Higgs Searches

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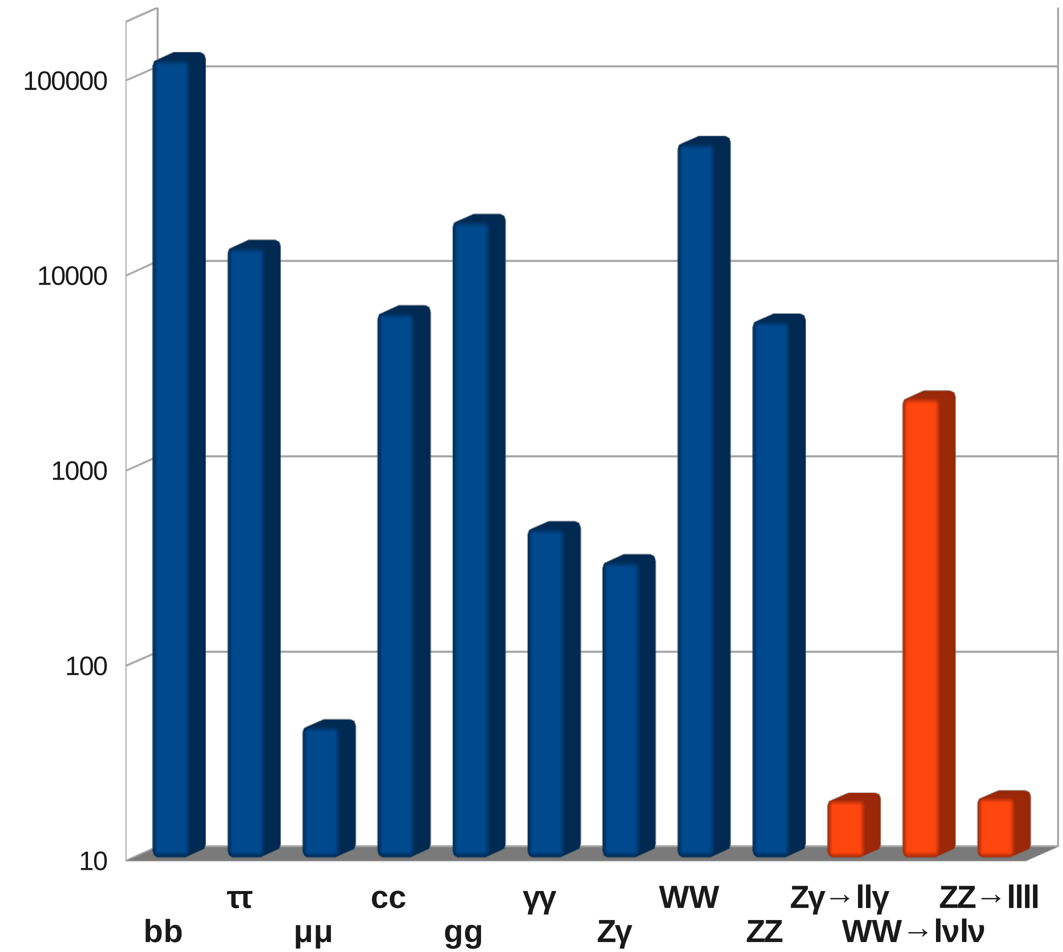
St Andrews
25th August 2012

- **H → γγ**
- **H → WW**
- **H → ττ**
- **H → bb**

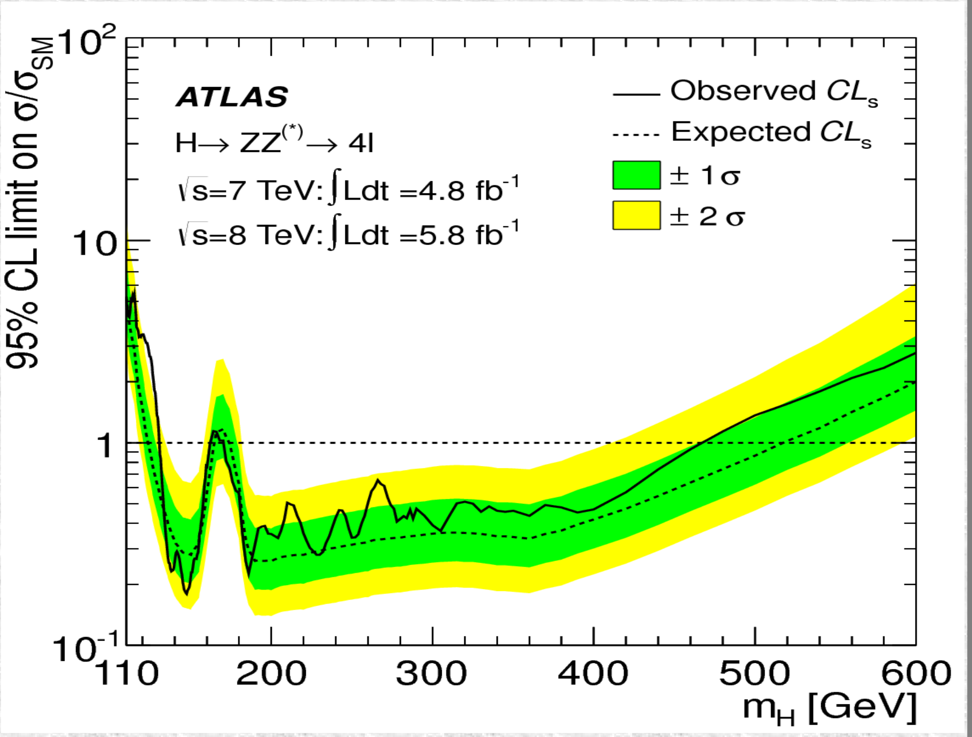
Rates by channel at 125GeV

- Data to June 2012
- From 10s to 100000 events per channel
  - Easy!
- But total pp events: $8x10^{14}$
- 20 Higgs to llll events
- Needs incredible background rejection



Meaning of limit plot

- I should have explained:
- X axis is m_H, not (m_{llll})
- Y axis is μ from Glenn's slide
- (m_H,μ) defines a theory
- $(m_H,1)$ is the SM
- If observed line is a 0.7 then an SM-like model with 70% rate or more is excluded @ 95% CL
  - If below 1 SM is ruled out for that m_H
- If outside green/yellow thats interesting too.



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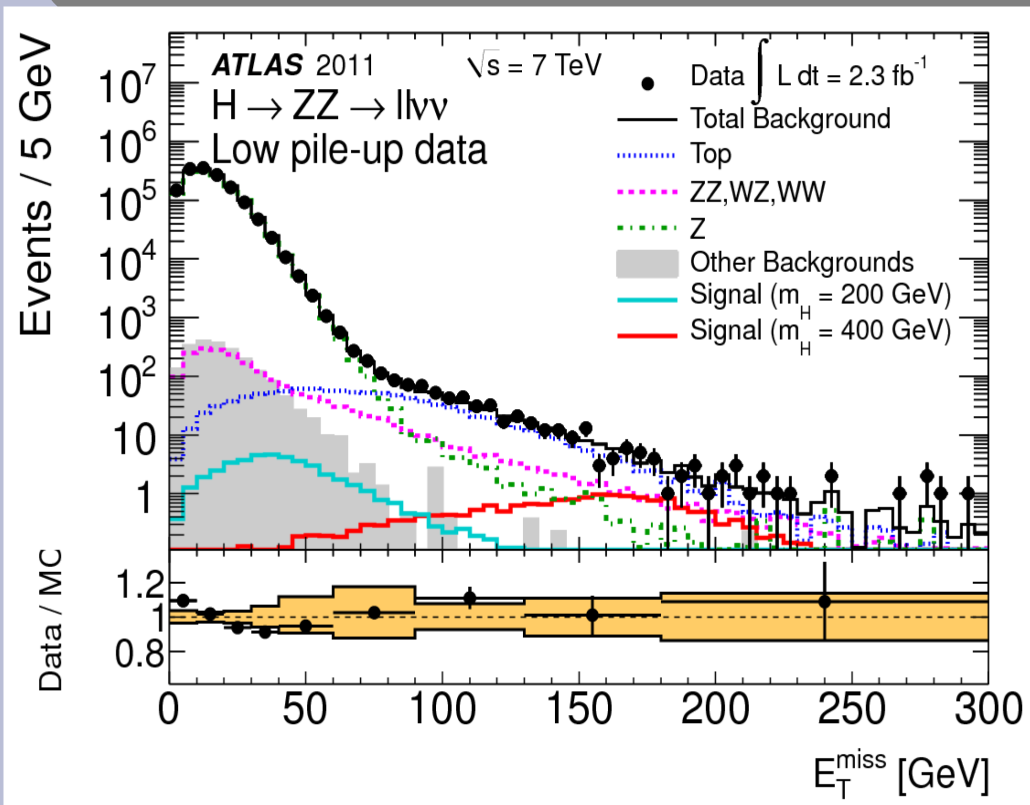
ZZ→llνν

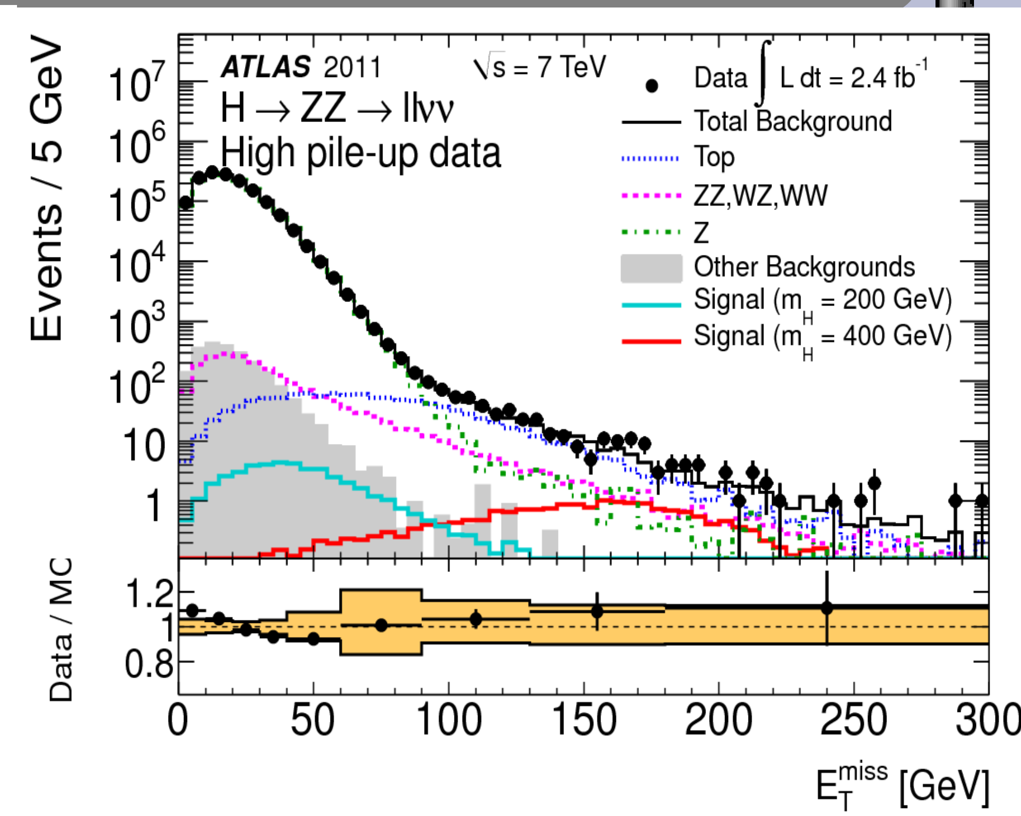
- Fully leptonic, but rate 6xllll
- However mass reconstruction is not possible
  - Two missing neutrinos means too much is lost
  - 4-vector of the Z→ll, p_T of Z→νν available

$$m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\,\mathrm{miss}}|^2}\right]^2 - \left[\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\mathrm{miss}}\right]^2$$

- Works best for m_H>300
  - Higgs is wide, so mass reconstruction less useful
  - Zs are boosted, so Z→νν has measurable p_T^{miss}
- E_t^{miss} needed for background rejection and signal

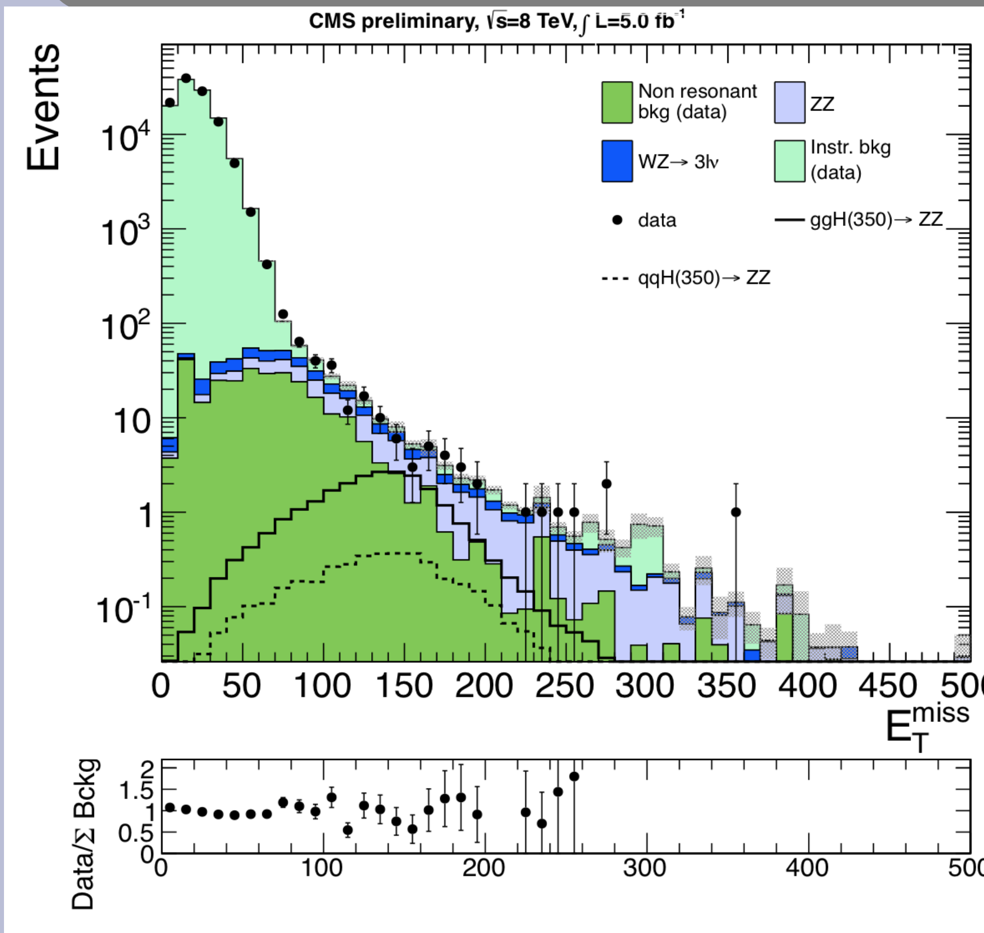
ZZ→llνν missing E_T

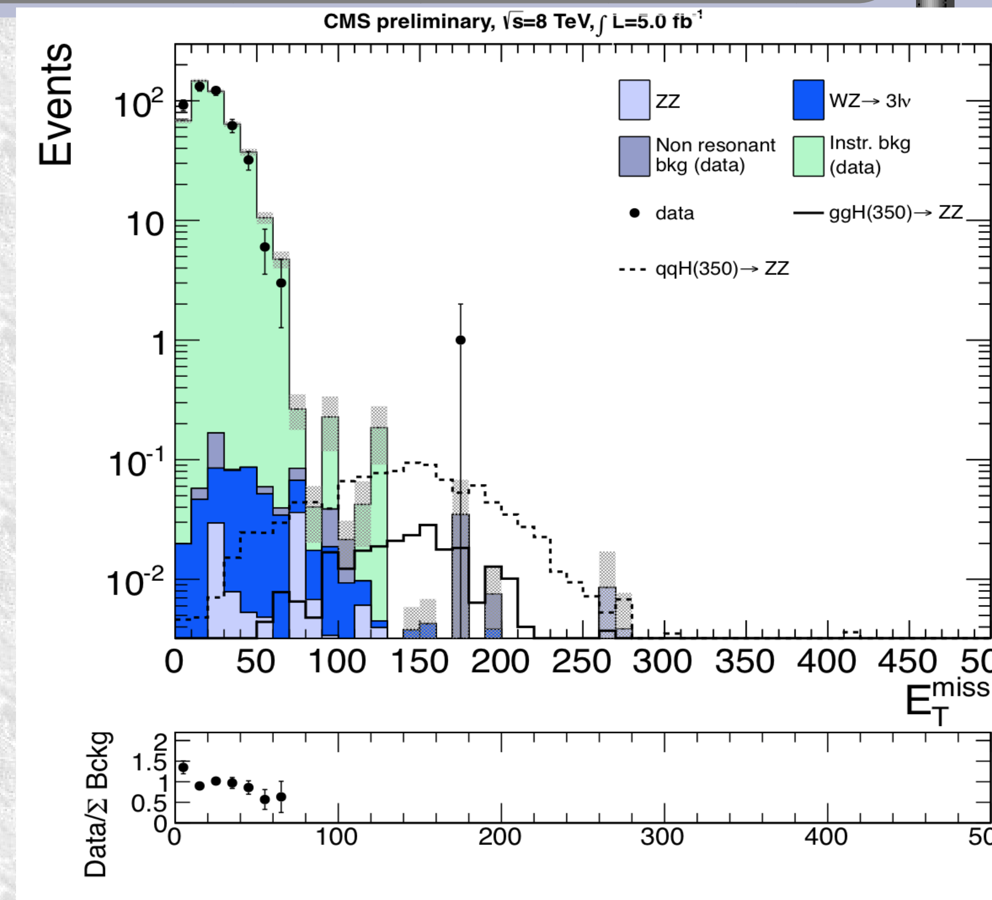




- 2011 ATLAS found pileup was hurting
  - Left is low pileup (~6)
  - Right is ~15
- Signal unchanged, but Z background rises

VBH H to ZZ to llνν

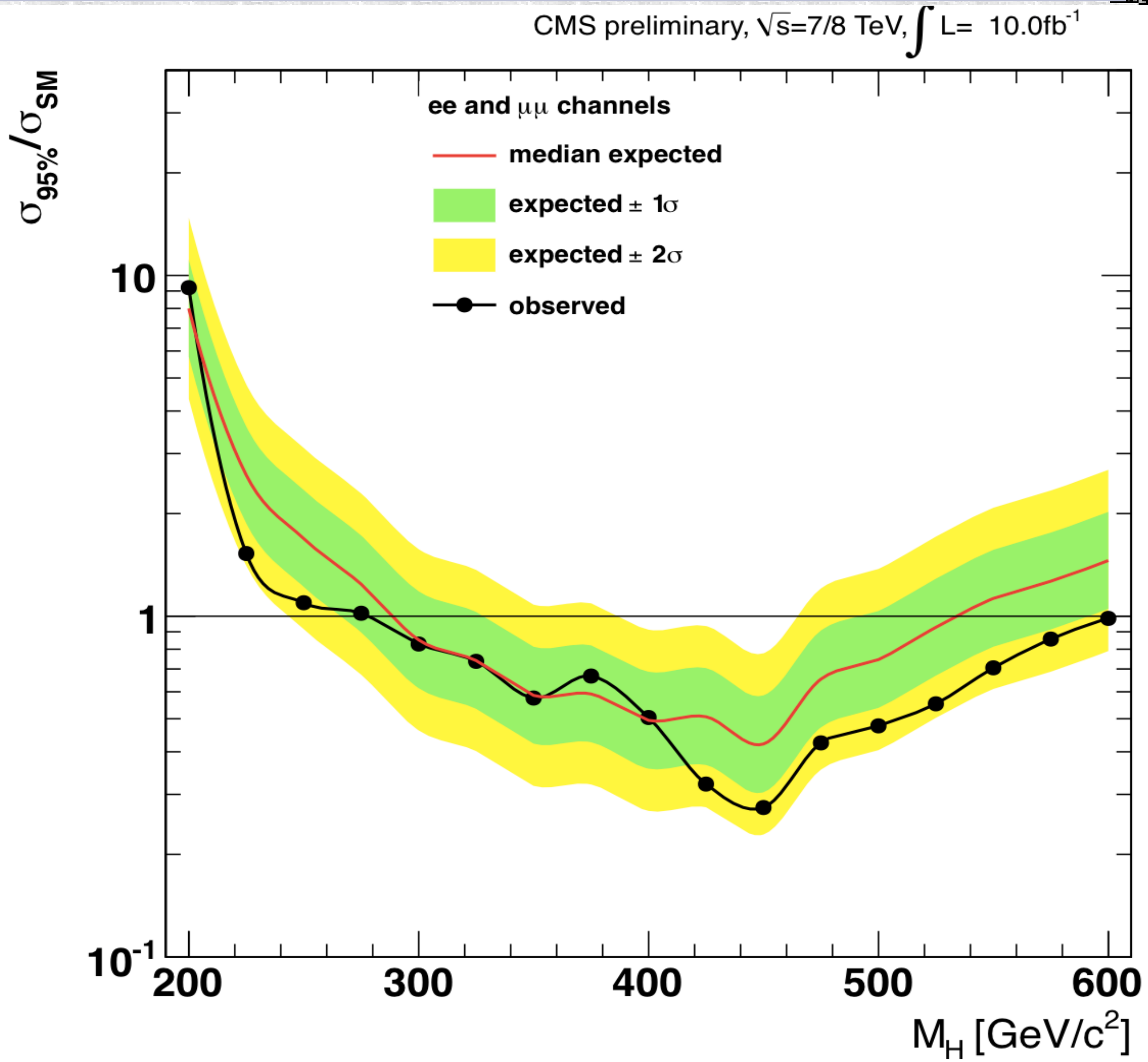




- CMS used VBF production to reduce background
  - Tag the forward jets...increase s/b 10x
- Gives much cleaner signal...but low rate

- No ATLAS 2012 results
- CMS exclude 275 to 600 using this channel alone

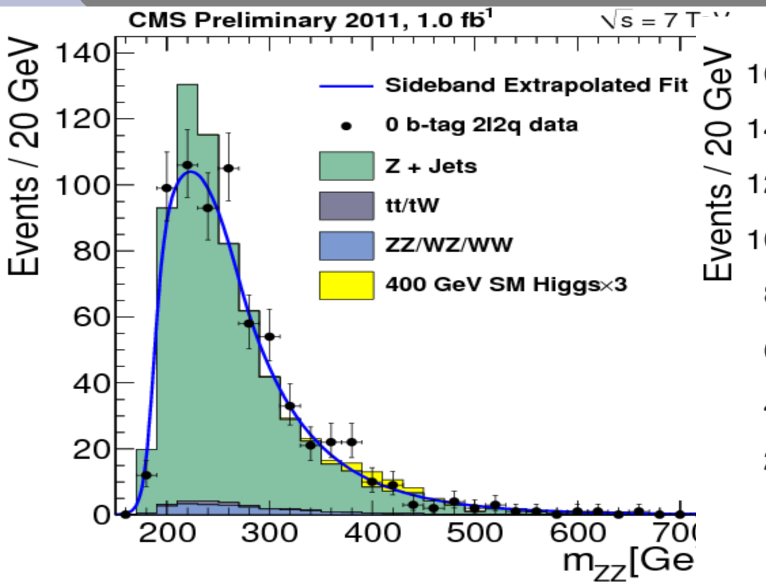
- Pileup can be fought!

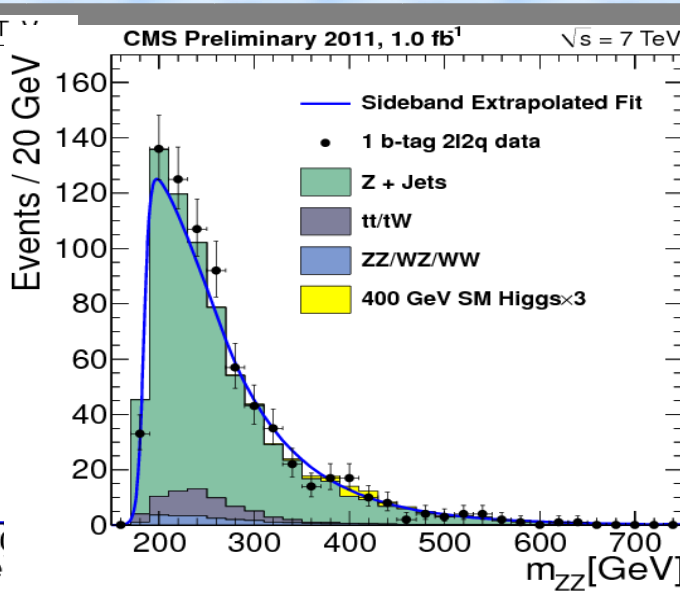


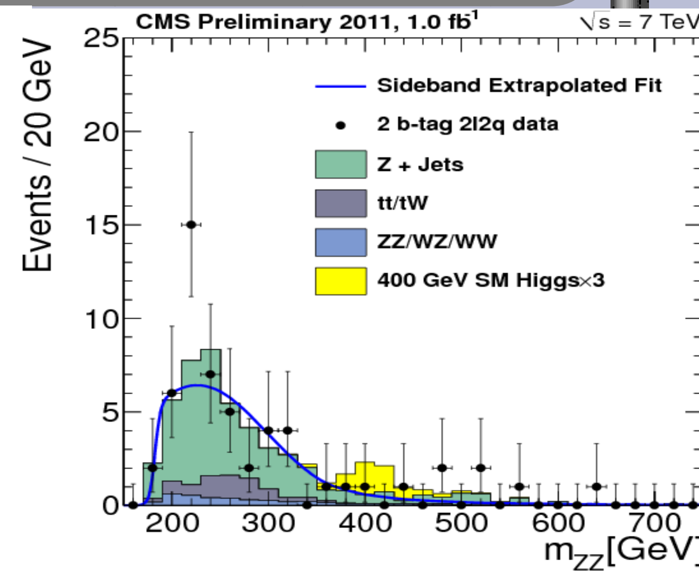
ZZ→llqq

- Highest rate for a ZZ process
  - Leptons provide 'easy' trigger
  - Need both Zs on shell so m_H over 200GeV
    - Work going on to bring this to low mass region
- Background reduction
  - Double constraint reduces tt contamination
  - Further reduced by MET veto
  - Z plus jets background dominant
- Use 2/3 subchannels:
  - Z to light quarks
    - CMS use quark v gluon tagging to enhance signal
  - Z to b quarks
- No 2012 results here yet

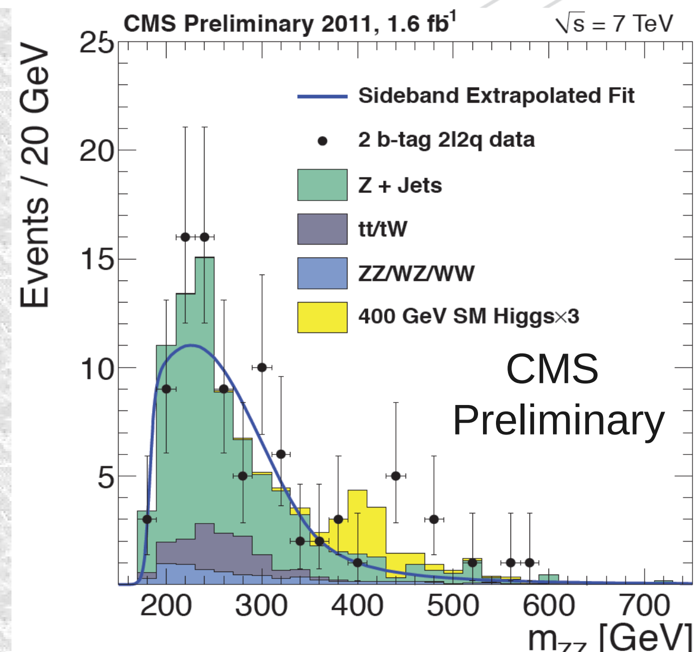
ZZ → llqq



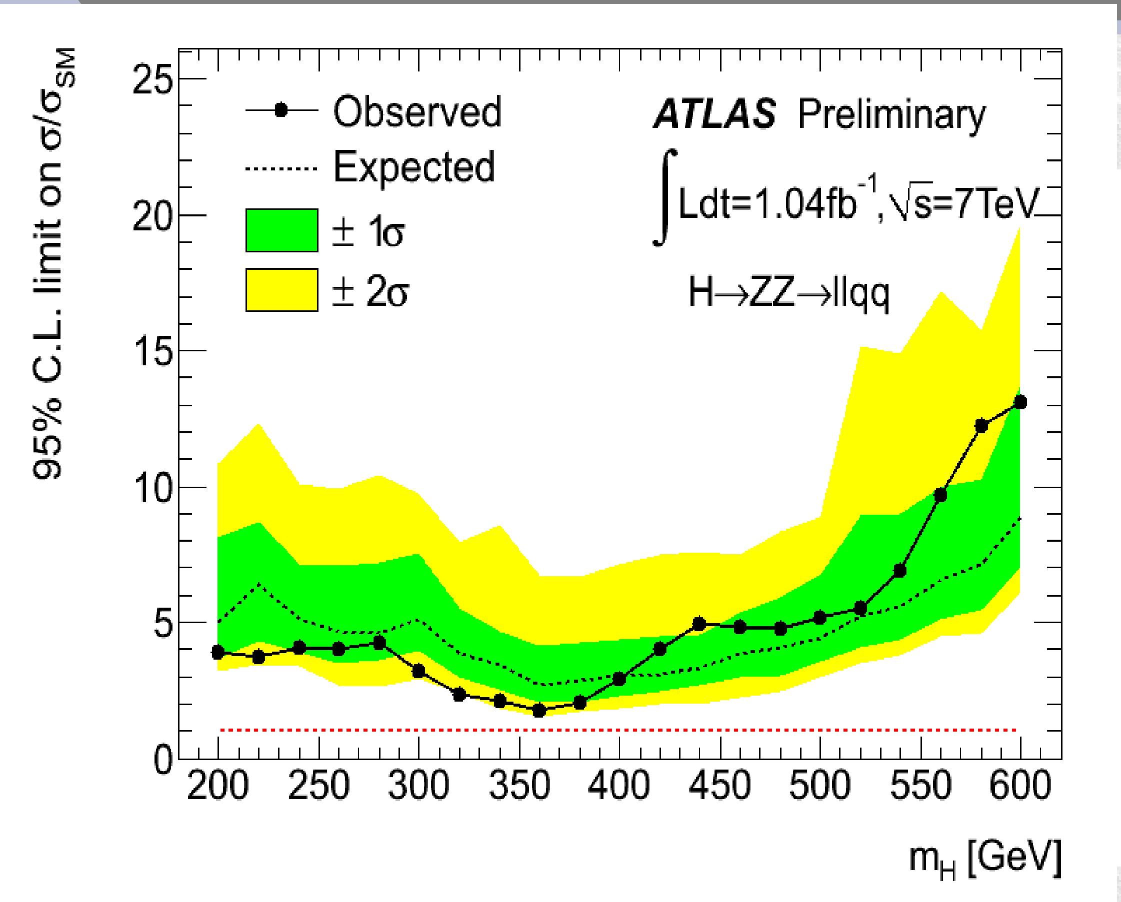


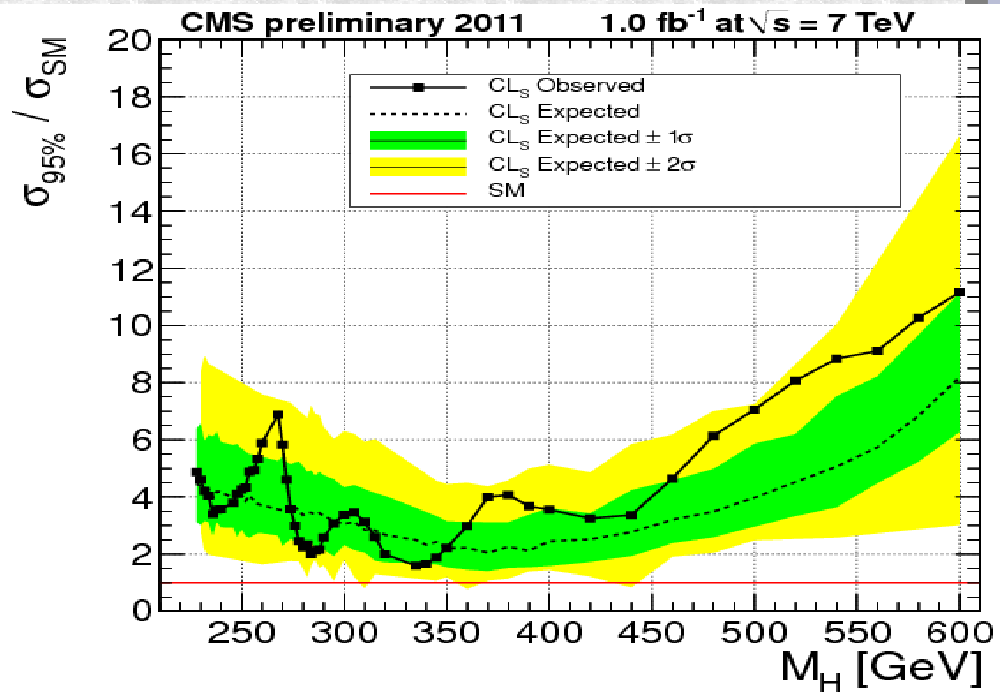


- Most backgrounds from data sidebands
  - Eg tt from $m_{ll}<m_Z-15$ or $m_{ll}>m_Z+15$
  - Z+jets use $m_{qq}<m_Z-15$ or $m_{qq}>m_Z+15$
- Small EW from simulation



llqq





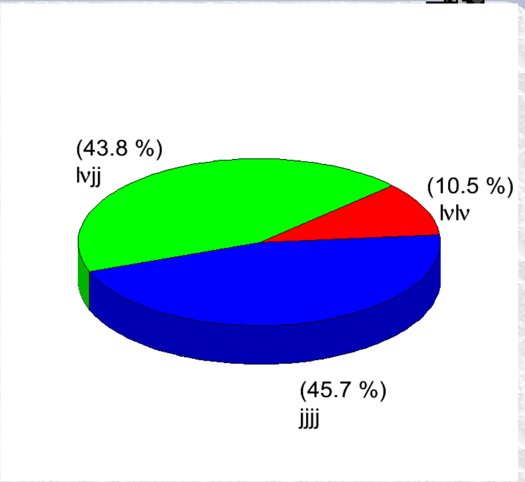
- CMS sensitivity 2xSM, ATLAS 3xSM at 350-400
- Fluctuations never up to 2σ

H to WW

- Dominant decay mode in m_H>130 GeV
- lνqq
  - Highest rate final state
  - Only one neutrino allows mass reconstruction
    - But only if both W's on shell
  - Ferocious W+jets background
- lνlν
  - All leptonic mode allows suppression of background
    - Even when one W is off mass shell
  - Good rate
  - Non-resonant WW and tt are major backgrounds
  -
  - But ultimately it is a counting experiment; delicate

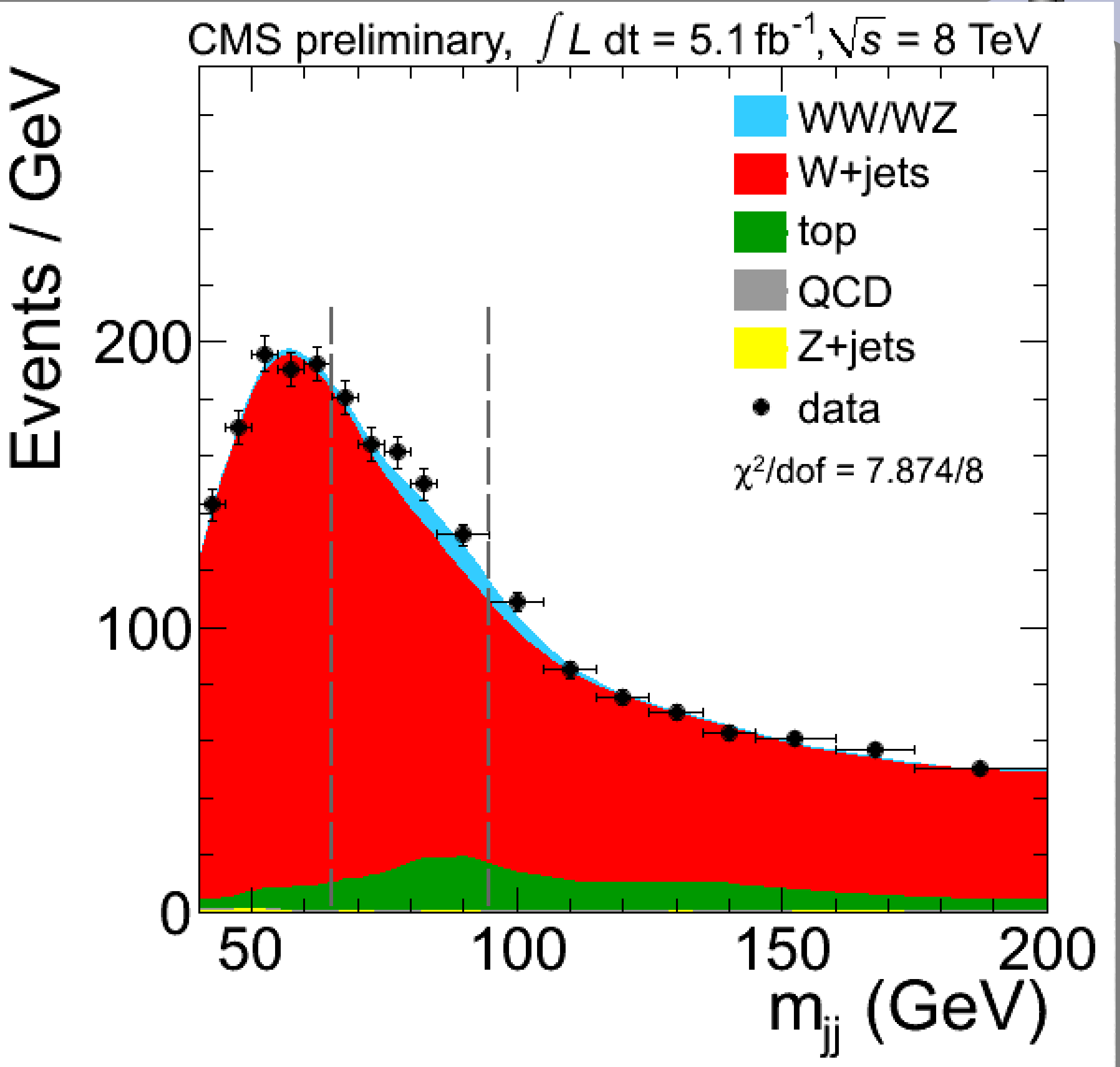
WW → lνqq

- Largest Higgs BR for high mass
- Presence of charged lepton gives QCD rejection
- But, like in $t\bar{t}$, semileptonic mode allows mass reconstruction
  - Missing p_T and m_W are 3 constraints
  - Obtain p_Z^ν from roots of quadratic
    - Only take real solutions
    - Take lower p_z option
- Suffers from LARGE background from W+jets
  - But smooth background
  - Signal is a bump
  - Analysis is relatively straightforward

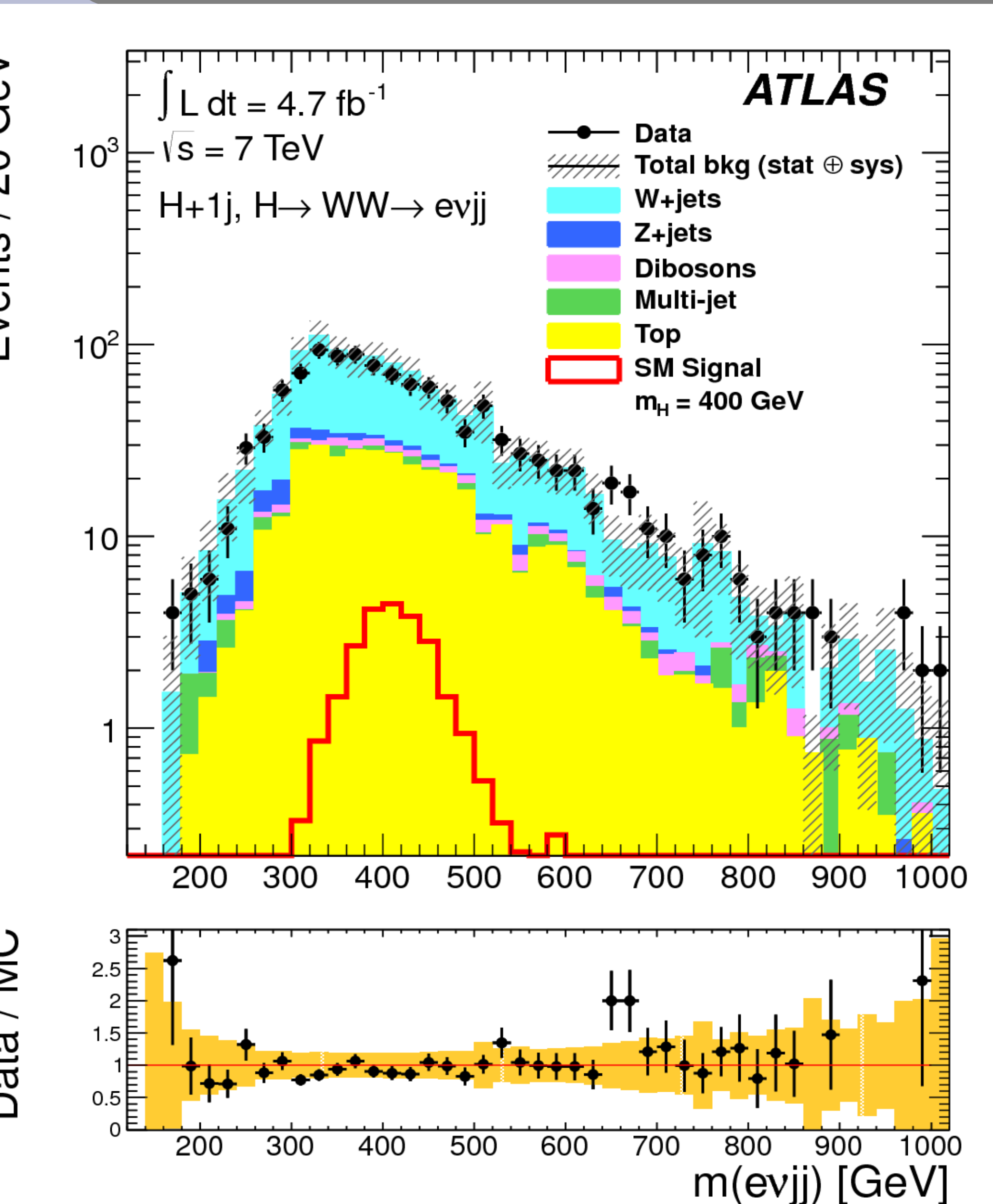


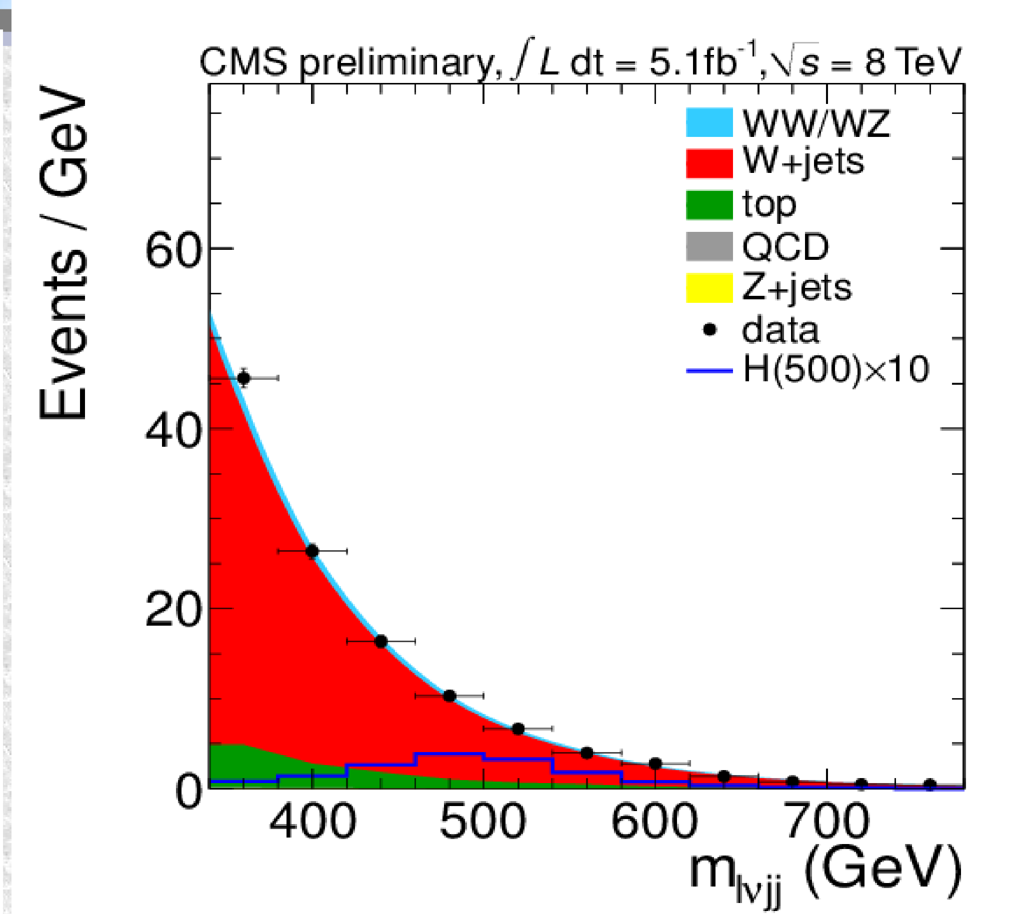
Select hadronic W

- CMS tune cuts as a function of m_H
- Boosted jet pair shows signs of W peak
- Cuts select relevant region



WW → lνqq

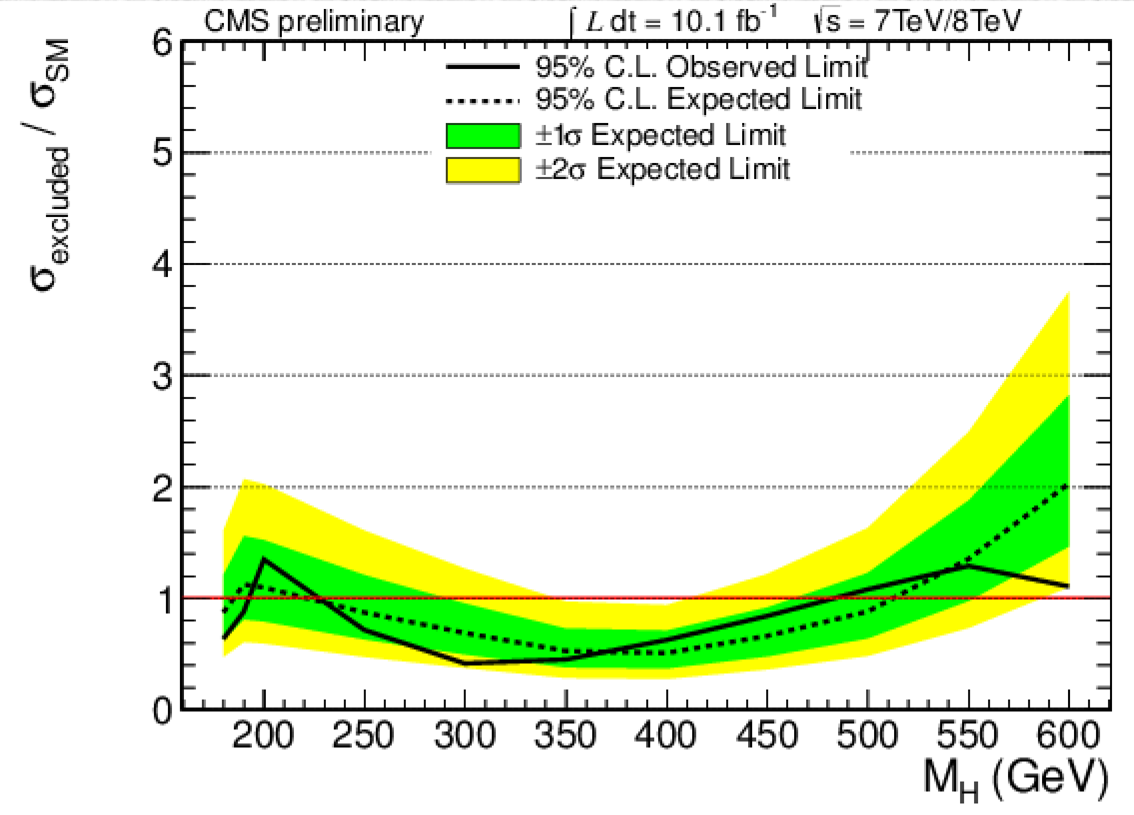




- Fit to smooth background
- Looking for a bump

WW → lνqq

- CMS use 2012 data
  - ATLAS only 2011
- Exclude 230 to 480 GeV Higgs using this mode
- No sign of excess



High Mass Higgs status

- Is it really dead?
  - llll, (llqq), llνν, lνqq and lνlν all exclude it
  - For some mass region
  - For 1 or 2 experiments
- The combination of these is very strong
  - But only for SM like strength
- If we already found 'the' Higgs
  - Then a second must have reduced coupling
  - So searching for a scalar high-mass resonances remains high priority
  - But should we assume SM width?

WW → lνlν

- The most sensitive channel for $130<m_H<200$
  - Still one of the 3 most important at 125GeV
  - But poor mass information due to neutrinos
- Good trigger, reasonable rate
  - Largest background is non-resonant WW
    - Also top when looking at WW+1 jet
  - Backgrounds measured from control regions
- Request two leptons
  - 15,25 GeV (ATLAS) 10,20GeV (CMS)
  - ATLAS only uses e-μ pairs in 2012 (ee/μμ have more bkgd.)
- Require missing E_T (E_t^{rel}) and $p_T(ll)$ for WW
- Select signal area with Δφ and m_{ll} selections
  - CMS using cut-based and multivariate
  - ATLAS prefers cut-based.
- Many backgrounds need estimation from data - tricky

$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$

- W^+W^- to $l^+\upsilon l^-\bar{\upsilon}$ has assorted backgrounds:

Background	Reduced with	Estimated using
D-Y (l+l-) production (inc. $\tau\tau \rightarrow e\mu$)	Missing E_{Tr}^{el}	ABCD method
WW non-resonant	$d\Phi_{ll}$, M_T cuts	Rate in control region
$t\bar{t}$ and single top	B tag, jet binning	Rate in control region
W+jets	Isolation, IP cuts	Loose lepton fake rate
QCD	Same as above	As above

H → WW → lυlυ

- Lepton thresholds

	e-e	μ-μ	e-μ
pT leading, GeV	25	25	25
pT subleading, GeV:ATLAS	20	15	e:15, μ:20
pT subleading, GeV:CMS	10	10	10
ETmissrel	40	40	25

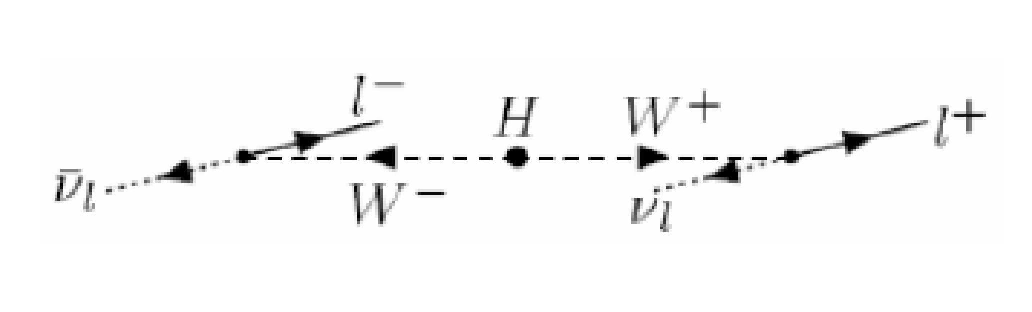
- MET

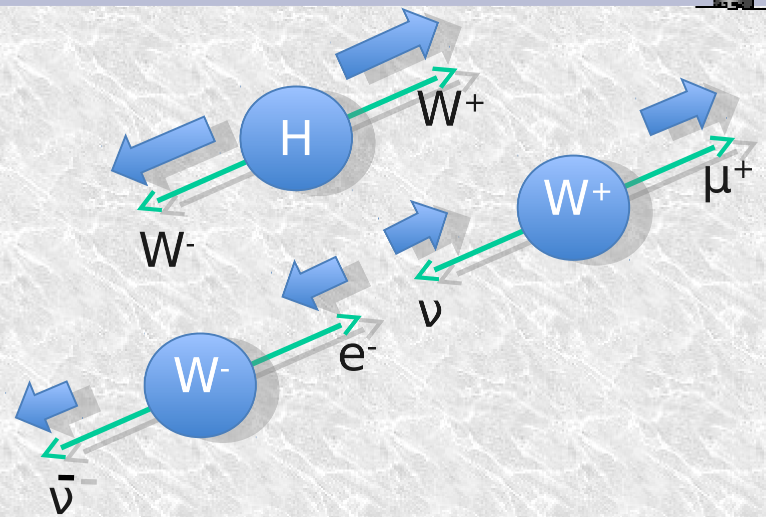
$$E_{\mathrm{T,rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} \cdot \sin\Delta\phi & \text{if } \Delta\phi < \pi/2 \\ & \Delta\phi = \min(\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \ell),\ \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j)) \end{cases}$$

- M_T

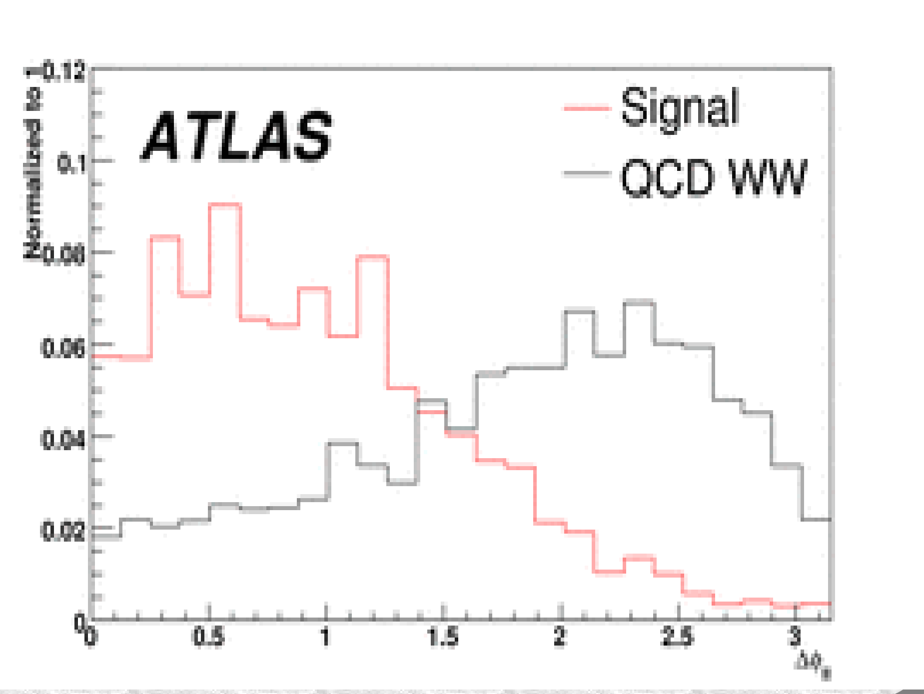
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2},$$

Spin correlation in H→WW(*)





- Spin 0 nature of Higgs differentiates from QCD WW
  - WW's spin opposite
  - Therefore decays correlated
- Cut on Δφ to select signal
- Normalise WW background from rejected region



Spin correlation issue

- Background is mostly qq→WW
  - But gg→WW also contributes
  - With different spin structure
  - Enhanced by cuts – but only 3%
- Or is it?
  - qq is NLO
  - gg is LO
  - K factor?
- We have no way to measure this

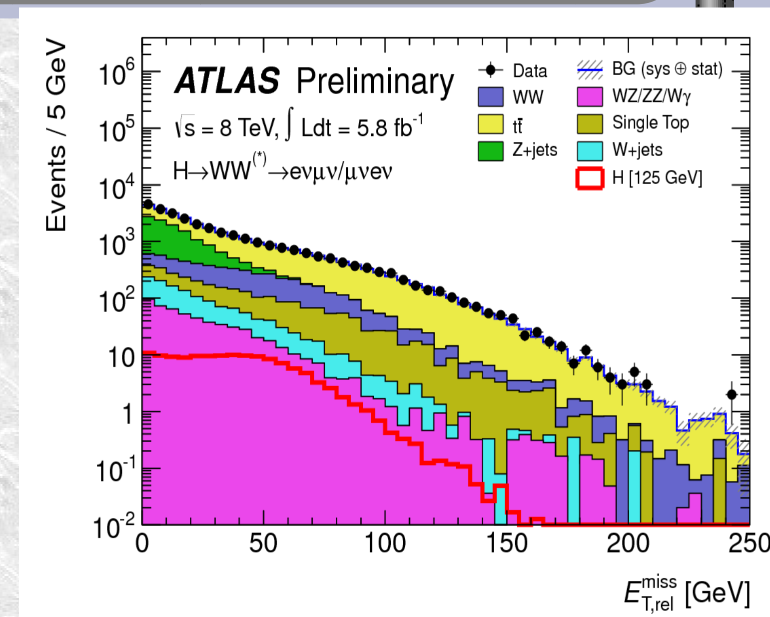
ArXiv: hep-ph/0503094

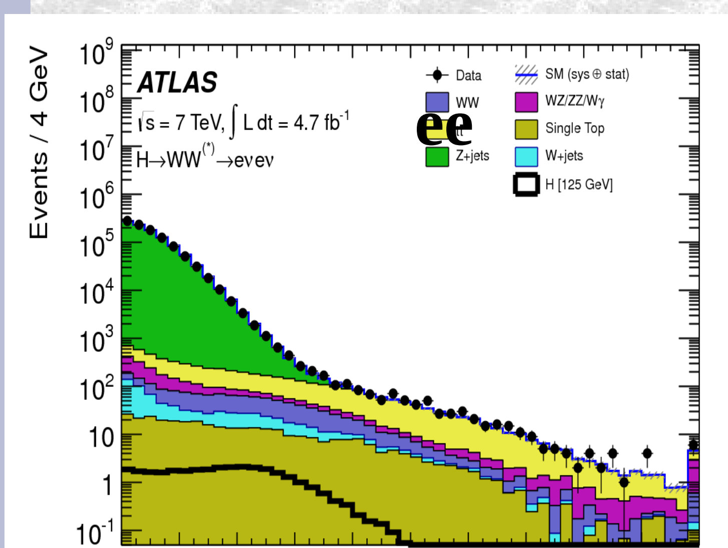
T. Binoth, M. Ciccolini, N. Kauer, M. Krämer

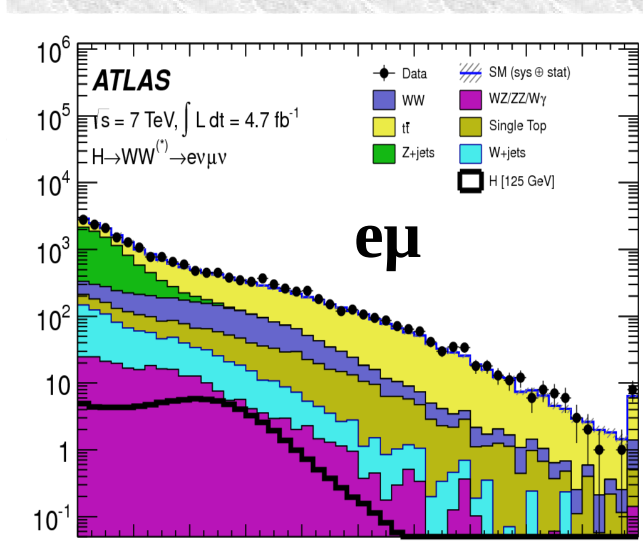
	$\sigma(pp \to W^*W^* \to \ell\bar{\nu}\bar{\ell}'\nu')$ [fb]				
	gg	$q\bar{q}$		$\frac{\sigma_{NLO}}{\sigma_{LO}}$	$\frac{\sigma_{NLO+gg}}{\sigma_{NLO}}$
		LO	NLO		
σ_{tot}	$53.61(2)^{+14.0}_{-10.8}$	$875.8(1)^{+54.9}_{-67.5}$	$1373(1)^{+71}_{-79}$	1.57	1.04
σ_{std}	$25.89(1)^{+6.85}_{-5.29}$	$270.5(1)^{+20.0}_{-23.8}$	$491.8(1)^{+27.5}_{-32.7}$	1.82	1.05
σ_{bkg}	$1.385(1)^{+0.40}_{-0.31}$	$4.583(2)^{+0.42}_{-0.48}$	$4.79(3)^{+0.01}_{-0.13}$	1.05	1.29

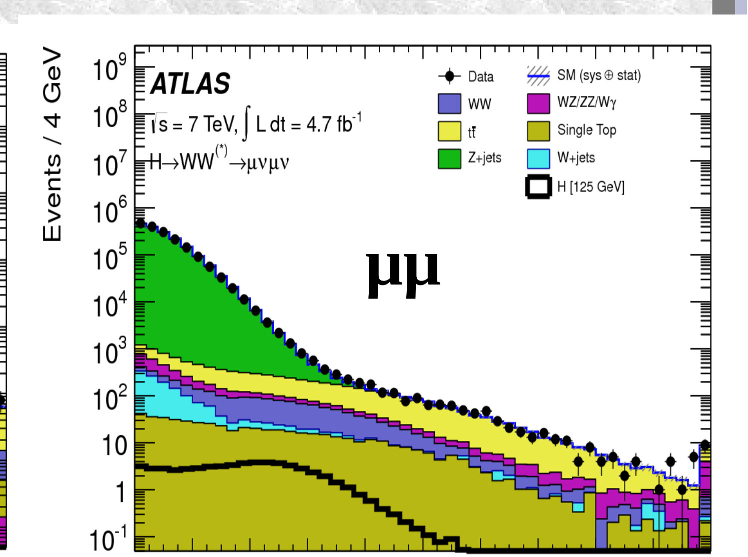
WW → lνlν

- Missing E_T
  - Vital tool against Z+jets events
    - costs in signal rate
  - Degraded in 2012
  - ATLAS dropped ee/μμ to suppress this

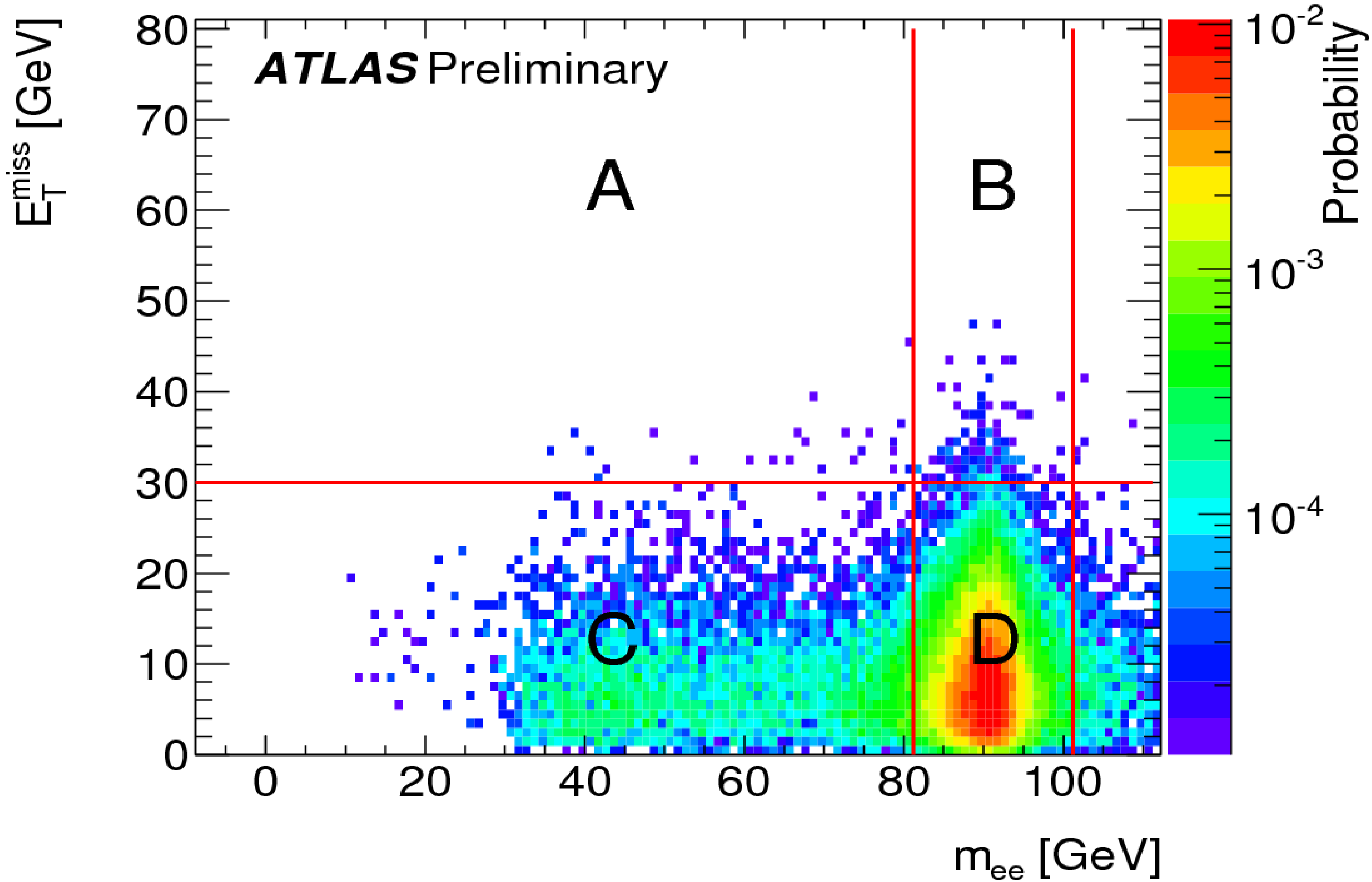






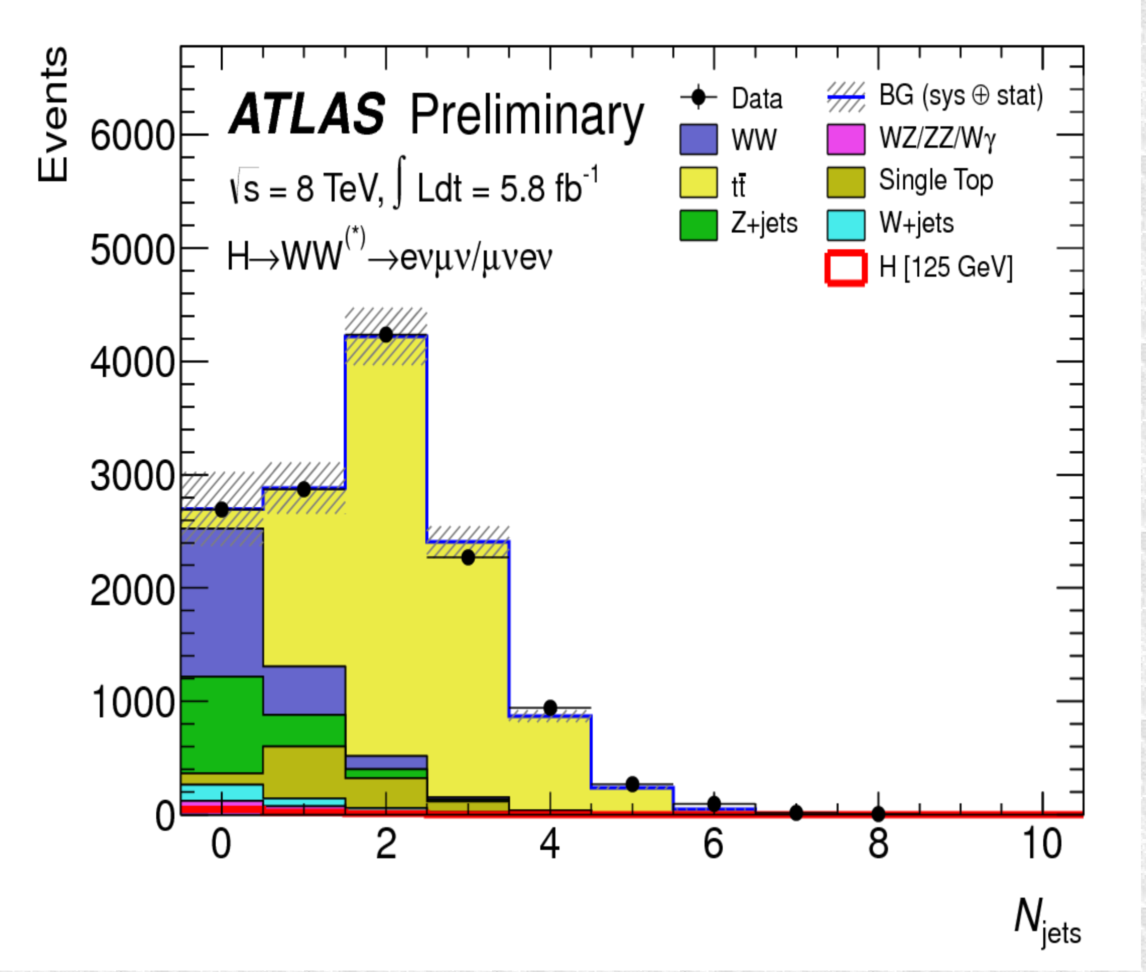


Z+jets background



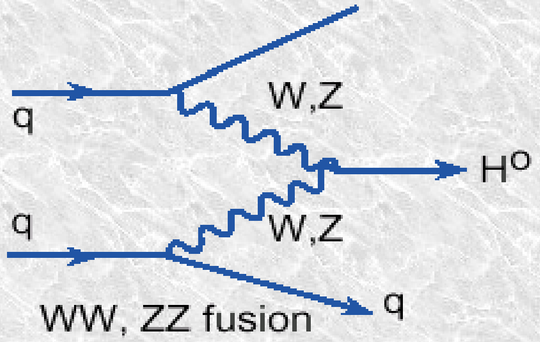
Jet binning

- The top background is dealt with by binning:
  - 0 jets
    - Very small top
  - 1 jet
    - B-veto jet
  - 2 jets
    - Used tag jets for VBF
- Top control: 1-jet with b-tag
  - Same leptons cuts as signal
    - acceptance from data

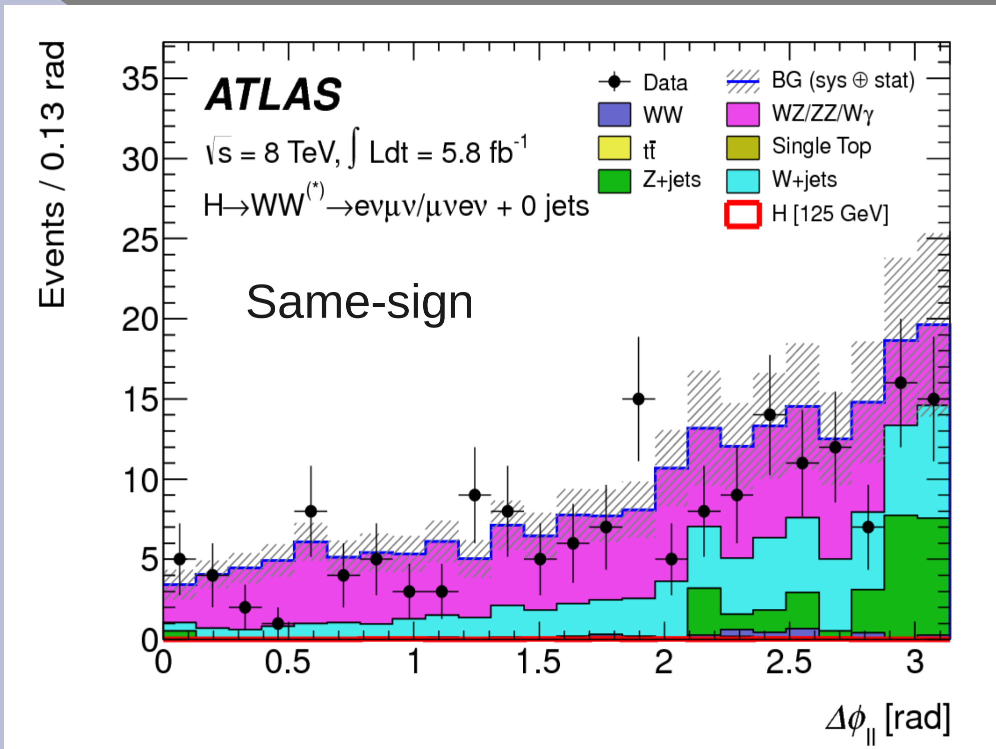


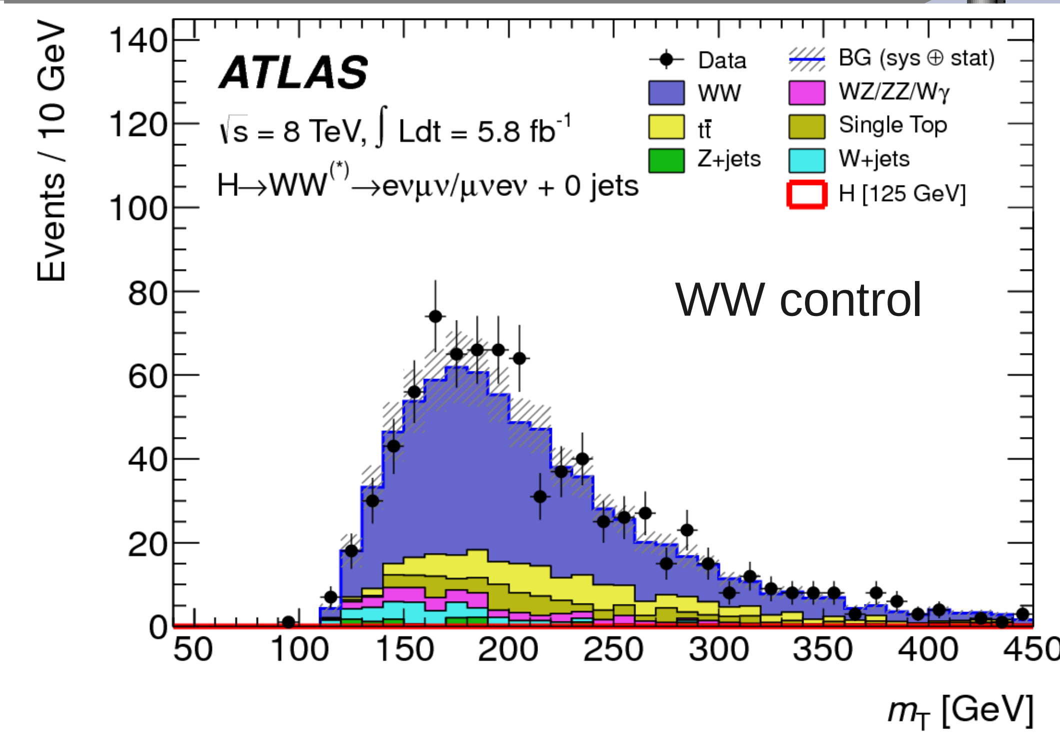
H→WW$^{(*)}$ via VBF

- VBF Higgs production gives two 'tag' jets
  - Reduced rate, but enhanced signal to background
    - If the central jet veto is applied
  - Requiring these jets gives additional complementary search
- Central Jet veto?
  - Issue here is reliability of efficiency calculation
  - No good estimation of this in data – more theoretical reliance
  - CMS did not apply jet veto
  - ATLAS did



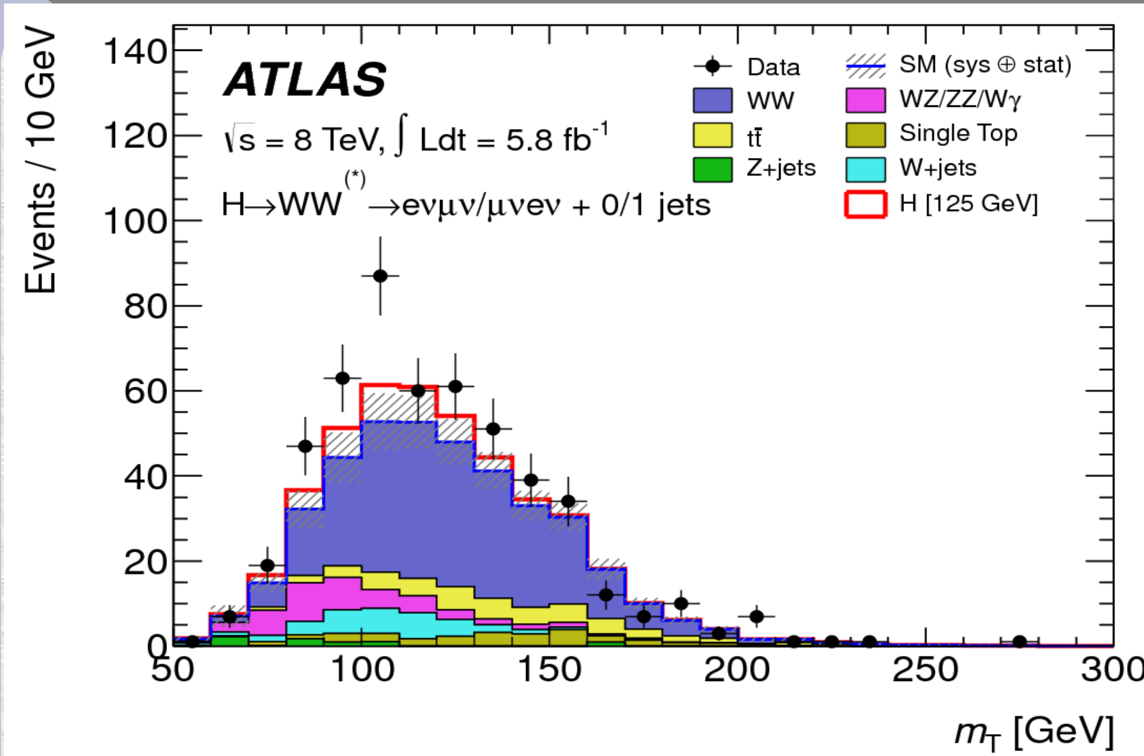
WW background extraction

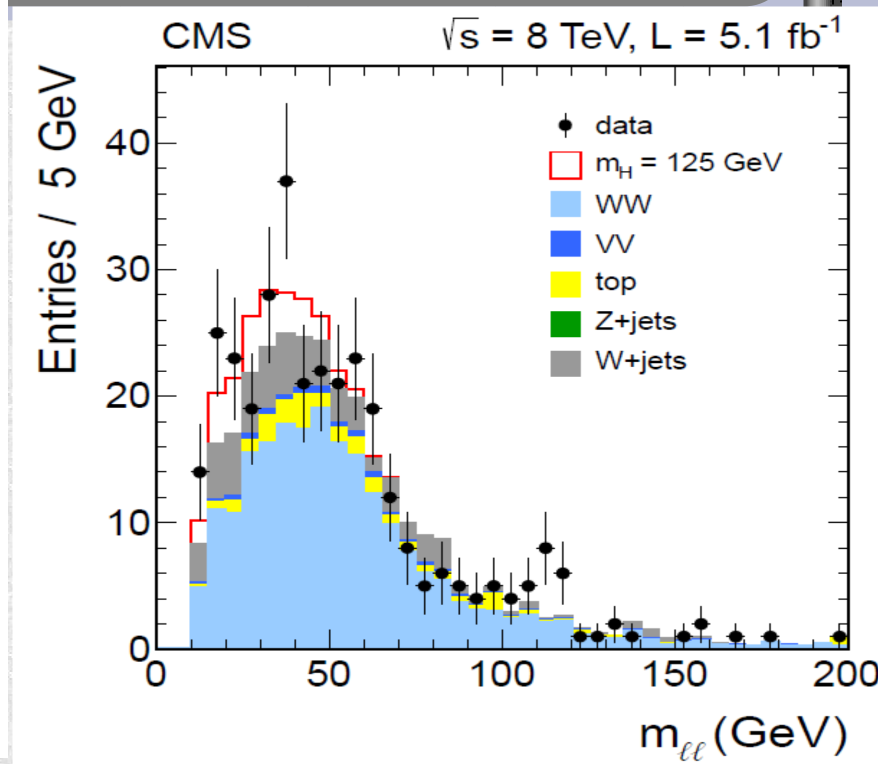




- Backgrounds are measured in control regions
  - ATLAS same-sign (left) check W+jets
  - ATLAS WW control (right) from high m_T events
    - Integrals must match data/MC by contruction.
    - But scale factors are near 1.

WW signal region

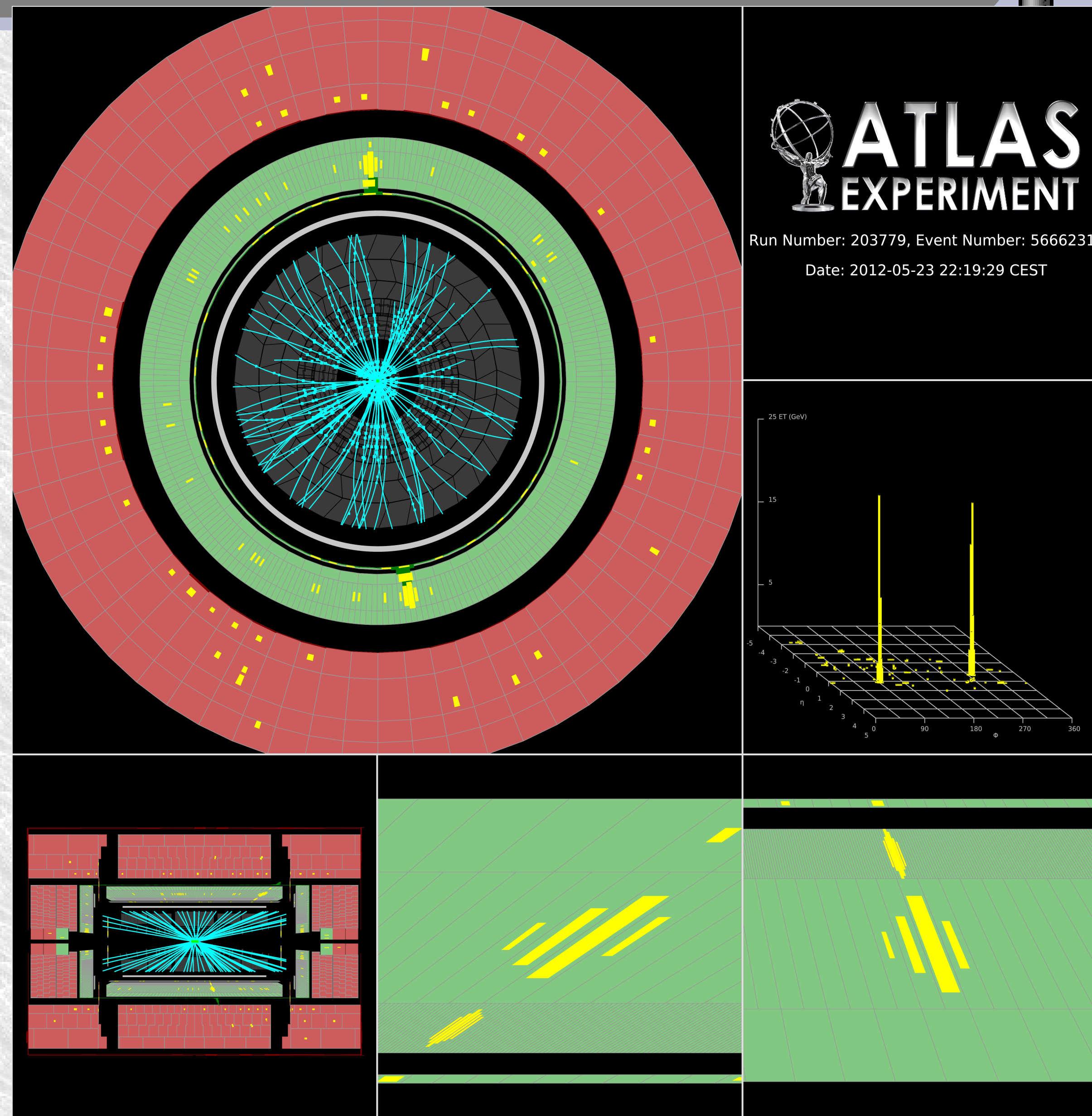




- Modelling of shapes from simulation
  - Tricky business, different codes compared
- Distinct excess in both experiments
  - In the region signal is expected

$H \rightarrow \gamma\gamma$

- Rare decay,
  - 2 per mille
  - $110 < m_H < 150$
- Drove ECAL design
  - Resolution in CMS
  - Pointing in ATLAS
- Mass resolution tested in $Z \rightarrow ee$
  - Need to know vertex position
    - Pileup hurts!
- Good jet rejection also essential



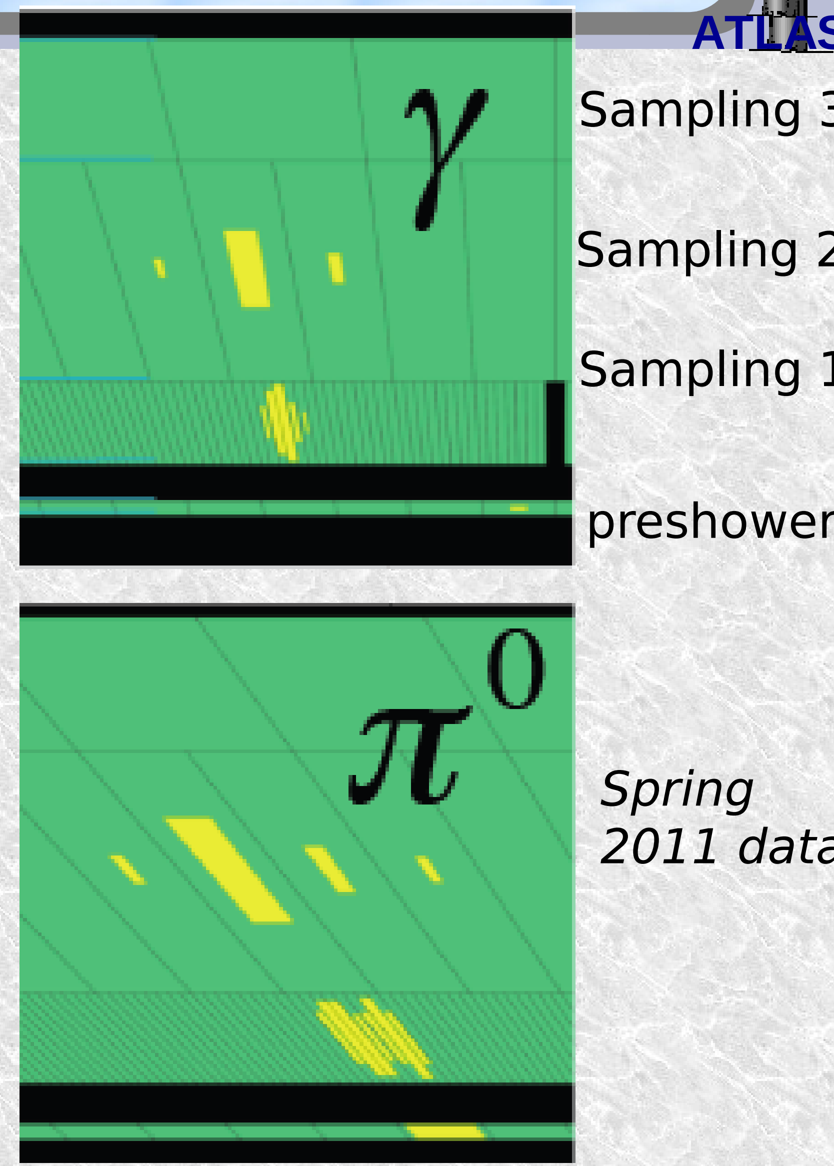
ATLAS

H to γγ event selection

Very simple basic signature:
Photon identification based both on lateral and longitudinal segmentation of the Electromagnetic calorimeter
Two high-quality isolated high-pT photons

$p_{T1} > 40$ GeV; $p_{T2} > 30$ GeV

$|\eta_{12}| < 1.37$ and $1.52 < |\eta_{12}| < 2.37$



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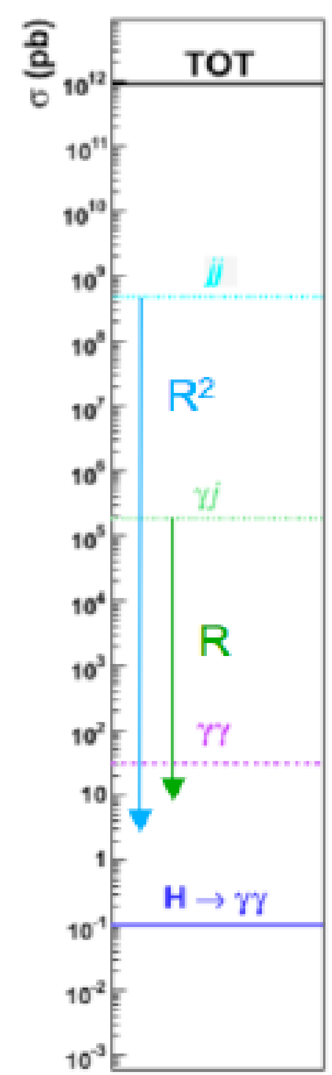
H → γγ

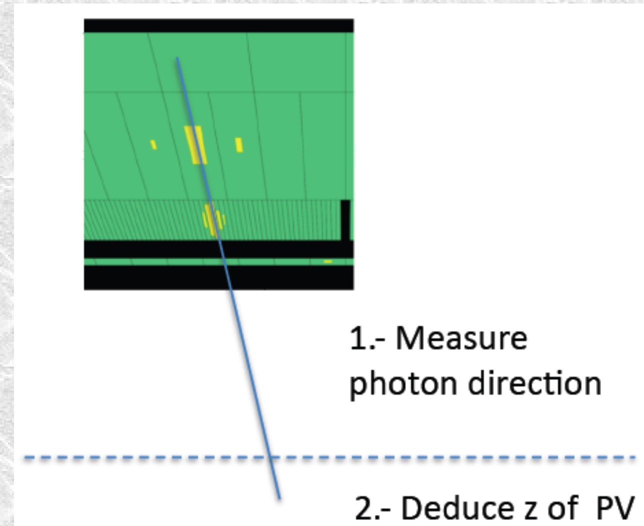
- Decay viaa top loop
- But trigger, mass resolution are good
- Large backgrounds of γγ, γ-jet and jet jet
  - Need O(10^4) jet rejection
  - Both detectors provide this
- Emphasis is on efficiency
- Background prediction have large errors
  - But can be taken from data in bump-hunt

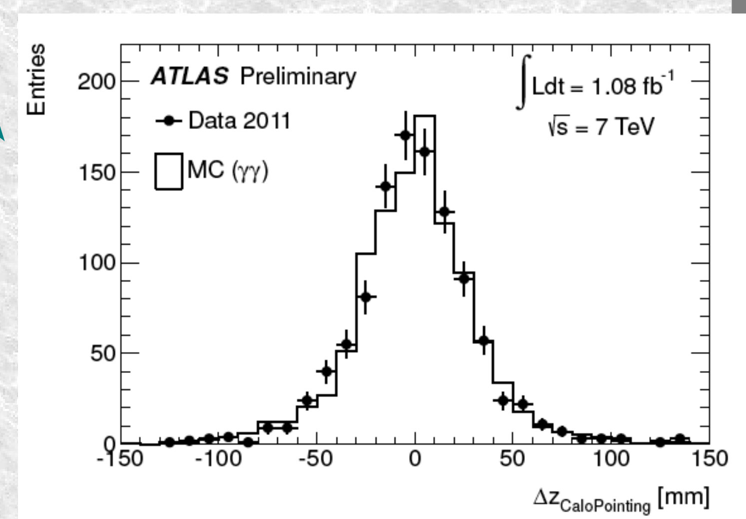


R ~ O(8000)

Primary Vertex

- Finding energy in a calorimeter does not tell you the photon momentum
  - You need to know the primary vertex position too
- Problem: pileup gives many
- ATLAS uses pointing from calorimeter to identify correct
- CMS photon conversion tracks, vertex p_T, vertex sum p_T

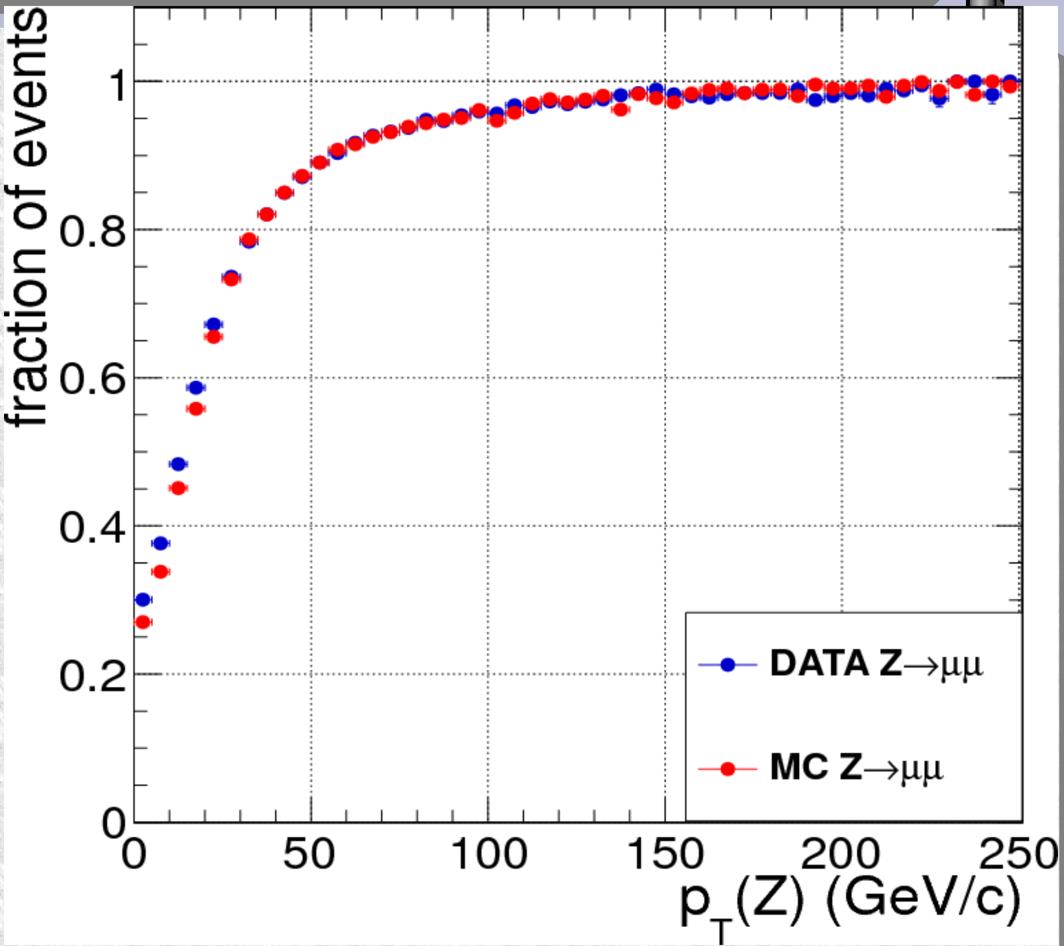


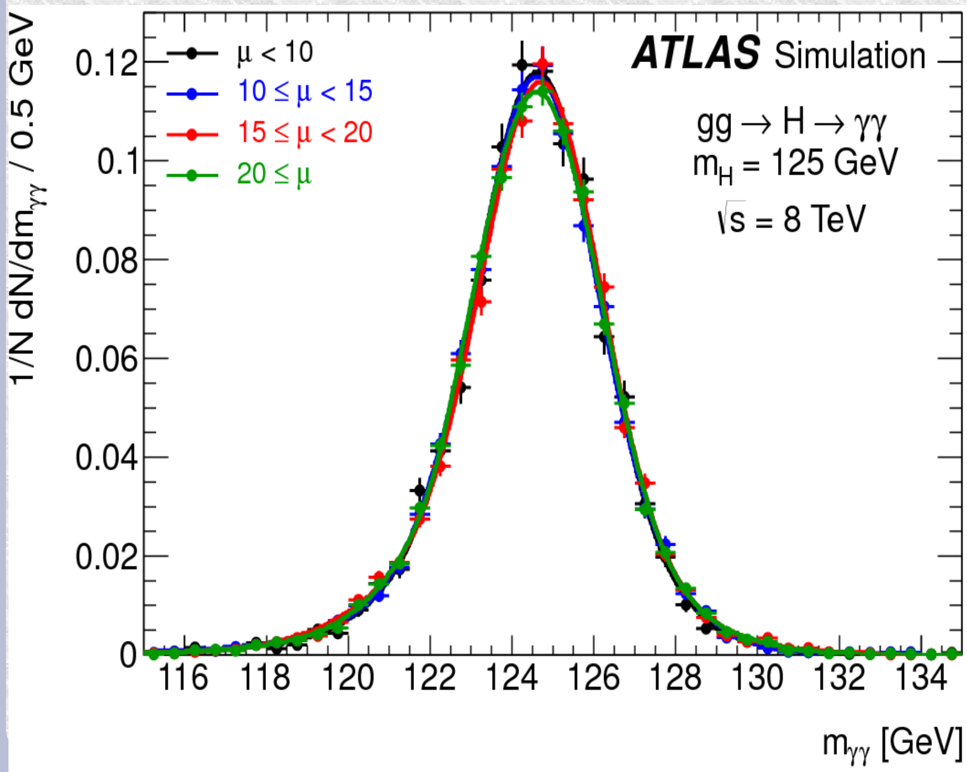


$\Delta z12 = z\gamma1 - z\gamma2$; $\Delta z12 \approx 3$ cm; $\delta z\gamma\gamma \approx 1.5$ cm;

Calculating H→γγ mass

- Need H decay position
  - CMS compare tracking vertices; match p_T etc
  - ATLAS only need vertex for VBF jets

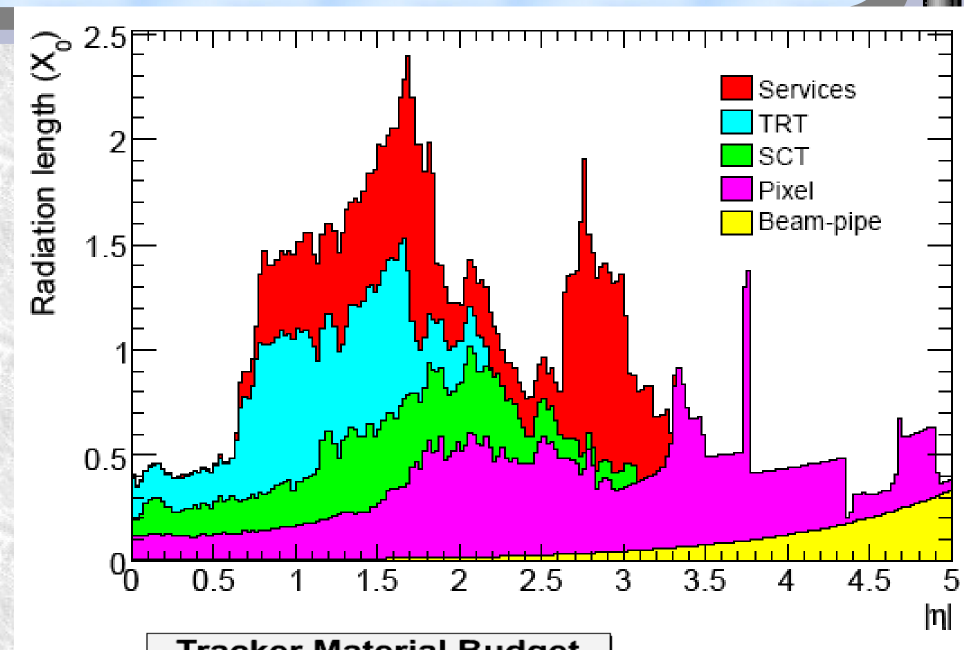


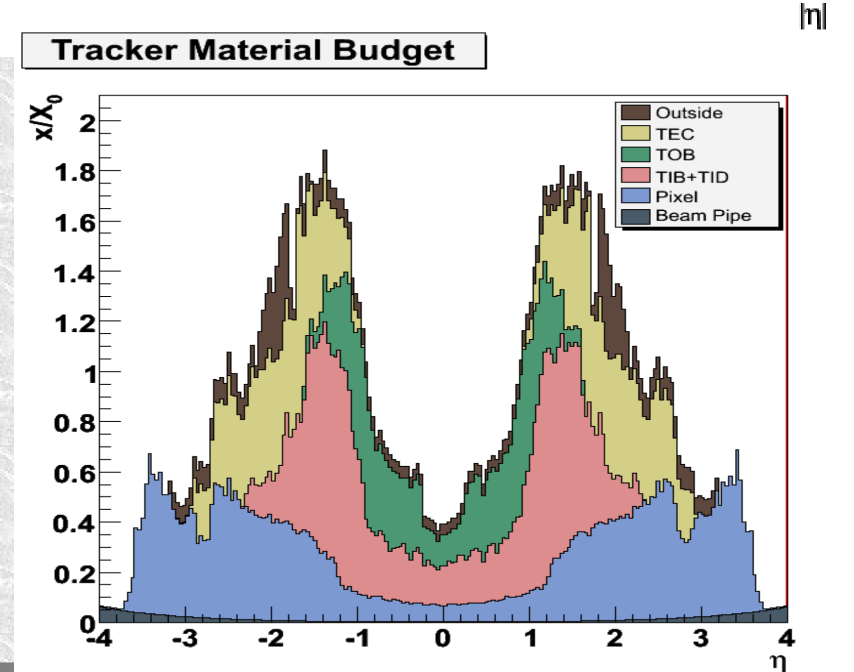


- ATLAS somewhat more pileup robust

H → γγ

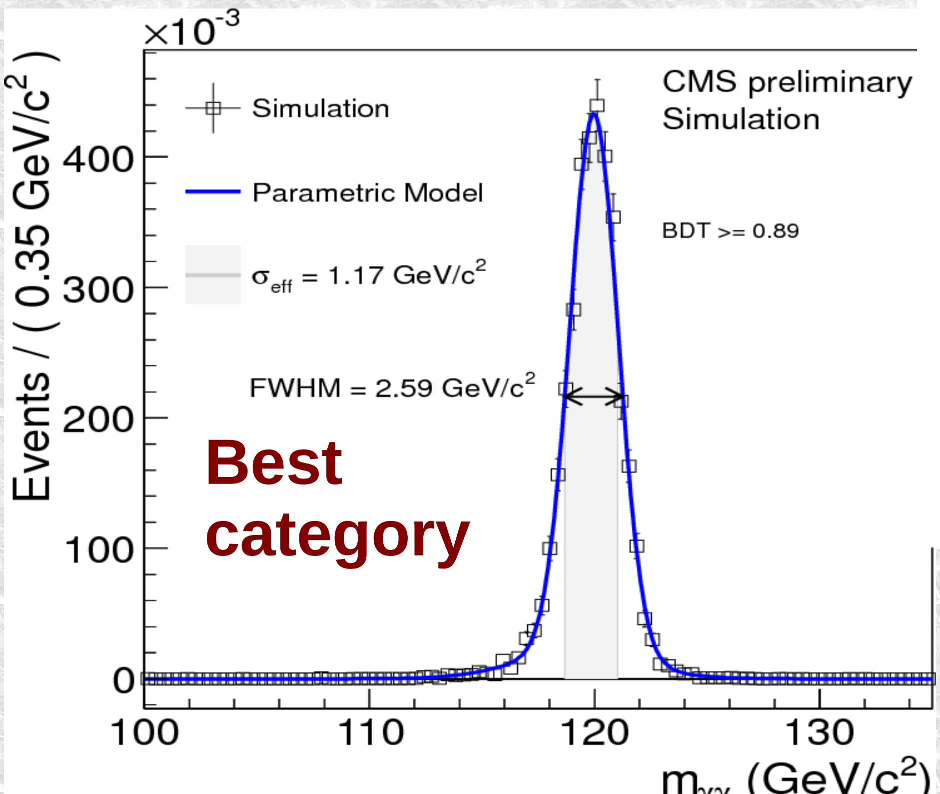
- Electron resolution checked using the Z peak
- Need to transport to photon with MC
- Different e/γ response in MC largest systematic uncertainty

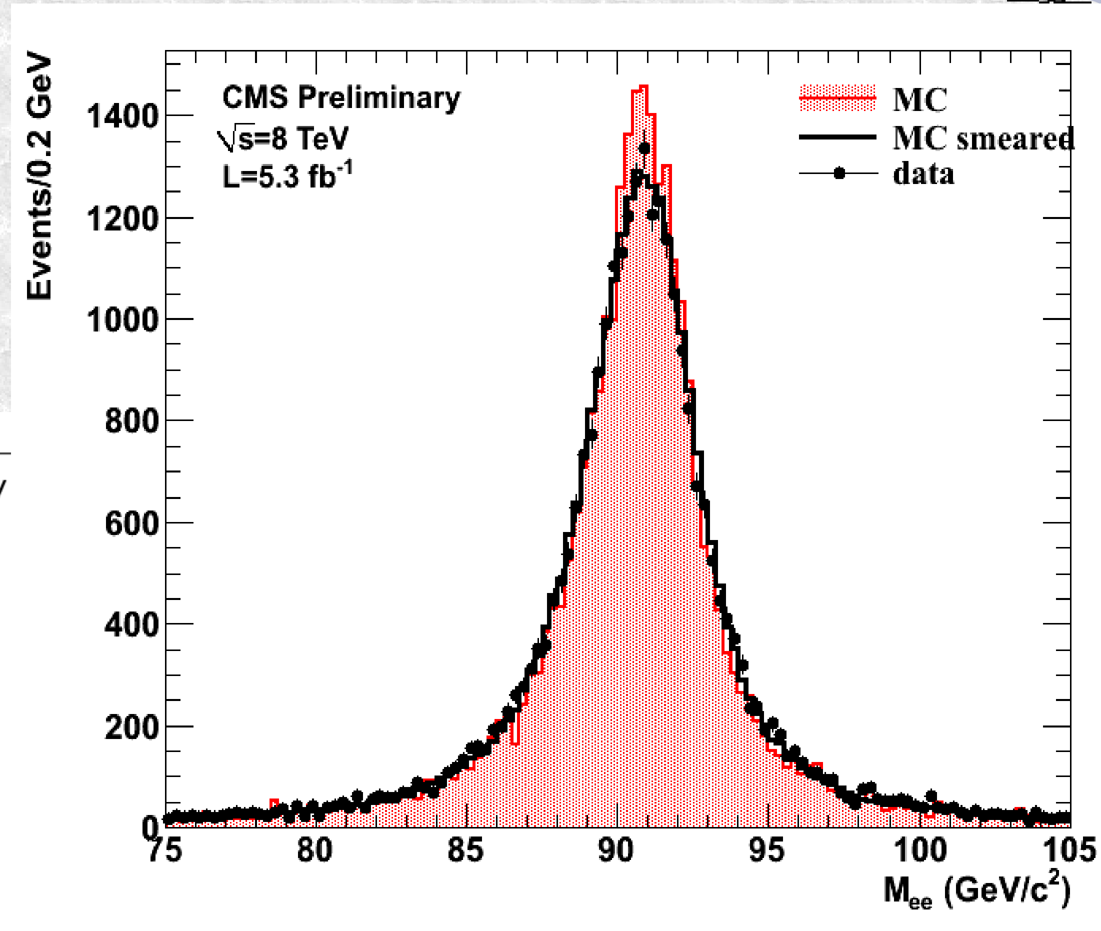




H→γγ mass resolution

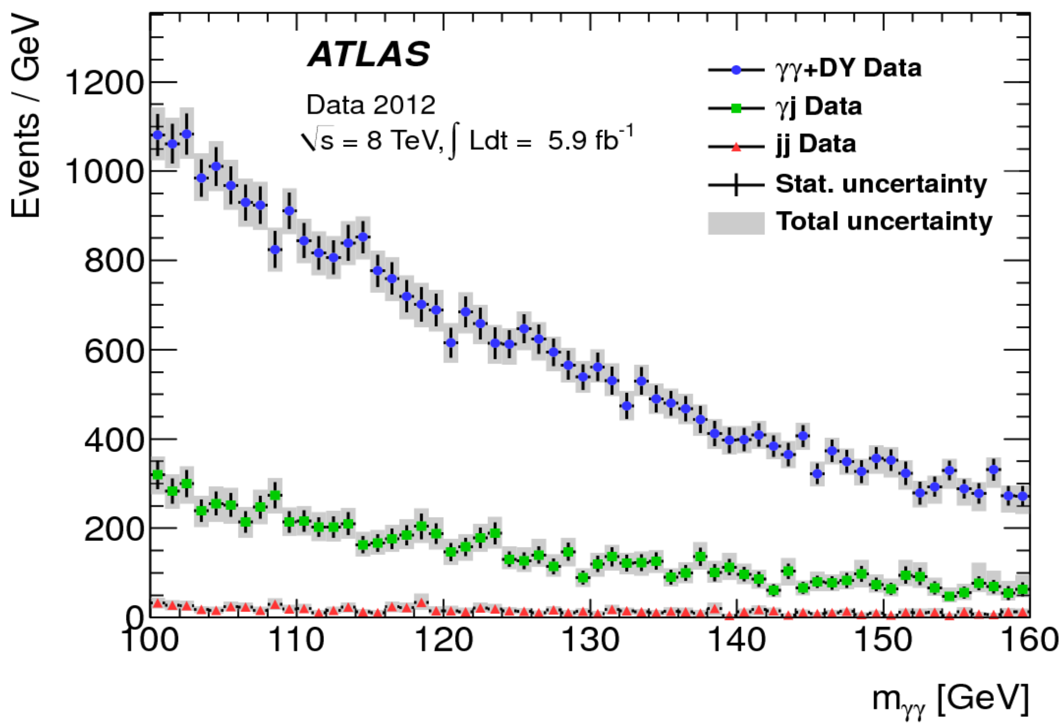
- Best check is Z→ee
  - But natural width degrades that
- Higgs will be narrower
  - Need to trust MC

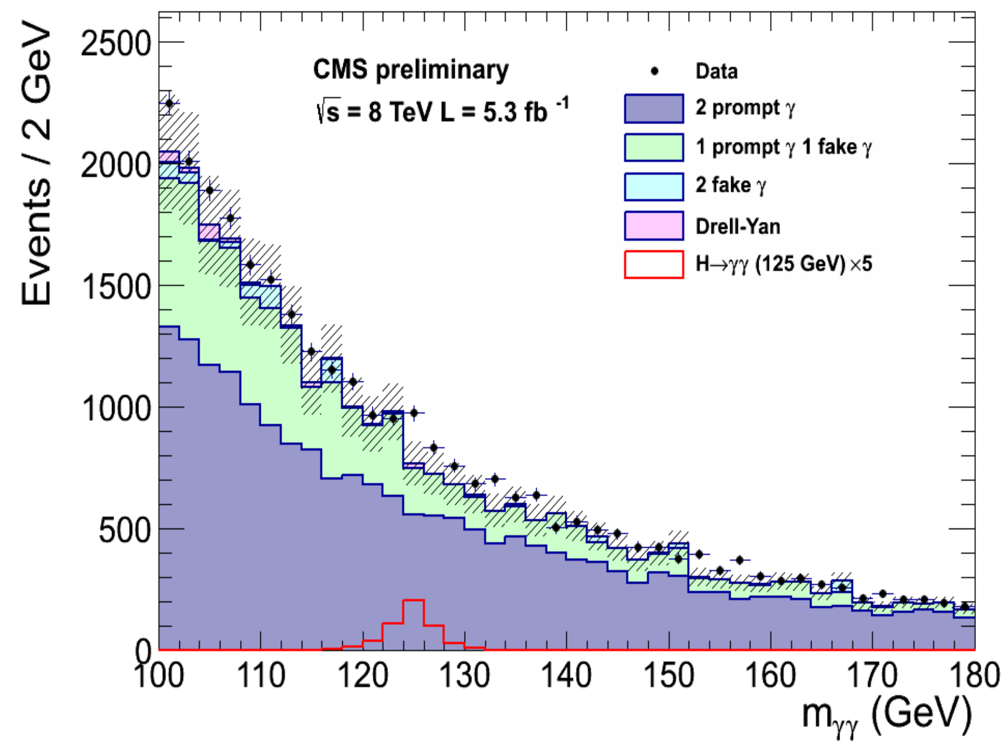




- ATLAS and CMS similar
  - CMS 'best' is most precise.

H→γγ sample makeup



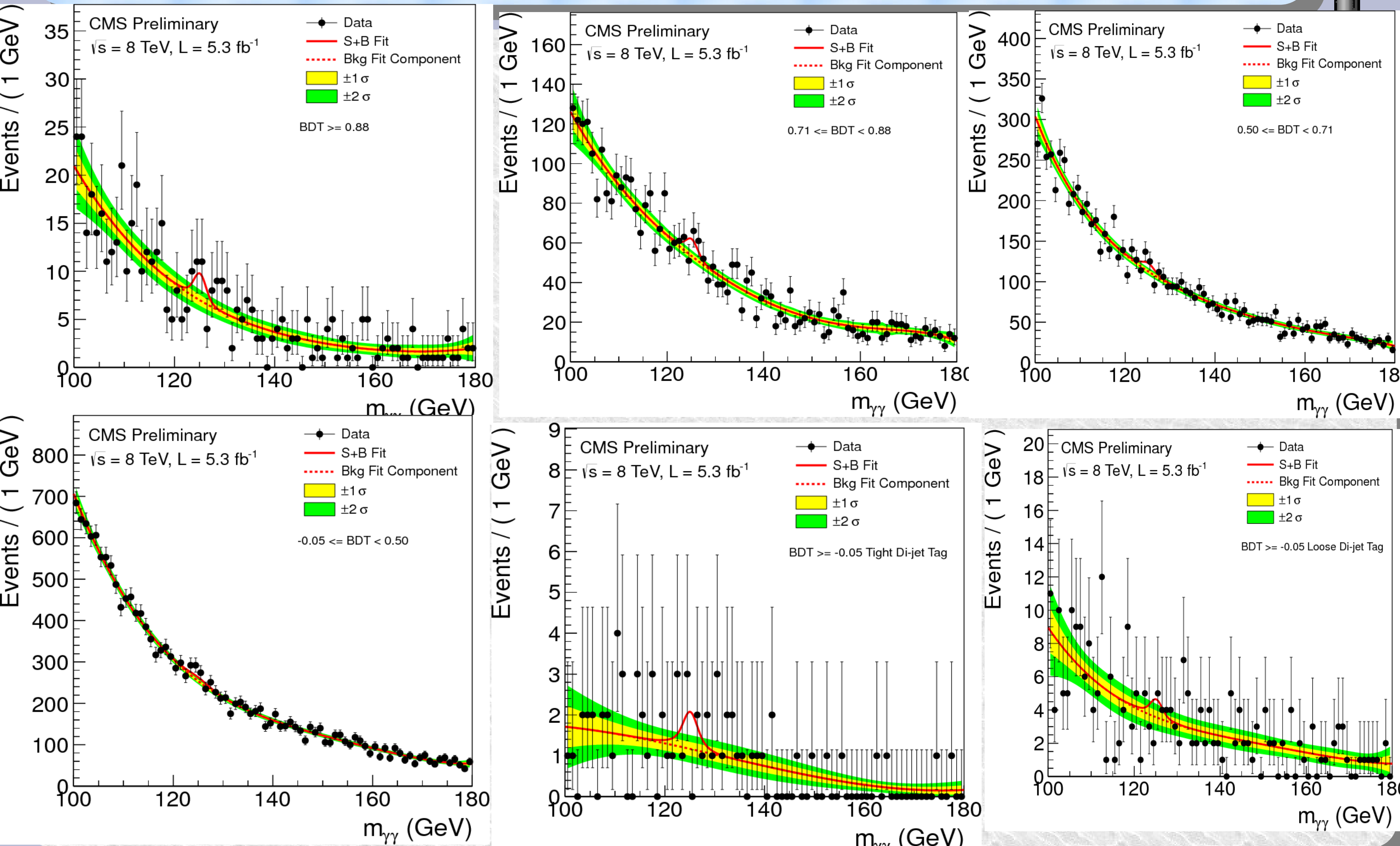


- Both experiments measure sample composition using sidebands of isolation
  - Plus Z→ee events mistaken for double conversions
- Samples are dominated by real di-photon.
  - But this is not explicitly used in the analysis

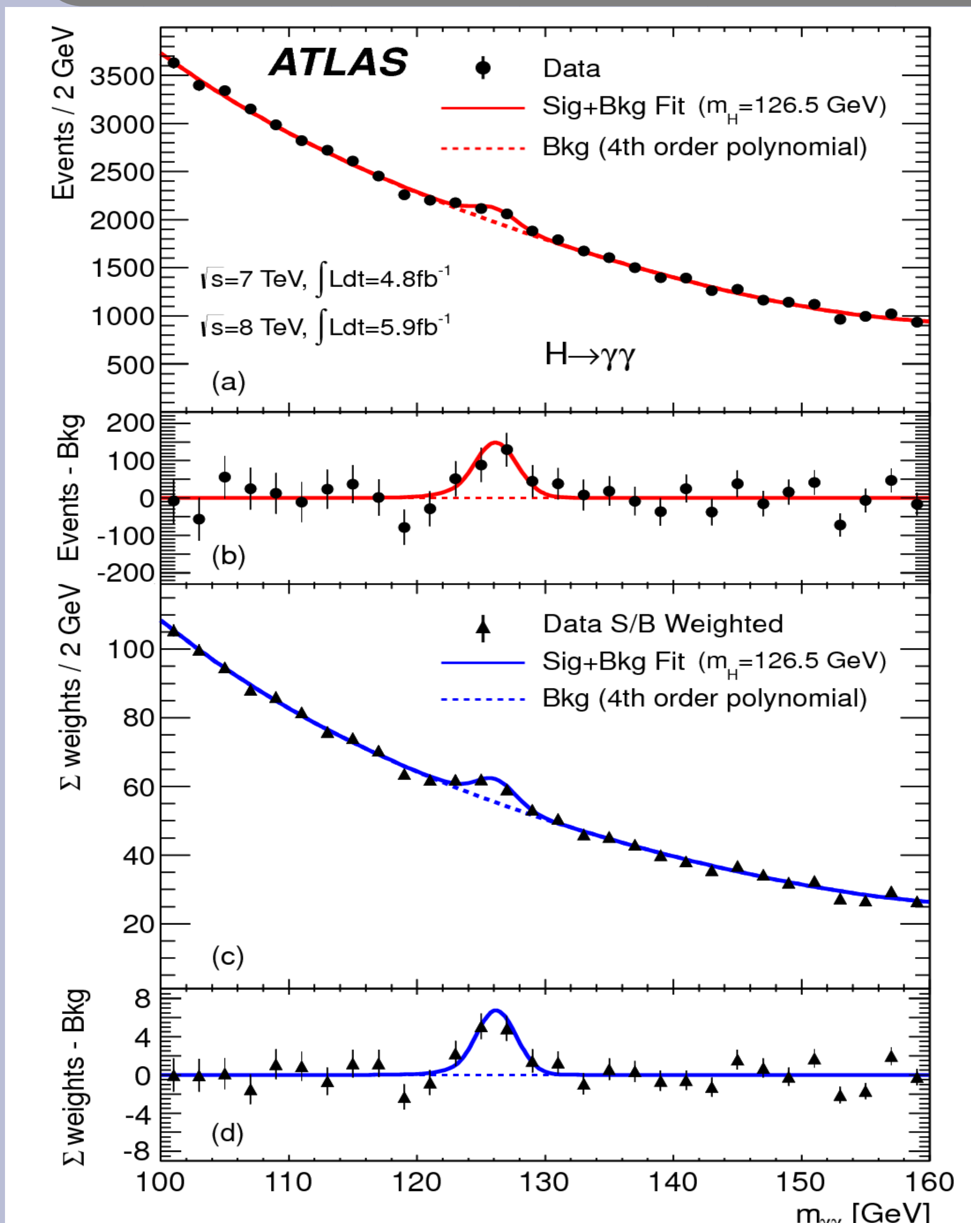
H→γγ analysis method

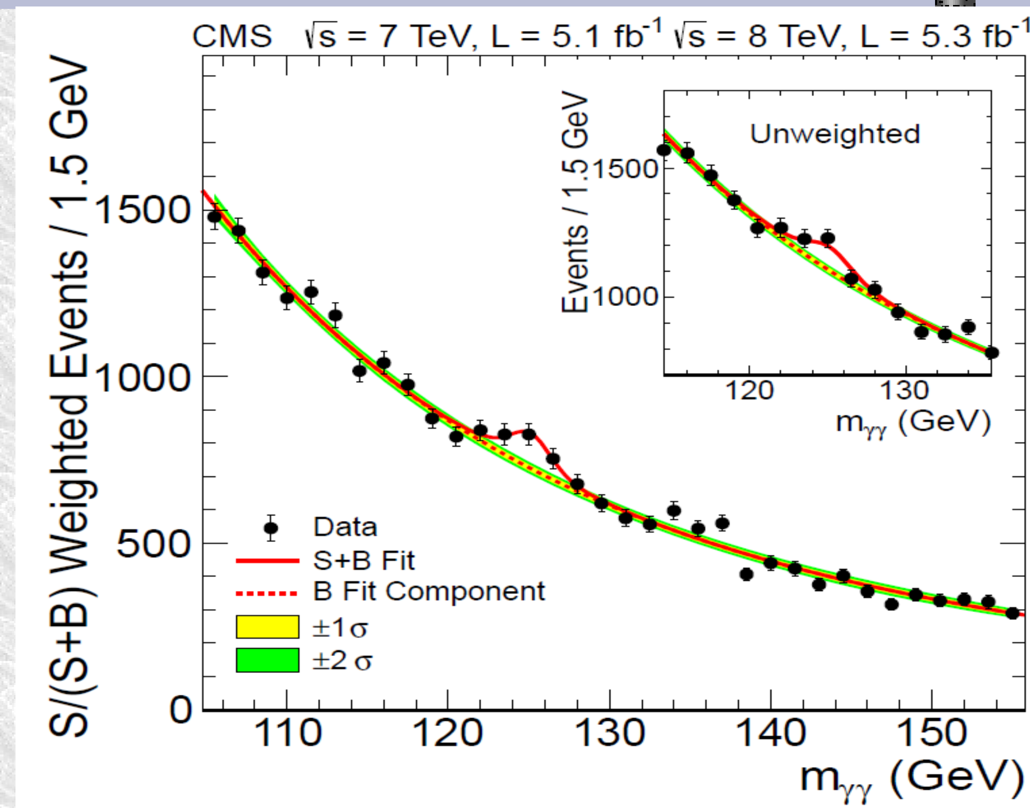
- In principle look at the m(γγ) spectrum for a bump
- But signal/background and resolution depend upon other variables
- Both experiments split into several categories, fit at once
  - ATLAS uses p_{Tt}, barrel/forward, converted/unconverted
  - CMS uses MVA to select categories
- One or two 2-jet categories sensitive to VBF added too
  - Gives more power
  - But also useful to understand physics of production
- But..too many plots to take in
  - 20 in ATLAS' case
  - So experiments weight categories and add them up.

CMS 2012 data



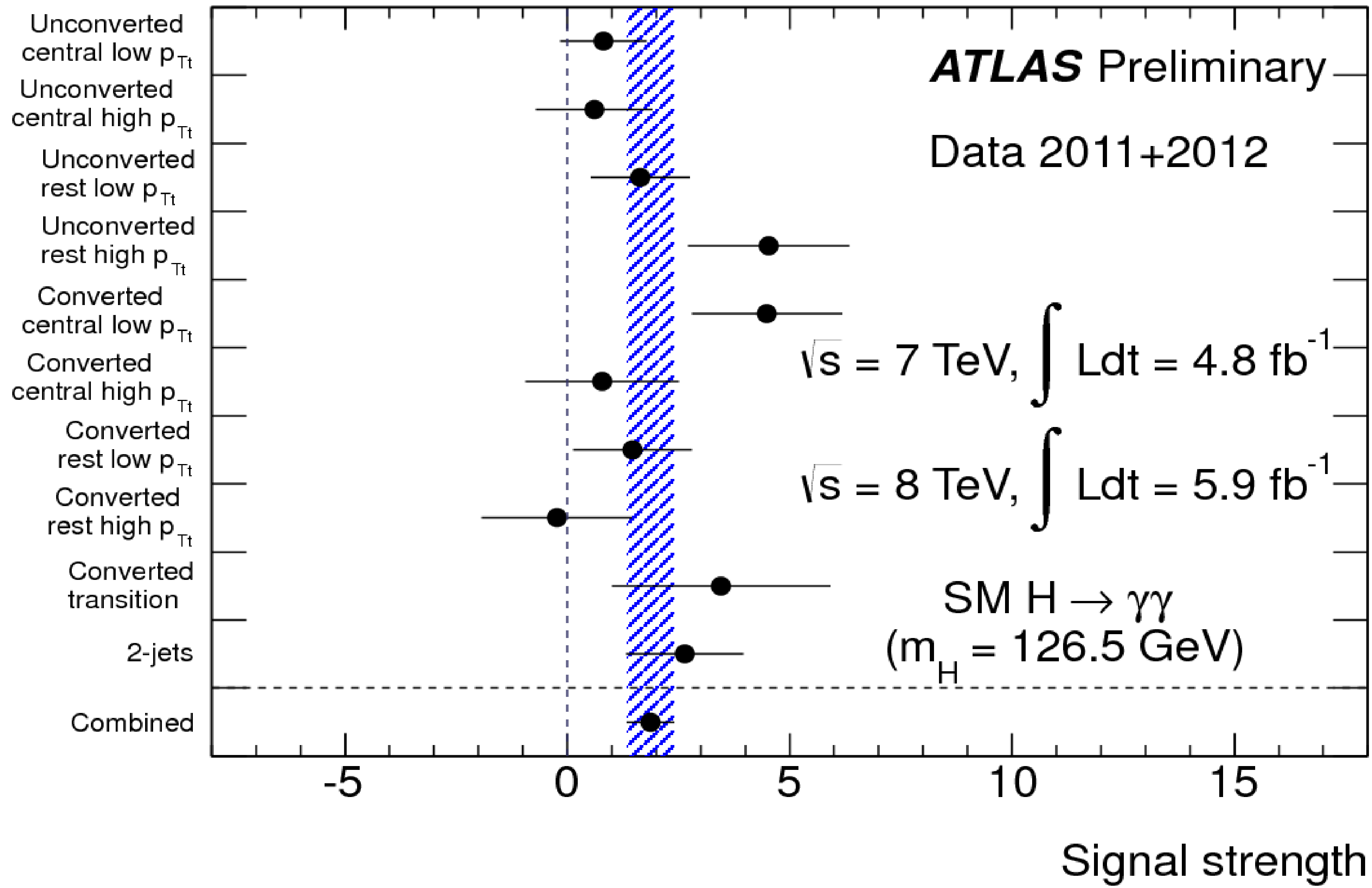
H → γ γ





- Both experiments see significant peaks around 125
- Weighted sum clearer

ATLAS' channel compatibility

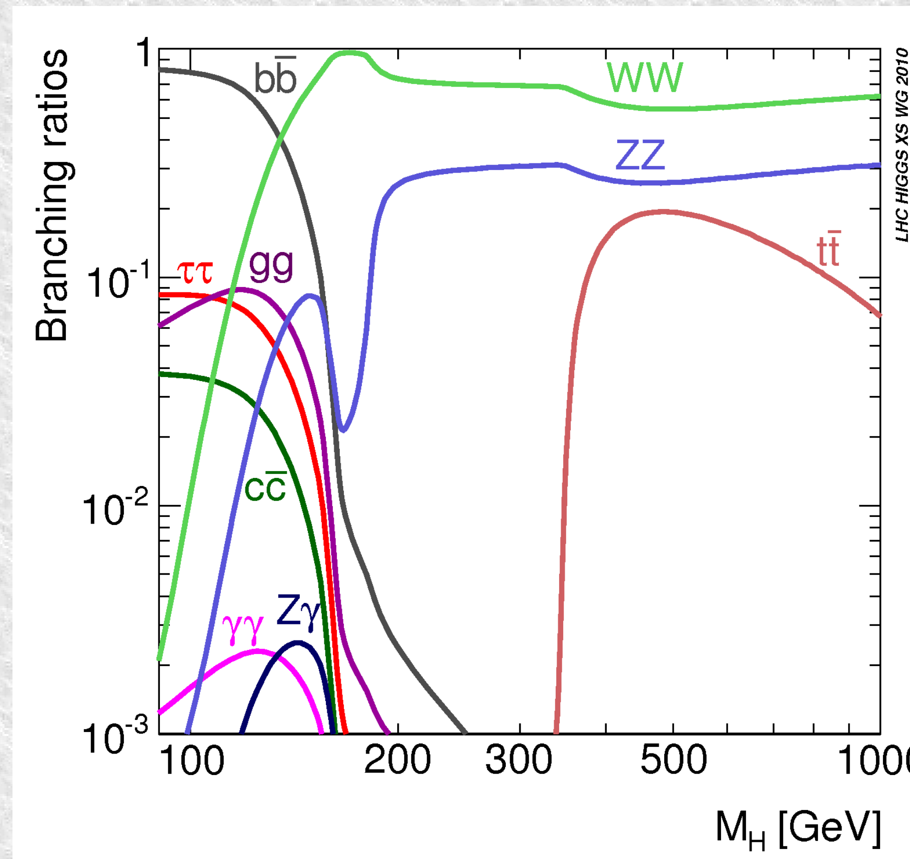


H $\rightarrow \gamma\gamma$ improvements?

- Mass resolution is a key issue
  - Calorimeter calibrations can be improved
  - Potential big gain for CMS
- Use of production mode
  - Gluon fusion dominates
  - 0,1,2 jets improve s/b
  - W,Z,tt associated also improve in future...
    - rates very low
    - But they are useful to understand what we have found

H → Zγ

- No experiment shows this
  - Old studies found it hard
- But if M_H ~ 140 it could be retried
- 50x less than ZZ
  - But 15x better B.r., so only 3x down
  - Similar mass resolution
- Zγ background worse than ZZ
- Spin structure helps.
  - Spin zero H and massless γ so Z is transverse polarised

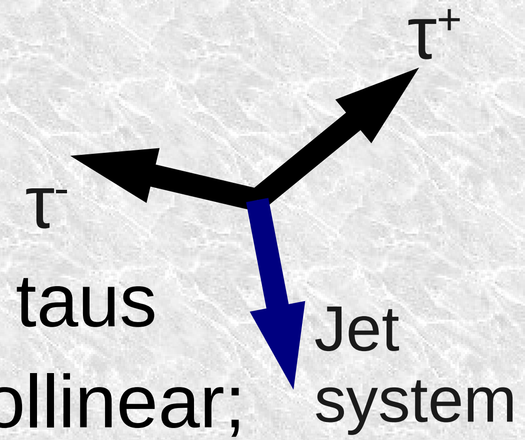


H → ττ

- Production mode
  - gg fusion – highest rate
  - Jet associated – mixes gg, VH and VBF
  - VBF – best s/b
- Decay ll, lh or hh
- Trigger:
  - One/both tau decay gives trigger lepton
  - Or hadronic tau triggers for hh mode
- Mass of H done many ways:
  - collinear approximation
  - Visible mass
  - 'Missing Mass Calculator'
- Z → ττ main background

$H \rightarrow \tau^+\tau^-$ mass

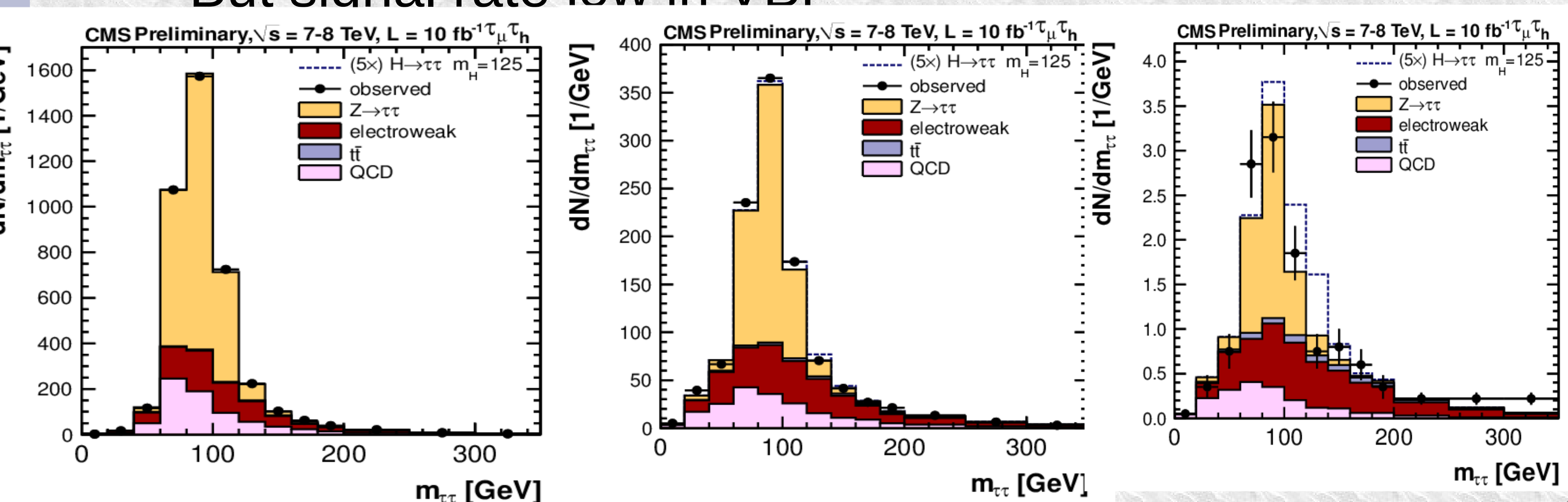
- 'Collinear approximation'; i.e. leptons follow tau direction
  - Impose p_T balance on system
  - Gives 2 constraints $\Sigma p_x=0$, $\Sigma p_y=0$
  - Solve for 2 unknowns: the p_T of the two taus
  - NB This does not work if the taus are collinear; need some p_T in the Higgs



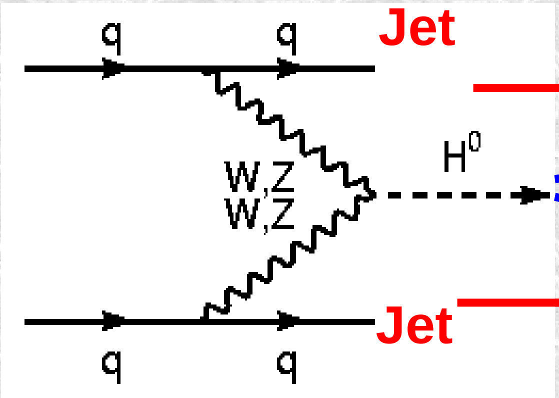
- Visible mass: Sum observed
- Missing mass calculator
  - Multi-dim maximisation of probability of observed system given m_H

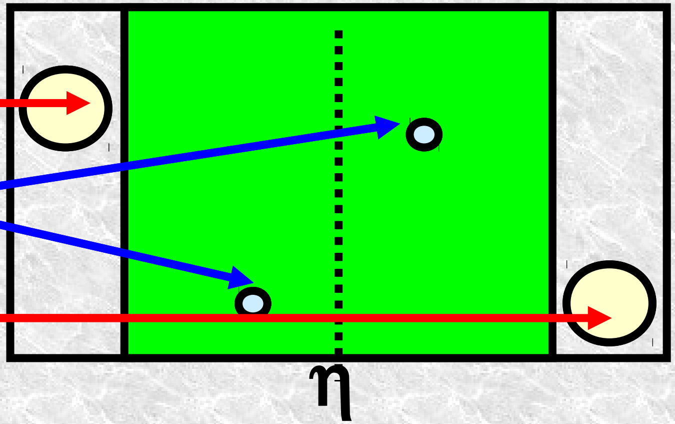
Analysis structure

- 0 jet, boosted and VBF
  - VBF: 2 jet p_T>30 & BDT selector > 0.5
  - Boosted: Fails above, 1 jet p_T>30
  - 0 jet: Rest
- S/b improving dramatically. 0 jet constrains syst.
  - But signal rate low in VBF

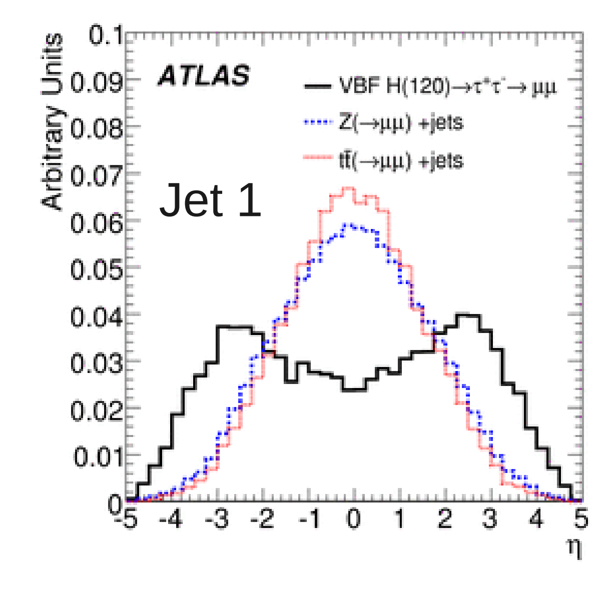


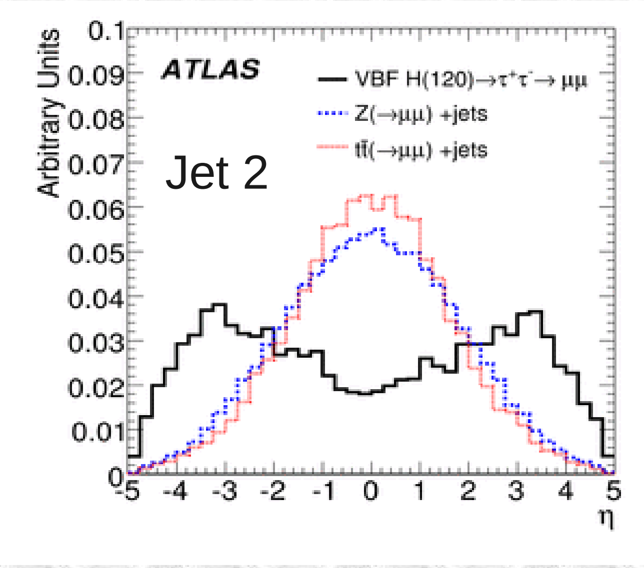
VBF: qq → qqH → ττ





- Two forward jets, P_T of order $M_W/2$
- Higgs products central
- No colourflow → suppressed central jets





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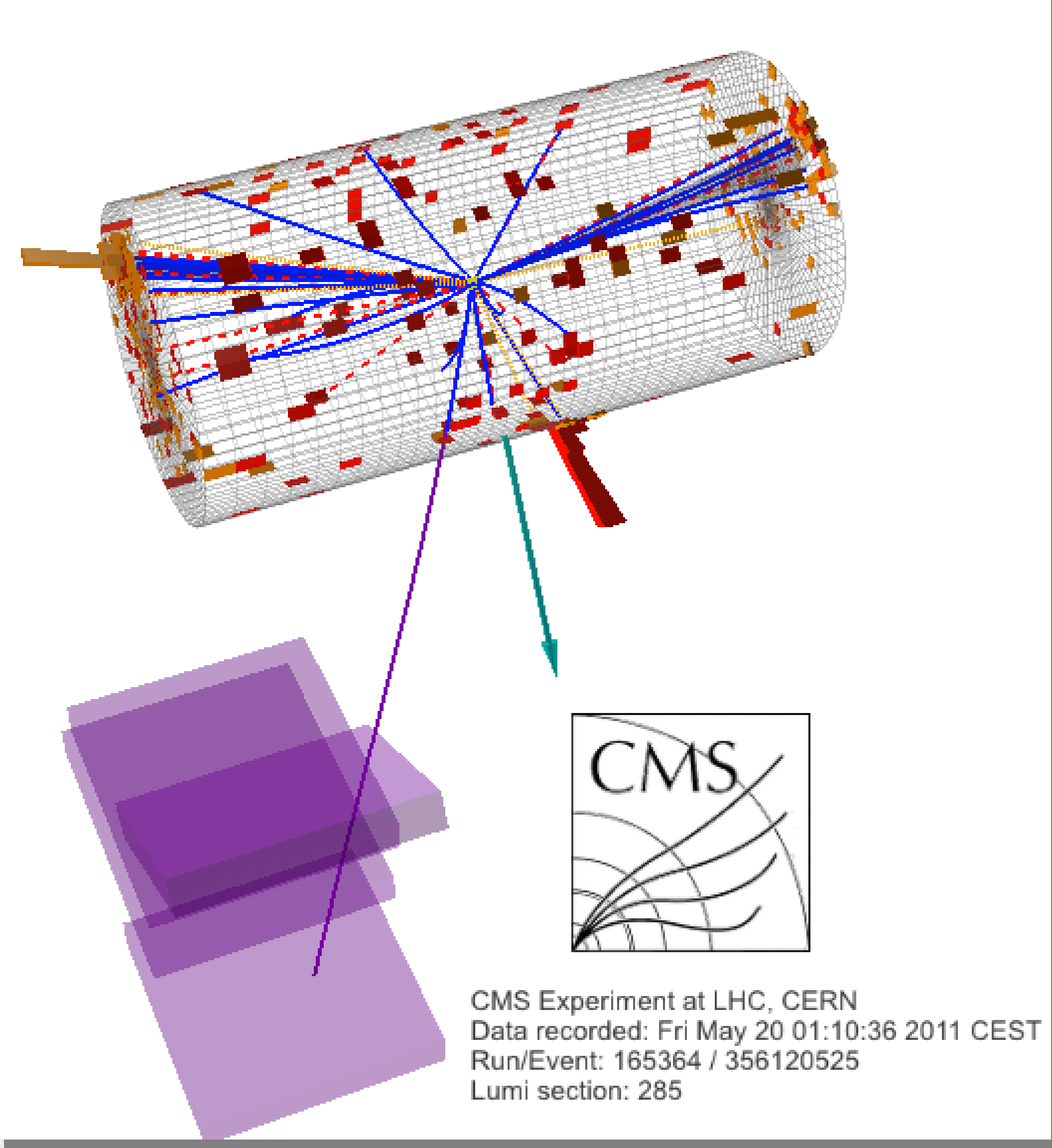
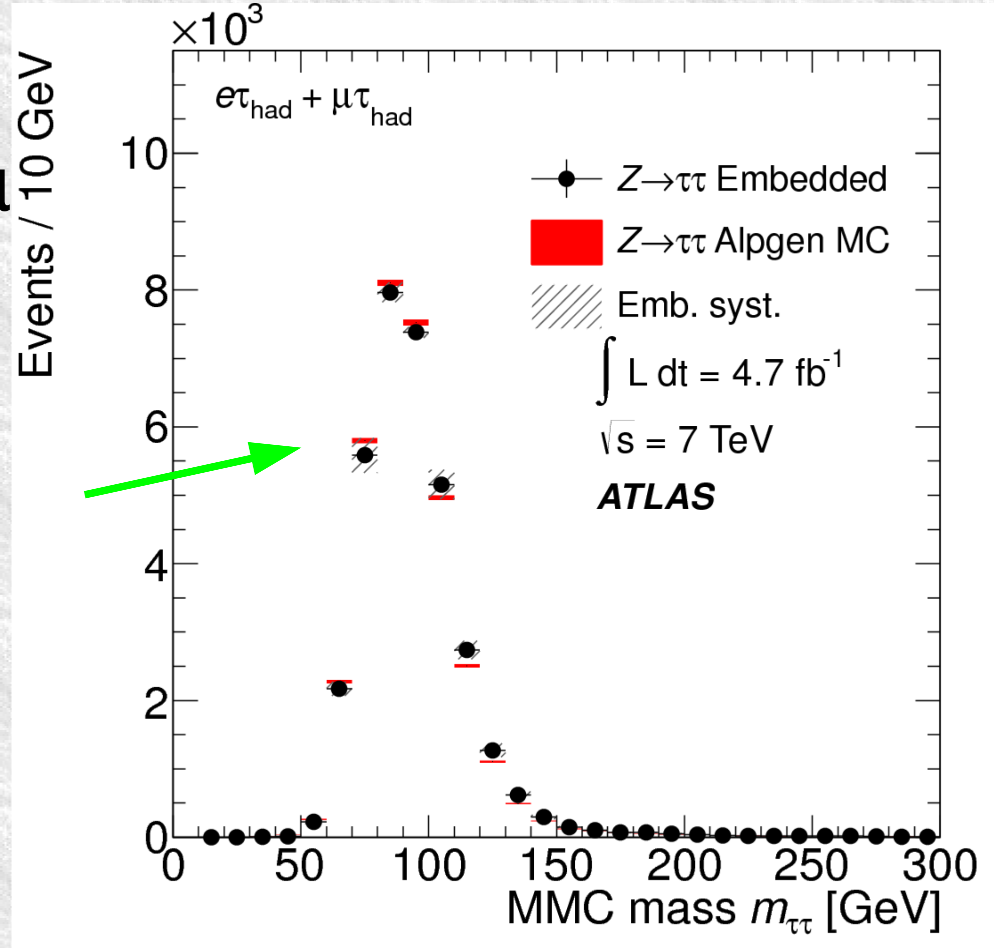
H → ττ

- CMS use many modes
- Including VBF search and 2012 data
  - With a beautiful picture
    - μ-τ candidate
    - Two forward jets
      - Mass 580GeV
    - Little central activity
  - Looks just as advertised
- e-μ, μ-μ, μ-τ, e-τ channels studied



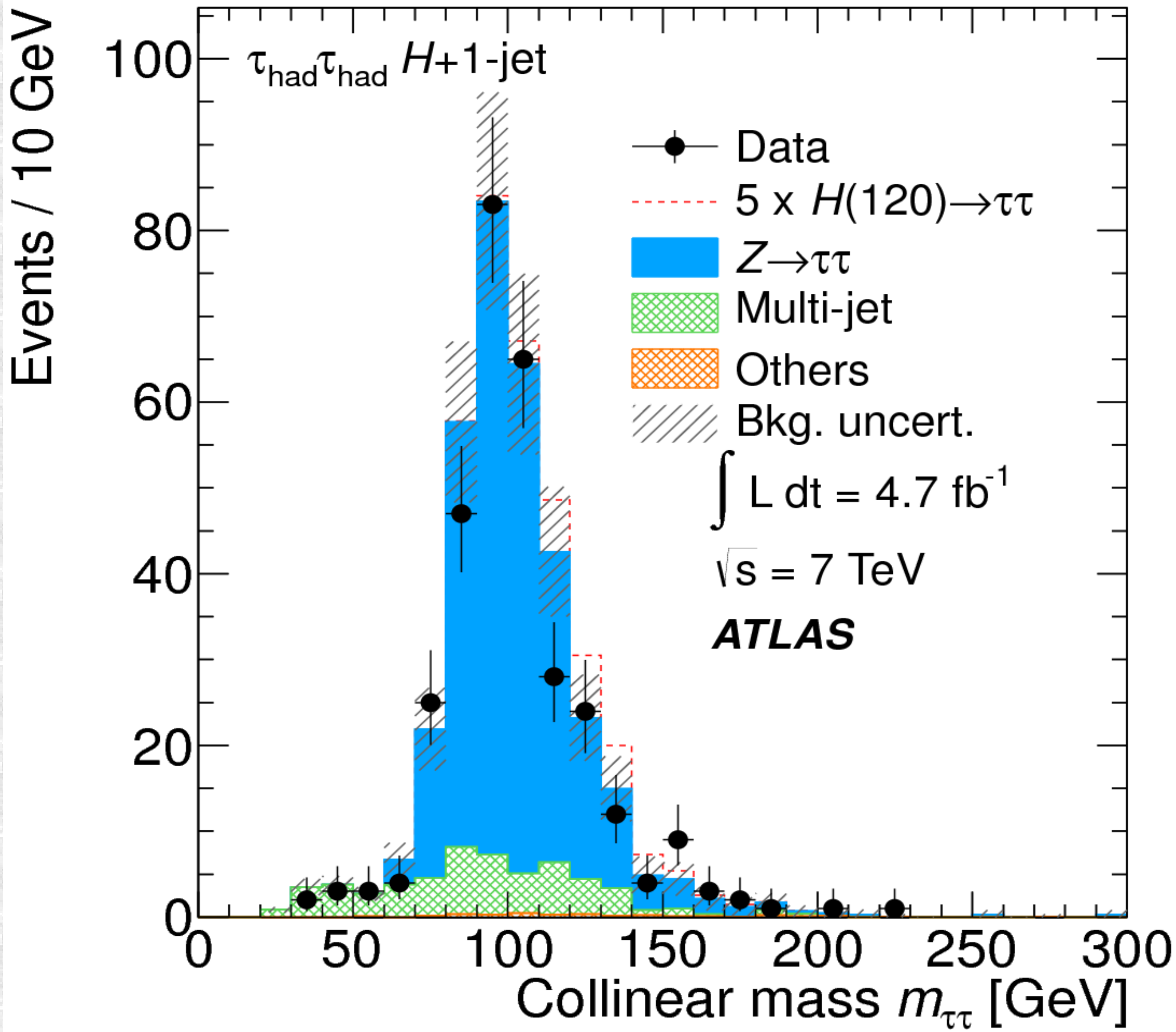
$Z \rightarrow \tau^+\tau^-$ background

- Z to tau tau
- Hard to model MET
  - Found using real Z to μμ
  - Remove μ, convert into a tau, use as input to simulation
  - Replace simulated tau into original event
- Used by both experiments



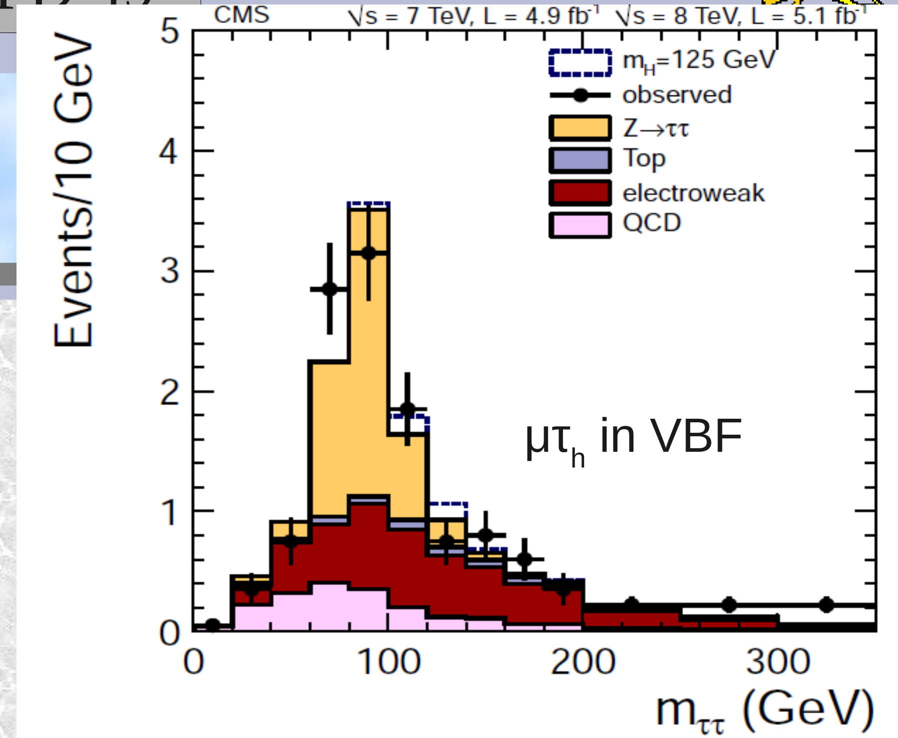
ττ→had/had in ATLAS

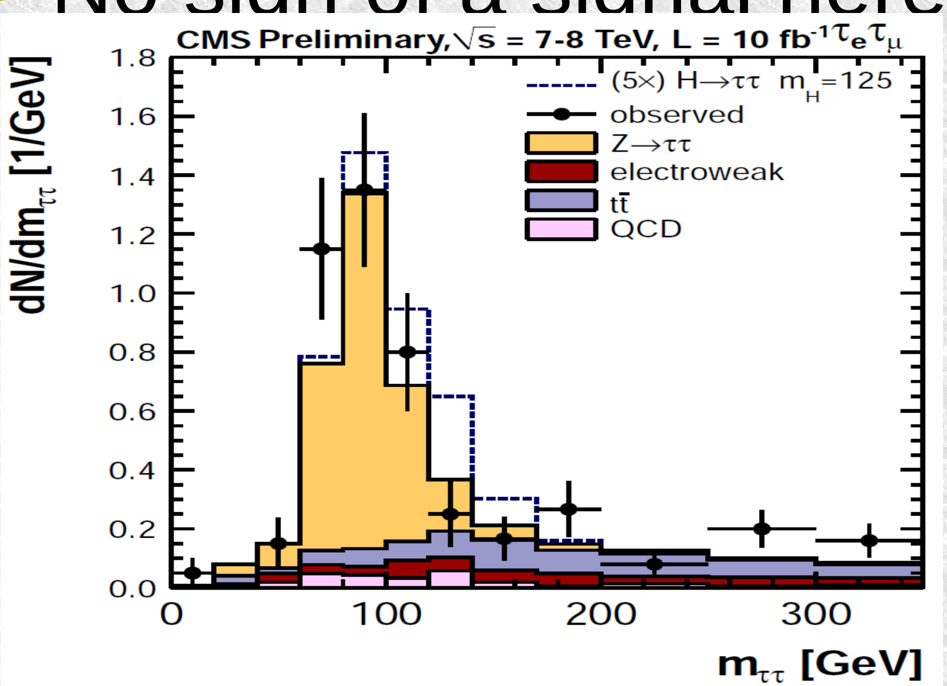
- 2011 results
- 20/29 GeV di-object trigger
- Only 1-jet category defined
  - lh in 4
  - Expect improvement
- QCD from data
- Z background from embedding

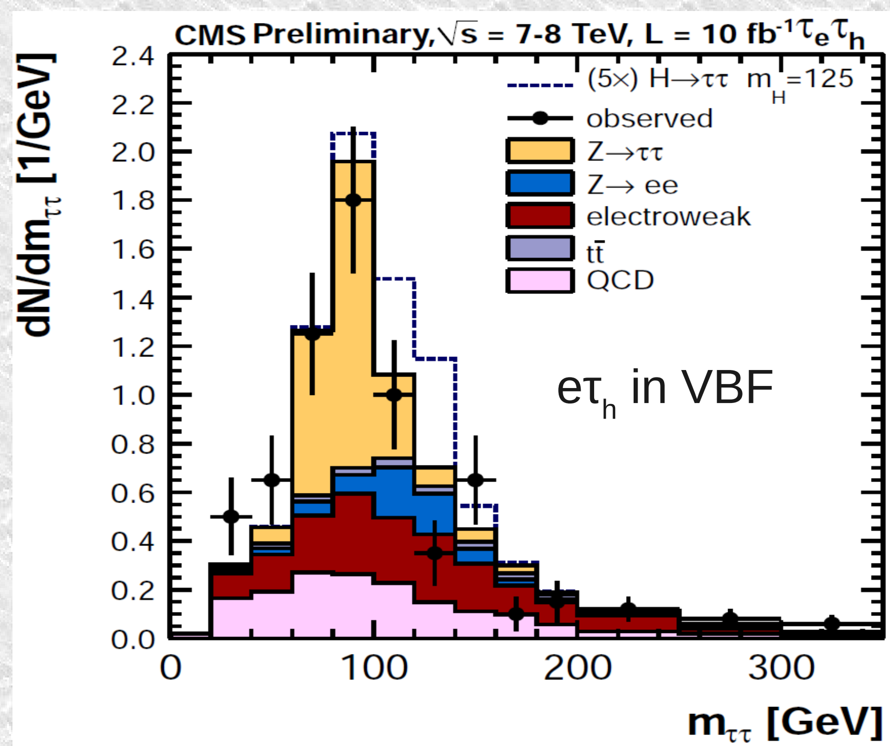


CMS VBF H → ττ

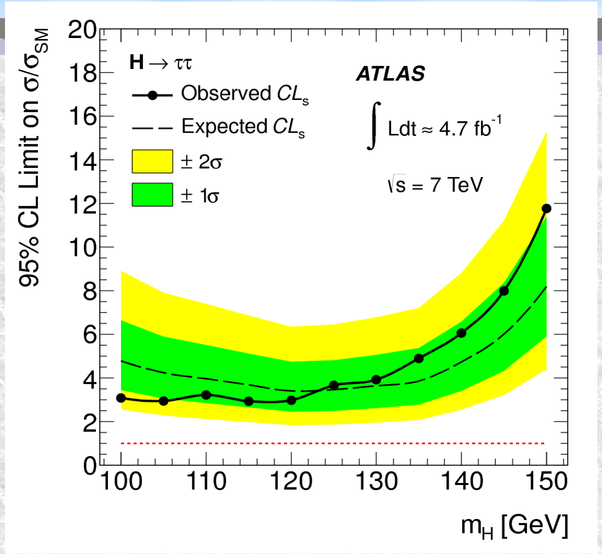
- Best fermion decay mode
- Using many combinations:
  - eτh, μτh, eμ, μμ decays
  - 0jet/1jet * high/low p_T, + VBF
- No sign of a signal here



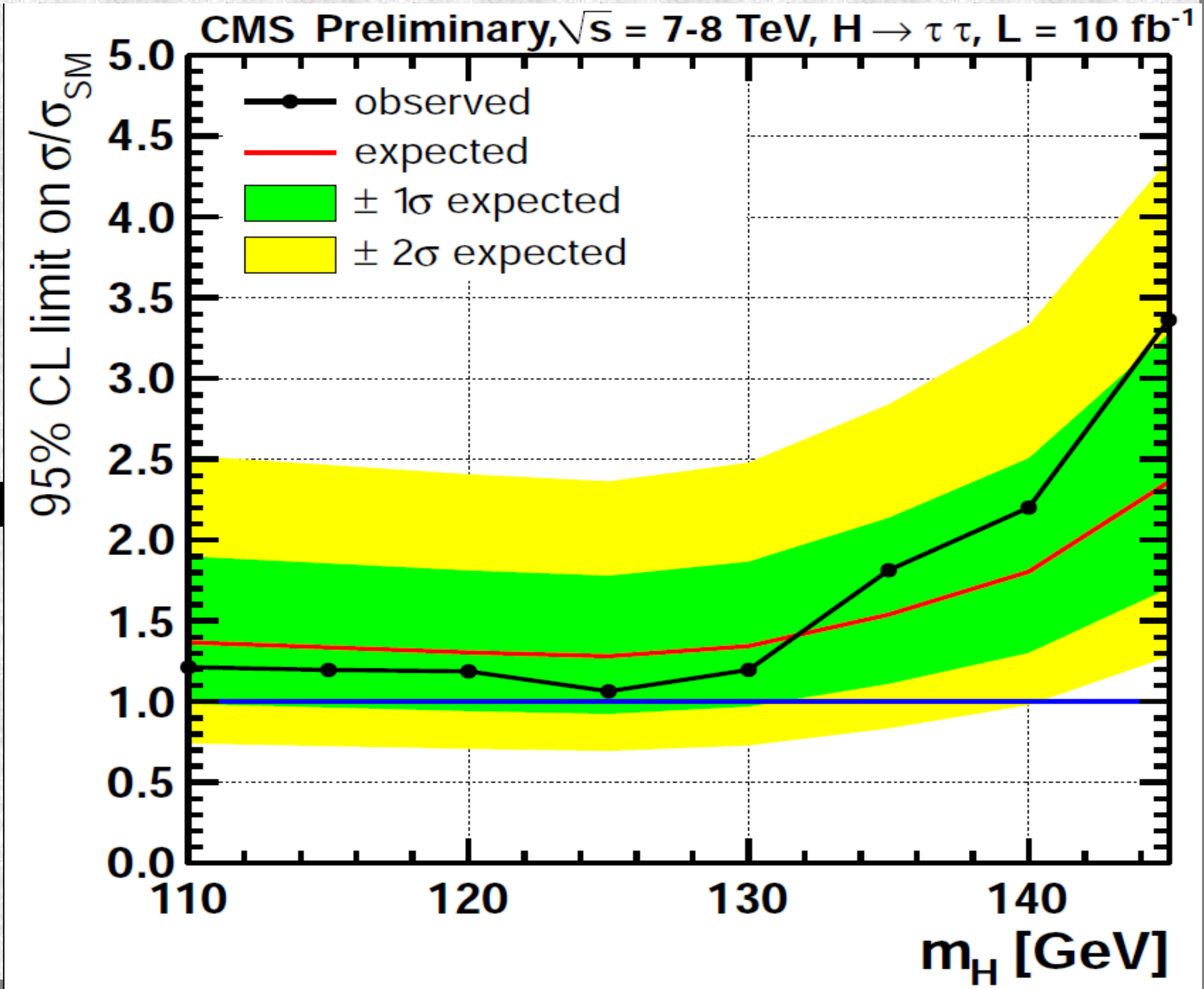




CMS H →ττ results



- ATLAS have 2011 result only
- CMS combined tau result has no excess
- Sets limit 1.1xSM Higgs



$H \to b\bar{b}$

- Dominant decay mode for m_H<130GeV
  - Gluon fusion is buried under background
  - VBF might be accessible
    - Trigger is hard.
    - Suggestion of photon associated?
      - ??
  - WH/ZH are best modes at Tevatron
    - Inclusive & boosted approaches at LHC
  - ttH is tough – many jets
    - Too much QCD radiation
    - Rate suppressed at 7/8TeV w.r.t. 14TeV

$VH \rightarrow b\bar{b}$

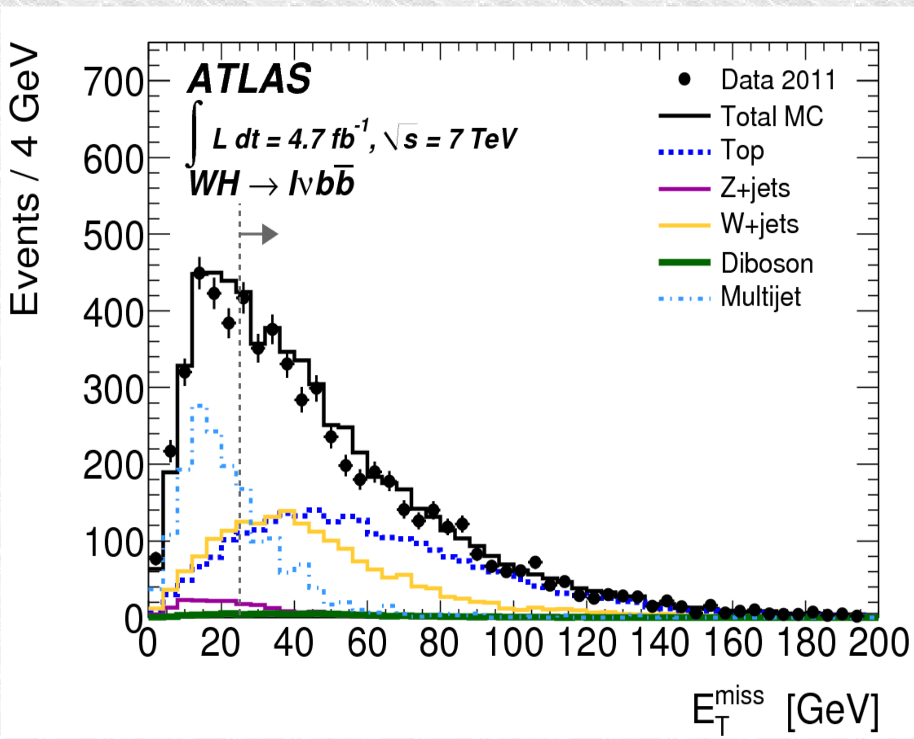
- Vbb has big backgrounds
  - Signal has harder p_T spectrum than most
    - This was suggested in context of boosted analyses
    - Not used (yet) but s/b at high p_T is exploited
- Three modes used, with sub-bins of p_T
  - ννbb :
    - p_T>120GeV to trigger events
  - lνbb :
    - p_T>120GeV to reduce $t \rightarrow Wb$ contribution
  - llbb:
    - p_T bins to exploit difference
- Fitting in multiple bins constrains e.g. Wbb p_T

$WH \to l\nu b\bar{b}$

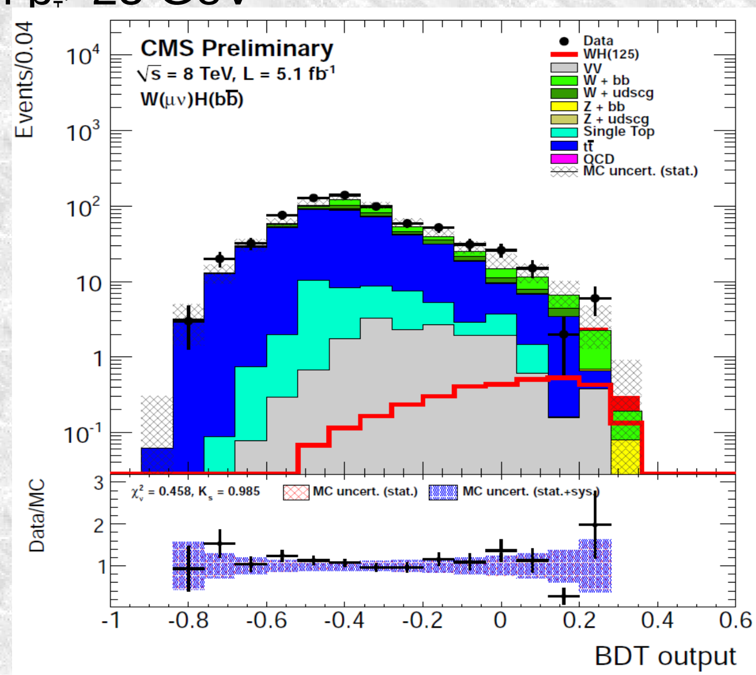
Select events with Z or W boson in the leptonic final state (used also to trigger the event), and with exactly two jets b-tagged with p_T>25 GeV

Backgrounds:

W+jets, Z+b-jets, top, QCD jets



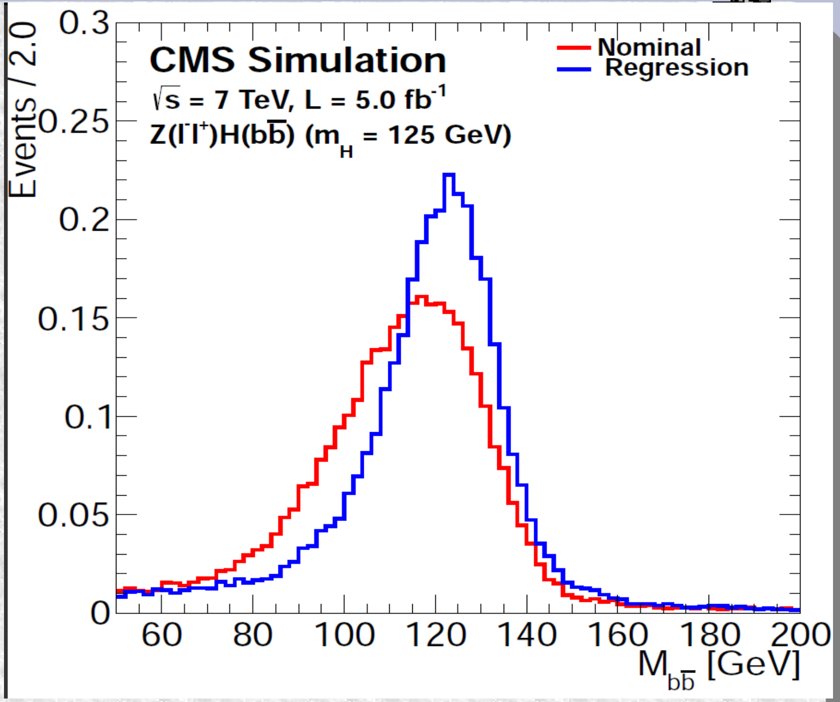
The E_t^{miss} for $WH \to l\nu bb$, showing the cocktail of backgrounds which complicates this channel



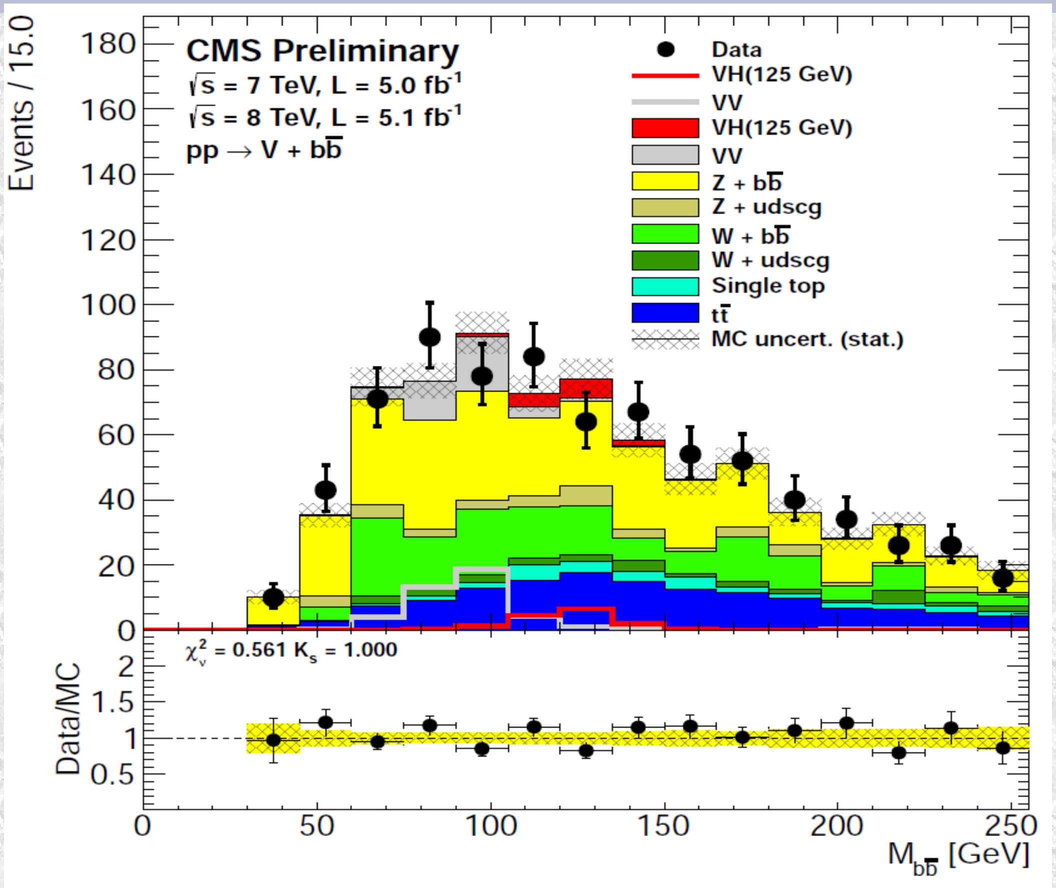
CMS use BDT to sort candidates in all channels

CMS H→bb mass resolution

- Optimisation of B jet energy scale a la CDF
  - secondary vertex position
  - 4-vector
  - Charged pt fraction
  - Jet shape
- Get 15% better resolution
  - 15% reduced background
  - Like 30% more luminosity



VH mass distribution



- This CMS plot combines all energies/channels in m_{bb} for display purposes
  - The analysis is BDT based

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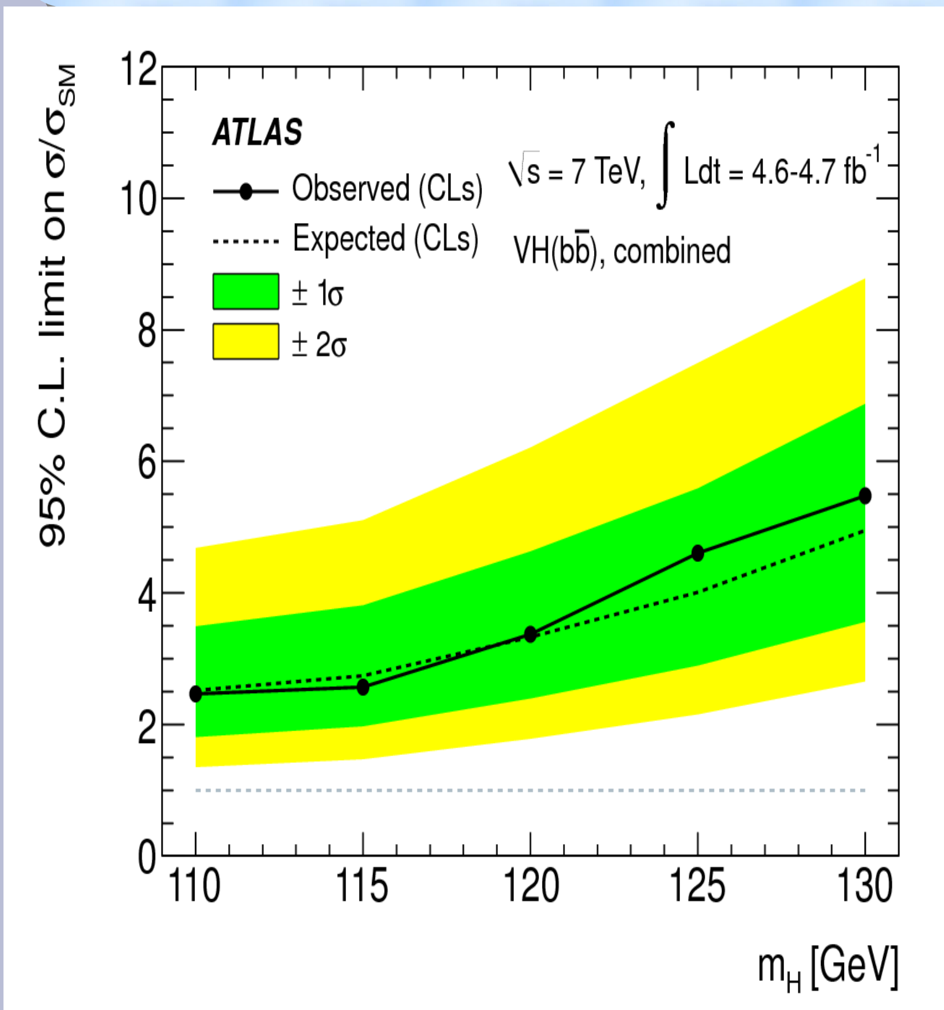
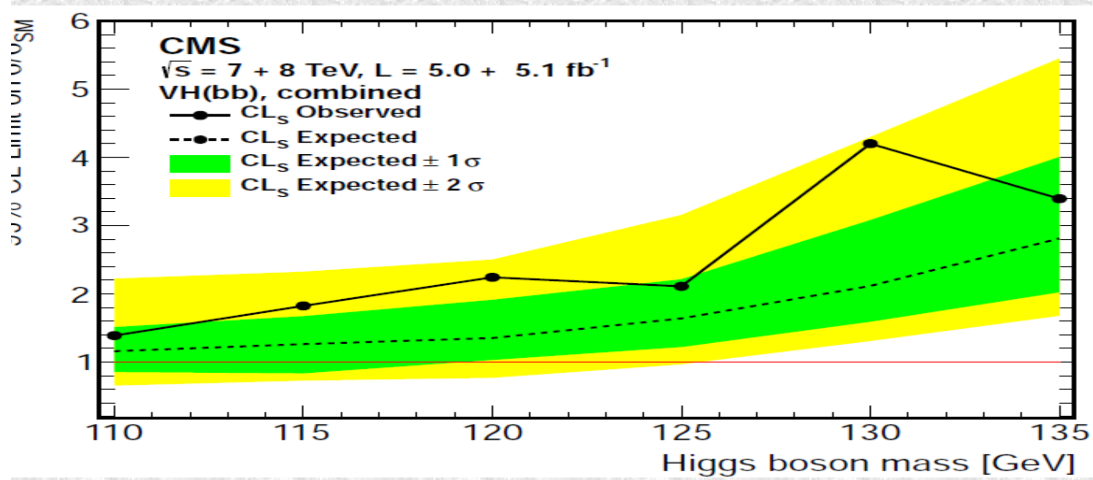
VH results



- CMS much more sensitive
  - 8TeV
  - Mass resolution improved
- Not much signal here!



- CMS sensitivity comparable to Tevatron
  - CDF: expected limit 1.39xSM at 125GeV
  - CMS: expected limit 1.64xSM at 125GeV

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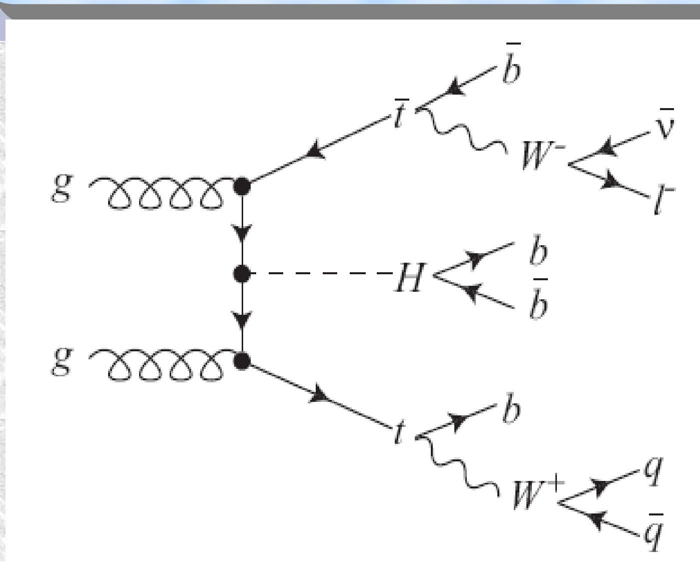
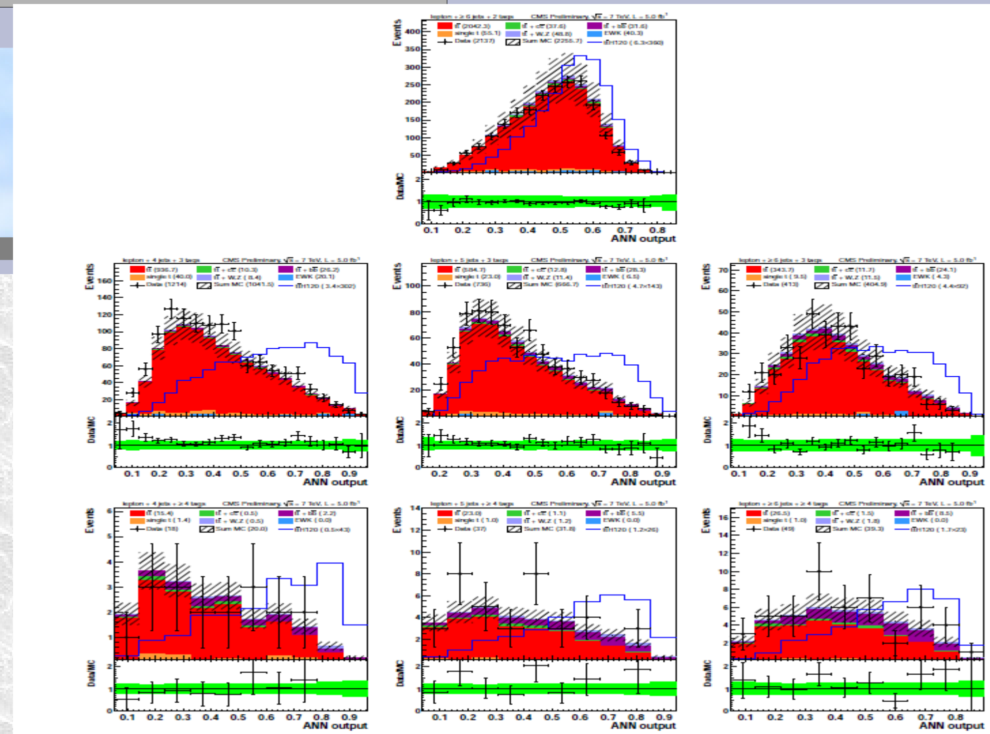
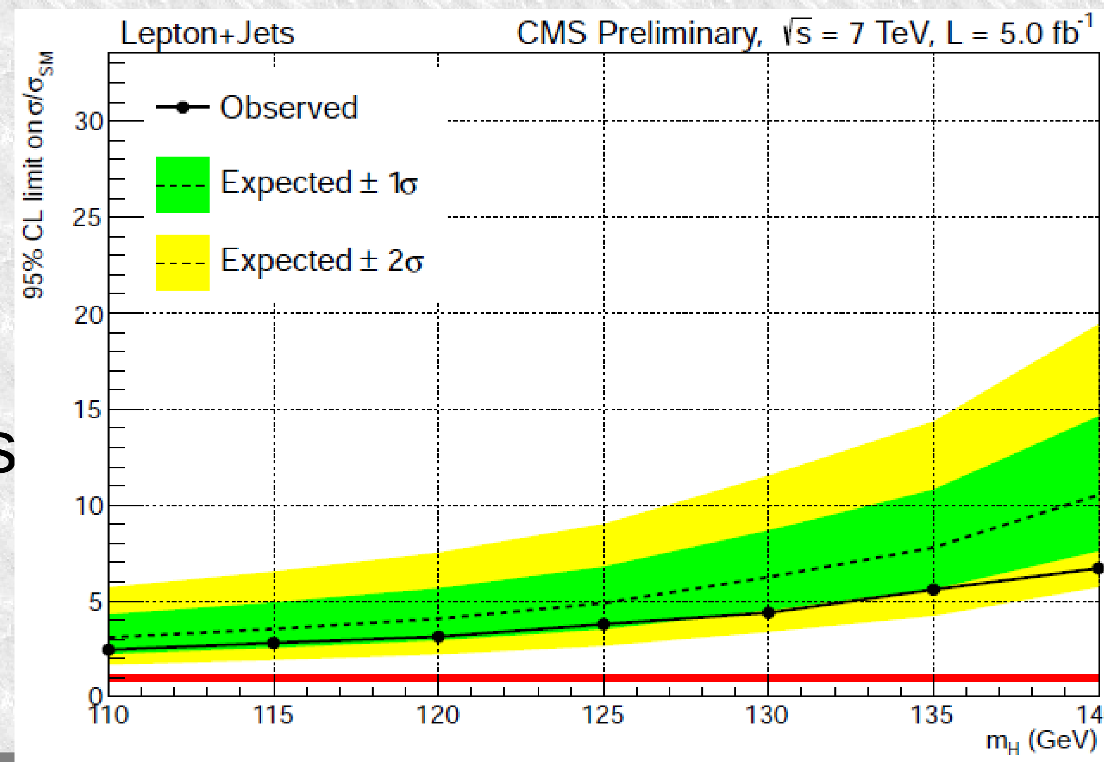
ttH, H to bb

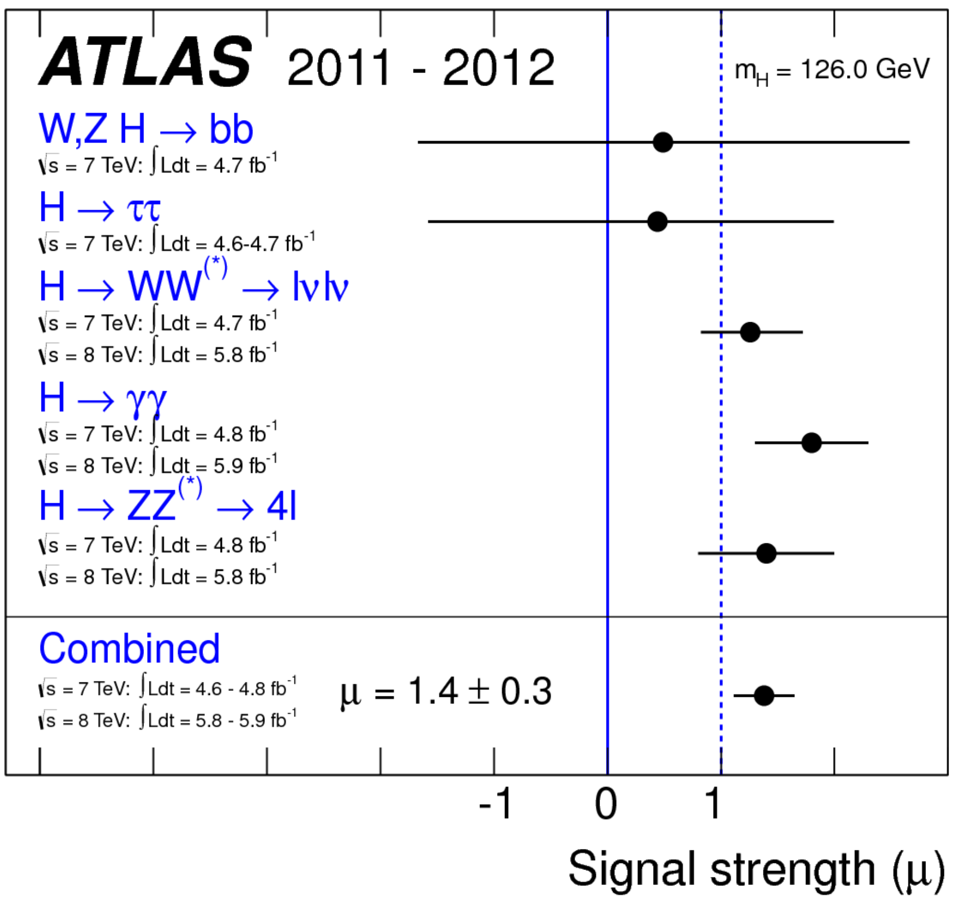


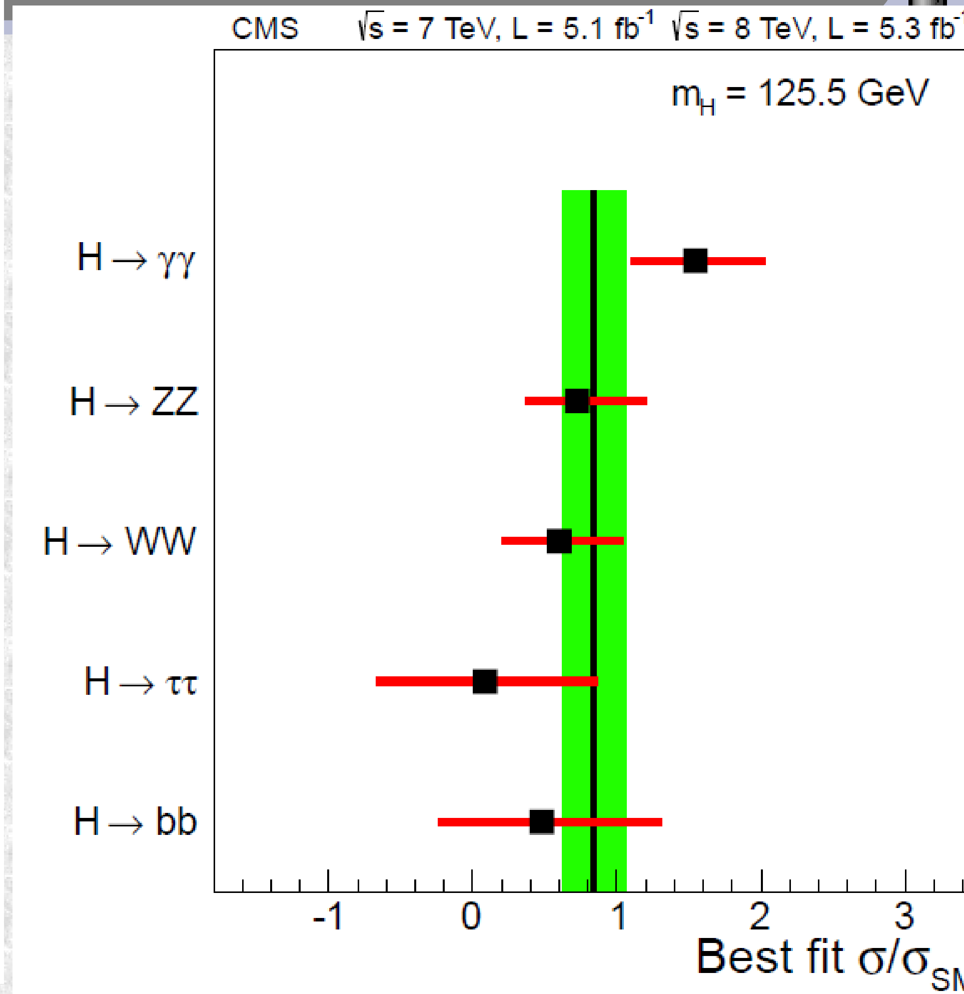


- New CMS result
  - 2011 data
- Multiple channel
  - 1 or 2 leptons
  - Many jet combinations
- Sensitivity 5xSM
  - Good start..
  - Constrains couplings



Conclusions





- Most channels favour a signal
  - More powerful ones (WW,ZZ,γγ) all do.
- Discuss combination/interpretation on Monday

Conclusion

- Tevatron still interesting, especially for m_H~115
  - But would 2σ exclusion of SM satisfy?
- A conclusive discovery requires LHC
- At least 2σ across 115-500 available in 2011

- Where we have got to I address tomorrow