The Hunt For The Higgs Boson

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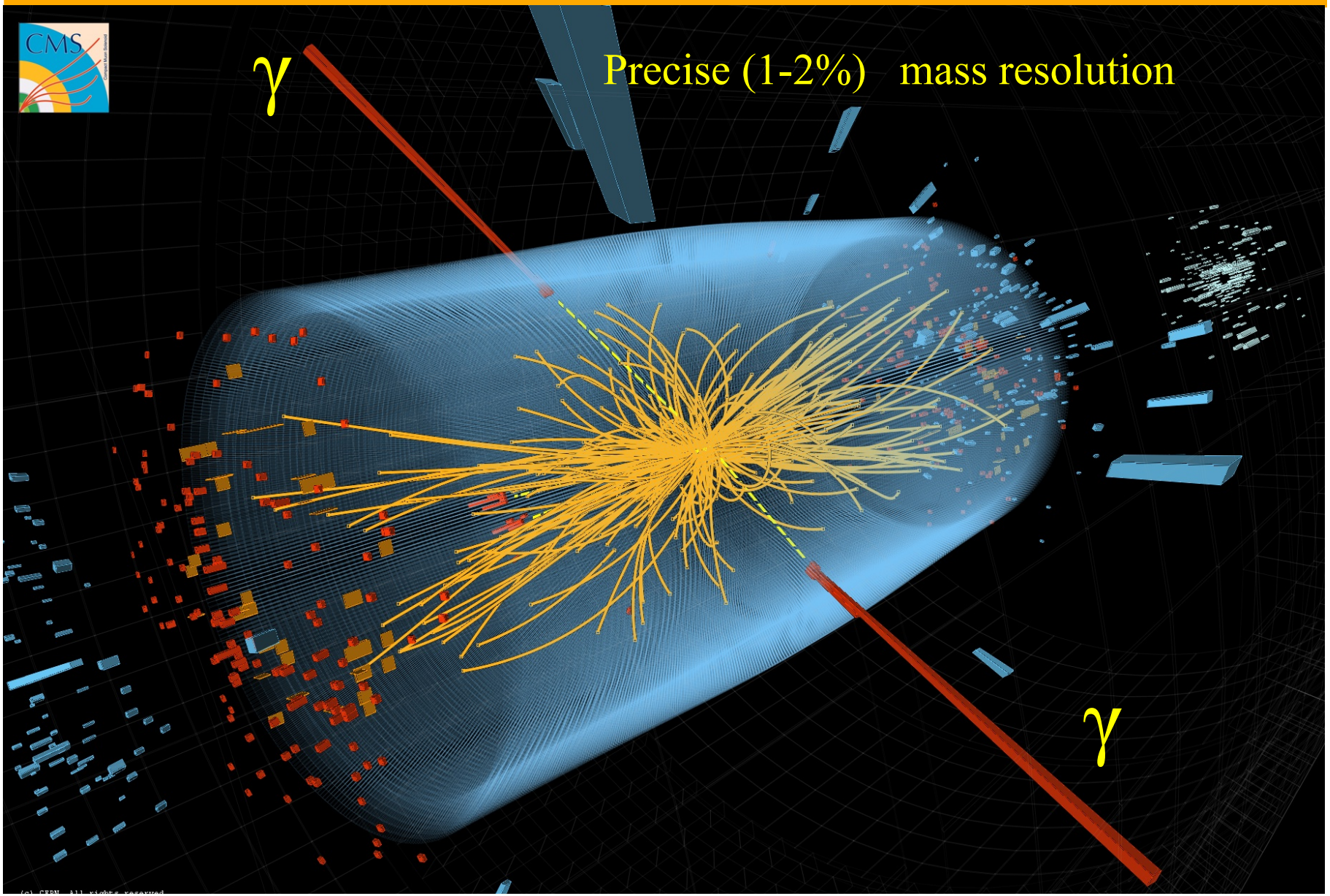
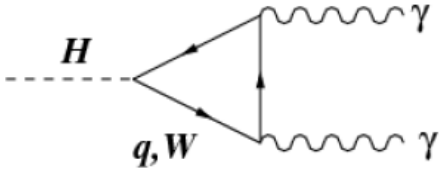
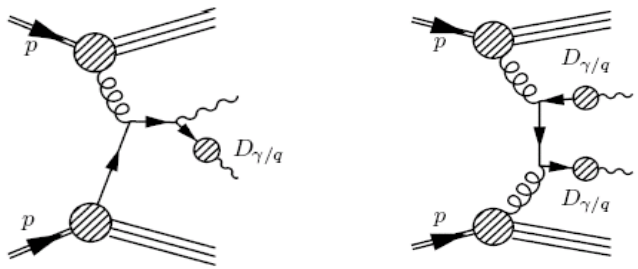
H → γγ



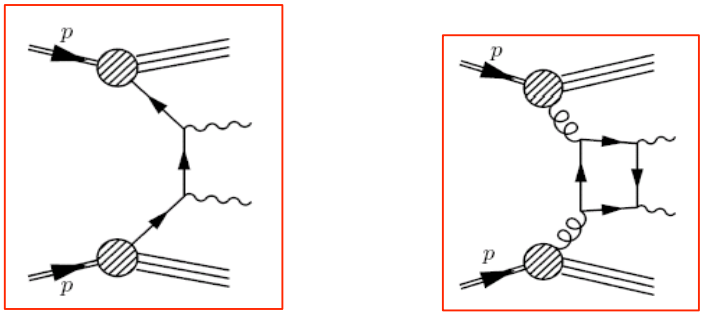
H → γγ



- A discovery channel in $110 < M_H < 150$ GeV
- Br (H→ γγ) ≈ 10^{-3}
- Search for a narrow peak with two isolated high E_T photons over a continuous diphoton background spectrum
- Background is large and composed of
  - Reducible: One or more misidentified (fake) photon (e.g. γ+jets)



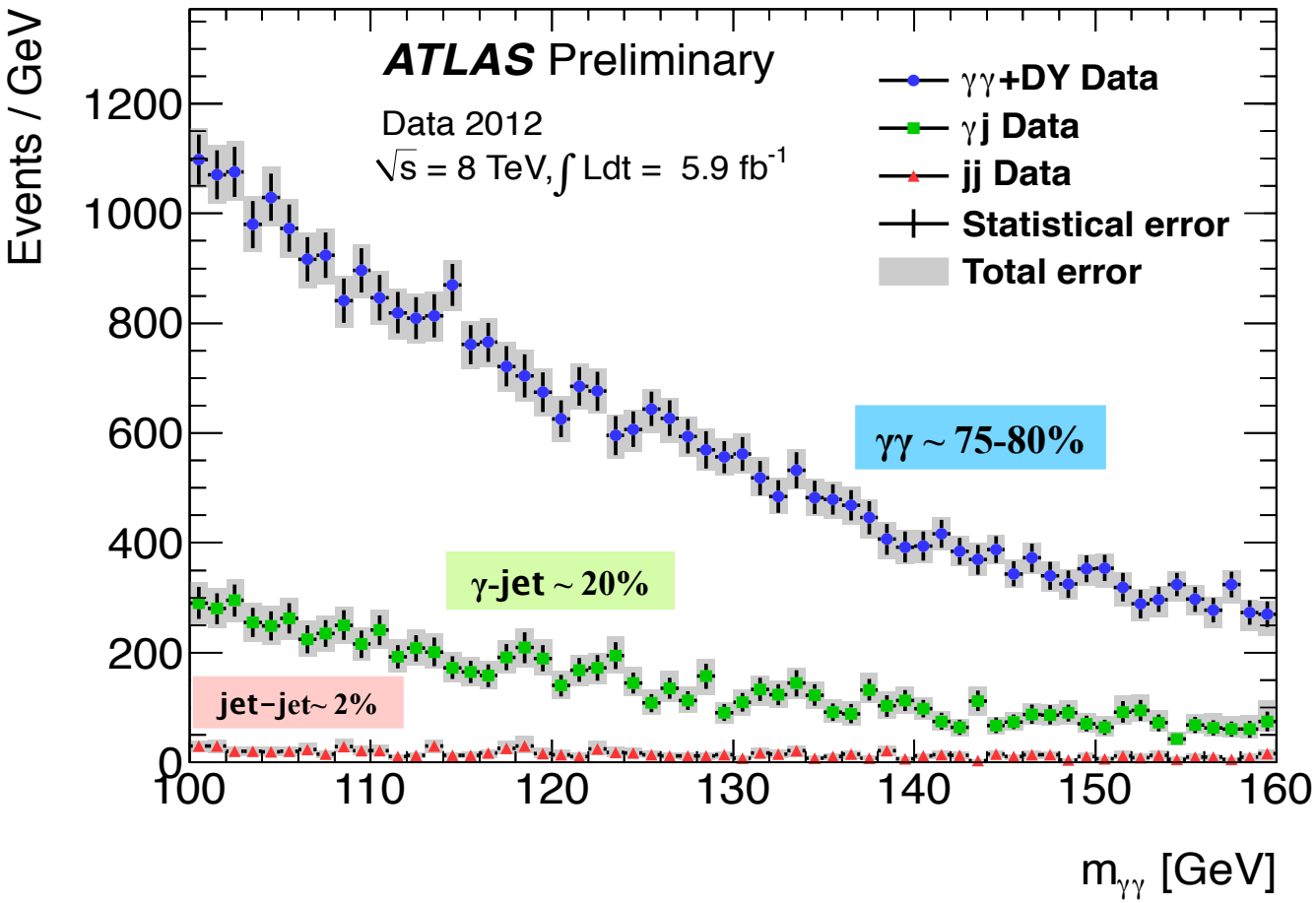
- Irreducible: both photons are real



Search sensitivity depends on background level

Background Composition In H → γγ

The γγ, γ-jet and jet-jet contributions can be decomposed using control samples defined by photon identification and isolation



Good news: Background level roughly as assumed back in ~2006 !

$H \rightarrow \gamma\gamma$: Important Analysis Aspects

$M^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)$

– ECAL Calibration, $M_{\gamma\gamma}$ energy scale & resolution

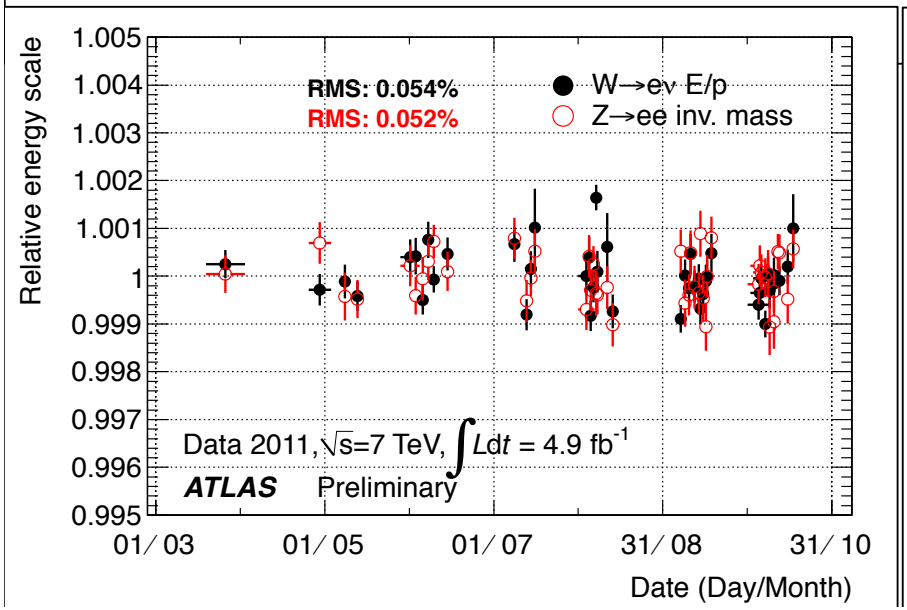
- Event selection and catagorization
- $\gamma\gamma$ vertex reconstruction in face of pileup
- Modeling of background spectrum

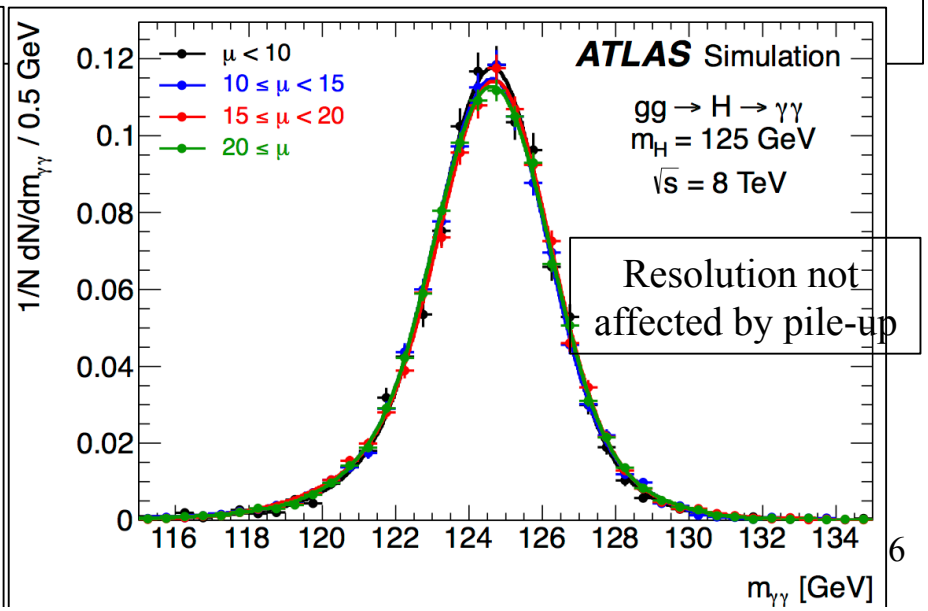
ATLAS & CMS differ in approach but ultimately arrive at similar search sensitivities

ECAL Calibration (ATLAS)

Understand calorimeter energy response
from Z, J/ψ → ee, W→ eν data and MC):

- E-scale at m_Z known to ~ 0.3%
- Stability vs time ~ 0.1%
- Linearity better than 1% (few-100 GeV)
- "Uniformity" (constant term of resolution):
- ~ 1% (2.5% for 1.37<|η|<1.8)

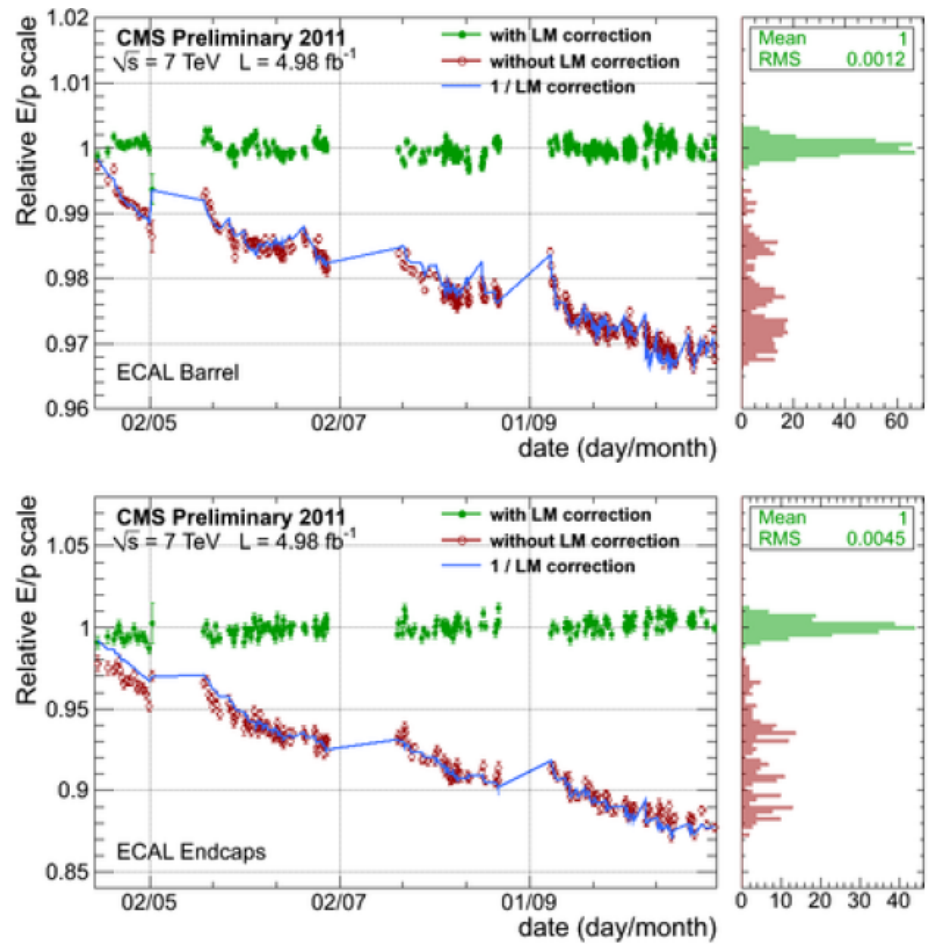




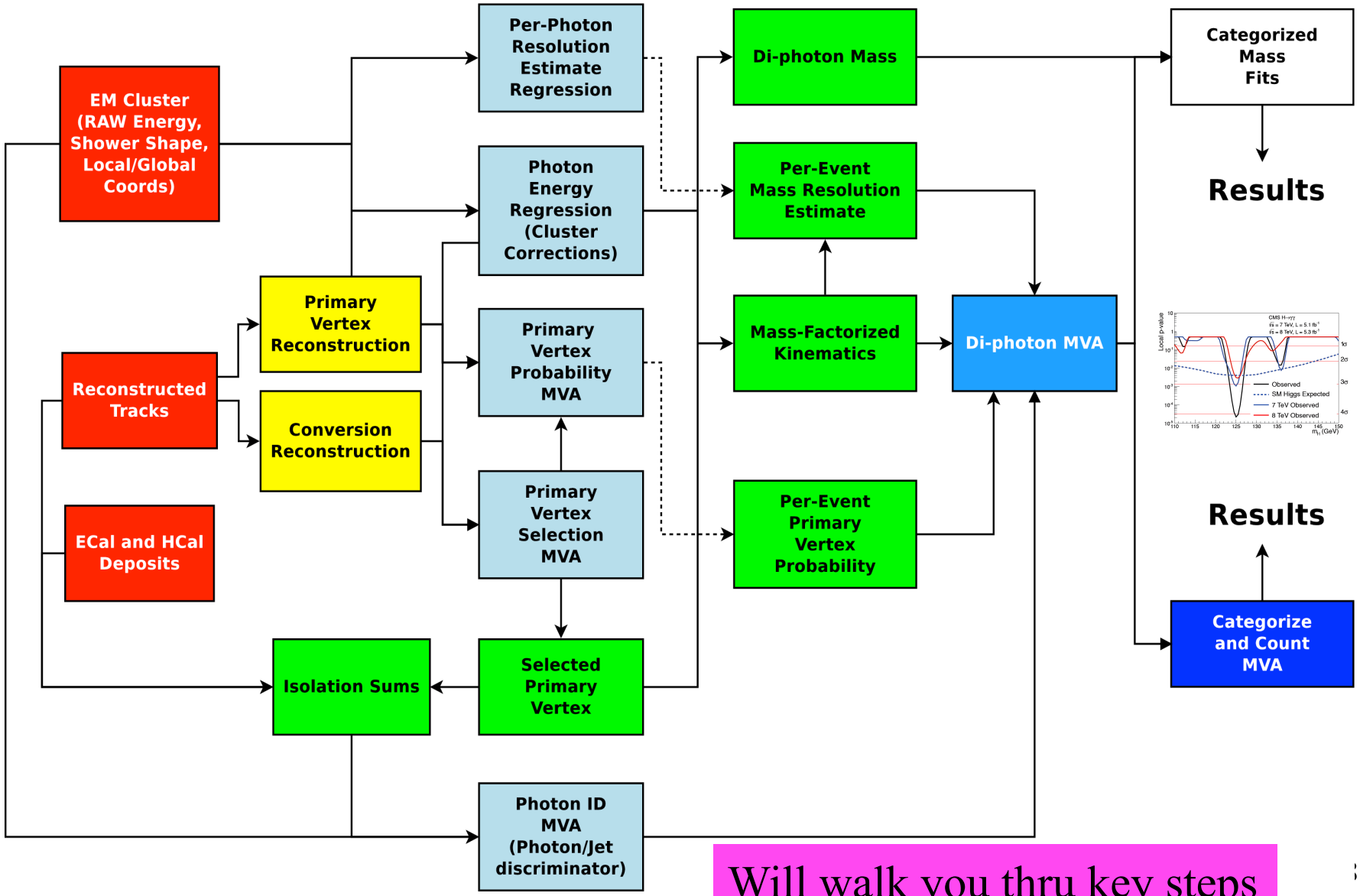
Resolution not affected by pile-up

In situ ECAL Calibration (CMS)

- Dedicated calibration scheme:
  - inter-crystal calibration: π^0, η
  - crystal transparency correction (laser monitoring system)
- The energy scale stability after the response corrections:
  - barrel: 0.12% (
  - endcap: 0.45%
- Exploit $W \rightarrow e\nu$ (E/p) and $Z^0 \rightarrow ee$ control samples to derive energy scale and resolution systematics



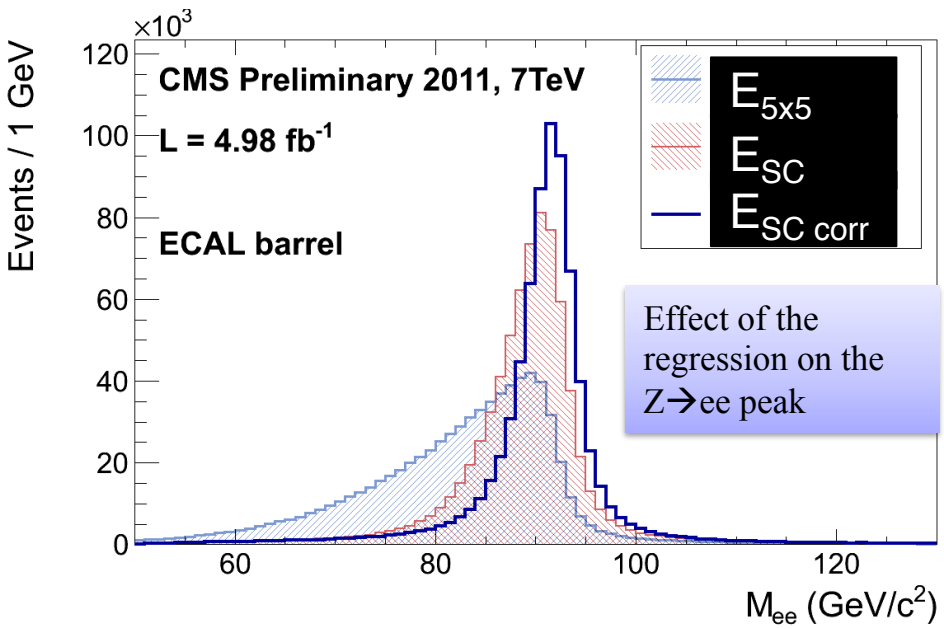
Roadmap For H→ γγ Search (CMS)

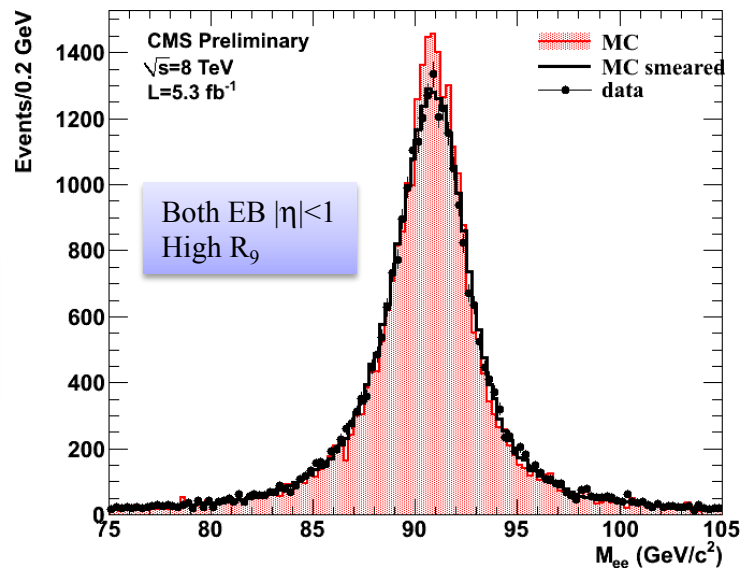


Will walk you thru key steps

γ Energy Correction & Resolution (CMS)

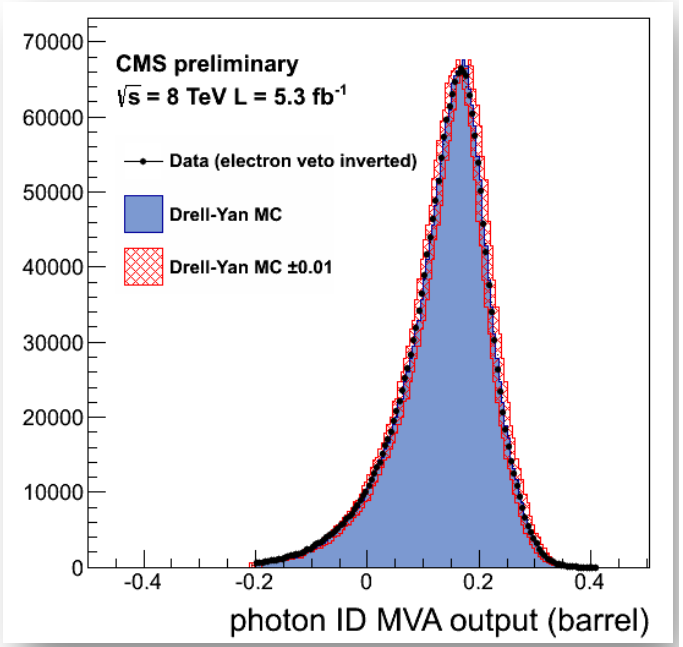
- ECAL cluster energies corrected using a MC trained MVA regression
  - Raw cluster energies & position
  - Lateral & longitudinal shower shapes
  - Local shower position w.r.t crystal geometry
  - Pileup estimators, etc
- Regression also used to estimate per-photon energy resolution
- Uses Z → ee events to measure energy scale and $M_{\gamma\gamma}$ resolution





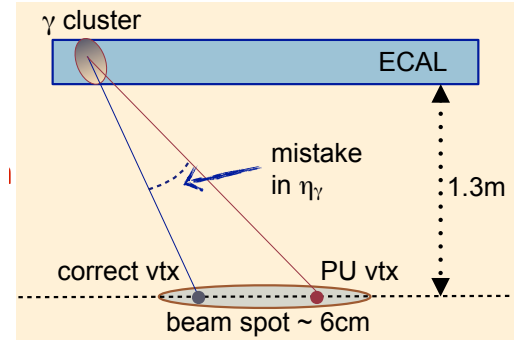
Photon Identification (CMS)

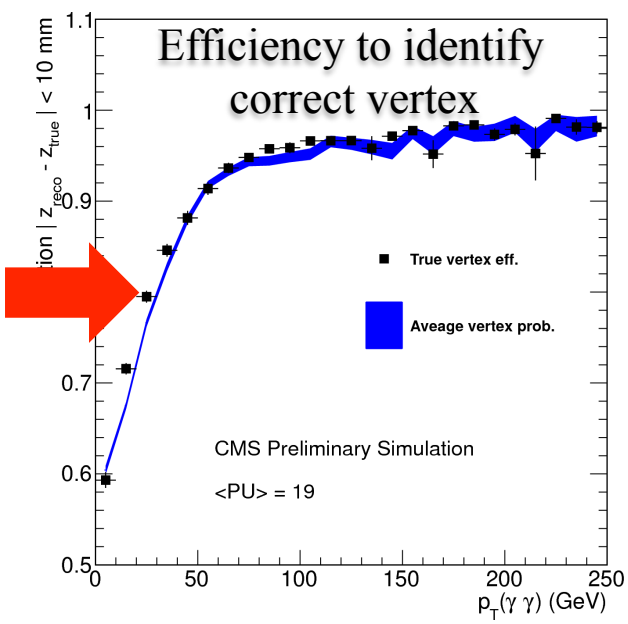
- Select di-photons with
  - $P_T^{\gamma 1} > M_{\gamma\gamma}/3$, $P_T^{\gamma 1} > M_{\gamma\gamma}/4$
- Photon Identification with a MVA method to separate prompt γ from π^0 produced in jets. Uses:
  - Isolation
  - Cluster shape
  - Per event energy density (pileup)
  - Pseudorapidity η
- Efficiency measured with Z→ ee events
- Electron veto eff measured with Z→ $\mu\mu\gamma$

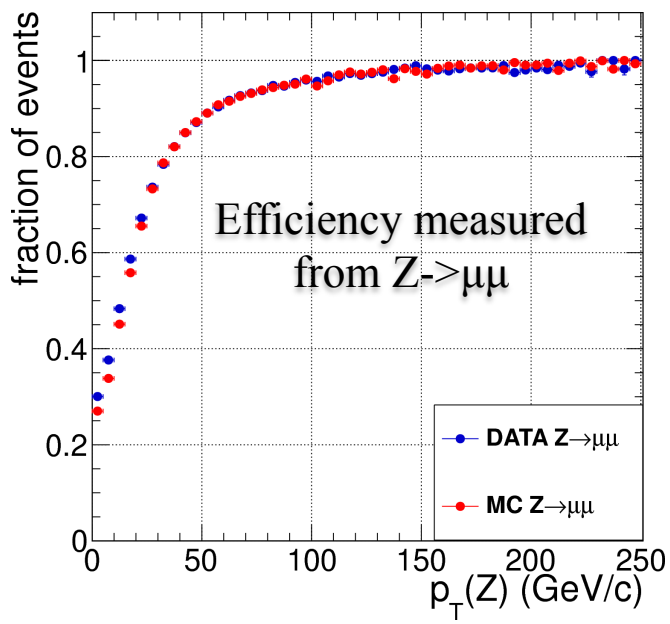


Selecting γγ Vertex (CMS)

- $M^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)$,
  - $M_{\gamma\gamma}$ resolution depends on vertex selection
  - Important for high pileup events→ many choices
- No pointing →vertex identified using tracks from
  - recoiling jets and underlying event & γ→ee, Input variables: Σp_t^2, Σp_t projected onto the γγ transverse direction, p_t asymmetry and conversions
  - correct choice in ~83 (80)% of cases for pileup in 2011 (2012)

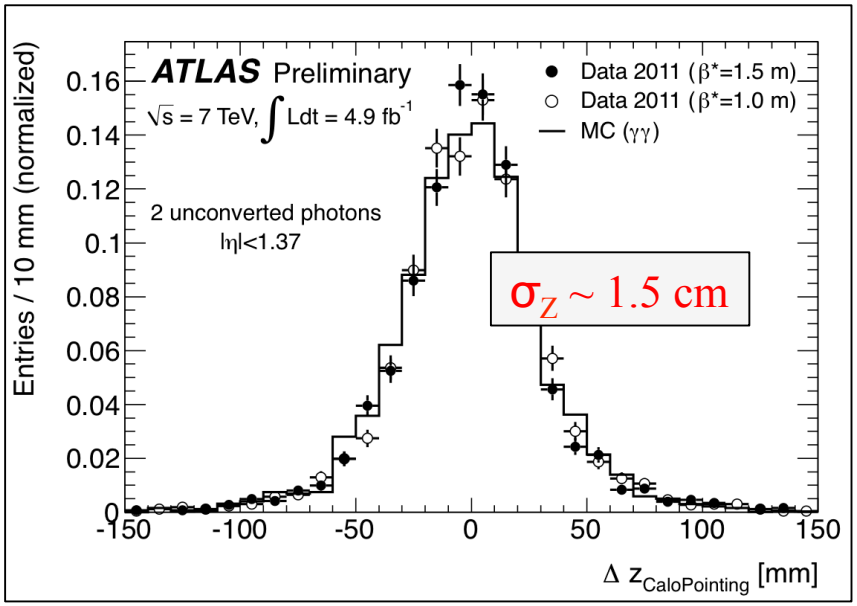


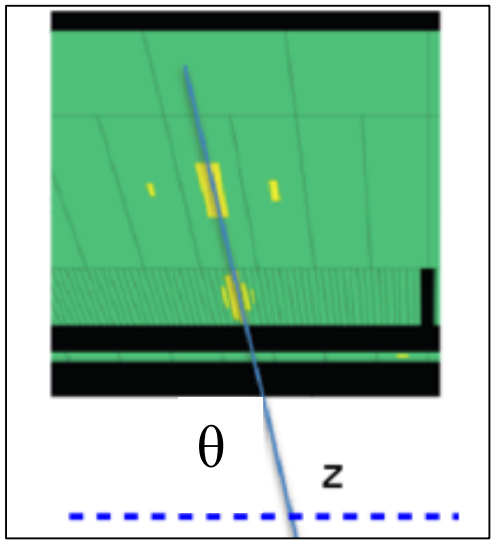




Selecting γγ Vertex (ATLAS)

- Measure γ direction with
  - EM calorimeter longitudinal segmentation (pointing to Z)
  - tracks from converted photons



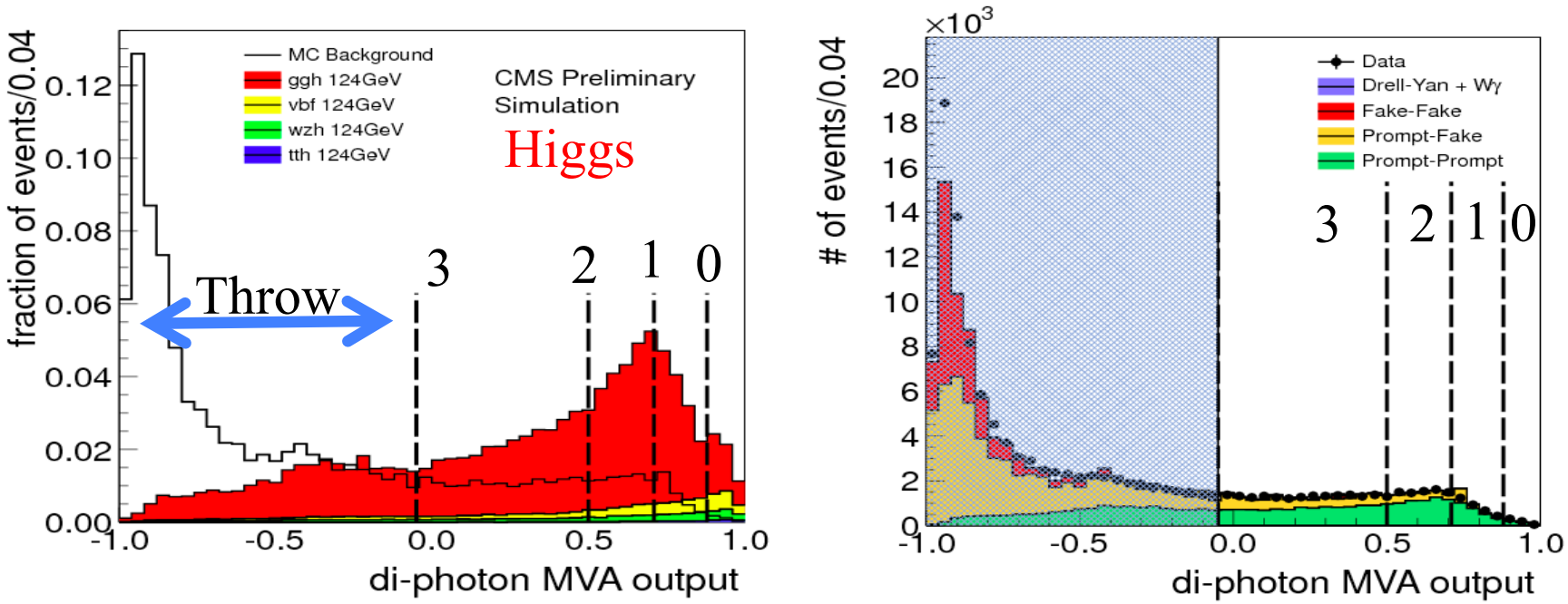


  - Good enough to make contribution to mass resolution from angular term negligible

Inclusive $\gamma\gamma$ Event Selection (CMS)

- Construct a MVA trained on signal & background MC. Input:
  - Photon ID MVA output of each photon
  - Expected $\gamma\gamma$ mass resolution and vertex probability
  - Kinematic variables: P_T of each γ and $\cos\Delta\phi$ between them
- MVA output independent of $M_{\gamma\gamma}$
- Form 4 $\gamma\gamma$ catagories
  - optimized to yield best expected limit in $H \rightarrow \gamma\gamma$

Inclusive γγ Event Catagorization (CMS)



Cat 0 : mostly $P_T^{\gamma\gamma} > 40$ GeV

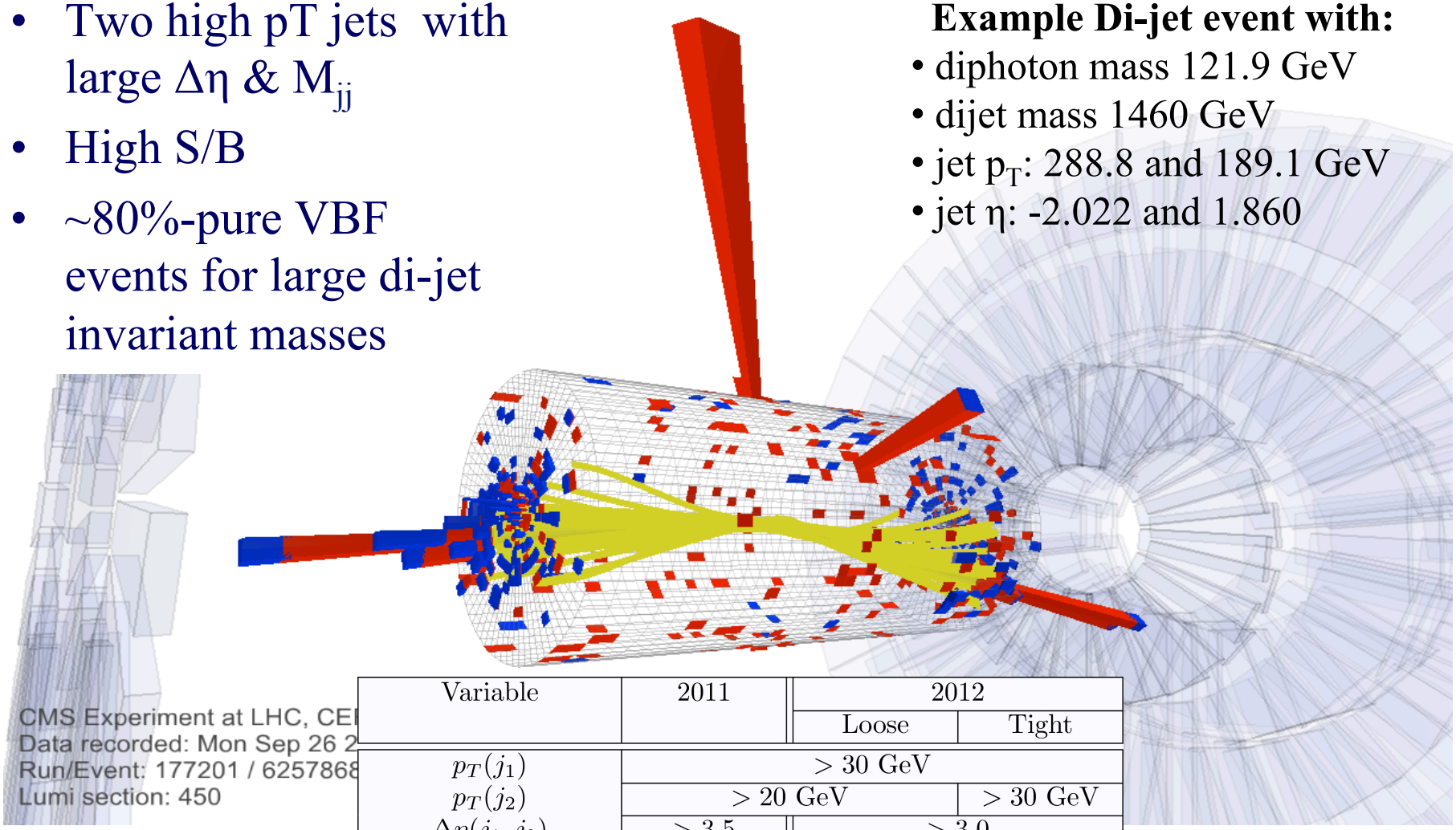
Cat1 : unconverted γ in barrel

Exclusive Dijet Tags: VBF-like Events

- Two high pT jets with large $\Delta\eta$ & M_{jj}
- High S/B
- ~80%-pure VBF events for large di-jet invariant masses

Example Di-jet event with:

- diphoton mass 121.9 GeV
- dijet mass 1460 GeV
- jet p_T: 288.8 and 189.1 GeV
- jet η: -2.022 and 1.860



Variable	2011	2012	
		Loose	Tight
$p_T(j_1)$	> 30 GeV		
$p_T(j_2)$	> 20 GeV		> 30 GeV
$\Delta\eta(j_1, j_2)$	> 3.5	> 3.0	
$\lvert\eta_{\gamma\gamma} - \frac{1}{2}(\eta_{j1} + \eta_{j2})\rvert$	< 2.5		
$\Delta\phi(jj, \gamma\gamma)$	> 2.6		
m_{jj}	> 350 GeV	> 250 GeV	> 500 GeV

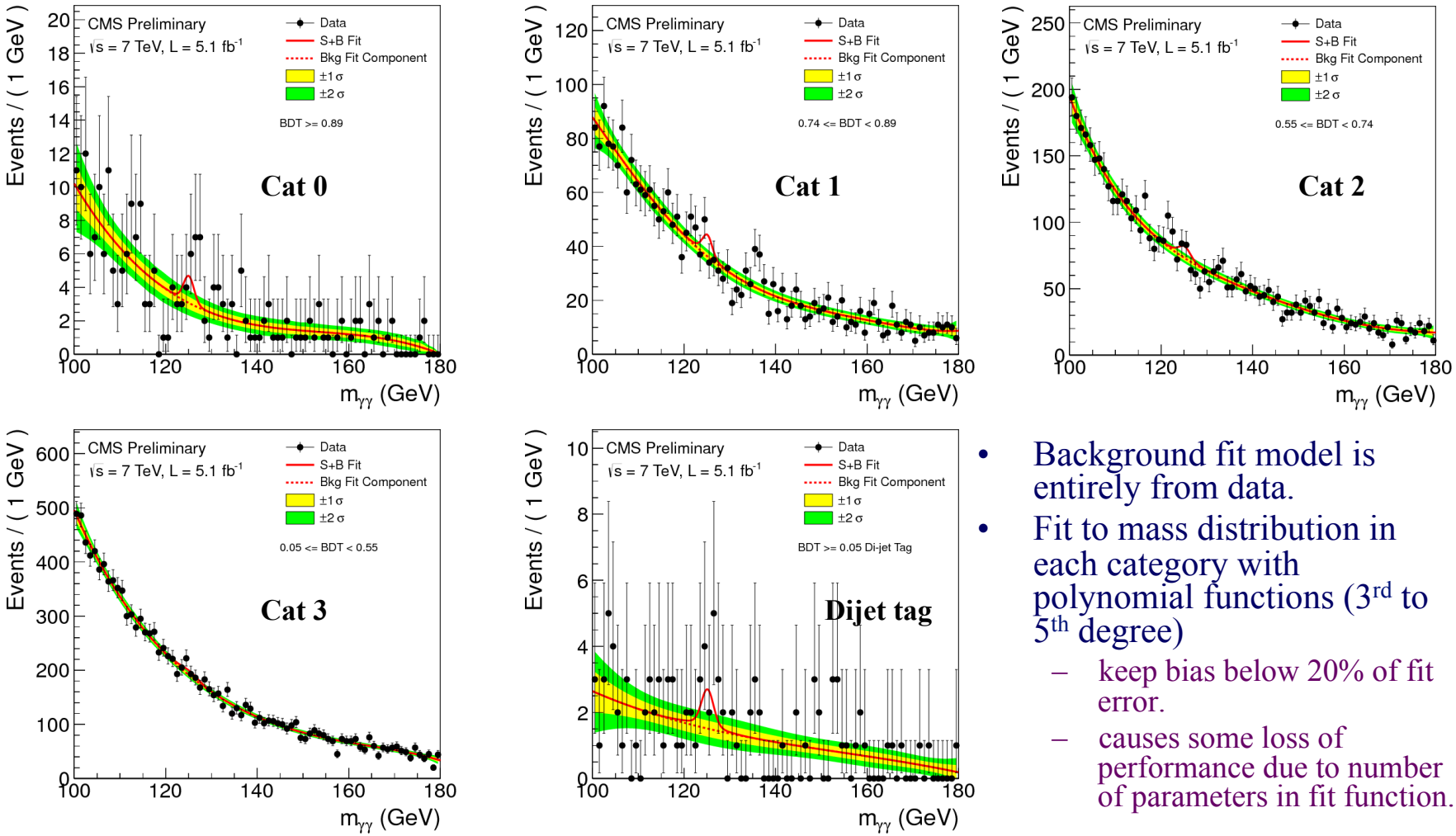
Performance By Catagory

Expected signal and estimated background

Event classes		SM Higgs boson expected signal (m_H=125 GeV)							Background $m_{\gamma\gamma}$ = 125 GeV (ev./GeV)
		Total	ggH	VBF	VH	ttH	σ_{eff} (GeV)	FWHM/2.35 (GeV)	
7 TeV 5.1 fb^{-1}	Untagged 0	3.2	61%	17%	19%	3%	1.21	1.14	3.3 ± 0.4
	Untagged 1	16.3	88%	6%	6%	1%	1.26	1.08	37.5 ± 1.3
	Untagged 2	21.5	91%	4%	4%	–	1.59	1.32	74.8 ± 1.9
	Untagged 3	32.8	91%	4%	4%	–	2.47	2.07	193.6 ± 3.0
	Dijet tag	2.9	27%	73%	1%	–	1.73	1.37	1.7 ± 0.2
8 TeV 5.3 fb^{-1}	Untagged 0	6.1	68%	12%	16%	4%	1.38	1.23	7.4 ± 0.6
	Untagged 1	21.0	88%	6%	6%	1%	1.53	1.31	54.7 ± 1.5
	Untagged 2	30.2	92%	4%	3%	–	1.94	1.55	115.2 ± 2.3
	Untagged 3	40.0	92%	4%	4%	–	2.86	2.35	256.5 ± 3.4
	Dijet tight	2.6	23%	77%	–	–	2.06	1.57	1.3 ± 0.2
	Dijet loose	3.0	53%	45%	2%	–	1.95	1.48	3.7 ± 0.4

Category 3 diphotons have the worst $M_{\gamma\gamma}$ resolution

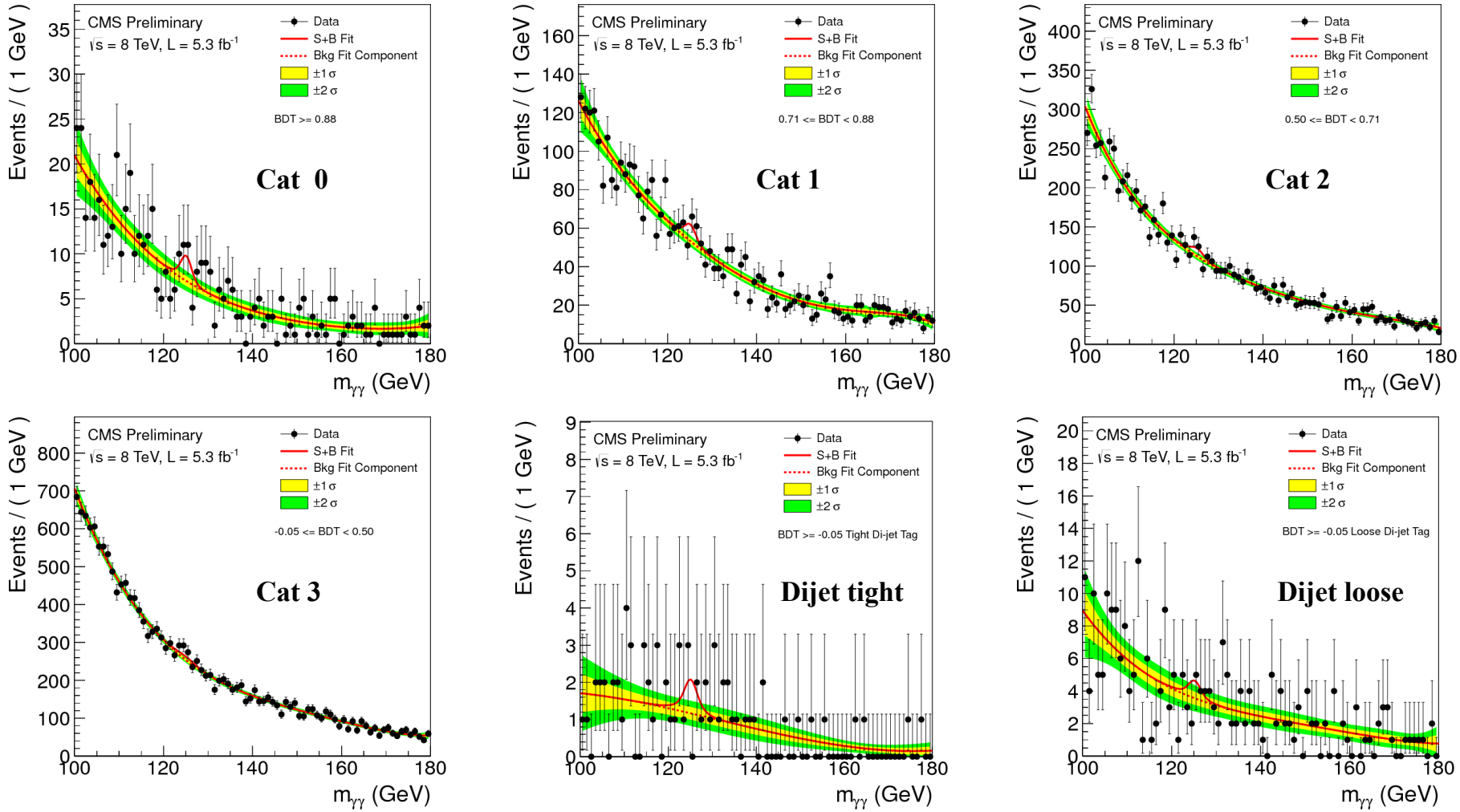
γγ Mass Distribution By Catagories (7 TeV)



- Background fit model is entirely from data.
- Fit to mass distribution in each category with polynomial functions (3rd to 5th degree)
  - keep bias below 20% of fit error.
  - causes some loss of performance due to number of parameters in fit function.

Catagories with good S/N show enhancement at ~125 GeV but not obvious to naked eye !

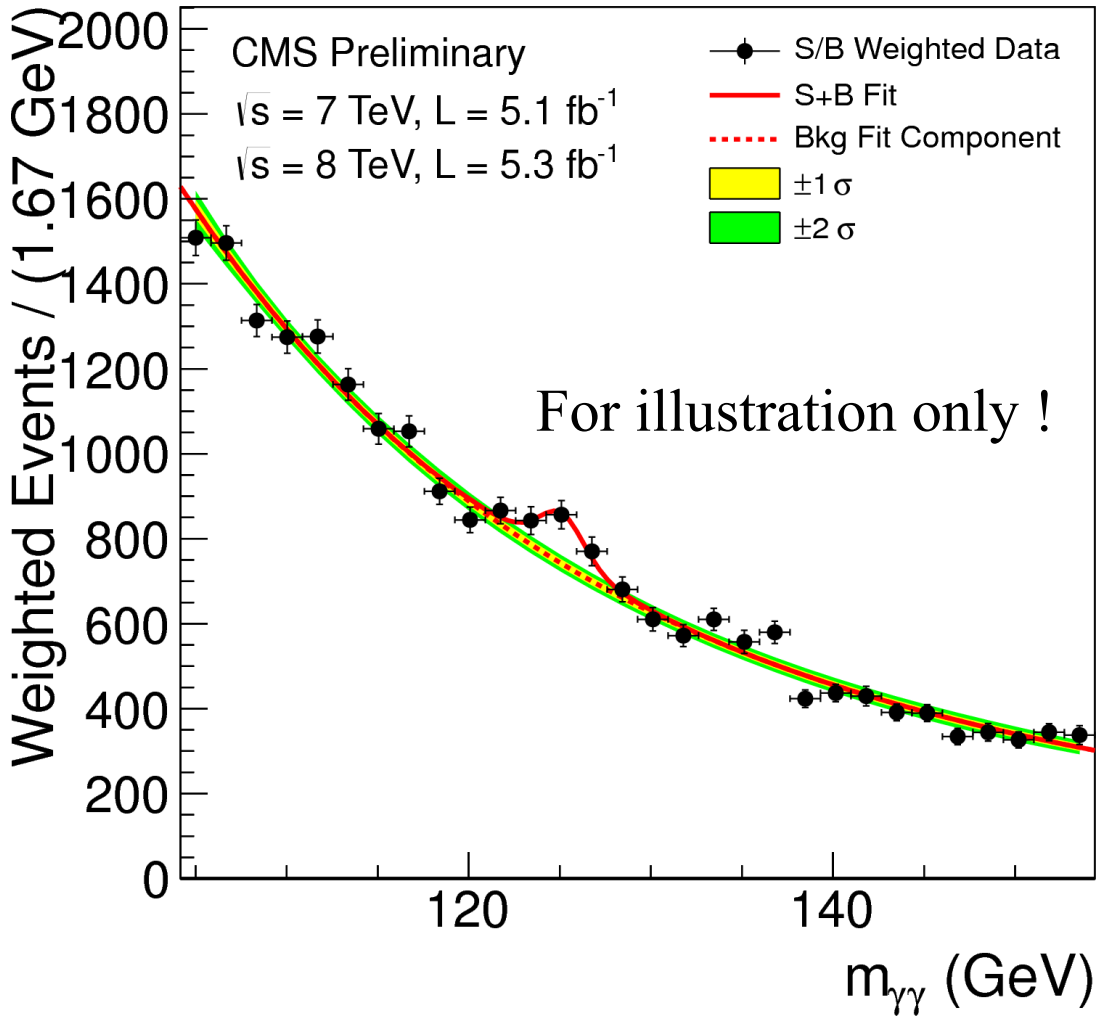
γγ Mass Distribution By Catagories (8 TeV)



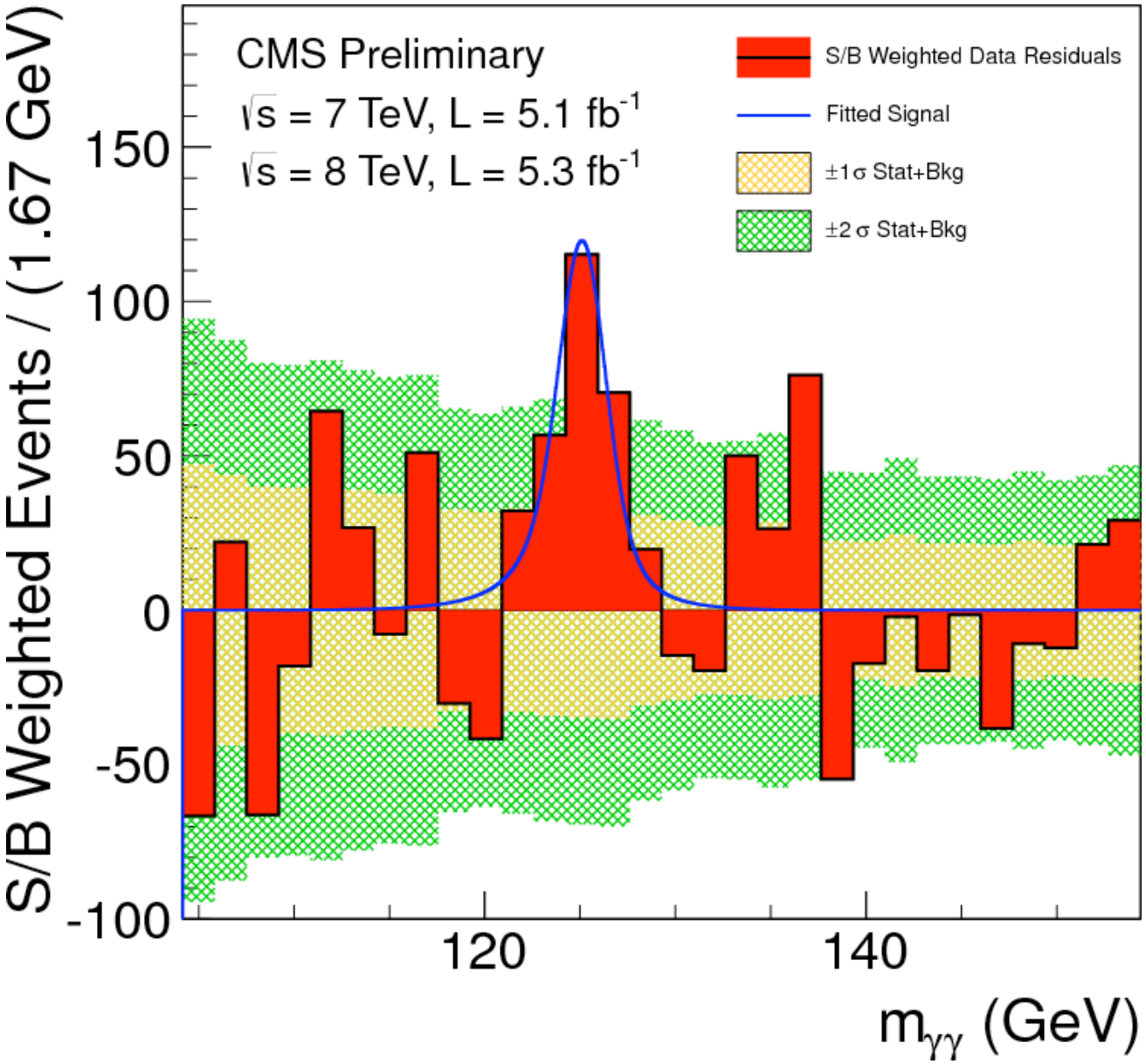
Fit all catagories simultaneously with a signal & background model

Combined Mass Distribution Weighted by S/B

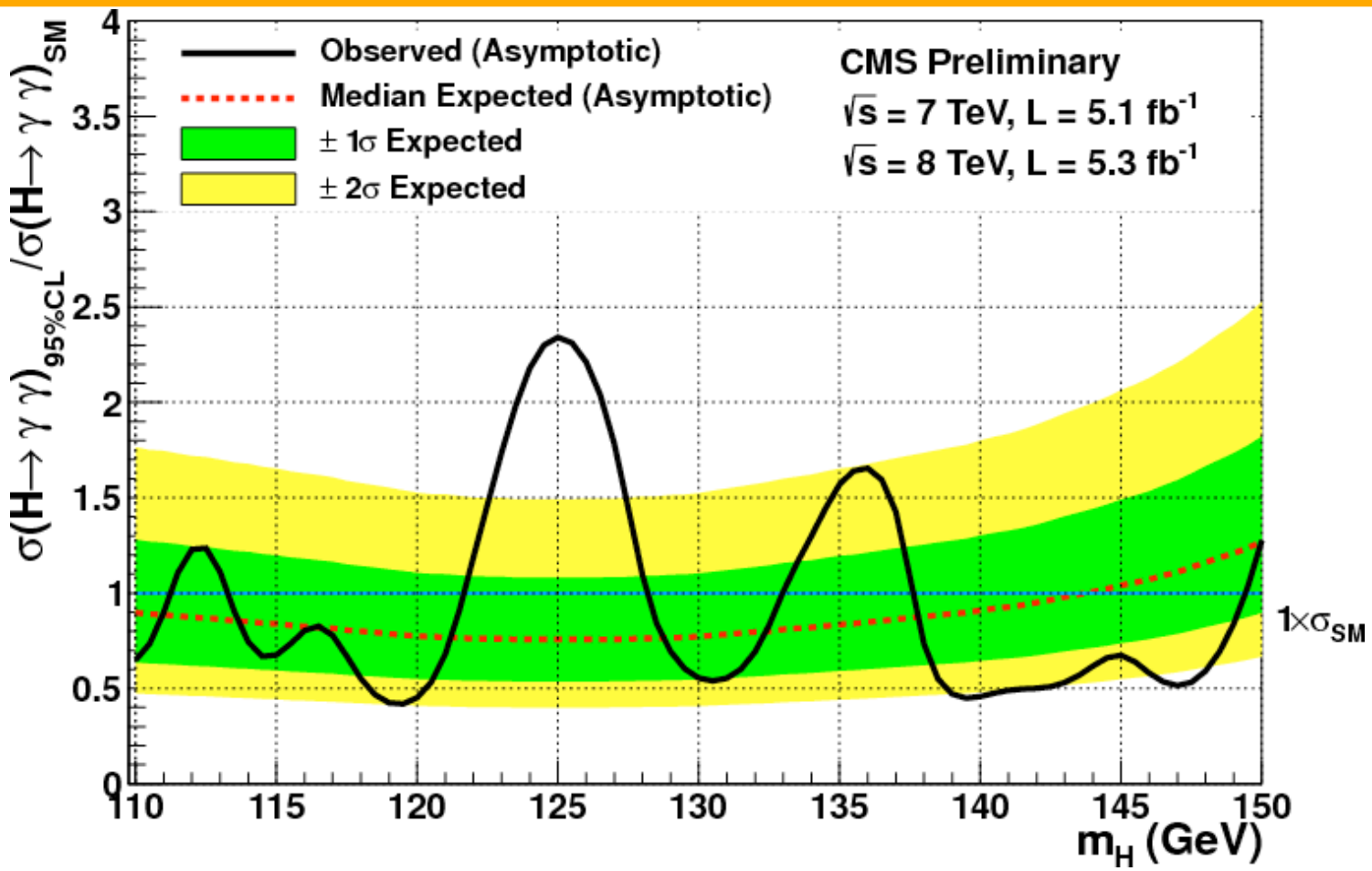
- Sum of mass distributions for each catagory, weighted by S/B
- B is integral of background model over a constant signal fraction interval



Background Subtracted Yield

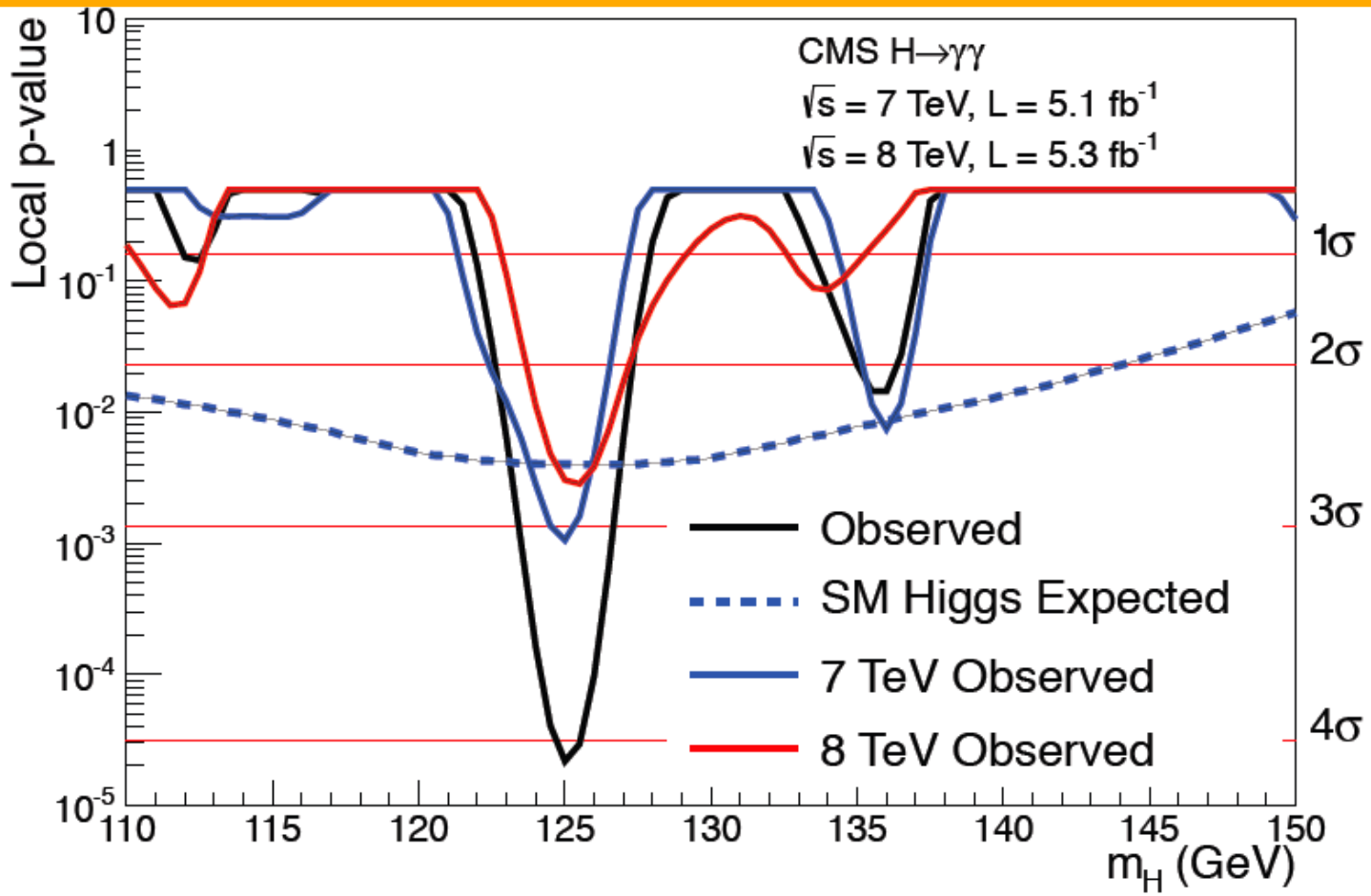


95% SM Higgs Exclusion Limit



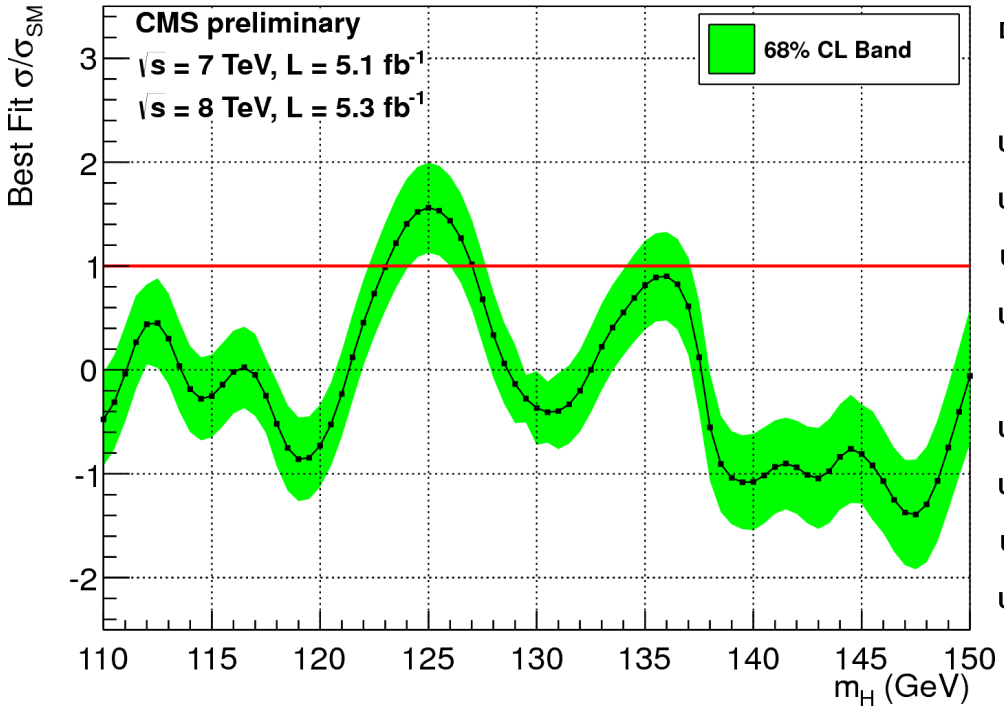
- Expected 95% CL exclusion 0.76 x σ_{SM} at M = 125 GeV
- Large range with expected exclusion below σ_{SM}
- Largest excess at 125 GeV

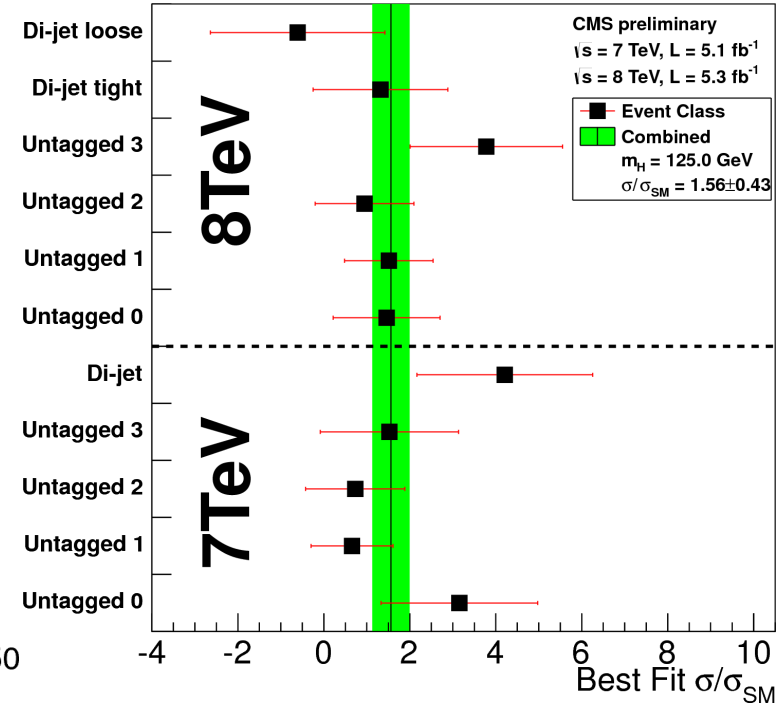
Scan Of p-values



- Minimum p-value at 125 GeV with a local significance of 4.1 σ
- Similar excess at same mass in 2011 and 2012
- Global significance in the full search range (110-150 GeV) 3.2 σ

Fitted Signal Strength σ/σ_{SM}



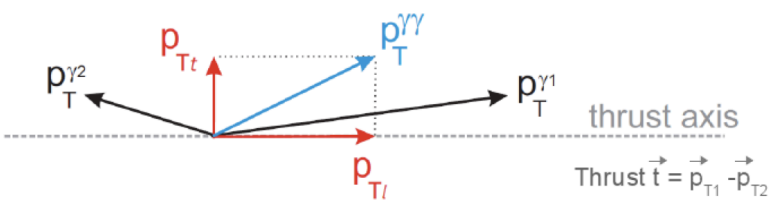


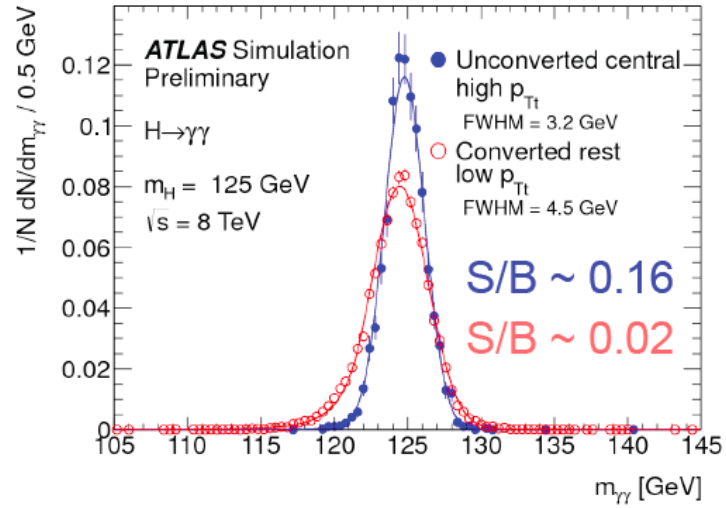
Combined best fit signal strength
$\sigma/\sigma_{SM} = 1.56 \pm 0.43$
consistent with but larger than SM

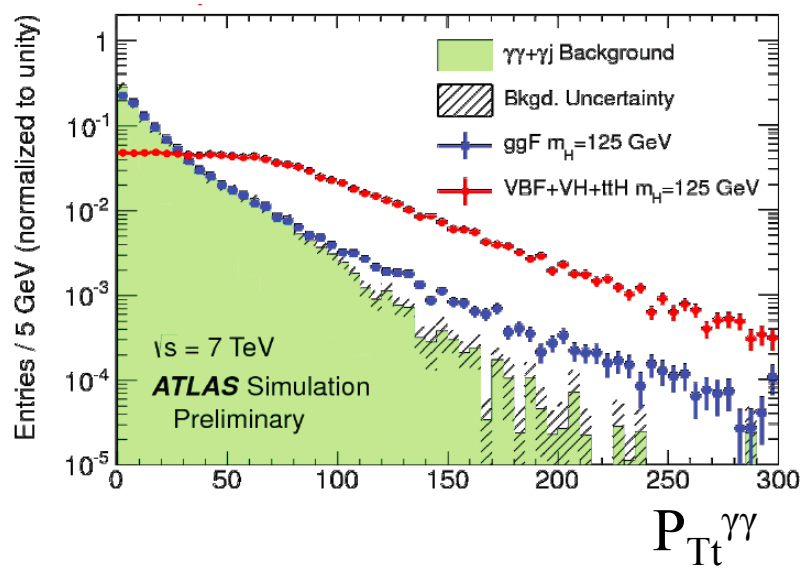
Best fit signal strength consistent between different classes and datasets

ATLAS Catagorization of γγ Events

- Catagorize events by S/B based on
  - Both γ unconverted or ≥ 1 converted
  - Both γ are central (|η| < 0.75)
  - One in EB-EE transition region
  - And the rest
  - $P_T^{\gamma\gamma}$ > 60 GeV or less
- Di-jet category
  - P_{Tt}^{jet} > 25-30 GeV
  - $\Delta\eta_{jets}$ > 2,8
  - M_{jj} > 400 GeV
  - Back to back jets & γγ (Δϕ >2.6)







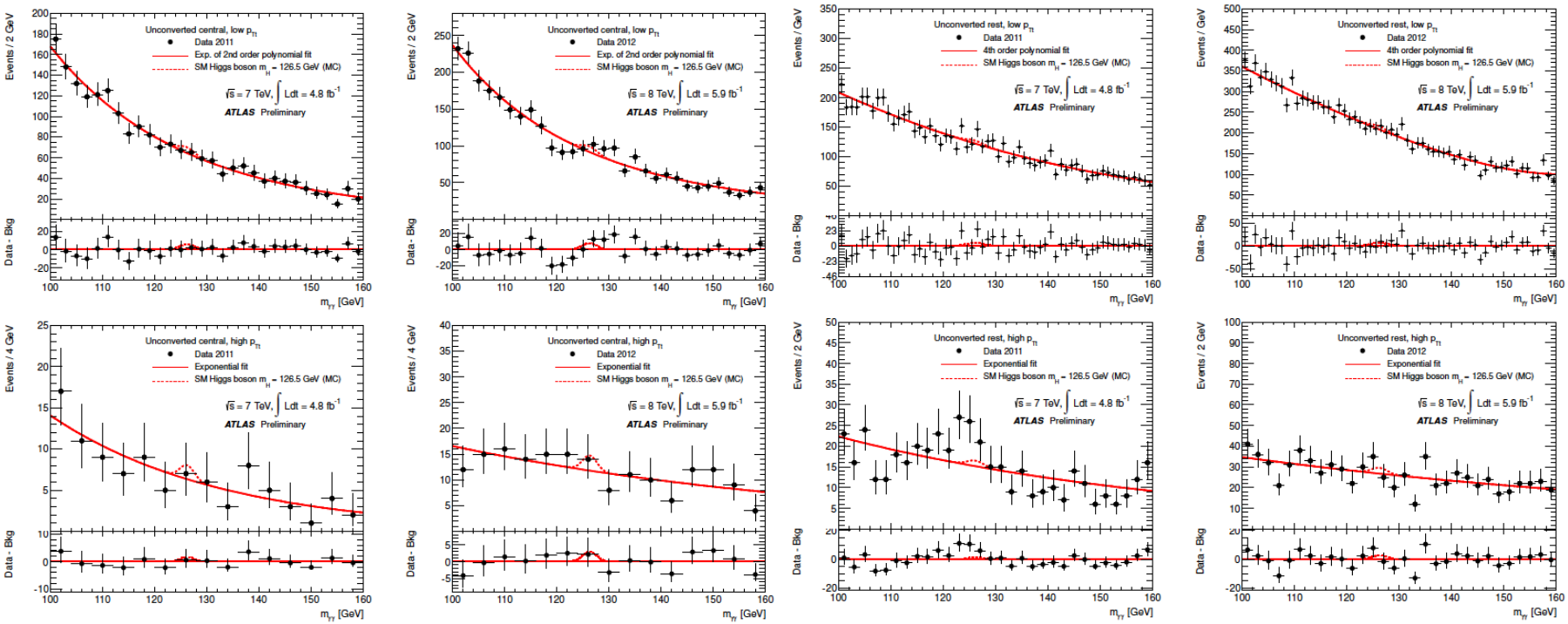
ATLAS Catagorization of γγ Events : 8 TeV

Strength of categorization: different resolution, different S/B ($1\% - 20\%$)

Category	σ_{CB} [GeV]	FWHM [GeV]	Observed [N_{evt}]	S [N_{evt}]	B [N_{evt}]
Inclusive	1.63	3.87	3693	100.4	3635
Unconverted central, low p_{Tt}	1.45	3.42	235	13.0	215
Unconverted central, high p_{Tt}	1.37	3.23	15	2.3	14
Unconverted rest, low p_{Tt}	1.57	3.72	1131	28.3	1133
Unconverted rest, high p_{Tt}	1.51	3.55	75	4.8	68
Converted central, low p_{Tt}	1.67	3.94	208	8.2	193
Converted central, high p_{Tt}	1.50	3.54	13	1.5	10
Converted rest, low p_{Tt}	1.93	4.54	1350	24.6	1346
Converted rest, high p_{Tt}	1.68	3.96	69	4.1	72
Converted transition	2.65	6.24	880	11.7	845
2-jets	1.57	3.70	18	2.6	12

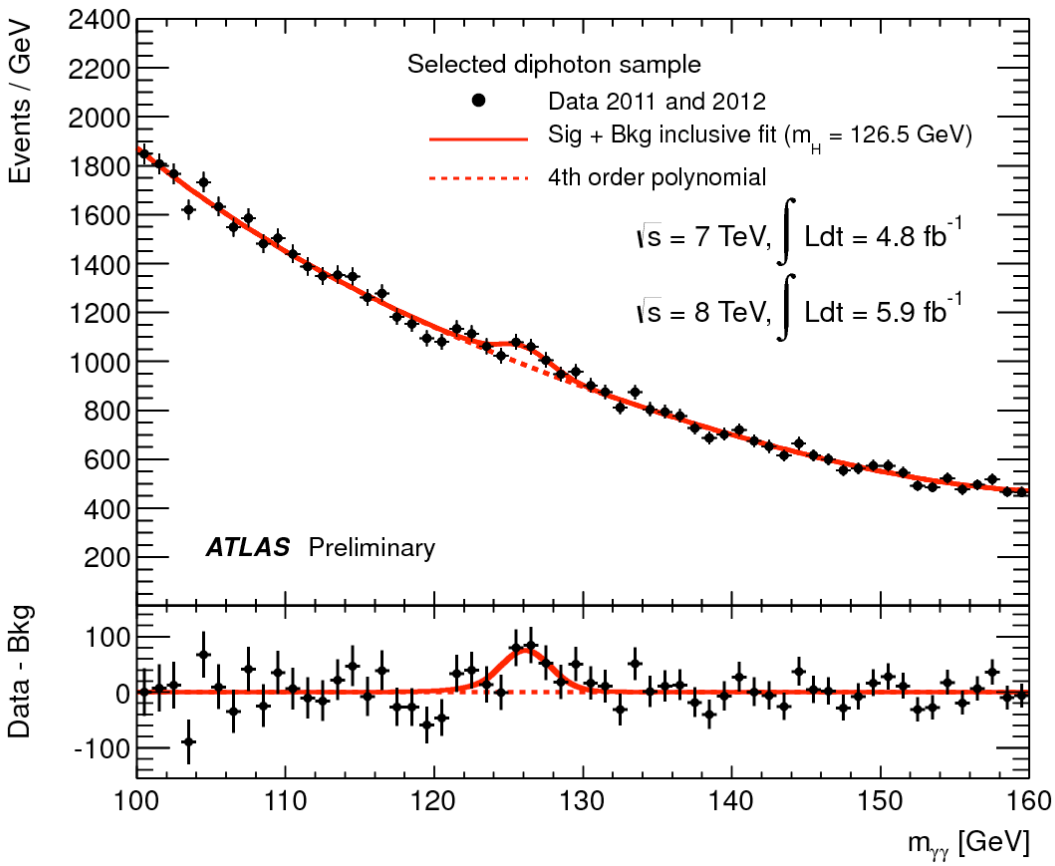
In all, 10 catagories, each fitted with a signal & background model

Fits In Some Catagories With Unconverted γ



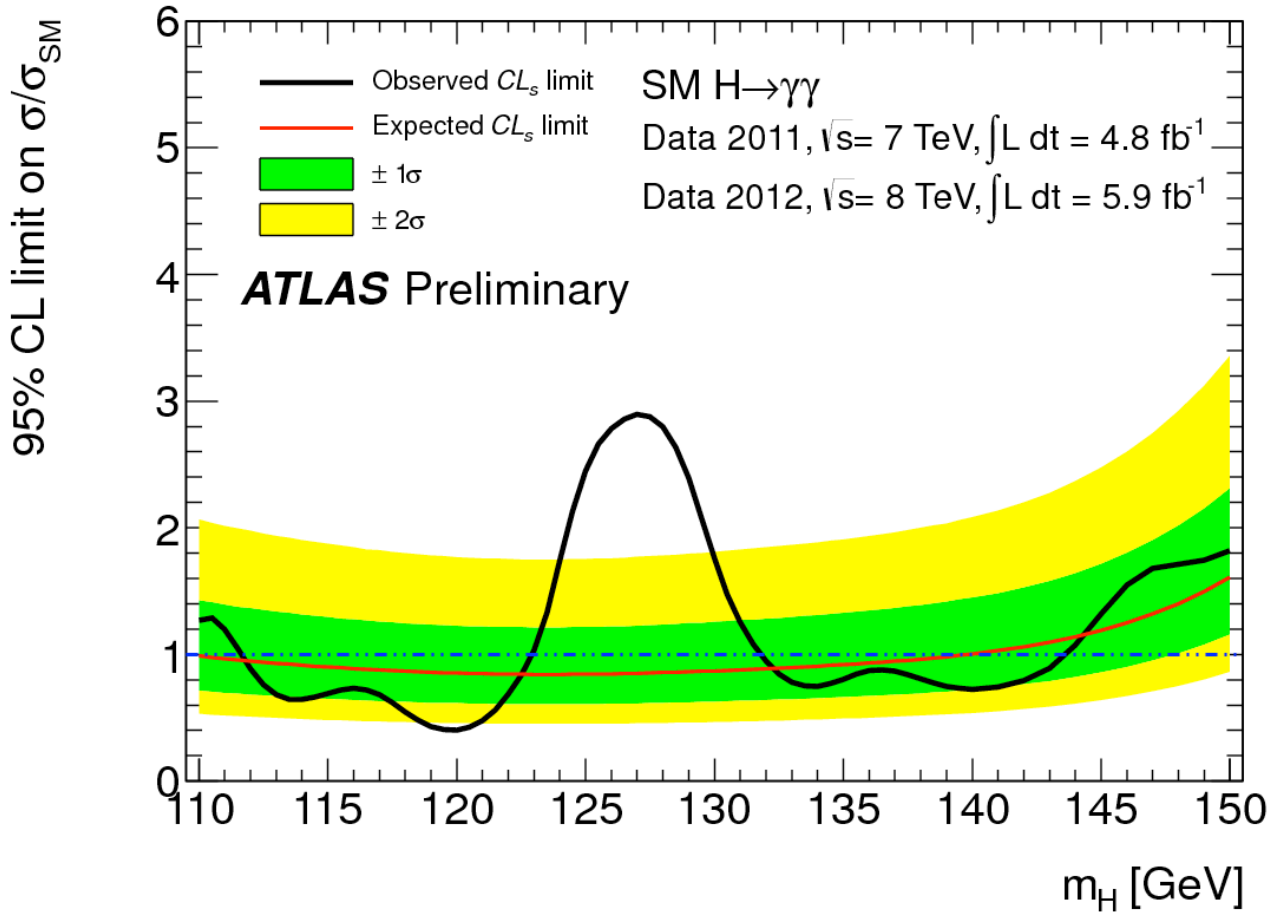
Excesses not easily visible to naked eye
but the S+B fitter recognizes them

$M_{\gamma\gamma}$ Distribution : Simply Summing All Catagories



Signal Yield	Observed	Expected
2011	146.9	79.4
2012	205.5	111.1

95% Exclusion Limit

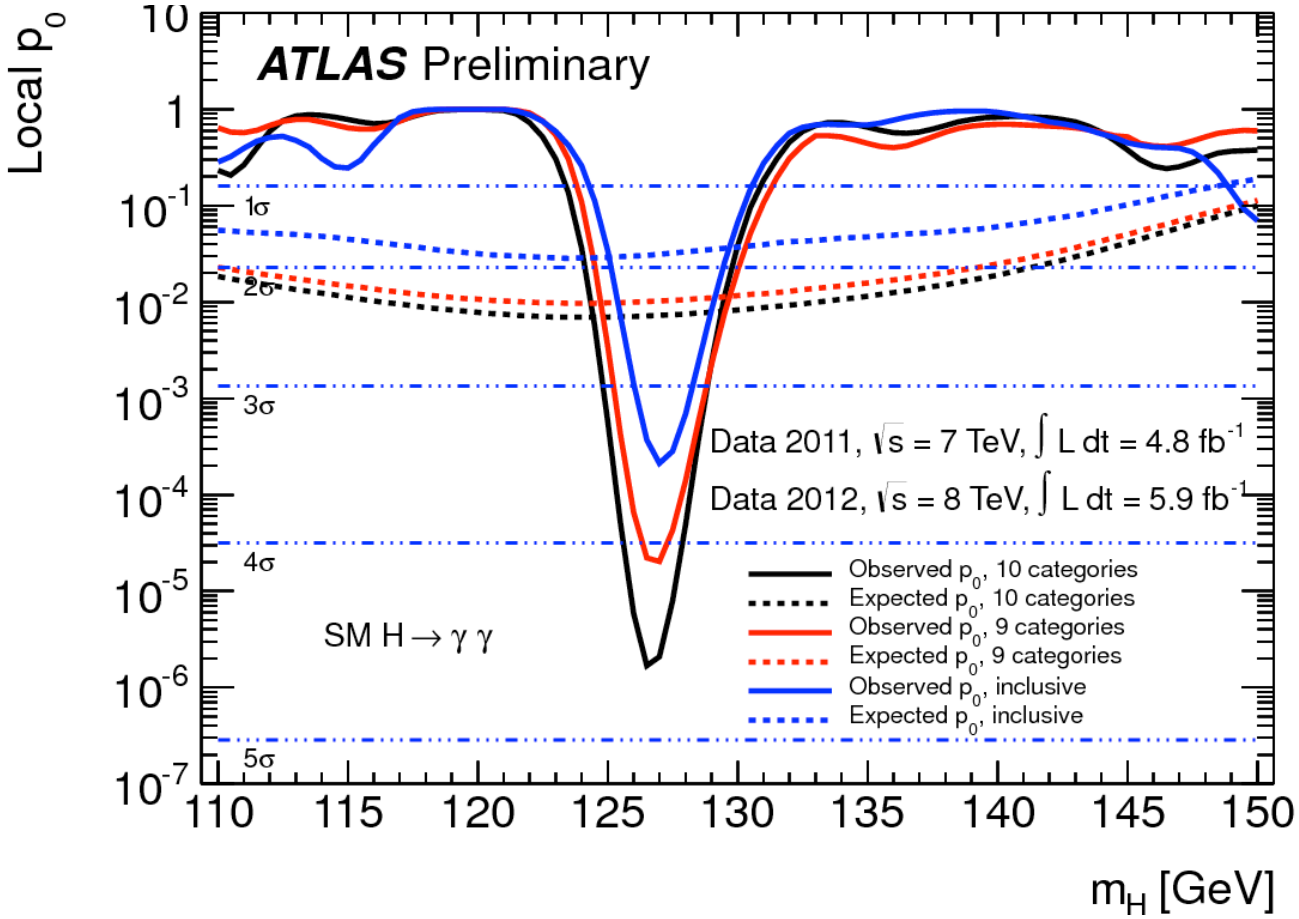


Sensitivity below SM expectation till M_H = 140 GeV

Observed exclusion : [112-122.5, 132-143] GeV

Observe significant excess over Bkgnd only hypothesis @ 126.5 GeV

p-Values: 7, 8 TeV and Combined

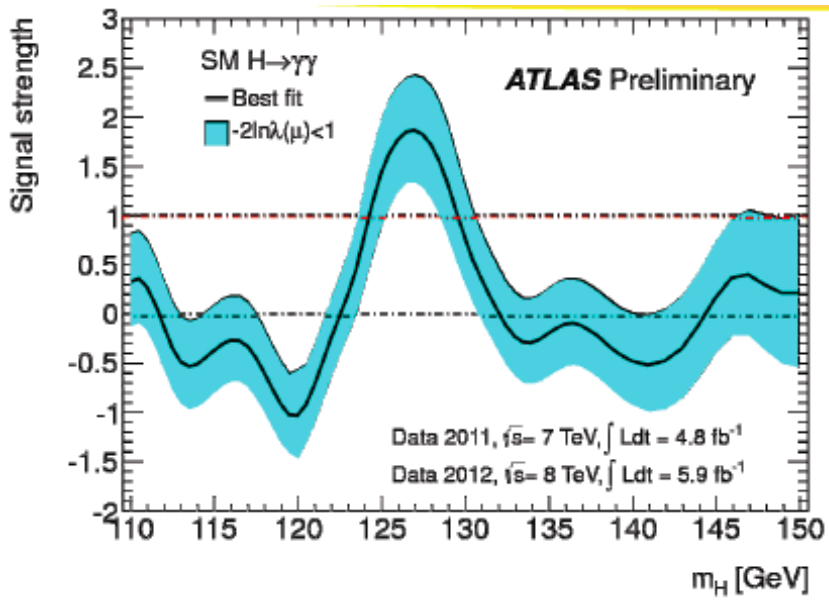


Most significant deviation from bkgnd-only hypothesis @ 126.5 GeV

Observed local significance 4.7σ, Expected = 2.4σ

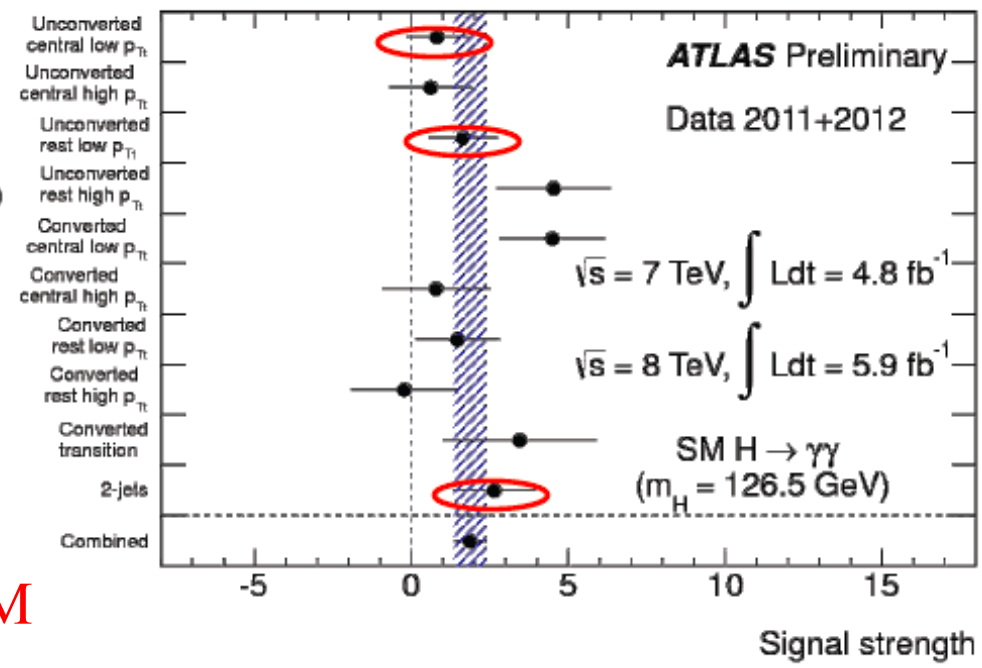
Similar sized excesses (3.5σ, 3.4σ) at compatibles masses !

Signal Strengths



- Fitted signal strength μ=1.9±0.5 at m_H=126.5 GeV

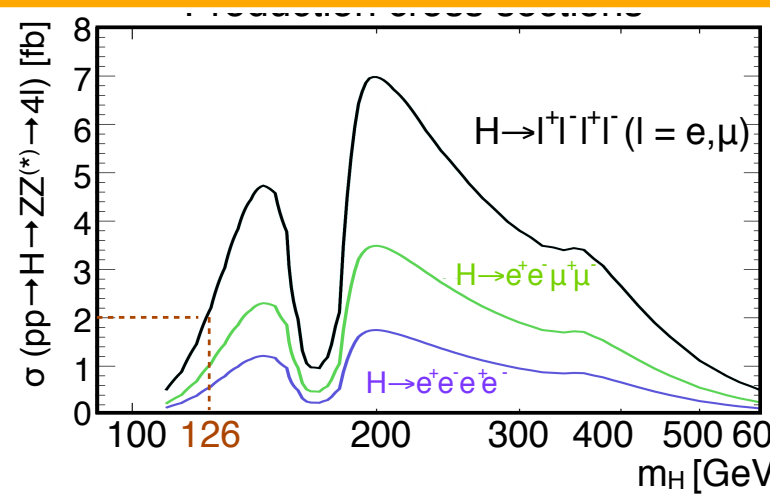
- Breakdown of results by fit categories
  - Most sensitive categories indicated
  - No particular surprises

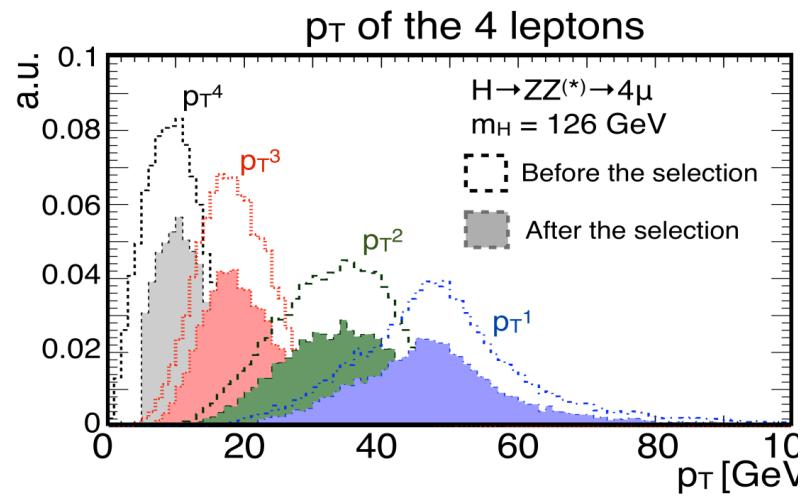


Observed rate consistent with SM but larger in central value (1.9)

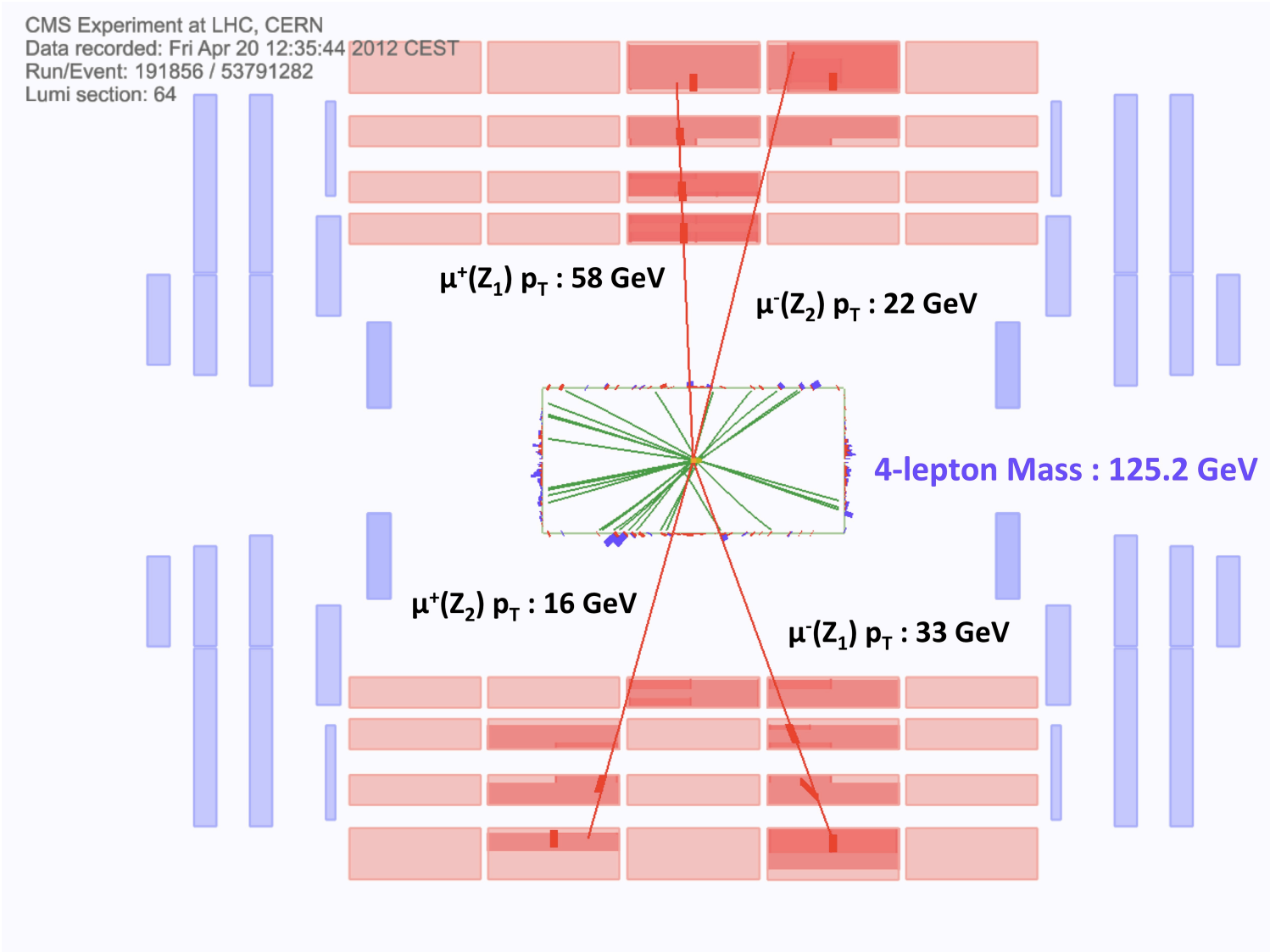
H → ZZ → 4l

- Golden channel : Four isolated leptons from one point in 3D space
- Benefits from excellent electron and muon energy resolution
  - M_{4l} mass resolution ≈ 1-2 %
- σ×Br(H→ ZZ→ 4l) quite small
  - Needs highest selection efficiency possible → Efficient lepton identification over a broad P_t range
- Backgrounds
  - Non-resonant pp→ ZZ→4l is largest and irreducible, has same topological signature as H → 4l
    - **But no narrow peak as in H**
  - Z+jets,ttbar, WZ…all reducible and important at low M_{4l}

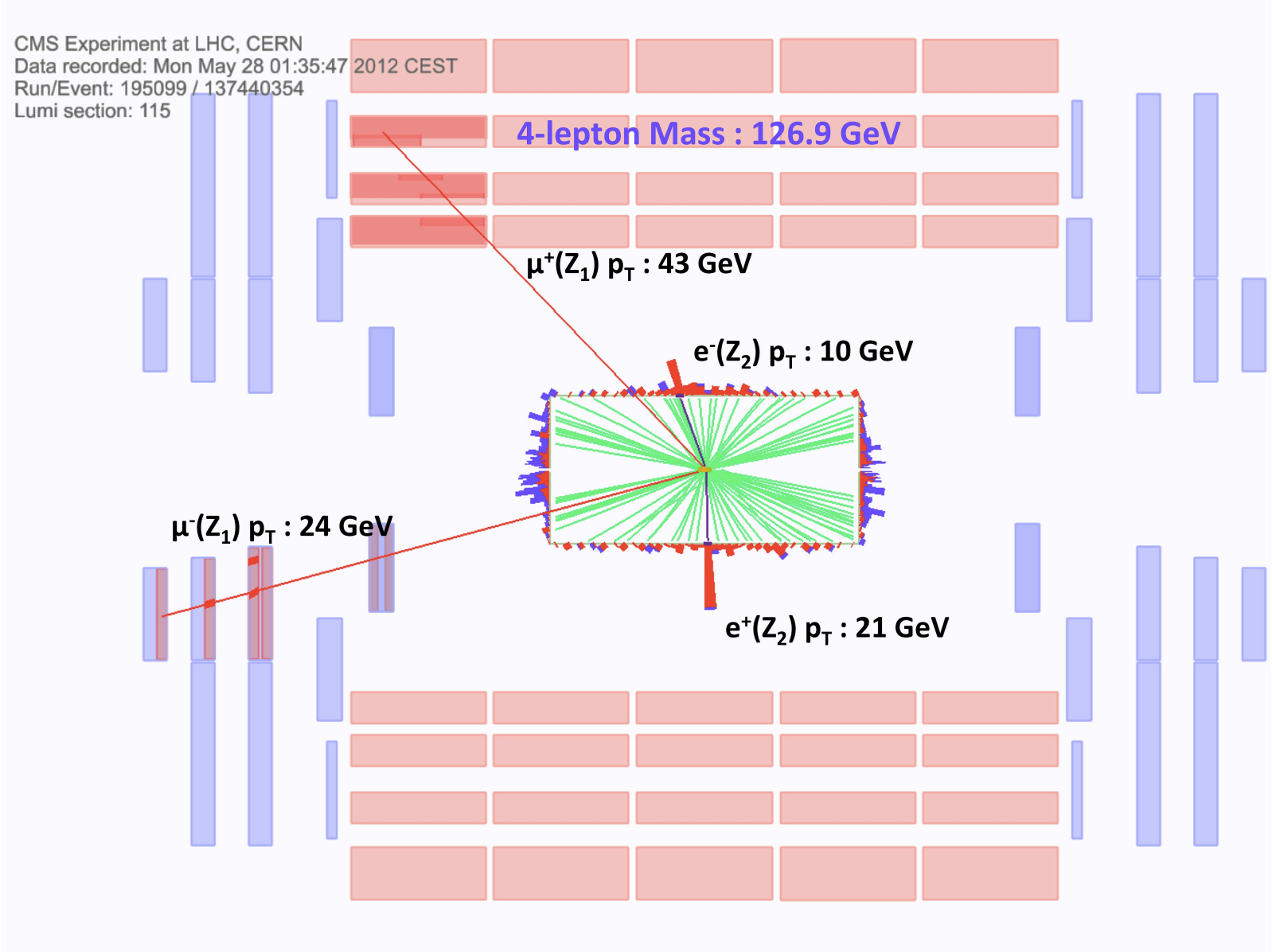




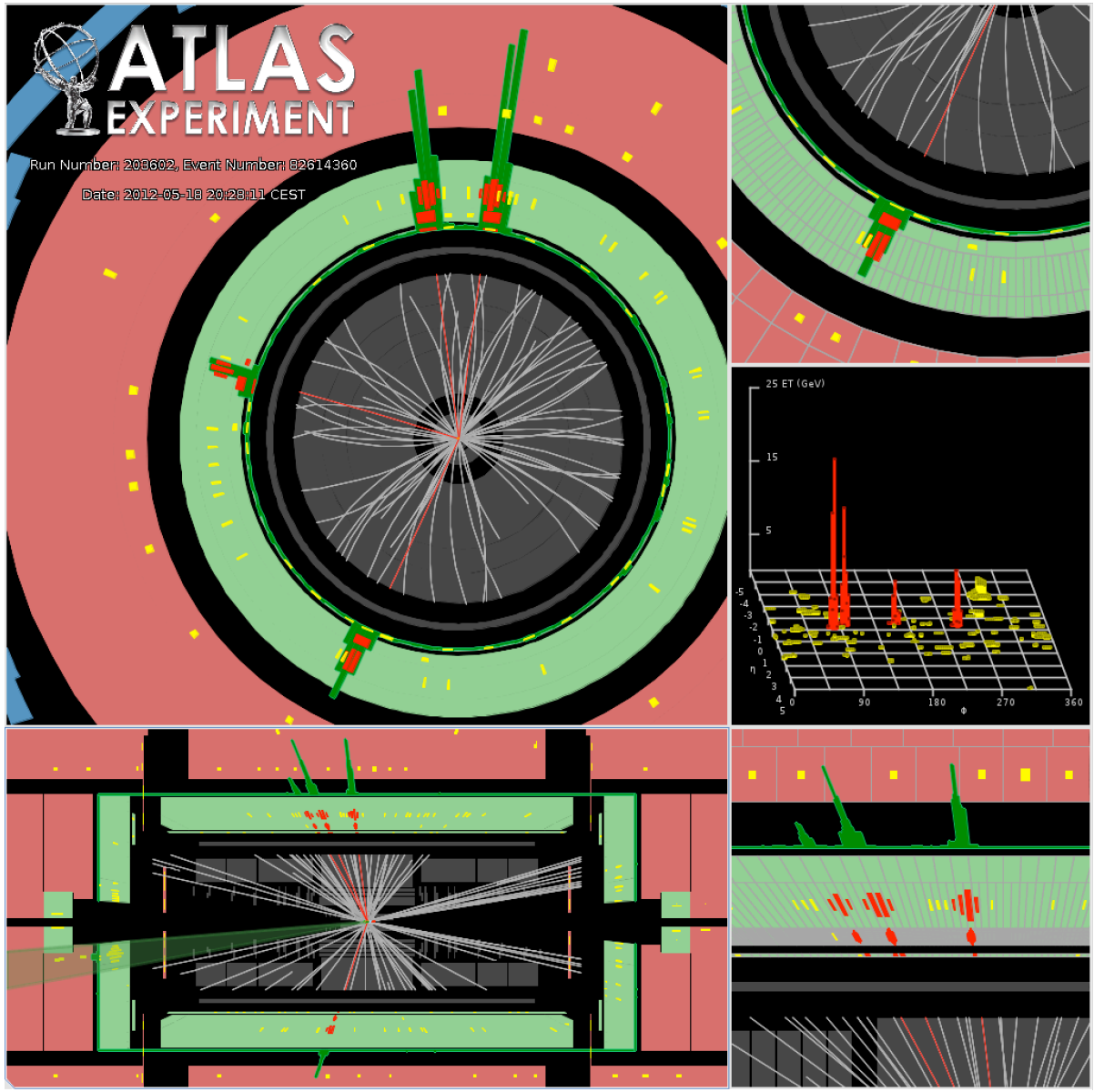
H → ZZ → 4μ


CMS Experiment at LHC, CERN
Data recorded: Fri Apr 20 12:35:44 2012 CEST
Run/Event: 191856 / 53791282
Lumi section: 64
$\mu^+(Z_1)$ p_T : 58 GeV
$\mu^-(Z_2)$ p_T : 22 GeV
4-lepton Mass : 125.2 GeV
$\mu^+(Z_2)$ p_T : 16 GeV
$\mu^-(Z_1)$ p_T : 33 GeV

H → ZZ → 2μ 2e

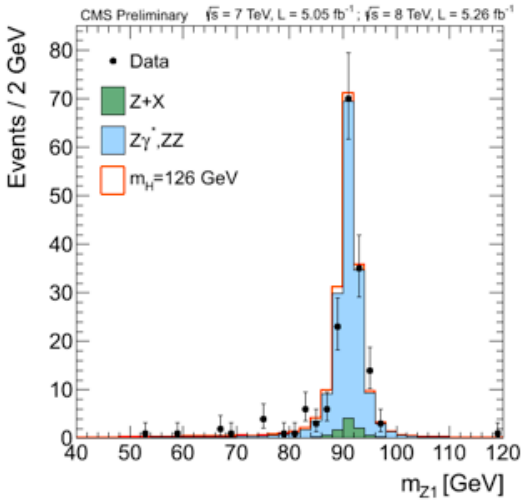

CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
4-lepton Mass : 126.9 GeV
μ+(Z1) pT : 43 GeV
e-(Z2) pT : 10 GeV
μ-(Z1) pT : 24 GeV
e+(Z2) pT : 21 GeV

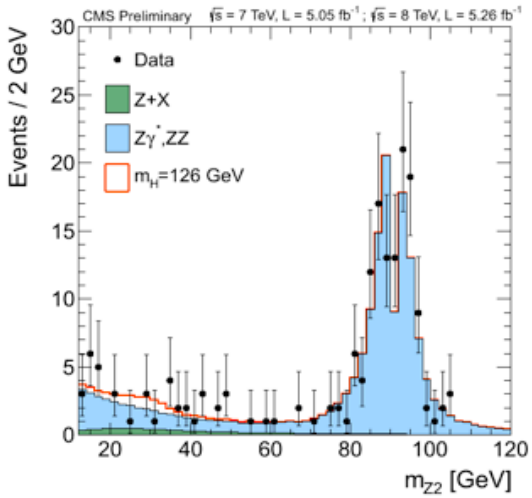
H → ZZ → 4e


ATLAS
EXPERIMENT
Run Number: 203602, Event Number: 82614360
Date: 2012-05-18 20:28:11 CEST
25 ET (GeV)
15
5
η
φ
0
90
180
270
360

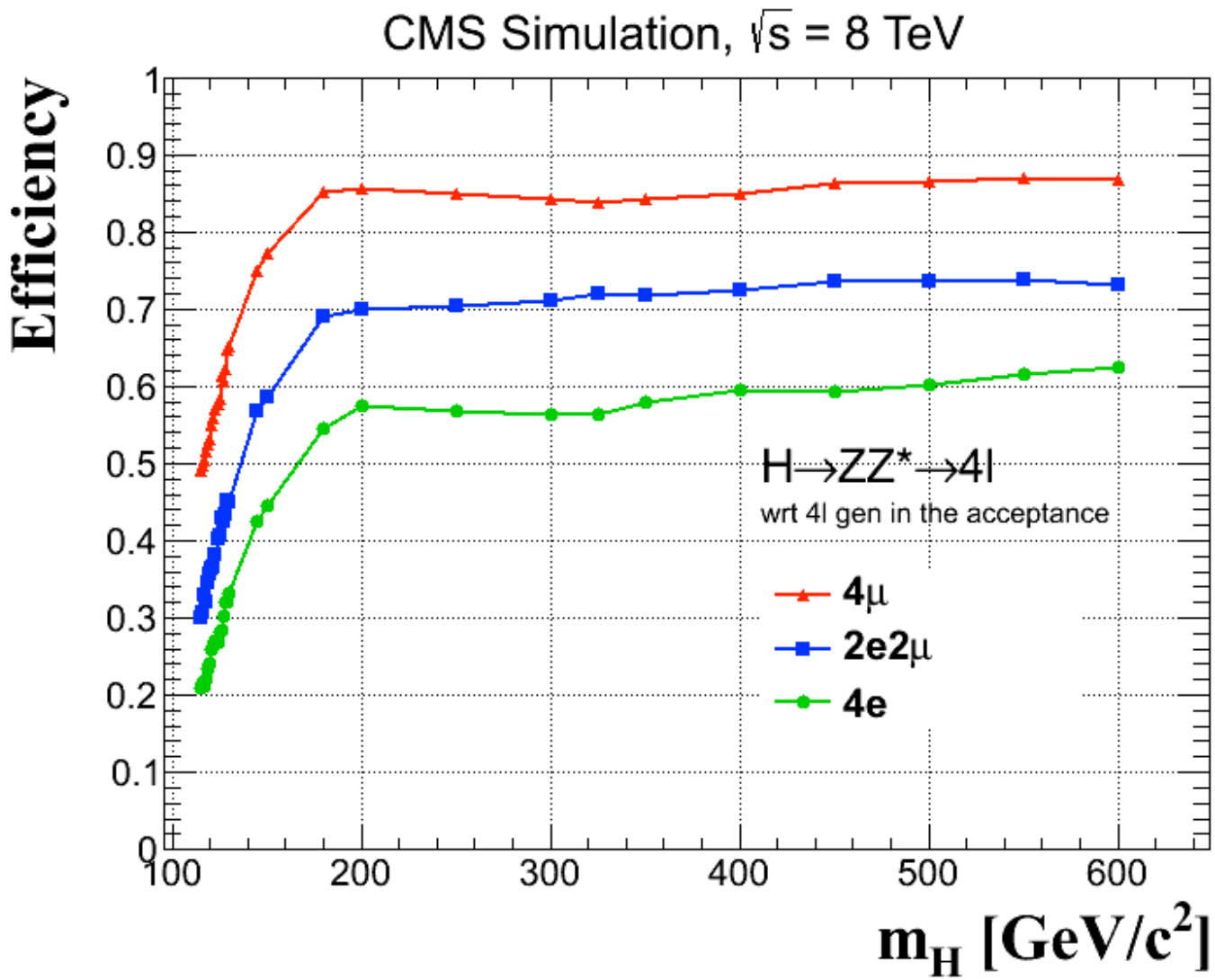
Event Selection : CMS

- Leptons compatible with primary vertex & isolated
  - muons: $p_T > 5$ GeV, $|\eta| < 2.4$
  - electrons: $p_T > 7$ GeV, $|\eta| < 2.5$
  - at least one lepton with $p_T > 20$ GeV
  - at least two leptons with $p_T > 10$ GeV
- First Z candidate (Z_1)
  - chosen as di-lepton pair with m(ll) closest to m_Z
  - $40 < m(ll) < 120$ GeV
- Second Z candidate (Z_2)
  - build from remaining highest p_T leptons
  - $12 < m(ll) < 120$ GeV





Typical Efficiency For H→ 4l Selection

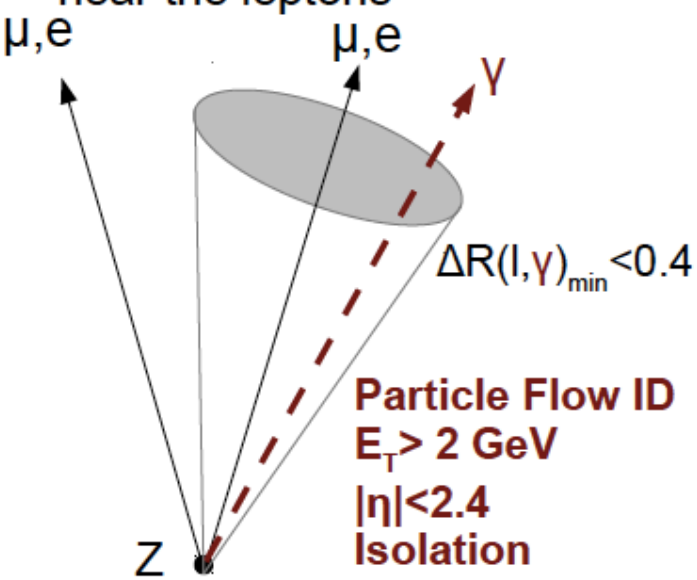


Pileup is not an issue in this mode

Final State Radiation Recovery

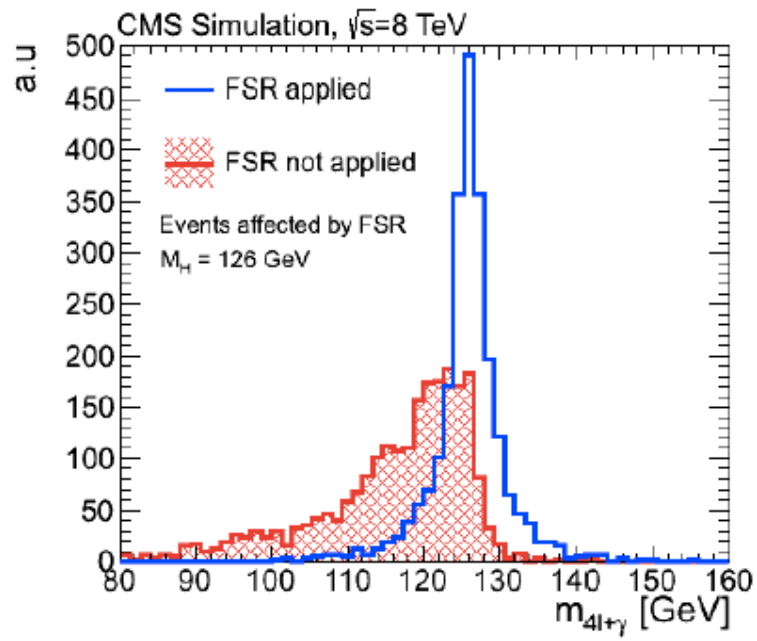
- Sometimes the leptons radiate photons, CMS attempts to find them

  - Applied on each Z for photons near the leptons

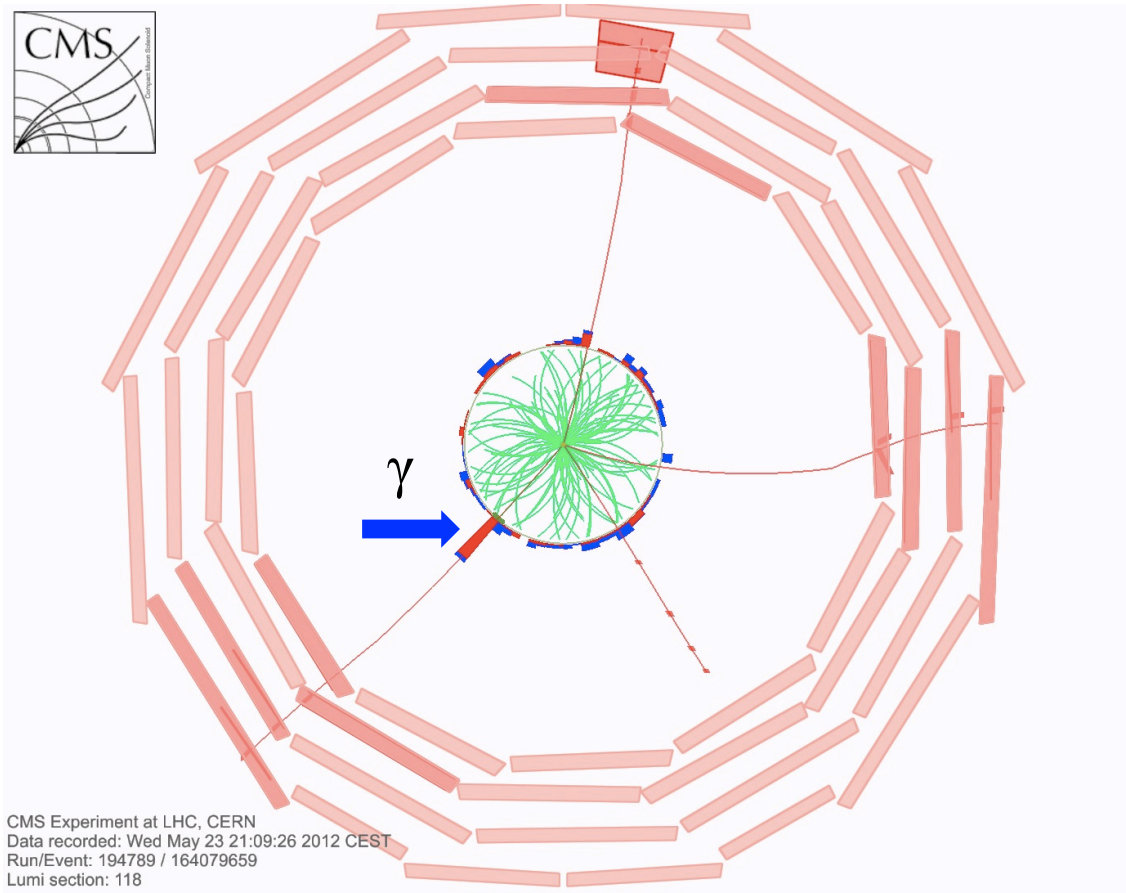


  - Associates the photon with Z if:
    - $M(ll+\gamma) < 95$ GeV
    - $|M(ll+\gamma)-M_Z| < |M(ll)-M_Z|$
  - Removes associated photons from lepton isolation calculation

  - Expected Performance
    - 6% of the events affected
    - 4.8% of the events: mass improved
    - 1.2% of the events: mass degraded
    - 2% more events added into sample after FSR recovery

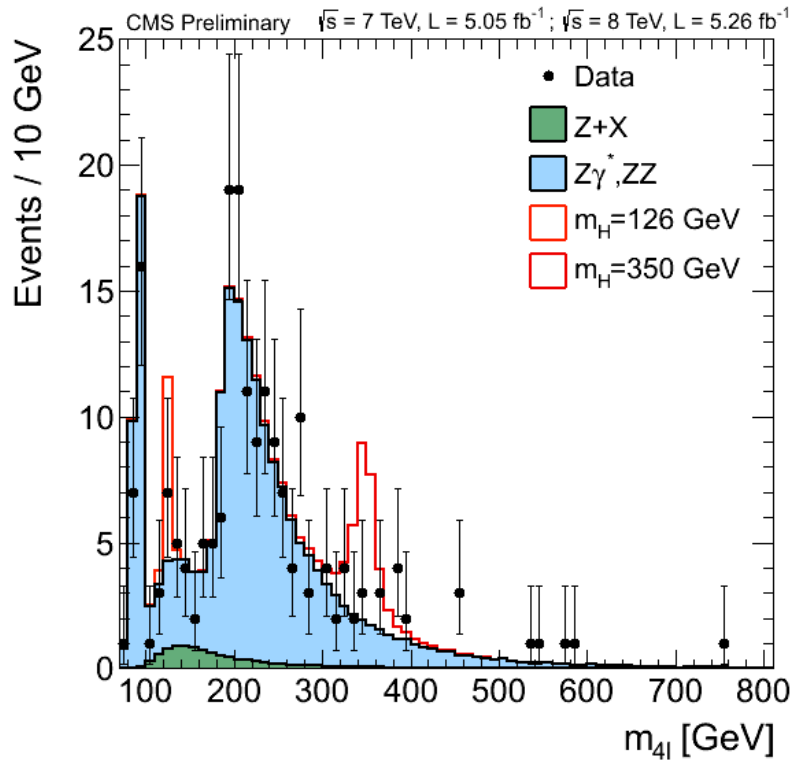


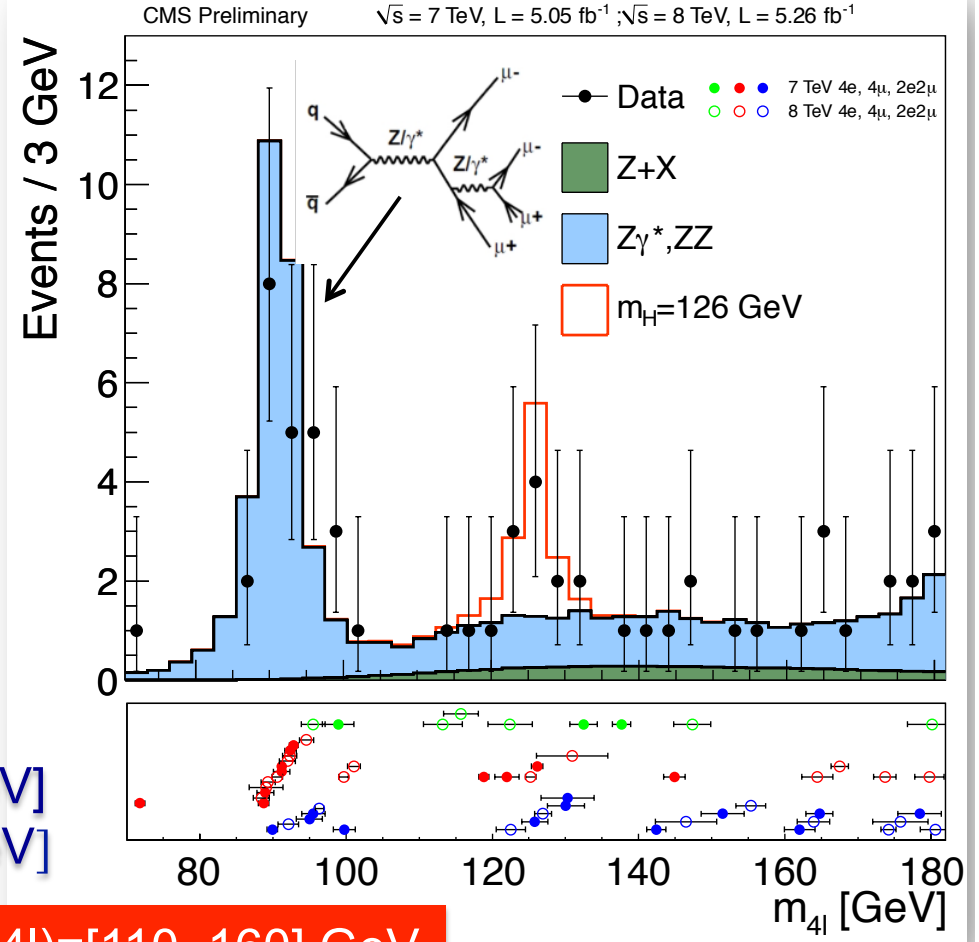
Example of Final State Radiation Recovery



FSR recovery has small impact on CMS Higgs search sensitivity (~ 3%) but enhances robustness for small statistics searches as currently

4l Mass Spectrum (CMS)





164 events expected in [100, 800 GeV]
172 events observed in [100, 800 GeV]

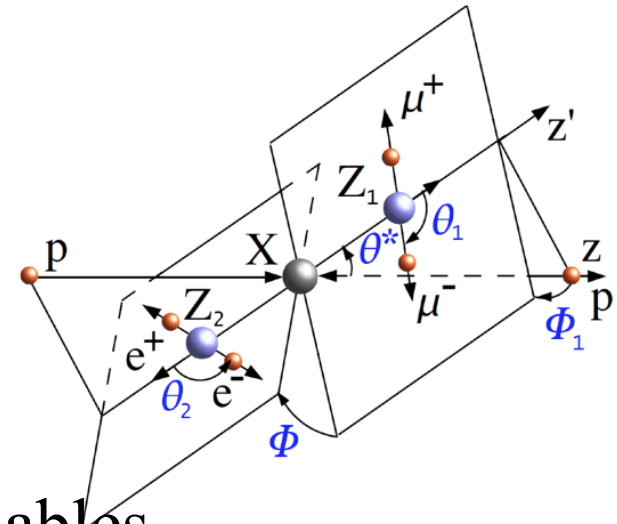
Yields in m(4l)=[110, 160] GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	2.65 ± 0.31	5.65 ± 0.59	7.17 ± 0.76	15.48 ± 1.01
Z+X	$1.20^{+1.08}_{-0.78}$	$0.92^{+0.65}_{-0.55}$	$2.29^{+1.81}_{-1.36}$	$4.41^{+2.21}_{-1.66}$
All backgrounds	$3.85^{+1.12}_{-0.84}$	$6.58^{+0.88}_{-0.81}$	$9.46^{+1.96}_{-1.56}$	$19.88^{+2.43}_{-1.95}$
$m_H = 126$ GeV	1.51 ± 0.48	2.99 ± 0.60	3.81 ± 0.89	8.31 ± 1.18

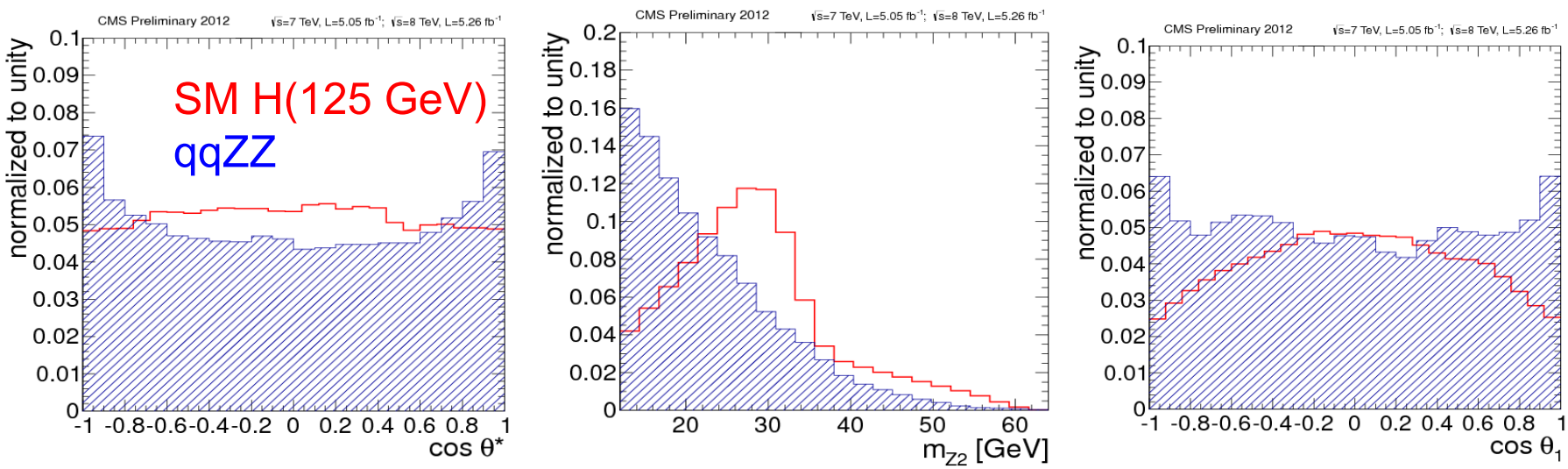
Angular Analysis In H → ZZ → 4l (CMS)

- H → ZZ → 4l Decay kinematic fully described by 5 angles and the 2 Z masses
  - discriminates spin 0 particle from background
  - MELA: matrix element likelihood analysis

    PR(D) 81, 075022(2010)

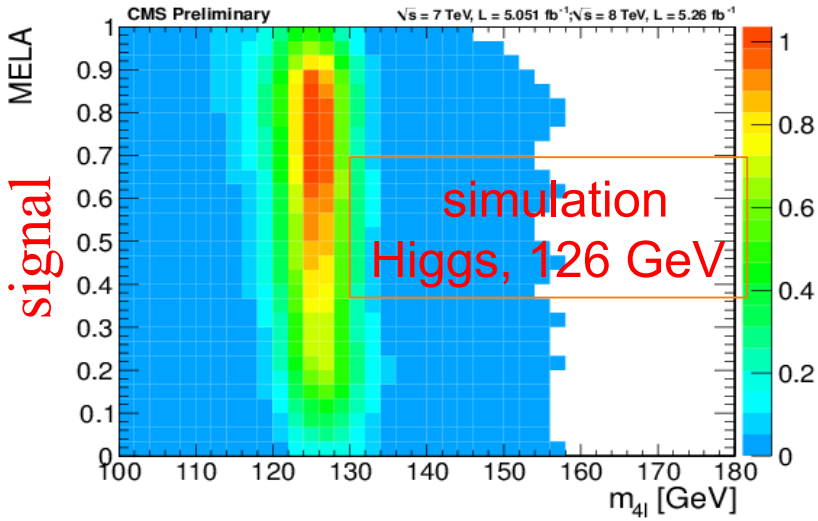


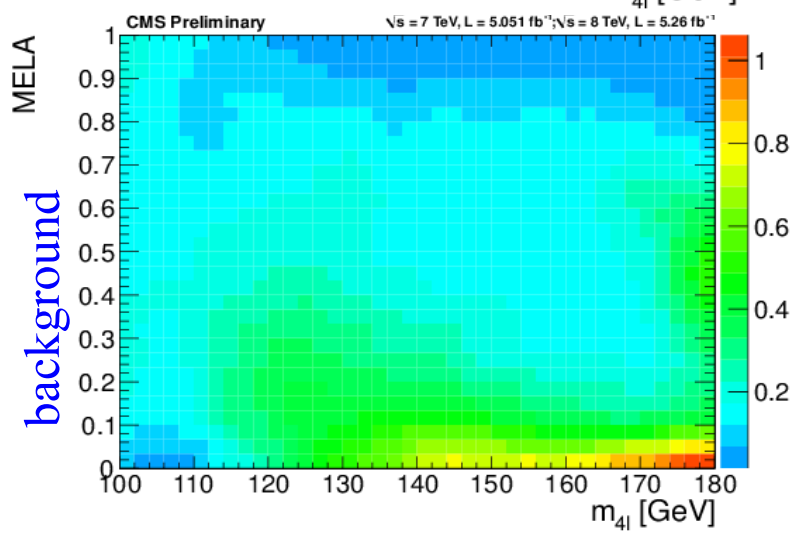
Some discriminating variables

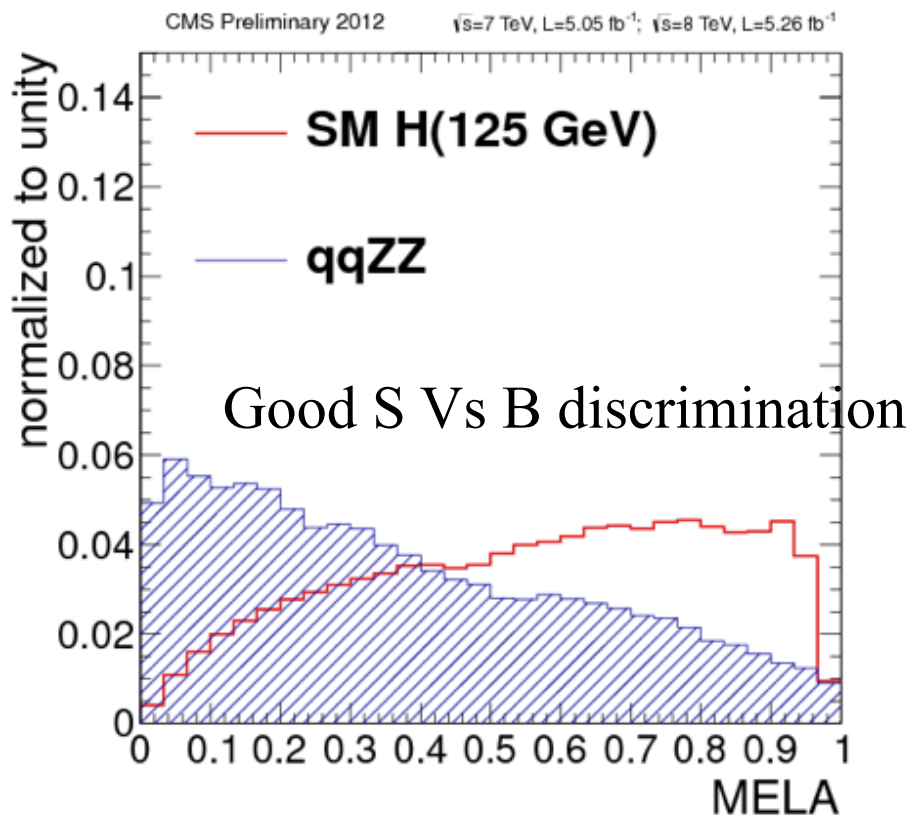


MELA Vs 4l Mass

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



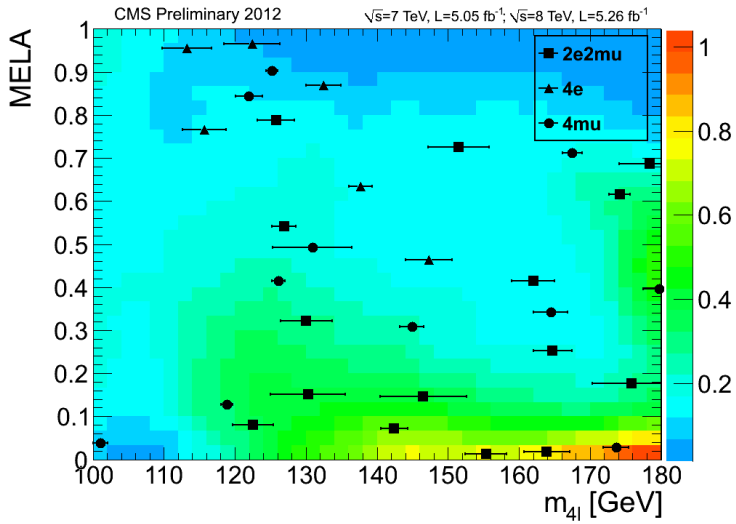


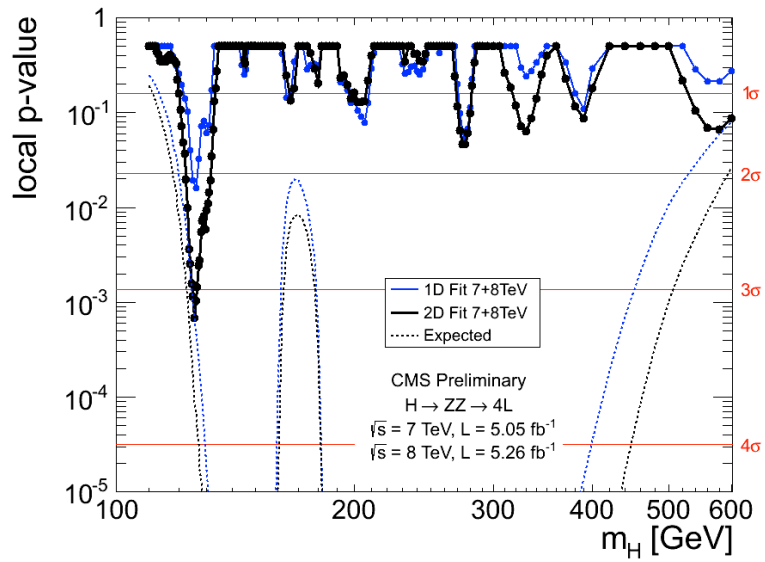


Good S Vs B discrimination

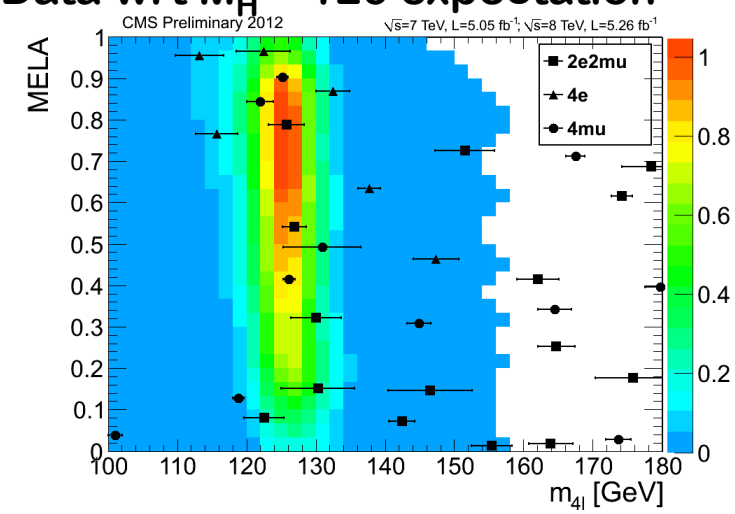
CMS : 2D Fit of MELA Vs 4l Mass

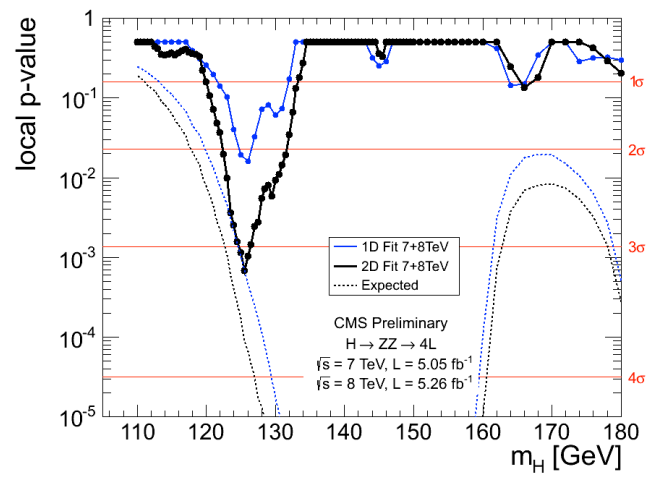
Data wrt background expectation





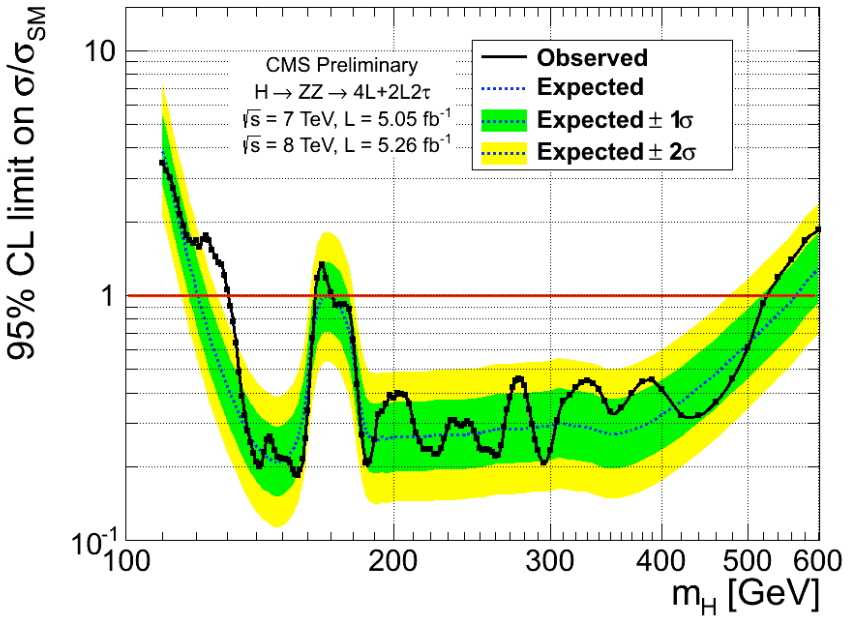
Data wrt M_H = 126 expectation

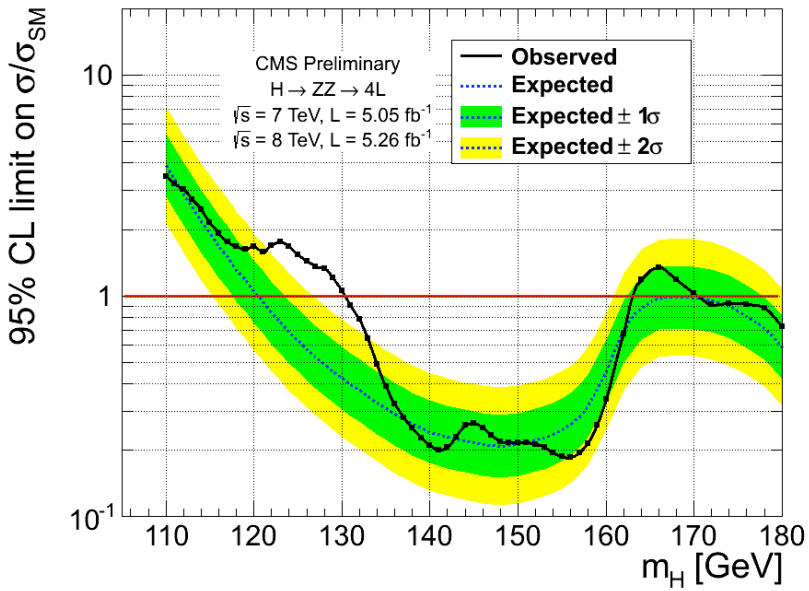




Expected local significance at 125.5 GeV: 3.8 σ
Observed local significance at 125.5 GeV: 3.2 σ

CMS Exclusion Limits: H → ZZ → 4l





Expected exclusion at 95% CL: 121-550 GeV
Observed exclusion at 95% CL: 131-162 and 172-530 GeV

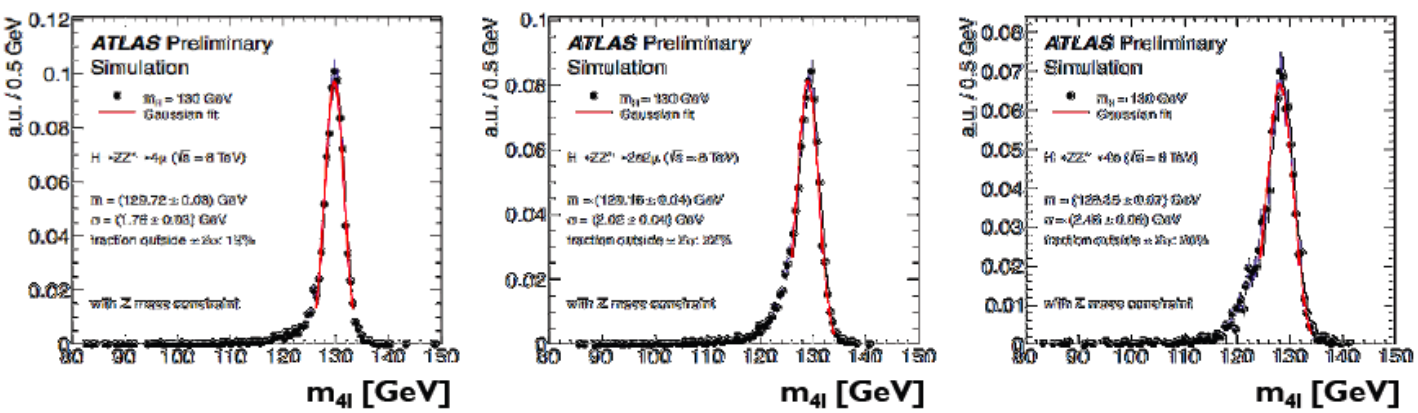
$H \rightarrow ZZ^{(*)} \rightarrow 4l$: ATLAS

Selection

- ***At least two pairs of opposite-charge, same-flavor leptons (e,μ)***
- ***p_T thresholds: 20, 15, 10, 7 GeV (6 GeV for muons)***
- ***$50 < m_{12} < 106$ GeV, m_{4l}-dependent cut on m_{34}, $m_{34} < 115$ GeV***
- ***All same-flavor, opposite-sign pairs m_{ll}>5 GeV (J/ψ veto)***
- ***$\Delta R(l,l') < 0.1$ (0.2) for all same (different)-flavor***
- ***Tracking and calorimeter isolation***
- ***Impact parameter significance***

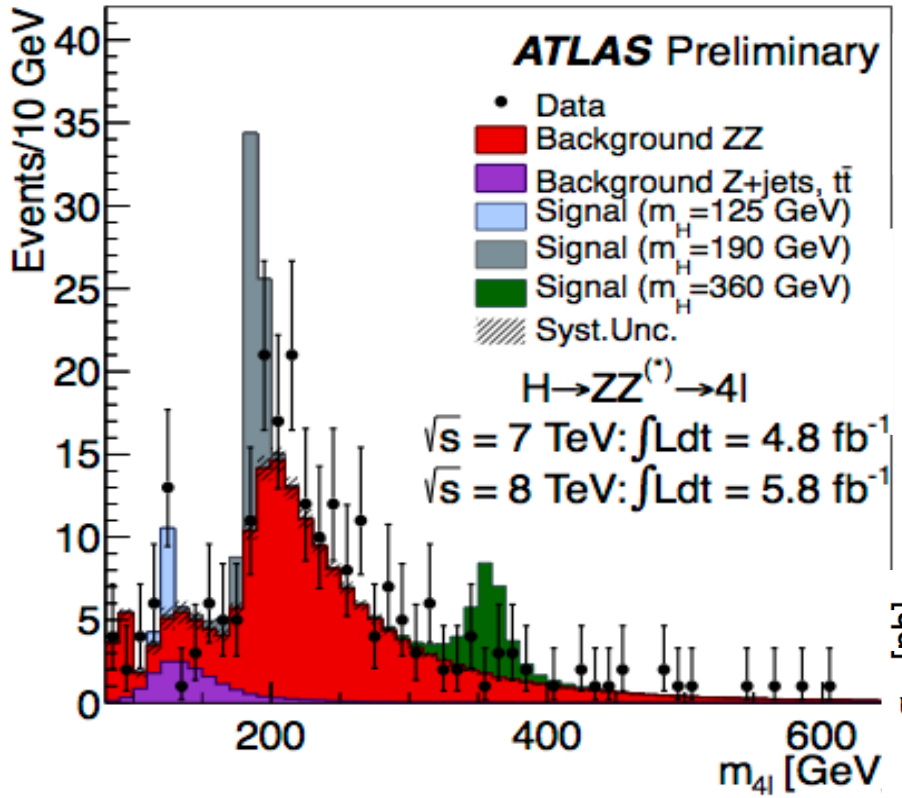
- ***Mass resolution in simulated events at m_H=130 GeV***

(with Z mass constraint for m_{12})



4μ: σ=1.8 GeV | 2e2μ: σ=2.0 GeV | 4e: σ=2.5 GeV

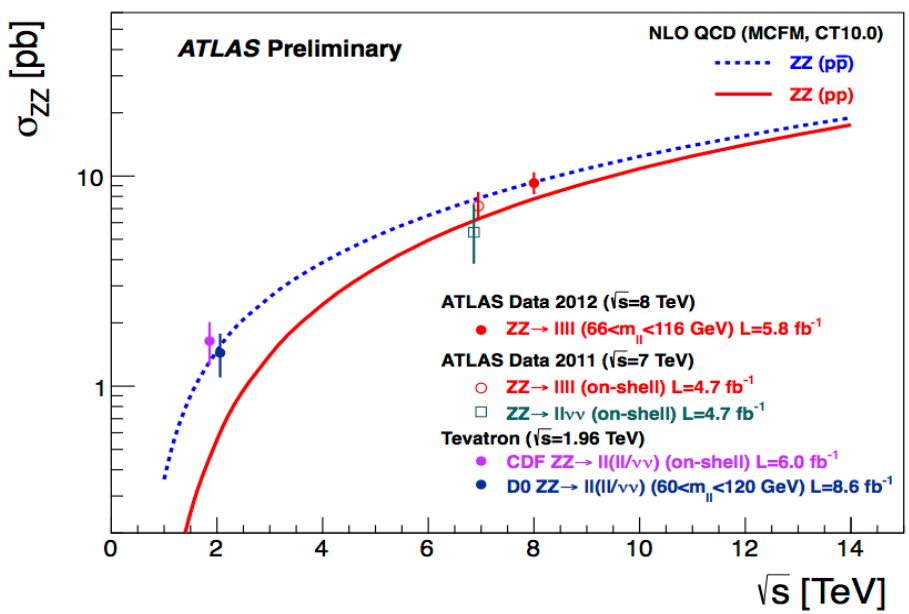
4l Spectrum: ATLAS



M_{4l}>160 GeV dominated by ZZ background:
147 ± 11 events expected; 191 observed

~1.3 times more ZZ events in data than SM prediction → in agreement with measured ZZ cross-section in 4l final states at 8 TeV

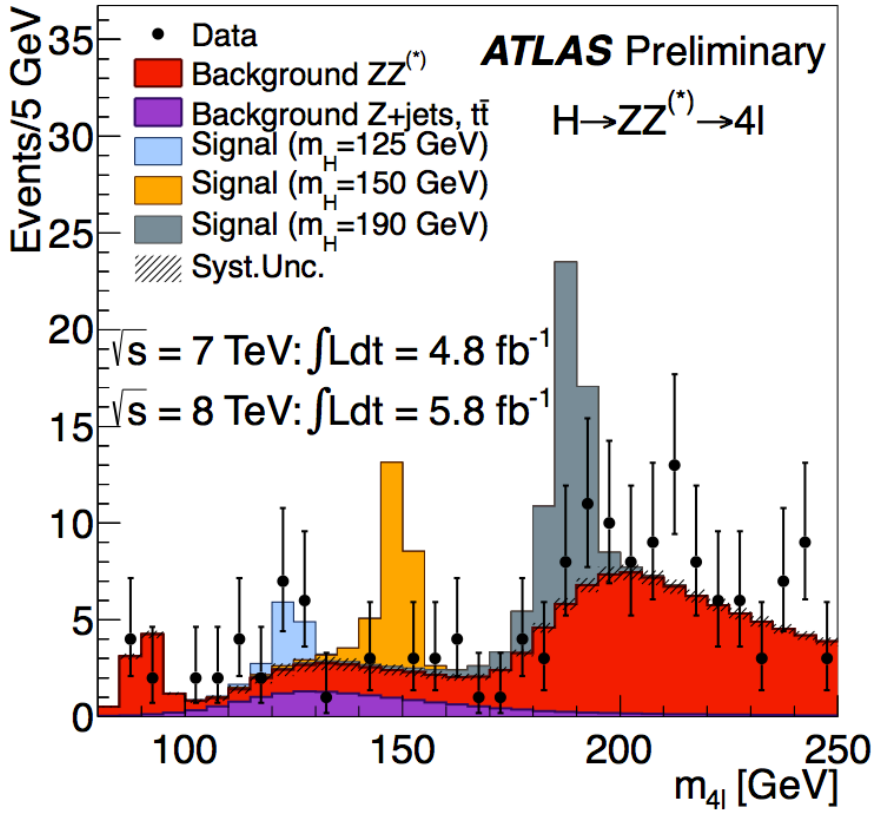
Measured σ (ZZ) = 9.3 ± 1.2 pb
SM (NLO) σ (ZZ) = 7.4 ± 0.4 pb



Discrepancy has negligible impact on the low-mass region < 160 GeV

(no change in results, if in the fit ZZ background is constrained within its uncertainty or left free)

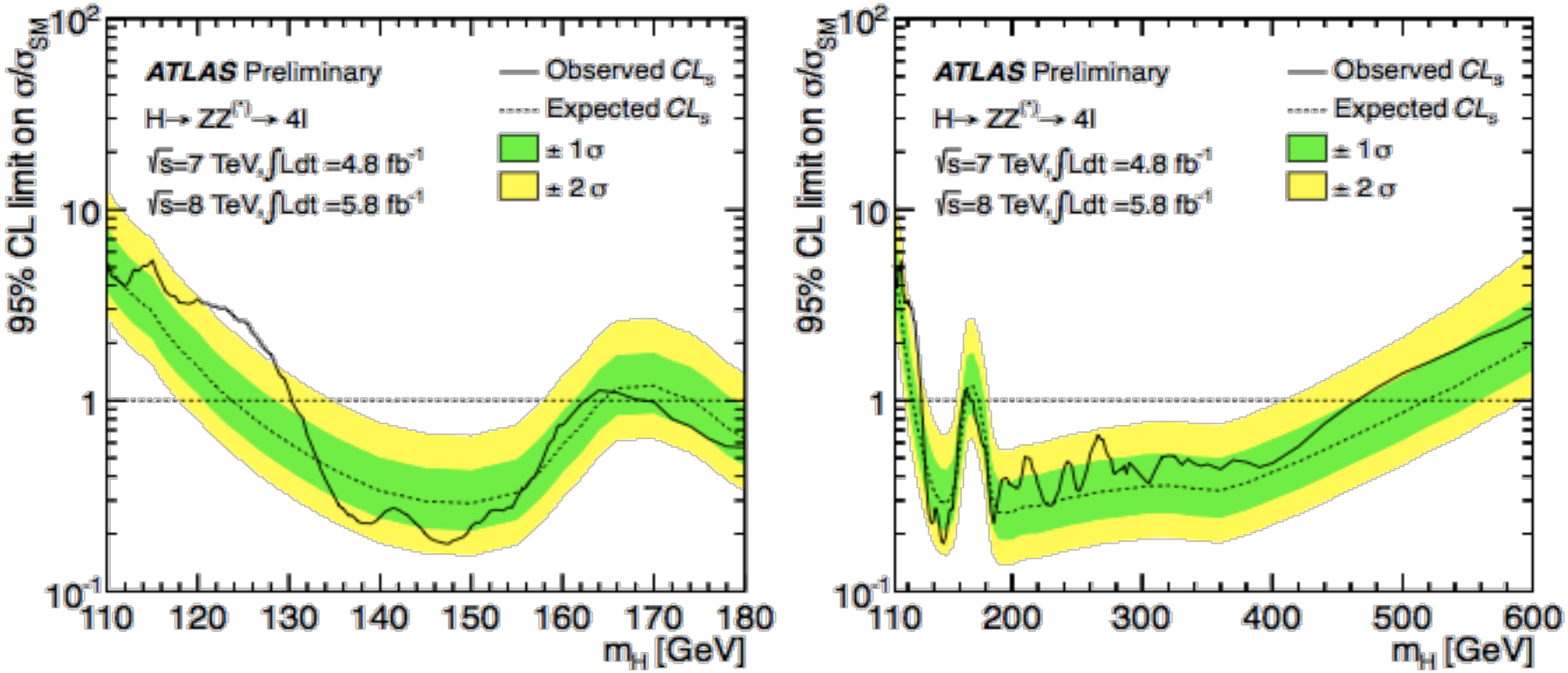
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ Low Mass Candidates



Event count in
$120 < m_{4l} < 130$ GeV

7+8 TeV	4μ	2e2μ + 2μ2e	4e	sum
Background	1.3 ± 0.1	2.2 ± 0.2	1.6 ± 0.2	5.1 ± 0.3
m_H=125 GeV	2.1 ± 0.3	2.3 ± 0.3	0.9 ± 0.1	5.3 ± 0.4
Data Observed	6	5	2	13
S/B	1.6	1.0	0.6	1.0

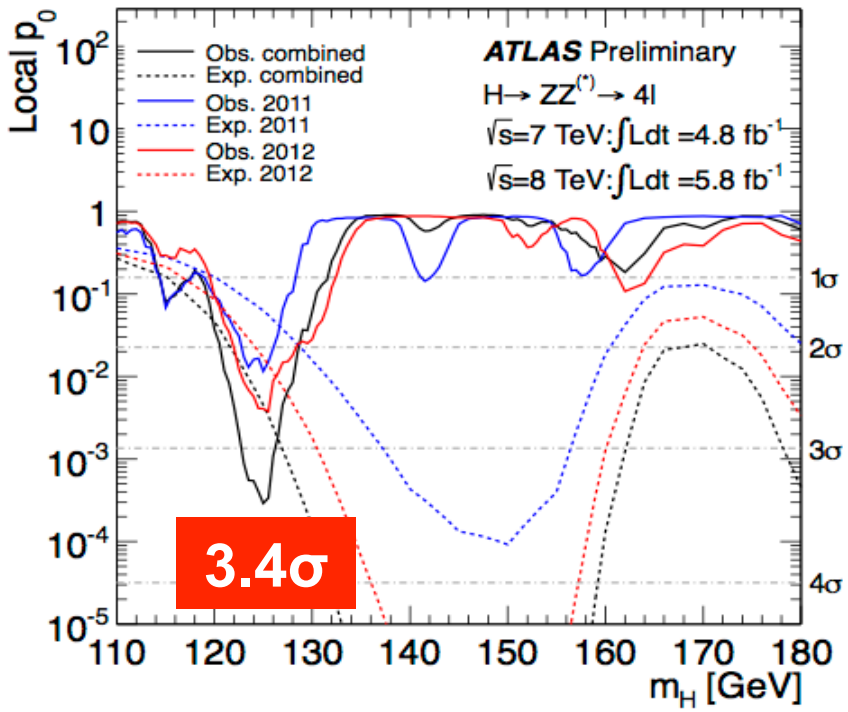
ATLAS Exclusion Limits: H → ZZ → 4l

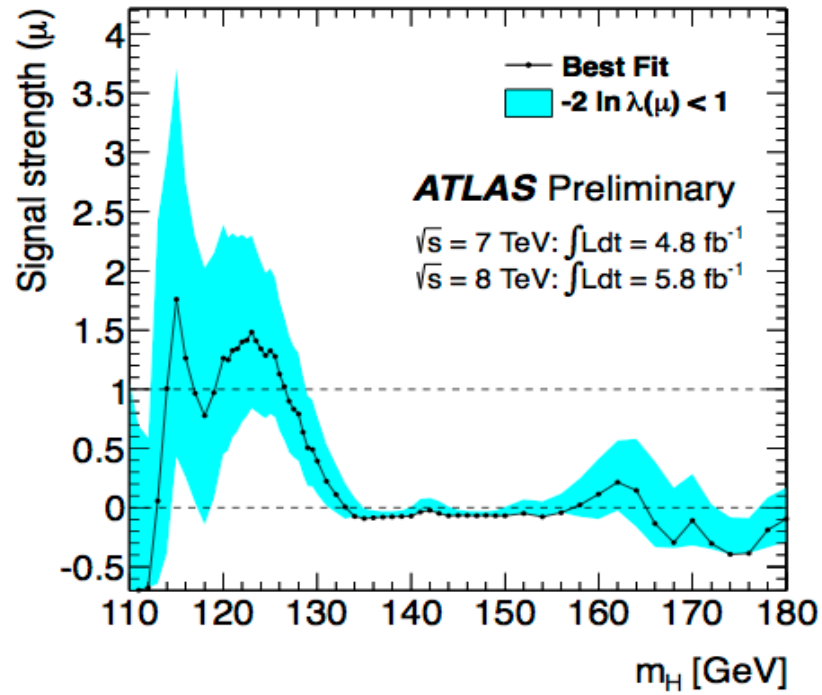


Exclusion at 95% C.L. :

- Expected $124 < m_H < 164$ GeV and $176 < m_H < 500$ GeV
- Observed $131 < m_H < 162$ GeV and $170 < m_H < 460$ GeV

Significance Of Observation In H → ZZ → 4l

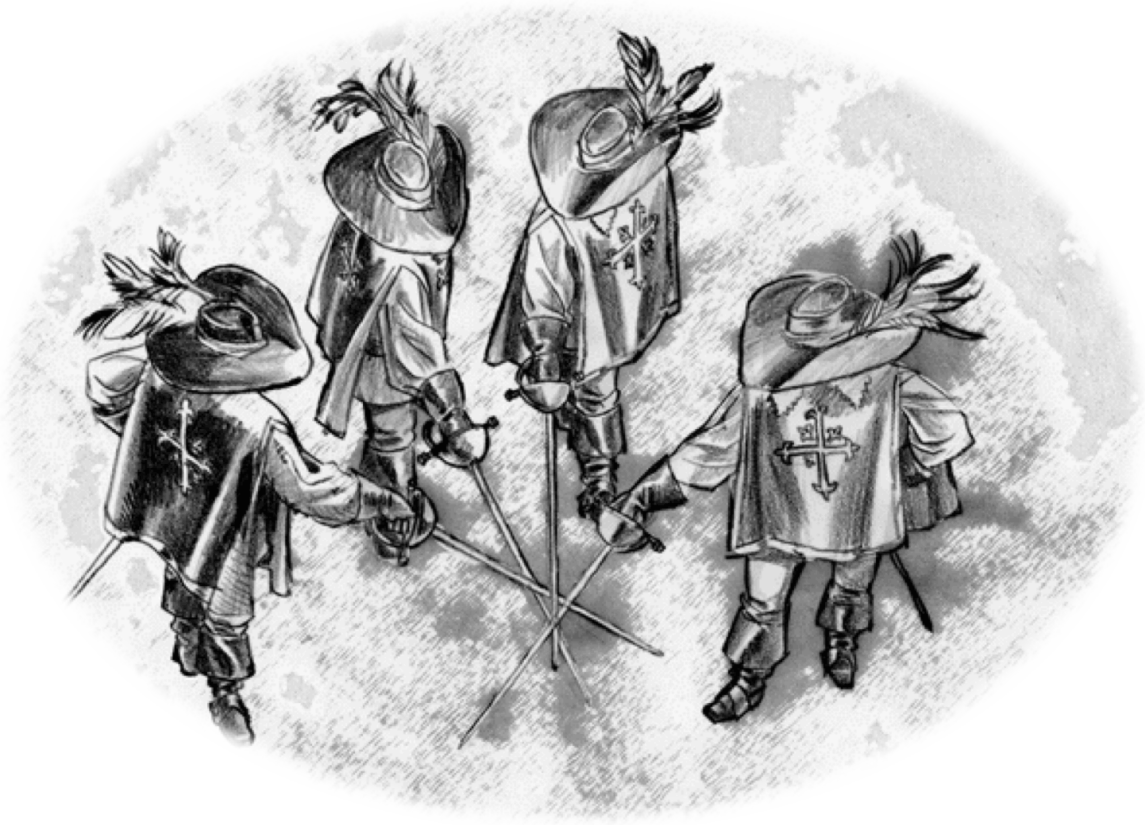




Best-fit value at 125 GeV: μ =1.3 ± 0.6

Data sample	m_H at max deviation	local p-value	local significance	expected
2011	125 GeV	1.1 %	2.3 σ	1.5 σ
2012	125.5 GeV	0.4 %	2.7 σ	2.1 σ
2011+2012	125 GeV	0.03 %	3.4 σ	2.6 σ

Global 2011+2012 (including LEE over full 110-141 GeV range): 2.5σ



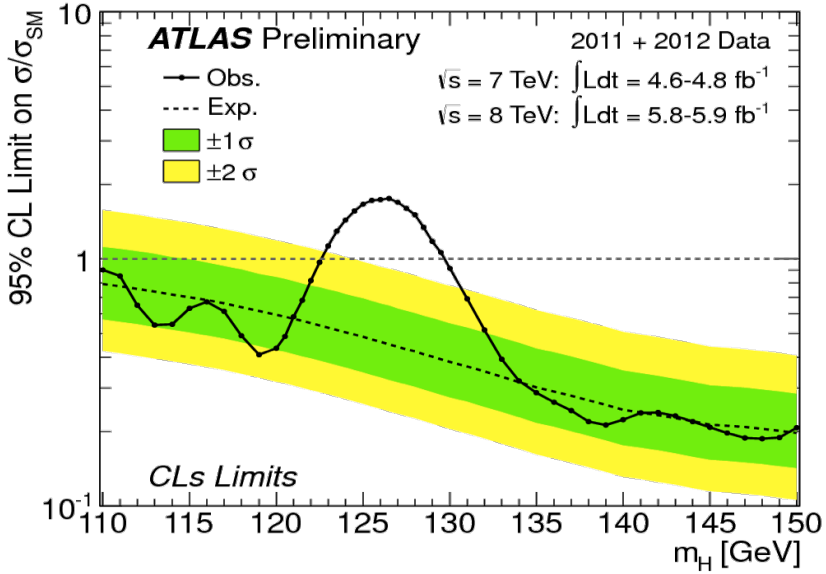
Combination Of SM Higgs Searches

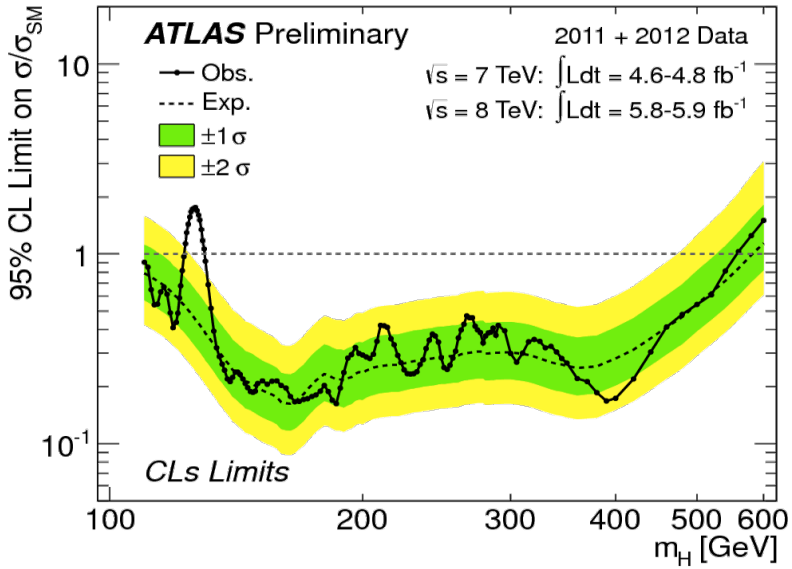
ATLAS Higgs Combination

• $H \rightarrow \gamma\gamma$	7 TeV (4.8 fb^{-1}) + 8 TeV (5.9 fb^{-1})
• $H \rightarrow ZZ^{(*)} \rightarrow 4$ leptons	7 TeV (4.8 fb^{-1}) + 8 TeV (5.8 fb^{-1})
• $H \rightarrow WW$	7 TeV (4.7 fb^{-1})
• $H \rightarrow \tau\tau$	7 TeV (4.7 fb^{-1})
• $W,Z\ H \rightarrow bb$	7 TeV (4.6-4.7 fb^{-1})

H → WW Result with 8 TeV data **not** used in July 4th Combination shown here But will be for the planned July 31st paper

ATLAS Exclusion Limits



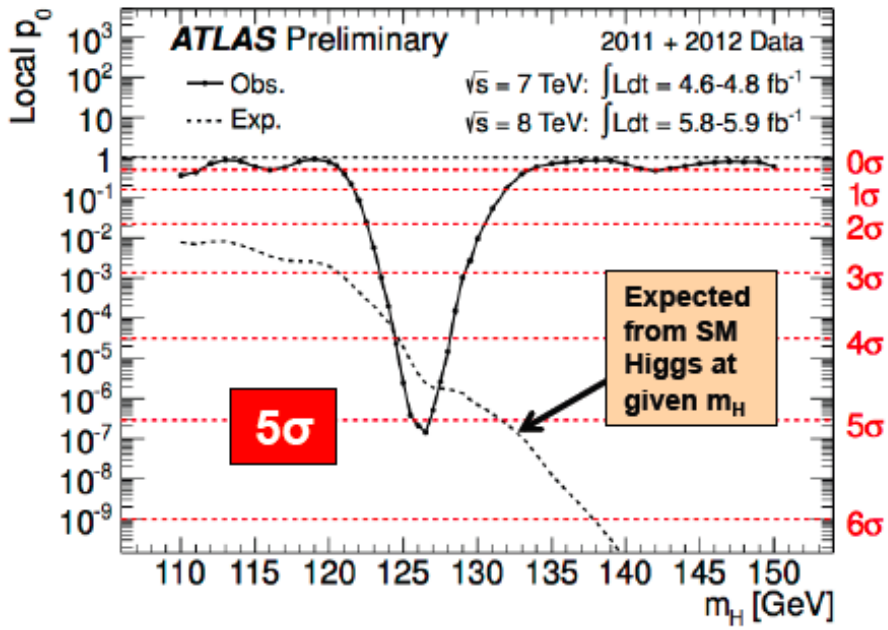


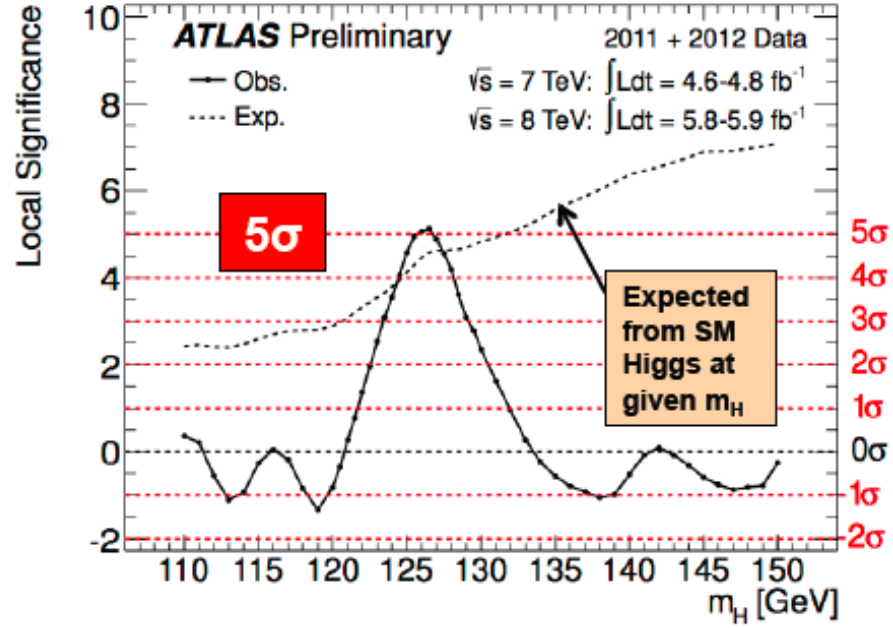
Exclusion at 95% C.L. :

- Expected $110 < m_H < 582$ GeV
- Observed $110 < m_H < 122.6$ GeV, $129.7 < m_H < 558$ GeV

Region around 126 GeV is not excluded

Significance Of Observation: ATLAS





Maximum excess observed at m_H = 126.5 GeV

Local significance *(including energy-scale systematics)*	***5.0 σ***
(p_0) *Probability that background fluctuates to the observed data (or higher)*	***3×10^{-7}***
Expected from SM Higgs m_H=126.5 GeV	***4.6 σ***

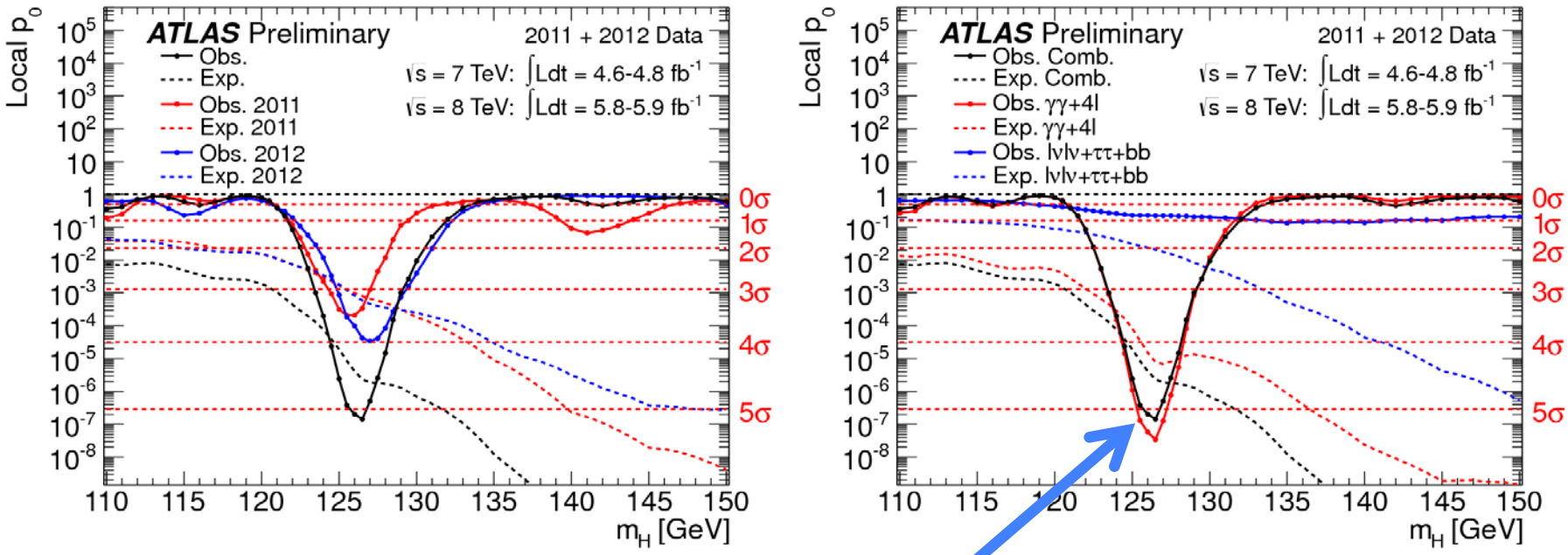
Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

Significance Of Observation: ATLAS

The excess is seen in both 2011 and 2012 data:

2011: 3.5σ (obs.) and 3.1σ (exp.)

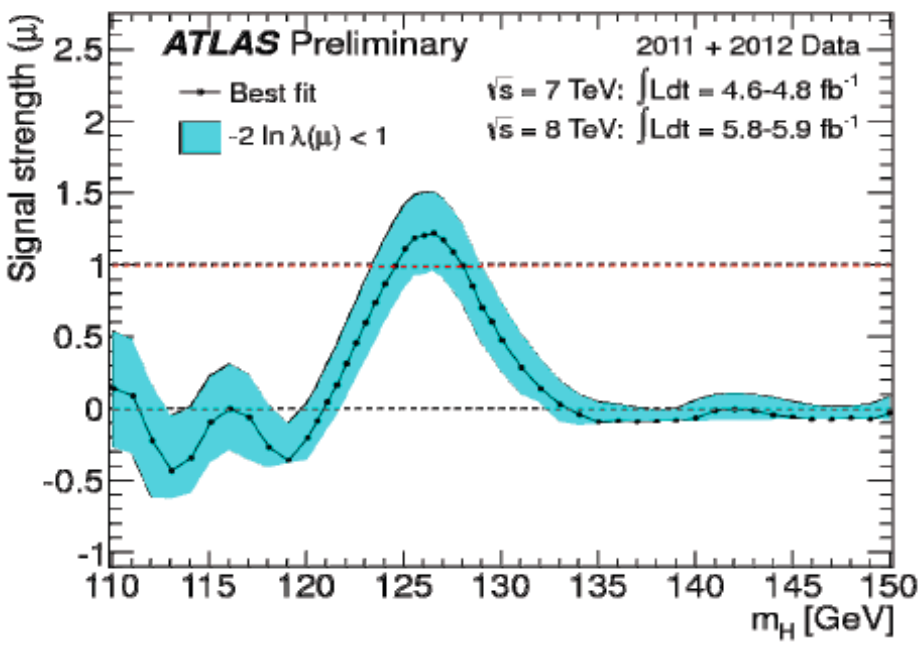
2012: 4.0σ (obs.) and 3.3σ (exp.)

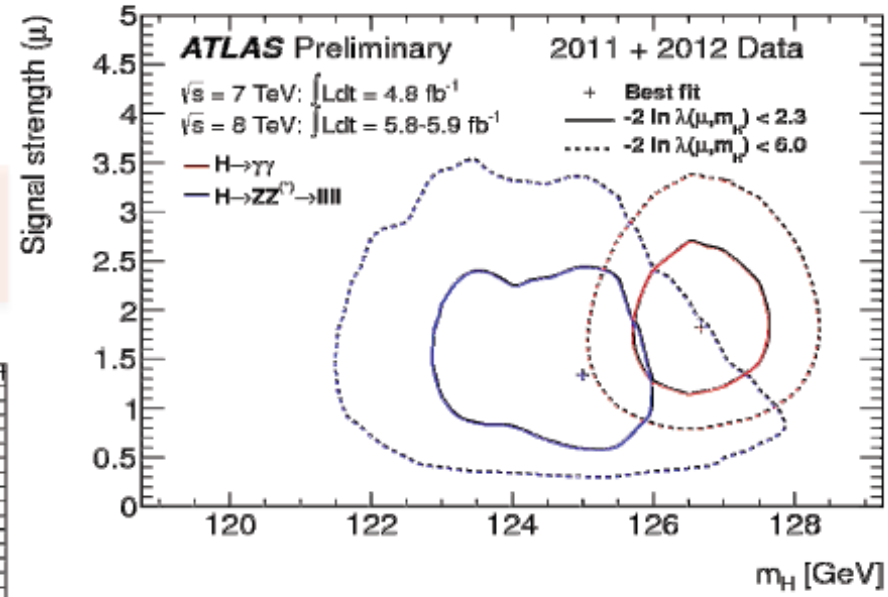


The excess for both years is dominated by H→γγ and H→ZZ→4 leptons

Investigating The Excess : ATLAS

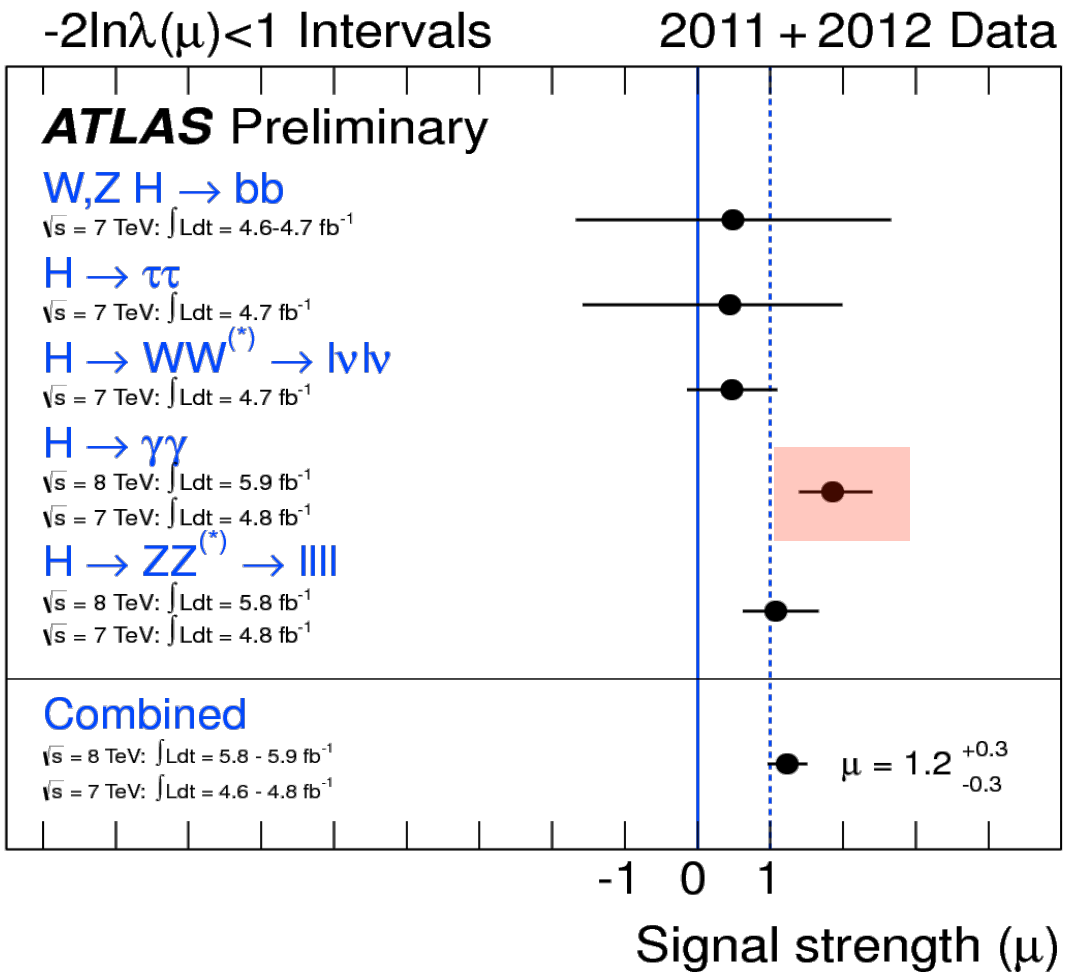
- ***Best fit signal strength (μ) vs m_H***
  - ***Scanning m_H to find best-fit value of μ at each m_H***
  - ***At 126.5 GeV, μ=1.2 ± 0.3***
    - ***Compatible with SM expectation (μ=1)***





- ***Let m_H and μ float, 2D contour plot around best fit values (~68% solid, 95% dashed)***
- ***Best fit masses for H→γγ and H→4-leptons are compatible.***

Anatomy Of The Excess : ATLAS



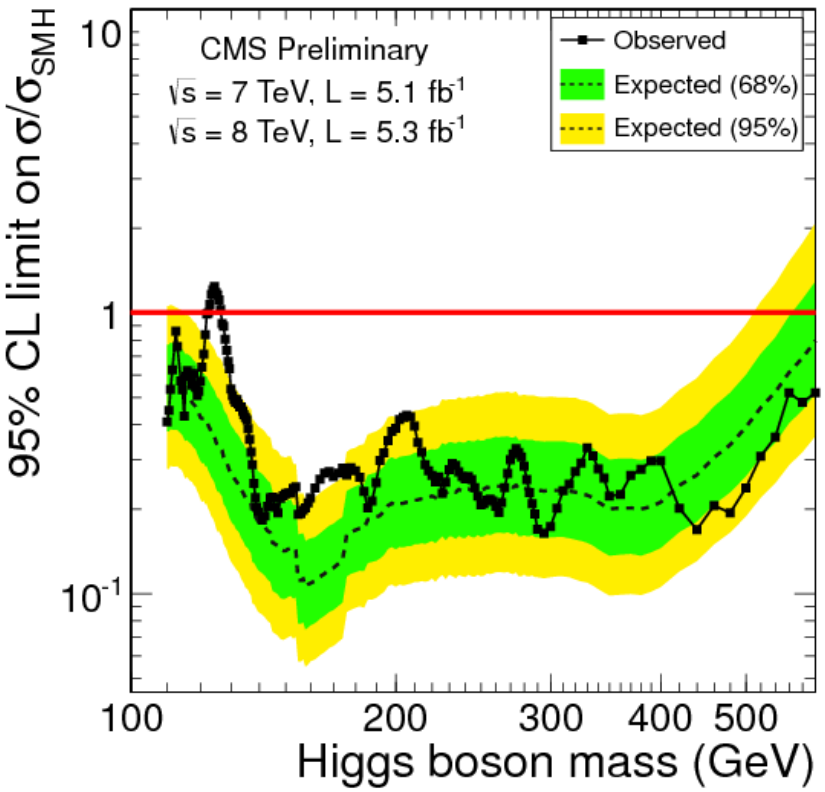
Combined signal strength:

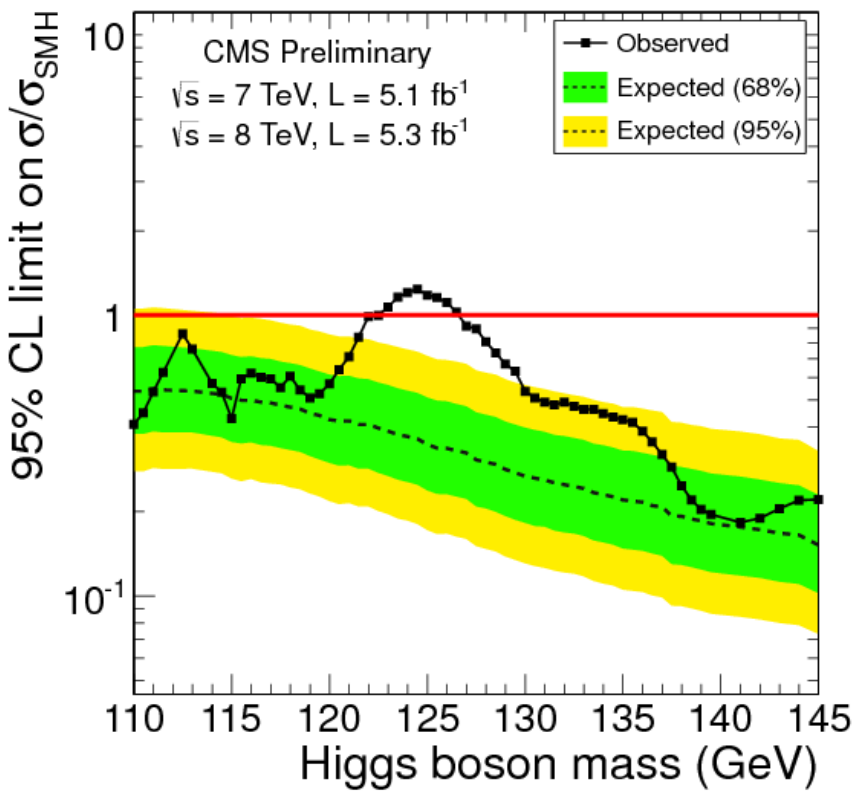
$\mu = 1.2 \pm 0.3$

Most important contributions from $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$, $H \to WW^* \to l\nu l\nu$

CMS Higgs Exclusion Limits

H→ γγ, ττ, bb, ZZ, WW search with 5.1 fb^{-1} @7 TeV & 5.3 fb^{-1} @8 TeV





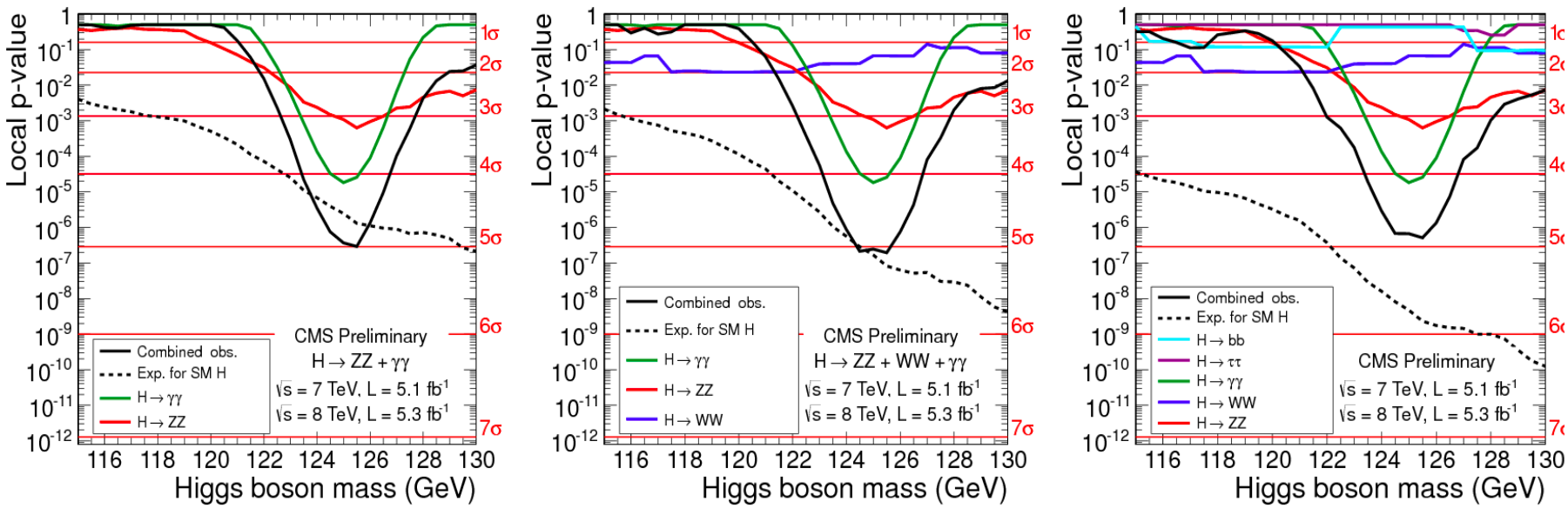
95% CL Exclusion: $110 < M_H < 122.5$, $127 < M_H < 600$ GeV

P-Value & Significance Of Observation: By Modes

γγ+ZZ
Obs: 5σ
Exp: 4.5σ

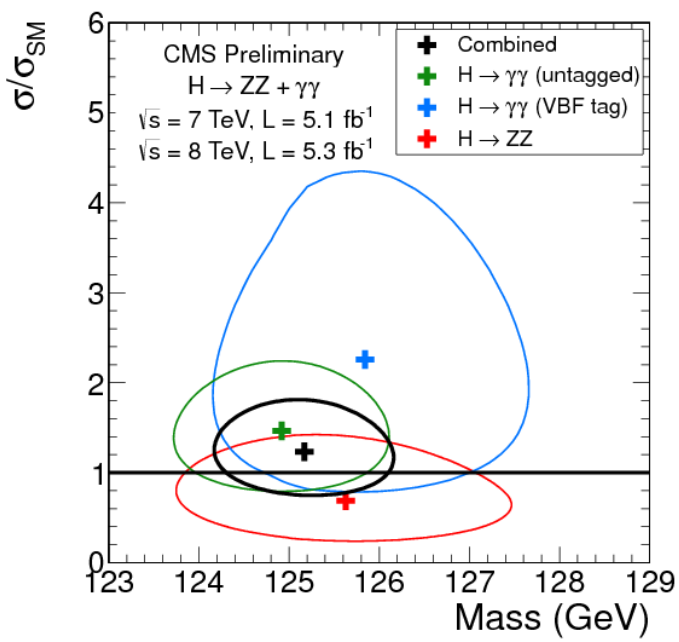
γγ+ZZ+WW
Obs: 5.1σ
Exp: 5.2σ

γγ+ZZ+WW+ττ+bb
Obs: 4.9σ
Exp: 5.9σ



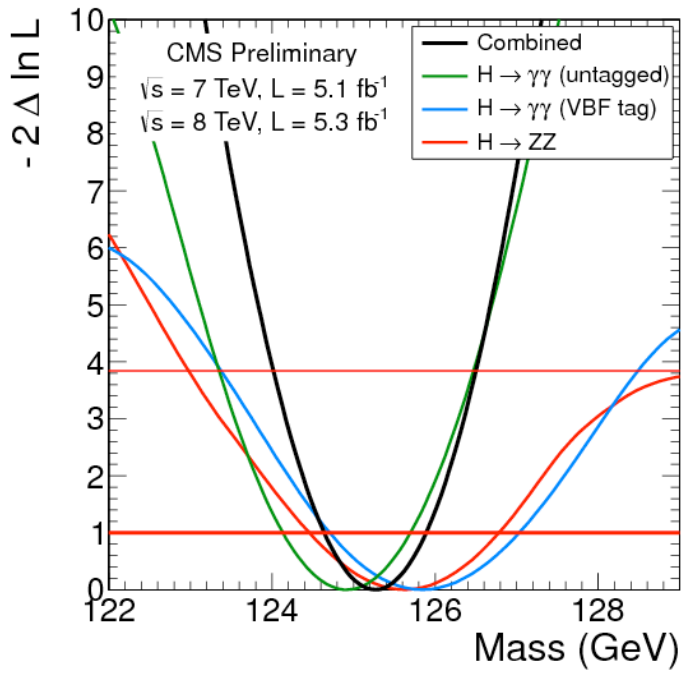
Mass Of The Observed State (CMS)

- To measure mass of observed state use only high mass resolution modes : $\gamma\gamma$ (inclusive), $\gamma\gamma$(VBF-tagged) and $ZZ \rightarrow 4l$ where a significant excess is observed
- Model dependent scan:
  - Assume that relative event yield between 3 channels are **fixed** but float the overall signal strength ($\mu=\sigma/\sigma_{SM}$)



Mass Of The Observed State (CMS)

- To extract value of M_X in a model-independent way:
  - Treat the three modes: γγ (inclusive), γγ(VBF-tagged) and ZZ→4l independently, each with its own signal cross section
  - Signal is assume to be due to a state with a unique mass

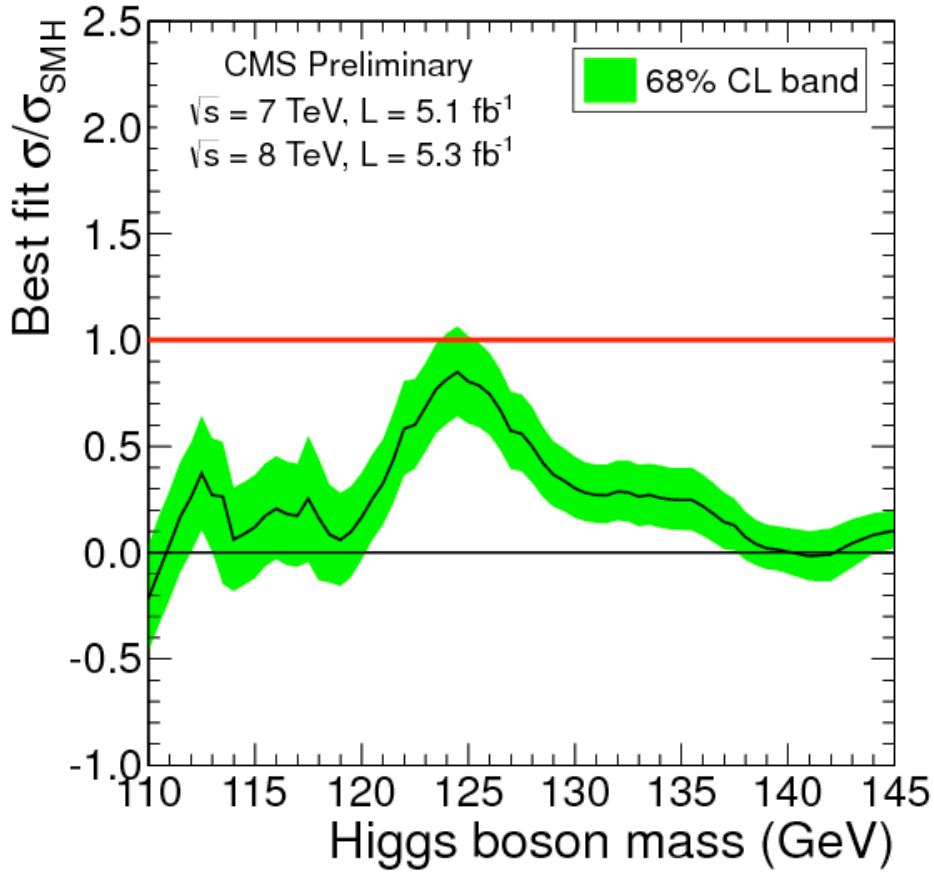


M_X = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV

Systematic uncertainty dominated by ECAL energy scale

Compatibility With SM Higgs boson Hypothesis

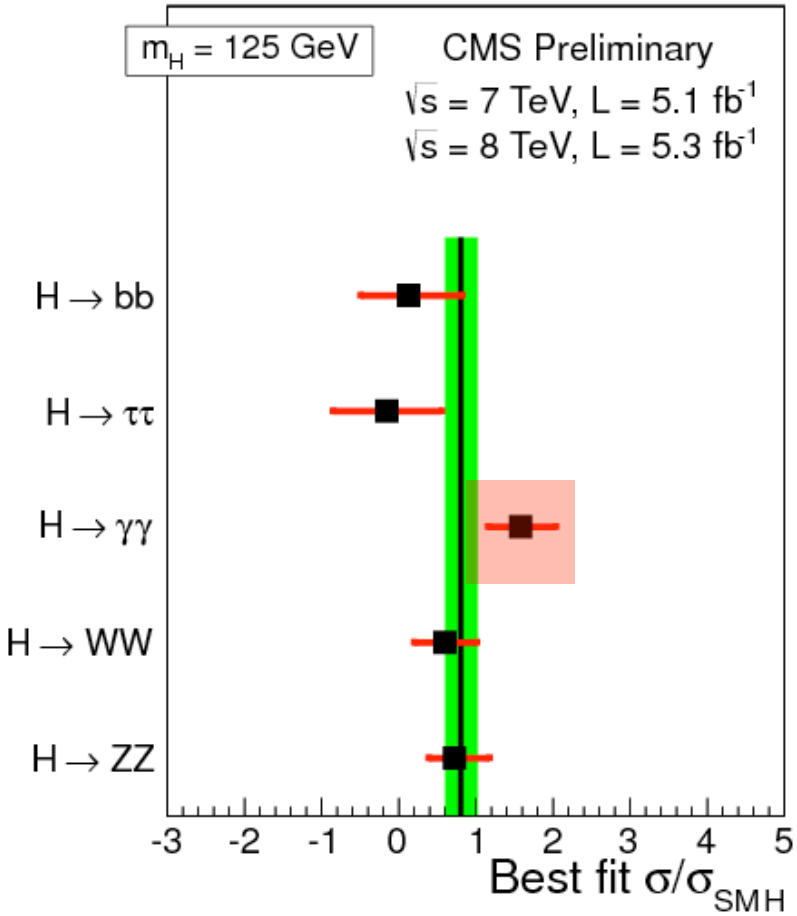
- Best fit value for common signal strength modifier $\mu=\sigma/\sigma_{SM}$

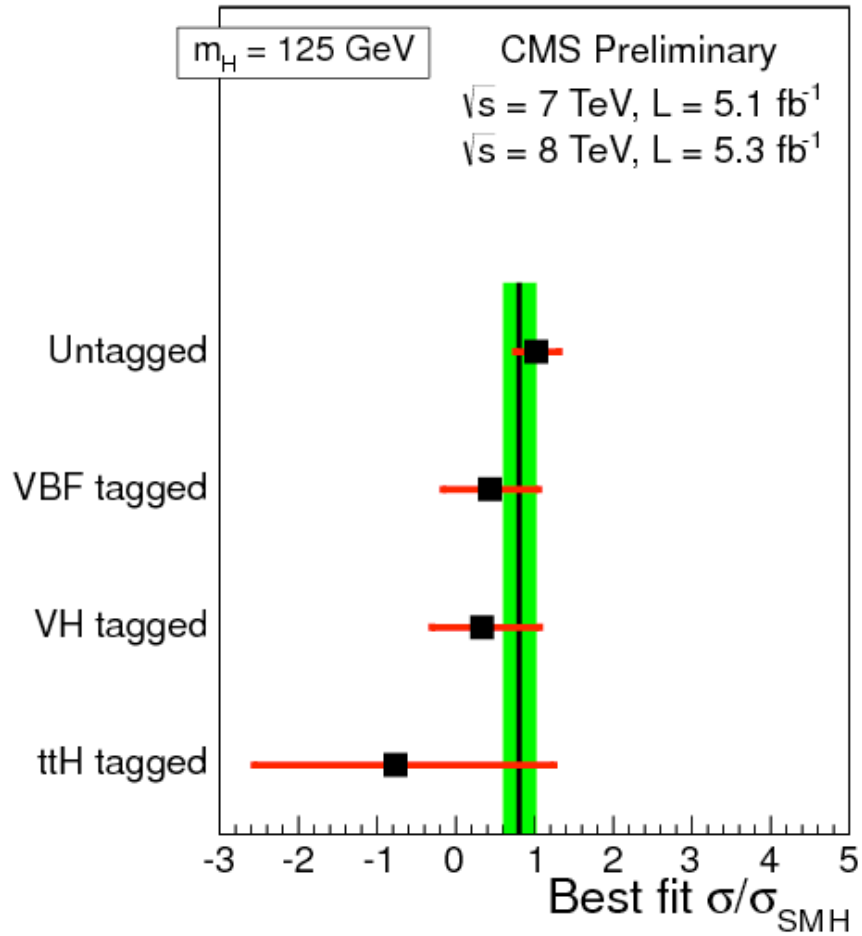


At M_H=125.3 GeV, best fit signal strength $\sigma/\sigma_{SM} = 0.8 \pm 0.22$

Compatibility With SM Higgs boson Hypothesis

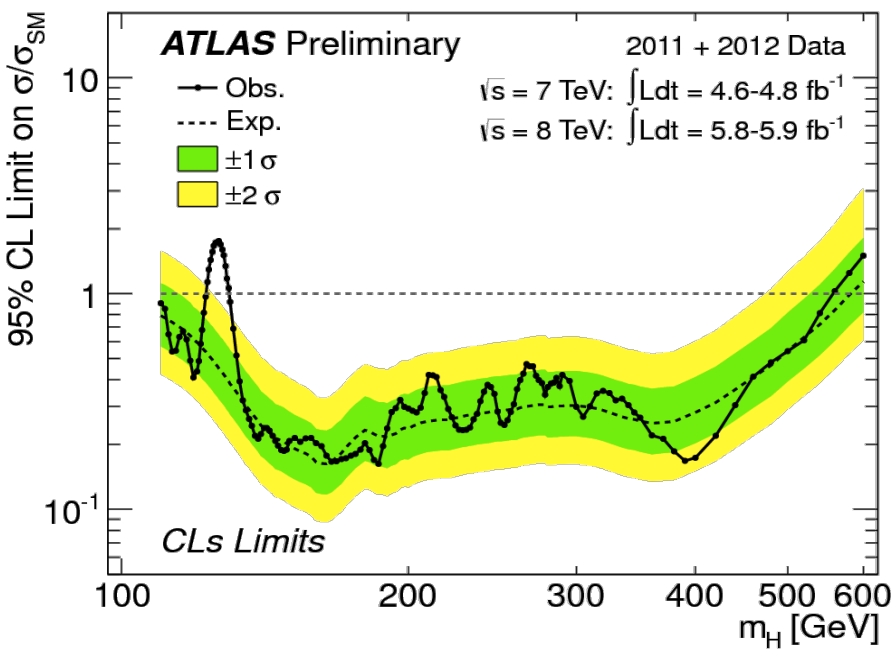
- By search modes & by a signature enhancing a specific production mechanism

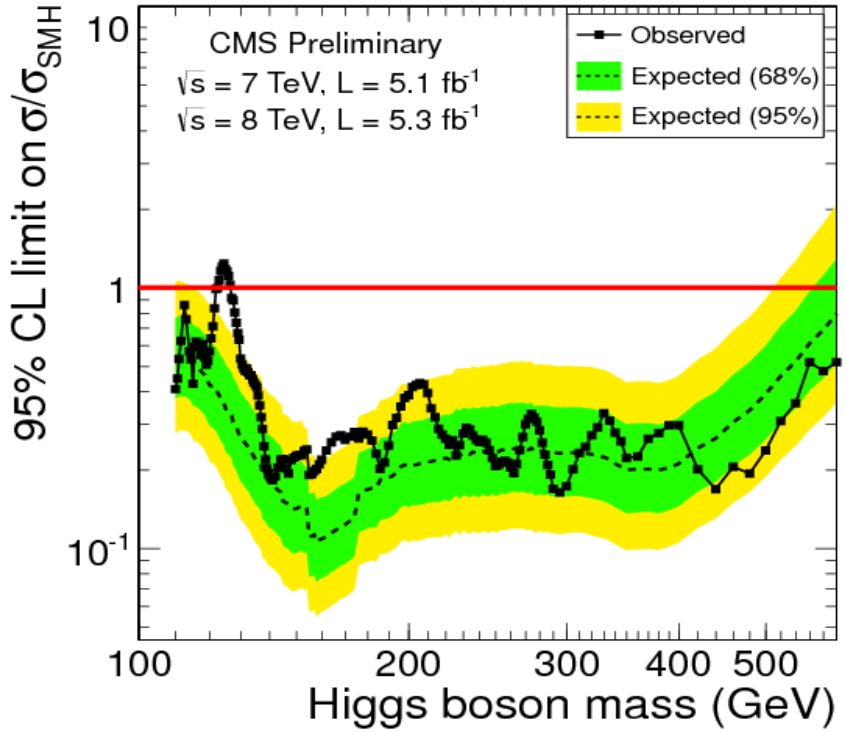




Summary & Conclusion

Search For The SM Higgs Boson





ATLAS

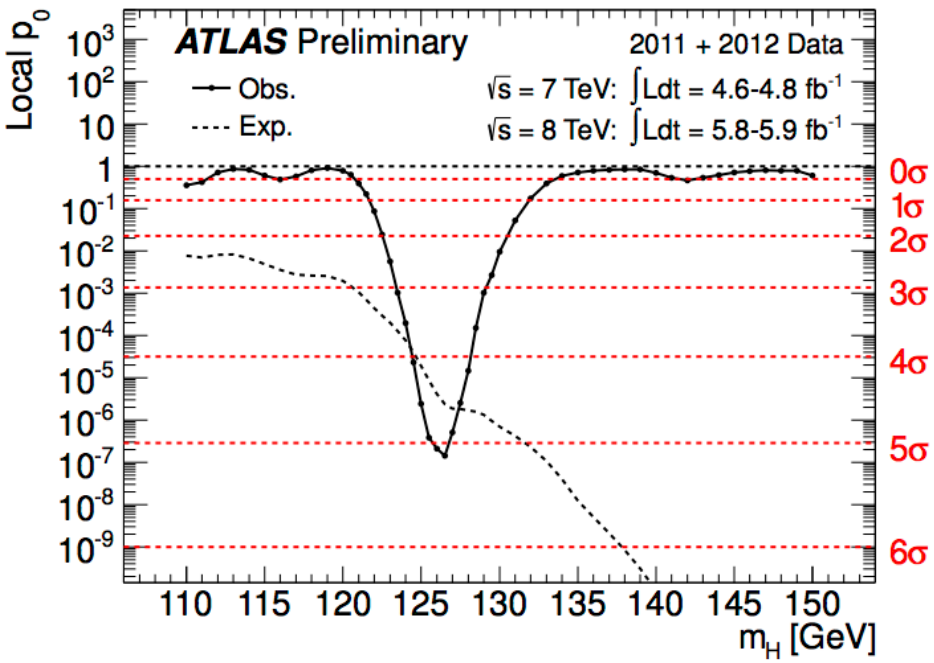
95% CL Exclusion: $110 < M_H < 122.6$, $127.9 < M_H < 558$ GeV

CMS

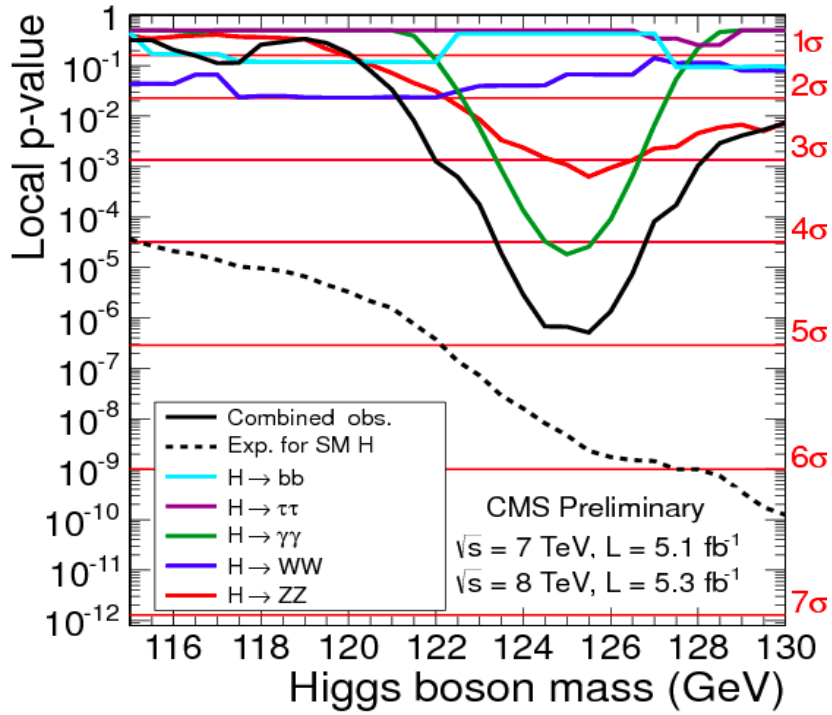
95% CL Exclusion: $110 < M_H < 122.5$, $127 < M_H < 600$ GeV

Observation Of A New Boson

- ATLAS & CMS observe a narrow state near M = 125 GeV with a significance of about 5σ

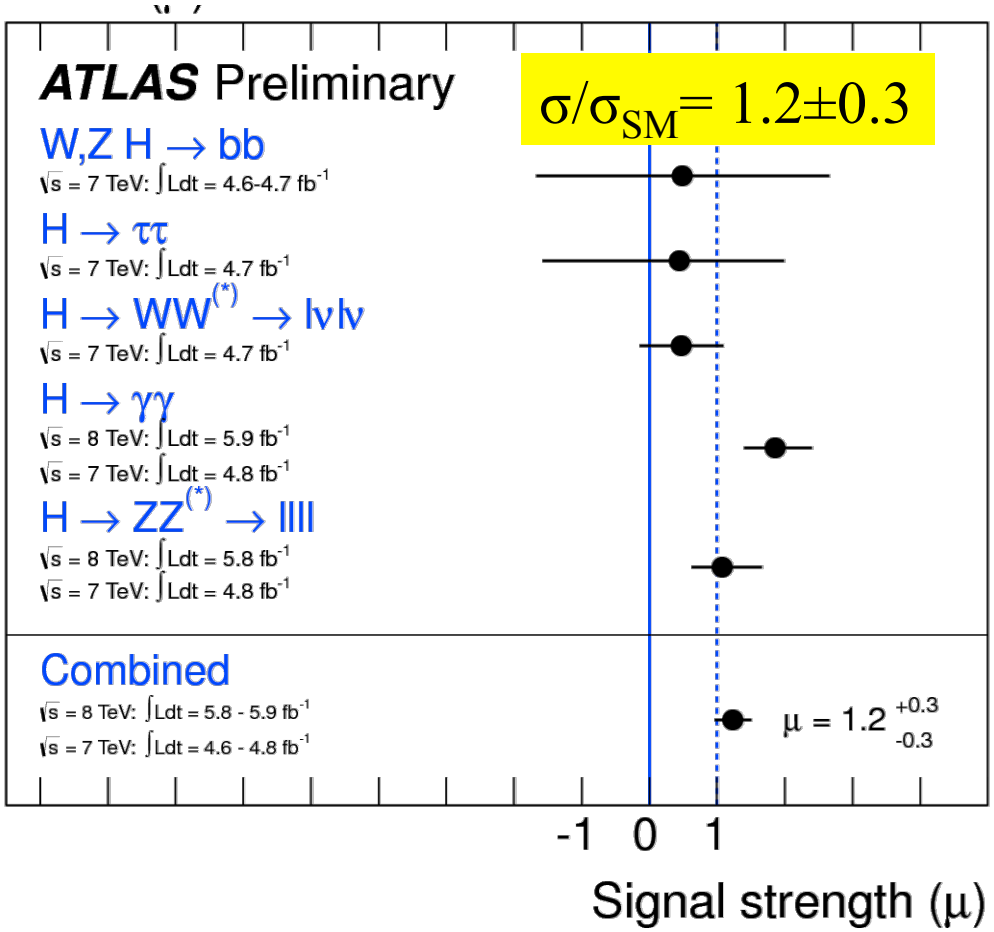


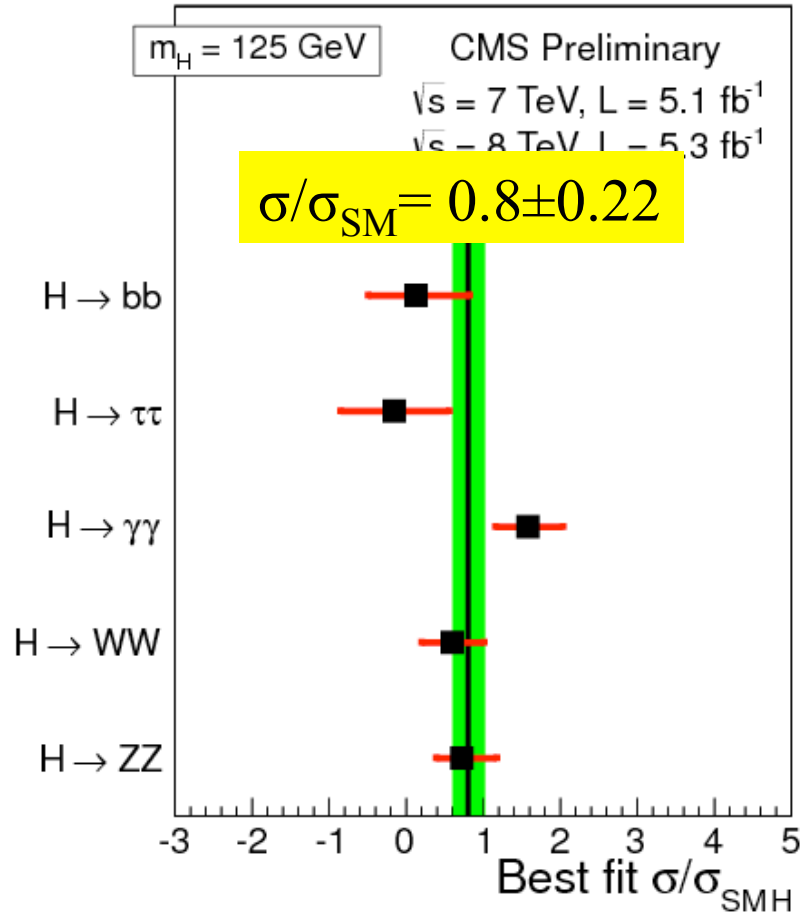
5σ at M_X = 126.5 GeV



4.9σ at M_X = 125.3 GeV

Best Fit Signal Strengths





Consistent with the SM Higgs boson although both experiments see a higher H→ γγ rate (μ_{ATLAS} = 1.9±0.5 , μ_{CMS} = 1.6±0.4)

Landmark Achievement In Particle Physics !

Next Steps

- Establishing the new particle is just the first part of a long journey
- LHC continues its excellent performance, ATLAS & CMS hope to accumulate another 20 fb^{-1} by end of 2012
  - ➔ total 40 fb^{-1} data
- Continue to investigate the observed resonance in a variety of channels
  - Precise measurement of the boson mass
  - Measure coupling to Vector bosons and fermions
  - Measure angular distribution in WW/ZZ modes to determine the spin and parity of the observed boson
- Exciting times ahead !

CMS Searches

H decay	H prod	Analyses Exclusive final states	No. of channels	m_H range (GeV)	m_H resolution	Lumi (fb^{-1}) 7 TeV	8 TeV
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	110–150	1-2%	5.1	5.3
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$ (low or high m_{jj} for 8 TeV)	1 or 2	110–150	1-2%	5.1	5.3
bb	VH-tag	($\nu\nu$, ee, $\mu\mu$, $e\nu$, $\mu\nu$ with 2 b-jets)$\otimes$ (low or high p_T^V)	10	110–135	10%	5.0	5.1
	ttH-tag	(ℓ with 4,5,$\geq$6 jets) $\otimes$ (3,$\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-tagged jets)	9	110–140		5.0	-
$H \to \tau\tau$	0/1-jets	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$)$\times$ (low or high $p_T^{\tau\tau}$) $\times$ (0 or 1 jets)	16	110–145	20%	4.9	5.1
	VBF-tag	($e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$) + $(jj)_{VBF}$	4	110–145	20%	4.9	5.1
	ZH-tag	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	110–160		5.0	-
	WH-tag	$\tau_h ee$, $\tau_h\mu\mu$, $\tau_h e\mu$	3	110–140		4.9	-
$WW \to \ell\nu qq$	untagged	($e\nu$, $\mu\nu$)$\otimes$($(jj)_W$ with 0 or 1 jets)	4	170–600		5.0	5.1
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\otimes$ (0 or 1 jets)	4	110–600	20%	4.9	5.1
$WW \to \ell\nu\ell\nu$	VBF-tag	$\ell\nu\ell\nu + (jj)_{VBF}$ (DF or SF dileptons for 8 TeV)	1 or 2	110–600	20%	4.9	5.1
$WW \to \ell\nu\ell\nu$	WH-tag	$3\ell 3\nu$	1	110–200		4.9	-
$WW \to \ell\nu\ell\nu$	VH-tag	$\ell\nu\ell\nu + (jj)_V$ (DF or SF dileptons)	2	118–190		4.9	-
$ZZ \to 4\ell$	inclusive	$4e$, 4μ, $2e2\mu$	3	110–600	1-2%	5.0	5.3
$ZZ \to 2\ell 2\tau$	inclusive	(ee, $\mu\mu$) $\times$ ($\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, $e\mu$)	8	200–600	10-15%	5.0	5.3
$ZZ \to 2\ell 2q$	inclusive	(ee, $\mu\mu$)$\times$($(jj)_Z$ with 0, 1, 2 b-tags)	6	130–164 200–600	3%	4.9	-
$ZZ \to 2\ell 2\nu$	untagged	((ee, $\mu\mu$) with MET) $\otimes$ (0 or 1 or 2 non-VBF jets)	6	200–600	7%	4.9	5.1
$ZZ \to 2\ell 2\nu$	VBF-tag	(ee, $\mu\mu$) with MET and $(jj)_{VBF}$	2	200–600	7%	4.9	5.1

Most analyses updated with 8 TeV data

References:https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Angular Analysis In H → ZZ → 4l (CMS)

- H → ZZ → 4l Decay kinematic fully described by 5 angles and the 2 Z masses
  - discriminates spin 0 particle from background
  - MELA: matrix element likelihood analysis

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

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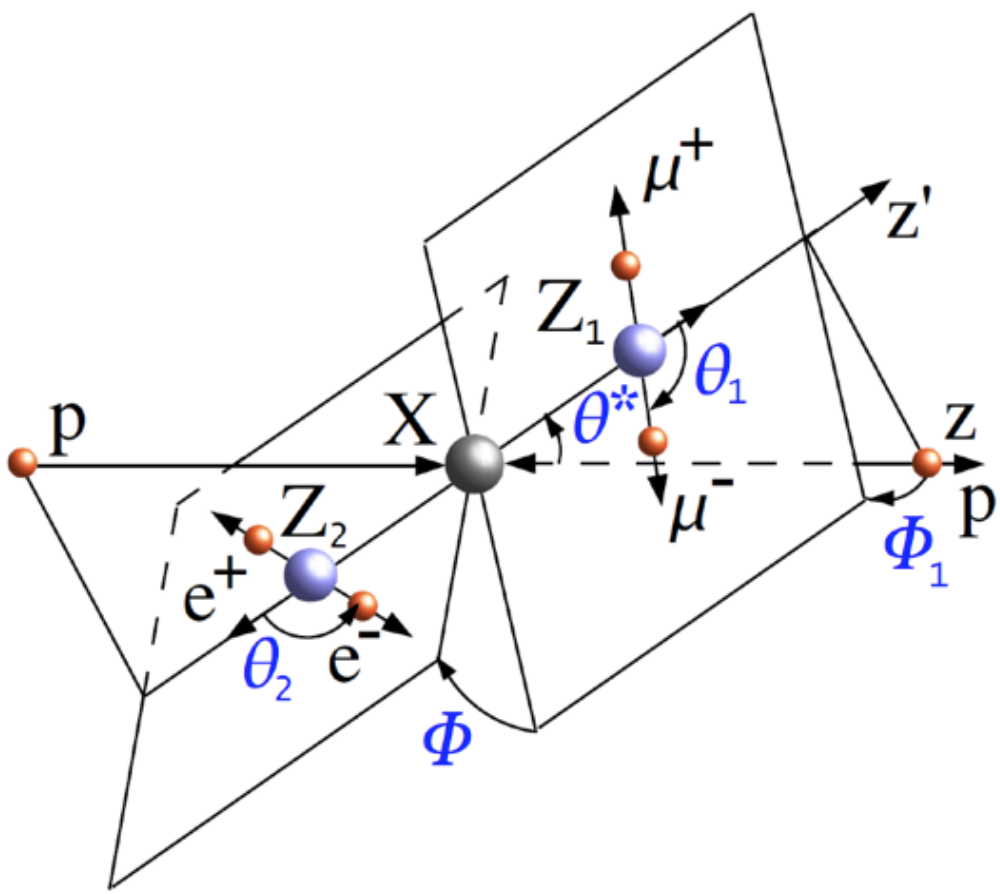
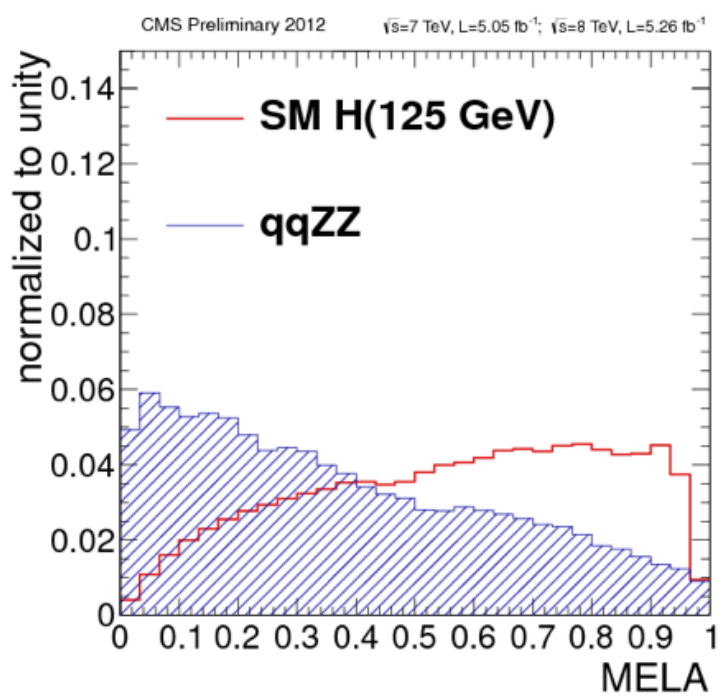


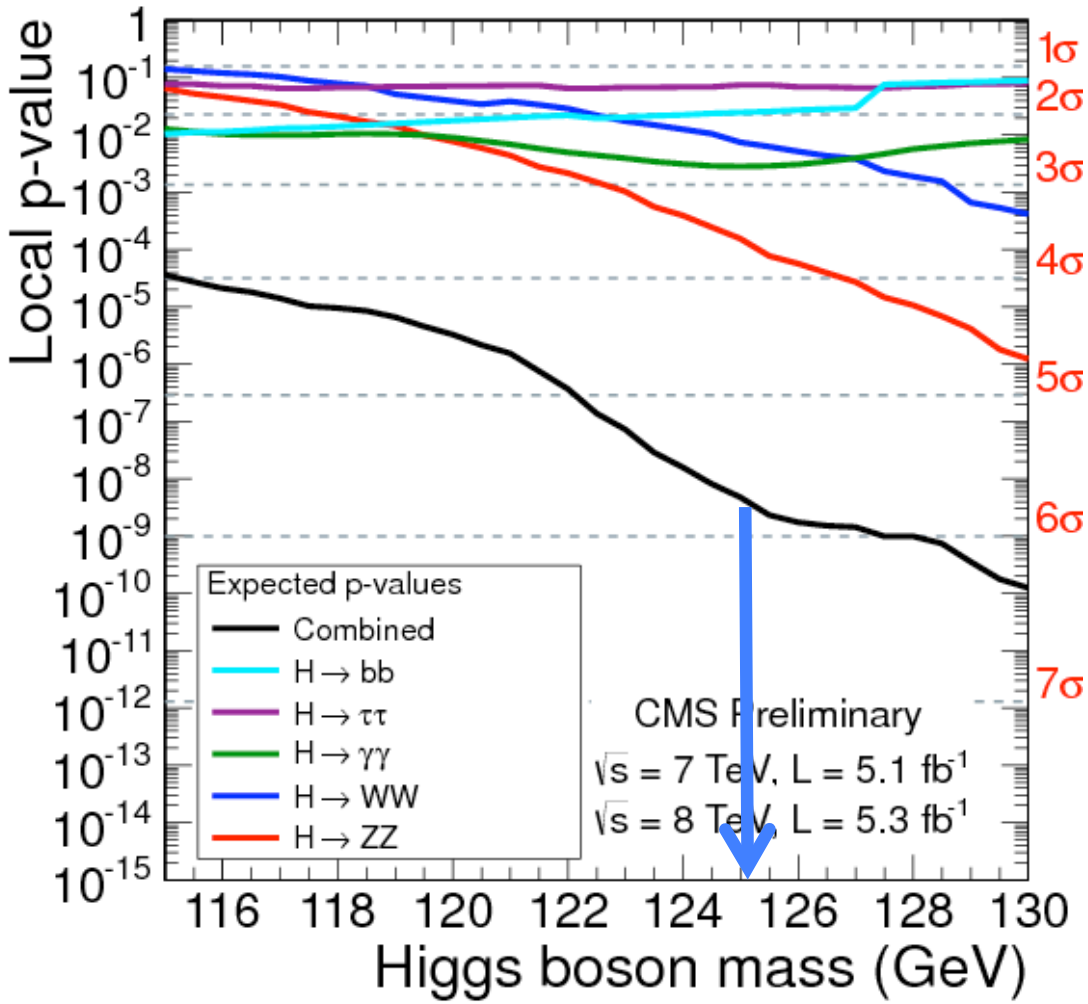


ATLAS Searches

Higgs Decay	Subsequent Decay	Sub-Channels	m_H Range [GeV]	$\int L\,dt$ [fb^{-1}]
		2011 $\sqrt{s}$ =7 TeV		
$H \to \gamma\gamma$	–	9 sub-channels $\{p_{T_t} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jets}\}$	110–150	4.8
$H \to ZZ^{(*)}$	$\ell\ell\ell'\ell'$	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	4.8
	$\ell\ell\nu\bar{\nu}$	$\{ee, \mu\mu\} \otimes \{\text{low, high pile-up}\}$	200–280–600	4.7
	$\ell\ell q\bar{q}$	$\{b\text{-tagged, untagged}\}$	200–300–600	4.7
$H \to WW^{(*)}$	$\ell\nu\ell\nu$	$\{ee, e\mu, \mu\mu\} \otimes \{\text{0-jets, 1-jet, 2-jets}\} \otimes \{\text{low, high pile-up}\}$	110–200–300–600	4.7
	$\ell\nu q\bar{q}'$	$\{e, \mu\} \otimes \{\text{0-jets, 1-jet, 2-jets}\}$	300–600	4.7
$H \to \tau^+\tau^-$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\{e\mu\} \otimes \{\text{0-jets}\} \oplus \{\ell\ell\} \otimes \{\text{1-jet, 2-jets}, VH\}$	110–150	4.7
	$\tau_{\text{lep}}\tau_{\text{had}}$	$\{e, \mu\} \otimes \{\text{0-jets}\} \otimes \{E_T^{\text{miss}} < 20\text{ GeV}, E_T^{\text{miss}} \geq 20\text{ GeV}\}$ $\oplus \{e, \mu\} \otimes \{\text{1-jet}\} \oplus \{\ell\} \otimes \{\text{2-jets}\}$	110–150	4.7
	$\tau_{\text{had}}\tau_{\text{had}}$	$\{\text{1-jet}\}$	110–150	4.7
$VH \to b\bar{b}$	$Z \to \nu\bar{\nu}$	$E_T^{\text{miss}} \in \{120-160, 160-200, \geq 200\text{ GeV}\}$	110-130	4.6
	$W \to \ell\nu$	$p_T^W \in \{< 50, 50-100, 100-200, \geq 200\text{ GeV}\}$	110-130	4.7
	$Z \to \ell\ell$	$p_T^Z \in \{< 50, 50-100, 100-200, \geq 200\text{ GeV}\}$	110-130	4.7
		2012 $\sqrt{s}$ =8 TeV		
$H \to \gamma\gamma$	–	9 sub-channels $\{p_{T_t} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{\text{2-jets}\}$	110–150	5.9
$H \to ZZ^{(*)}$	$\ell\ell\ell'\ell'$	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	110–600	5.8

July 17th, H→ WW→ (lν)(lν) mode updated with 5.8 fb^{-1} 8 TeV data

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

Discovery Expectation with ≈10 fb^{-1} Data

Median expected *p*-value for observing an excess at mass m_H in assumption that the SM Higgs boson with that mass exists