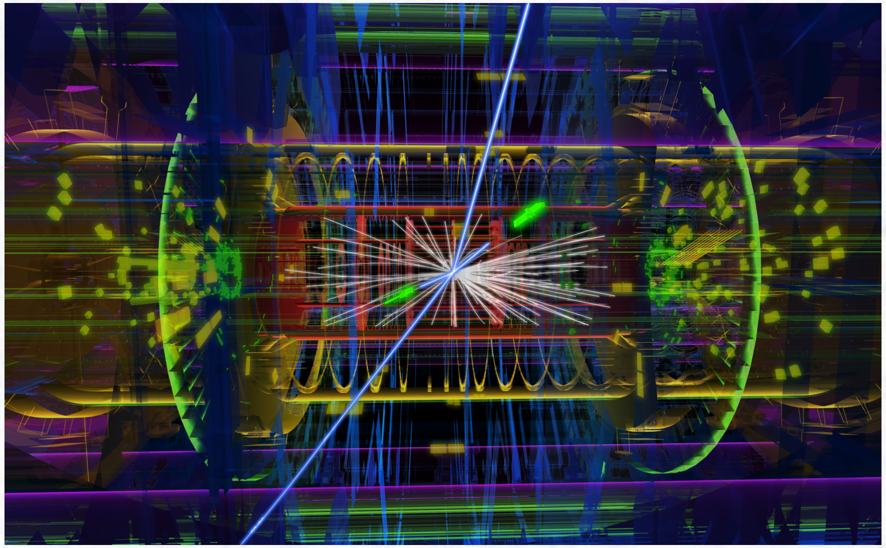
Higgs analyses at the LHC

Part Ib: H → ZZ* and WW*
Part II: The fermionic channels



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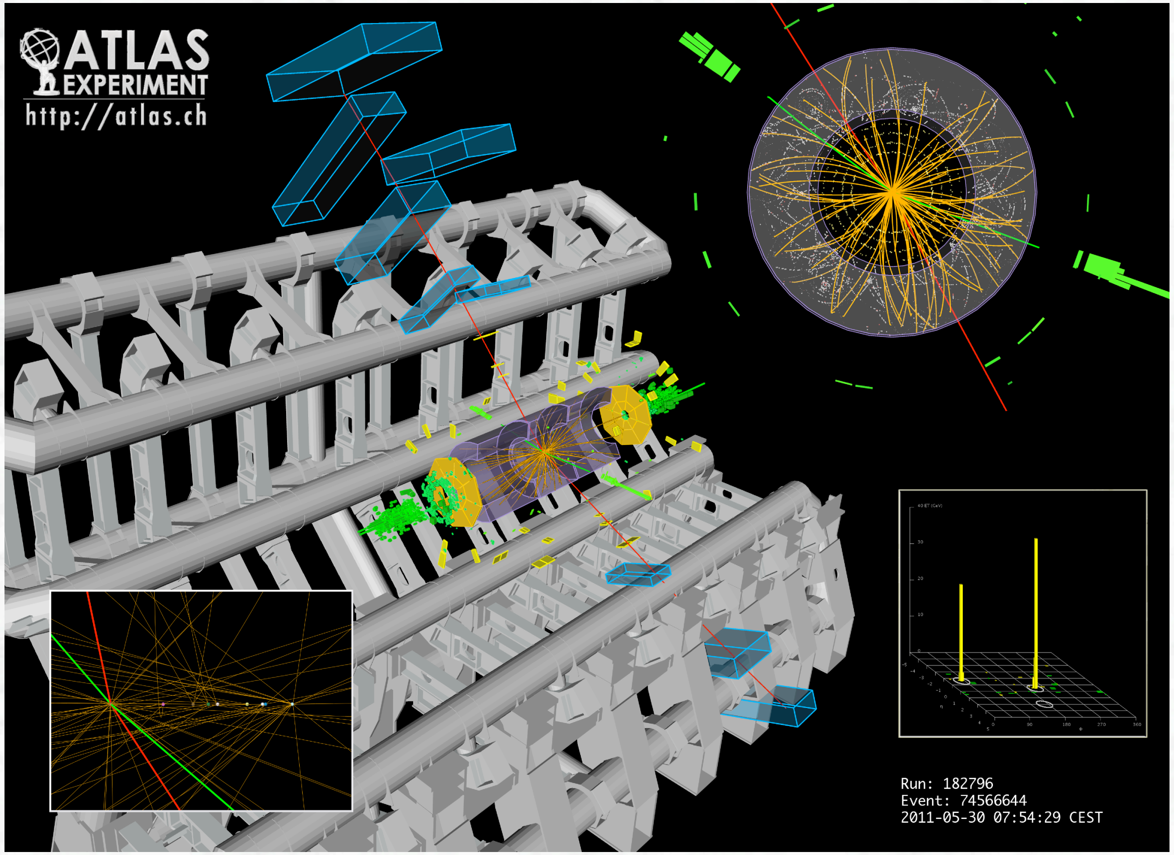
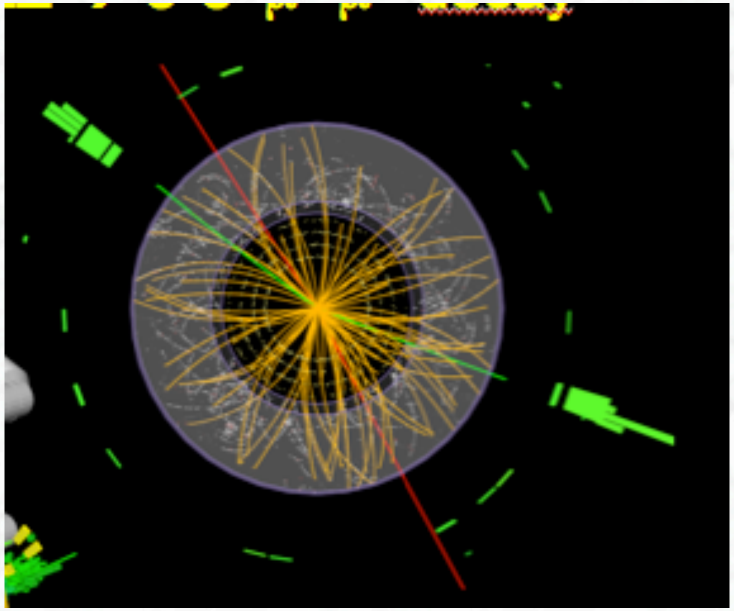
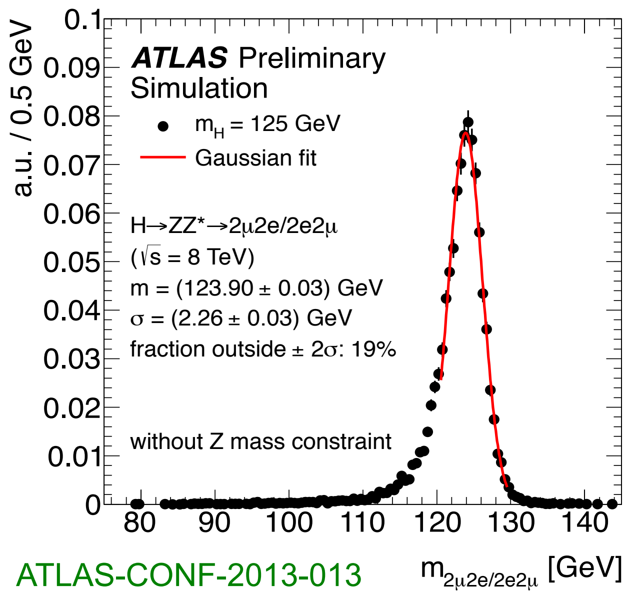
$H \rightarrow ZZ^* \rightarrow e^+e^- \mu^+ \mu^-$



- Clean experimental signature (4 leptons), good S/B
- Very small signal rate (leptonic branching ratios)

Search for the H → ZZ* → ℓ⁺ℓ⁻ ℓ⁺ℓ⁻ decay





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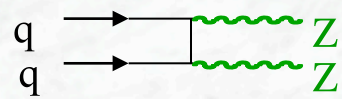
- The "golden mode": 4 isolated leptons
  e: $P_T > 20$, 15, 10, 7 GeV, $|\eta| < 2.47$
  μ: $P_T > 20$, 15, 10, 6 GeV, $|\eta| < 2.7$
  One pair consistent with Z mass (m_{12})
  Mass of other pair: $m_{min} < m_{34} < 115$ GeV

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

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

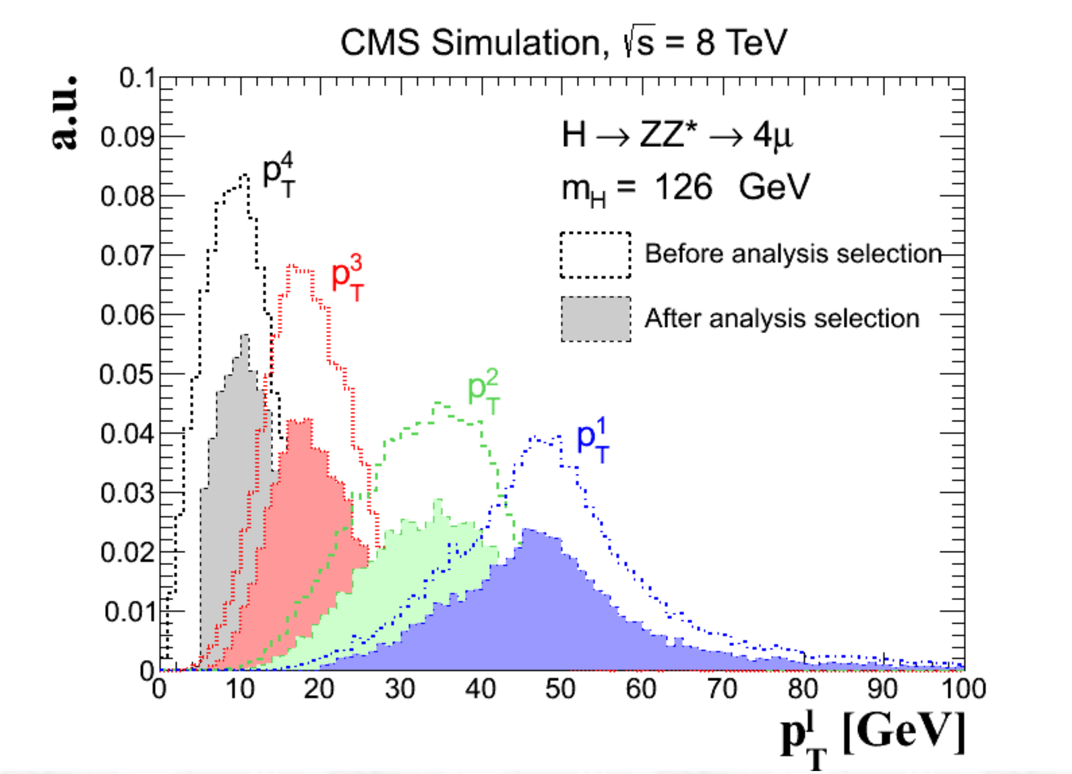
- Low signal rate, but also low background
  - Mainly from ZZ continuum



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

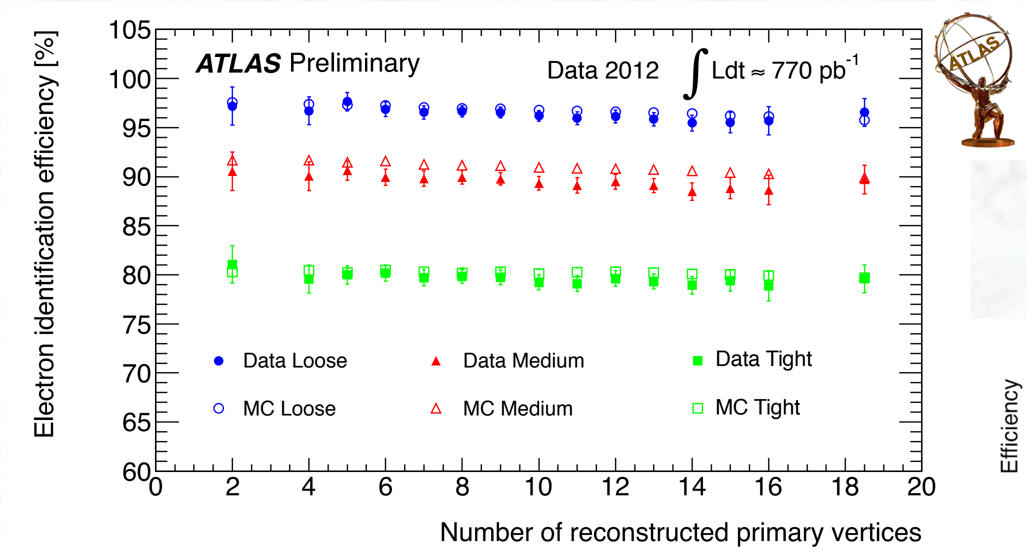
126 GeV is a low mass for ZZ* decays

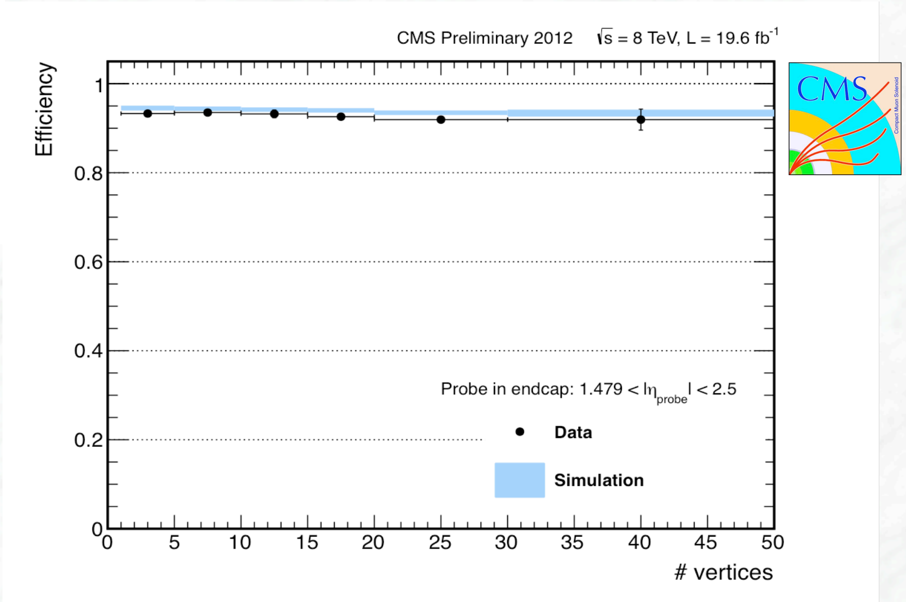
→ low p_T leptons are required



Electron performance

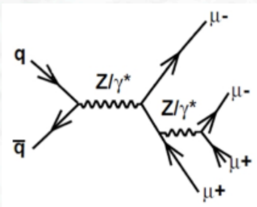
Stability of the electron identification: efficiency versus number of reconstructed primary vertices

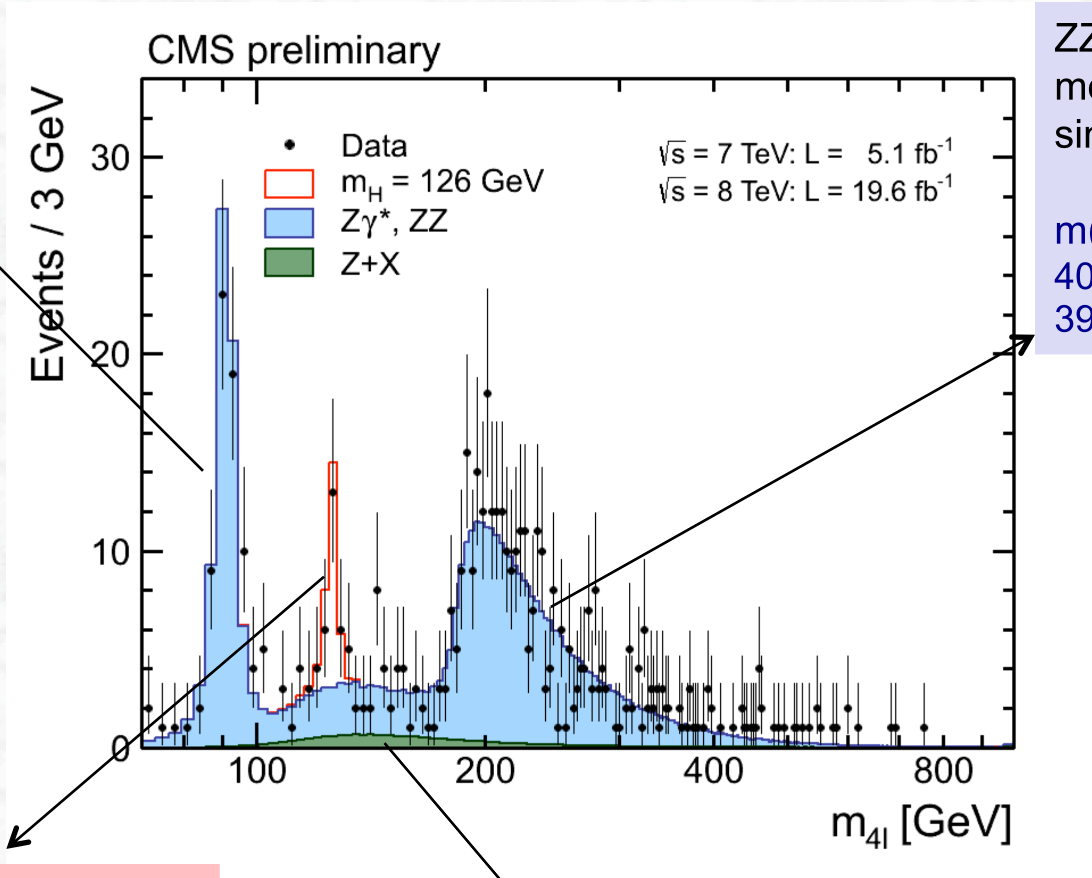




CMS: 4ℓ invariant mass spectrum

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





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

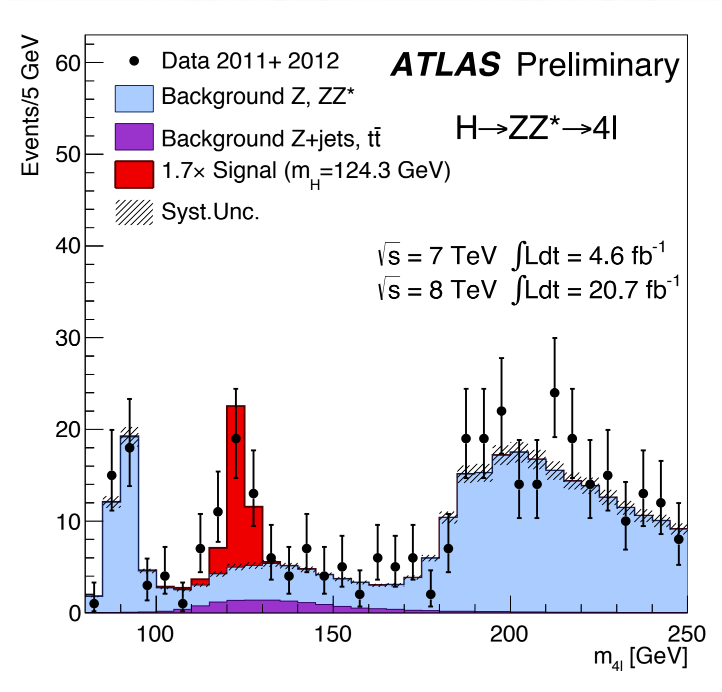
m(4ℓ) > 140 GeV:
403 events observed
390 events expected

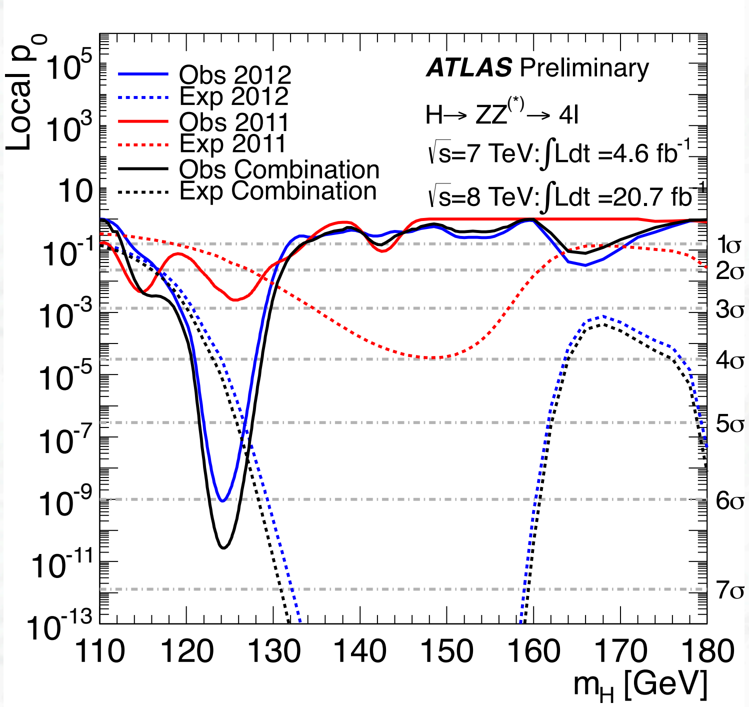
H → ZZ* signal

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

Reducible tt, Zbb, and Z+jets background, data driven estimates

ATLAS: 4ℓ invariant mass spectra





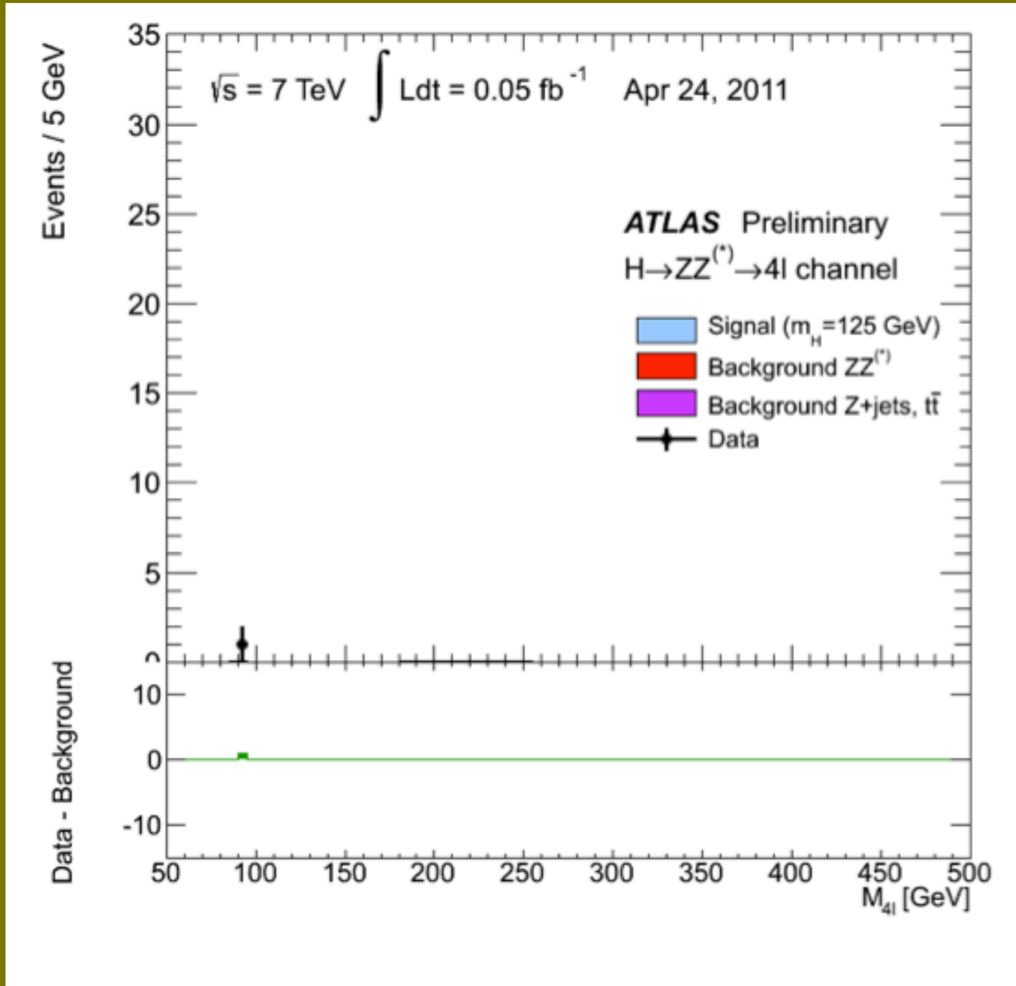
Mass range 120 – 130 GeV	Expected signal	Background	Data
√s = 7 TeV	2.2	2.3	5
√s = 8 TeV	13.7	8.8	27

$m_{4\ell}$ > 160 GeV: 376 events observed
348 ± 26 expected from background (mainly ZZ)
√s = 7 + 8 TeV

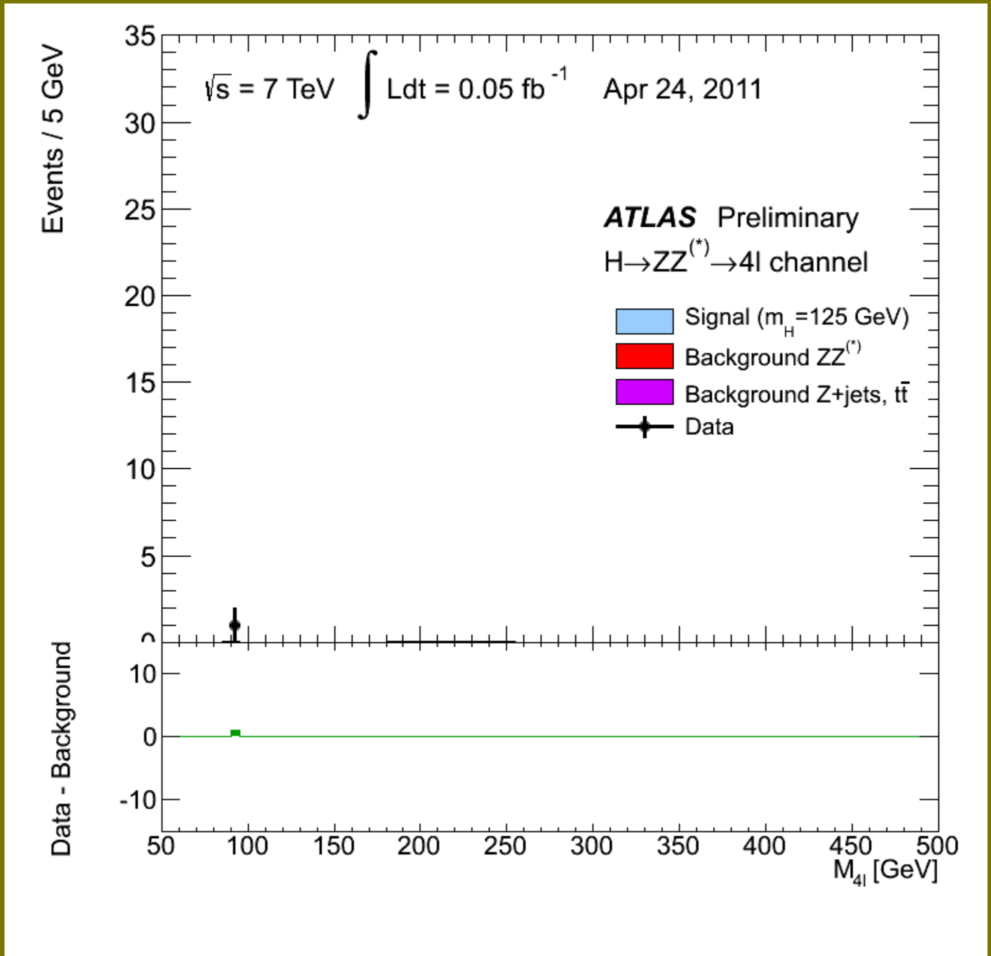
- maximum deviation at 124.3 GeV
  p_0 value: ~2.7 10^{-11} (6.6σ obs.)
  (4.4σ exp.)

- Independent discovery-level observation

Time evolution of the H → ZZ → 4ℓ signal

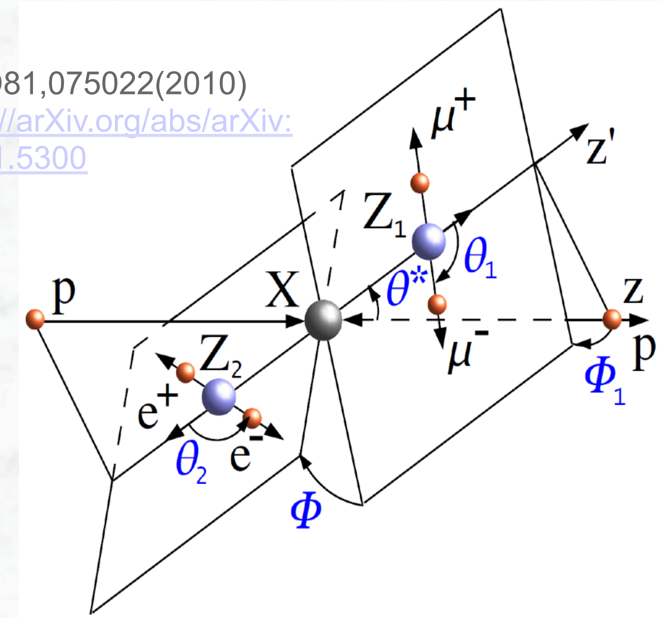


Time evolution of the H → ZZ → 4ℓ signal



CMS: use additional information on decay kinematics, MELA discriminant

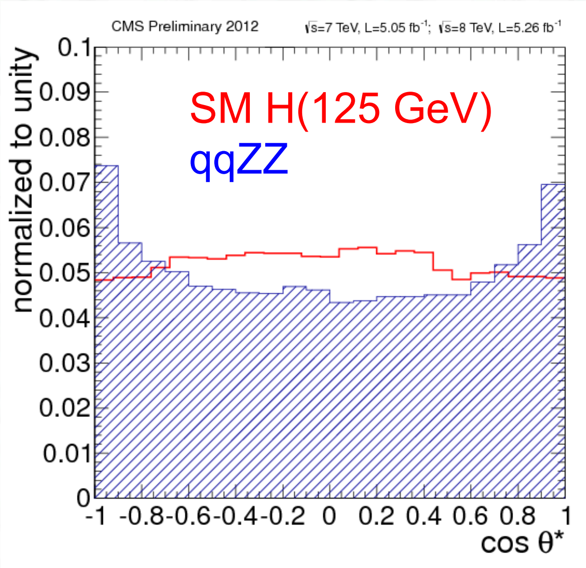
PRD81,075022(2010)
http://arXiv.org/abs/arXiv:1001.5300

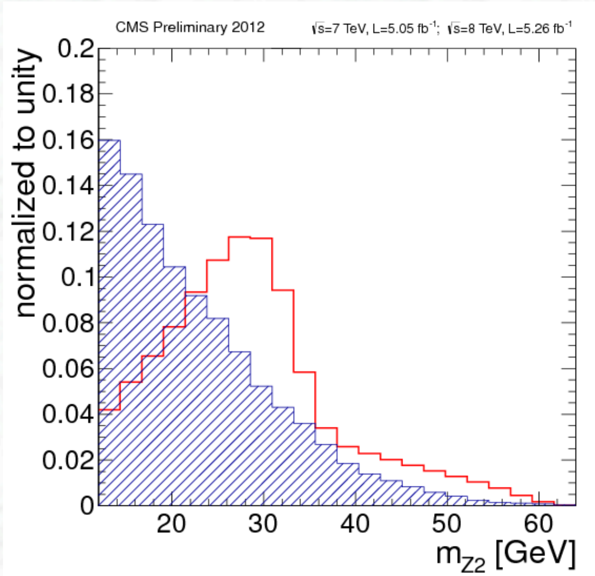


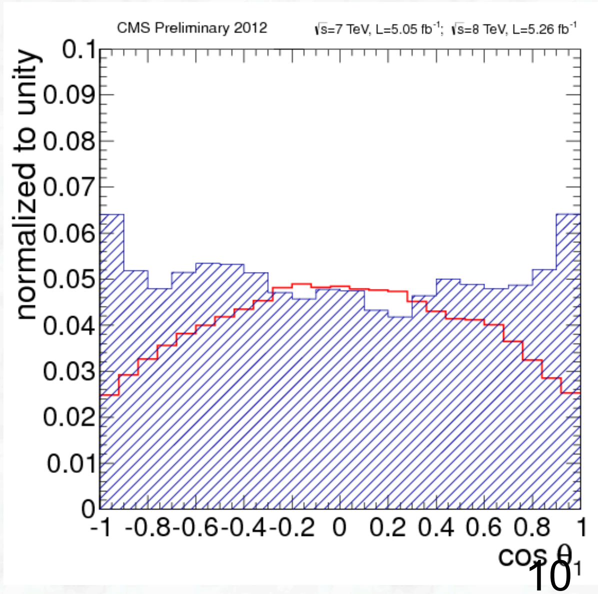
Matrix Element Likelihood Analysis:

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

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

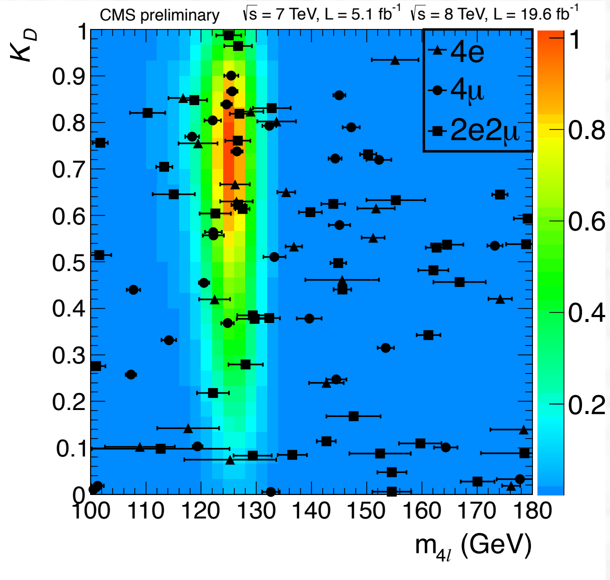


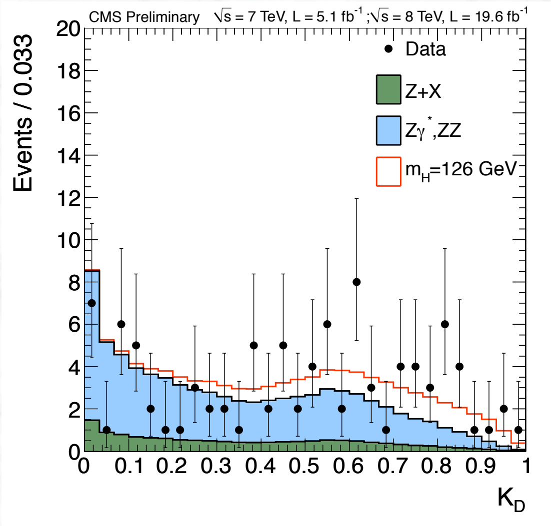




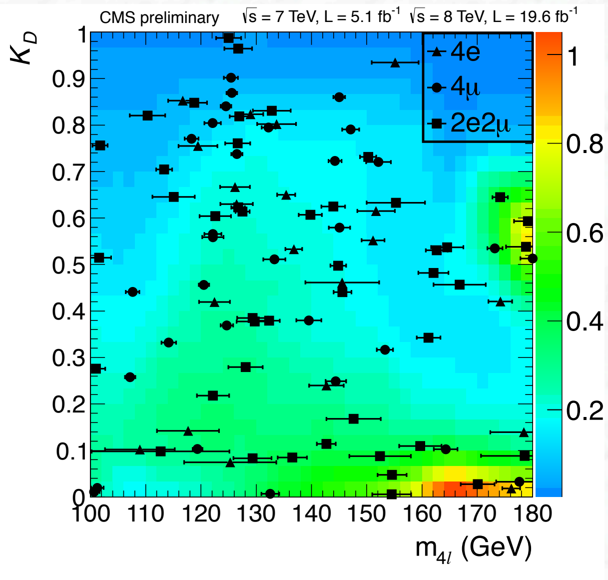
2D analysis using $\{m_{4\ell}, MELA=K_D\}$

contours = signal expectation

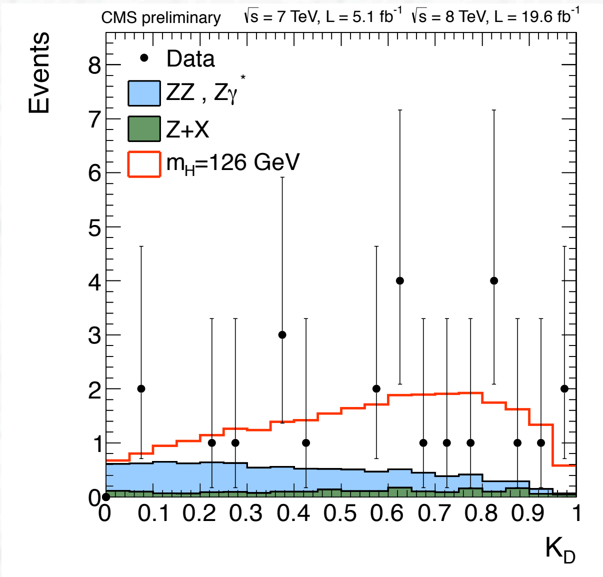




contours = background expectation



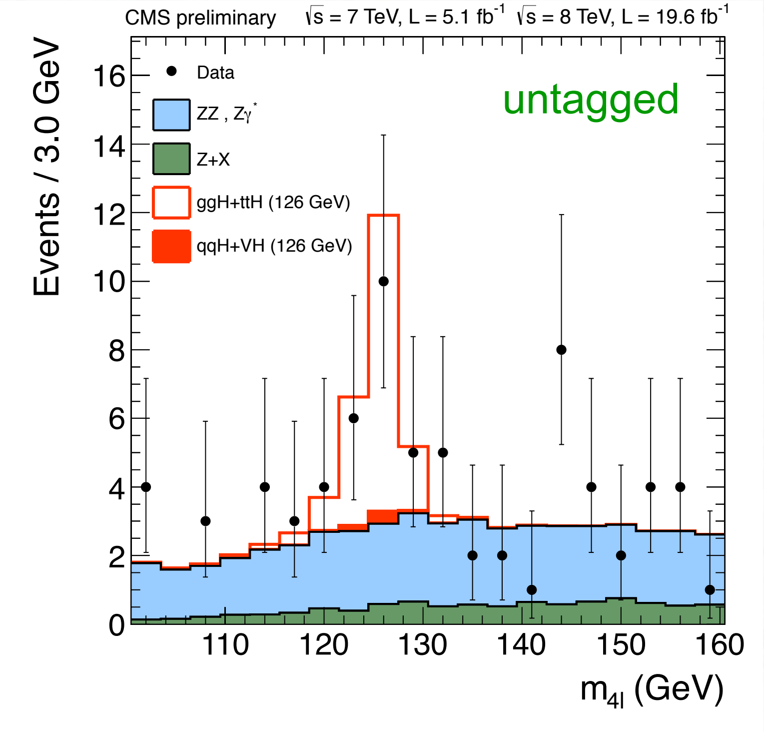
$121.5 < m_{4l} < 130.5$ GeV

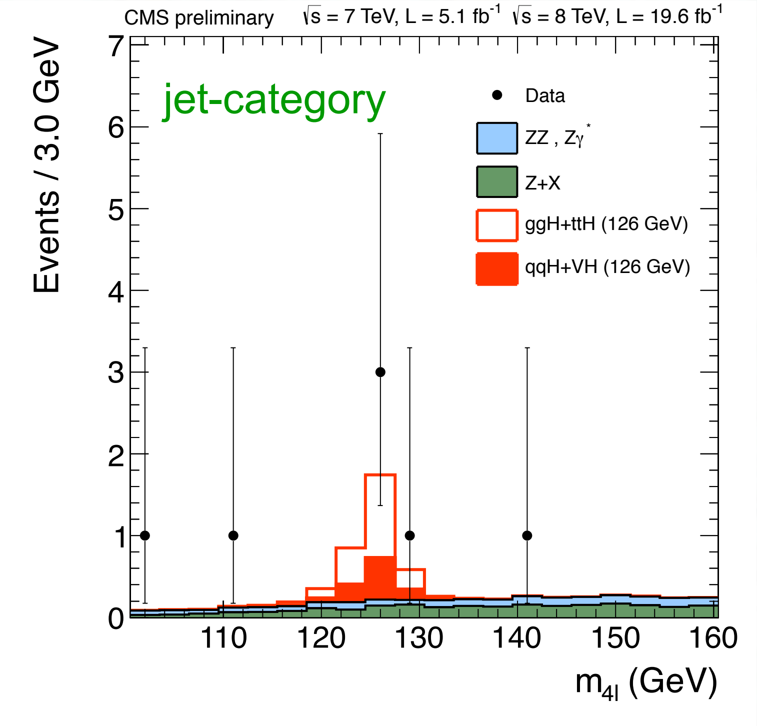


CMS: further refinement via jet categorization

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

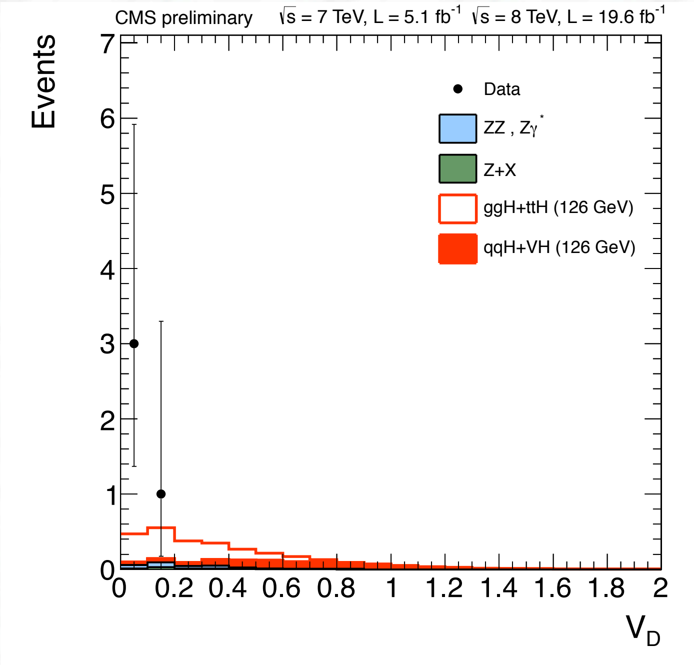
(ii) Untagged: all other events (VBF fraction ~5%)

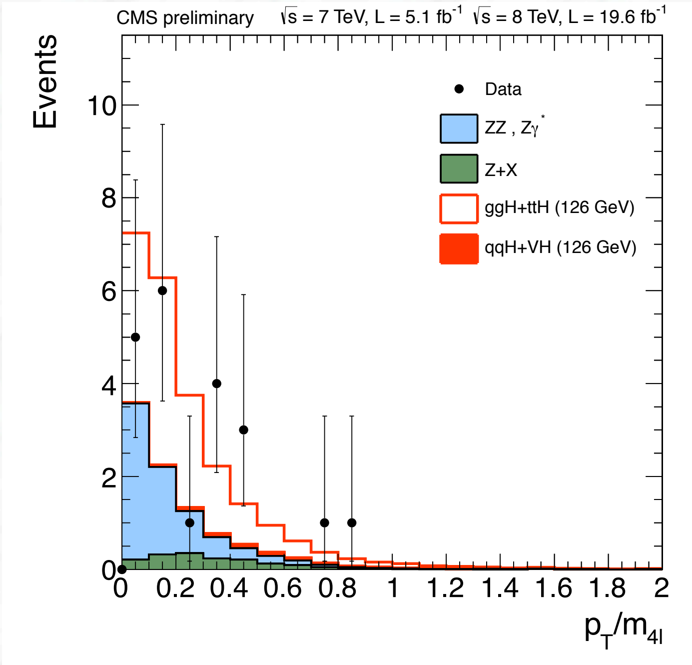




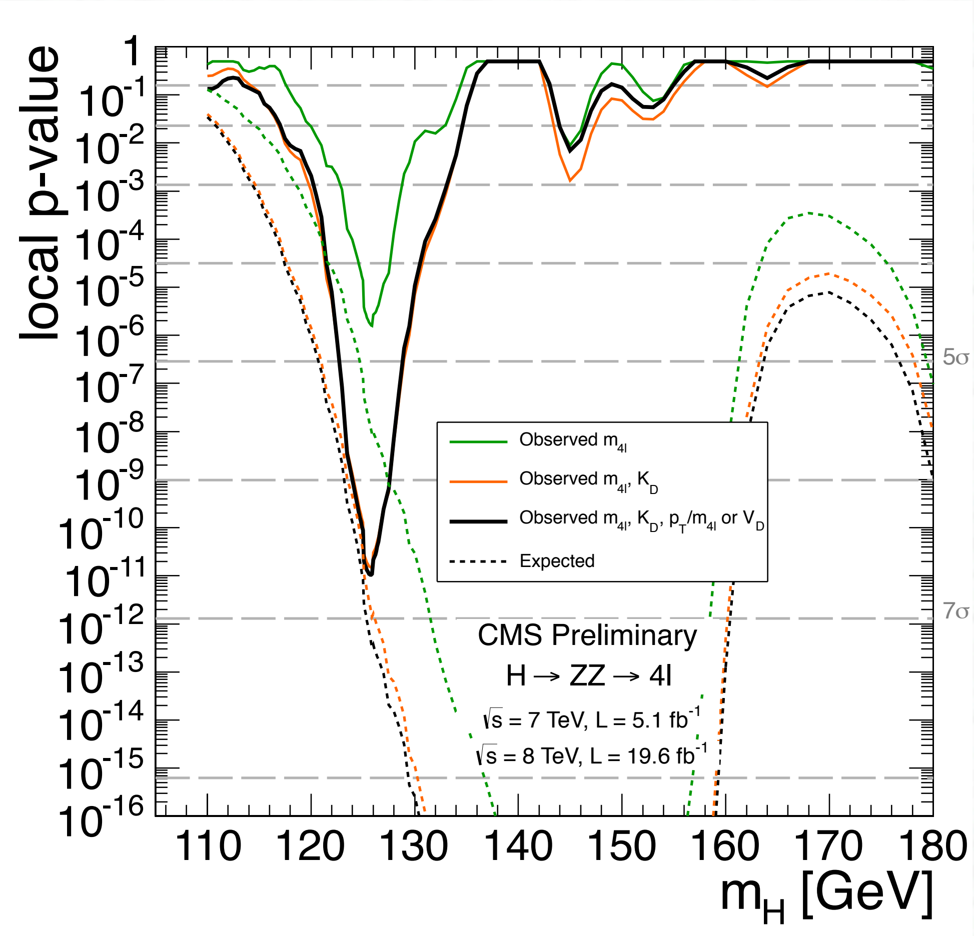
CMS: further refinement via additional discriminants -to separate production modes-

- VBF-discriminant: $V_D = \alpha\, |\Delta\eta_{jj}| + \beta\, m_{jj}$
- P_T boost: $P_T(4\ell) / m_{4\ell}$





CMS H → ZZ* significance

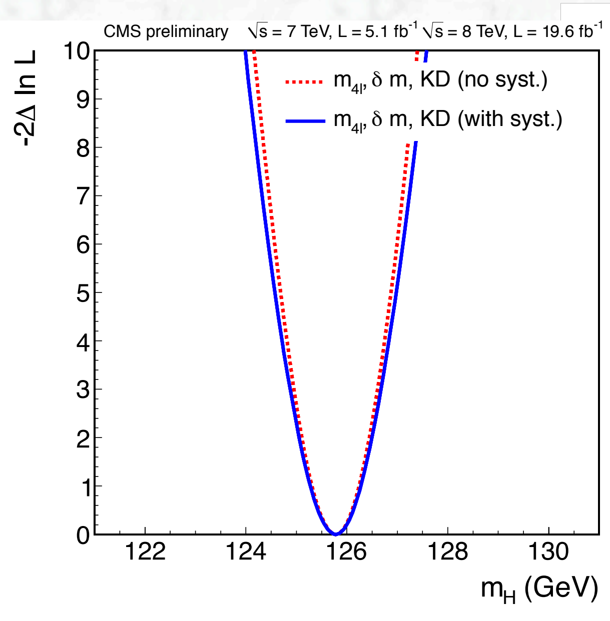


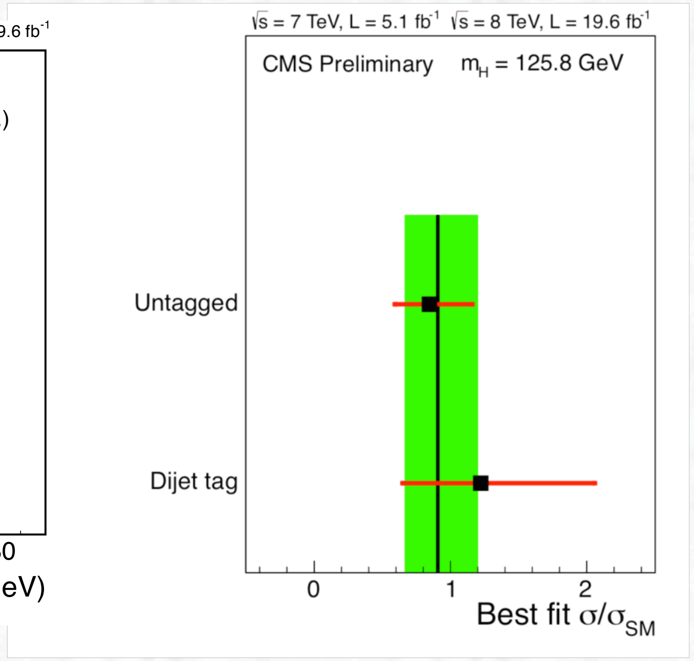
	Expected	Observed
3D (m_{4l}, K_D, V_D or p_T/m_{4l})	7.2 σ	6.7 σ
2D (m_{4l}, K_D)	6.9 σ	6.6 σ
1D(m_{4l})	5.6 σ	4.7 σ

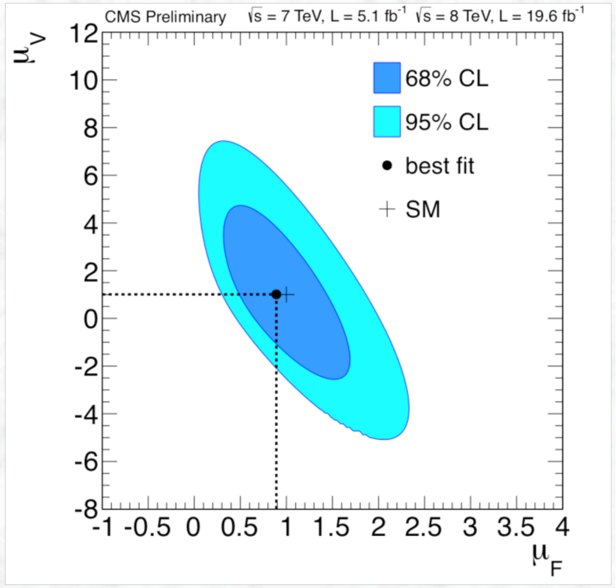
at 125.8 GeV (minimum of local p value)

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

Mass and signal strength for $H \to ZZ^*$







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

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

Mass and signal strength for H → ZZ*

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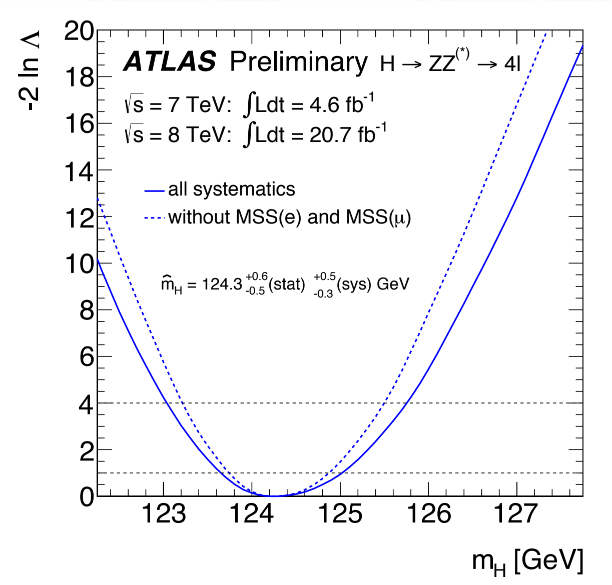
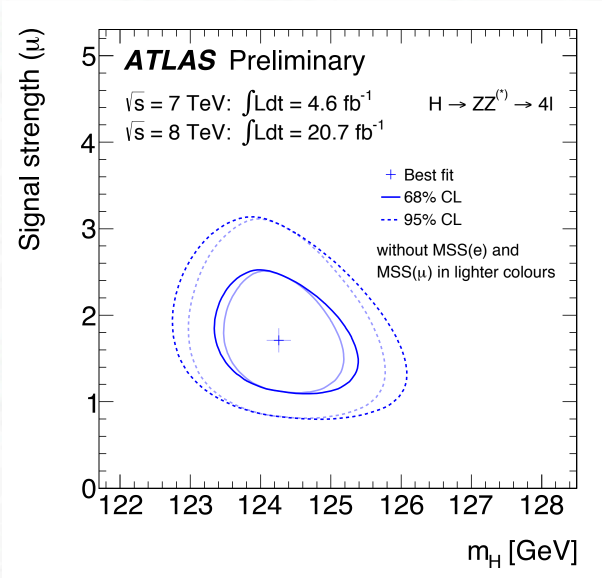
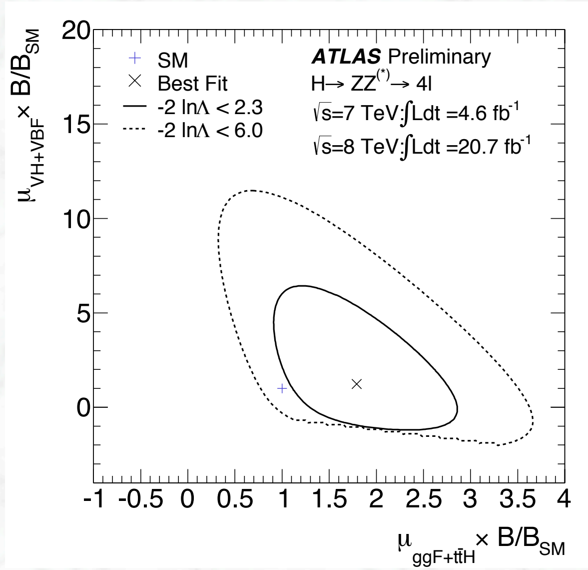


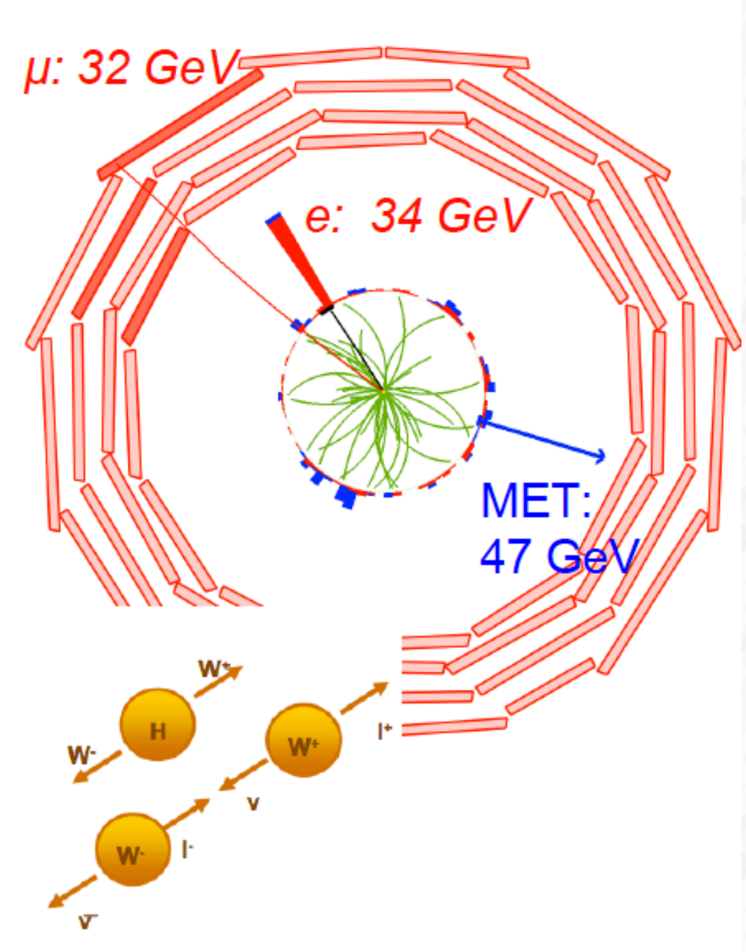




Mass: $m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\ \text{GeV}$

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

Search for H → WW → ℓν ℓν decay



- Two high p_T leptons (e or μ)

  Leptons from Higgs decay (spin-0 particle) are expected to have a small angular separation

- Two neutrinos

  → large missing transverse energy

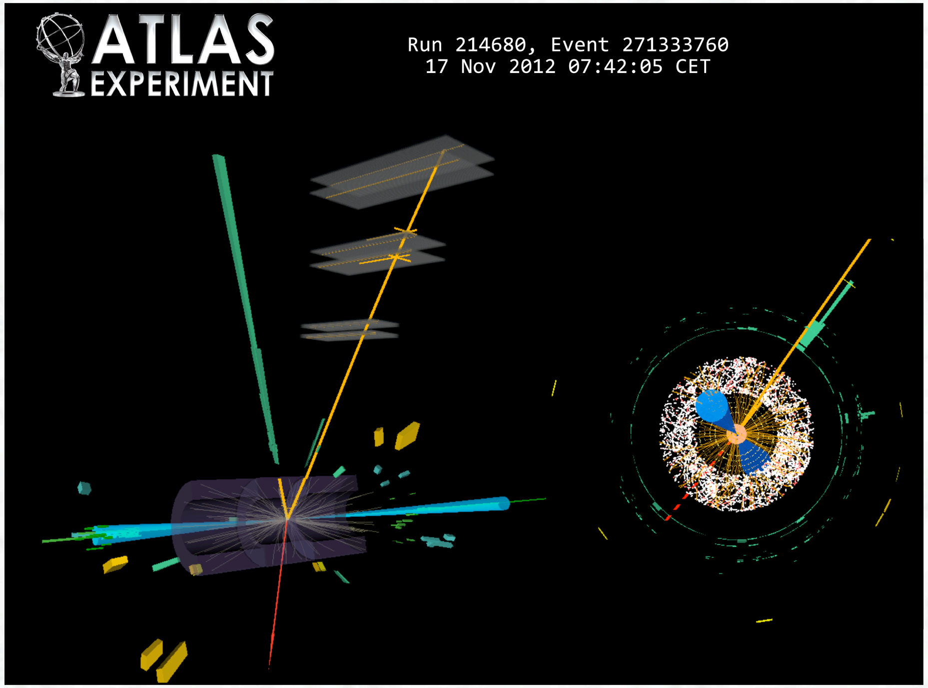
  → Higgs boson mass cannot be reconstructed, use transverse mass

- Highest sensitivity around 160 GeV

  (nearly 100% H → WW branching ratio)

  → Tevatron sensitivity and early LHC sensitivity in that mass region

What are the main backgrounds?



Final state signature:

- Two isolated, high p_T leptons;
  use all combinations: $e\mu$, μe,
  ee, $\mu\mu$

- Missing transverse momentum

- Jets
  Depend on production process:
  gluon fusion (0, 1 jets), VBF: 2 jets

→ Split analysis in jet multiplicity
0,1 and 2 jets

Major backgrounds:

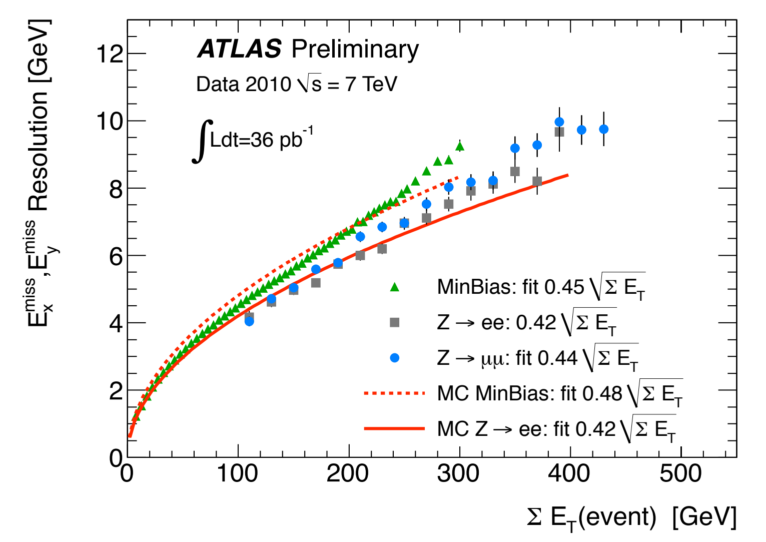
- Di-boson production, in particular WW production (0 jet, 1 jet)
- tt background (1, 2 jets)
- Z+jets [Drell-Yan], in particular for ee/$\mu\mu$ pairs;
  More difficult to reject at high luminosity

Missing Transverse Energy

- The missing transverse energy is a key signature for many measurements

- Calculated by summing all energy deposits in the calorimeter (based on identified objects: e, γ, τ, jets >20 GeV, soft energy depositions incl. tracks, and muons

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,SoftTerm}} + E_{x(y)}^{\text{miss},\mu},$$



- Resolution depends on total transverse energy (→ plot from early data taking)

Resolution of E_x^{miss} and E_y^{miss} as a function of the total transverse energy in the event. The resolution in Z→ee and Z→μμ events is compared with the resolution in minimum bias events for data taken at √s = 7 TeV.

- Missing transverse energy measurement is strongly affected by pile-up !

  → needs pile-up suppression

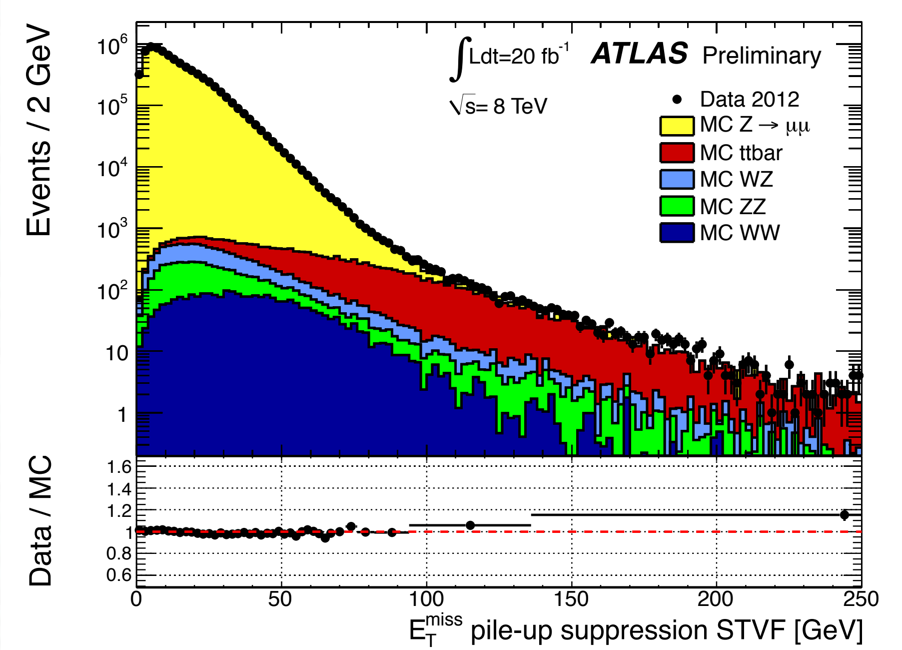
Missing Transverse Energy (cont.)

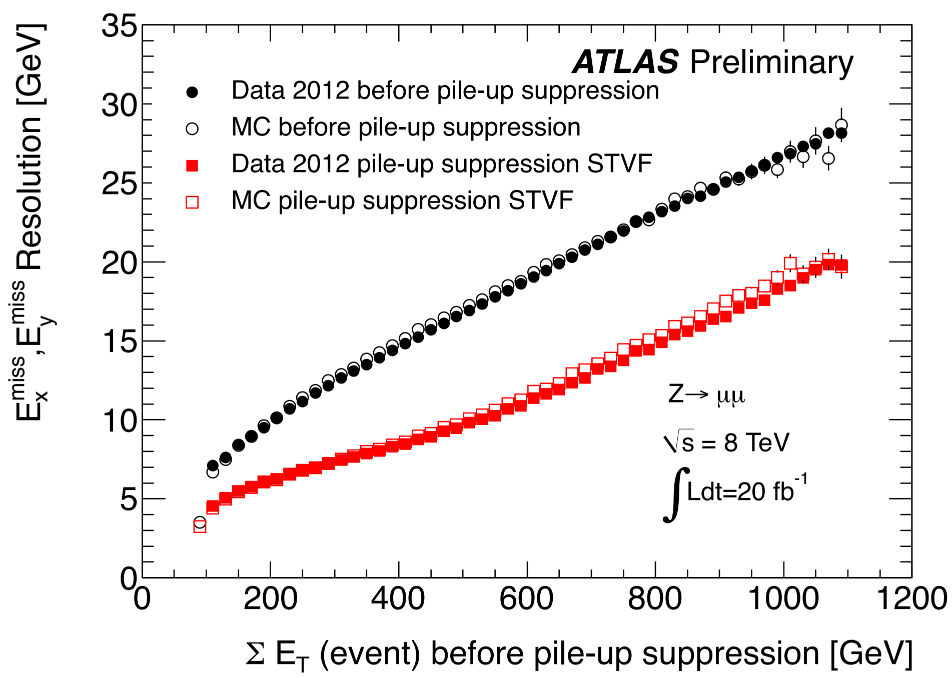
- Suppress pile-up contributions using tracking detector
- Include only jets whose tracks have a high vertex fraction

$$\mathrm{JVF} = \sum_{\mathrm{tracks_{jet},PV}} p_{\mathrm{T}} / \sum_{\mathrm{tracks_{jet}}} p_{\mathrm{T}}$$

- Scale Soft Term by Vertex Fraction

$$\mathrm{STVF} = \sum_{\mathrm{tracks_{SoftTerm},PV}} p_{\mathrm{T}} / \sum_{\mathrm{tracks_{SoftTerm}}} p_{\mathrm{T}}$$





- Good description of the missing transverse energy distribution/resolution by the Monte Carlo simulation

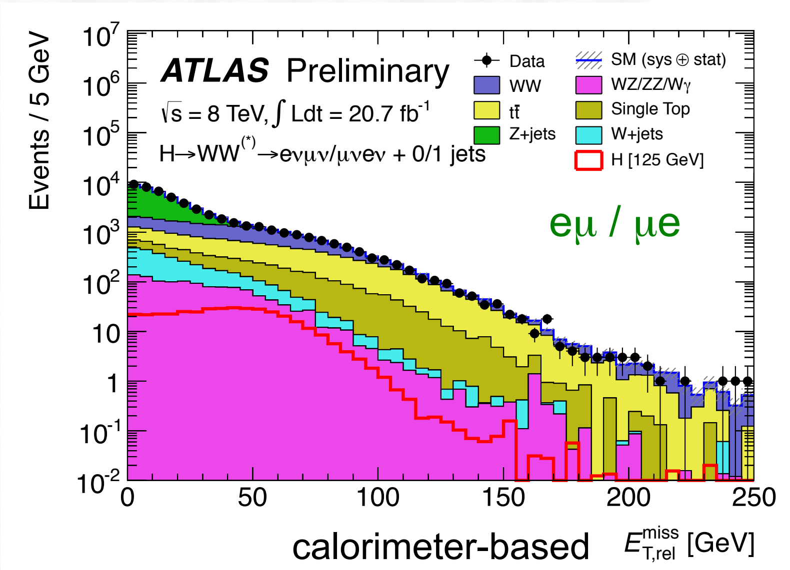
Search for H → WW → ℓν ℓν

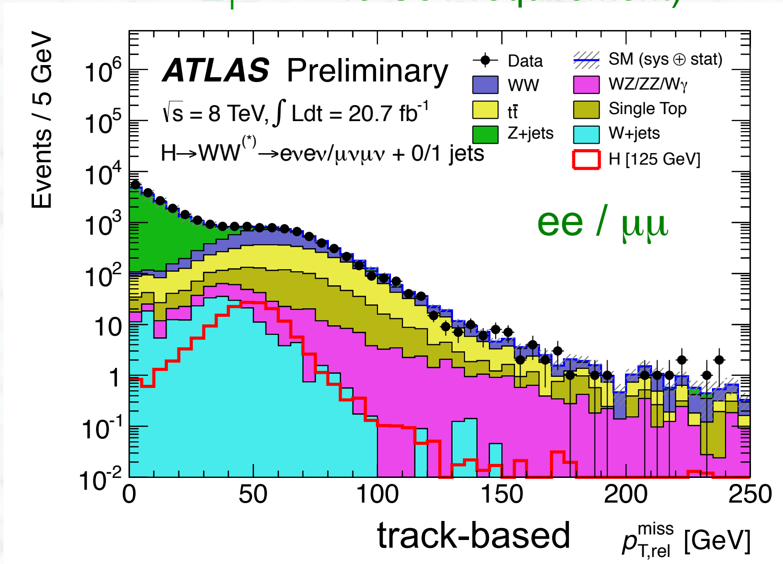
Category	$N_{\mathrm{jet}} = 0$	$N_{\mathrm{jet}} = 1$	$N_{\mathrm{jet}} \geq 2$
Pre-selection:	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_{\mathrm{T}}^{\mathrm{lead}} > 25$ and $p_{\mathrm{T}}^{\mathrm{sublead}} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$		

E_T^{miss} distribution of eμ events (after pre-selection)

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

P_T^{miss} distribution of ee / μμ events (after pre-selection and E_T^{miss} > 45 GeV requirement)





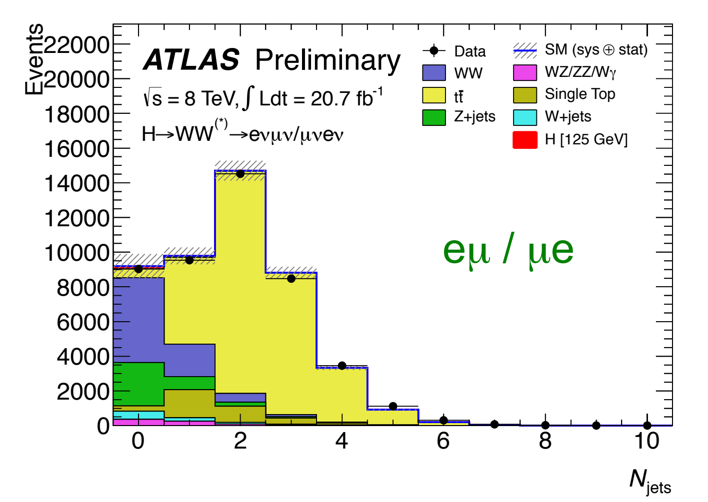
➔ Good description of the background composition
➔ Z/γ* + jets (Drell-Yan) background is still significant in ee / μμ analysis, even after tight calorimeter E_T^{miss} requirement

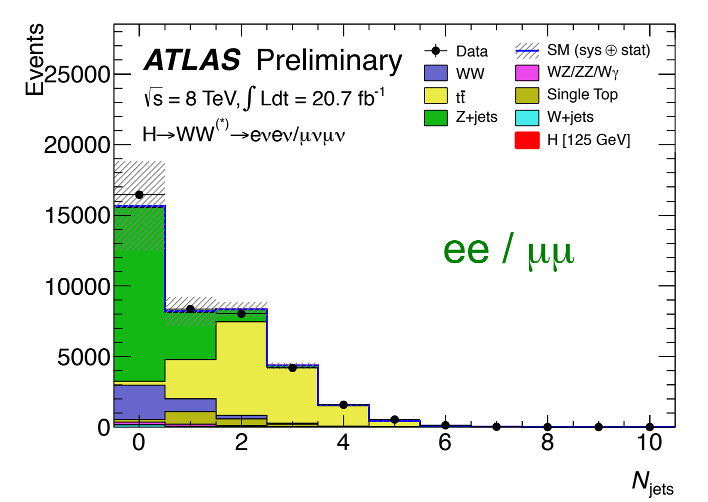
Search for H → WW → ℓν ℓν (cont.)

- Additional discrimination: - missing transverse energy (calorimeter and track-based)
  - cut on soft recoil energy opposite to the leptons in ee/μμ events

Category	$N_{\rm jet} = 0$	$N_{\rm jet} = 1$	$N_{\rm jet} \geq 2$
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{\rm T,rel}^{\rm miss} > 25$ $ee + \mu\mu$: $E_{\rm T,rel}^{\rm miss} > 45$ $ee + \mu\mu$: $p_{\rm T,rel}^{\rm miss} > 45$ $ee + \mu\mu$: $f_{\rm recoil} < 0.05$	$e\mu + \mu e$: $E_{\rm T,rel}^{\rm miss} > 25$ $ee + \mu\mu$: $E_{\rm T,rel}^{\rm miss} > 45$ $ee + \mu\mu$: $p_{\rm T,rel}^{\rm miss} > 45$ $ee + \mu\mu$: $f_{\rm recoil} < 0.2$	$e\mu + \mu e$: $E_{\rm T}^{\rm miss} > 20$ $ee + \mu\mu$: $E_{\rm T}^{\rm miss} > 45$ $ee + \mu\mu$: $E_{\rm T,STVF}^{\rm miss} > 35$ -

- Jet multiplicity distributions after pre-selection and E_T^{miss} cuts:

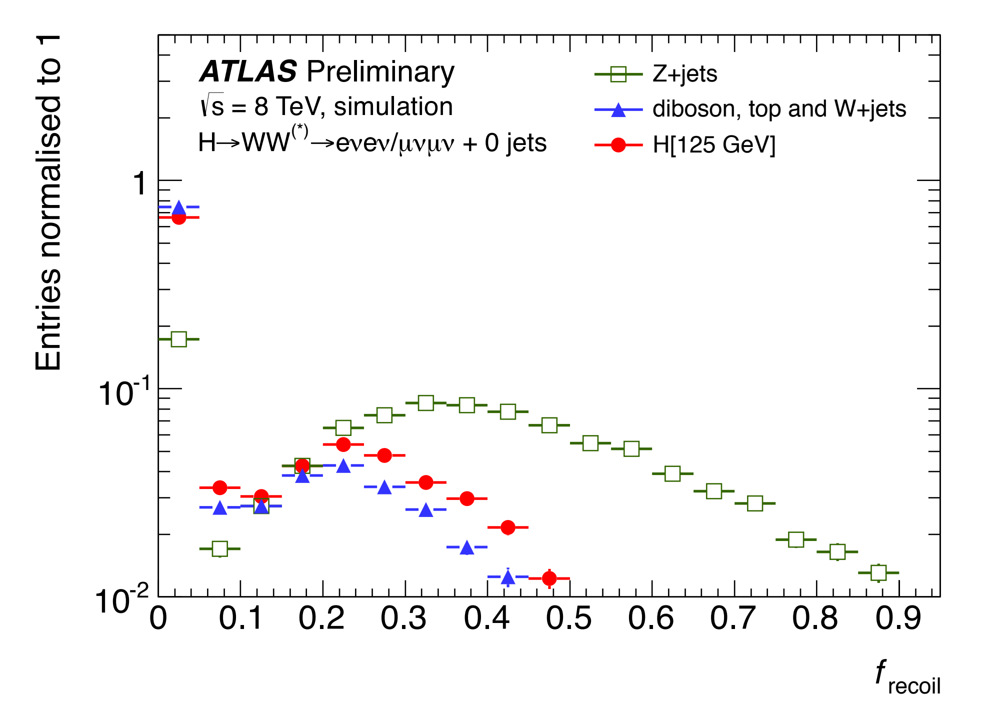




→ Multiplicity well described, background composition depends strongly on N_{jet}

Search for H → WW → ℓν ℓν (cont.)

- Recoil energy fraction:



f_{recoil} := ratio of the recoil momentum and $p_T(ll)$ (N_{jet} = 0) or $p_T(llj)$ (N_{jet} = 1)

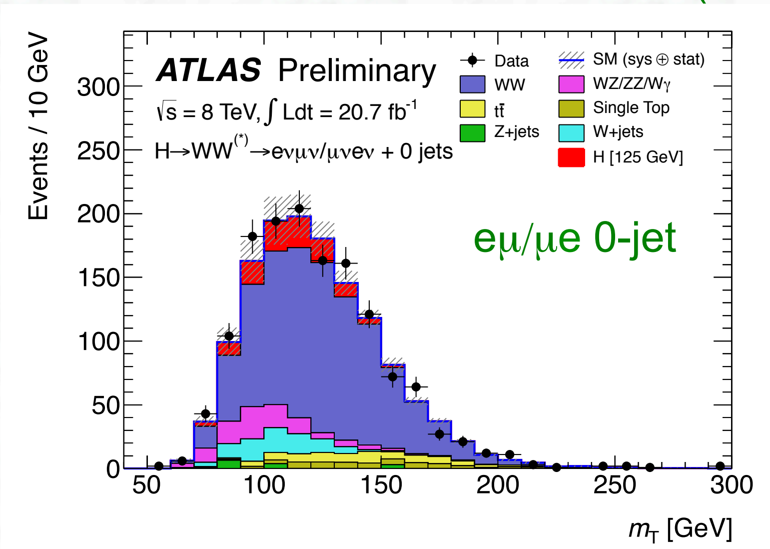
Search for H → WW → ℓν ℓν (cont.)

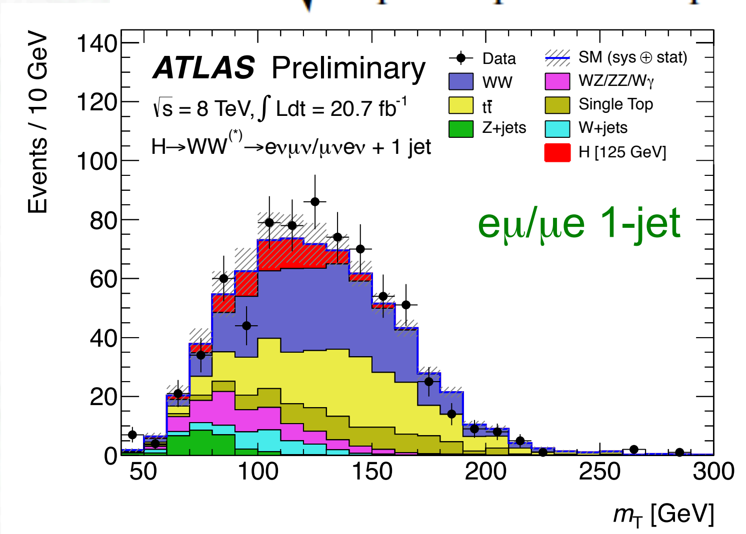
- Additional (topological) selection:

Category	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
General selection	- $\lvert\Delta\phi_{\ell\ell,MET}\rvert > \pi/2$ $p_{\mathrm{T}}^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_{\mathrm{T}}^{\text{tot}} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\lvert\Delta y_{jj}\rvert > 2.8$ No jets ($p_{\mathrm{T}} > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \to WW^{(*)} \to \ell\nu\ell\nu$	$m_{\ell\ell} < 50$ $\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	$m_{\ell\ell} < 50$ $\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	$m_{\ell\ell} < 60$ $\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$

Transverse mass distributions (after all cuts)

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





Search for H → WW → ℓν ℓν (cont.)

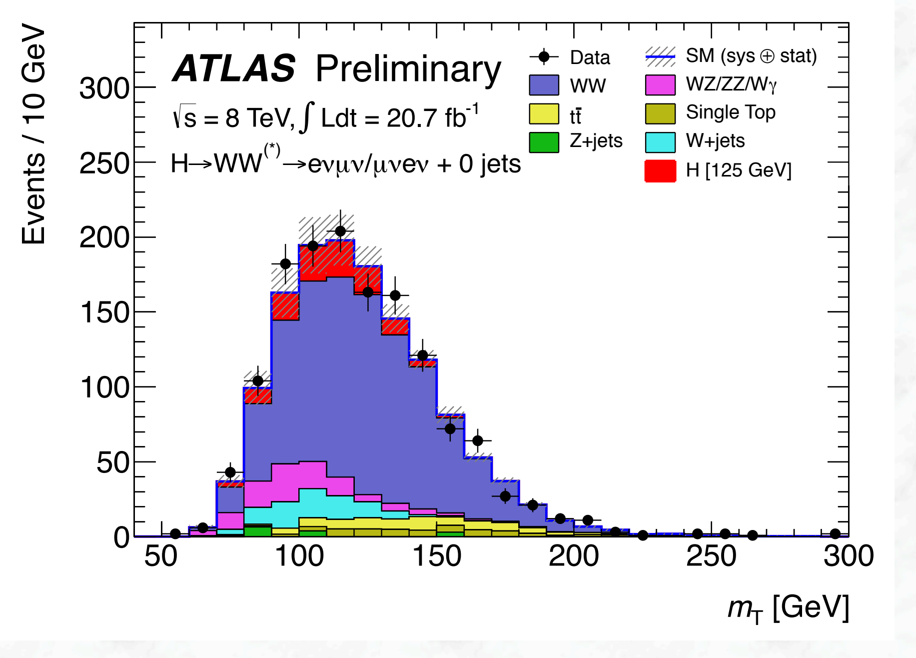
Background normalization:

"The key issue" in analyses with non-resonant or low mass-resolution channels

- Signal fraction is small and non-resonant, even after further selection cuts are applied
- Large uncertainties in theoretical predictions (scale uncertainties, backgrounds in special kinematical configurations, e.g. VBF topology)

Example:

Final transverse mass m_T distribution in the ATLAS analysis, after all selection cuts



Search for H → WW → ℓν ℓν (cont.)

Background normalization:

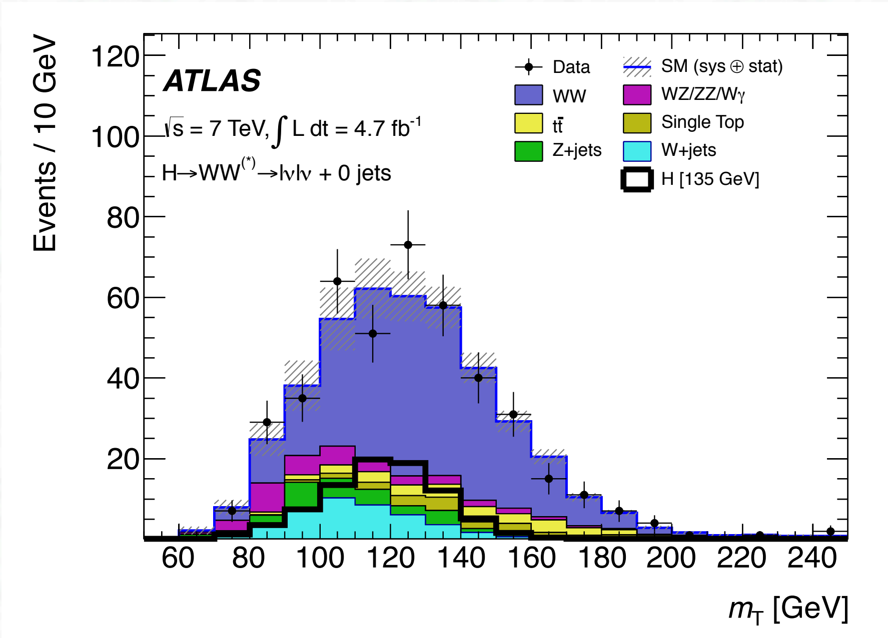
"The key issue" in analyses with non-resonant or low mass-resolution channels

- Signal fraction is small and non-resonant, even after further selection cuts are applied
- Large uncertainties in theoretical predictions (scale uncertainties, backgrounds in special kinematical configurations, e.g. VBF topology)

- Even more important at discovery threshold (low luminosity)

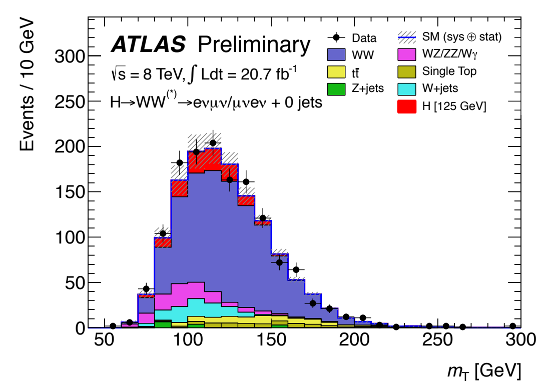
Example:

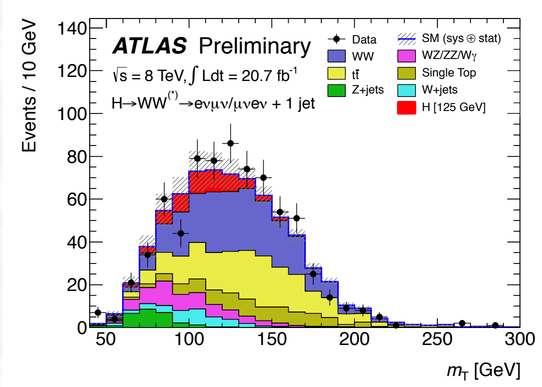
Final transverse mass m_T distribution in the ATLAS analysis, after all selection cuts, 2011 data, L = 4.7 fb^{-1}



Background estimation in H → WW → ℓν ℓν (cont.)

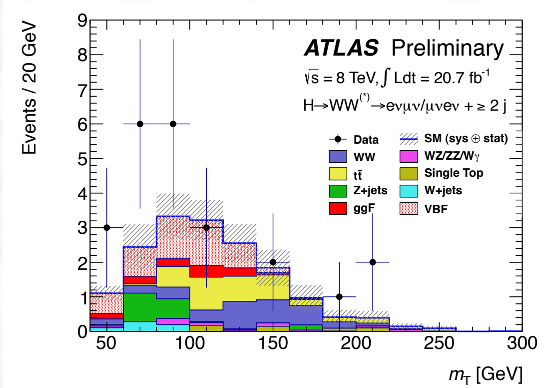
- As seen before, many different processes contribute to the background, with different relative importance in the different jet bins
- Use Control Regions (CR) in data (ideally dominated by one particular background) to normalize backgrounds
- Extrapolate back to the signal region using Monte Carlo simulation
- Due to correlations among sub-channels, background estimations have to be interlinked





Summary of background treatment:

Channel	WW	Top	$Z/\gamma^* \to \tau\tau$	$Z/\gamma^* \to \ell\ell$	W+jets	VV
$N_{\text{jet}} = 0$						
$e\mu + \mu e$	CR	CR	CR	MC	Data	MC + VR
$ee + \mu\mu$	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	Data	Data	MC + VR
$N_{\text{jet}} = 1$						
$e\mu + \mu e$	CR	CR	CR	MC	Data	MC + VR
$ee + \mu\mu$	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	CR ($e\mu + \mu e$)	Data	Data	MC + VR
$N_{\text{jet}} \geq 2$						
$e\mu + \mu e$	MC	CR (merged)	CR	MC	Data	MC
$ee + \mu\mu$	MC	CR (merged)	CR ($e\mu + \mu e$)	Data	Data	MC

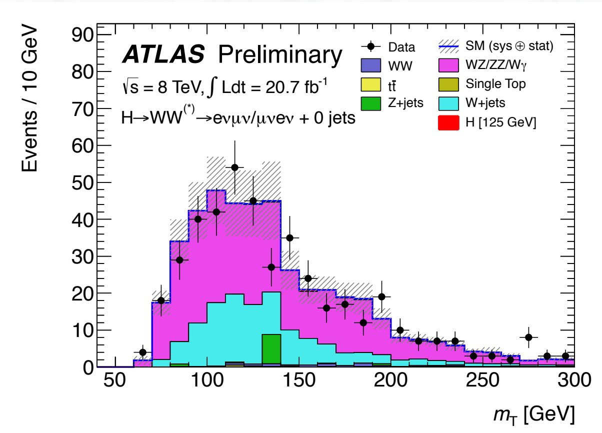


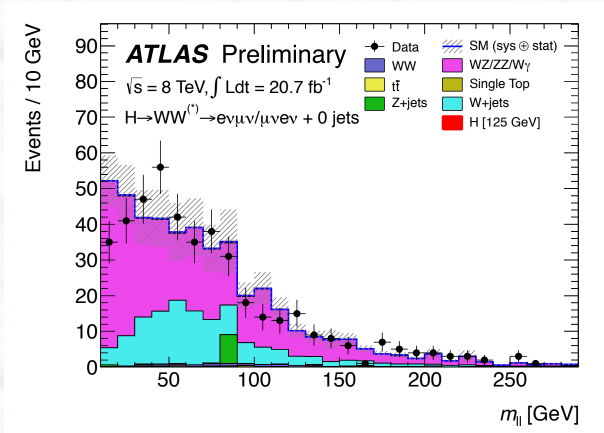
CR = Control region, enhanced by particular background
VR = Verification region, for cross-checks

Background estimation in $H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$ (cont.)

- W + jet background:
  Use a control region in which one of the leptons fails the identification/isolation criteria;
  Determine fake factors as function of p_T and η, apply them in signal region

  Cross-check in sample with same-sign leptons (W+jet contributes to same-sign background)





Uncertainties:

W+jets: ±30%

WZ/ZZ/Wγ: 16% - 22%

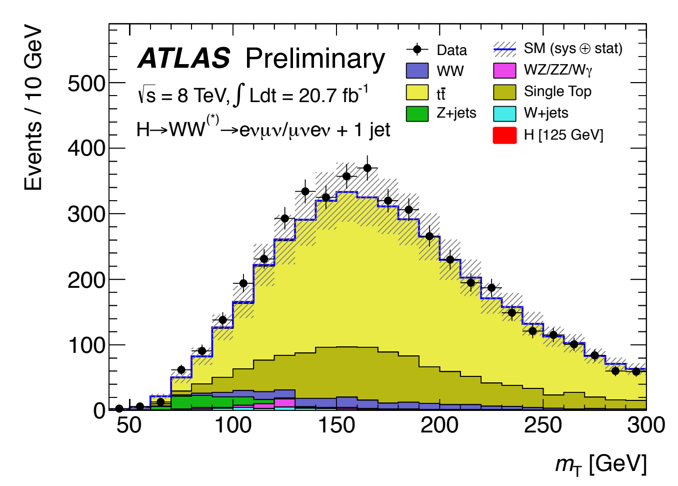
- $Z/\gamma^* \rightarrow \ell\ell$ + jet background (Drell-Yan):

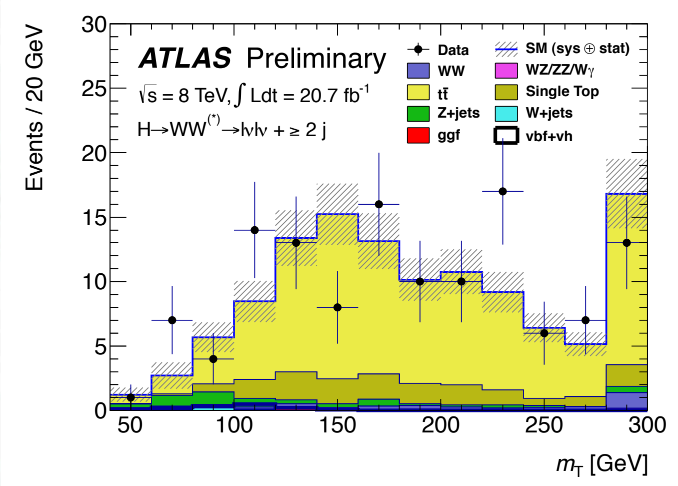
  Use data-driven method: f_{recoil} distribution
  Measure f_{recoil} efficiencies in $Z \rightarrow ee$, $\mu\mu$ events
  (Z mass peak region, which is cut out in signal selection $|m_{ll} - m_Z| < 15$ GeV)

Background estimation in $H \rightarrow WW \rightarrow \ell\nu\,\ell\nu$ (cont.)

- tt + single top (tW, tb, tqb): Control regions via b-tags

Normalize top background to the data in a control region defined by $N_{b\text{-}jet} = 1$ and $m_{\ell\ell}$ and $|\Delta\phi_{\ell\ell}|$ requirements removed





- Normalization factors: 1.04 ± 0.02 (stat) (N_{jet} = 1) and 0.59 ± 0.07 (stat) (N_{jet} = 2)

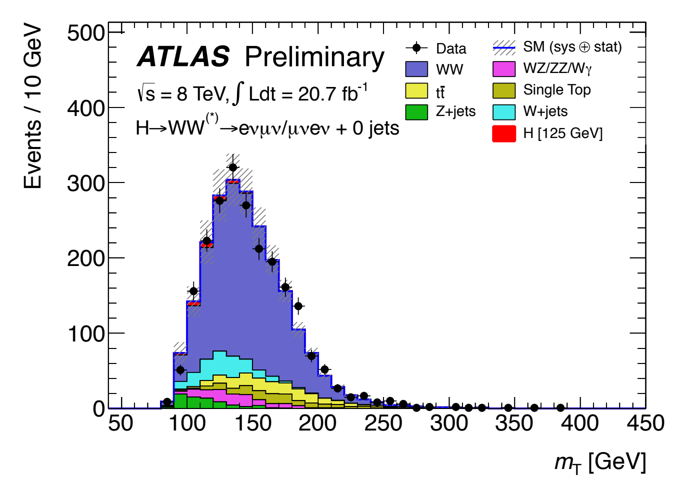
  (most likely, the latter reflects the limitation of the tt simulation in the special phase space region of: m_{jj} > 500 GeV, $|\Delta\eta|$ > 2.8, and jet veto in central region)
  Total uncertainty: ± 28% (N_{jet} = 1) and ± 39% (N_{jet} = 2)

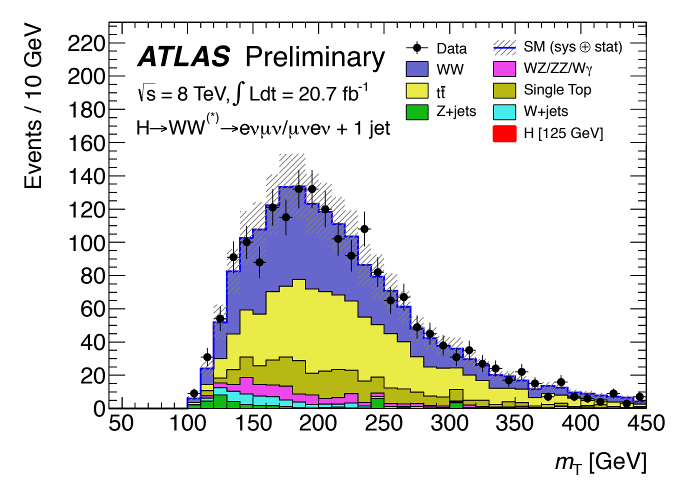
- Normalization for N_{jet}=0: normalization from data in a CR region with large E_T^{miss}, b-tag (dominated by top events); estimate fraction of top events with N_{jet} = 0 from Monte Carlo;
  Normalization factor: 1.07 ± 0.03 (stat), uncertainty: : ± 13%

Background estimation in H → WW → ℓν ℓν (cont.)

- WW background: Dominant in the N_{jet} = 0 sample

Normalize in a control region, close to signal region defined by 50 GeV < $m_{\ell\ell}$ < 100 GeV, and $|\Delta\phi_{\ell\ell}|$ requirements removed





- Normalization factors: 1.16 ± 0.04 (stat) (N_{jet} = 0) and 1.03 ± 0.06 (stat) (N_{jet} = 1)

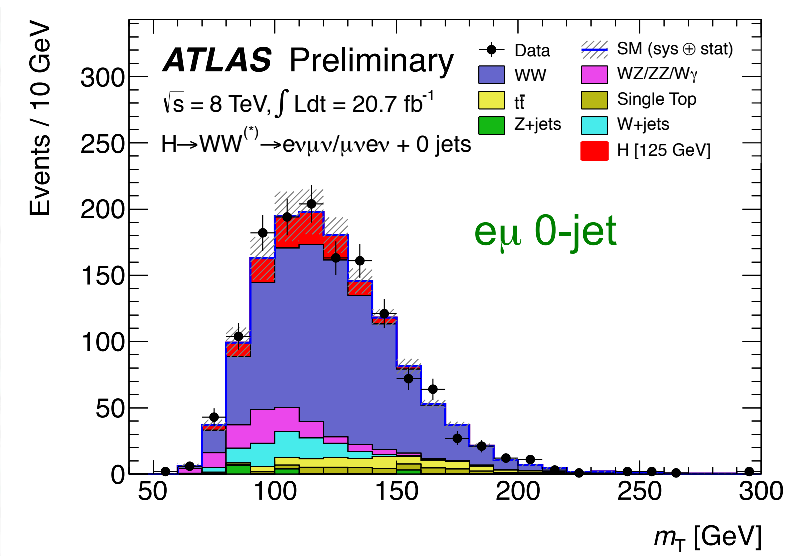
  Total uncertainty: ±7.4% (N_{jet} = 0), ±37% (N_{jet} = 1), and ± 37% (N_{jet} = 2)

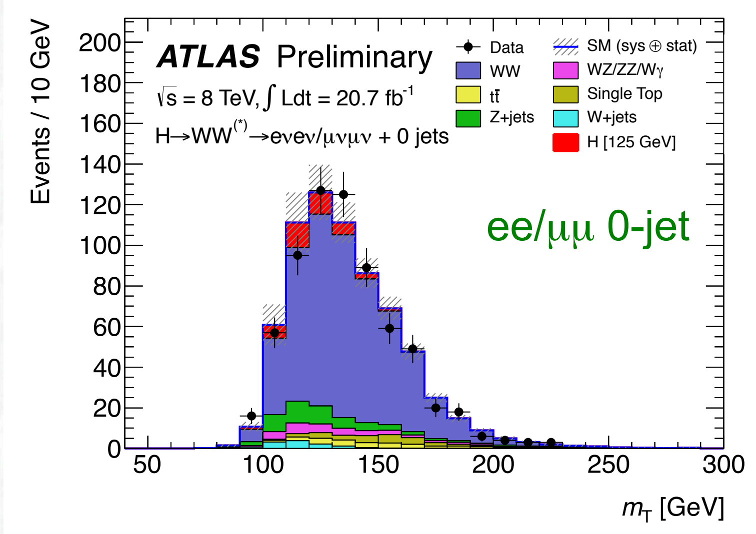
- WW and top background estimates are anti-correlated (most affected: N_{jet} = 1)

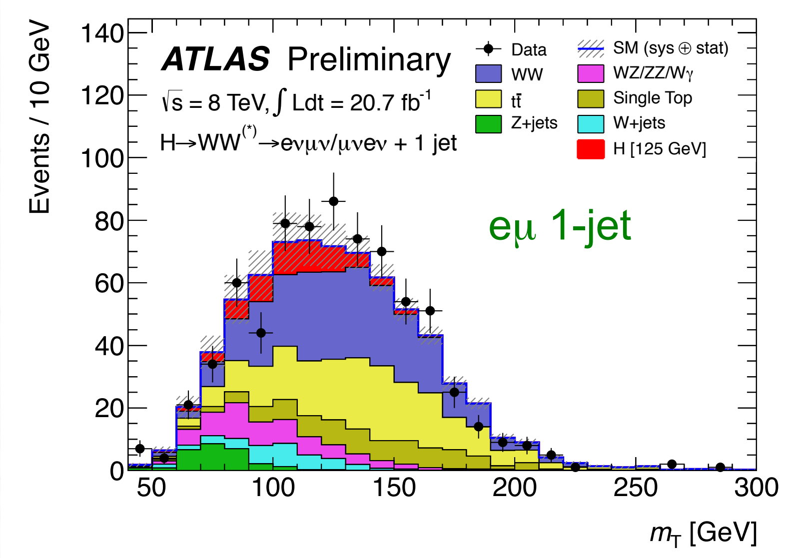
- For N_{jet} = 2: WW background estimation from Monte Carlo
  (difficult to define a control region that is not dominated by tt background)

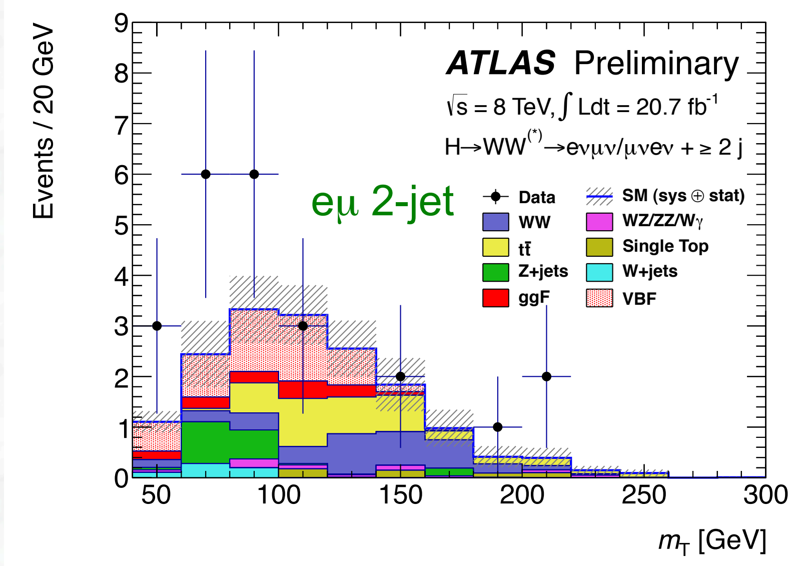
Transverse mass distributions

ATLAS-CONF-2013-030









Clear excess above backgrounds in all sub-channels (jet multiplicities)

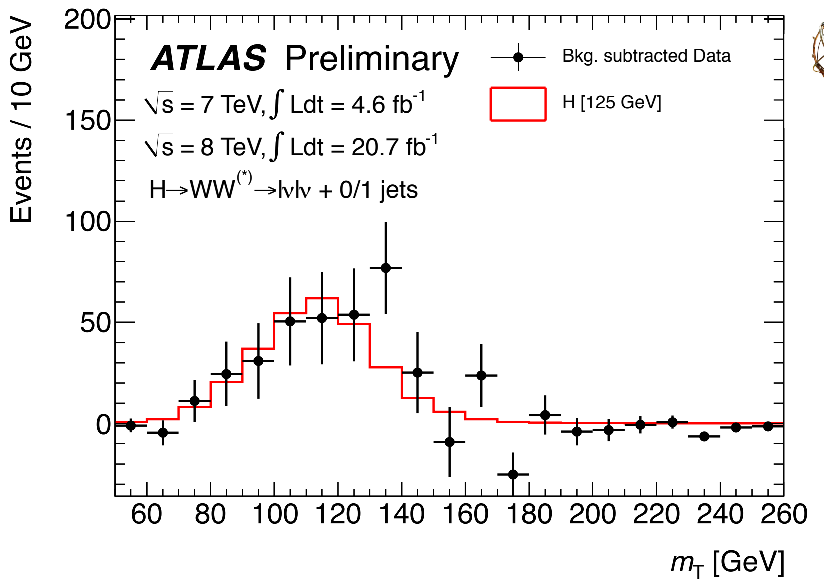
Search for H → WW → ℓν ℓν (cont.)
- number of estimated background and expected signal events (after final cuts)

$\sqrt{s}$ = 7 TeV, L = 4.6 fb^{-1}

N_{jet}	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	N_{W+jets}
= 0	154	161 ± 11	25 ± 5	113 ± 10	12 ± 2	5 ± 1	4 ± 1	6 ± 2	21 ± 5
= 1	62	47 ± 6	7 ± 2	16 ± 6	5 ± 1	10 ± 3	6 ± 2	5 ± 2	5 ± 1
≥ 2	2	4.6 ± 0.8	1.4 ± 0.2	0.7 ± 0.2	-	0.7 ± 0.5	0.1 ± 0.1	2.4 ± 0.6	0.3 ± 0.1

$\sqrt{s}$ = 8 TeV, L = 20.7 fb^{-1}

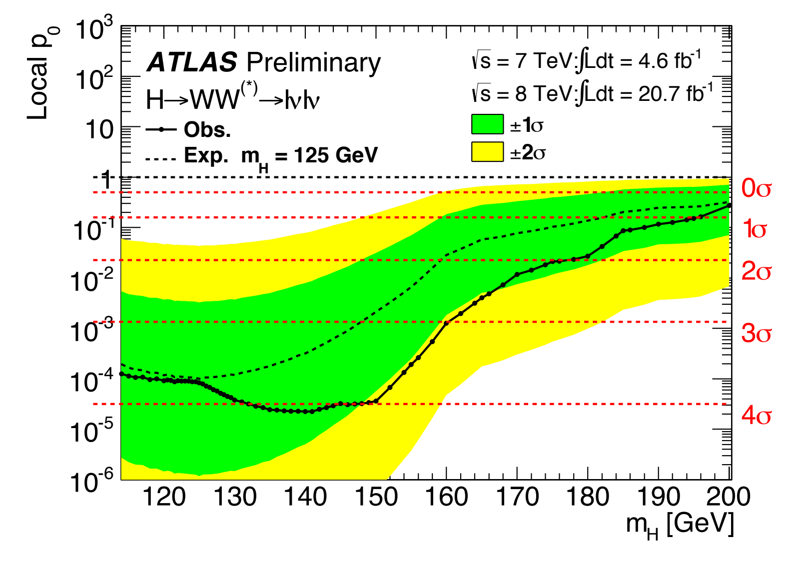
N_{jet}	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	N_{W+jets}
= 0	831	739 ± 39	97 ± 20	551 ± 41	58 ± 8	23 ± 3	16 ± 2	30 ± 10	61 ± 21
= 1	309	261 ± 28	40 ± 13	108 ± 40	27 ± 6	68 ± 18	27 ± 10	12 ± 6	20 ± 5
≥ 2	55	36 ± 4	10.6 ± 1.4	4.1 ± 1.5	1.9 ± 0.4	4.6 ± 1.7	0.8 ± 0.4	22 ± 3	0.7 ± 0.2



Background-subtracted m_T distribution for N_{jet} =0,1 and 7 and 8 TeV data added

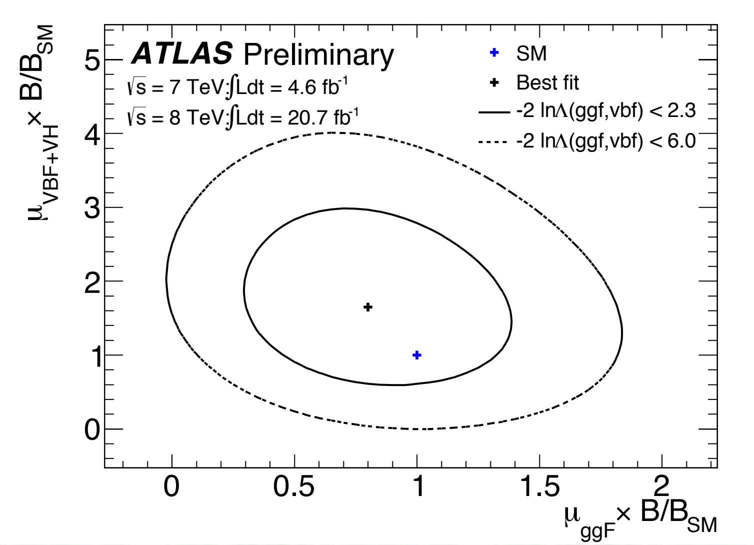
Results on the search for H → WW → ℓν ℓν decays

ATLAS-CONF-2013-030



Shallow minimum of p_0 value at 140 GeV

p_0 (125 GeV) = 8 10^{-5} (3.8σ observed)
(3.7σ expected)



Signal strength:
(combination of 7 TeV and 8 TeV data, at 125 GeV)

μ = 1.01 ± 0.21 (stat) ± 0.12 (syst) ± 0.19 (theo)

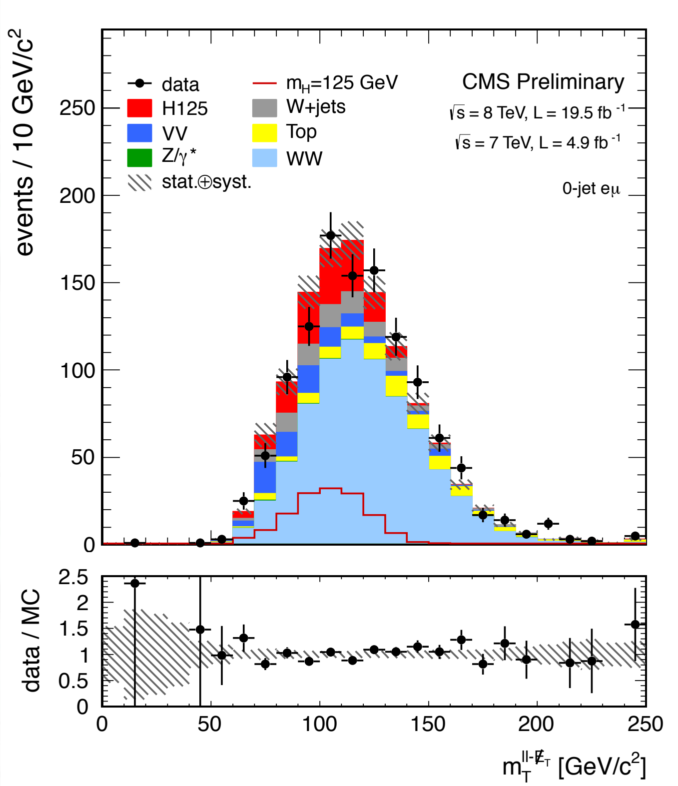
μ_{VBF} = 1.66 ± 0.79

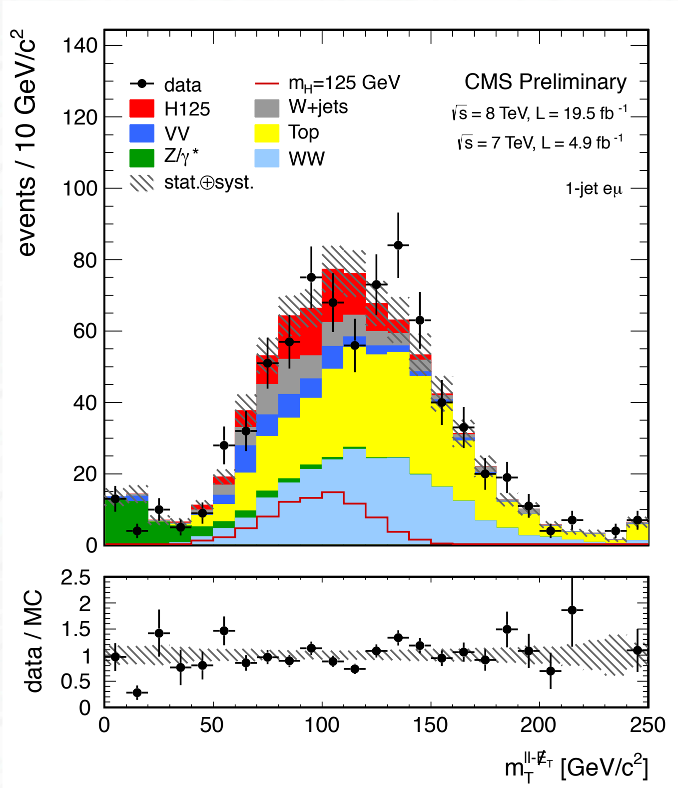
μ_{ggF} = 0.82 ± 0.36

Leading uncertainties on the signal strength μ:

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	W+ jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

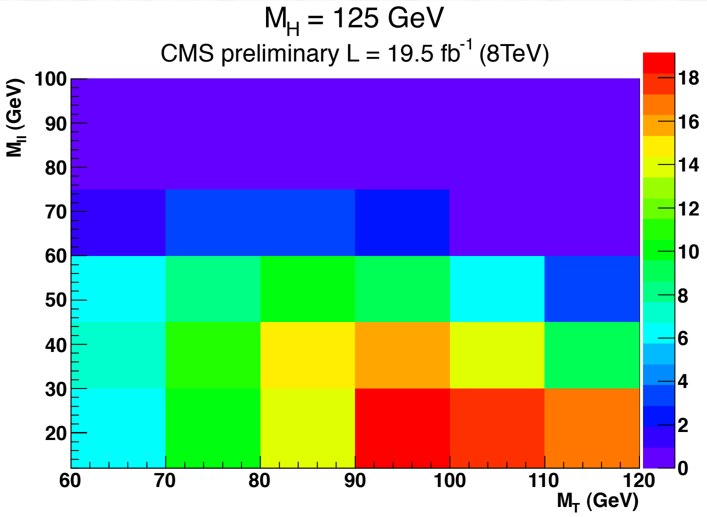
Transverse mass distributions after final cuts for the $H \rightarrow WW \rightarrow \ell\nu\ \ell\nu$ search



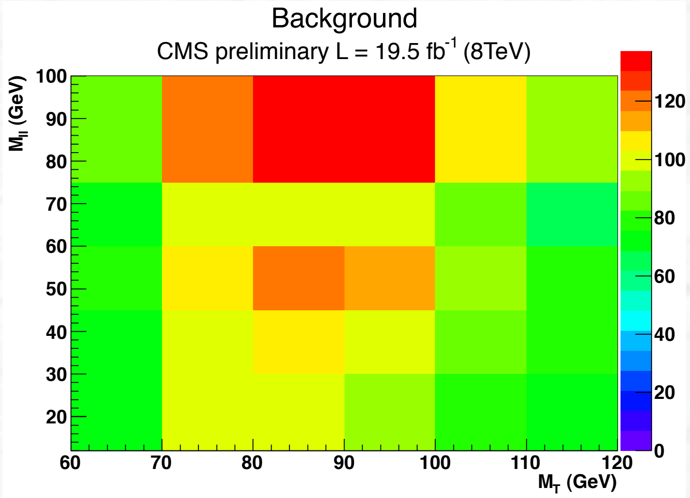


- Clear excess visible in both channels

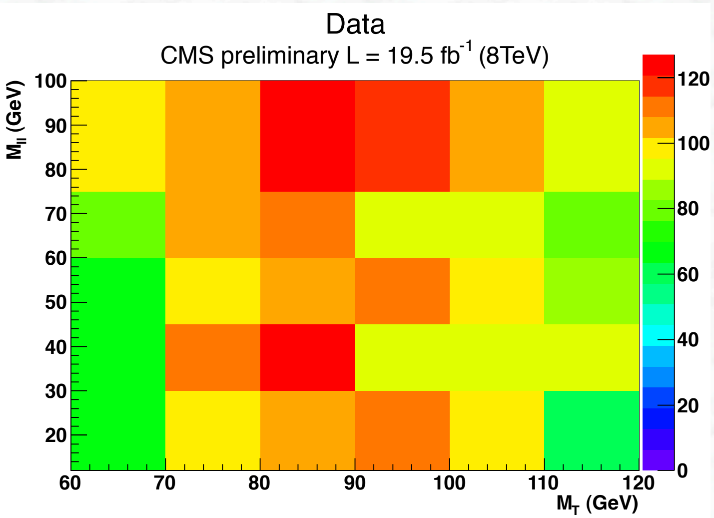
Signal extraction via 2-dimensional fit: m_T versus $m_{\ell\ell}$

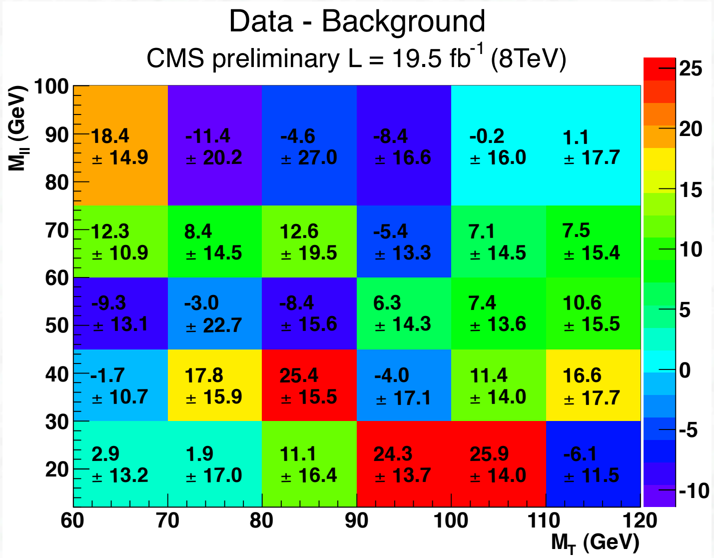


2-dim. distribution for the signal hypothesis with m_H = 125 GeV, 0-jet category



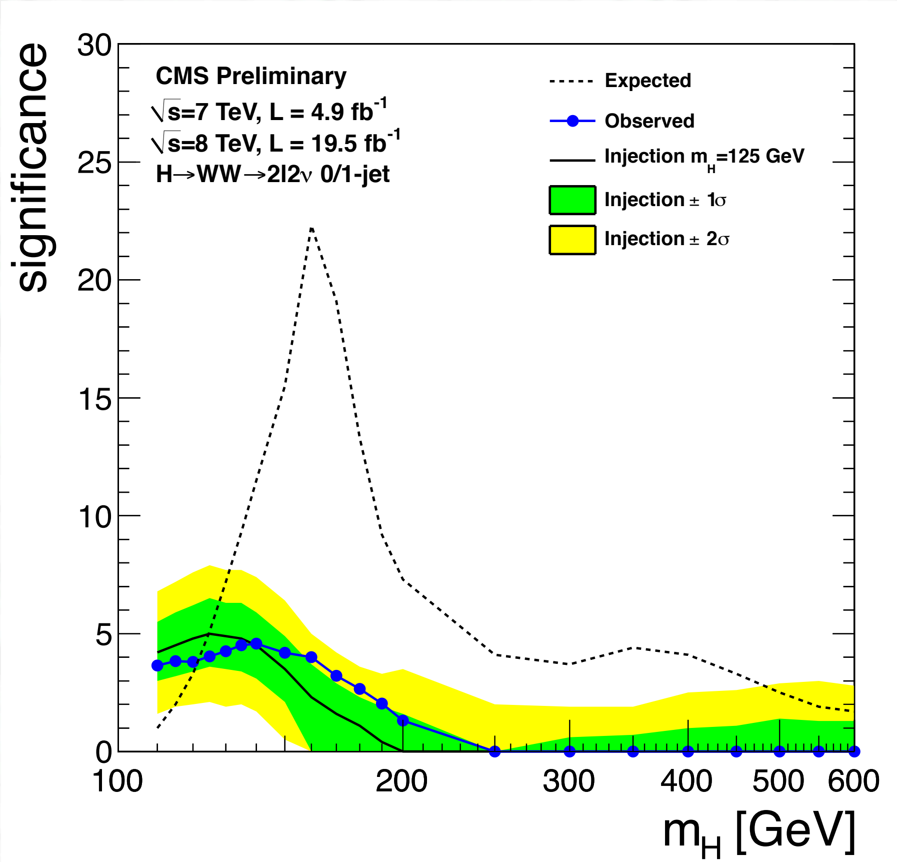
2-dim. distribution for the background hypothesis, 0 jet category

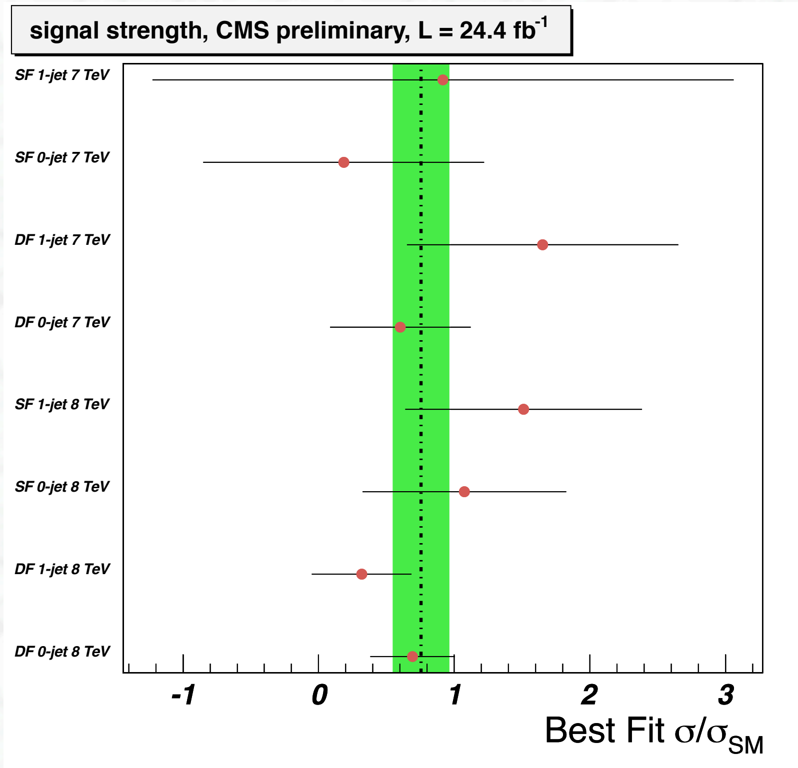




- Start with relaxed cuts, 2-dimensional fit to extract signal parameter μ

H → WW → ℓν ℓν: signal significance and signal strength



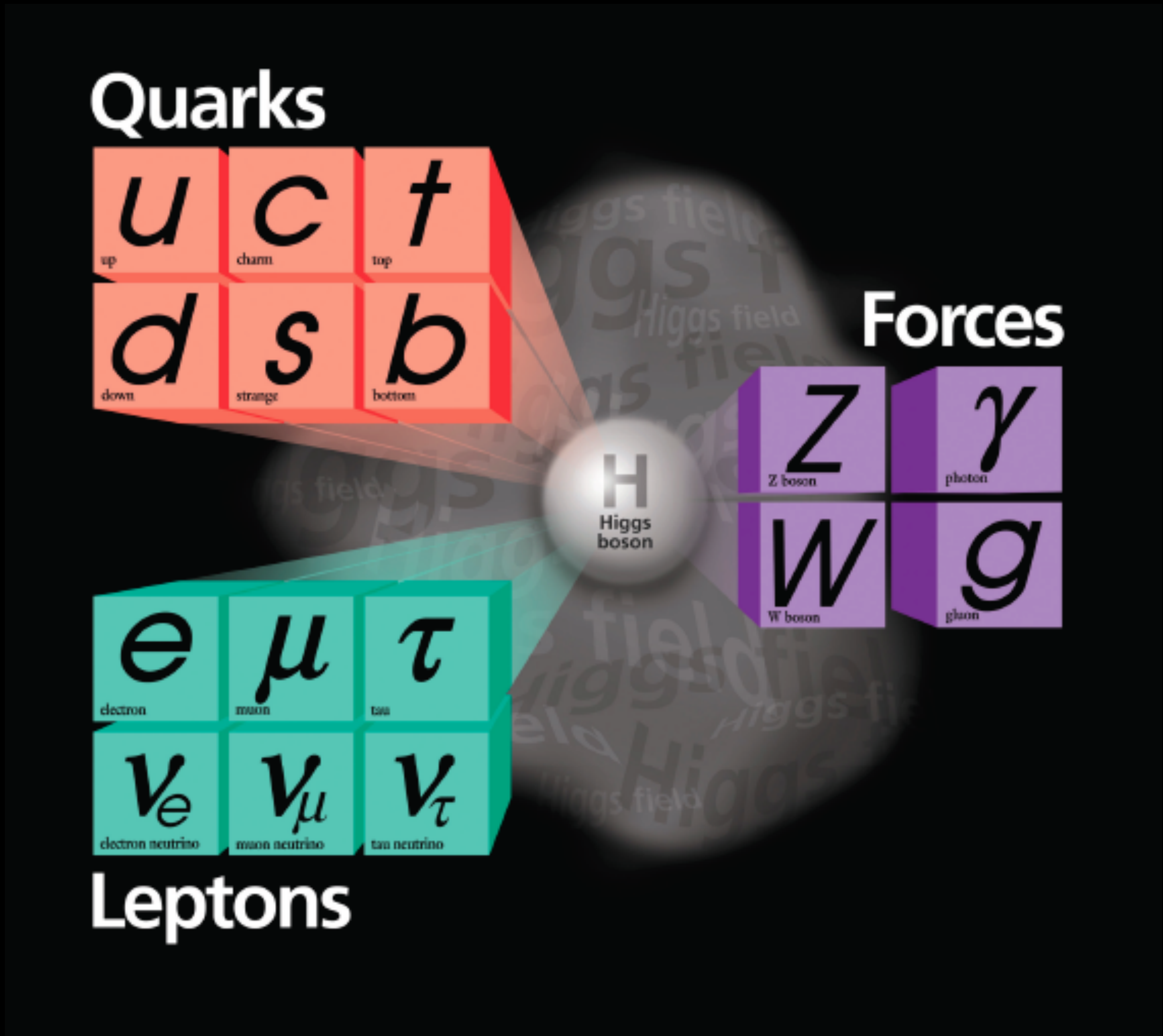


Expected for m_H = 125 GeV:	5.1σ
Observed at 125 GeV:	4.0σ

$\mu = 0.8 \pm 0.2$

Sub-channels give consistent results

Couplings to quarks and leptons ?



Search for H → ττ and H → bb decays

Search for H → ττ decays

- Hadronic τ decays (challenging signature)
  Use multivariate technique to separate τ decays from jets

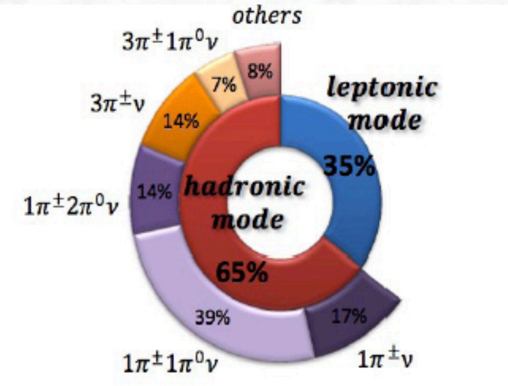
- 2-4 neutrinos in final state, mass reconstruction difficult;
  Using "Missing mass calculation" *)

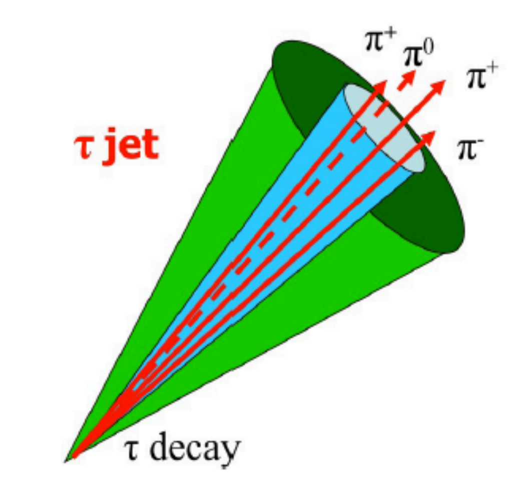
- Major background: Z → ττ decays;
  Modelled using data:
  "Embedding technique" replace muons in real Z → μμ events by simulated taus

- Signal-to-background ratio improves for
  VBF-topology or high-p_T Higgs ("boosted" category)

- Analysis is split into three sub-channels:

  - H → ττ → ℓ νν ℓ νν
  - H → ττ → ℓ νν had ν
  - H → ττ → had ν had ν

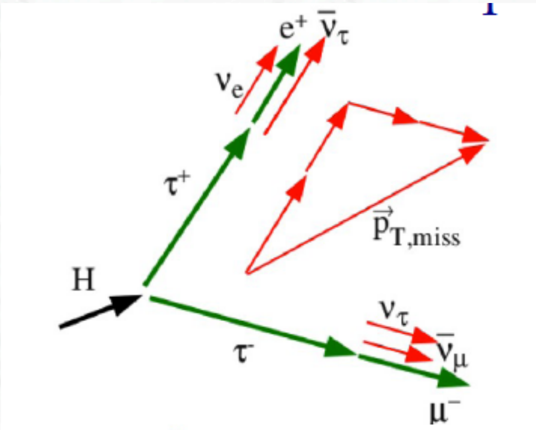




*) Nucl. Instrum. Methods A654 (2011) 481

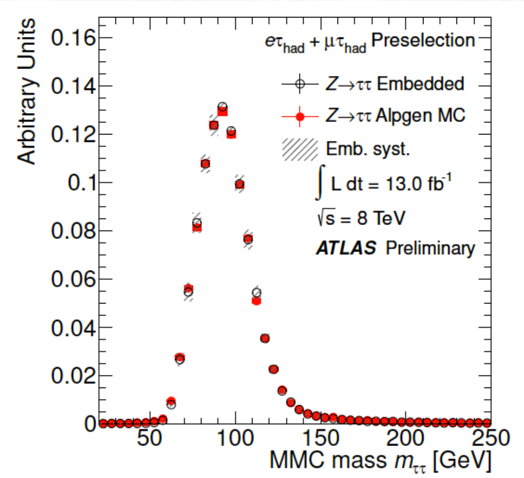
Di-tau mass reconstruction

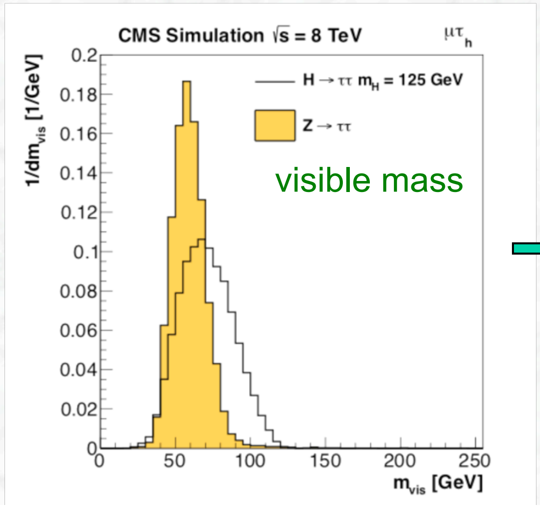
- Despite the presence of two neutrinos in the final state, the ττ invariant mass can be reconstructed;

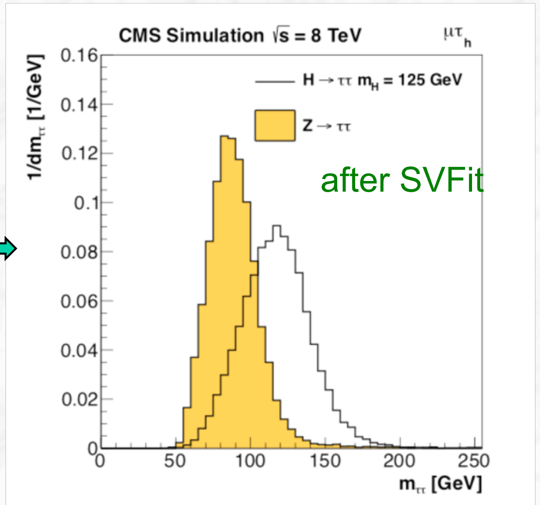


- Simple method: collinear approximation;
  Assume that the neutrinos fly in the direction of the visible decay products; use measured E_T^{miss} to constrain neutrino momenta
  (Good approximation for "boosted" taus, e.g. for high-p_T Higgs decays (H+1jet or VBF-topology))

- Today: more sophisticated methods used by ATLAS and CMS
  ATLAS: Missing Mass Calculator (MMC), Nucl. Instrum. Methods A654 (2011) 481;
  CMS: SVFit, documented in CMS PAS HIG-13-004;
  Basic idea: under-constrained kinematic system, use maximum-likelihood fit method (scan over all possible neutrino directions)



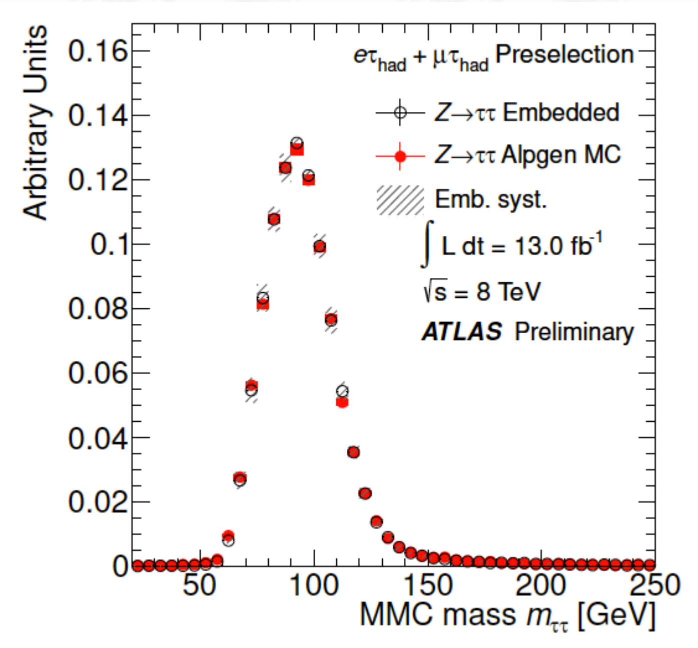


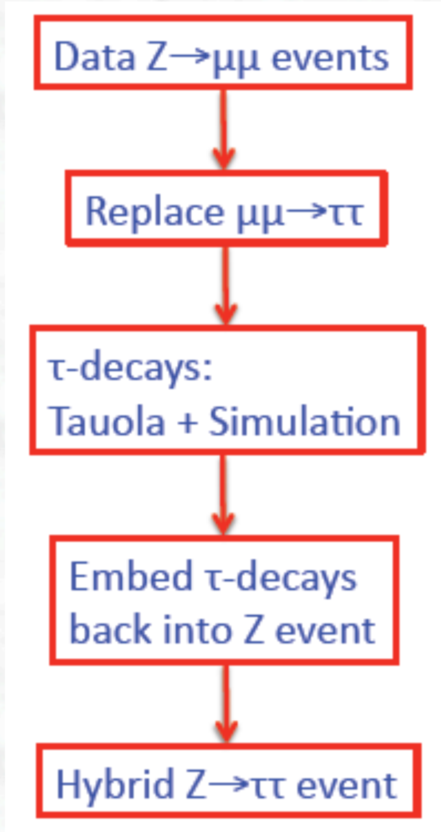


Z → ττ embedding

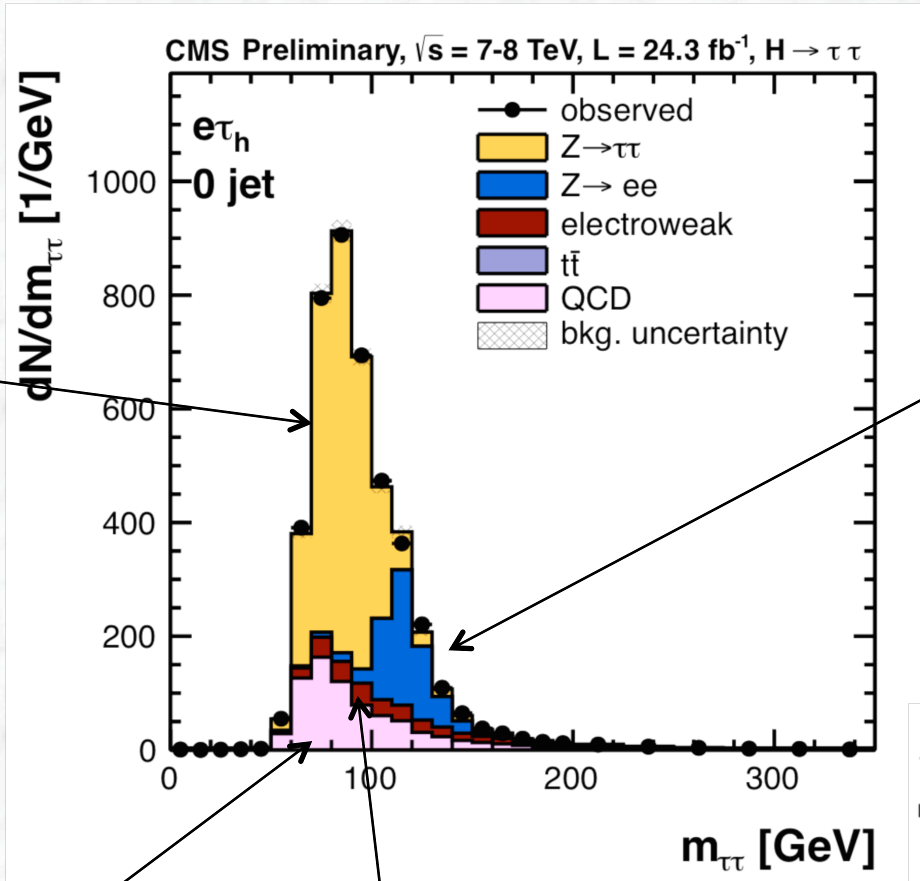
- Z → ττ is the dominant (overwhelming) background
- Due to the small expected H → ττ signal, its shape must be precisely known!

➔ Use data (Z → μμ decays) to model all properties (jet activity, underlying event, pile-up, ..), except tau decays, from data → overall smaller syst. uncertainties





H → ττ background conditions/normalizations



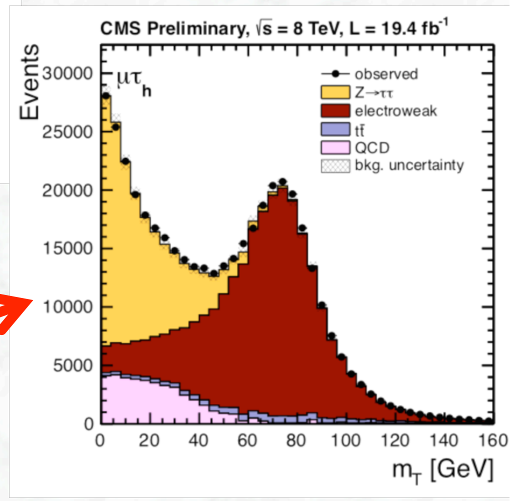
Z → ττ

embedding

Z → ℓℓ (ℓ fakes a τ_h)

shape from Monte Carlo simulation

normalization from peak in visible mass region



Multijet background (QCD)

l / τ_h fakes:

- use same-sign data
- variation of isolation

W+jets
mainly jet → τ_h fakes;
use transverse mass distribution for normalization

H → ττ categorization

$e\tau_h$, $\mu\tau_h$, $e\mu$, $\mu\mu$

No. of jets →

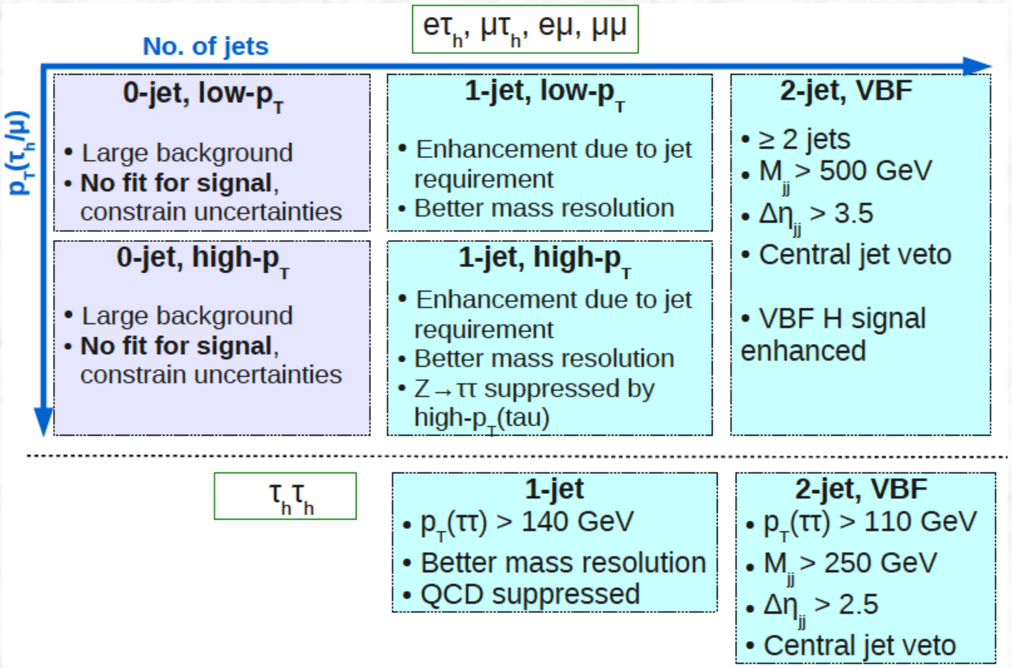
$p_T(\tau_h/\mu)$ ↓

0-jet, low-p_T	1-jet, low-p_T	2-jet, VBF
• Large background • **No fit for signal**, constrain uncertainties	• Enhancement due to jet requirement • Better mass resolution	• ≥ 2 jets • M_{jj} > 500 GeV • $\Delta\eta_{jj}$ > 3.5 • Central jet veto • VBF H signal enhanced
0-jet, high-p_T	**1-jet, high-p_T**	
• Large background • **No fit for signal**, constrain uncertainties	• Enhancement due to jet requirement • Better mass resolution • Z→ττ suppressed by high-p_T(tau)	

$\tau_h\tau_h$

1-jet	2-jet, VBF
• $p_T(\tau\tau)$ > 140 GeV • Better mass resolution • QCD suppressed	• $p_T(\tau\tau)$ > 110 GeV • M_{jj} > 250 GeV • $\Delta\eta_{jj}$ > 2.5 • Central jet veto

H → ττ categorization



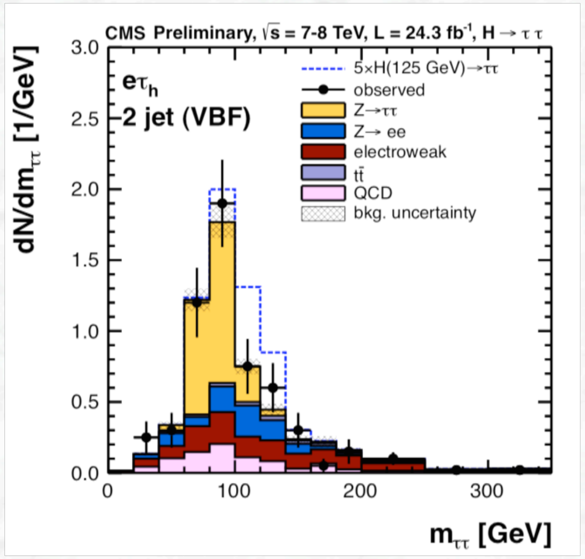
A simplified version:

	VBF	Boosted	1-jet	0-jet	VH
ATLAS	✔	✔	✔	✔	✕
CMS	✔	✔ had-had	✔ Low/high $P_T(\tau)$	To constrain systematics	✔

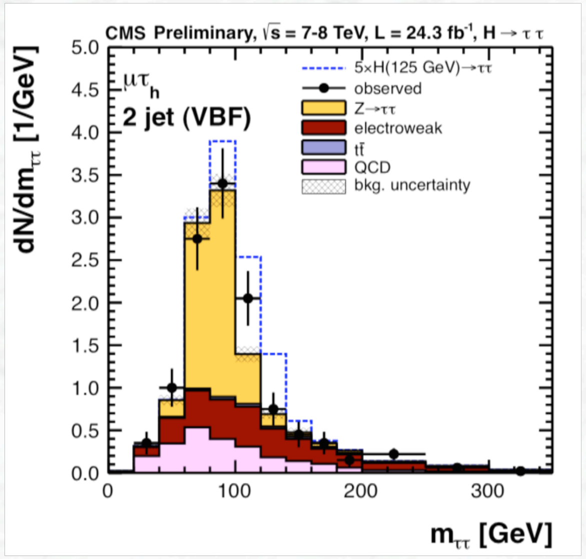
Reconstructed mass distributions

Full data set

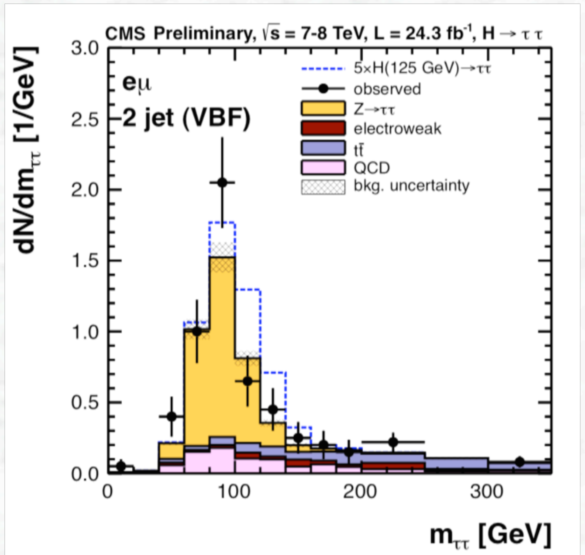
eτ, VBF



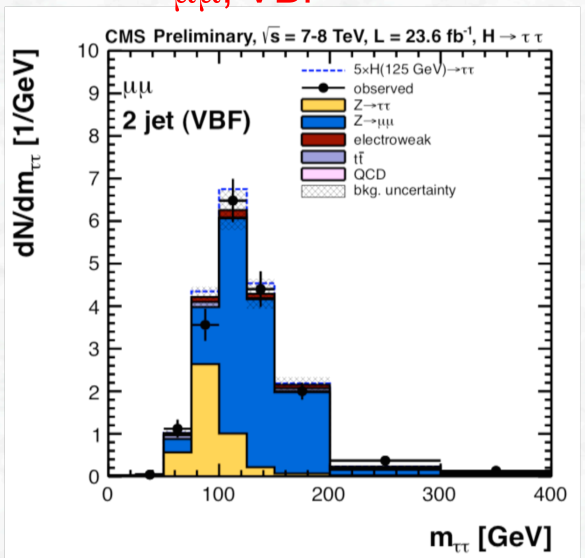
μτ, VBF



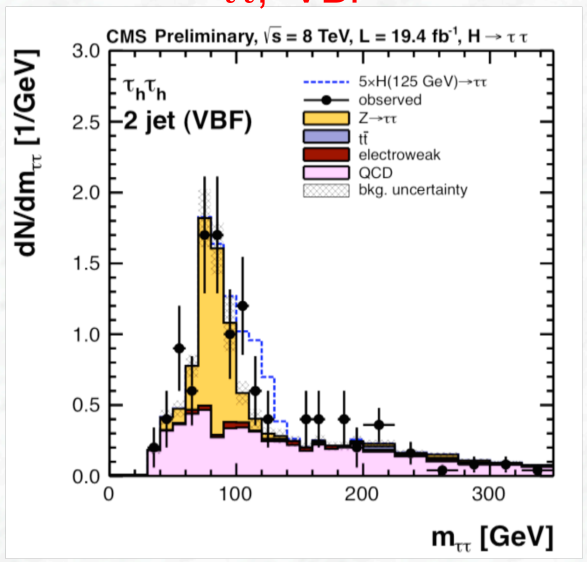
eμ, VBF



μμ, VBF



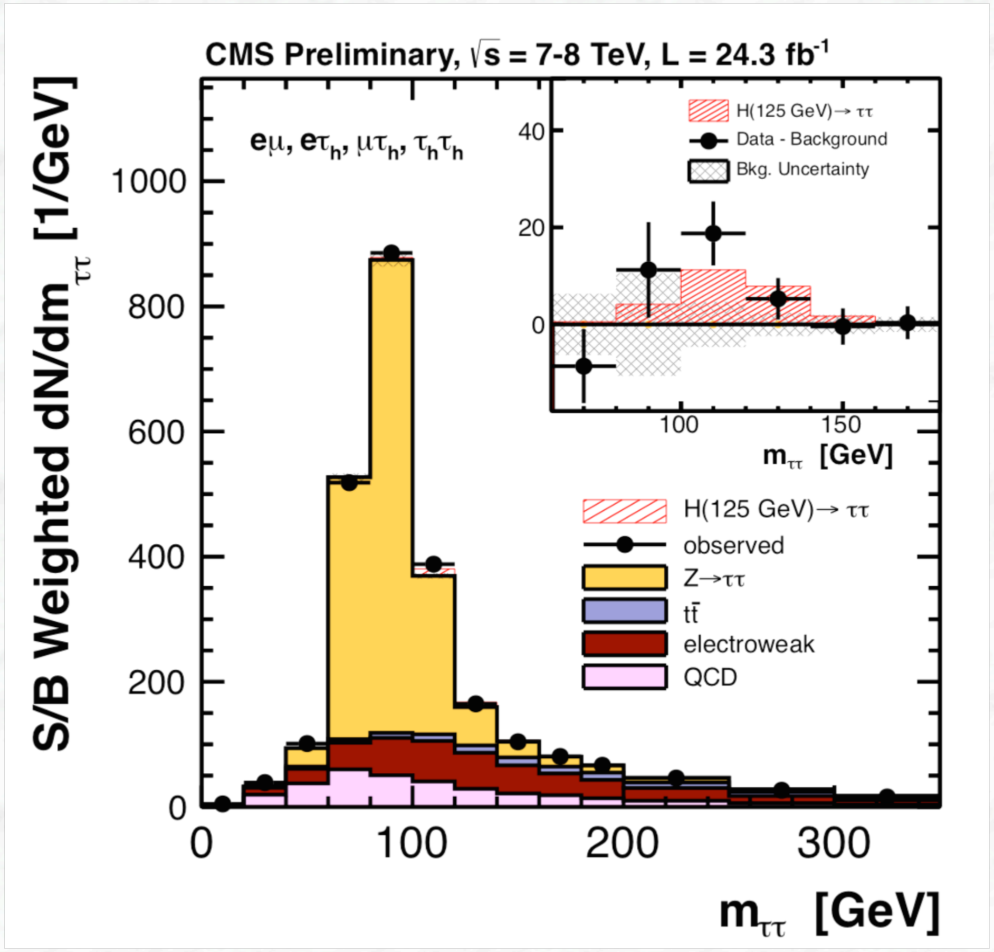
ττ, VBF



Standard Model Higgs boson signal multiplied by factor 5

CMS PAS HIG-13-004

Combined reconstructed mass distribution



Combined observed and expected $m_{\tau\tau}$ distributions; The distributions obtained in each category are weighted by the ratio between the expected S/B yields in the category.

Major systematic uncertainties

I. Experimental uncertainties

- Normalization of $Z \rightarrow \tau\tau$ background
  (ATLAS study: 4-16% uncertainty)

- Uncertainties on τ identification and trigger efficiencies

- Tau energy scale
  CMS example: 8% on signal yield,

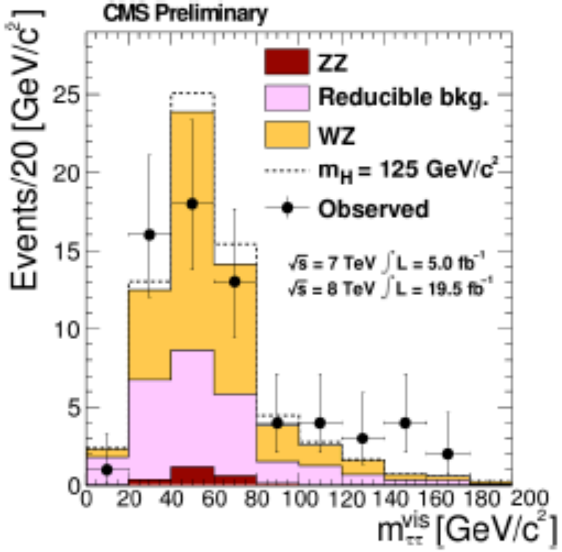
II. Theoretical uncertainties

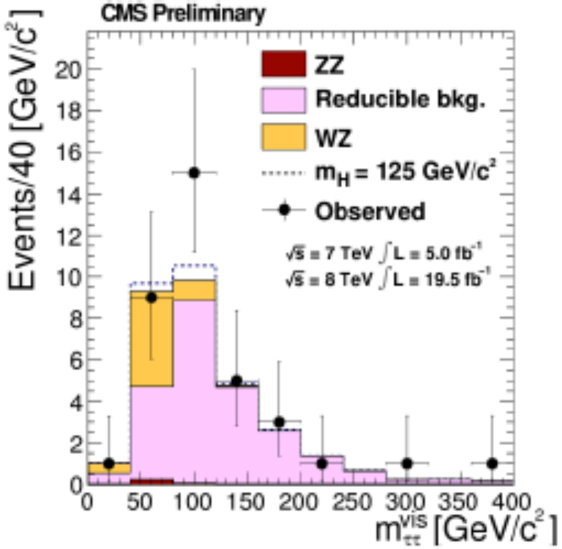
- signal cross sections and acceptance;
  depends on production process and on the category

  (e.g. scale uncertainty in gluon fusion yield is 10% in 1-jet/high p_T category,
  and 30% in the VBF category; scale uncertainty in VBF production yield is 4%)

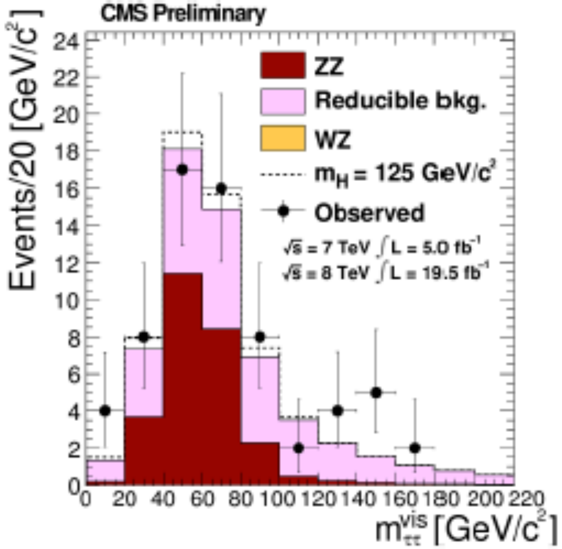
Search for H → ττ decays in VH production

WH channel





ZH channel



W(l)H(lτ_h)

- Main background irreducible WZ
- Same-sign of two leptons to suppress Z→ll+(jet→τ_h fake)

W(l)H($\tau_h\tau_h$)

- Main when one or two fake τ_h (reducible)
- Z→ll+2(jet→τ_h) fakes reduced by vetoing events with 2[nd] lepton

Z(ll)H(LL)

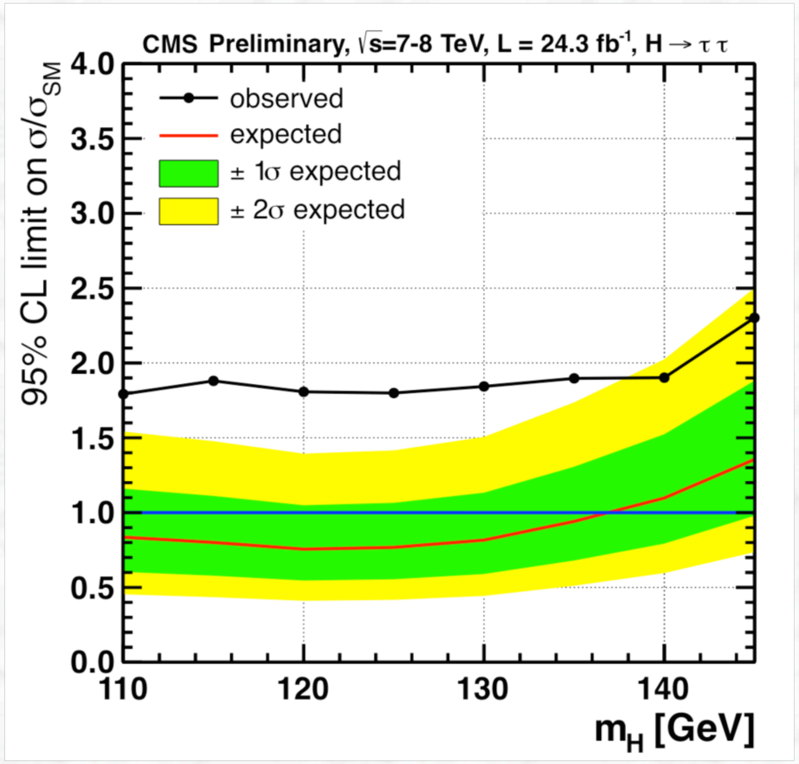
- Four final states
  - eτ_h, μτ_h, $\tau_h\tau_h$, eμ
- Require Z→ll candidate
- Irreducible background from ZZ, reducible from Z→ll+2jets

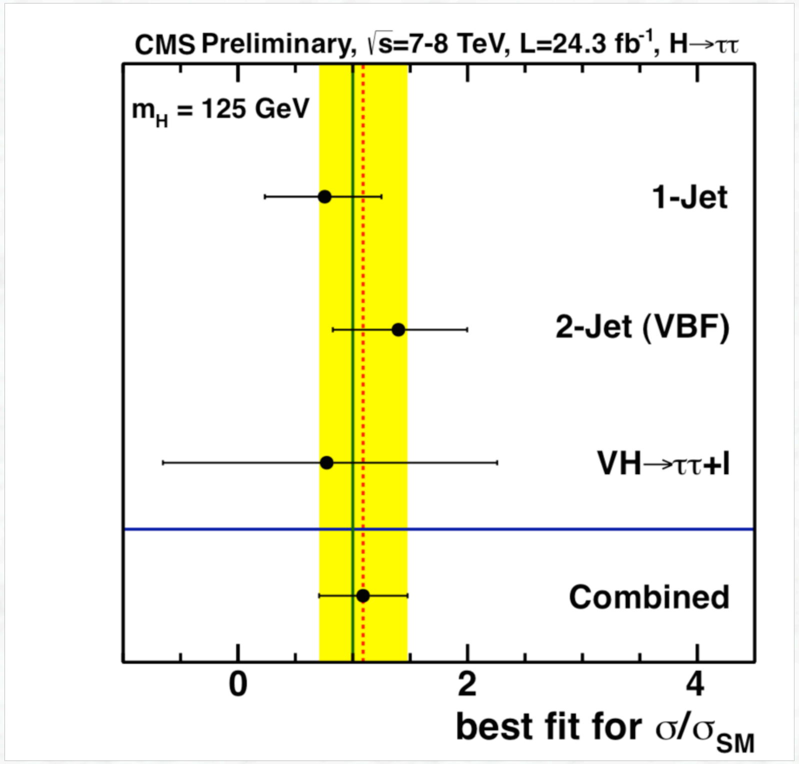
All VH channels: Reducible backgrounds with jet→l/τ_h fakes measured from data using fake-rate method

Combined CMS results (incl. VH)

- First "evidence" for direct fermionic ($H\tau\tau$) coupling

CMS PAS HIG-13-004





m_H = 125 GeV:

Observed 95% CL: 1.80 σ_{SM}

Expected (no Higgs): 0.77 σ_{SM}

Fitted signal strength (all sub-channels):

$\mu = 1.1 \pm 0.4$

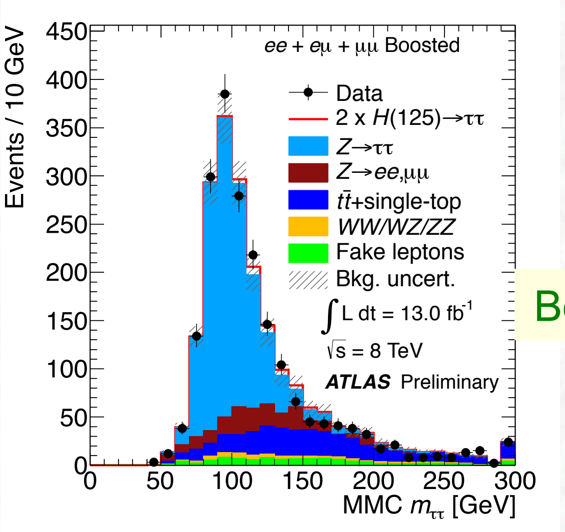
Reconstructed mass distributions

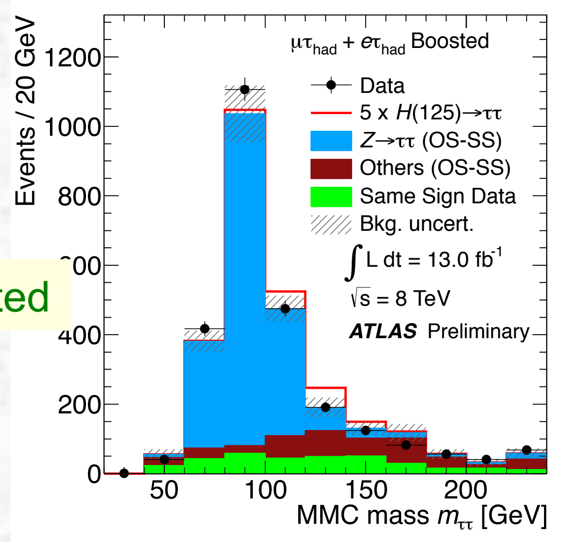
L = 13 fb^{-1} (2012)

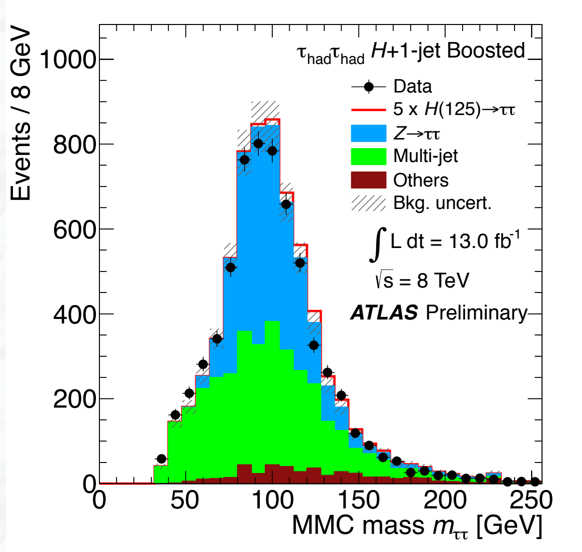
lepton-lepton

e/μ – hadron

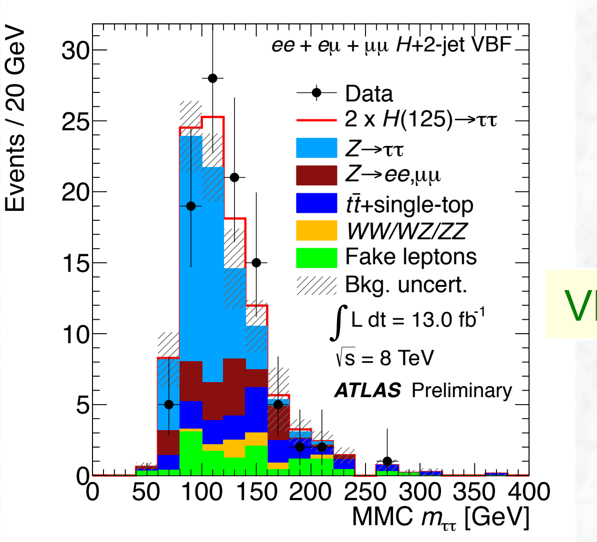
hadron – hadron

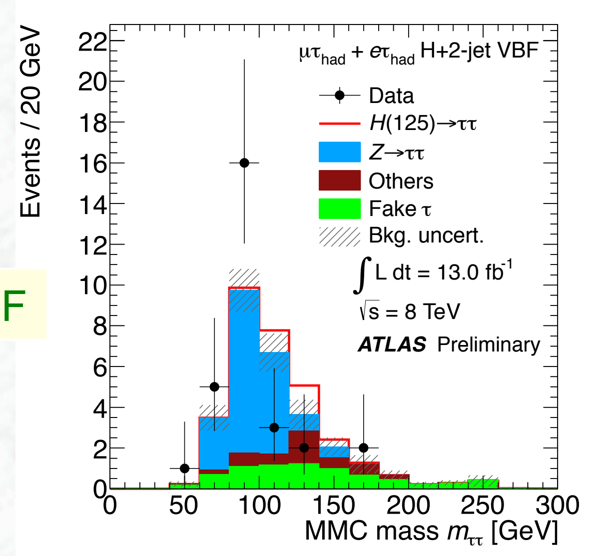


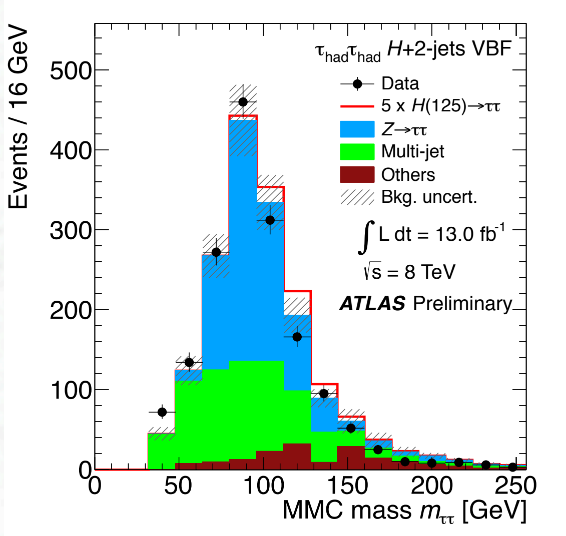




Boosted







VBF

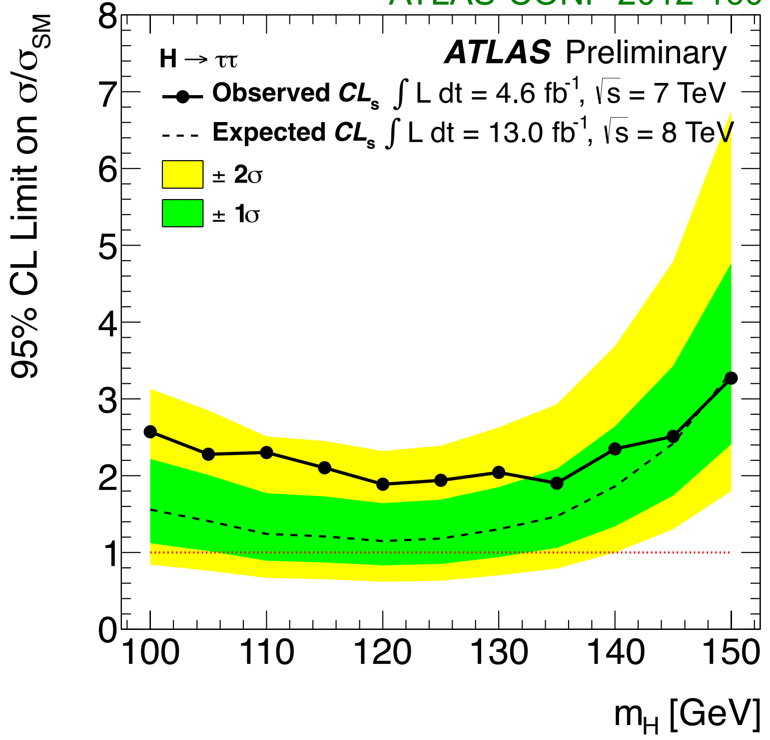
SM Higgs signal (multiplied by factors)

ATLAS-CONF-2012-160

Results on the search for H → ττ decays

- Discovery sensitivity for a signal not yet reached
- → 95% C.L. limits on cross section
  (normalized to SM cross sections)

ATLAS-CONF-2012-160



m_H = 125 GeV:

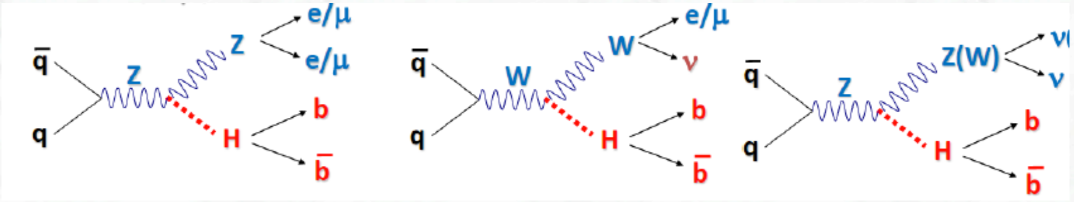
Observed 95% CL: 1.9 σ_{SM}
Expected (no Higgs): 1.2 σ_{SM}

Fitted signal strength (all sub-channels):

μ = 0.7 ± 0.7

Updated analysis, including the full data sample, eagerly awaited !
Important to settle the question of fermionic couplings

Search for VH production with H → bb decays



- Exploit three leptonic vector boson decay modes
  → split analysis in 0, 1, and 2-lepton categories

- Require 2 b-tagged jets
  (working point for 70% efficiency)

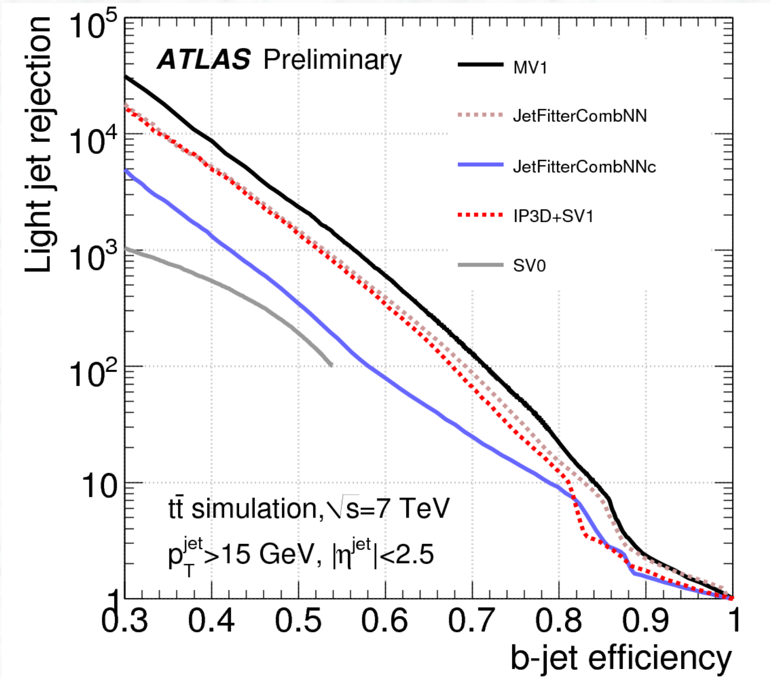
- Major background: W/Z bb, W+jets, tt

- Signal-to-background ratio improves for "boosted Higgs boson",
  split analysis in bins of $p_T(V)$

ATLAS: in total 15 categories
(0,1,2 jets × p_T bins)

CMS: multivariate analysis

ATLAS-CONF-2012-161



Event selection for H → bb analyses

(i) Basic event selection for the three channels

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^{jet_1} > 45$ GeV $p_T^{jet_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_T^{miss} > 120$ GeV $p_T^{miss} > 30$ GeV $\Delta\phi(\boldsymbol{E}_T^{miss}, \boldsymbol{p}_T^{miss}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_T^{miss}, \text{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_T^{miss}, b\bar{b}) > 2.8$	$E_T^{miss} > 25$ Gev	$E_T^{miss} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

(ii) Further topological criteria in intervals of $p_T(V)$

	p_T^V [GeV]	0-90	90-120	120-160	160-200	>200
All Channels	$\Delta R(b, \bar{b})$	0.7-3.4	0.7-3.0	0.7-2.3	0.7-1.8	<1.4
1-lepton	E_T^{miss} [GeV]	>25				>50
	m_T^W [GeV]	40-120			<120	

Definition of signal and control regions

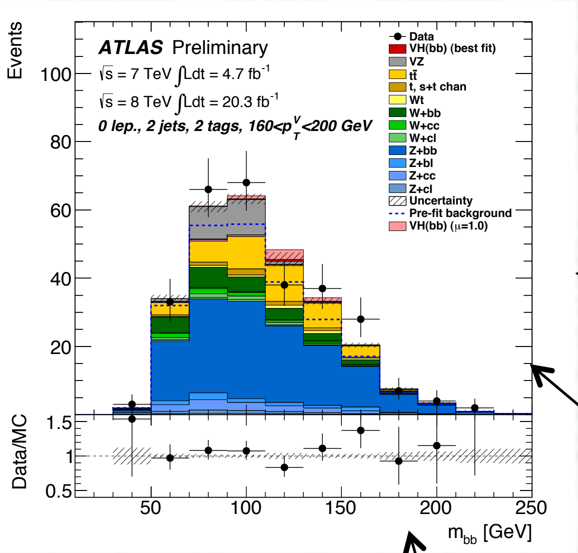
		2jets, 1tag	3jets, 1tag	2jets, 2tag	3jets, 2tag	top e-μ CR
3 p_T^V bins x	**0-lepton**	CR	CR	SR	SR	-
5 p_T^V bins x	**1-lepton**	CR	CR	SR	SR	-
5 p_T^V bins x	**2-lepton**	CR	CR	SR	SR	CR

CR=Control Region (low S/B)
SR=Signal Region

top e-μ CR: 1 electron+1 muon, $m_{\ell\ell}$>40 GeV

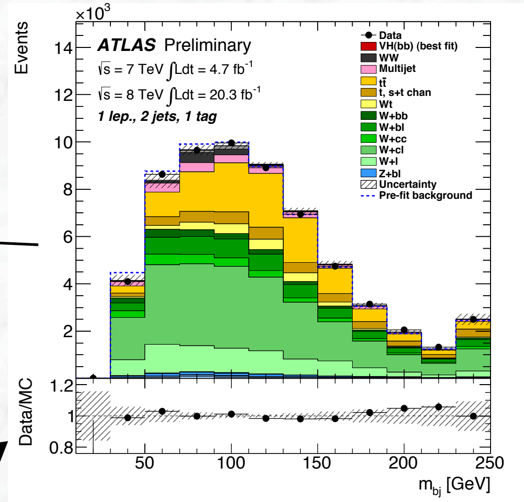
- Common nuisance parameters across regions
- Systematic uncertainties on extrapolation between control and signal regions

Background normalization, interplay of regions



Signal region: 0 leptons, 2 jets, 2 b-tags

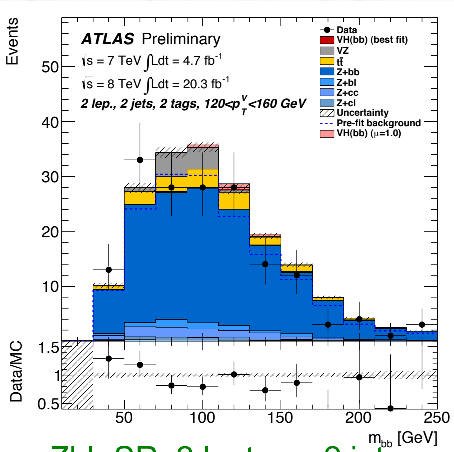
W+jets



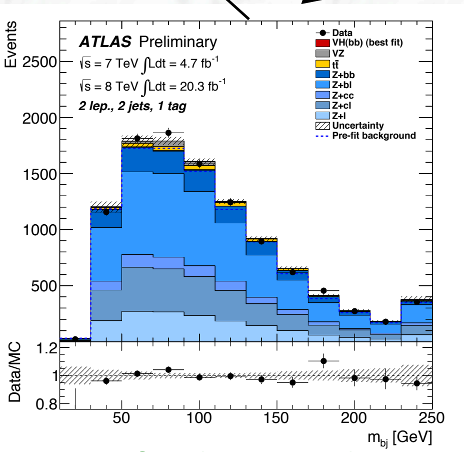
W+jets CR: 1 leptons, 2 jets, 1 b-tag

Z+jets, Zbb

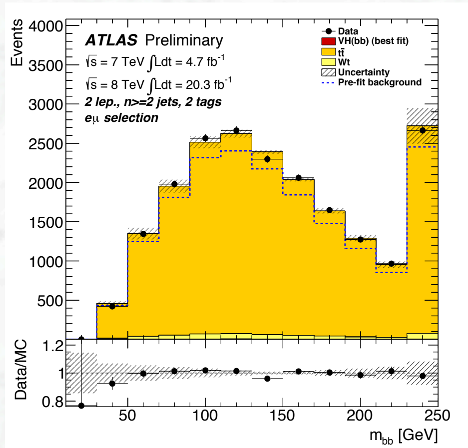
Top



Zbb SR: 2 leptons, 2 jets, 2 b-tags



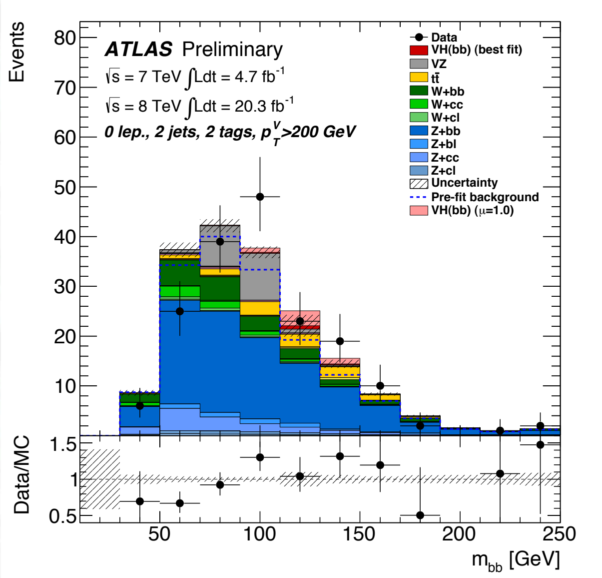
Z+jets CR: 2 leptons, 2 jets, 1 b-tags



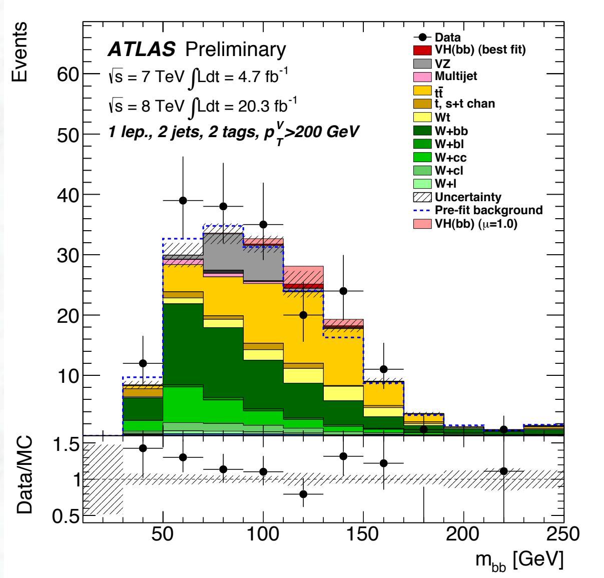
Top CR: 2 leptons, >=2 jets, 2 b-tags

Reconstructed mass distributions

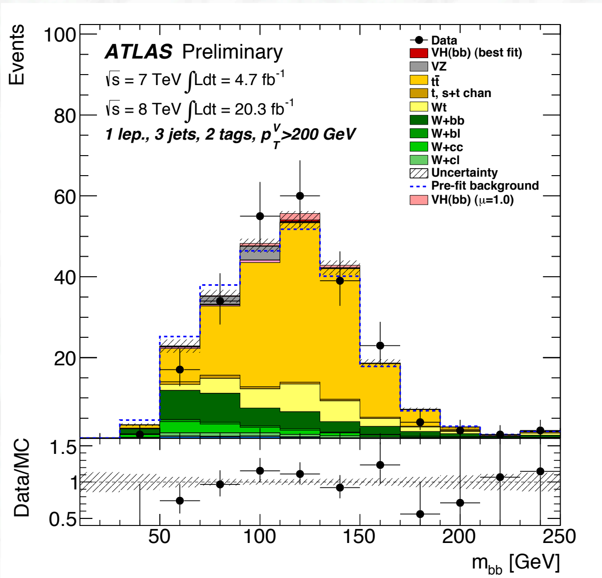
-full data set, 7 and 8 TeV (a selection, high p_T bins)-



0 lepton



1 lepton

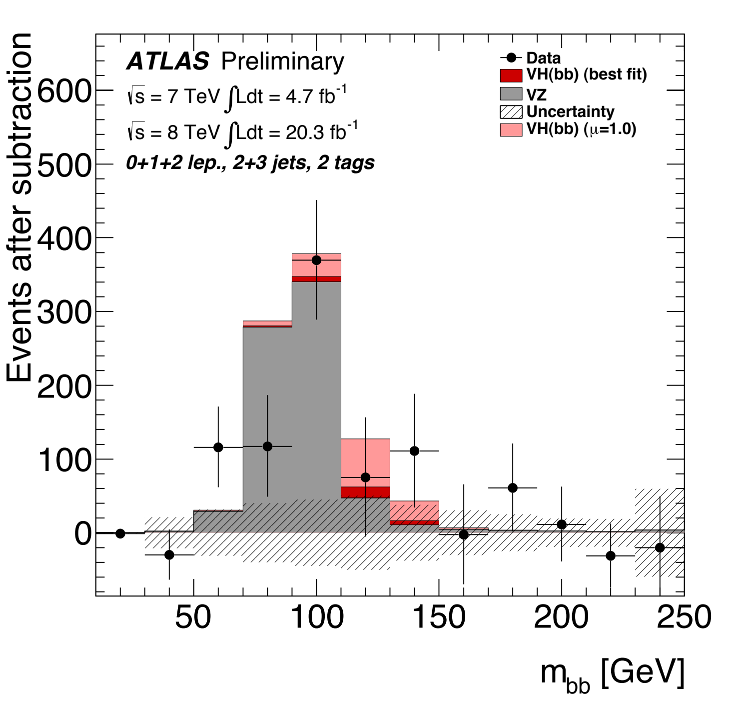


2 leptons

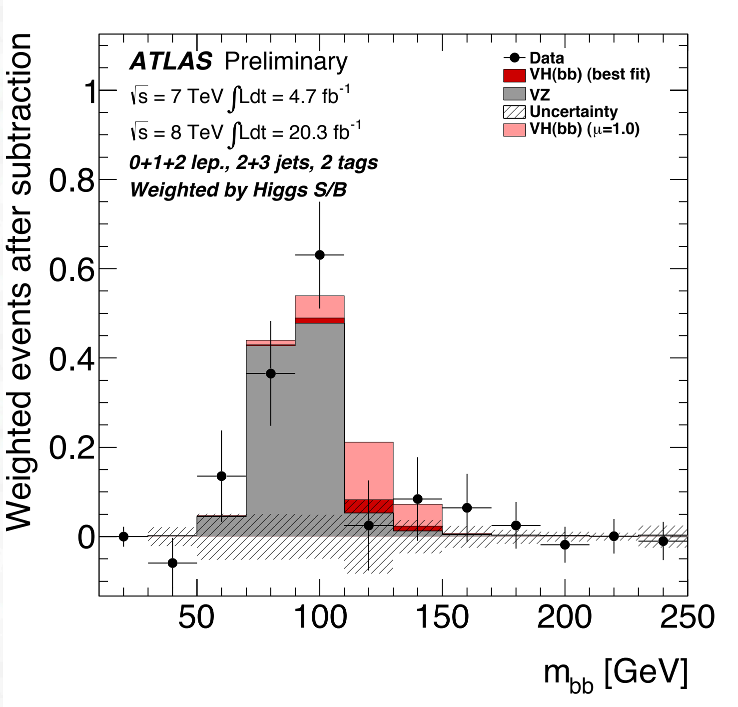
ATLAS-CONF-2013-079

Demonstration of di-boson production with Z → bb in ATLAS

combination (all bins, channels)
data - background



weighted distribution, by S/B ratio



Di-boson signal established

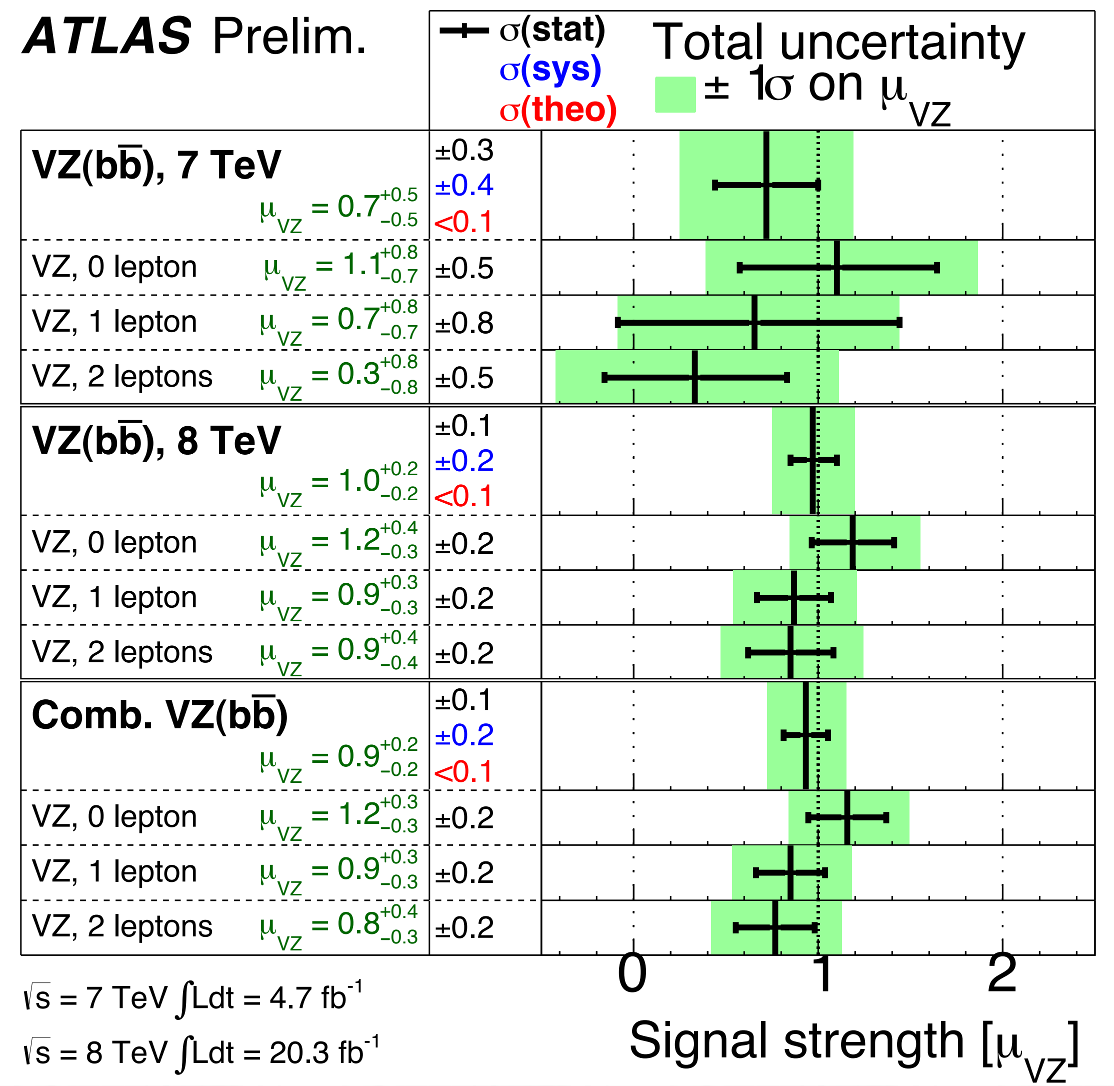
(important "calibration" signal; a Standard Model Higgs boson signal is included as background)

Significance 5.1σ

$\mu_{WZ+WW} = 0.90 \pm 0.20$

ATLAS-CONF-2013-079

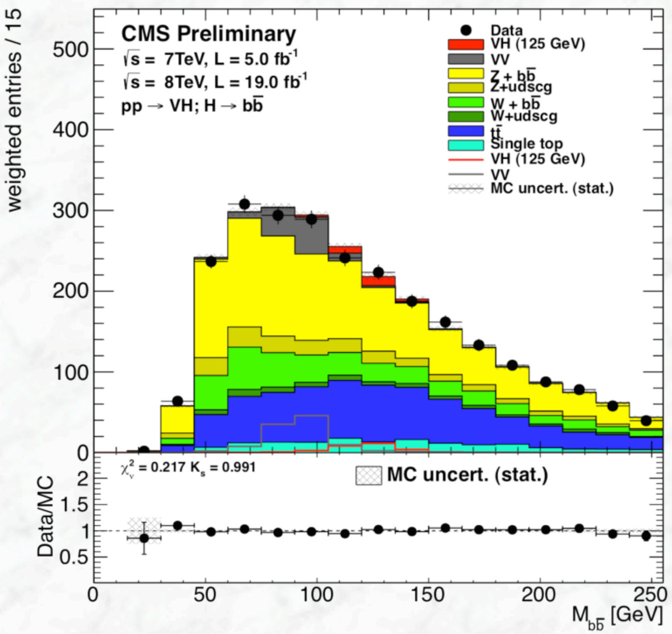
Di-boson signal strength



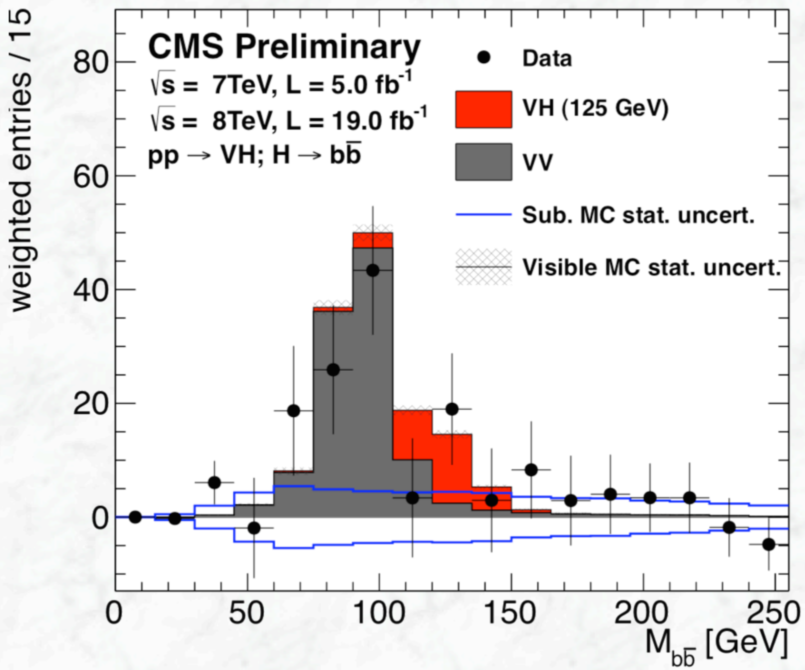
ATLAS-CONF-2013-079

Demonstration of di-boson production with Z → bb in CMS

Weighted (by S/B ratio) m_{bb} mass distribution



Weighted (by S/B ratio) background-subtracted m_{bb} mass distribution



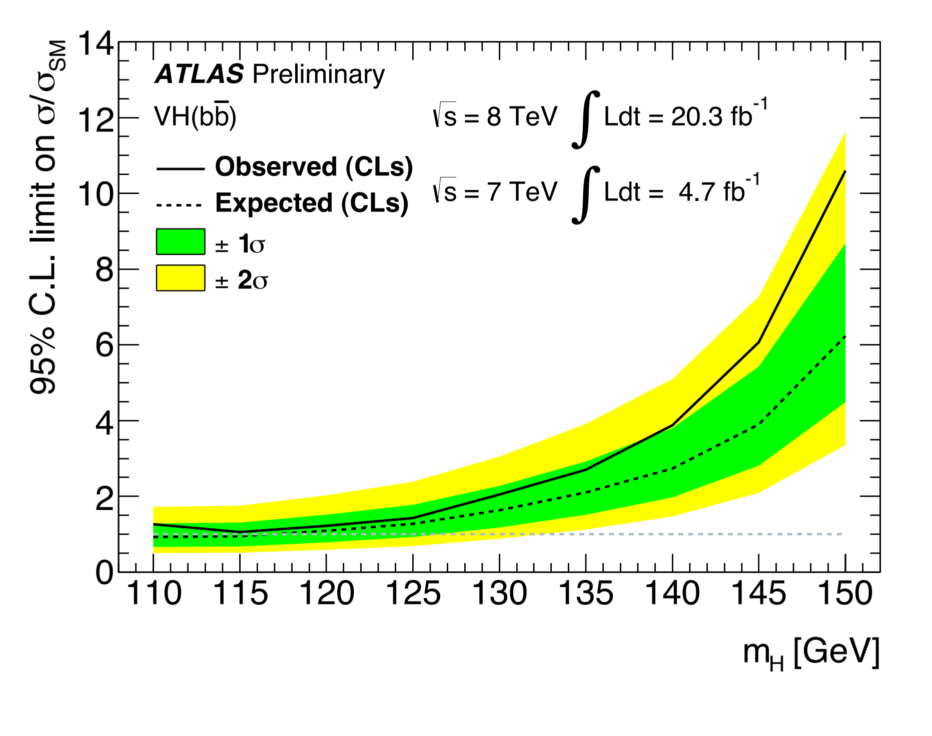
- Di-boson signal established

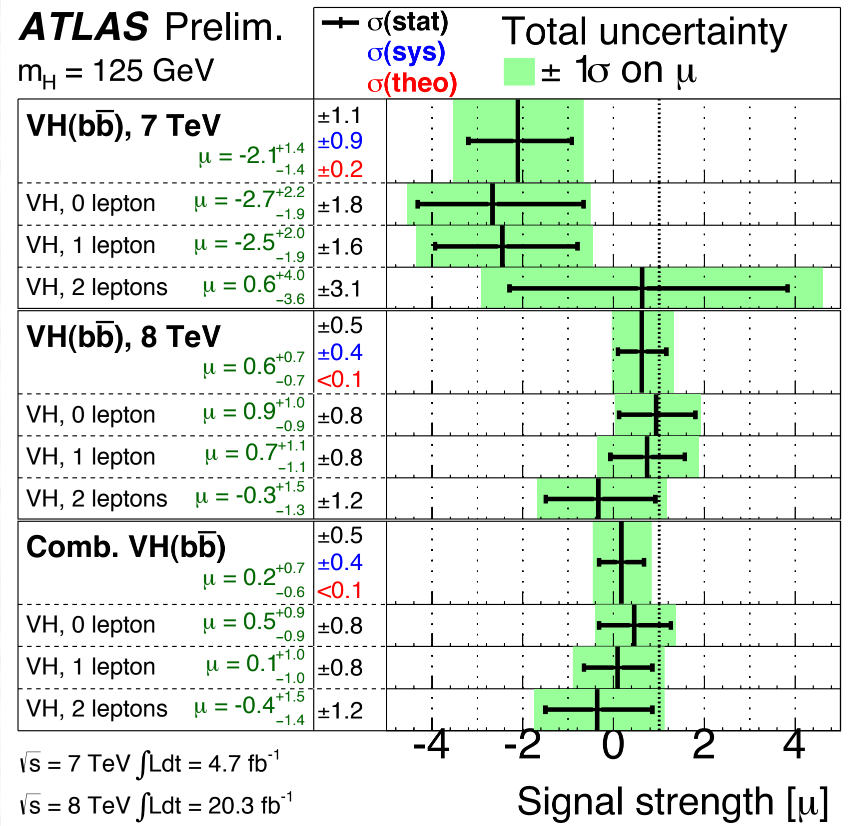
- Signal size consistent with expectations from Standard Model

CMS PAS HIG-13-012

ATLAS results on the search for VH, H → bb decays

ATLAS-CONF-2013-079





m_H = 125 GeV:

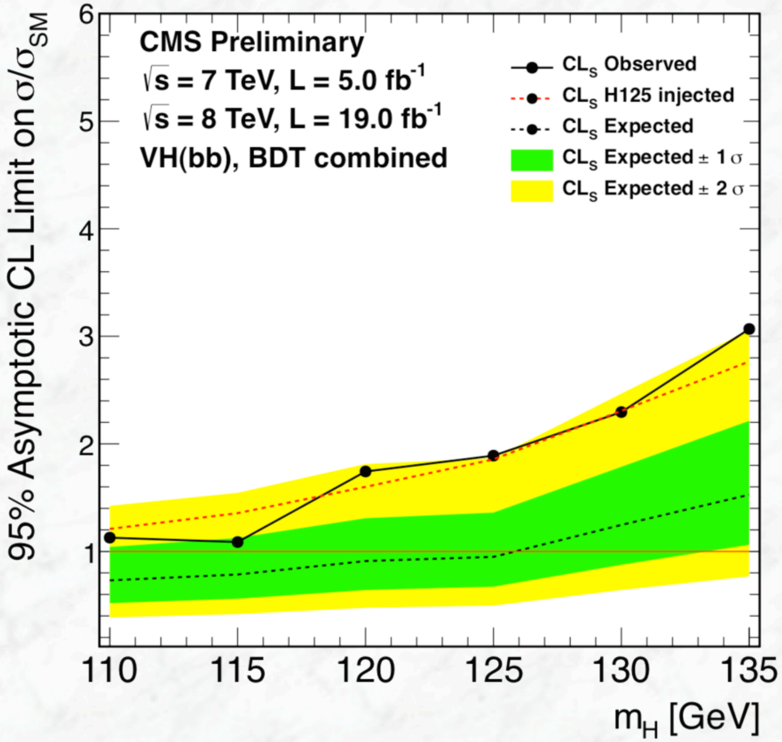
Observed 95% CL: 1.4 σ_{SM}
Expected (no Higgs): 1.3 σ_{SM}

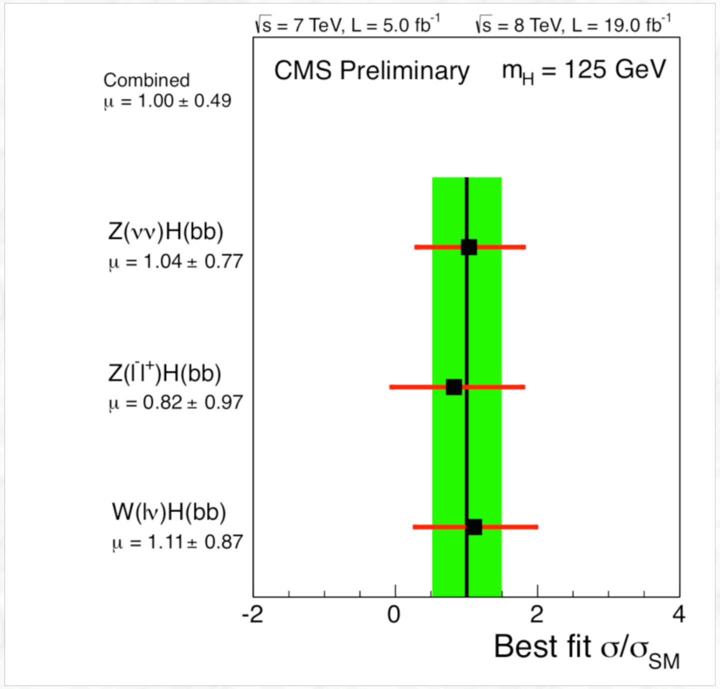
μ_H = 0.2 ± 0.5 (stat) ± 0.4 (syst)

Probability of obtaining a result more background-like than the observed in the presence of a SM signal (μ=1) is 0.11

CMS results on the search for VH, H → bb decays

CMS PAS HIG-13-012





m_H = 125 GeV:

Observed 95% CL: 1.89 σ_{SM}
Expected (no Higgs): 0.95 σ_{SM}

μ_H = 1.00 ± 0.49

End of Lecture II