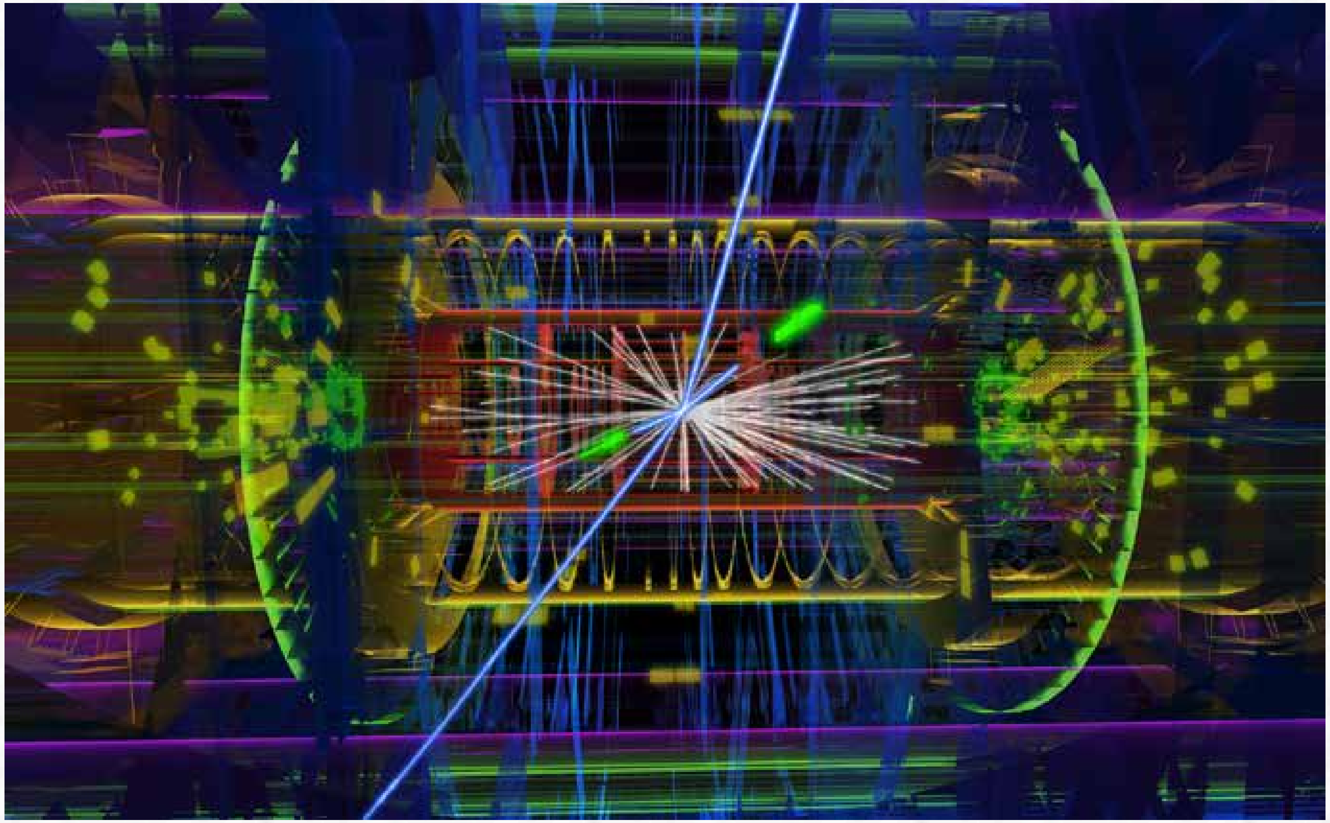
Higgs analyses at the LHC



Karl Jakobs
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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)

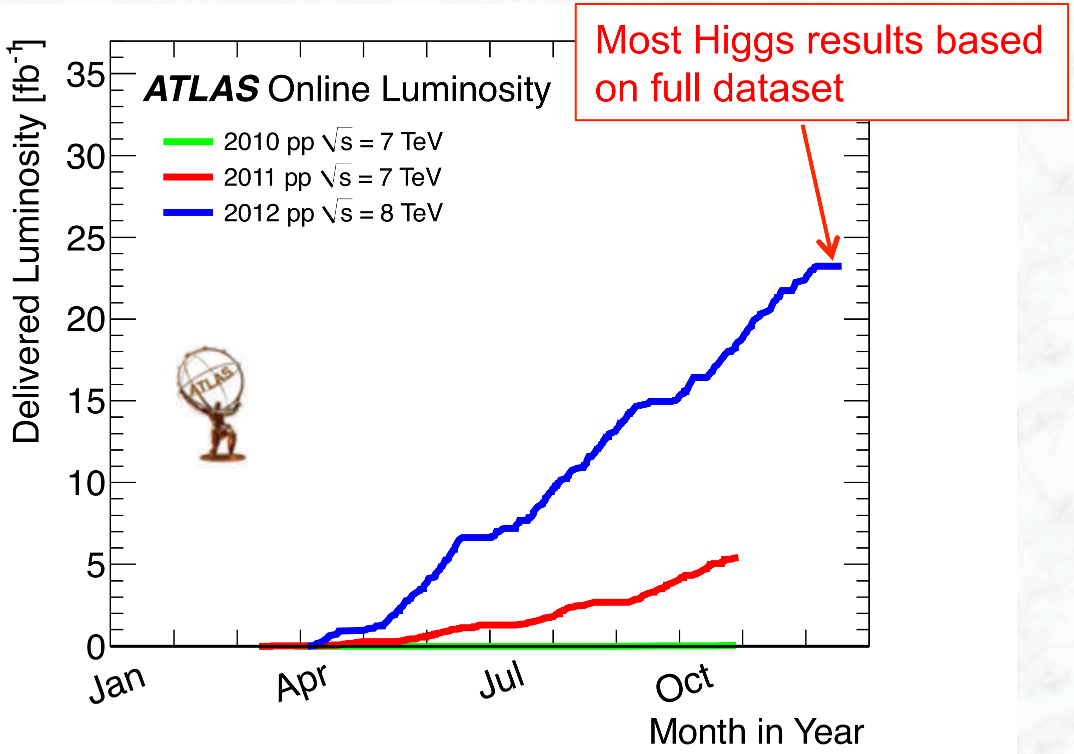
    $H \rightarrow ZZ^*$

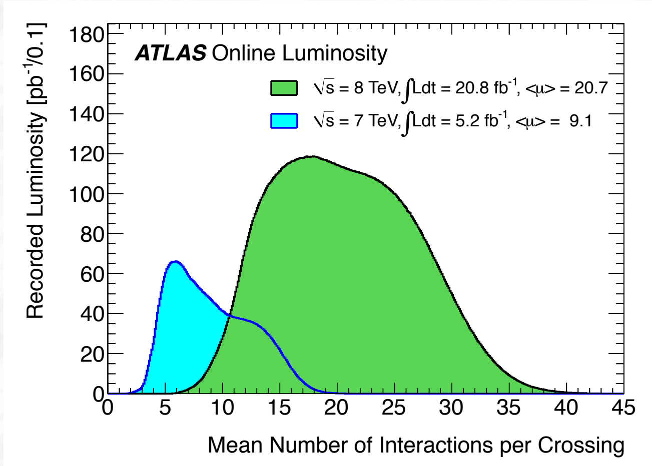
- Lecture II: The more challenging decay modes
  - $H \rightarrow WW^*$
  - Decays into fermions?

- Lecture III: Higgs boson parameters
  - How to measure its properties
  - Couplings to fermions and boson
  - Spin / parity

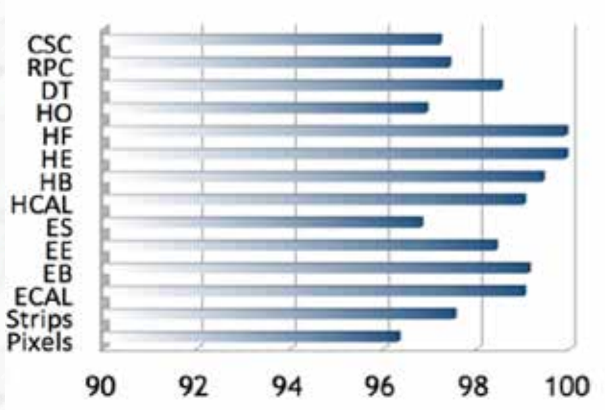
Disclaimer: I will try to discuss important analyses and measurements. The coverage is not complete, i.e. not all results available are presented; Results from both general purpose experiments, ATLAS and CMS, are shown, but there might still be a bias towards the experiment I am working on. This bias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

Summary of LHC and ATLAS/CMS performance



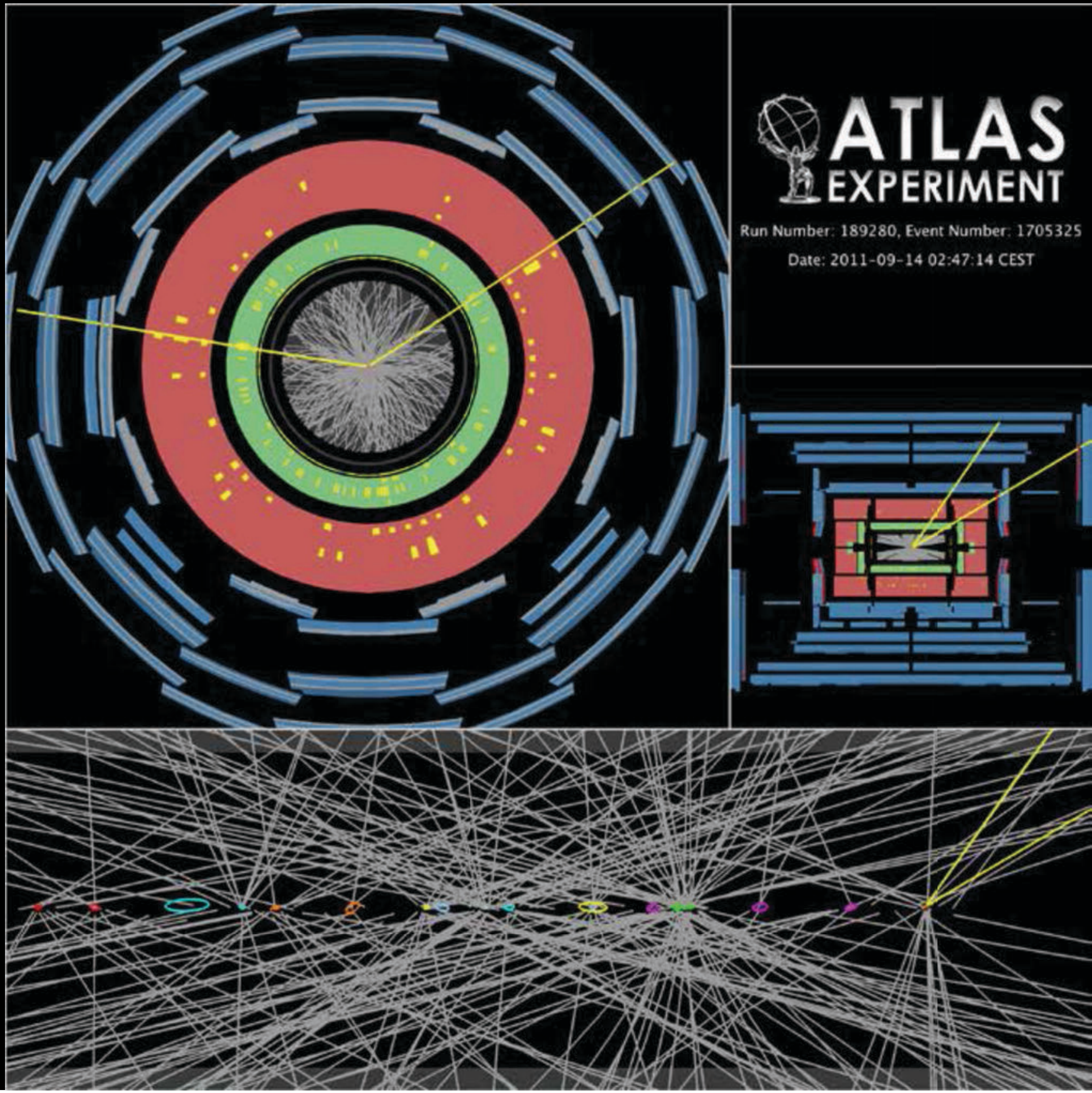


CMS detector efficiency

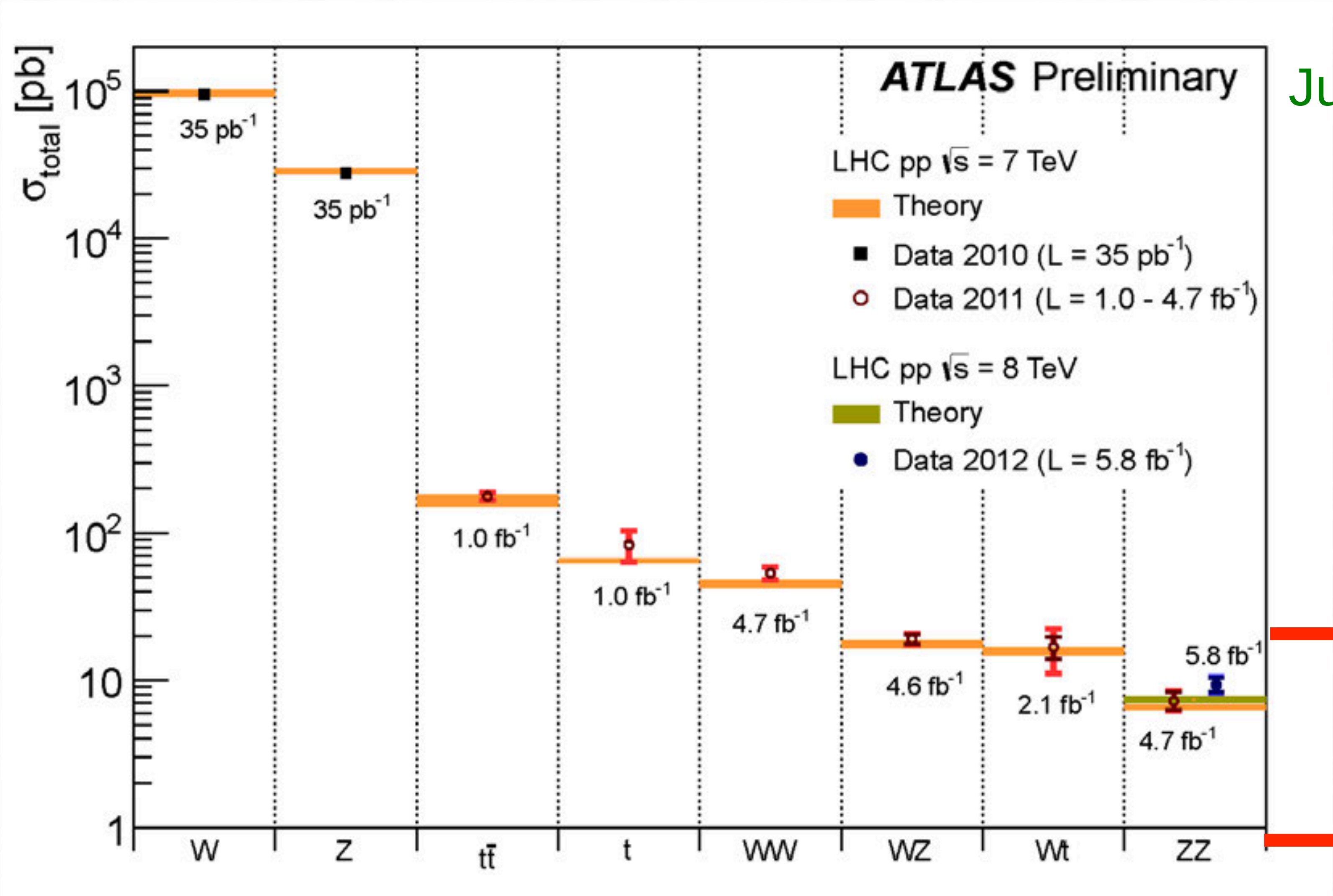


- Excellent LHC performance in 2011 and 2012
- Peak luminosities > 7 10^{33} cm^{-2} s^{-1}
- High level of pileup: mean of ~21 interactions / beam crossing in 2012
- Excellent performance of the experiments: (Data recording efficiency: ~93.5% (ATLAS) high fraction of working detector channels for most 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

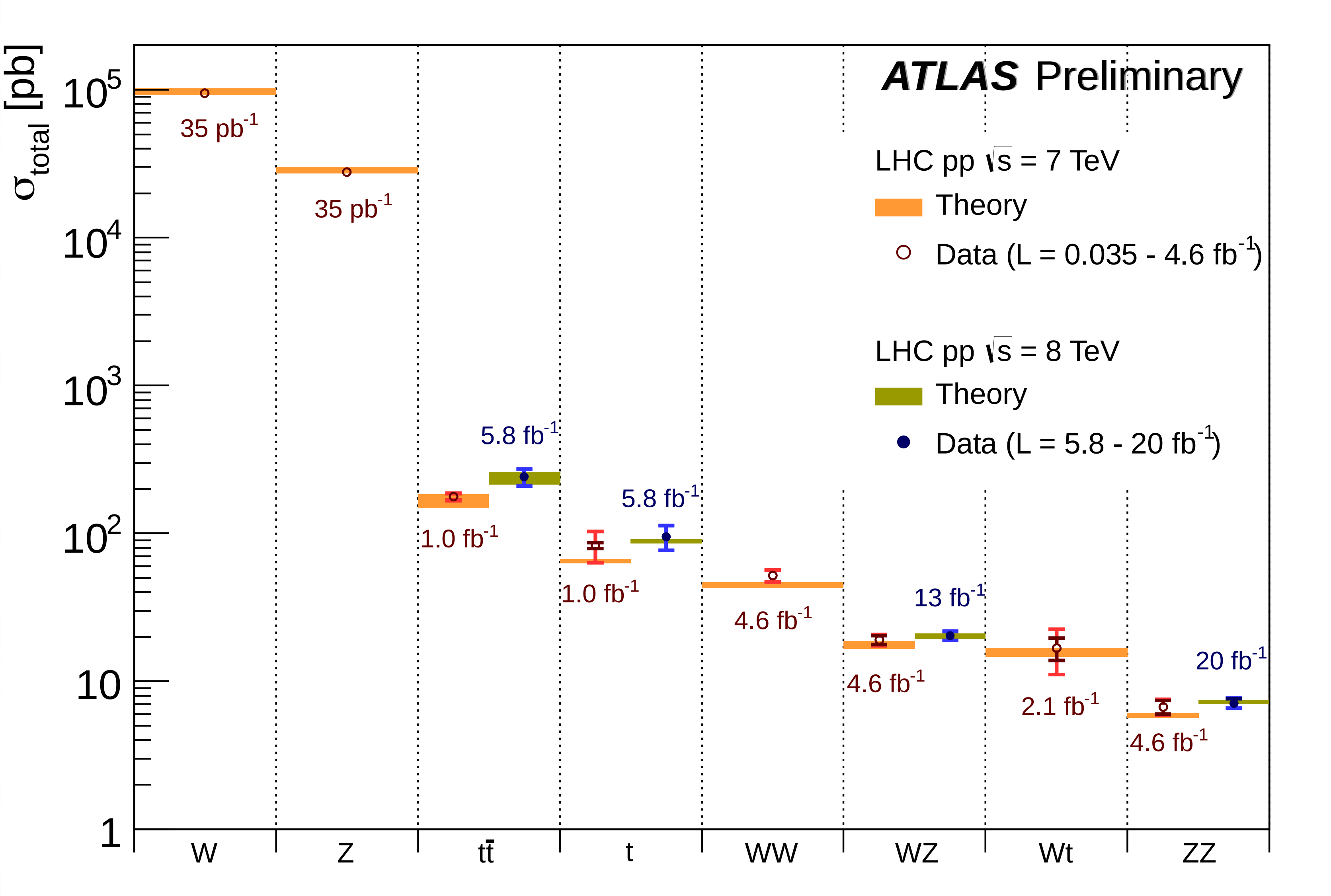


July 2012

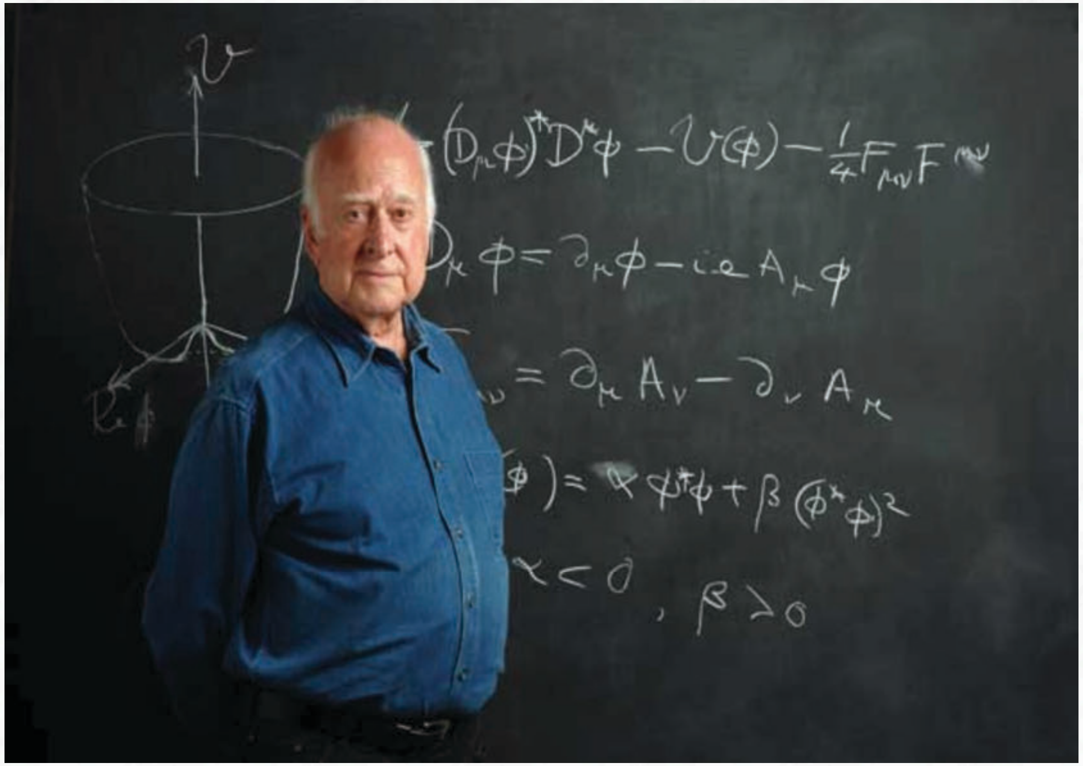
H (20pb)

H → ZZ (0.5 pb)

Standard Model processes at the LHC



The Brout-Englert-Higgs Mechanism

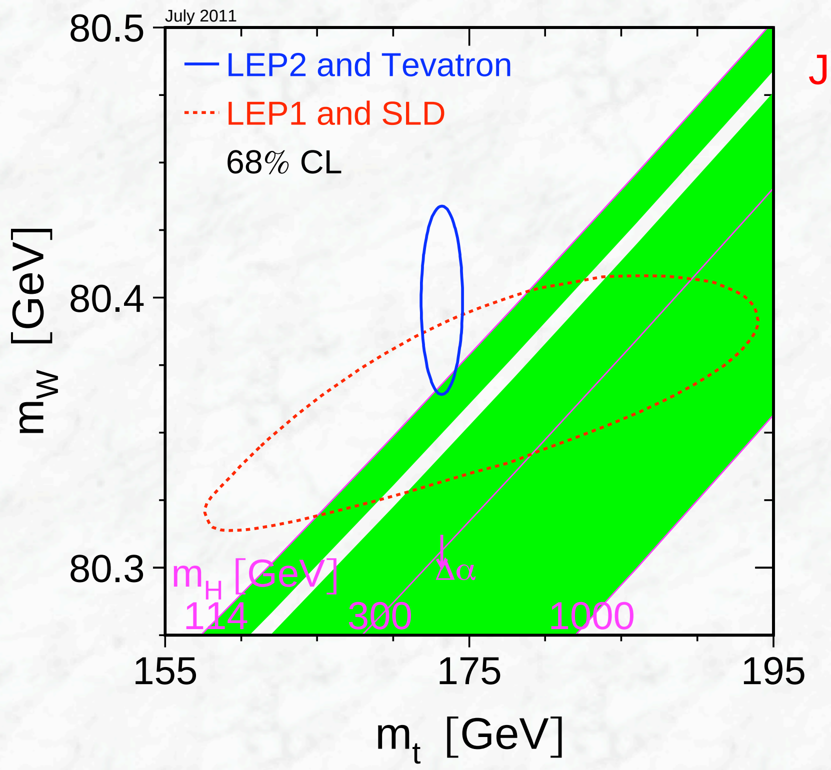


→ Lecture by M. Schmaltz

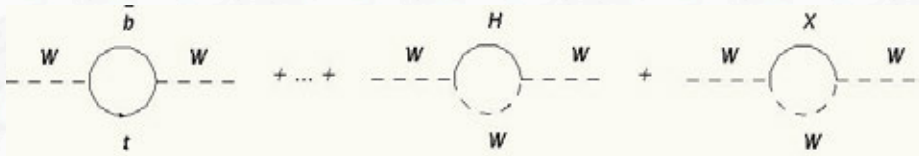
F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

Constraints on the Higgs boson mass (before LHC)

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



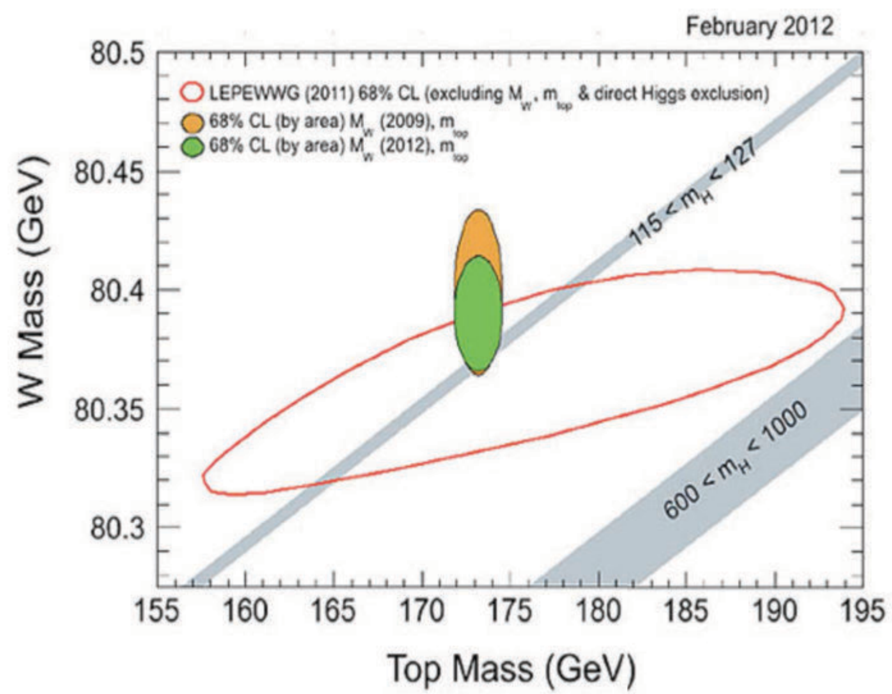
July 2011



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

- Indirect constraints from precision measurements (quantum corrections)

Constraints on the Higgs boson mass (Feb. 2012)



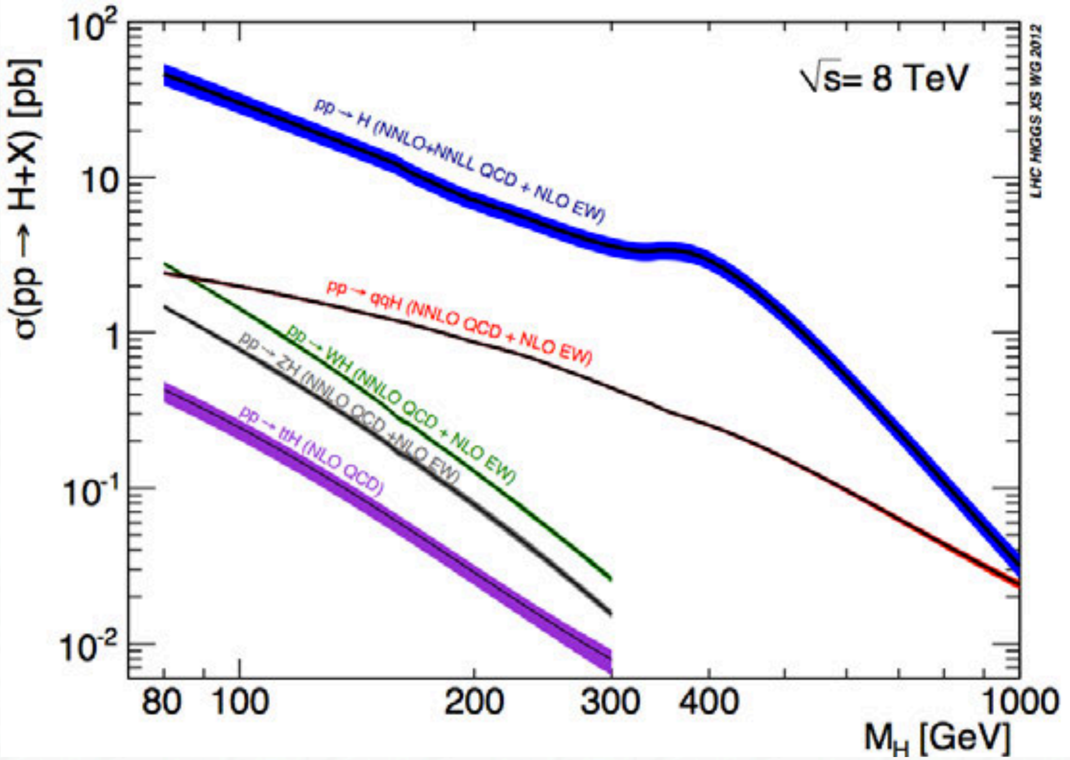
February 2012

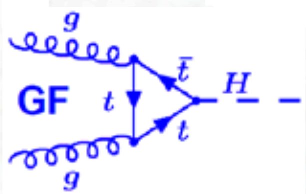
Two impressive results (2011/12):

- 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)

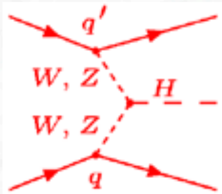
- Impressive precision in m_W (and m_t) achieved at the Tevatron
  (might provide the basis for the ultimate test of the Standard Model)

Higgs Boson Production



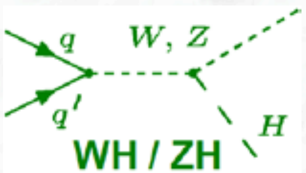


Gluon fusion

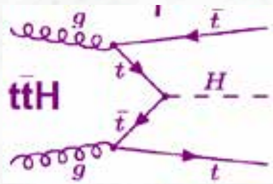


VBF

Vector boson fusion



WH/ZH associated production

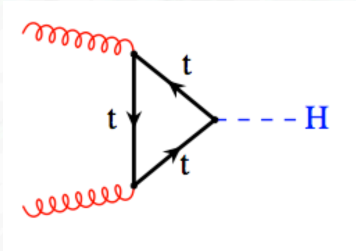


tt associated production

*) 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)

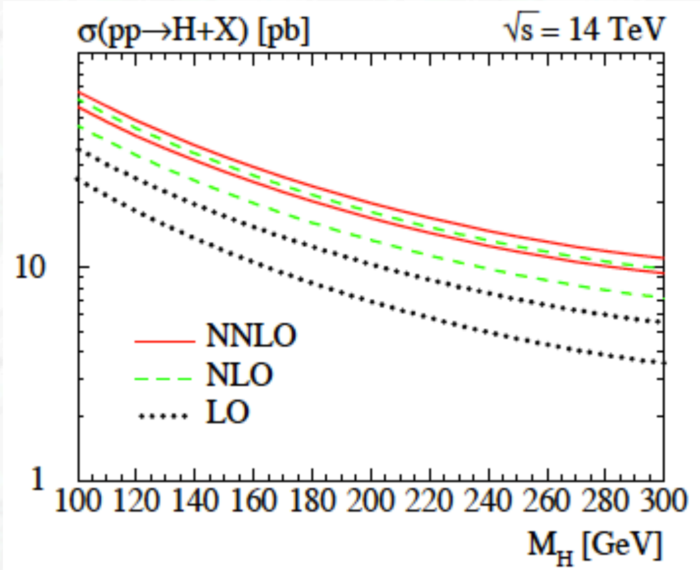
- Large K-factors (NLO, NNLO corrections)

  - 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



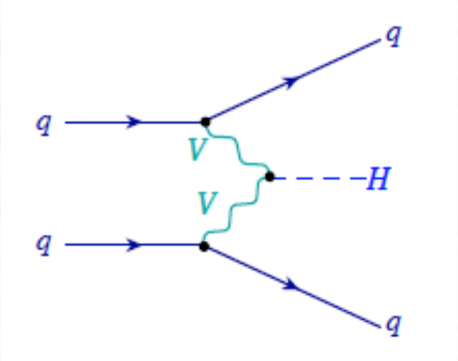
- Spira, Djouadi, Graudenz, Zerwas (1991)
- Dawson (1991)

- 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)

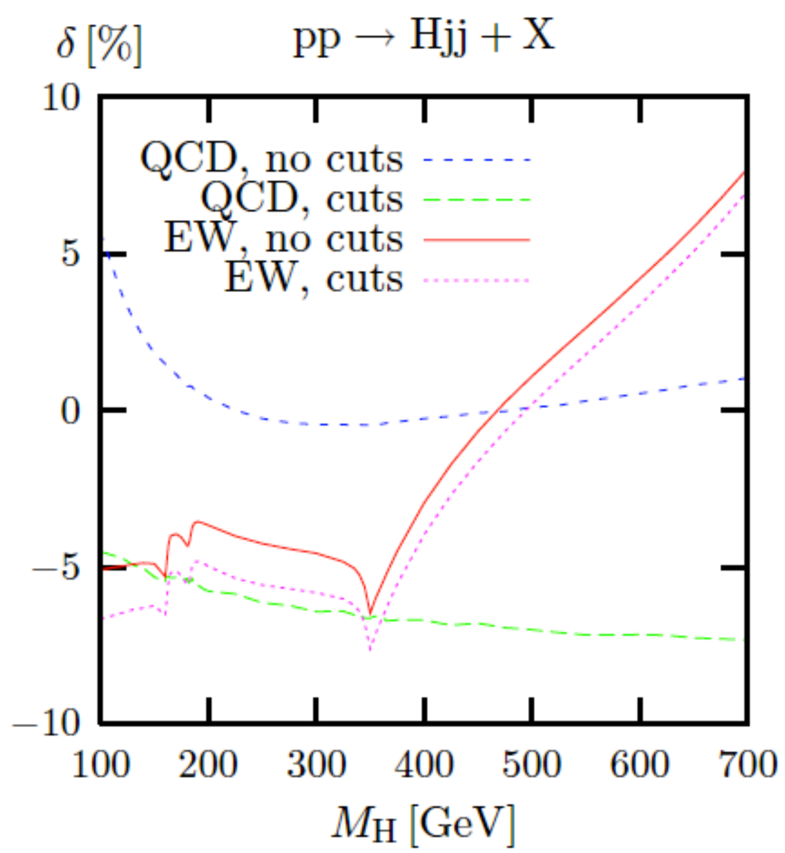
- Sensitivity to W/Z couplings

- Both NLO QCD and el.weak corrections
  have been calculated
  (moderate K-factors)
  Approx. NNLO QCD calculation available
  (Bolzoni et al. 2010)

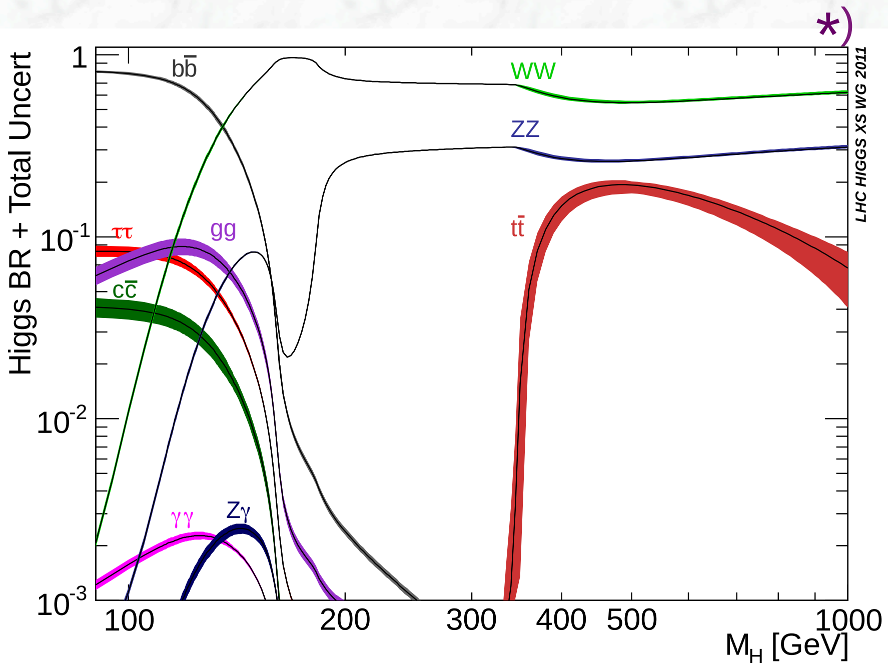
- Effective K-factor depends on
  experimental cuts

Example: typical VBF cuts
P_T(jet) > 20 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
- γγ final states (despite small branching ratio)
- ττ final states (more difficult)
- In addition: H → bb decays via associated lepton signatures (VBF, VH or ttH production)

SM predictions (m_H = 125.5 GeV):

BR (H→ WW) = 22.3%	BR (H → bb) = 56.9%
BR (H → ZZ) = 2.8%	BR (H → ττ) = 6.2%
BR (H → γγ) = 0.24%	BR (H →μμ) = 0.022%

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

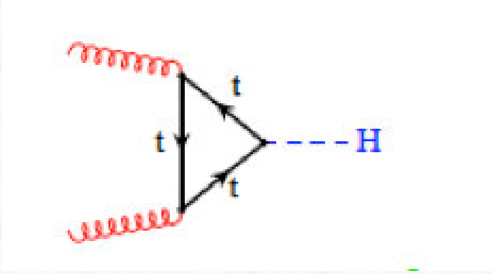
125 GeV is a perfect mass !

~89 % of Higgs boson decays accessible

*) LHC Higgs cross-section working group

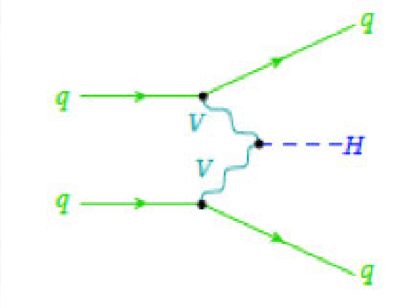
The important Higgs boson search channels at the LHC

(i) The bosonic decay channels



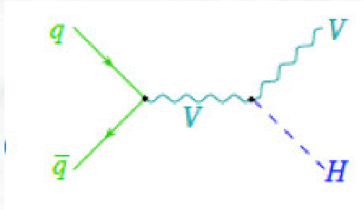
Important channels: H → $\gamma\gamma$
H → ZZ → $\ell^+\ell^-\ \ell^+\ell^-$
H → WW → $\ell\nu\ \ell\nu$

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



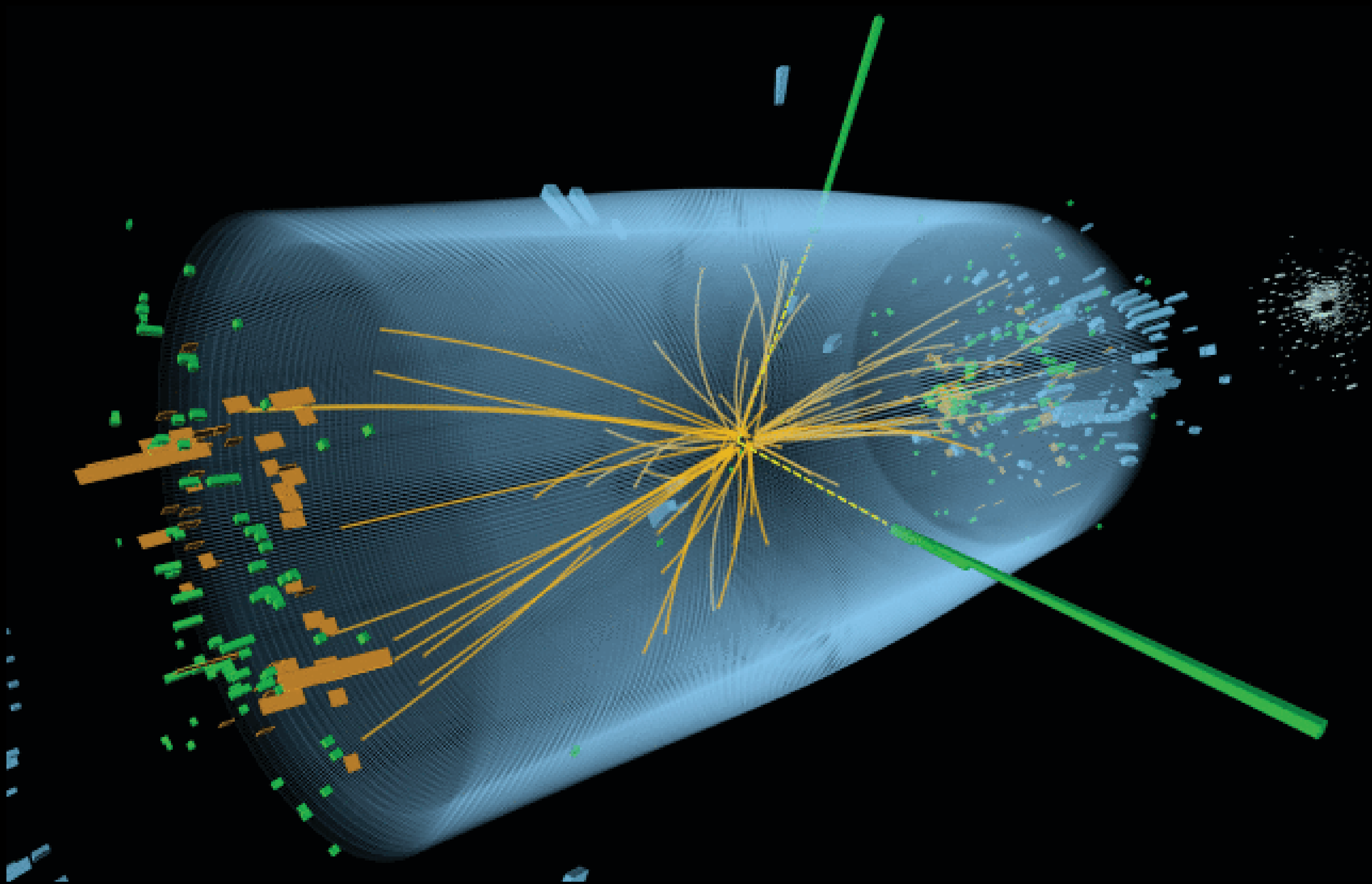
(ii) The fermionic decay channels

Important channels: qq H → qq $\tau\ \tau$
VH, V → ll (l=e,μ,ν) H → bb

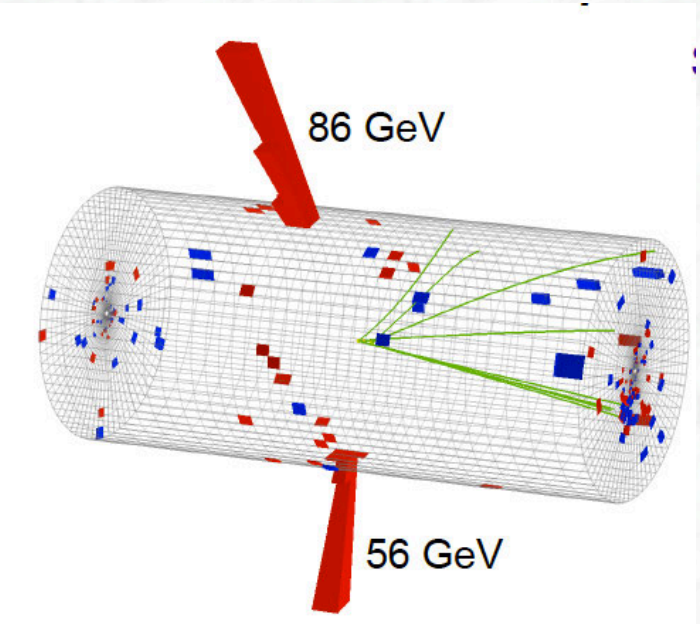


- Associated production essential for bb decays (suppression against overwhelming backgrounds from multijet production)
- exploit VBF topology (tag jets, no colour flow in central region) high-p_T topologies

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



Result of the ATLAS search for H → γγ

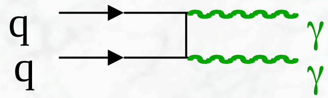


- Two photons (isolated) with large transverse momentum (P_T > 40, 30 GeV)

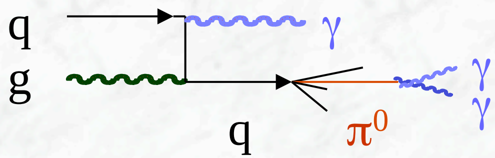
- Mass of the Higgs boson can be reconstructed $m_{\gamma\gamma}$

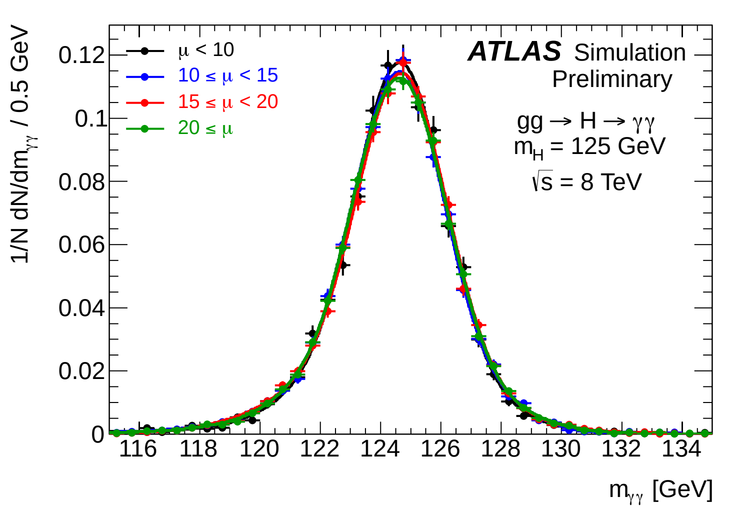
  Both experiments have a good mass resolution
  ATLAS: ~1.7 GeV/c² for m_H ~120 GeV
  Different calorimeters → different γ-performance

- Challenge: signal-to-background ratio
  - irreducible γγ background



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





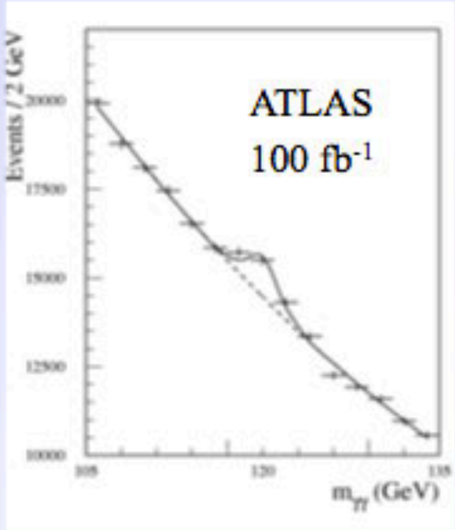
pile-up-robust mass reconstruction

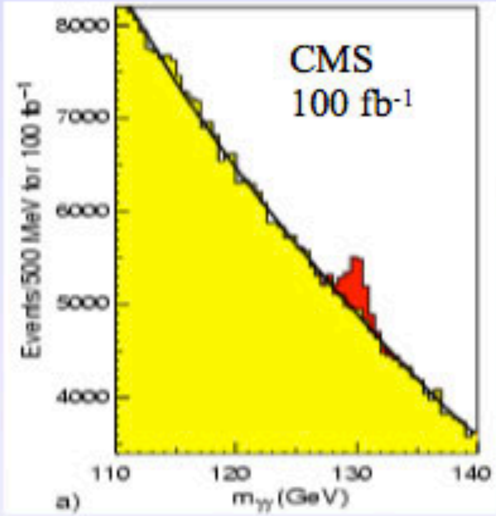
How does the expected signal look like ?

What is the signal-to-background situation

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

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





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

Mass resolution: $m_H = 100$ GeV/c^2

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

Signal / background ~ 4% (Sensitivity in mass range 100 – 140 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

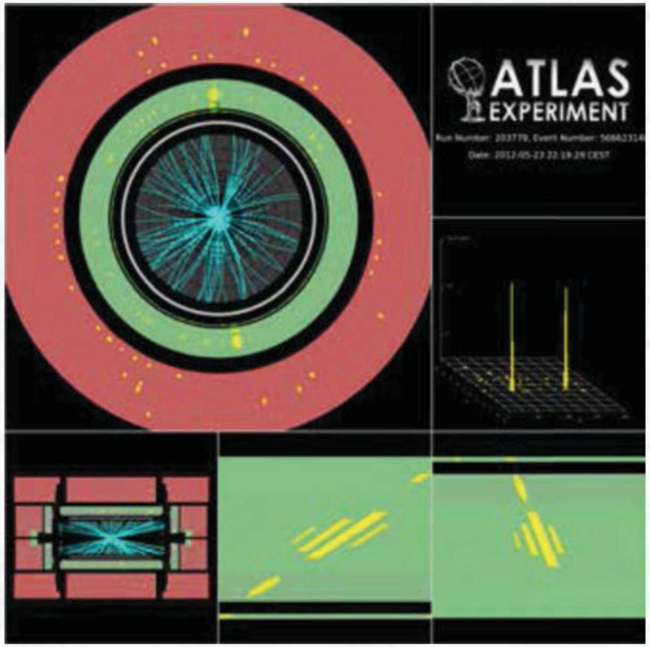
*) detailed simulations indicate that the γ-jet and jet-jet background can be suppressed to the level of 10-20% of the irreducible $\gamma\gamma$-background

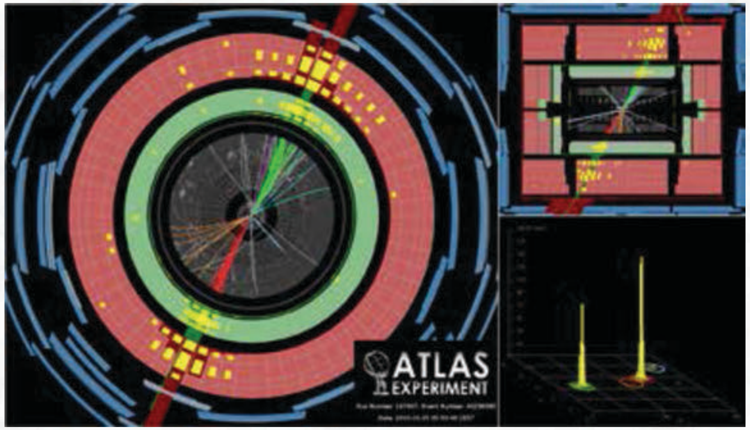
The key ingredients:

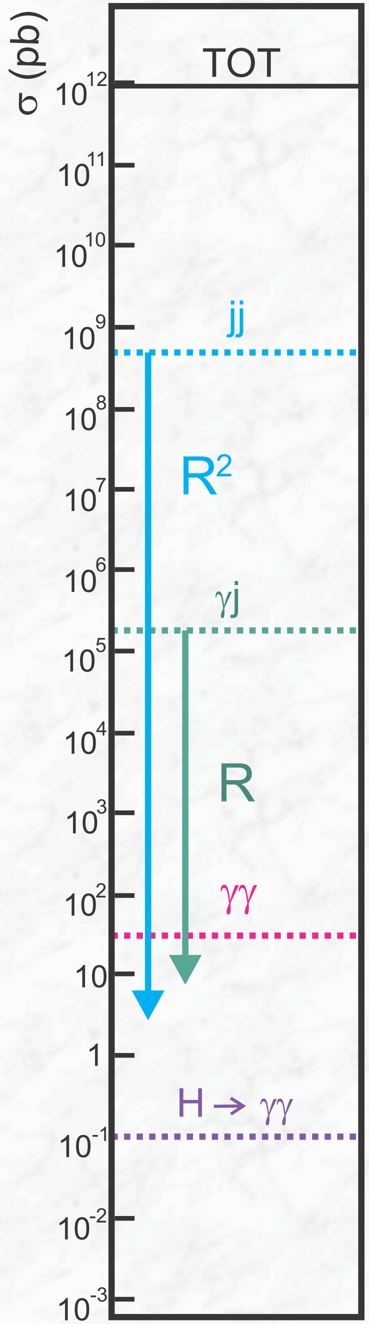
1. Good photon identification (γ/jet separation)

2. Good mass resolution

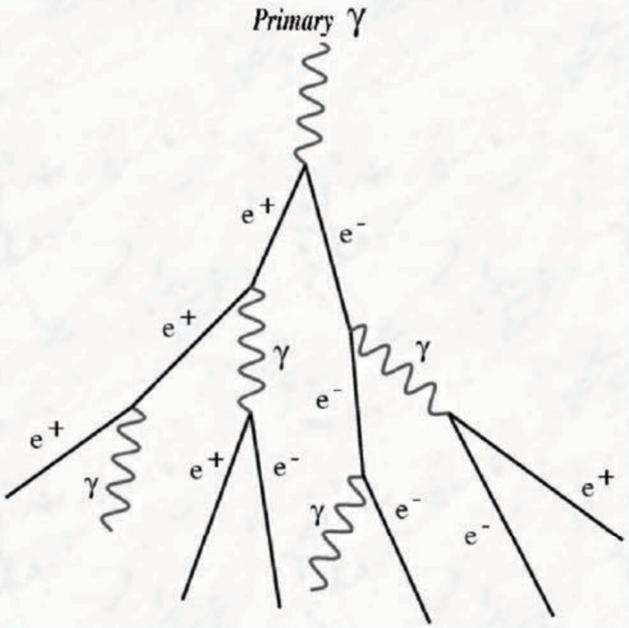
➔ excellent electromagnetic calorimetry



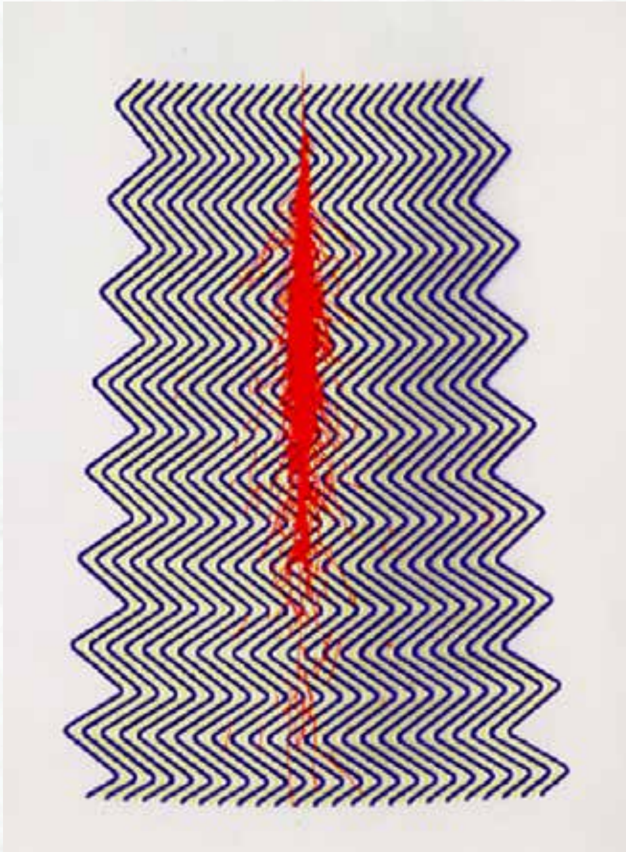




Identifying Photons – Basics of Calorimeter Design



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)

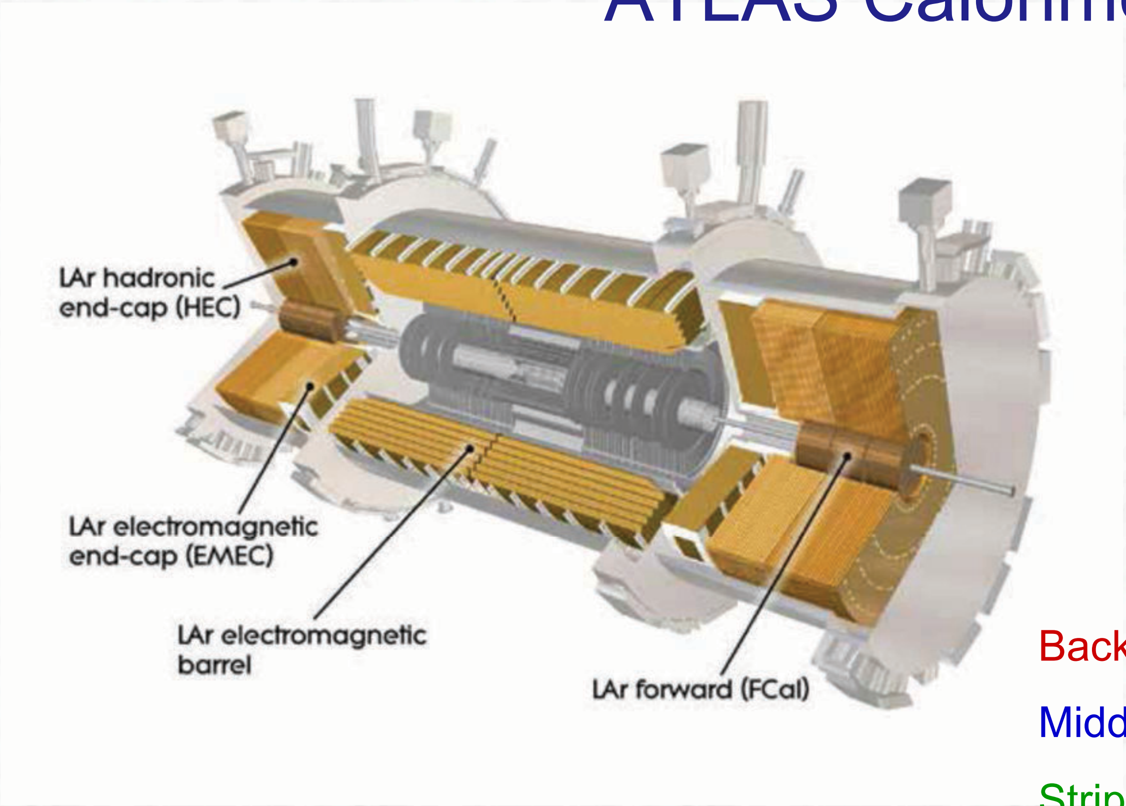
Not too wide here.

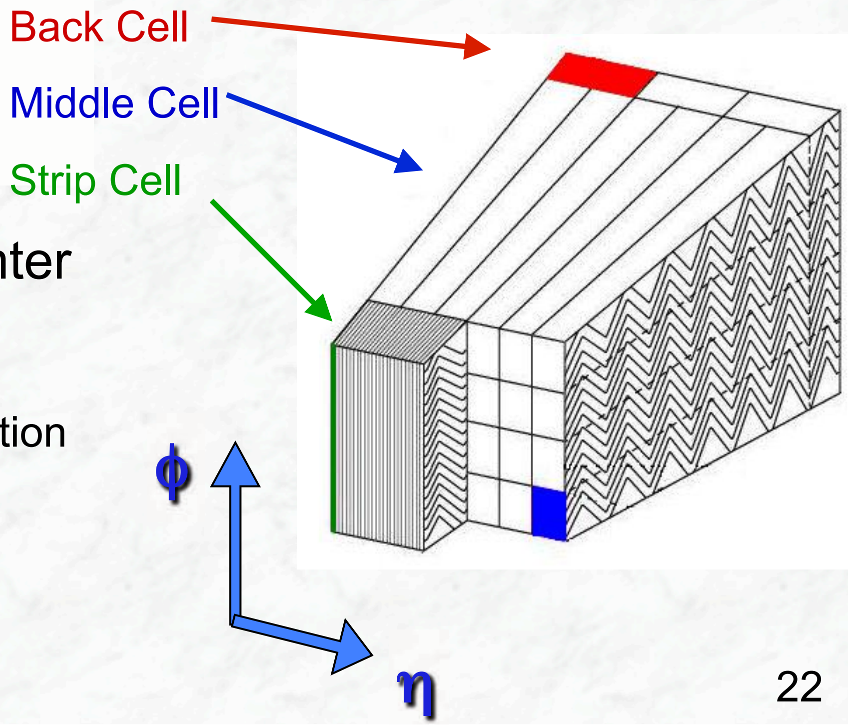
One photon and not two nearby ones (again, a likely π^0)

Not too much energy here.

Indicative of a hadronic shower: probably a neutron or K_L.

ATLAS Calorimetry



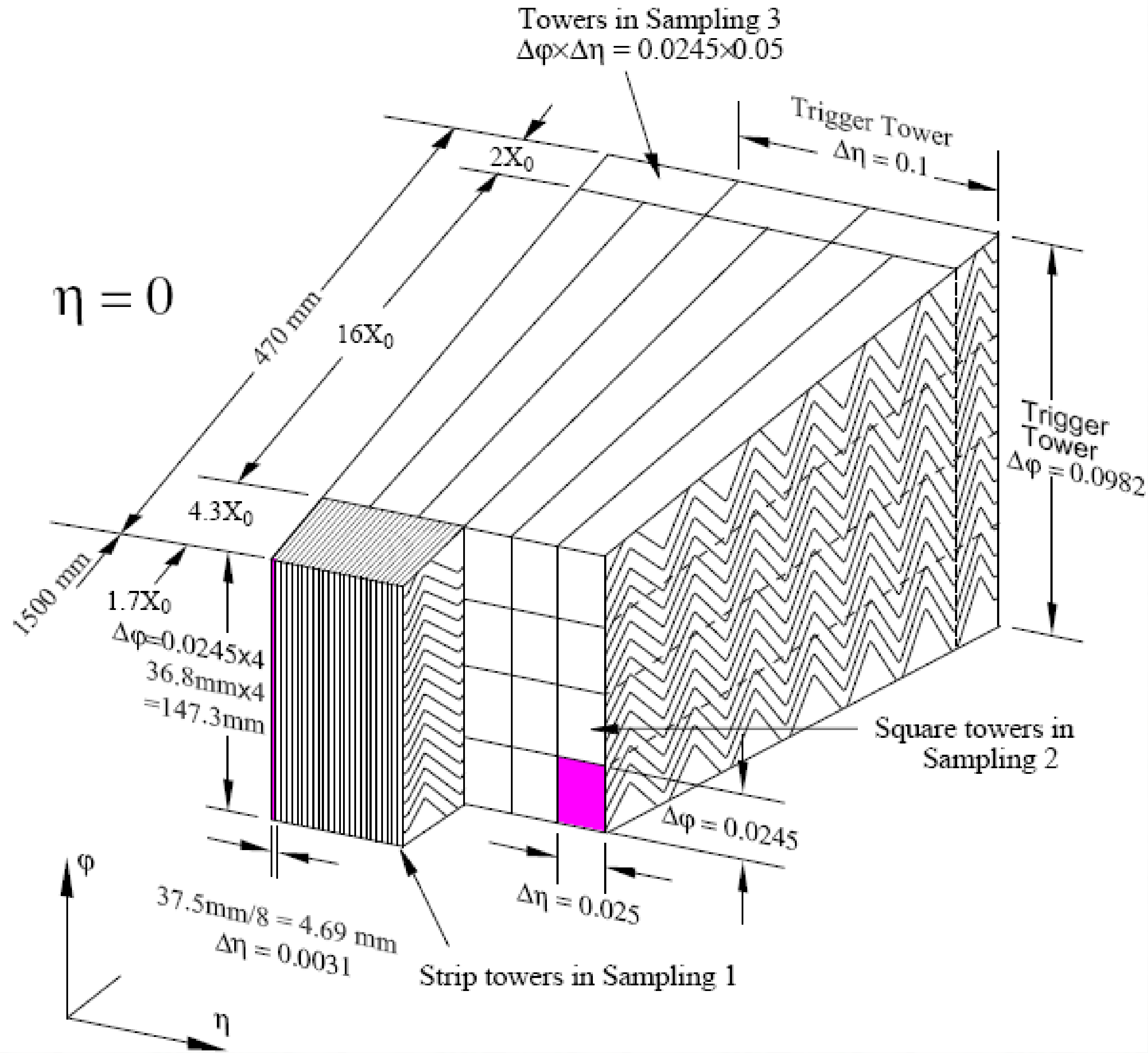


- Liquid argon sampling el.magn. calorimter

→ - Electrical signals, high stability
- High granularity and longitudinal segmentation
- Radiation resistant
- Good energy resolution

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

Structure of the ATLAS el. magn. calorimeter

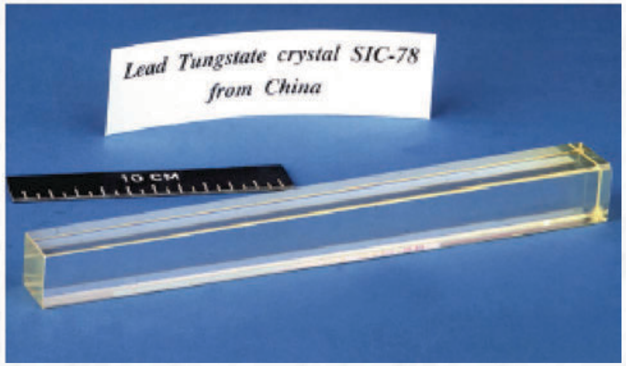


ATLAS Calorimeter in Real Life

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

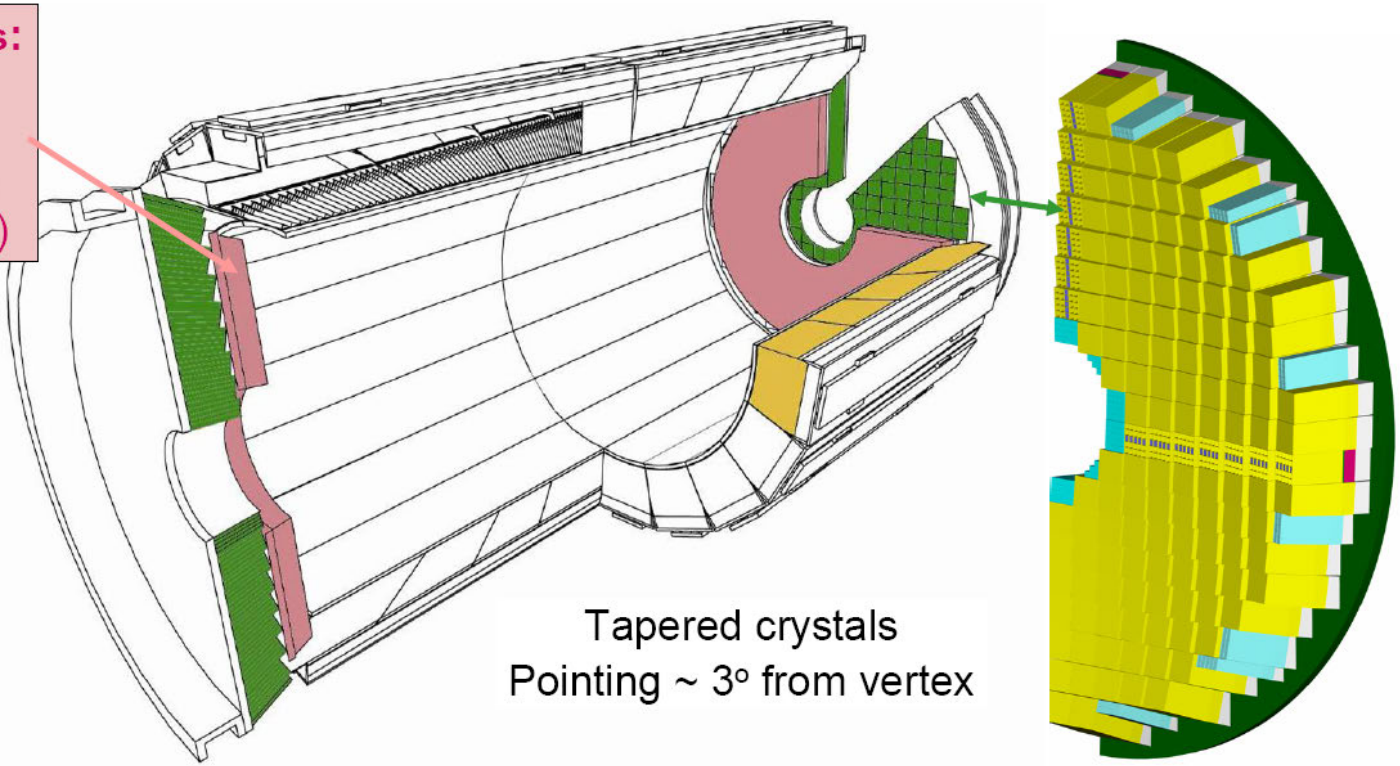


$$\frac{\Delta E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus 0.55\% \oplus \frac{0.16\,\text{GeV}}{E}$$

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

CMS el. magn. Calorimeter

Pb/Si Preshowers:
4 Dees
(2/endcap)
4300 Si strips
(~ 63 x 1.9 mm^2)

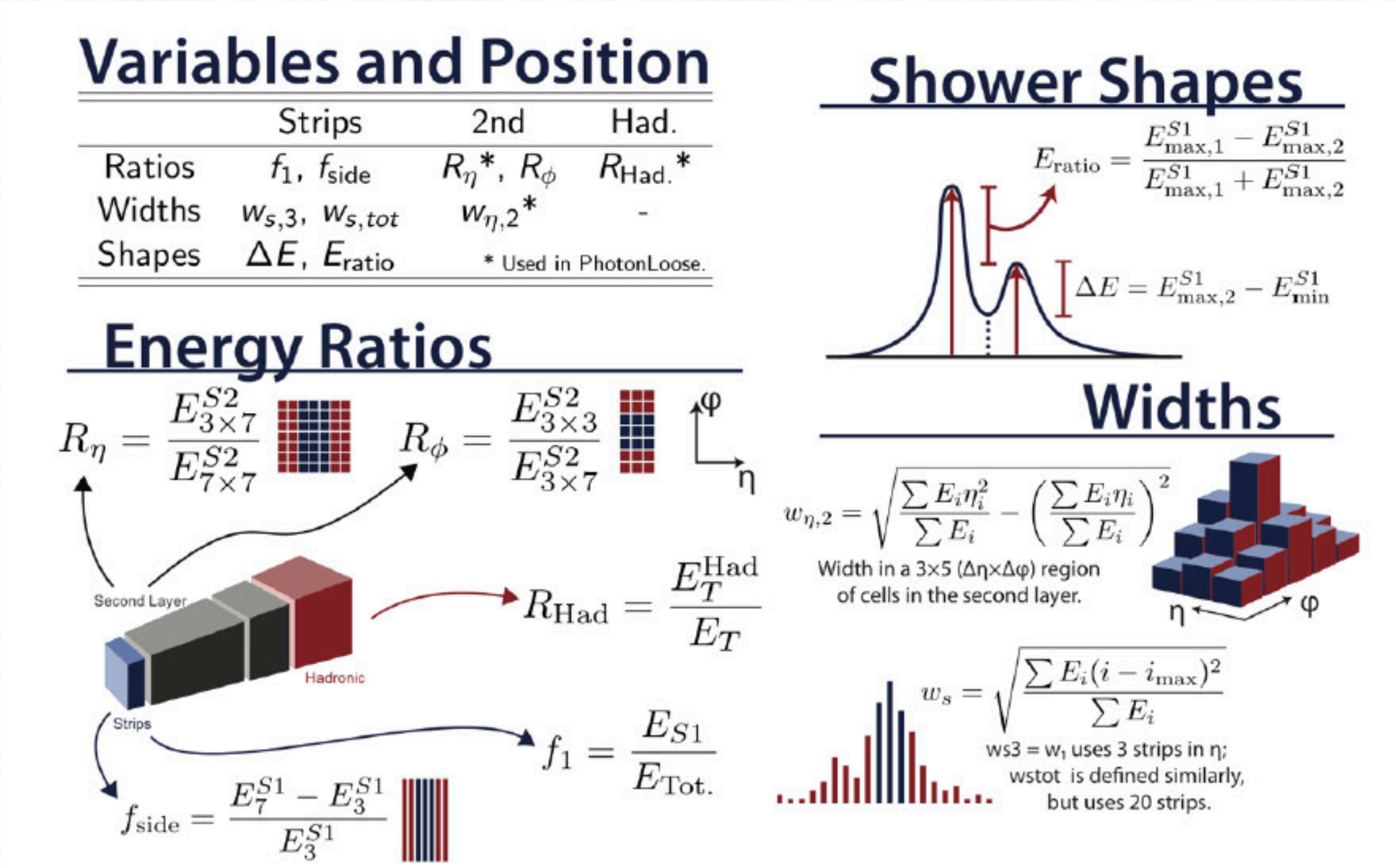


Barrel: 36 Supermodules (18 per half-barrel)
61200 Crystals (34 types) – total mass 67.4 t
Dimensions: ~ 25 x 25 x 230 mm^3 (25.8 X^0)
$\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175$

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

ATLAS photon identification

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

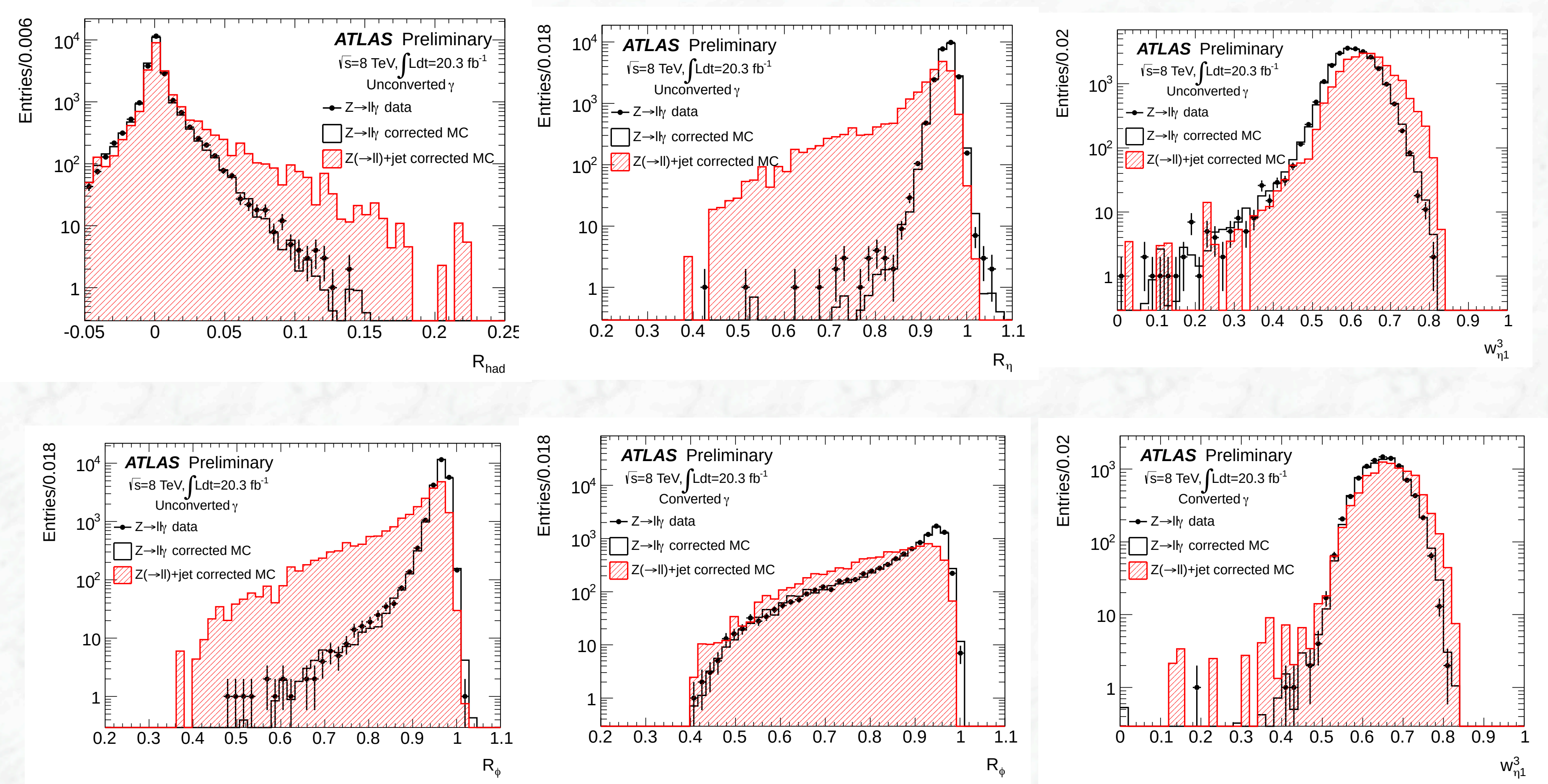


ATLAS photon identification at high pile-up (2012 data)

Photon shower shape variables: (i) Data versus Monte Carlo agreement

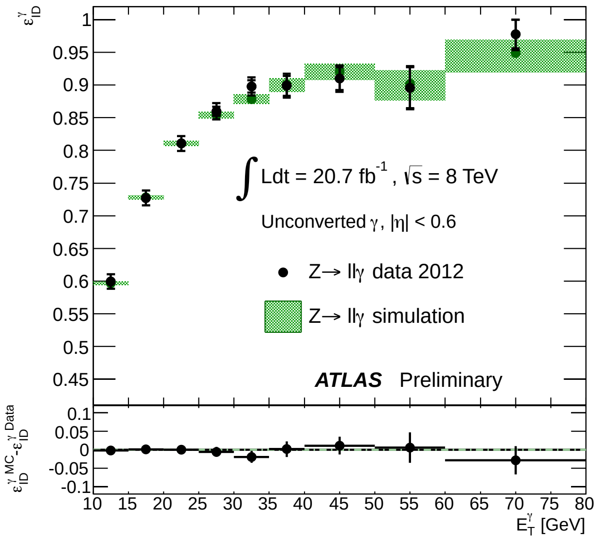
(ii) Photon / jet separation

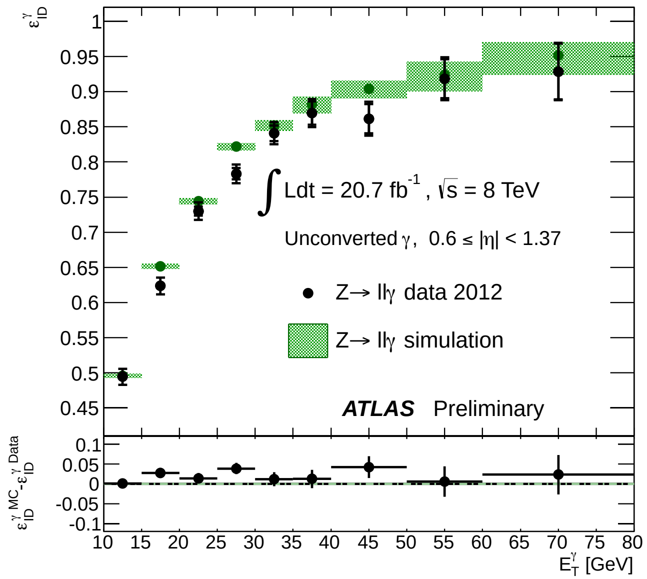
Extracted at high luminosity (2012 data, 20.3 fb^{-1}) from $Z \rightarrow ee\gamma$ and $Z \rightarrow \mu\mu\gamma$ events

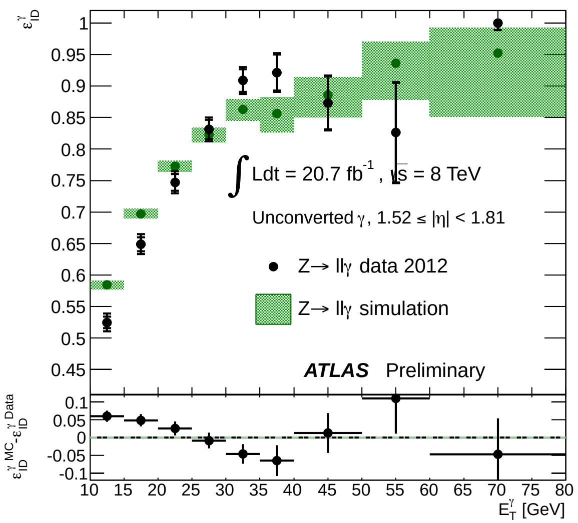


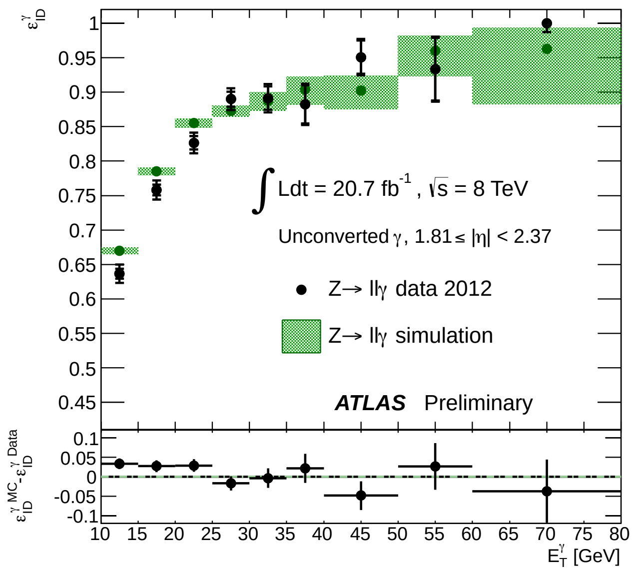
ATLAS photon identification efficiency from Z → llγ data

-unconverted photons-

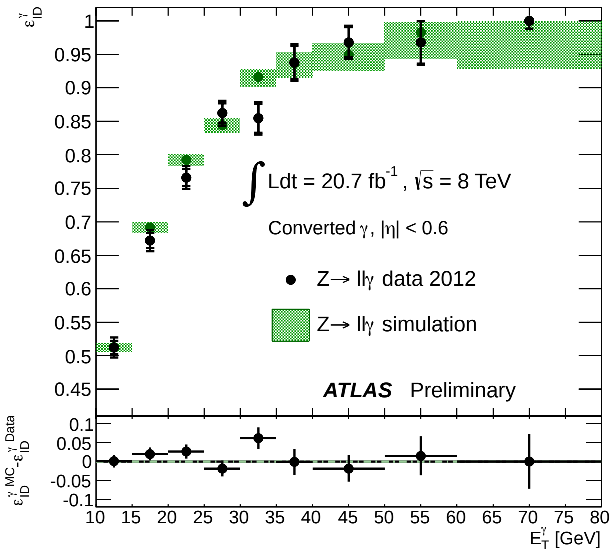


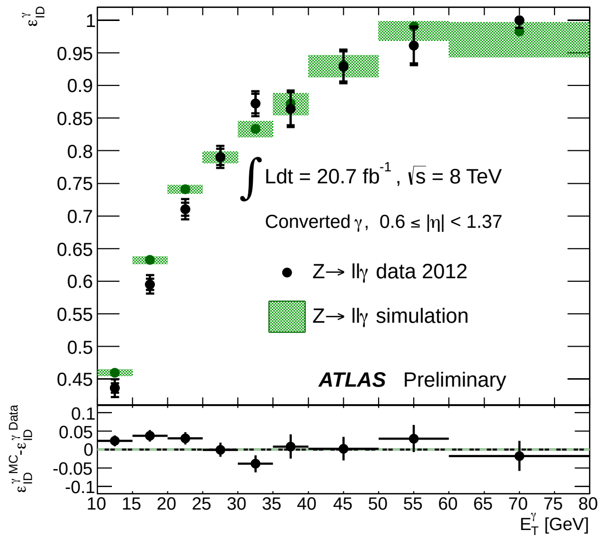


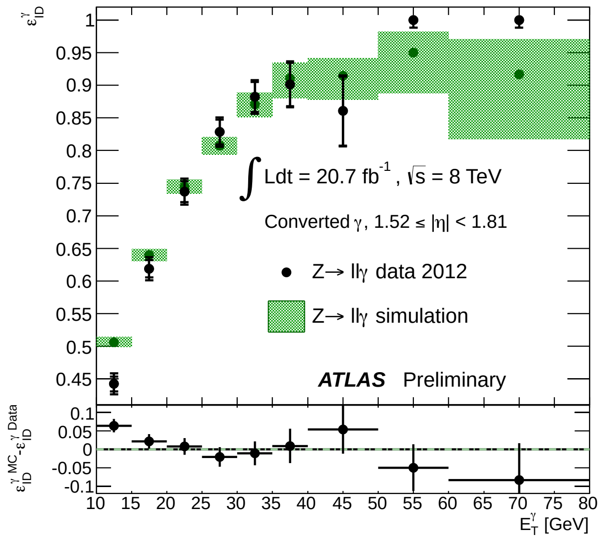


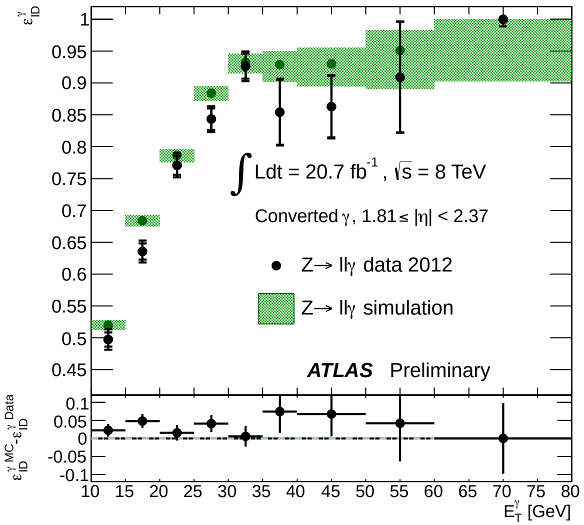


ATLAS photon identification efficiency from Z → llγ data
-converted photons-









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.

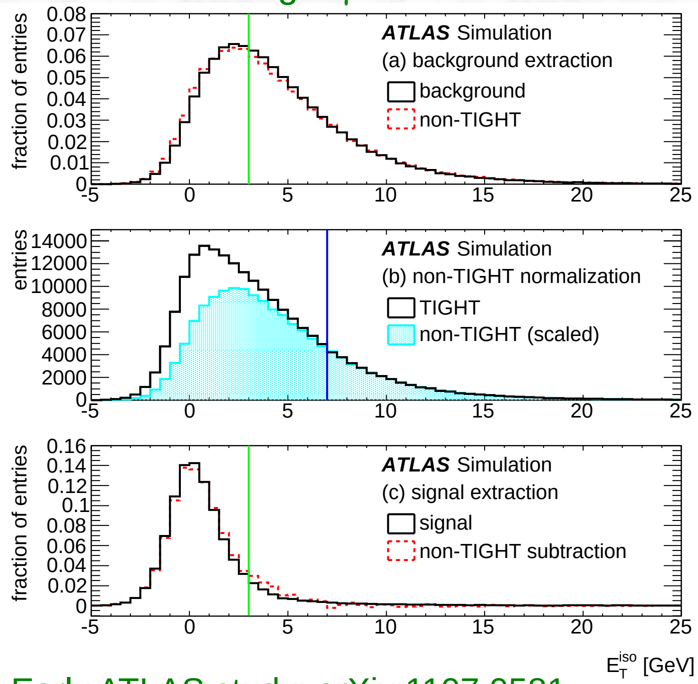
- Try to measure the γγ background first (cross section) and determine its fake contribution

- 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 in cone of

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

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

ATLAS simulation: E_T^{iso} for tight and non-tight γ candidates

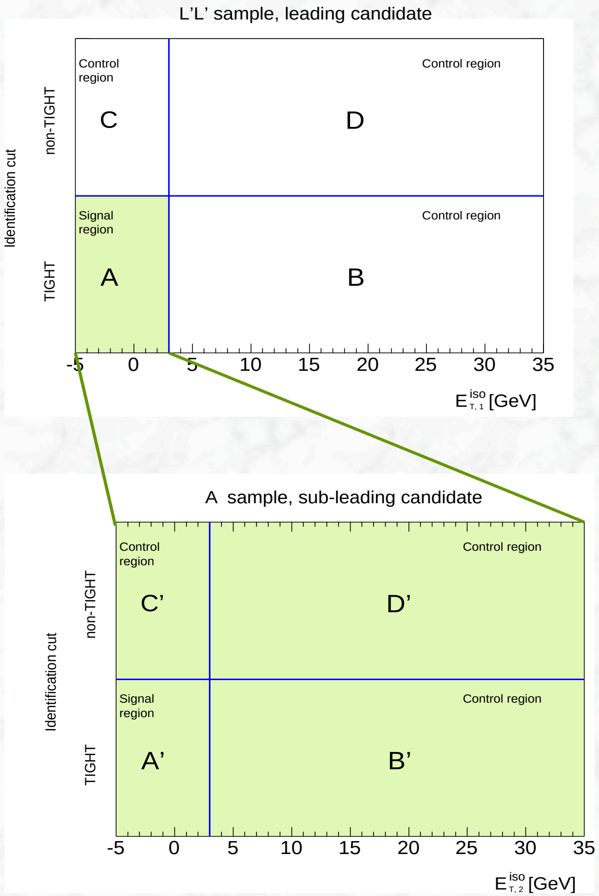


Early ATLAS study: arXiv:1107.0581

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)



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

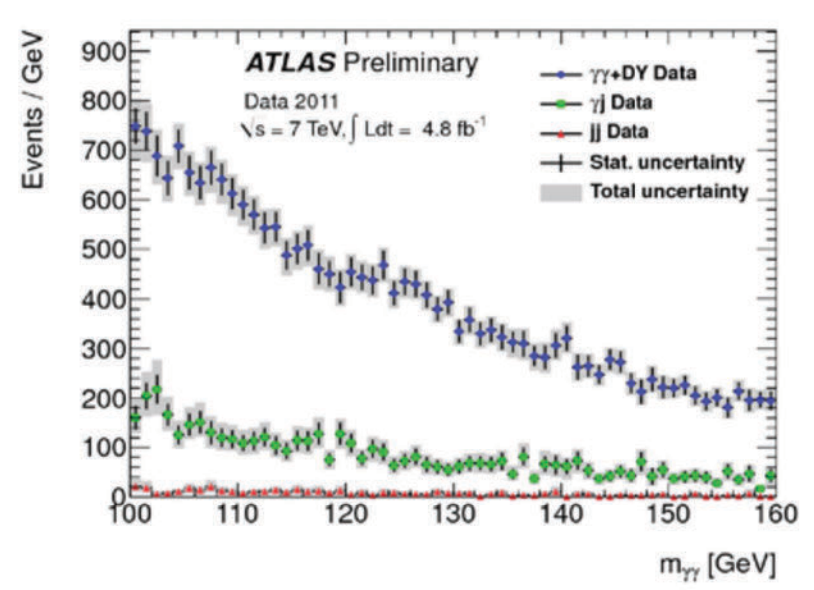
where: c_1 = signal fraction failing the isolation requirement (from E_T^{iso} distribution)

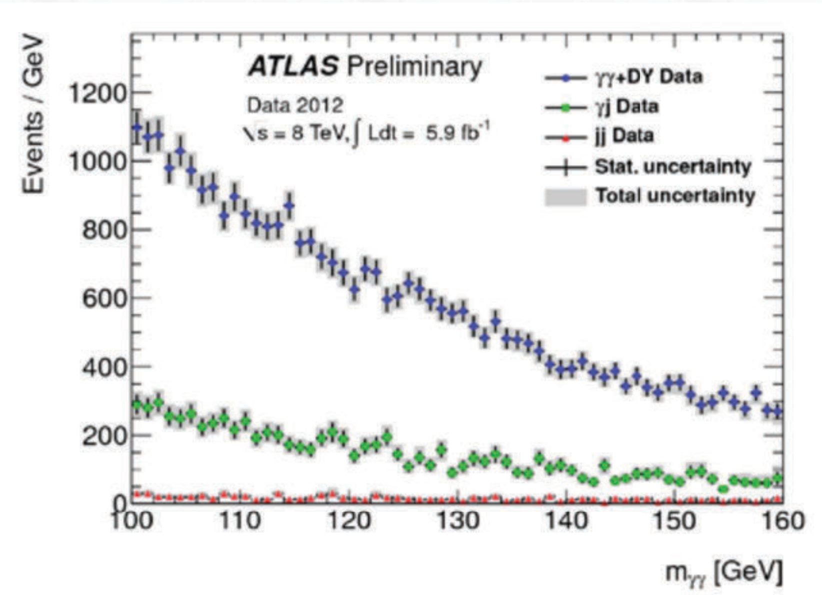
c_2 = signal fraction failing the tight selection (from Monte Carlo simulation)

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

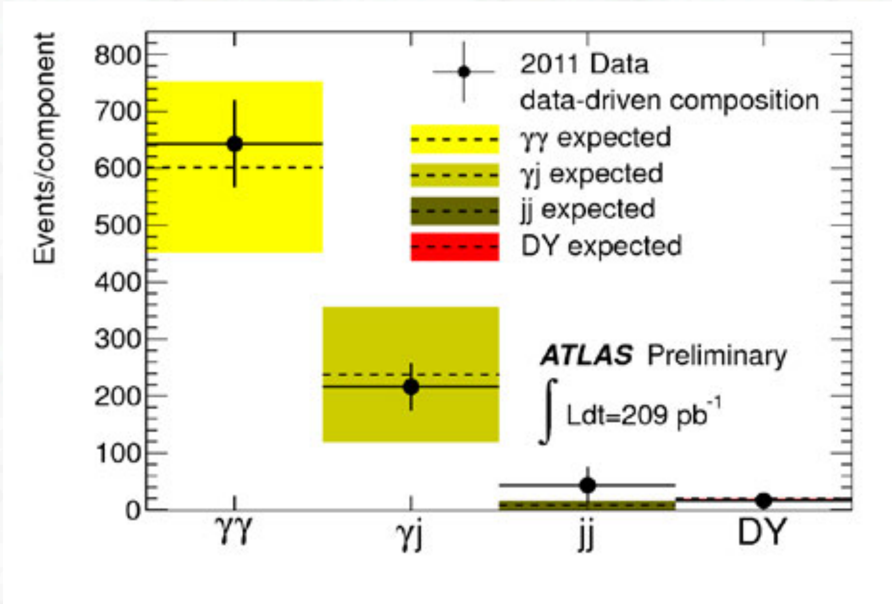
- Extract genuine $\gamma\gamma$, γj, jj fractions bin-by-bin, e.g. in the $\gamma\gamma$ mass distribution

Results on di-photon background





- The background is dominated by real di-photons (γj fraction ~25%, jj fraction ~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

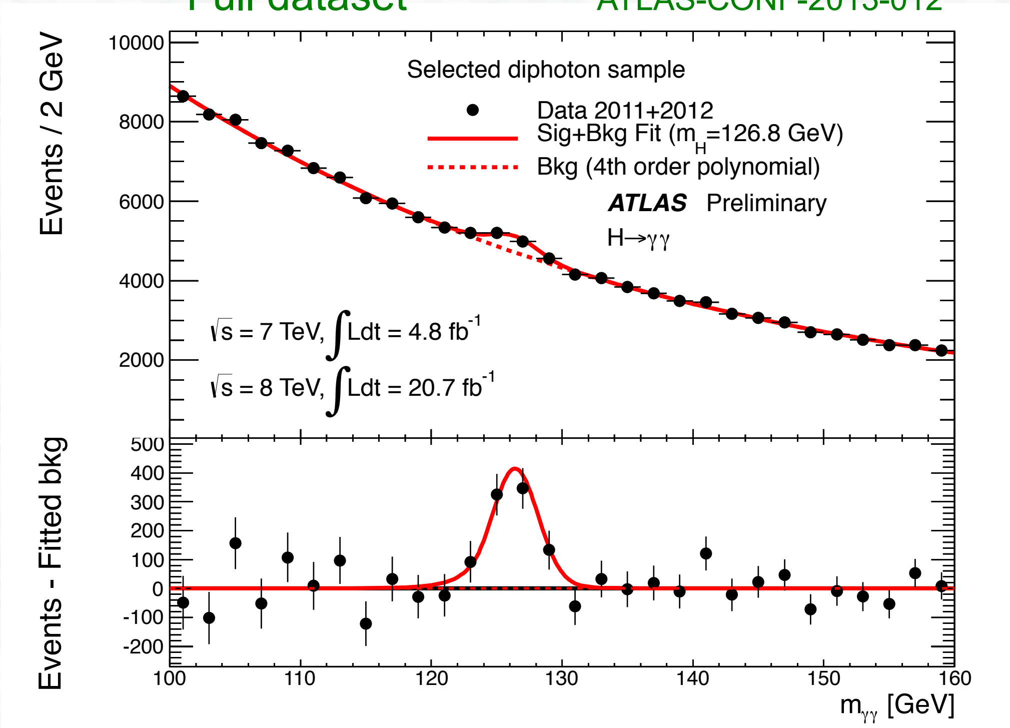


note: no absolute MC prediction necessary for Higgs analysis, but useful to extract functional form of the background

Result of the ATLAS search for H → γγ

- one of the famous plots-

Full dataset ATLAS-CONF-2013-012



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

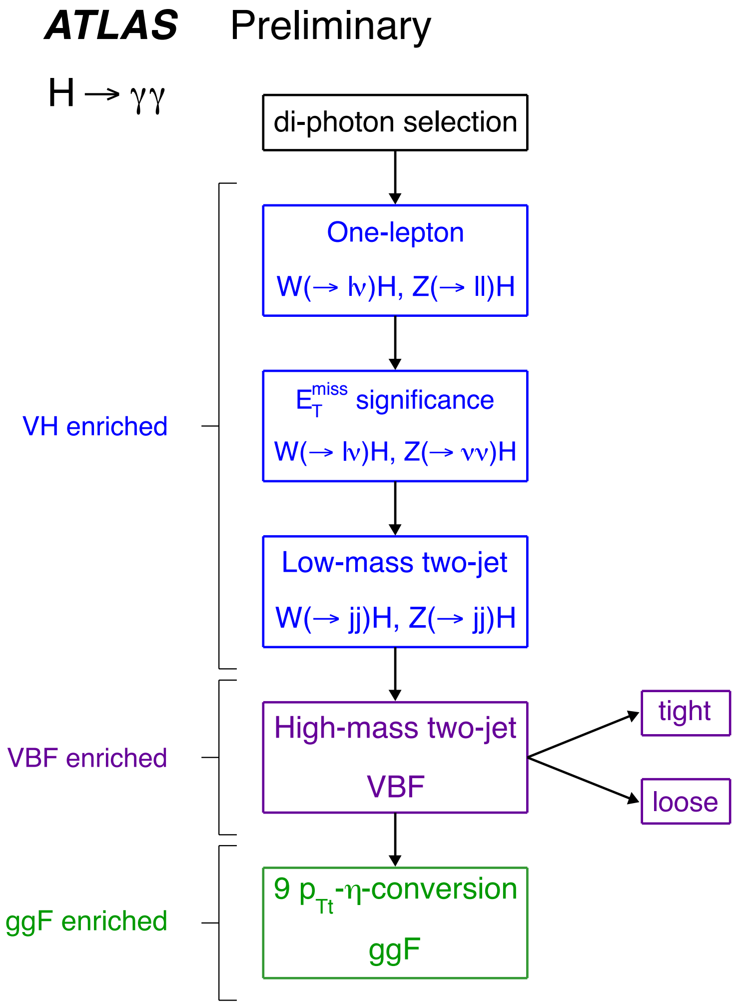
$\sqrt{s}$ = 7 TeV	23 788 events
$\sqrt{s}$ = 8 TeV	118 893 events

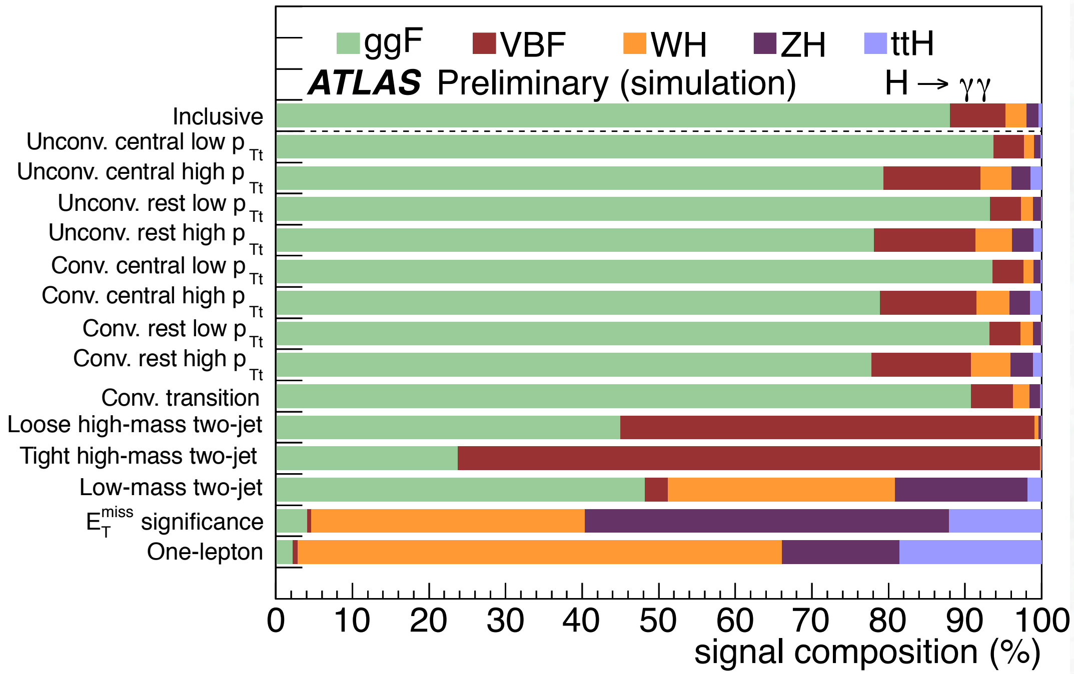
- Clear excess seen around $m_{\gamma\gamma}$ = 126 GeV
- Background obtained from sidebands, interpolation in the region of the excess
- This plot, shown in many places, is actually not really used in the analysis.
  Both experiments (ATLAS and CMS) split γγ sample in categories.

Categorisation of H → γγ candidate events

ATLAS-CONF-2013-012

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

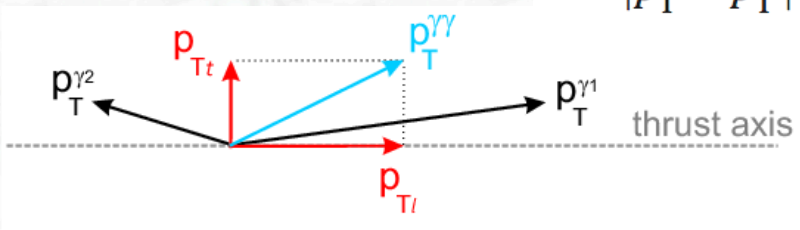


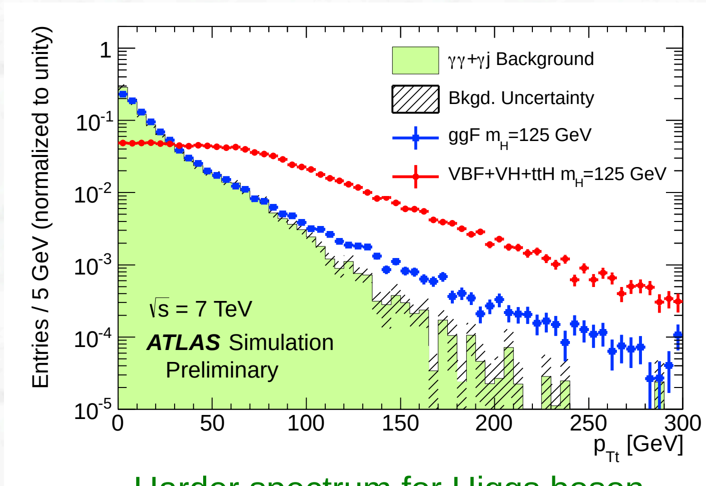


- VH enriched: one-lepton, E_T^{miss}, low-mass di-jets
- VBF enriched (tag-jet configuration, $\Delta\eta$, m_{jj})
- gluon fusion: 9 categories, exploit different mass resolution for different detector regions, γγ conversion status and p_{Tt}

- What is p_{Tt} ?

$$\hat{t} = \frac{\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}}{|\vec{p}_T^{\gamma_1} - \vec{p}_T^{\gamma_2}|}$$

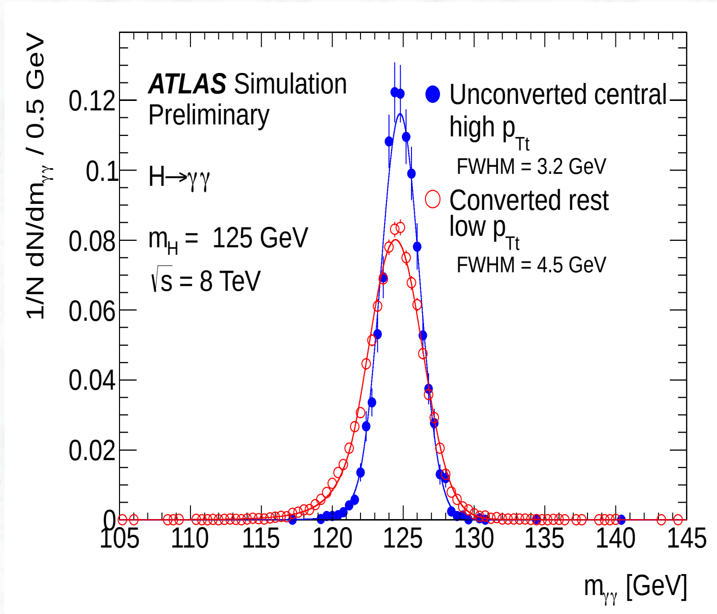




Harder spectrum for Higgs boson signal (VBF, gluon fusion)

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

- Nine gluon-fusion enriched categories
  - Main argument: γ 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 (√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.

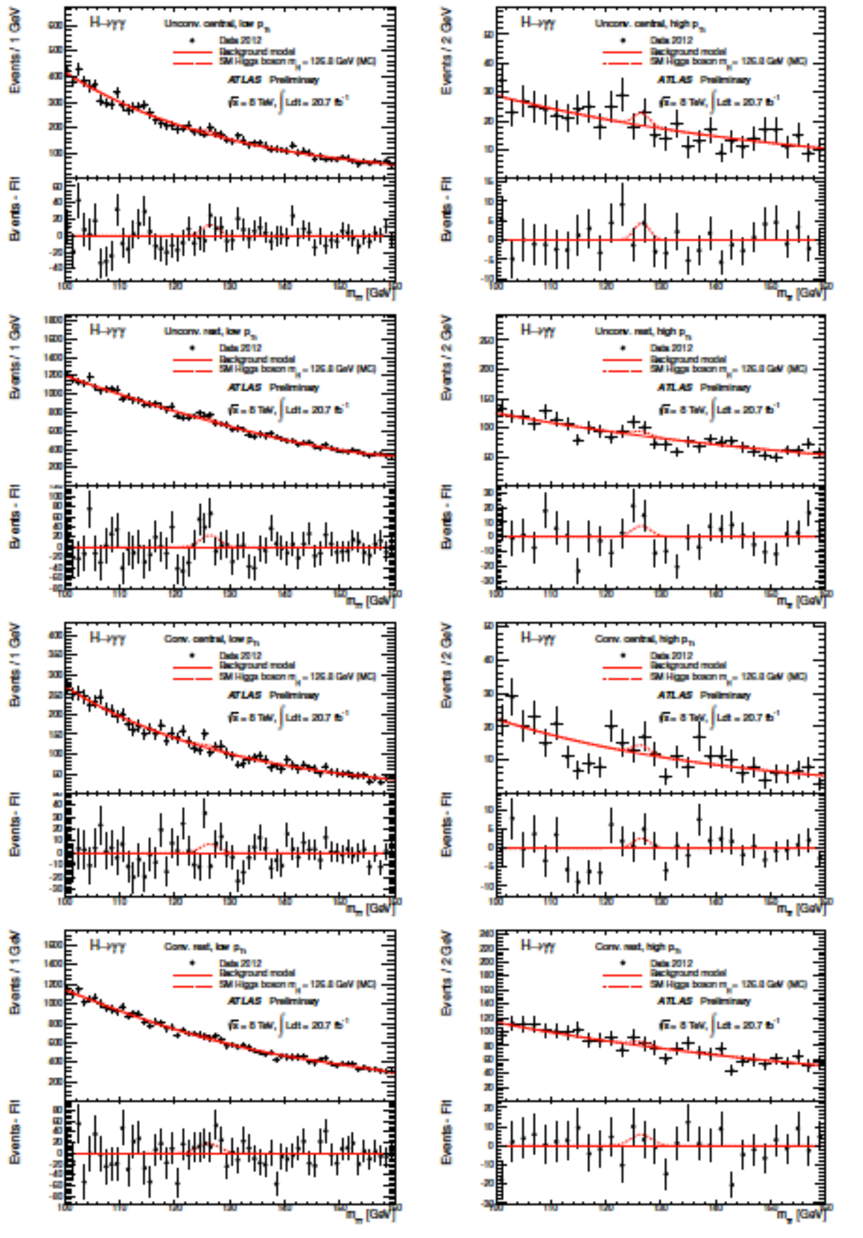
$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	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

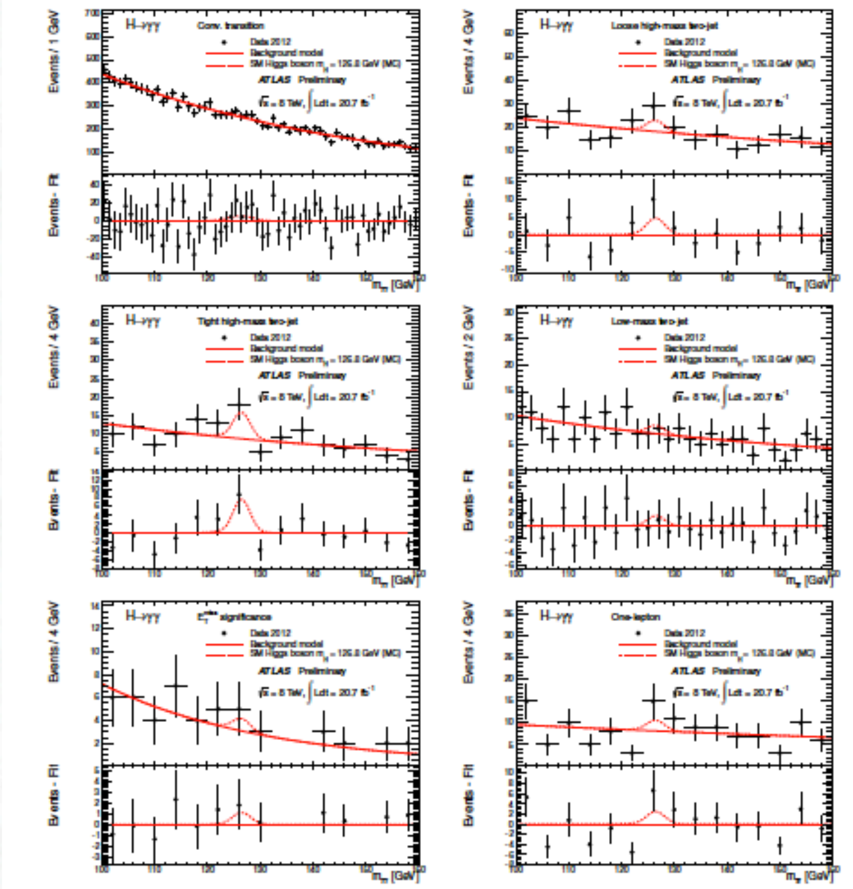
Production fractions in various categories (√s = 8 TeV)

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 $H \to \gamma\gamma$ 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 $gg \to H$, VBF, WH, ZH, ttH processes are detailed.

$\sqrt{s}$	8 TeV						
Category	N_D	N_S	$gg \to H$ [%]	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

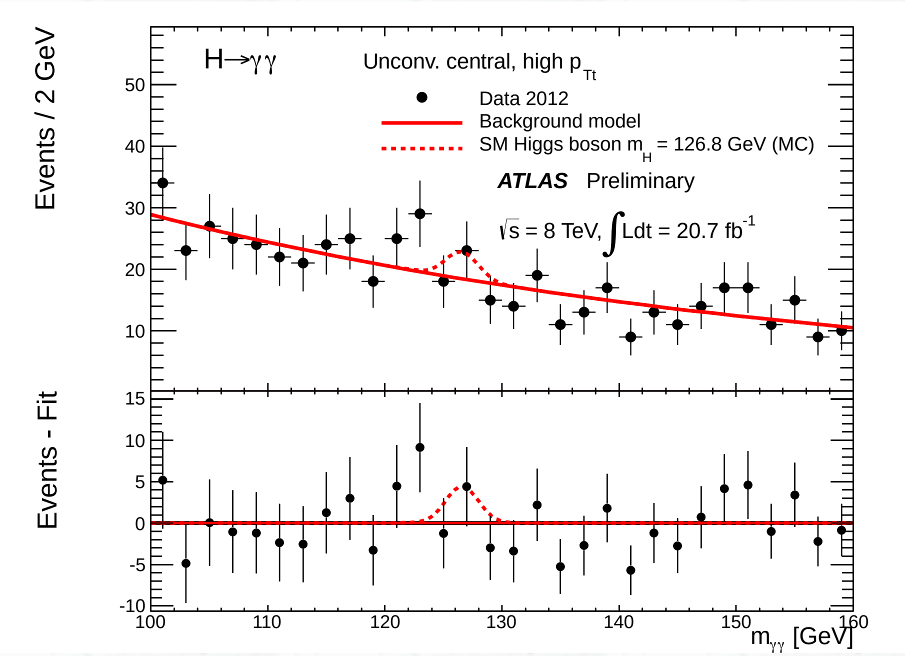
Results in each bin (√s = 8 TeV)

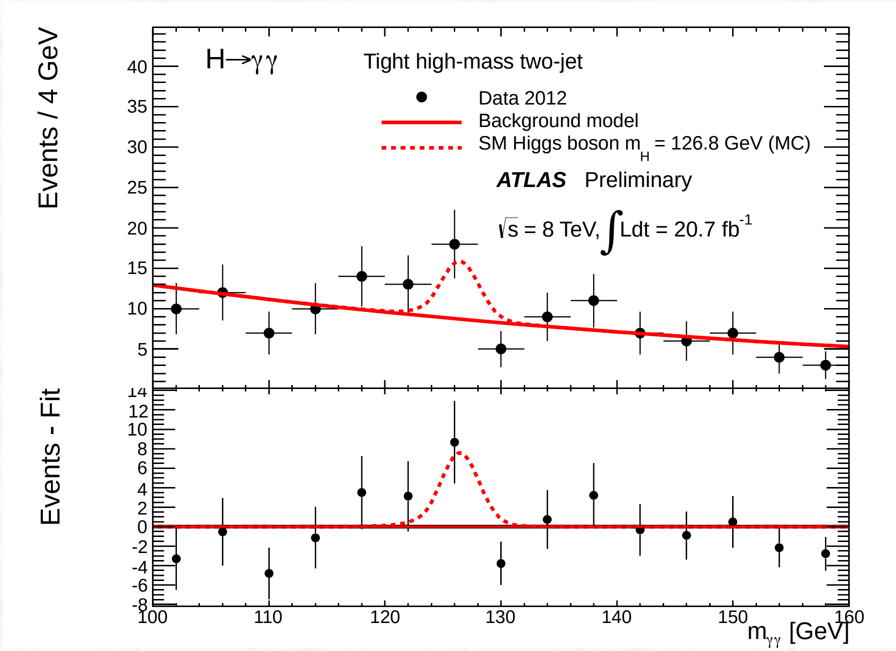




- Background levels quite different in different categories
- Individual background fits (polynomials or exponential functions; variations → systematic uncertainties)

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



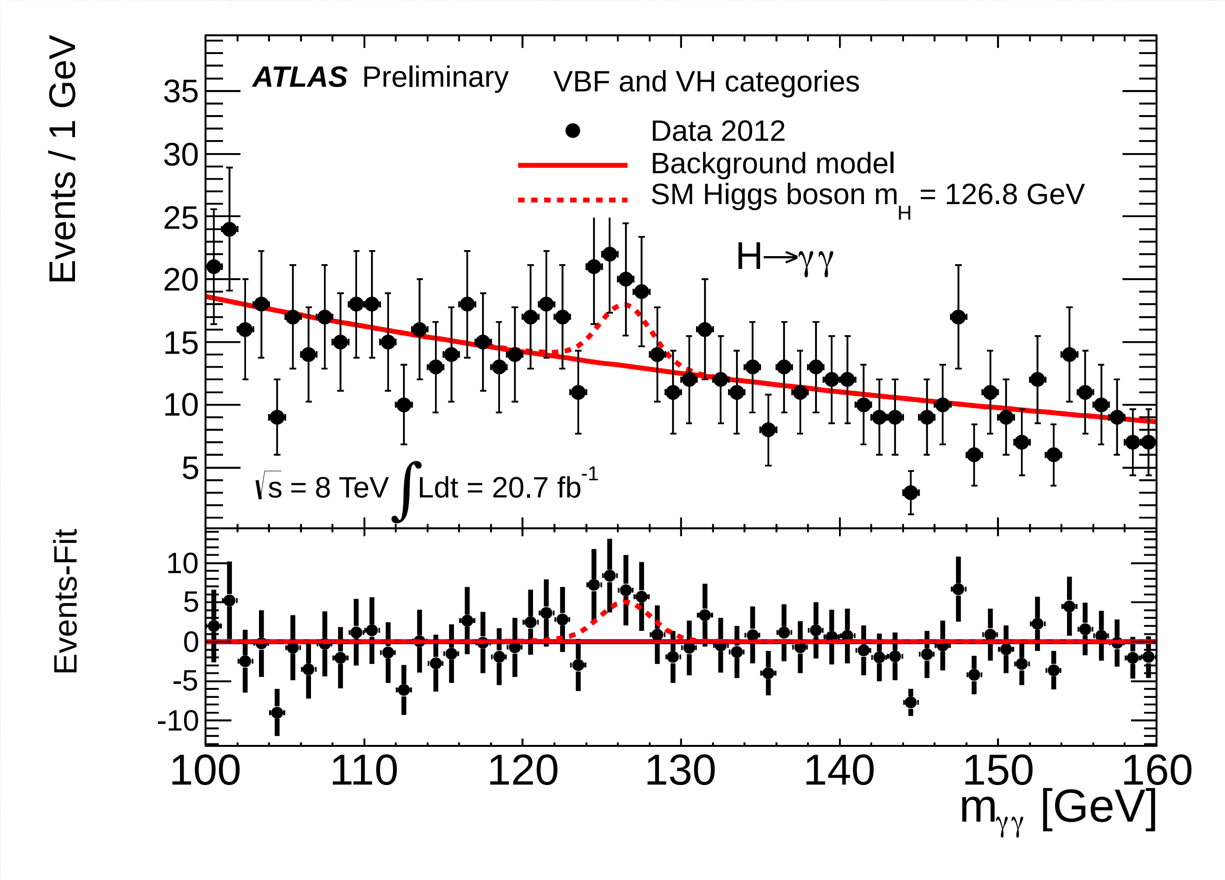


Unconcerted, central calorimeter, high p_{Tt}

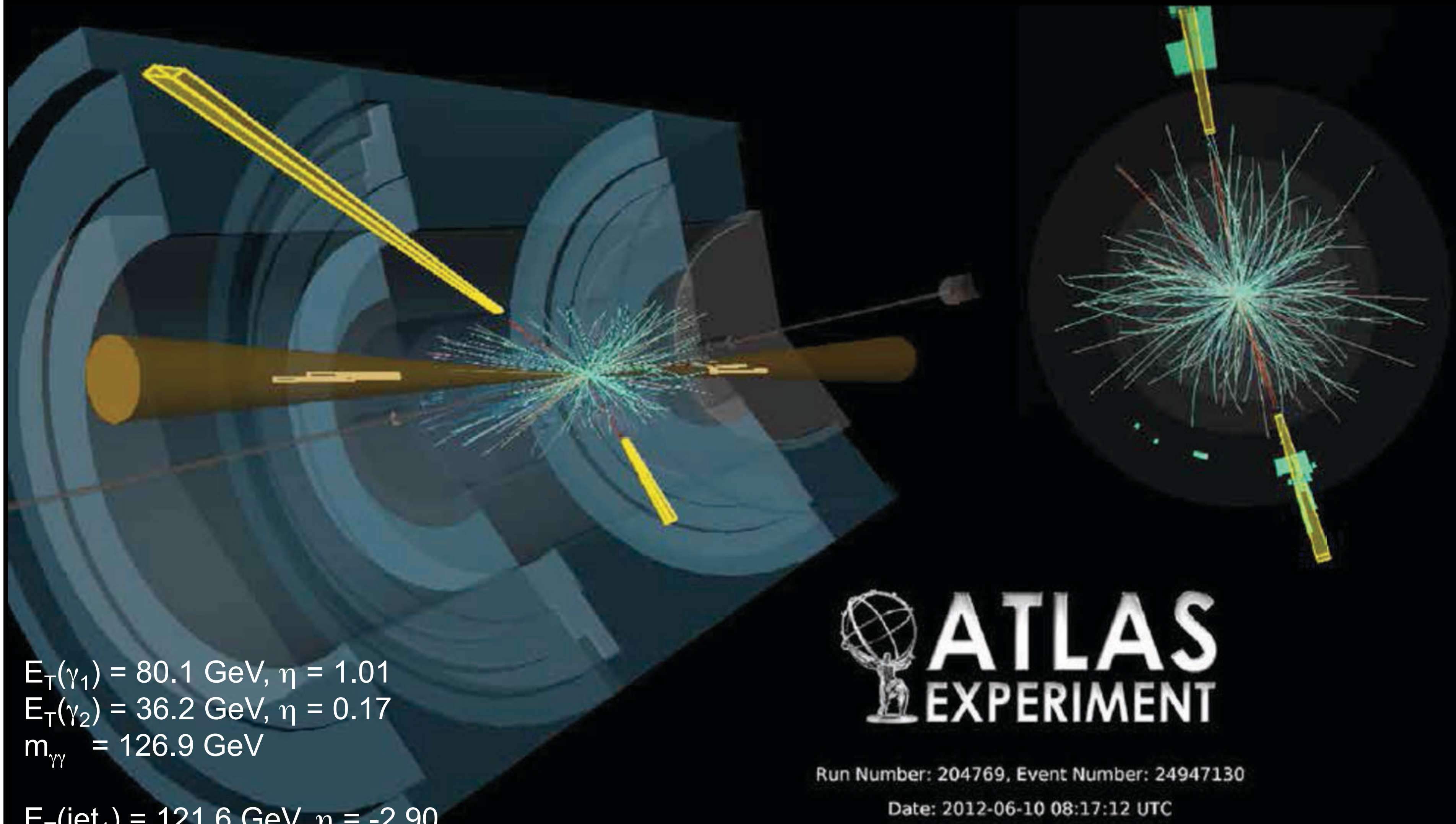
Tight high mass two jets (VBF category)

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

- sensitive to W/Z couplings-



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

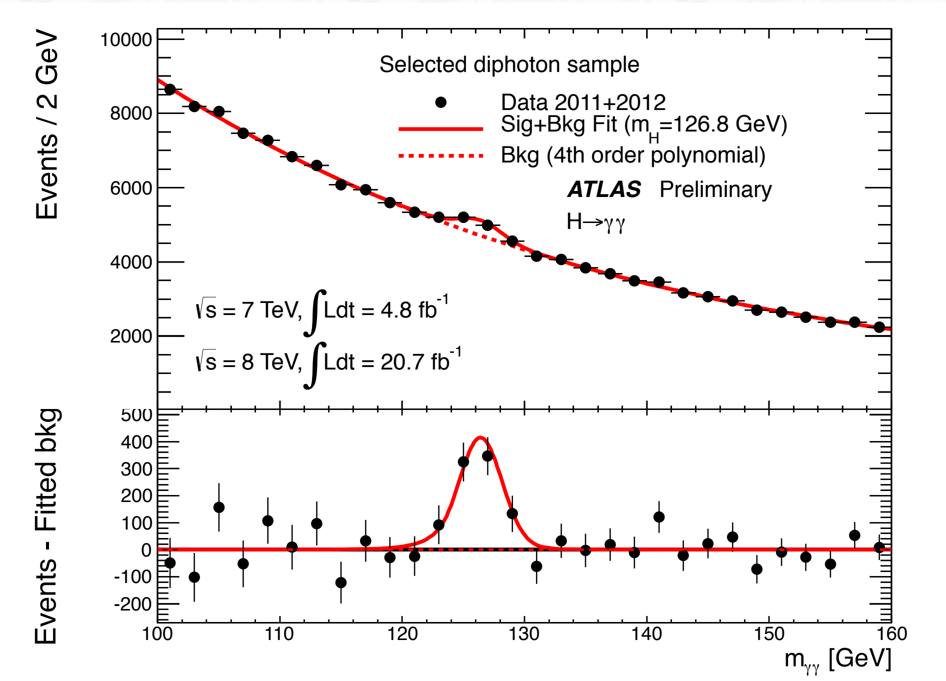


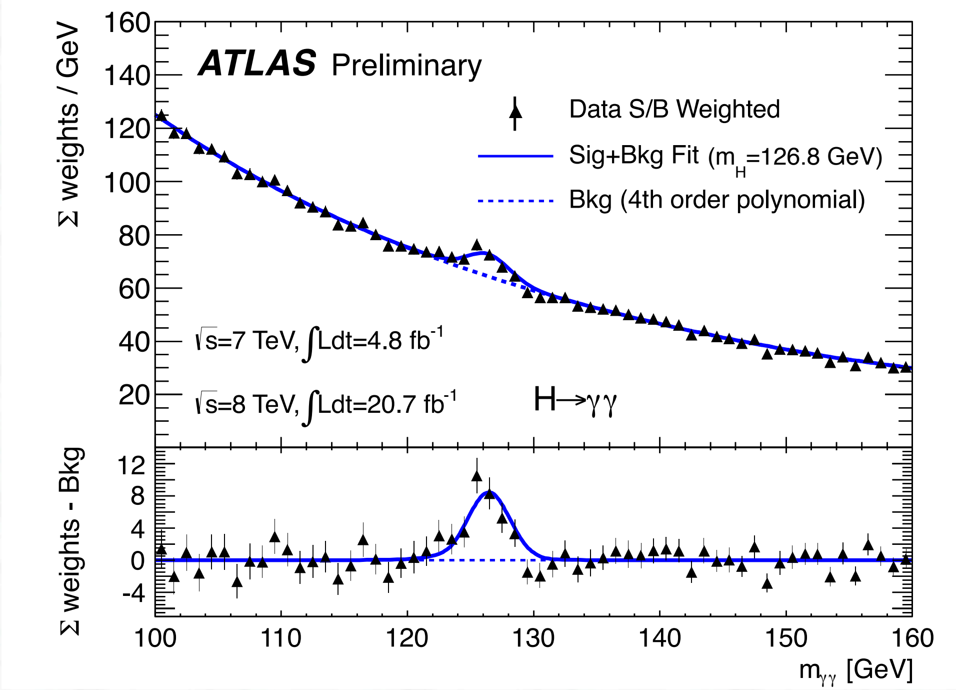
$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

$E_T(jet_1)$ = 121.6 GeV, η = -2.90
$E_T(jet_2)$ = 82.8 GeV, η = 2.72
m_{jj} = 1.67 TeV

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

ATLAS-CONF-2013-012



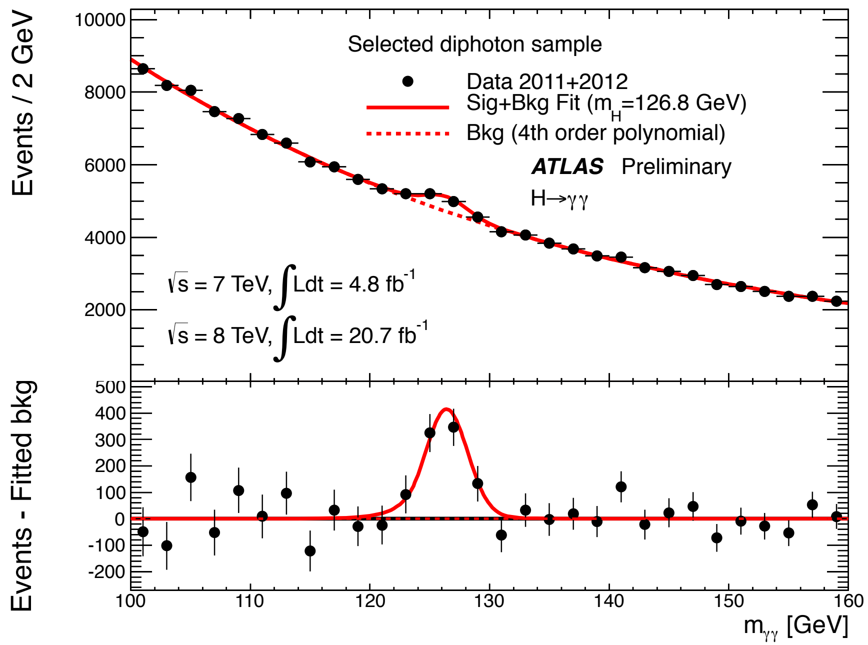


- Sum of the 10 ($\sqrt{s}$ = 7 TeV) and 14 ($\sqrt{s}$ = 8 TeV) mass distributions.
- The fact that different events are worth more than others is hidden.

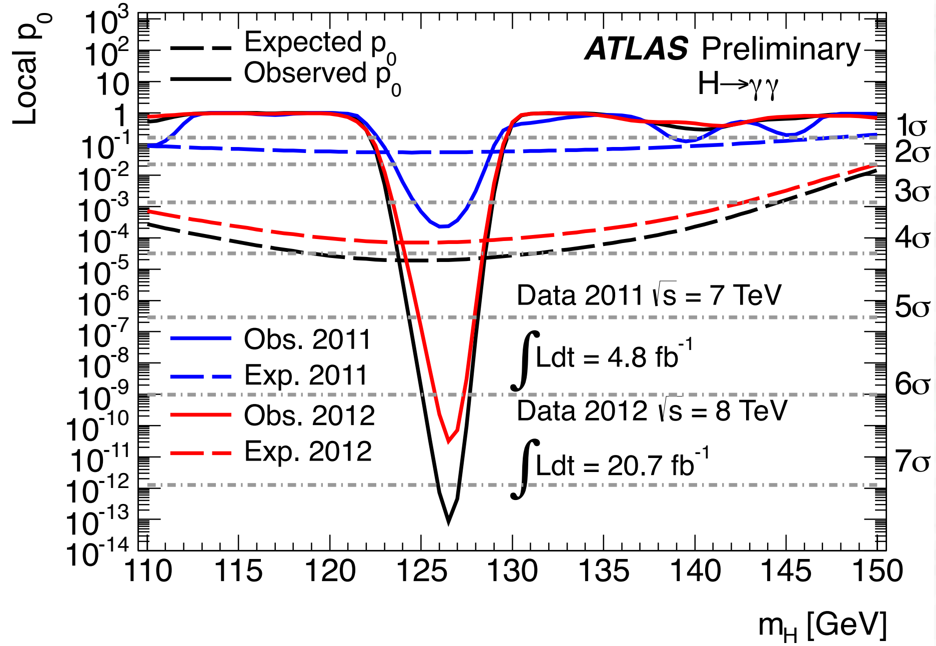
- Weighted sum of the 10 ($\sqrt{s}$ = 7 TeV) and 14 ($\sqrt{s}$ = 8 TeV) mass distributions, according to S/B
- However, it looks like we are plotting events.

Result of the ATLAS search for H → γγ

Full dataset ATLAS-CONF-2013-012



ATLAS-CONF-2013-012



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

  μ = 0 background-only hypothesis
  μ = 1 Standard Model Higgs boson signal strength (in addition to background)

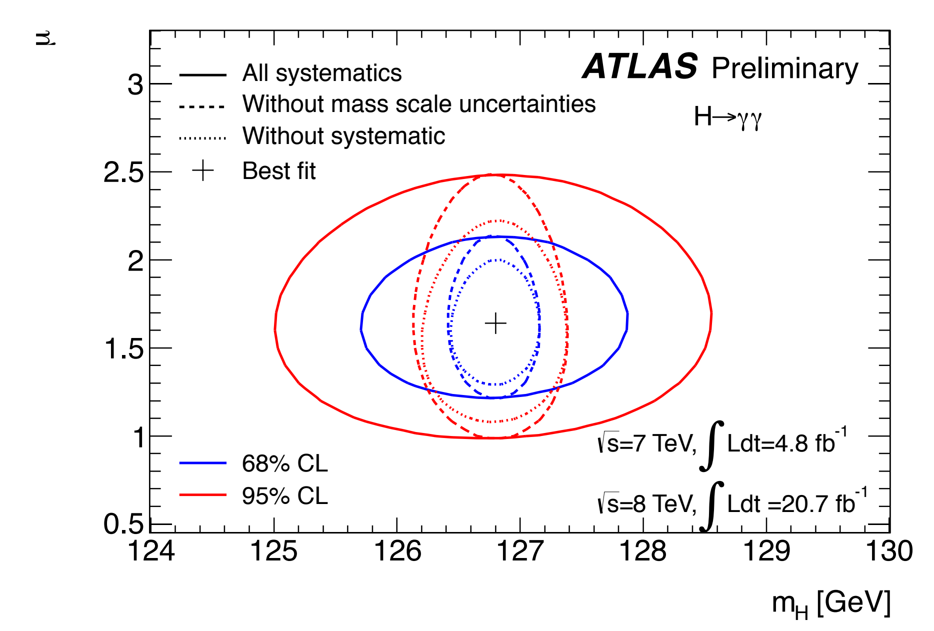
- Hypothesized values of μ are tested with a statistics $\Lambda(\mu)$ based on the profile likelihood ratio (→ lectures by Kyle Cranmer)

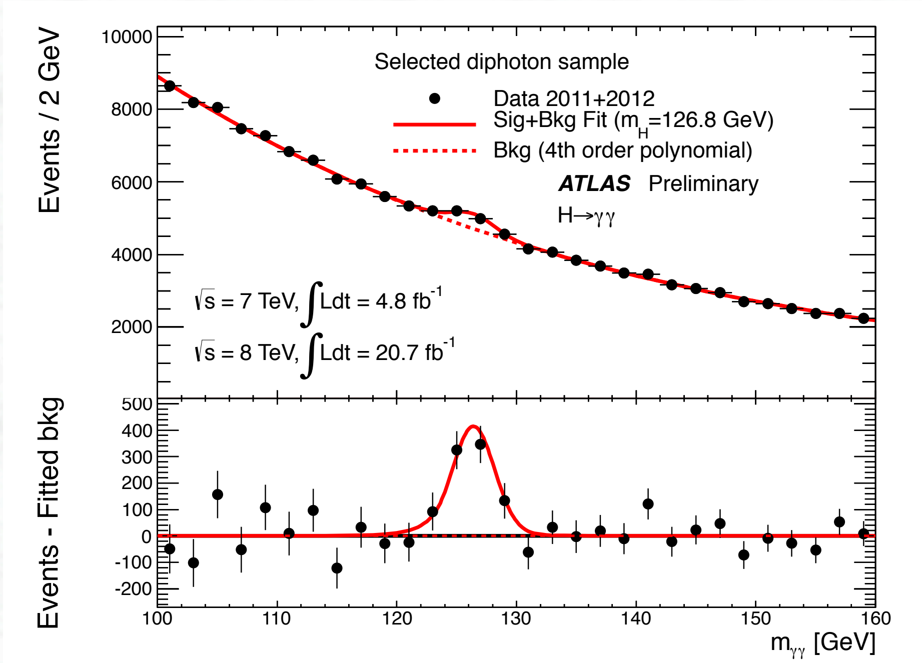
- The test statistics is based on likelihood functions

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

Result of the ATLAS search for H → γγ

-mass and signal strength-



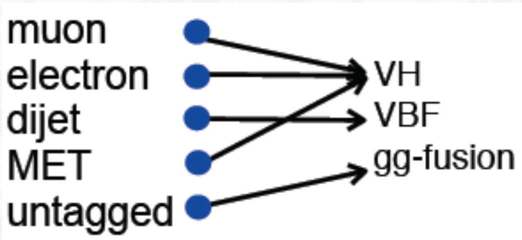


Mass: $m_H = 126.8 \pm 0.2\,(\mathrm{stat}) \pm 0.7\,(\mathrm{syst})$ GeV

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

Categorisation of H → γγ candidate events in CMS

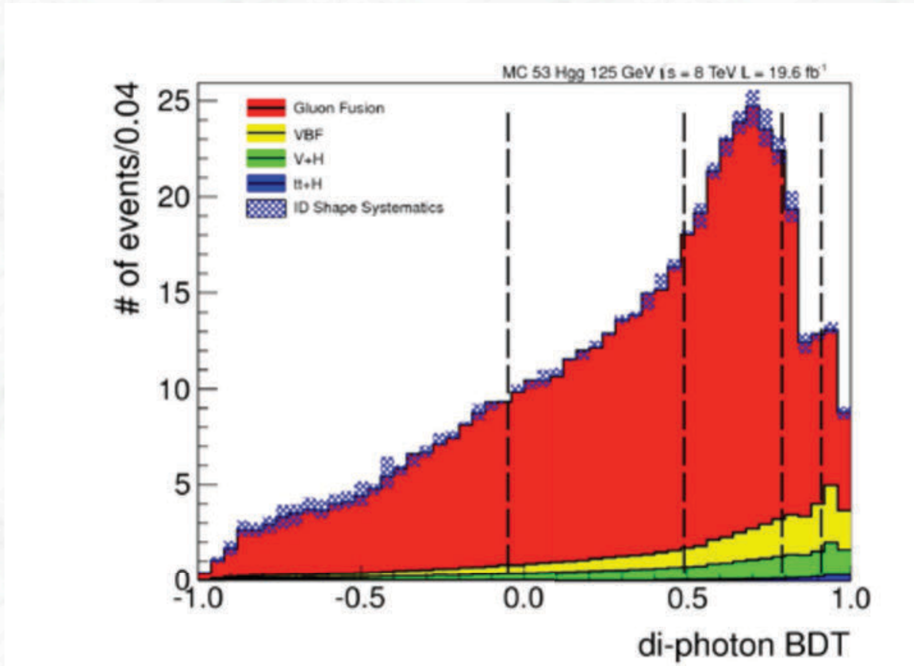
- CMS uses a similar categorization as ATLAS



- Untagged events:

  - Multivariate di-photon categories
    BDT classification
    (di-photon kinematics (except $m_{\gamma\gamma}$),
    di-photon mass resolution, photon ID)

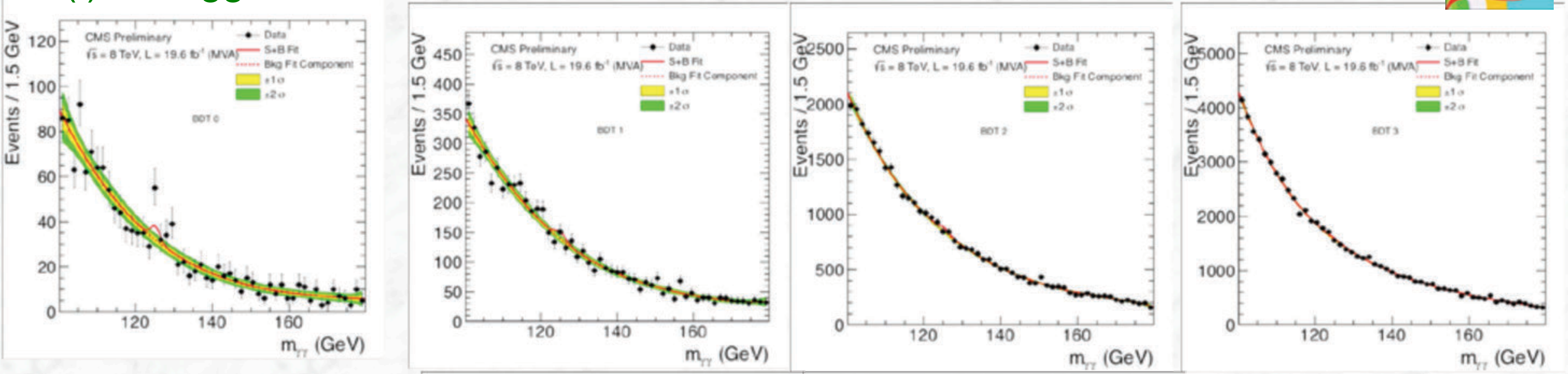
  - Cut-based analysis, in categories
    (similar to ATLAS)



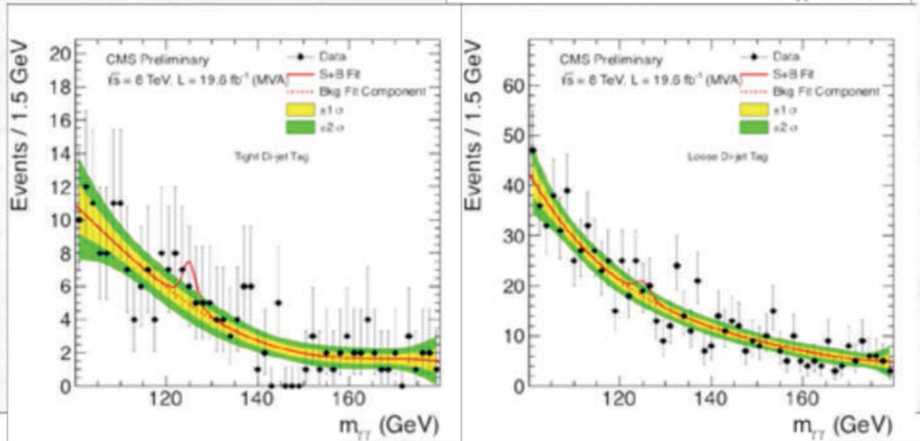
MVA has ~15% better expected sensitivity

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

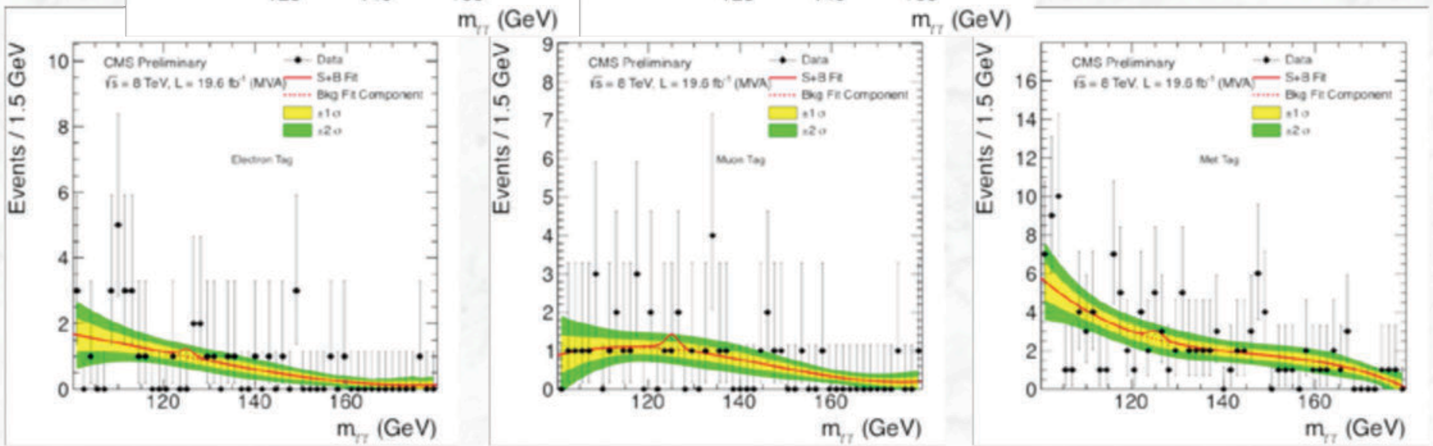
(i) untagged



(ii) VBF/jet tagged

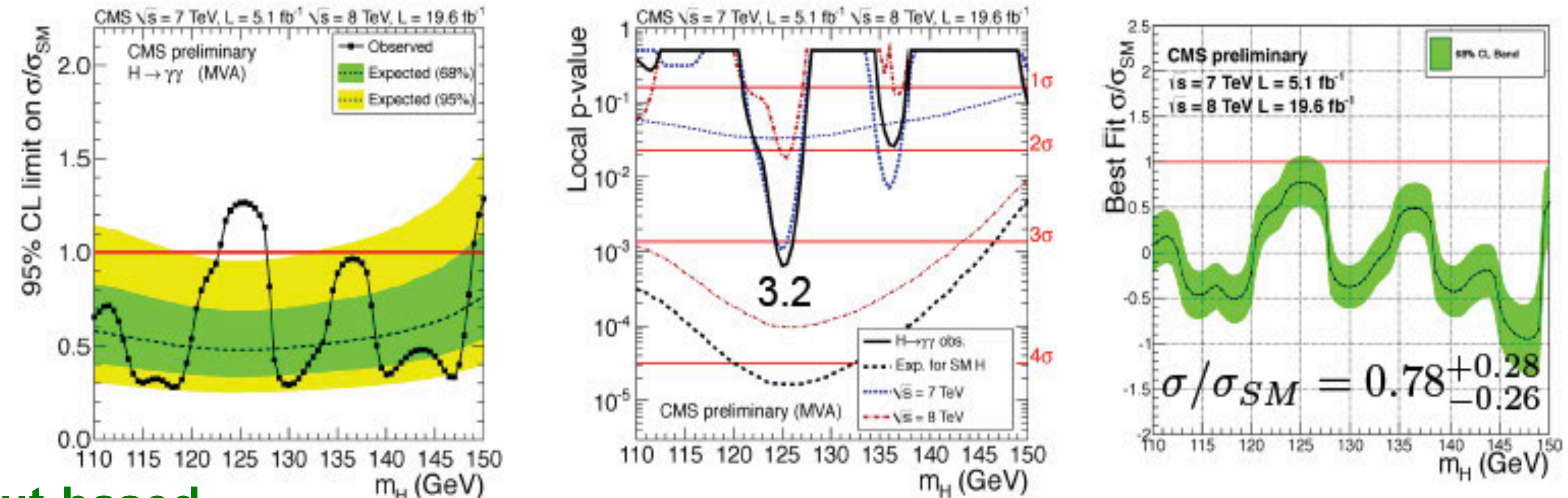


(iii) Lepton/ E_T^{miss} tagged

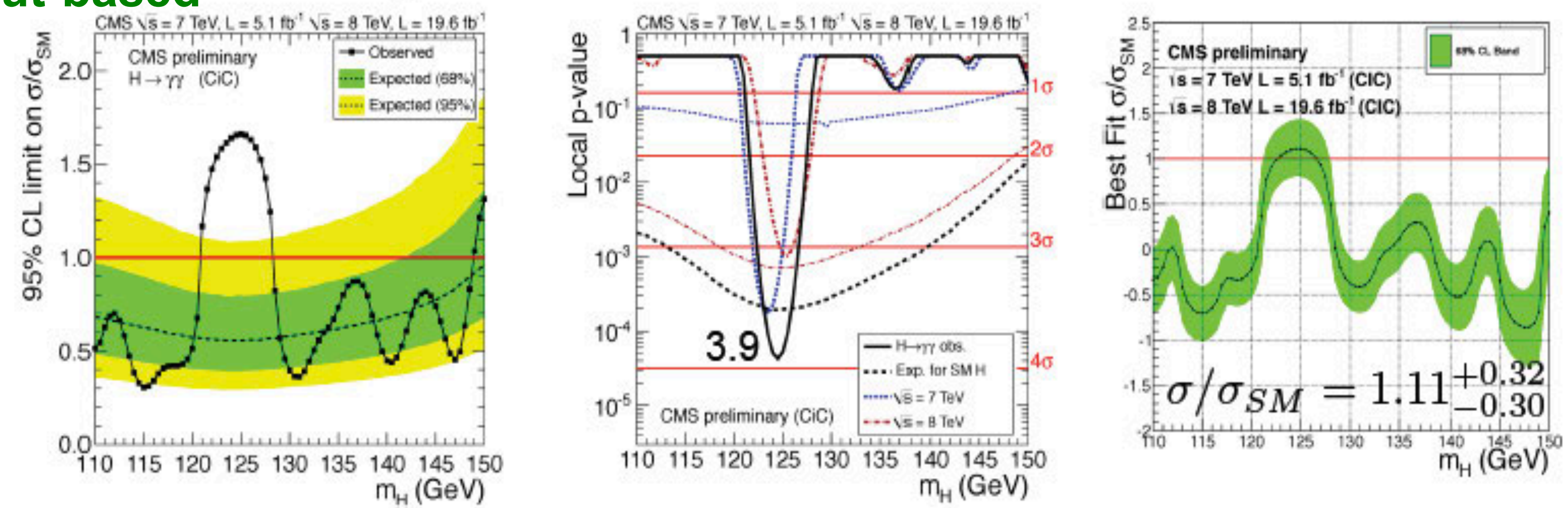


Result of the CMS search for H → γγ

(i) MVA



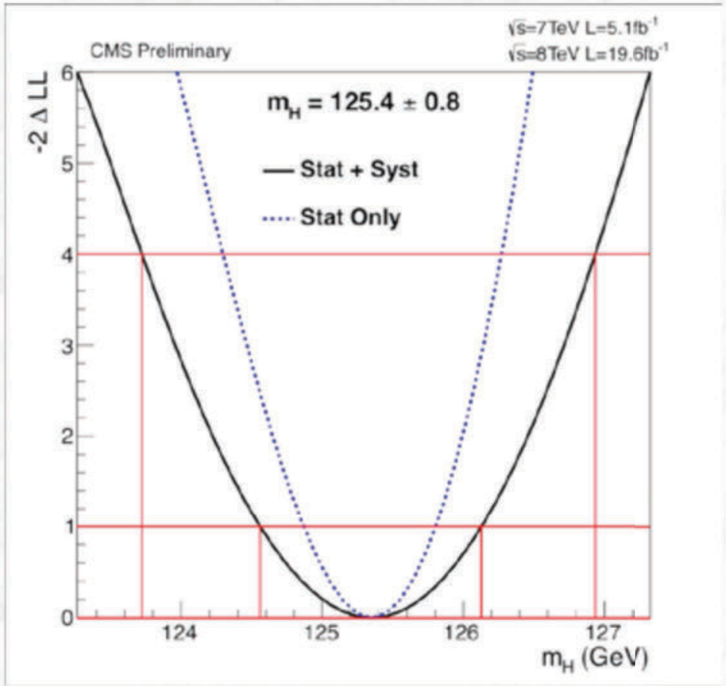
(ii) cut-based

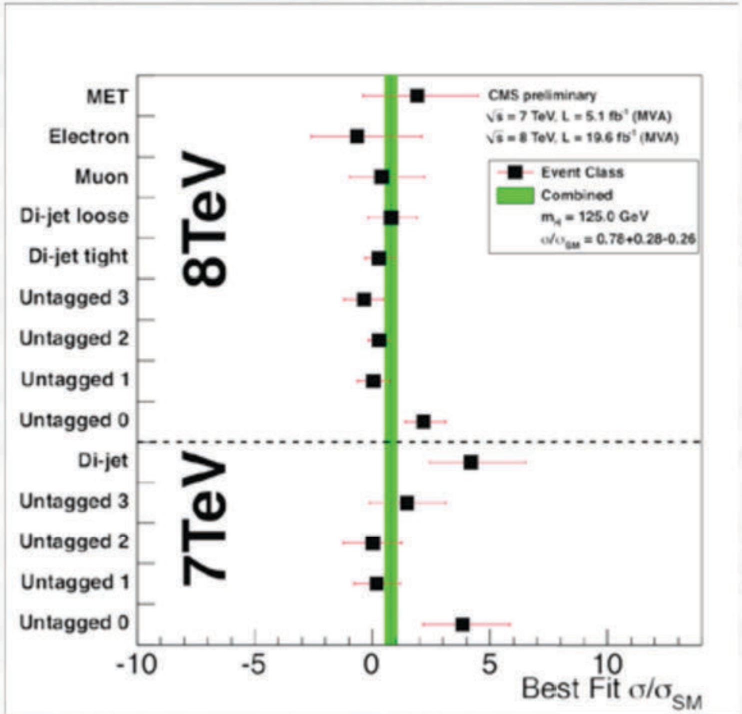


The two results are compatible (within 1.5σ) after taking correlations into account

Result of the CMS search for H → γγ

-mass and signal strength (MVA analysis)-

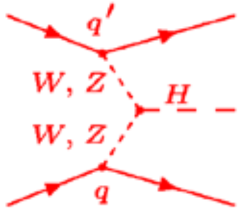


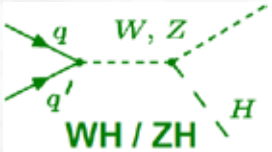


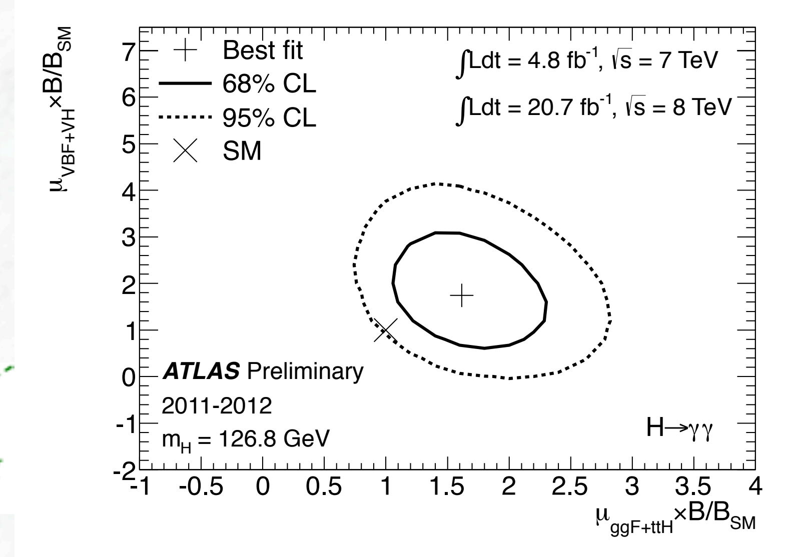
Mass: $m_H = 125.4 \pm 0.5\,(\text{stat}) \pm 0.6\,(\text{syst})\ \text{GeV}$

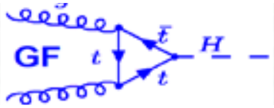
Signal strength: $\mu := \sigma / \sigma_{SM} = 0.78^{+0.28}_{-0.26}\,(\text{syst})$

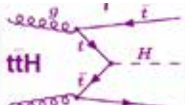
Separation of different production processes for H → γγ

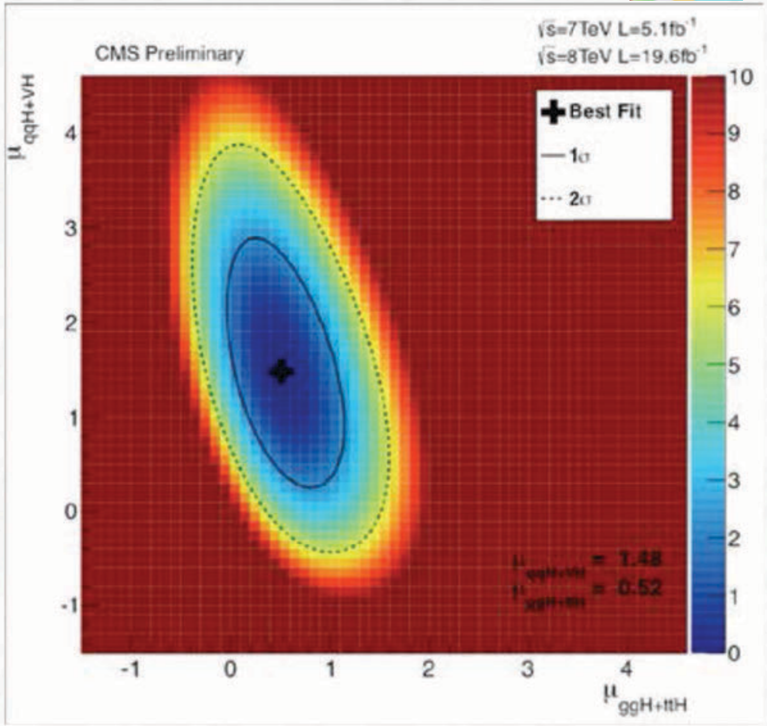


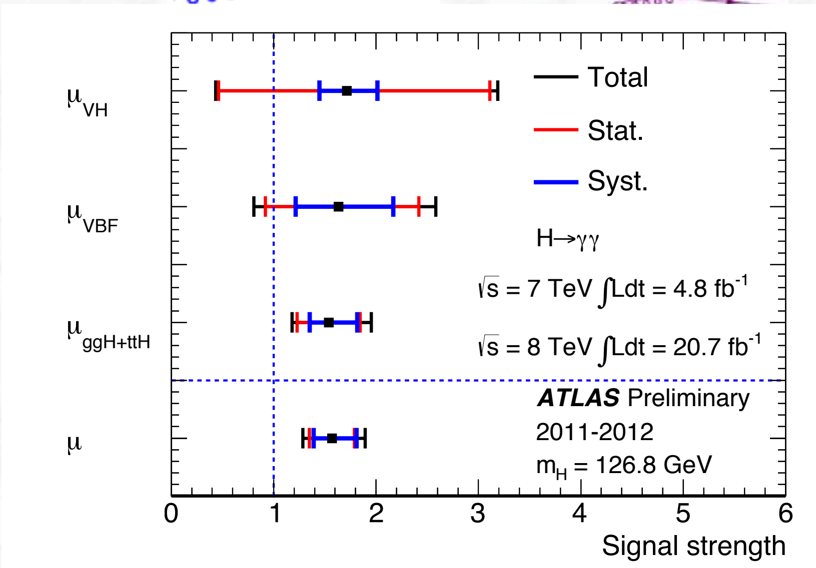






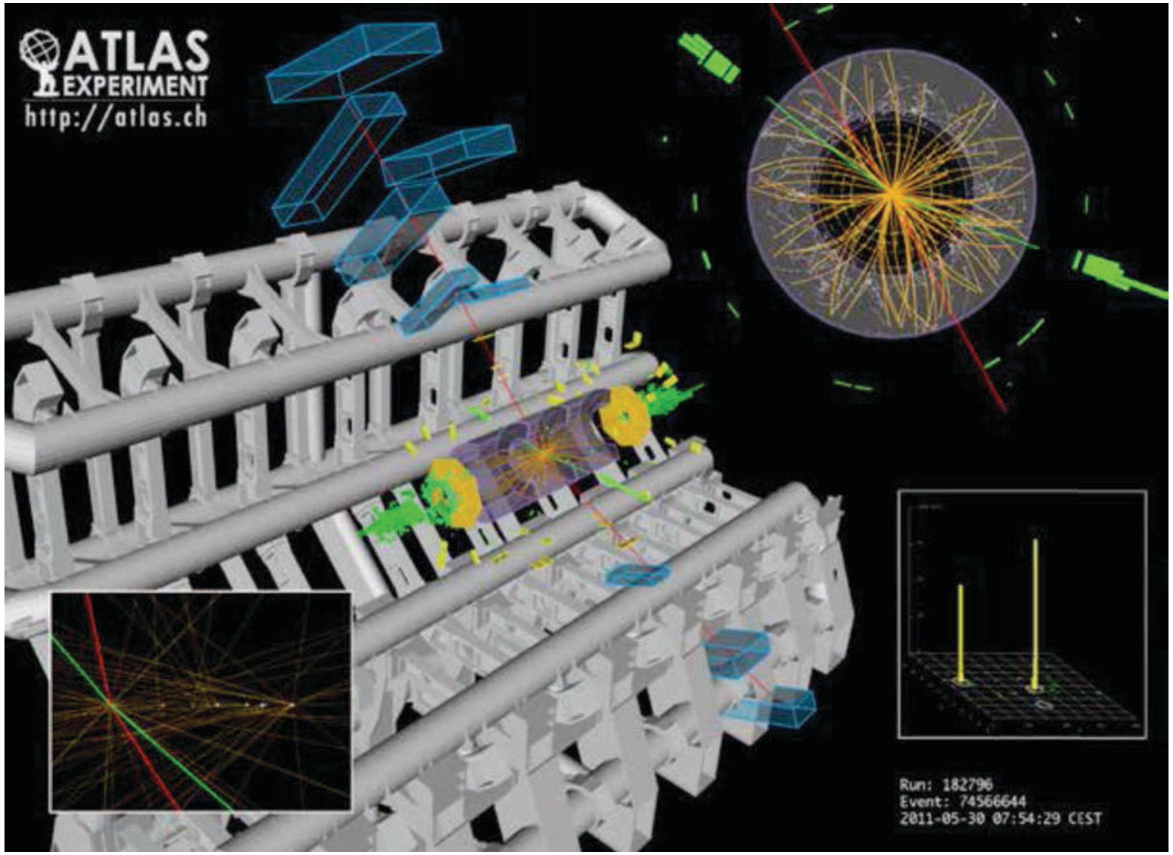






Important “evidence” for VBF production in both experiments

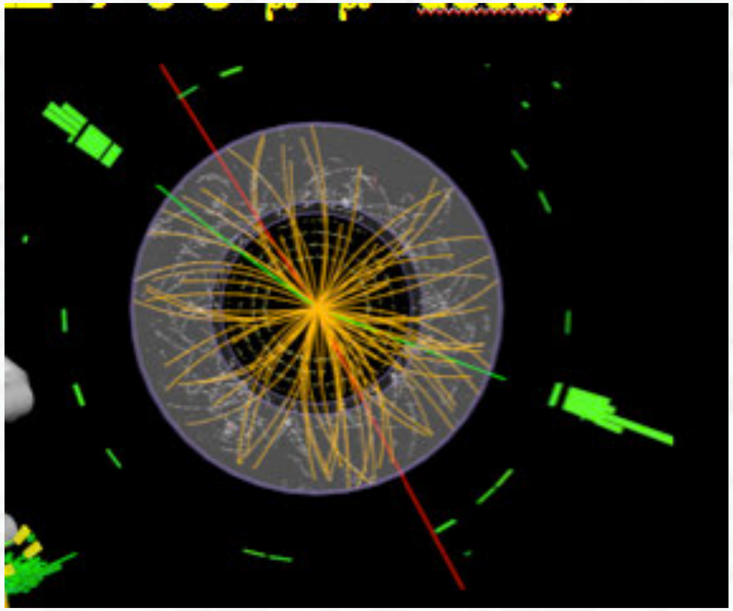
$H \rightarrow ZZ \rightarrow e^+e^- \mu^+ \mu^-$



- Clean experimental signature (4 leptons), good S/B
- Mass reconstruction possible, with good resolution

- Very small signal rate (leptonic branching ratios)

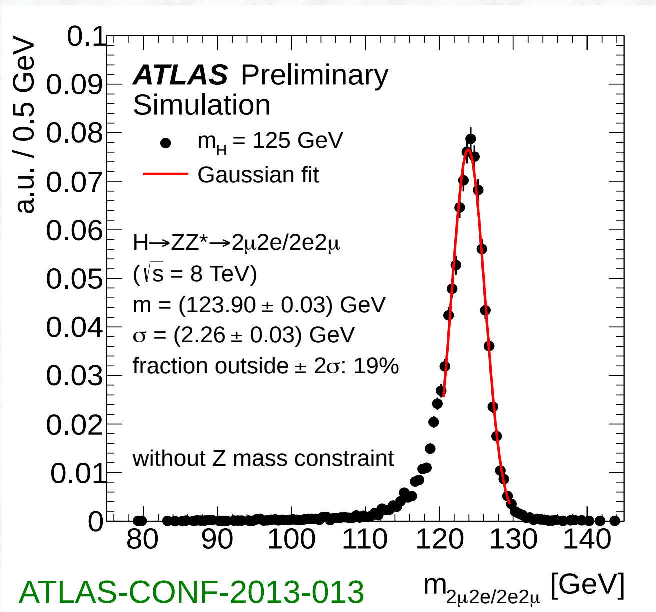
Search for the H → $ZZ^{(*)}$ → $\ell^+\ell^-\ \ell^+\ell^-$ decay



- The "golden mode": 4 isolated leptons
  e: P_T > 20 , 15, 10, 7 GeV, $|\eta|$ < 2.47
  μ: P_T > 20 , 15, 10, 6 GeV, $|\eta|$ < 2.7
  One pair consistent with Z mass (m_{12})
  Mass of other pair: $m_{min} < m_{34} <$ 115 GeV

- Mass of the Higgs boson can be reconstructed $m_{4\ell}$

  Good mass resolution $m_{4\ell}$; For m_H = 125 GeV:
  4e: ~2.7 (2.4) GeV without (with) Z mass constraint
  4μ: ~2.0 (1.6) GeV without (with) Z mass constraint



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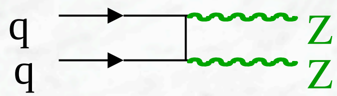
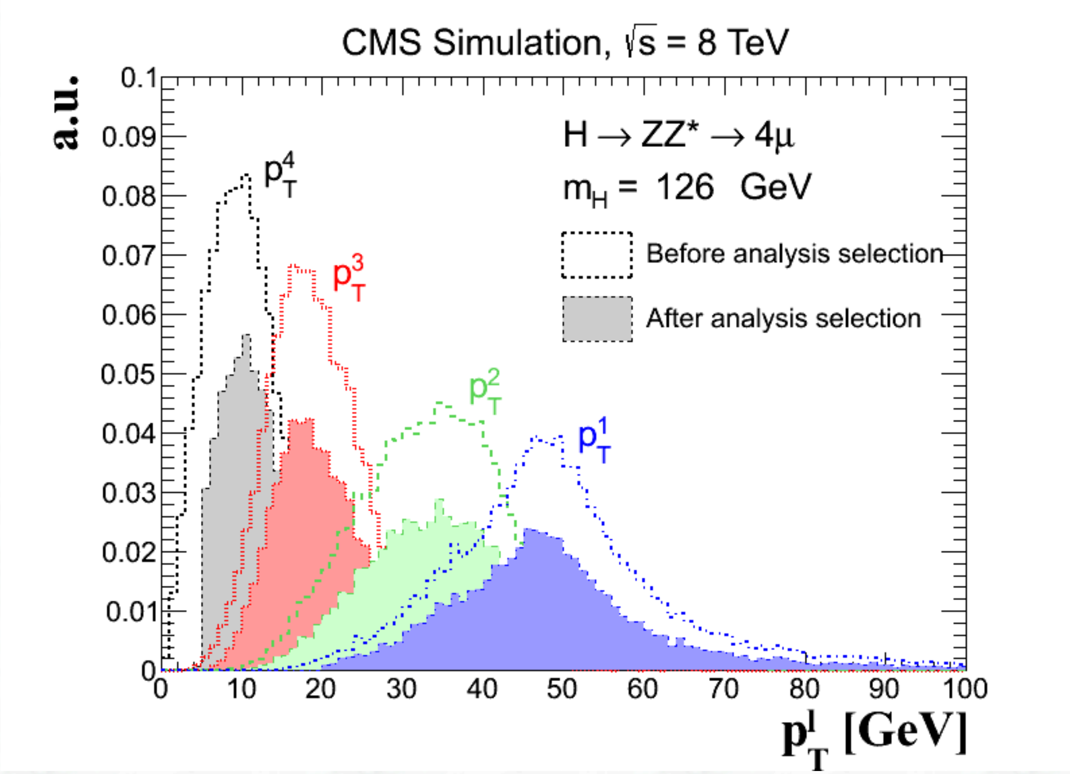
- Low signal rate, but also low background
  - Mainly from ZZ continuum



- In addition from tt and Z+jet production:
  (two prompt leptons from W / Z decays and two leptons from (heavy) quark decays)

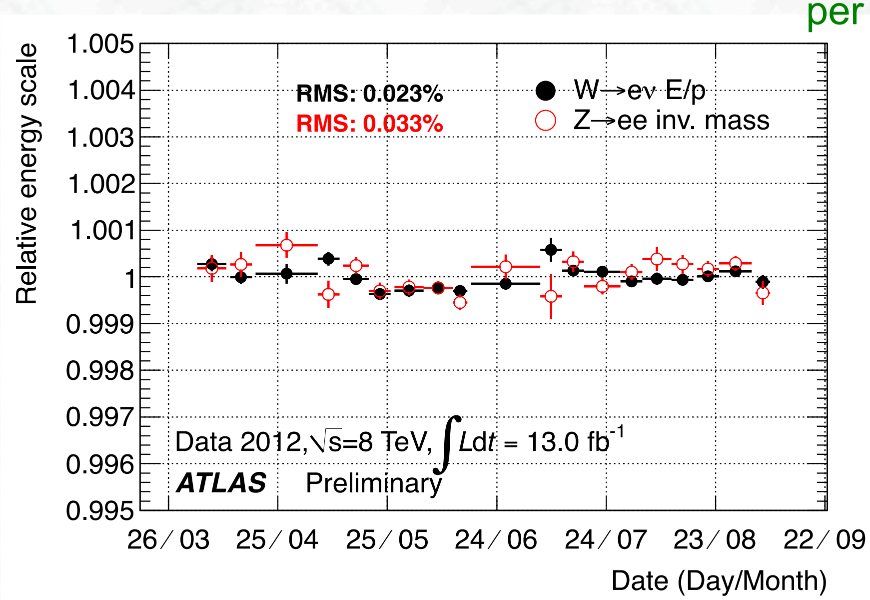
126 GeV is a low mass for ZZ* decays

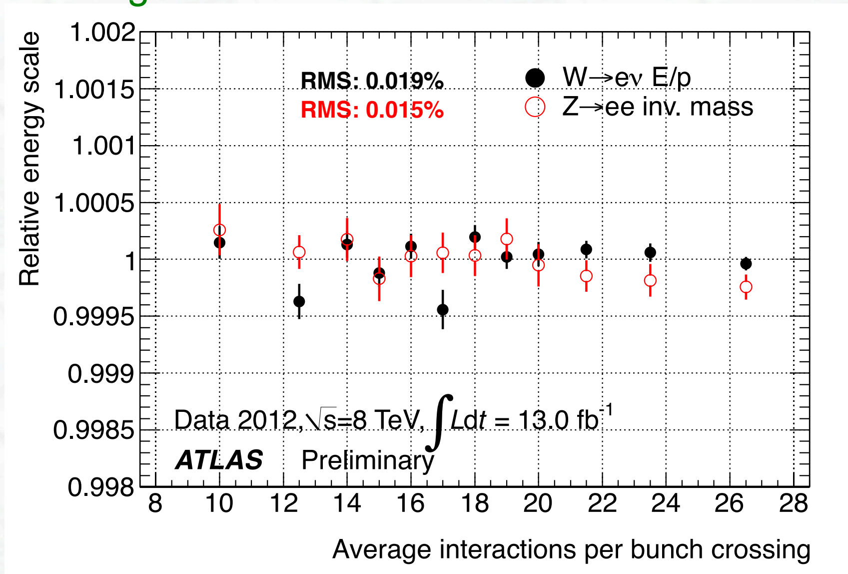
→ low p_T leptons are required

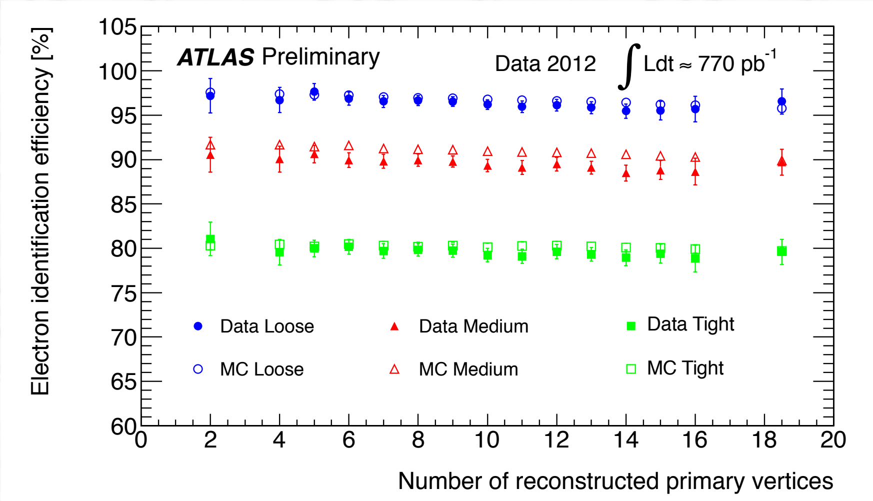


ATLAS electron performance

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



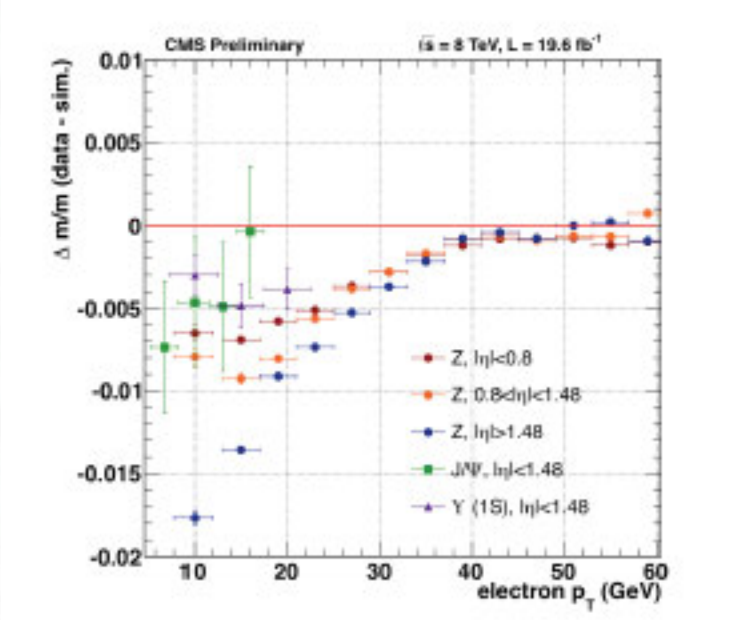




Stability of the electron identification:

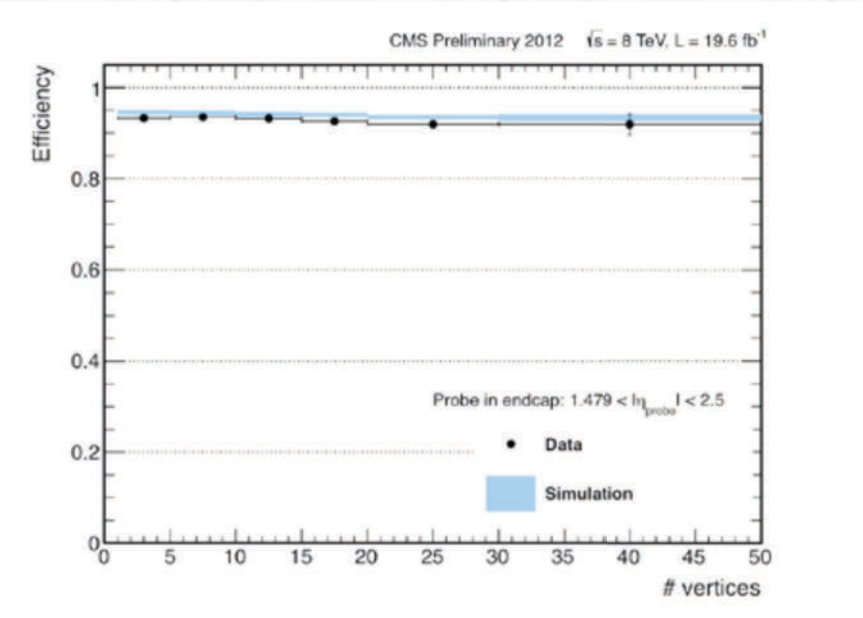
Efficiency versus rec. number of primary vertices

CMS electron performance



Stability of electron scale:

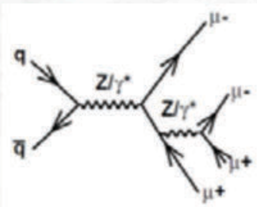
~0.2% for p_T > 35 GeV

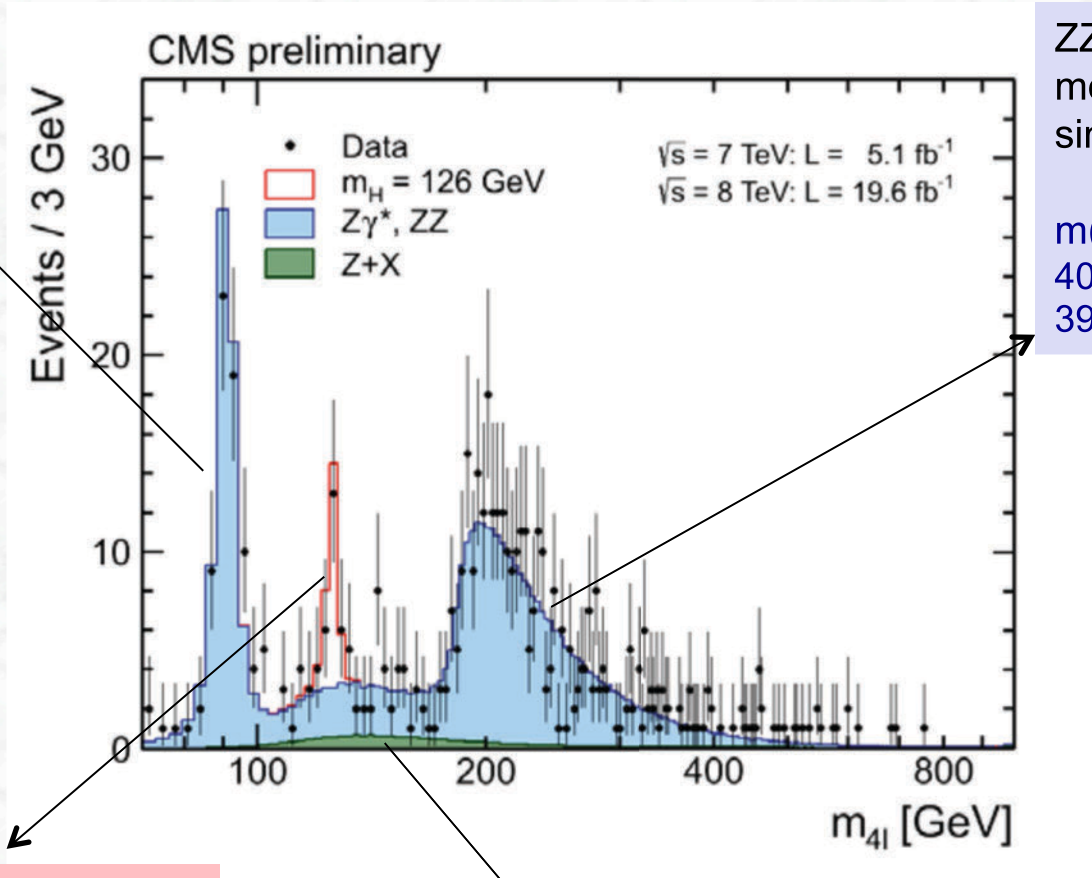


Electron efficiency versus number of rec. primary vertices

CMS: 4ℓ invariant mass spectrum

Z → 4ℓ peak
(good data / MC agreement)





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

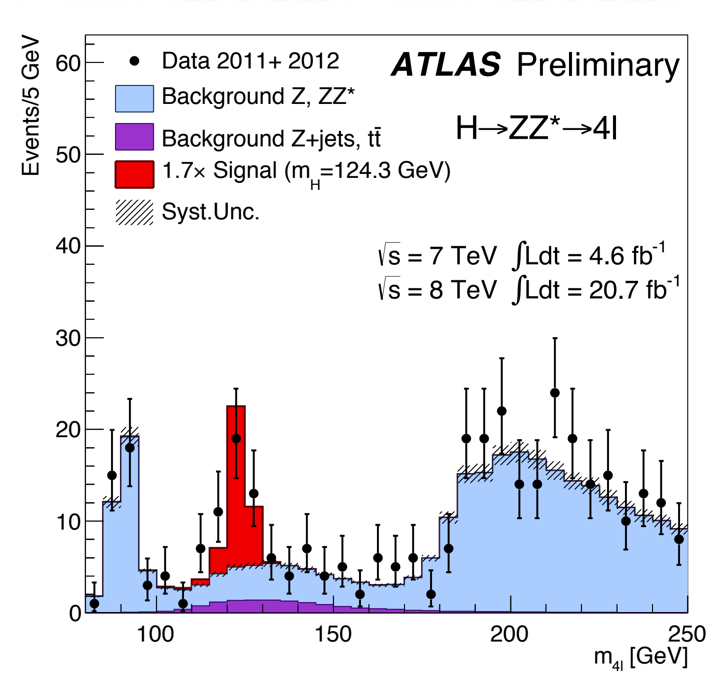
m(4ℓ) > 140 GeV:
403 events observed
390 events expected

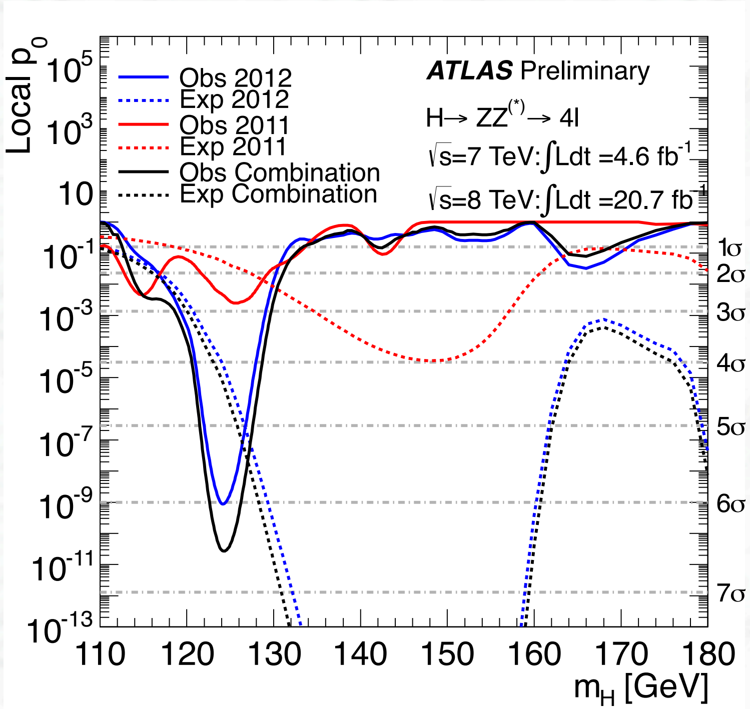
H → ZZ signal

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

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: ~2.7 10^{-11} (6.6σ obs.)
  (4.4σ exp.)

- Independent discovery-level observation

Background estimates

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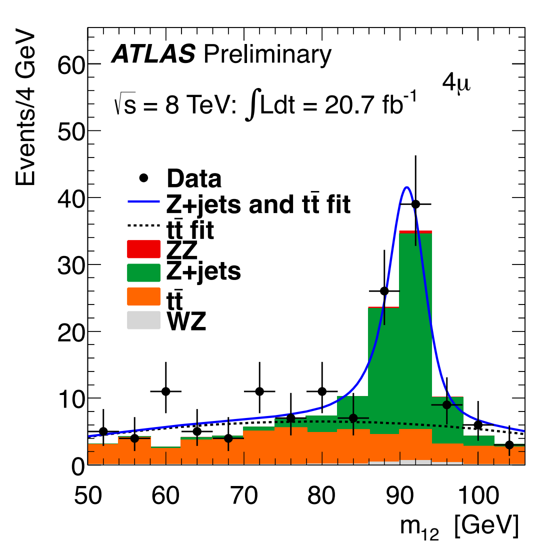
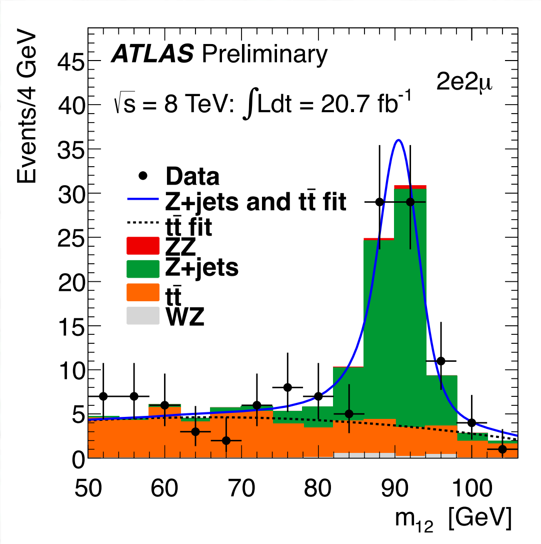
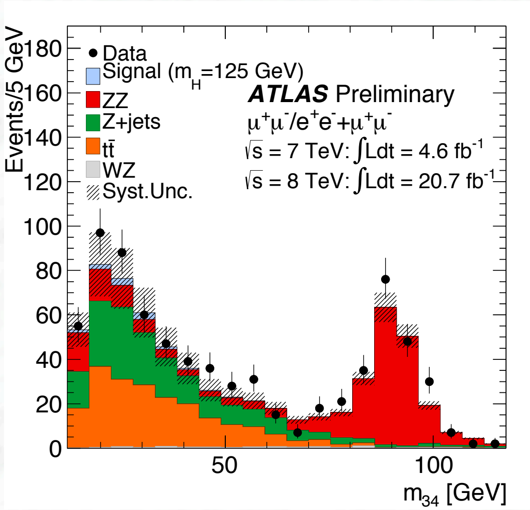
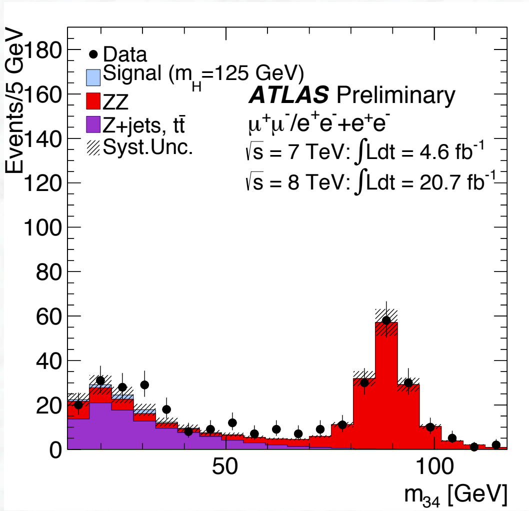




control region:

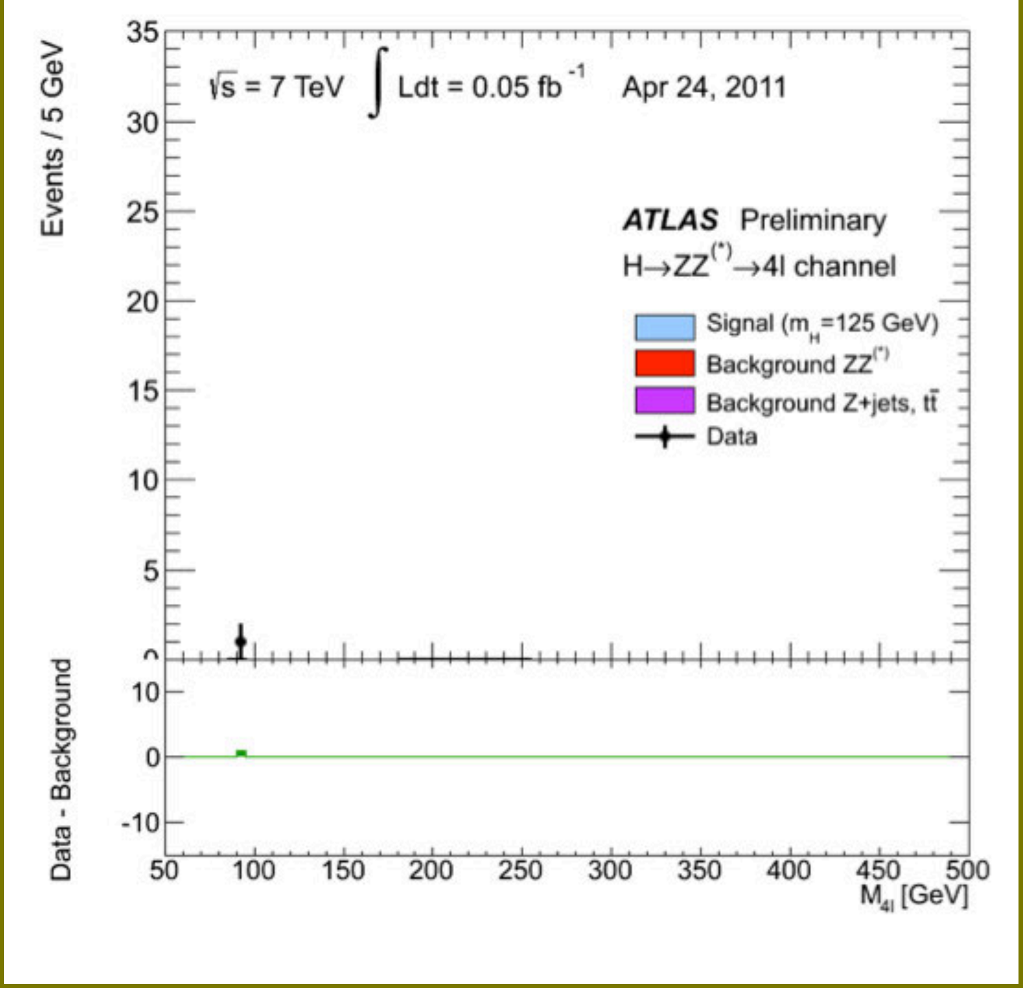
- isolation requirements not applied to the two sub-leading muons
- one muon fails impact parameter cut



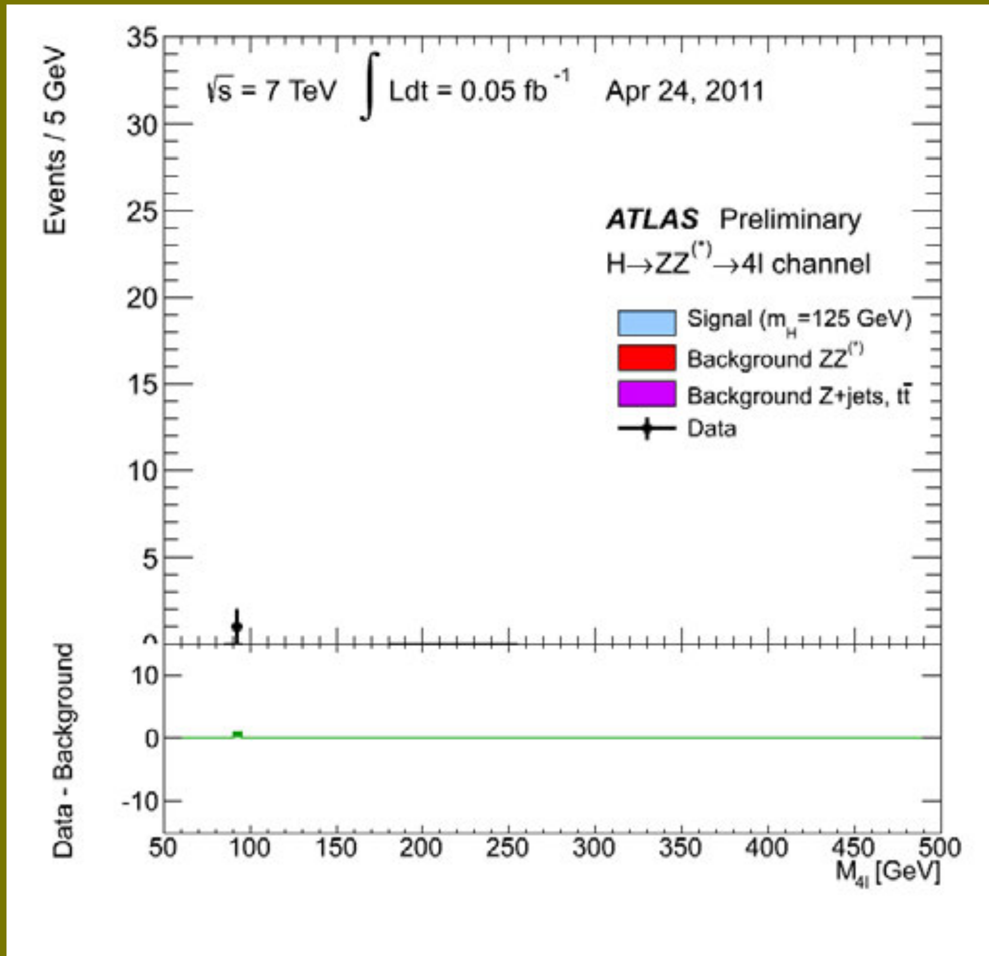


- Irreducible ZZ* background taken from Monte Carlo simulation (NLO)
- Reducible Z+jets and tt background: measured using various background-enriched control regions and transferred to signal region using Monte Carlo simulation

Time evolution of the H → ZZ → 4ℓ signal

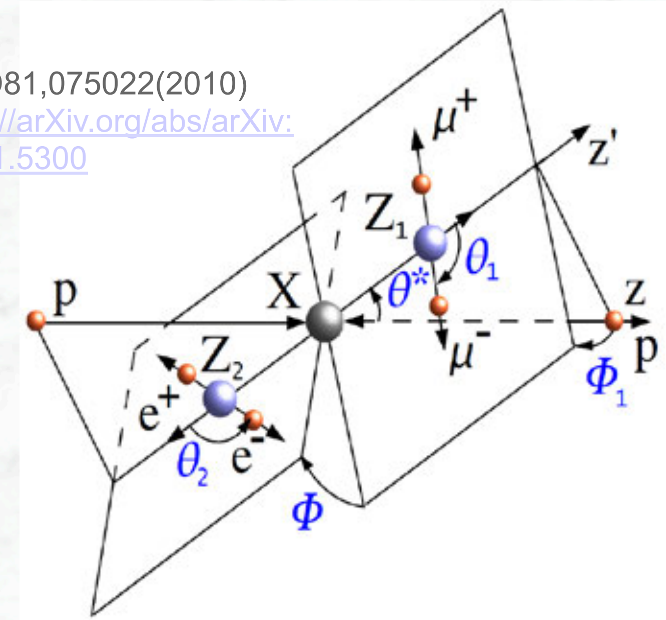


Time evolution of the H → ZZ → 4ℓ signal



CMS: use additional information on decay kinematics, MELA discriminant

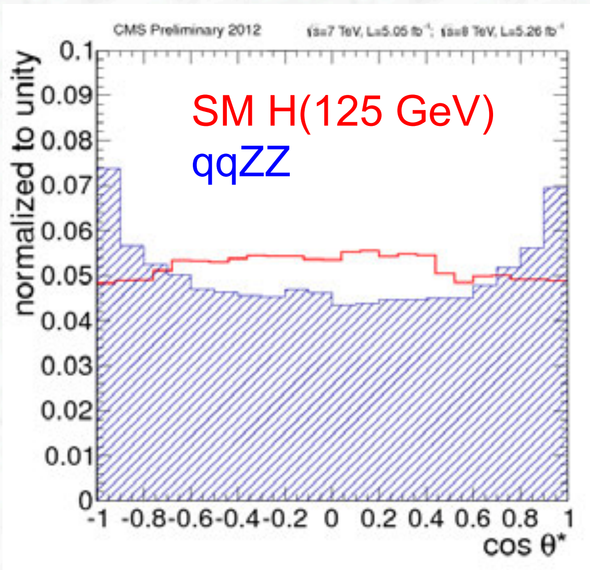
PRD81,075022(2010)
http://arXiv.org/abs/arXiv:1001.5300

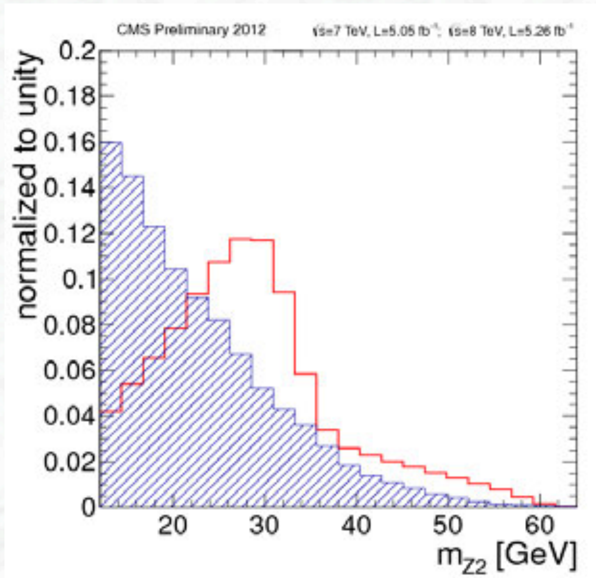


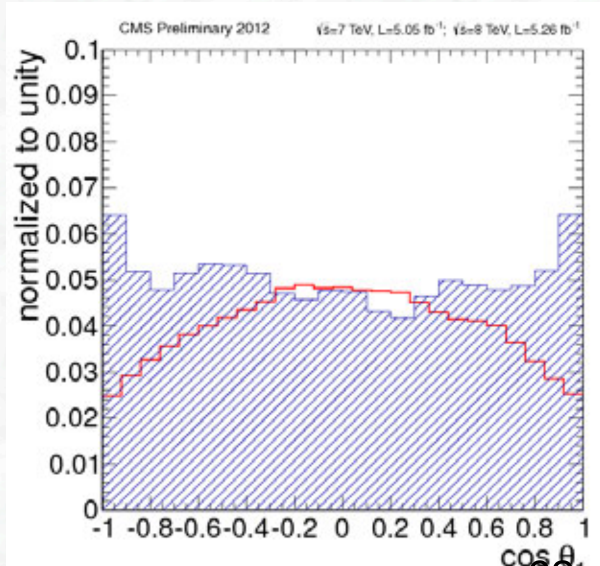
Matrix Element Likelihood Analysis:

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

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

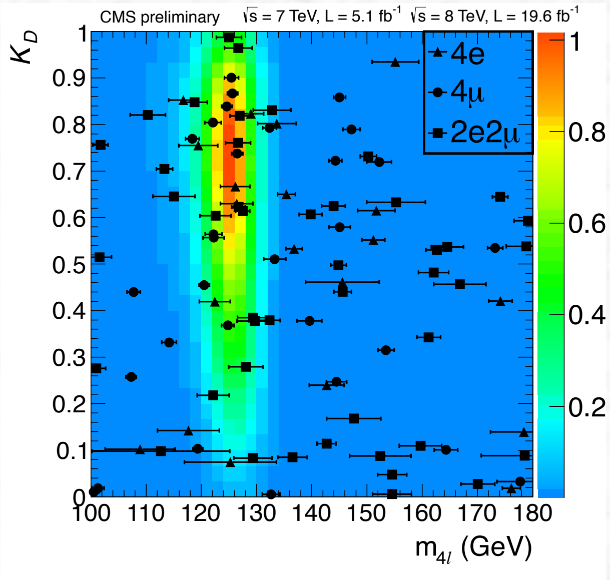


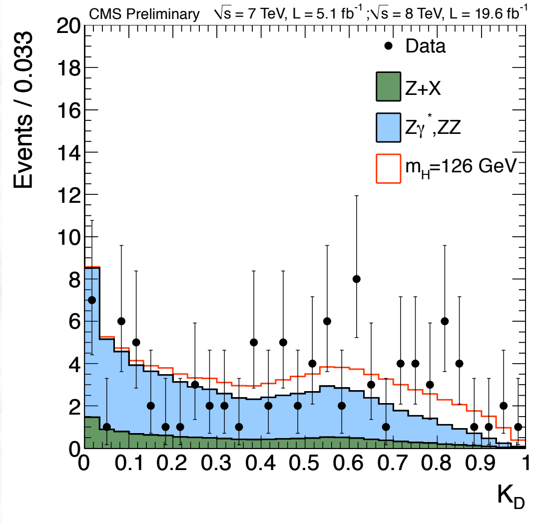




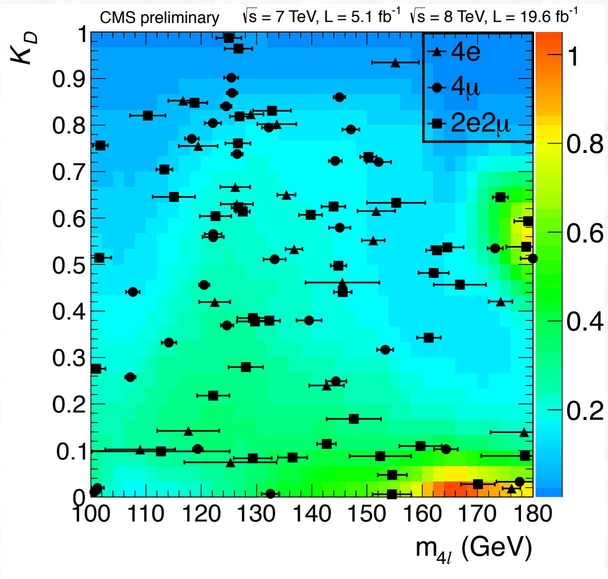
2D analysis using {$m_{4\ell}$, MELA=K_D}

contours =
signal expectation

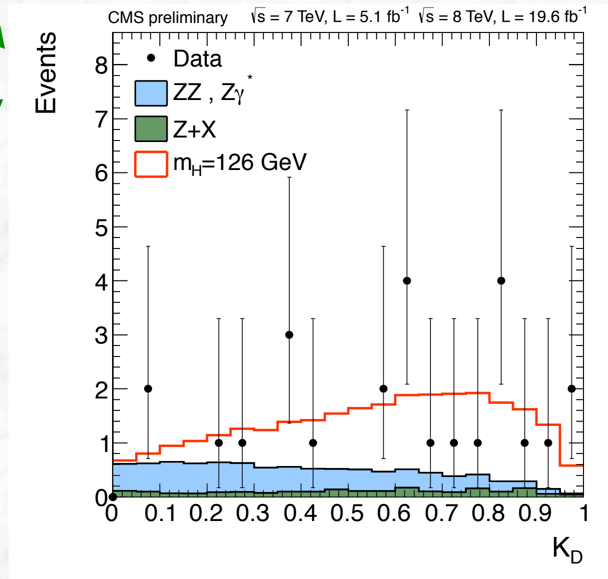




contours =
background expect.



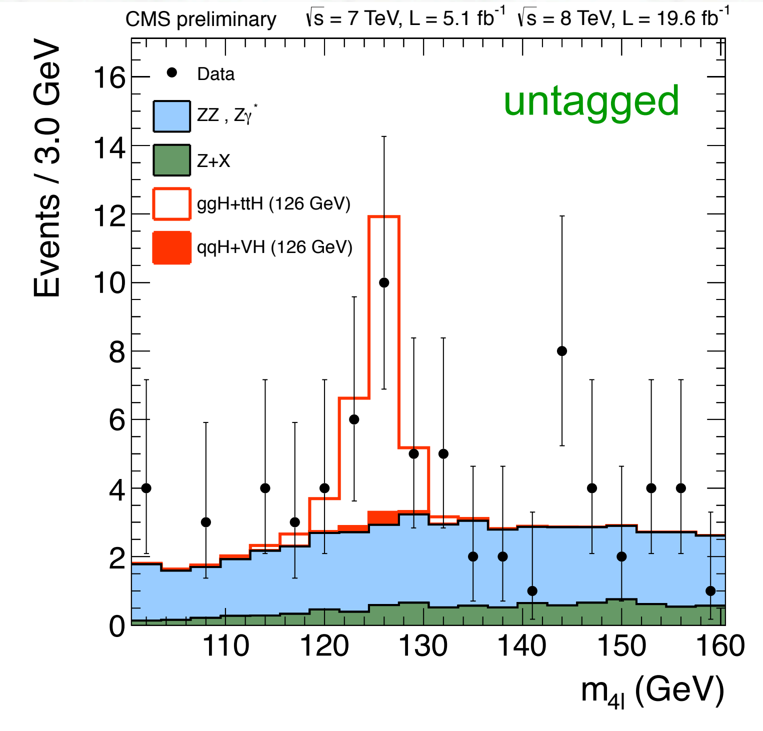
$121.5 < m_{4l} < 130.5$ GeV

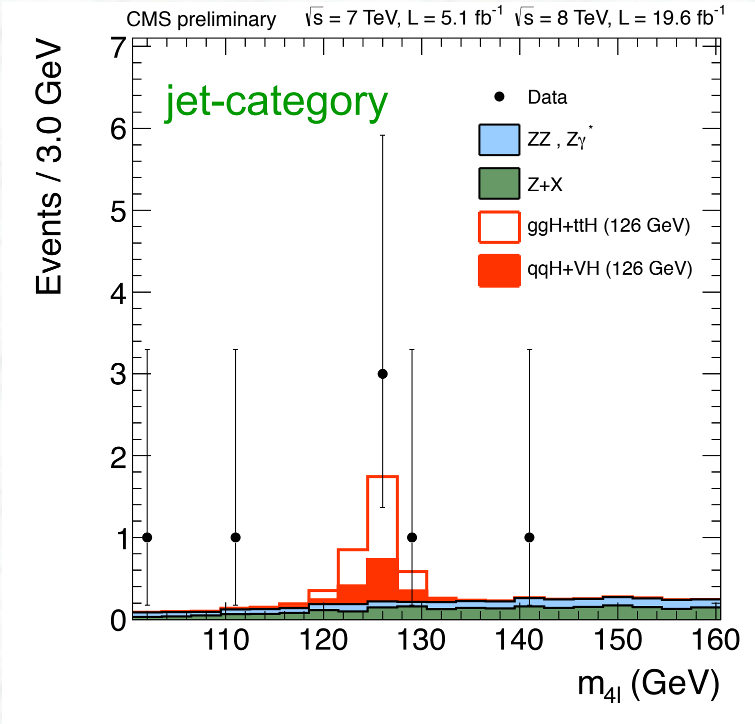


CMS: further refinement via jet categorization

(i) Jet-category: require two jets with E_T > 30 GeV
(enhanced VBF fraction (~20%))

(ii) Untagged: all other events (VBF fraction ~5%)

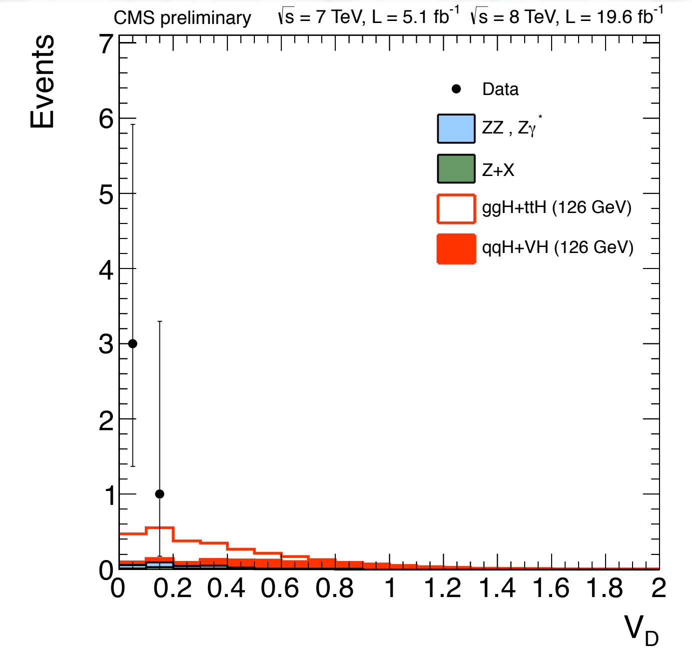


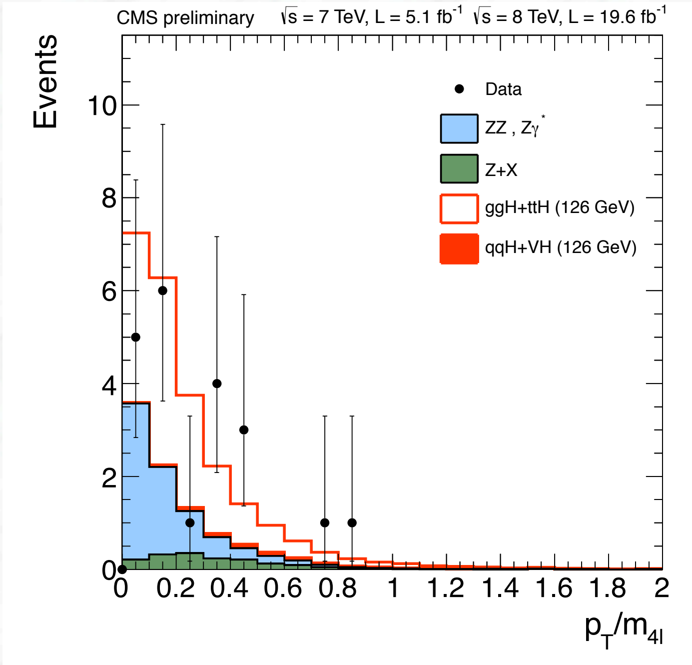


CMS: further refinement via additional discriminants -to separate production modes-

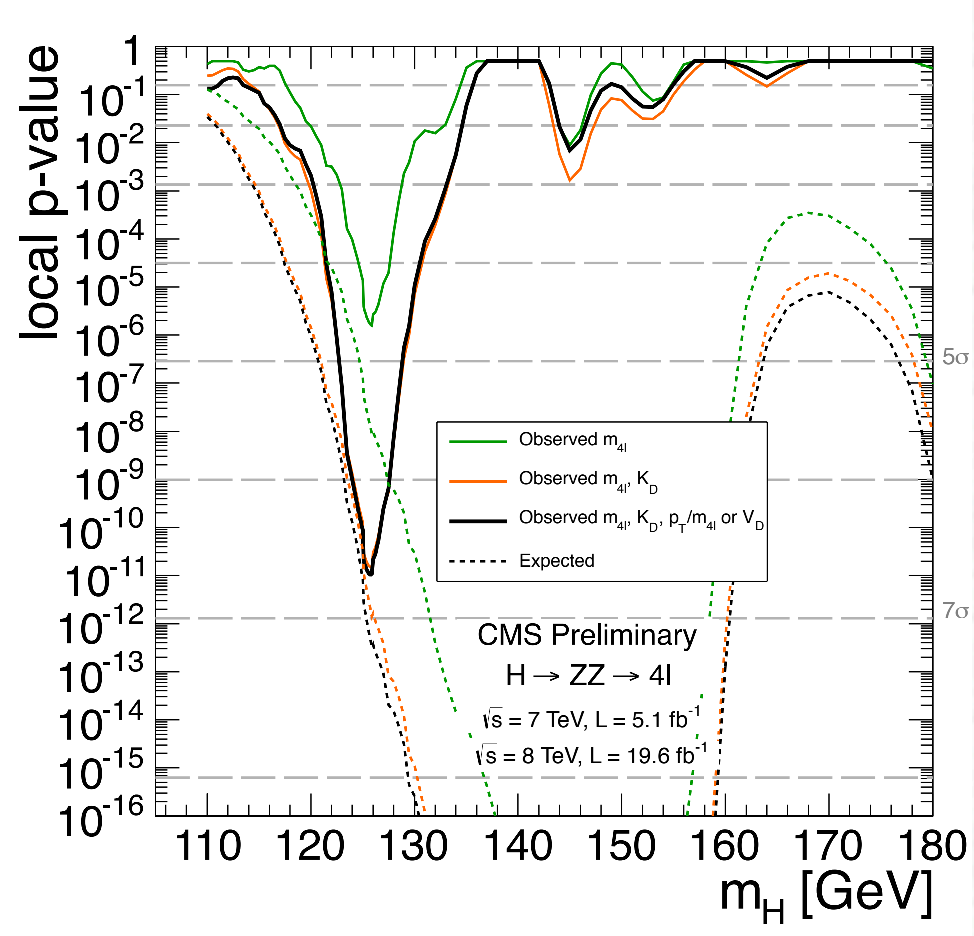
- VBF-discriminant: $V_D = \alpha\,|\Delta\eta_{jj}| + \beta\, m_{jj}$

- P_T boost: $P_T(4\ell) / m_{4\ell}$





CMS H → ZZ significance

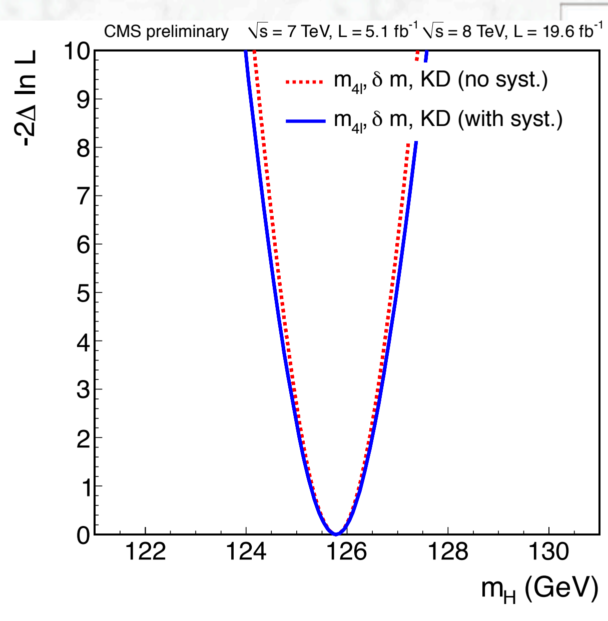


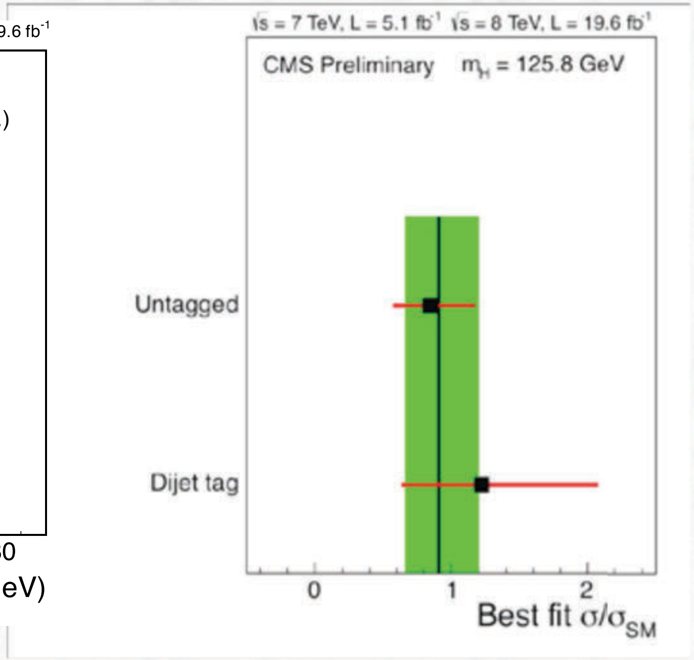
	Expected	Observed
3D (m_{4l}, K_D, $V_{D\ or}\ p_{T}/m_{4l}$)	7.2 σ	6.7 σ
2D (m_{4l}, K_D)	6.9 σ	6.6 σ
1D(m_{4l})	5.6 σ	4.7 σ

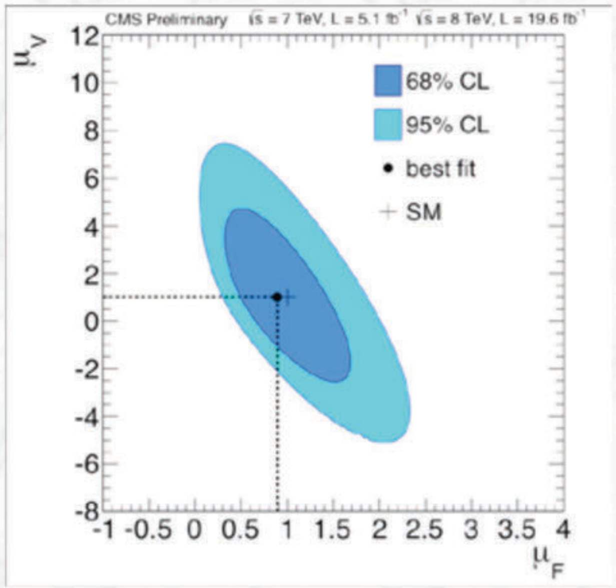
at 125.8 GeV (minimum of local p value)

- Stand-alone discovery in the H → ZZ – 4l channel
- Additional discriminants improve sensitivity, as expected

Mass and signal strength for H → ZZ*







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

Signal strength:
(m_H = 125.8 GeV) $$\mu = 0.9^{+0.3}_{-0.2}$$

Mass and signal strength for H → ZZ*

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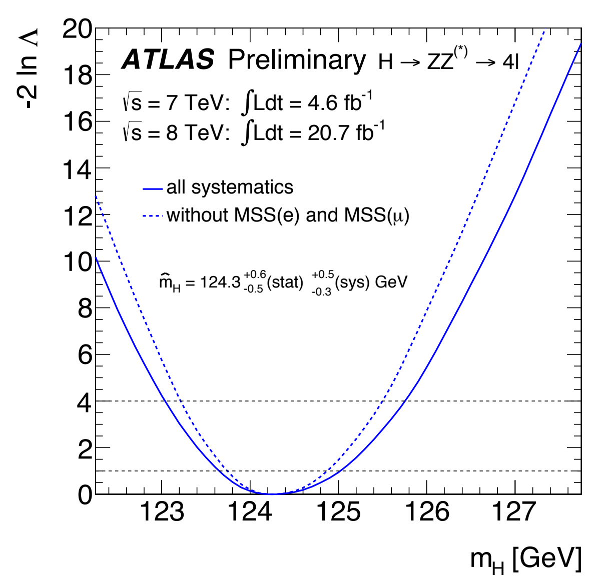
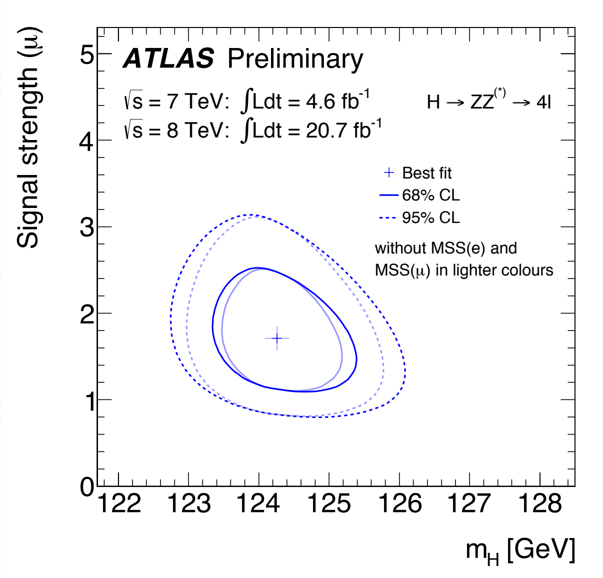
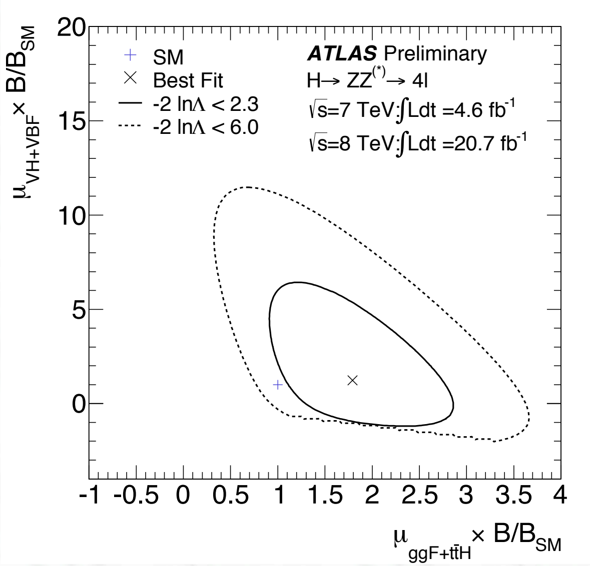






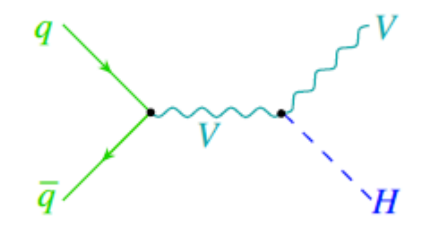
Mass: $m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\ \text{GeV}$

Signal strength:
(m_H = 124.3 GeV) $\mu = 1.7 \pm 0.5$

End of Lecture I

Backup Slides

WH / ZH associated production:



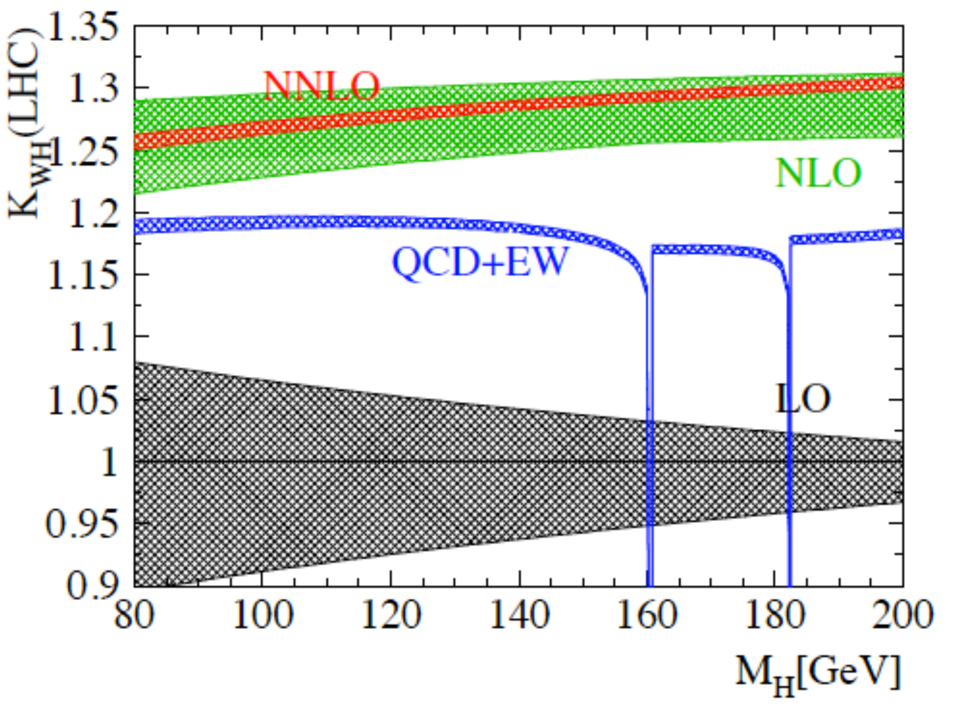
- Weak at the LHC,
  Relatively stronger at the Tevatron

- Allows for a Higgs-decay-independent trigger
  W → lν, Z → ll

- Sensitivity to W/Z couplings

- Moderate K-factors
  (NLO corrections)

Both NLO QCD and el.weak corrections available

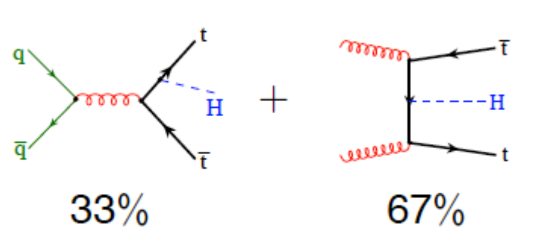


Brein, Djouadi, Harlander, (2003)

Han, Willenbrock (1990)

Ciccolini, Dittmaier, Krämer (2003)

ttH associated production:



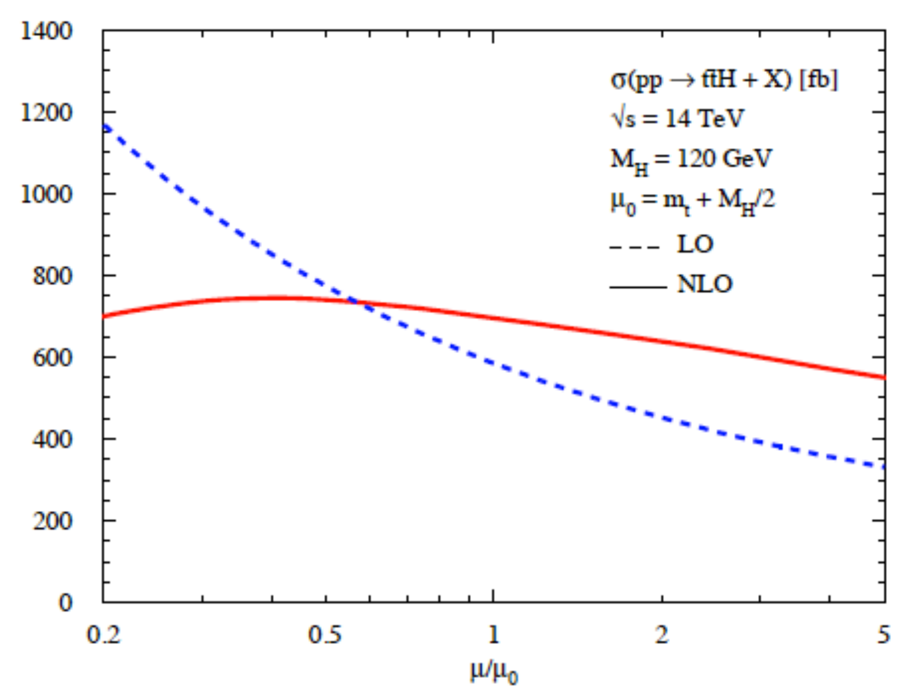
- Weak and difficult at the LHC
- Sensitivity to top-Yukawa coupling
- Moderate K-factors
  (NLO corrections)

NLO QCD corrections available,
scale uncertainty drastically reduced

scale: $\mu_0 = m_t + m_H/2$

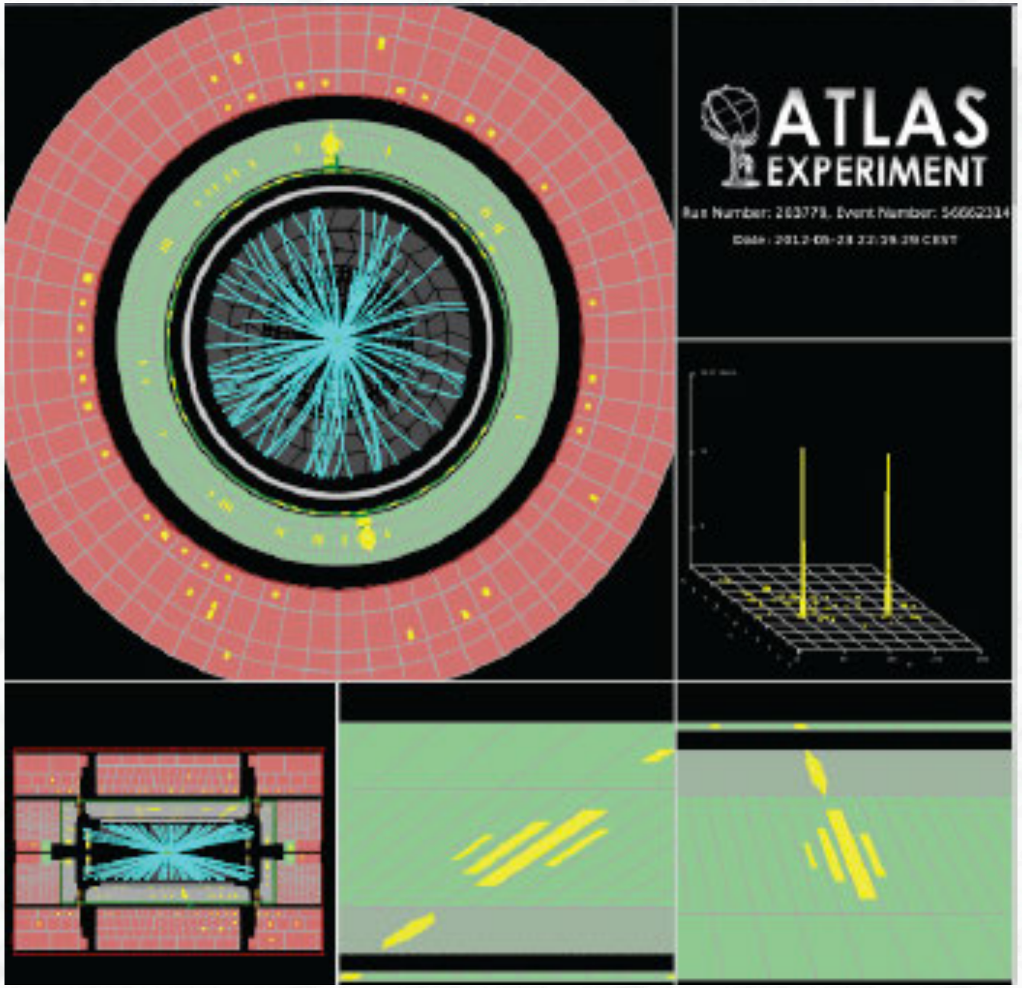
LHC: K ~ 1.2

Tevatron: K ~ 0.8



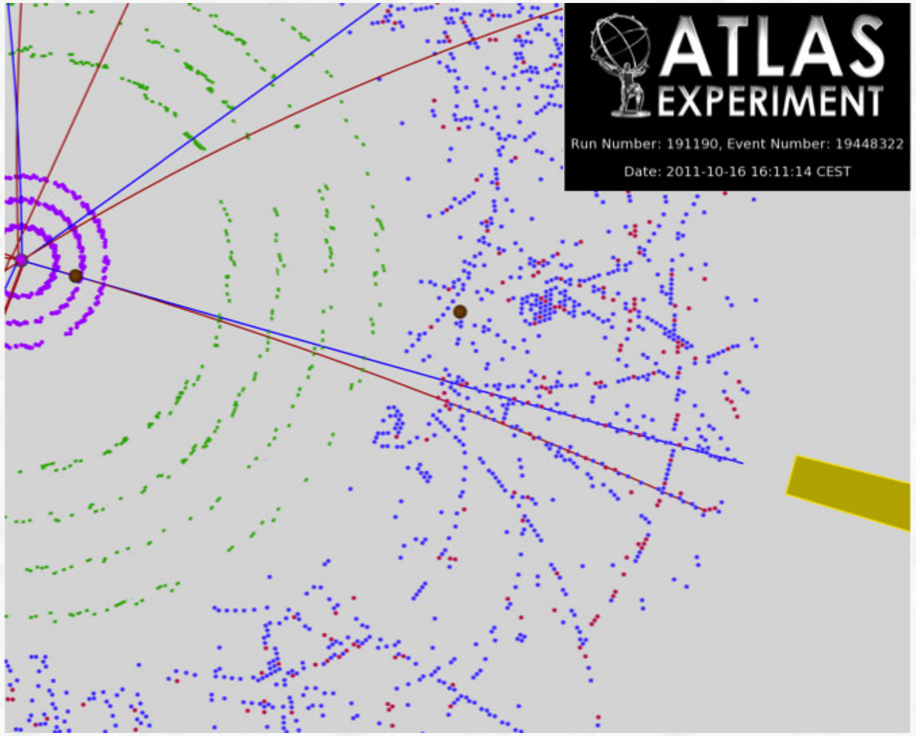
Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (2001)
Dawson, Reina, Wackeroth, Orr, Jackson (2001, 2003)

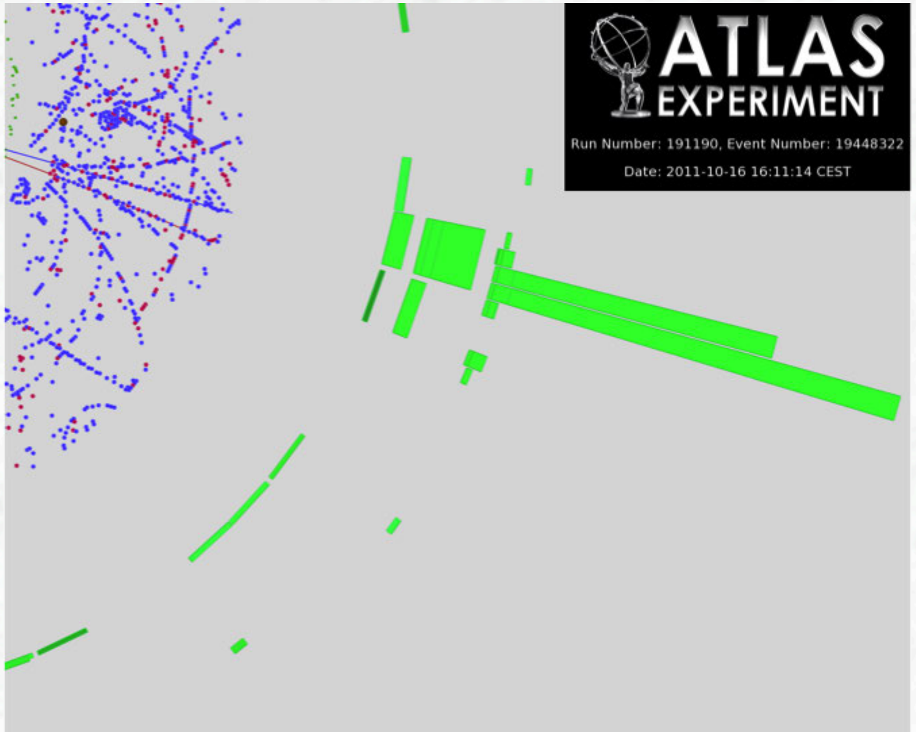
A $\gamma\gamma$ event in ATLAS



- Photons are obvious, even with pile-up
  - Note that low p_T tracks are suppressed in the display
- One can see how the EM showers can be used to point back to the primary vertex
- Three photon regions: central, endcap, transition
  - The transition region is difficult

The Conversion in More Detail





The tracks from $\gamma \rightarrow e^+e^-$ are clear and distinct. Red hits are high threshold TRT hits and confirm that these are in fact electrons.

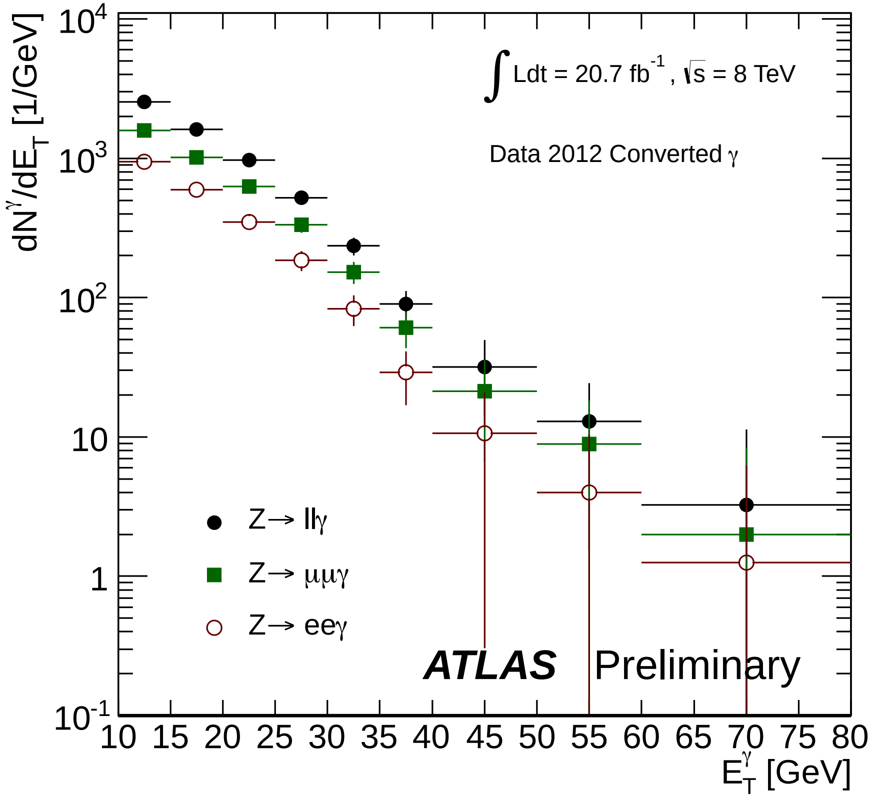
The shape of the EM cluster in the calorimeter is consistent with two electrons very near each other.

ATLAS photon identification

Shower shape variables used in the ATLAS photon identification (loose, tight):

Category	Description	Name	Loose	Tight
Acceptance	$\|\eta\| < 2.37$, $1.37 < \|\eta\| < 1.52$ excluded	–		✓
Hadronic leakage	Ratio of E_T in the first sampling of the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| < 0.8$ and $\|\eta\| > 1.37$)	R_{had_1}	✓	✓
	Ratio of E_T in all the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$)	R_{had}	✓	✓
EM Middle layer	Ratio in η of cell energies in 3×7 versus 7×7 cells	R_η	✓	✓
	Lateral width of the shower	w_2	✓	✓
	Ratio in ϕ of cell energies in 3×3 and 3×7 cells	R_ϕ		✓
EM Strip layer	Shower width for three strips around maximum strip	$w_{s\,3}$		✓
	Total lateral shower width	$w_{s\,\mathrm{tot}}$		✓
	Fraction of energy outside core of three central strips but within seven strips	F_{side}		✓
	Difference between the energy associated with the second maximum in the strip layer, and the energy reconstructed in the strip with the minimal value found between the first and second maxima	ΔE		✓
	Ratio of the energy difference associated with the largest and second largest energy deposits over the sum of these energies	E_{ratio}		✓

Measured inclusive γ spectrum from Z → llγ events, 2012 data



Statistical treatment

- All results are based on profile likelihood method

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

μ = parameter(s) of interest
θ = nuisance parameters

- $L(\hat{\mu}, \hat{\theta})$ Unconditional maximum likelihood estimate (μ and θ adjusted to maximise L)

- $L(\mu, \hat{\hat{\theta}}(\mu))$ Conditional maximum likelihood estimate: (a specific μ value (fixed), θ adjusted to maximise L for this μ)

- -2 ln Λ(μ) follows a χ^2 distribution with n d.o.f. ($\mu_{1,\ldots n}$)

- Nuisance parameters θ are constraint by probability density functions (Gaussian constraints, log-normal distributions, Poisson,… also explored: “rectangular” pdfs for some specific systematic uncertainties)