The Higgs Boson: Searches For Fermionic Decays

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ATLAS, CMS, CDF & D0 Collaborations

Outline

- Motivation & (very) brief theory trivia
- Covered in this talk
  - Searches for SM $H \to bb$
  - Searches for SM $ttH(\to bb)$
  - Searches for SM $H \to \tau\tau$
  - Searches for SM $H \to \mu\mu$
  - A few words on future prospects
- Not covered in this talk
  - Results on BSM $H \to ff$ searches
- Disclaimer
  - Analyses technical details will be provided in parallel session talks
    - ATLAS: Goetz Gaycken, link
    - CMS: Andrew Gilbert, link
    - Tevatron: Koji Sato, link

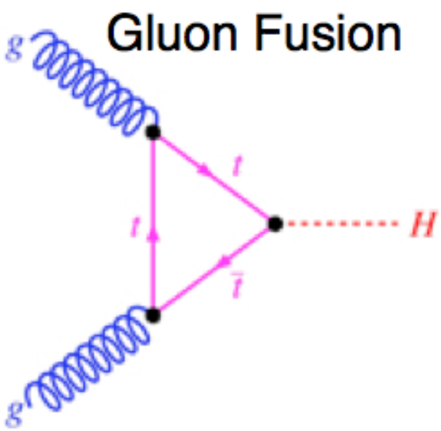
Higgs-like Boson is Found! What's next?

- July 4th 2012: CMS & ATLAS announced the discovery of a new boson with mass ~125 GeV which decays to $\gamma\gamma$, ZZ, WW pairs
- Is this newly discovered boson a SM Higgs boson or does it have non-SM like properties?
  - Are decay rates, spin & CP properties consistent with SM Higgs?
- **Search for H→fermions decays is one of the most important goals for the Higgs program**
  - Are $\Gamma_{H \to ff}$ consistent with SM predictions?
  - Is it the same Higgs decaying to H→VV & H→ff?
    - Is mass the same? CP properties?

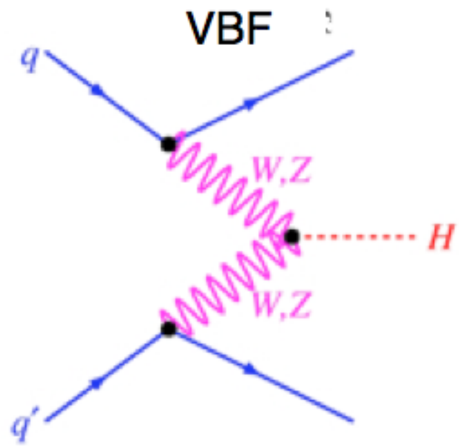
$$\Gamma_{H \to ff} = \frac{N_C M_H}{8\pi v^2} m_f^2 \sqrt{1 - \frac{4m_f^2}{M_H^2}}$$

Decay	Br@125 GeV
H→bb	57.8%
H→ττ	6.37%
H→μμ	0.0217%

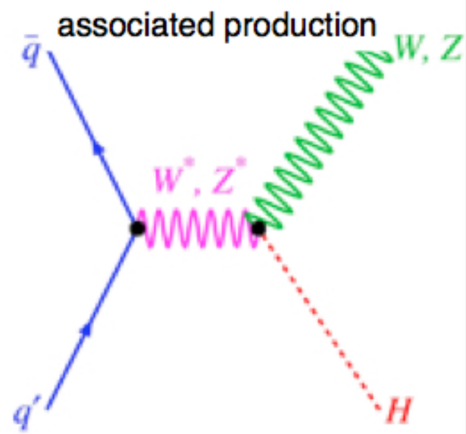
SM Higgs Production Trivia (for M_H=125 GeV)



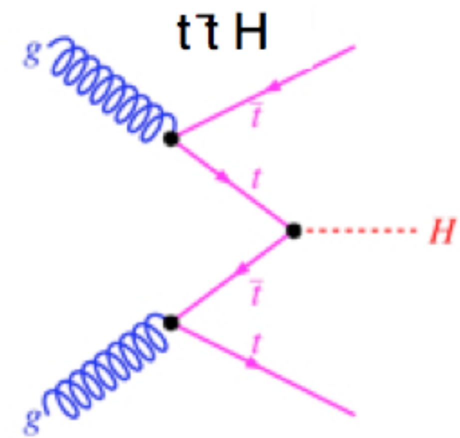
Largest production mode: ~88%
Utilized by H→ττ & H→μμ analyses



Unique signature of two jets with large M_{jj} & $|\Delta\eta_{jj}|$
Utilized by H→ττ & H→bb



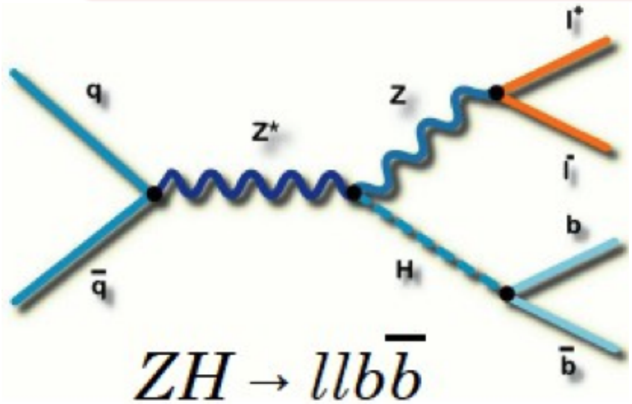
Unique signature with leptons & neutrinos
Utilized by VH(→ττ) & VH(→bb)



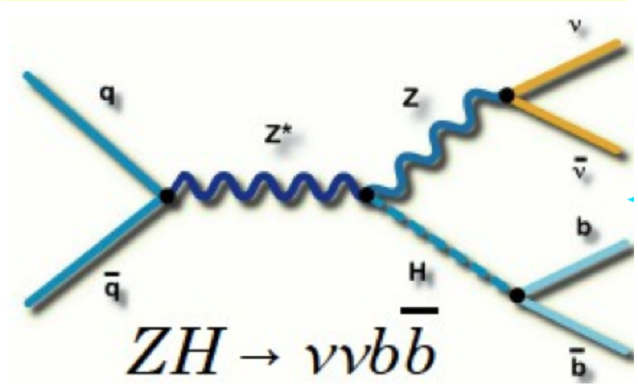
Unique signature with 2 top quarks
Utilized by ttH search

	gg→H	VBF	VH	ttH
LHC: 8 TeV	19.5 pb	1.57 pb	1.08 pb	0.13 pb
Tevatron: 1.96 TeV	0.949 pb	0.065 pb	0.208 pb	0.0043 pb

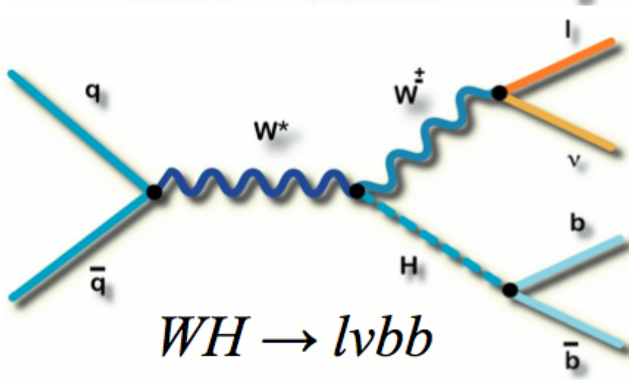
Searches For VH With H→bb



- ZH→ll+bb
  - **Signature:** two opposite sign leptons and 2 b-tagged jets
  - **Major backgrounds**: Z+ heavy flavor jets

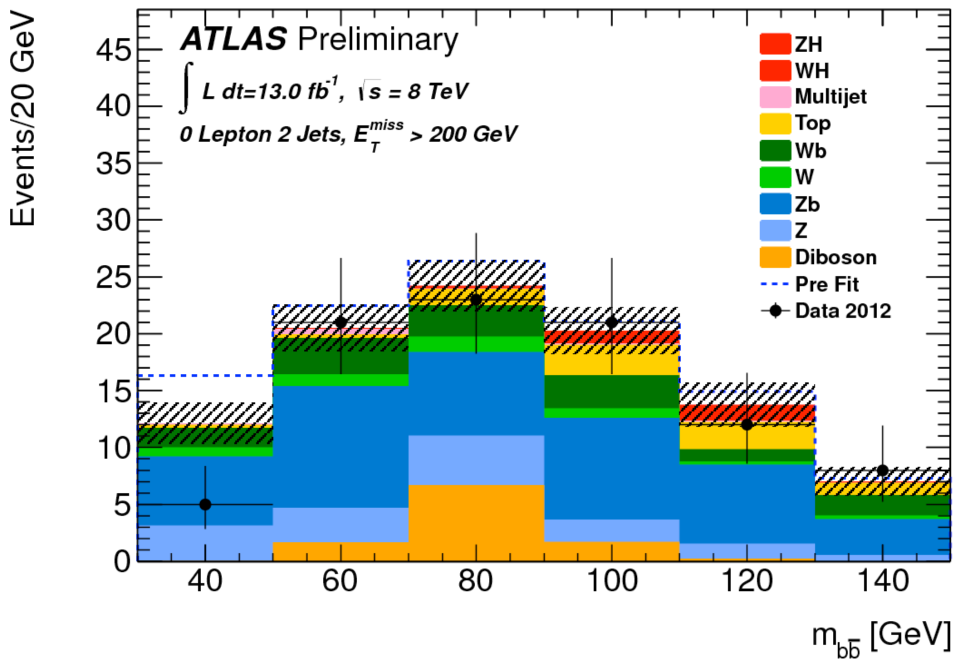


- ZH→νν+bb
  - **Signature:** large MET and 2 b-tagged jets
  - **Major backgrounds**: top, Z/W+ heavy flavor jets

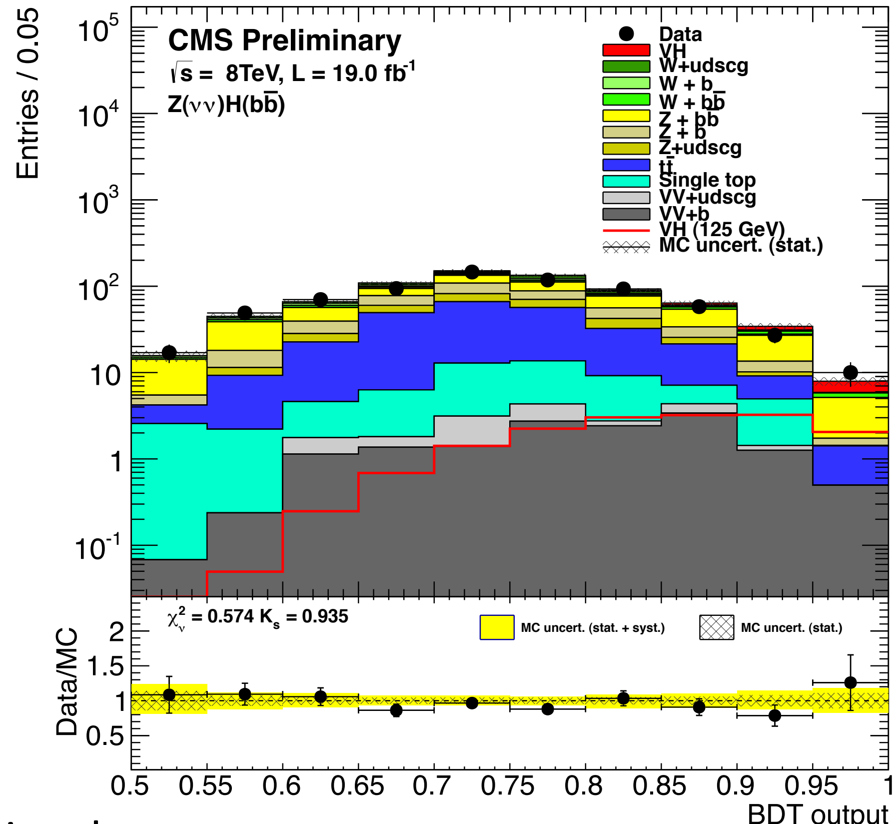


- WH→l/τhad+ν+bb
  - **Signature:** one lepton or hadronic τ, MET and 2 b-tagged jets
  - **Major backgrounds**: top, W+ heavy flavor jets

LHC Results for VH(→bb): Examples of Distributions



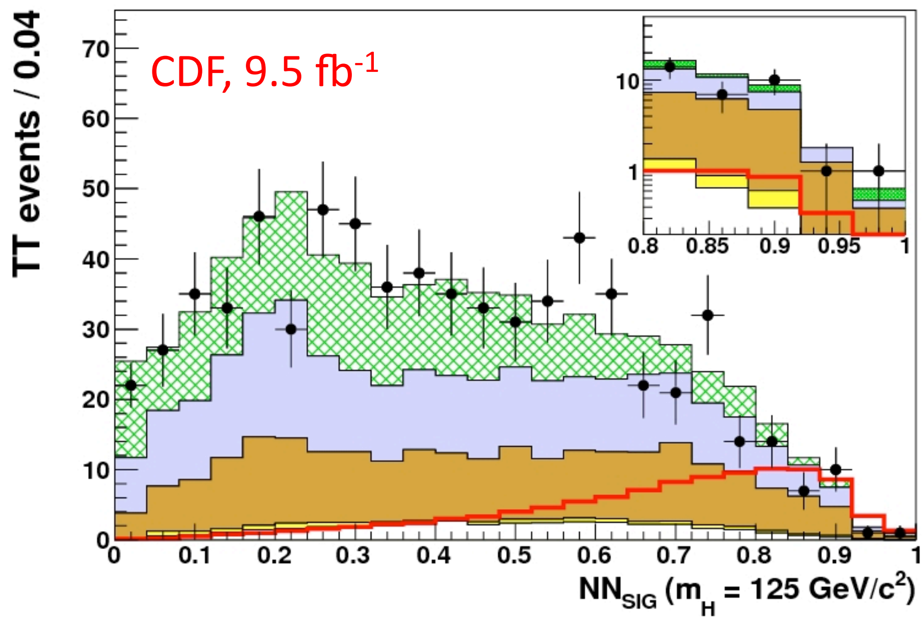
Examples of distributions for ZH→νν+bb

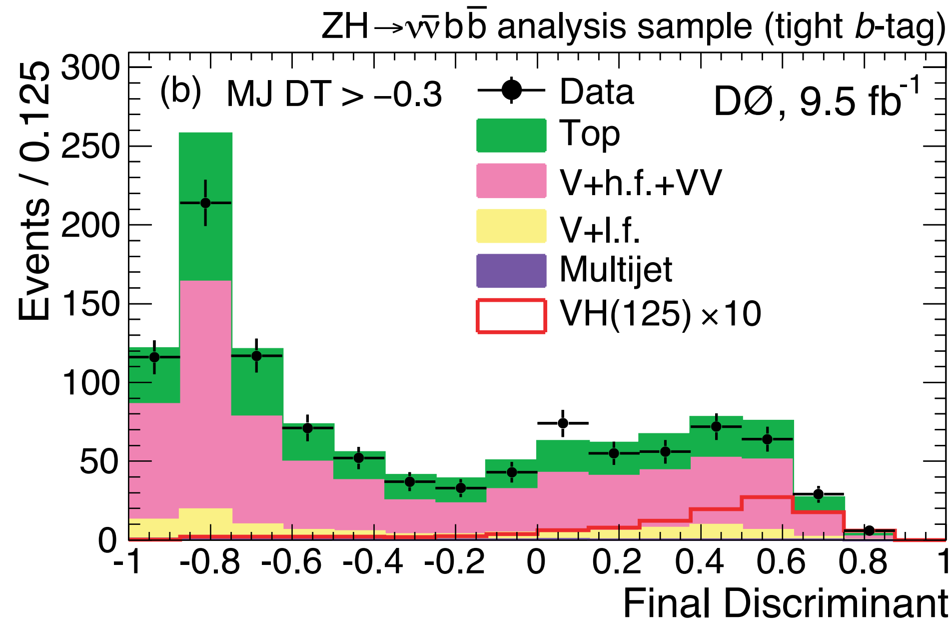


- ATLAS
  - Cut-based analysis uses M_{bb} to extract signal
- CMS
  - Multivariate analyses use MVA-score distribution for signal extraction
- Leading sources of experimental uncertainties
  - B-tagging efficiency, jet energy scale & resolution, background normalization

Tevatron Results for VH(→bb): Examples of Distributions

Two tight b-tags

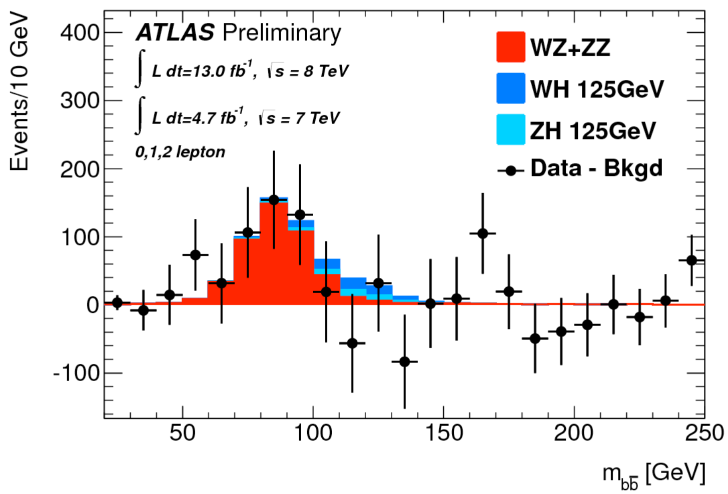


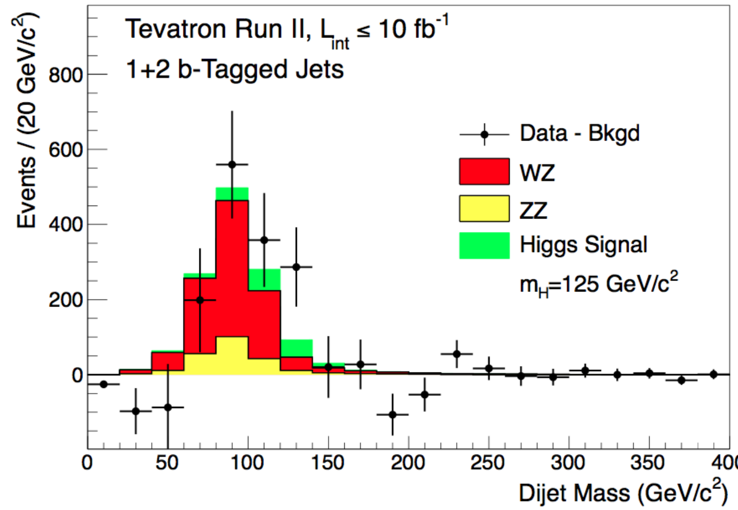


Examples of distributions for ZH→νν+bb

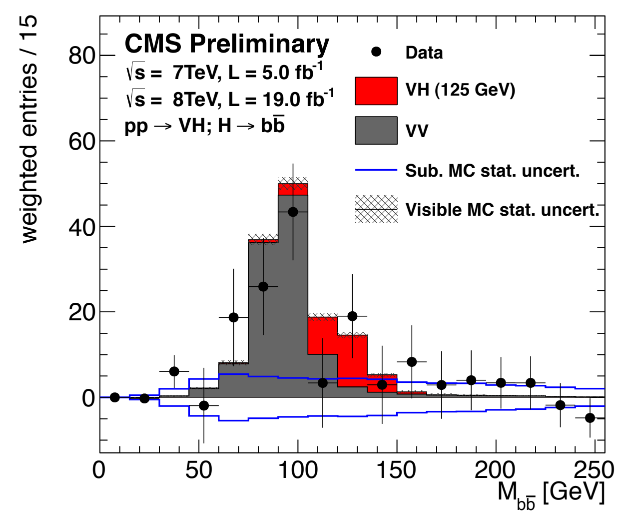
- Tevatron experiments
  - Multivariate analyses use MVA-score distribution for signal extraction
- Leading sources of experimental uncertainties
  - B-tagging efficiency, jet energy scale & resolution, background normalization

Building Confidence in VH(→bb) Results

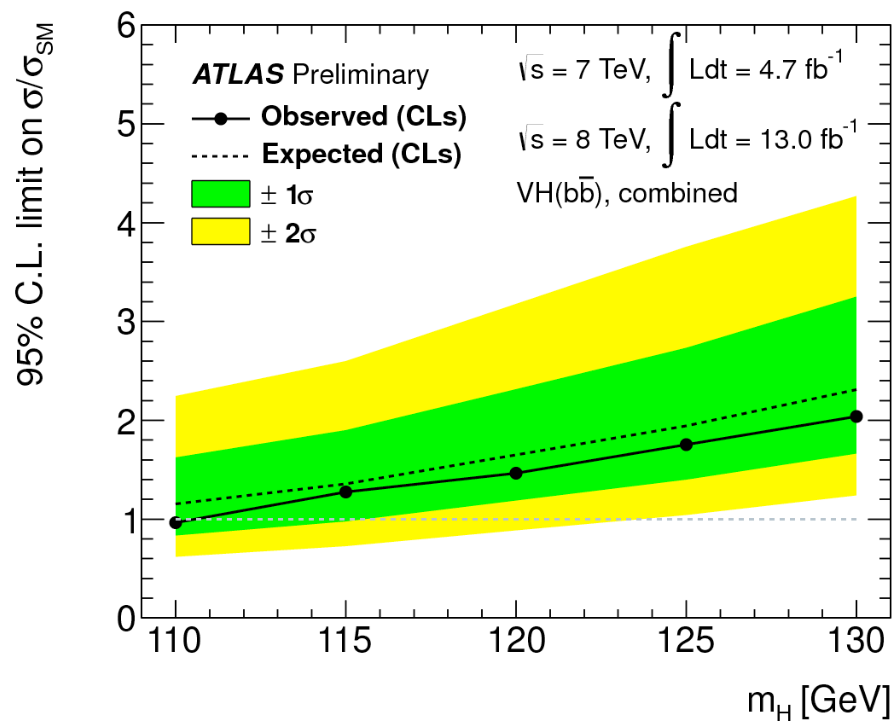


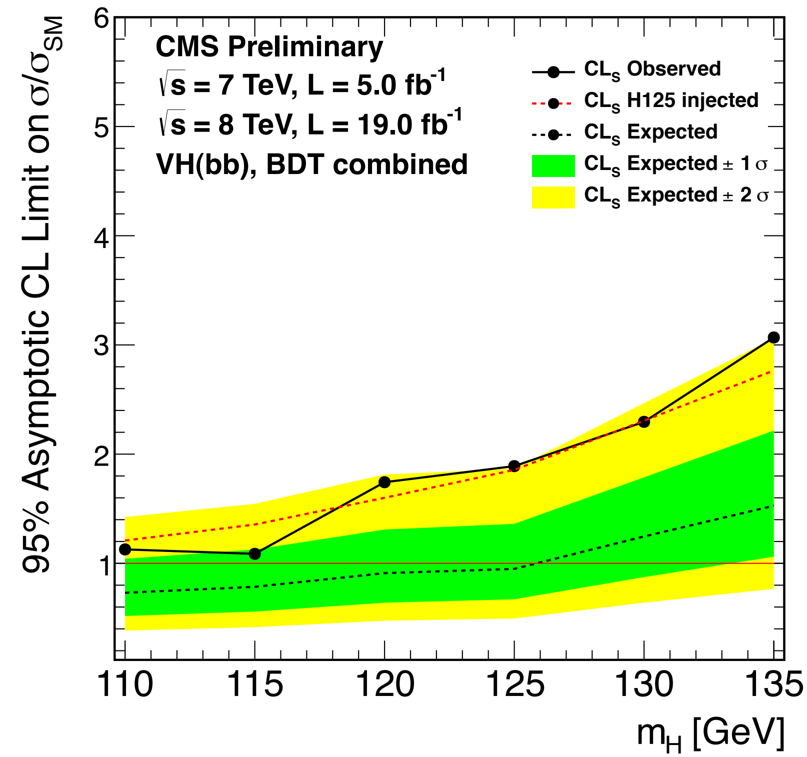


- Analysis techniques validated in numerous data control regions
- **Most important check comes from measurements of VZ(→bb) production using the same analysis techniques as in VH search**
- Fitted diboson signal strength
  - ATLAS: μ_D=1.09±0.20±0.22
  - CMS: $\mu_D=1.19^{+0.28}_{-0.23}$ (8 TeV only)
  - Tevatron: μ_D=0.68±0.14±0.14



LHC Results For VH With H→bb

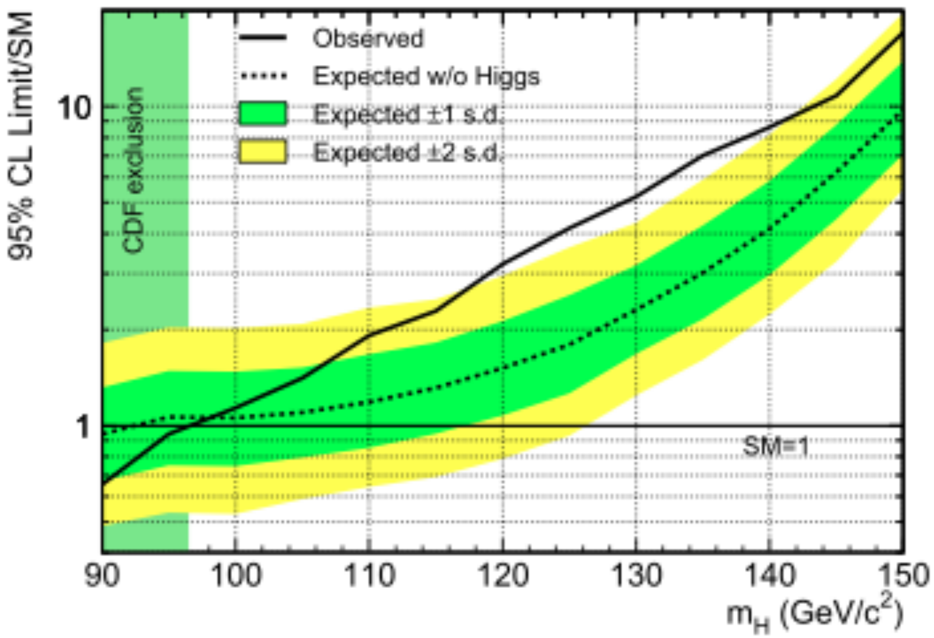




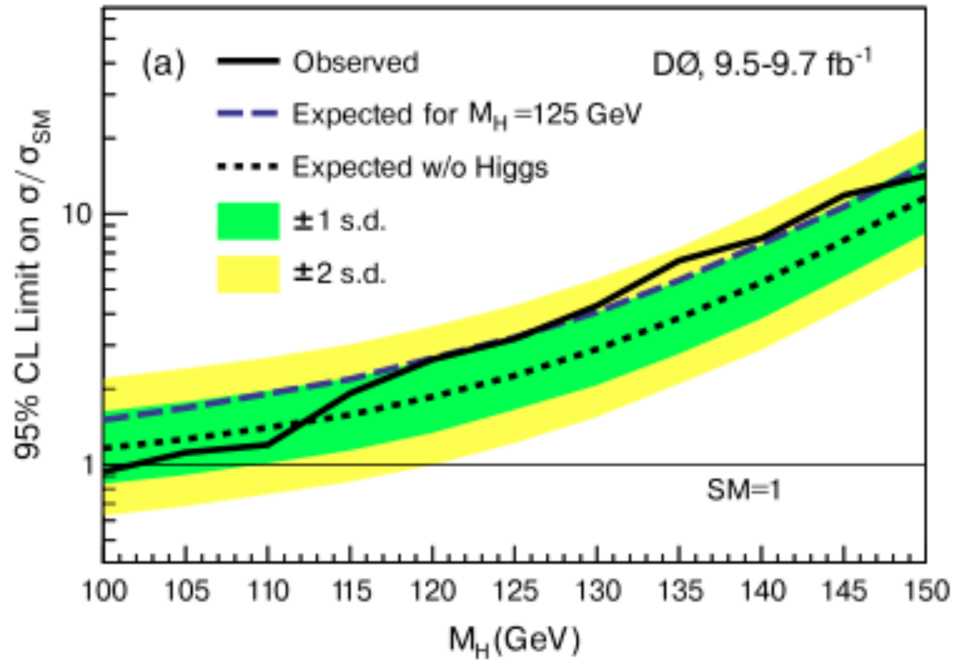
- ATLAS: 17.7 fb^{-1} of 7+8 TeV data
  - 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 1.9×SM, observed 1.8×SM
- CMS: 24.0 fb^{-1} of 7+8 TeV data
  - 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 0.95×SM, observed 1.89×SM
  - Local significance at @ 125 GeV is p_0=2.1σ

Tevatron Results For VH With H→bb

CDF VH(→bb) results

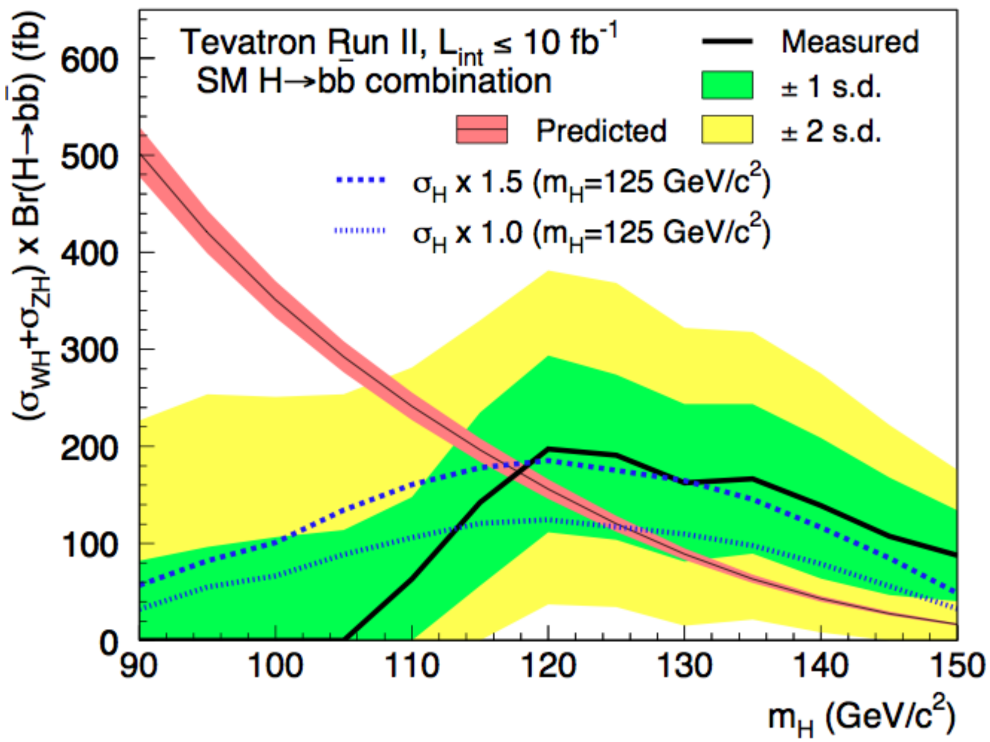


D0 VH(→bb) results



- CDF: 9.5-9.7 fb^{-1} of 1.96 TeV data
  - Observe excess in a range of 120-140 GeV
  - Best fitted signal strength: R_{fit}(VH→Vbb)=$1.72^{+0.92}_{-0.87}$
- D0: 9.5-9.7 fb^{-1} of 1.96 TeV data
  - 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 2.3×SM, observed 3.2×SM

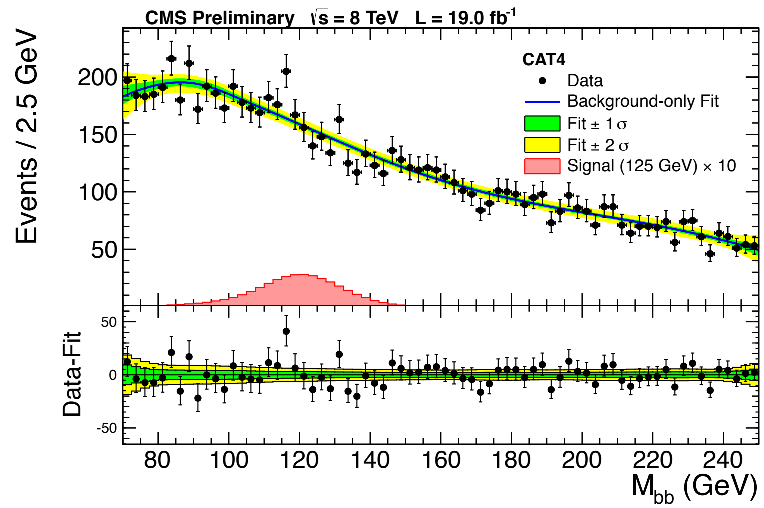
Tevatron Results For HV With H→bb

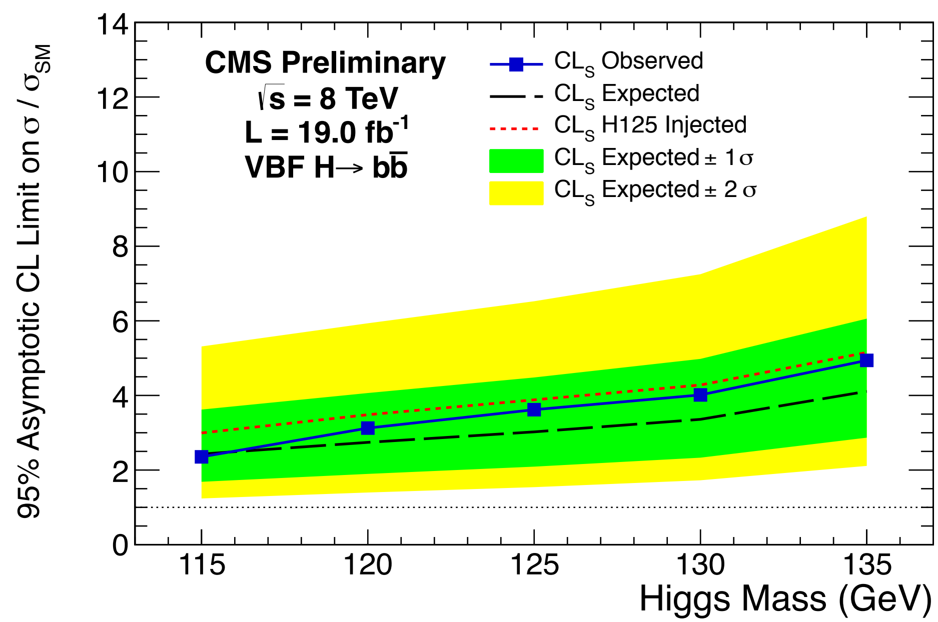


- Combined Tevatron result for VH(→bb) based on <10 fb^{-1} of data at 1.96 TeV
  - Excess of data over background predictions in the range of 120-140 GeV
  - Best fitted signal strength: $R_{fit}(VH\rightarrow Vbb)=1.59^{+0.69}_{-0.72}$

CMS Search for H→bb in VBF Channel

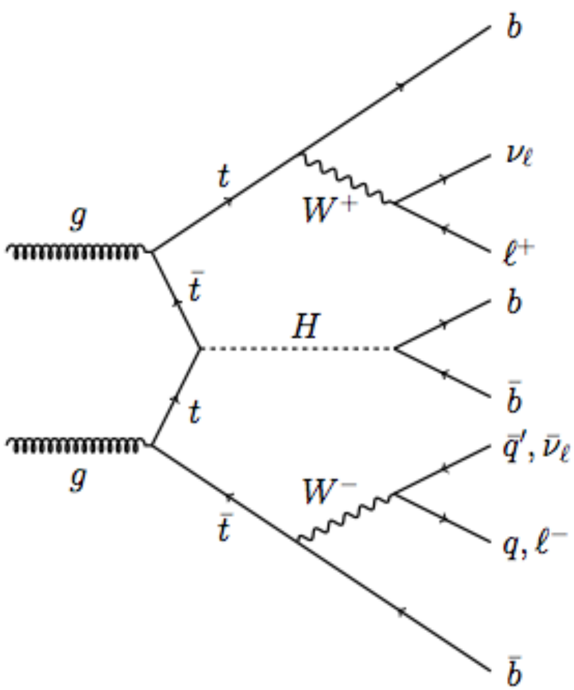
- First LHC search for H→bb in VBF production
- Analysis overview
  - 19 fb^{-1} at 8 TeV
  - 4 energetic jets, 1 or 2 b-tagged jets
  - Event classification based on ANN using kinematic properties of not-tagged jets
  - Signal extracted by fitting M_{bb}
- 95% CL upper limit on σ/σ_{SM} @ 125 GeV:
  - Expected 3.0×SM
  - Observed 3.6×SM



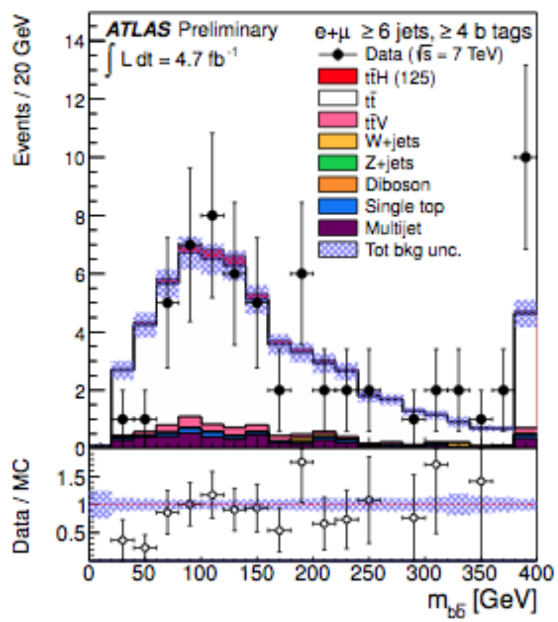


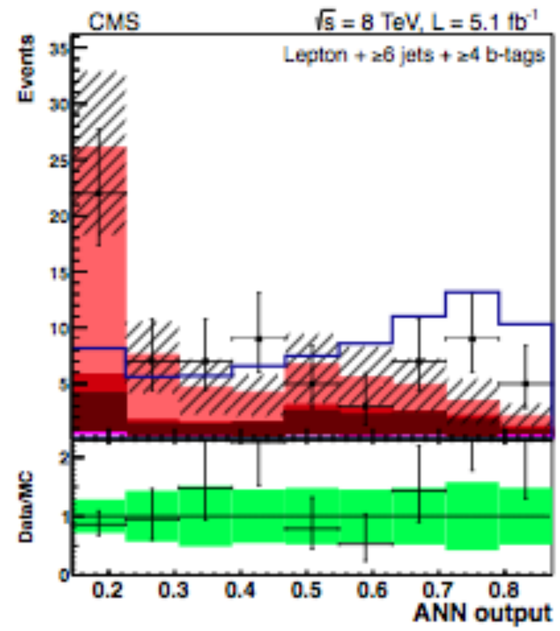
Search For ttH(→bb) Production

- ttH production is directly sensitive to ttH coupling
- Dominant background is top quark pair production
- **ATLAS:** lν+jets final state; cut-based analysis; event categories based on N_{jets} & $N_{b\text{-}tag}$
- **CMS:** lν+jets & 2l2ν+jets final state; MVA analysis; event categories based on $N_{leptons}$, N_{jets} & $N_{b\text{-}tag}$

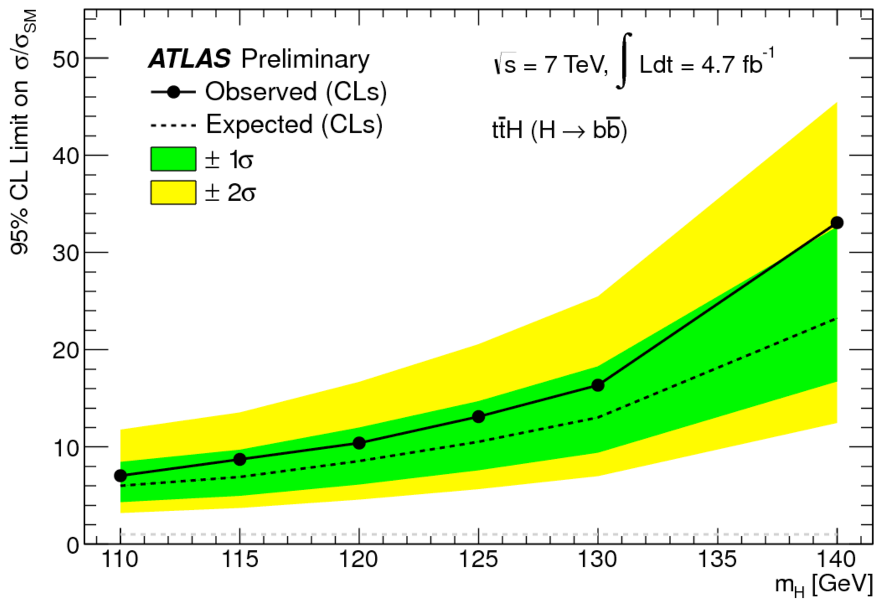


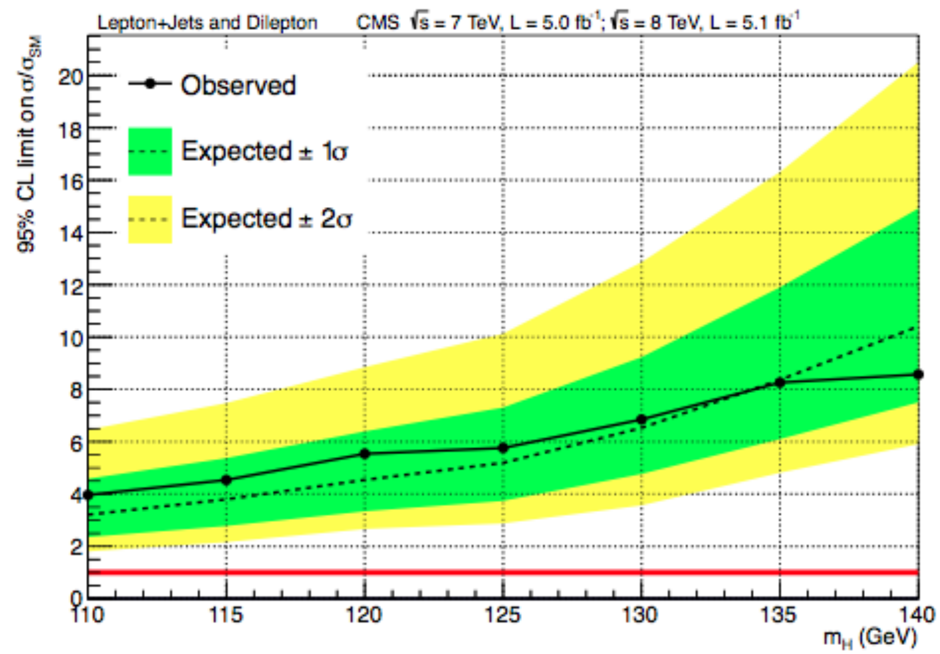
Examples of final discriminants used in fits for signal





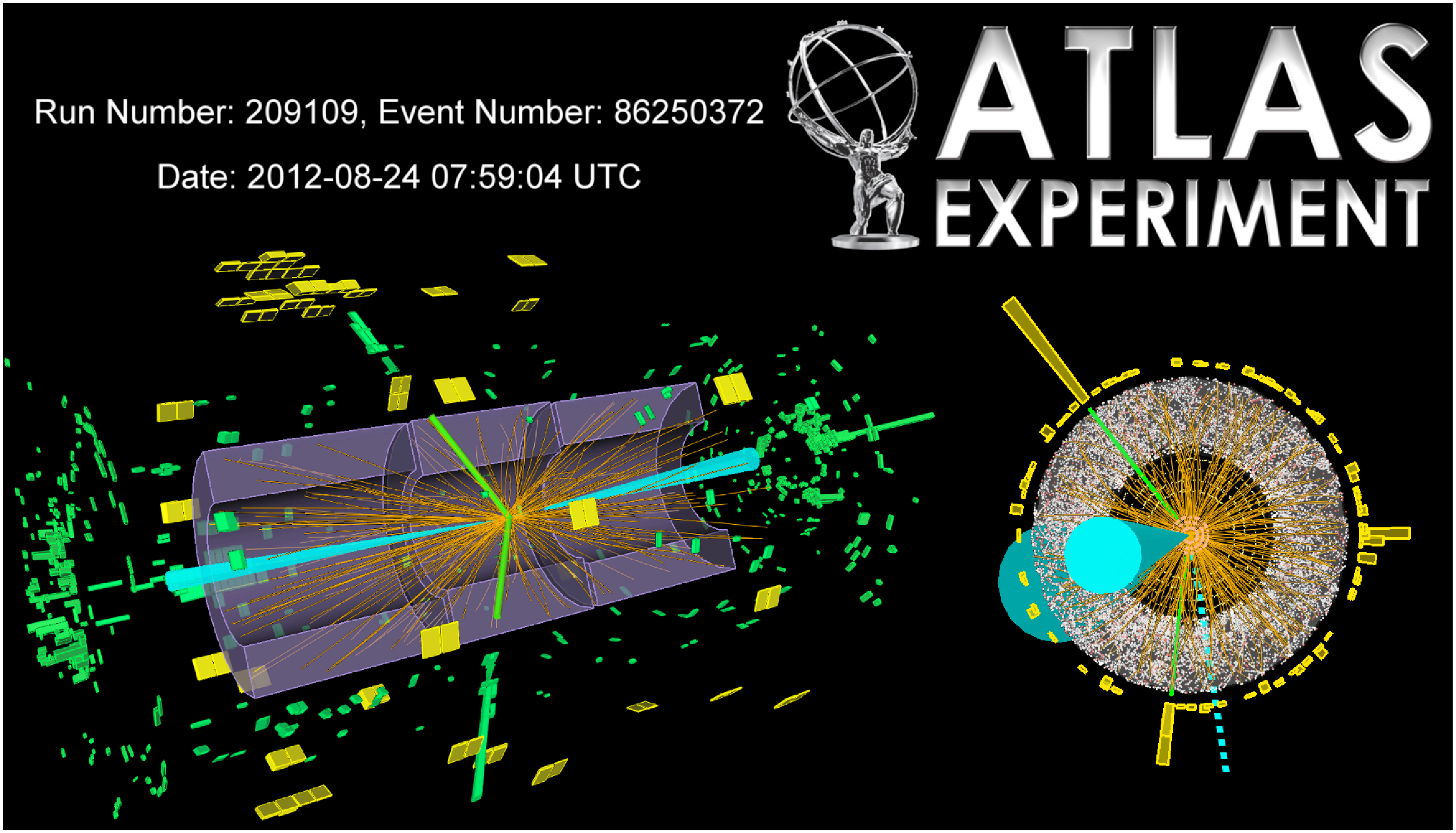
Search For ttH(→bb) Production





- ATLAS: 4.7 fb^{-1} of 7 TeV data
  – 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 10.5×SM, observed 13.1×SM
- CMS: 10.1 fb^{-1} of 7+8 TeV data
  – 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 5.1×SM, observed 5.8×SM

Searches for H→ττ



Searches For $H\rightarrow\tau\tau$ At ATLAS & CMS

- Final states of tau decays
  - $H\rightarrow\tau\tau\rightarrow 2l+4\nu$ (lep-lep): Br=12.4%
  - $H\rightarrow\tau\tau\rightarrow l+\tau_{had}+3\nu$ (lep-had): Br=45.6%
  - $H\rightarrow\tau\tau\rightarrow 2\tau_{had}+2\nu$ (had-had): Br=42%
- VH events in CMS analysis
  - $W(l+\nu)+H(l\tau_{had}+2\tau_{had})$
  - Z(2l)+H(2l)
  - $VH\rightarrow VWW^*$ are treated as part of the signal

- ATLAS & CMS analysis categories
  - **VBF**: require 2 jets with large $\Delta\eta_{JJ}$ & M_{JJ}
  - **Boosted**: require boosted $\tau\tau$ system
    - $P_T(H)>100/140$ GeV or high P_T jet
  - **1-jet** with/without MET cut
  - **0-jet** with/without MET cut

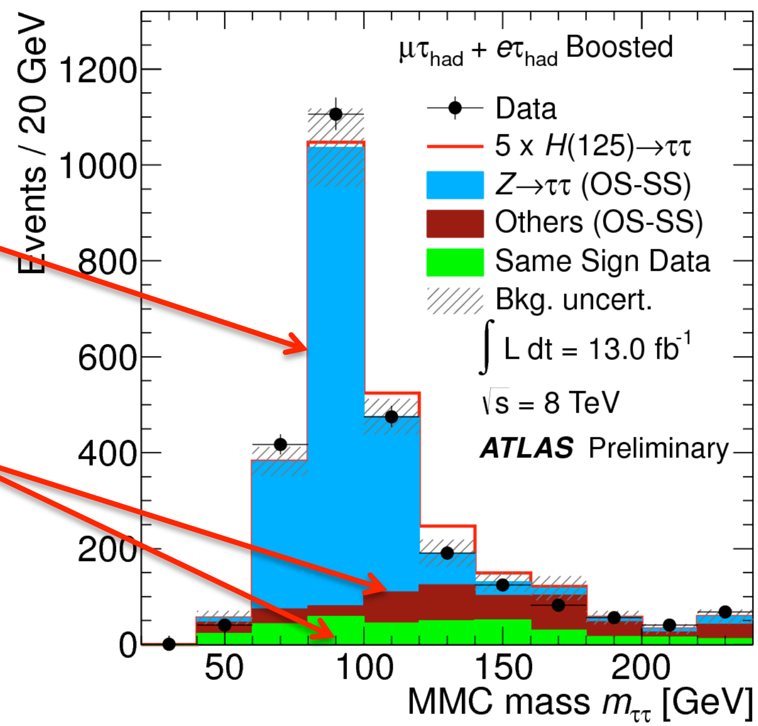
	VBF	Boosted	1-jet	0-jet	VH
ATLAS	✔	✔	✔	✔	✗
CMS	✔	✔ had-had	✔ Low/high $P_T(\tau)$	To constrain systematics	✔

Controlling Major Backgrounds in H→ττ Seahces

Z→ττ: major background; modeled by data (embedding)

"Fakes": QCD, W+jets, top; data-driven or modeled by data

Diboson production: smallest background; modeled by MC



Data Z→μμ events

Replace μμ→ττ

τ-decays: Tauola + Simulation

Embed τ-decays back into Z event

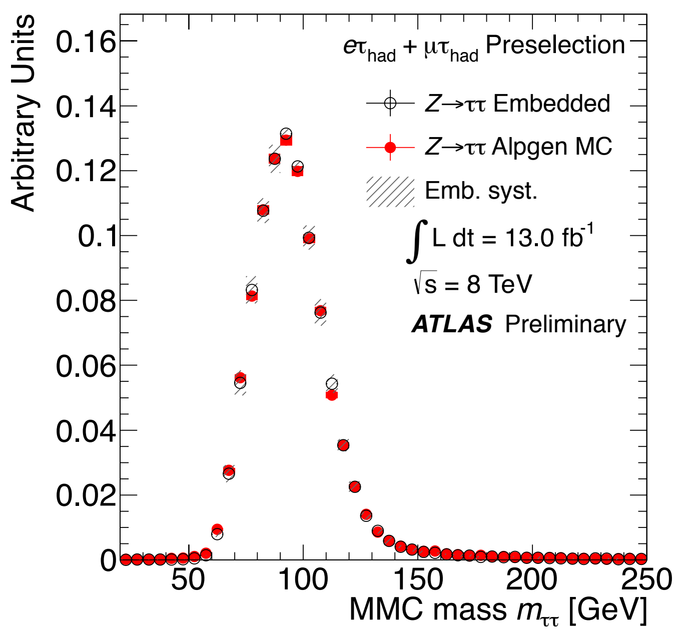
Hybrid Z→ττ event

- **Z→ττ embedding:** except for τ-decays, all properties of a Z→ττ event are modeled by actual data

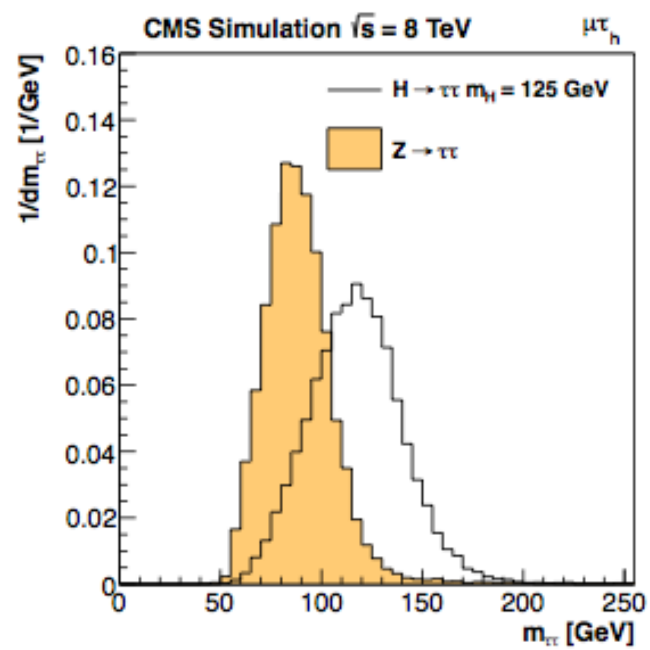
Di-Tau Mass Reconstruction in H→ττ Searches

- **Good M(ττ) resolution is single most effective tool against Z→ττ**
- **ATLAS:** Missing Mass Calculator (MMC), NIM A 654 (2011) 481
- **CMS:** SVfit, documented in CMS PAS HIG-13-004
- MMC & SVfit: sophisticated techniques to reconstruct M(ττ) in presence of neutrinos from τ-decays
- MMC & SVfit improve analysis sensitivity by 20%-30% compared to M_{vis}

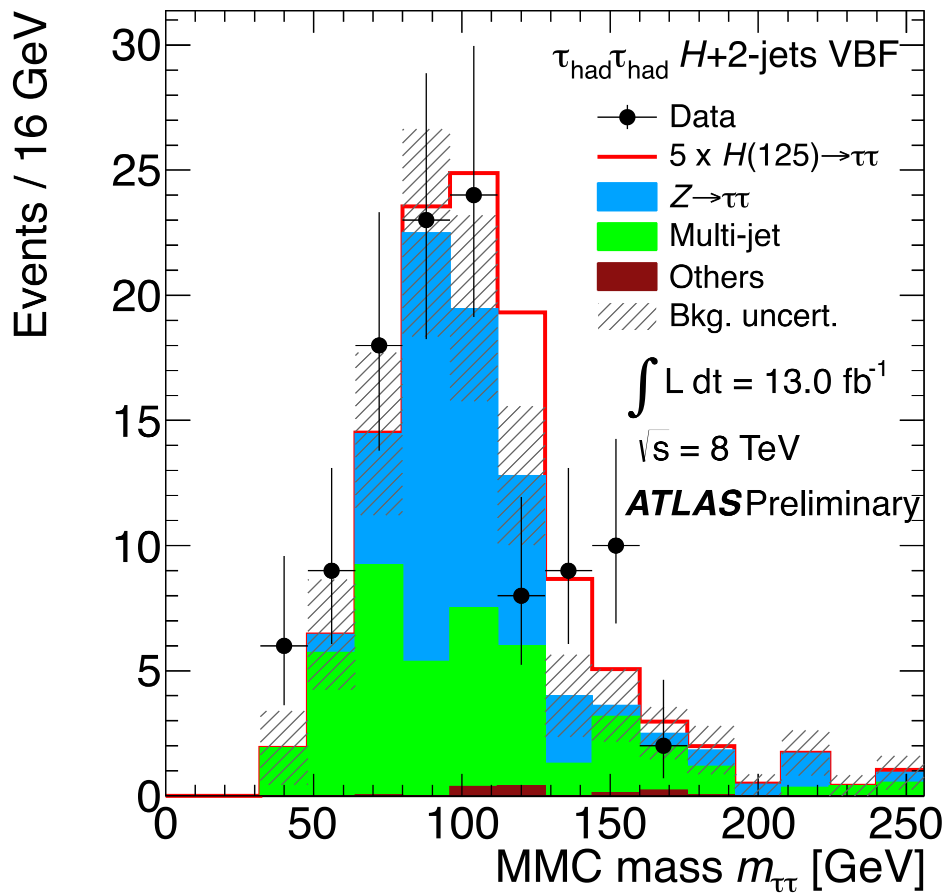
ATLAS-CONF-2012-160

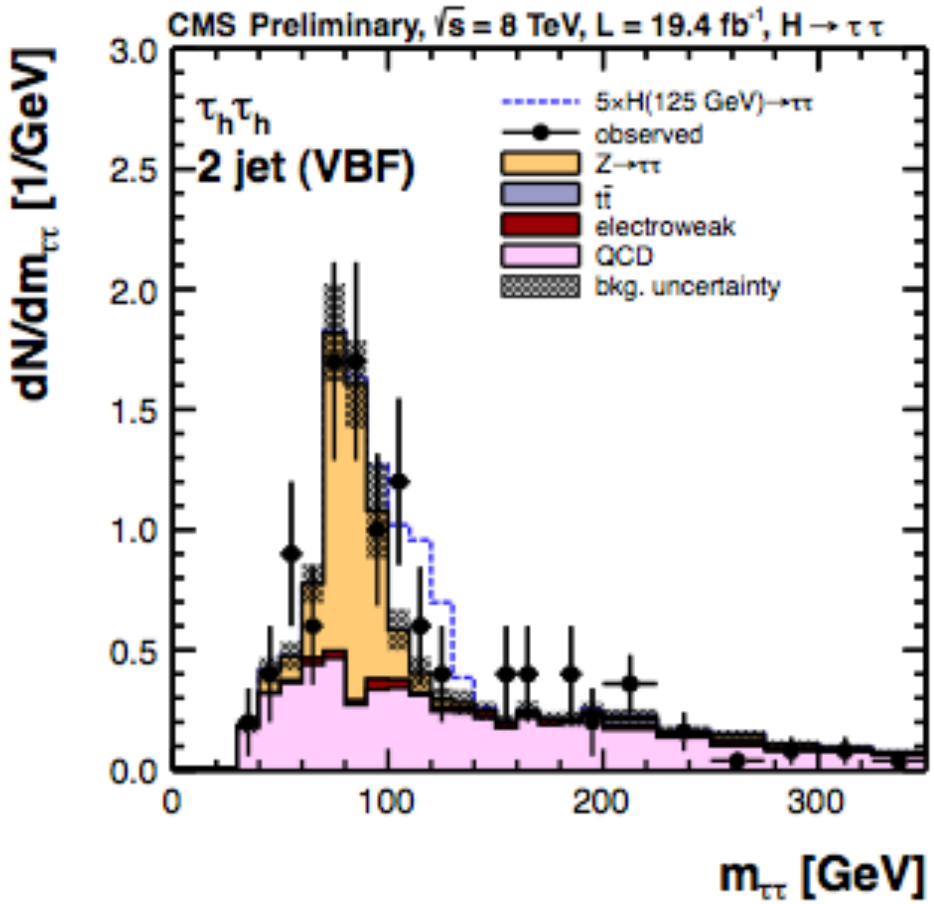


CMS PAS HIG-13-004



LHC Results for H→ττ: Examples of M(ττ)





$H \to \tau\tau \to 2\tau_{had} + 2\nu$ (had-had) channel

LHC Results for H→ττ: Systematic Uncertainties

- ATLAS & CMS analyses have similar systematic uncertainties
  - CMS used 0-jet events to constrain some of the systematic uncertainties
- Leading sources of experimental uncertainties
  - Tau energy scale
    - ATLAS example of effect on Z→ττ background: 4-15%
  - Normalization of Z→ττ background
    - ATLAS example of effect on Z→ττ background: 4-16%
  - TauID & trigger
    - CMS example: 8%
- Theoretical uncertainties on signal cross-section and acceptance
  - 10%-30% depending on category

Example of fitted nuisance parameters in CMS analysis

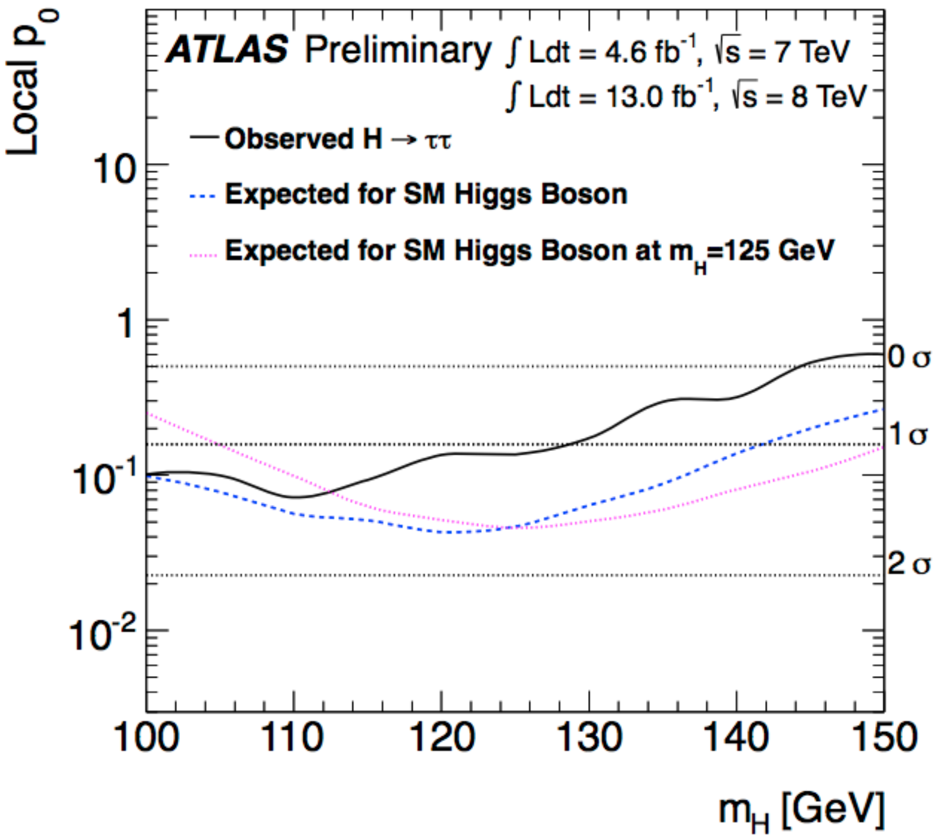
Tau ID & Trigger: $0.0 \pm 8.0\% \to -5.5 \pm 1.9\%$

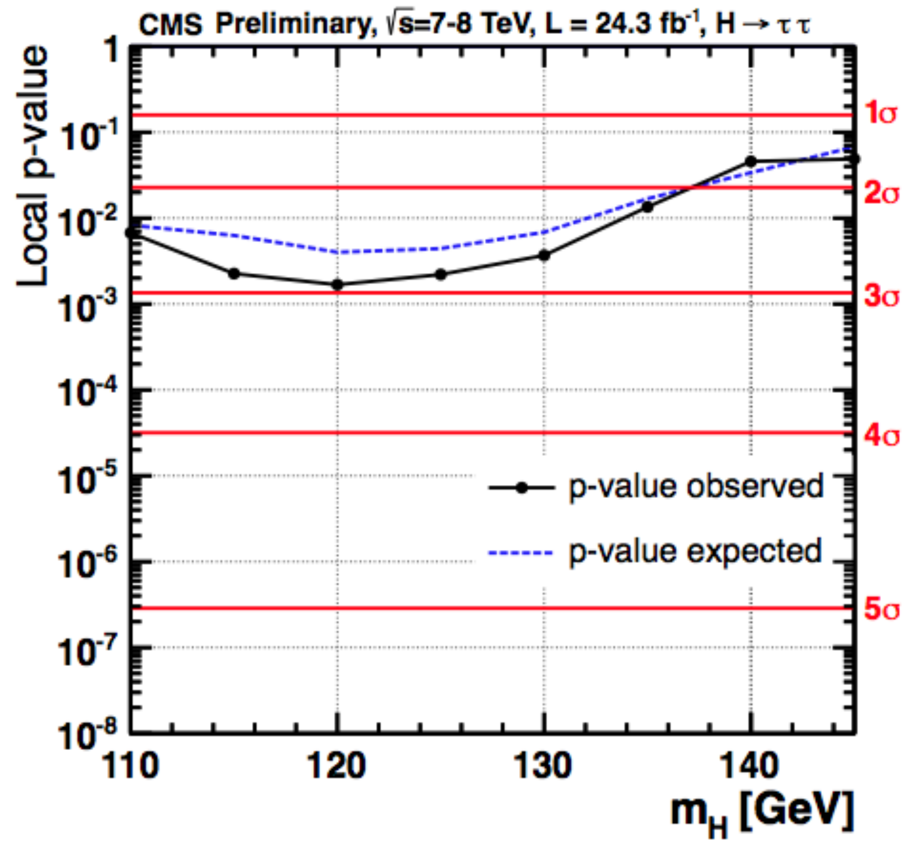
$Z \to \ell\ell$: μ fakes τ_h: $0.0 \pm 30.0\% \to +10.2 \pm 15.9\%$

Tau Energy Scale ($\mu\tau_h$ channel): $0.0 \pm 3.0\% \to -0.8 \pm 0.2\%$

Tau Energy Scale ($e\tau_h$ channel): $0.0 \pm 3.0\% \to -1.3 \pm 0.5\%$

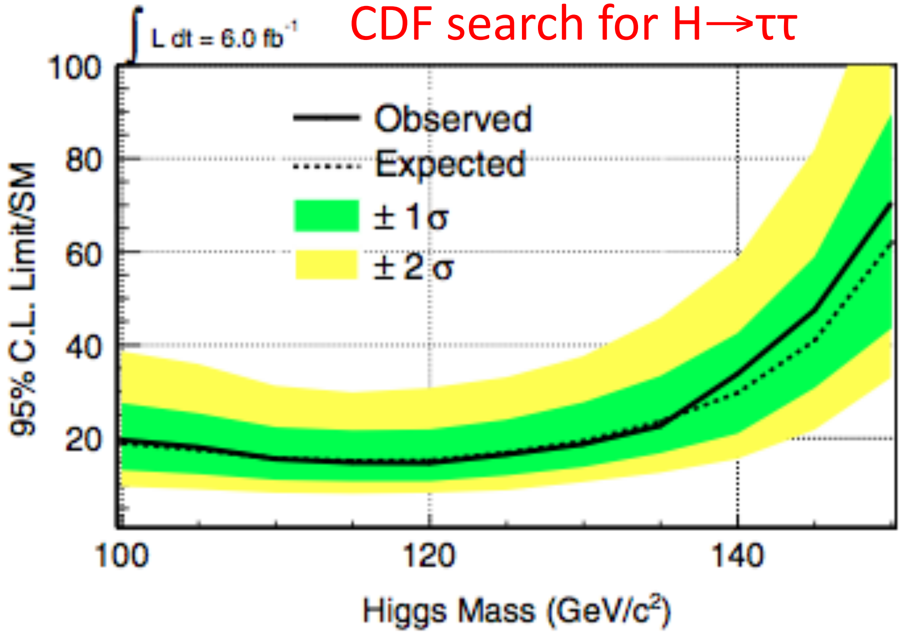
LHC Results for H→ττ

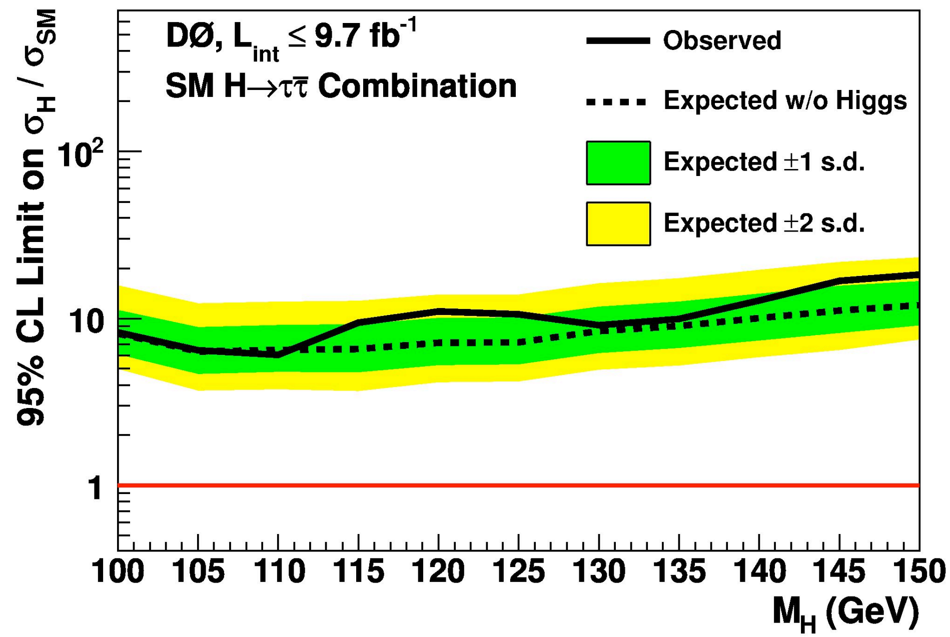




- ATLAS: 17.6 fb^{-1} of 7+8 TeV data
  - Local significance @ 125 GeV: expected p_0=1.7σ, observed p_0=1.1σ
- CMS: 24.3 fb^{-1} of 7+8 TeV data
  - Local significance @ 125 GeV: expected p_0=2.62σ, observed p_0=2.85σ
- **CMS & ATLAS data are consistent with the presence of SM H→ττ signal**

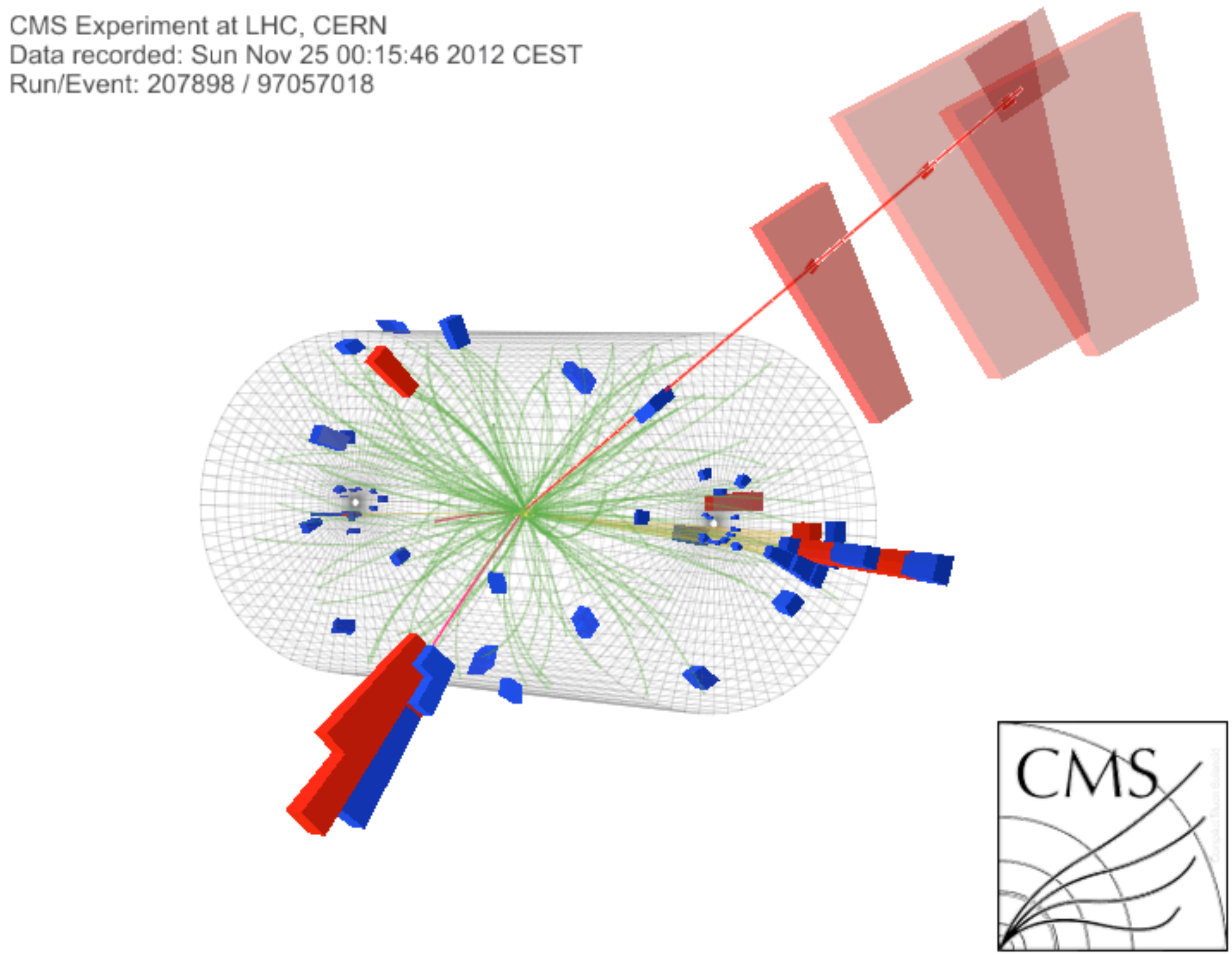
Tevatron Results for H→ττ





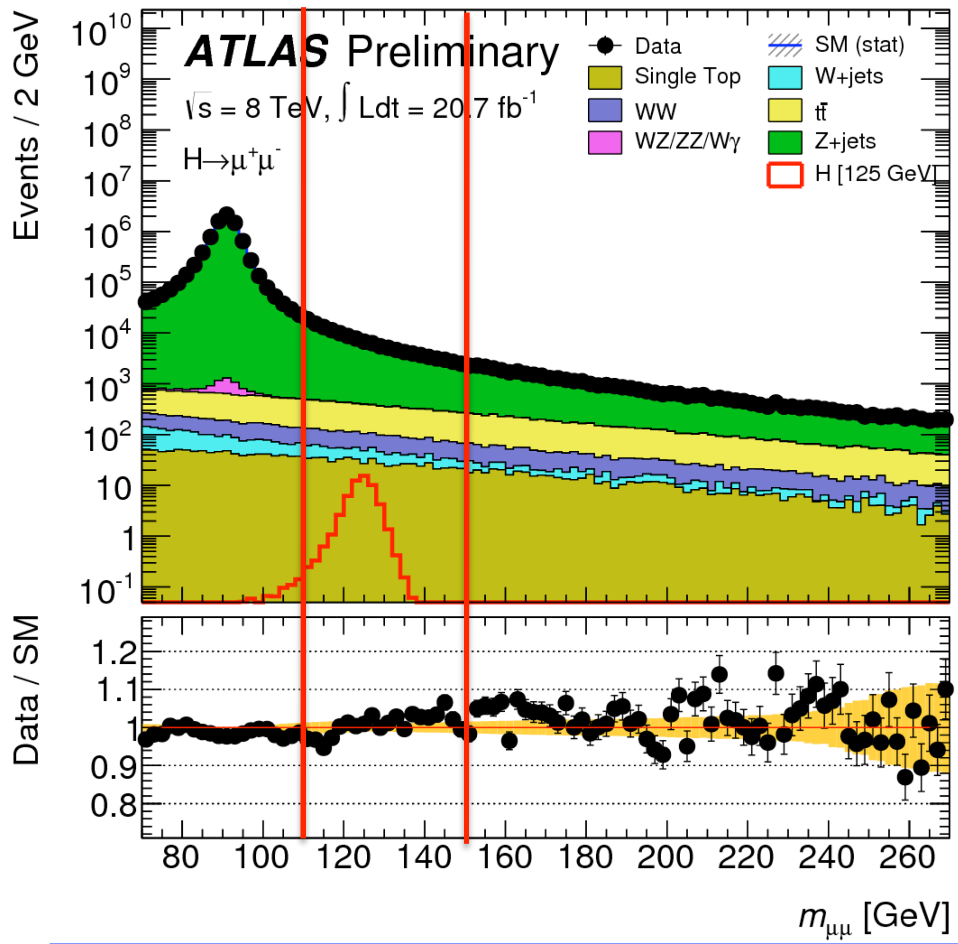
- CDF search for H→ττ: 6 fb^{-1} of 1.96 TeV data
  - Lepton+τ_{had} final state; 1-jet & 2-jet analysis categories
  - 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 16.9×SM, observed 16.4×SM
- D0 search for H→ττ: 9.7 fb^{-1} of 1.96 TeV data
  - Combination of VH→$\tau_h\tau_h\mu$ and l+τ_h+jj results
  - 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 7.25×SM, observed 10.84×SM
    - These results are for H→ττ enriched sub-sample

VBF H→ττ Candidate in CMS Data



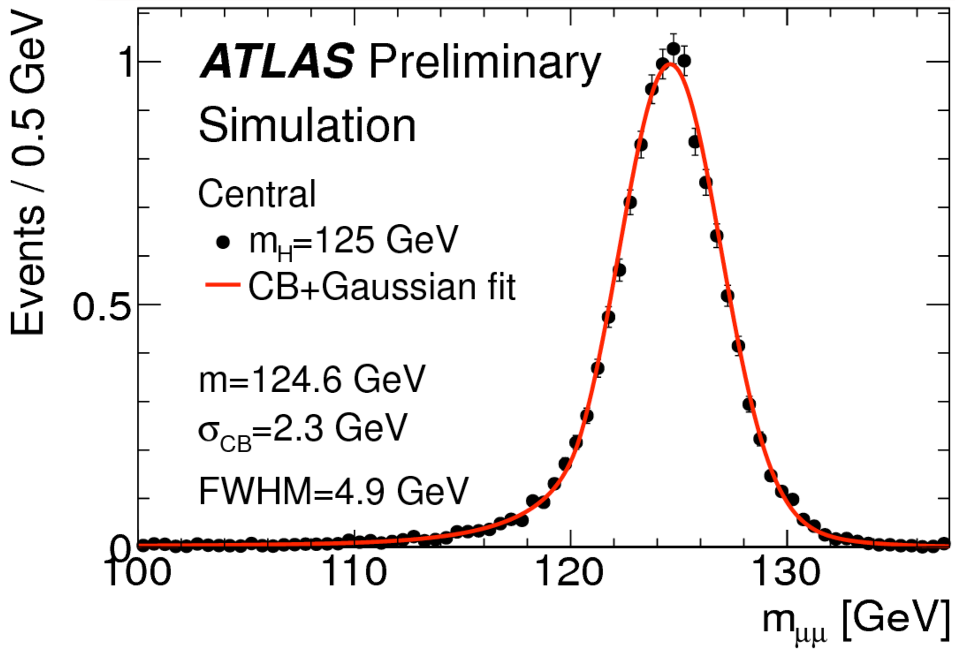
ATLAS Search for H→μμ: Analysis Overview

- Analysis strategy
  - Inclusive search
  - **Fit M(μμ) with analytic Signal +Bckg shape**
  - Two analysis categories:
    - Central: |η(μ1,2)|<1.0
    - Non-central: rest
- Event selection for signal region
  - Two isolated opposite-sign muons
  - $P_T(\mu 1)>25$ GeV, $P_T(\mu 2)>15$ GeV
  - $P_T(\mu\mu)>15$ GeV

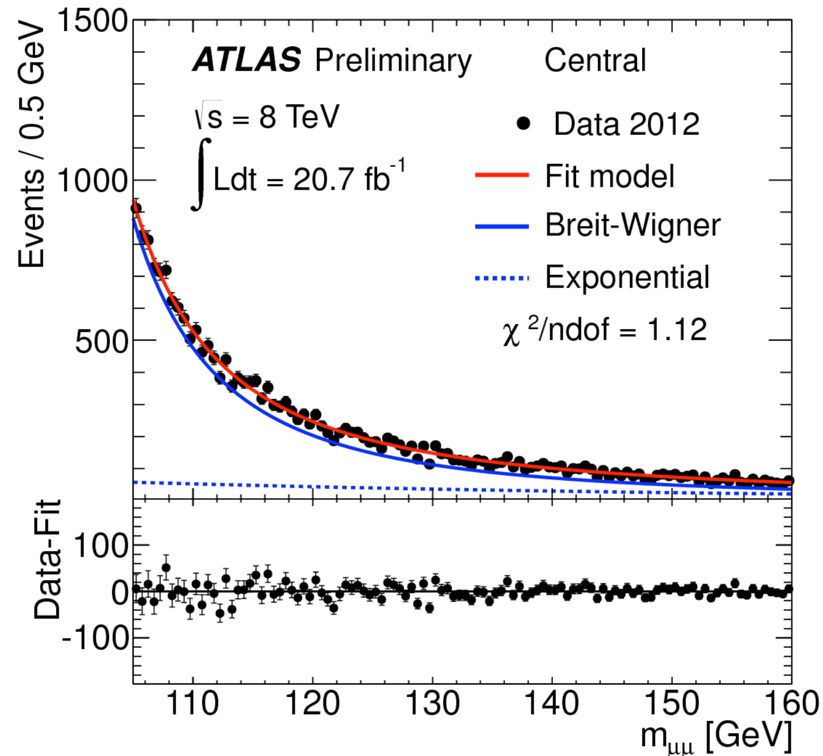


Search window: 110-150 GeV
MC background predictions are not used in the search (for optimization only)

Searches for H→μμ: Signal & Background Models



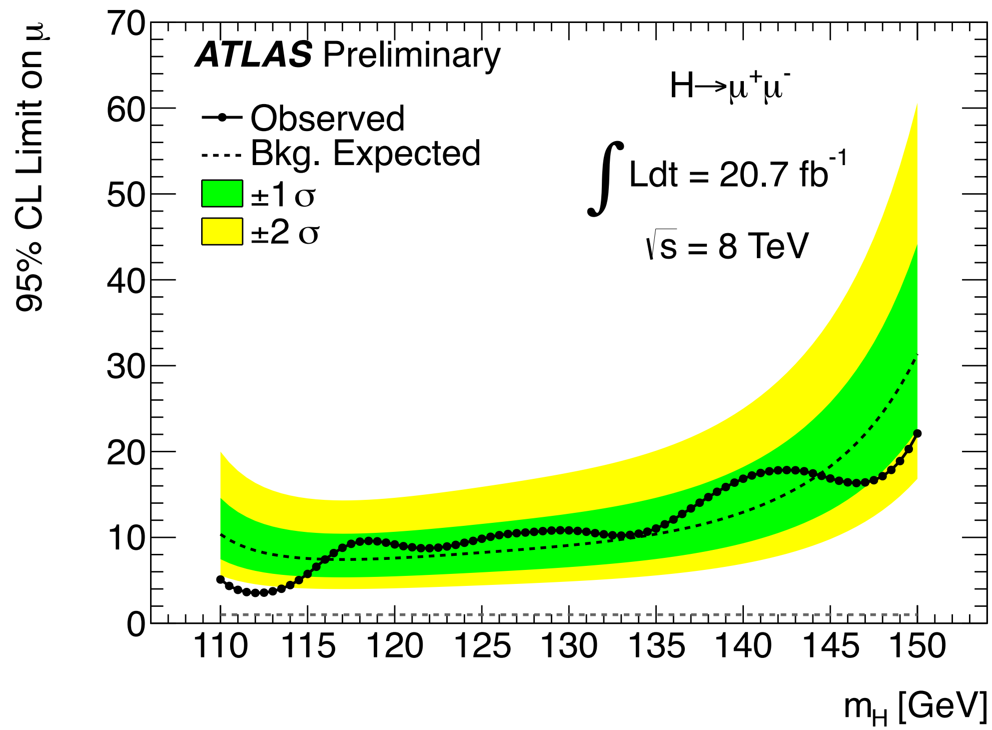
Signal parameterization in central region



Fit to data

- Signal model is a sum of Crystal Ball (CB) and Gaussian (GS) PDFs
- Background model is a sum of Breit-Wigner and exponential PDFs
  - No statistically significant biases in fits to simulation and control regions

ATLAS Results for H→μμ



- Systematic uncertainties on signal normalization @125 GeV
  - Cross-section: 15%
  - Br(H→μμ): <6%
  - Acceptance uncertainty
    - Theory: <2.6%
    - Experimental: <4.2%

- ATLAS results with 20.7 fb^{-1} of data at 8 TeV
  - No significant deviations outside uncertainty bands are observed
  - 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 8.2×SM, observed 9.8×SM

Summary

- Extensive searches for fermionic decays of Higgs boson at both LHC and Tevatron
- No individual experiment has yet reached 3 sigma level sensitivity in searches for $H \to bb$ & $H \to \tau\tau$ decays
- Overall, Tevatron & LHC data are consistent with the presence of SM $H \to bb$ & $H \to \tau\tau$ decays
  - $>2\sigma$ excess in the search for $H \to bb$ in VH channel at Tevatron
  - 2.1σ excess in the search for $H \to bb$ in VH channel at CMS
  - Tantalizing hints of $H \to \tau\tau$ decays in recent CMS analysis
    - expected $p_0=2.62\sigma$, observed $p_0=2.85\sigma$
- First results for $H \to \mu\mu$ search obtained by ATLAS experiment
  - As expected, no sensitivity for SM $H \to \mu\mu$ yet

Future Prospects & Goals

- Expected with the 7+8 TeV data
  - New and improved search for H→bb with full 7+8 TeV dataset
    - By ATLAS collaboration
  - New and improved search for H→ττ with full 7+8 TeV dataset
    - New result by ATLAS collaboration
  - New and improved search for H→μμ with full 7+8 TeV dataset
    - Updated result by ATLAS and new result by CMS
  - New and improved search for ttH with full 7+8 TeV dataset in all Higgs decay modes
    - sometime this year by both CMS & ATLAS
  - Need to start thinking about LHC combination for H→bb & H→ττ
- ATLAS and CMS goals for the next LHC run
  - Observation of H→ττ decays and measurements in H→ττ channel
  - Evidence for and possibly observation of H→bb decays in VH channel
- Stay tuned!!!

List Of Latest Publications

- ATLAS H→bb: ATLAS-CONF-2012-161
- CMS H→bb: CMS-PAS-HIG-13-012, CMS-PAS-HIG-13-011
- CDF H→bb: PRD87.052008, PRL109.111804, PRL109.111803, JHEP02.004, PRL109.1811802
- D0 H→bb: PRL109.121804, PRL109.121803, PLB716.285, arXiv:1301.6122, arXiv:1303.3276
- Tevatron combination: arXiv:1303.6346
- ATLAS ttH(→bb): ATLAS-CONF-2012-135
- CMS ttH(→bb): arXiv:1303.0763
- ATLAS H→ττ: ATLAS-CONF-2012-160
- CMS H→ττ: CMS-PAS-HIG-13-004, CMS-PAS-HIG-12-053
- CDF H→ττ: PRL108.181804
- D0 H→ττ: arXiv:1302.5723, arXiv:1211.6993
- ATLAS H→μμ: ATLAS-CONF-2013-010

Backup Slides

ATLAS VH(→bb) Analysis: Event Selection

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 $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV $+ \leq 1$ extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV + 0 extra jets	2 b-tags $p_T^1 > 45$ GeV $p_T^2 > 20$ GeV -
Missing E_T	$E_T^{miss} > 120$ GeV $p_T^{miss} > 30$ GeV $\Delta\phi(E_T^{miss}, p_T^{miss}) < \pi/2$ $\text{Min}[\Delta\phi(E_T^{miss}, \text{jet})] > 1.5$ $\Delta\phi(E_T^{miss}, b\bar{b}) > 2.8$	-	$E_T^{miss} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

0-lepton channel					
E_T^{miss} (GeV)	120-160		160-200		>200
$\Delta R(b, \bar{b})$	0.7-1.9		0.7-1.7		<1.5
1-lepton channel					
p_T^W (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.6	<1.4
E_T^{miss} (GeV)	> 25				> 50
m_T^W (GeV)	> 40			-	
2-lepton channel					
p_T^Z(GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.8	<1.6

ATLAS VH(→bb) Analysis: Systematics

Uncertainty [%]	0 lepton	1 lepton	2 leptons
b-tagging	6.5	6.0	6.9
c-tagging	7.3	6.4	3.6
light tagging	2.1	2.2	2.8
Jet/Pile-up/E_T^{miss}	20	7.0	5.4
Lepton	0.0	2.1	1.8
Top modelling	2.7	4.1	0.5
W modelling	1.8	5.4	0.0
Z modelling	2.8	0.1	4.7
Diboson	0.8	0.3	0.5
Multijet	0.6	2.6	0.0
Luminosity	3.6	3.6	3.6
Statistical	8.3	3.6	6.6
Total	25	15	14

Uncertainty [%]	0 lepton		1 lepton	2 leptons
	ZH	WH	WH	ZH
b-tagging	8.9	9.0	8.8	8.6
Jet/Pile-up/E_T^{miss}	19	25	6.7	4.2
Lepton	0.0	0.0	2.1	1.8
$H \to bb$ BR	3.3	3.3	3.3	3.3
VH p_T-dependence	5.3	8.1	7.6	5.0
VH theory PDF	3.5	3.5	3.5	3.5
VH theory scale	1.6	0.4	0.4	1.6
Statistical	4.9	18	4.1	2.6
Luminosity	3.6	3.6	3.6	3.6
Total	24	34	16	13

CMS VH(→bb) Analysis: Event Selection

Variable	W(μν)H	W(eν)H	W(τν)H	Z(ℓℓ)H	Z(νν)H
$m_{\ell\ell}$	–	–	–	$75 < m_{\ell\ell} < 105$	–
$p_T(j_1)$	> 30	> 30	> 30	> 20	$> 60\,(> 60, > 80)$
$p_T(j_2)$	> 30	> 30	> 30	> 20	> 30
$p_T(jj)$	> 100	> 100	> 120	–	$> 110\,(> 140, > 190)$
$p_T(V)$	$100-130\,(130-180\;\; > 180)$	$[100-150]\,(> 150)$	< 250	$[50-100], ([100-150], > 150)$	–
CSV_{max}	0.898	0.898	0.898	0.679	0.898
CSV_{min}	> 0.5	> 0.5	> 0.4	> 0.5	> 0.5
$\Delta\phi(V,H)$	> 2.95	> 2.95	> 2.95	–	> 2.95
$\Delta R(jj)$	–	–	$= 0$	$-, (-, < 1.6)$	–
N_{aj}	$= 0$	$= 0$	$= 0$	–	$= 0$
N_{al}	$= 0$	$= 0$	> 80	–	$= 0$
E_T^{miss}	> 45	> 45	–	$< 60.$	$[100-130]\,([130-170], > 170)$
$\Delta\phi(E_T^{miss}, jet)$	–	–	–	–	$> 0.7\,(> 0.7, > 0.5)$
$\Delta\phi(E_T^{miss}, E_T^{miss(trks)})$	–	–	–	–	< 0.5
$\Delta\phi(E_T^{miss}, \ell)$	$< \pi/2$	$< \pi/2$	–	–	–
$p_T(\tau)$	–	–	> 40	–	–
$p_T(track)$	–	–	> 20	–	–

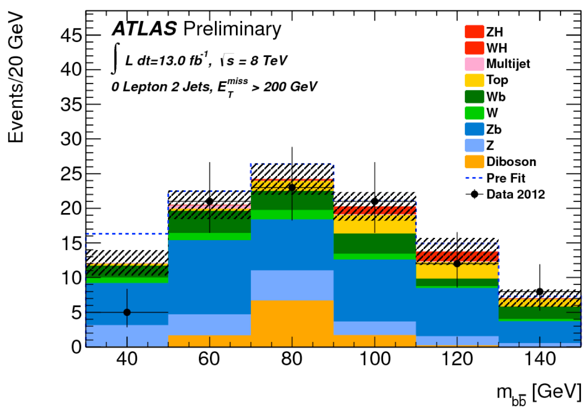
CMS VH(→bb) Analysis: Inputs To MVA

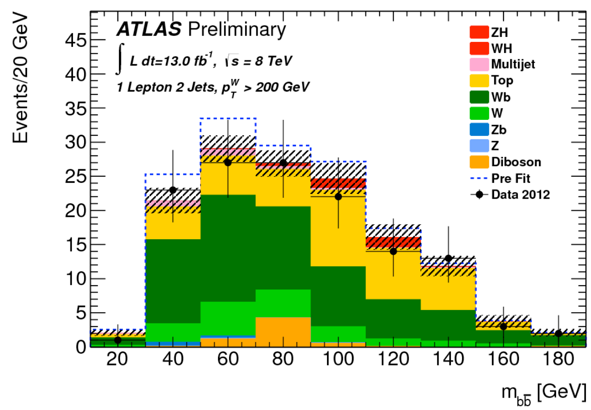
Variable
$p_T(j)$: transverse momentum of each Higgs daughter
$m(jj)$: dijet invariant mass
$p_T(jj)$: dijet transverse momentum
$p_T(V)$: vector boson transverse momentum (or E_T^{miss})
CSV_{max}: value of CSV for the Higgs daughter with largest CSV value
CSV_{min}: value of CSV for the Higgs daughter with second largest CSV value
$\Delta\phi(V, H)$: azimuthal angle between V (or E_T^{miss}) and dijet
$\lvert\Delta\eta(jj)\rvert$: difference in η between Higgs daughters
$\Delta R(jj)$: distance in η–ϕ between Higgs daughters
N_{aj}: number of additional jets
$\Delta\theta_{pull}$: color pull angle [34]
$\Delta\phi(E_T^{miss}, jet)$: azimuthal angle between E_T^{miss} and the closest jet (only for $Z(\nu\nu)H$)
$maxCSV_{aj}$: maximum CSV of the additional jets in an event (only for $Z(\nu\nu)H$ and $W(\ell\nu)H$)
$min\Delta R(H, aj)$: mimimum distance between an additional jet and the Higgs candidate (only for $Z(\nu\nu)H$ and $W(\ell\nu)H$)
Angular variables: HV system mass, Angle Z-Z*, Angle Z-l, Angle H-jet (only for $Z(\ell\ell)H$)

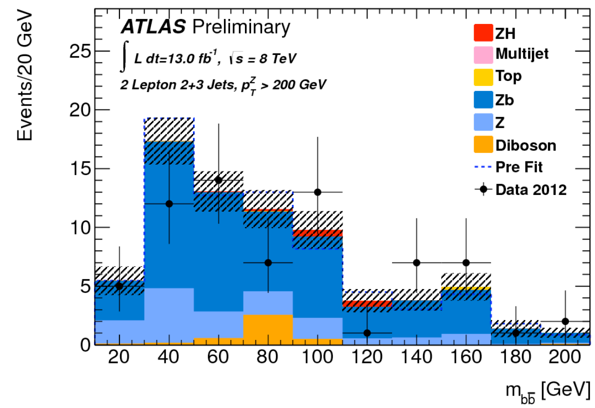
CMS VH(→bb) Analysis: Systematics

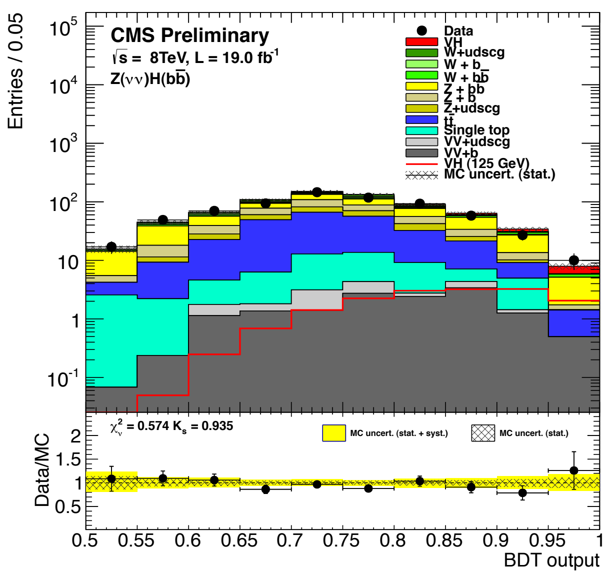
Source	Type	Yield uncertainty (%) range	Contribution to uncertainty (%)	Removal effect on total uncertainty (%)
Luminosity	normalization	2.2-4.4	< 2	< 0.1
Lepton efficiency and trigger (per lepton)	normalization	3	< 2	< 0.1
$Z(\nu\nu)H$ triggers	shape	3	< 2	< 0.1
Jet energy scale	shape	2–3	5.0	0.5
Jet energy resolution	shape	3–6	5.9	0.7
Missing transverse energy	shape	3	3.2	0.2
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	normalization	4	3.9	0.3
Signal cross section (p_T boost, EWK/QCD)	normalization	2/5	3.9	0.3
Signal Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	normlization	10	15.9	5.2
Single-top (simulation estimate)	normalization	15	5.0	0.5
Dibosons (simulation estimate)	normalization	15	5.0	0.5
MC modeling (V+jets and $t\bar{t}$)	shape	10	7.4	1.1

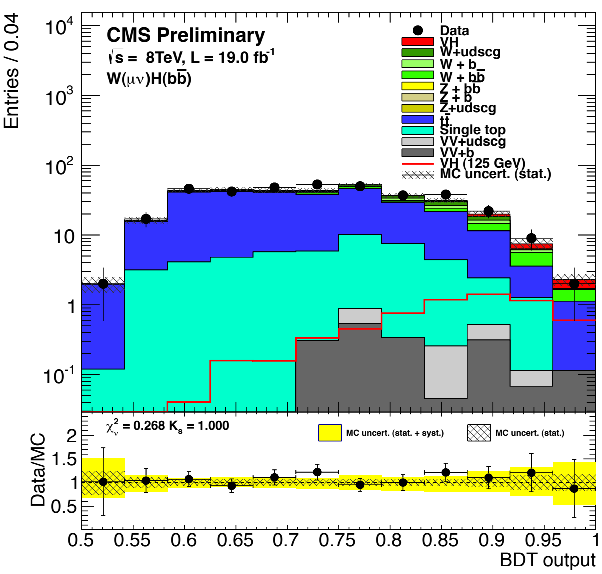
LHC Results for VH(→bb): Examples of Distributions

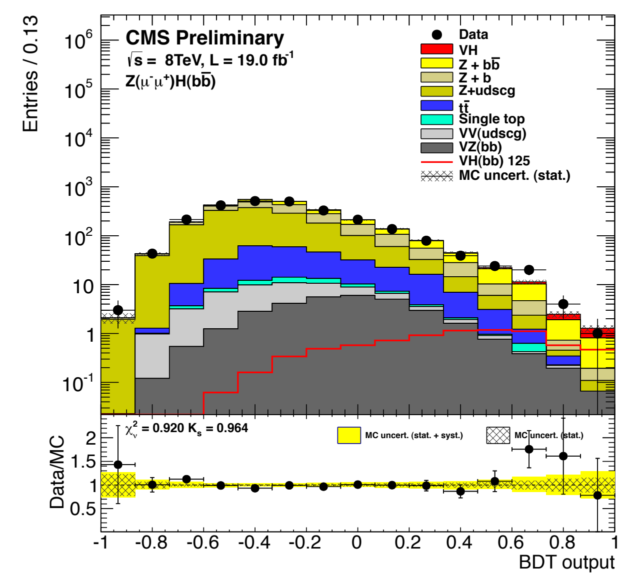












ZH→νν+bb WH→lν+bb ZH→ll+bb

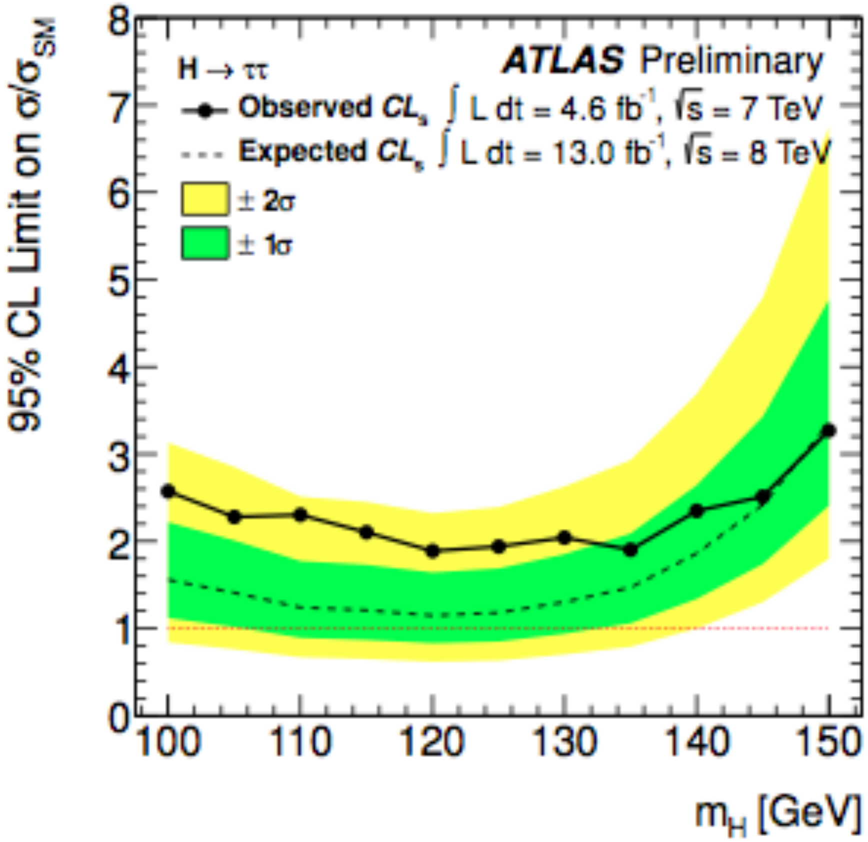
Tevatron Results For VH With H→bb

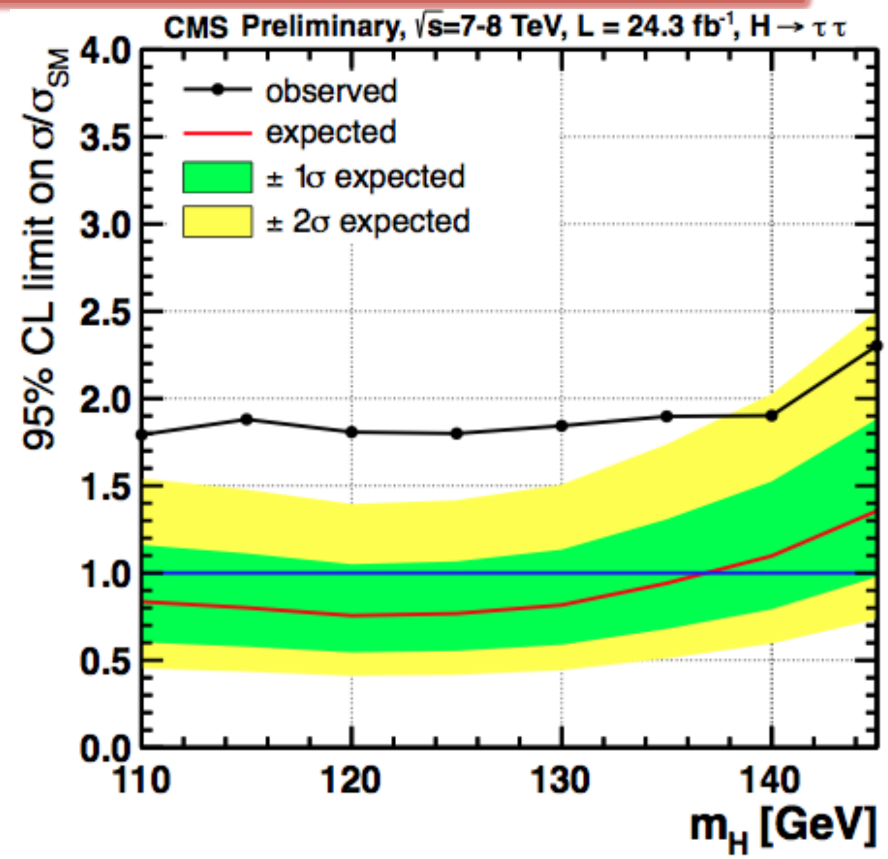
Summary of 95% CL limits on σ/σ_{SM} @ 125 GeV for Tevatron experiments

Channel	D0		CDF	
	Expected	**Observed**	Expected	**Observed**
ZH→ll+bb	5.1	**7.1**	3.9	**7.1**
ZH→νν+bb	3.9	**4.3**	3.33	**3.06**
WH→lν+bb	4.7	**5.2**	2.8	**4.9**

- CDF and D0 experiments employ sophisticated multivariate analysis techniques in all searches for VH(→bb)
  - Validity of techniques is confirmed in rigorous checks with data control regions
- Results are based on 9.5-9.7 fb^{-1} of 1.96 TeV data
- No individual Tevatron experiment has reached 3σ level sensitivity

LHC Results for H→ττ

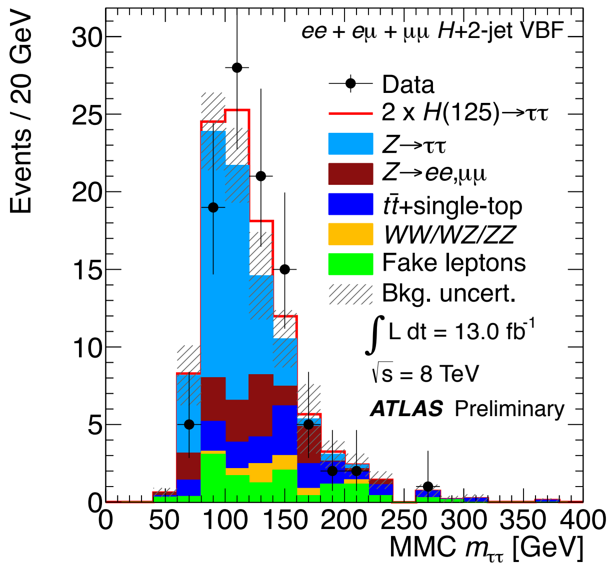




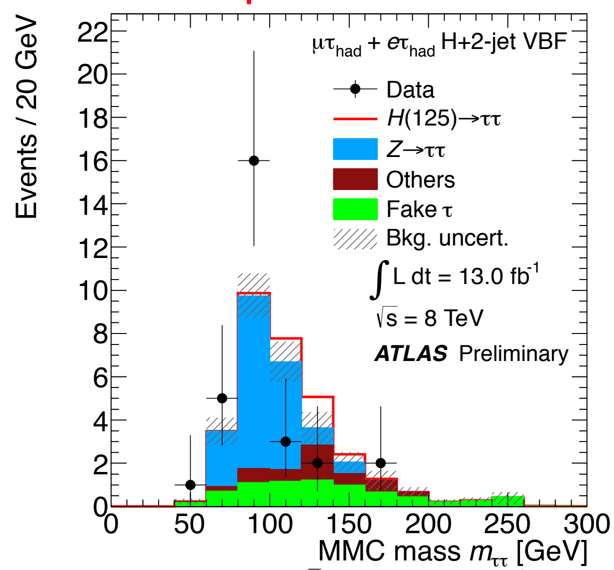
- ATLAS: 17.6 fb^{-1} of 7+8 TeV data
  - 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 1.2×SM, observed 1.9×SM
- CMS: 24.3 fb^{-1} of 7+8 TeV data
  - 95% CL limit on σ/σ_{SM} @ 125 GeV: expected 0.77×SM, observed 1.80×SM

LHC Results for H→ττ: Examples of M(ττ)

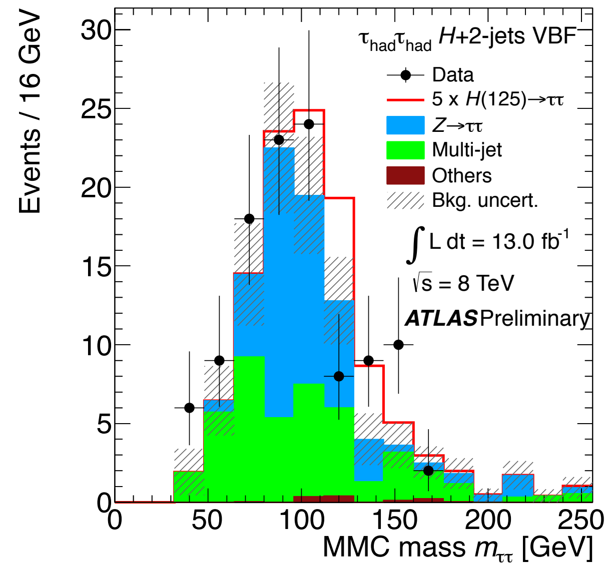
Lep-lep channel

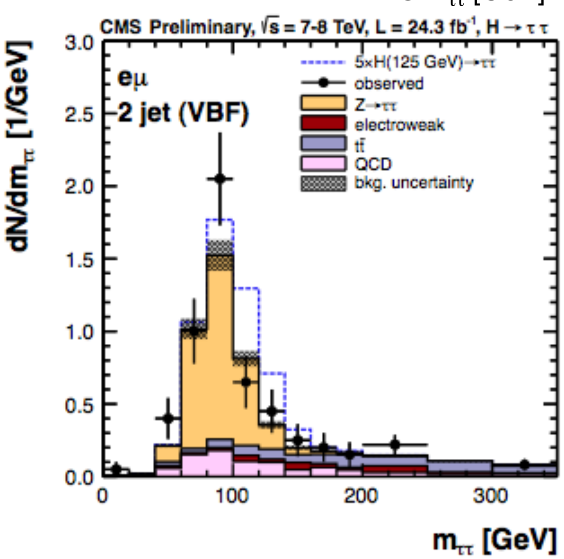


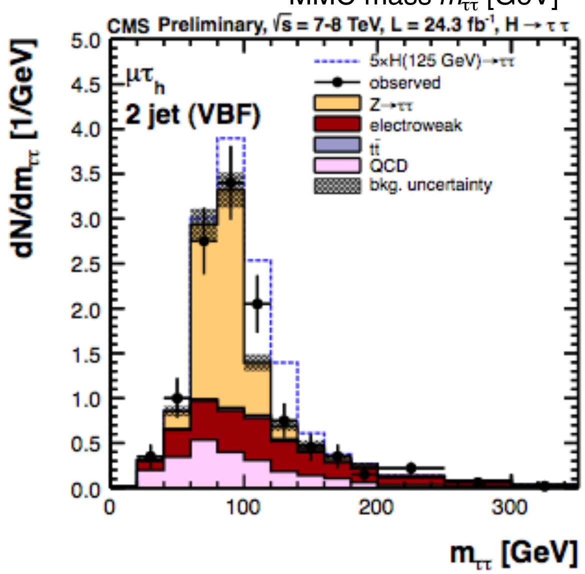
Lep-had channel

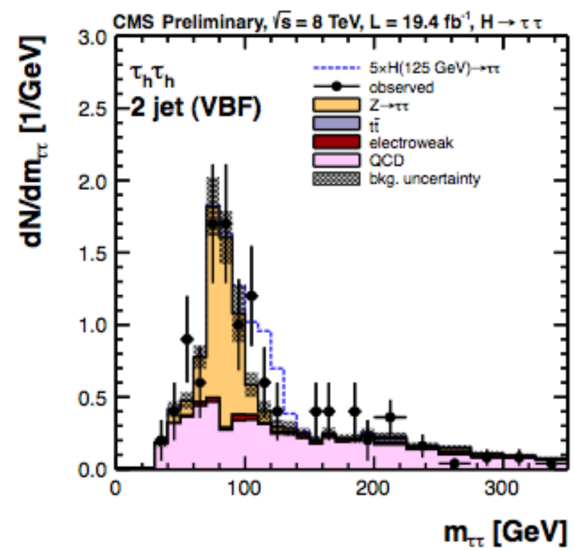


Had-had channel









LHC Results for H→ττ: Systematic Uncertainties

Example of systematic uncertainties on event yields in ATLAS analysis

Uncertainty	$H \to \tau_{\rm lep}\tau_{\rm lep}$	$H \to \tau_{\rm lep}\tau_{\rm had}$	$H \to \tau_{\rm had}\tau_{\rm had}$
		$Z \to \tau^+\tau^-$	
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	5%	4% (non-VBF), 16% (VBF)	9–10%
		Signal	
Jet Energy Scale	1–5% (S)	3–9% (S)	2–4% (S)
Tau Energy Scale	–	2–9% (S)	4–6% (S)
Tau Identification	–	4–5%	10%
Theory	8–28%	18–23%	3–20%
Trigger Efficiency	small	small	5%

- CMS analysis has similar systematic uncertainties
  - CMS used 0-jet events to constrain some of the systematic uncertainties

Example of fitted nuisance parameters in CMS analysis →

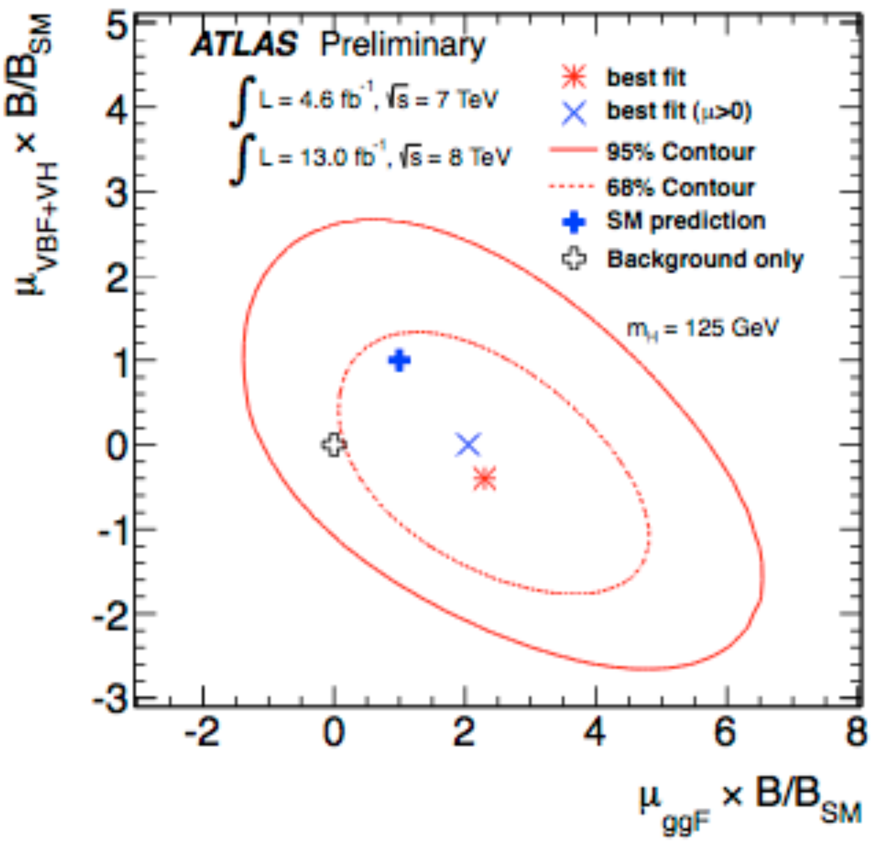
Tau ID & Trigger: $0.0 \pm 8.0\% \to -5.5 \pm 1.9\%$

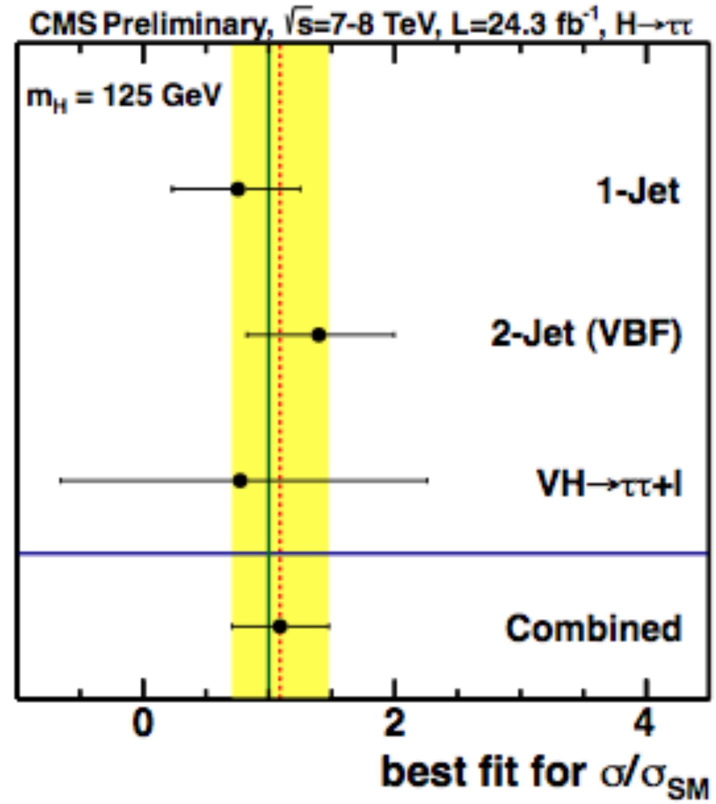
$Z \to \ell\ell$: μ fakes τ_h: $0.0 \pm 30.0\% \to +10.2 \pm 15.9\%$

Tau Energy Scale ($\mu\tau_h$ channel): $0.0 \pm 3.0\% \to -0.8 \pm 0.2\%$

Tau Energy Scale ($e\tau_h$ channel): $0.0 \pm 3.0\% \to -1.3 \pm 0.5\%$

LHC Results for H→ττ





- ATLAS: 17.6 fb^{-1} of 7+8 TeV data
  - Best-fit signal strength, $\mu=\sigma/\sigma_{SM}$, @ 125 GeV is $\mu=0.7\pm0.7$
- CMS: 24.3 fb^{-1} of 7+8 TeV data
  - Best-fit signal strength, $\mu=\sigma/\sigma_{SM}$, @ 125 GeV is $\mu=1.1\pm0.4$

CMS Results for H→ττ

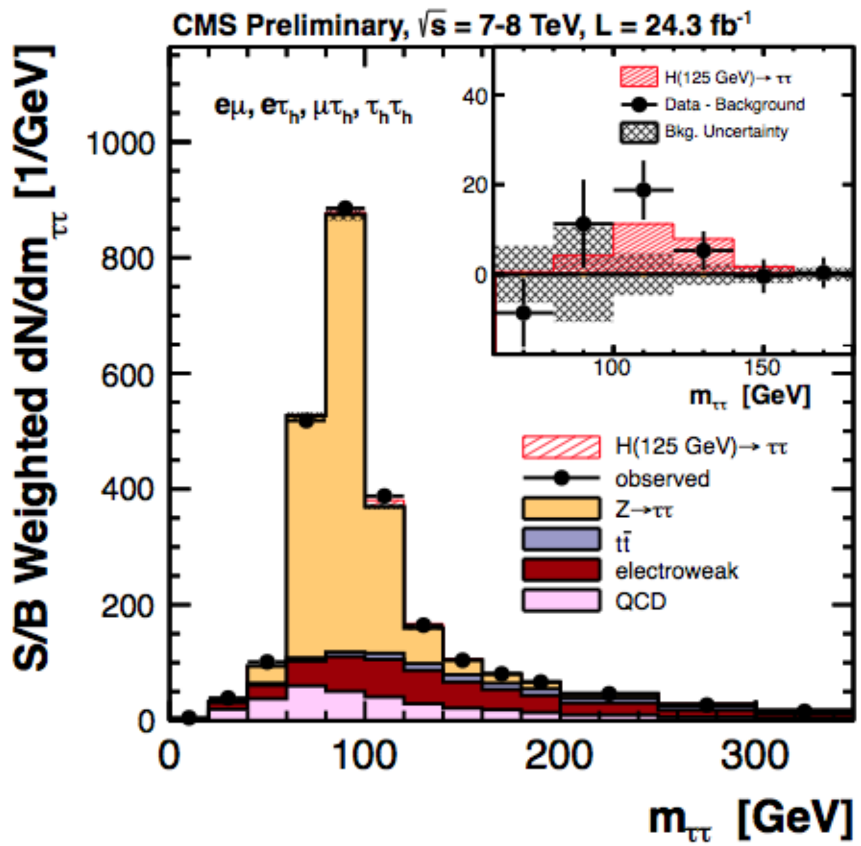
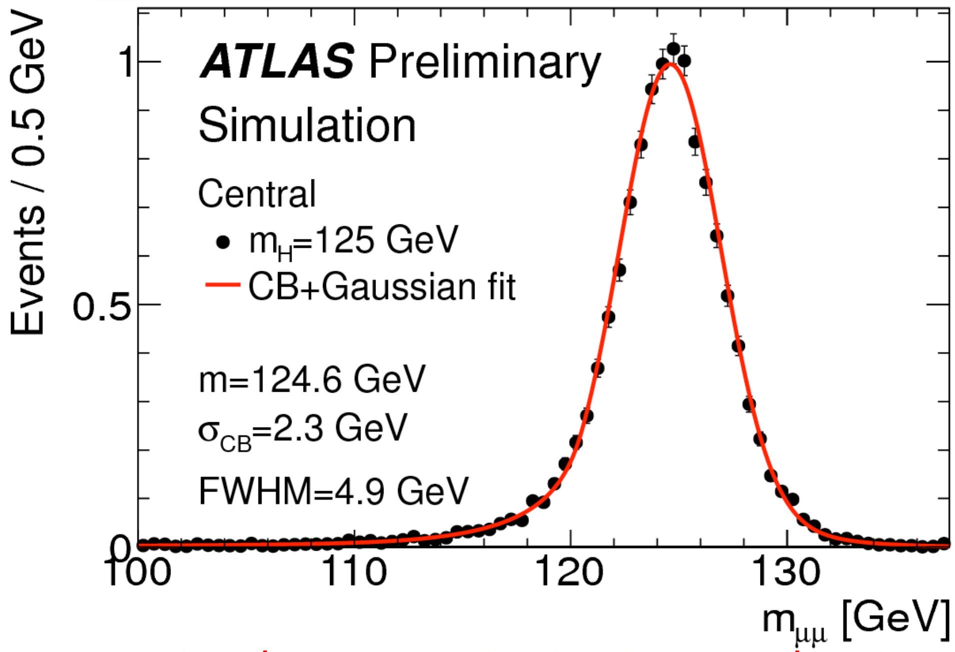
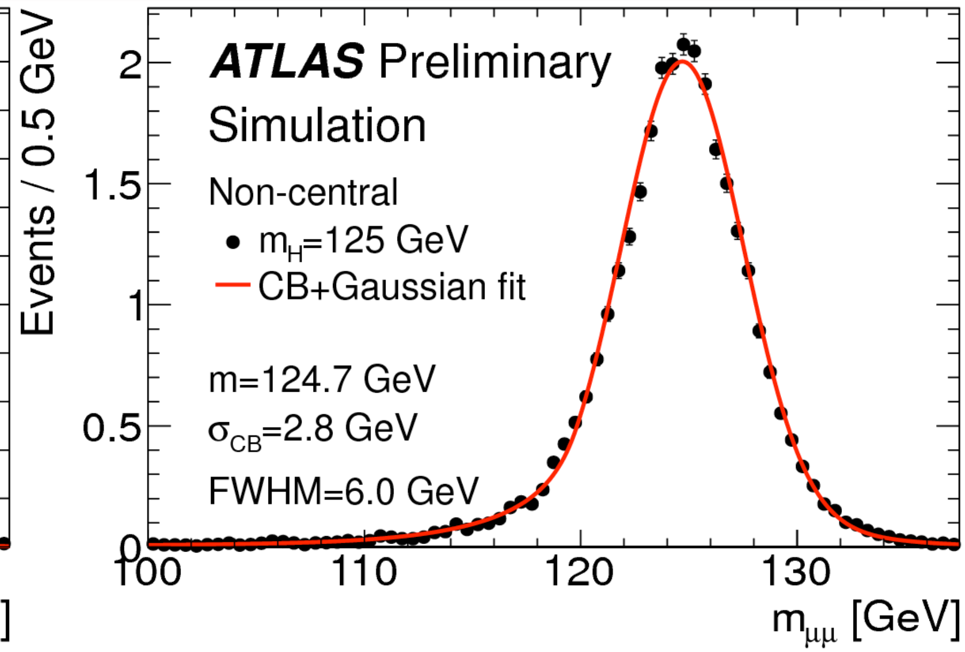


Figure 9: Combined observed and expected $m_{\tau\tau}$ distributions for the $\mu\tau_h$, $e\tau_h$, $e\mu$ and $\tau_h\tau_h$ channels. The distributions obtained in each category of each channel are weighted by the ratio between the expected signal and background yields in the category. The insert shows the corresponding difference between the observed data and expected background distributions, together with the expected signal distribution for a standard-model Higgs signal at $m_H = 125$ GeV, with a focus on the signal region.

Searches for H→μμ: Signal Model



Signal parameterization in central region

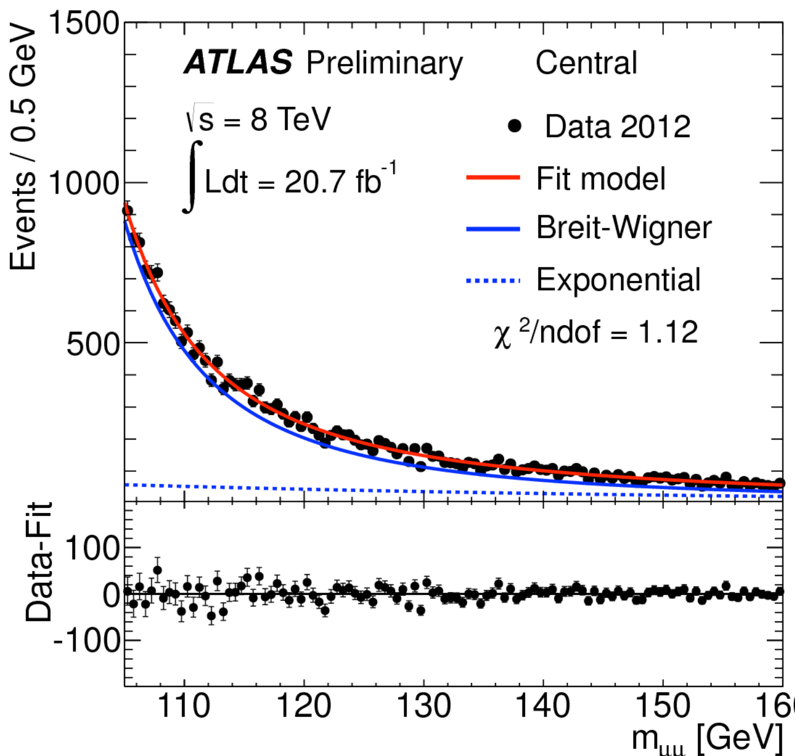


Signal parameterization in non-central region

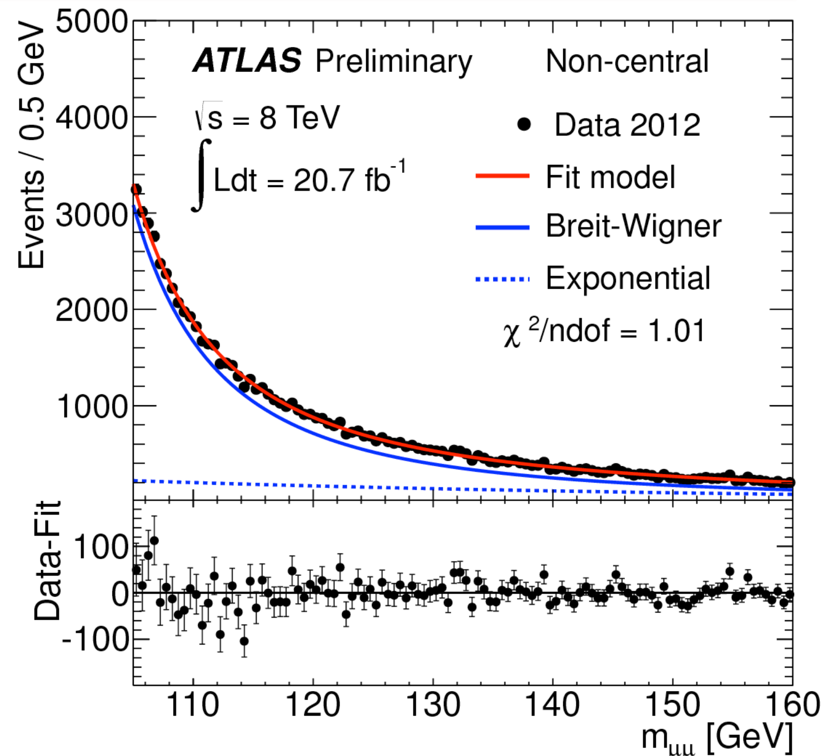
$$P_S(x) = f_{CB} \cdot CB(x, m, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \cdot GS\,(x, m, \sigma_G)$$

- Signal model is a sum of Crystal Ball (CB) and Gaussian (GS) PDFs

Searches for H→μμ: Background Model



Fit to data in central region

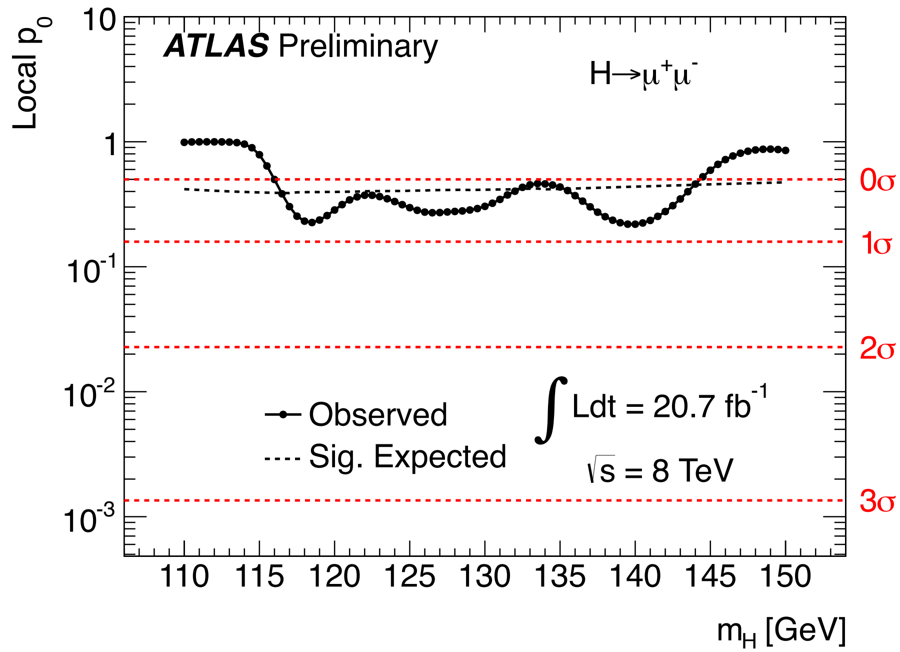


Fit to data in non-central region

$$P_{BG}(x) = f_{BW} \cdot BW(x, M_Z, \Gamma_Z) + (1 - f_{BW}) \cdot P(e^{B \cdot x})$$

- Background model is a sum of Breit-Wigner and exponential PDFs
  - No statistically significant biases in fits to simulation and control regions

ATLAS Results for H→μμ



- No significant deviations are observed for local significance with 20.7 fb^{-1} of ATLAS data at 8 TeV

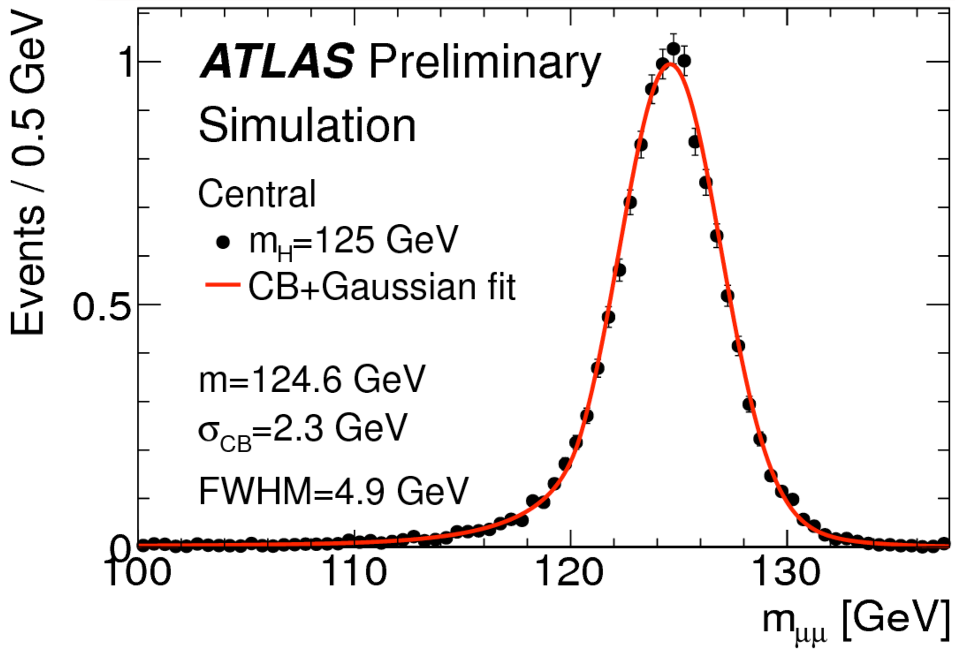
Systematic uncertainties in ATLAS H→μμ Search

Uncertainty	Upward [%]	Downward [%]
Ren./Fac. Scale	0.1	-0.3
ISR	1.3	-2.5
FSR	-0.4	0.1
PDF	0.2	0.2
Total inclusive	+1.3	-2.6

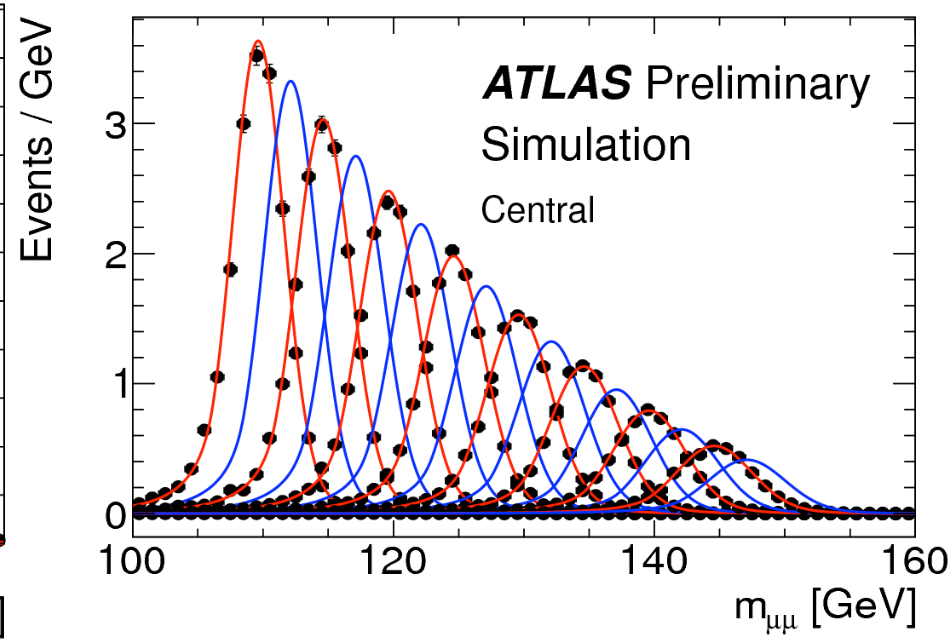
Source of Uncertainty	Treatment in the analysis
Luminosity	3.6%
Muon Selection Efficiency	0.3-1% as a function of η and p_T
Muon Momentum Scale and Resolution	$< 1\%$
Muon Trigger	$< 1\%$
Muon Track Isolation	$< 1\%$
Pile-up reweighting	$< 1\%$

- Systematic uncertainties for signal normalization

Searches for H→μμ: Signal Model



Signal parameterization in central region

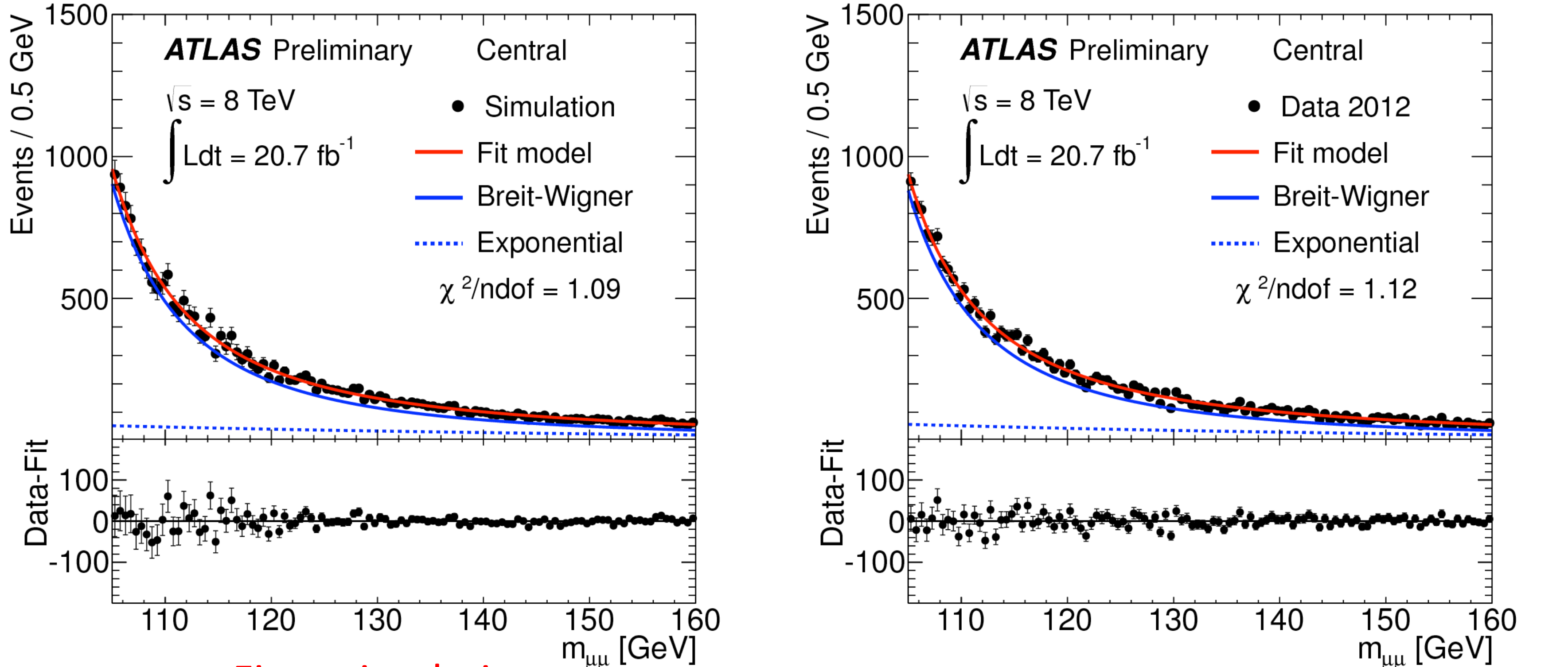


Example of signal shape interpolation

$$P_S(x) = f_{CB} \cdot CB(x, m, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \cdot GS\,(x, m, \sigma_G)$$

- Signal model is a sum of Crystal Ball (CB) and Gaussian (GS) PDFs

Searches for H→μμ: Background Model



Fit to simulation | Fit to data

$$P_{BG}(x) = f_{BW} \cdot BW(x, M_Z, \Gamma_Z) + (1 - f_{BW}) \cdot P(e^{B \cdot x})$$

- Background model is a sum of Breit-Wigner and exponential PDFs
  - No statistically significant biases in fits to simulation and control regions