



Run Number: 182796,  
Event Number: 74566644  
Date: 2011-05-30, 06:54:29 CET

$E_T$ Cut > 0.3 GeV  
 $P_T$ Cut > 2.0 GeV  
Vertex Cuts:  
Z direction < 1cm  
Rphi < 1cm  
Muon: blue  
Electron: Black  
Cells: TILES, EMC

# Observation of a Higgs-like particle at the LHC

Stathes Paganis (The University of Sheffield)

Sheffield PPPA seminar, 5-Dec-2012

# Introduction/Outline

On the 4<sup>th</sup> of July 2012, ATLAS and CMS experiments announced the observation of a new narrow resonance at a mass of  $\sim 125$ -126 GeV. Studies of the properties of this particle are now in full force with the aim to establish if the particle is the long sought Higgs boson of the Higgs mechanism responsible for the EW gauge symmetry breaking.

Here I present the latest results from ATLAS/CMS with a focus in  $\gamma\gamma$  and  $ZZ \rightarrow 4l$

- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ \rightarrow 4 \text{ leptons (e, } \mu)$

Phys. Lett. B 716 (2012) 1-29

# Elementary particles are Quantum Fields

Fields	Symbol	Spin	Possible States (Polarisation)
Scalar	$\phi$	0	1
Vector	$A^\mu$	1	3 (2 if massless)
Tensor-2	$T^{\mu\nu}$	2	5
Spinor $-\frac{1}{2}$	$\psi(x)$	$\frac{1}{2}$	2 (up, down)

Scalar

$$\phi(x) = \phi_R + i\phi_{im} = r \cdot e^{i\theta(x)}$$

$$\begin{pmatrix} \phi_1(x) \\ \phi_2(x) \\ \vdots \\ \phi_N(x) \end{pmatrix}$$

We can have multiplets of fields.

Then, the particle is the multiplet

$$\begin{pmatrix} p \\ n \end{pmatrix}$$

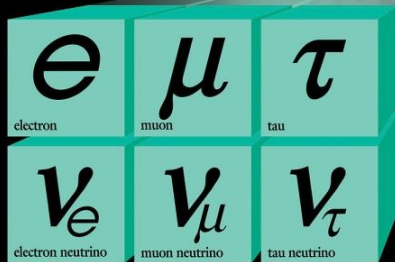
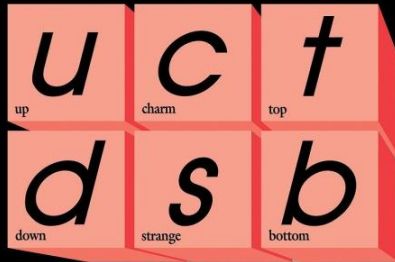
Example:  
The nucleon!  
(isospin)

Fermions come in two “chiralities”: Left and Right

In QM particles are field excitations: “lumps” of field energy.

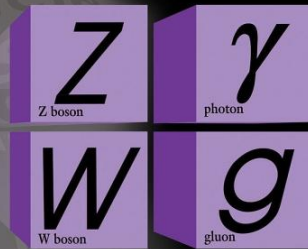
# The Standard Model

## Quarks



## Leptons

## Forces



Includes all elementary particles and their interactions.

Has passed all experimental tests and predicts observables to better than 1%.

Predicts the unification of EM & Weak interactions.

Predicts a new particle: the Higgs boson.

Is this the “final theory” ?

Can't be:

→ there is no gravity

→ Cannot tell us why Higgs appears with this mass.

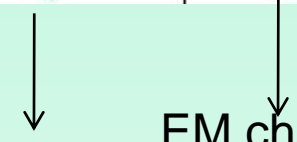
→ Cannot explain why the masses of the fermions are so different

→ Dark matter, Dark energy ?

→ ...

# The ElectroWeak part of the SM

<i>SU(2)xU(1) electroweak unification particles</i>		<i>Weak isotopic charge</i>	<i>Weak hypercharge</i>	<i>Electric charge</i>
<b>Quark doublet</b>	$\mathbf{u}_L$	<b>+1/2</b>	<b>+1/3</b>	<b>+2/3</b>
	$\mathbf{d}_L$	<b>-1/2</b>	<b>+1/3</b>	<b>-1/3</b>
Quark singlets	$\mathbf{u}_R$	0	+4/3	+2/3
	$\mathbf{d}_R$	0	+2/3	-1/3
<b>Lepton doublet</b>	$(\mathbf{v}_e)_L$	<b>+1/2</b>	<b>-1</b>	<b>0</b>
	$\mathbf{e}_L$	<b>-1/2</b>	<b>-1</b>	<b>-1</b>
Lepton singlet	$\mathbf{e}_R$	0	-2	-1
<b>Boson triplet</b>	$\mathbf{W}_+$	+1	0	+1
	$\mathbf{W}_0/\mathbf{Z}_0$	0	0	0
	$\mathbf{W}_-$	-1	0	-1
Boson singlet	$\mathbf{B}$	0	0	0
<b>Speculative Higgs boson doublet</b>	$\boldsymbol{\varphi}_+$	<b>+1/2</b>	<b>+1</b>	<b>+1</b>
	$\boldsymbol{\varphi}_0$	<b>-1/2</b>	<b>+1</b>	<b>0</b>


  
 Weak charges      EM charges

# Example: Higgs Field vs Higgs Boson

Field



Particle

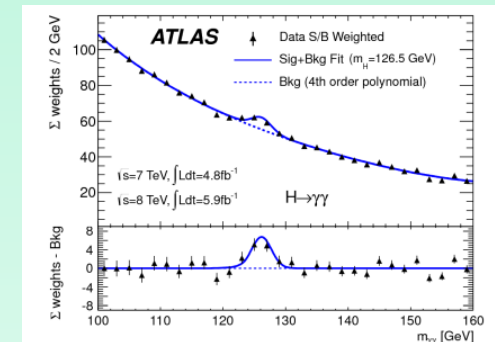
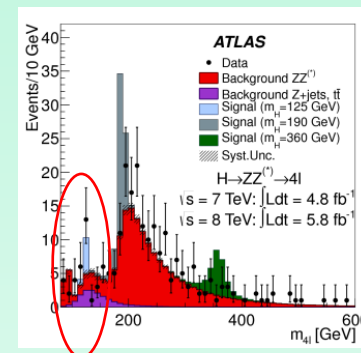


Manifestation of Higgs field:

Interaction carriers acquire mass:

W/Z bosons  $\sim 100$  x the proton mass

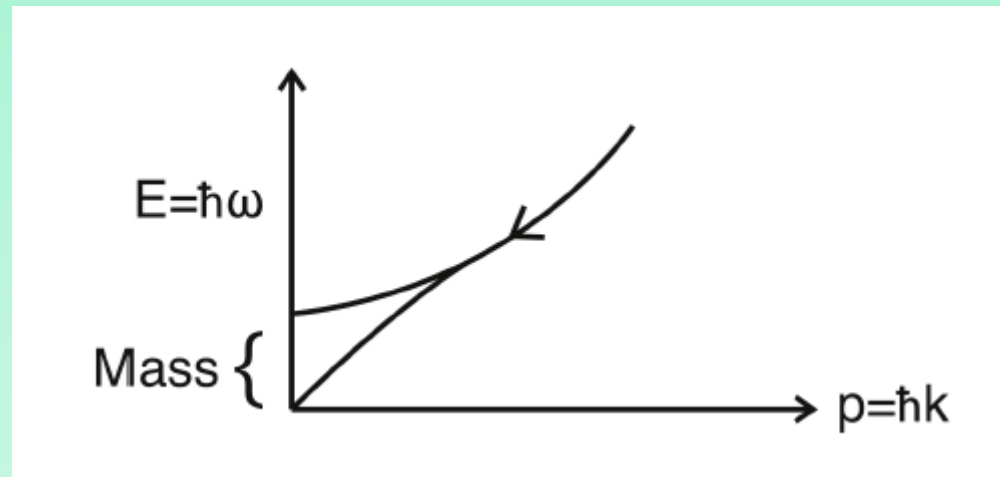
Use the ATLAS detector the find the particle



# QM: what is mass?

$$E^2 = p^2 + m^2$$

$$(\hbar \omega)^2 = (\hbar k)^2 + m^2$$



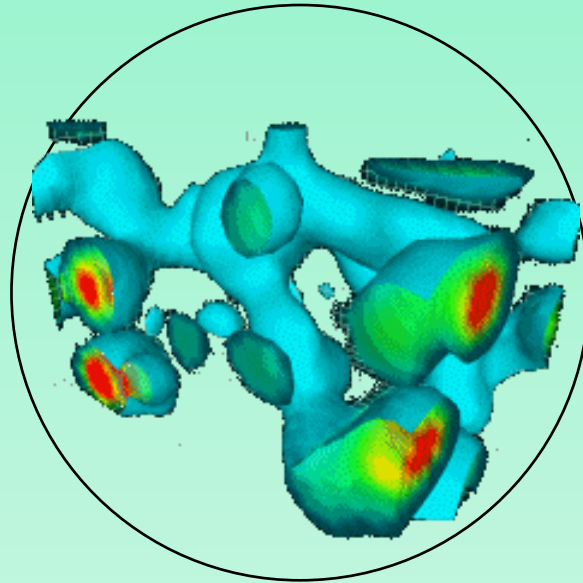
Dispersion Relation

Mass is the energy stored in the field at the limit of zero wavenumber.

Mass is the energy required to shift the field everywhere in space at the same time.  
I.e. there is a restoring force (or an elastic medium) requiring energy for a shift of the field

$$L \sim m^2 \phi^2(x)$$

# QM: the origin of the proton mass



Composite particles (protons) have most of their mass coming from interaction and not from their constituents bare mass (mass without mass, Nobel Prize 2004, QCD).

In a world without Higgs, the QCD transition would break Eweak theory.  
Proton would be heavier than neutron  $\rightarrow$  no Hydrogen atom...

# Elementary Particles carry labels

$$\Psi \quad E, p, L, spin, Q, chirality, \dots$$

Labels characterize the particle (electron at an energy level, with spin  $\frac{1}{2}$ ,  $Q=-1$ , ...)

But where do these labels come from?

# Symmetries in QM: the basis of our theories

Symmetry:

When our physical system is changed: the equations that describe the system are not changing.

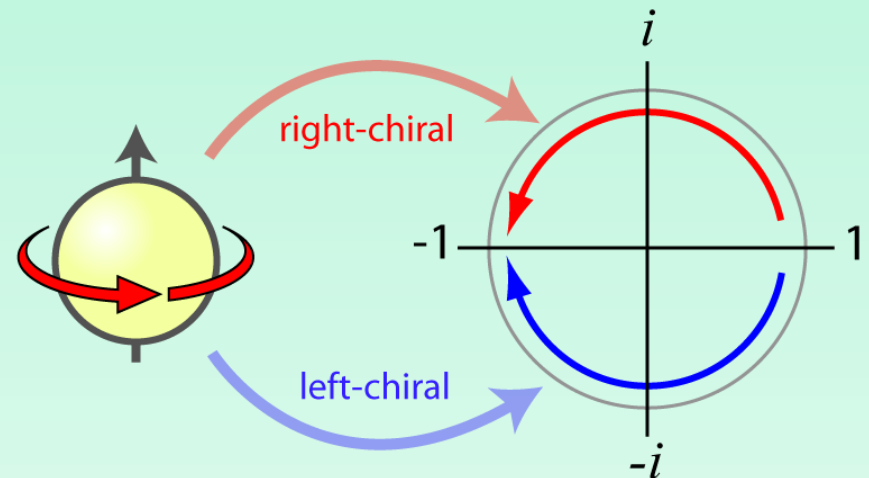
Symmetries lead to conservation laws (Noether's theorem): Energy, momentum, L, ...

In quantum mechanics the symmetry principle becomes central.

Fermions have (conserved) **spin** 1/2: invariance after  $4\pi$  rotations in internal 2D space which has a twist.



Fermions have (conserved?) **chirality** left right: the way you rotate in the internal space. Clockwise or anti-Clockwise.

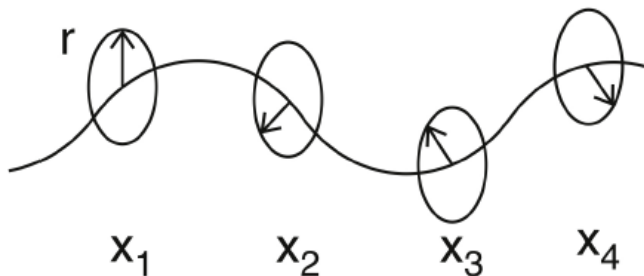


# Symmetries in QM: towards the EM interaction

Particles like the electron are complex fields: phase rotations are unobservable:

$$\phi^2 = \phi(x)\phi^*(x) = e^{i\theta}\phi(x)e^{-i\theta}\phi^*(x) = \phi^2$$

phase invariance  $\rightarrow$  Charge conservation

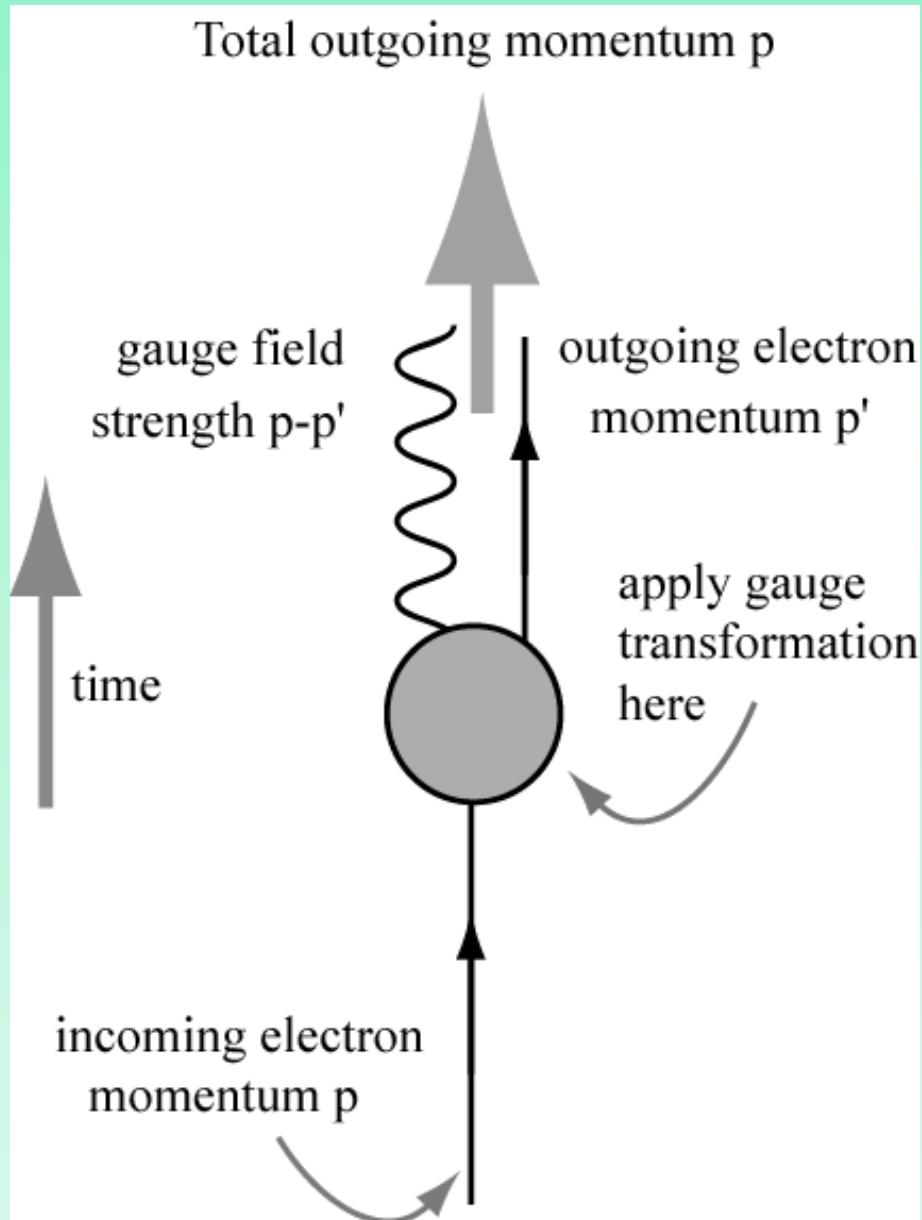


Can we change the phases arbitrarily at every point in space?

No, it costs energy.

However, we can “communicate” the phase difference from point to point (change it appropriately) so that the symmetry holds  $\rightarrow$  energy is conserved and charge is conserved!

# Interactions: due to phase rotation freedom



## U(1) rotations

Observers cannot tell the difference between a (bare) electron and an electron together with a cloud of collinear massless vector fields.

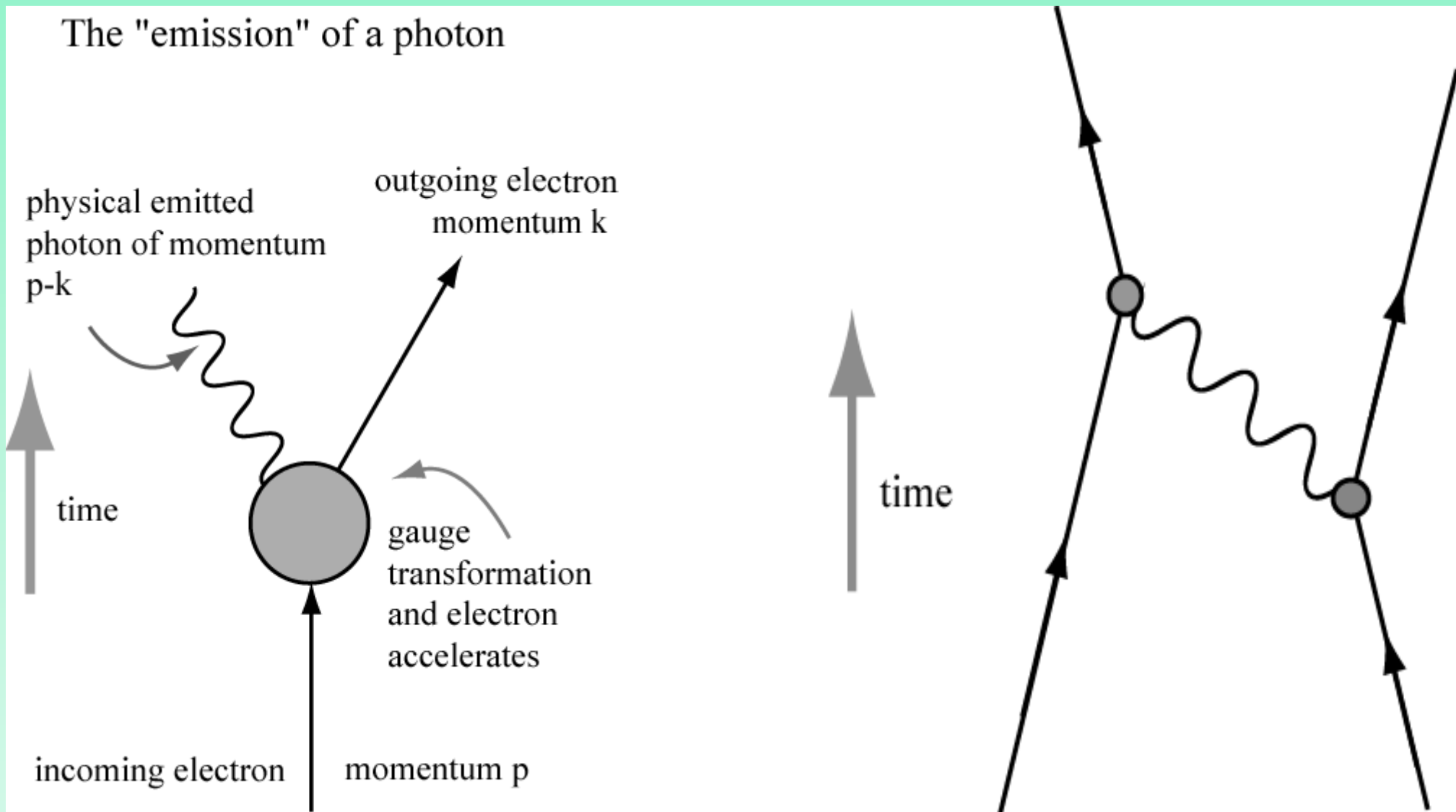
These vector fields are identified as the photons.

They “couple” to the electrons.  
The strength of this coupling is the e-charge.

This works **ONLY for massless vector fields.**

“U(1) Gauge Symmetry”

# EM Interactions: due to phase rotation freedom



# More gauge symmetries → More interactions

But, we can have doublets, or triplets, etc, of fields in space. Is there more freedom?

$$\phi \rightarrow \begin{pmatrix} e \\ \nu \end{pmatrix}$$

$$e^{-i\mathcal{G}(x)} \phi \rightarrow e^{-i\vec{\tau}\hat{n}\mathcal{G}(x)} \begin{pmatrix} e \\ \nu \end{pmatrix}$$

This is exactly like our familiar spin space (SU(2) rotations). Similar to the proton neutron isospin.

Rotations in this 2D complex space that leave our system invariant are possible if we introduce 3 massless “photons”: two electrically charged and one neutral.

Like the EM charge there is a **weak charge**.

Note: they can mix “e” with “ν”

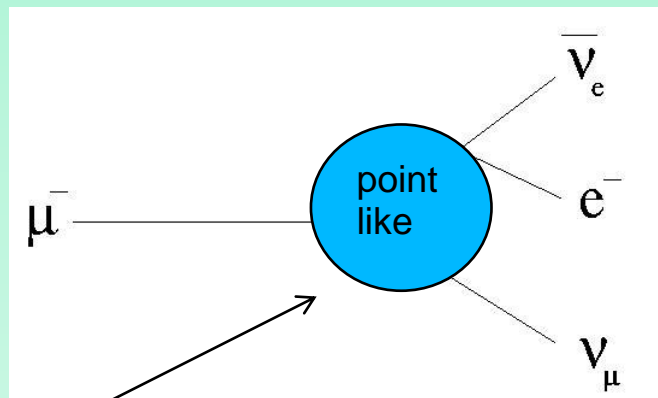
In fact one can combine these single phase (U(1)) and spin space rotations, SU(2) to one interaction, with 4 types of photons.

$$SU(2)_L \times U(1) \quad (\text{why only Left?})$$

# But ... we observed the muon decay (1936)

- Fermi Theory:

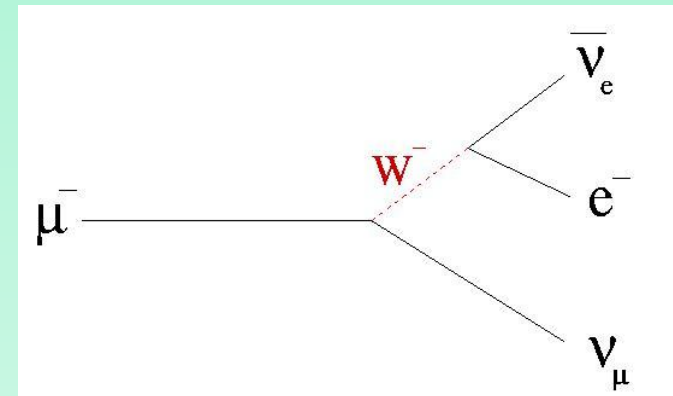
$$-i2\sqrt{2}G_F g_{\mu\nu} \bar{u}_\mu \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) u_{\nu_\mu} \bar{u}_{\nu_e} \gamma^\nu \left(\frac{1-\gamma_5}{2}\right) u_e$$



$$G_F = 1.16637 \times 10^{-5} \text{ GeV}^{-2}$$

- EWeak Theory:

$$\frac{ig^2}{2} \frac{1}{k^2 - M_W^2} g_{\mu\nu} \bar{u}_\mu \gamma^\mu \left(\frac{1-\gamma_5}{2}\right) u_{\nu_\mu} \bar{u}_{\nu_e} \gamma^\nu \left(\frac{1-\gamma_5}{2}\right) u_e$$



$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$$

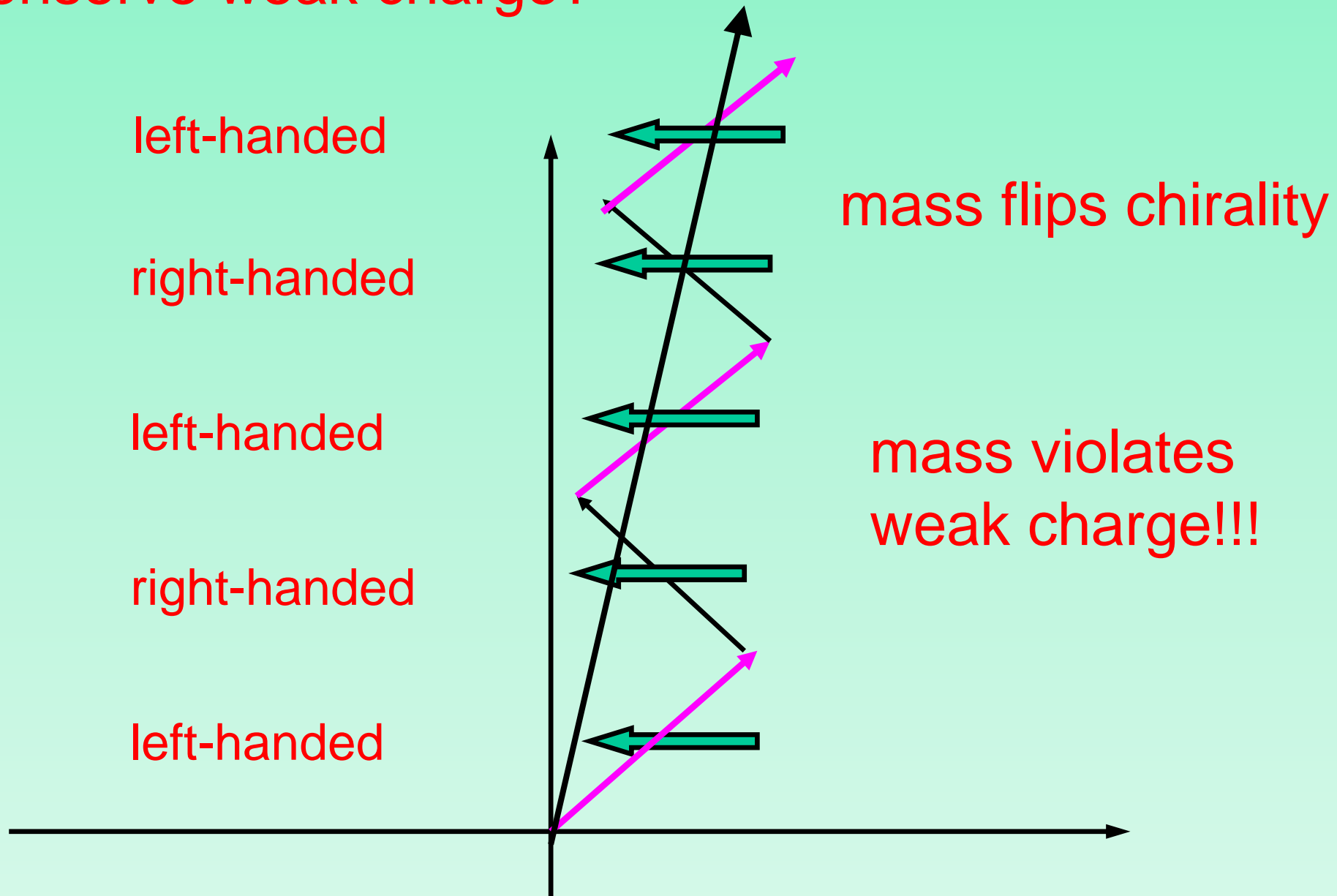
↑ weak charge

# Puzzle

How can we give mass to  $W/Z$  (and also to electrons and fermions) without breaking the weak interaction gauge invariance ?

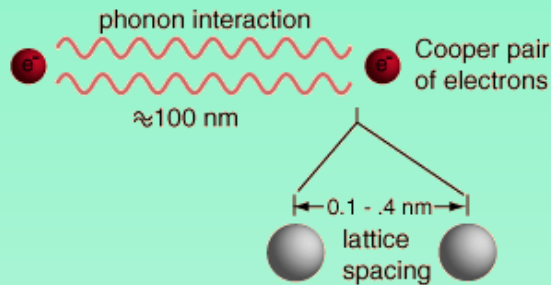
→ Preserving the conservation of the weak (isospin) charge ?

# Puzzle2: how do we make a massive fermion but conserve weak charge?

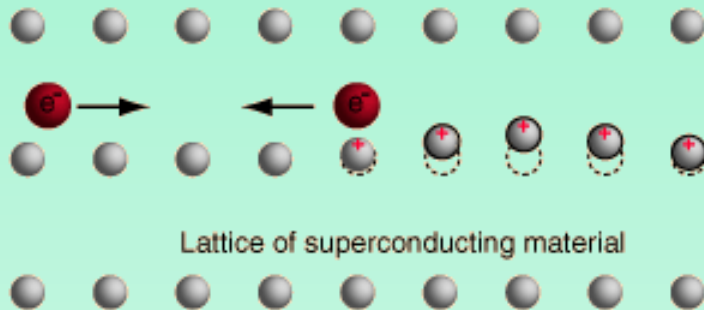


**Mass Violates Electroweak Gauge Symmetry!!!**

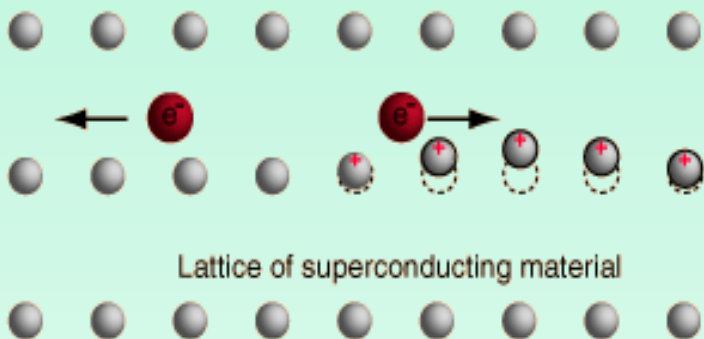
# BCS Superconductivity



Electron pairs couple over a range of 100 nm which is three orders larger in magnitude than the lattice spacing



A passing electron attracts the lattice, causing a slight ripple toward its path.



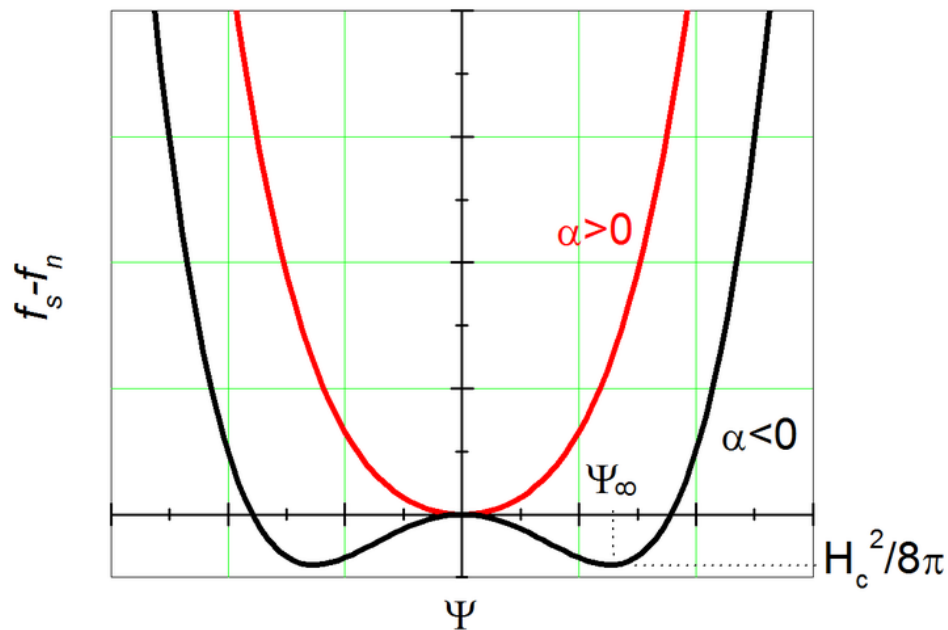
Another electron passing in the opposite direction is attracted to that displacement.

This leads to the effective attractive interaction between two electrons mediated via lattice vibration or phonons which binds them as **cooper pairs**. These Cooper pairs condense below a critical temperature  $T_C$  to give superconducting state.

# BCS Superconductivity

A new field now fills the vacuum: non-zero condensate of cooper pairs.  
Vacuum is now “charged” due to the Cooper pairs have charge -2.

The magnetic field is zero in the superconductor → photons “appear massive”  
meaning they are now short ranged since they cannot penetrate the SC!



Landau-Ginzburg effective theory

$$f_s - f_n = \alpha |\Psi|^2 + \frac{\beta}{2} |\Psi|^4$$

$$|\Psi|_{\min}^2 = -\frac{\alpha}{\beta}$$

# Eweak: introduce the Higgs boson field

This must be a weak doublet.

Fills the vacuum (“hidden in the vacuum”):

It is a condensate, ie it has a non-zero density.

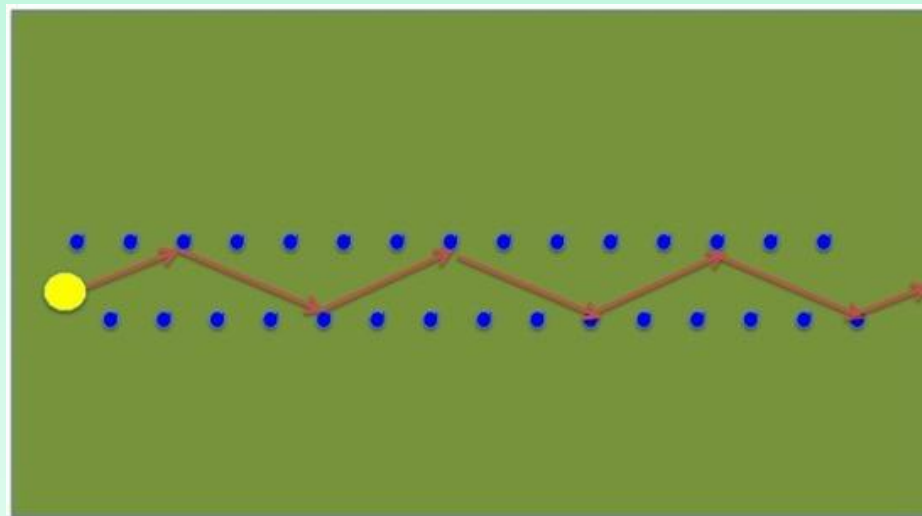
It has weak charge (but not electric charge).

It gives non-zero energy density to the vacuum (i.e. cosmological constant)

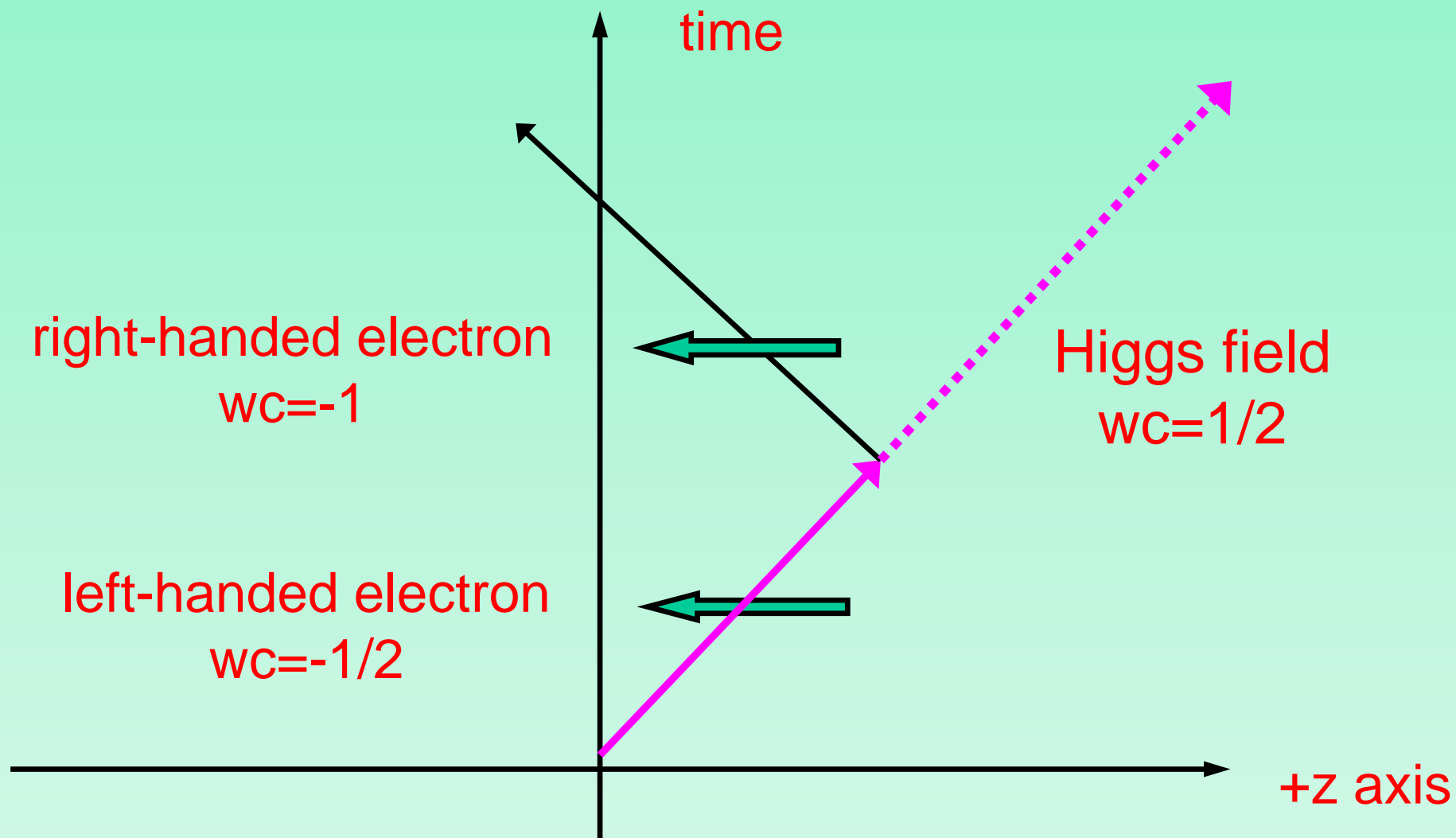
Gauge bosons (W/Z) having weak charge acquire mass through interaction with the charged vacuum. → idea taken from Superconductivity BCS theory, and Landau-Ginzburg phenom.



Englert, Brout, Higgs (1964).  
(Guralnik, Hagen, Kibble)

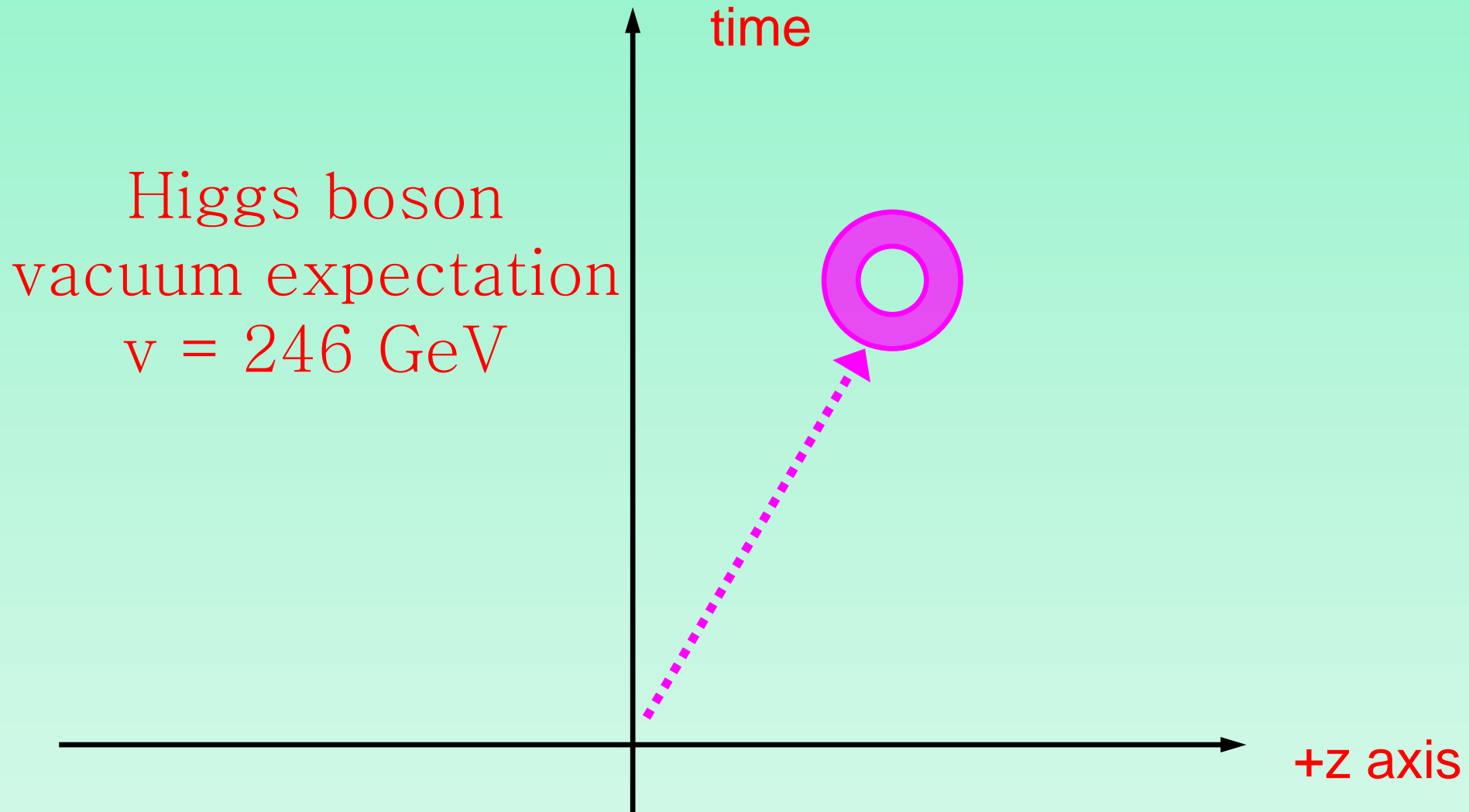


# Couple to the Higgs



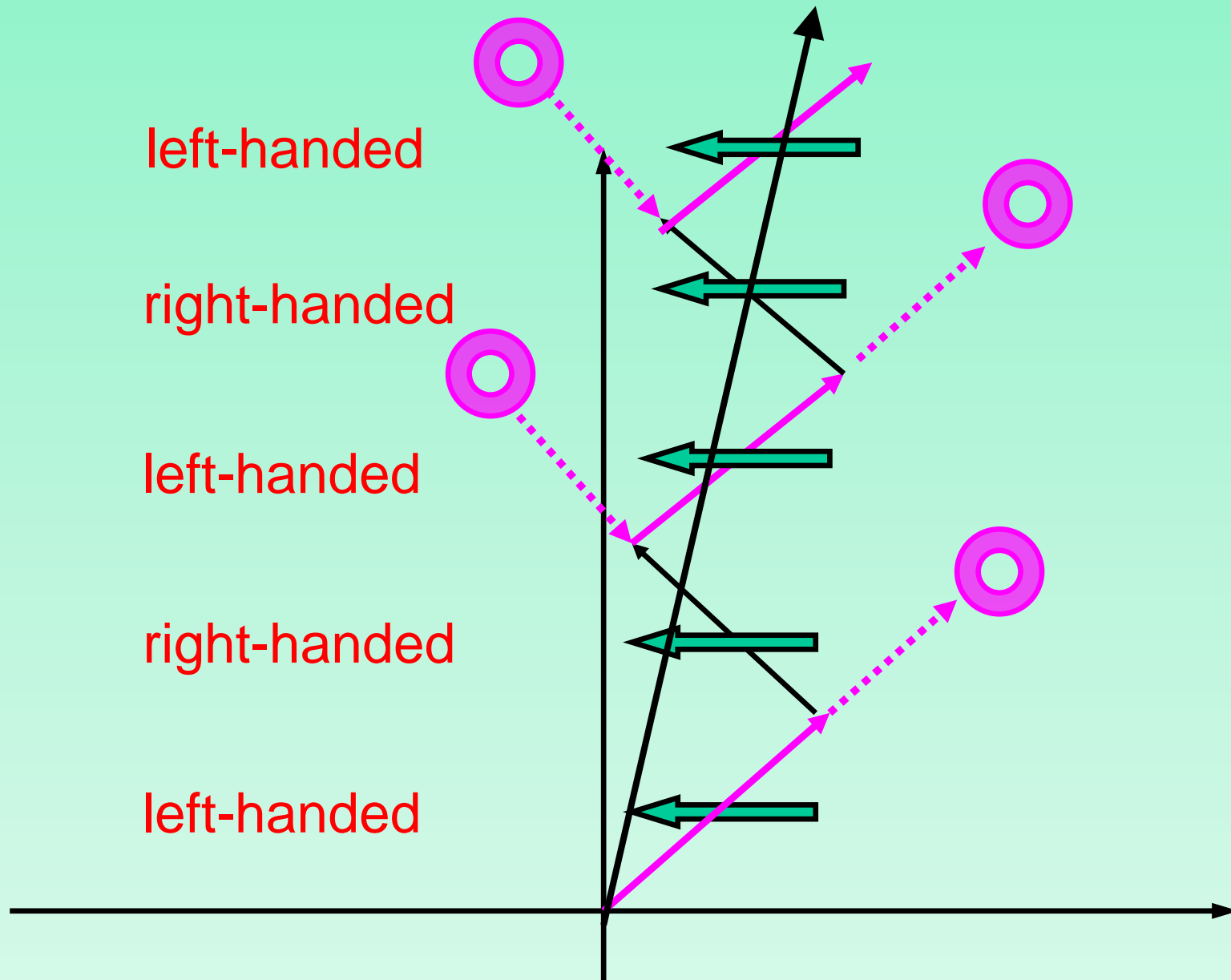
**Weak charge is conserved !**

# Higgs Boson Condenses in vacuum



**Weak charge is hidden in vacuum !!**

# Fermion Masses in Electroweak Theory



Fermion Mass requires Higgs to maintain  
Electroweak Gauge Symmetry!!!

# Higgs in SM: a single c weak doublet

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

With  $SU(2) \times U(1)$  invariant scalar potential

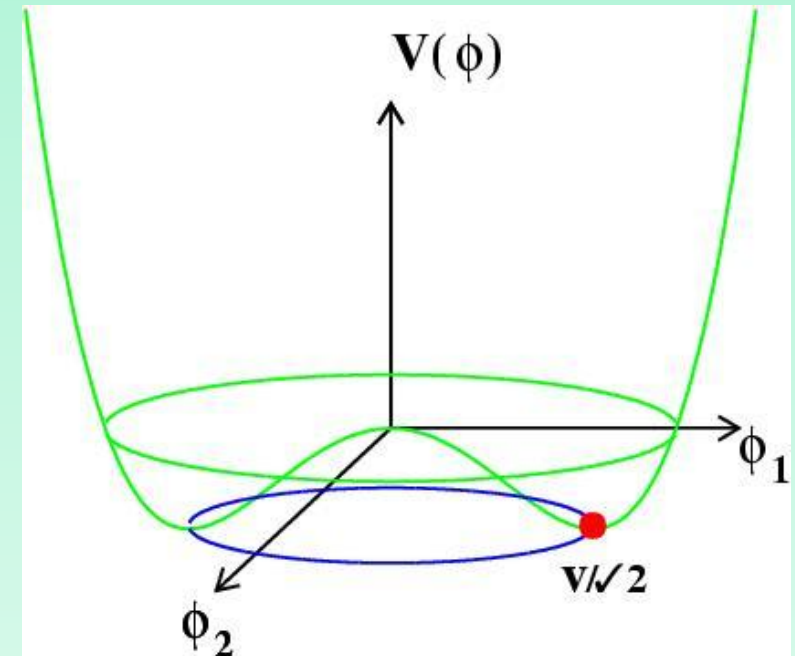
$$V = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

for  $\mu < 0$  the minimum is at

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

With a single real excitation particle  $H$  surviving:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$



# Higgs Parameters

- $G_F$  measured precisely

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{1}{2v^2}$$

$$v^2 = (\sqrt{2}G_F)^{-1} = (246 \text{ GeV})^2$$

- Higgs potential has 2 free parameters,  $\mu^2$ ,  $\lambda$

$$V = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

- Trade  $\mu^2$ ,  $\lambda$  for  $v^2$ ,  $M_H^2$

$$V = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

$$v^2 = -\frac{\mu^2}{2\lambda}$$
$$M_H^2 = 2v^2\lambda$$

- Need to measure the  $H^3$  and  $H^4$  coefficients.
- A priori, Higgs mass can be anything

# Recap: Higgs Field vs Higgs Boson

Field

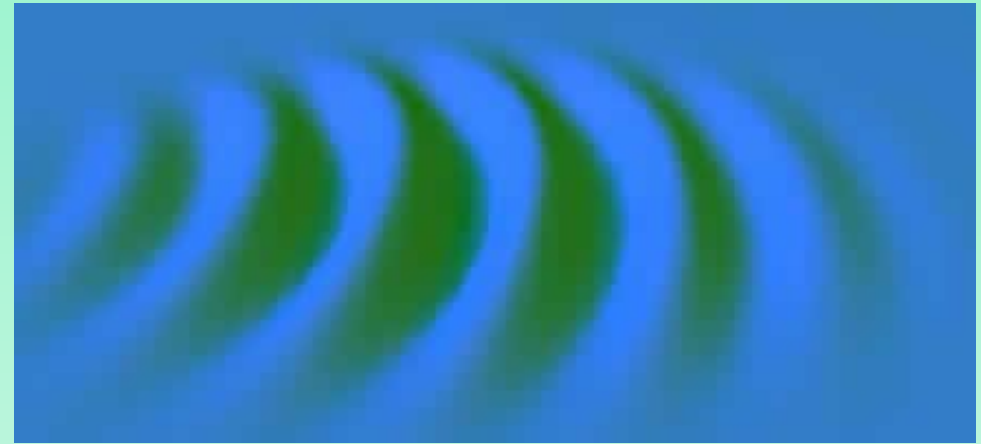


Manifestation of Higgs field:

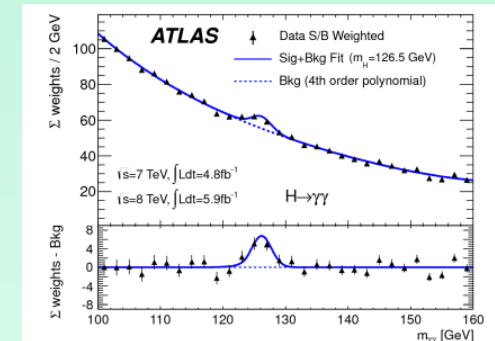
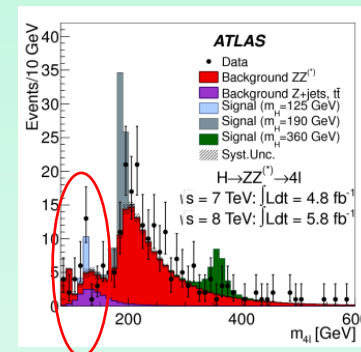
Interaction carriers acquire mass:

W/Z bosons  $\sim 100$  x the proton mass

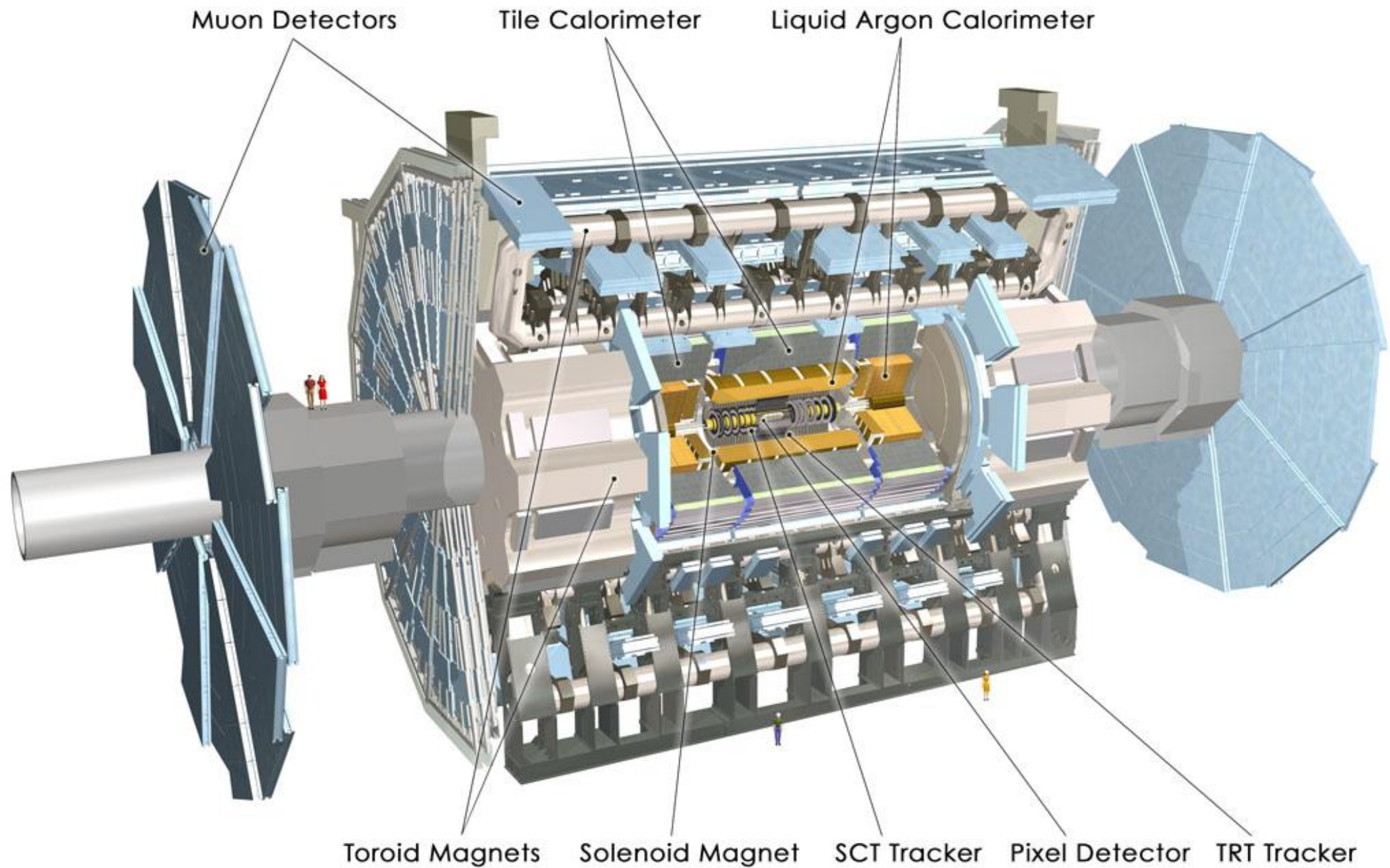
Particle



Use the ATLAS detector to find the particle



# The ATLAS Detector



# muons travelling through ATLAS

Muons are reconstructed using the tracker and the muon chambers.

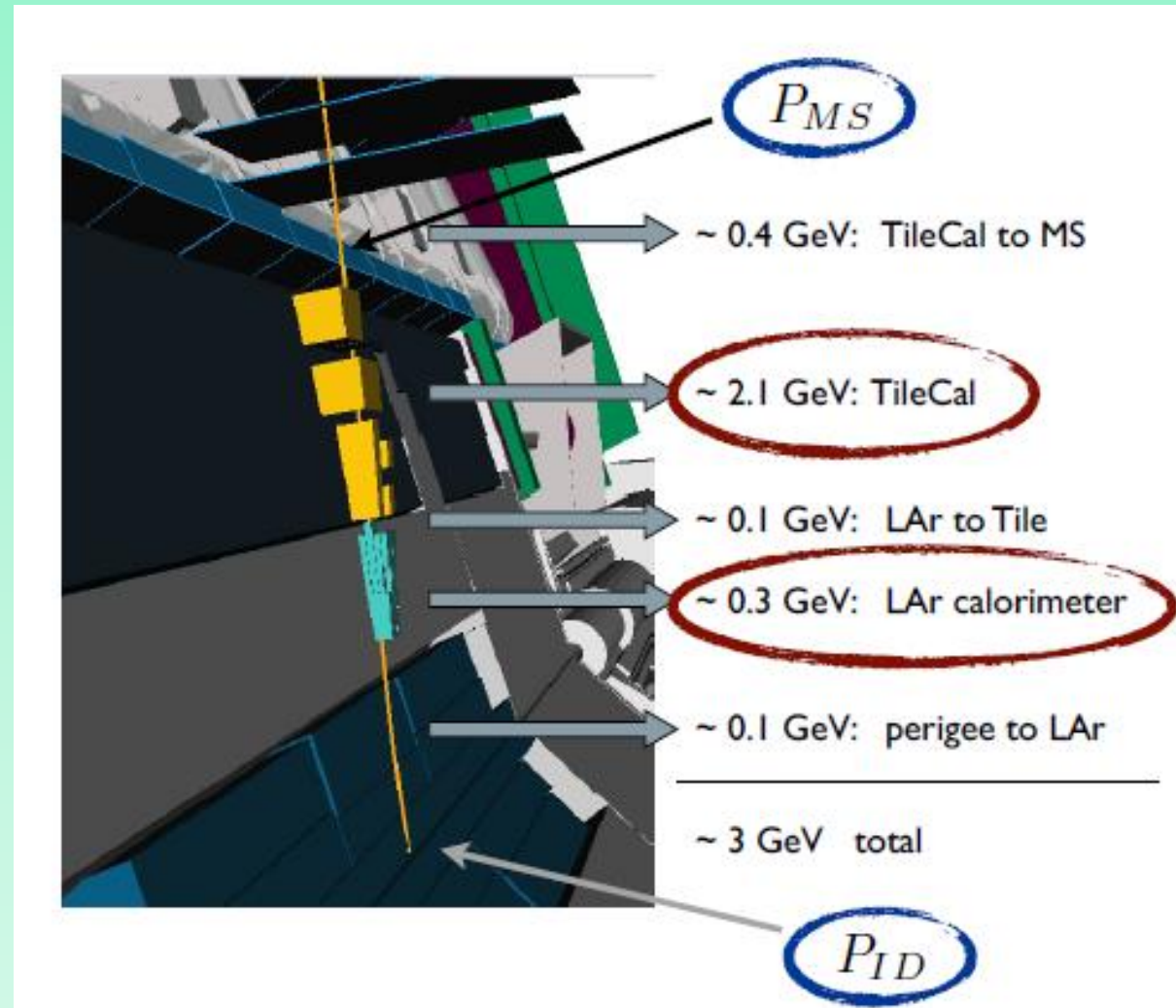
Here we are interested in  $Z \rightarrow \mu\mu$

These are “isolated” without much hadronic debris.

Background (from top and b decays) is removed by using isolation cuts.

But we also have FSR (photon lost?):

$$Z \rightarrow \mu\mu\gamma$$



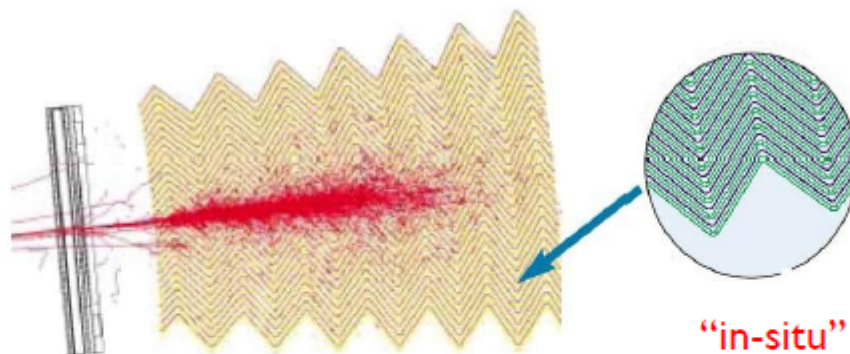
# Electrons and photons reco-ed in LAr calo

A photon showers in the EMC. Most of its energy is lost in Pb

Electrons in EM shower ionize LAr

Ionization electrons produce current

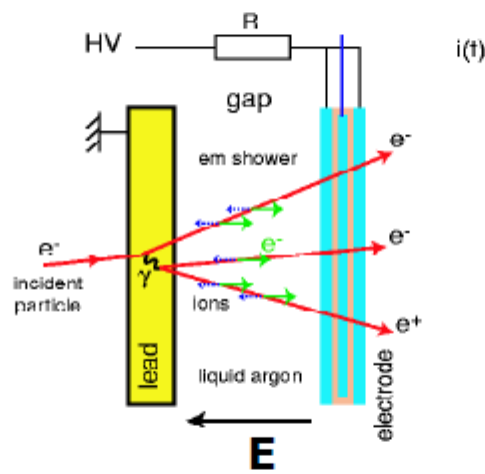
Current is collected, amplified, shaped, sampled and digitized for each EMC cell



“in-situ”  
intercalibration



Photon energy scale is adjusted to EM scale from  $Z \rightarrow ee$  events

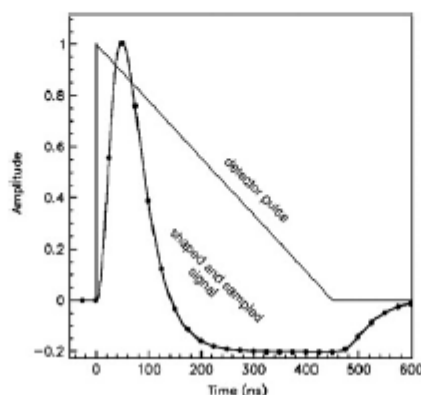


“calibration hit”  
calibration

Cluster energy is corrected for loss to get photon energy

cluster  
corrections

Cluster energies are corrected for detectors effects



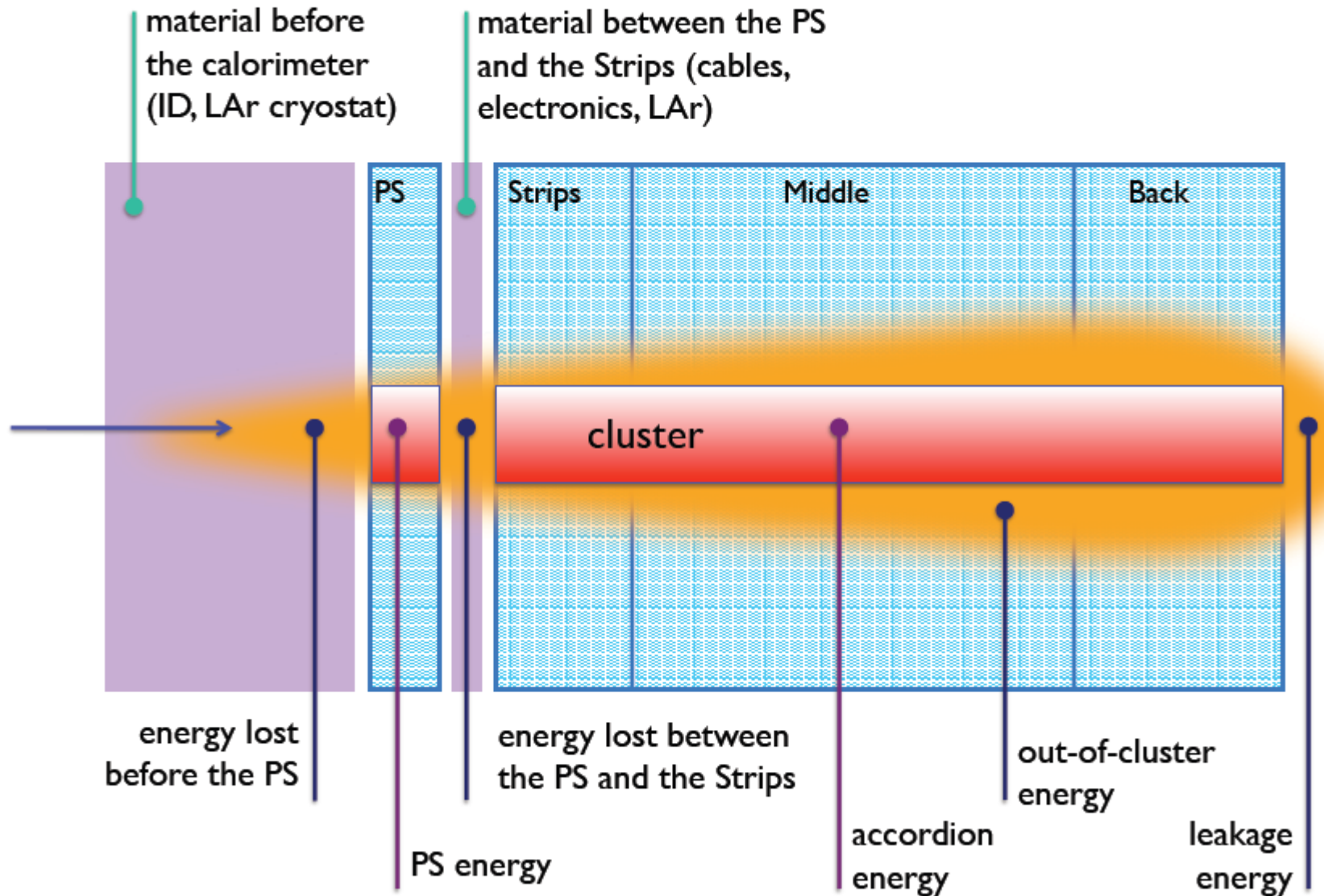
clustering

Cells are grouped in clusters

electronic  
calibration

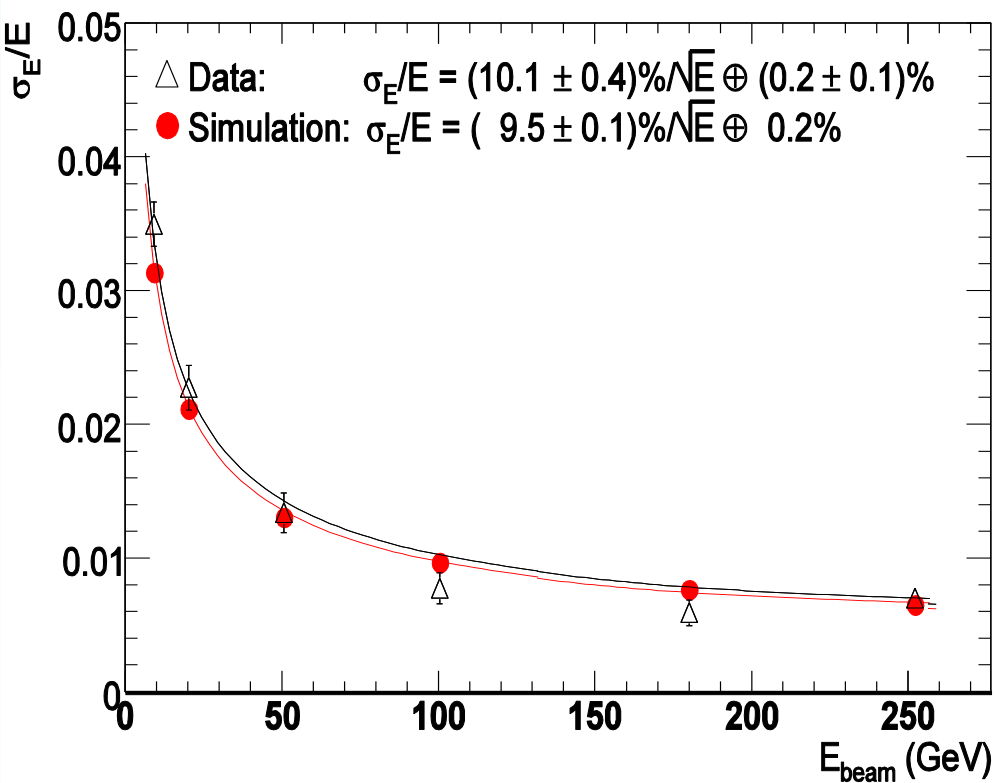
Energy in a cell is reconstructed from signal samples

# From cluster energy to photon energy

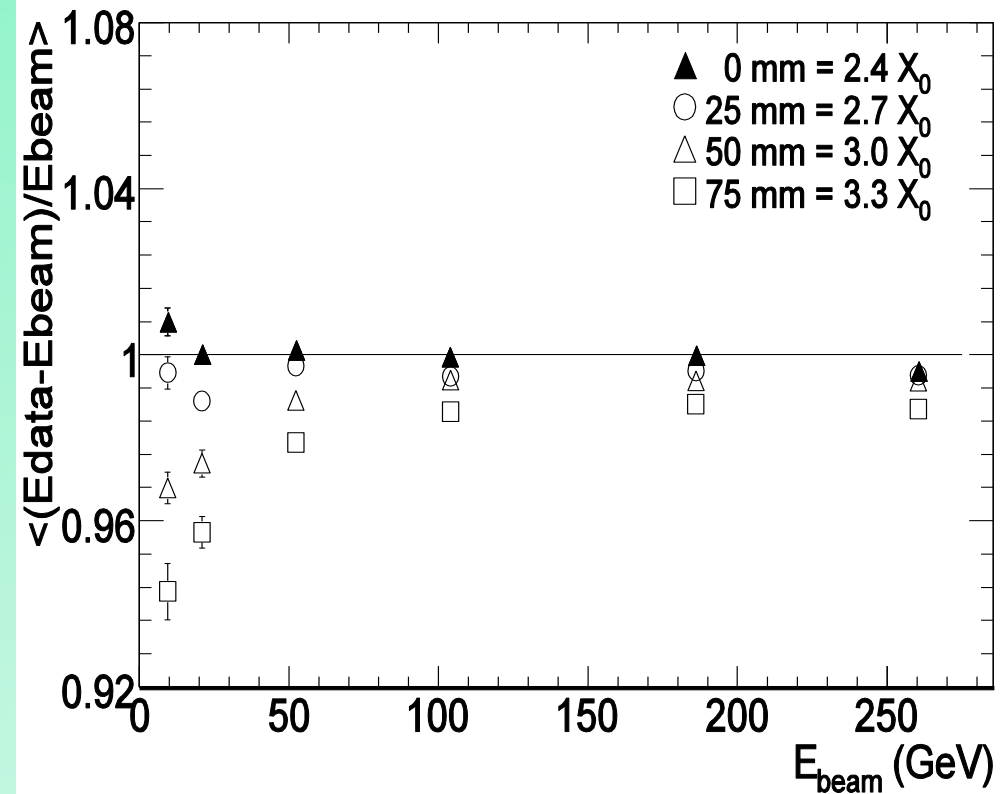


# Combined Test Beam 2004

NIMA 614, 400 (2010)



Electron resolution

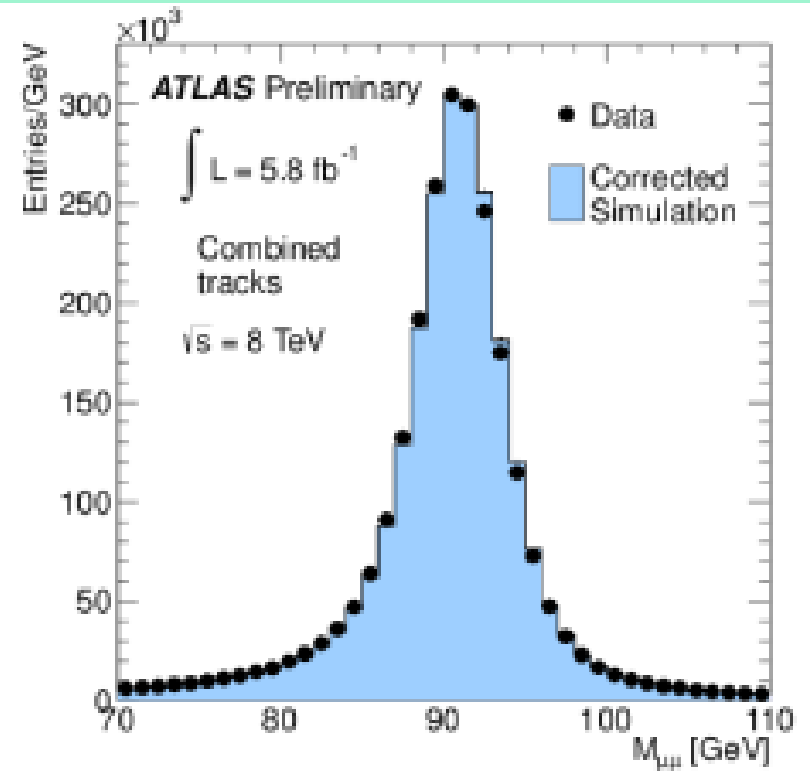
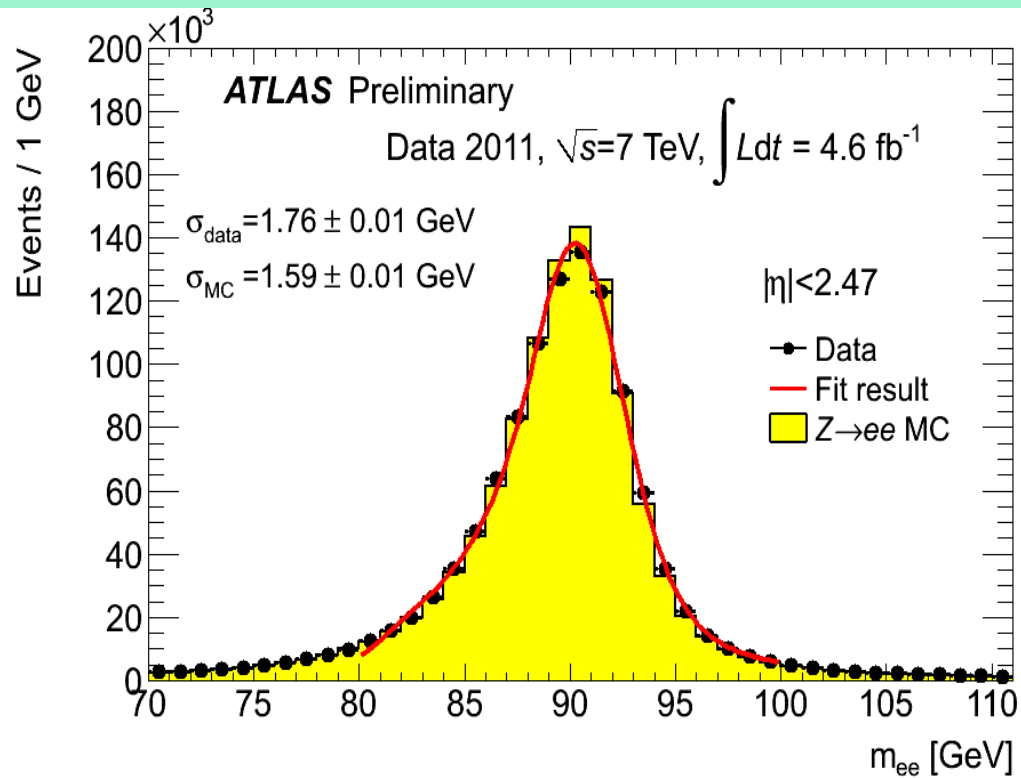


Electron Linearity for different amounts of material in front of the calorimeter

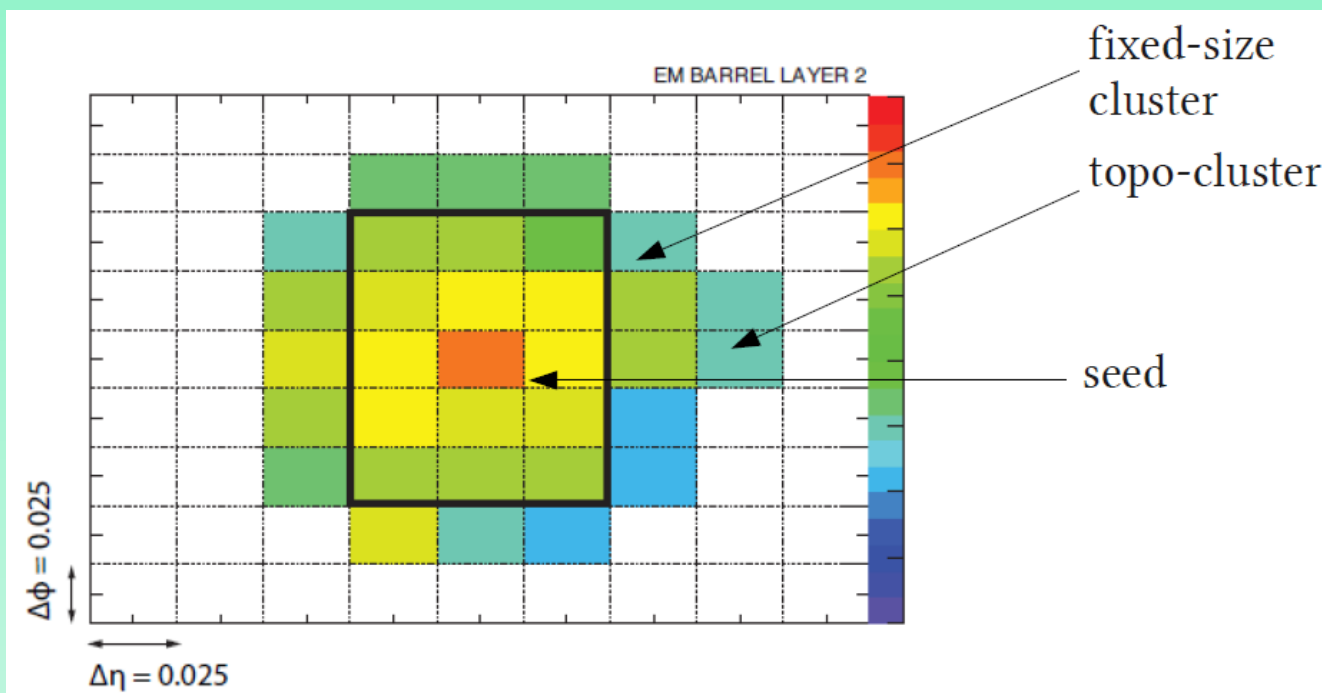
In CTB we also run a photon run: first check of converted vs non-converted calibration in ATLAS

JINST 6 (2011) P04001

# $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ reconstruction

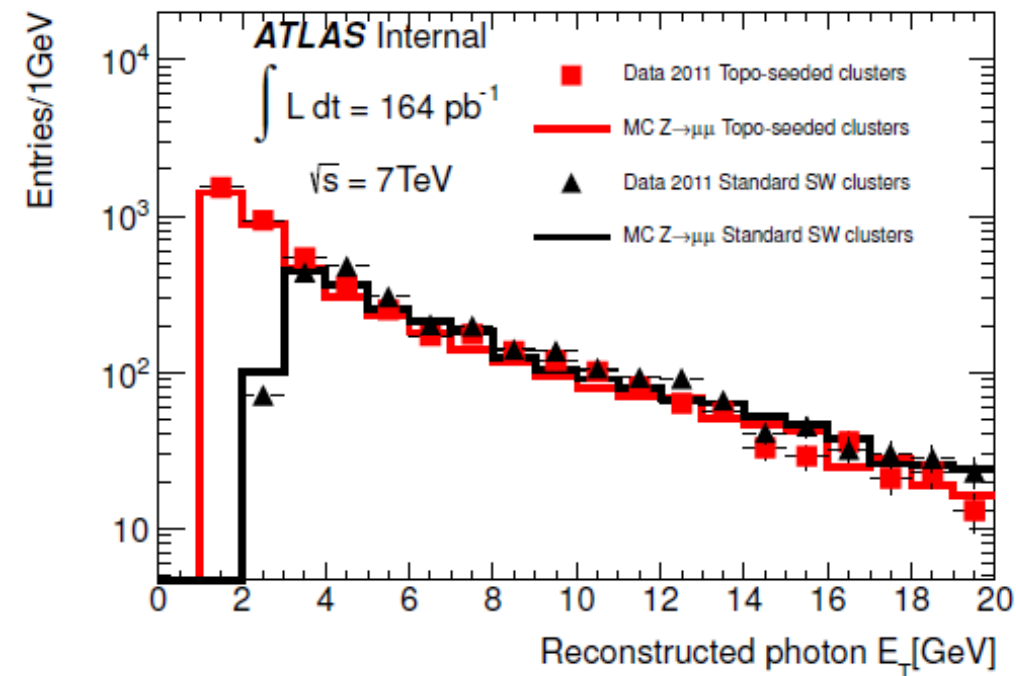


# Special photon clustering: EMTopo-seeded 3x5



Xu Da, PhD, Sheffield

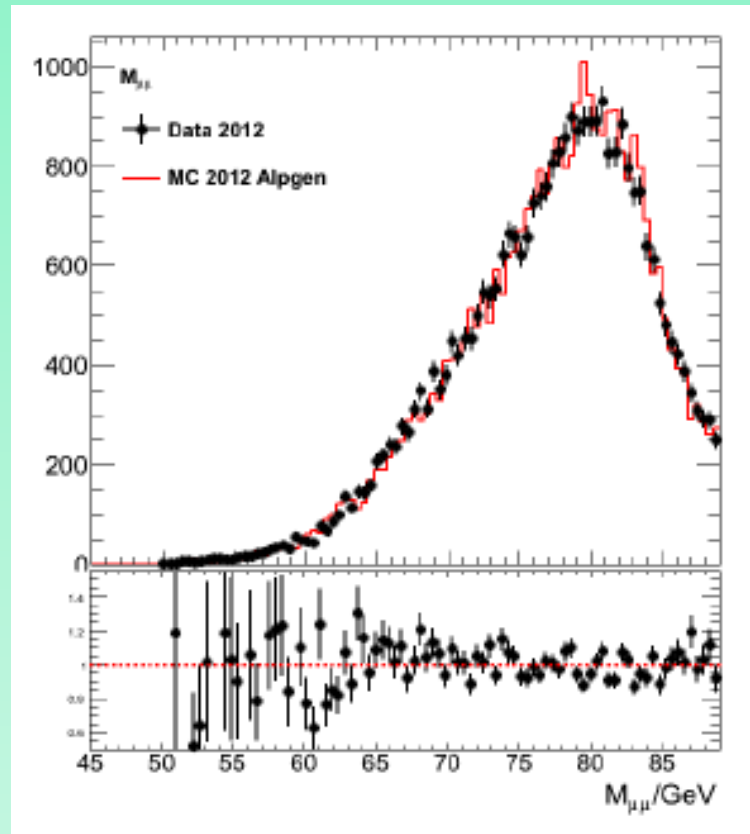
ATLAS-CONF-2012-143



These clusters allow us to go down to 1 GeV, where std egamma clustering is inefficient. These are calibrated and corrected for average muon energy deposition in the cluster.

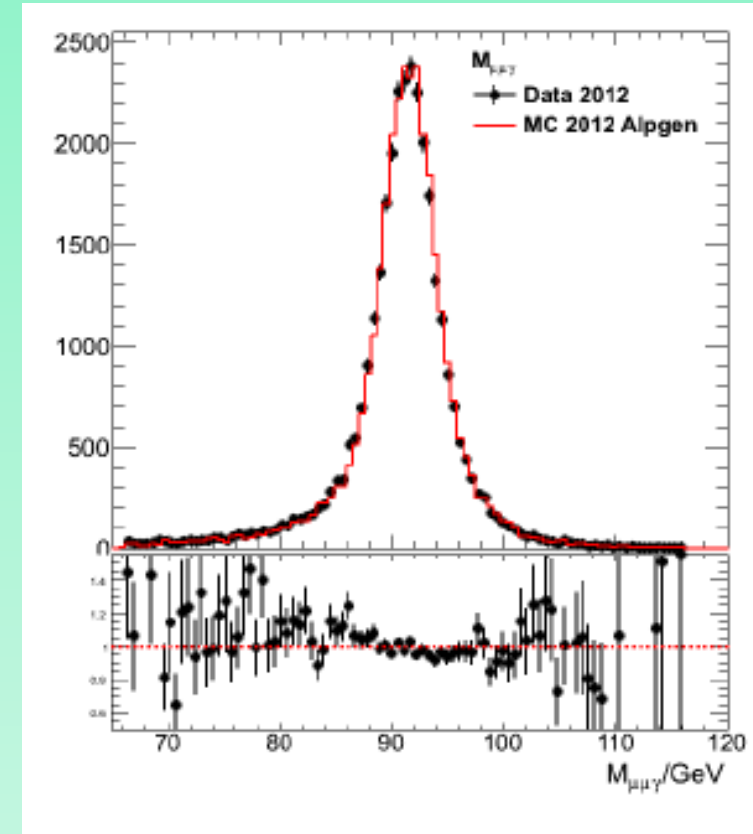
Note: std egamma clusters (photons or electrons) can be used above 3 GeV without problems.

# Effects of these photons on the Z mass



Brais Lopez  
(Sheffield)

→ Add collinear photon



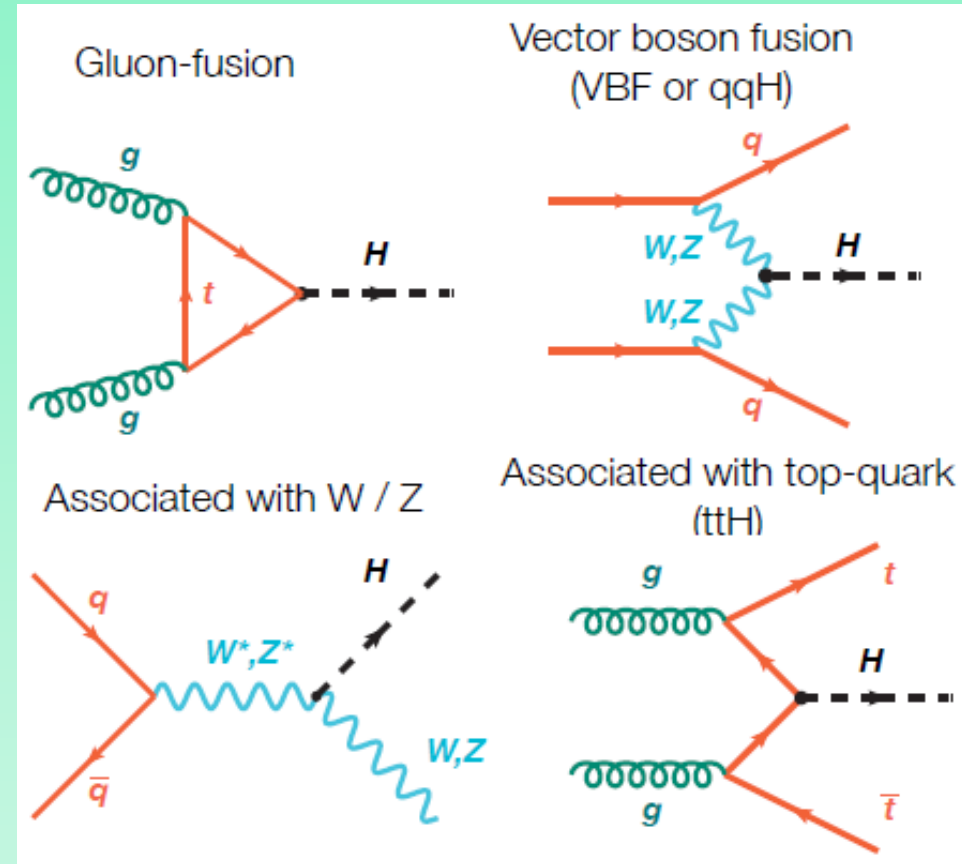
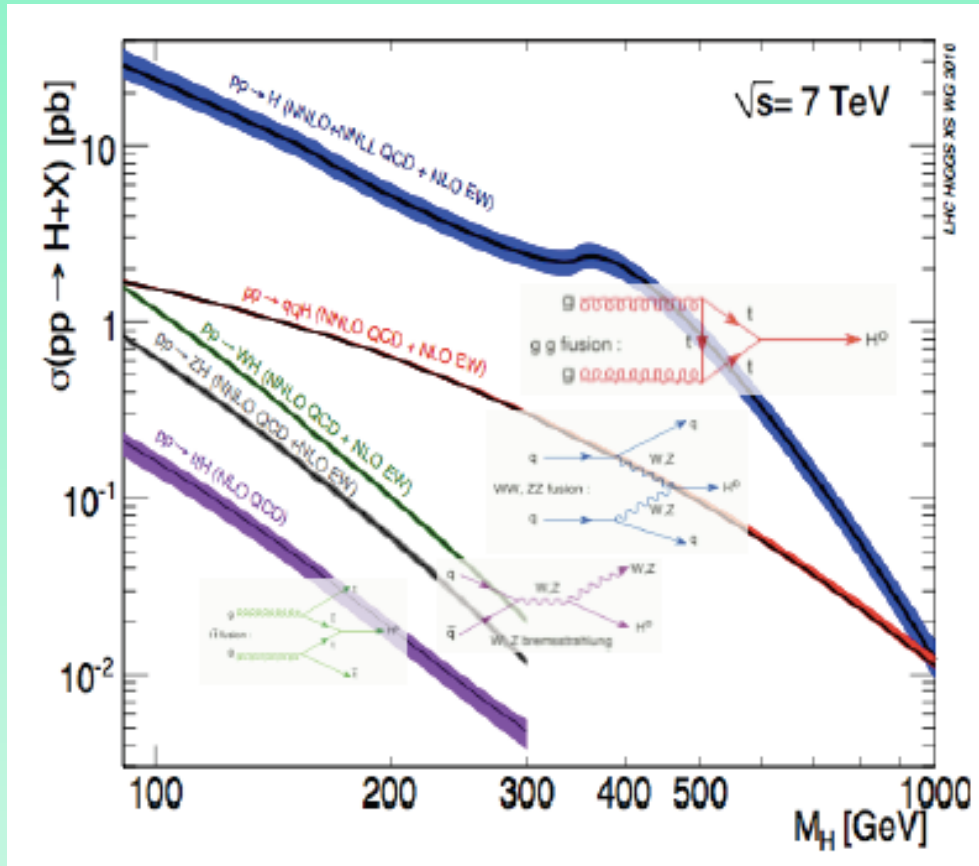
Background 0.3% (!)

These photons check the EM Calo energy scale to 0.3% !

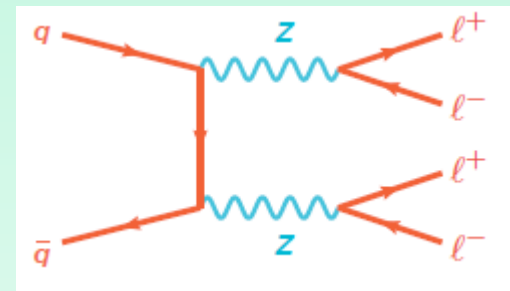
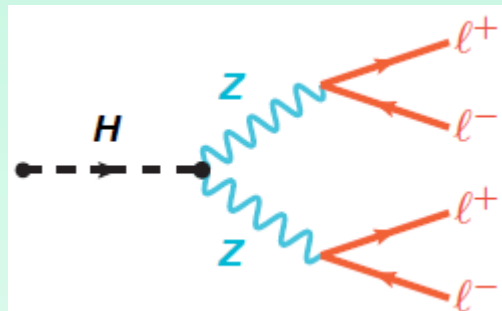
Electrons are checked down to 0.1% using the idea we introduced in 2004: E1/E2 vs PS.

NIM A614 (2010) 400-432

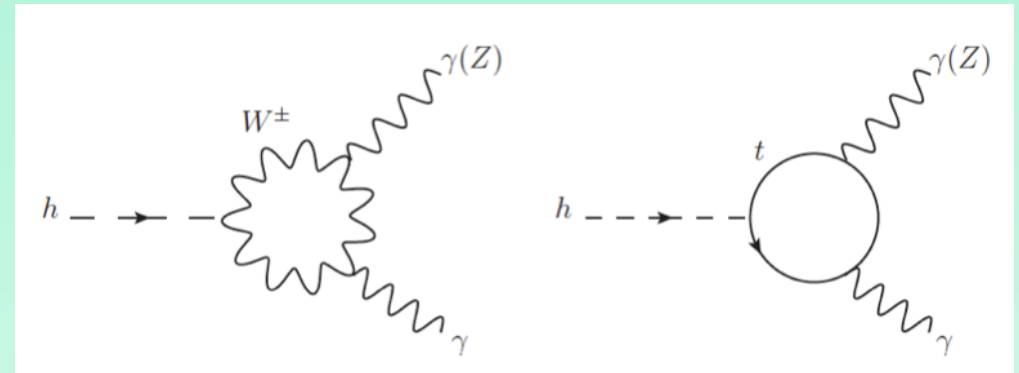
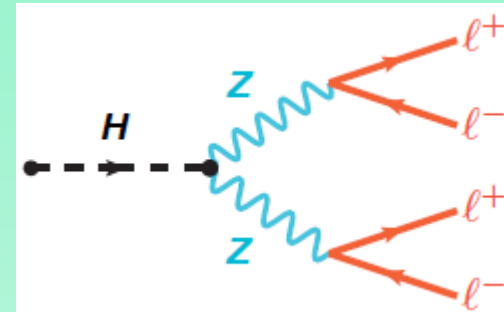
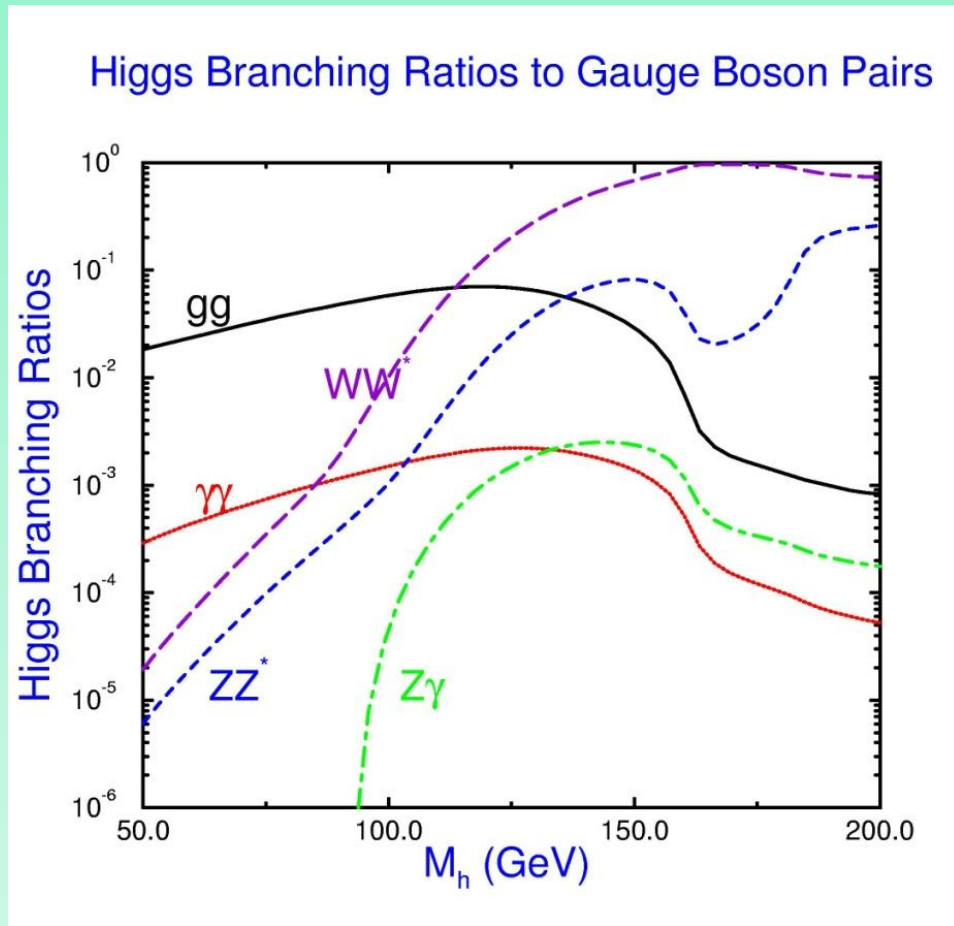
# Higgs production at the LHC



Golden channel: Higgs  $\rightarrow$  4 leptons



# Higgs decays to gauge bosons



WW, ZZ,  $\gamma\gamma$ , and  $Z\gamma$  all available at 125GeV !

WW has no peak,  $Z\gamma$  has huge backgrounds

Higgs couples directly to the ZZ

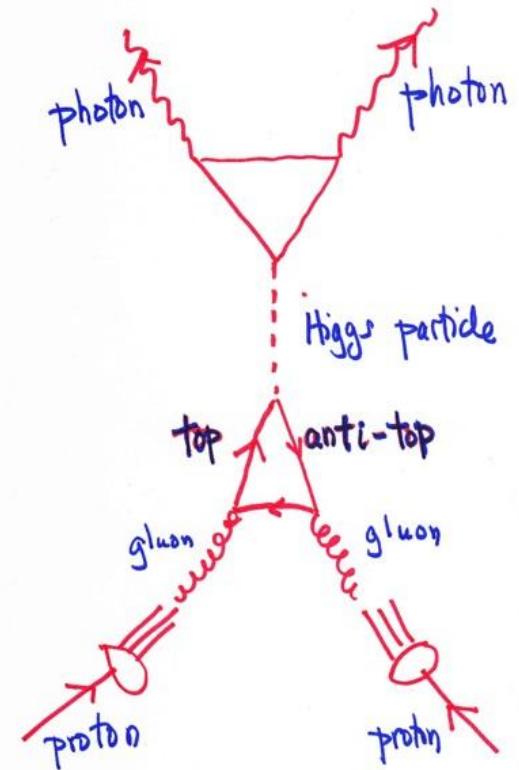
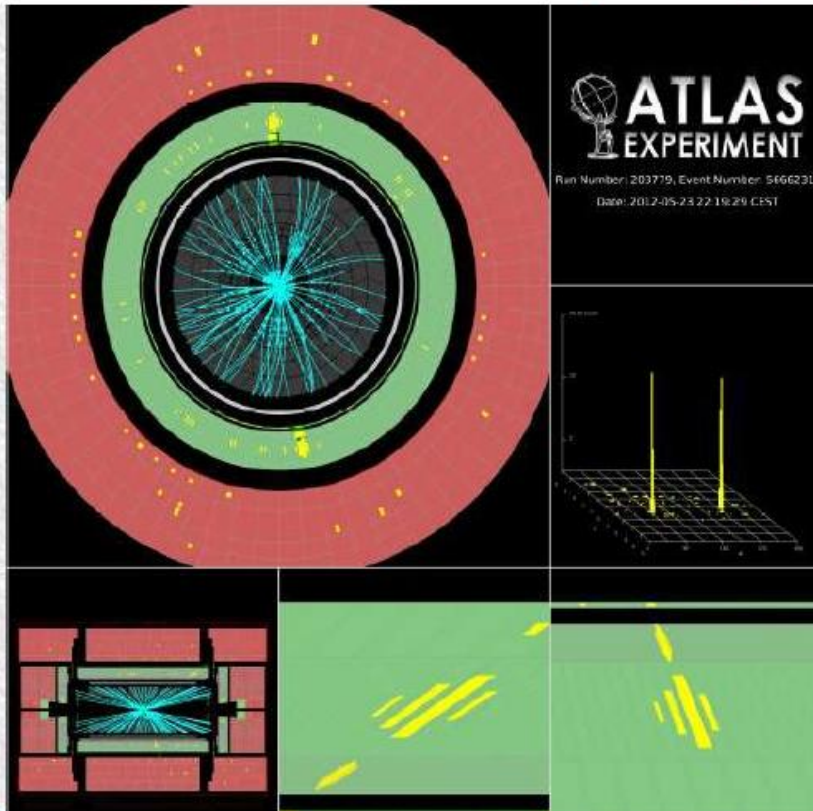
Higgs goes through a loop to  $\gamma\gamma$ ,  $Z\gamma$

# Higgs $\rightarrow \gamma\gamma$

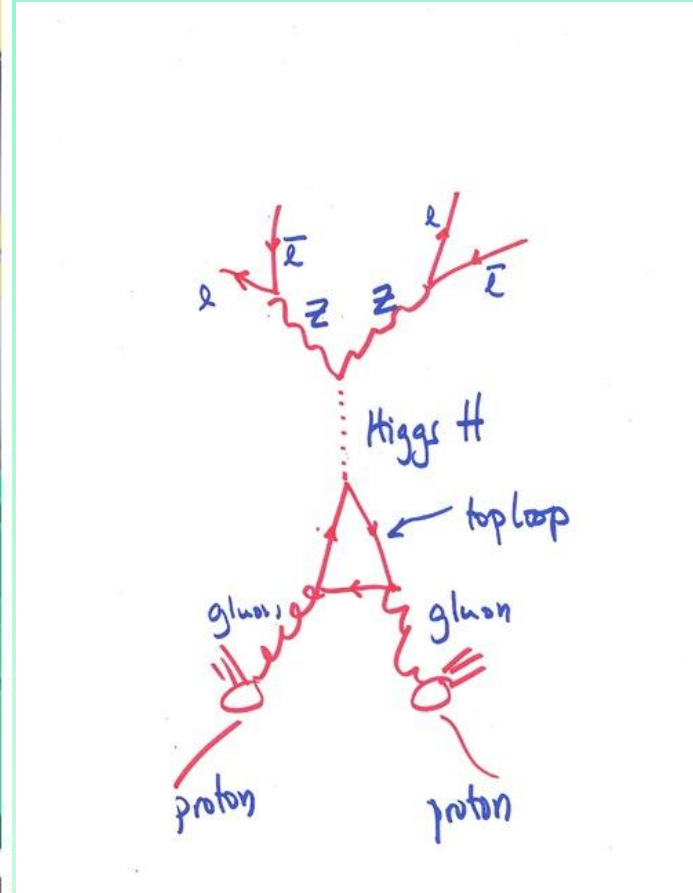
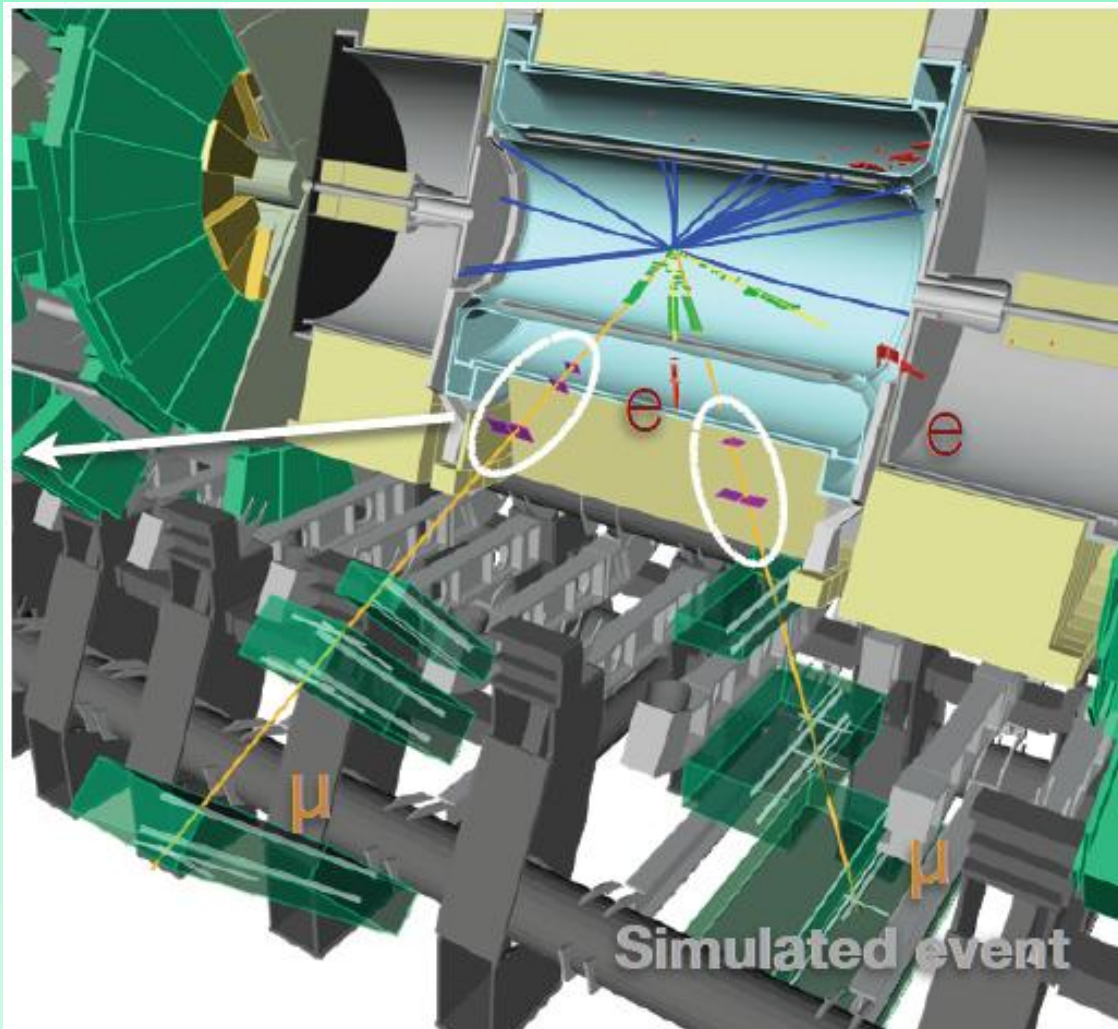
## The $\gamma\gamma$ channel in ATLAS

[B. Murray '12]

- Rare decay,
  - 2 per mille
  - $110 < m_H < 150$
- Drove ECAL design
  - Pointing geometry
- To measure mass need to know vertex position
  - Pileup hurts!
  - But pointing reduces impact
- Good jet rejection also essential



# Higgs $\rightarrow$ ZZ\* $\rightarrow$ 2 $\mu$ 2e



$$H \rightarrow \gamma\gamma$$

# $\gamma\gamma$ event selection summary

Uncertainty	Description
Fiducial cuts	$E_{T,\gamma 1} > 40$ GeV, $E_{T,\gamma 2} > 30$ GeV, $ \eta  < 2.37$ , excluding $1.37 <  \eta  < 1.52$
Photon ID	EM shower-shape based. NeuralNet-based for 2011
Photon Isolation	Summed $E_T$ in a calo cone $\Delta R < 0.4$ around photon excluding the photon cluster, not to exceed 4GeV.
Categories	10 categories based on photon $\eta$ , $P_{T,t}$ , converted, unconverted, dijet.

Photons: converted, unconverted.

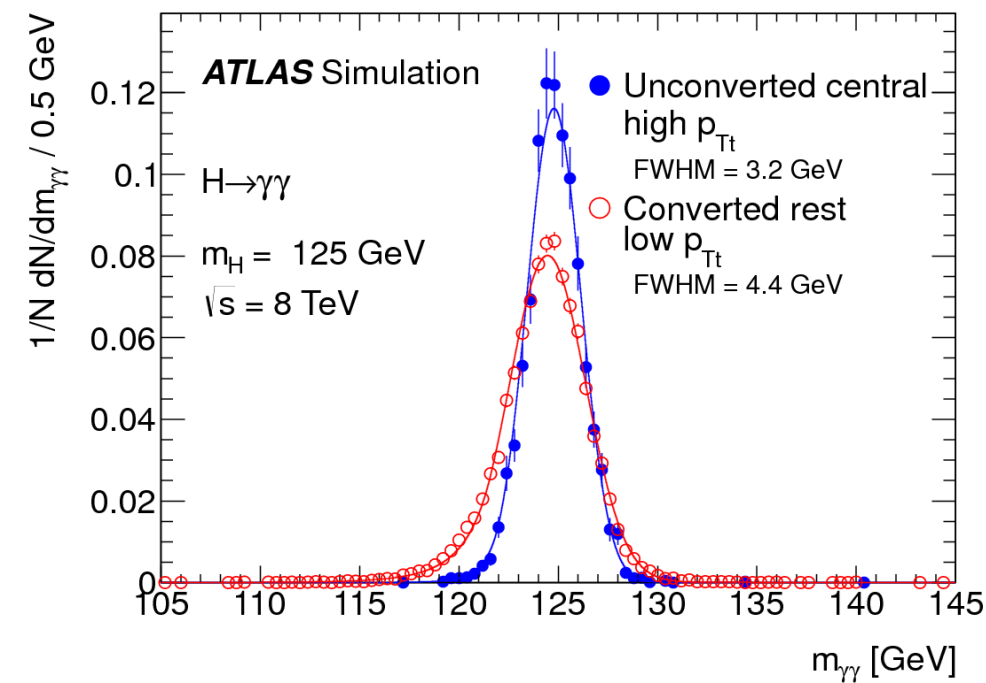
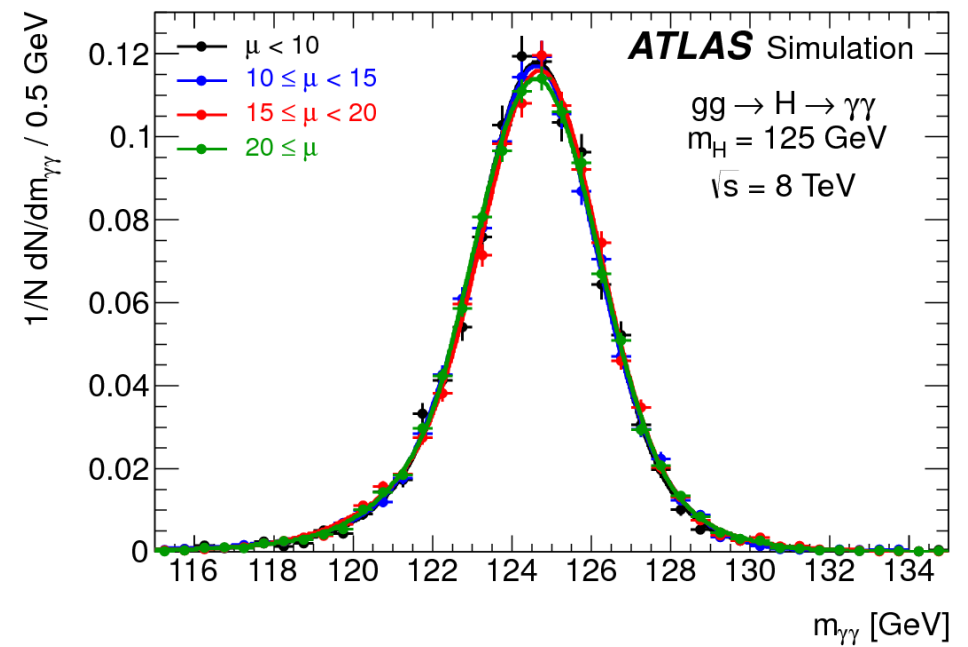
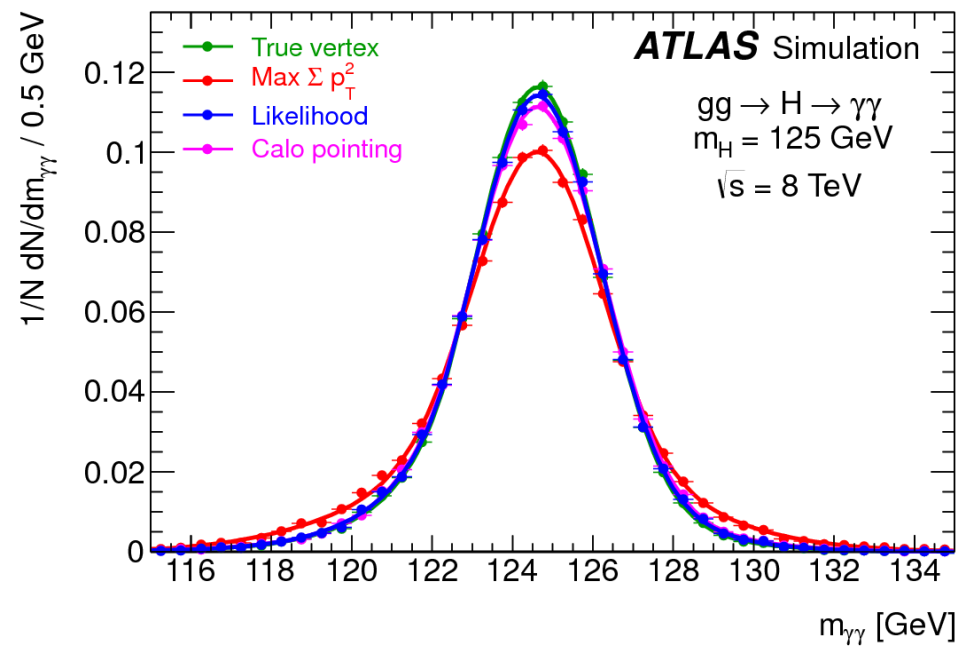
Photon energy: from LAr EM cluster energy

Photon position:  $\eta$  from calorimeter and the primary vertex,  $\phi$  from calorimeter

Dijet category improves sensitivity to VBF.

Search performed in the 110-150 GeV  $\gamma\gamma$  mass range.

# $\gamma\gamma$ signal mass resolution



## Higgs Mass Resolution:

for different methods of longitudinal vertex position reconstruction. Calorimetric pointing and likelihood lead to improved resolution.

Not affected by increased levels of pileup.

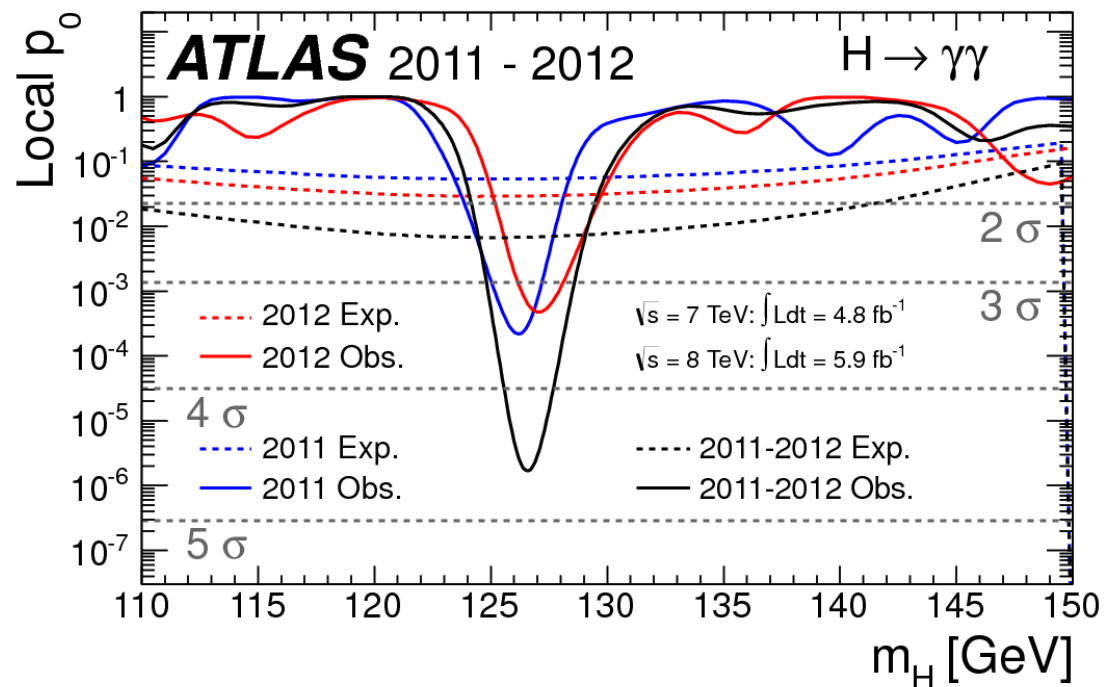
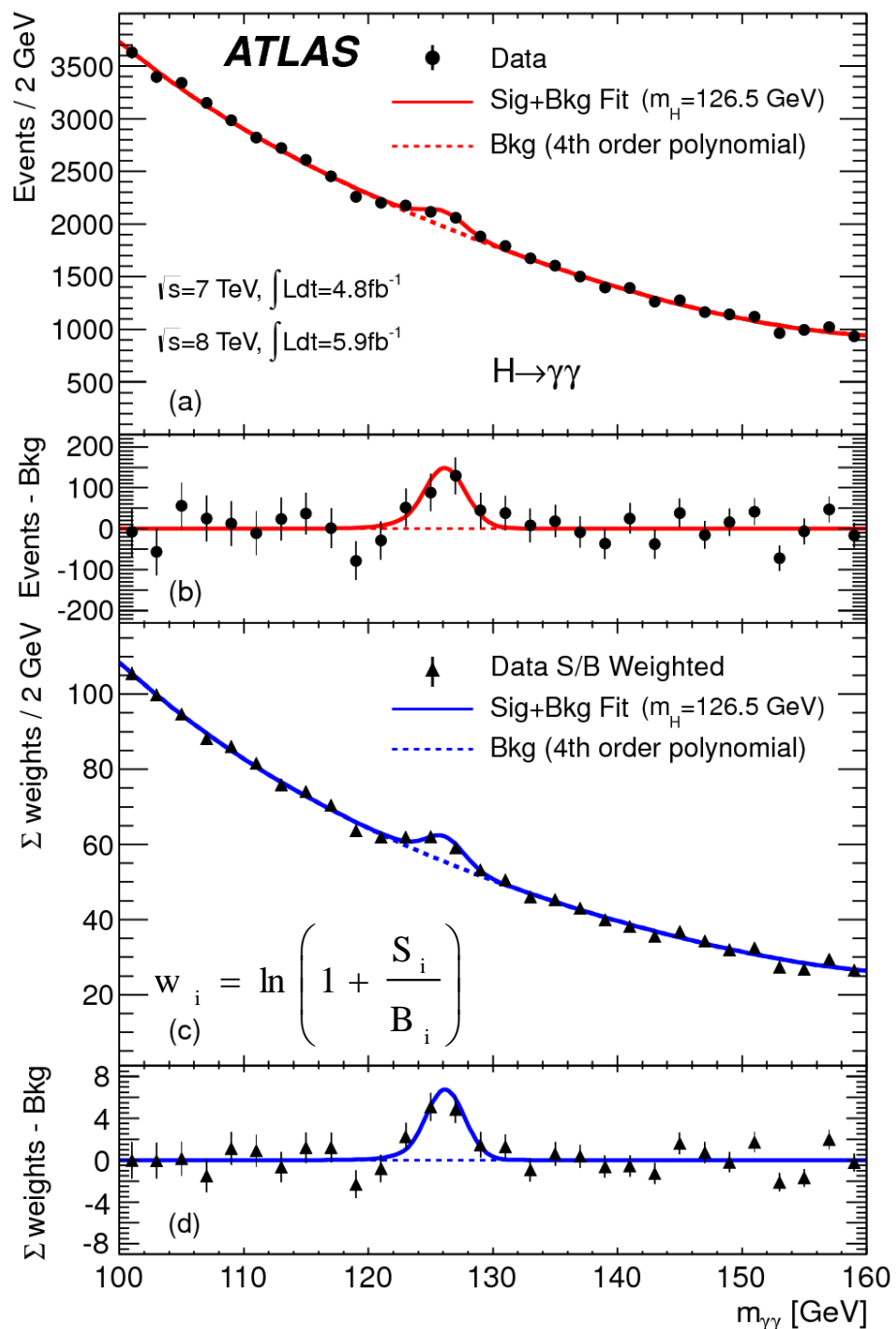
Varies from category to category.

# Systematic Uncertainties

Uncertainty	Description
Signal yield uncertainty from $\gamma$ ID efficiency	$\pm 8\%$ , $\pm 11\%$ (7TeV, 8TeV)
Pile-up modelling	$\pm 4\%$
Theory uncertainties in Higgs kinematics (affecting event migration between categories)	$\pm 9\%$
Signal resolution uncertainty	$\pm 14\%$
Trigger	$\pm 1\%$
Photon isolation	$\pm 0.4\%$ , $\pm 0.5\%$ (7TeV, 8TeV)
Luminosity	$\pm 1.8\%$ , $\pm 3.6\%$ (7TeV, 8TeV)

Uncertainties in the expected fractions of events per category (includes migrations) due to material effects, jet energy scale, pile-up effects, PDFs and jet vertex fraction, have been included.

# $\gamma\gamma$ invariant mass and local Significance



Combination of all categories leads to a  $4.5\sigma$  significance.

# $\gamma\gamma$ invariant mass from CMS

## $X \rightarrow \gamma\gamma$ : S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B  
(B is integral of background model over a constant signal fraction interval)

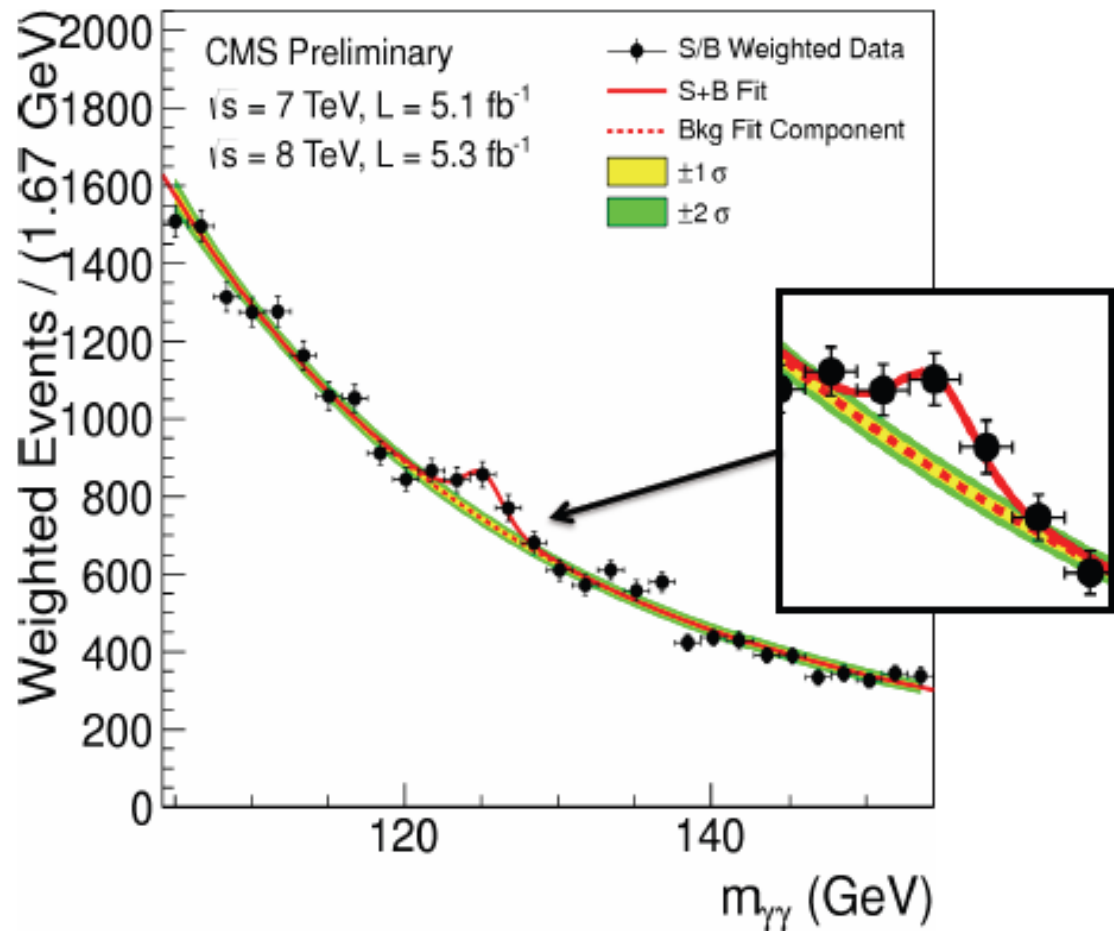
w/r to Moriond

New E calibration  
(2011 data)

$\Delta M/M \sim 1-2\%$   
(2.6% all categories combined)

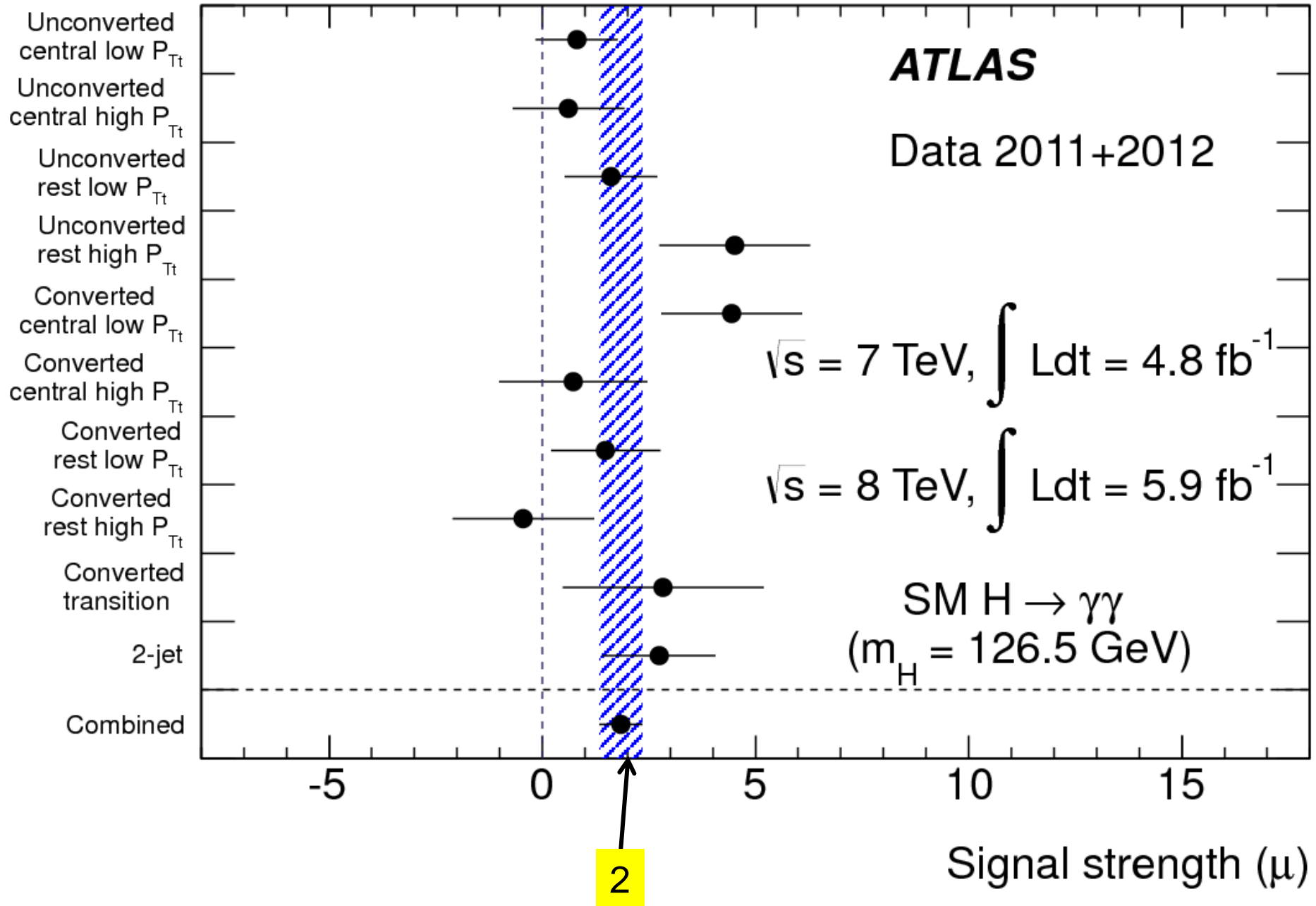
Re-optimized  $\gamma$  isolation  
using Pflow

Two di-jet tag categories  
with different purities



# $\gamma\gamma$ signal strength per category (at 126.5 GeV)

(blue band corresponds to the error of the combined result)



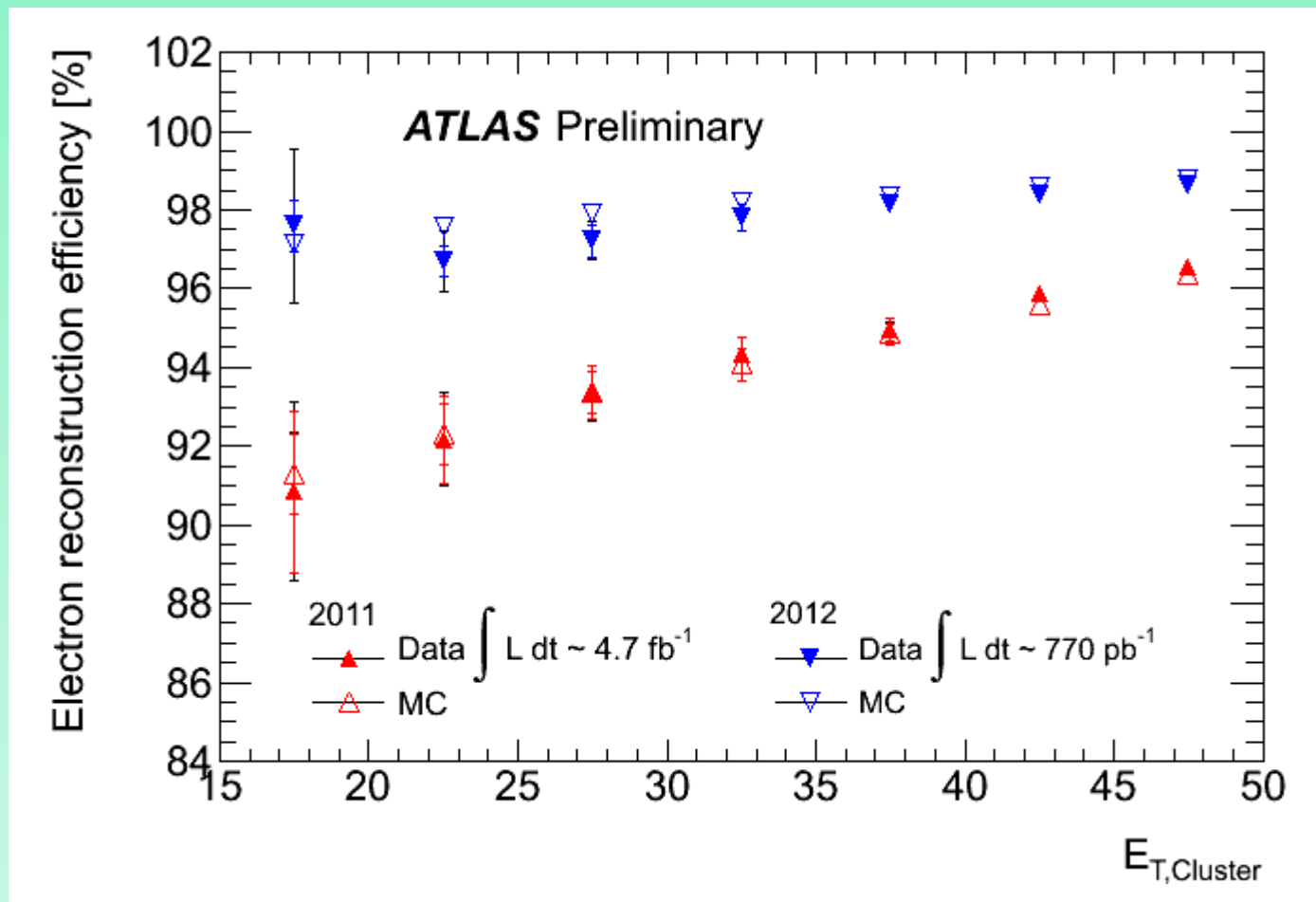
$$H \rightarrow ZZ^{(*)} \rightarrow l^+ l^- l^+ l^-$$

$$\sigma \times \text{BR} = 2.8 \text{ fb (8 TeV)}$$

# 4-lepton event selection summary

Selection	Description
Final states	$e^+e^-e^+e^-$ , $\mu^+\mu^-\mu^+\mu^-$ , $\mu^+\mu^-e^+e^-$ , $e^+e^-\mu^+\mu^-$
Fiducial cuts	All leptons $p_{T,\mu} > 6$ GeV, $p_{T,e} > 7$ GeV, Leading $p_T > 20$ GeV Subleading $p_T > 15$ GeV Third $p_T > 10$ GeV $ \eta_\mu  < 2.7$ , $ \eta_e  < 2.47$
Lepton Isolation	Track sum ET and Calo sum ET inside a $\Delta R < 0.2$ cone around the Z leptons.
e ( $\mu$ ) Impact Parameter	$d0/\sigma_{d0} < 6.5$ (3.5)
Leading dilepton (12)	Same flavour opposite charge with M closest to 91.18 GeV. Pairs must satisfy $m_{12} > 50$ GeV, $m_{34} > 17.5$ GeV.
Leading Z mass cut	$50 < m_{12} < 106$ GeV
Subleading Z mass cut	$M_{\min}(m_{4l}) < m_{34} < 115$ GeV ( $M_{\min}$ is a minimum mass cut that depends on the 4-lepton mass)

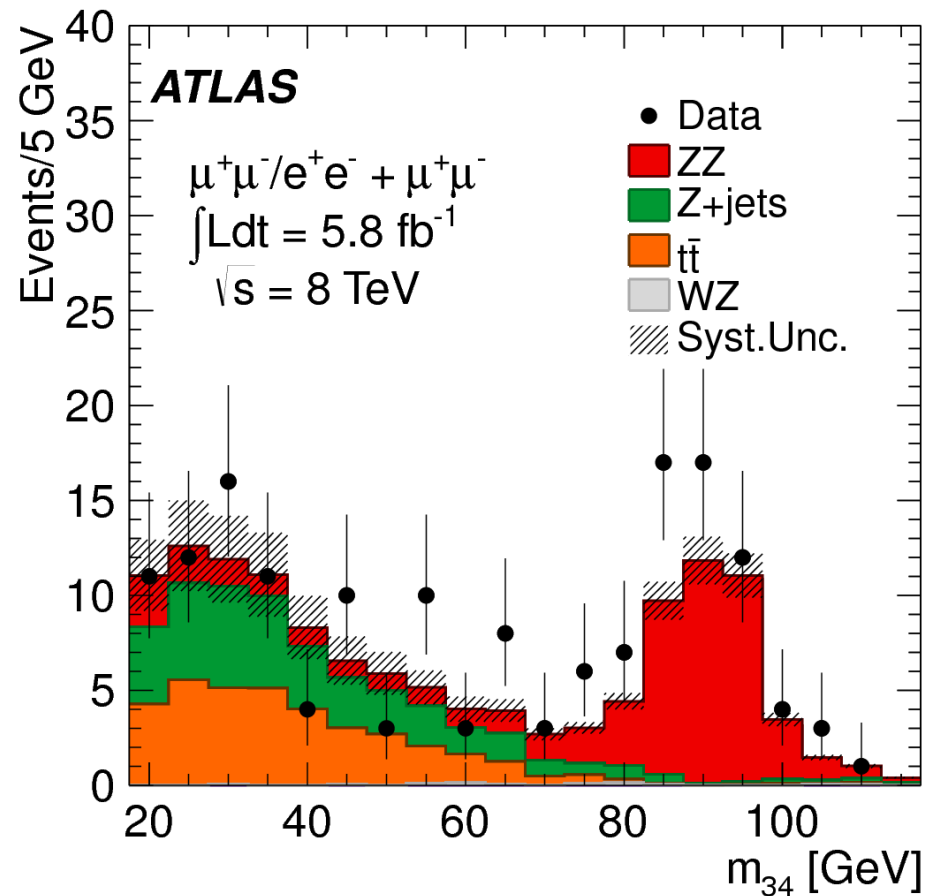
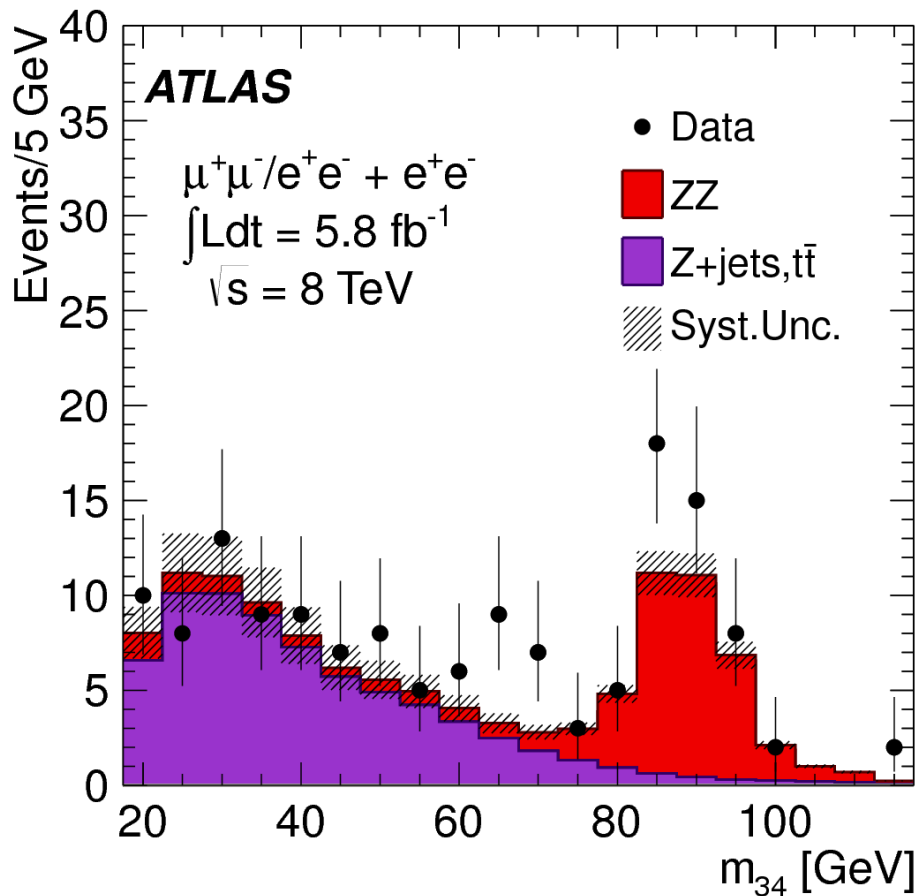
# Lepton Reconstruction



Electron reconstruction/identification improved in 2012: New pattern finding/track fitting, Improved track-cluster matching, to recover electrons undergoing hard bremsstrahlung, GSF.

Muon reconstruction: use ID tracks matched with partial or complete track segments in the muon spectrometer, and ID tracks+energy deposits in the calo ( $|\eta| < 0.1$  pt > 15 GeV). Standalone muons ( $2.5 < |\eta| < 2.7$ ).

# Background measurements from data



A number of methods was used to determine the various backgrounds using data. A subset of the analysis cuts is applied to define a control region.

One example is to use the invariant mass of the subleading dilepton  $M_{34}$  to control the Z+jets and  $t\bar{t}$  backgrounds. For these leptons the isolation and impact parameter cuts are not applied. All other analysis cuts are applied.

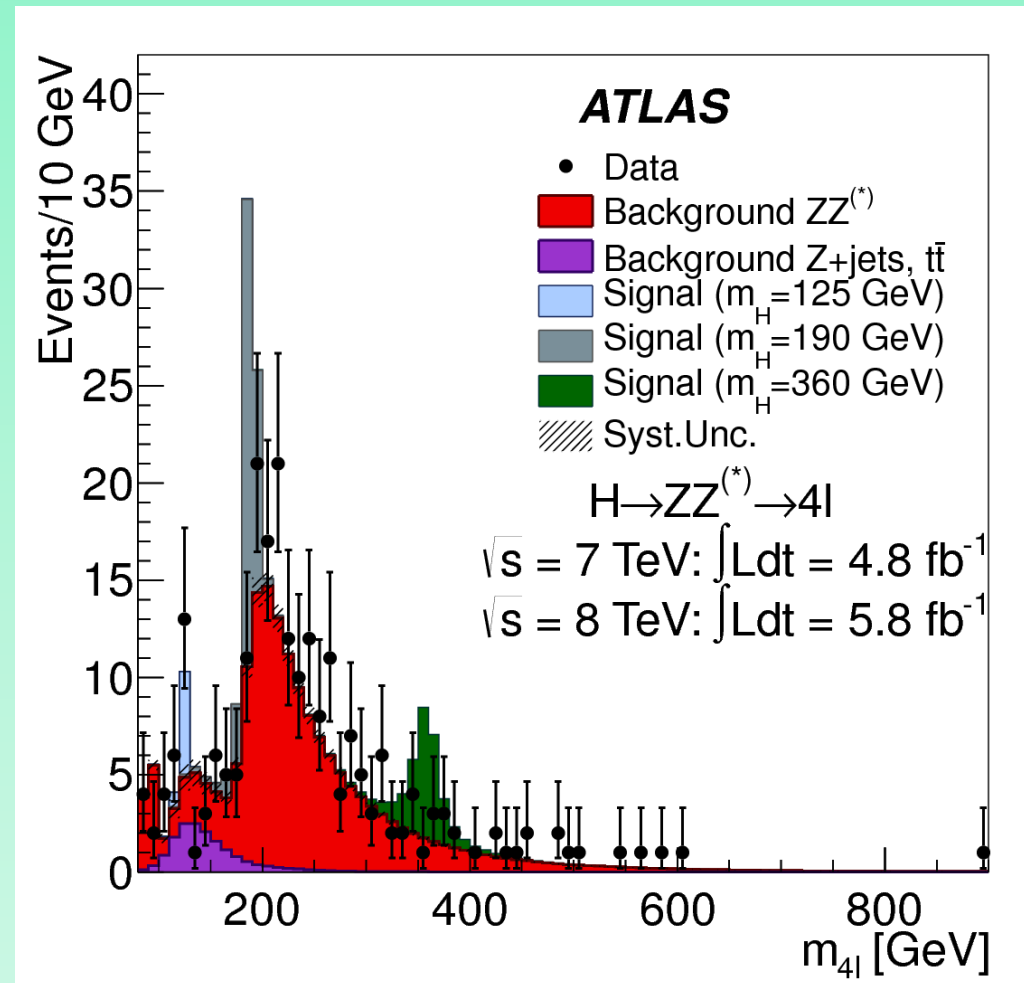
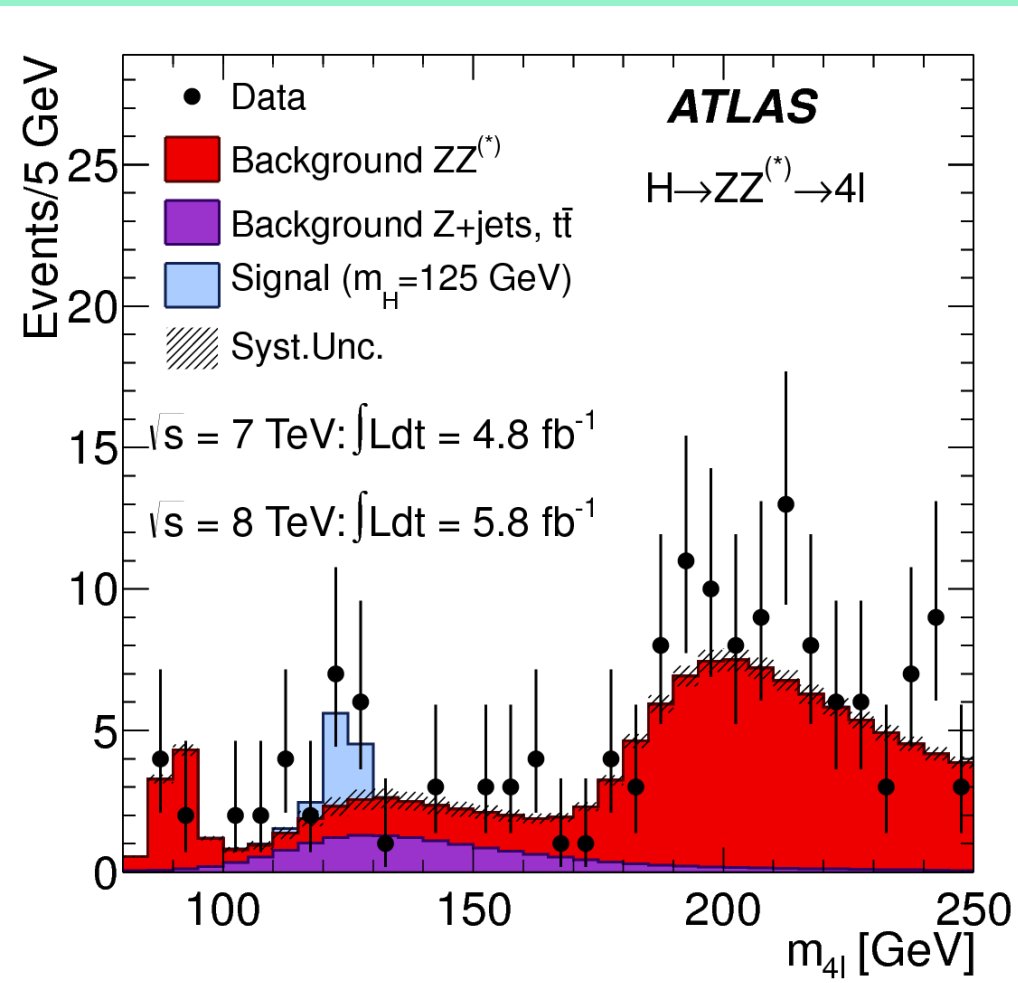
# Systematic Uncertainties

Uncertainty	Description
$\mu$ acceptance uncertainty due to reco and ID efficiency uncertainties	from $\pm 0.7\%$ ( $\pm 0.5\%, \pm 0.5\%$ ) for $4\mu$ ( $2e2\mu, 2\mu 2e$ ) at 600GeV to $\pm 0.9\%$ ( $\pm 0.8\%, \pm 0.5\%$ ) for $4\mu$ ( $2e2\mu, 2\mu 2e$ ) at 115GeV
e acceptance uncertainty due to reco and ID efficiency uncertainties	from $\pm 2.6\%$ ( $\pm 1.7\%, \pm 1.8\%$ ) for $4e$ ( $2e2\mu, 2\mu 2e$ ) at 600GeV to $\pm 8.0\%$ ( $\pm 2.3\%, \pm 7.6\%$ ) for $4e$ ( $2e2\mu, 2\mu 2e$ ) at 115GeV
ZZ* bkg uncertainty (QDC scale)	$\pm 5\%$
ZZ* bkg uncertainty ( $\alpha_s$ + PDF)	$\pm 4\%$ ( $\pm 8\%$ ) for processes initiated by quarks (gluons)
Z+jets and ttbar backgrounds	estimated from control regions

ZZ normalization comes from MC.

Dependence of ZZ\* uncertainties on  $m_{4l}$  has been taken into account

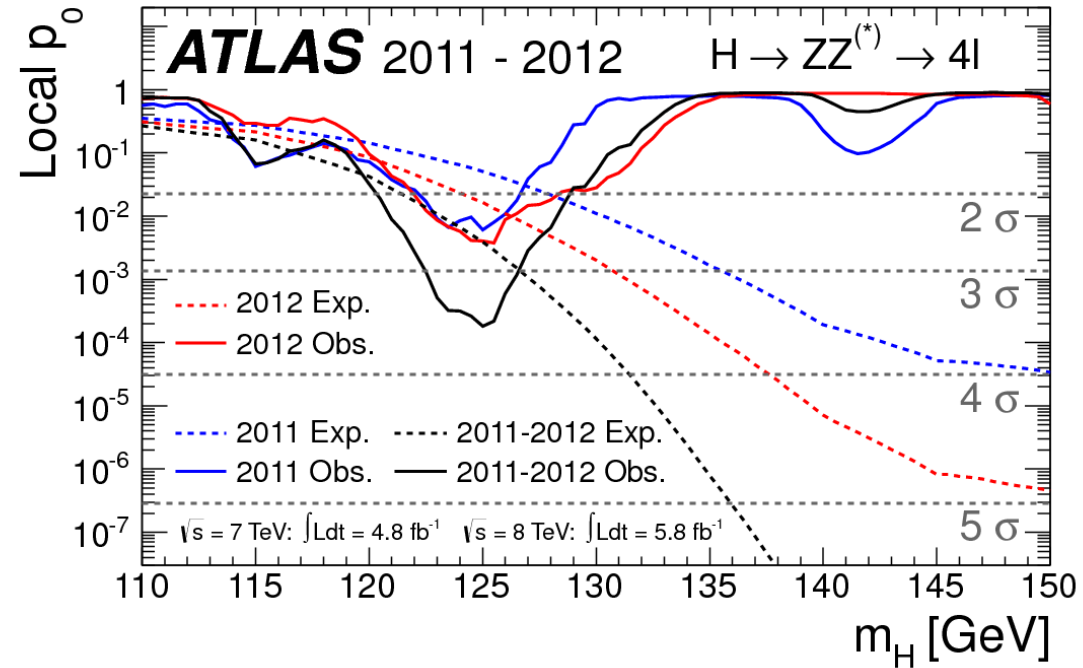
# 4-lepton invariant mass



Observed excess in 120-130 GeV

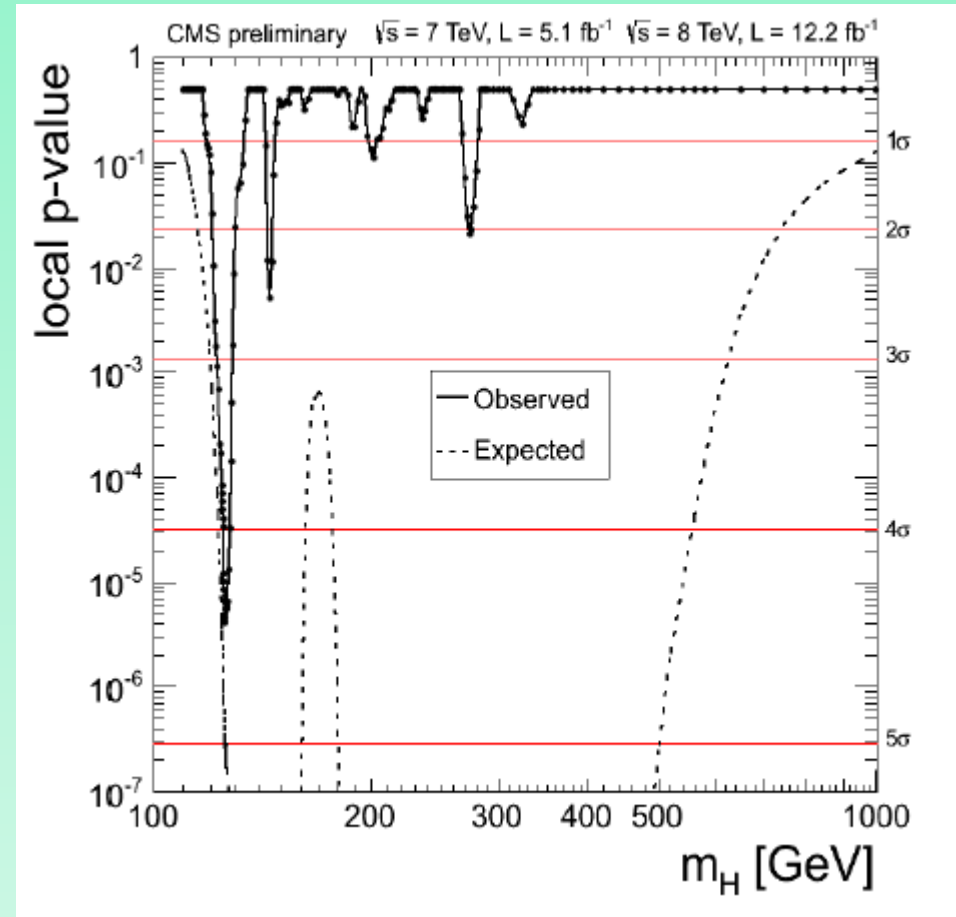
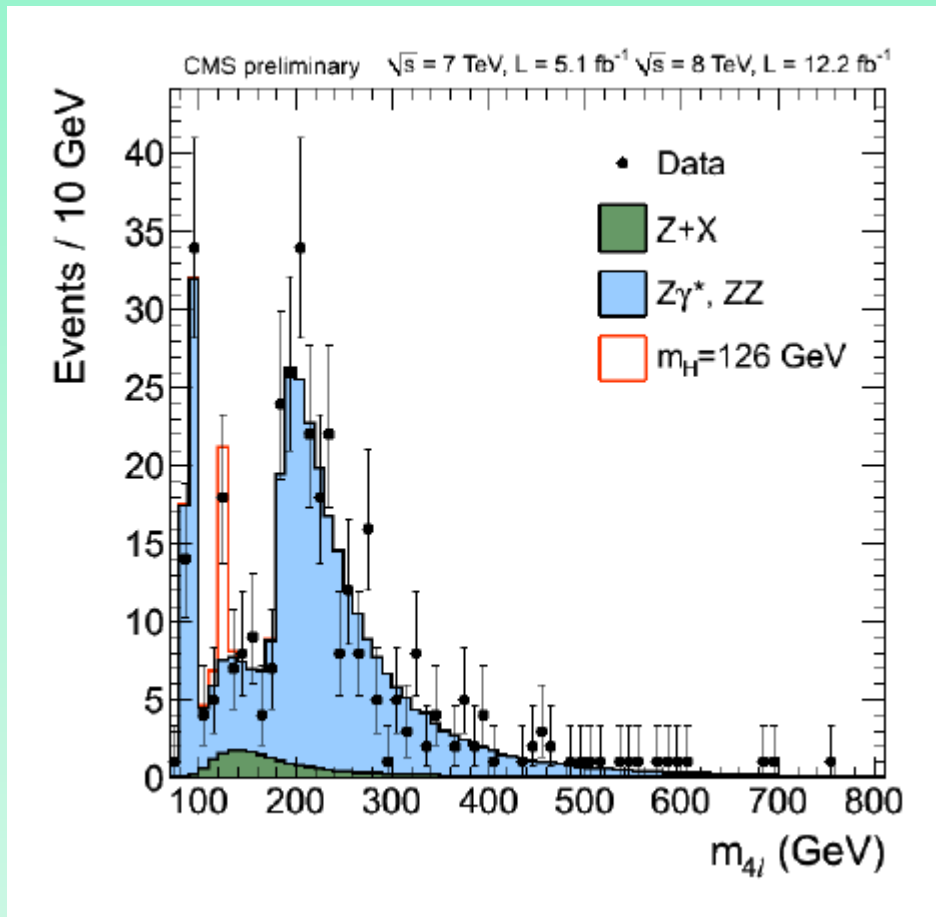
# 4-lepton expected and observed events: 120-130GeV

$m_H$ [ GeV ]	exp. signal	exp. $ZZ^{(*)}$	exp. $Z + \text{jets}, t\bar{t}$	obs
$4\mu$				
120	$1.16 \pm 0.16$	$0.91 \pm 0.04$	$0.12 \pm 0.04$	4
125	$2.09 \pm 0.30$	$1.12 \pm 0.05$	$0.13 \pm 0.04$	6
130	$3.25 \pm 0.46$	$1.25 \pm 0.05$	$0.13 \pm 0.04$	3
$2e2\mu$ and $2\mu2e$				
120	$1.29 \pm 0.19$	$0.69 \pm 0.05$	$1.13 \pm 0.17$	3
125	$2.29 \pm 0.33$	$0.80 \pm 0.05$	$1.27 \pm 0.19$	5
130	$3.52 \pm 0.51$	$0.82 \pm 0.05$	$1.31 \pm 0.19$	3
$4e$				
120	$0.49 \pm 0.07$	$0.36 \pm 0.03$	$0.97 \pm 0.19$	2
125	$0.90 \pm 0.14$	$0.44 \pm 0.04$	$1.09 \pm 0.20$	2
130	$1.33 \pm 0.21$	$0.51 \pm 0.05$	$1.13 \pm 0.21$	1

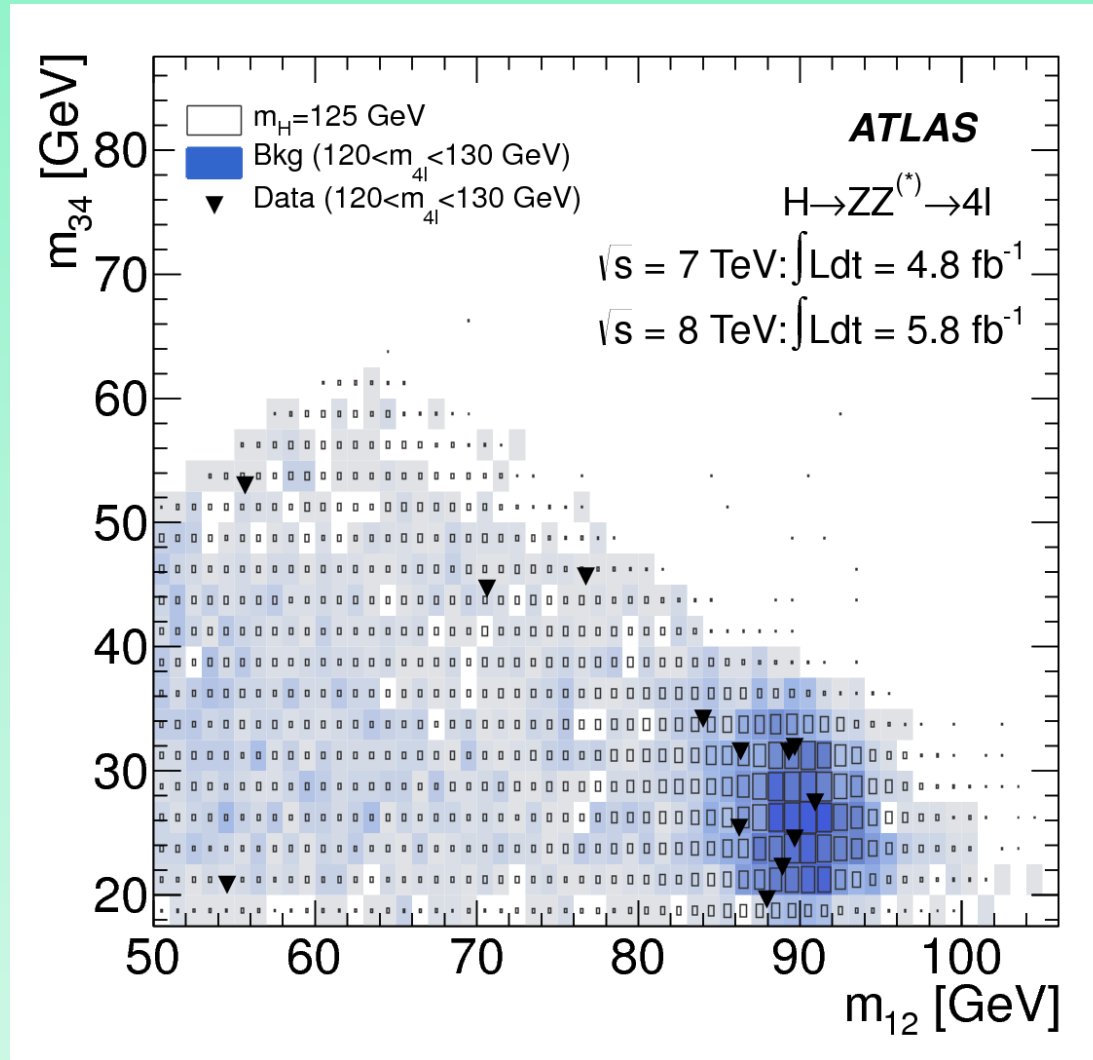


Maximum local significance of  $3.6\sigma$  observed at 125 GeV.  
 No other significant excess is observed in  $m_H$ .

# (new) CMS result: November 2012



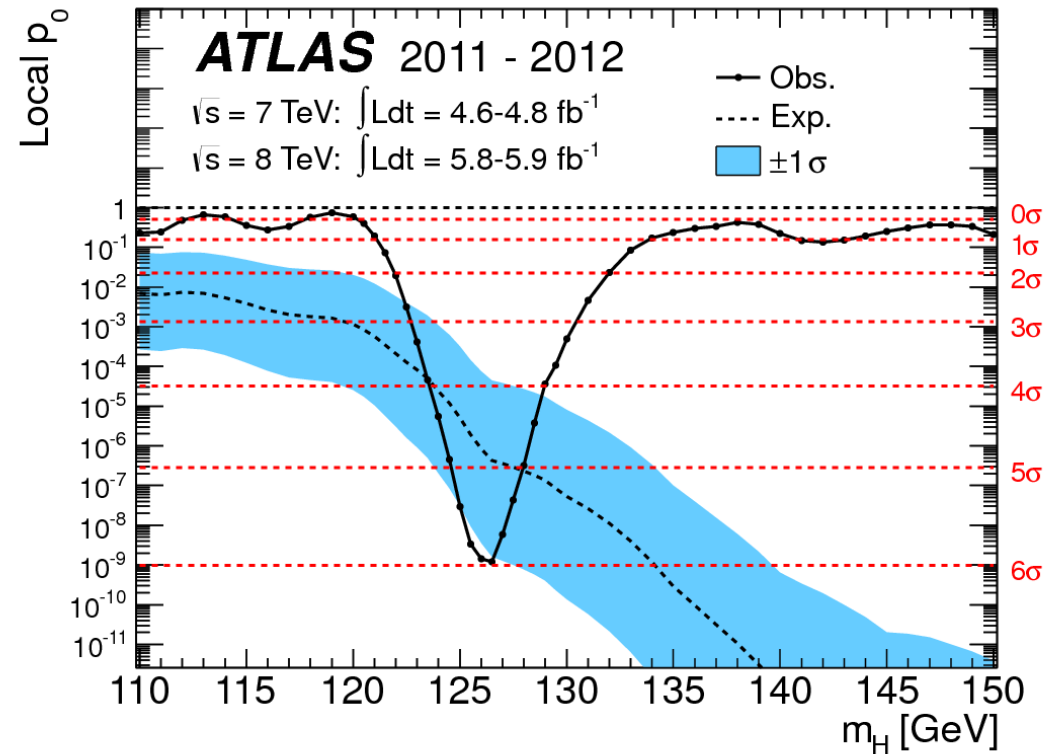
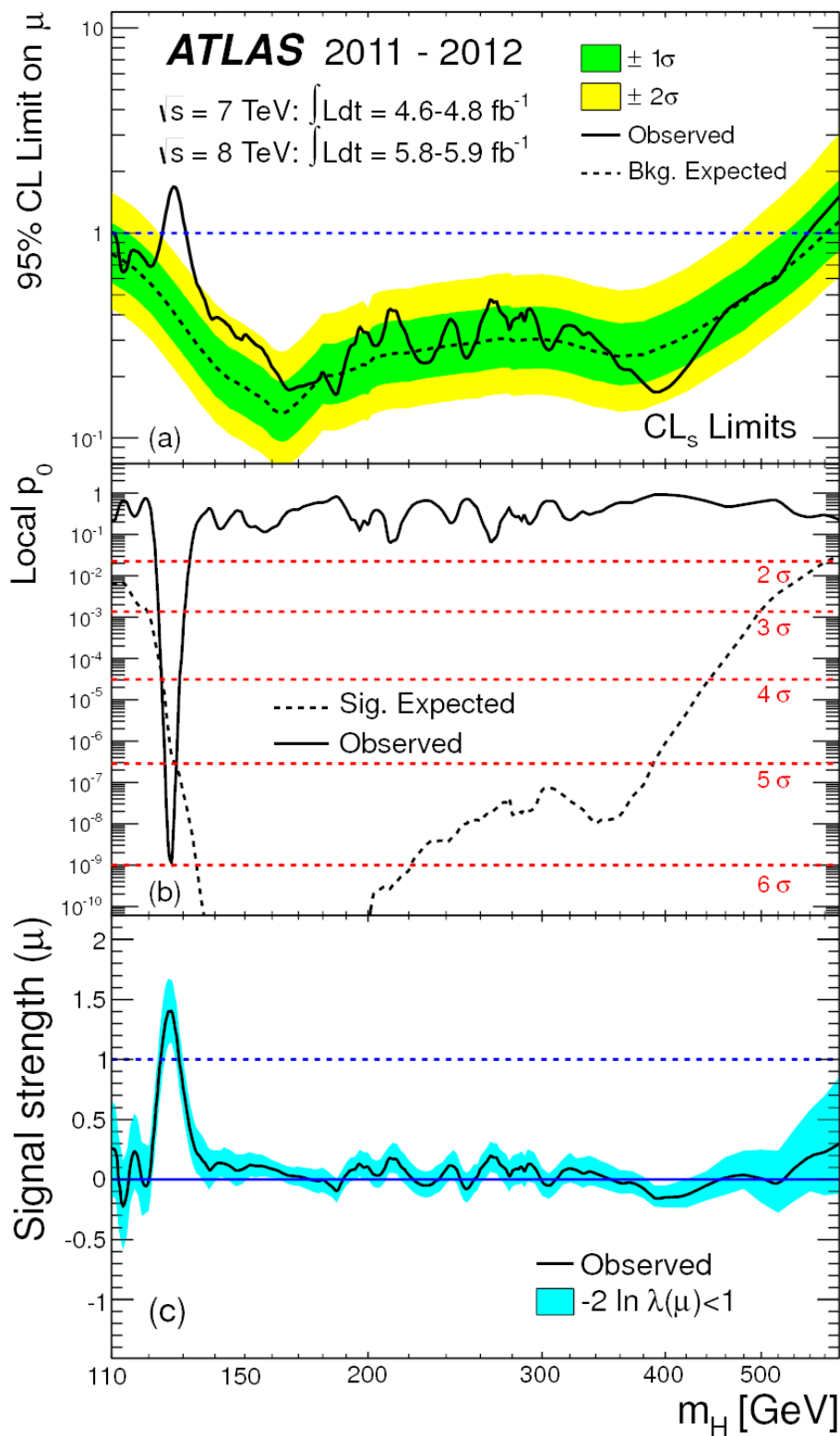
# $m_{34}$ vs $m_{12}$ for $120 < m_{4l} < 130$ GeV



Distribution of the  $m_{34}$  versus the  $m_{12}$  invariant mass for the selected candidates in the  $m_{4l}$  range 120 to 130 GeV. The expected distributions for a SM Higgs with  $m_H = 125$  GeV and for the total background are shown. The sizes and intensity of the boxes indicate the relative density.

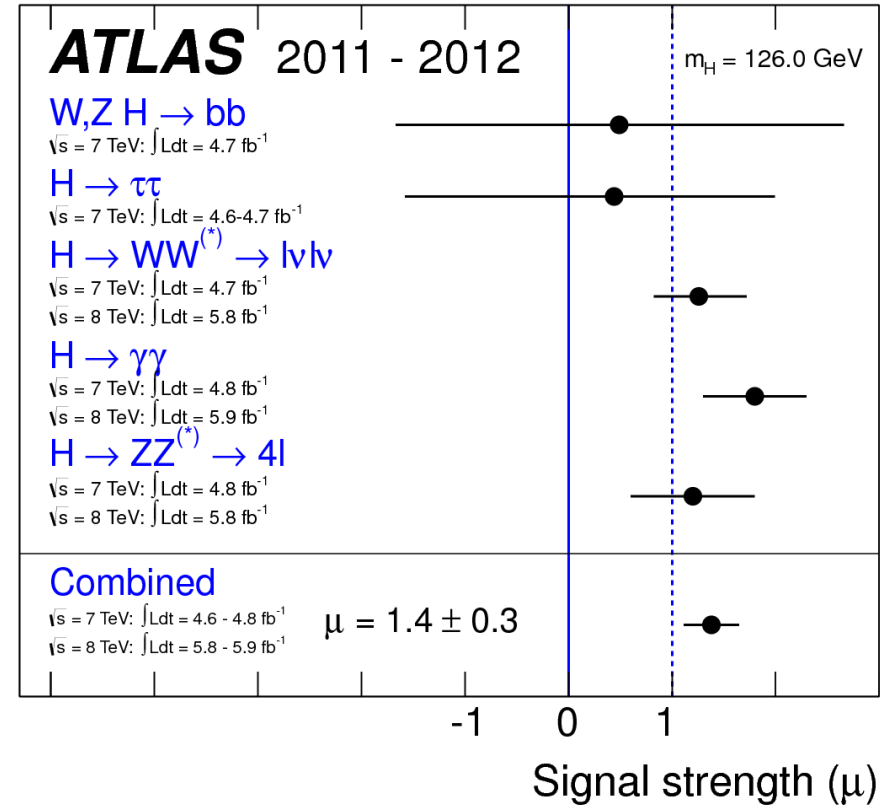
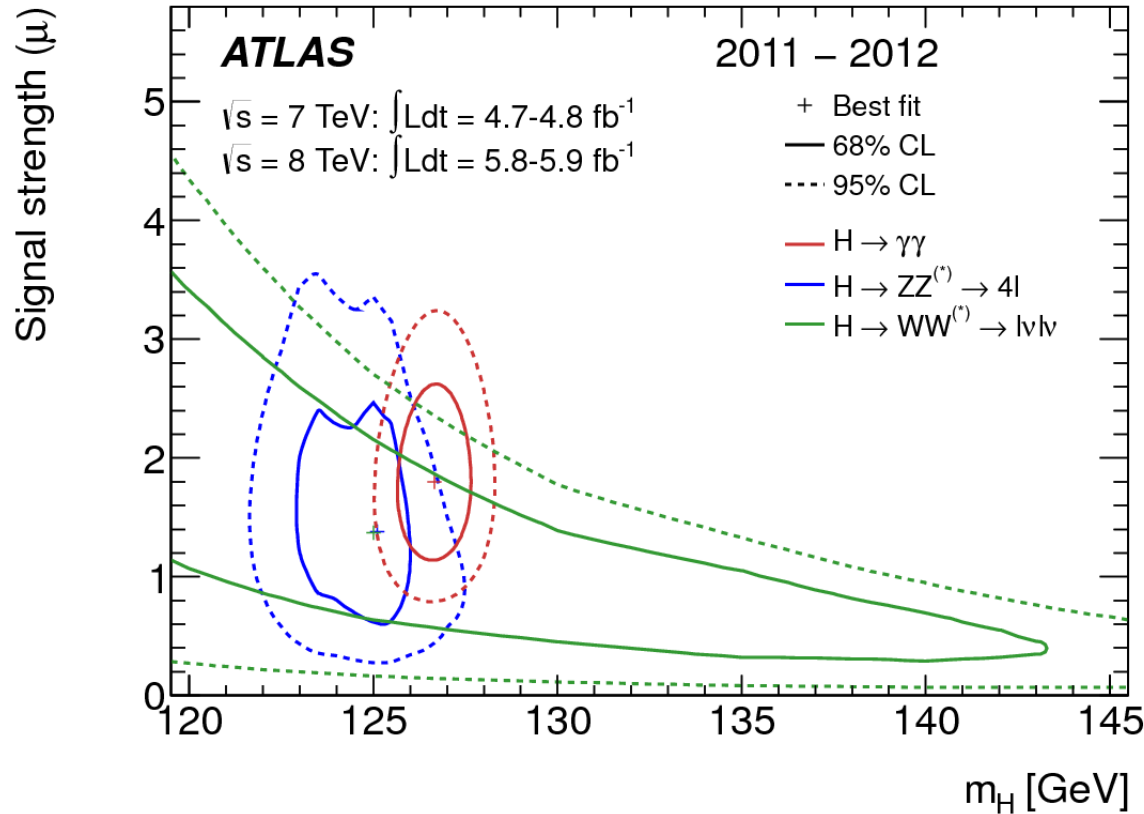
# Combination

# Exclusion Region and Combined Significance



Combination of all channels (including 2011  $\tau\tau$ ,  $bb$ , etc) leads to a  $5.9\sigma$  significance.

# Mass and Signal strength $\mu$ wrt Standard Model

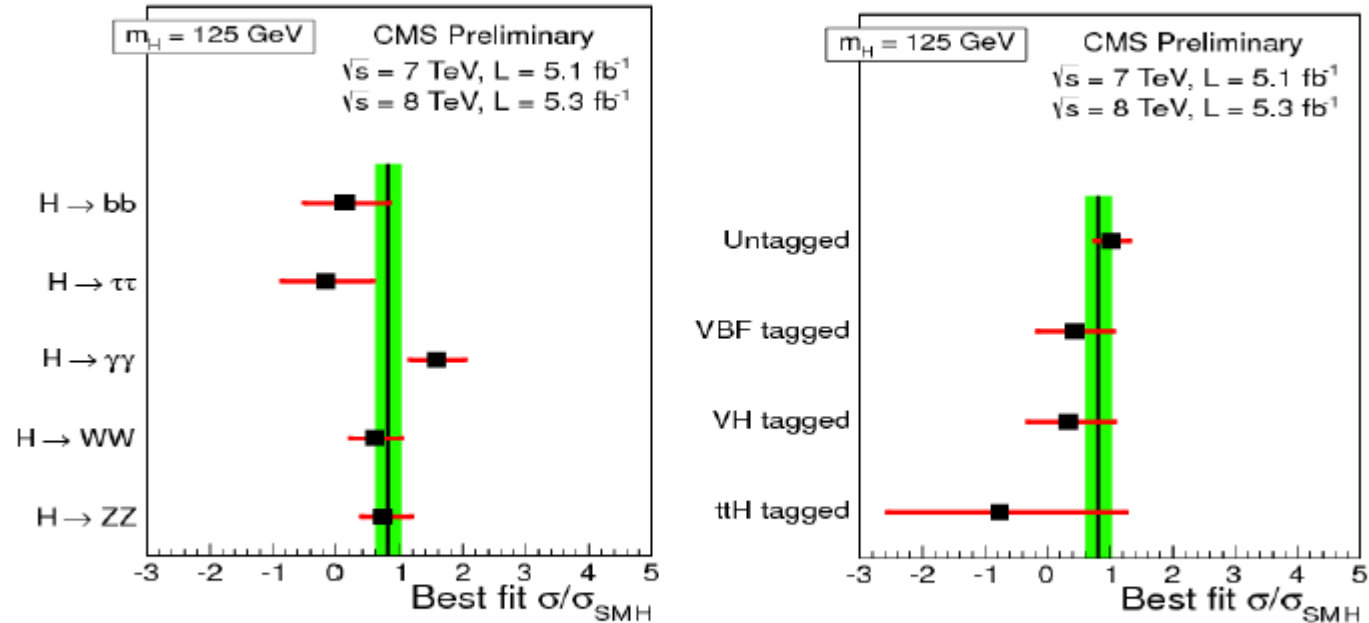


Extracted mass:  $126 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \text{ GeV}$   
 (using only 4-lepton and  $\gamma\gamma$  channels)

Combined Signal Strength:  $1.4 \pm 0.3$

# CMS Signal strength $\mu$ wrt Standard Model

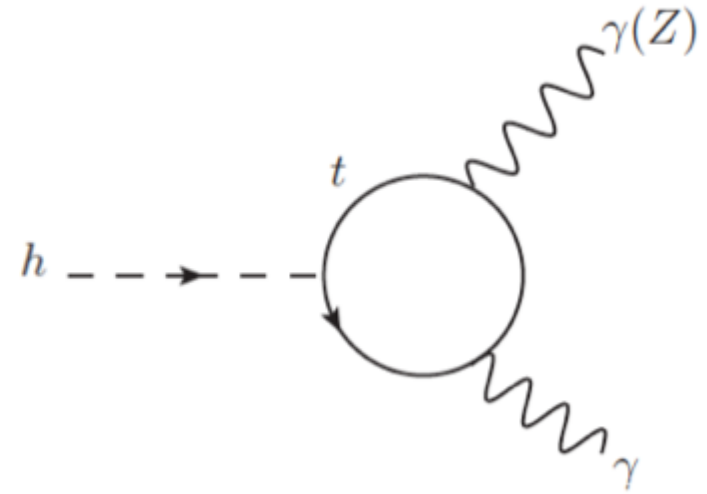
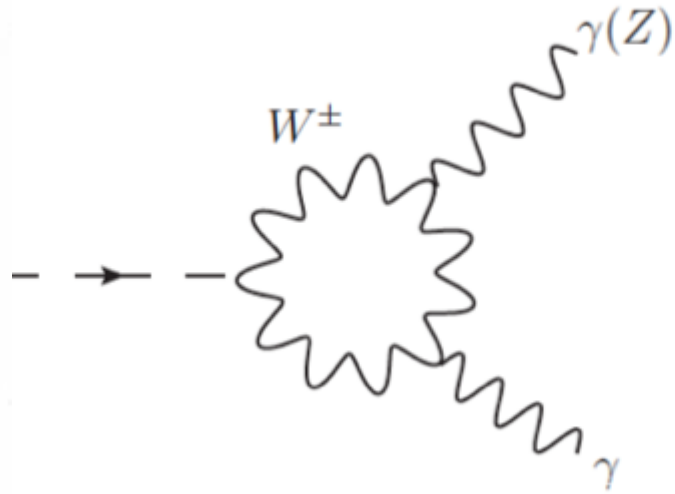
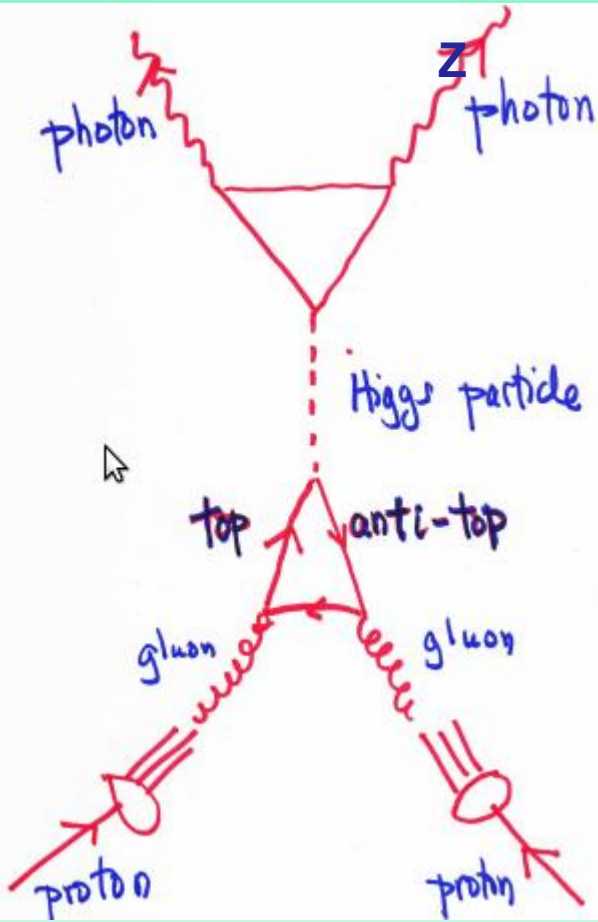
## Signal Strength vs Production & Topology



Slightly better sensitivity when combining channels by decay mode or production topology.  
Compatible with SM Higgs within uncertainties

Clear tension between  $\gamma\gamma$  and  $ZZ \rightarrow 4l$ , also seen by CMS!  
→ Look for signal in the Higgs  $\rightarrow Z\gamma$  channel!

# Higgs $\rightarrow Z\gamma$ : our gateway to beyond the Std Model?



In SM, the W loop is dominant.

New BSM physics heavy particles may run in the loop increasing the  $H \rightarrow \gamma\gamma$  yield with respect to the SM. The  $Z\gamma$  yield is related to the  $\gamma\gamma$  yield. Note that the yield of  $Z\gamma$  relative to  $\gamma\gamma$  depends on the spin and other properties of the new particles.

So, measuring both  $Z\gamma$  and  $\gamma\gamma$  yields is significant for understanding the properties of particles running in the loop.

# Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(H \rightarrow b\bar{b})}{\Gamma(H \rightarrow \tau^+\tau^-)} \approx 3 \frac{m_b^2}{m_\tau^2}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

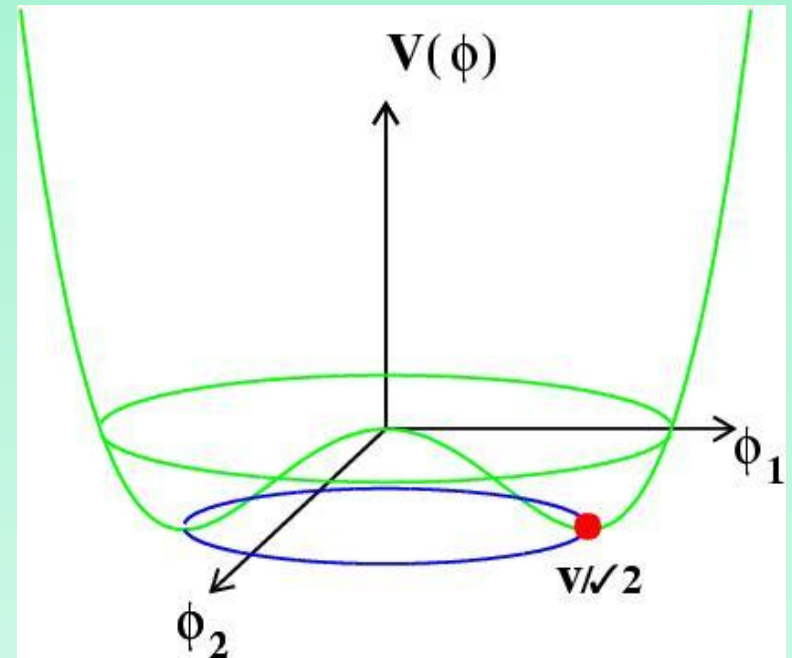
- Measure self interactions

$$V = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H^3 + \frac{M_H^2}{8v^2} H^4$$

# Can we reconstruct the Higgs potential?

$$V = \frac{M_H^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$

$$SM : \lambda_3 = \lambda_4 = \frac{M_H^2}{2v^2}$$



• Fundamental test of model!

• We have no idea how to measure  $\lambda_4$

# Does it have the correct Quantum Numbers?

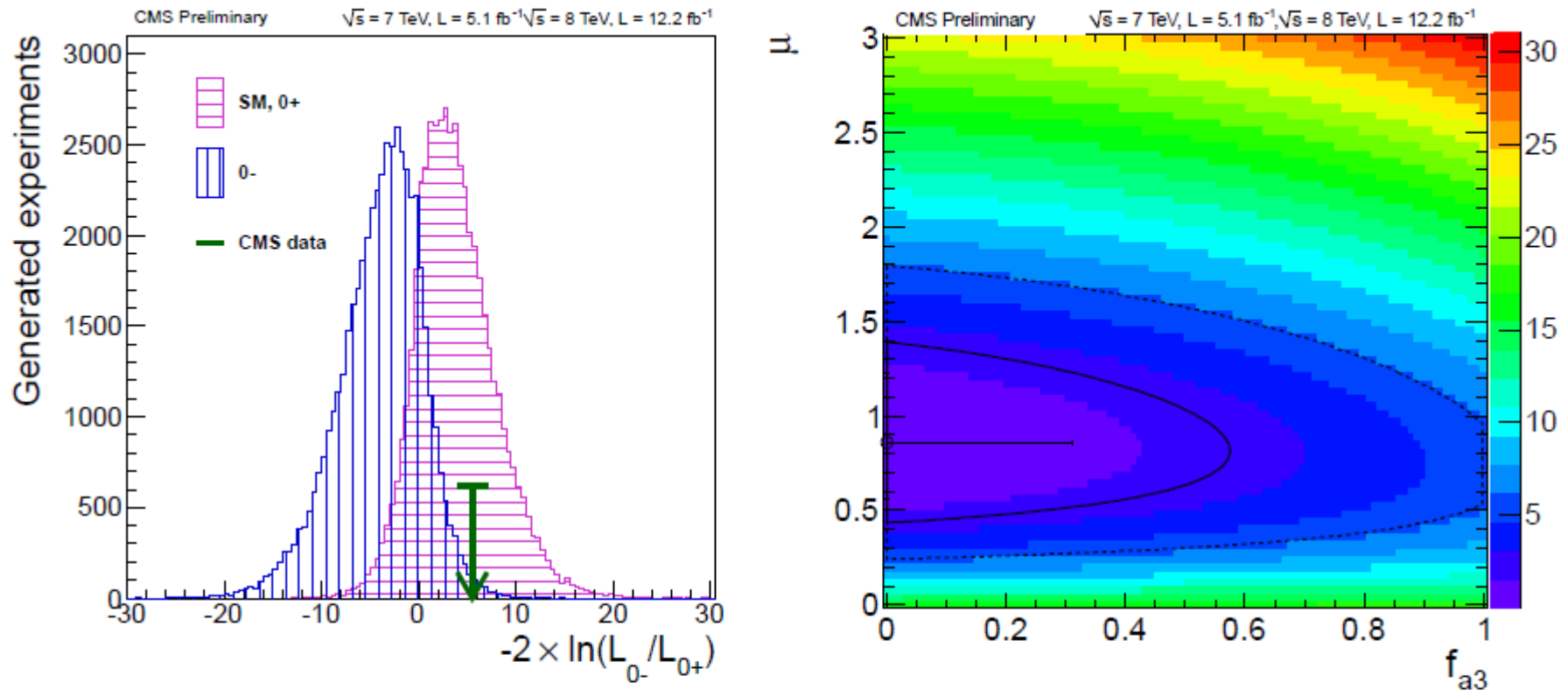
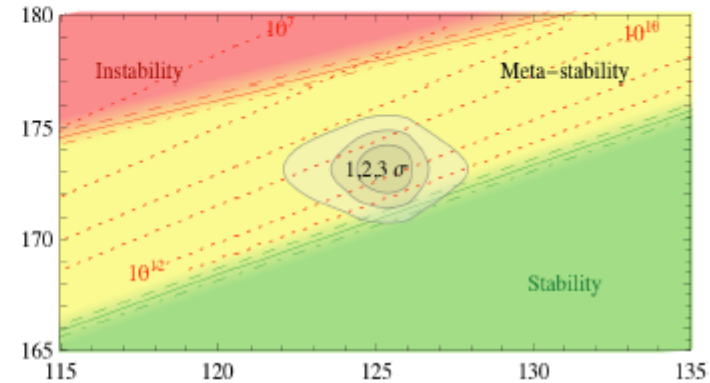
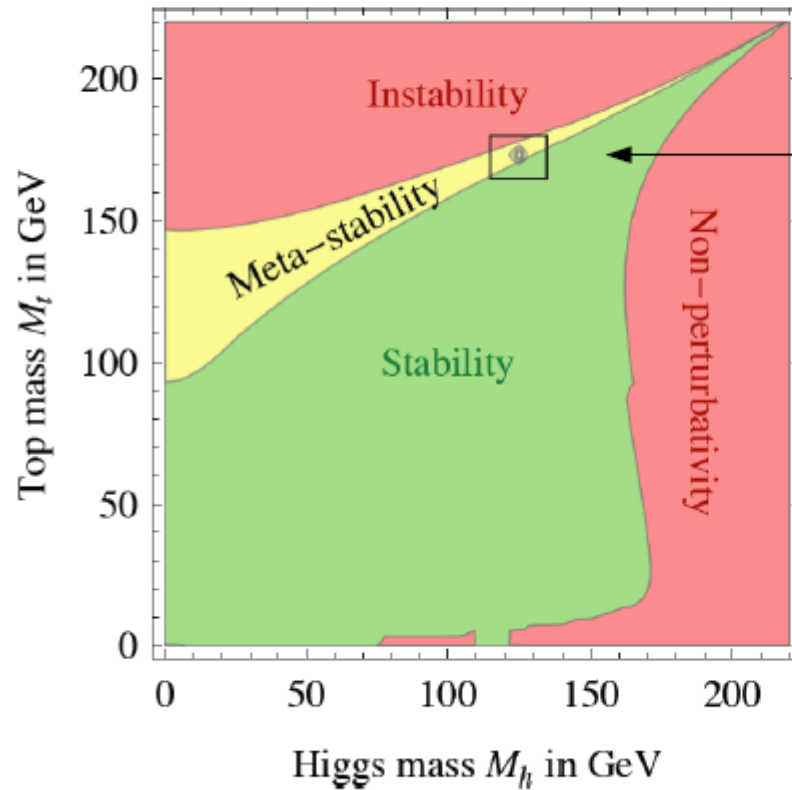


Figure 9: Left: Distribution of  $q = -2 \ln(\mathcal{L}_{0^-} / \mathcal{L}_{0^+})$  for two signal types ( $0^+$  horizontally hatched histogram,  $0^-$  vertically hatched histogram) for  $m_H = 126$  GeV shown with a large number of generated experiments. The arrow indicates the observed value. Right: Distribution of  $-2 \ln \mathcal{L}$  as a function of  $f_{a3}$  and  $\mu$ . The central point shows the minimum value of  $-2 \ln \mathcal{L}$ , the solid and dashed contours show 68% and 95% CL contours in two dimensions. The one-dimensional 68% CL intervals are shown with the cross.

# Do we live in a special universe?

G. Isidori, Higgs Hunting 2012



Looking at the plane from a more distant perspective, it appears more clearly that “we live” in a quite “peculiar” region...

# 4<sup>th</sup> of July: Higgs group celebrates discovery



# Conclusions

ATLAS has performed a search for the SM Higgs boson with an integrated luminosity of  $\sim 10.7 \text{ fb}^{-1}$ .

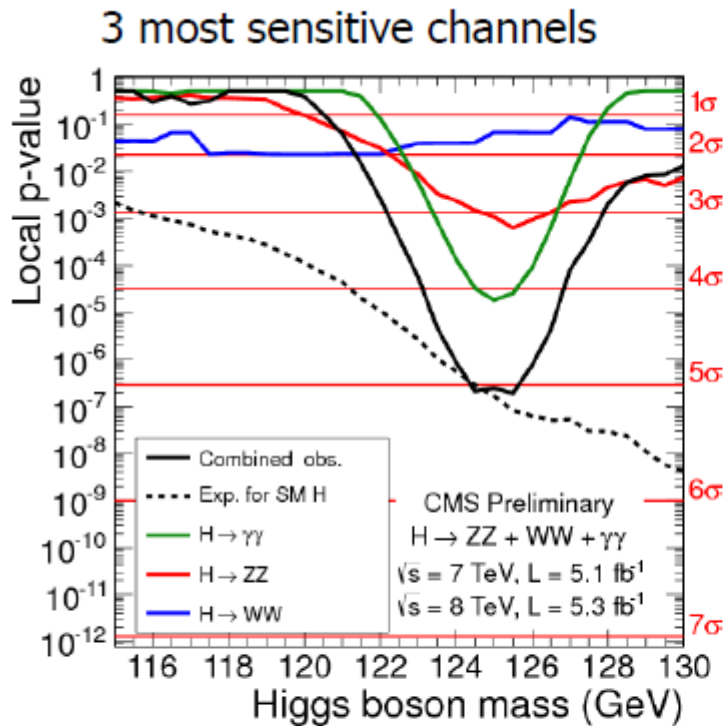
A  $5.9\sigma$  excess of events is observed in the region 121-131 GeV. The excess is dominated by the high mass resolution channels  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ \rightarrow 4l$  in addition to  $H \rightarrow WW \rightarrow l\nu l'\nu$ .

The SM Higgs boson is excluded at the 95% or higher CL in 111-559 GeV apart from the narrow range 121-131 GeV where a clear excess is observed.

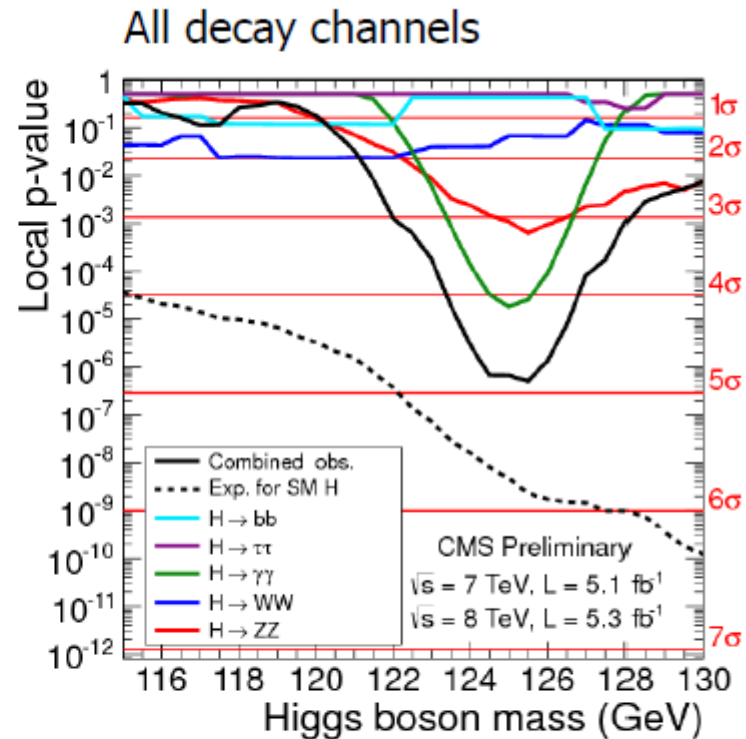
The measured invariant mass of the new particle (ATLAS) is:

$$126 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \text{ GeV}$$

# CMS combination



Slight increase of significance  
 when including  $H \rightarrow WW^*$   
 Expect further increase with new  
 MVA analysis HIG-12-038



Local significance of excess: **4.9  $\sigma$**   
 Expected for SM Higgs signal: **5.9  $\sigma$**

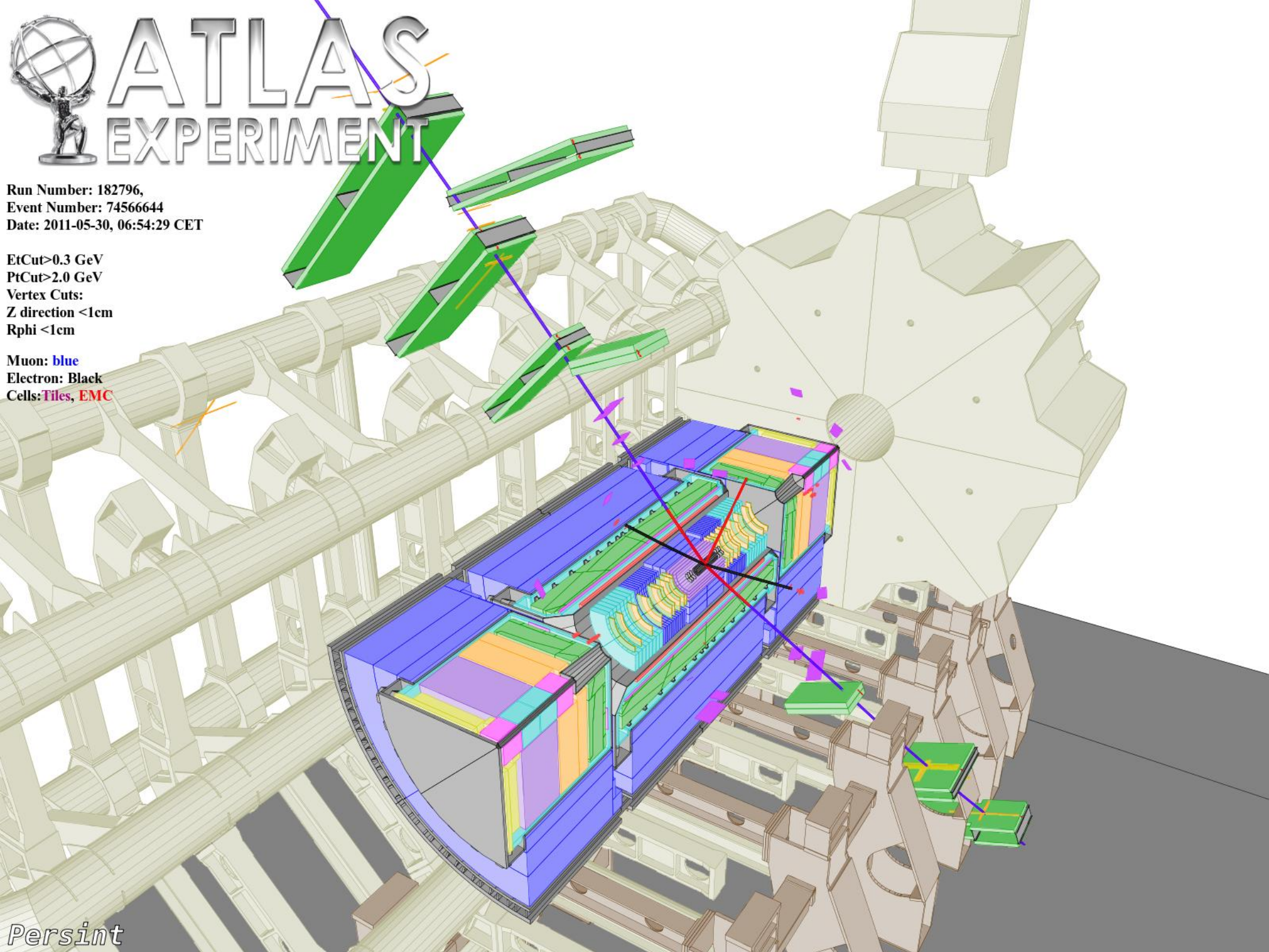


# ATLAS EXPERIMENT

Run Number: 182796,  
Event Number: 74566644  
Date: 2011-05-30, 06:54:29 CET

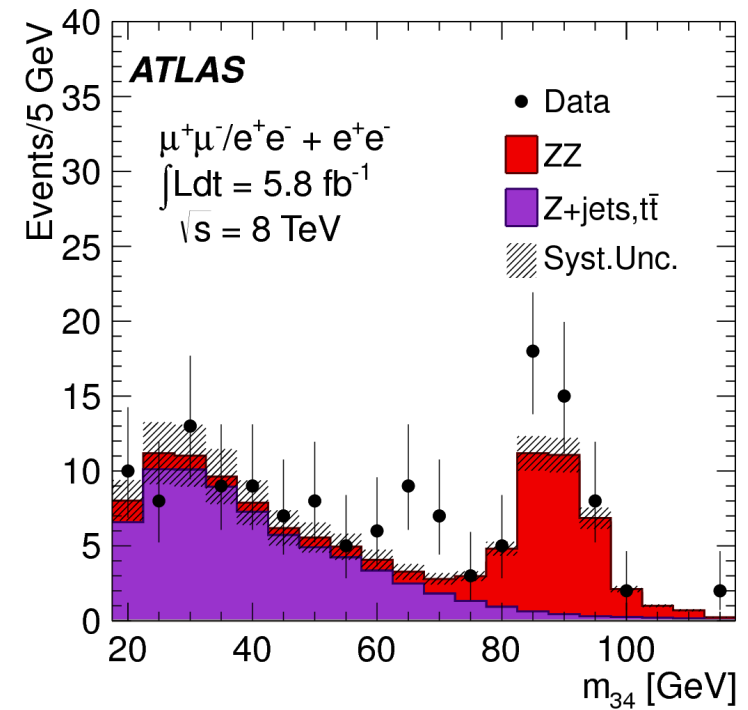
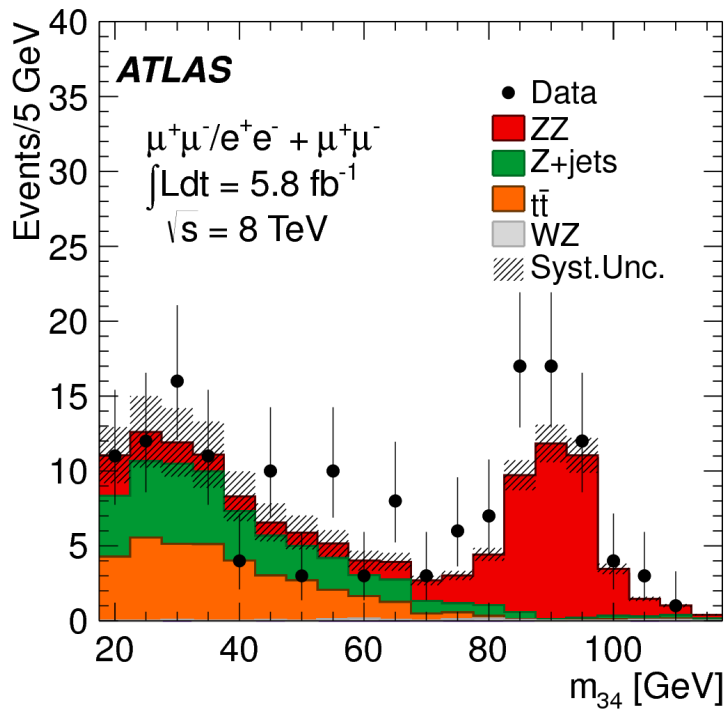
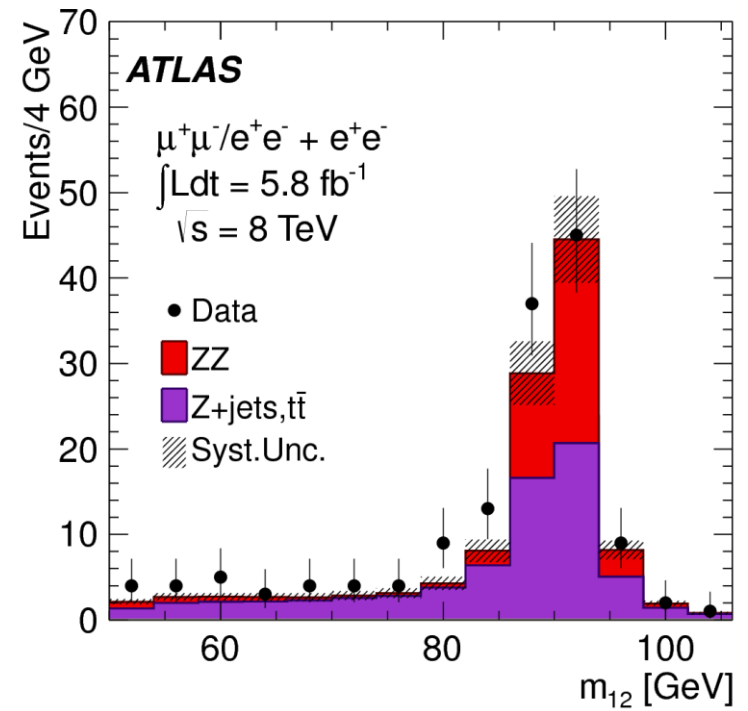
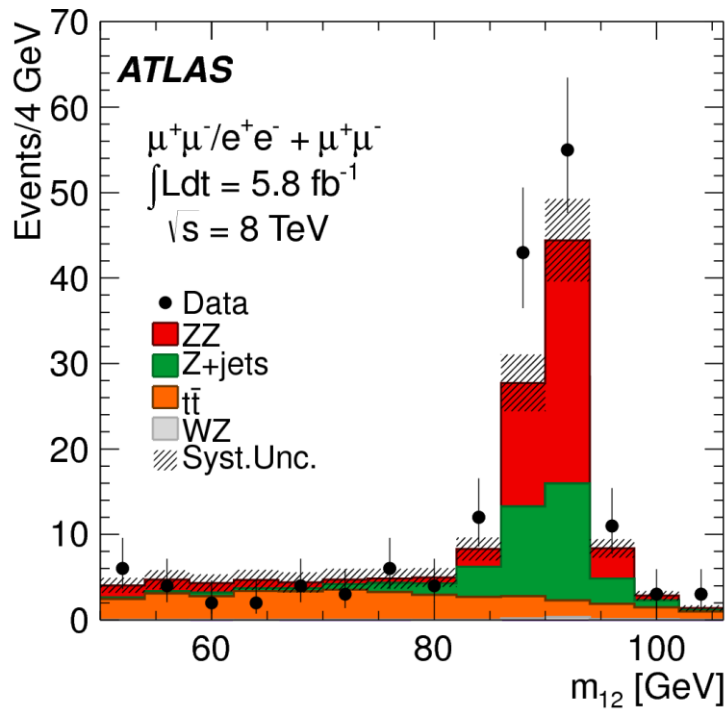
EtCut > 0.3 GeV  
PtCut > 2.0 GeV  
Vertex Cuts:  
Z direction < 1cm  
Rphi < 1cm

Muon: blue  
Electron: black  
Cells: Tiles, EMC



# Additional Slides

# Z+ee and Z+ $\mu\mu$ 4lepton control regions



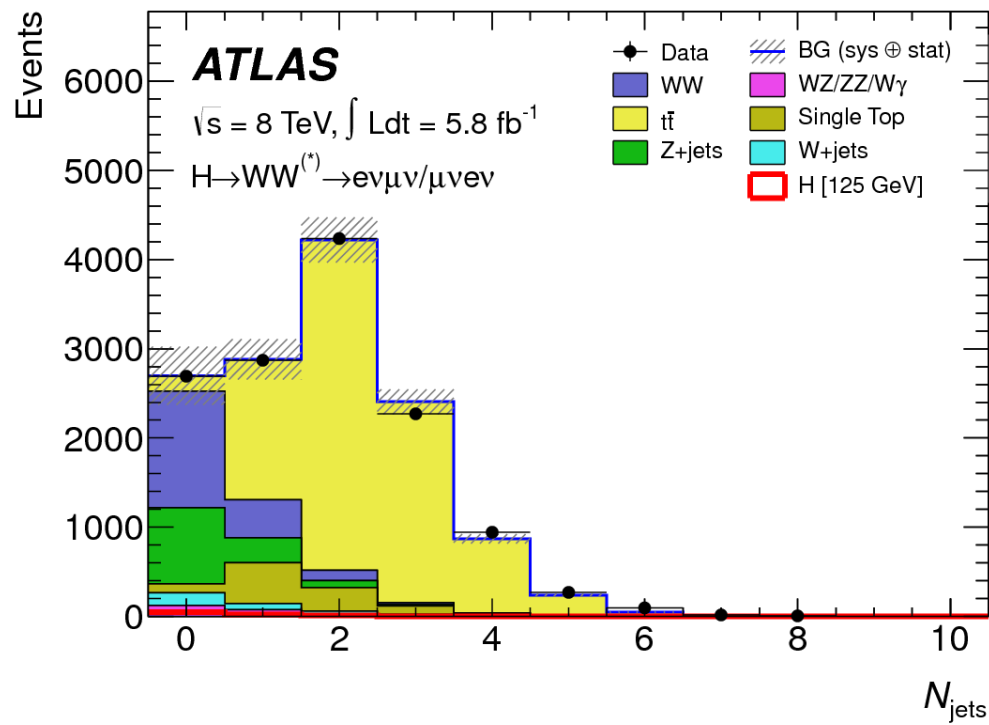
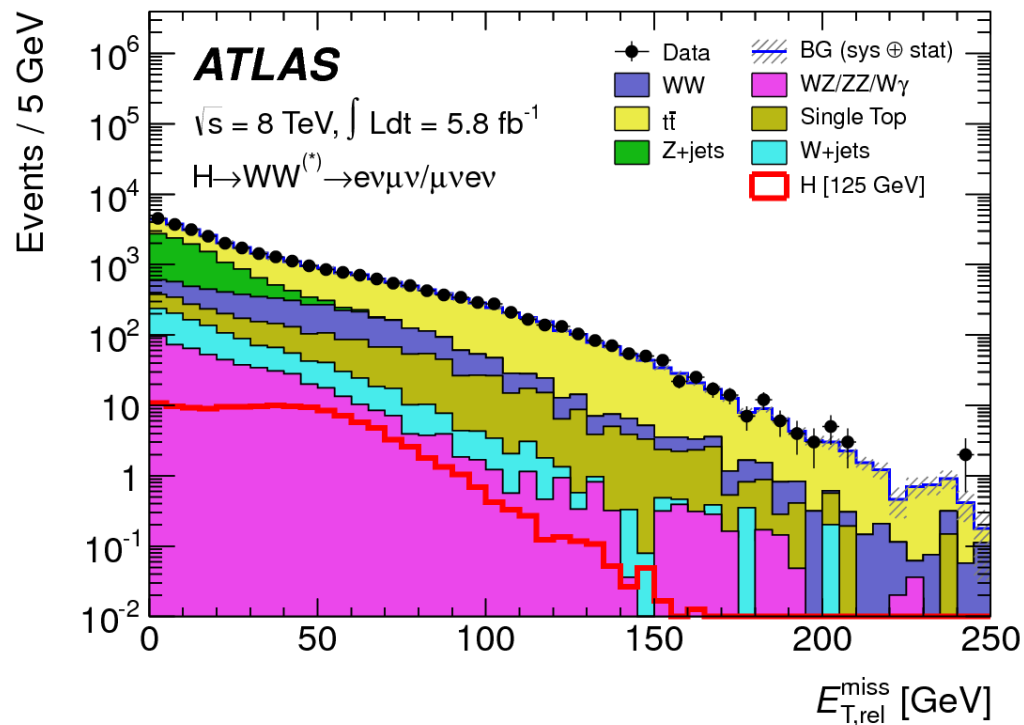
# Summary of characterization of excess

**Table 7**

Characterisation of the excess in the  $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ ,  $H \rightarrow \gamma\gamma$  and  $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$  channels and the combination of all channels listed in Table 6. The mass value  $m_{\max}$  for which the local significance is maximum, the maximum observed local significance  $Z_l$  and the expected local significance  $E(Z_l)$  in the presence of a SM Higgs boson signal at  $m_{\max}$  are given. The best fit value of the signal strength parameter  $\hat{\mu}$  at  $m_H = 126$  GeV is shown with the total uncertainty. The expected and observed mass ranges excluded at 95% CL (99% CL, indicated by a \*) are also given, for the combined  $\sqrt{s} = 7$  TeV and  $\sqrt{s} = 8$  TeV data.

Search channel	Dataset	$m_{\max}$ [GeV]	$Z_l$ [ $\sigma$ ]	$E(Z_l)$ [ $\sigma$ ]	$\hat{\mu}(m_H = 126 \text{ GeV})$	Expected exclusion [GeV]	Observed exclusion [GeV]
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$	7 TeV	125.0	2.5	1.6	$1.4 \pm 1.1$		
	8 TeV	125.5	2.6	2.1	$1.1 \pm 0.8$		
	7 & 8 TeV	125.0	3.6	2.7	$1.2 \pm 0.6$	124-164, 176-500	131-162, 170-460
$H \rightarrow \gamma\gamma$	7 TeV	126.0	3.4	1.6	$2.2 \pm 0.7$		
	8 TeV	127.0	3.2	1.9	$1.5 \pm 0.6$		
	7 & 8 TeV	126.5	4.5	2.5	$1.8 \pm 0.5$	110-140	112-123, 132-143
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$	7 TeV	135.0	1.1	3.4	$0.5 \pm 0.6$		
	8 TeV	120.0	3.3	1.0	$1.9 \pm 0.7$		
	7 & 8 TeV	125.0	2.8	2.3	$1.3 \pm 0.5$	124-233	137-261
Combined	7 TeV	126.5	3.6	3.2	$1.2 \pm 0.4$		
	8 TeV	126.5	4.9	3.8	$1.5 \pm 0.4$		
	7 & 8 TeV	126.5	6.0	4.9	$1.4 \pm 0.3$	110-582 113-532 (*)	111-122, 131-559 113-114, 117-121, 132-527 (*)

# H → WW, missing Et and Jet multiplicity



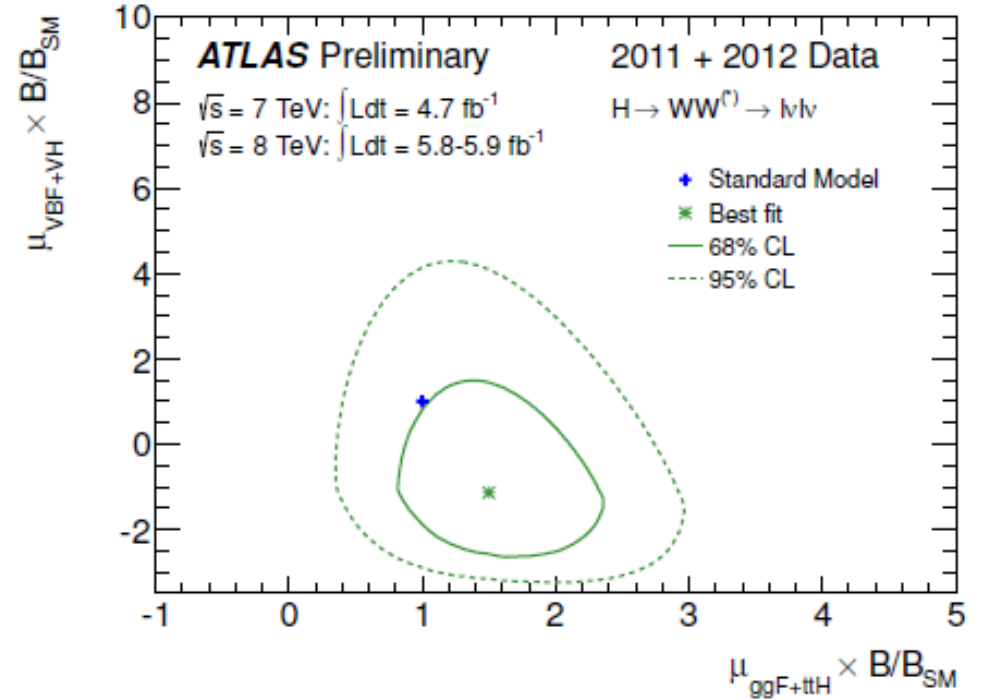
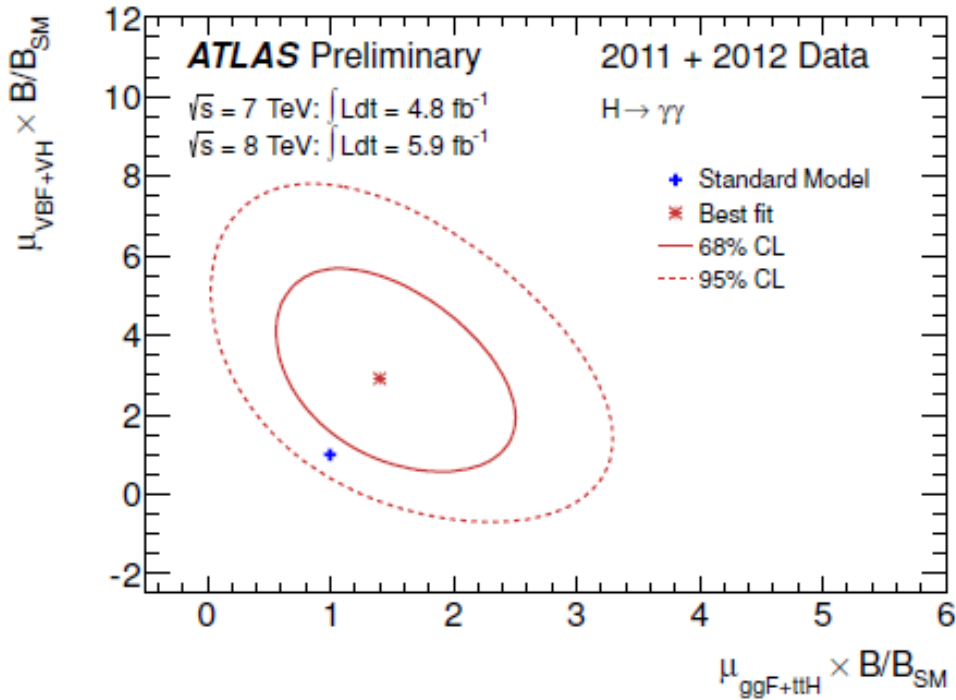
# Numbers of observed and expected SM signal events

Decay	Sub-channel	$N_{obs}$	$\langle N_B \rangle$	$\langle N_{ggF} \rangle$	$\langle N_{VBF} \rangle$	$\langle N_{WH} \rangle$	$\langle N_{ZH} \rangle$	$\langle N_{ttH} \rangle$
$H \rightarrow \gamma\gamma$	low- $p_{Tt}$	7013	6820.3	138.0	6.3	3.1	1.8	0.4
	high- $p_{Tt}$	320	290.6	14.0	2.9	1.8	1.0	0.4
	2-jet	36	24.2	1.3	3.4	0.0	0.0	0.0
$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$	–	14	5.4	5.6	0.5	0.1	0.1	0.0
$H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$	0-jet	667	573.5	75.3	0.8	0.3	0.4	0.0
	1-jet	183	140.8	16.7	1.7	0.3	0.2	0.0
	2-jet	3	3.7	0.3	1.3	0.0	0.0	0.0
$H \rightarrow \tau^+\tau^-$	0-jet	9277	9304.8	17.6	0.6	0.1	0.3	0.0
	1-jet	393	406.2	3.6	1.0	0.1	0.2	0.0
	2-jet	22	28.2	0.3	0.9	0.0	0.0	0.0
	VH	164	151.9	0.7	0.1	0.2	0.3	0.0
$H \rightarrow b\bar{b}$	ZH	322	320.7	0.0	0.0	0.0	4.0	0.0
	WH	1266	1311.4	0.0	0.0	11.1	0.0	0.0

Number of selected events, bkg and expected SM signal contribution for a 126GeV Higgs boson from various production modes satisfying all selection requirements.

These numbers refer to mass windows that contain about 90% of the signal. Categories that do not provide significant discrimination for the production mode are merged.

# Likelihood contours for $H \rightarrow \gamma\gamma$ and $H \rightarrow WW \rightarrow l\nu l\nu$ VBF+VH vs ggF+ttH



Likelihood contours for the  $H \rightarrow \gamma\gamma$  and  $H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$  in the  $(\mu_{\text{ggF} + \text{ttH}}, \mu_{\text{VBF} + \text{VH}})$  plane including the BR factor  $B/B_{\text{SM}}$ . The quantity  $\mu_{\text{ggF} + \text{ttH}}$  ( $\mu_{\text{VBF} + \text{VH}}$ ) is a common scale factor for the ggF and ttH (VBF and VH) production cross sections.

$$H \rightarrow WW^{(*)} \rightarrow l^+ \nu \quad l^- \bar{\nu}$$

Focus in 2012 data:  $e\mu, \mu e$  final states  
 $\sigma \times \text{BR} = 112 \text{ fb (8 TeV)}$

# WW event selection summary

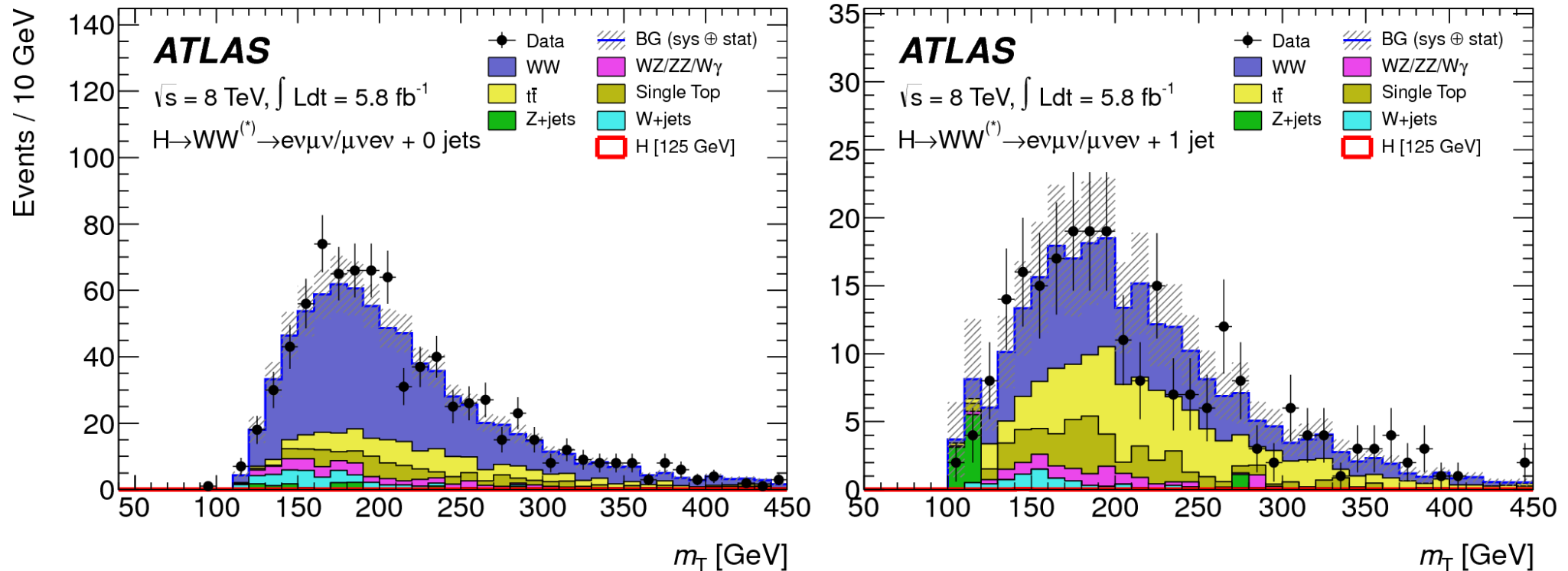
Fiducial cuts	$p_{T,l1} > 25 \text{ GeV}, p_{T,l2} > 15 \text{ GeV},$ $ \eta_\mu  < 2.5,  \eta_e  < 2.47, \text{ excluding } 1.37 <  \eta_e  < 1.52$
Lepton Isolation	Track sum ET and Calo sum ET inside a $\Delta R < 0.3$ cone around the Z leptons.
Dilepton Invariant mass	$m_{ll} < 50 \text{ (80) GeV},$ for 0 - 1 (2) jet channels
Dilepton PT (0-jet channel)	$\left  \vec{p}_T^{ll} \right  = \left  \vec{p}_T^{l1} + \vec{p}_T^{l2} \right  > 30 \text{ GeV}$
Missing ET (relative)	ET,rel > 25 GeV
Categories	H + 0 jets, H + 1 jet, H + 2 jets
For 2012 (8TeV) only the $e\mu$ final state is used ( $5.8 \text{ fb}^{-1}$ )	

Transverse mass is the discriminant used in the search:

$$m_T = \sqrt{\left(E_T^{ll} + E_T^{\text{miss}}\right)^2 - \left|\vec{p}_T^{ll} + \vec{E}_T^{\text{miss}}\right|^2}$$

$$E_T^{ll} = \sqrt{\left|\vec{p}_T^{ll}\right|^2 + m_{ll}^2}$$

# Background measurements from data

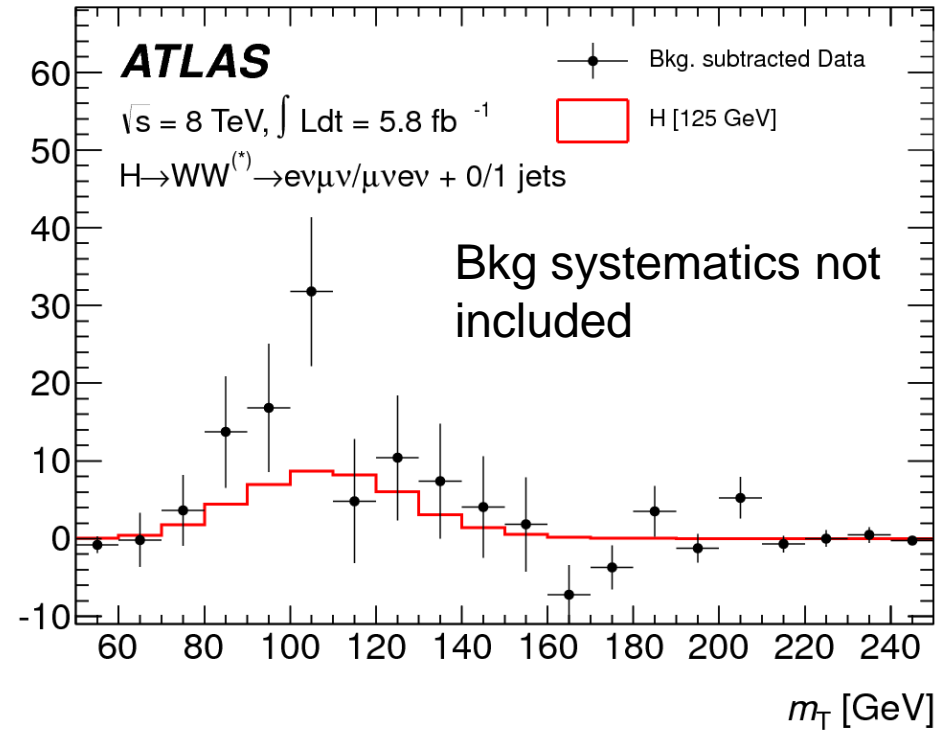
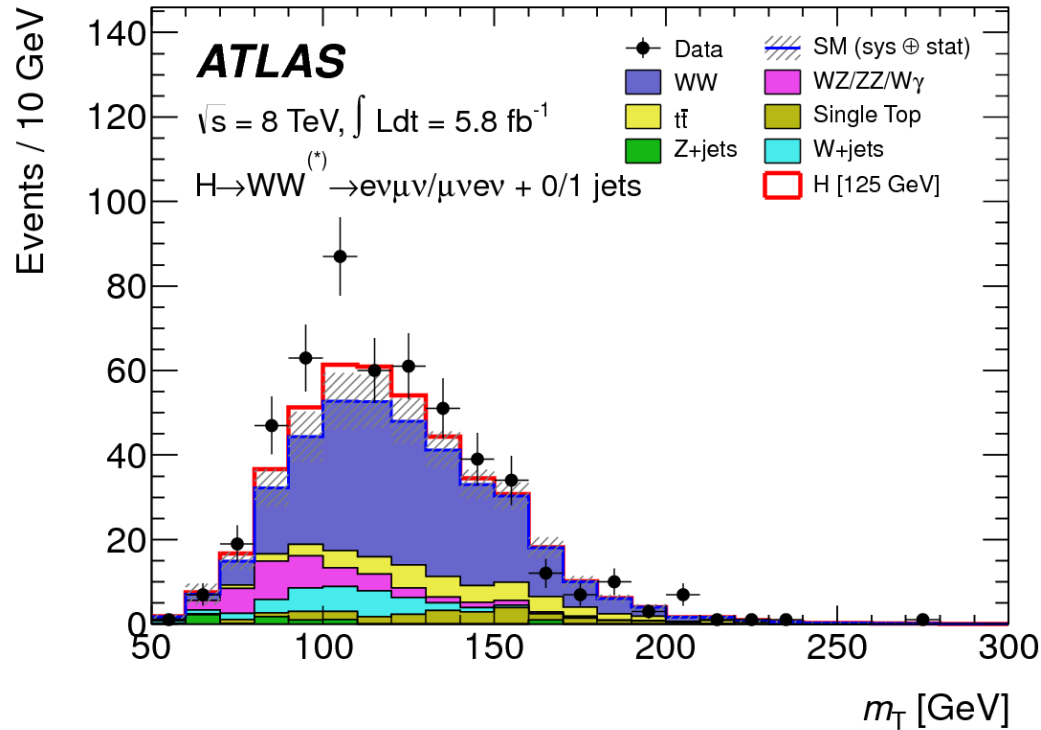


Example control regions  
for  $WW + 0 \text{ jets}$  (mostly  $WW$ )  
and  $WW + 1 \text{ jet}$  (large  $t\bar{t}$  + single top fraction).

# Systematic Uncertainties

Uncertainty	Description
Theoretical uncertainties associated to the <b>signal</b>	$\pm 17\%$ (0-jets), $\pm 36\%$ (1-jet)
Jet energy scale (max effect on <b>signal</b> )	$\pm 7\%$ in W+0jet
Jet energy scale (max effect on bkg)	$\pm 4\%$ in W+1jet
Jet energy resolution (max effect on <b>signal</b> )	$\pm 4\%$ in W+1jet
Jet energy resolution (max effect on bkg)	$\pm 2\%$ in W+1jet
Pile-up to JES (max effect on <b>signal</b> )	$\pm 4\%$ in W+1jet
Pile-up to JES (max effect on bkg)	$\pm 2\%$ in W+1jet
Missing ET effect in total yield	$\pm 3\%$ ( $\pm 3\%$ ) signal (bkg)
b-jet tagging efficiency	$\pm 10\%$ in W+1jet
W+jet prediction effect in the total bkg	$\pm 5\%$

# WW Observed and expected events



$0.75m_H < m_T < m_H$  for  $m_H = 125 \text{ GeV}$ .

	0-jet	1-jet	2-jet
Signal	$20 \pm 4$	$5 \pm 2$	$0.34 \pm 0.07$
WW	$101 \pm 13$	$12 \pm 5$	$0.10 \pm 0.14$
$WZ^{(*)}/ZZ/W\gamma^{(*)}$	$12 \pm 3$	$1.9 \pm 1.1$	$0.10 \pm 0.10$
$t\bar{t}$	$8 \pm 2$	$6 \pm 2$	$0.15 \pm 0.10$
$tW/tb/tqb$	$3.4 \pm 1.5$	$3.7 \pm 1.6$	-
Z/ $\gamma^*$ + jets	$1.9 \pm 1.3$	$0.10 \pm 0.10$	-
W + jets	$15 \pm 7$	$2 \pm 1$	-
Total background	$142 \pm 16$	$26 \pm 6$	$0.35 \pm 0.18$
Observed	185	38	0

# Right and Left-handed fermions

A massless right-handed fermion

A massless left-handed fermion

