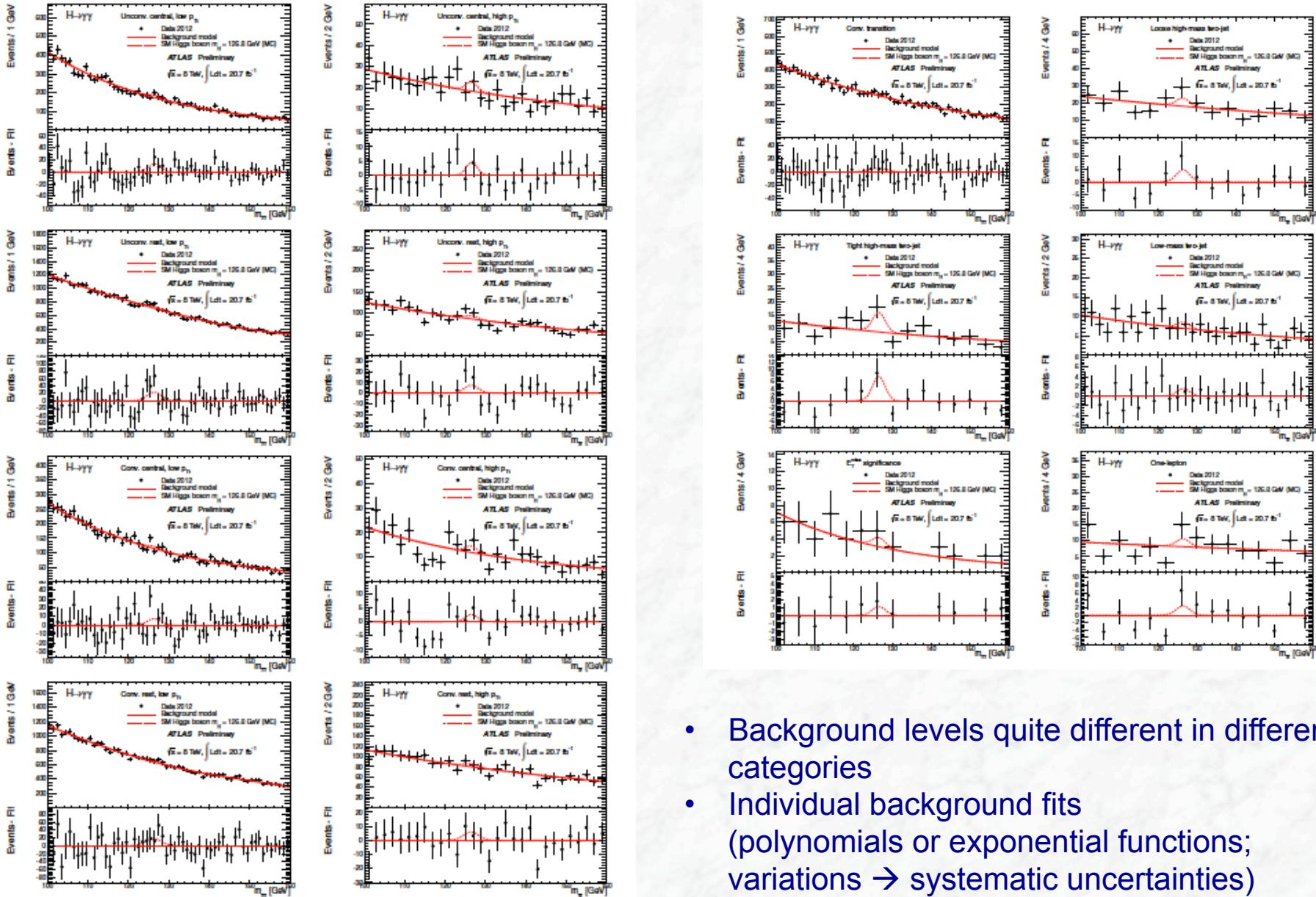
Category	σ_{CB} (GeV)	8 TeV			
		Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03

Production fractions in various categories ($\sqrt{s} = 8$ TeV)

Table 1: Number of events in the data (N_D) and expected number of SM Higgs signal events (N_S) for $m_H = 126.5$ GeV from the $H \rightarrow \gamma\gamma$ analysis, for each category in the mass range 100-160 GeV at $\sqrt{s} = 8$ TeV. Numbers for the 7 TeV analysis can be found in Ref. [4]. The statistical uncertainties in N_S are less than 1%. The fractions of expected signal events from the $gg \rightarrow H$, VBF, WH, ZH, ttH processes are detailed.

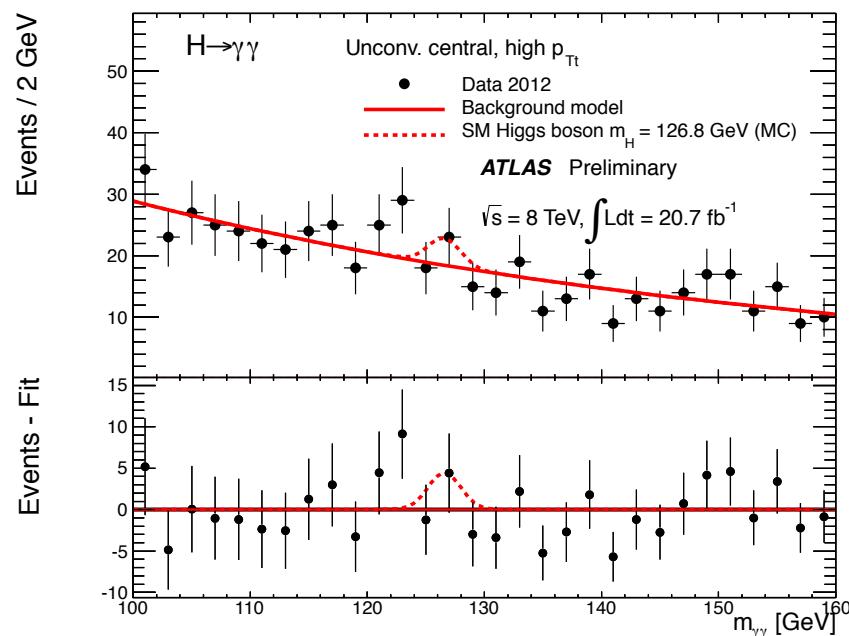
\sqrt{s}	8 TeV						
Category	N_D	N_S	$gg \rightarrow H$ [%]	VBF [%]	WH [%]	ZH [%]	ttH [%]
Unconv. central, low p_{Tt}	10900	51.8	93.7	4.0	1.4	0.8	0.2
Unconv. central, high p_{Tt}	553	7.9	79.3	12.6	4.1	2.5	1.4
Unconv. rest, low p_{Tt}	41236	107.9	93.2	4.0	1.6	1.0	0.1
Unconv. rest, high p_{Tt}	2558	16.0	78.1	13.3	4.7	2.8	1.1
Conv. central, low p_{Tt}	7109	33.1	93.6	4.0	1.3	0.9	0.2
Conv. central, high p_{Tt}	363	5.1	78.9	12.6	4.3	2.7	1.5
Conv. rest, low p_{Tt}	38156	97.8	93.2	4.1	1.6	1.0	0.1
Conv. rest, high p_{Tt}	2360	14.4	77.7	13.0	5.2	3.0	1.1
Conv. transition	14864	40.1	90.7	5.5	2.2	1.3	0.2
Loose high-mass two-jet	276	5.3	45.0	54.1	0.5	0.3	0.1
Tight high-mass two-jet	136	8.1	23.8	76.0	0.1	0.1	0.0
Low-mass two-jet	210	3.3	48.1	3.0	29.7	17.2	1.9
E_T^{miss} significance	49	1.3	4.1	0.5	35.7	47.6	12.1
One-lepton	123	2.9	2.2	0.6	63.2	15.4	18.6
All categories (inclusive)	118893	395.0	88.0	7.3	2.7	1.5	0.5

Results in each bin ($\sqrt{s} = 8$ TeV)

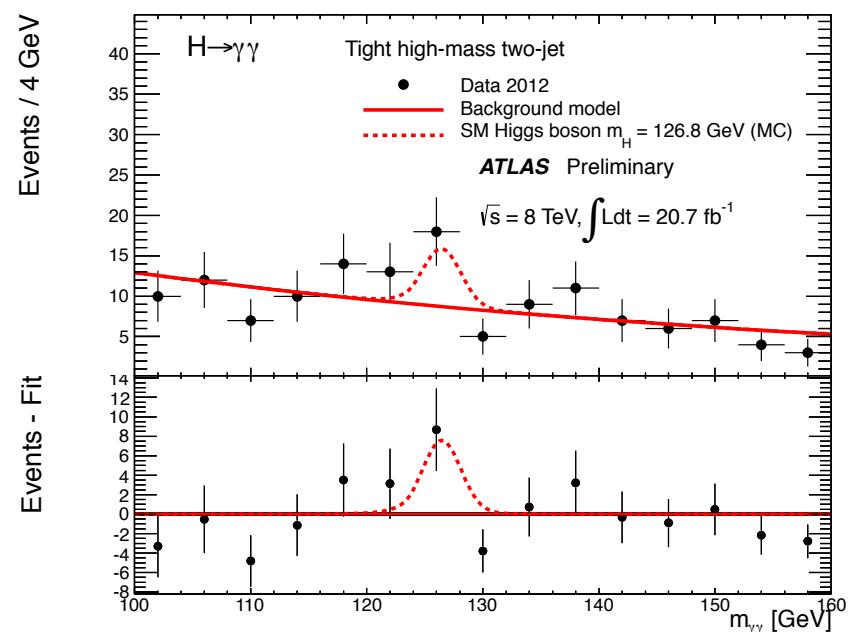


- Background levels quite different in different categories
- Individual background fits (polynomials or exponential functions; variations → systematic uncertainties)

Two categories with best S/B ($\sqrt{s} = 8$ TeV)



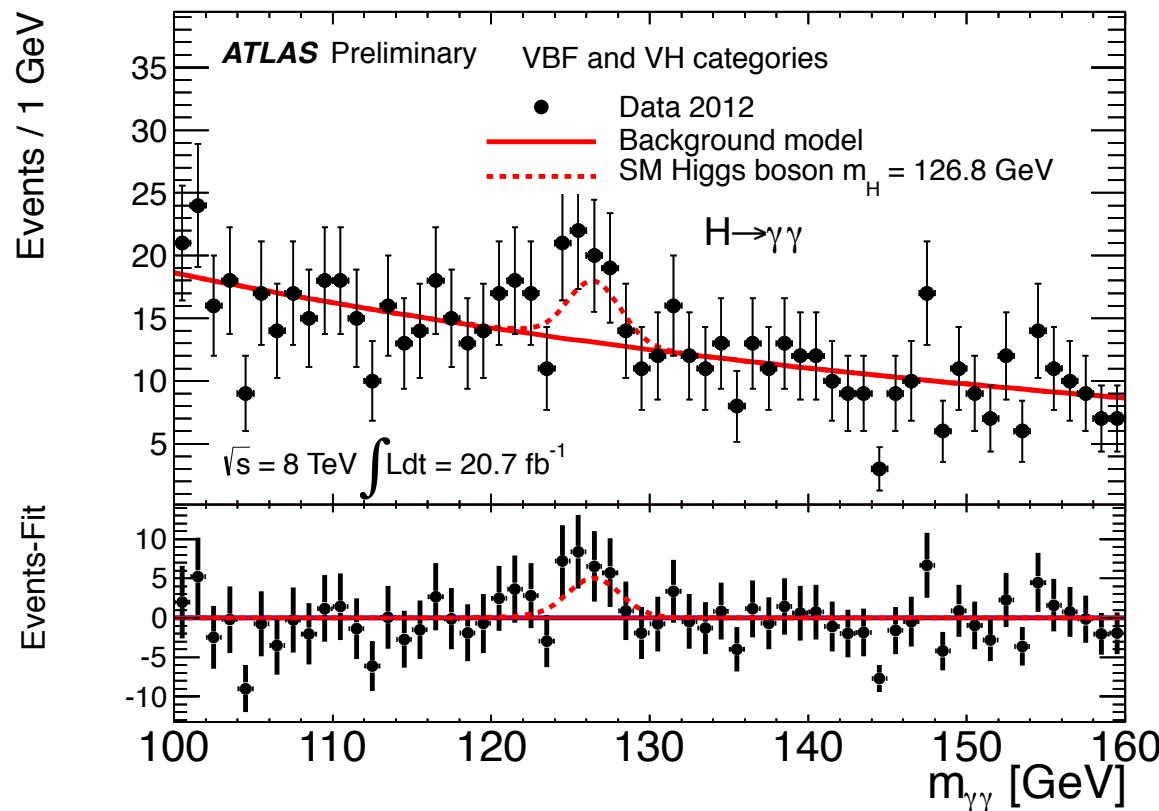
Unconventional, central calorimeter,
high p_{Tt}



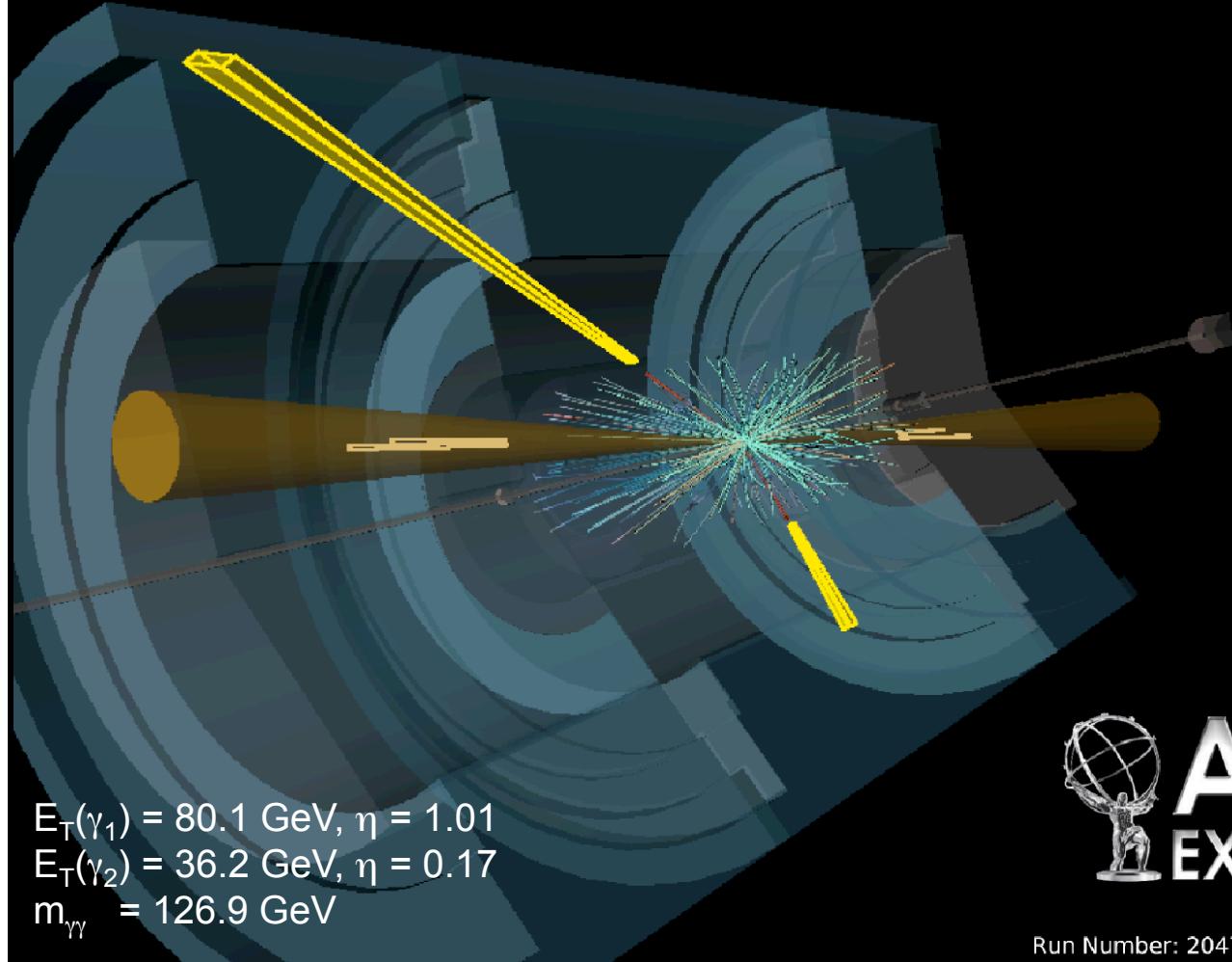
Tight high mass two jets
(VBF category)

Sum of VBF and VH categories ($\sqrt{s} = 8$ TeV)

- sensitive to W/Z couplings-



$H \rightarrow \gamma\gamma$ VBF candidate event



$E_T(\gamma_1) = 80.1$ GeV, $\eta = 1.01$

$E_T(\gamma_2) = 36.2$ GeV, $\eta = 0.17$

$m_{\gamma\gamma} = 126.9$ GeV

$E_T(jet_1) = 121.6$ GeV, $\eta = -2.90$

$E_T(jet_2) = 82.8$ GeV, $\eta = 2.72$

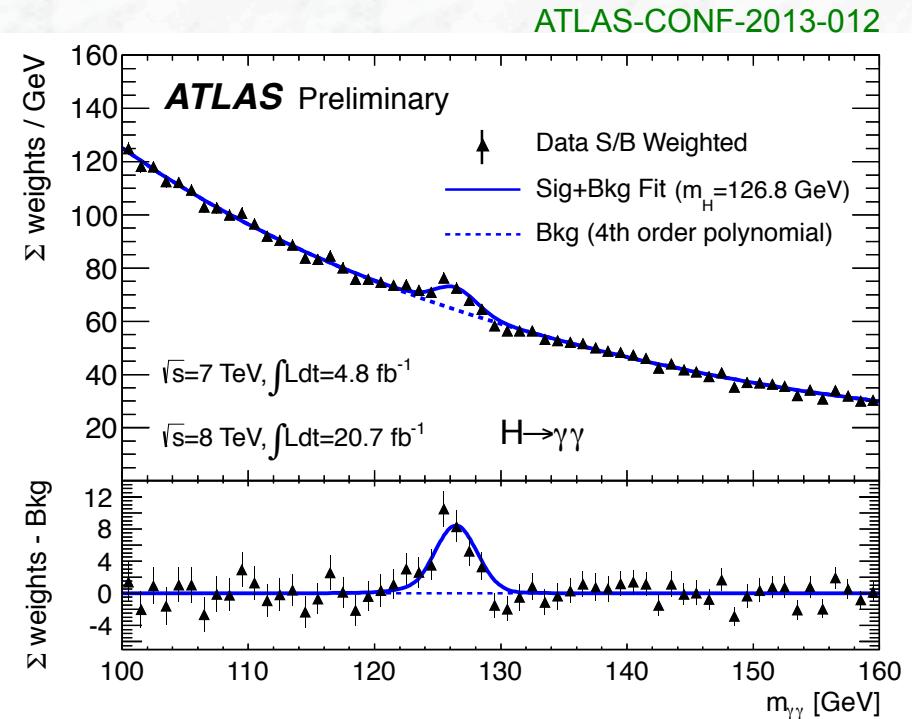
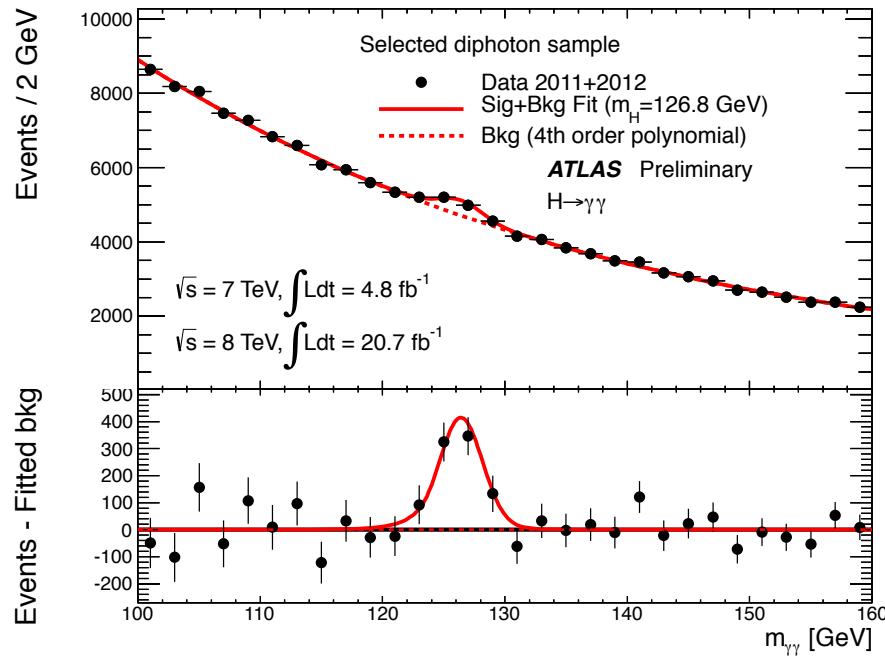
$m_{jj} = 1.67$ TeV



Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

The final plots -or different misleading ways to present results-

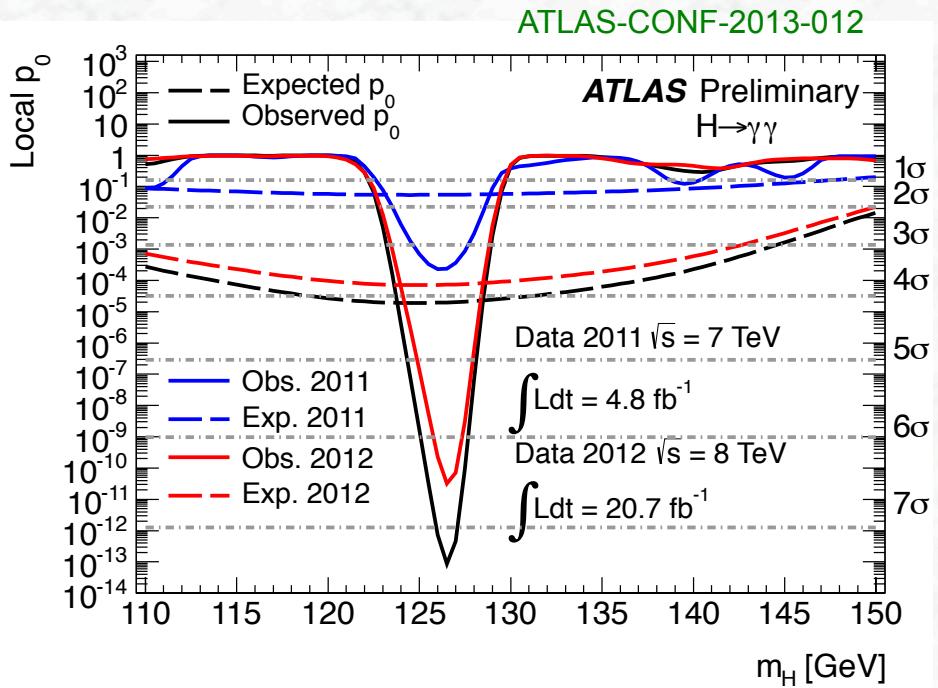
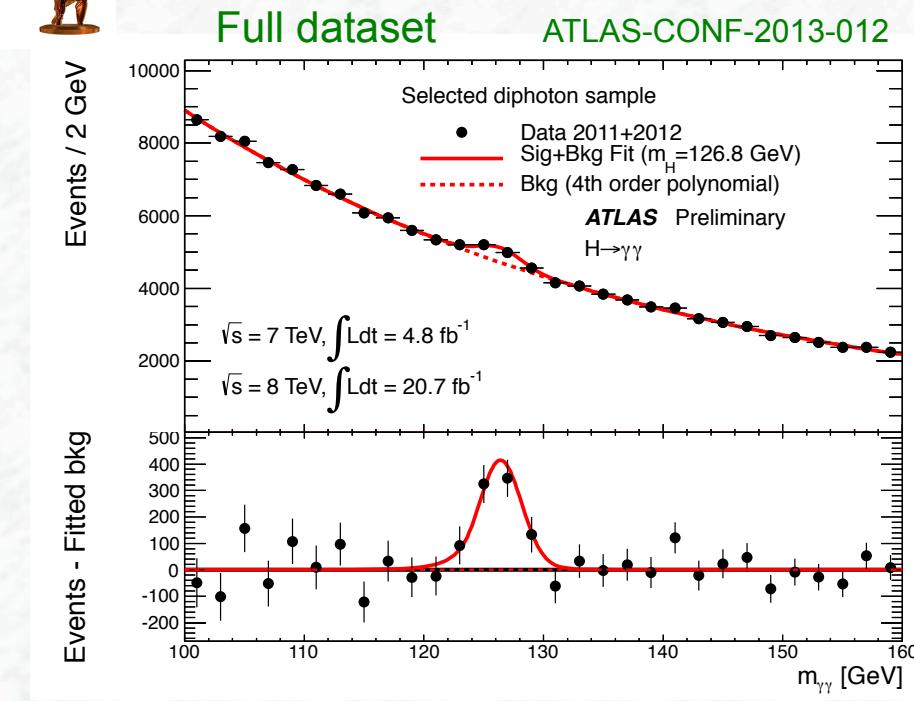


- Sum of the 10 ($\sqrt{s} = 7 \text{ TeV}$) and 14 ($\sqrt{s} = 8 \text{ TeV}$) mass distributions.
- The fact that different events are worth more than others is hidden.

- Weighted sum of the 10 ($\sqrt{s} = 7 \text{ TeV}$) and 14 ($\sqrt{s} = 8 \text{ TeV}$) mass distributions, according to S/B
- However, it looks like we are plotting events.



Result of the ATLAS search for $H \rightarrow \gamma\gamma$



- p_0 value for consistency of data with background-only: $\sim 10^{-13}$ (7.4 σ observed) for the combined 7 TeV and 8 TeV data; (4.3 σ expected)
(minimum found at $m_{\gamma\gamma} = 126.5$ GeV)
 - Establishes the discovery of the new particle in the $\gamma\gamma$ channel alone

Statistical procedure, Higgs boson signal strength

- Parameter of interest: signal strength factor μ
(acts as scale factor on the total number of events predicted by the Standard Model for a Higgs boson signal)

$\mu = 0$ background-only hypothesis

$\mu = 1$ Standard Model Higgs boson signal strength (in addition to background)

- Hypothesized values of μ are tested with a statistics $\Lambda(\mu)$ based on the profile likelihood ratio
(→ lectures by Kyle Cranmer)

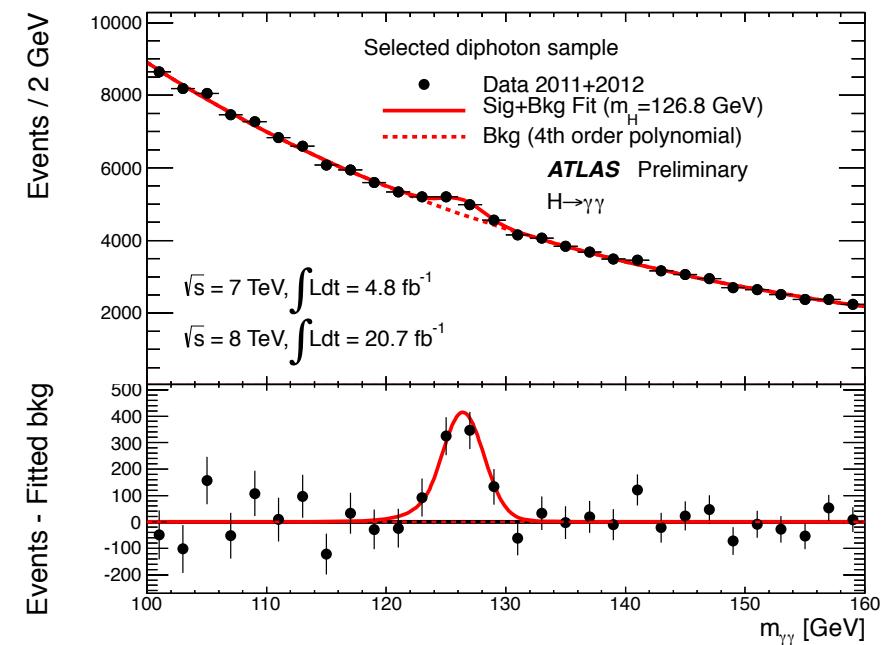
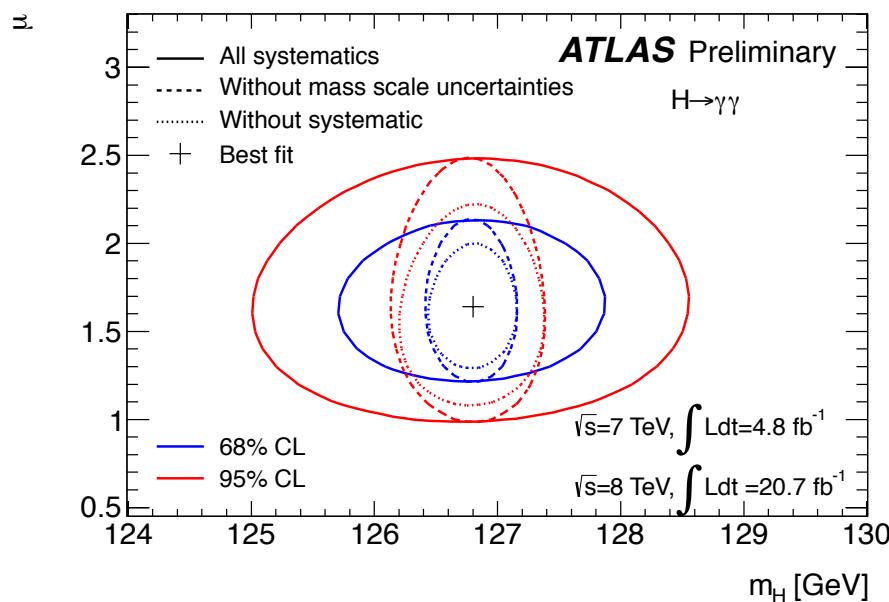
- The test statistics is based on likelihood functions

(using signal and background models,
systematic uncertainties are introduced as nuisance parameters with
constraints (e.g. Gaussian))



Result of the ATLAS search for $H \rightarrow \gamma\gamma$

-mass and signal strength-



Mass:

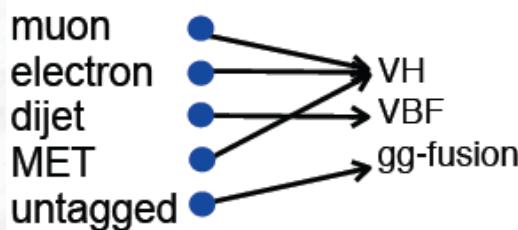
$$m_H = 126.8 \pm 0.2 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ GeV}$$

Signal strength:

$$\mu := \sigma / \sigma_{\text{SM}} = 1.57 \pm 0.22 \text{ (stat)} {}^{+0.24}_{-0.18} \text{ (syst)}$$

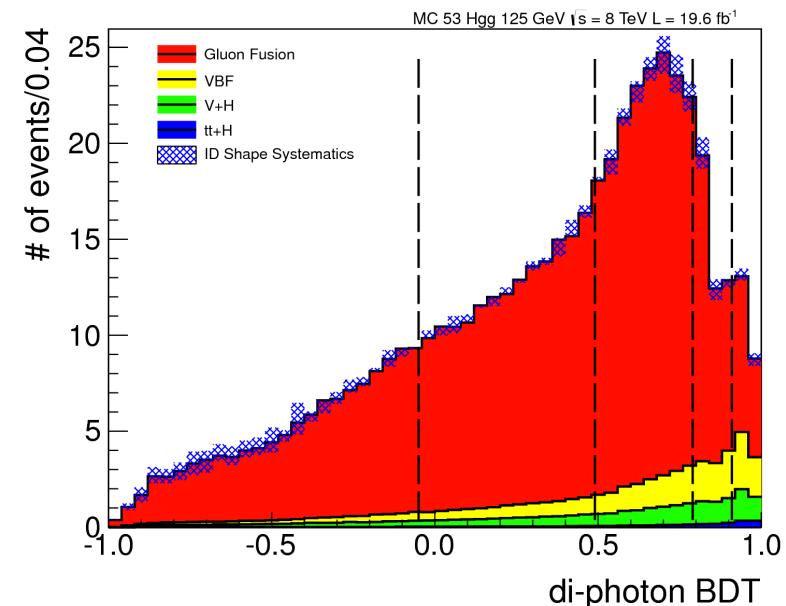
Categorisation of $H \rightarrow \gamma\gamma$ candidate events in CMS

- CMS uses a similar categorization as ATLAS



- Untagged events:

- Multivariate di-photon categories
BDT classification
(di-photon kinematics (except $m_{\gamma\gamma}$),
di-photon mass resolution, photon ID)
- Cut-based analysis, in categories
(similar to ATLAS)

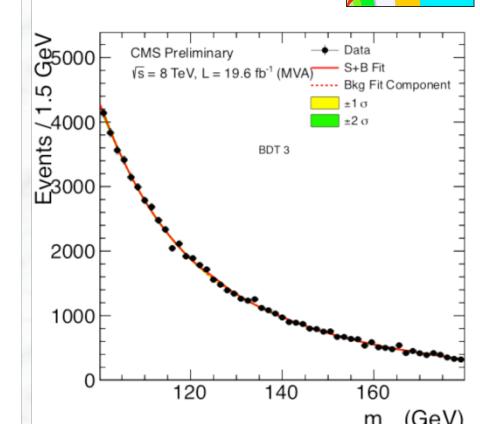
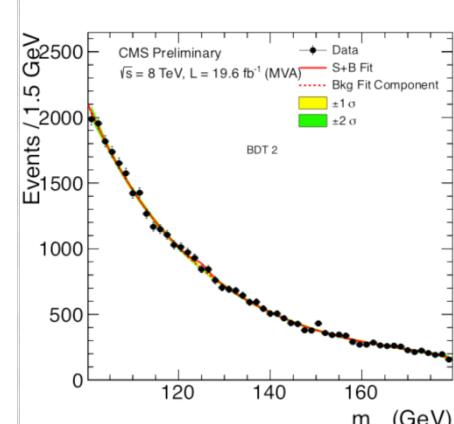
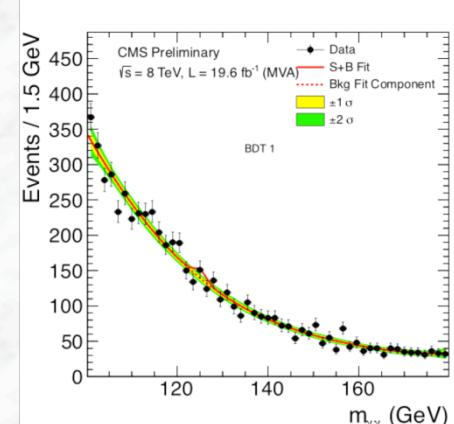
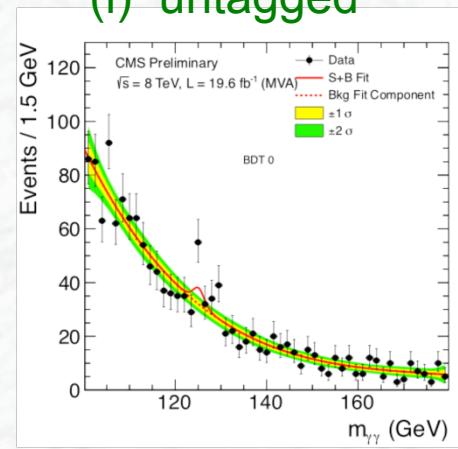


MVA has ~15% better expected sensitivity

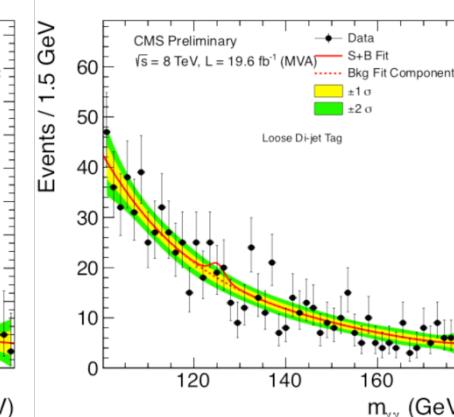
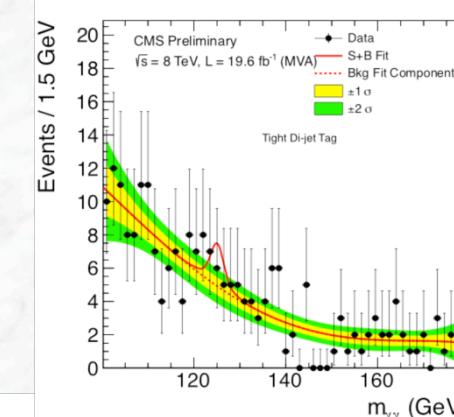


$m_{\gamma\gamma}$ spectra at $\sqrt{s} = 8$ TeV

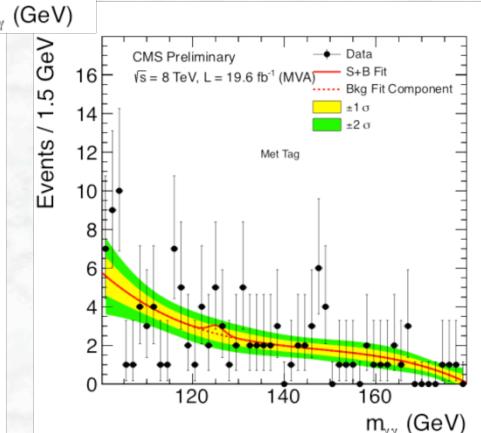
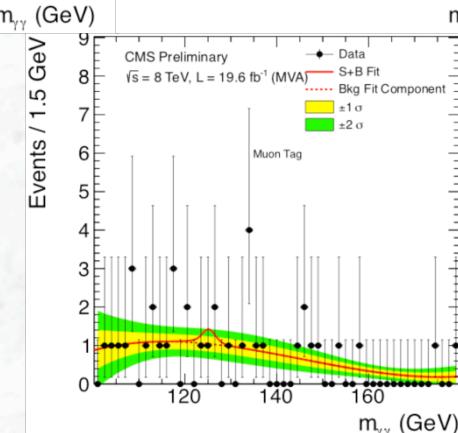
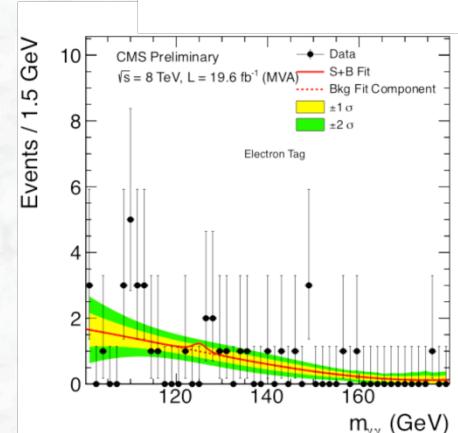
(i) untagged



(ii) VBF/jet tagged



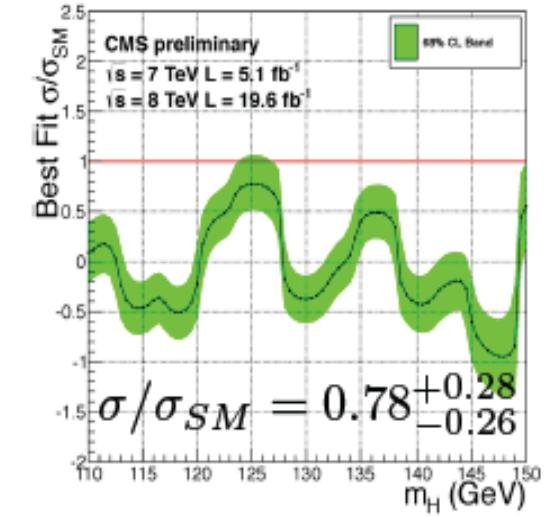
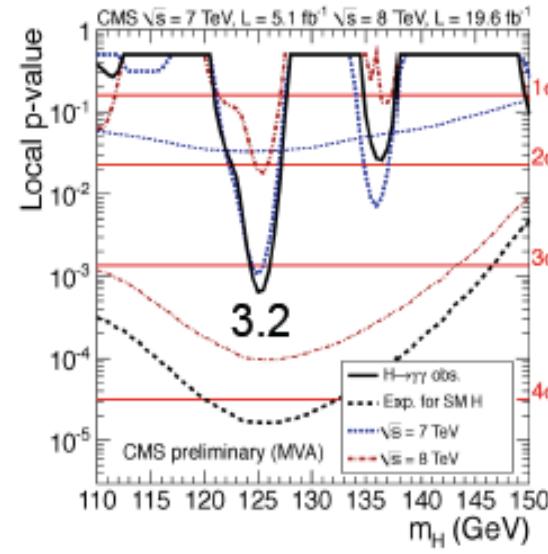
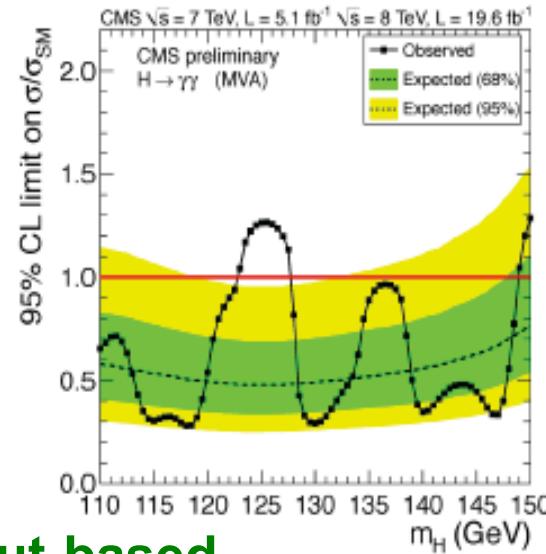
(iii) Lepton/ E_T^{miss} tagged



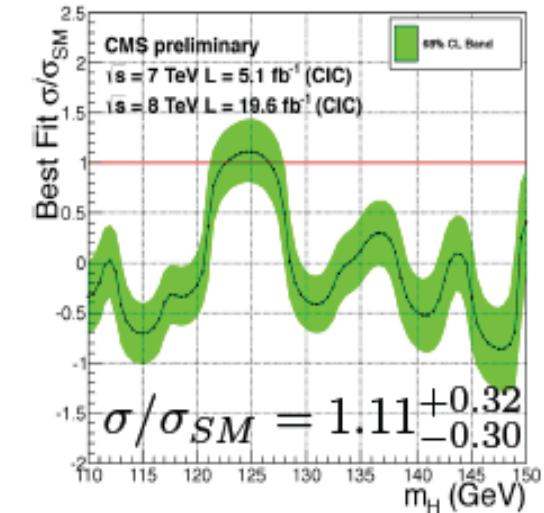
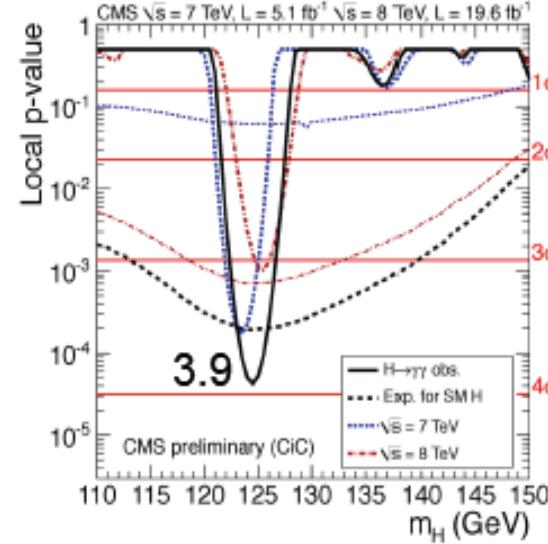
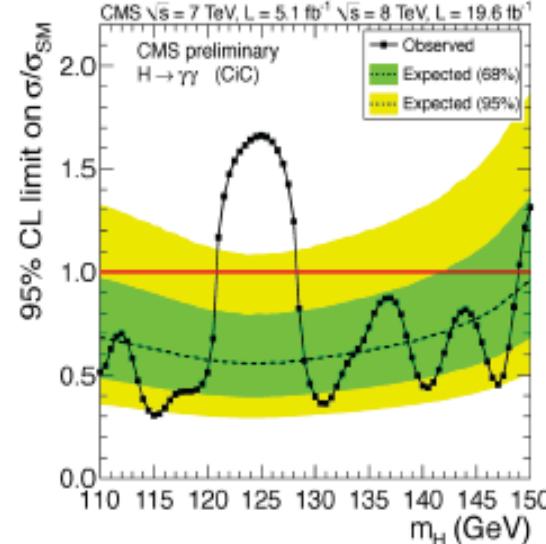
Result of the CMS search for $H \rightarrow \gamma\gamma$



(i) MVA



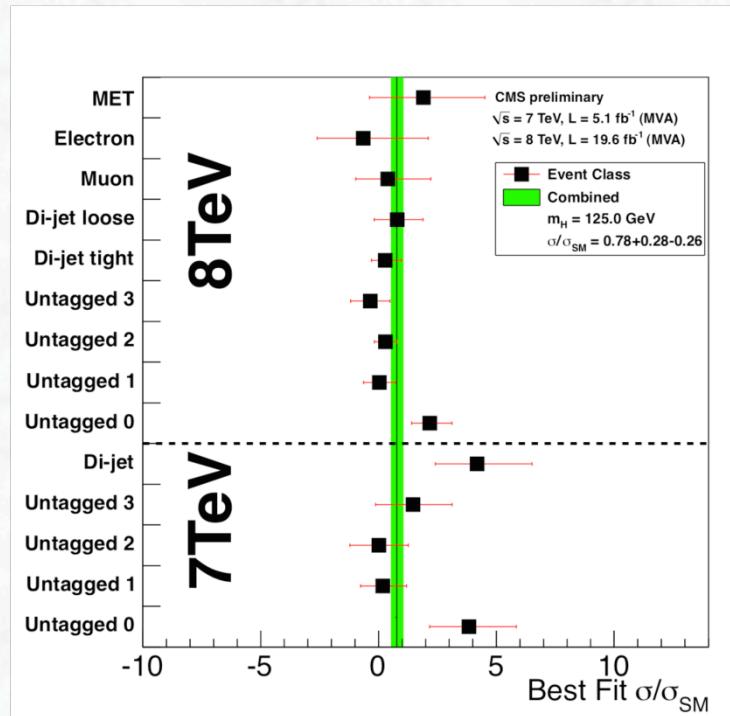
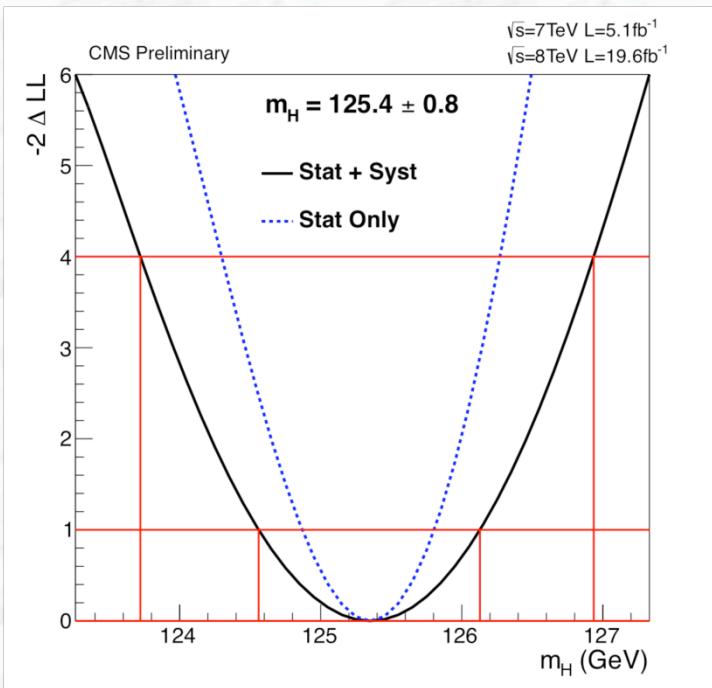
(ii) cut-based



The two results are compatible (within 1.5σ) after taking correlations into account

Result of the CMS search for $H \rightarrow \gamma\gamma$

-mass and signal strength (MVA analysis)-



Mass:

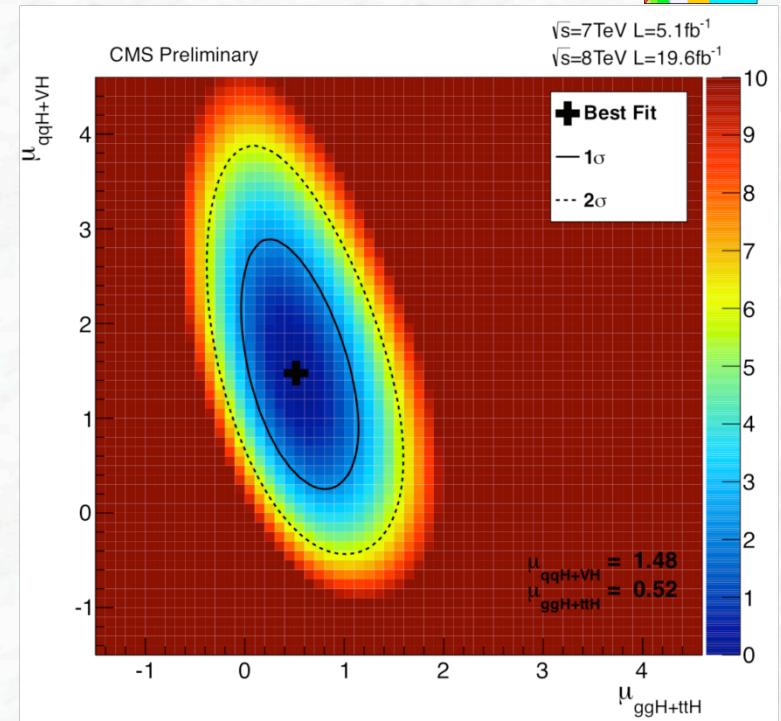
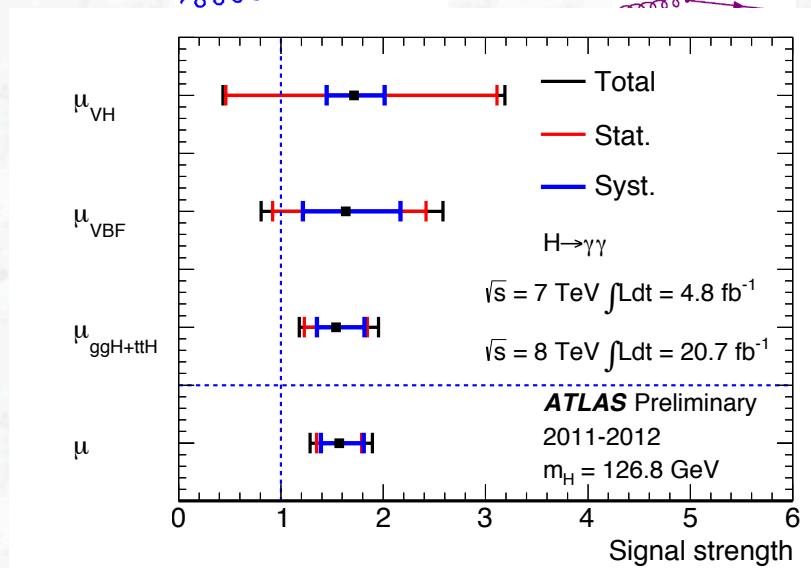
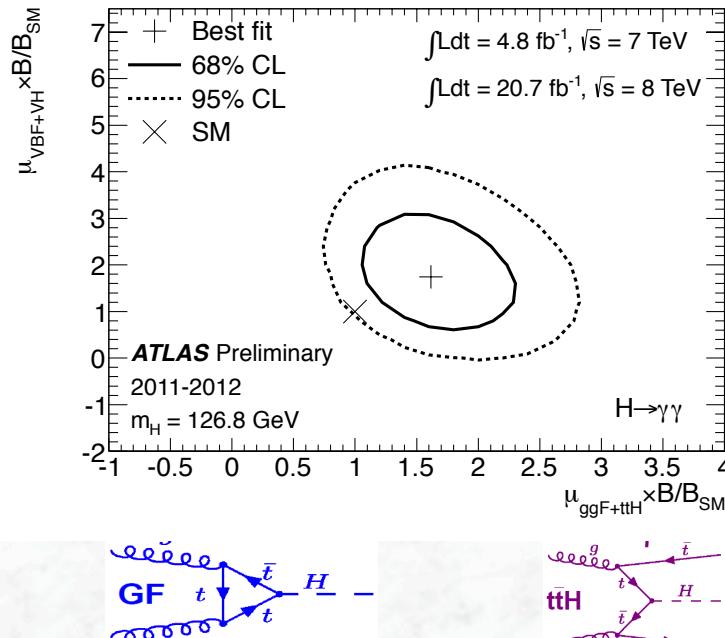
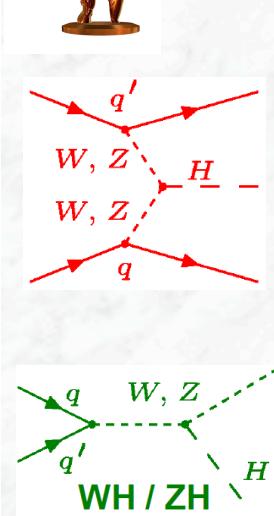
$$m_H = 125.4 \pm 0.5 \text{ (stat)} \pm 0.6 \text{ (syst)} \text{ GeV}$$

Signal strength:

$$\mu := \sigma / \sigma_{SM} = 0.78^{+0.28}_{-0.26} \text{ (syst)}$$

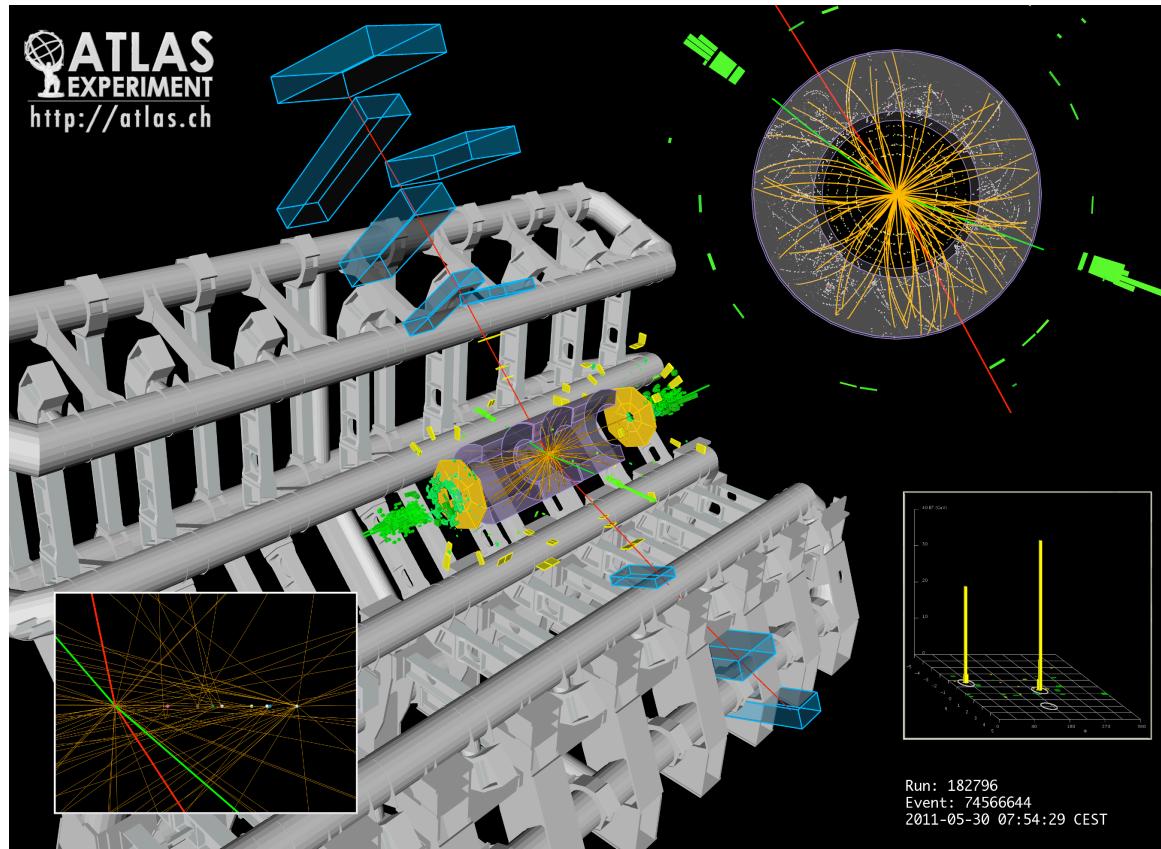


Separation of different production processes for $H \rightarrow \gamma\gamma$



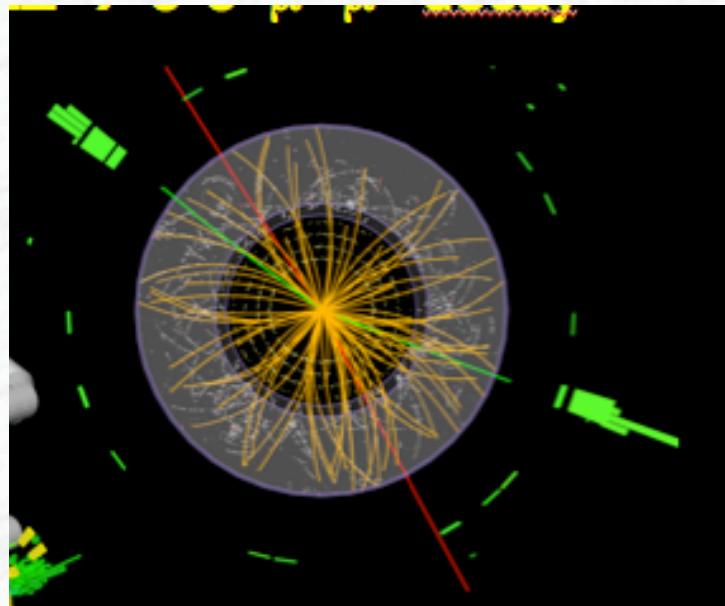
Important “evidence” for VBF production in both experiments

$$H \rightarrow ZZ \rightarrow e^+e^- \mu^+ \mu^-$$

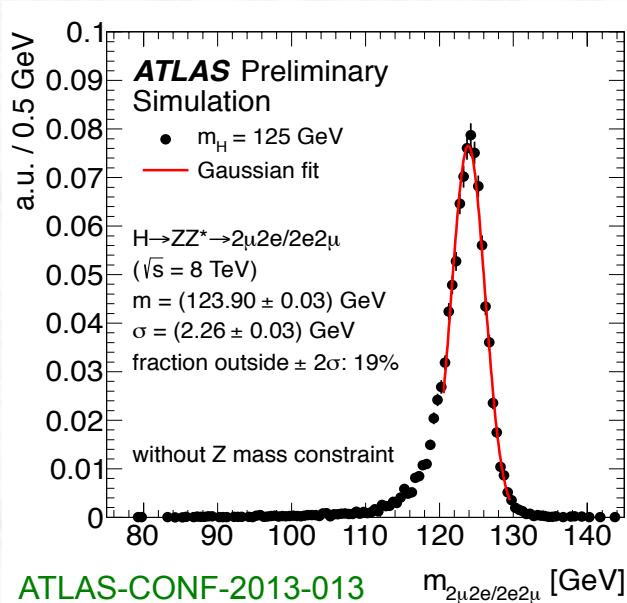


- Clean experimental signature (4 leptons), good S/B
- Mass reconstruction possible, with good resolution
- Very small signal rate (leptonic branching ratios)

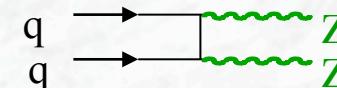
Search for the $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^- \ell^+\ell^-$ decay



- The “golden mode”: 4 isolated leptons
 $e: P_T > 20, 15, 10, 7 \text{ GeV}, |\eta| < 2.47$
 $\mu: P_T > 20, 15, 10, 6 \text{ GeV}, |\eta| < 2.7$
 One pair consistent with Z mass (m_{12})
 Mass of other pair: $m_{\min} < m_{34} < 115 \text{ GeV}$
- Mass of the Higgs boson can be reconstructed $m_{4\ell}$
 Good mass resolution $m_{4\ell}$; For $m_H = 125 \text{ GeV}$:
 4e: ~2.7 (2.4) GeV without (with) Z mass constraint
 4μ: ~2.0 (1.6) GeV without (with) Z mass constraint

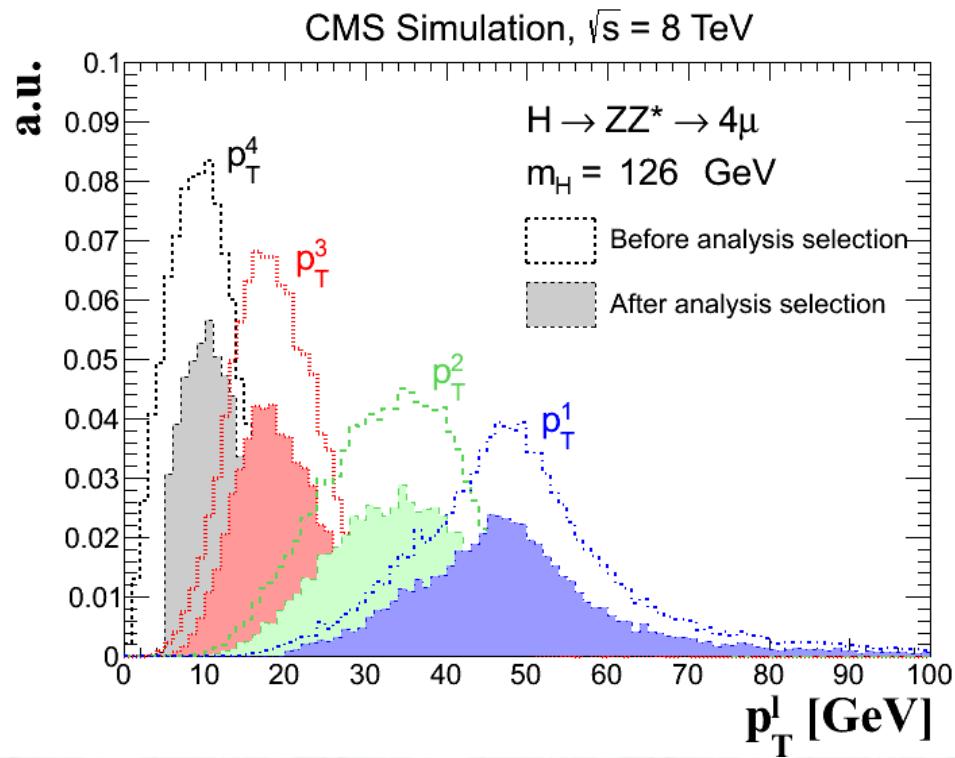


- Low signal rate, but also low background
 - Mainly from ZZ continuum
- In addition from $t\bar{t}$ and $Z + \text{jet}$ production:
 (two prompt leptons from W/Z decays and two leptons from (heavy) quark decays)



126 GeV is a low mass for ZZ^* decays

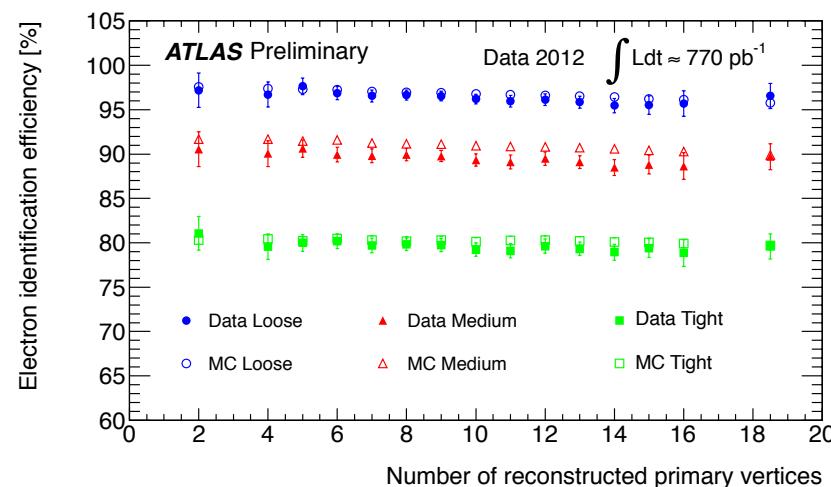
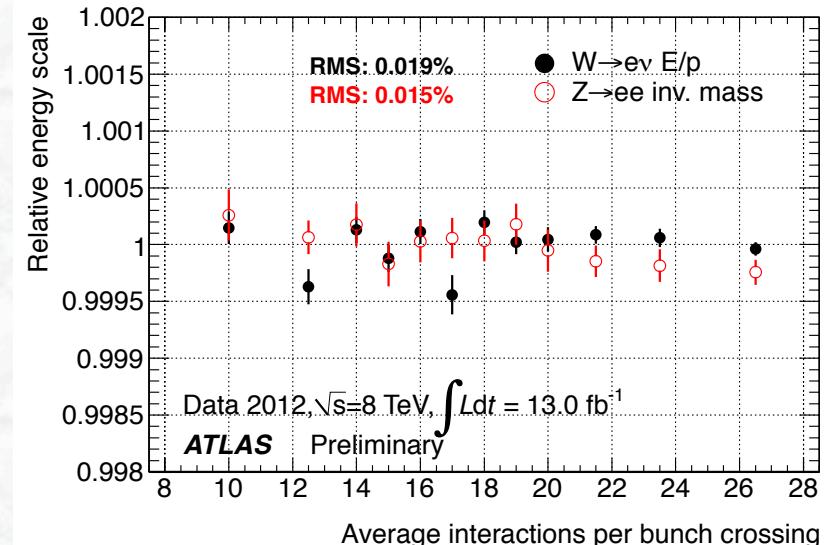
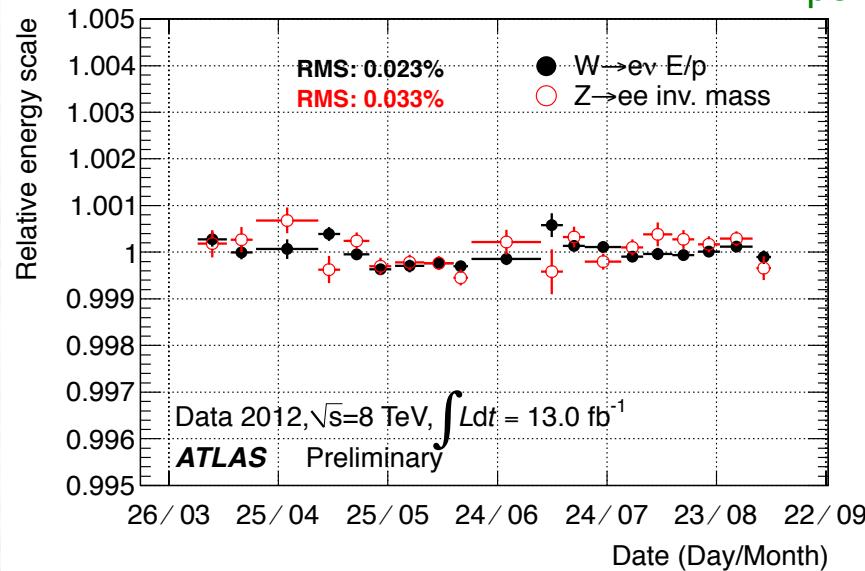
→ low p_T leptons are required





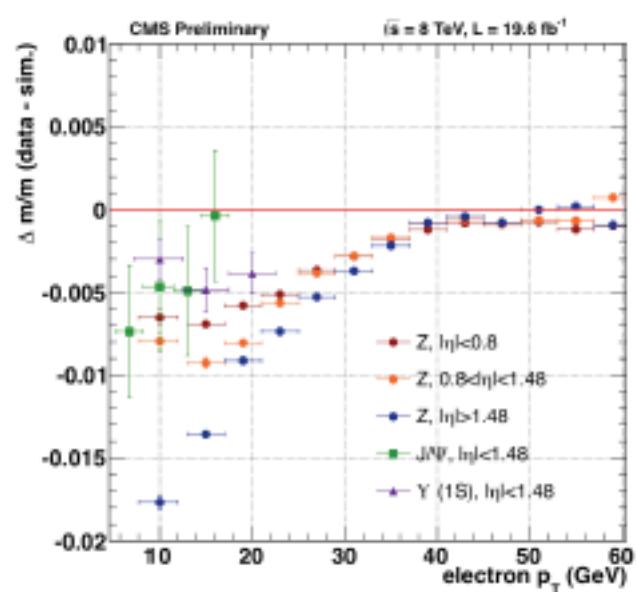
ATLAS electron performance

Stability of the electron energy scale: (i) With time
(ii) As function of average number of interactions per bunch crossing



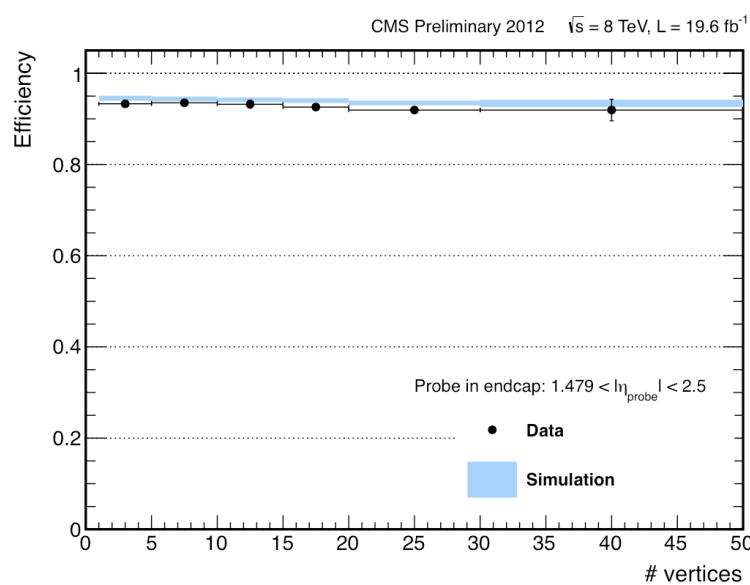
Stability of the electron identification:
Efficiency versus rec. number of primary vertices

CMS electron performance



Stability of electron scale:

~0.2% for $p_T > 35 \text{ GeV}$

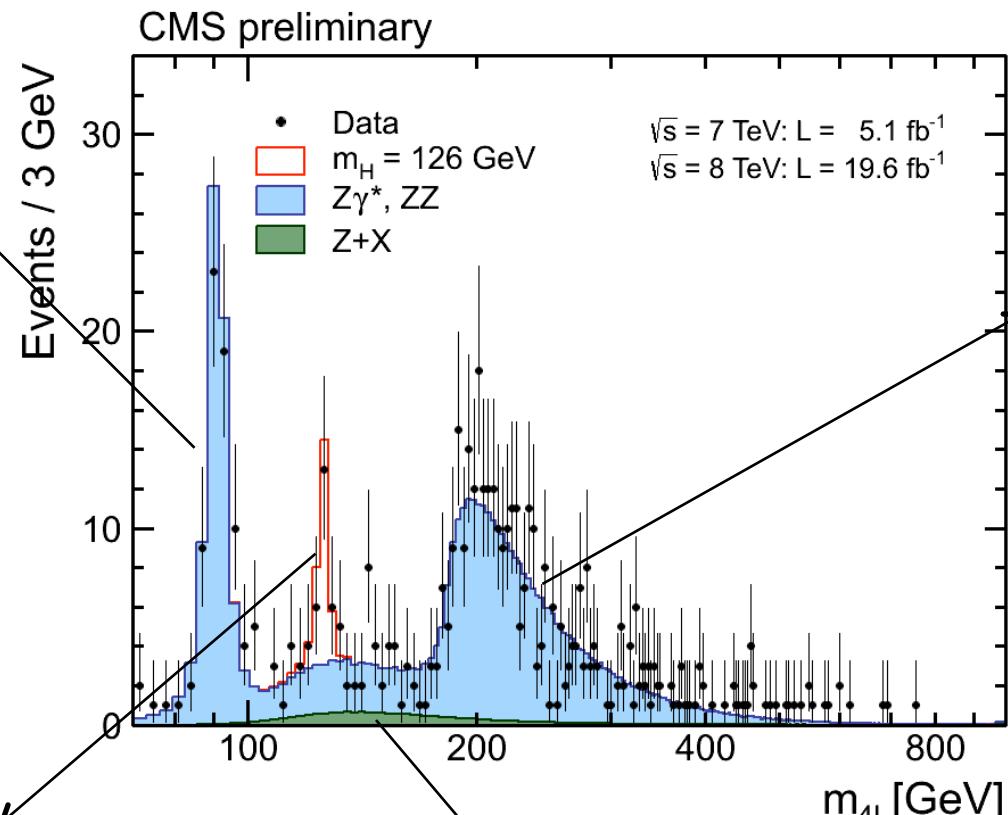
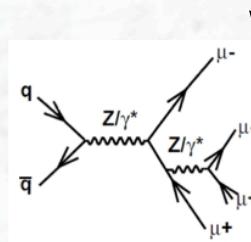


Electron efficiency versus
number of rec. primary vertices

CMS: 4ℓ invariant mass spectrum



$Z \rightarrow 4\ell$ peak
(good data / MC agreement)



$H \rightarrow ZZ$ signal

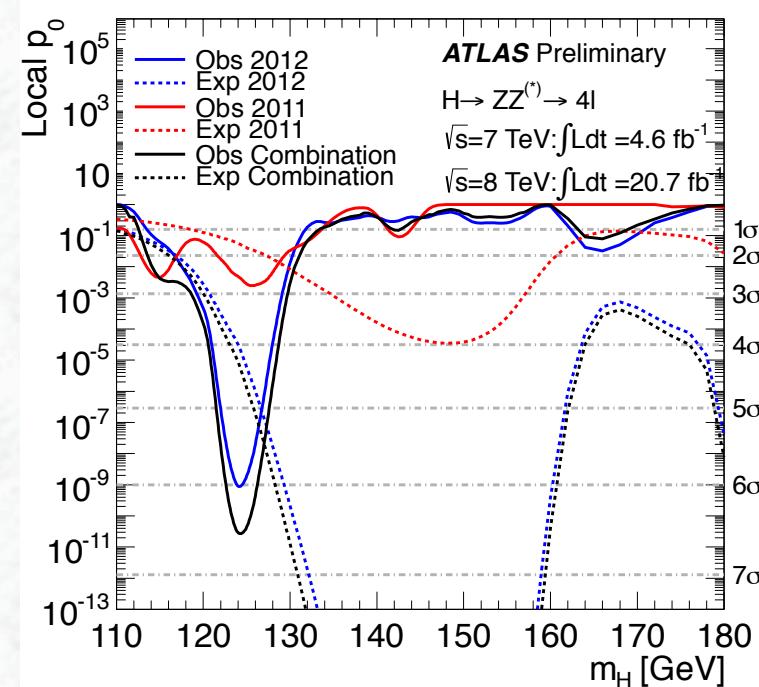
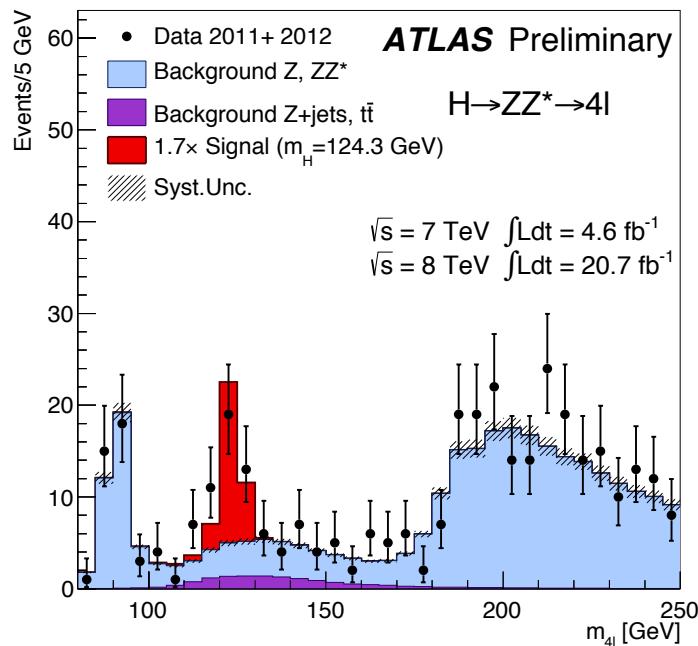
$121.5 < m(4\ell) > 130.5$ GeV:
S+B: 28 events expected
25 events observed

ZZ continuum background,
modelled by Monte Carlo
simulation (NLO)

$m(4\ell) > 140$ GeV:
403 events observed
390 events expected

Reducible tt and Zbb, Z+jets background,
data driven estimates

ATLAS: 4ℓ invariant mass spectra



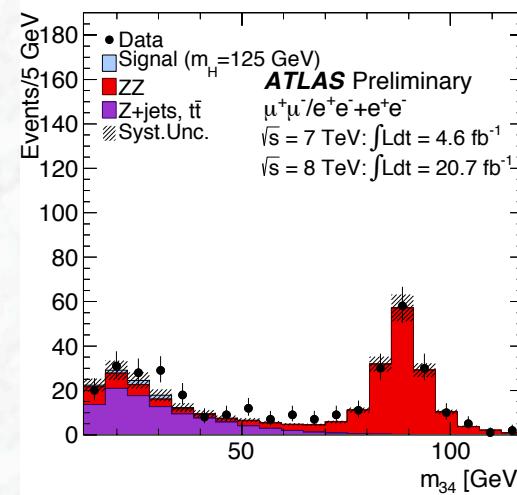
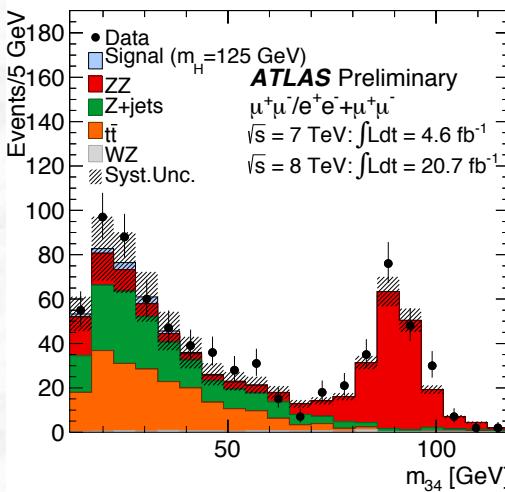
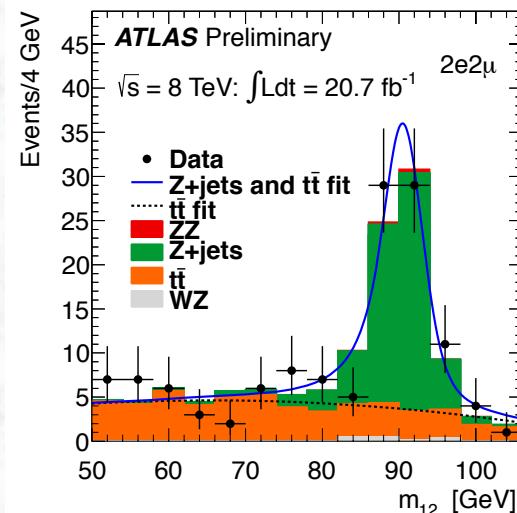
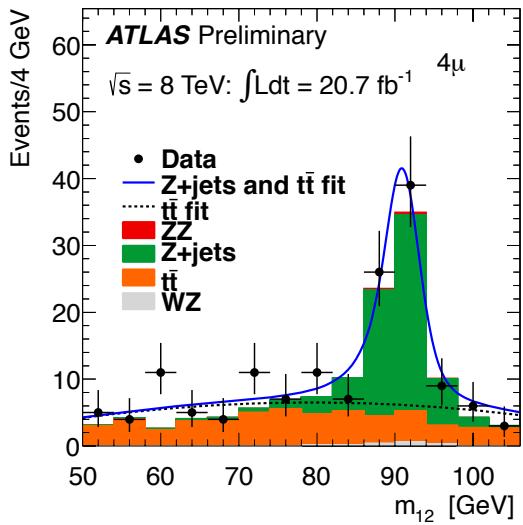
Mass range 120 – 130 GeV	Expected signal	Background	Data
$\sqrt{s} = 7$ TeV	2.2	2.3	5
$\sqrt{s} = 8$ TeV	13.7	8.8	27

$m_{4\ell} > 160$ GeV: 376 events observed
 348 ± 26 expected from
 $\sqrt{s} = 7 + 8$ TeV background (mainly ZZ)

- maximum deviation at 124.3 GeV
 p_0 value: $\sim 2.7 \cdot 10^{-11}$ (6.6σ obs.)
(4.4σ exp.)
- Independent discovery-level observation

Background estimates

ATLAS-CONF-2013-013

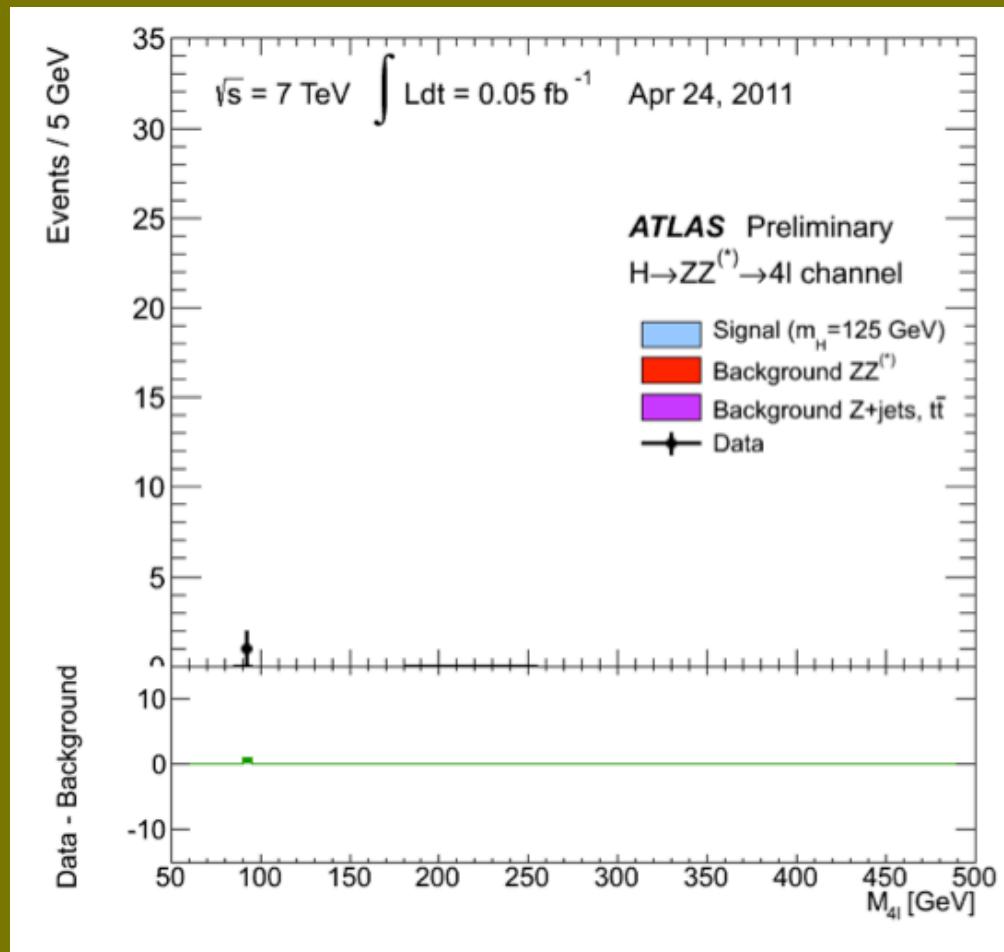


control region:

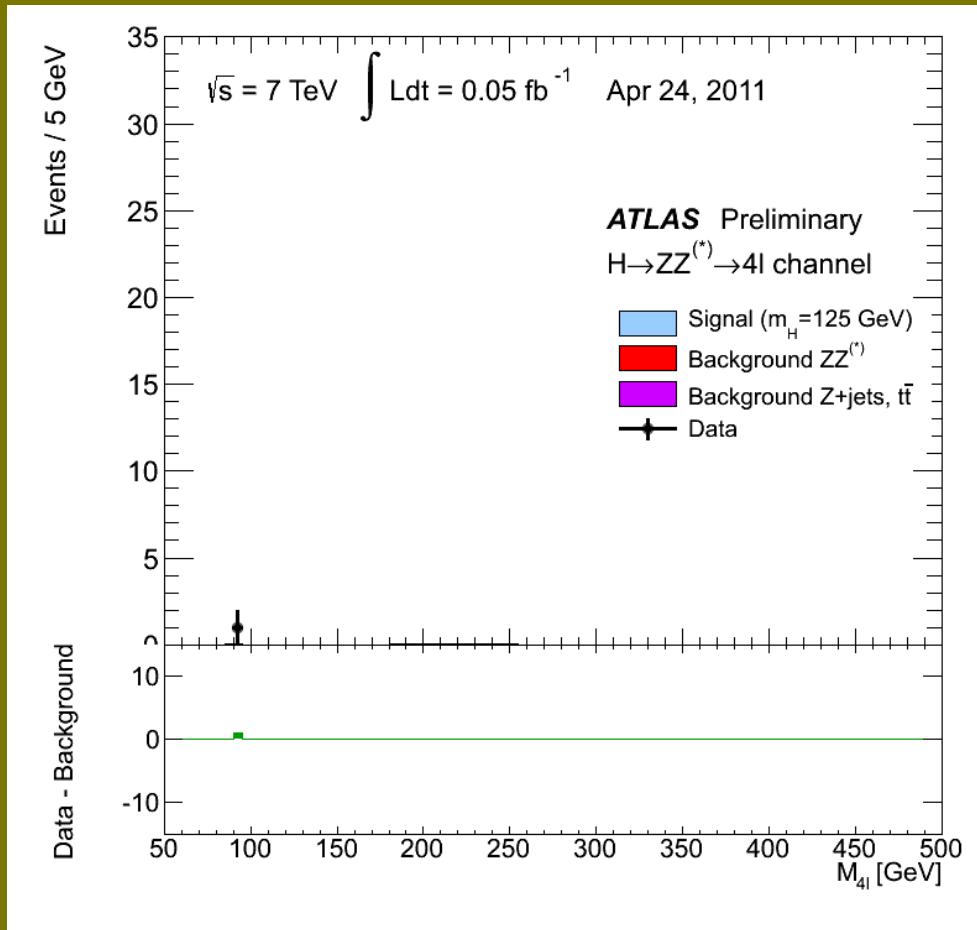
- isolation requirements not applied to the two sub-leading muons
- one muon fails impact parameter cut

- Irreducible ZZ* background taken from Monte Carlo simulation (NLO)
- Reducible Z+jets and tt background: measured using various background-enriched control regions and transferred to signal region using Monte Carlo simulation

Time evolution of the $H \rightarrow ZZ \rightarrow 4\ell$ signal



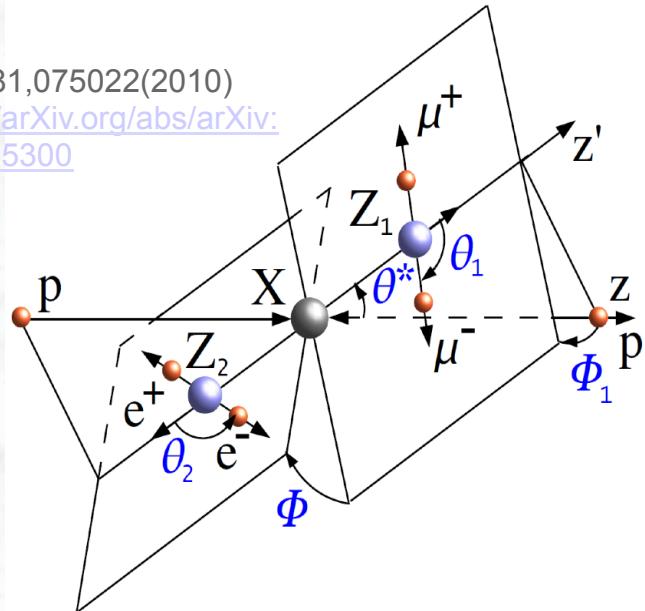
Time evolution of the $H \rightarrow ZZ \rightarrow 4\ell$ signal



CMS: use additional information on decay kinematics, MELA discriminant

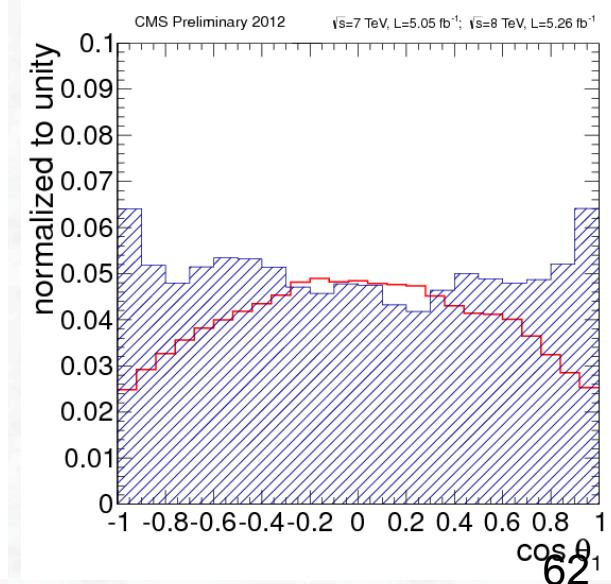
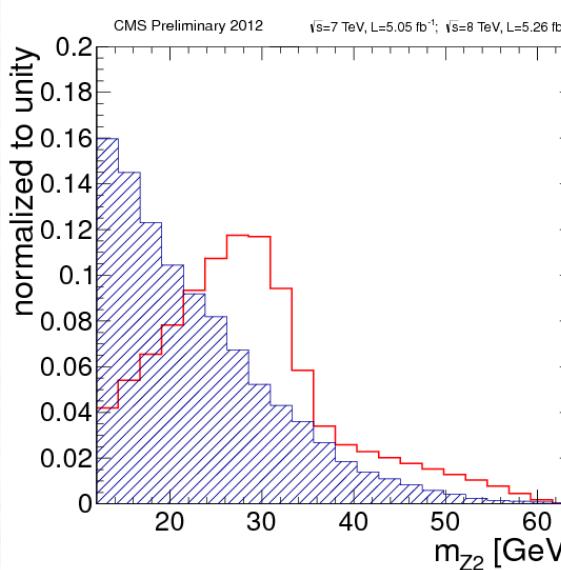
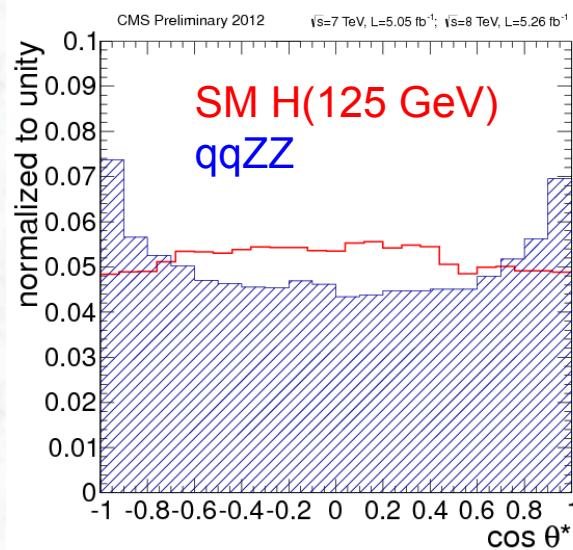


PRD81,075022(2010)
[http://arXiv.org/abs/arXiv:
 1001.5300](http://arXiv.org/abs/arXiv:1001.5300)



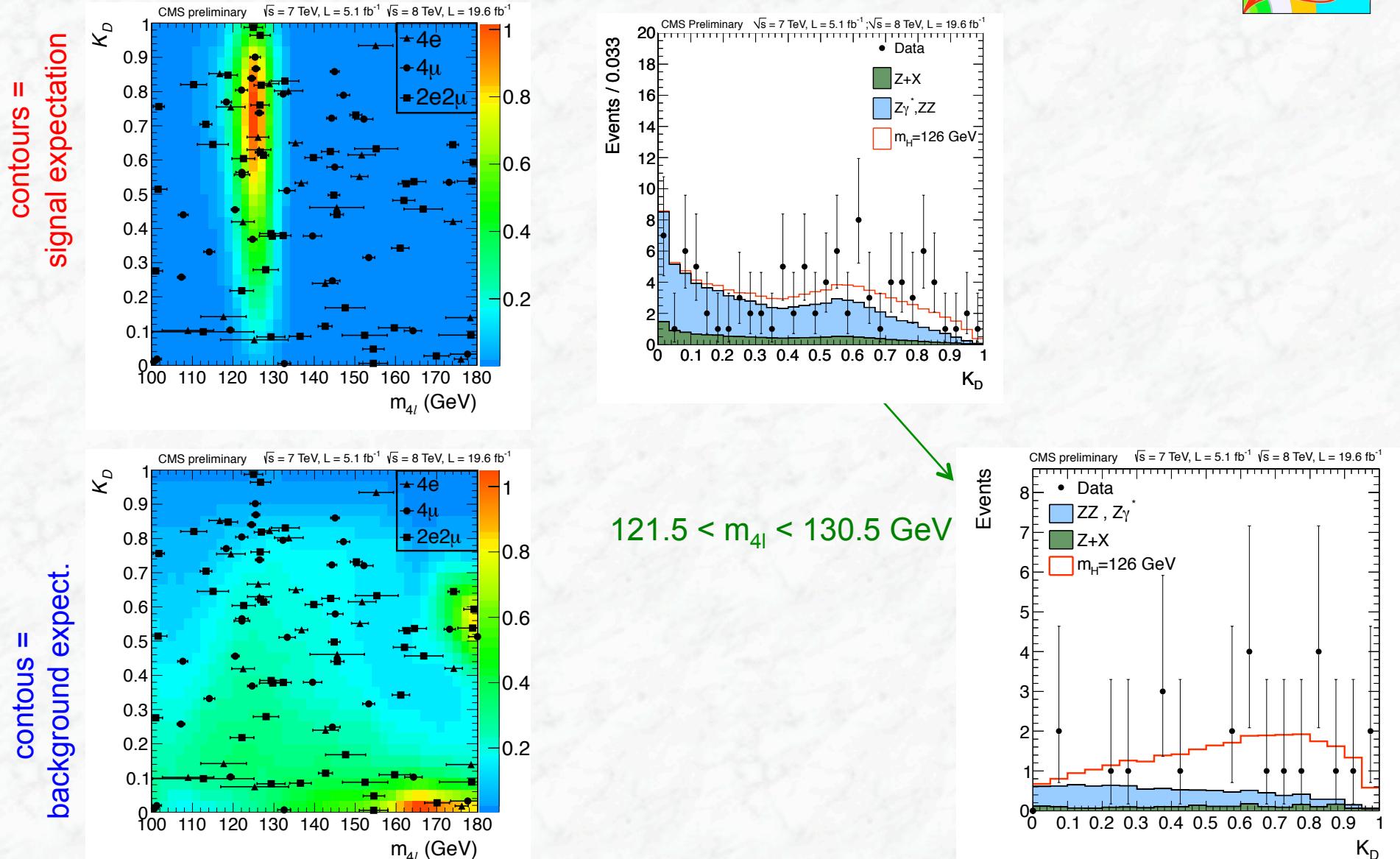
Matrix Element Likelihood Analysis:
 uses kinematic inputs for
 signal to background discrimination
 $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}$$





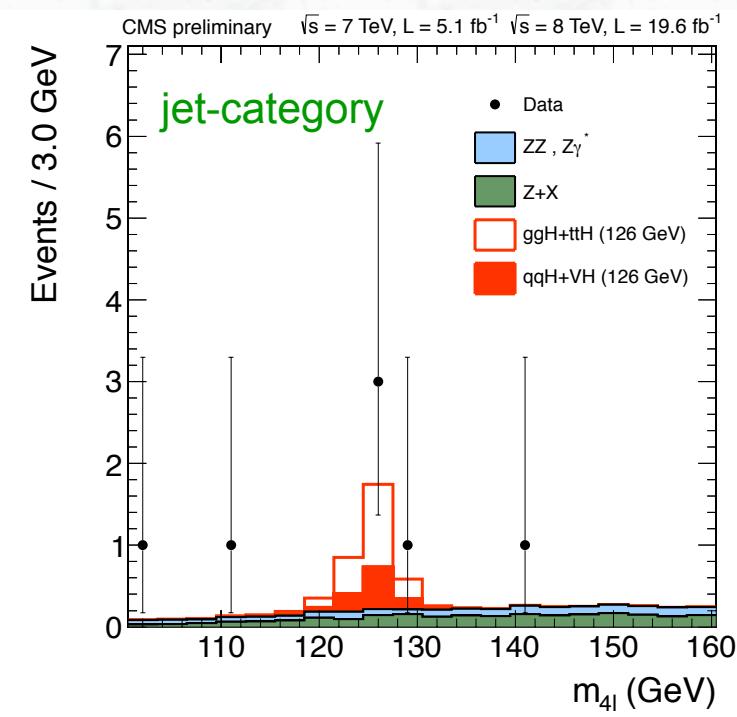
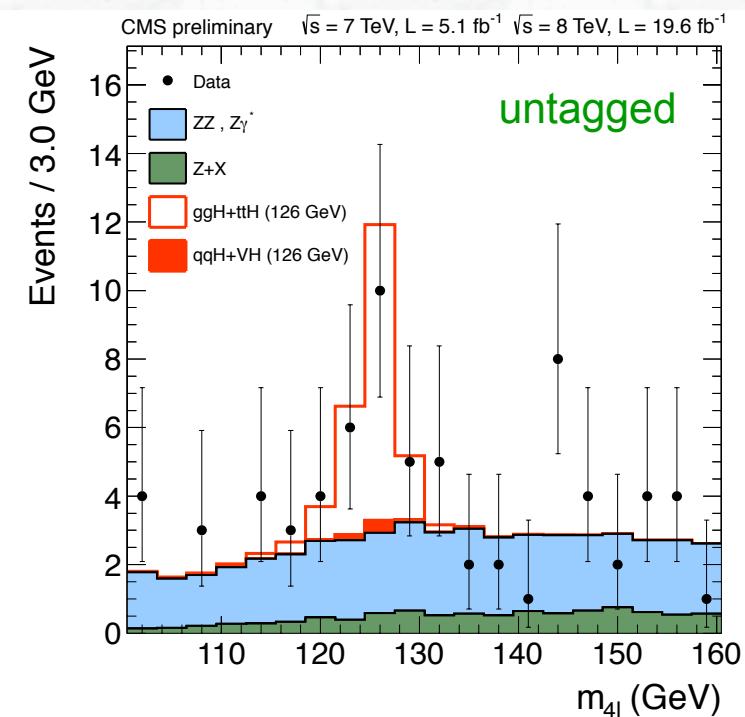
2D analysis using $\{m_{4l}, \text{MELA}=K_D\}$



CMS: further refinement via jet categorization



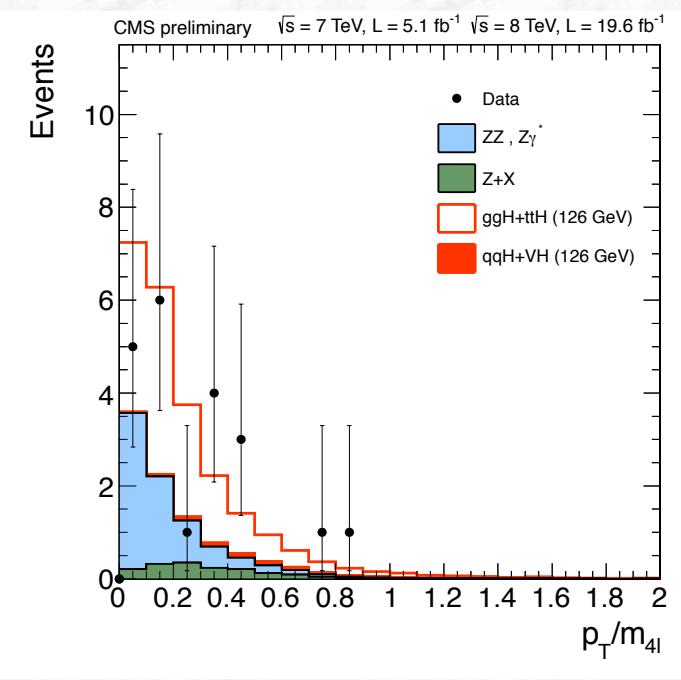
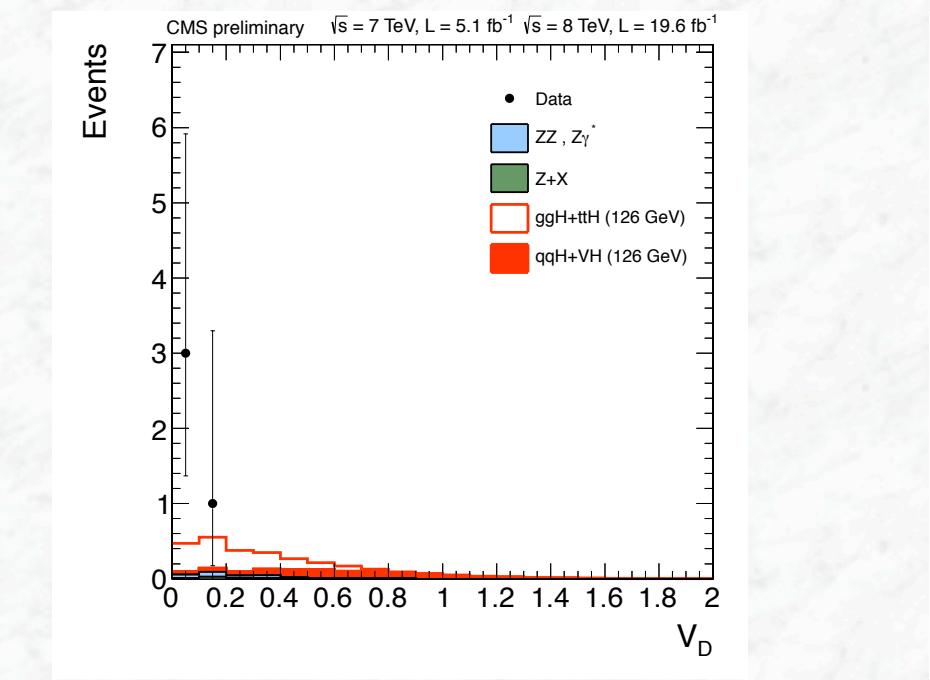
- (i) Jet-category: require two jets with $E_T > 30 \text{ GeV}$
(enhanced VBF fraction (~20%))
- (ii) Untagged: all other events (VBF fraction ~5%)



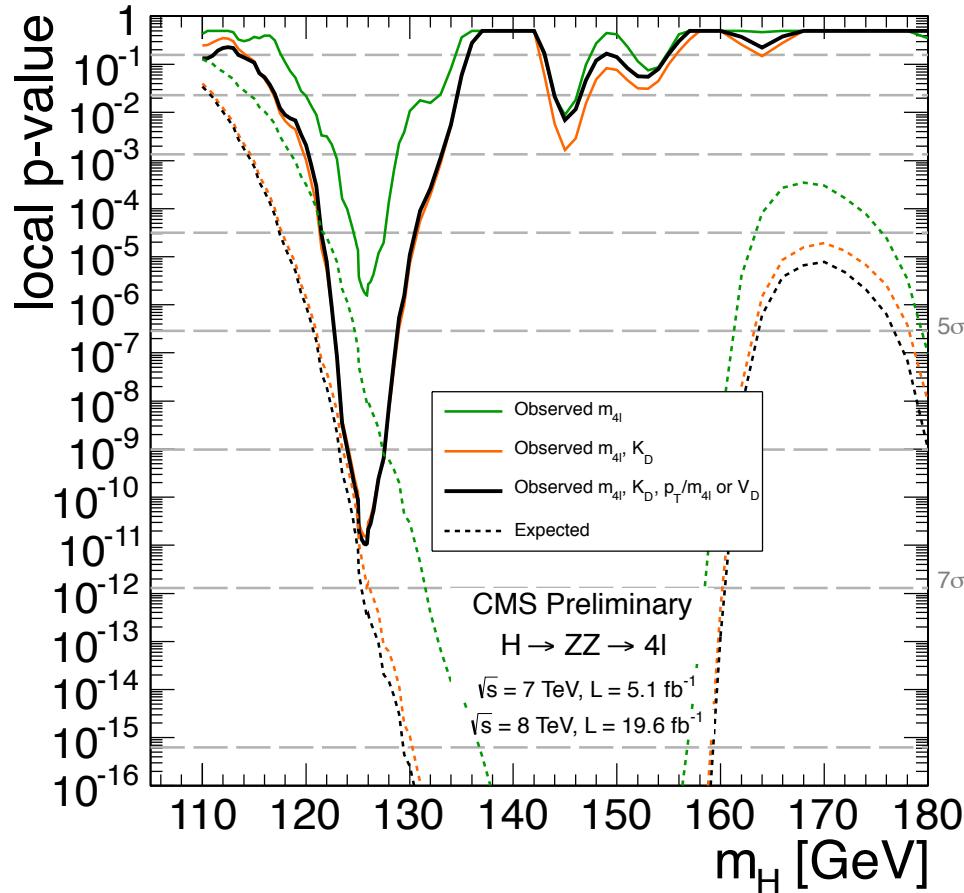
CMS: further refinement via additional discriminants -to separate production modes-



- VBF-discriminant: $V_D = \alpha |\Delta\eta_{jj}| + \beta m_{jj}$
- P_T boost: $P_T(4l) / m_{4l}$



CMS $H \rightarrow ZZ$ significance

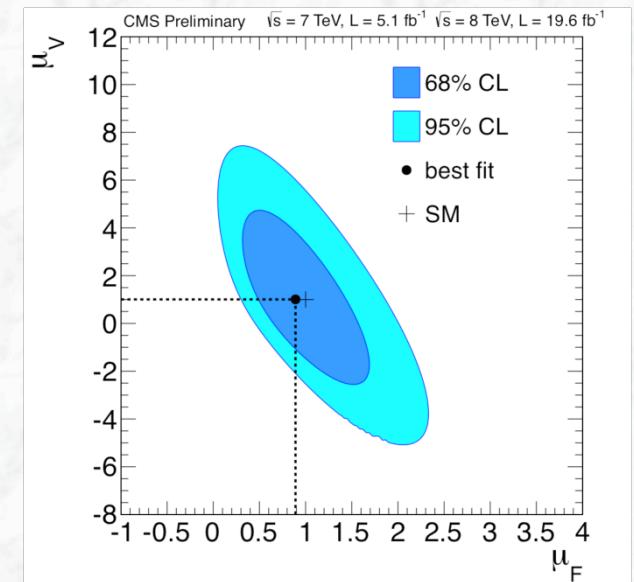
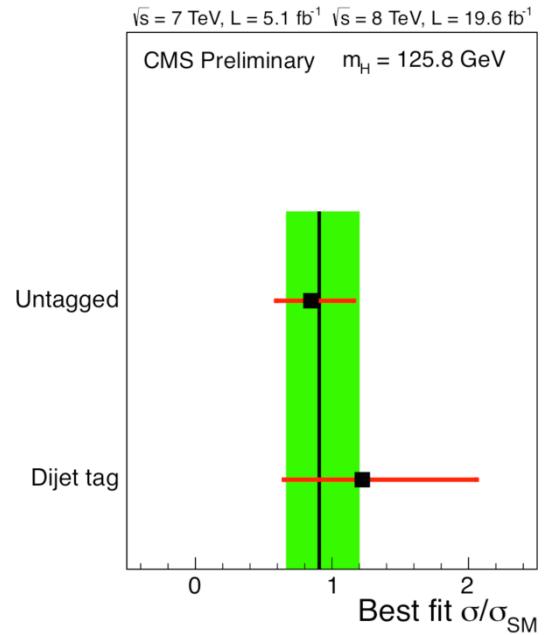
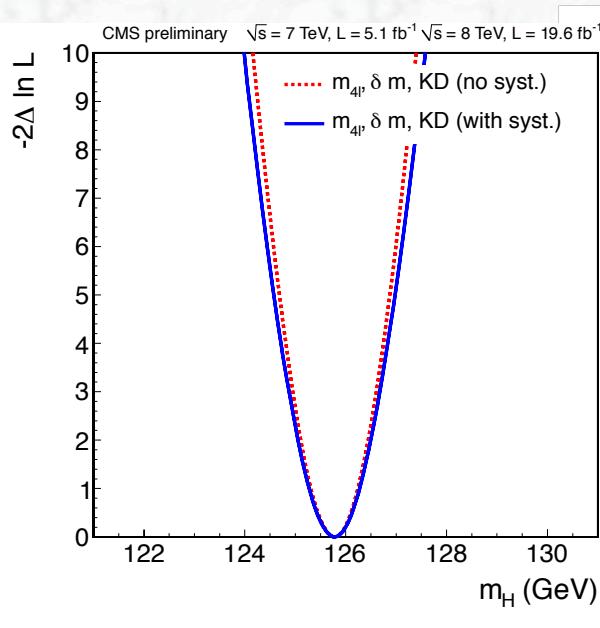


	Expected	Observed
3D (m_{4l}, K_D, V_D or p_T/m_{4l})	7.2 σ	6.7 σ
2D (m_{4l}, K_D)	6.9 σ	6.6 σ
1D(m_{4l})	5.6 σ	4.7 σ

at 125.8 GeV (minimum of local p value)

- Stand-alone discovery in the $H \rightarrow ZZ - 4l$ channel
- Additional discriminants improve sensitivity, as expected

Mass and signal strength for $H \rightarrow ZZ^*$



Mass:

$$m_H = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{syst}) \text{ GeV}$$

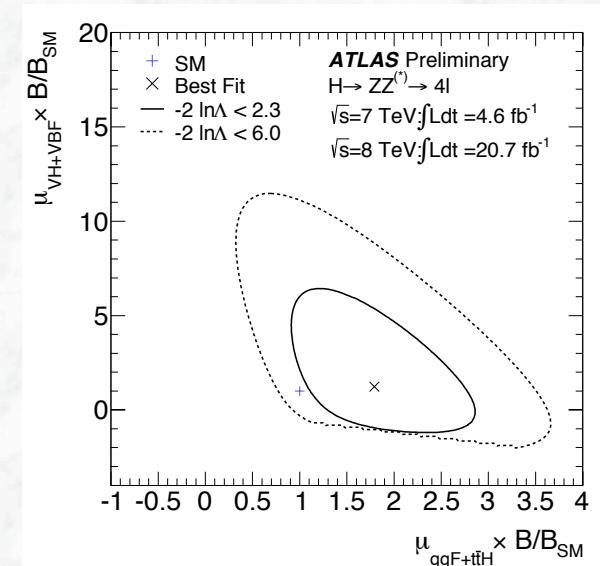
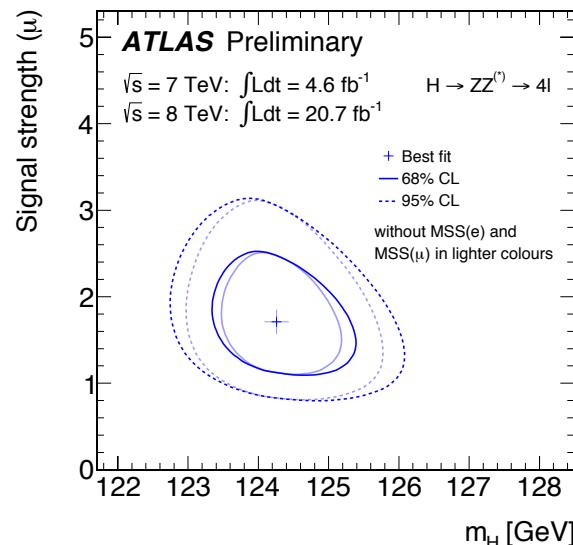
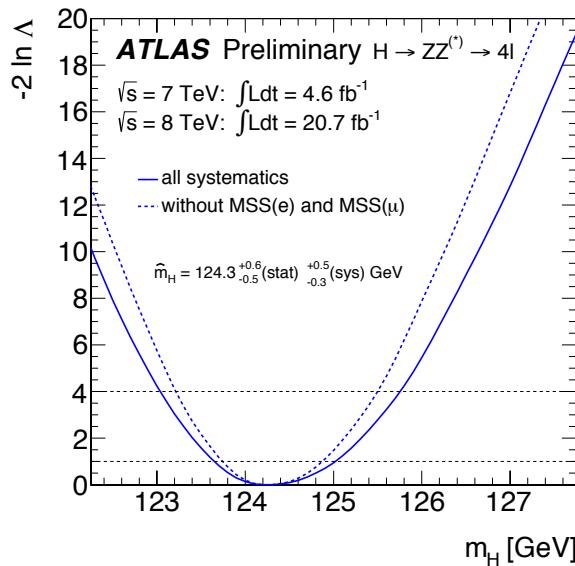
Signal strength:
($m_H = 125.8 \text{ GeV}$)

$$\mu = 0.9^{+0.3}_{-0.2}$$



Mass and signal strength for $H \rightarrow ZZ^* \rightarrow 4l$

ATLAS-CONF-2013-013



Mass:

$$m_H = 124.3^{+0.6}_{-0.5} (\text{stat})^{+0.5}_{-0.3} (\text{syst}) \text{ GeV}$$

Signal strength:
($m_H = 124.3 \text{ GeV}$)

$$\mu = 1.7 \pm 0.5$$