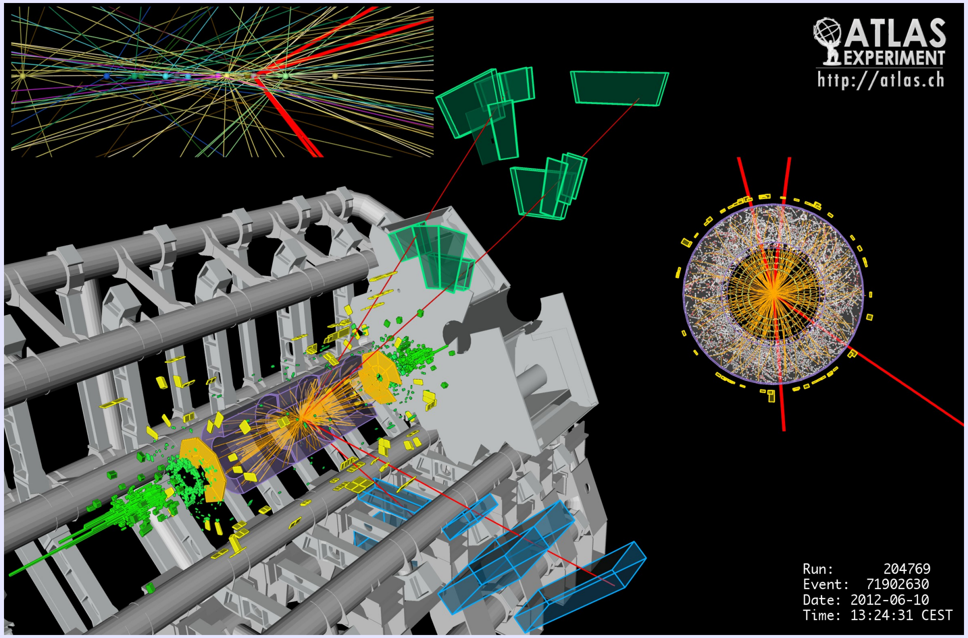
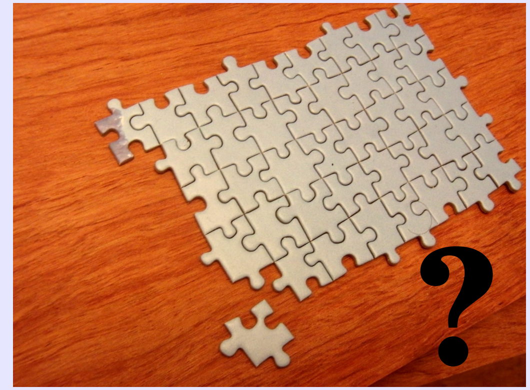




Discovery of a new particle in the Higgs searches at the LHC

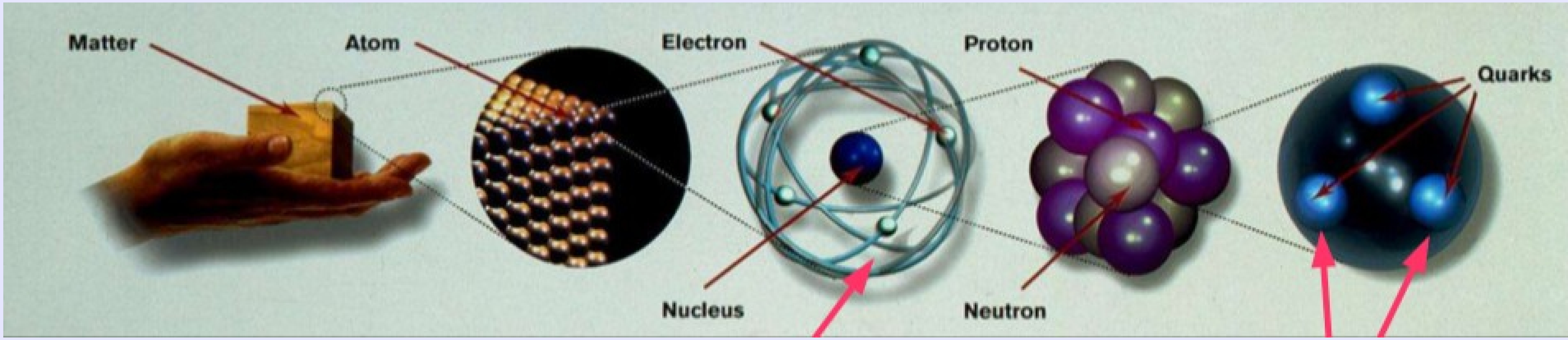
LIP

Patricia Conde Muíño

CCQS, Evora (8-12 Outubro 12)

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA EDUCAÇÃO E CIÊNCIA
QREN QUADRO DE REFERÊNCIA ESTRATÉGICO NACIONAL
COMPETE PROGRAMA OPERACIONAL FACTORES DE COMPETITIVIDADE

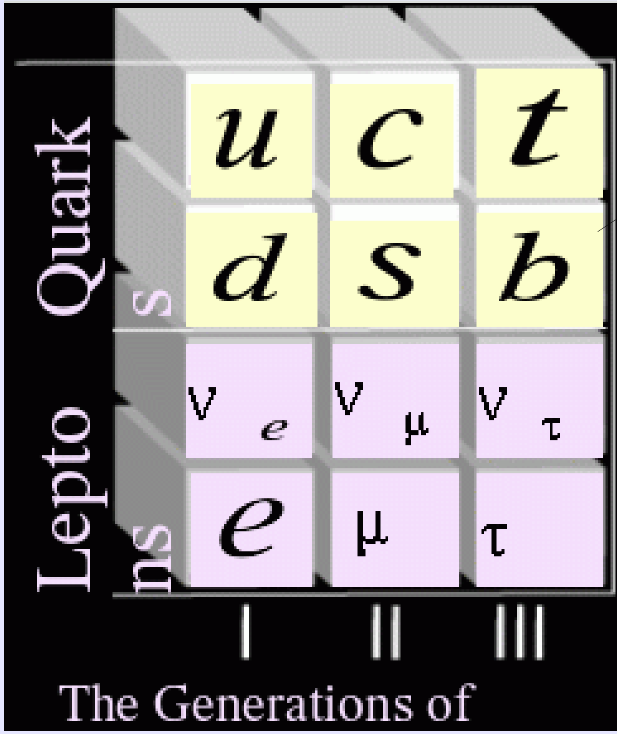
Fundamental constituents of mater



Electron

Quarks
u y d

Fundamental particles



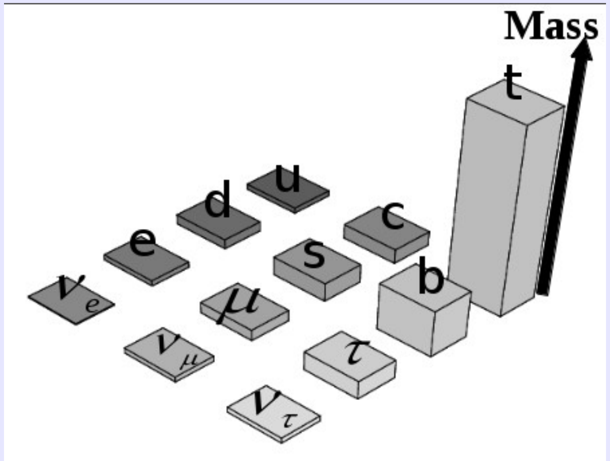
Fermions

Bosons:

	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon

The Standard Model of Particle Physics

- Standard Model of particle interactions developed ~25 years ago
  - Very successful!
  - Prediction of neutral currents & heavy vector bosons
    - Found at LEP. Mayor success!
  - LEP precision measurements show that SM describes accurately many physics processes
- However there are still some questions
- One of the missing points is the generation of mass
  - Not demonstrated yet
  - Introduced through the Higgs mechanism



Electroweak interactions

- Description electroweak interactions in the SM implemented via a gauge theory based on $SU(2)_L x U(1)_Y$ symmetry
  - Lagrangian of free massless particles:

$$\mathcal{L} = -\frac{1}{2} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

Kinetic terms and self interaction for W fields and B fields

$$+ \bar{\psi}_L \gamma^\mu \left(i\partial_\mu - g' \frac{Y}{2} B_\mu - g \frac{1}{2} \boldsymbol{\tau} \cdot \boldsymbol{W}_\mu \right) \psi_L$$

$$+ \bar{\psi}_R \gamma^\mu \left(i\partial_\mu - g' \frac{Y}{2} B_\mu \right) \psi_R$$

Fermion interactions

  - Lagrangian transforms as a singlet of the symmetry groups
- We know that fermions & bosons have masses
- However: introducing mass terms in this lagrangian breaks the symmetry, leading to a non-renormalizable theory

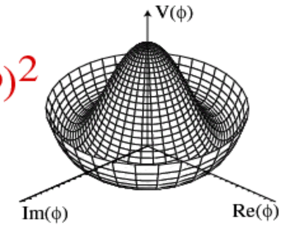
The Higgs mechanism

HIGGS FIELD

Complex weak isospin scalar doublet Φ with scalar potential $V[\Phi]$

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \qquad V[\Phi] = \mu^2\Phi^\dagger\Phi + \lambda\,(\Phi^\dagger\Phi)^2$$

$$(\lambda > 0,\ \mu^2 < 0)$$



STANDARD MODEL

Yang-Mills $SU(2)_L \times U(1)_Y$

massless gauge bosons W_μ and B_μ

and *massless* fermions ψ

$$\mathcal{L} = -\frac{1}{2}\boldsymbol{W}_{\mu\nu}\cdot\boldsymbol{W}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$+\left|\left(i\partial_\mu - g'\frac{Y}{2}B_\mu - g\frac{1}{2}\boldsymbol{\tau}\cdot\boldsymbol{W}_\mu\right)\Phi\right|^2 - V(\Phi)$$

$$+\bar{\psi}_L\gamma^\mu\left(i\partial_\mu - g'\frac{Y}{2}B_\mu - g\frac{1}{2}\boldsymbol{\tau}\cdot\boldsymbol{W}_\mu\right)\psi_L$$

$$+\bar{\psi}_R\gamma^\mu\left(i\partial_\mu - g'\frac{Y}{2}B_\mu\right)\psi_R$$

SPONTANEOUS SYMMETRY BREAKING

One component acquires non-zero vacuum expectation value

$$\langle 0|\Phi|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \longrightarrow \Phi(x) = \frac{1}{\sqrt{2}}\exp\left(i\frac{\xi\cdot\tau}{2v}\right)\begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

The masses

MASSIVE GAUGE BOSONS

$$W^{\pm}_{\mu} = \frac{1}{2}(W^1_{\mu} \mp iW^2_{\mu}) \qquad M_W = \frac{gv}{2}$$

$$Z_{\mu} = -B_{\mu}\sin\theta_W + W^3_{\mu}\cos\theta_W \qquad M_Z = \frac{M_W}{\cos\theta_W}$$

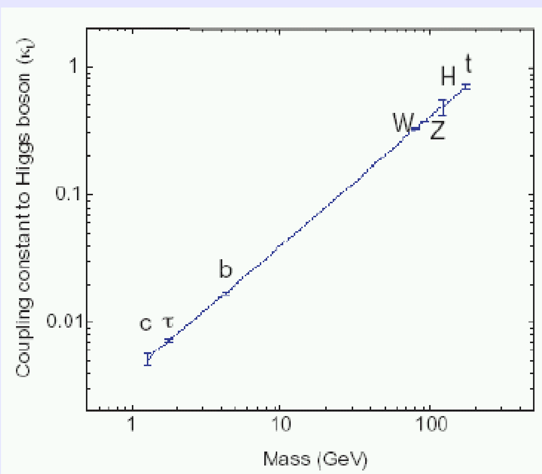
$$A_{\mu} = B_{\mu}\sin\theta_W + W^3_{\mu}\cos\theta_W \qquad M_{\gamma} = 0$$

MASSIVE FERMIONS

Yukawa couplings of Higgs to fermions

$$g_f\left[\bar{\psi}_L \Phi \psi_R + \bar{\psi}_R \Phi^{\dagger} \psi_L\right]$$

$$e.g., \; m_e = \frac{g_e v}{\sqrt{2}}$$



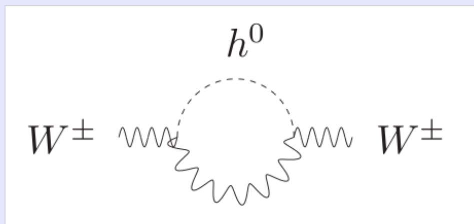
- Mass of each particle is proportional to its Higgs coupling!
- Slope is predicted by $v = 2M_W/g = 246$ GeV
- Yukawa couplings: free parameters, determined from fermion masses

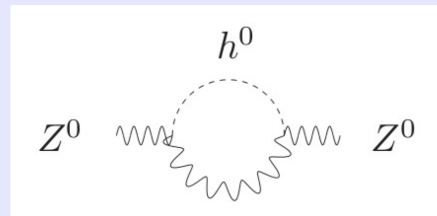
Requires a massive scalar field ⇒ the Higgs Boson

Higgs Mass ($v\sqrt{\lambda}$) is a free parameter and must be determined by experiment

Corrections to EW observables

- Electroweak observables are sensitive to masses of top quark and Higgs through radiative corrections





$$M_W^2 = \rho\, M_Z^2 \cos^2\theta_W$$

$$(\rho-1) \sim M_{top}^2$$

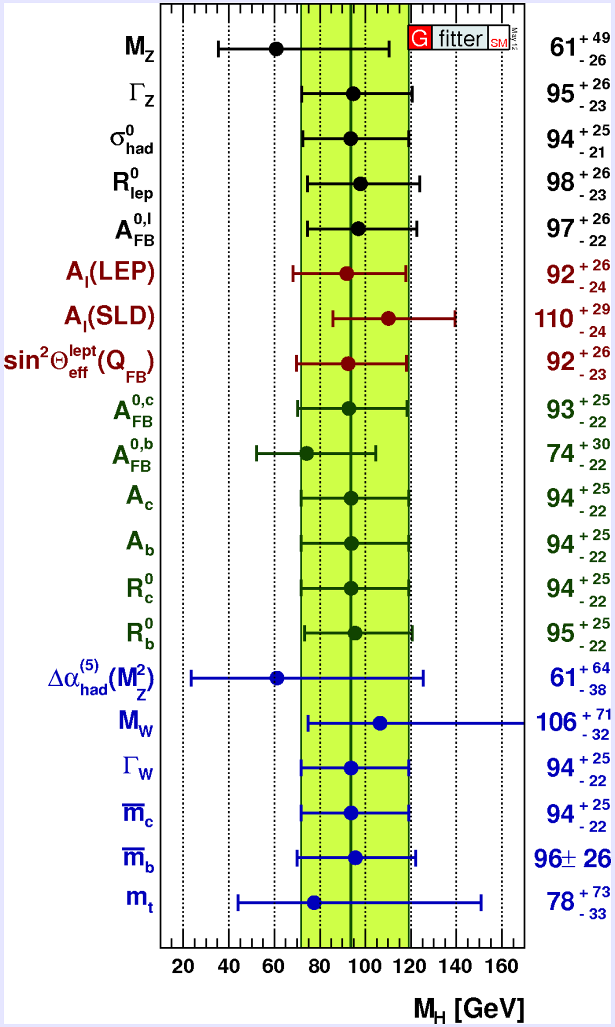
$$(\rho-1) \sim \ln M_H$$

- Precise measurements of electroweak observables can be used to constraint the Higgs boson mass

Sensitivity to Higgs mass is only logarithmic:
Need ultra-precise measurements!

Experimental constraints before the LHC

- Large list of observables used in global fits to the electroweak precision data

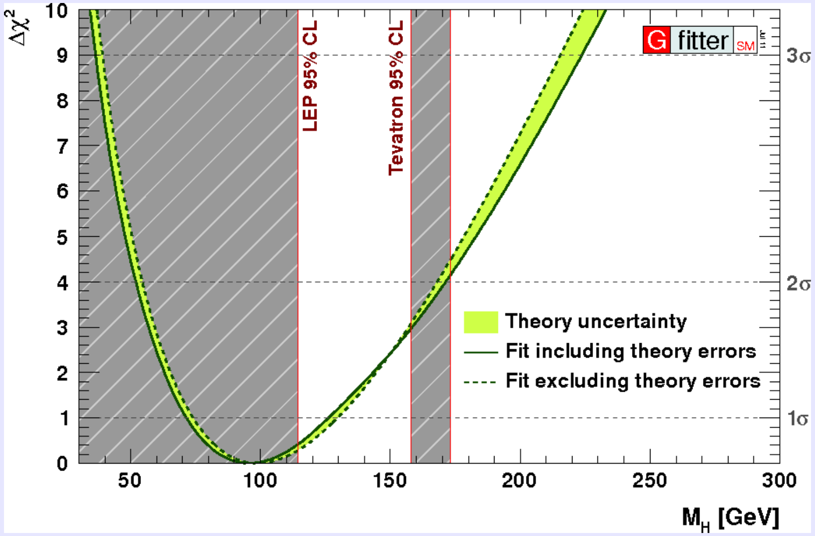


Experimental constraints before the LHC

Fits to the EW observables predict:

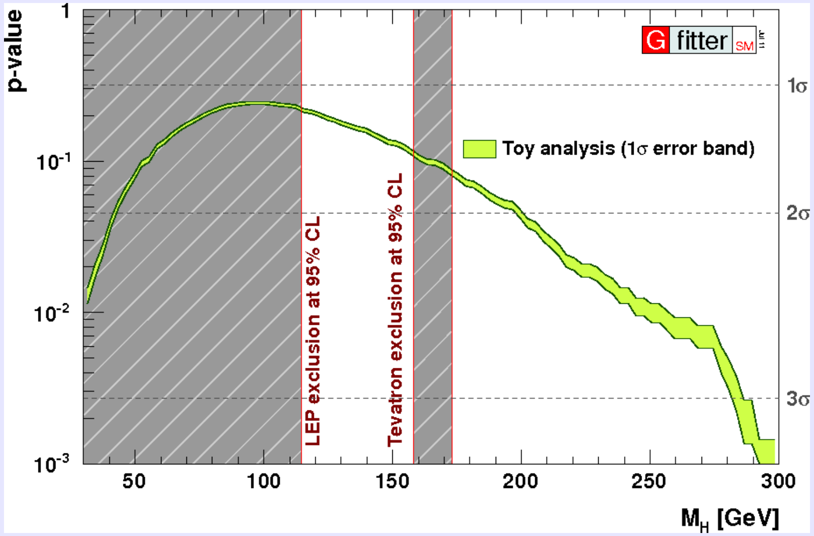
- Best Fit mass: $m_H = 94^{+25}_{-22}$ GeV
- Upper limit at 95% CL from fits:
  - $m_H < 169$ GeV

But the fit is not too bad for masses up to 200 GeV or so.



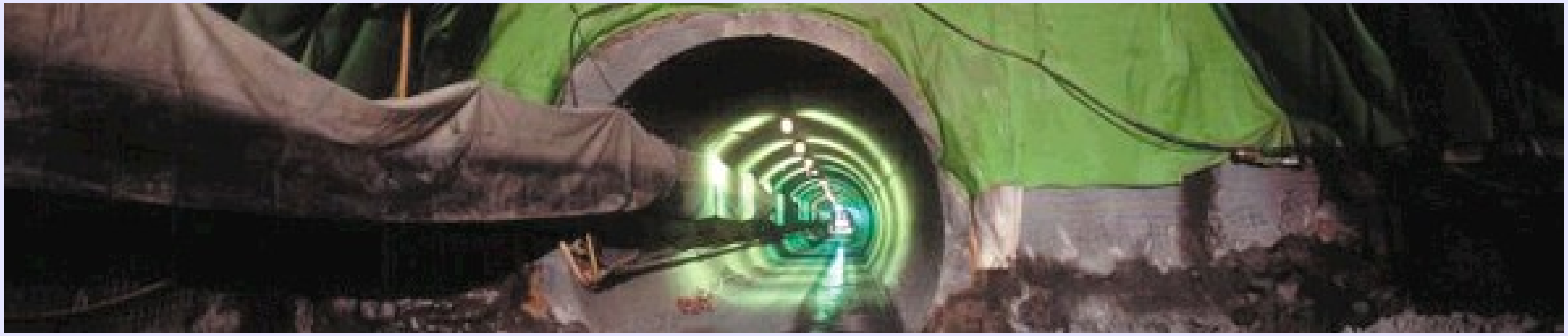
Direct searches excluded the regions at 95% CL:

- LEP: $m_H < 114.5$ GeV
- Tevatron: $147 < m_H < 180$ GeV

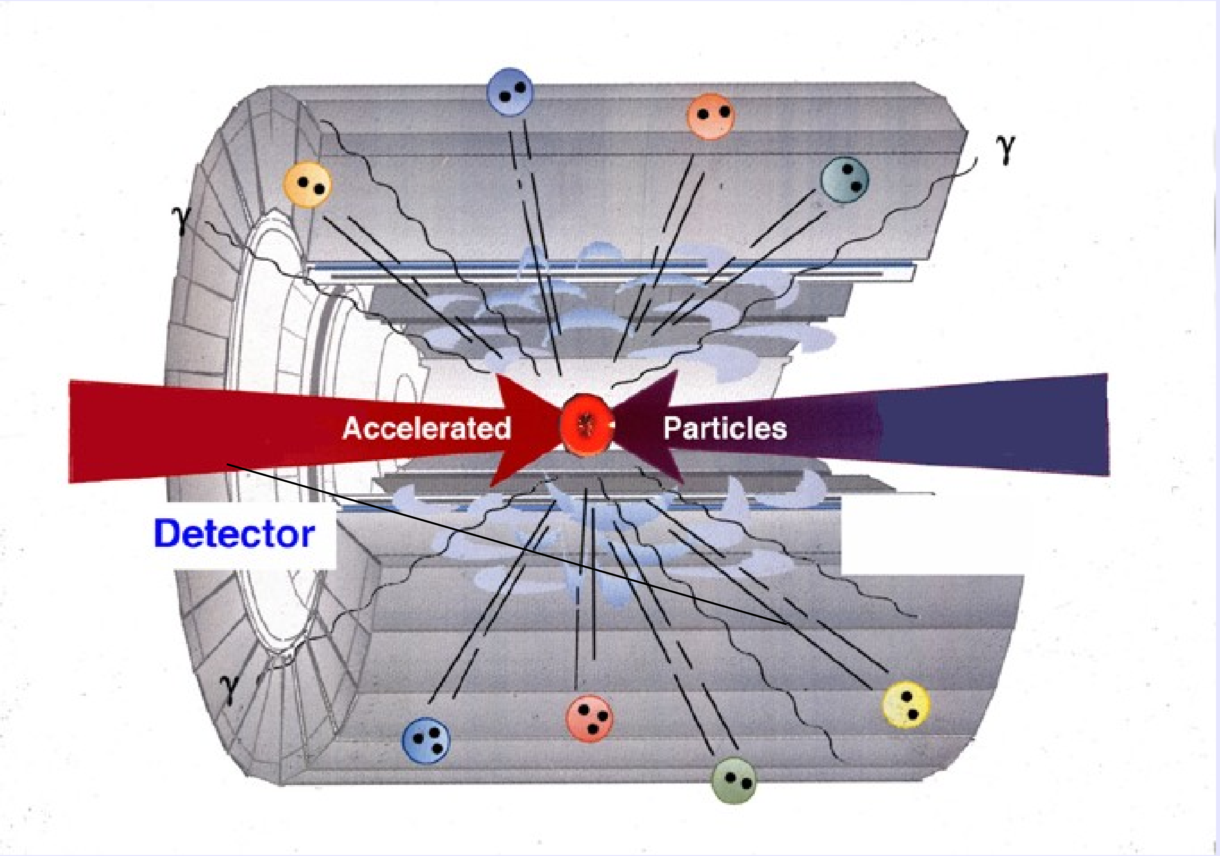


The Higgs search at the LHC

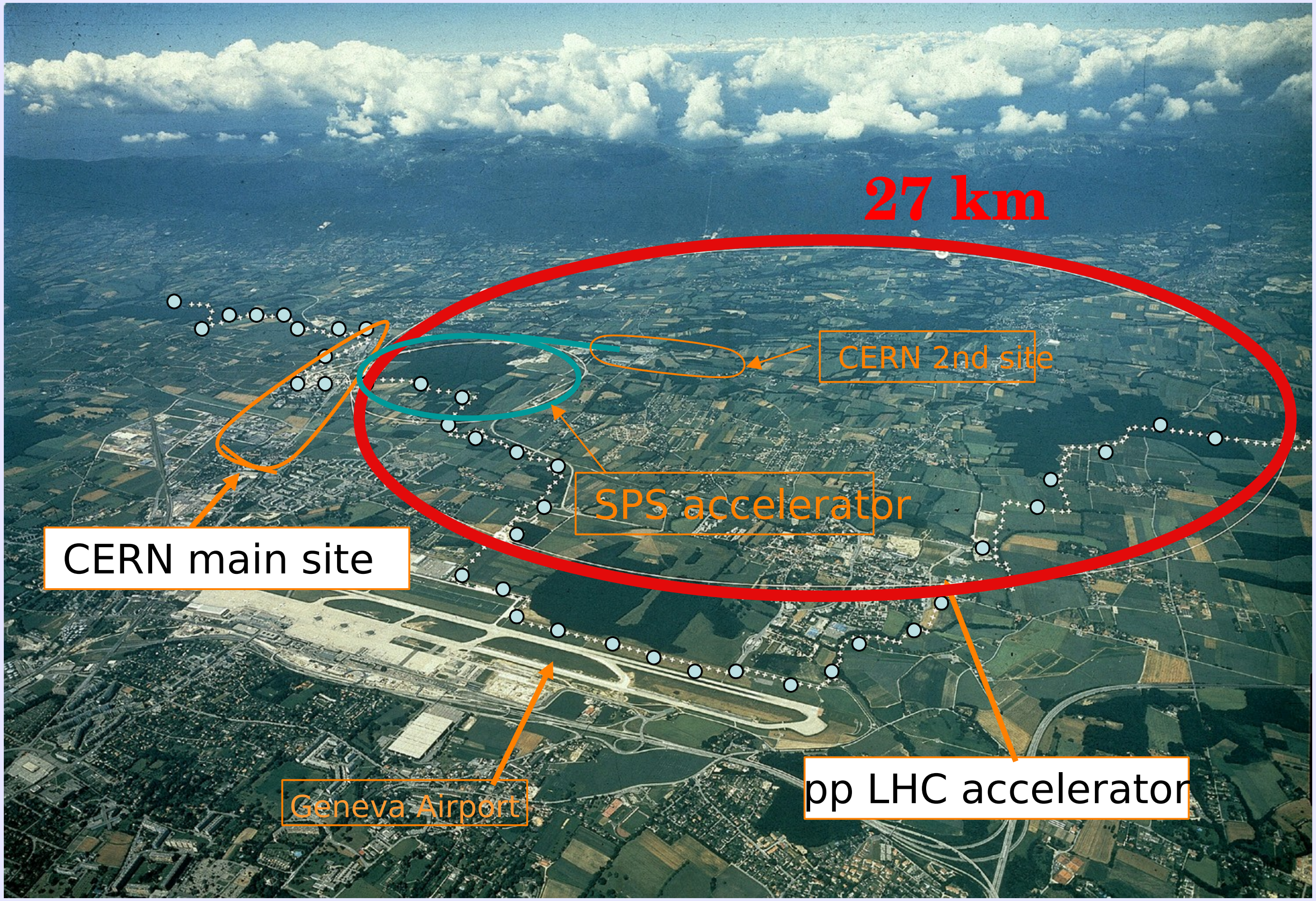
Unveiling the mister y of mass...



Experimental method

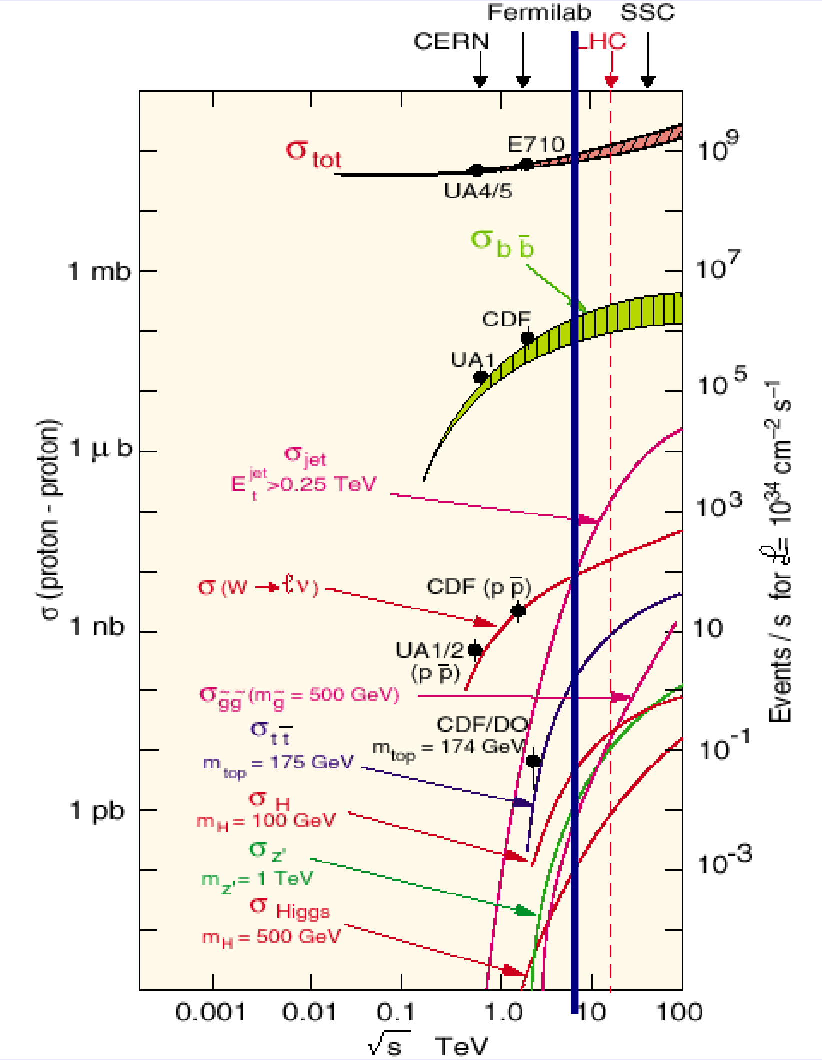


The Large Hadron Collider



- pp collisions at
  - 8 TeV in 2012
  - 7 TeV in 2010/11
- 40 MHz p bunch crossing rate
- Up to ~40 collisions per bunch crossing!
- Four experiments: ATLAS, CMS, LHCb, ALICE

Cross sections in pp collisions



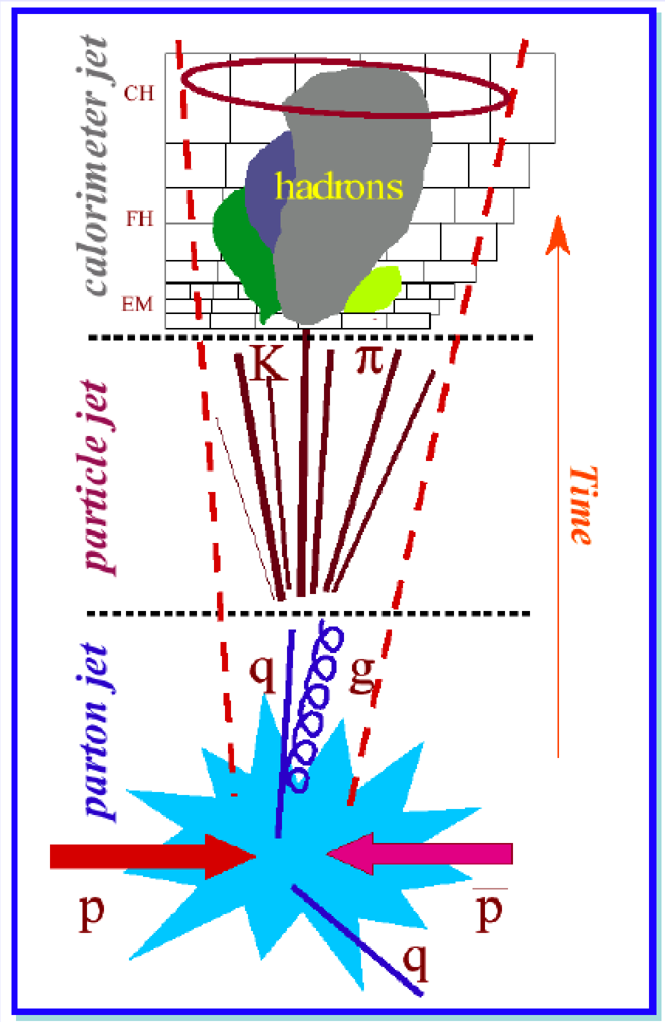
Total production cross section at LHC:

- $\sim 10^3 \cdot \sigma(bb)$
- $\sim 10^7 \cdot \sigma(W \to \mu\nu)$
- $\sim 10^8 \cdot \sigma(tt)$
- $\sim 5\times10^{10} \cdot \sigma(H)$ (m_H ~ 100 GeV)

σ(di-jet) for jets with E_T > 7 GeV is ~ 50% of σ(tot)

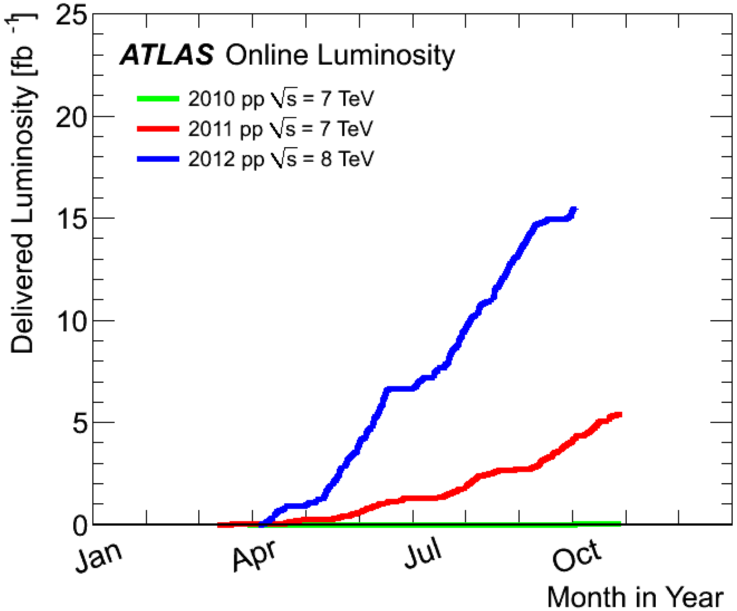
- Most interactions produce jets
- Need to identify clear signatures that distinguish the processes of interest from this background
  - Isolated leptons, photons, ...

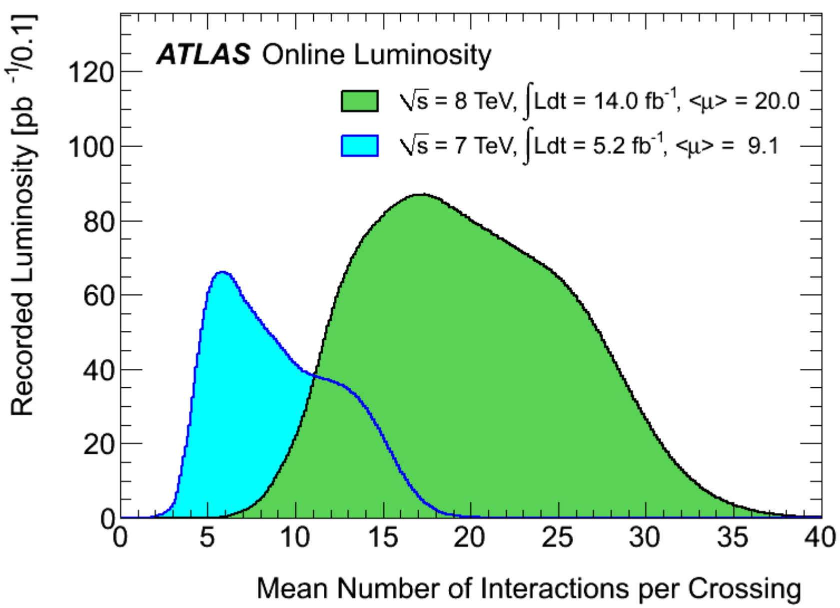
Jets



- Most interactions produce jets
- Jets are the result of the hadronization of quarks and gluons produced in the collision
- Need to identify clear signatures that distinguish the processes of interest from this background
  - Isolated leptons, photons, ...

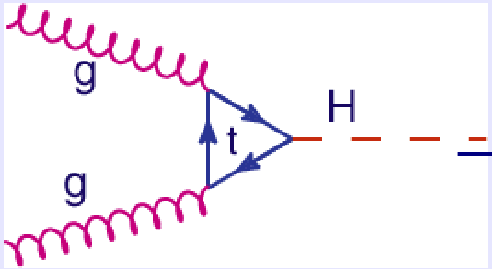
LHC delivered data

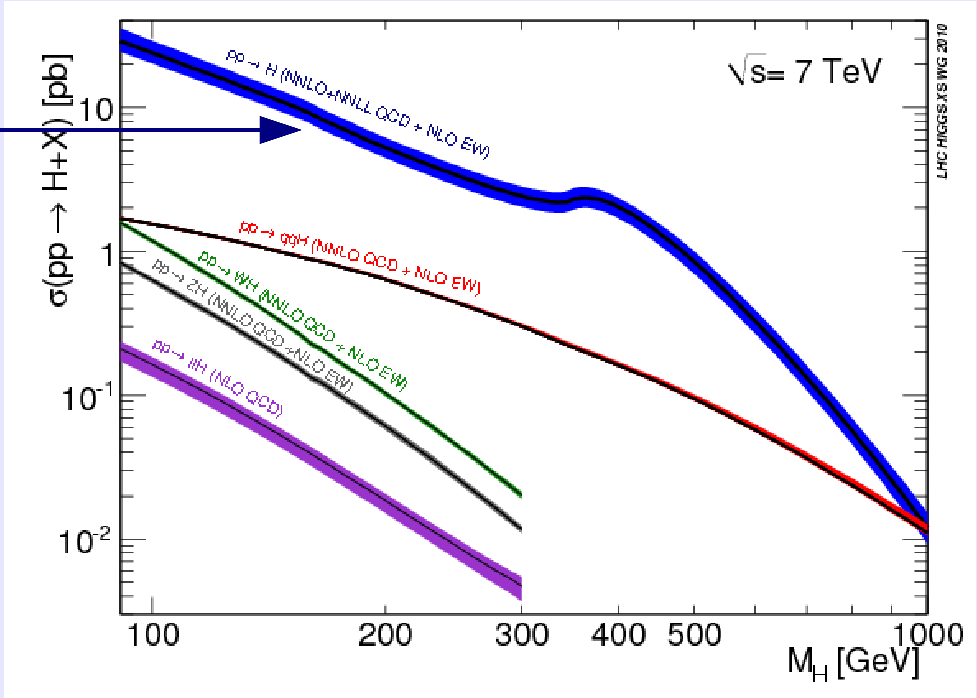




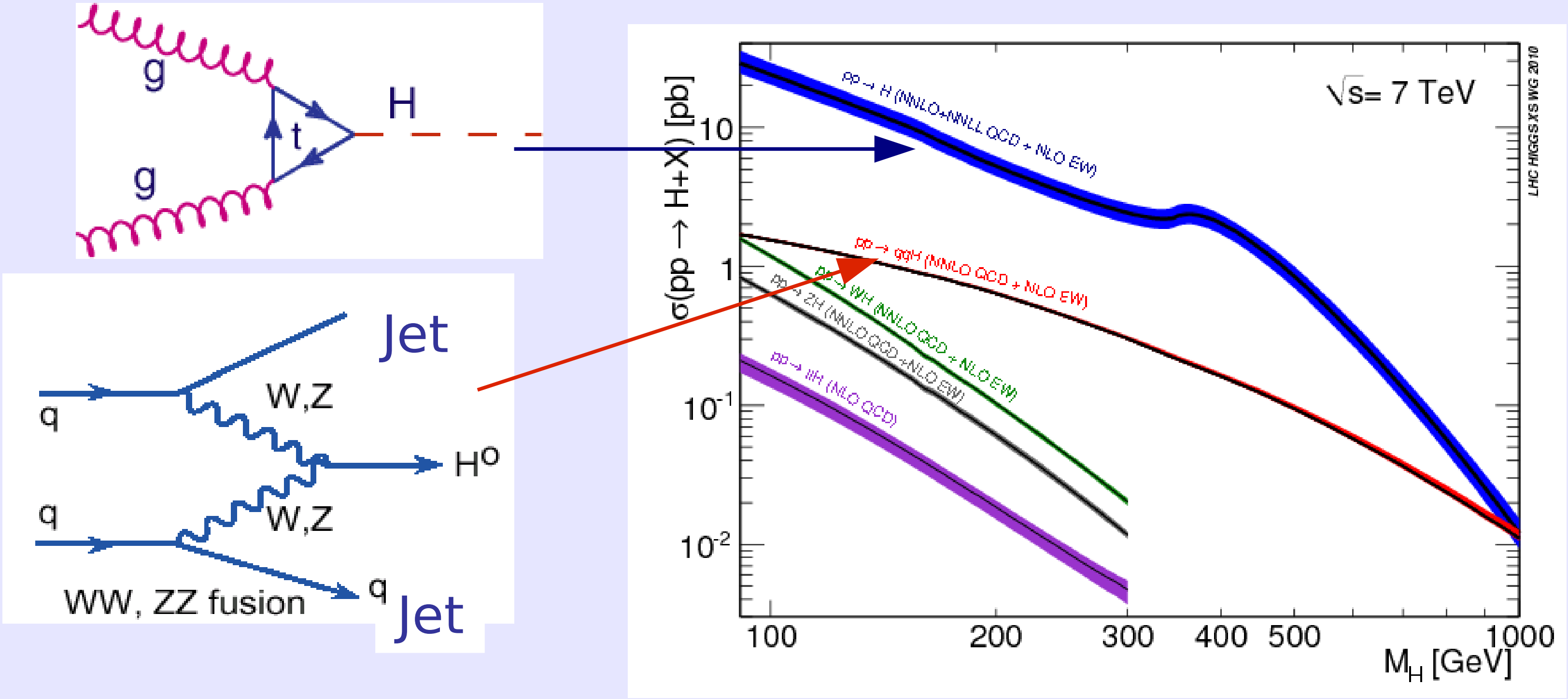
- Total amount of data collected so far:
  - 5.2 fb^{-1} of 7 TeV pp collisions
  - 14 fb^{-1} of 8 TeV pp collisions
- Harsh pile-up conditions in 2012: average of 20 interactions/bunch crossing!
  - Up to 40 in some runs!

Higgs production

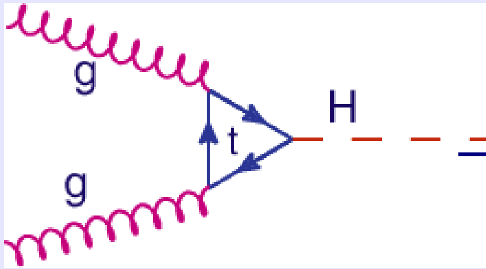


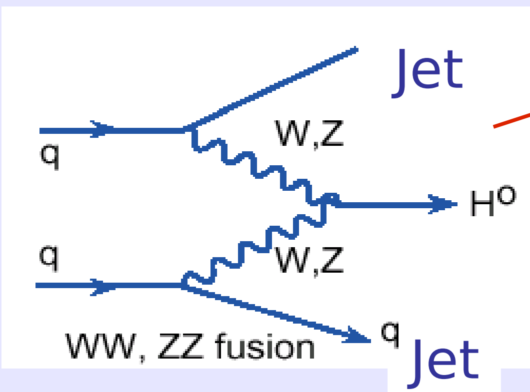


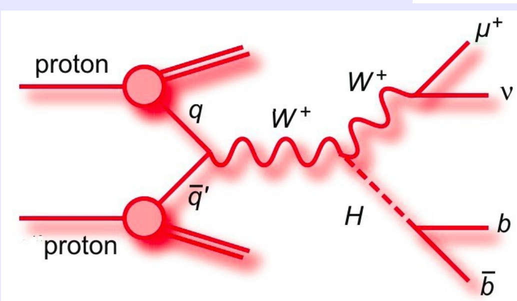
Higgs production

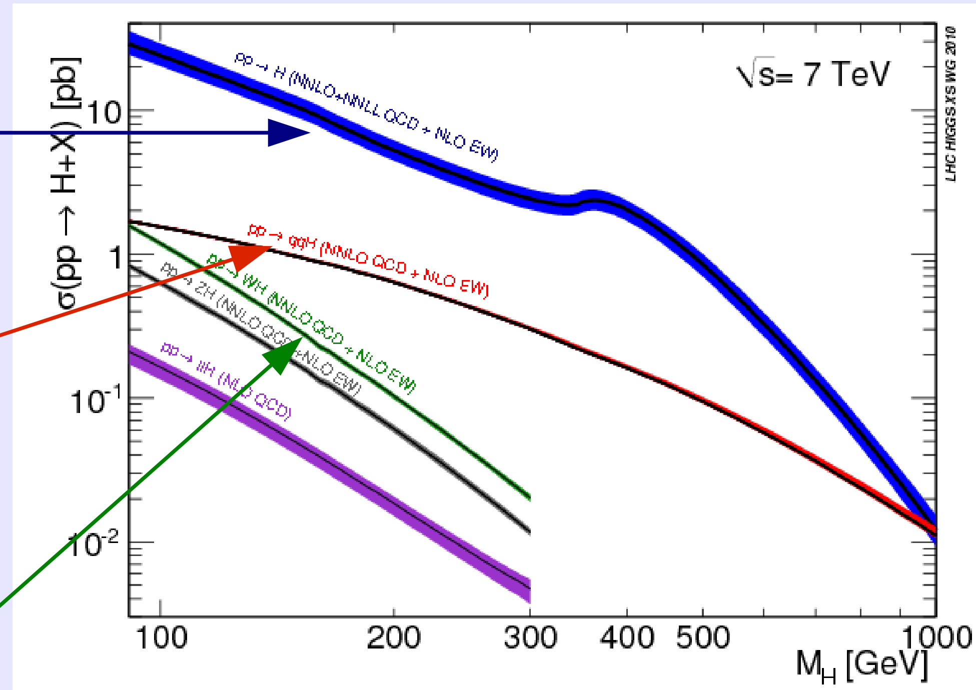


Higgs production

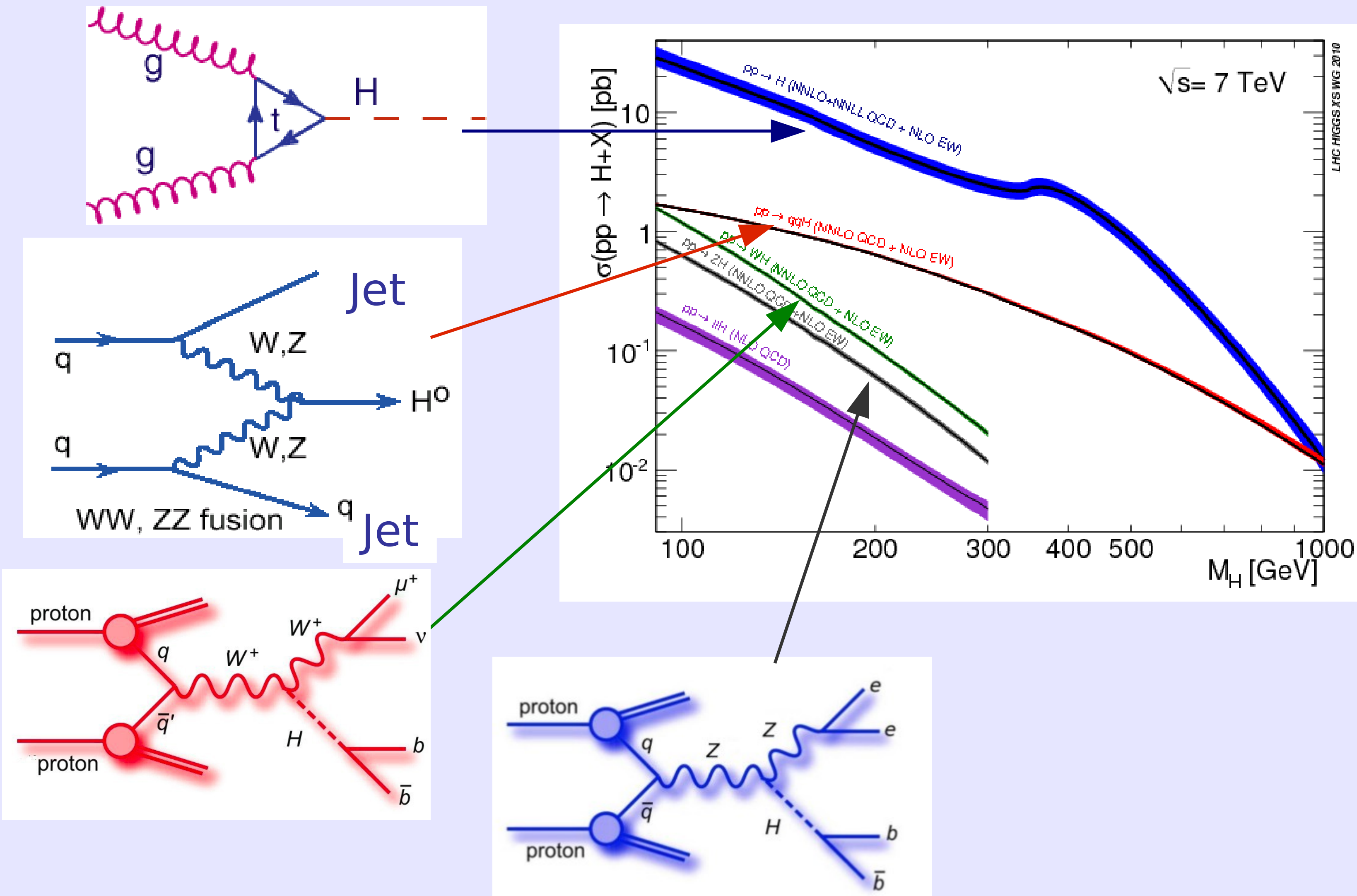




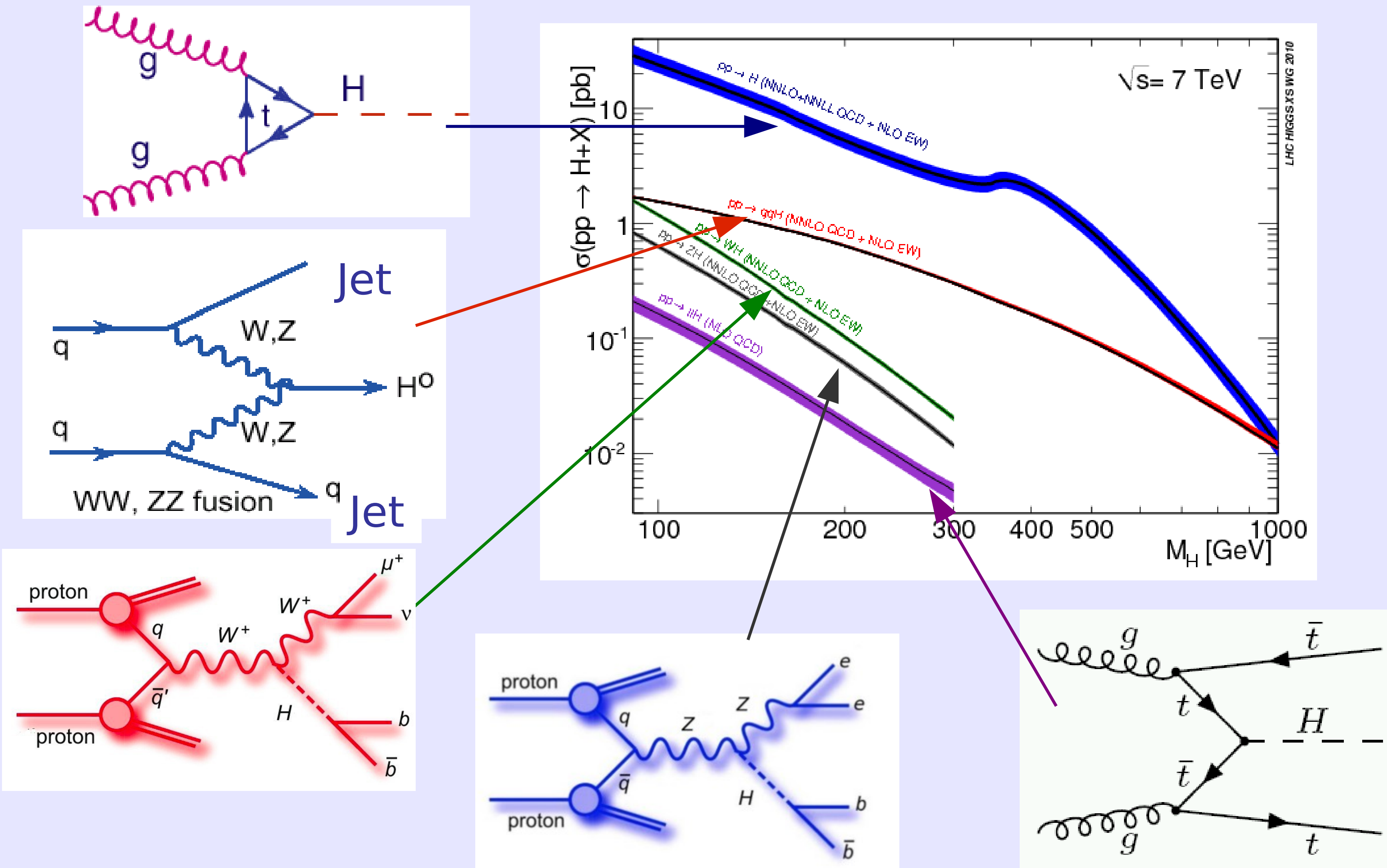




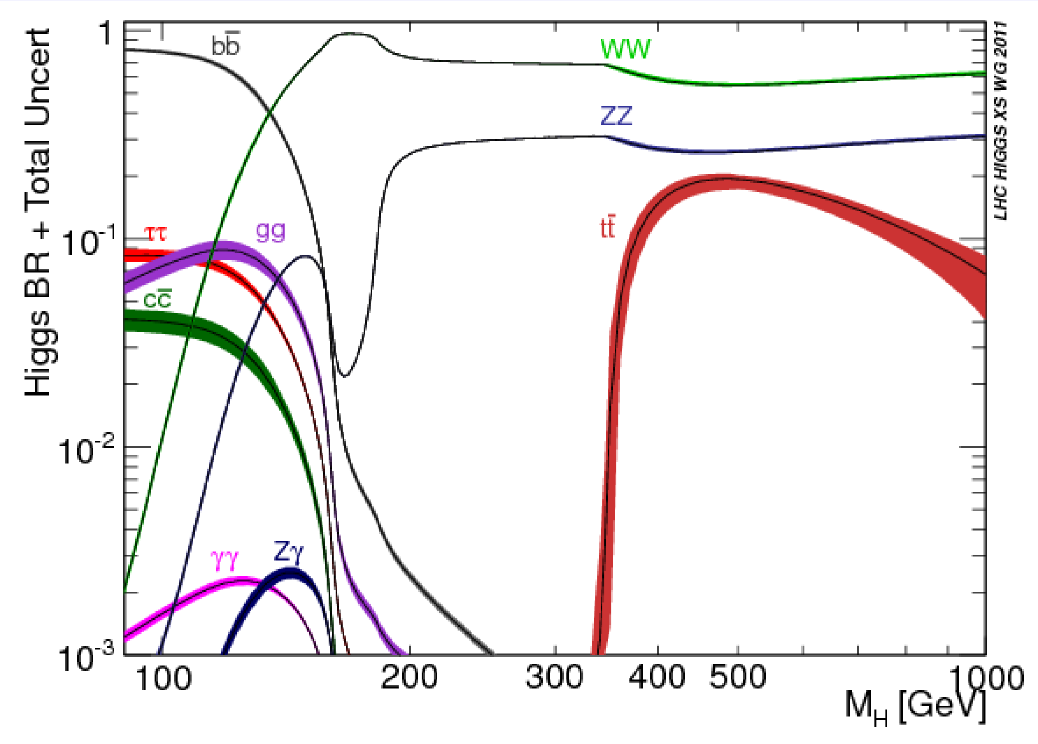
Higgs production



Higgs production

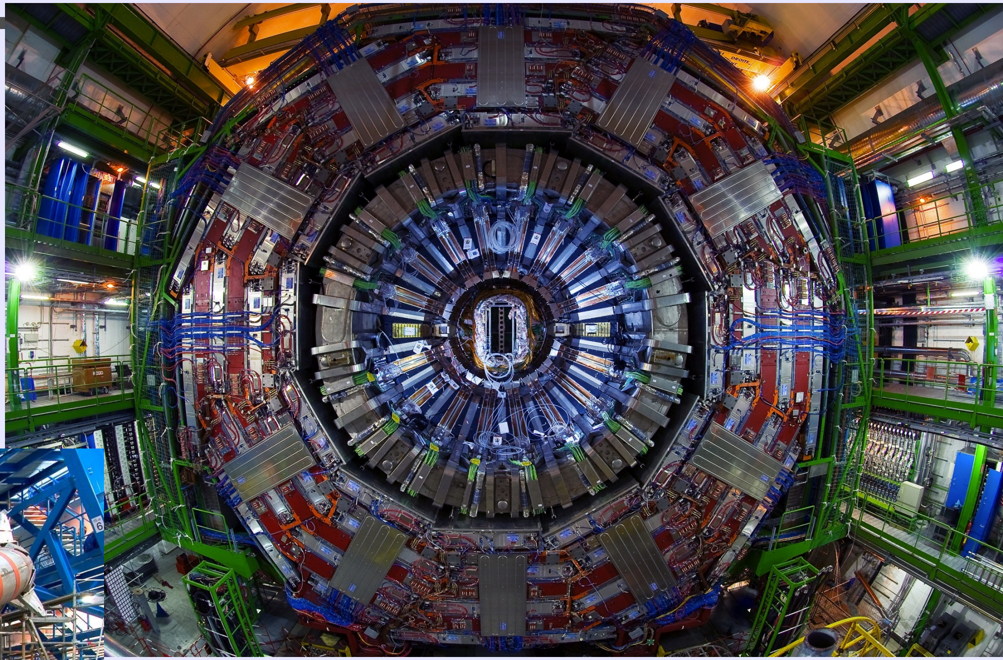


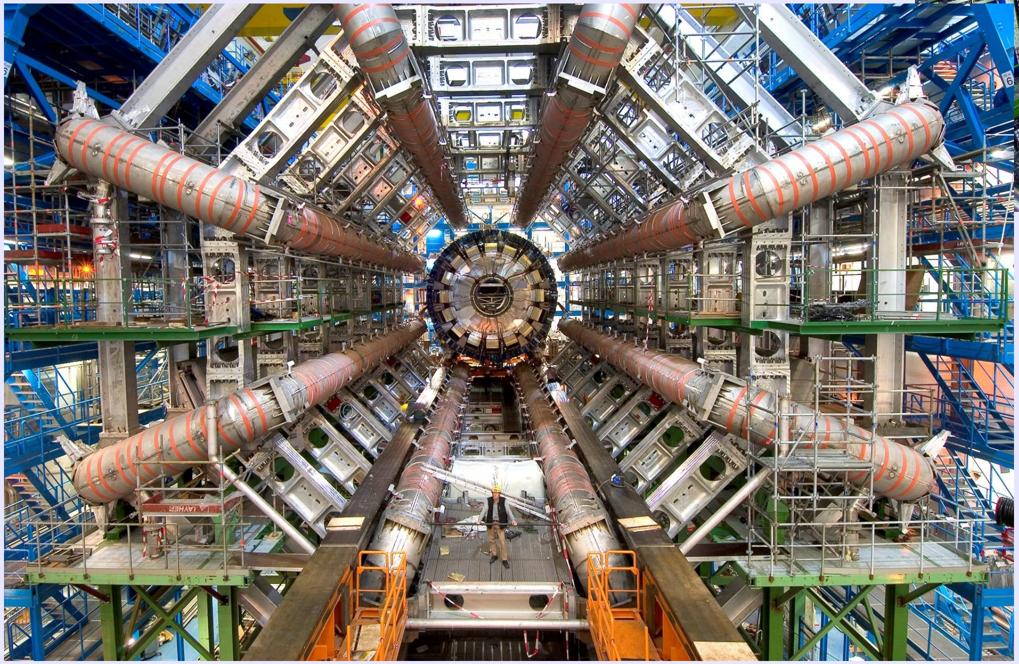
Standard Model Higgs decays



- Search channel: the combination of one/more production modes and a decay mode characterized by particular experimental signatures

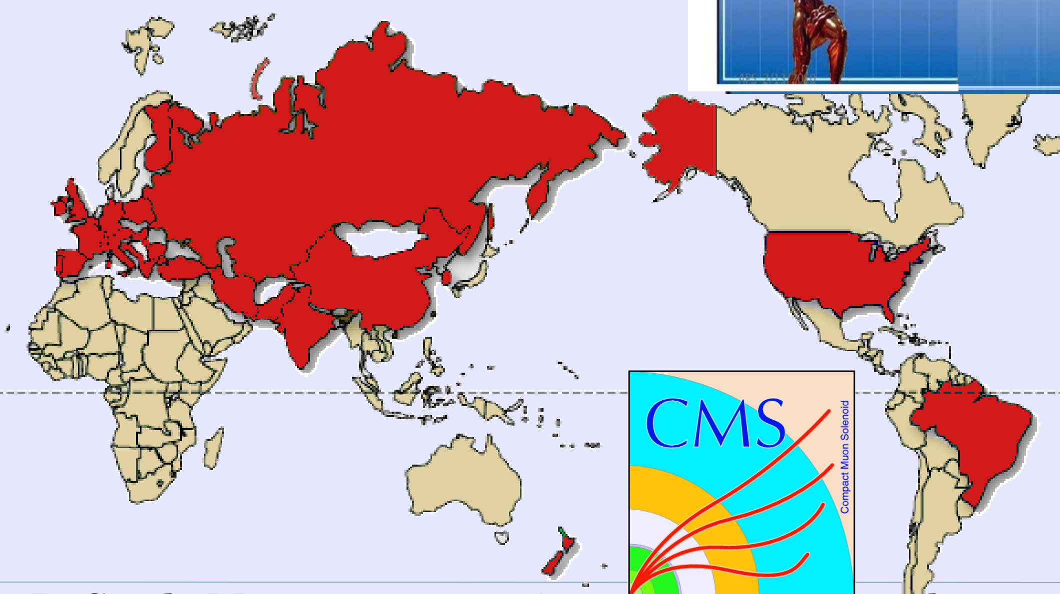
The ATLAS and CMS detectors





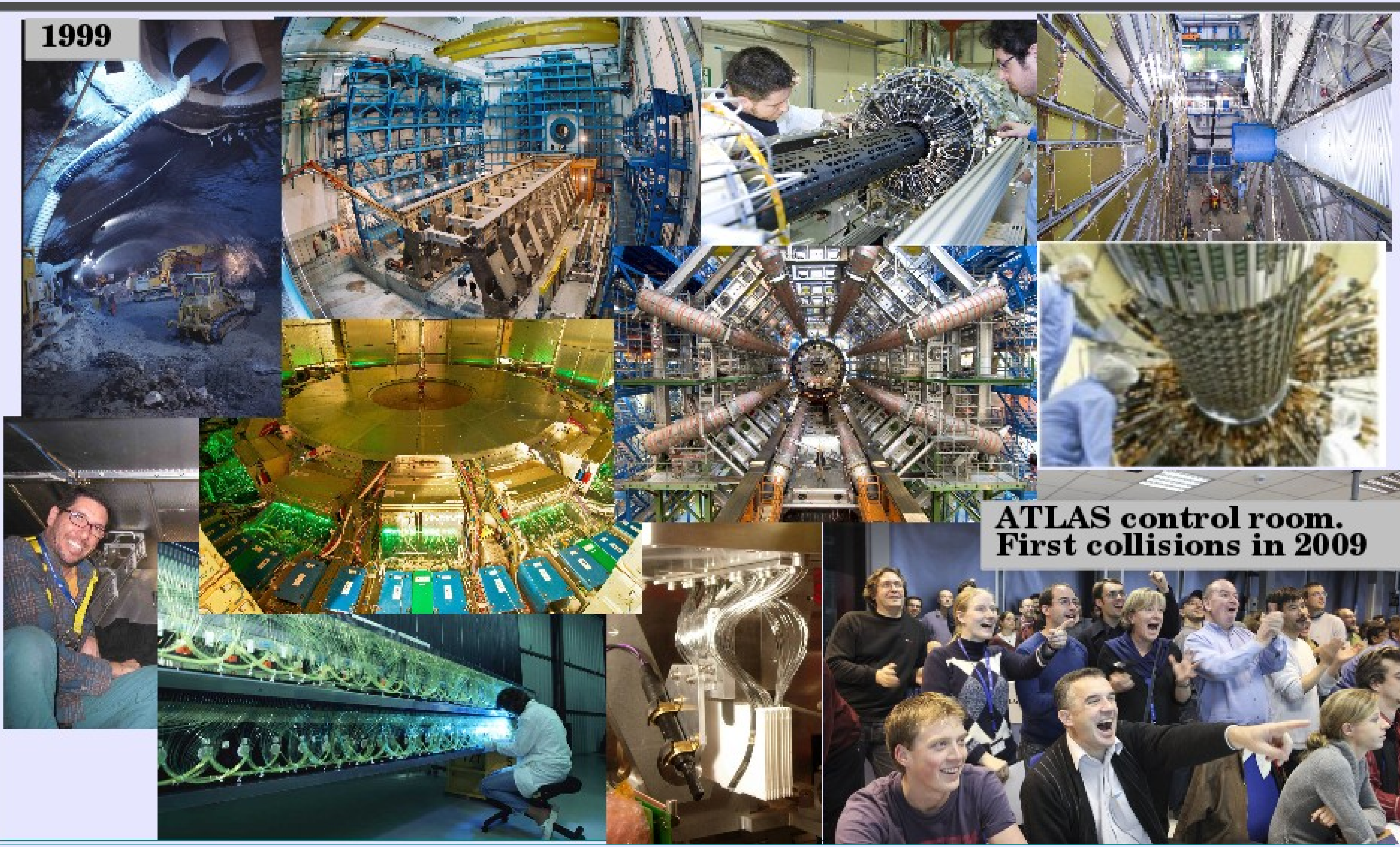
ATLAS and CMS Collaborations

- Each of them composed of
  - >4000 members
  - >3000 physicists
  - ~180 institutions
  - ~40 countries

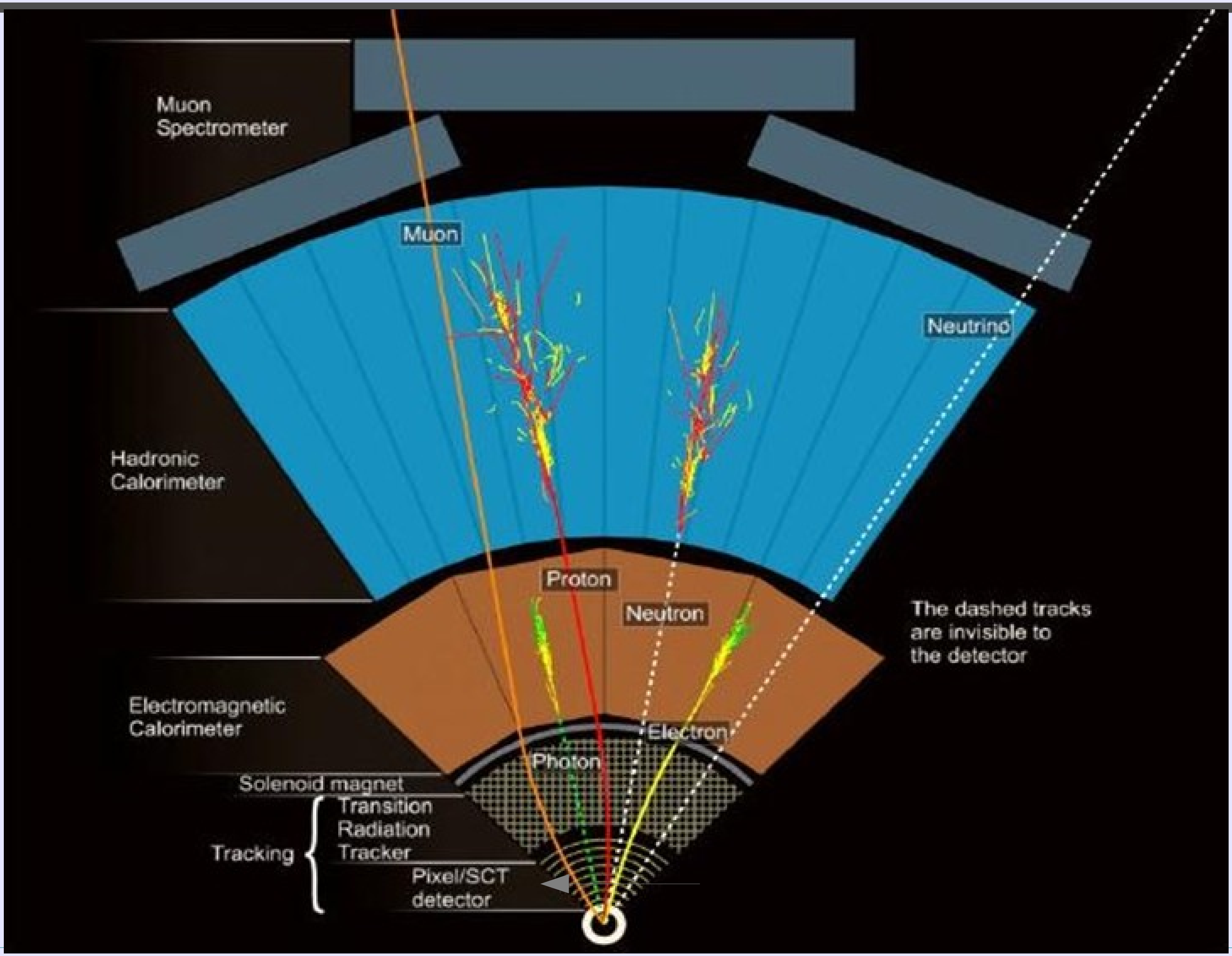


- Examples of a truly global collaboration!

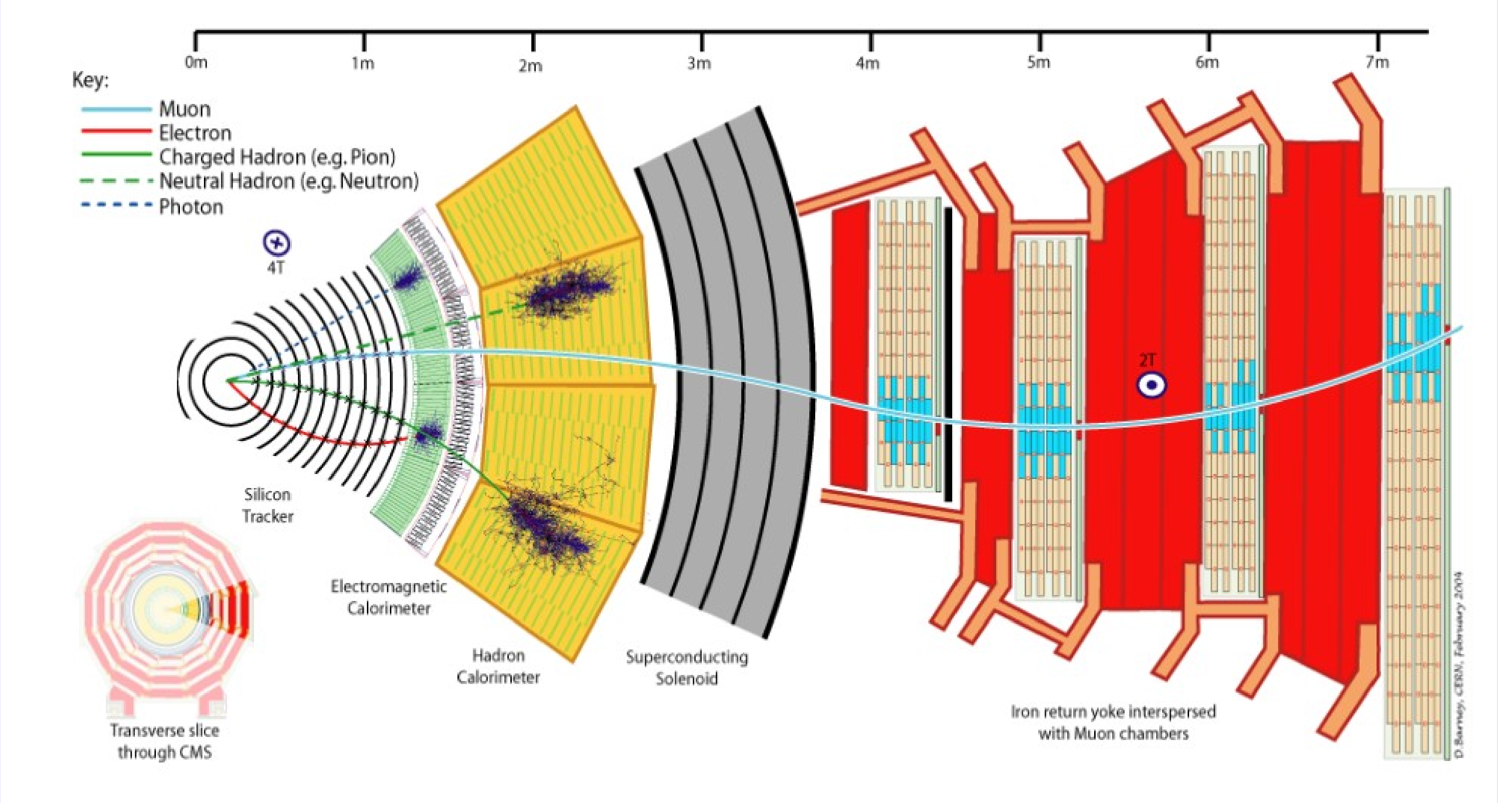
More than 20 years of continuous work...



Particle identification



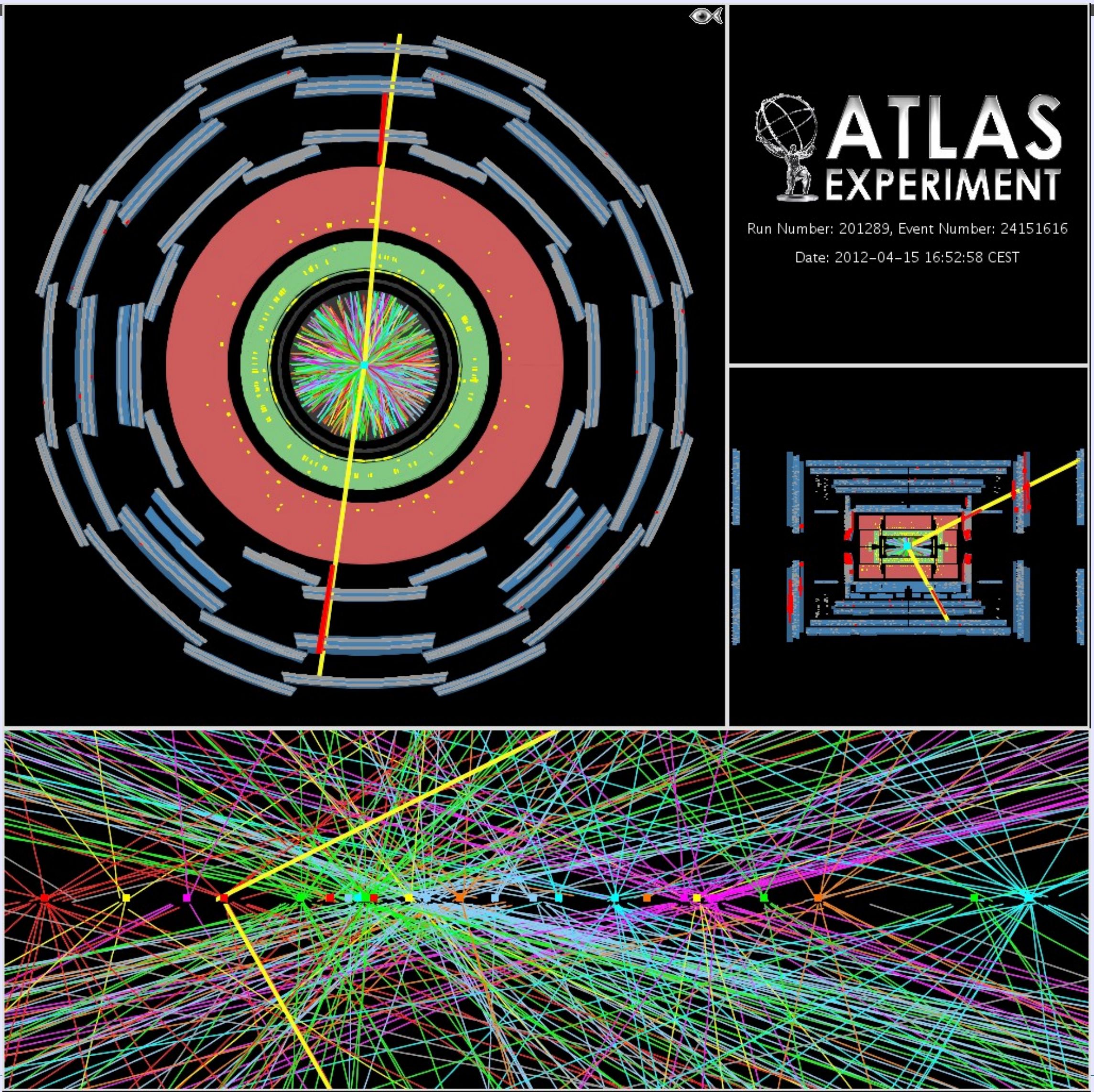
Particle identification @CMS



Global Event Description—Particle flow algorithm

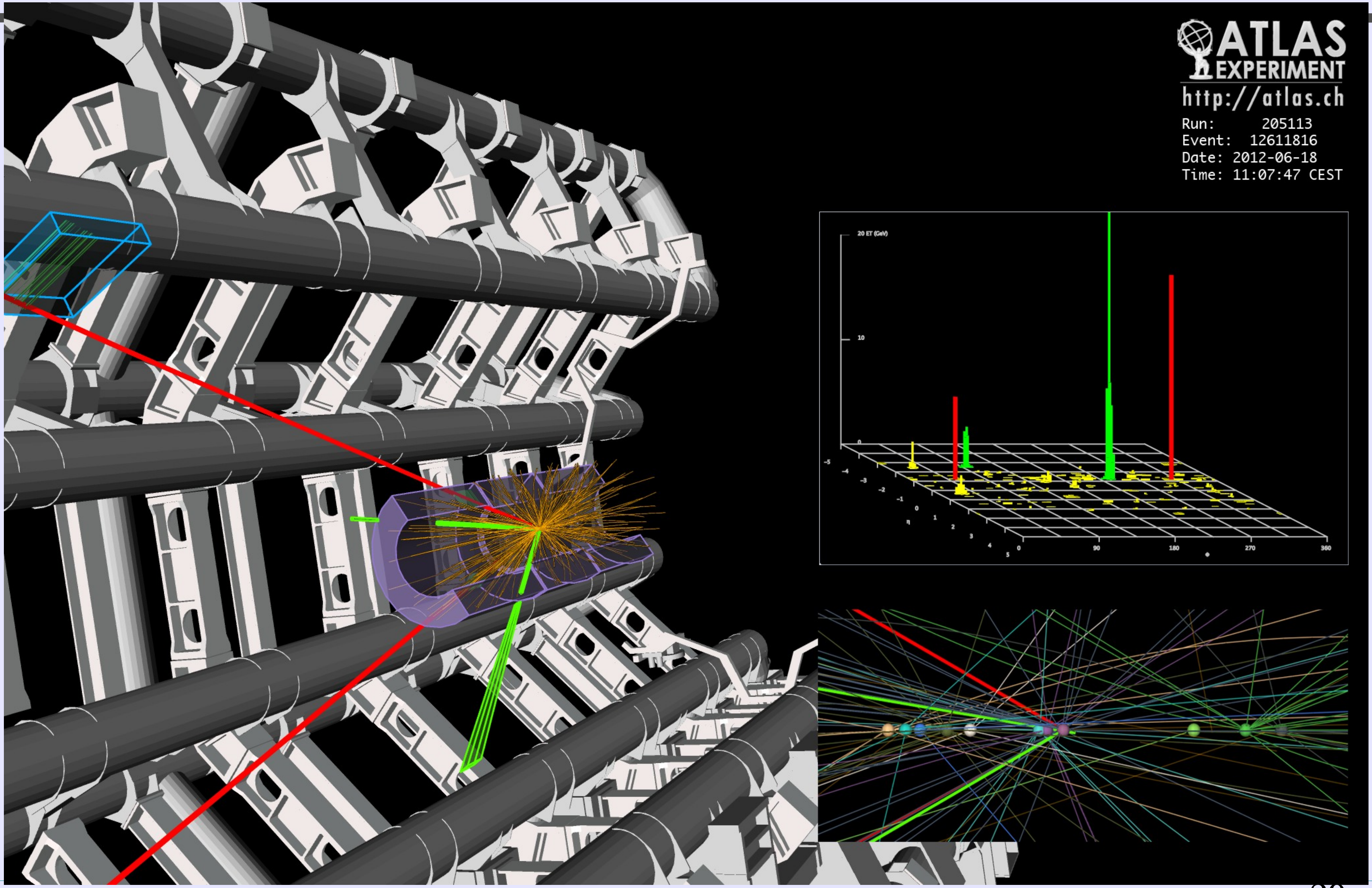
- Combines and links signals from different sub-detectors
- Provides optimal event description for a list of particles (e, μ, γ, hadrons, missing transverse energy)

Difficult pile-up conditions



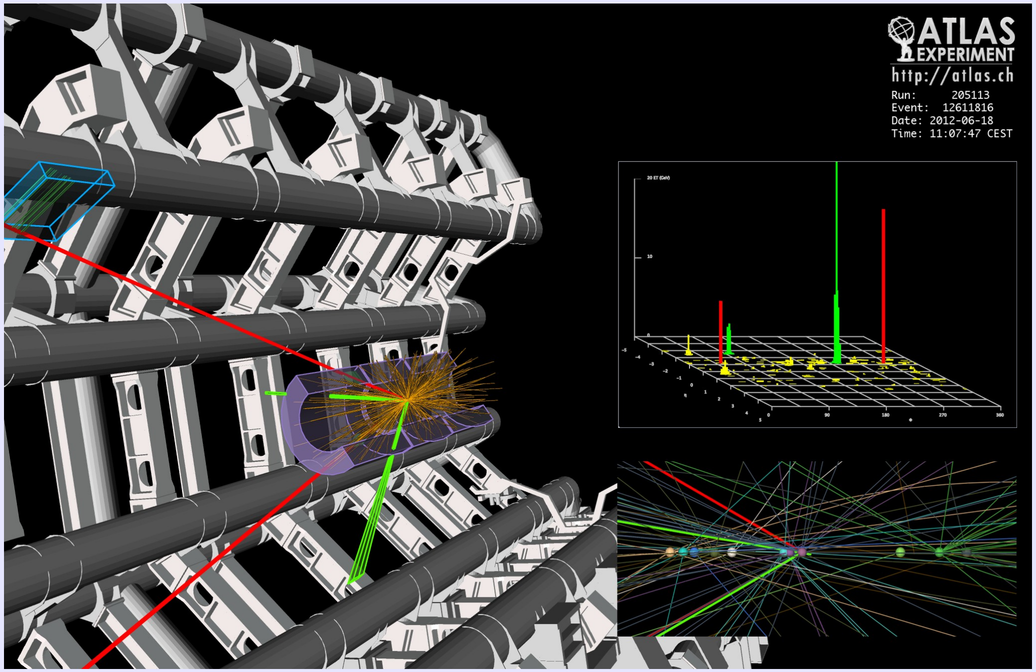
- $Z \rightarrow \mu\mu$ event with 20 reconstruction vertices
- ATLAS 2012 data taking (8 TeV pp collisions)

H→ZZ→4l analysis



H→ZZ→4l analysis

arXiv:1207.7214



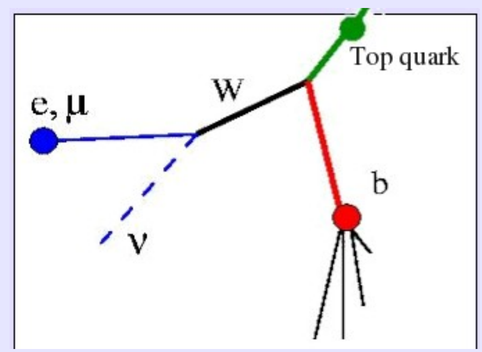
$H \to ZZ^* \to \mu\mu$ ee candidate event

Selection:

- 4 isolated leptons with high p_T
- Z mass constraint on one l pair

Main backgrounds:

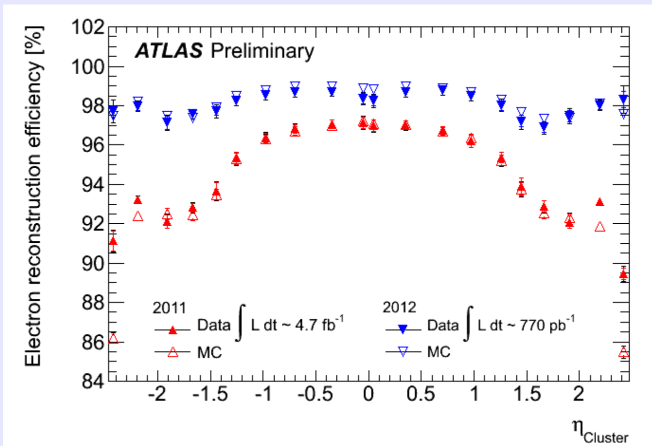
- Continuum $ZZ^* \to 4l$ production
- Z+jets, tt

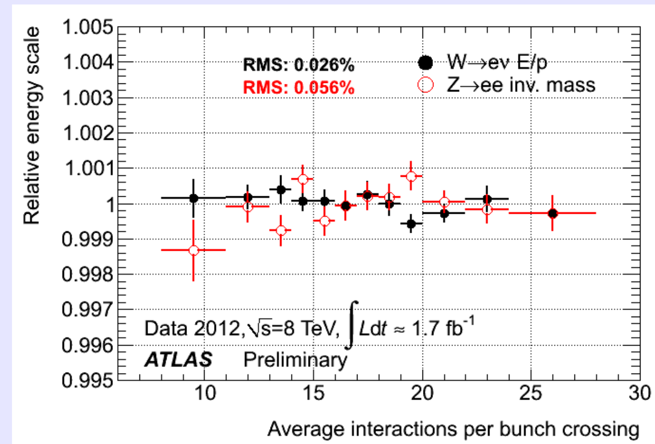


Discriminating variable: m_{4l}

H→ZZ→4l analysis (II)

- Improvement in electron identification and reconstruction



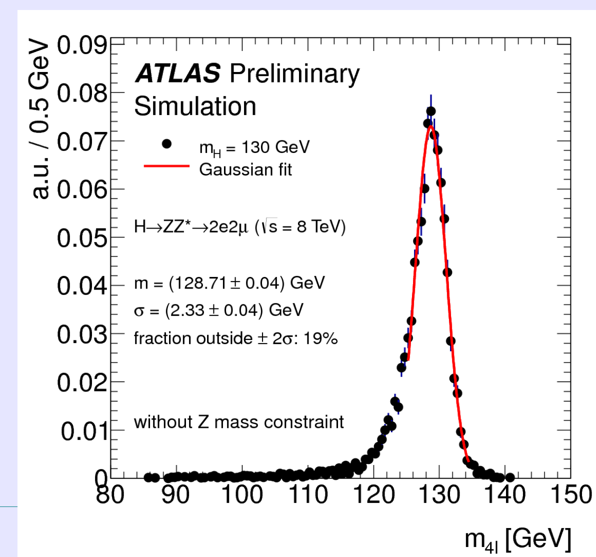


Excellent mass resolution

- 1.8-2.5 GeV (4μ, 4e)

Very good e/μ reconstruction efficiency

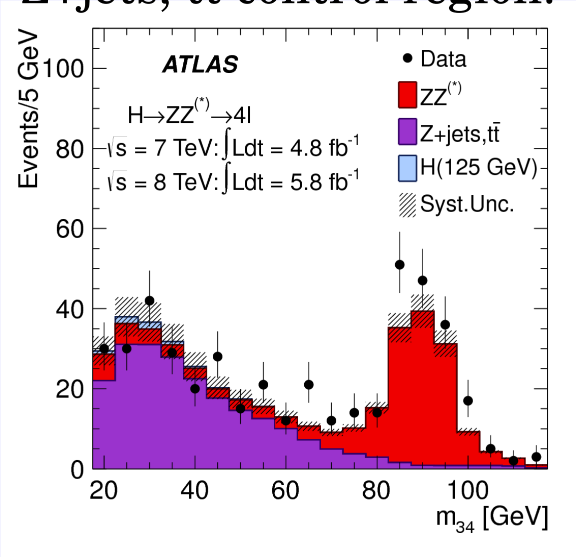
- ~97% for muons with p_T>6 GeV
- ~98% /95% for e reconstruction/ID



Background estimation

- ZZ continuum estimated with MC simulation
- Z+jets and tt backgrounds estimated using control regions
  - Transfer factors from control to signal regions from MC

Z+jets, tt control region:



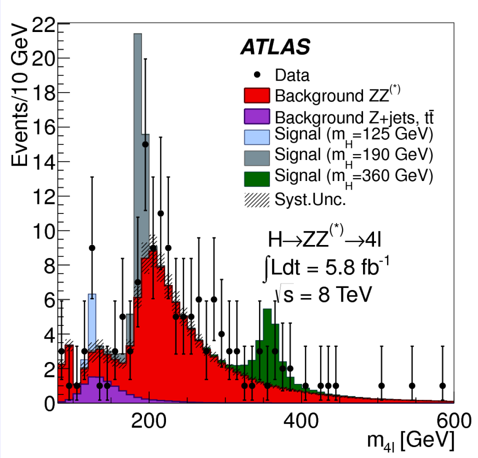
- No isolation & transverse impact parameter requirements on the sub-leading lepton pair

- Expected tt and Z+jet background yield

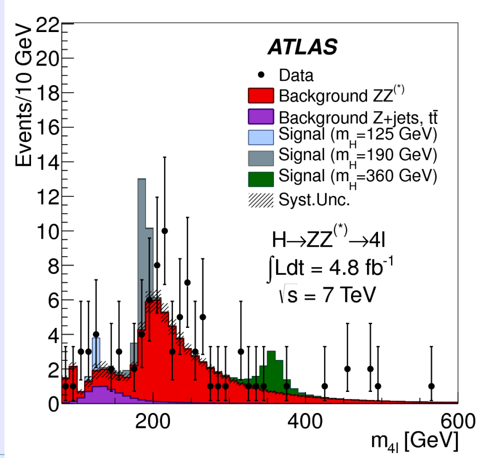
Background	Estimated numbers of events $\sqrt{s}$ = 7 TeV	Estimated numbers of events $\sqrt{s}$ = 8 TeV
	4μ	
Z+jets	0.3± 0.1 ±0.1	0.5± 0.1 ±0.2
$t\bar{t}$	0.02±0.02±0.01	0.04±0.02±0.02
	$2e2\mu$	
Z+jets	0.2± 0.1 ±0.1	0.4± 0.1 ±0.1
$t\bar{t}$	0.02±0.01±0.01	0.04±0.01±0.01
	$2\mu 2e$	
Z+jets, $t\bar{t}$	2.6± 0.4 ±0.4	4.9± 0.8 ±0.7
	$4e$	
Z+jets, $t\bar{t}$	3.1± 0.6 ±0.5	3.9± 0.7 ±0.8

H→ZZ→4l results

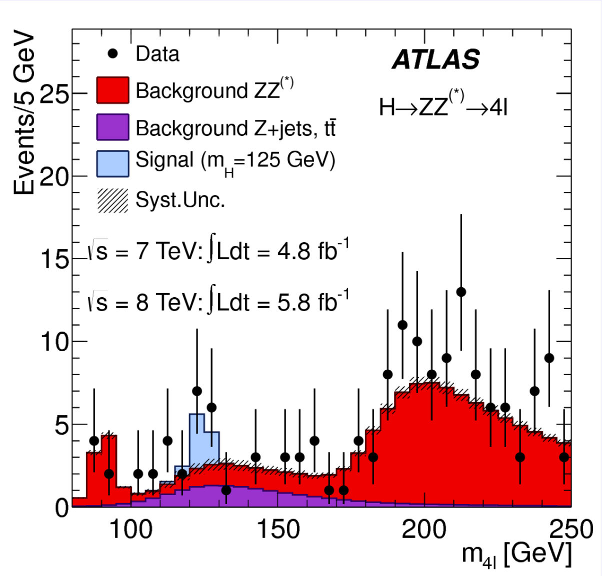
- 2012 4l mass spectrum



- 2011 4l mass spectrum

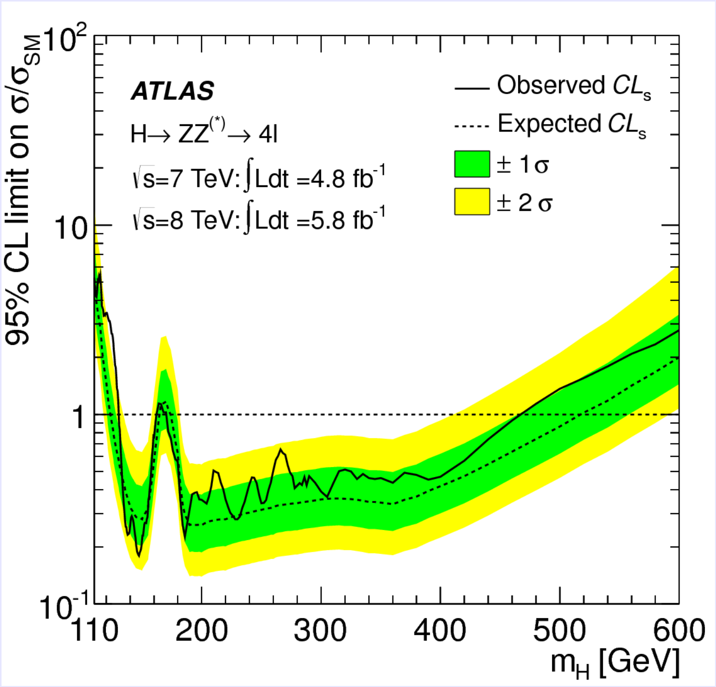


- 2011+2012 low mass region



- Expected events in a window of 125±5 GeV
  - Background: 5.1 ± 0.8
  - Signal (125 GeV): 5.3 ± 0.8
- Observed events: 13

H→ZZ→4l results

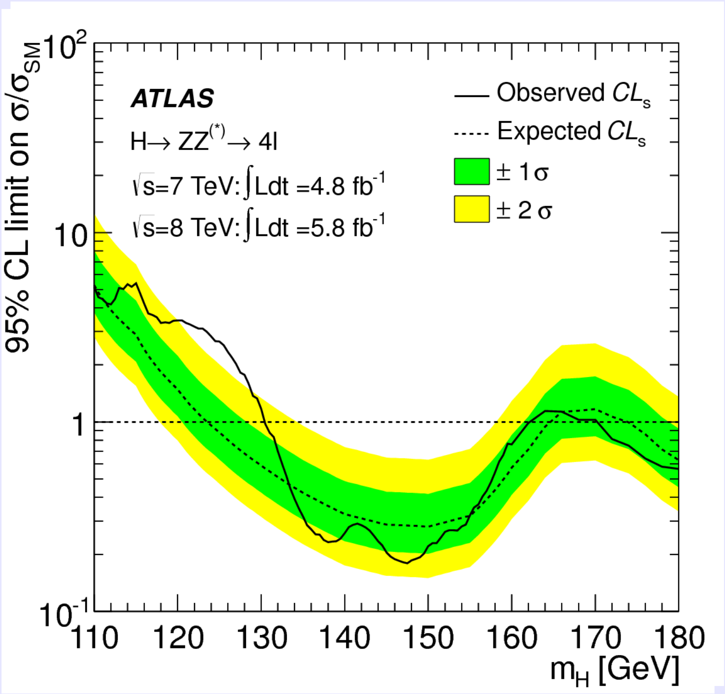


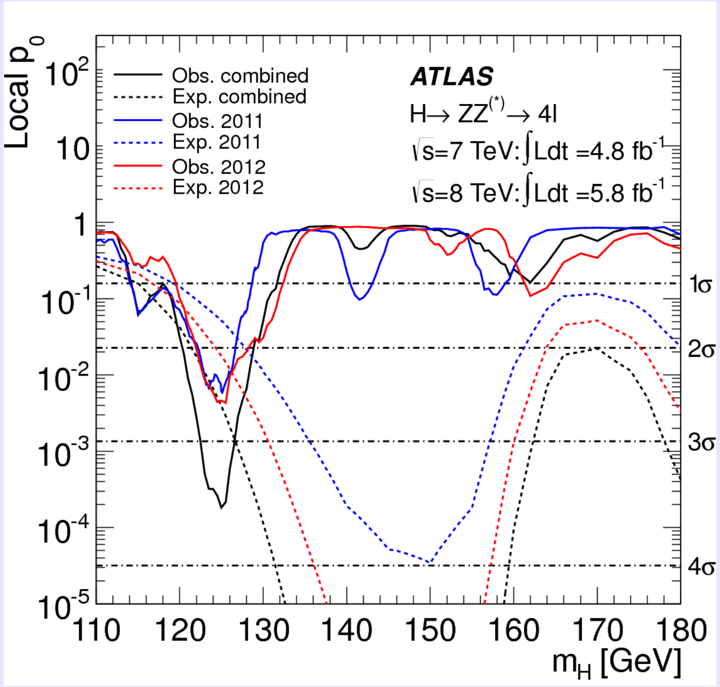
- Expected exclusion:
  - 124-164 GeV, 176-500 GeV
- Observed exclusion:
  - 131-162 GeV, 170-460 GeV

Excess of events observed near 125 GeV

- Maximum significance: 3.4σ at 125 GeV
- Probability of background fluctuation
  - 3×10^{-4}

H→ZZ→4l results





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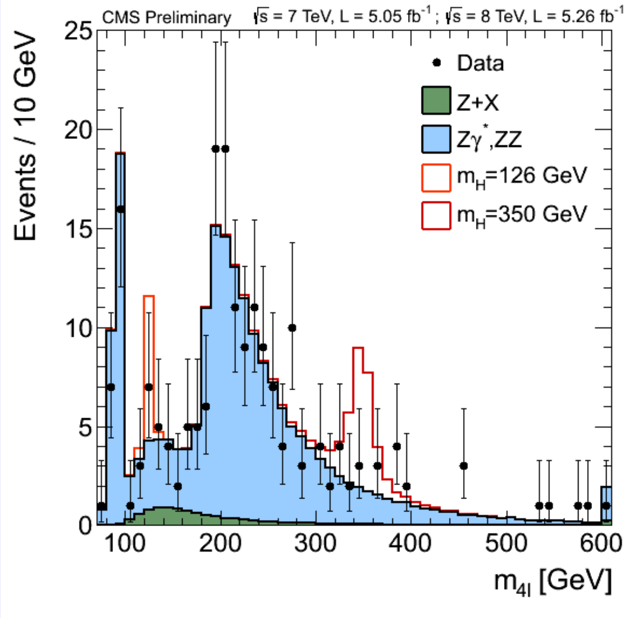
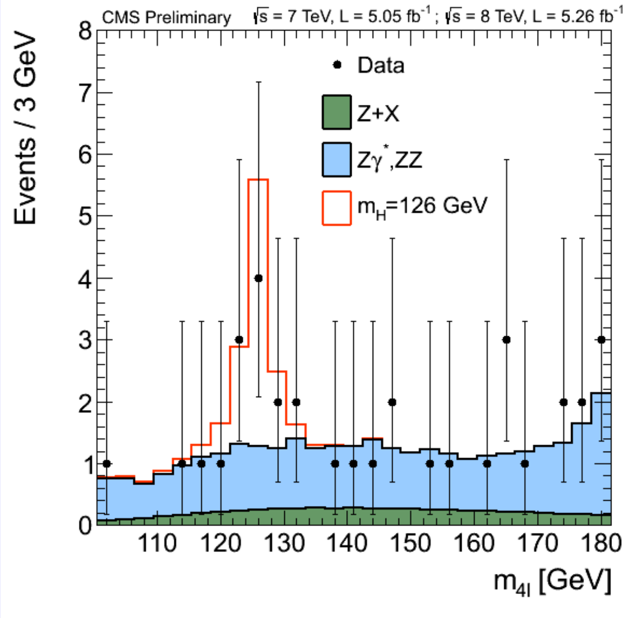
  - 3×10^{-4}

CMS H→ZZ→4l results





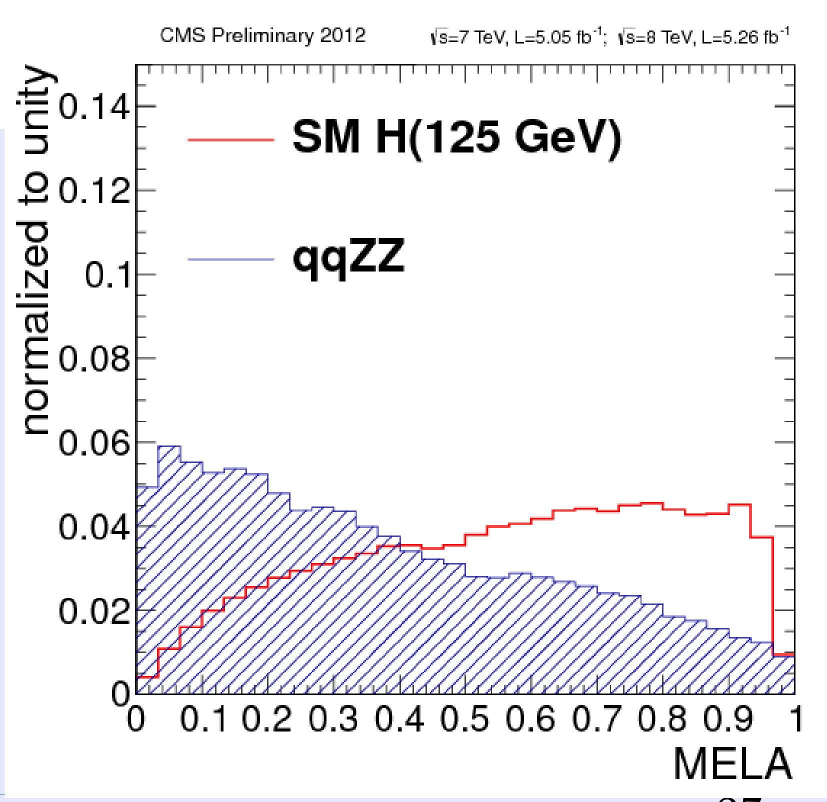
Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.7 ± 0.3	5.7 ± 0.6	7.2 ± 0.8	15.6 ± 1.4
Z + X	$1.2^{+1.1}_{-0.8}$	$0.9^{+0.7}_{-0.6}$	$2.3^{+1.8}_{-1.4}$	$4.4^{+2.2}_{-1.7}$
All backgrounds ($110 < m_{4\ell} < 160$ GeV)	$3.9^{+1.1}_{-0.8}$	$6.6^{+0.9}_{-0.8}$	$9.5^{+2.0}_{-1.6}$	$20.0^{+3.2}_{-2.6}$
Observed ($110 < m_{4\ell} < 160$ GeV)	6	6	9	21
Signal ($m_{\mathrm{H}} = 125$ GeV)	1.37 ± 0.44	2.75 ± 0.56	3.44 ± 0.81	7.56 ± 1.08
All backgrounds (signal region)	$0.71^{+0.20}_{-0.15}$	$1.25^{+0.15}_{-0.13}$	$1.83^{+0.36}_{-0.28}$	$3.79^{+0.47}_{-0.45}$
Observed (signal region)	1	3	5	9

MELA

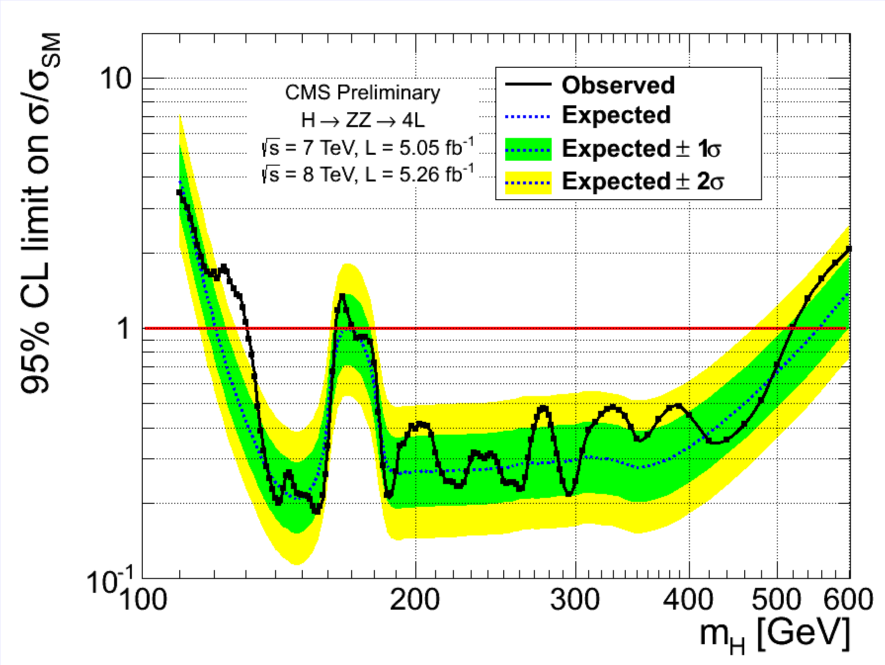
MELA: Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to ZZ background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

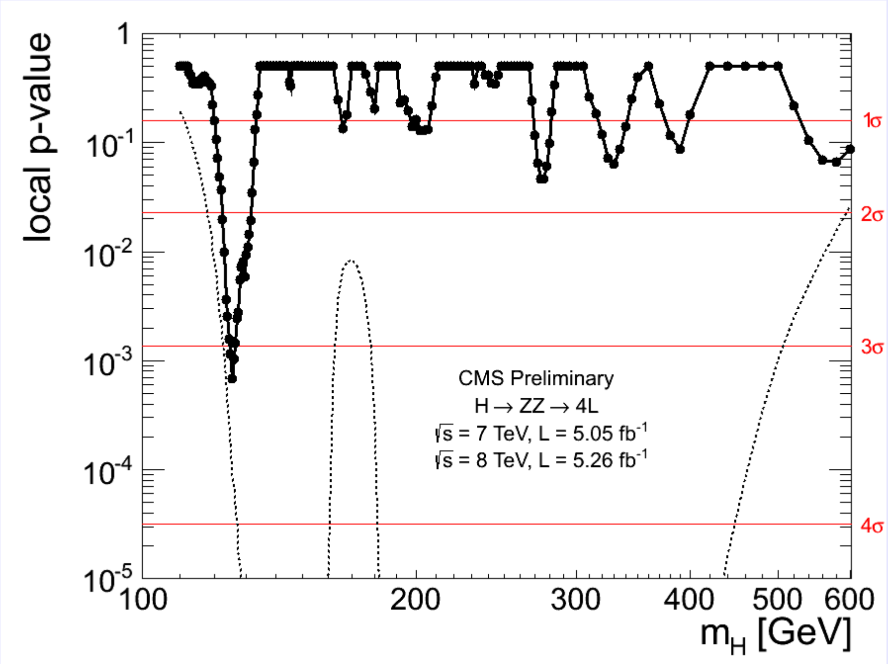
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

- MELA improves Signal-Background discrimination in ~20% with respect to using only the mass



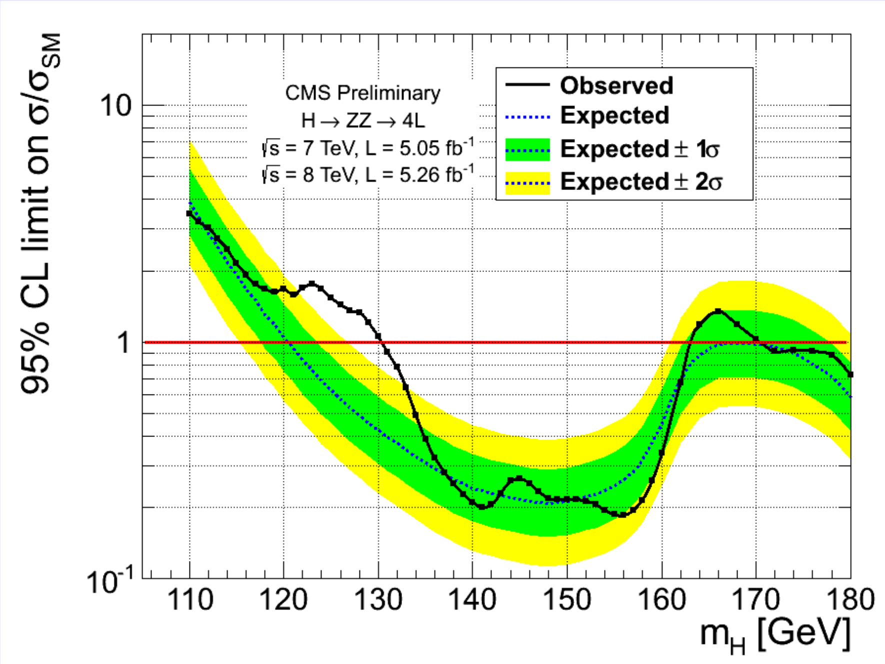
CMS H→ZZ→4l results

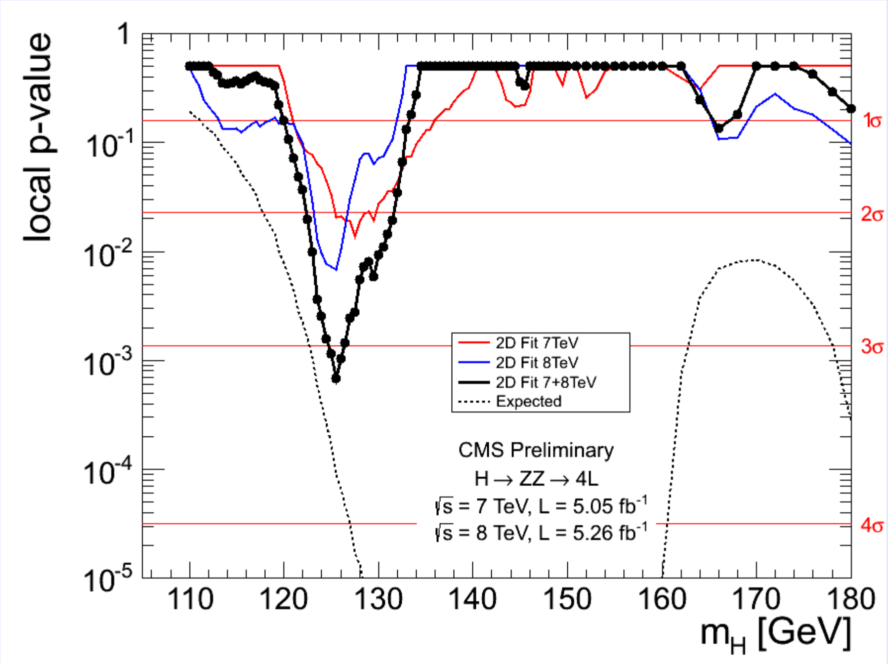




- 95% CL exclusion region: 131–162 GeV, 172–525 GeV
- Excess of events at 125.5 GeV with local significance 3.2σ

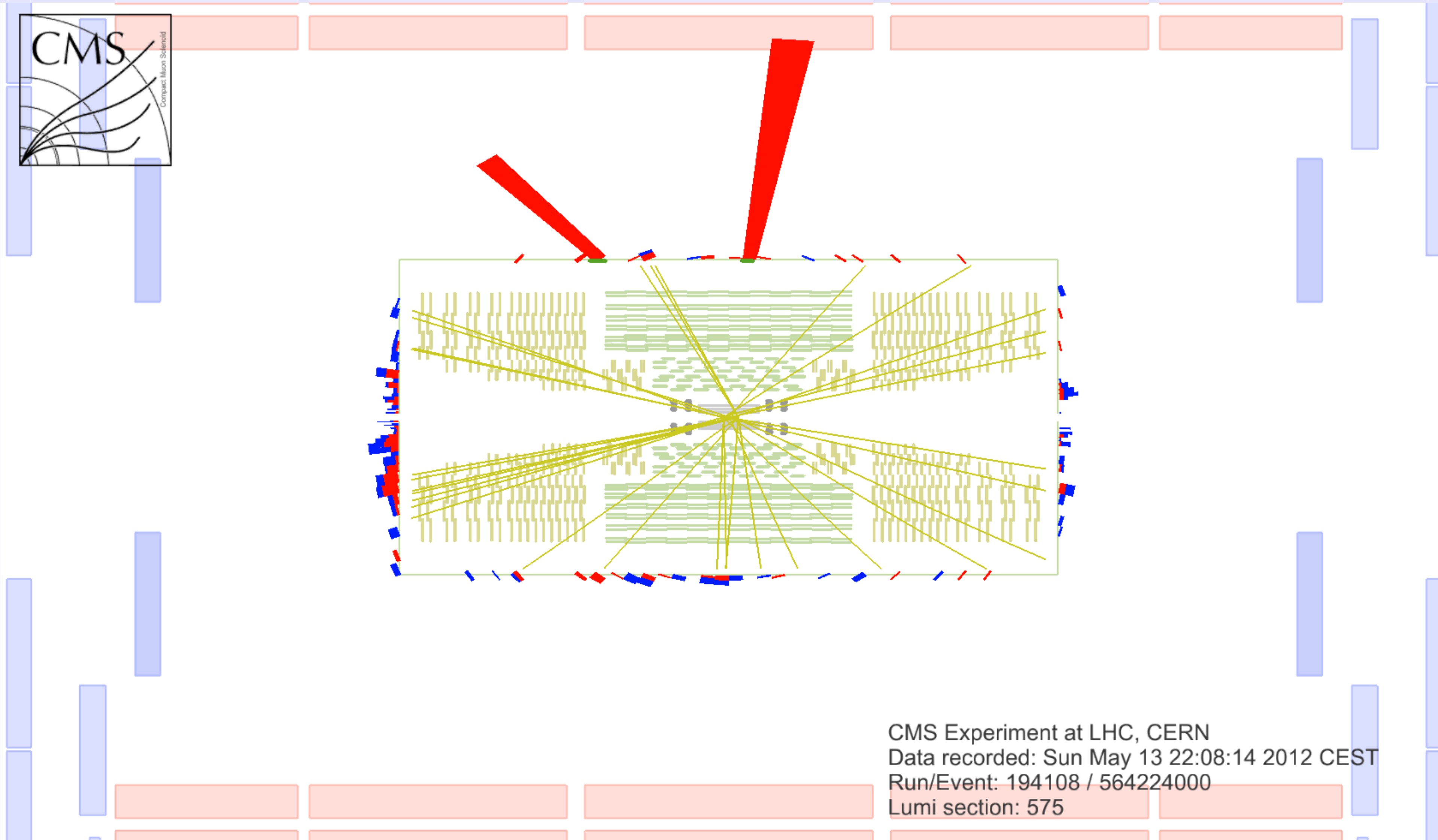
CMS H→ZZ→4l results





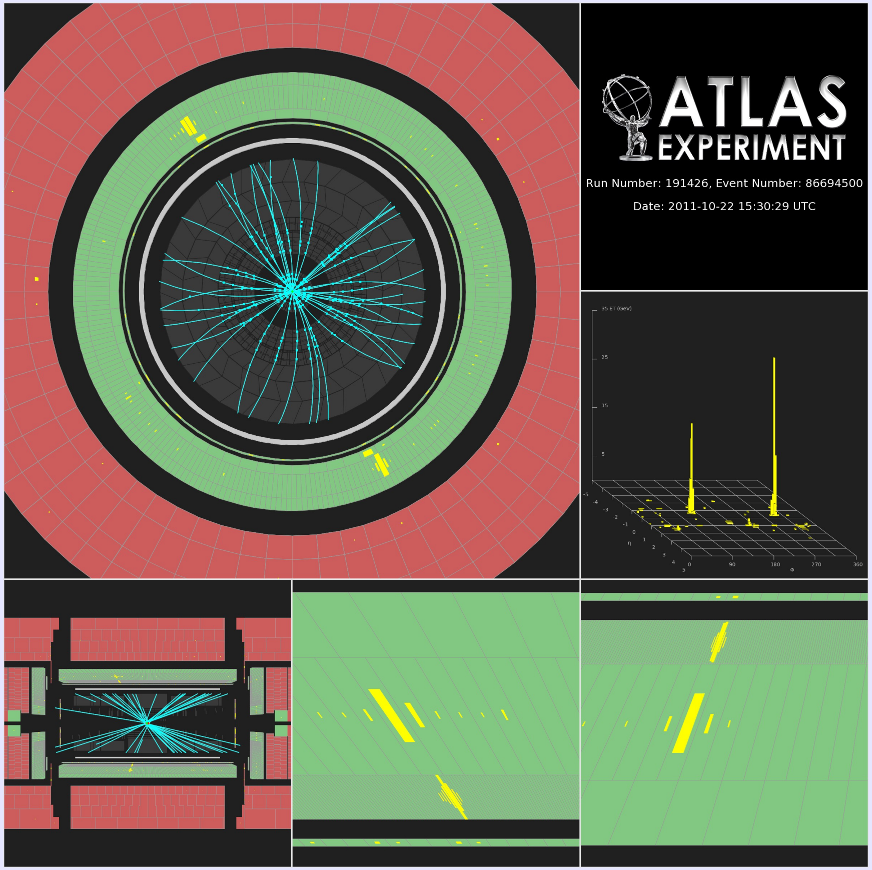
- 95% CL exclusion region: 131–162 GeV, 172–525 GeV
- Excess of events at 125.5 GeV with local significance 3.2σ

H→γγ


CMS
CMS Experiment at LHC, CERN
Data recorded: Sun May 13 22:08:14 2012 CEST
Run/Event: 194108 / 564224000
Lumi section: 575

$H\to\gamma\gamma$ analysis

arXiv:1207.7214



$H\to\gamma\gamma$ candidate event

- Two isolated photons
- Search for a narrow peak on a large continuum

Main background:

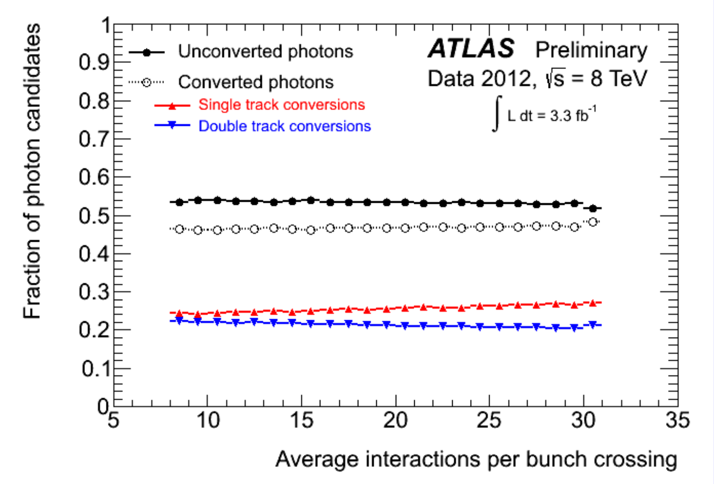
- Continuum $\gamma\gamma$ production
- γ+jet, jet+jet

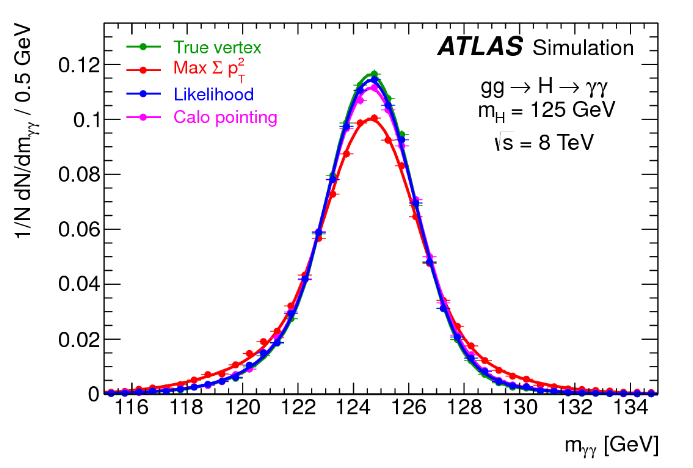
Analysis improvements:

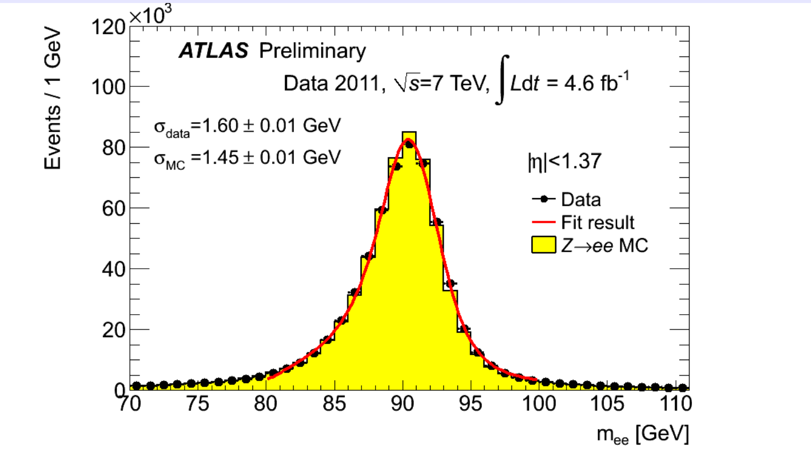
- Optimised kinematic requirements
- Neural network based photon ID for 2011 data
- Optimized photon ID for 2012
  - stable in a high pileup environment
- Added category with 2 jets
  - Sensitive to VBF production

γ identification & energy measurement

- Stable photon ID peformance with pile-up
- Calorimeter E response studied with Z, J/ψ and W decays
  - Energy scale at m_Z known to ~ 0.5%
  - Linearity better than 1%
- Excellent mass resolution (1.6-3.1 GeV)
  - Use calorimeter segmentation to associate photon to primary vertex (σ_z ~ 15 mm)



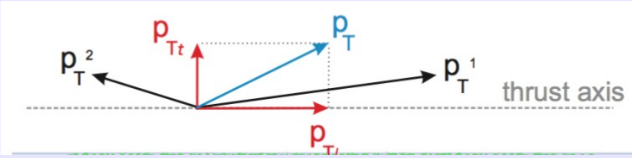


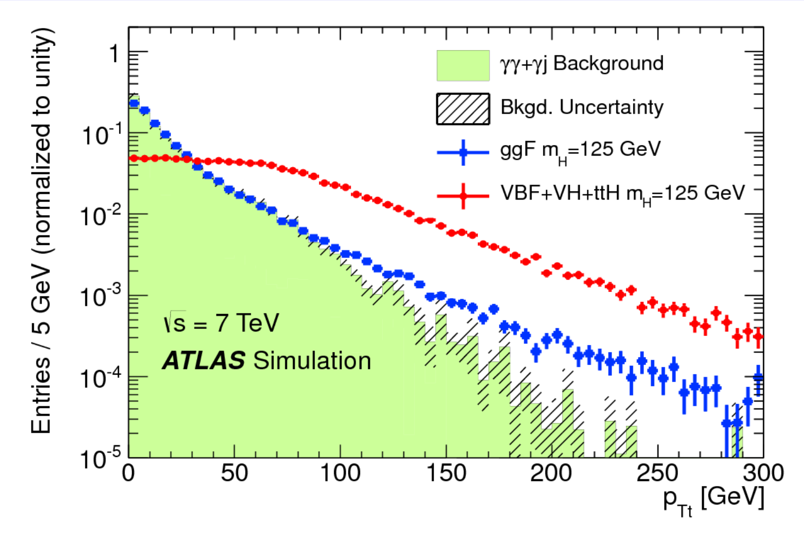


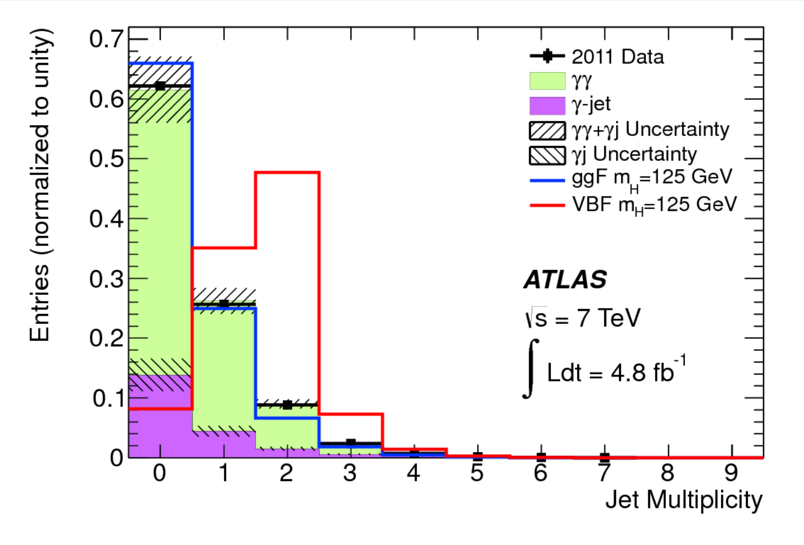
H→γγ analysis categories

10 analysis categories based

- Converted/unconverted photons
- Photon location in the detector
- Di-photon transverse momentum with respect to thrust
- New two jet category: $\Delta\eta_{jj}$>2.8, m_{jj}>400 GeV, di-jet and di-γ back to back
  - Sensitive to vector boson fusion production







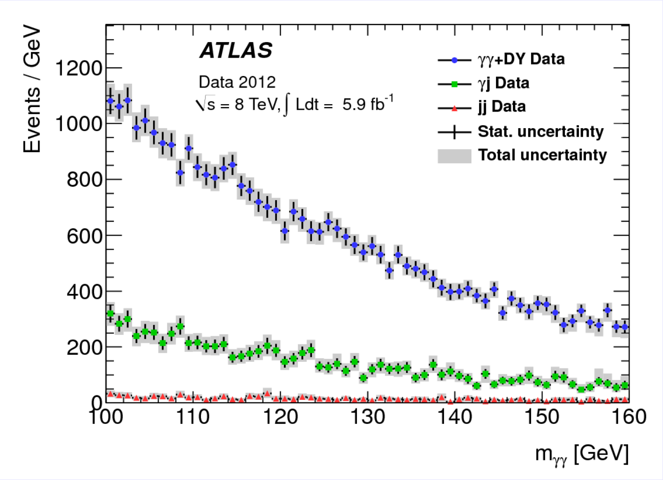
H→γγ background modelling

Background composition:

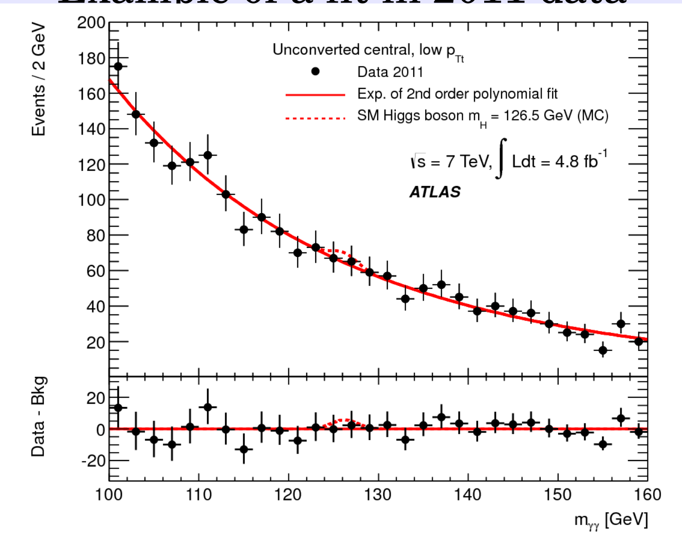
- Dominated by continuum γγ production, followed by γ+jet, jet+jet

Background estimated by fitting the di-photon mass distribution

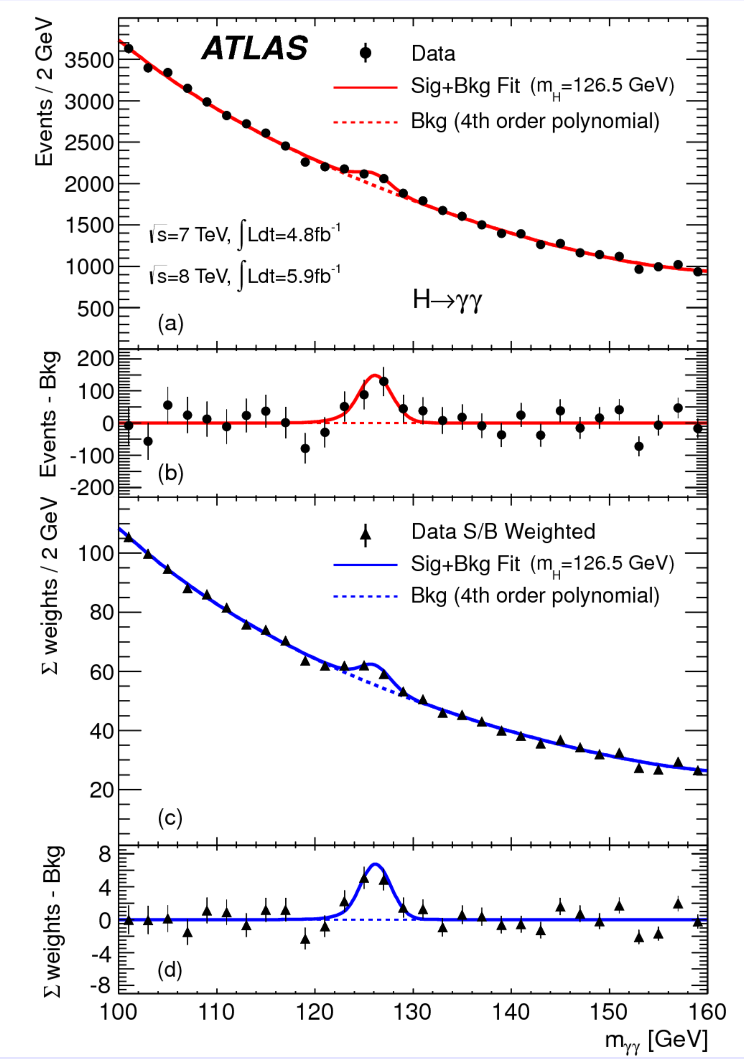
- Studied for each category with high-statistics MC before looking at data
- Considered: n-order Bernstein polynomial, exp(P2), exponential
- Choice based on largest expected sensitivity for 125 GeV signal
- Largest residual bias seen in MC experiments over 110-150 GeV taken as signal yield systematic

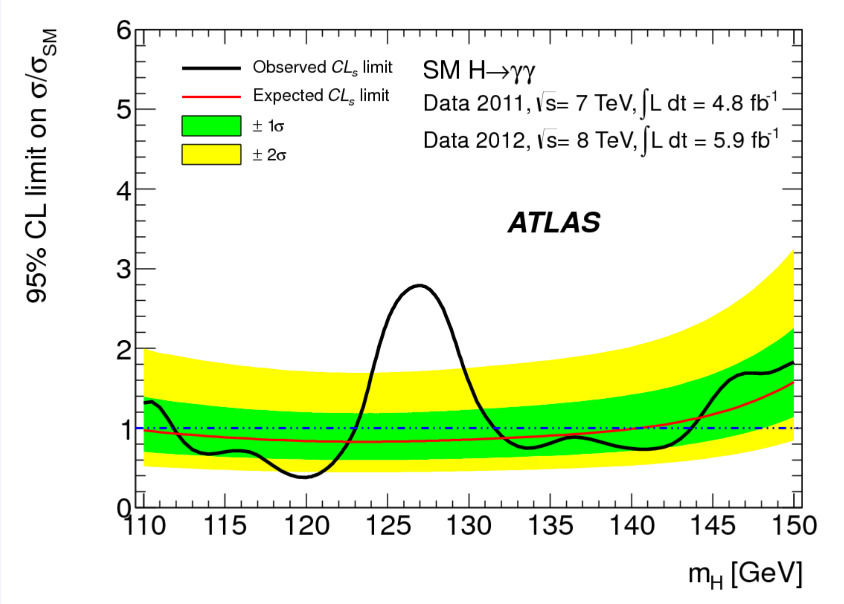


Example of a fit in 2011 data



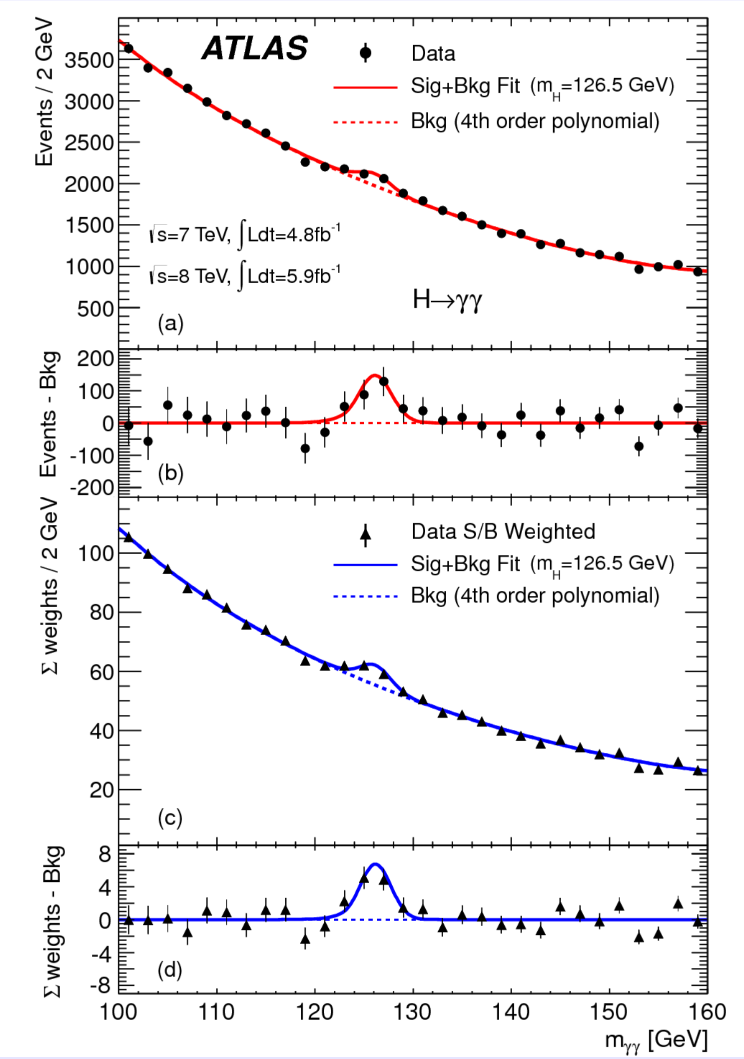
H→γγ results

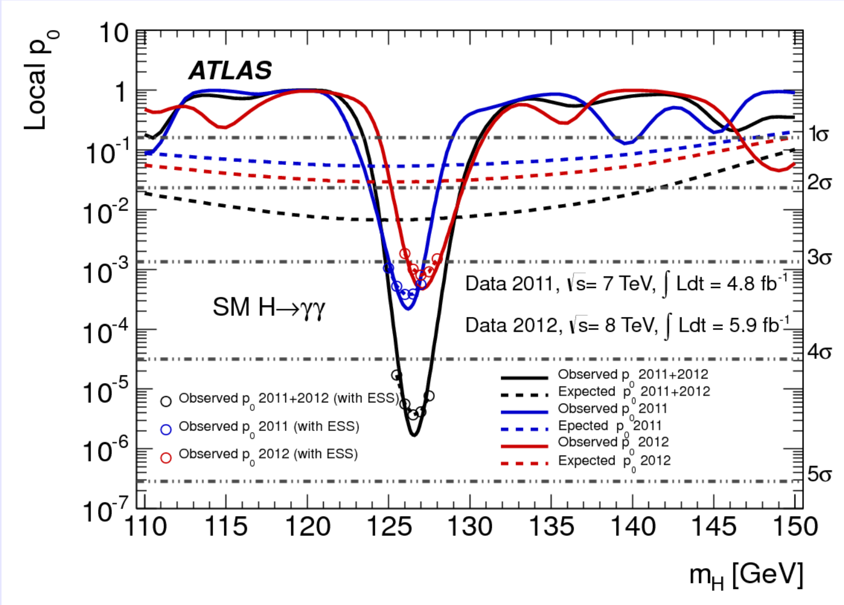




- Exclusion at 95% CL:
  - Expected: 110-139.5 GeV
  - Observed: 112−122.5 GeV,132−143 GeV
- Excess of events at 126.5 GeV
  - Local significance of 4.5σ (expected 2.4σ)
  - Consistent results in 2011 and 2012 data

H→γγ results





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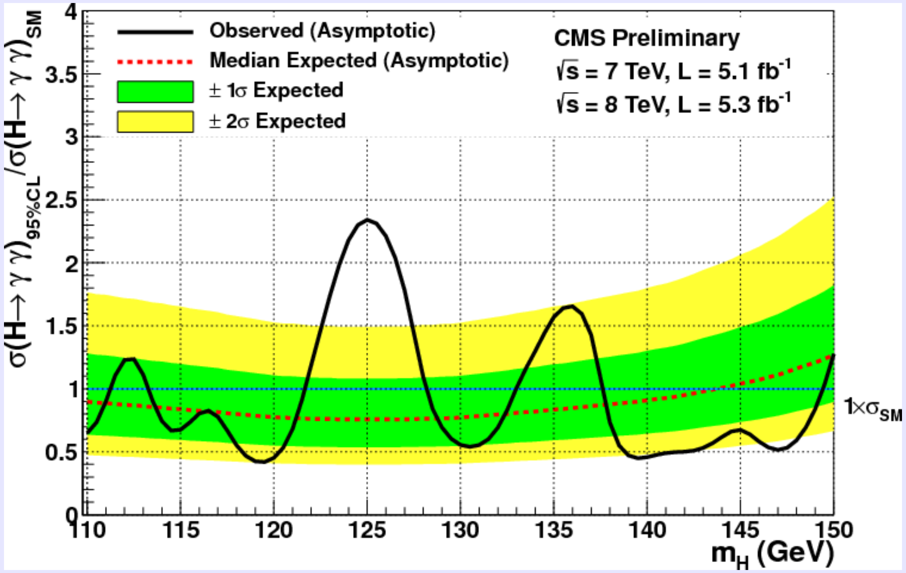
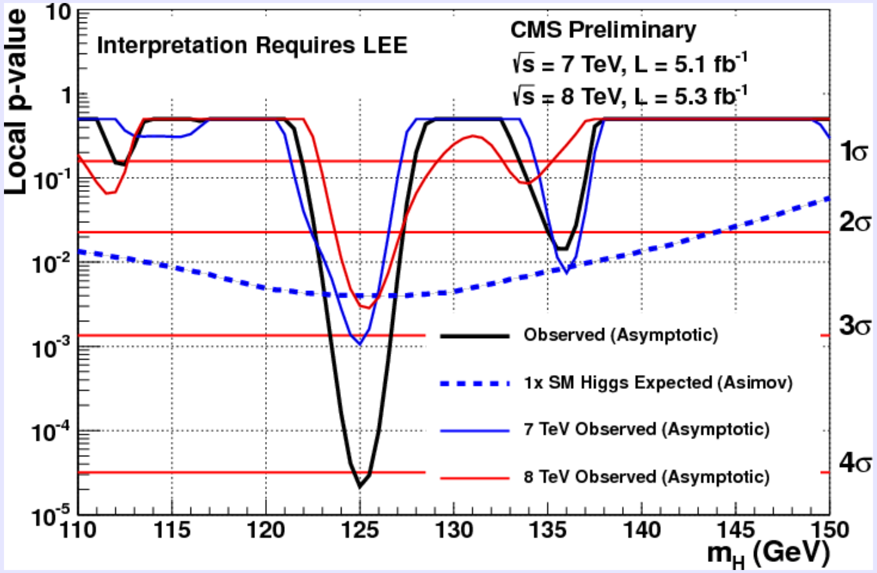
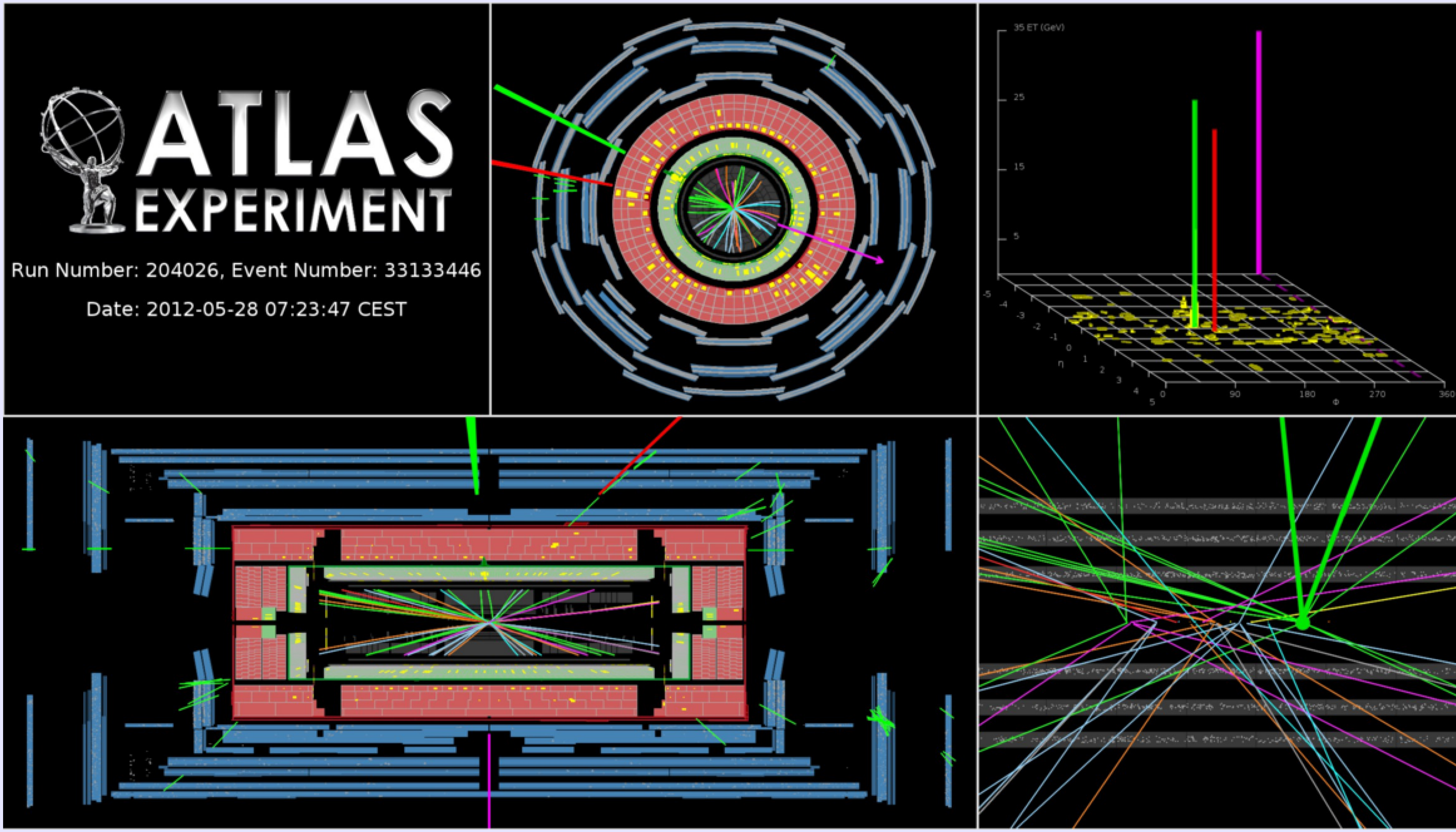
CMS H→γγ results





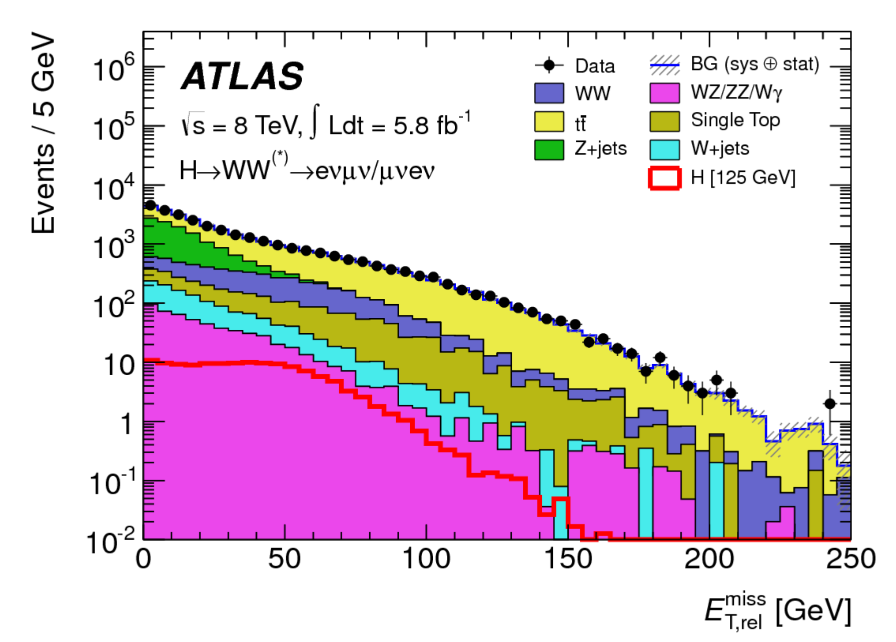
- Expected 95% CL exclusion: 0.76xSM at 125 GeV
- Observed 95% CL exclusion: 110-111, 113-123,129-132,138-149 GeV
- Excess of events at 125 GeV with local significance 4.1σ
  - Global significance 3.2σ

$H \to WW \to \mu\nu e\nu$ candidate event



H→WW→lνlν

arXiv:1207.7214



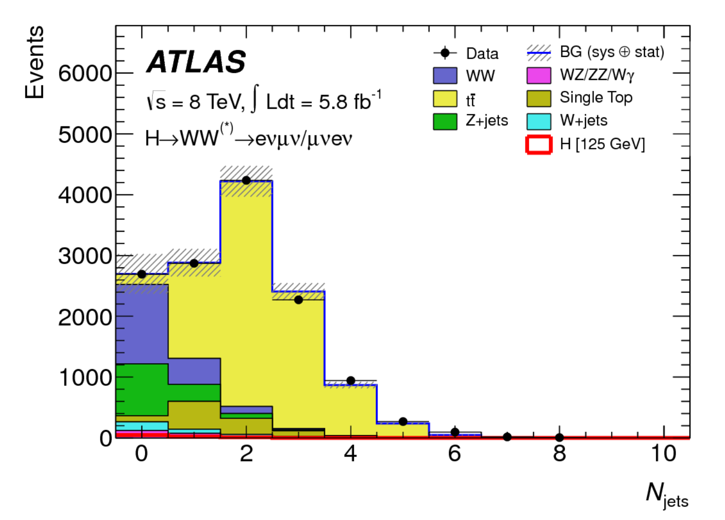
Main backgrounds

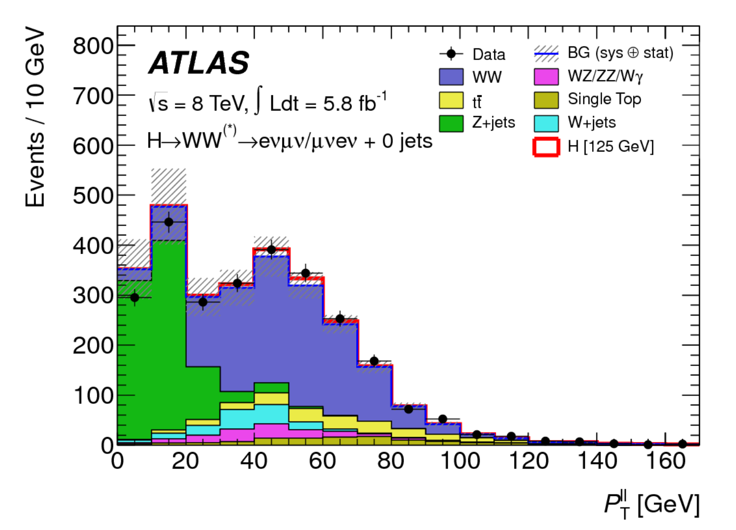
- WW, tt, Wt
- W+jets, Wγ, ZZ, Drell-Yan

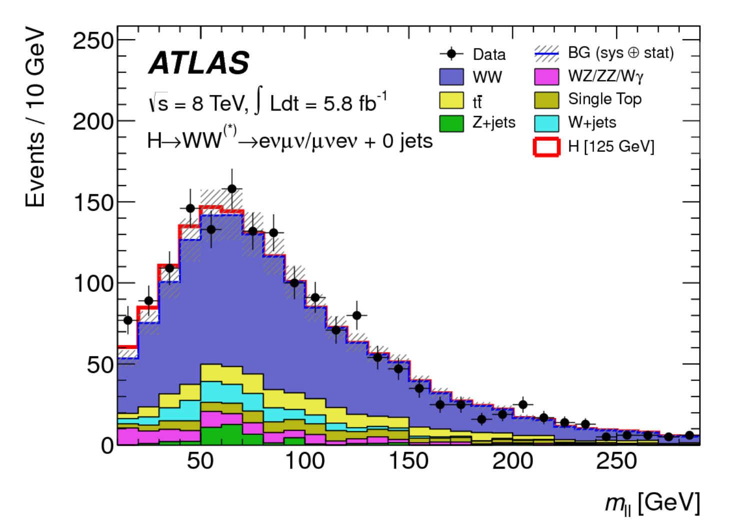
- Two opposite sign isolated leptons and large missing E_T
- Relies on the whole detector working perfectly
- 0-, 1-, 2-jet categories
  - Sensitive to different production modes

Further H→WW→lνlν event selection

- For signal, spin correlations and V-A nature of the W decay results in small $\Delta\phi_{ll}$ and m_{ll}
- Different background composition in each category
  - Different selection conditions
- B-jet veto to reduce top background
- 2-jet analysis: $|\Delta y_{jj}|>3.8$, $m_{jj}>500$ GeV







Background estimation

W+jets:

- Control sample: one loosely identified lepton
- Transfer factor to signal region evaluated with a data sample dominated by QCD jets

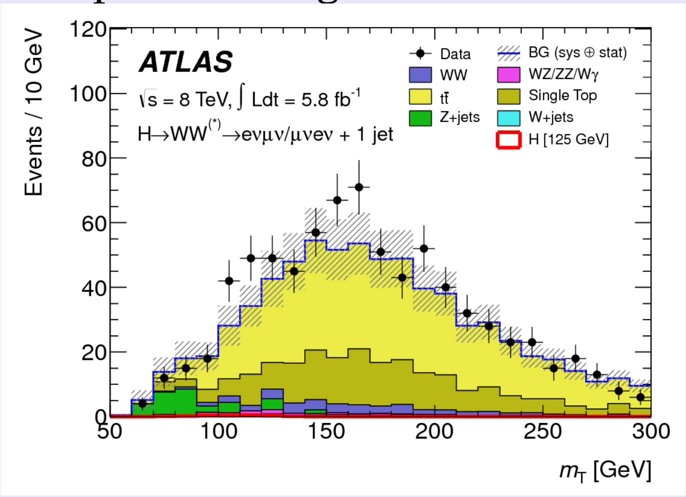
Top:

- Control sample: remove jet multiplicity or b-tagging conditions depending on the channel
- Correction factors applied to a purely MC-based estimation: 1.11±0.06, 1.11±0.05, 1.01±0.26 for the 0-,1-,2-jet analysis

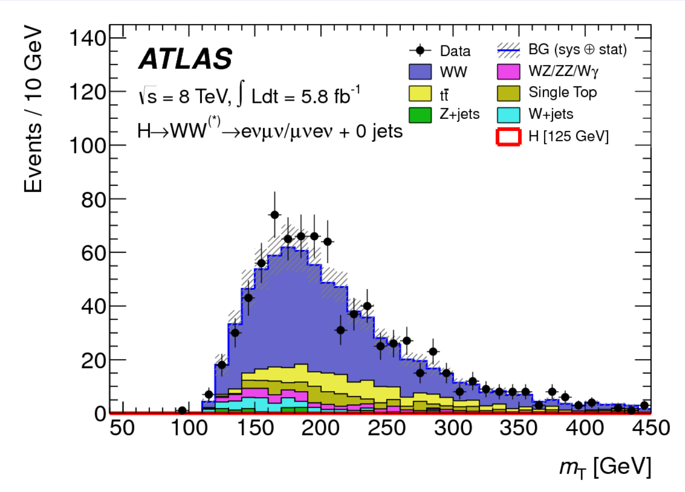
WW:

- Remove $\Delta\phi_{ll}$ cut, change m_{ll} cut to m_{ll}>80 GeV
- Use data-driven estimate of other backgrounds in WW control region

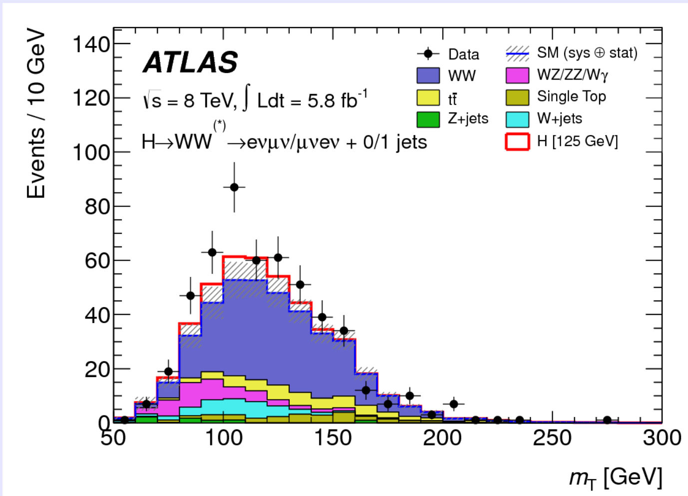
Top control region

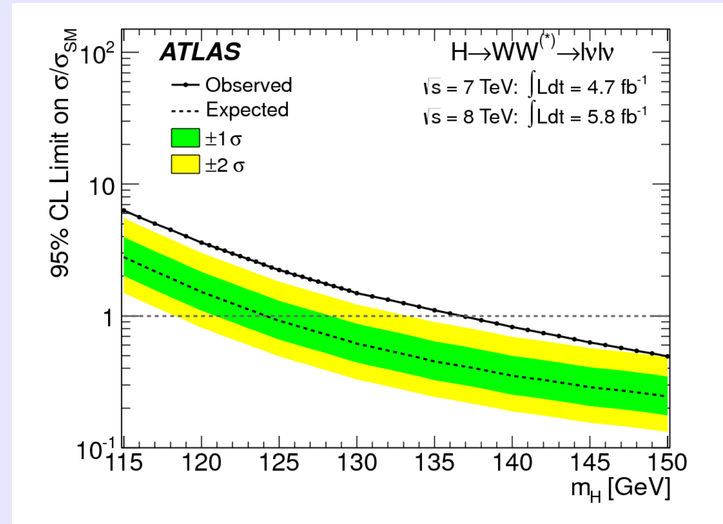


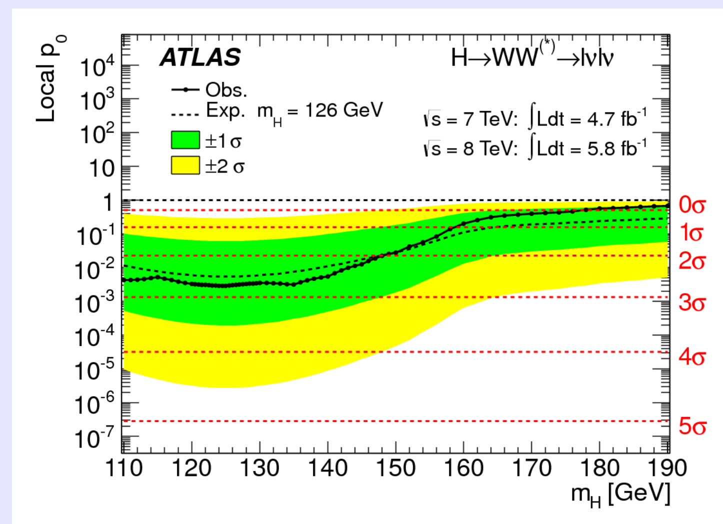
WW control region



H→WW→lνlν results

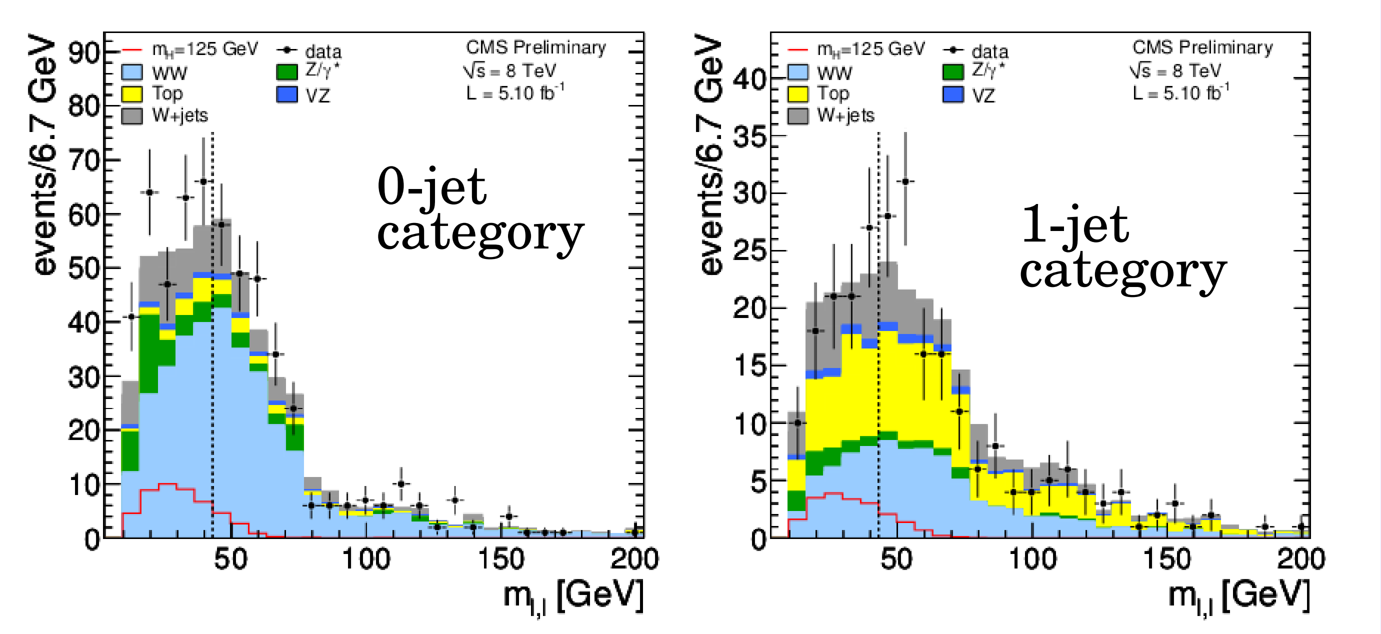




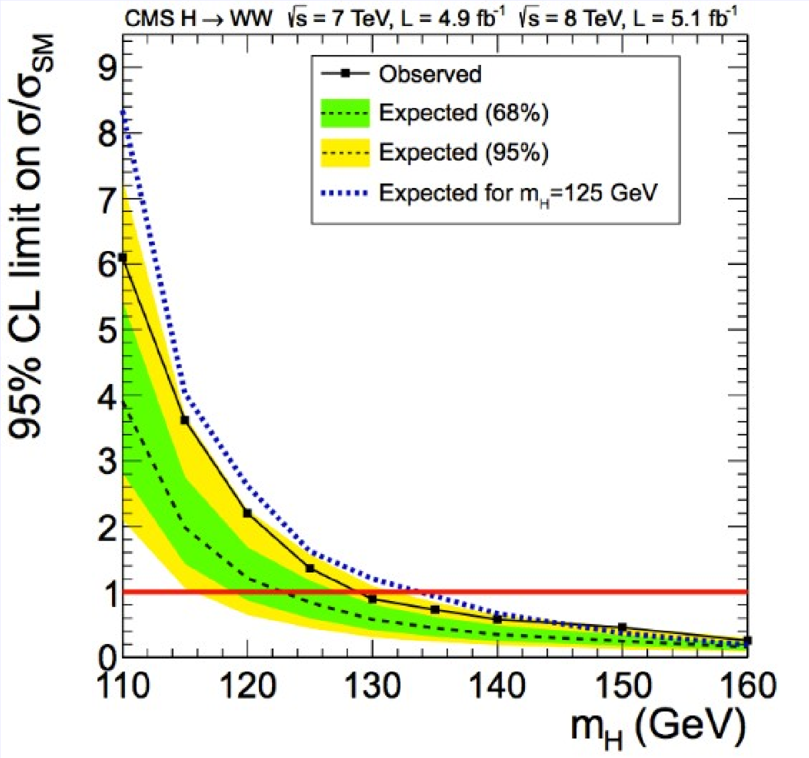


- Excess of events observed
  - Broad excess (poor mass resolution)
  - Minimum p_0 at 125 GeV ($p_0 = 3\times10^{-3}$)
  - Local significance at 125 GeV 2.8σ

CMS H→WW results

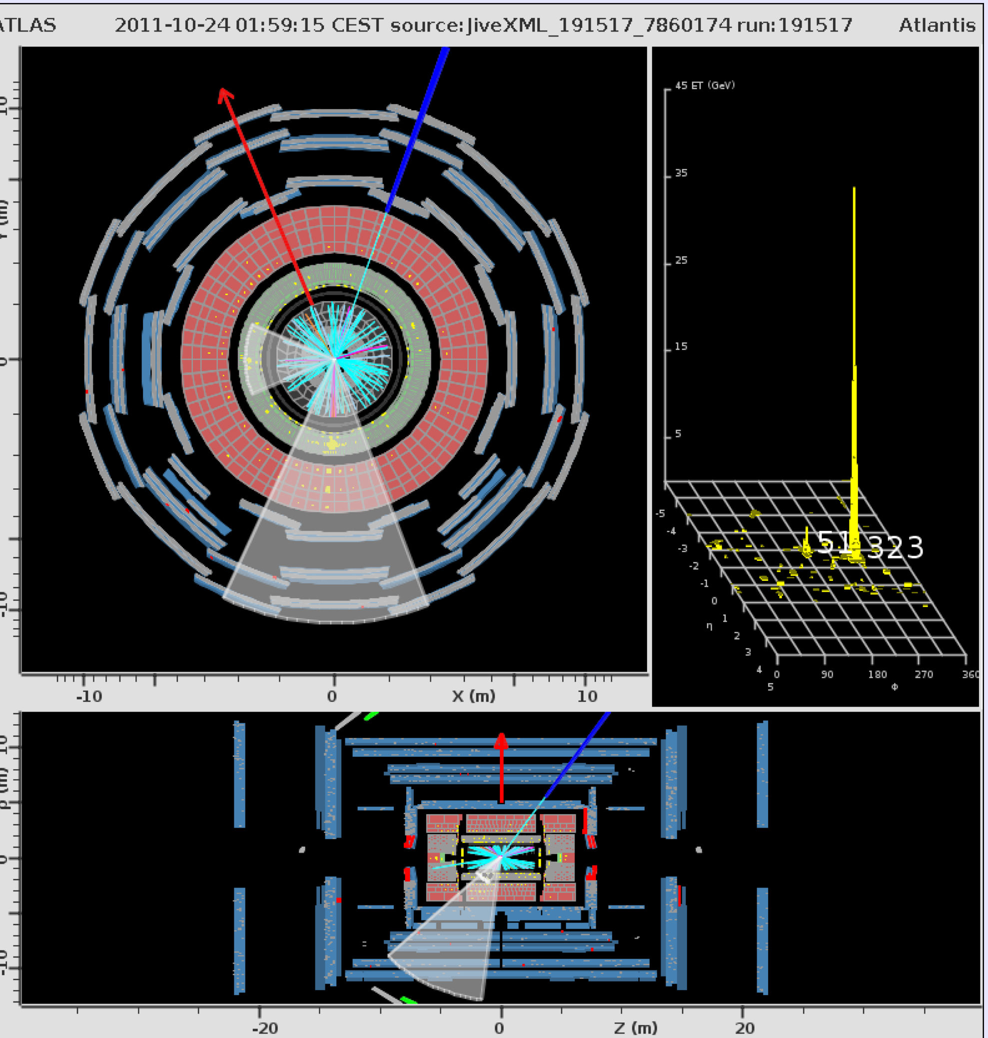


Category:	0-jet $e\mu$	0-jet $\ell\ell$	1-jet $e\mu$	1-jet $\ell\ell$	2-jet $e\mu$	2-jet $\ell\ell$
WW	87.6 ± 9.5	60.4 ± 6.7	19.5 ± 3.7	9.7 ± 1.9	0.4 ± 0.1	0.3 ± 0.1
$WZ + ZZ + Z\gamma$	2.2 ± 0.2	37.7 ± 12.5	2.4 ± 0.3	8.7 ± 4.9	0.1 ± 0.0	3.1 ± 1.8
Top	9.3 ± 2.7	1.9 ± 0.5	22.3 ± 2.0	9.5 ± 1.1	3.4 ± 1.9	2.0 ± 1.2
$W +$ jets	19.1 ± 7.2	10.8 ± 4.3	11.7 ± 4.6	3.9 ± 1.7	0.3 ± 0.3	0.0 ± 0.0
$W\gamma^{(*)}$	6.0 ± 2.3	4.6 ± 2.5	5.9 ± 3.2	1.3 ± 1.2	0.0 ± 0.0	0.0 ± 0.0
All backgrounds	124.2 ± 12.4	115.5 ± 15.0	61.7 ± 7.0	33.1 ± 5.7	4.1 ± 1.9	5.4 ± 2.2
Signal ($m_H = 125\,\text{GeV}$)	23.9 ± 5.2	14.9 ± 3.3	10.3 ± 3.0	4.4 ± 1.3	1.5 ± 0.2	0.8 ± 0.1
Data	158	123	54	43	6	7



- Broad excess of events between 110 and 140 GeV
- Local significance at 125 GeV
  - Expected: 2.4σ
  - Observed: 1.6σ

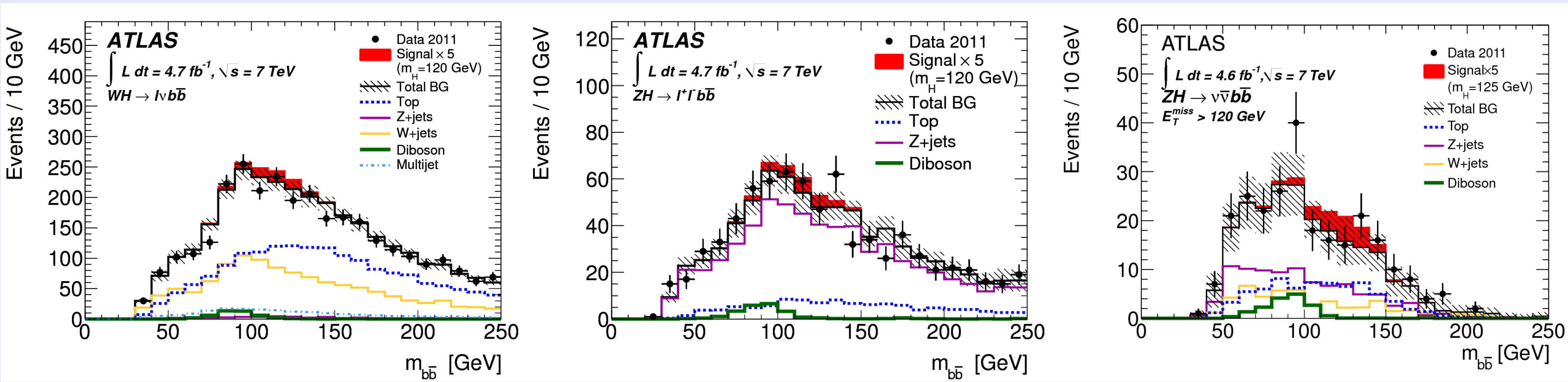
VH→bb ATLAS search



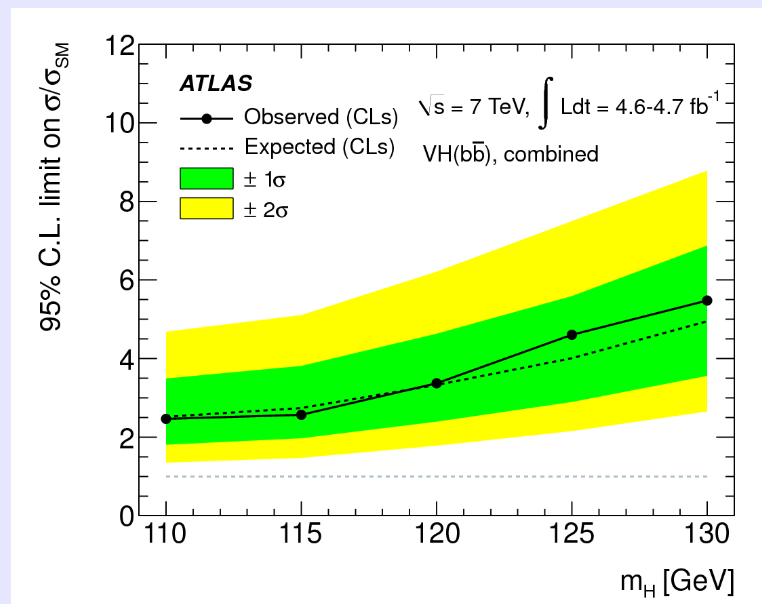
WH→μνbb candidate event

- Three channels studied
  - WH → lν bb
  - ZH → llbb
  - ZH → ννbb
- Signatures
  - High p_T isolated leptons
  - Exactly 2 b-jets
  - Large missing E_T (lνbb, ννbb)
- Different categories based on p_T^V/E_T^{miss}
- Backgrounds: W/Z+jets, top, di-boson, QCD jets

ATLAS VH→bb results with 2011 data

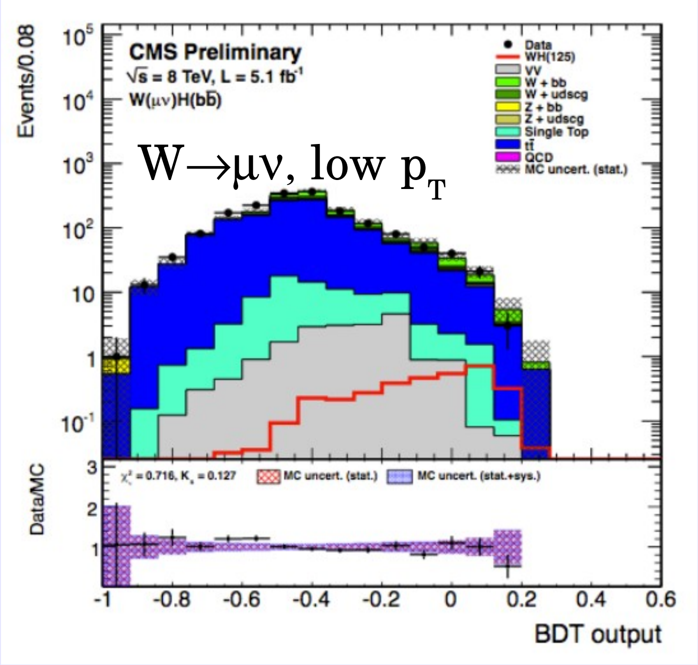


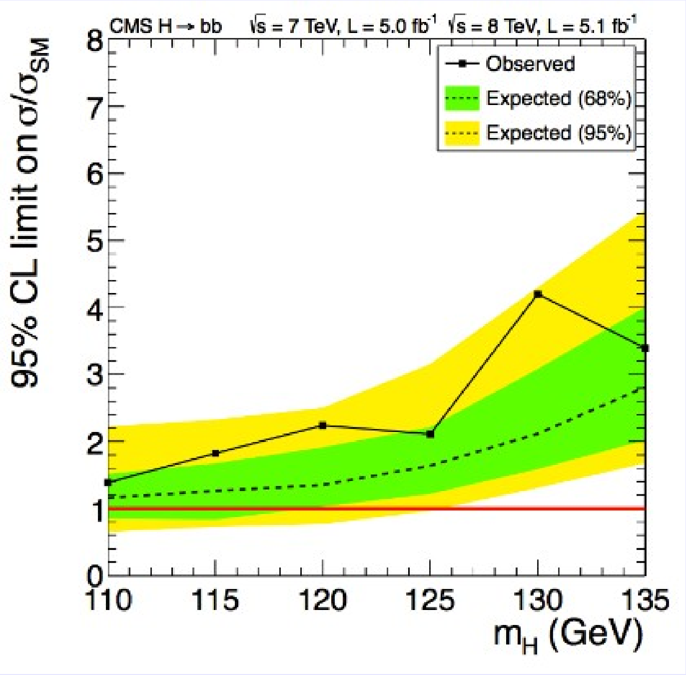
- No observable excess for m_H between 110-130 GeV
- Expected limit: 2.6 - 5.1× σ_{SM}
- Observed limit: 2.7 - 5.3´ $\sigma_{SM,}$



CMS VH→bb results with 2011/12 data

- Use a MVA that combines event information (kinematical variables, b-tagging, ...)

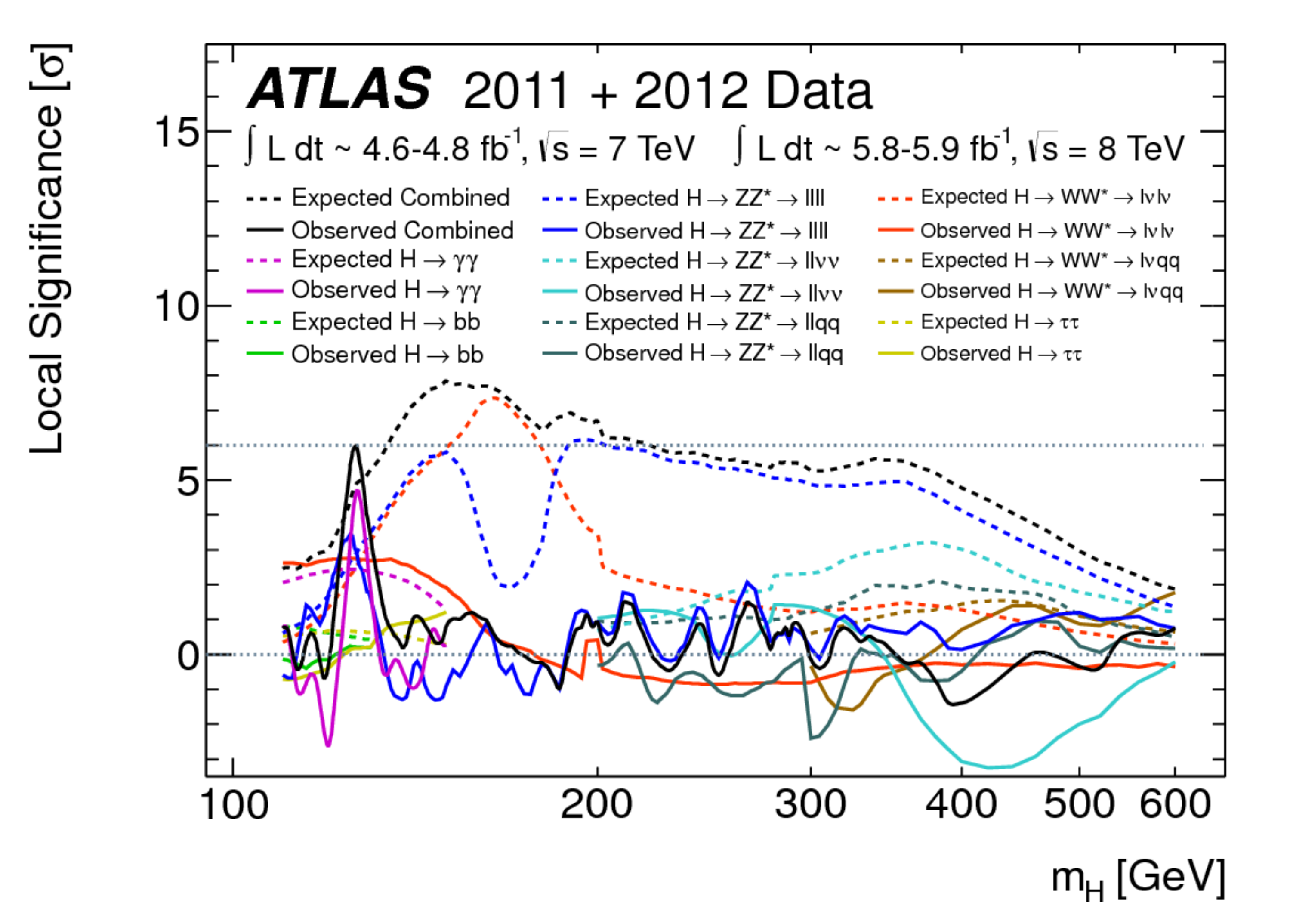




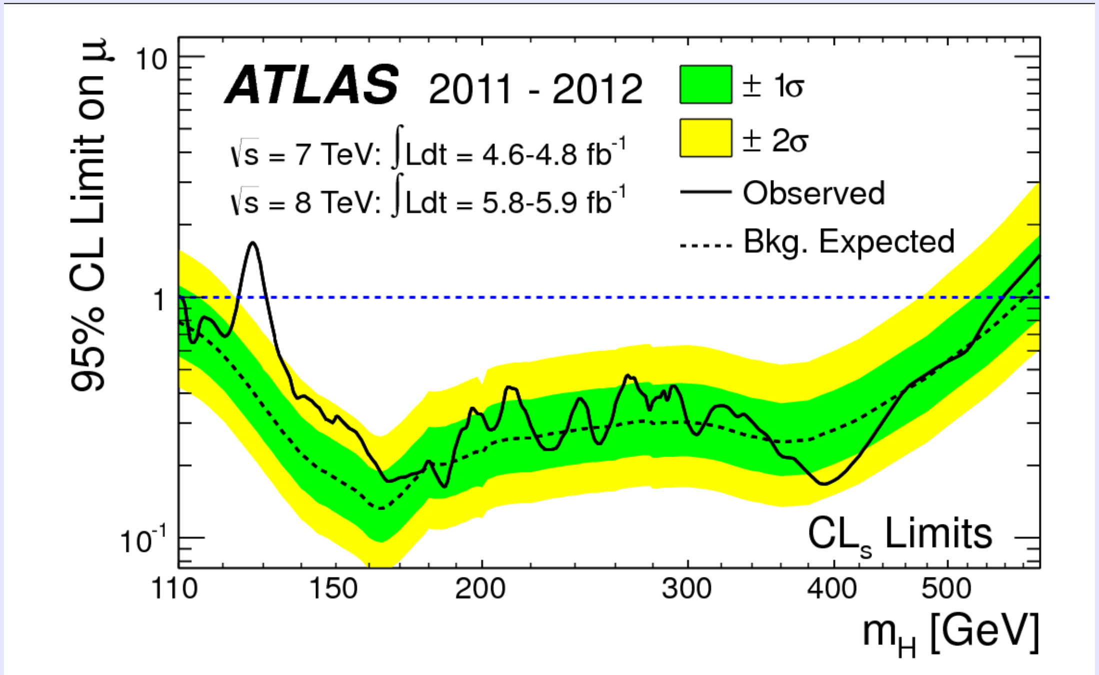
- Very small excess at 125 GeV

ATLAS combination of 2011/12 results

arXiv:1207.7214

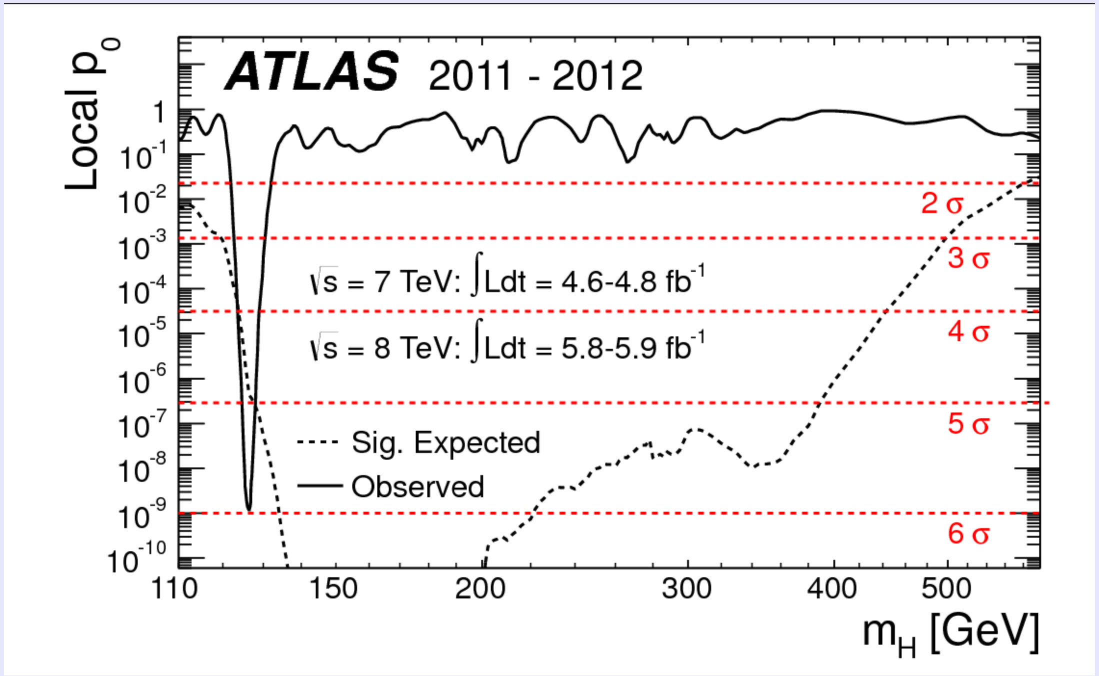


ATLAS combination of 2011/12 results



- SM excluded at 95% CL from 111-122, 131-559 GeV
- Excess of events observed at ~126 GeV
  - Local/global significance of 5.9σ/5.1σ
  - $P_0 = 1.7\times10^{-9}$
- Best fit mass: 126.0 ± 0.4 (stat) ± 0.4 (sys) GeV (only ZZ and γγ channels used)

ATLAS combination of 2011/12 results



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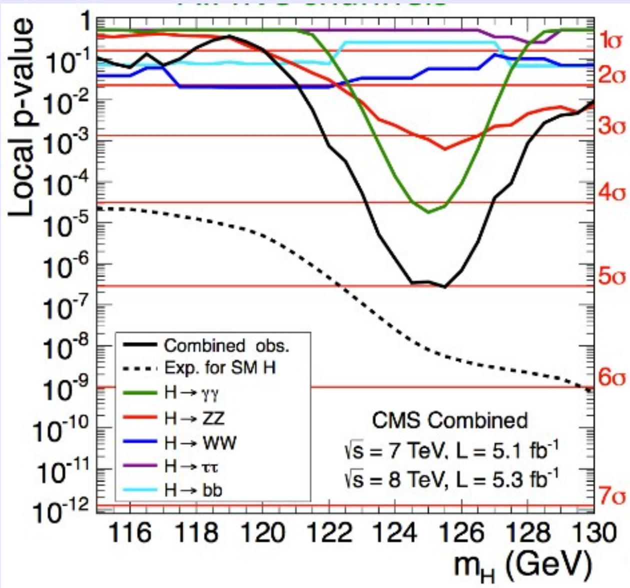
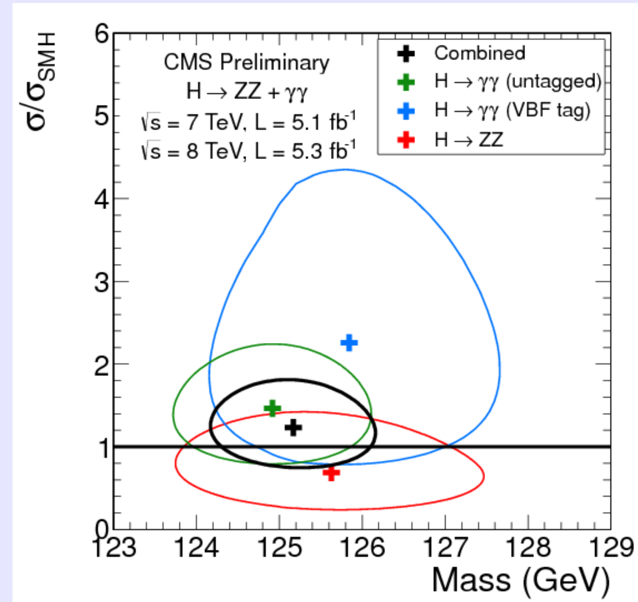
CMS combination of 2011/12 data





Local excess significance of different combinations

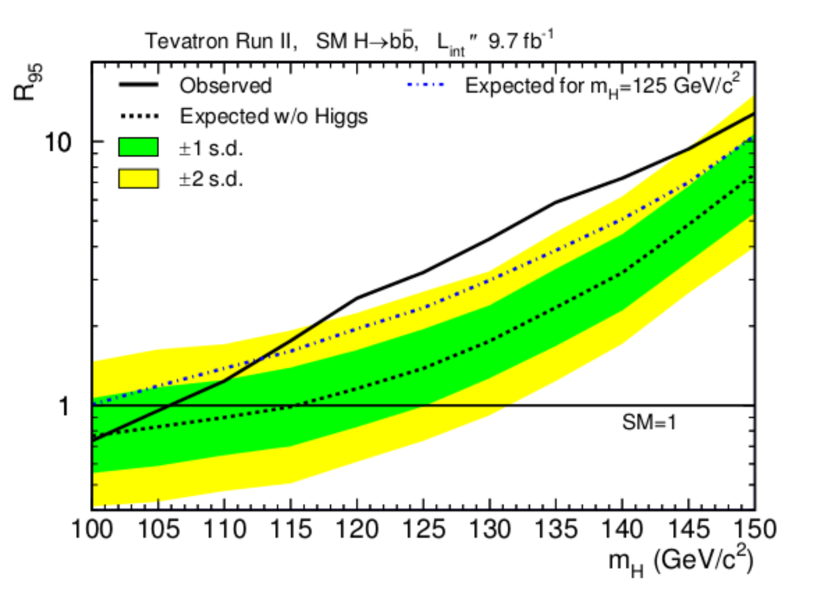
Decay mode or Combination	Expected (σ)	Observed (σ)
$\gamma\gamma$	2.8	4.1
ZZ	3.6	3.1
$\tau\tau$ + bb	2.4	0.4
$\gamma\gamma$ + ZZ	4.7	5.0
$\gamma\gamma$ + ZZ + WW	5.2	5.1
$\gamma\gamma$ + ZZ + WW + $\tau\tau$ + bb	5.8	5.0

Best fitted mass:

m = 125.3± 0.4(stat.) ± 0.5(syst.) GeV

Tevatron VH searches

- p-anti-p collider at Fermilab (USA) ($\sqrt{s}$ = 1.96 TeV)
- Searched for the Higgs boson in the low mass range in associated production mode
- Combined results of the CDF and D0 collaborations



- Excess of events observed
  - Local significance of 3.3σ
  - Global significance of 2.8σ
- Signal strength ~2 times the expected SM value

And now... what?


For use in case of
5σ Higgs discovery
1. Check label for "Champagne". (Do not use "Cava") Remove protective cover.
2. Gently twist cork to release fluid. (Aim away from face)
3. Apply fluid to Champagne flutes. Repeat until all flutes are filled.
CHAMPAGNE
CHARLES
DE COURANCE
Cuvée Chardonnay

Is this the SM Higgs boson?

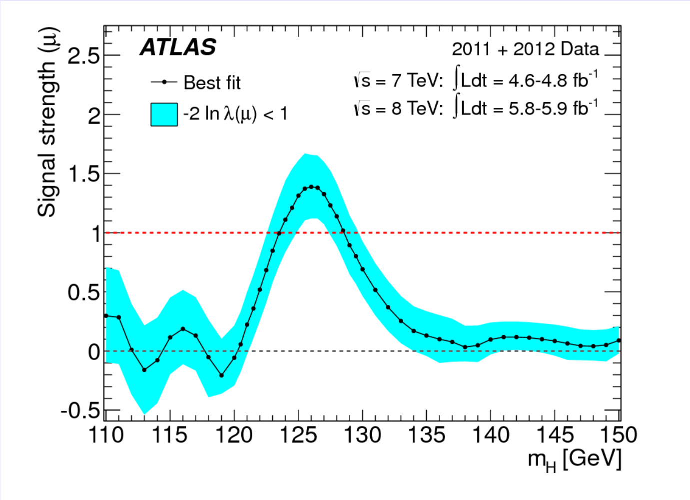
What we know:

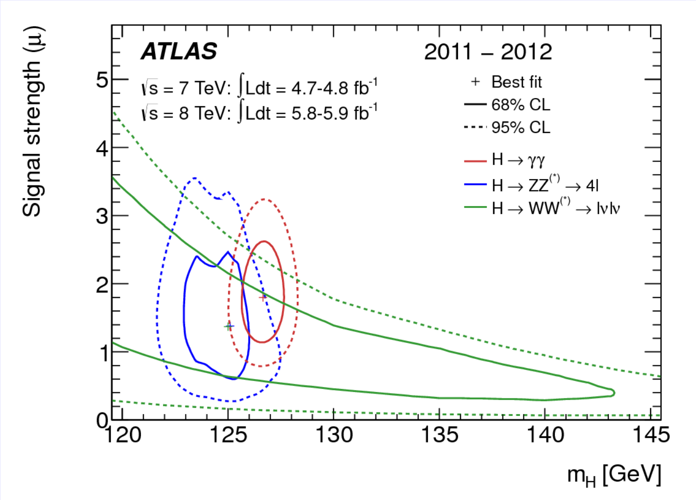
- Mass: 125-126 GeV
- It has charge 0
- It decays to $\gamma\gamma \Rightarrow$ it should be a boson and due to Landau-Yan theorem it cannot have spin 1

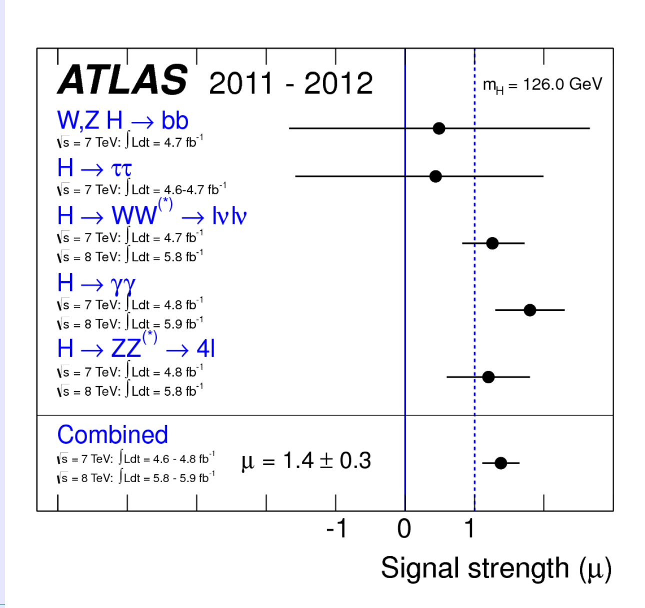
To be sure, we need to measure precisely:

- Couplings to all the known particles
  - Fermions, vector bosons
  - Coupling proportional to mass?
- Spin, CP
- Only one Higgs or more?
- Elementary or composite?
- Self interactions?

Signal strength

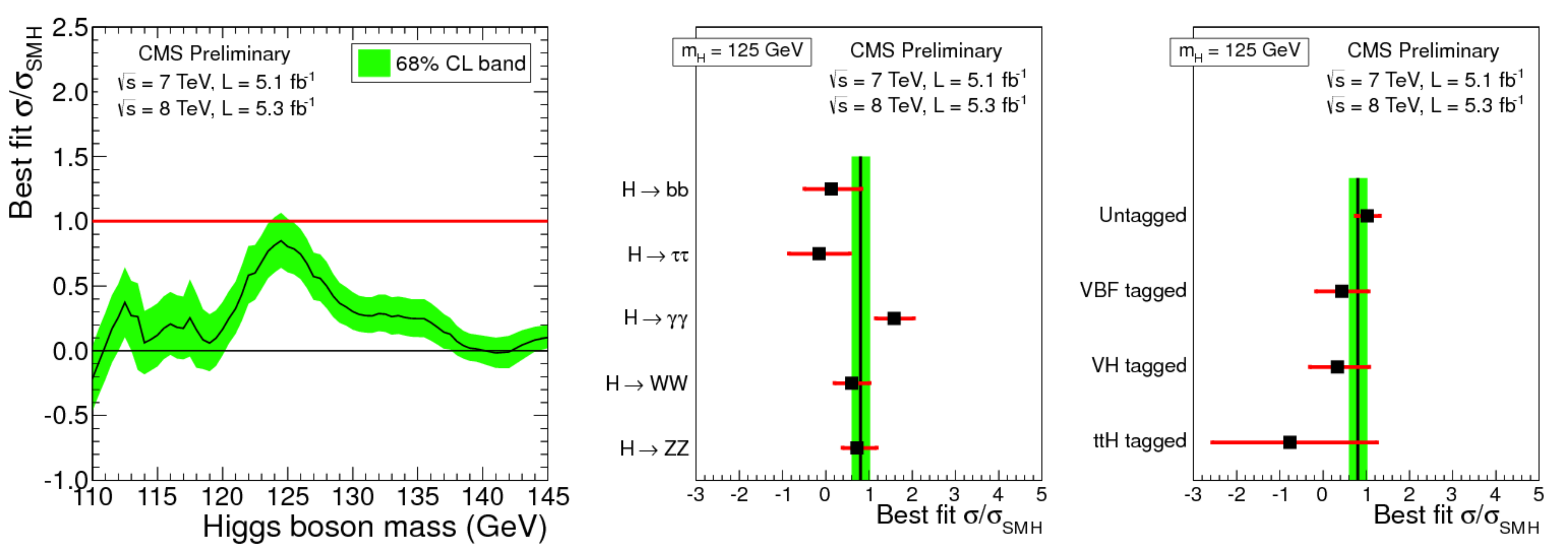






- $\mu = 1.4 \pm 0.3$ for m_H=126 GeV
  - Consistent with SM hypothesis
- 20% probability that a single Higgs boson-like particle produces mass peaks separated by more than the observed mass difference

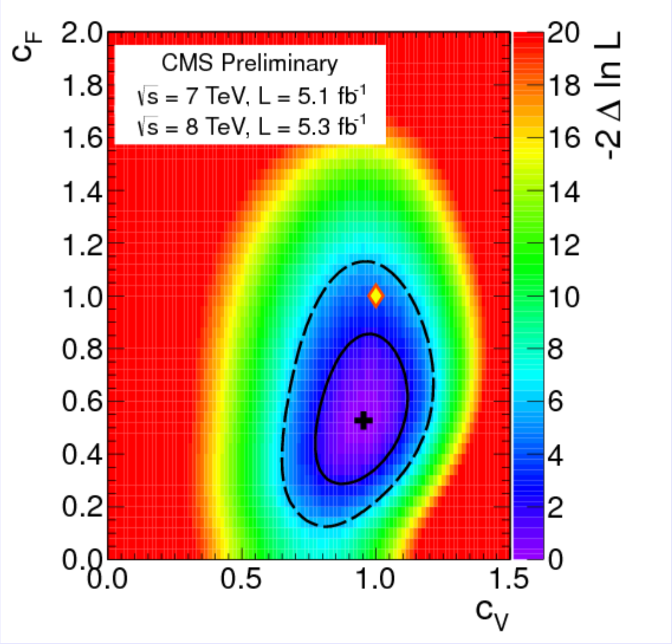
Signal strength



Couplings to fermions and bosons

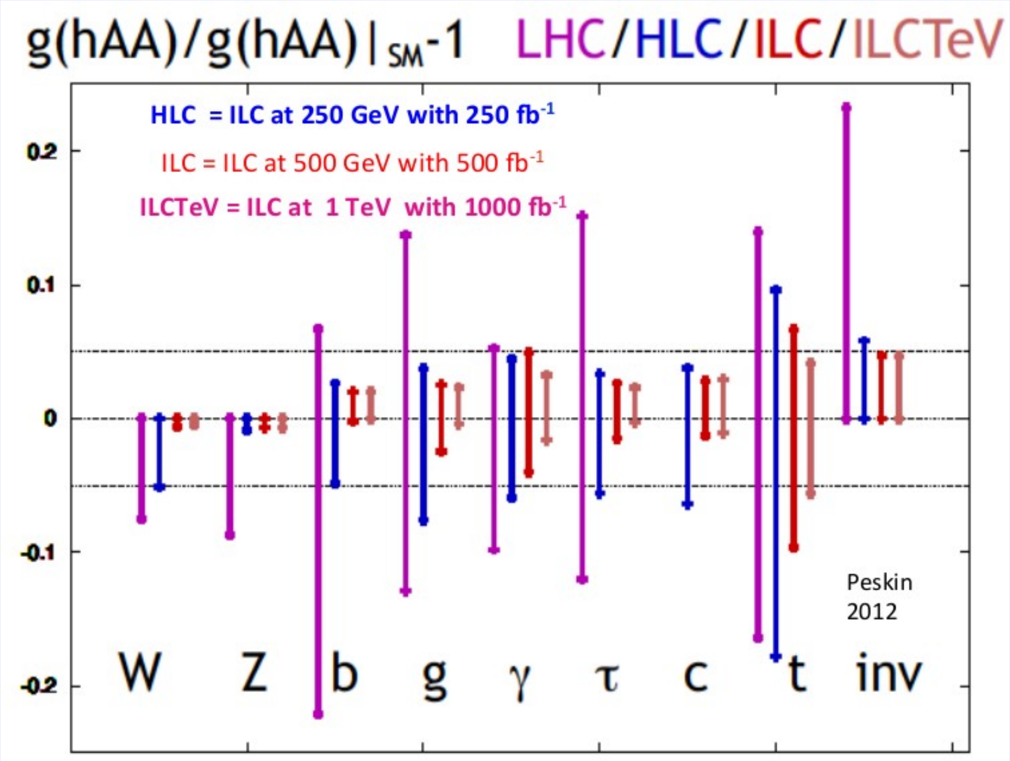
Production	Decay	LO SM	
VH	$H \to bb$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ttH	$H \to bb$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
VBF	$H \to \tau\tau$	$\sim \frac{C_V^2 \times C_F^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to \tau\tau$	$\sim \frac{C_F^2 \times C_F^2}{C_F^2}$	$\sim C_F^2$
ggH	$H \to ZZ$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
ggH	$H \to WW$	$\sim \frac{C_F^2 \times C_V^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to WW$	$\sim \frac{C_V^2 \times C_V^2}{C_F^2}$	$\sim C_V^4/C_F^2$
ggH	$H \to \gamma\gamma$	$\sim \frac{C_F^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^2$
VBF	$H \to \gamma\gamma$	$\sim \frac{C_V^2 \times (8.6 C_V - 1.8 C_F)^2}{C_F^2}$	$\sim C_V^4/C_F^2$

- Interpret the new particle as the Higgs boson
- Scale vectorial and fermionic couplings by C_V and C_F
- Best fit: $(C_V, C_F) = (1.0, 0.5)$



But...

➤ To be sure about the nature of this particle and measure its properties accurately we will need at least the full LHC luminosity



Summary and conclusions

- The SM Higgs boson is responsible of all the other particle's masses
- Searched for SM Higgs boson in 12 different channels, $110 < m_H < 600$ GeV
- Excluded SM Higgs at 95% CL in the mass range 111-122, 131-559 GeV
- Observed a new particle with

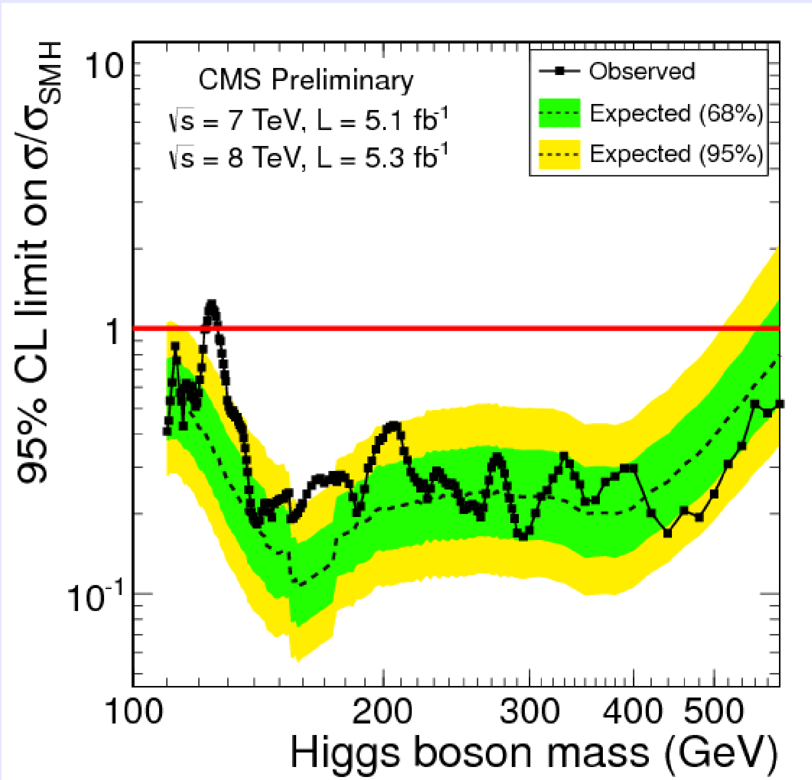
	ATLAS	CMS
Local significance:	5.9s	5.0s
Global significance:	5.1s	4.5s
P_0:	1.7×10^{-9}	
Mass:	126 ± 0.4(stat) ± 0.4(sys) GeV	125.3± 0.4(stat.)± 0.5(syst.) GeV

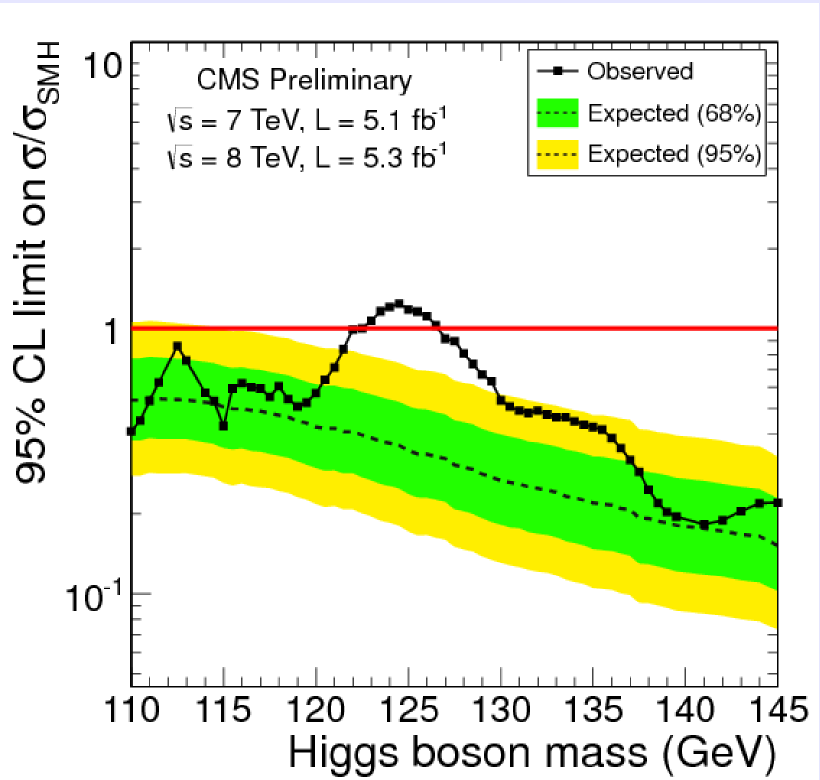
- Signal strength compatible with SM expectation

This is an historical moment, result of many years of hard work, but only the start of many more years of future work

Backup

CMS combination of 2011/12 data



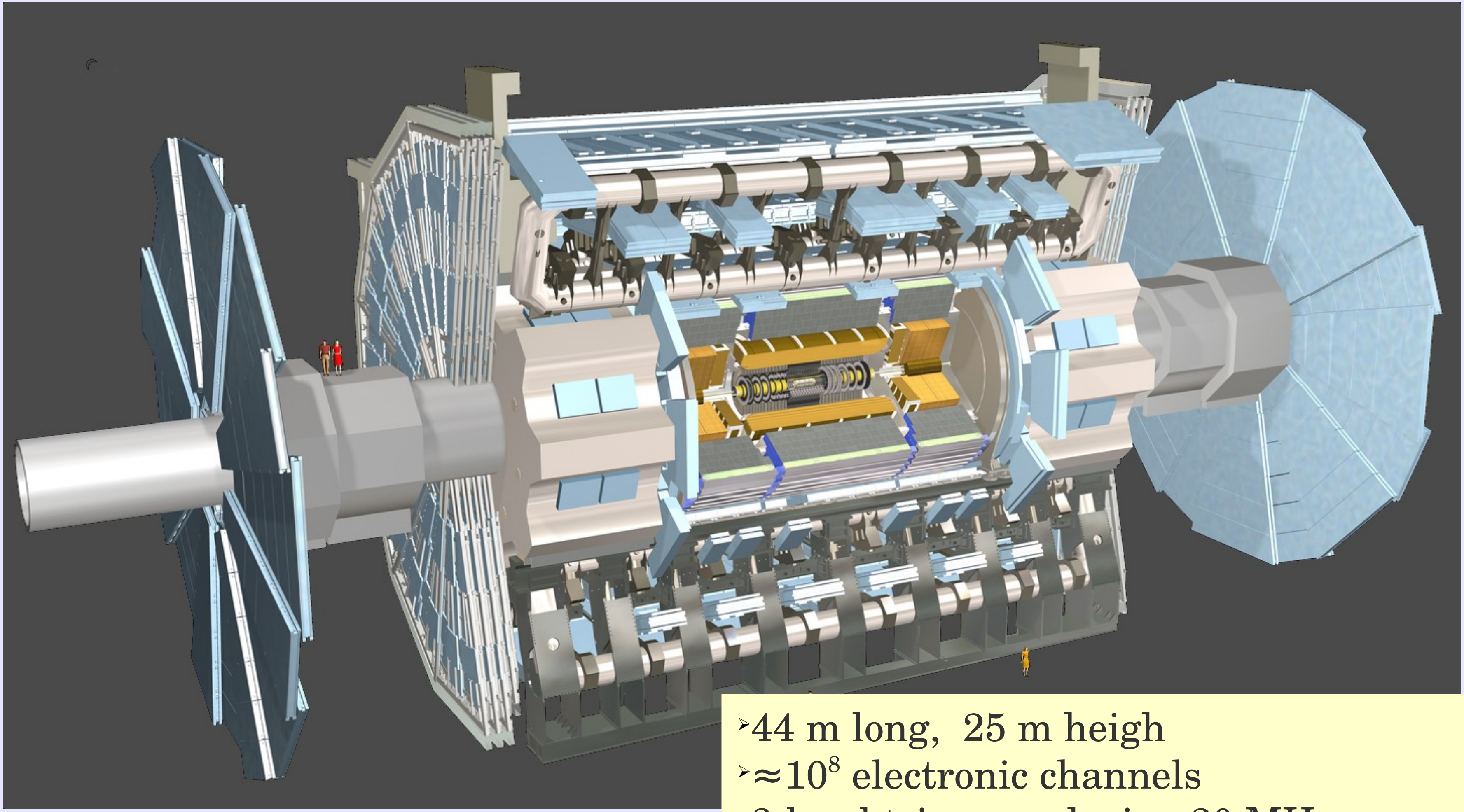


Combination of 2011+2012 results

Higgs decay channel	Sub-channel	Mass range (GeV)	L(fb^{-1})
$H\to ZZ$	ll l'l' $ll\nu\nu$ llqq	110-600 200-600 200-600	4.8+5.8 4.7 4.7
$H\to\gamma\gamma$		110-150	4.8+5.9
$H\to WW$	$l\nu qq$ $l\nu l\nu$	300-600 110-600	4.7 4.7+5.8
$H\to\tau\tau$	$ll4\nu$ $l\tau_{had}3\nu$ $\tau_{had}\tau_{had}2\nu$	110-150	4.7 4.7 4.7
$VH\to bb$	$l\nu bb$ llbb $\nu\nu bb$	110-130	4.7 4.7 4.6

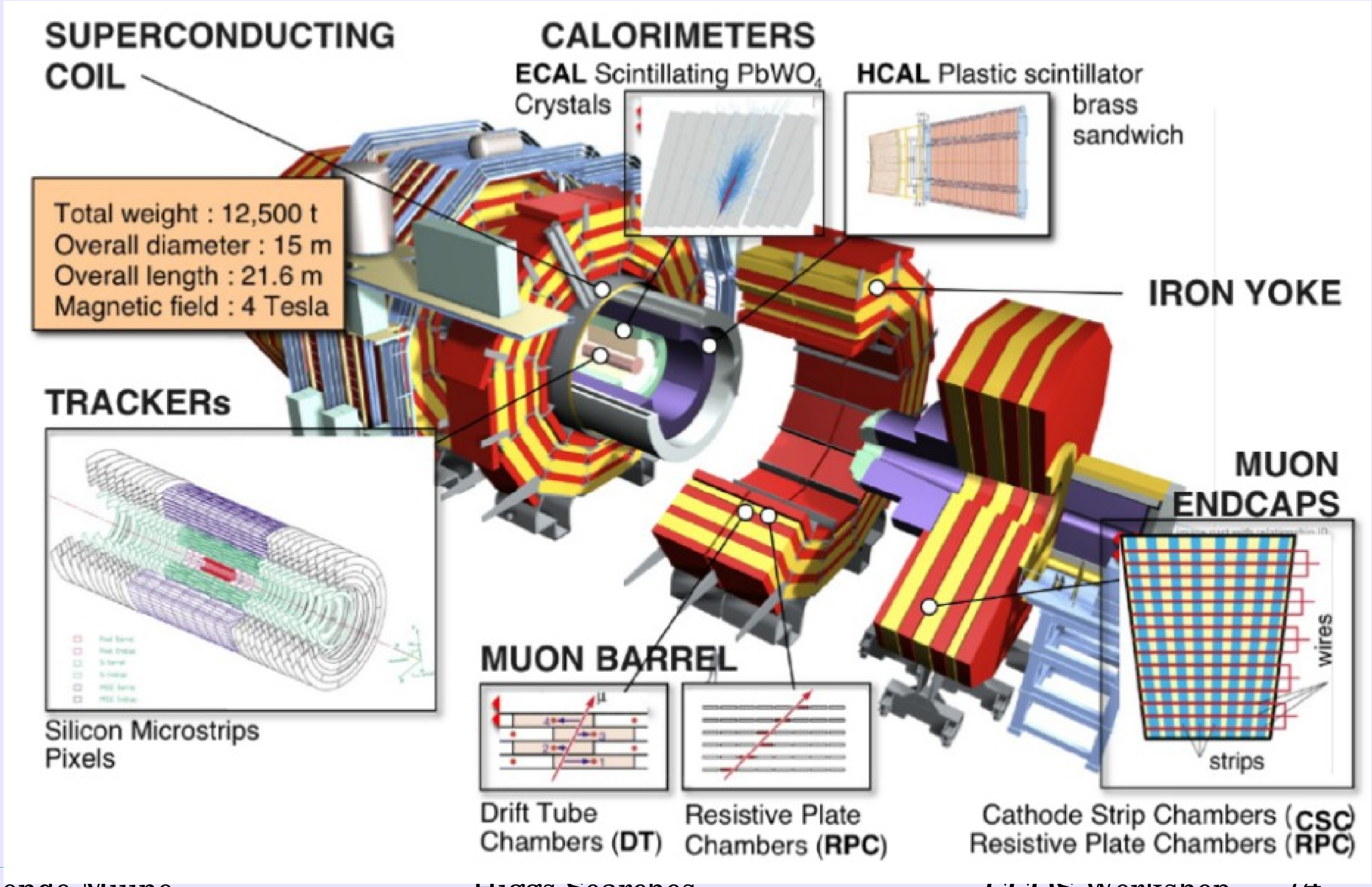
References: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

The ATLAS detector



- 44 m long, 25 m heigh
- $\approx 10^8$ electronic channels
- 3-level trigger reducing 20 MHz collision rate to 400 Hz of events to tape

The CMS detector



ATLAS 2012 searches

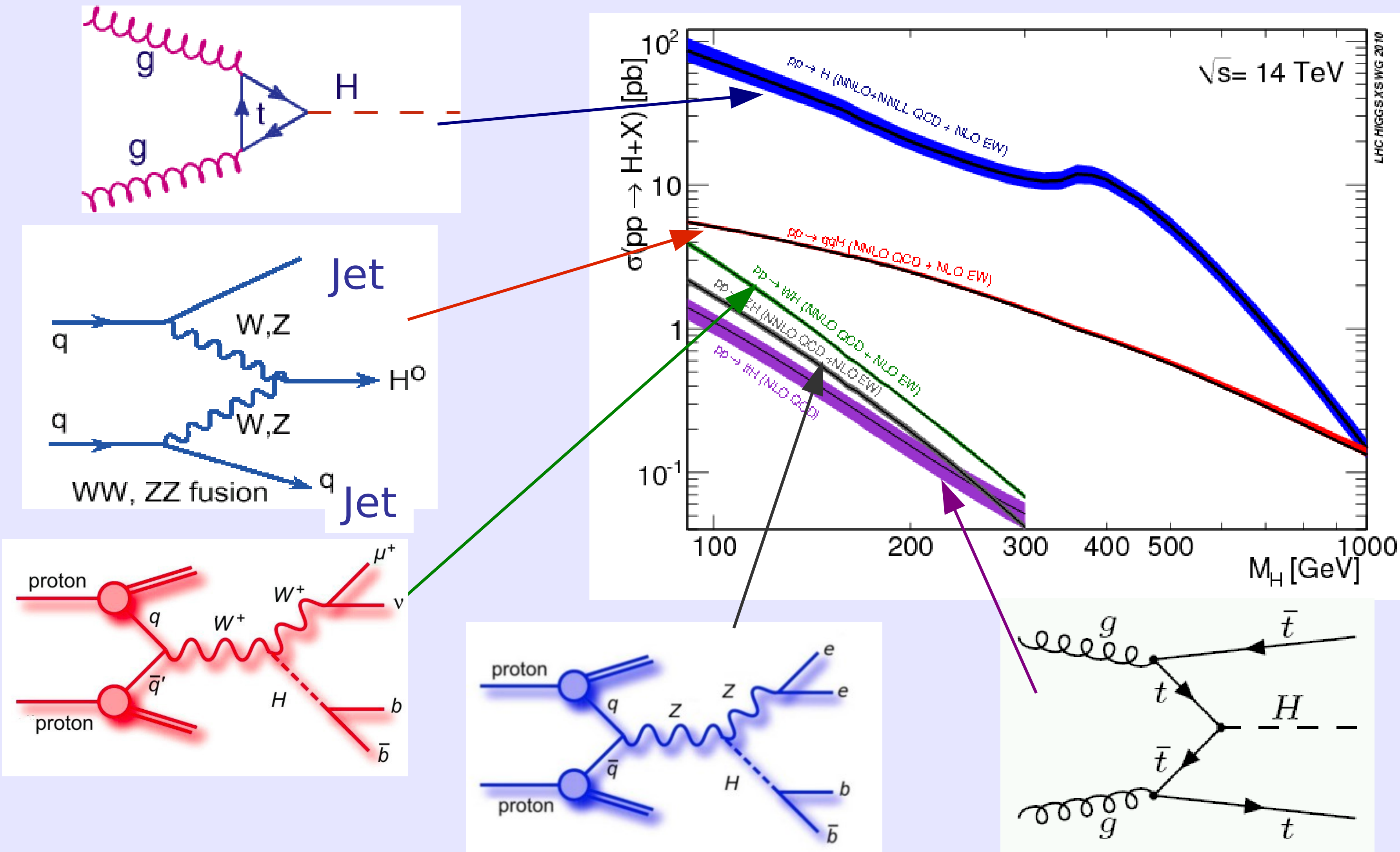
Focus on most sensitive channels at low mass:

- $H\to\gamma\gamma$, $H\to ZZ\to 4l$
  - Good mass resolution
  - Selection based on e, γ, μ (easier in a high pile-up environment)
- $H\to WW\to l\nu l\nu$
  - Poor mass resolution
  - Focus on the $e\mu$ final state
    - Provides 85% of the sensitivity
    - Lower Drell-Yan background than in the same flavour final states

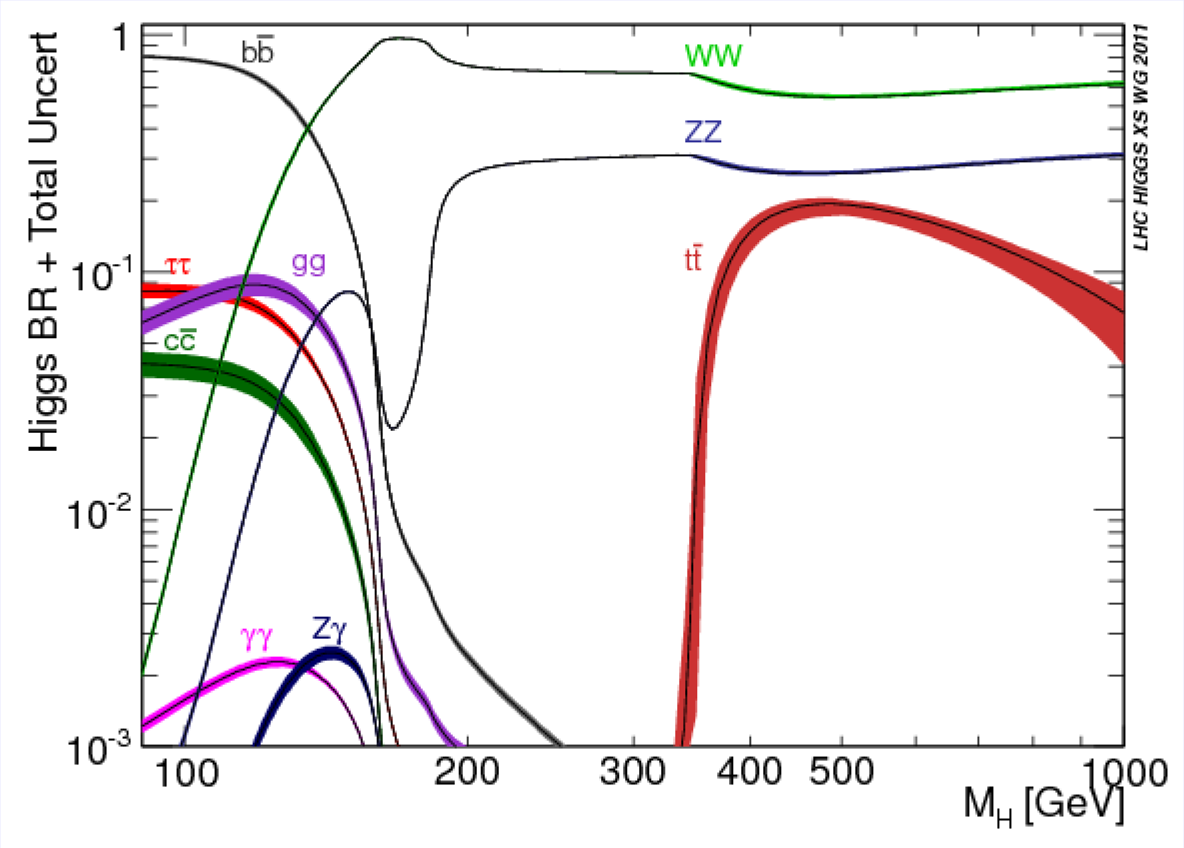
Analysis strategy:

- Re-optimise analyses for high pileup and low m_H based on MC and 2011 control regions
- All selections and analysis techniques fixed before looking at 2012 data

Higgs production

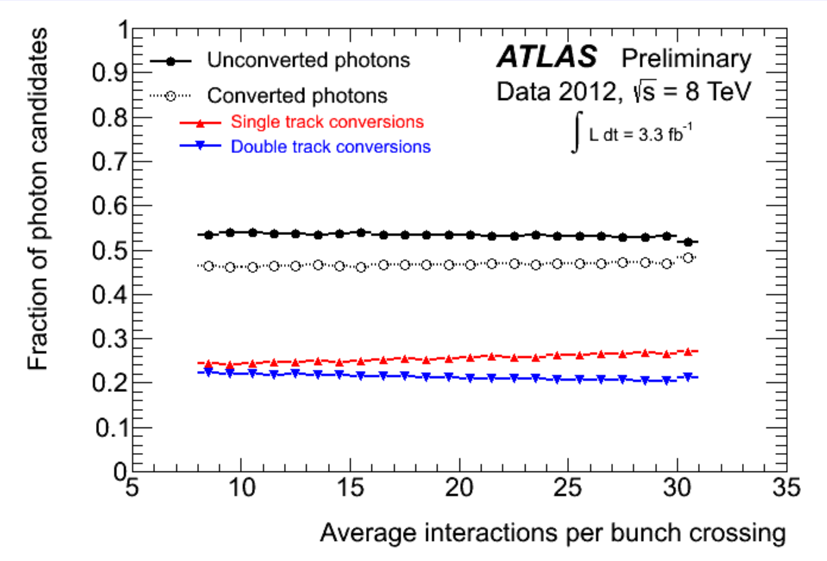


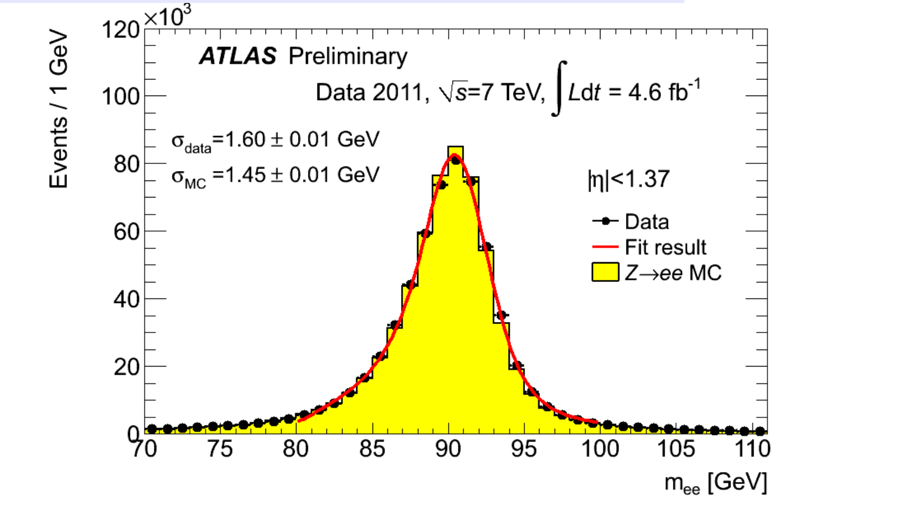
Higgs decays in the SM



γ identification & energy measurement

- Very stable photon ID peformance with pile-up
- Calorimeter E response studied with Z, J/ψ and W decays
  - Energy scale at m_Z known to ~ 0.5%
  - Linearity better than 1%
  - Uniformity: 1% -1.7 %

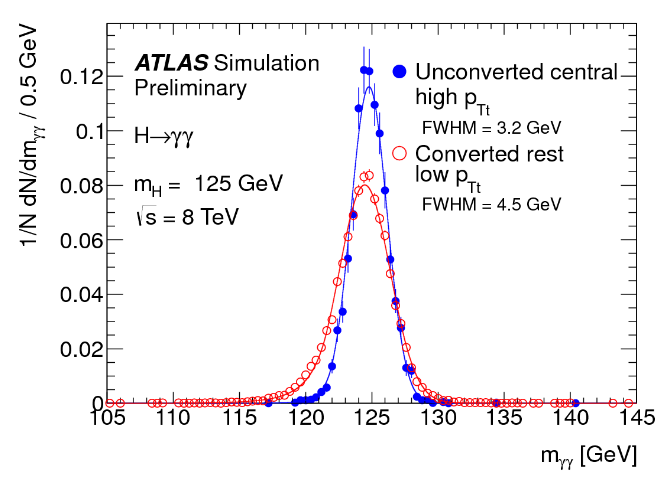


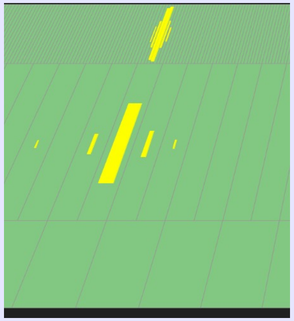


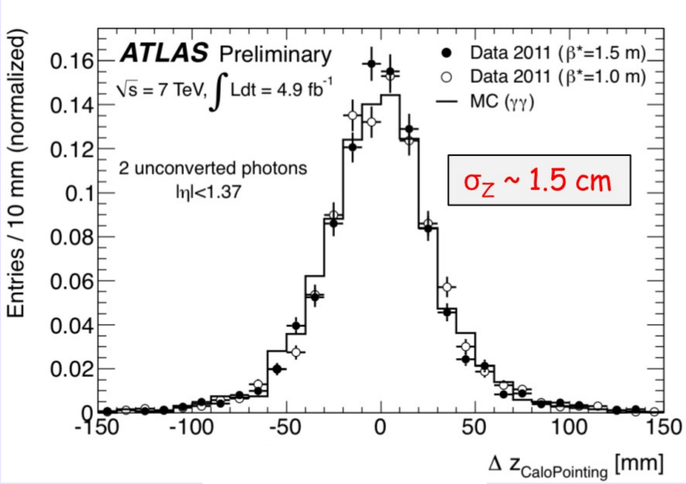
Mass resolution

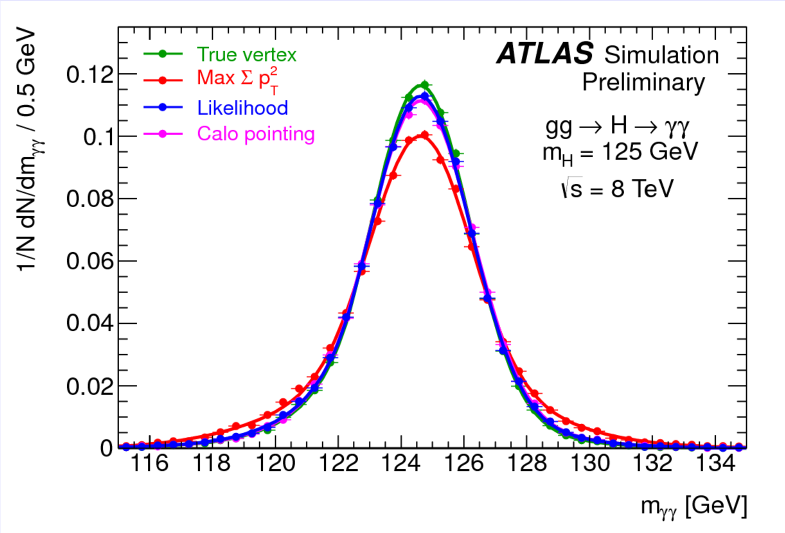
Excellent mass resolution of σ = 1.6-3.1 GeV

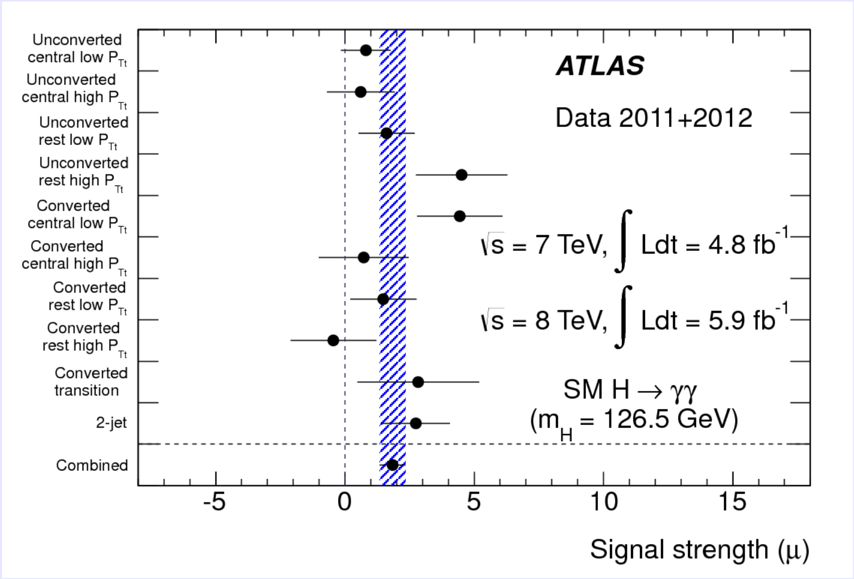
- Use calorimeter segmentation to find primary vertex
- Resolution σ_z ~ 15 mm
    - Improved to 6 mm when both γ convert

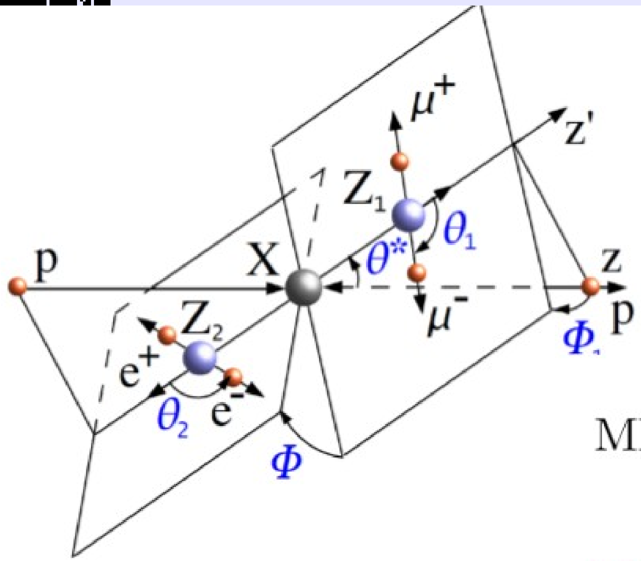









Unconverted central low P_{Tt}
Unconverted central high P_{Tt}
Unconverted rest low P_{Tt}
Unconverted rest high P_{Tt}
Converted central low P_{Tt}
Converted central high P_{Tt}
Converted rest low P_{Tt}
Converted rest high P_{Tt}
Converted transition
2-jet
Combined
ATLAS
Data 2011+2012
$\sqrt{s}$ = 7 TeV, $\int Ldt = 4.8\ fb^{-1}$
$\sqrt{s}$ = 8 TeV, $\int Ldt = 5.9\ fb^{-1}$
SM $H \rightarrow \gamma\gamma$
(m_H = 126.5 GeV)
-5
0
5
10
15
Signal strength (μ)

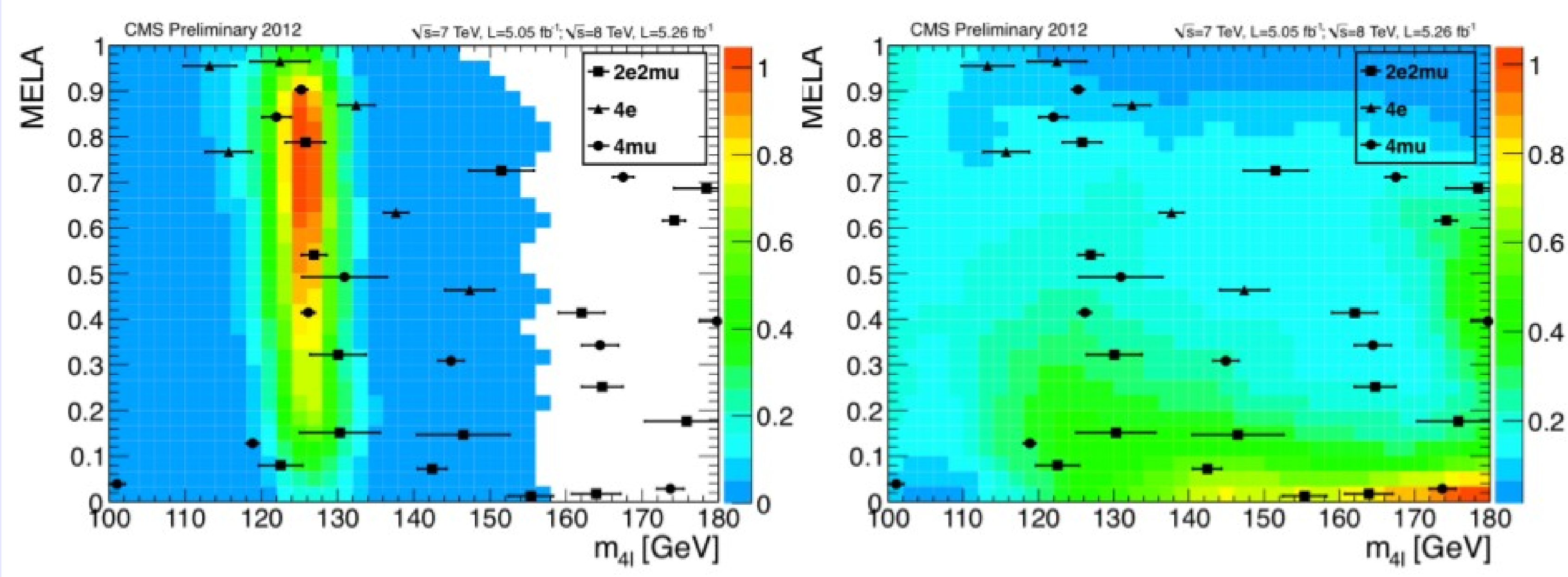


MELA: Matrix Element Likelihood Analysis:

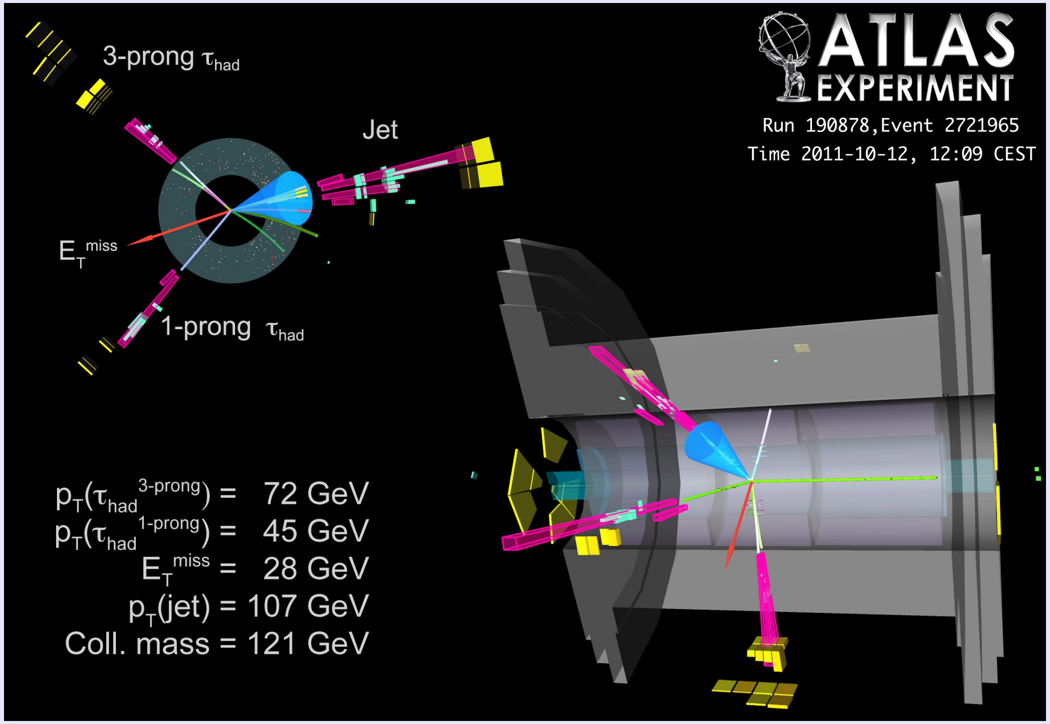
uses kinematic inputs for
signal to ZZ background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

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

MELA Improves the sensitivity by ~20%
compared to using the mass alone



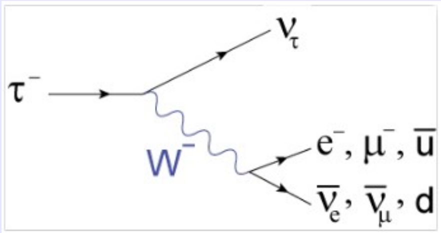
$H \to \tau\tau$ ATLAS search

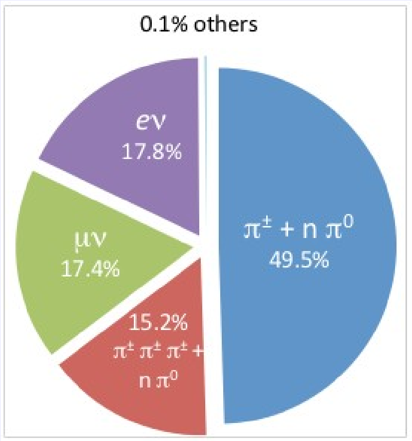


- Three decay channels studied
- Analysis categories: 0,1 jet (dominated by gg fusion), 2 jet (VH and VBF)
- Backgrounds
  - $Z \to \tau\tau$ (irreducible), estimated from embedded $Z \to \mu\mu$ data
  - τ/lepton fakes, data control regions

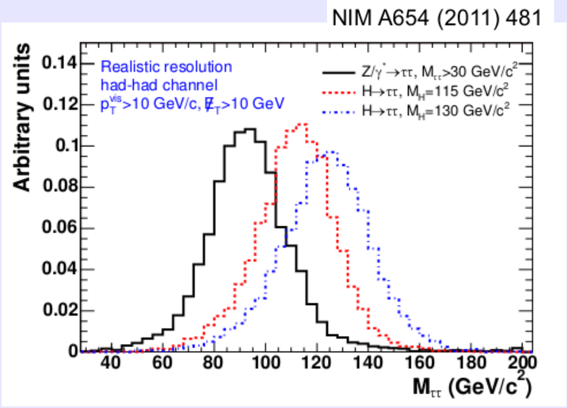
Tau reconstruction

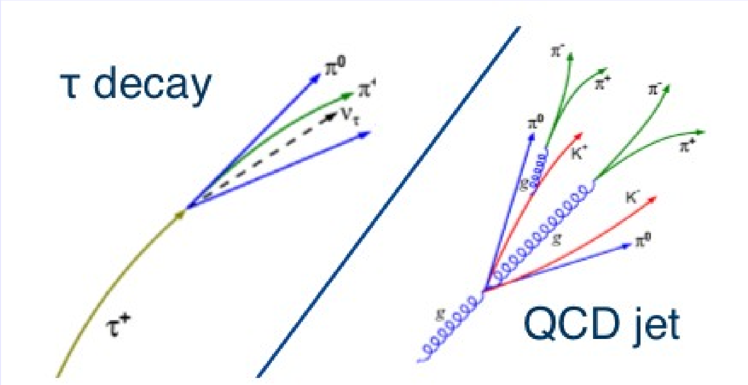
- Neutrinos in the final state
  - Difficult to reconstruct di-τ mass
  - Challenging to suppress jet background





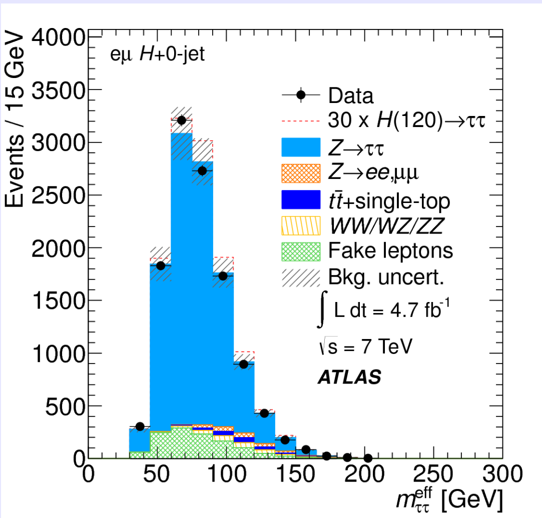
- Constrain the neutrino momenta using tau decay kinematics to improve di-τ mass resolution

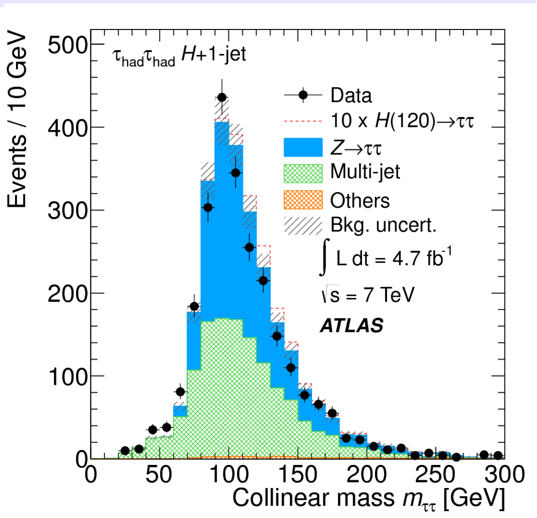


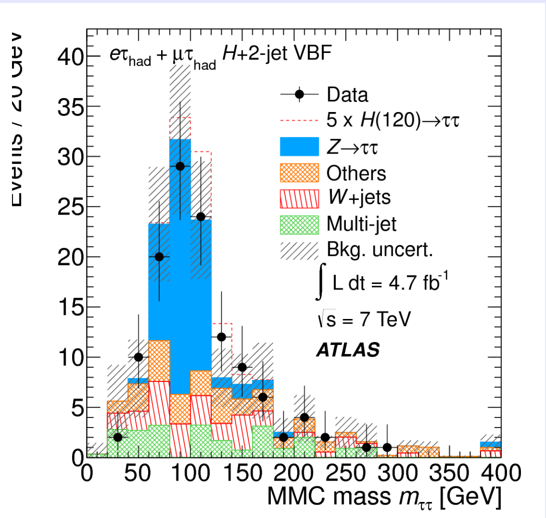


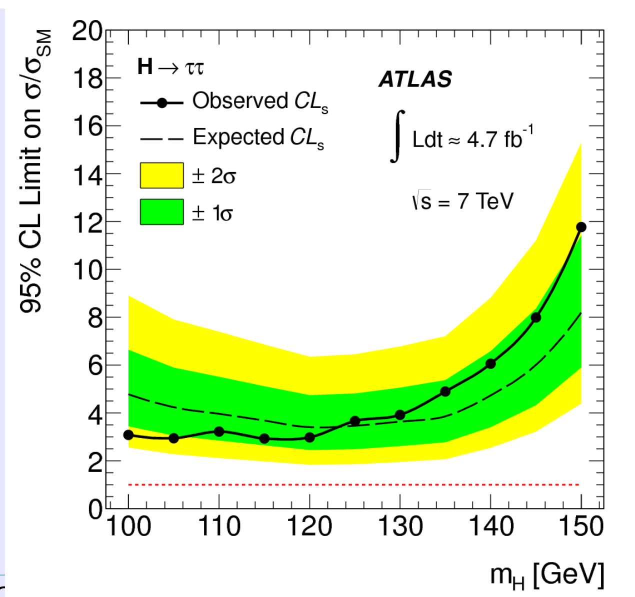
- Use a MVA to select hadronic τ's
- Efficiency: 60% (h/H/A), 30%(H^+)
- Miss-identification: 5% (h/H/A) 0.1-1% (H^+)

ATLAS H→ττ results with 2011 data





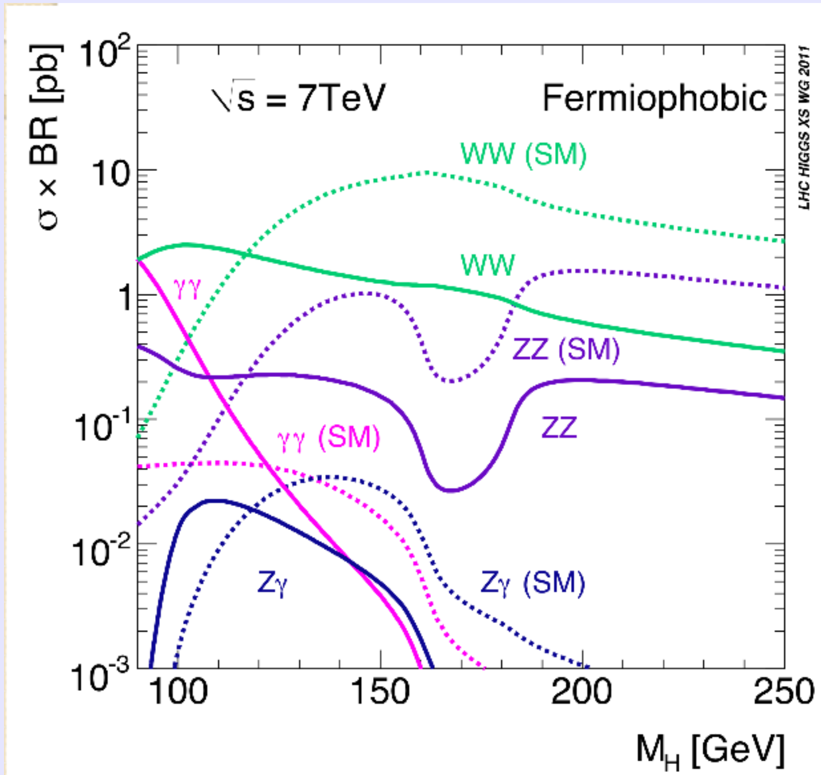




- No observable excess for 110< m_H < 150 GeV
- Observed limit: 2.9-11.7xσ_{SM}
- Expected limit: 3.4-8.2xσ_{SM}

Higgs searches beyond the SM

Fermiophobic H→γγ



Fermiophobic scenario:

- No Higgs couplings to fermions
- SM couplings to bosons
- Only two production modes: VBF, VH
- Only final states with γ, Z, W bosons

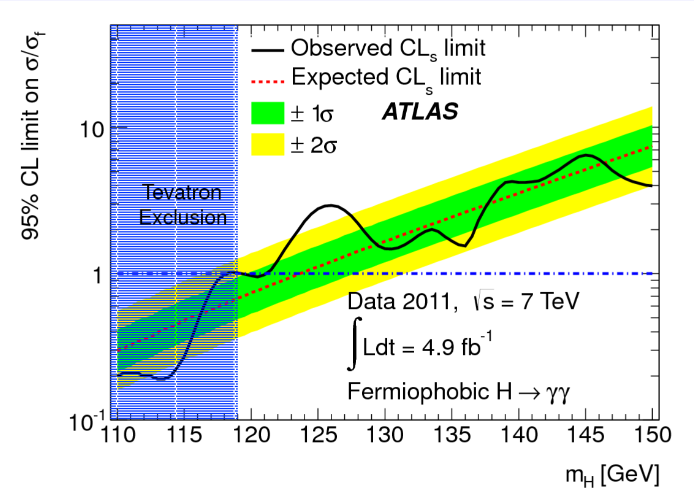
Analysis strategy:

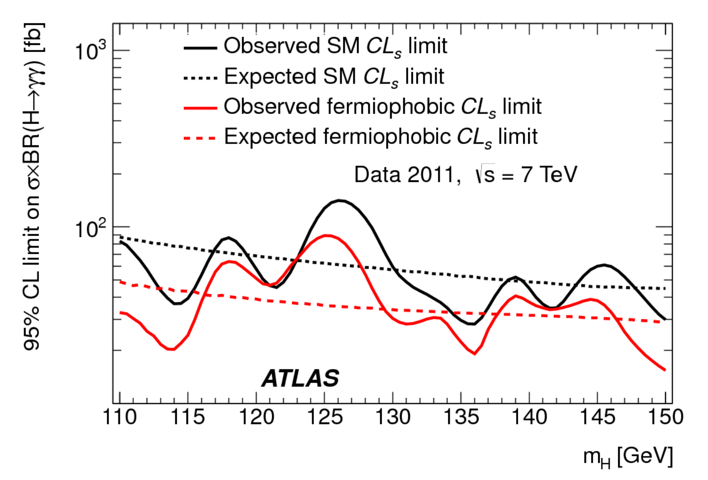
- Similar to standard H→γγ analysis (but only 9 categories, no di-jet bin)
- Only 2011 data analysed

2011 Fermiophobic H→γγ results

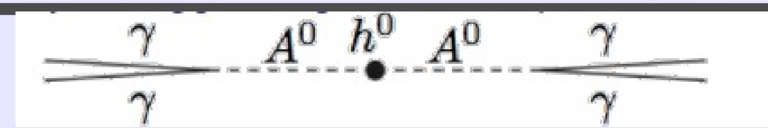
Exclusion limits at 95% CL:

- Expected: 110-123.5 GeV
- Observed: 110-118, 119.5-121 GeV
    - Improved upon previous LEP/Tevatron limits
- Largest excess at 125.5 GeV
    - Local significance: 2.9σ
    - Global significance: 1.6σ
- Results not yet conclusive
    - Need to analyse more data



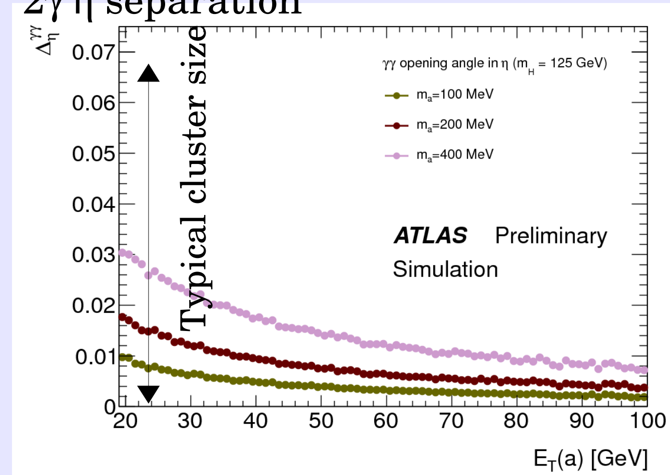


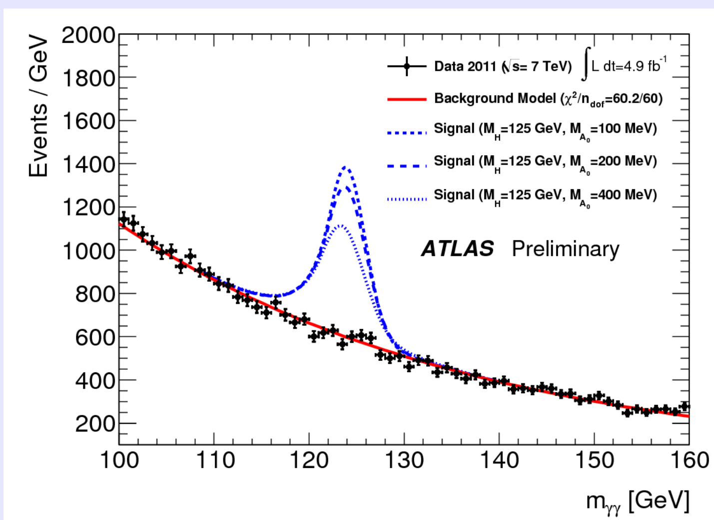
$H \to a^0 a^0 \to 4\gamma$

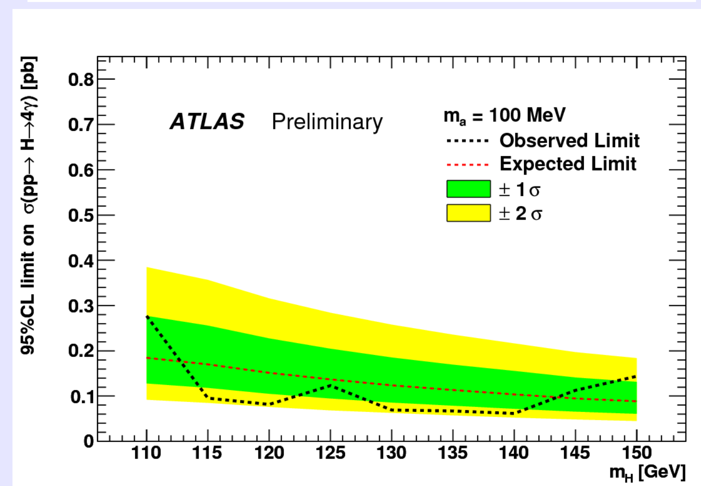


- Higgs decay to two light pseudoscalars a^0
- a^0 decay to collimated photons
  - Similar signature to $H \to \gamma\gamma$ analysis
  - Relaxed photon ID for broader showers
- No signal observed in 2011 data sample
- Calculated a^0 cross section limits for decay lengh <~0.5m, $100 < m_a < 400$ MeV

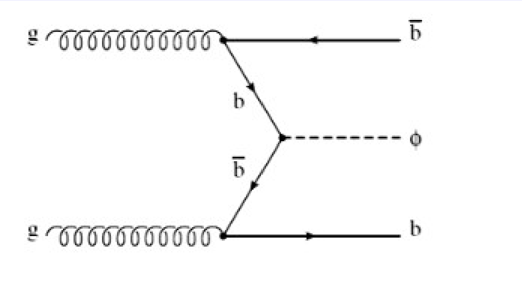
2γ η separation







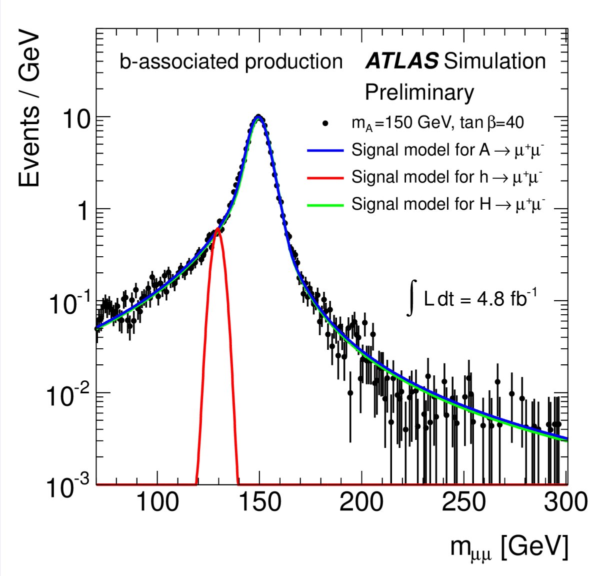
MSSM neutral Higgs boson searches



- 3 neutral Higgs bosons: h, H, A
- Production via gluon fusion and b-quark annihilation
- Cross section rises with tanβ
- Decay to bb (10%), ττ (10%) and μμ (0.04%)

Search performed in

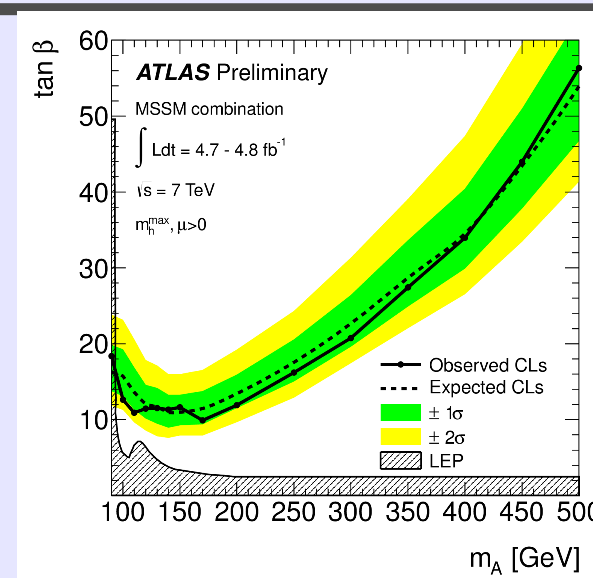
- ττ channel:
  - Similar to SM search but with b-tagged/vetoed selection
  - τ final states: $ll4\nu$, $l\tau_{had}3\nu$, $\tau_{had}\tau_{had}2\nu$
- μμ
  - clean, good mass resolution
  - Two analysis (b-tagging/vetoed selections)
  - 2011 complete data sample

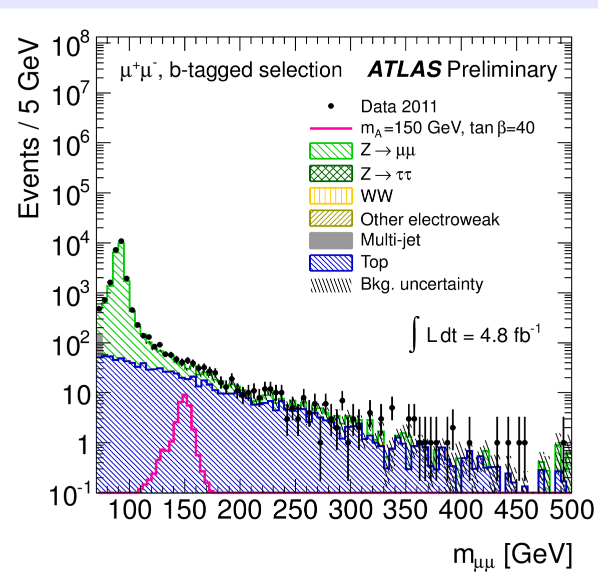


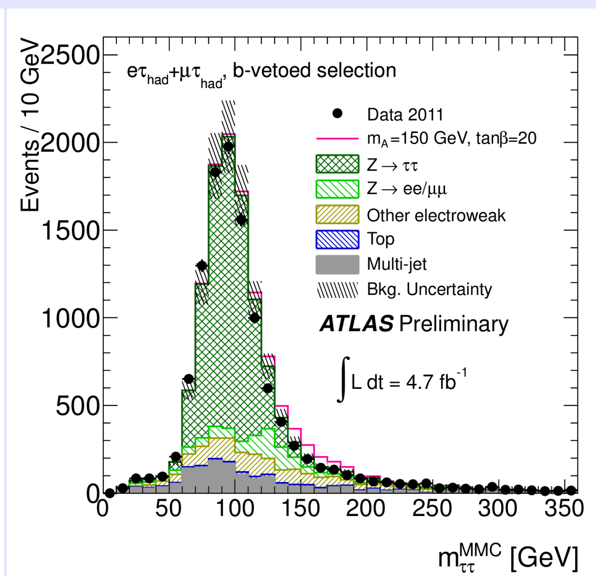
MSSM neutral Higgs boson searches

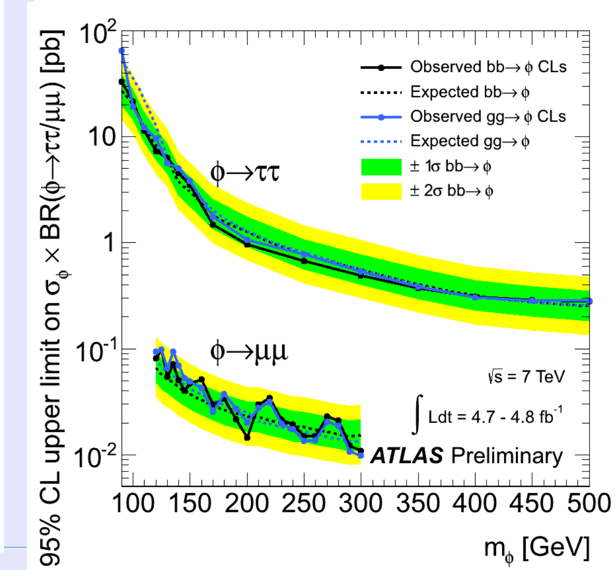
No excess of events observed

- Combined exclusion at 95% CL in m_A-tanβ
- There is still room for MSSM Higgses in large region
- Calculated also more model independent production cross section limit vs m_ϕ

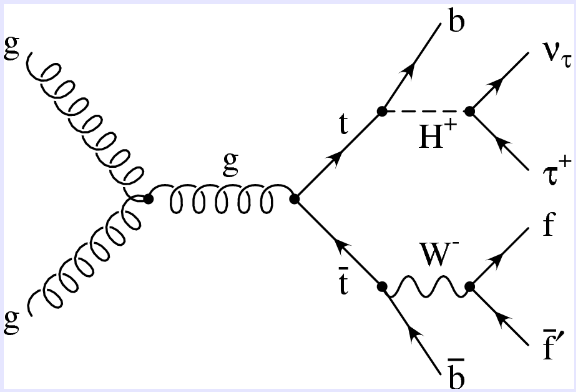








MSSM $H^{\pm} \to \tau\nu$



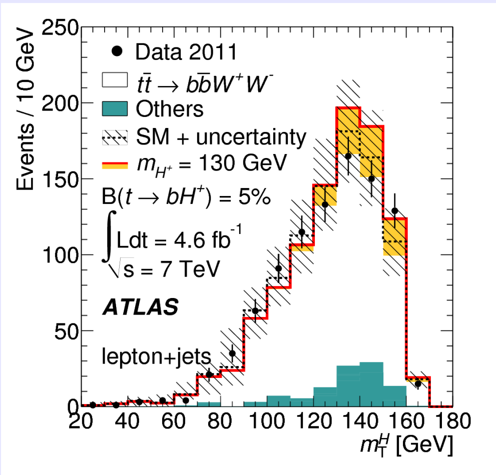
- Search focus on a light charged Higgs produced in top decays
- For tanβ > 3, $H^{\pm} \to \tau\nu$ dominates
- Channel topology organized according to W and Higgs decay

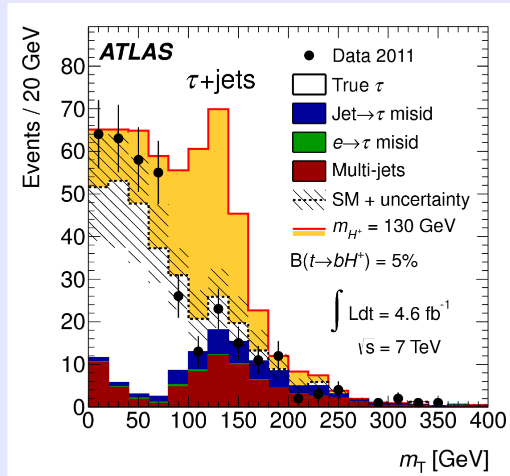
$$t\bar{t} \to b\bar{b}H^{\pm}W^{\mp} \to b\bar{b}(\tau_{lep}\nu)(q\bar{q})$$
$$t\bar{t} \to b\bar{b}H^{\pm}W^{\mp} \to b\bar{b}(\tau_{had}\nu)(\ell\nu)$$
$$t\bar{t} \to b\bar{b}H^{\pm}W^{\mp} \to b\bar{b}(\tau_{had}\nu)(q\bar{q})$$

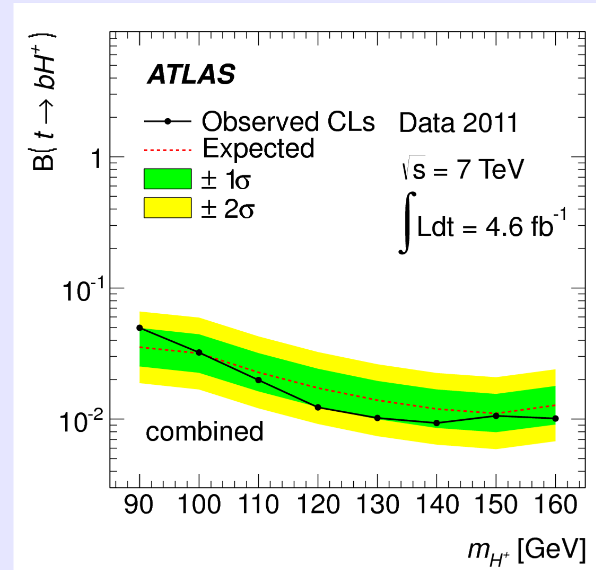
- Selection:

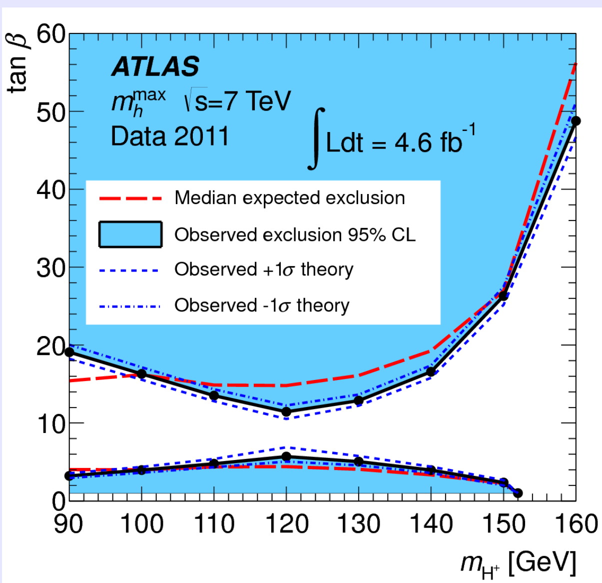
Tau(lep) + W(→ jets)	Tau(had) + W(→ jets)	Tau(had) + W(→ lν)
1 isolated e/μ, p_T > 25/20 GeV	1 τ_{had} with p_T > 40 GeV	1 isolated e/μ, p_T > 25/20 GeV
		1 τ_{had} with p_T > 20 GeV
At least 4 jets (pT>20 GeV) with exactly 2 b-tagged	At least 4 jets (pT>20 GeV) with at least 1 b-tagged	At least 2 jets (pT>20 GeV), with at least 1 b-tagged
MET & Topological cuts	MET & Topological cuts	vertex ΣpT > 100 GeV

MSSM $H^{\pm} \rightarrow \tau\nu$ results



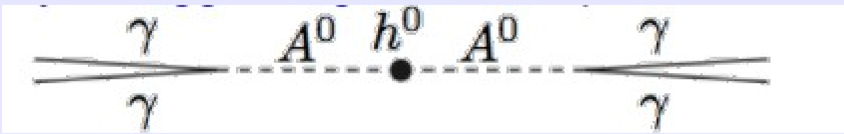


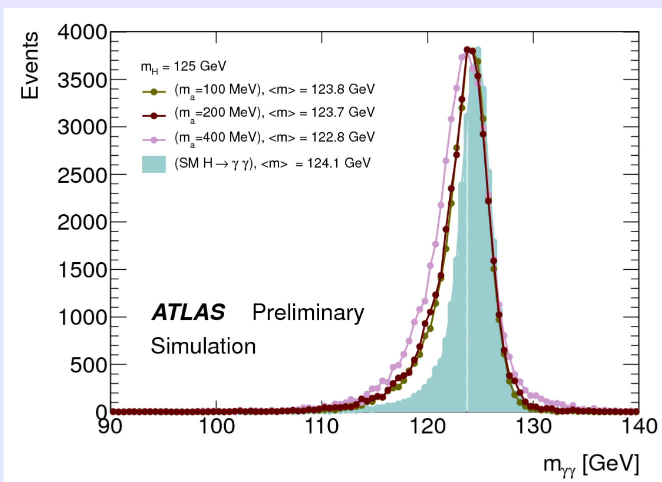


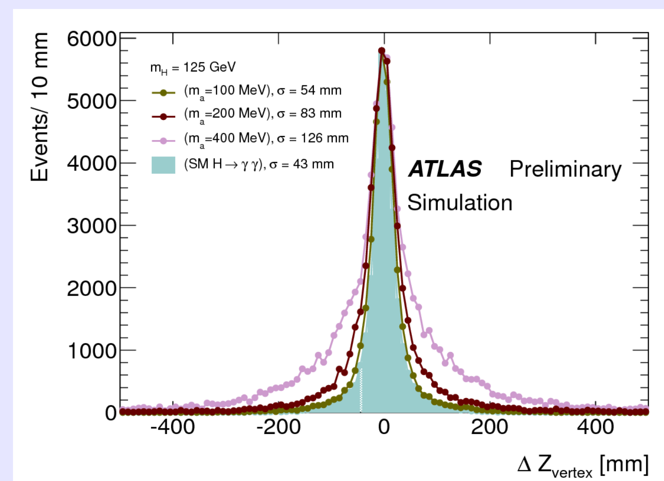


- No signal observed
- Calculated limits on $BR(t \rightarrow bH^{\pm})$
- Low mass $H^{\pm}$ allowed phase space in the MSSM scenario is heavily constrained

$H \to a^0 a^0 \to 4\gamma$







MSSM $H^{\pm} \to cs$ results

Important at low tanβ:

- BR(H→cs) ~ 40%, tanβ<1

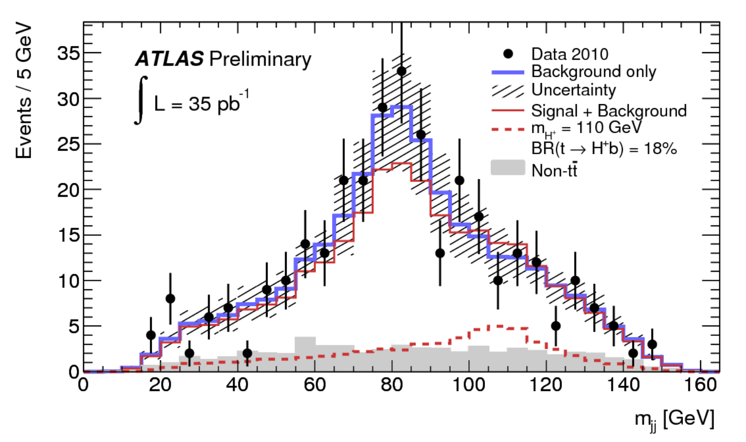
Search channel:

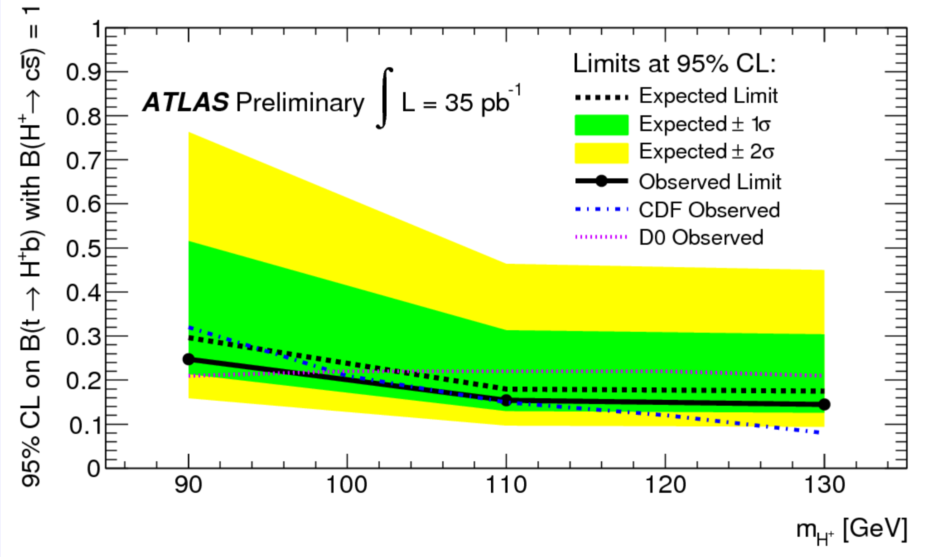
- tt → bbWH → bb (lν) (cs)

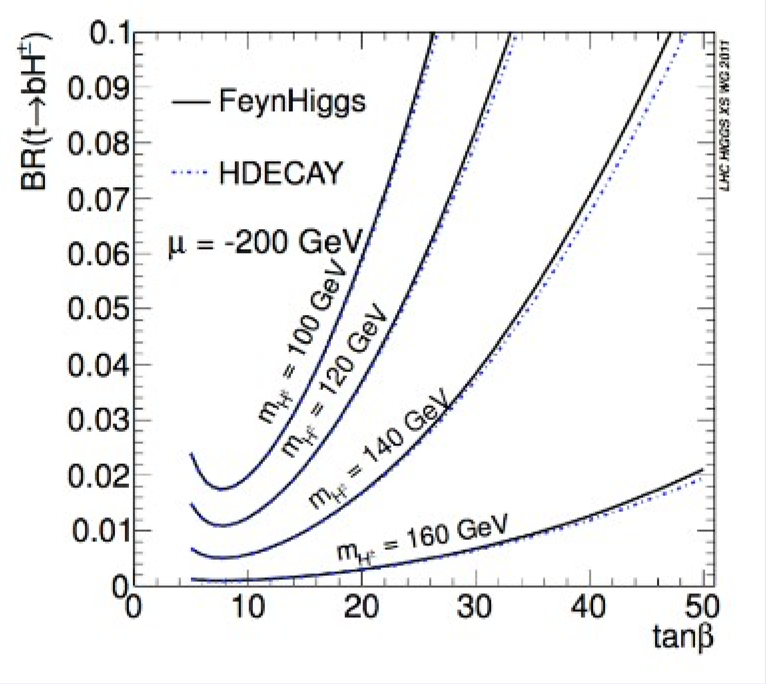
Event selection:

- 1 isolated e/μ, pT > 20 GeV
- Large missing E_T
- At least four jets, one b-tagged jet

New results will be available soon!






BR(t→bH±)
FeynHiggs
HDECAY
μ = -200 GeV
m_H± = 100 GeV
m_H± = 120 GeV
m_H± = 140 GeV
m_H± = 160 GeV
LHC HIGGS XS WG 2011
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
tanβ