Search for a Higgs boson in fermionic and rare decays at the LHC

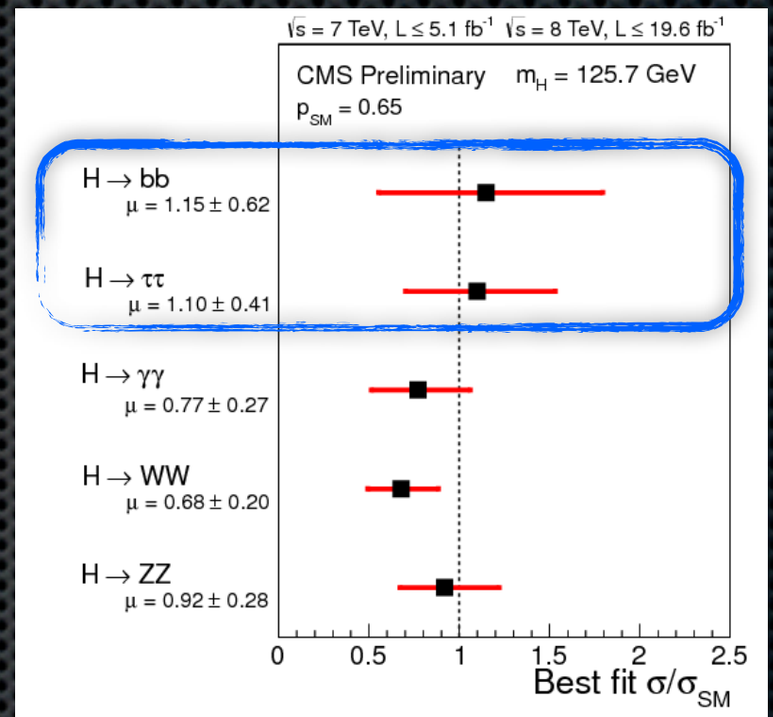
Alejandro Alonso
Niels Bohr Institute (University of Copenhagen)
On behalf of the **ATLAS** and **CMS** collaborations

24 May 2013, **Photon** 2013

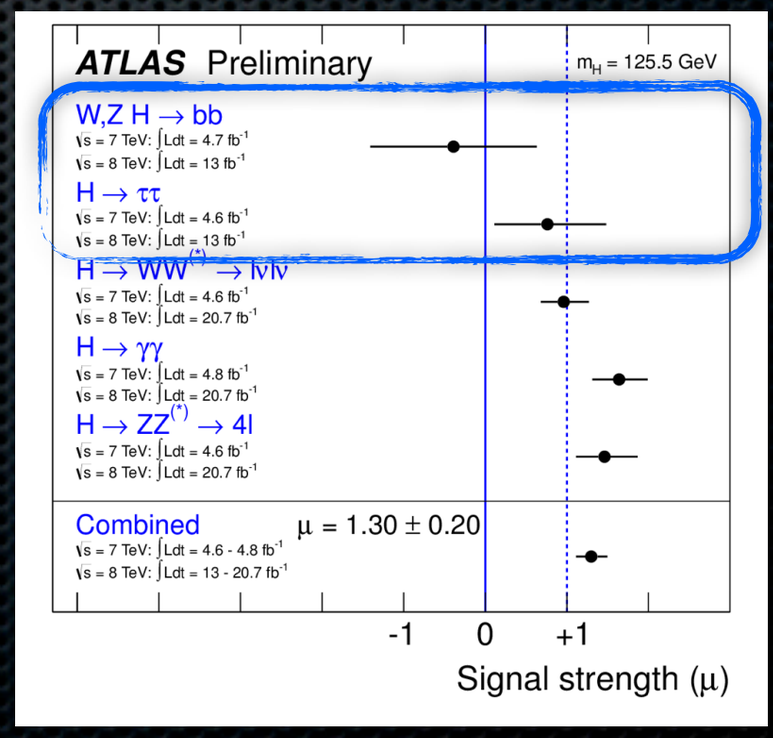
Outline

- **Motivation**
- **H → ττ** HIG-13-004-pas, ATLAS-CONF-2012-160
  - Gluon fusion and VBF
  - VH (CMS)
- **H → μμ** ATLAS-CONF-2013-010
- **H → bb**
  - ttH (H → bb): CMS-HIG-12-035, ATLAS-CONF-2012-135
  - VBF (H → bb): HIG-13-011-pas
  - VH (H → bb): HIG-13-012-pas, ATLAS-CONF-2012-161
- **ZH, H → invisible** ATLAS-CONF-2013-011
- **Summary**

HIG-13-005

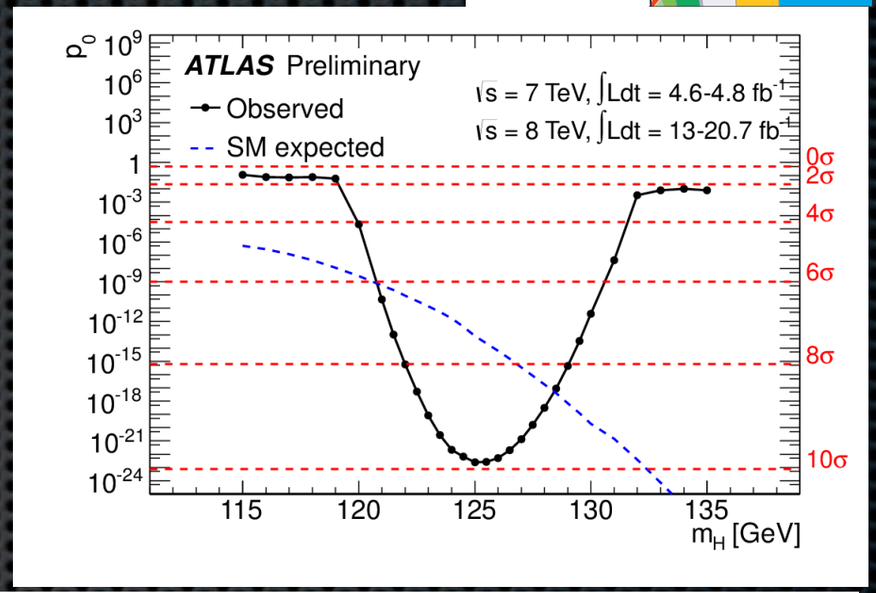


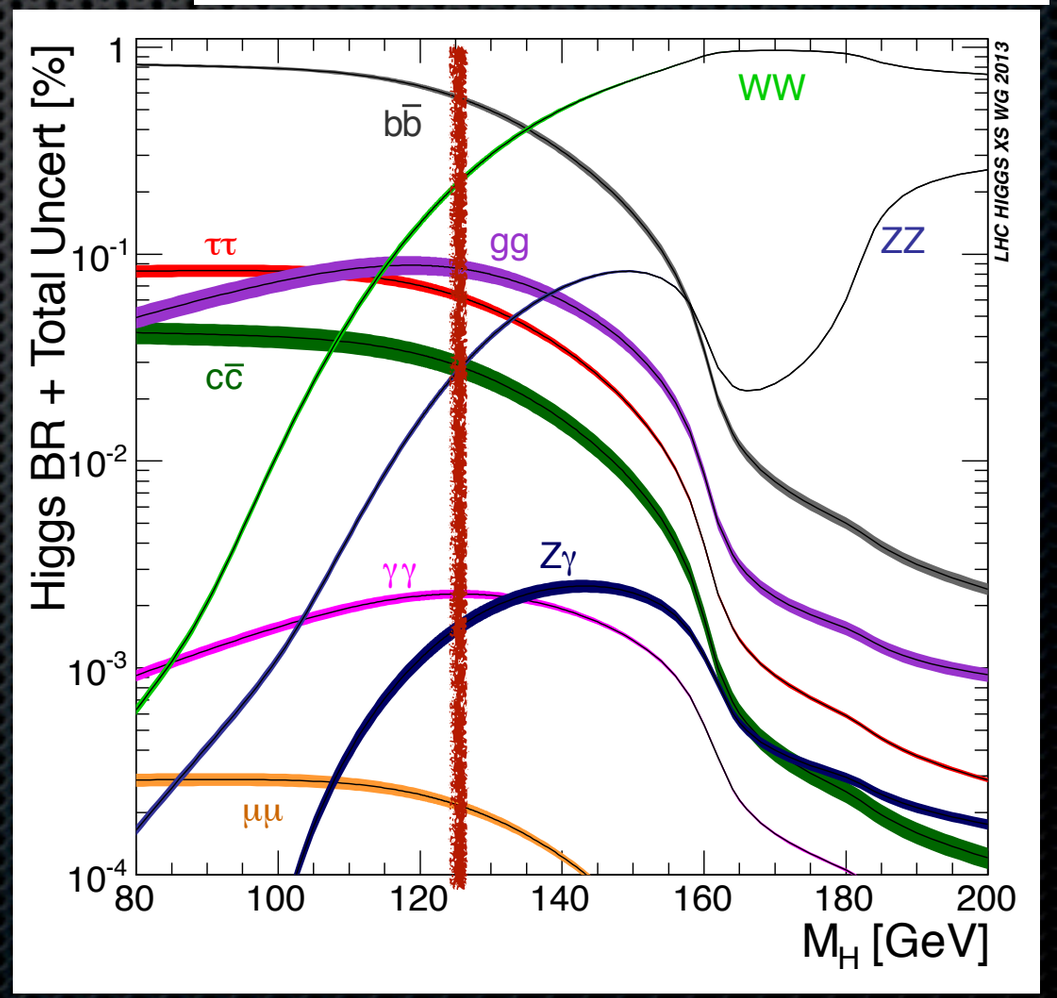
ATLAS-CONF-2013-034



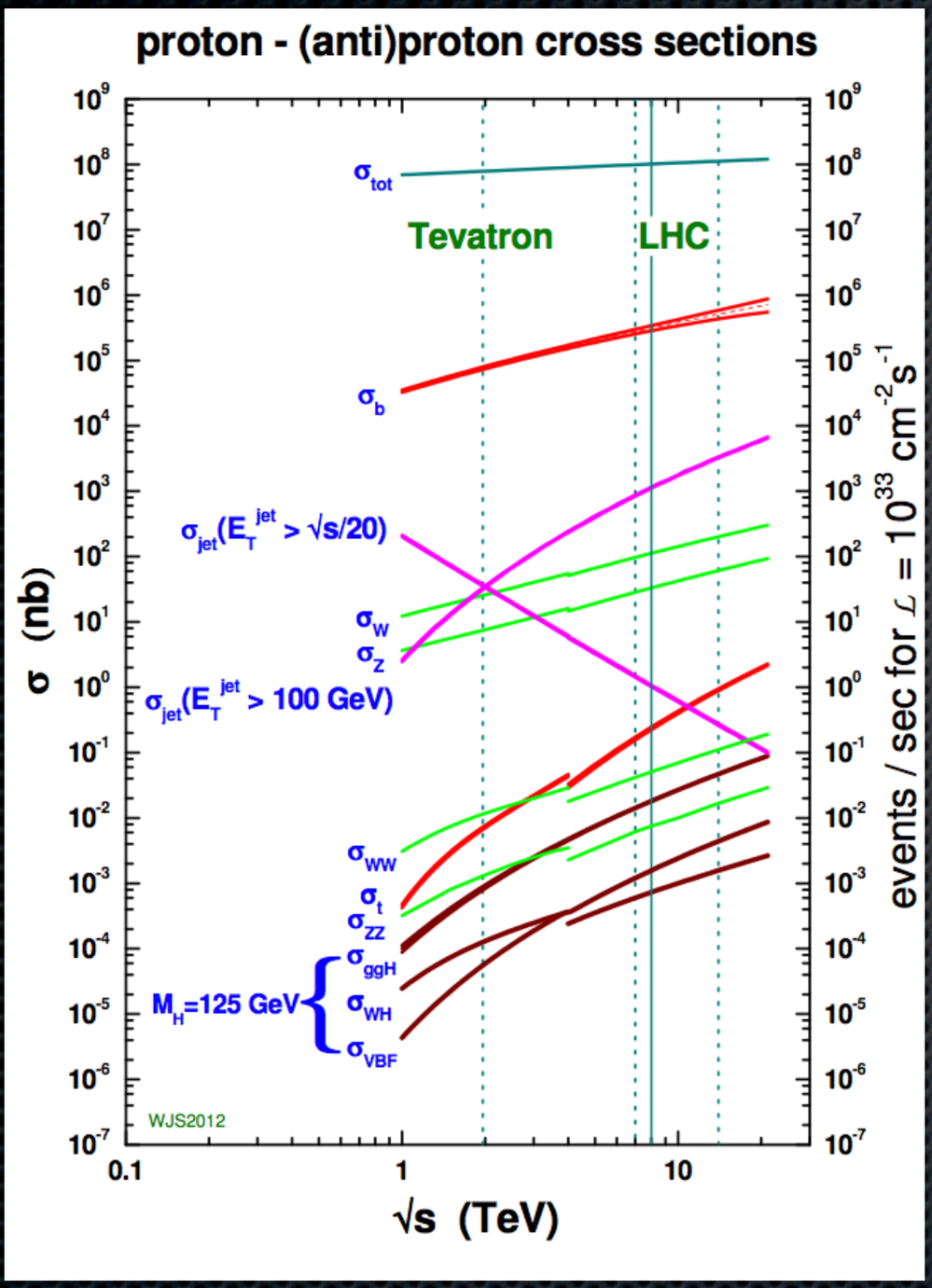
Motivation

- Recent discovery of the Higgs boson in CMS and ATLAS
  - Most sensitive channels: ZZ, WW and γγ
- Interaction of Higgs with matter well predicted by theory
  - Quadratic dependence of the decay rate on the fermion mass
- The SM Higgs boson decays mainly into fermions.
  @ m_H = 125 GeV:
  - **BR(H → bb)** = 57.7 ± 1.9 %
  - **BR(H → ττ)** = 6.3 ± 0.4 %
  - **BR(H → cc)** = 2.9 ± 0.4 %
  - **BR(H → μμ)** = 0.0217 ± 0.0013 %
- The measurement of couplings between the Higgs and the fermions is fundamental to determining the nature of the Higgs boson





Experimental Challenges

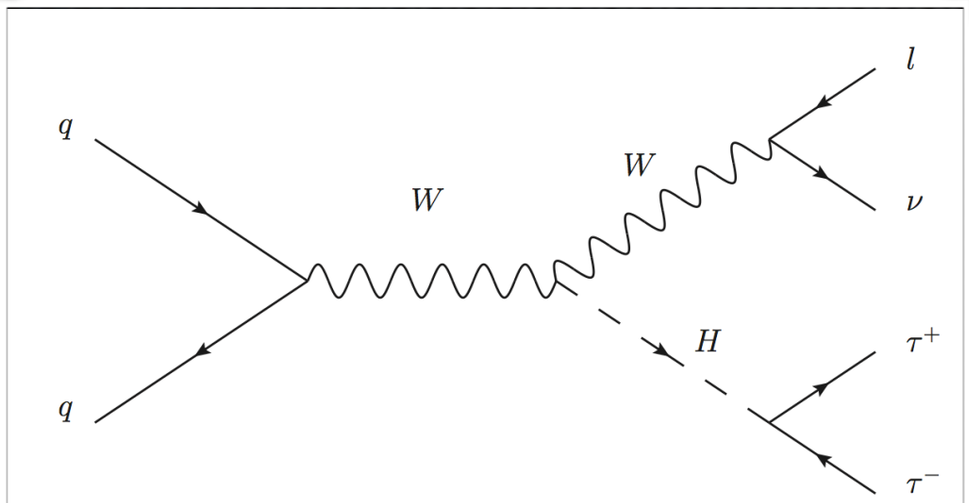


- **B-jet** production ~10^6 larger than H → bb
- **DY/Z** → ττ, ~10^5 larger than H → ττ
- Huge contribution of **QCD** which may "*fake*" other objects

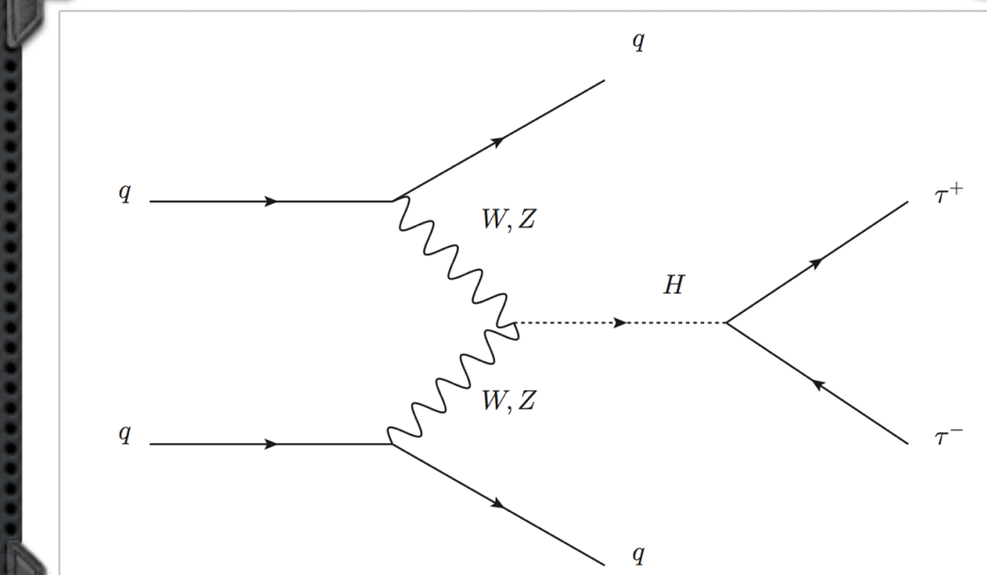
	CMS	ATLAS
b-jet tagging	Combined Secondary Vertex alg MVA combining IP of tracks and second vertex with-in the vertex 70% efficiency, 2% light jets	Uses secondary & subsequent vertices along b-had ANN 70% efficiency work-point mistag light jets ~1%
Hadronic Tau	Particle Flow Alg: Combines the information from all the detectors. *Hadron-plus-strips* candidates with 1,3 charged pions and up to 2 neutral pions	Jets + tracks (TES) BDT 60% efficiency work-point few %QCD jets, < 1% electrons
Electron	PFA em deposition + track compatible (ET/pT)	electron/EM cluster matching Quality cuts
Muon	MS and ID tracks matching Quality cuts	MS and ID tracks matching Quality cuts

H → ττ

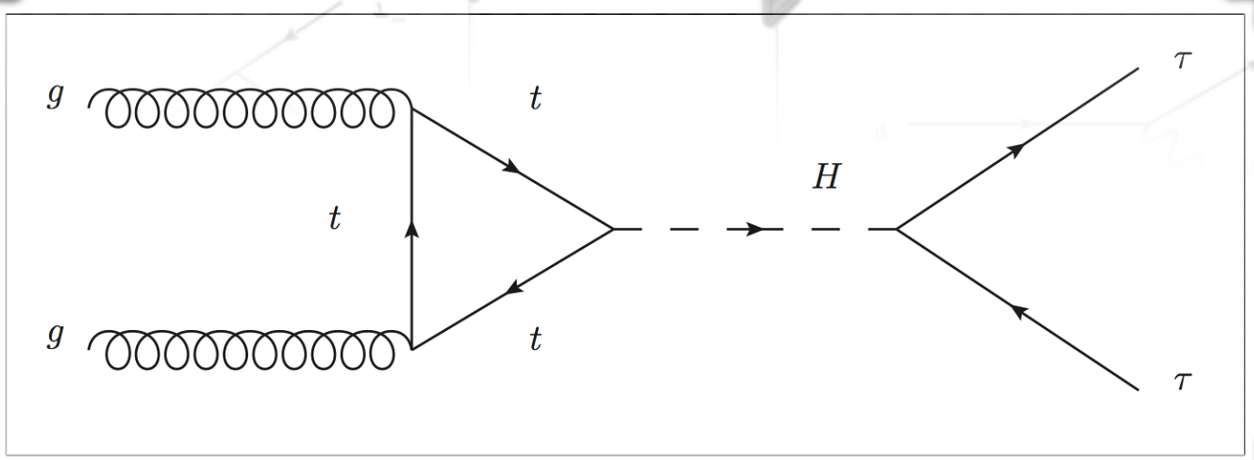
VH



VBF



ggF



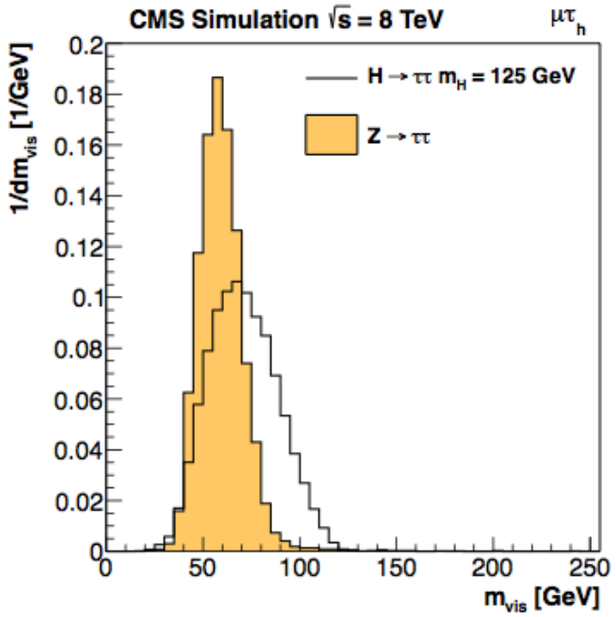
$H \rightarrow \tau\tau$ strategy

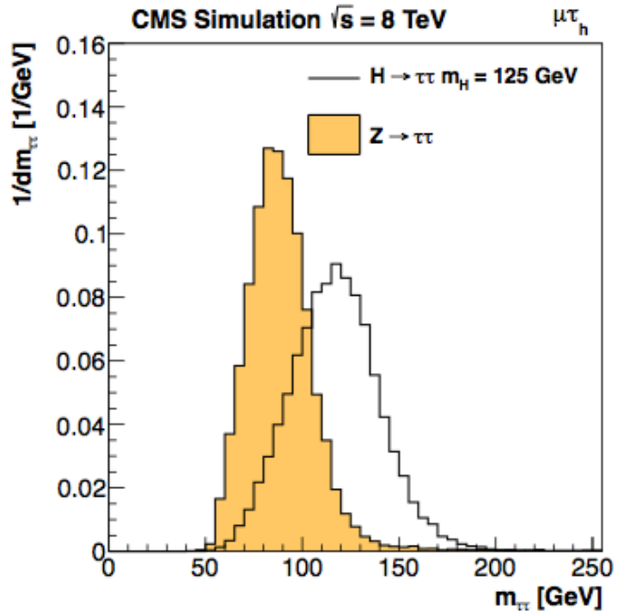
- Largest BR in leptonic channels

- ***CMS*:**
  - lep-lep: eμ, μμ
  - lep-had: μτ, eτ,
  - had-had: ττ
  - **Categories**:
    - 0-jet, **1-jet, VBF** and **VH**
- Fit di-τ mass using **SVFit**
  - Max Likelihood to get best mass given the METx and METy

- ***ATLAS*:**
  - lep-lep: eμ, μμ, ee **BR ~12%**
  - lep-had: μτ, eτ, **BR ~44%**
  - had-had: ττ **BR ~44%**
  - **Categories**:
    - **Boosted** and **2-jet VBF** (all tau decays)
    - **1 QCD** jets (lep-lep, lep-had)
    - **2-jet VH** (lep-lep)
- Fit di-τ mass using **MMC** (Missing Mass Calculator)

SVFit:

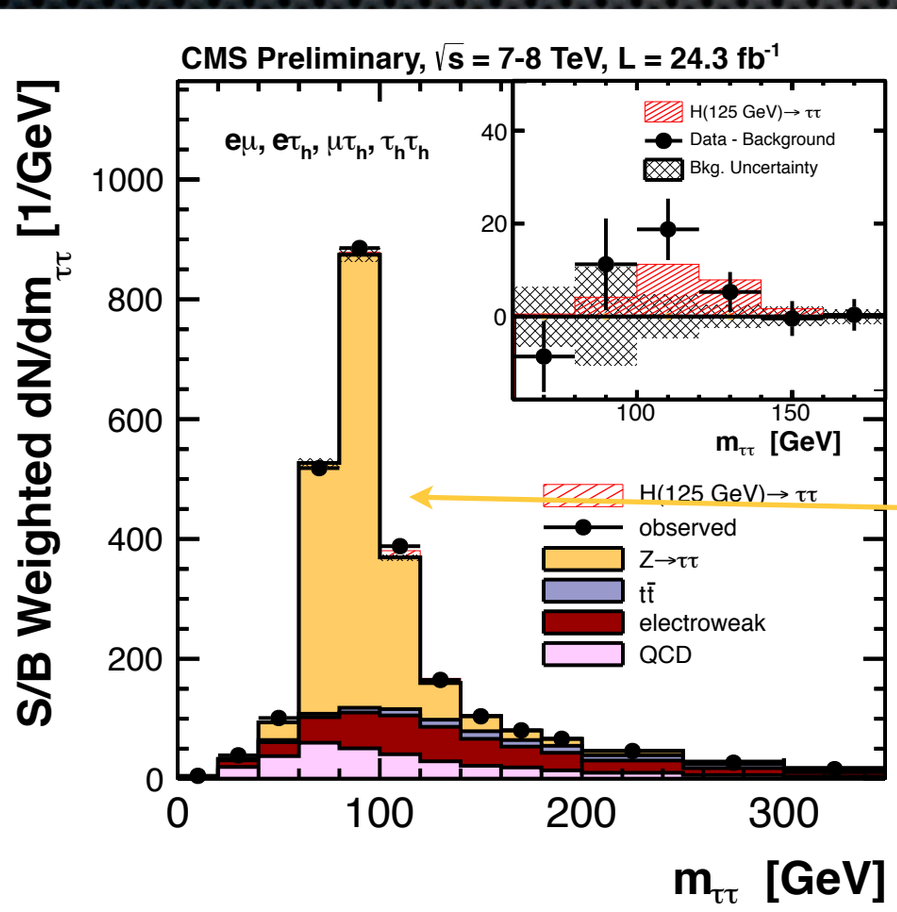




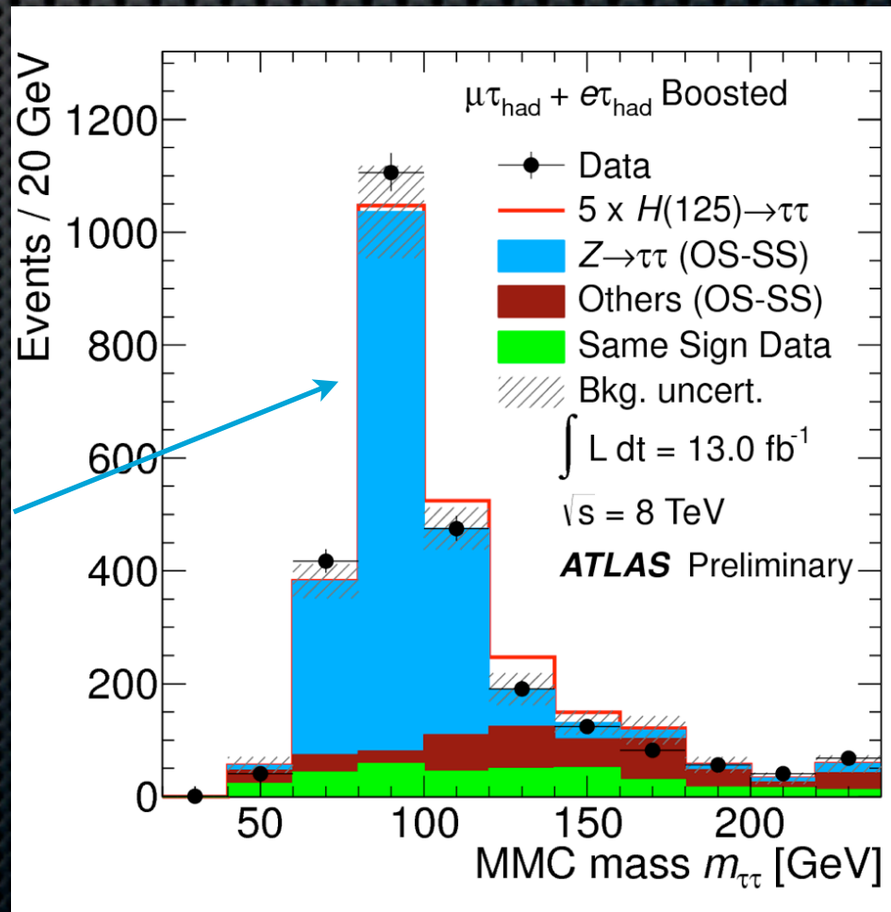
H → ττ Backgrounds

- ***CMS*:**
  - Z → ττ: Data-driven method:
    - Replace muons in Z →μμ sample by MC τ
  - Electroweak:
    - From MC with data corrections
  - QCD: From SS data using OS/SS ratio

- ***ATLAS*:**
  - Z → ττ: Data-driven method:
    - Replace muons in Z →μμ sample by MC τ
  - W + jets, Z → ll + jets, top and diboson:
    - From MC with data driven scale factors
  - QCD: data-driven estimate
  - Uncertainties:
    Tau energy Scale and theoretical uncertainties

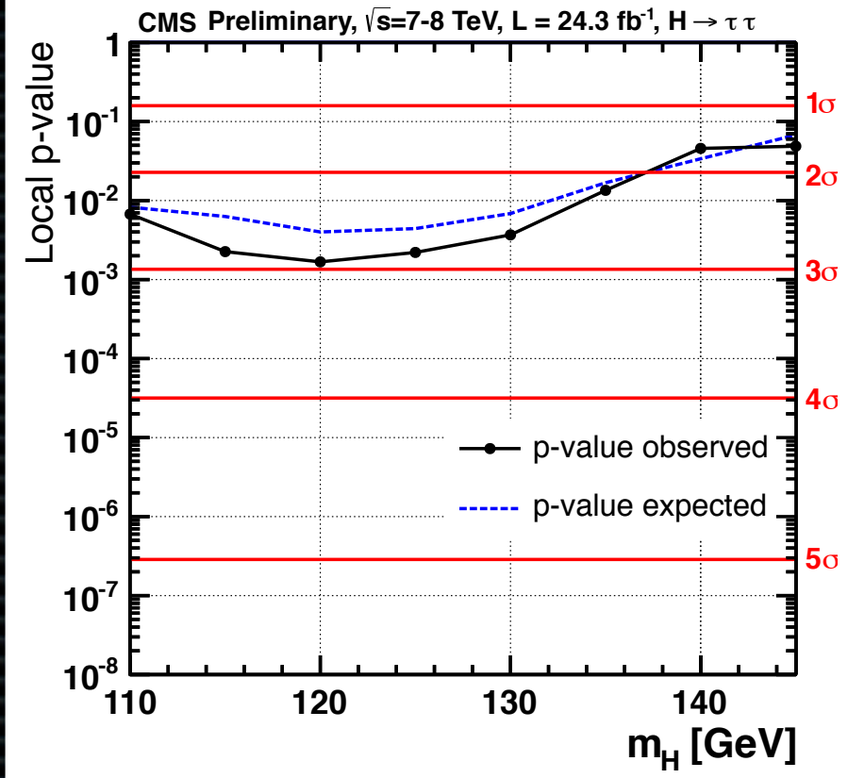


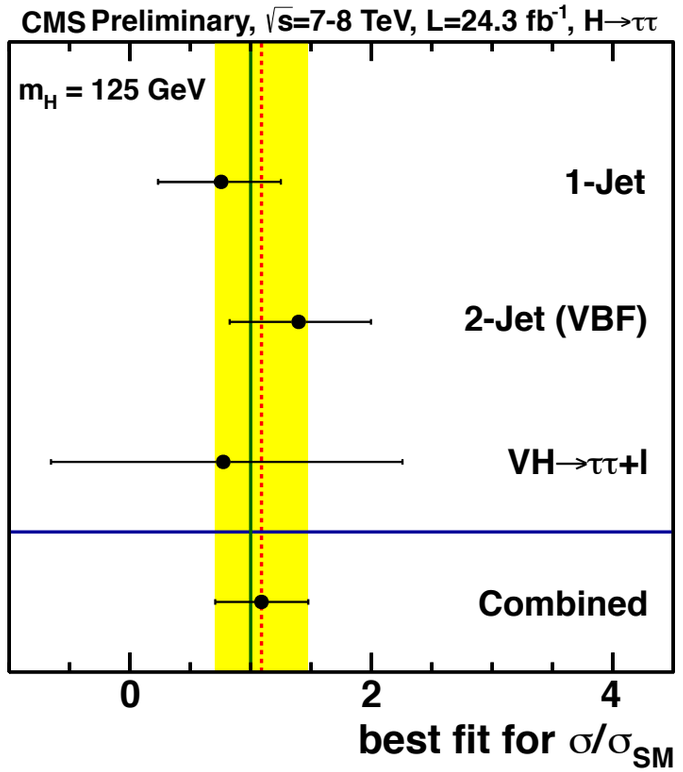
Embedding



H → ττ results

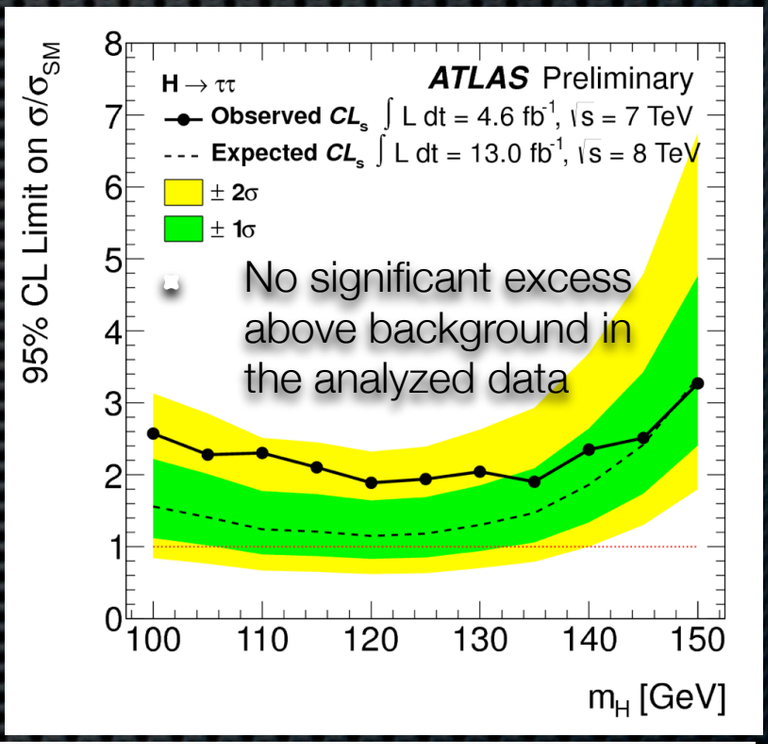
- ***CMS***:
  - Significance for m_H = 125 GeV:
    2.9σ measured, 2.5σ expected
  - Best fit: μ = 1.1 +- 0.4 @ 125 GeV

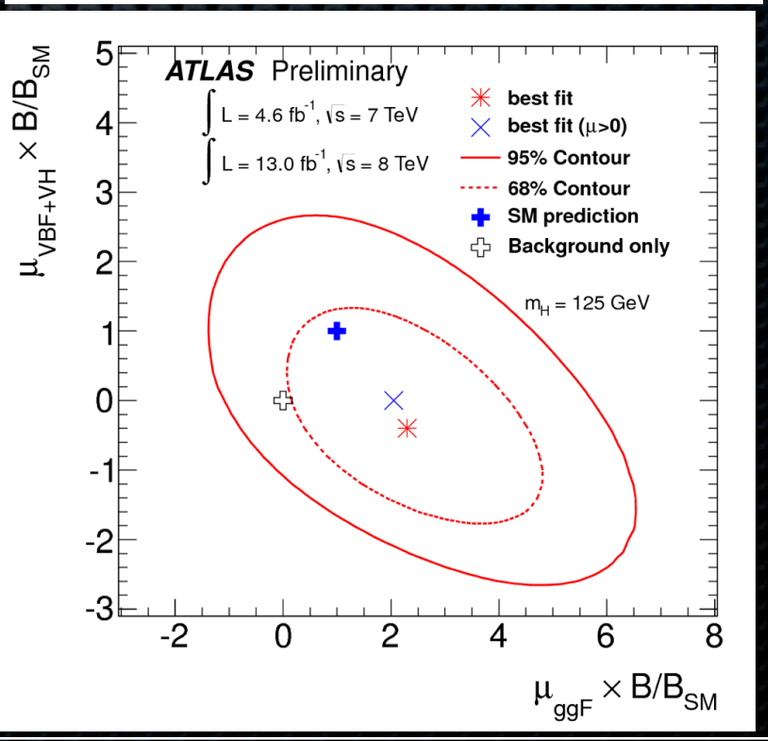




- Local p_0 value:
  - Local probability (p_0) that a background fluctuation is more signal-like than the observed data
  - Evaluates consistency of data in the signal region with the background model

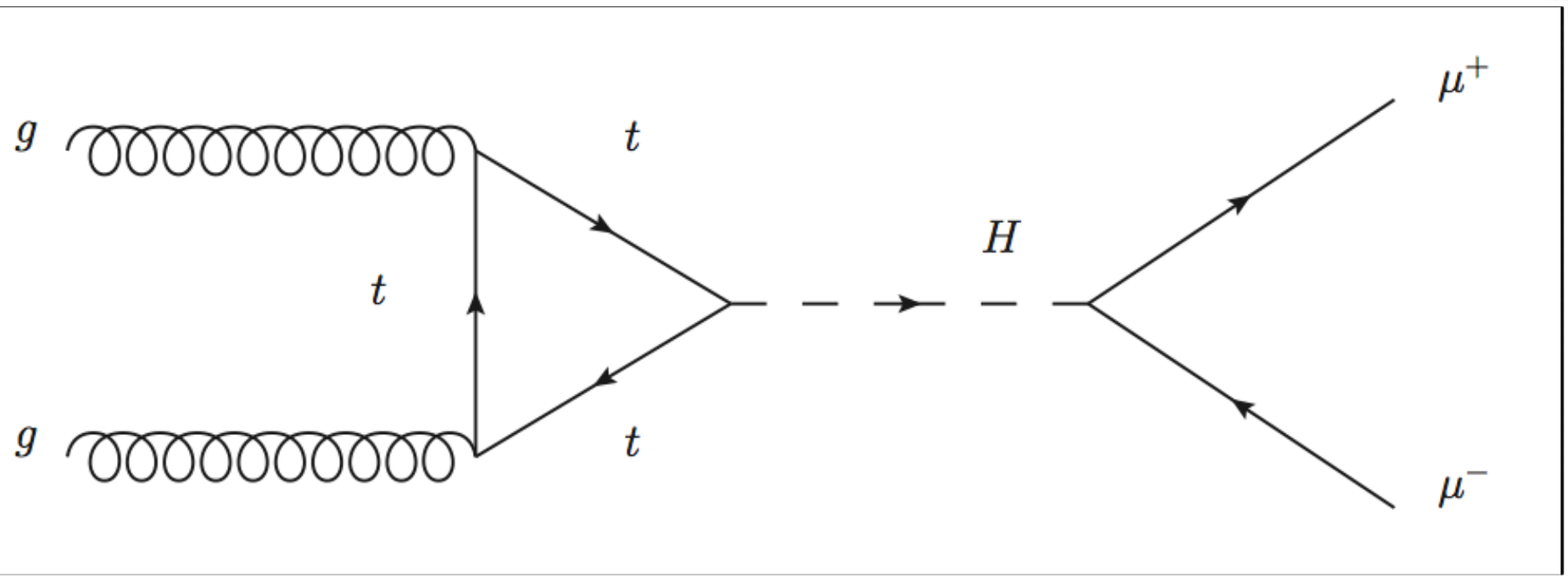
- ***ATLAS:***
  - 95% CL on σ/σ_{SM} for m_H = 125 GeV:
    1.9 measured, 1.2 expected





$H \rightarrow \mu\mu$

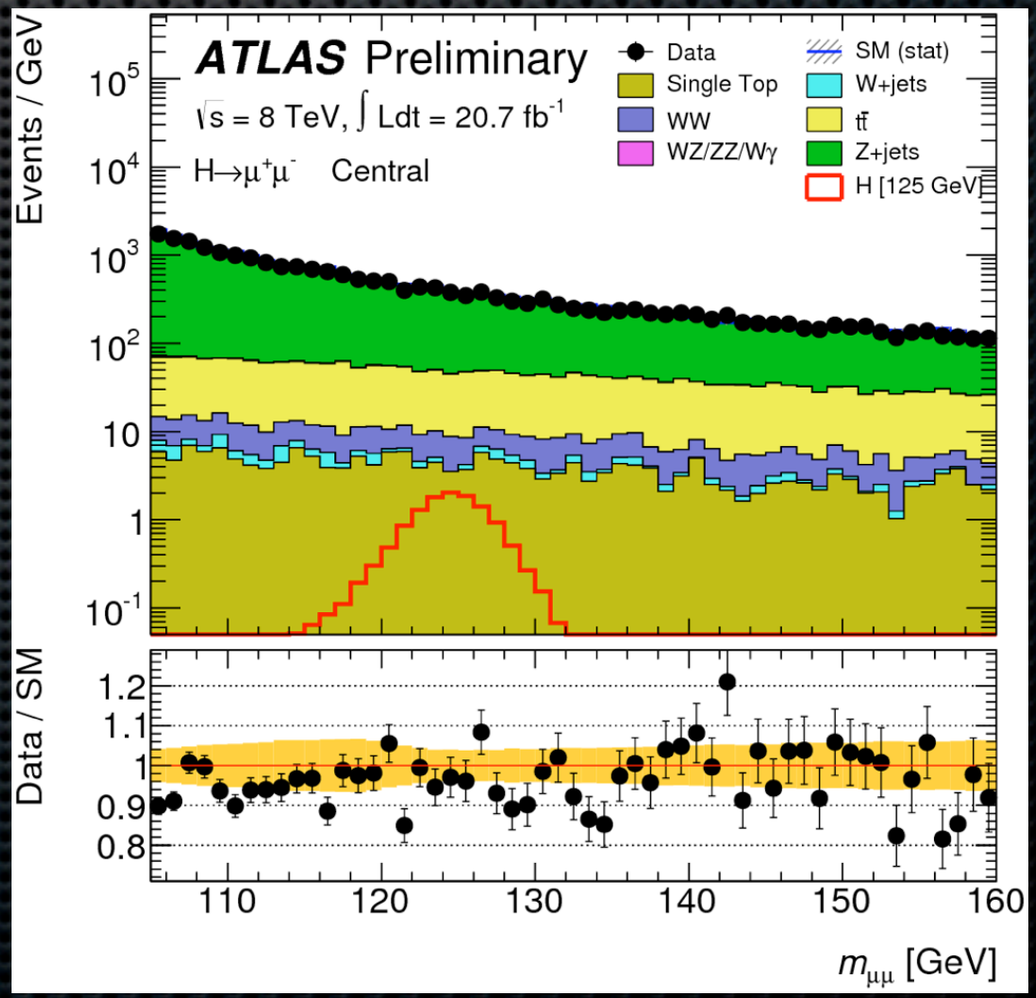
- Direct probe the SM Higgs coupling to 2nd generation fermions



$H \rightarrow \mu\mu$

- Selection:
  - Reject W+jets and QCD:
    - 2 isolated opposite-sign muon
      Leading muon: $p_T > 25$ GeV
      Subleading muon: $p_T > 15$ GeV
  - Reject DY, Z+jets:
    - Di-muon transverse moment > 15 GeV (DY)
      Remove 60% BCK keeps 80% signal
      Di-muon invariant mass > 105 GeV
  - Control regions:
    - Di-μ low Transverse momentum: < 15 GeV
    - High di-μ mass > 150 GeV
    - High E_T^{miss}: > 40 GeV
    - b-jet tagged >=1
- Event categories:
  - **Central**, both muons in $|\eta| < 1.0$
    More precise momentum measurement
  - **Non-Central**: Rest of muons

	$\lvert m_H - m_{\mu\mu}\rvert \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15810 ± 130
W+jets	88 ± 6
Total Bkg.	17700 ± 130
Observed	17442

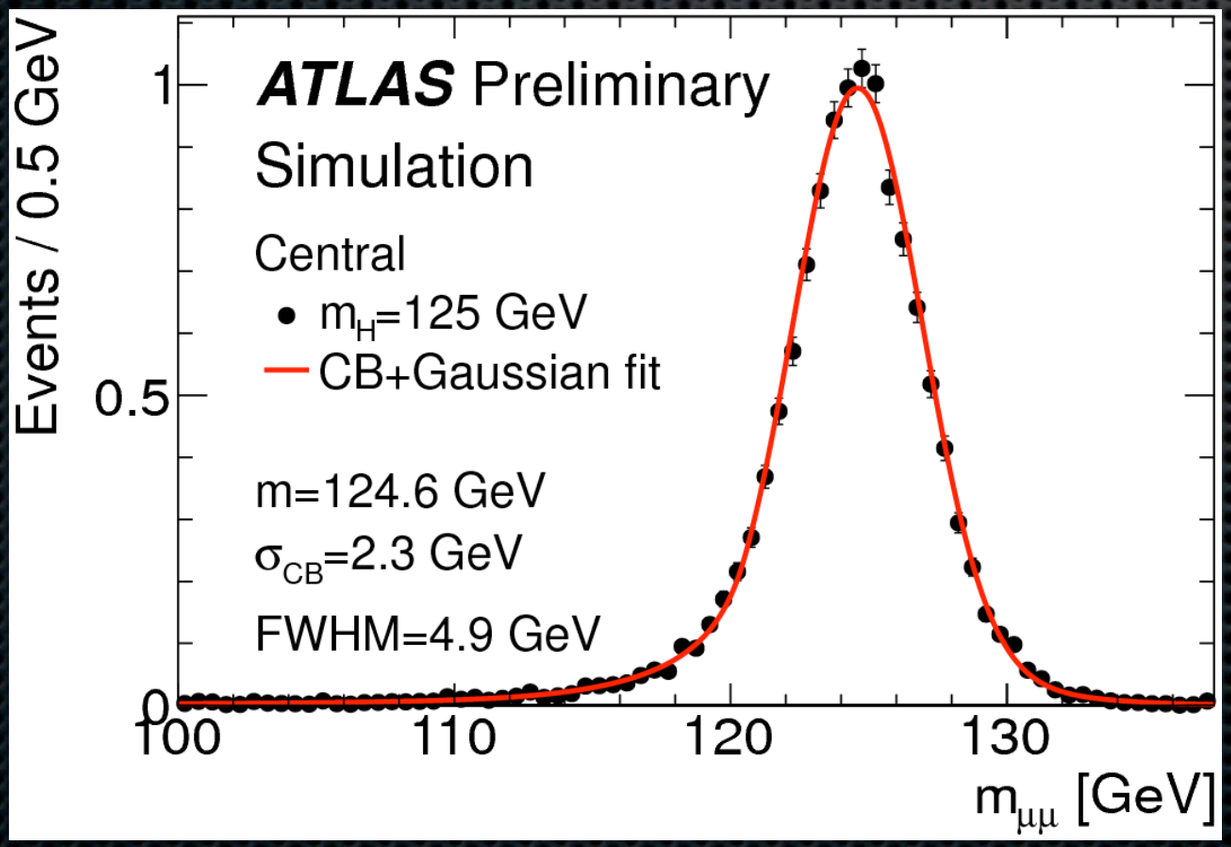


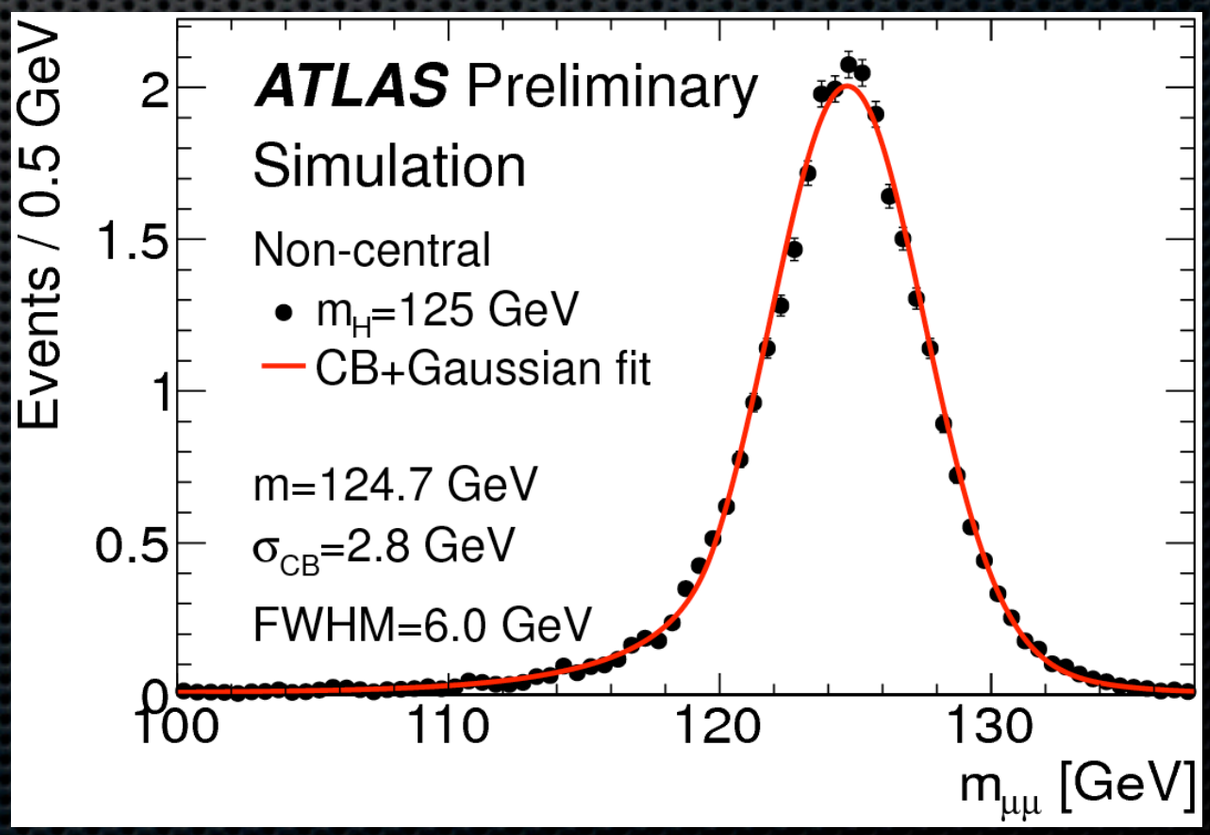
H → μμ: Signal model

- **Signal width dominated by detector**
  - Higgs width 4.1 MeV for mass 125GeV
- **Signal shape obtained from simulated Higgs signal samples with all the contributions**
  - **Crystal-ball function:**
    Bulk part of the signal and low mass tail due to FSR
  - **Remaining resolution effects**:
    described by a gaussian

$$f_{sig}(m_{\mu\mu}, \{\alpha_i\}) = \sum f_i F_i(m_{\mu\mu}, \{\alpha_i\})$$
$$F_1(m_{\mu\mu}, \{\alpha_1\}) = F^i_{CB}(m_{\mu\mu}, \overline{m}, \sigma_{CB}, \alpha, n)$$
$$F_2(m_{\mu\mu}, \{\alpha_2\}) = F_{Gaus}(m_{\mu\mu}, \overline{m}, \sigma_G)$$

$m_{\mu\mu}$ is ~2.3 GeV at 125 GeV

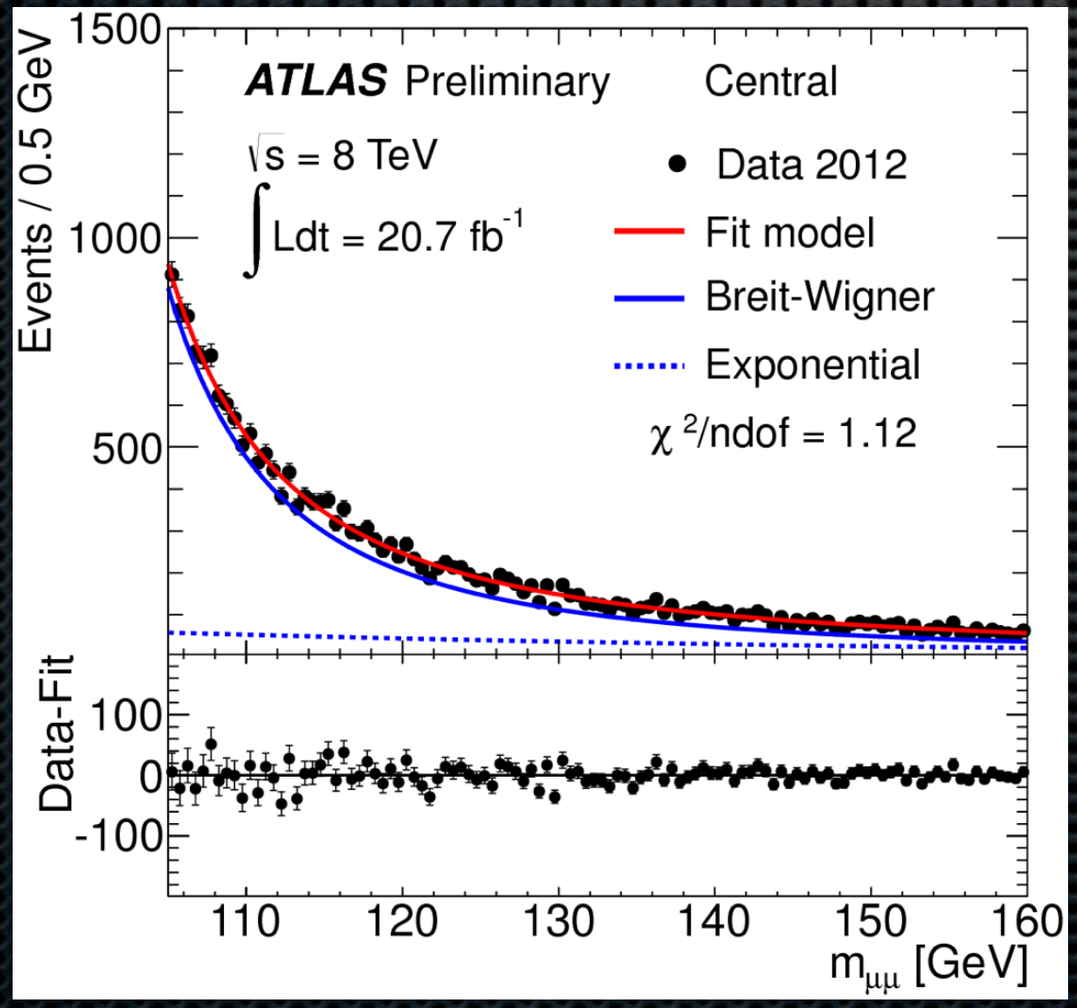


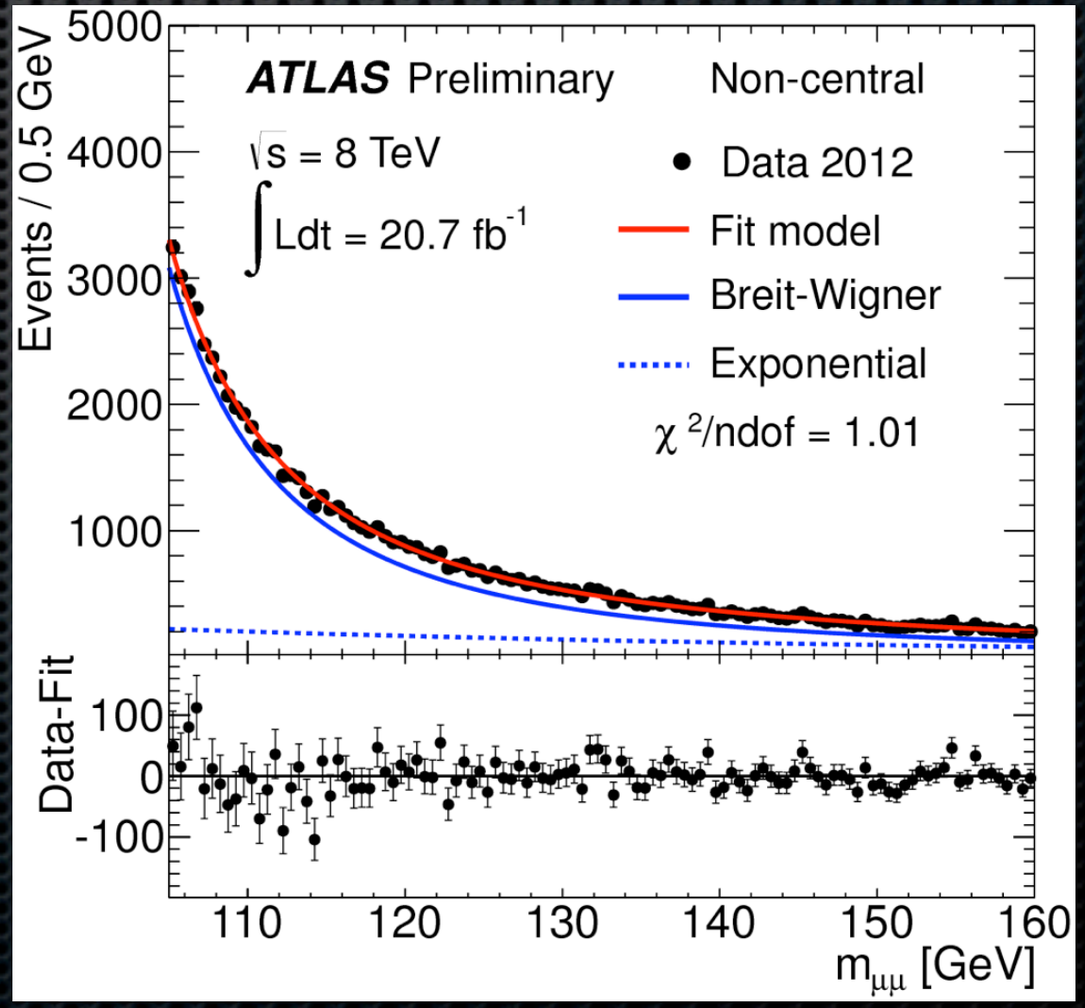


H → μμ: Background model

- Falling edge of the mass spectrum by a Breit-Wigner
- Non-resonant background as exponential
- **Fit range: 105-160 GeV**
- **Sufficient flexible to describe shape variation in data**

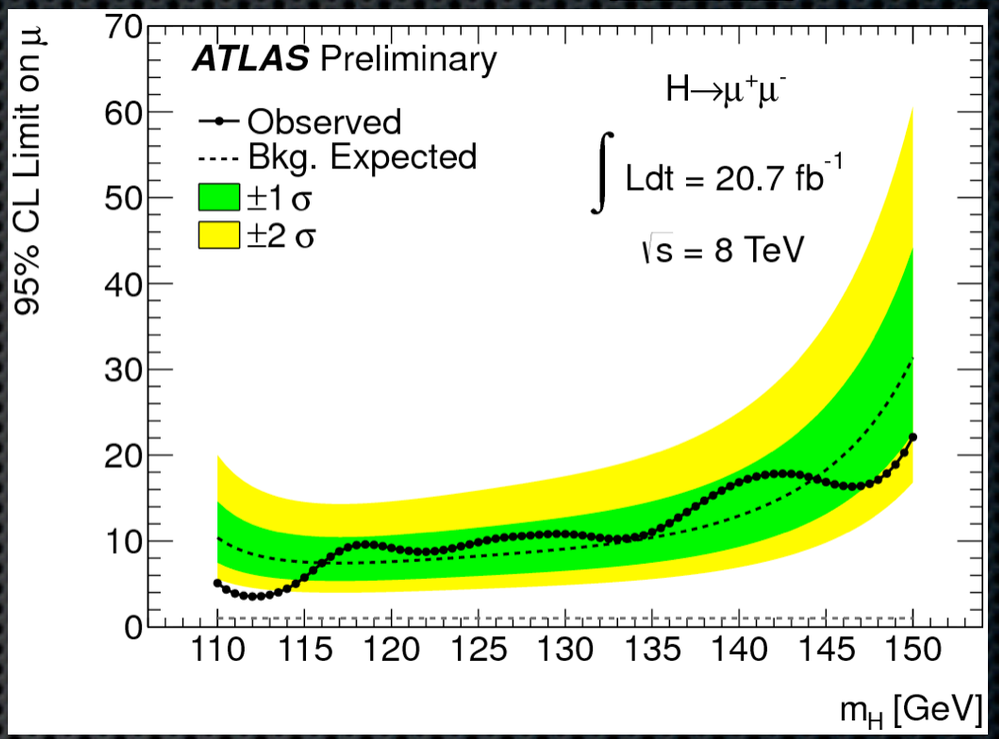
$$f_{bkg}(m_{\mu\mu}, \alpha_i, \beta_i) = fF(m_{\mu\mu}, \alpha_i) + (1-f)G(m_{\mu\mu,\beta_i})$$
$$F(m_{\mu\mu}, \alpha_i) = F_{BW}(m_{\mu\mu}, \Gamma_{Z_0}, M_{Z_0})$$
$$G(m_{\mu\mu,\beta_i}) = e^{Bm_{\mu\mu}}$$

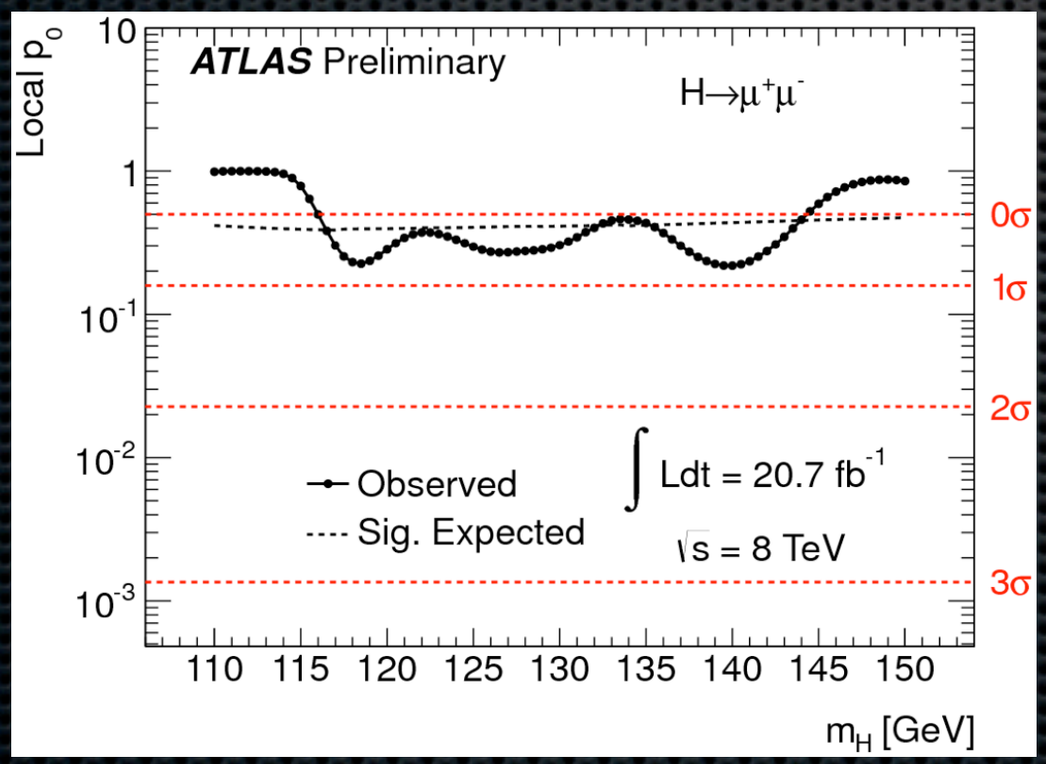




H → μμ : Results

- Exclusion limits:
  Given the absence of signal, 95% CL upper limits on the Higgs boson production are determined using a modified frequentist CL method
  - 95% CL limit on σ/σ_{SM} for m_H = 125 GeV:
    - **9.8 measured, 8.2 expected**
    - **No deviation for the 2σ uncertainty band is observed**

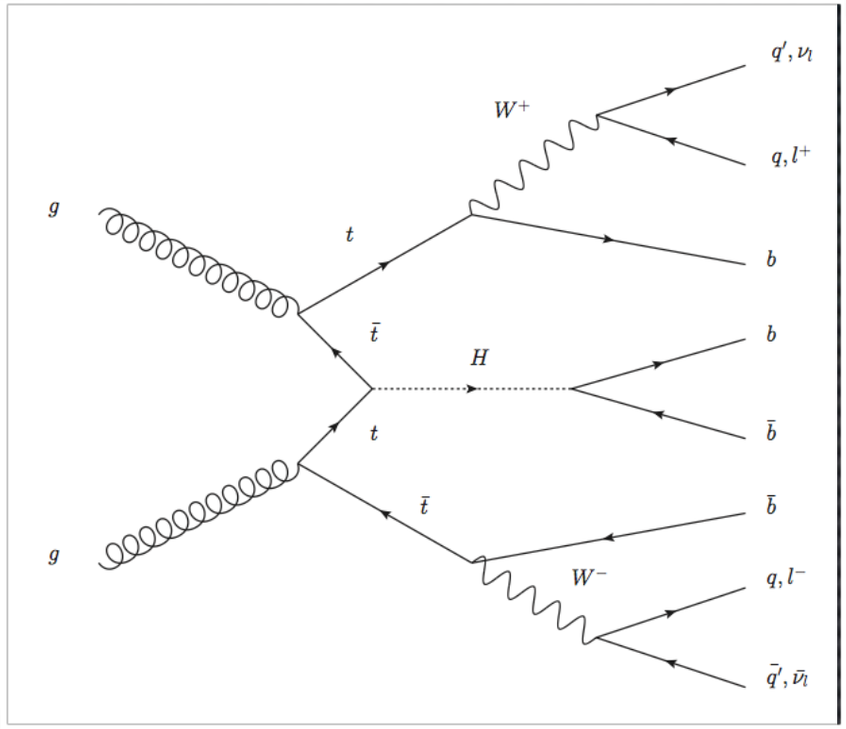




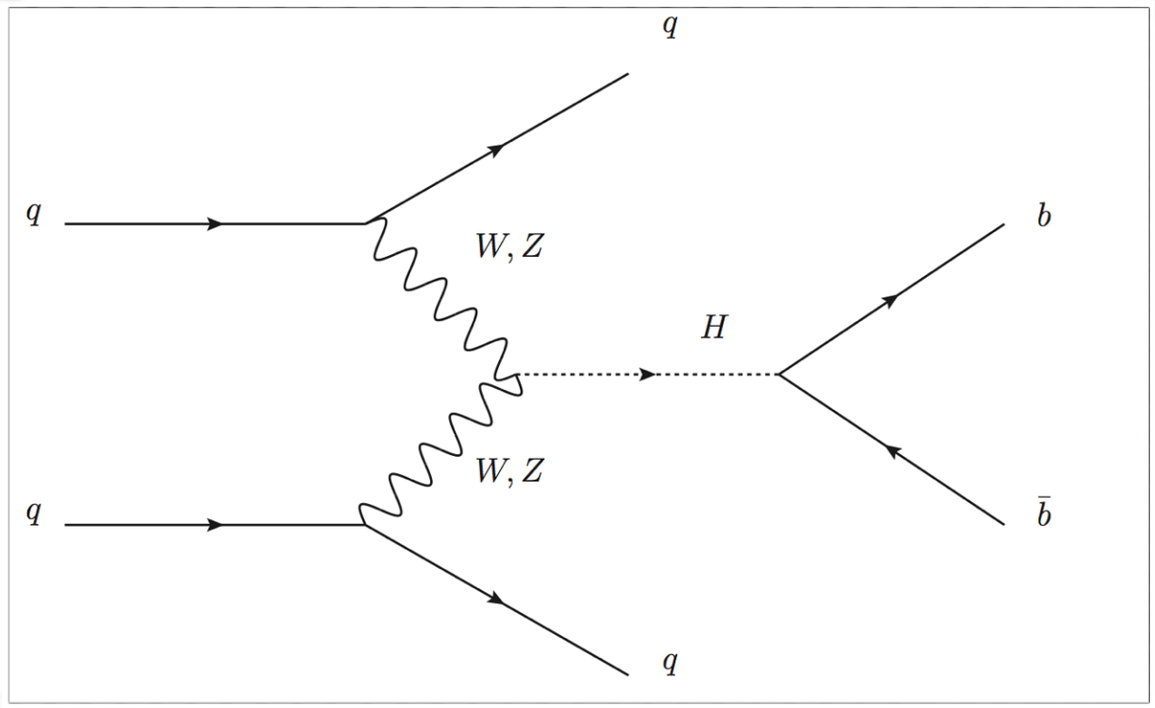
- Local p_0 value:
  - Local probability (p_0) that a background fluctuation is more signal-like than the observed data
  - Evaluates consistency of data in the signal region with the background model

H → bb

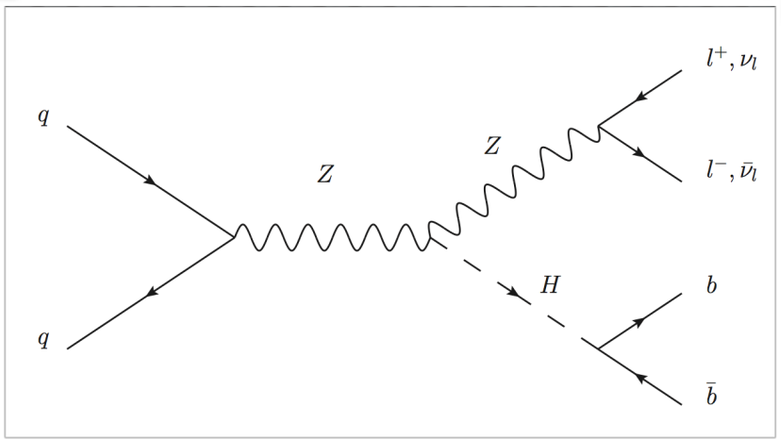
ttH



VBF



VH



ttH, H→ bb

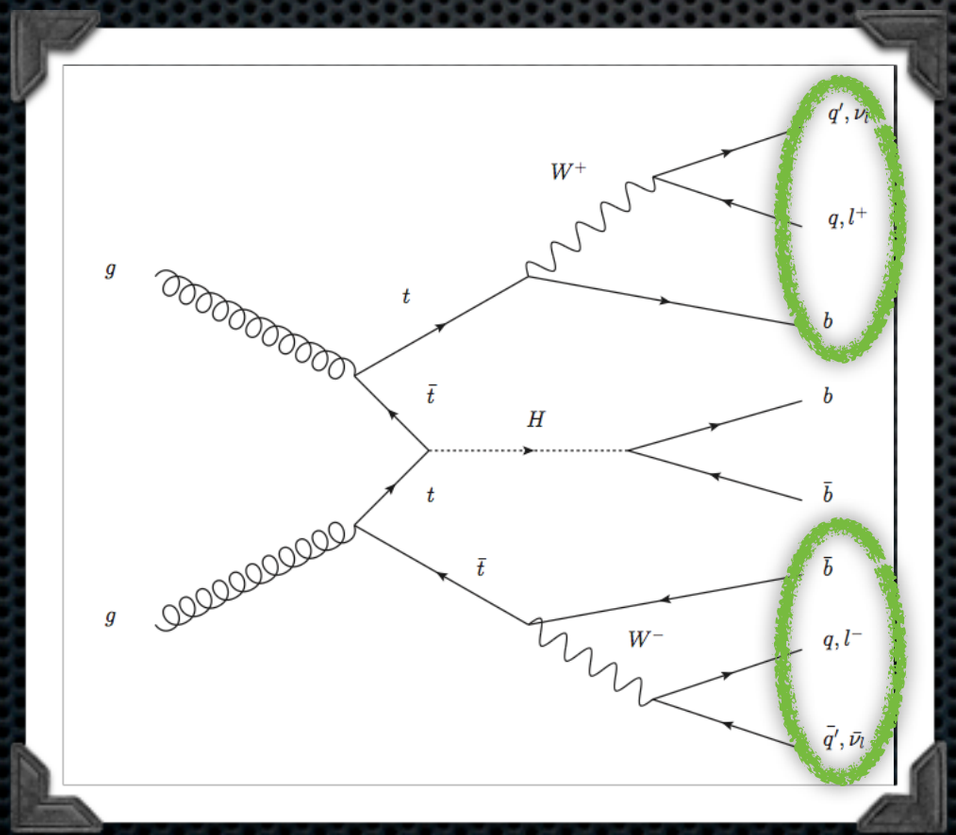
- **CMS**, not full **2012** dataset:
  - Semileptonic and di-leptonic events
  - Categories: njets and n bjets
    - 4j2b - 6j4b
    - Use Artificial Neural Network to discriminate

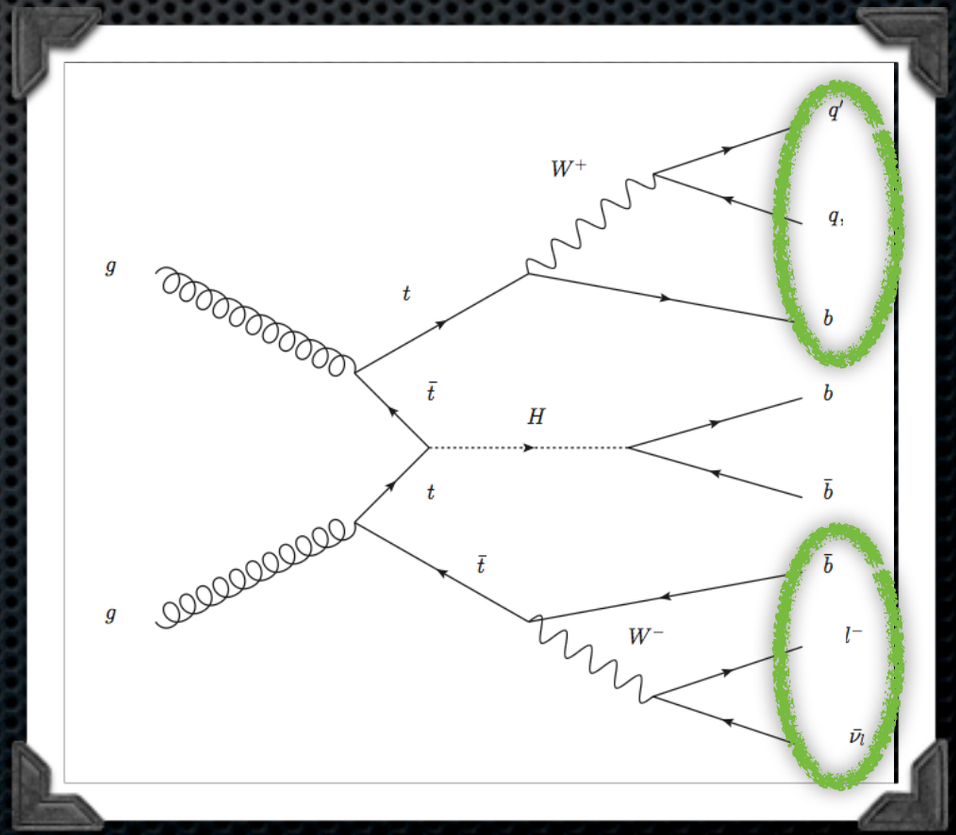
- **ATLAS**, only 2011 dataset:
  - Semi-leptonic decay
    - >= 3 b-jets
    - >= 6 jets

- 1 e or 1 mu
- MET
- 4 b-jets
- 2 light jets

Kinematical Likelihood fitter

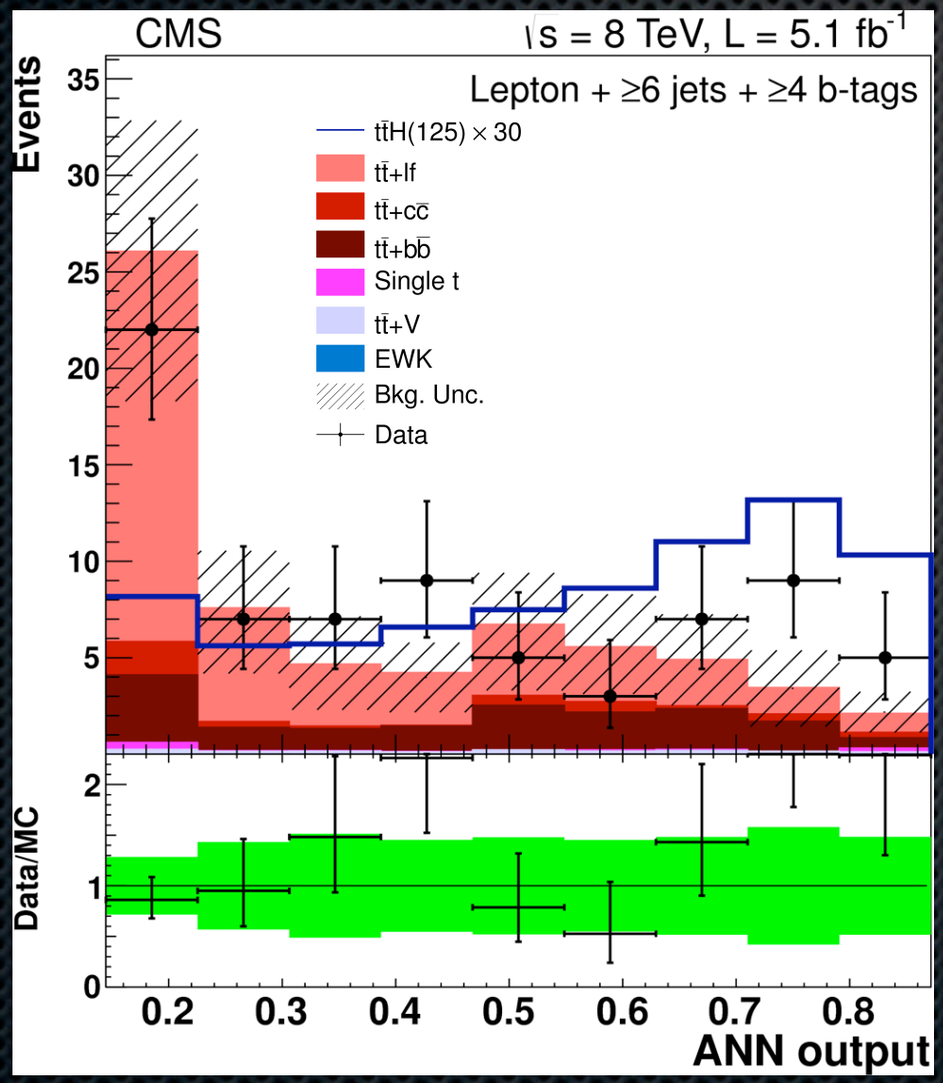
- 2 W Bosons
- 2 top-quarks
- 1 Higgs boson





ttH, H→ bb

- **CMS**, not full **2012** dataset:
  - Semileptonic and di-leptonic events
  - Categories: njets and n bjets
    - 4j2b - 6j4b
    - Use Artificial Neural Network to discriminate

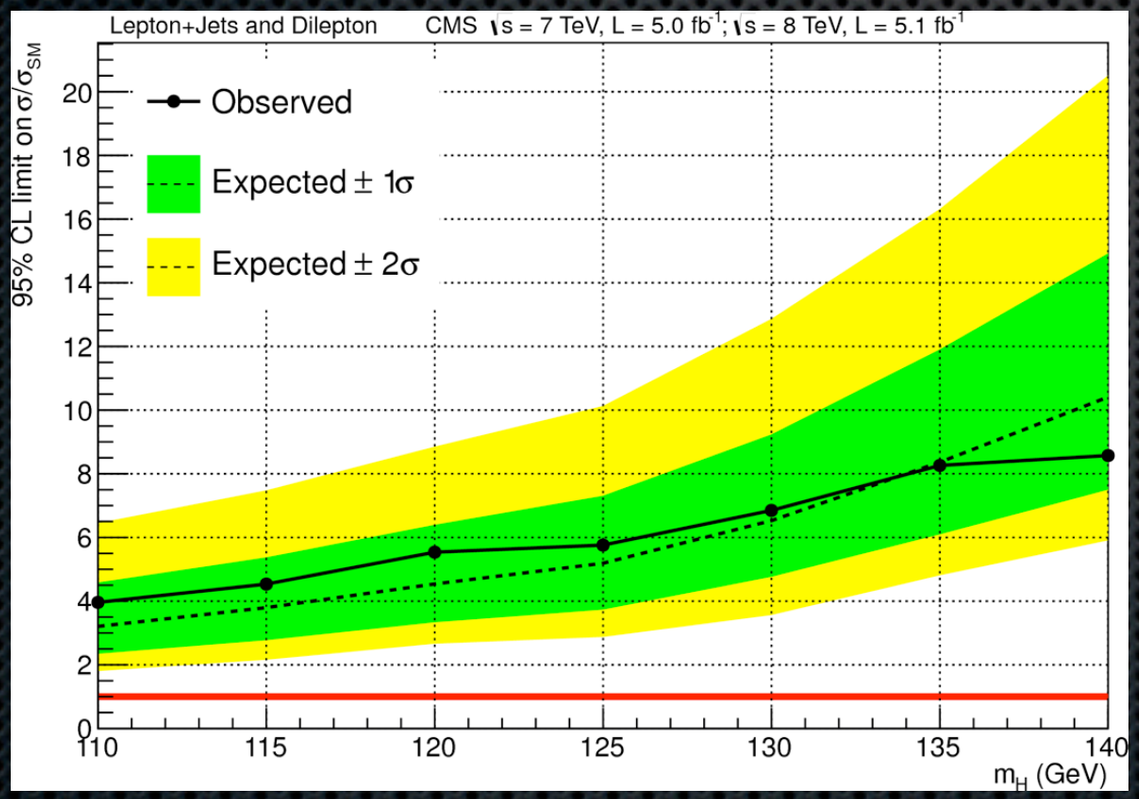


- **ATLAS**, only 2011 dataset:
  - No constraint on m_{bb}, used as discriminant!
  - Main background tt production
  - Uncertainties:
    - b and c tagging
    - Distributions fitted to data

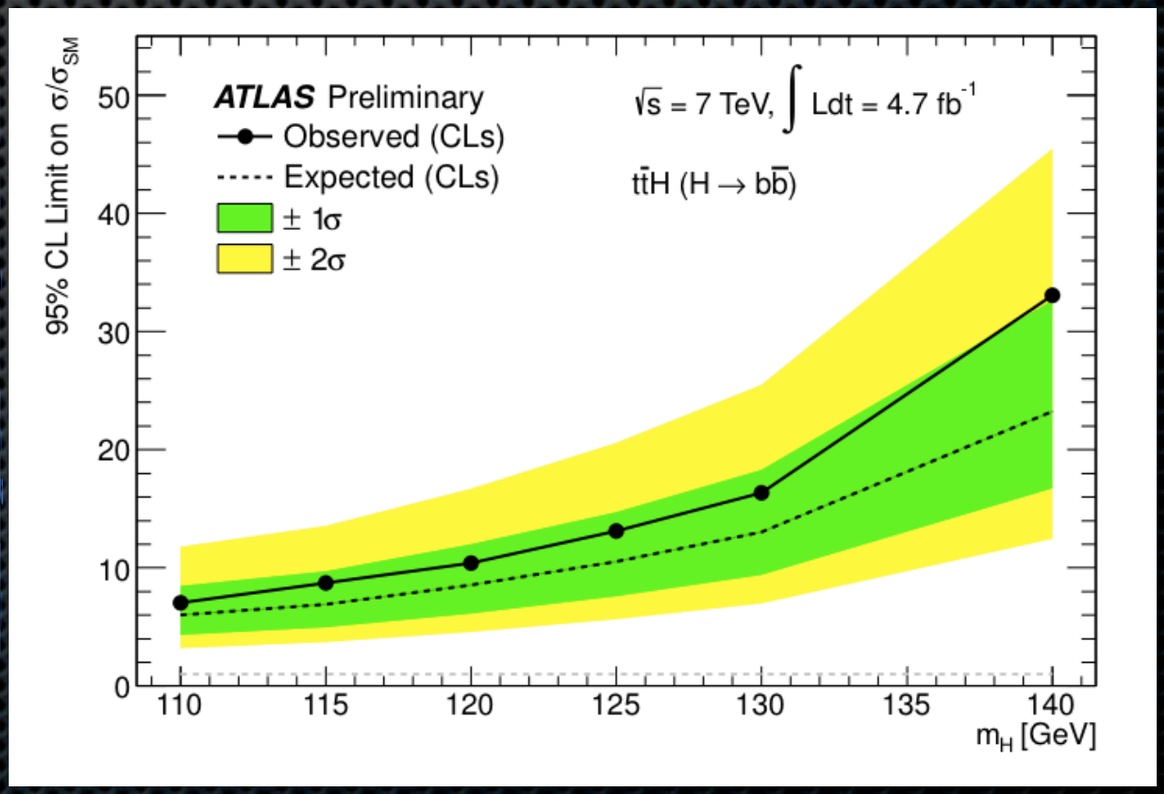
ttH, H→ bb

No Deviations from prediction
More data will be need

- ***CMS***:
  - 95% CL on σ/σ_{SM} for $m_H = 125$ GeV:
    5.8 measured, 5.2 expected

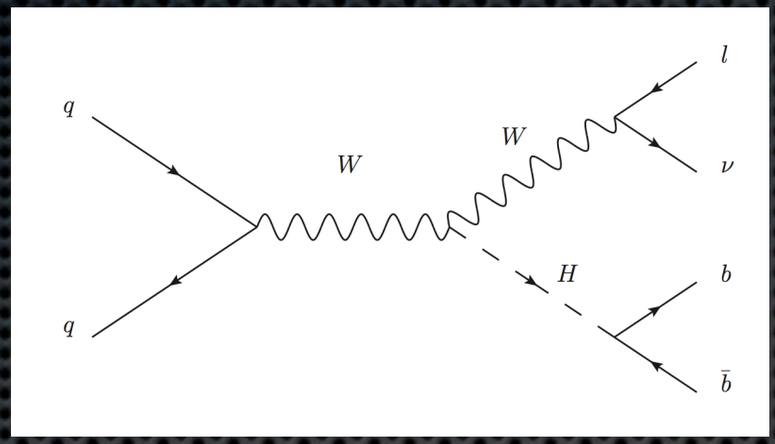


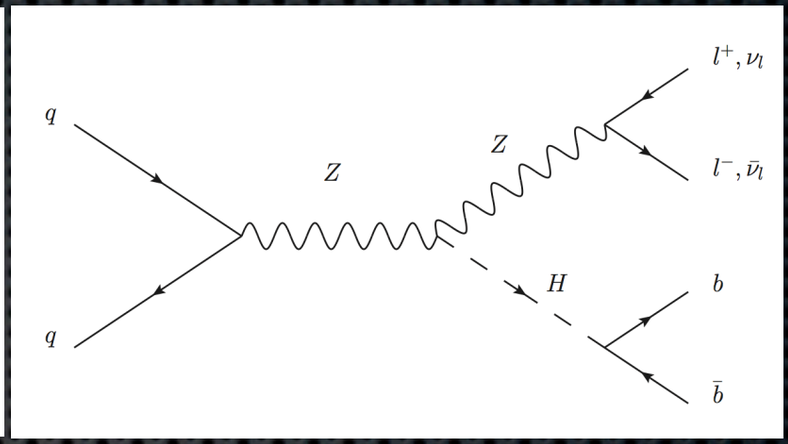
- ***ATLAS***:
  - 95% CL on σ/σ_{SM} for $m_H = 125$ GeV:
    13.1 measured, 10.5 expected

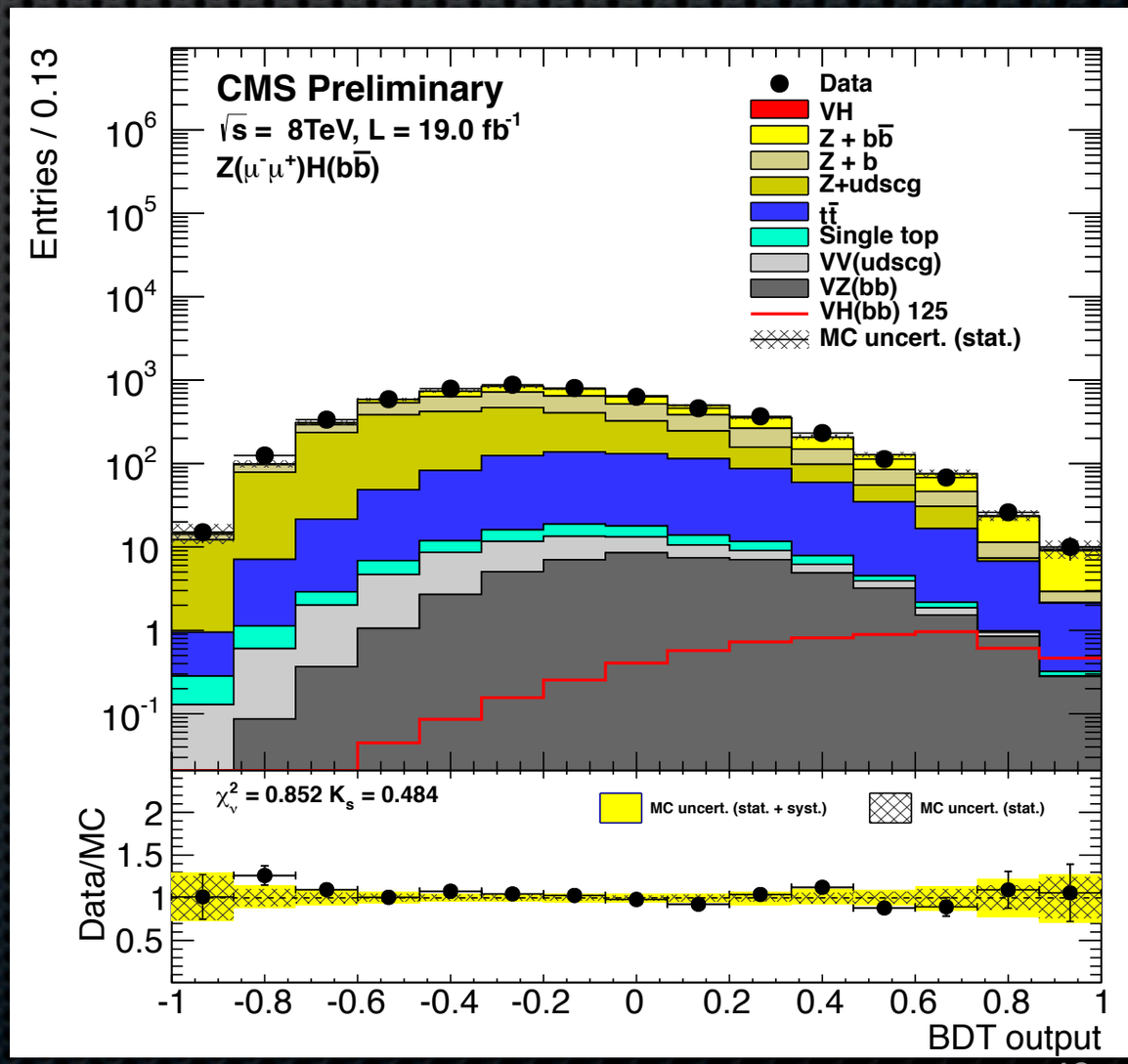


H→ bb, VH

- ***CMS:***
  - Dijet selection in boosted regime
  - 6 Modes:
    - W → eν, μν
    - W → τν
    - Z → ee, μμ
    - Z → νν
  - Final states:
    - Leptons, taus
    - E_T^{miss}
    - b-tag jets
  - Backgrounds normalization:
    - W/Z + jets, tt from data
    - Diboson, single top from MC
  - **BDT** regression to improve m_{bb} reconstruction
  - **BDT** to discriminate signal over background (14 categories)
    - **Binned in vector boson pT**

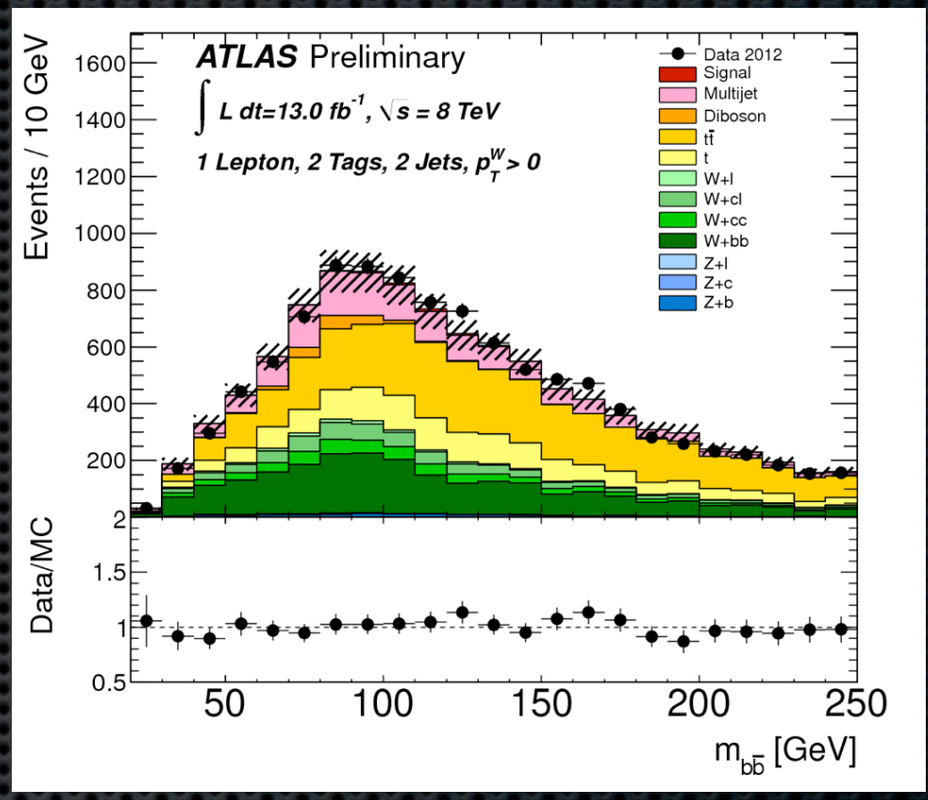


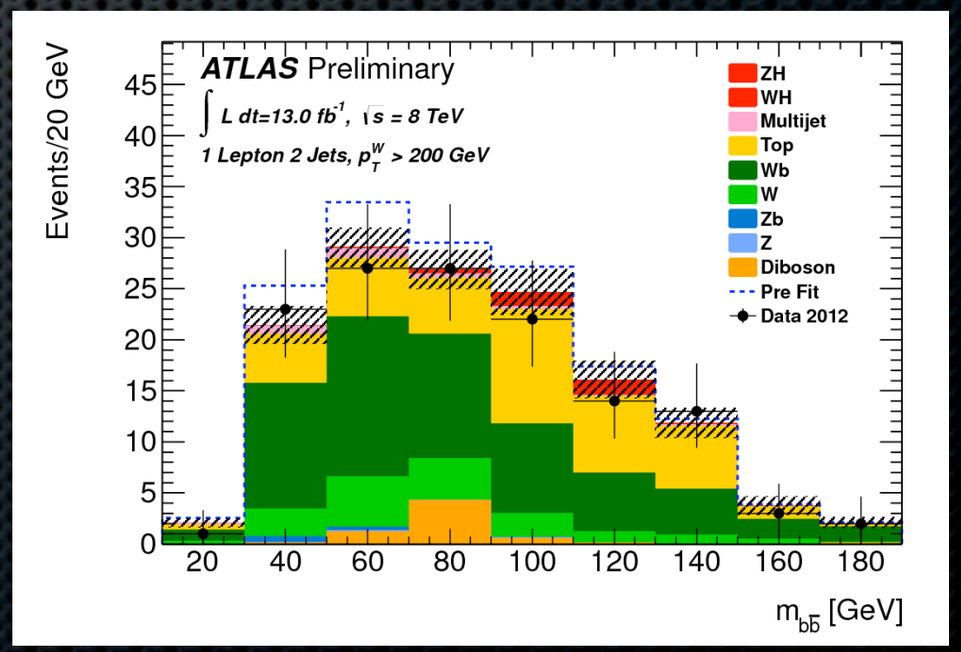




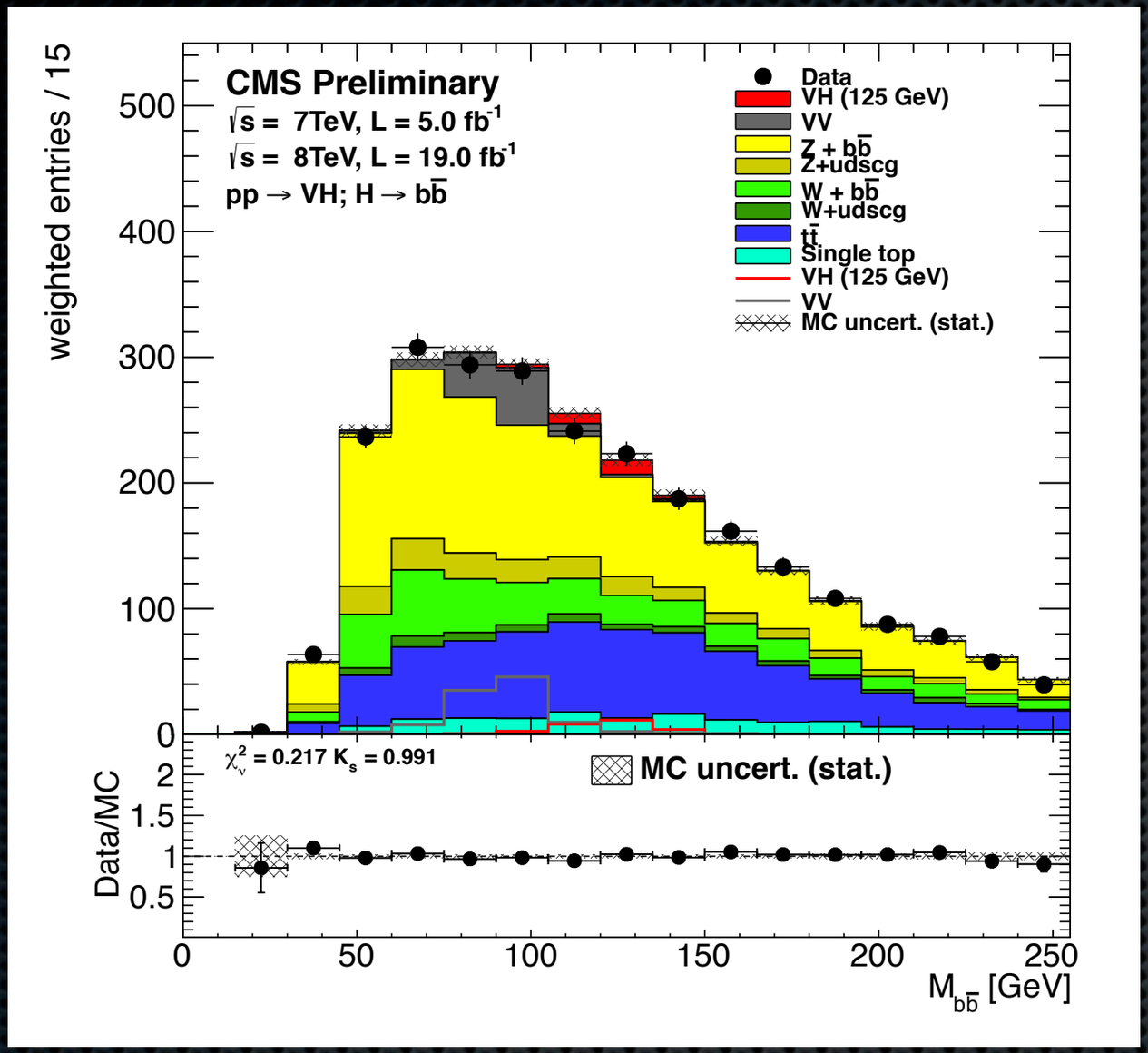
H→ bb, VH

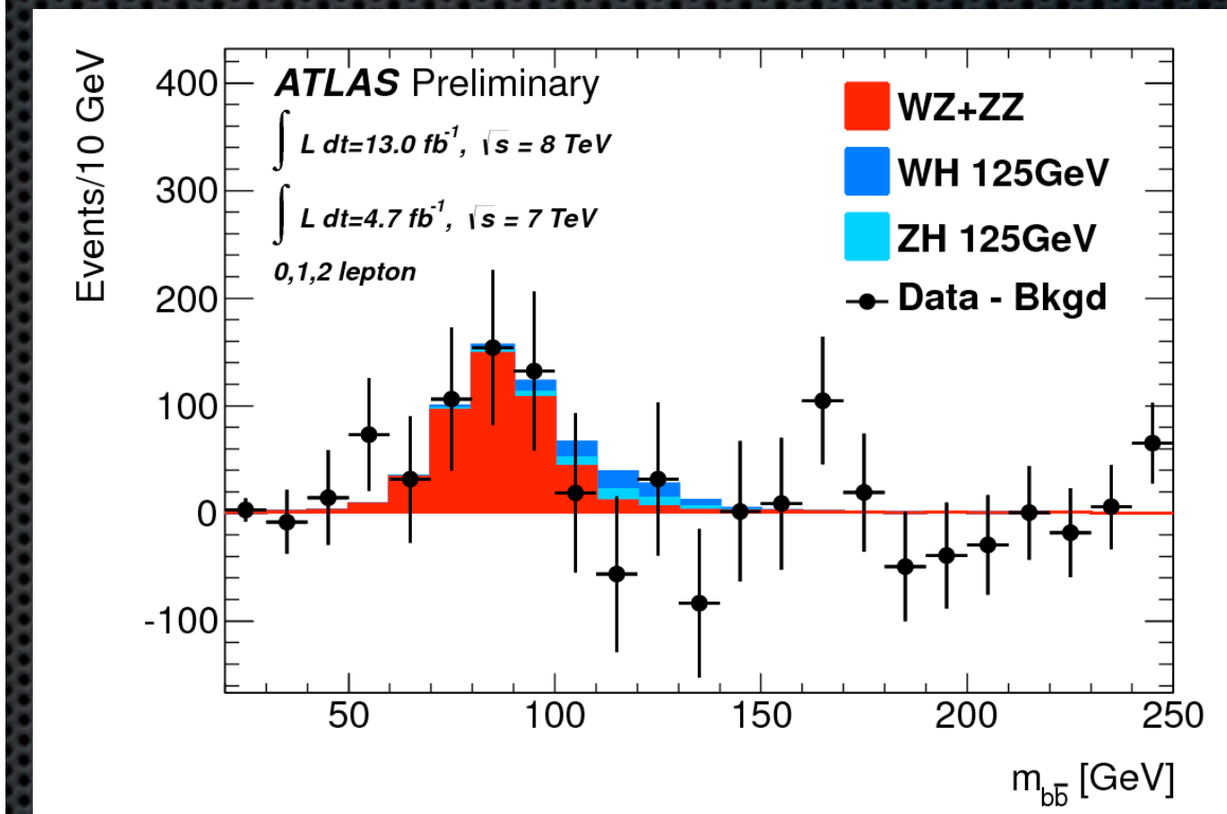
- ***ATLAS:***
  - 2 or 3 jets, and 2 b-tag jets
  - To improve sensitivity, analysis performed in bins of vector boson p_T (p_T ll/lnu) or E_T^{miss}: 16 bins.
  - m_{bb} used as discriminating variable
  - 0 leptons: ZH → vvbb.
    $E_T^{miss} > 120$ GeV
  - 1 lepton: WH → lvbb.
    One high p_T lepton
    $E_T^{miss} > 25$ GeV
    $40 < m_t$ (lv) < 120 GeV
  - 2 leptons: ZH → ll bb
    2 OS high p_T leptons
    $E_T^{miss} < 60$ GeV
    $83 < m_{ll} < 99$ GeV
  - Backgrounds:
    - Shapes from simulation, normalized using data
    - Multijet BKG, from data-driven techniques
    - Diboson shape and norm. from MC





H→ bb, VH





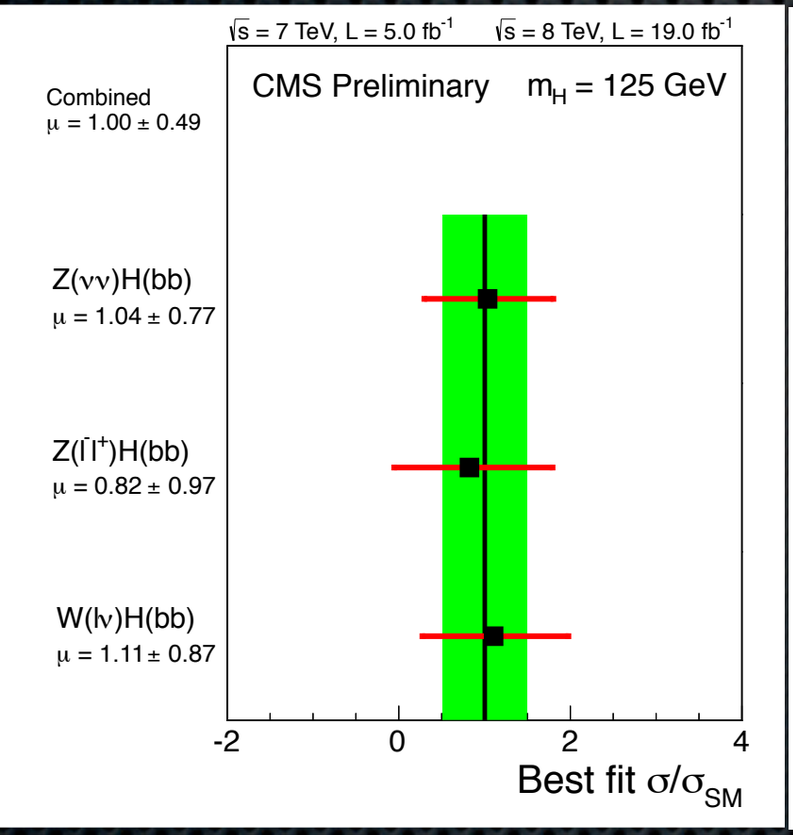
- **Combined mass plots**
  Weighted by s/(s+b) for each category

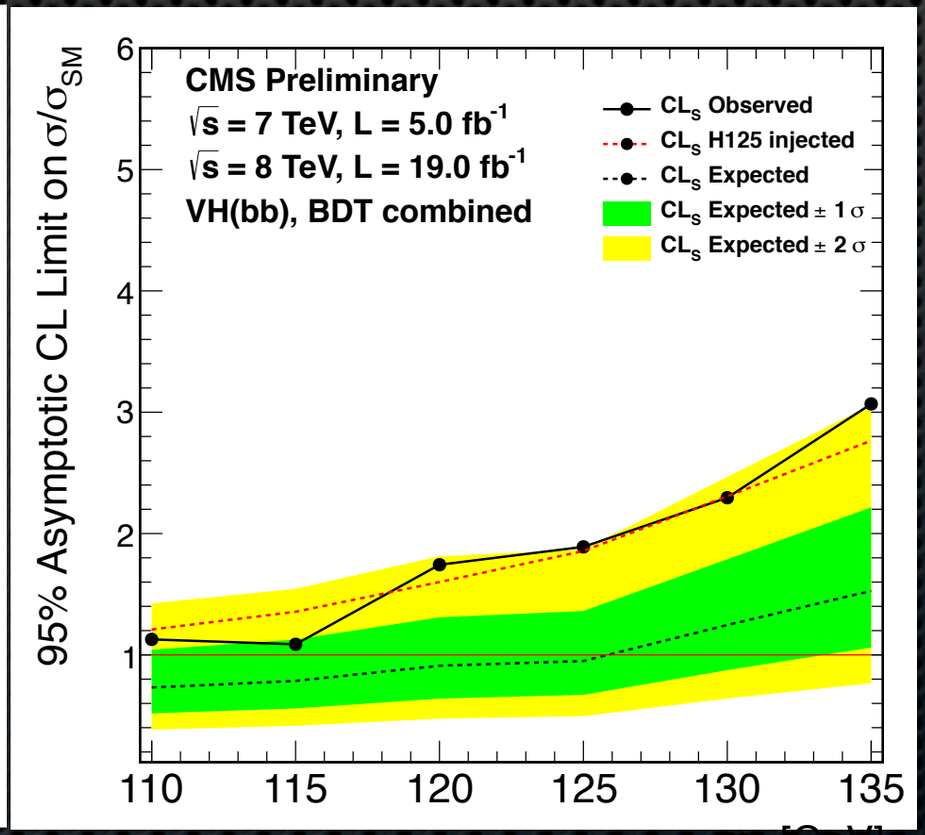
- **All backgrounds (no dibosons) extracted**
- **Observation of VZ (CMS and ATLAS)**
  - **5 times VH cross-section**
  - **Validate the analysis!**

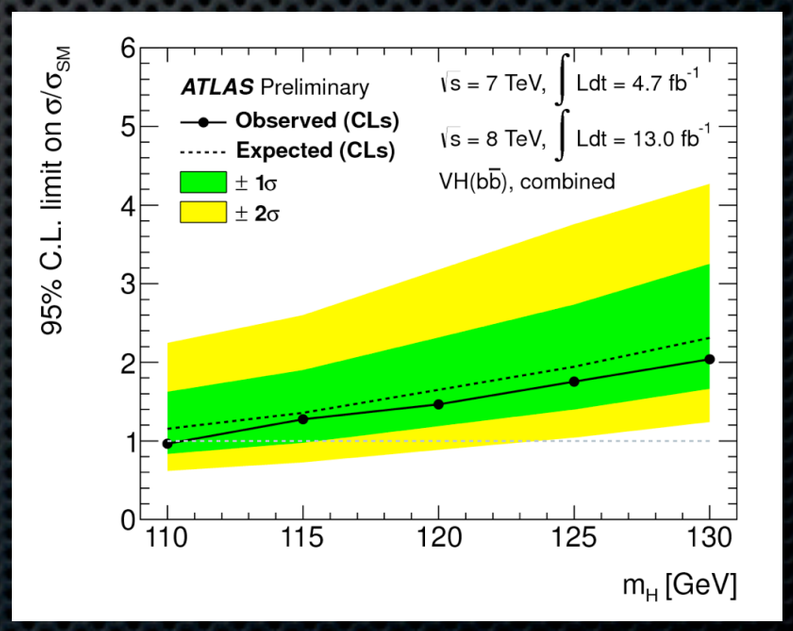
H→ bb, VH Results

- ***CMS***:
  - Significance for m_H = 125 GeV:
    2.1σ measured, 2.1σ expected
  - Best fit: μ = 1.0 ± 0.5 @ 125 GeV

- ***ATLAS:***
  - No Deviations from SM
  - Exclusion limit, m_H=125 GeV
    - Observed = 1.8
    - Expected = 1.9

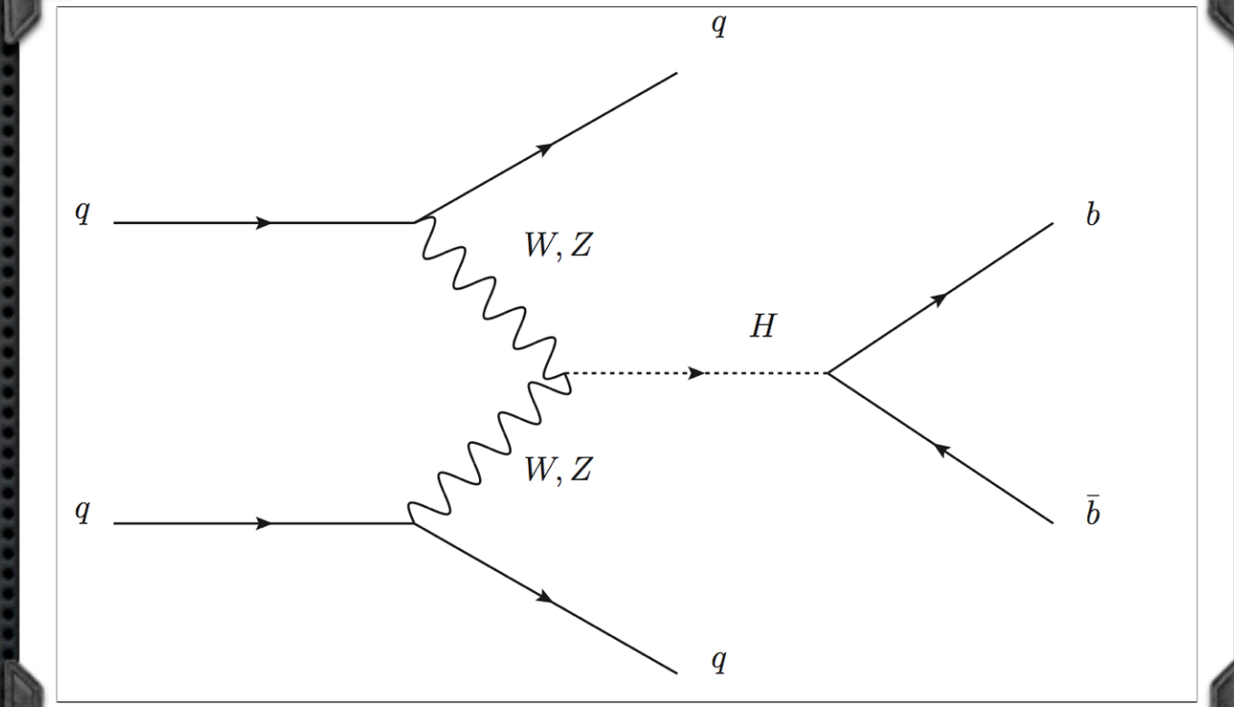






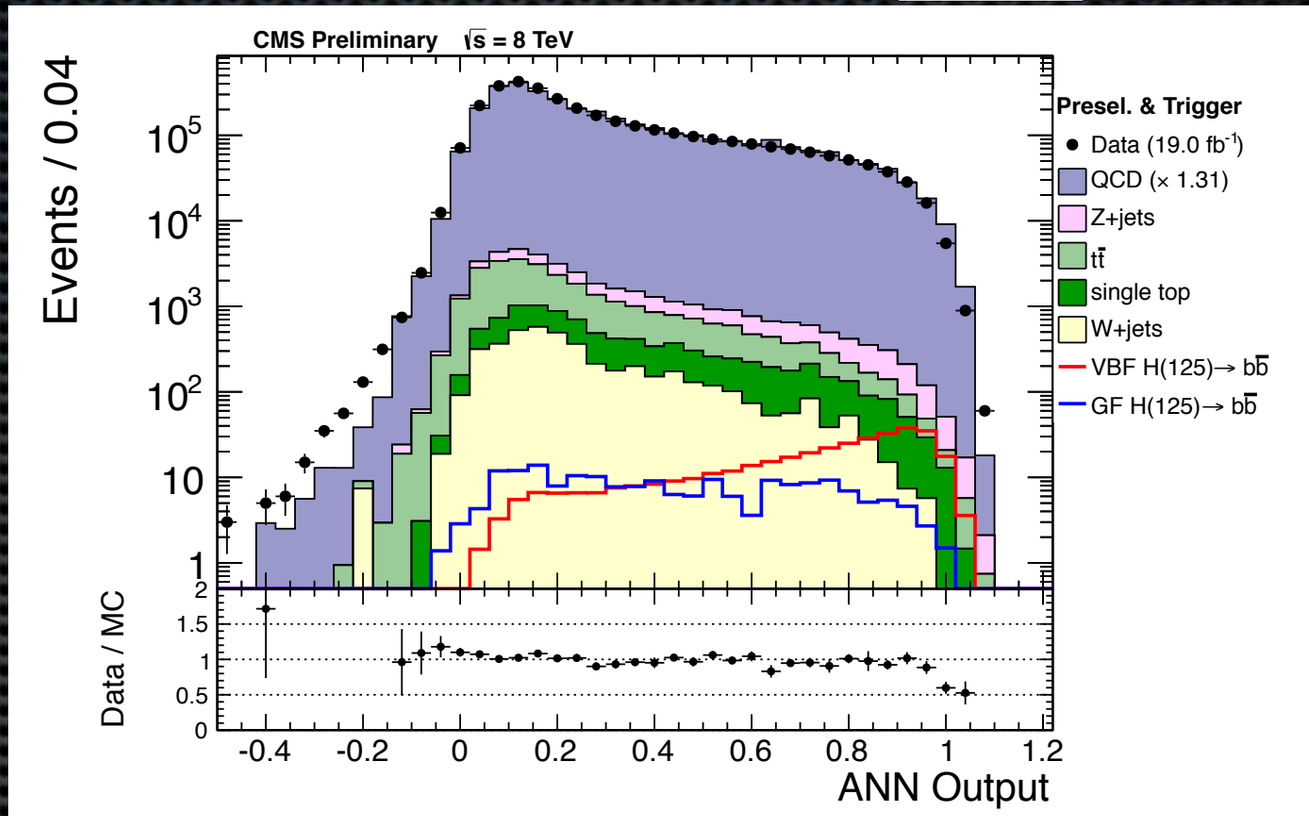
H→ bb, VBF

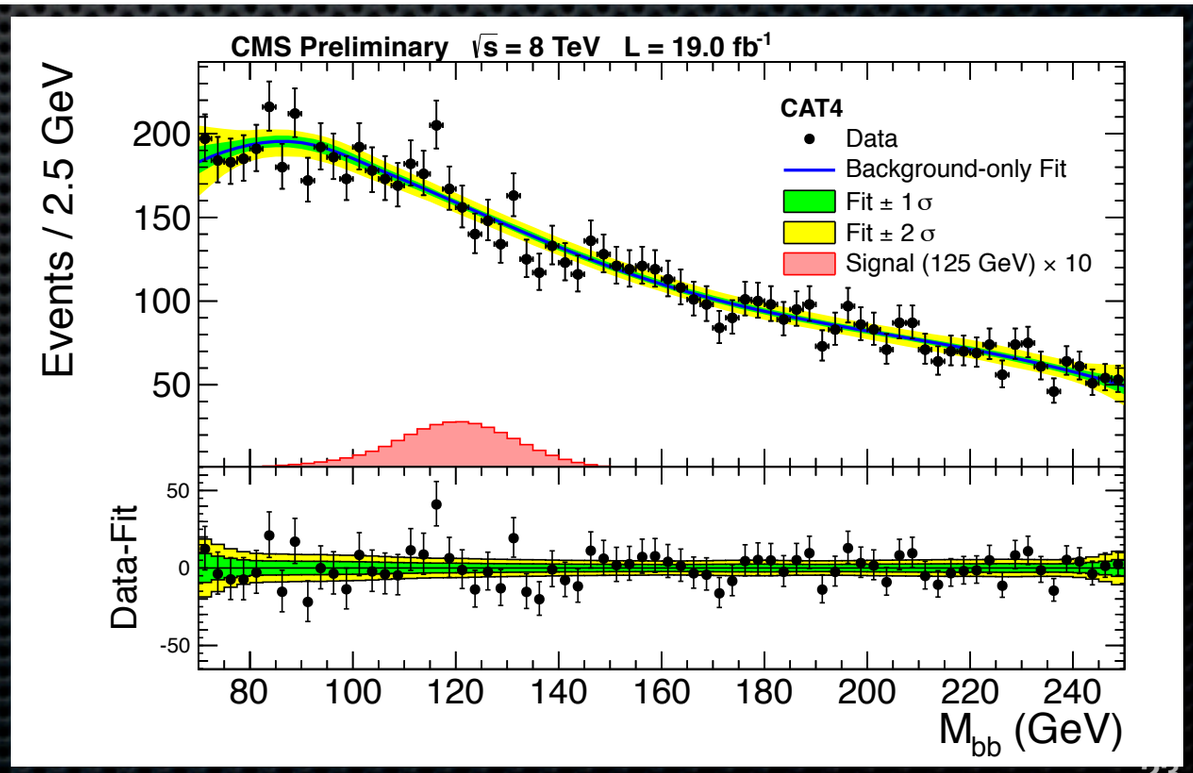
- **Released 16 May 2013**
- Full hadronic state:
  - QCD dominated (4jets)
  - b-tagging, VBF selection
- Mass of b-jets to extract signal:
  - Resolution improvement with regression
  - Jets up to $|\eta| < 4.7$
  - Categories using Neural Network:
    - 4 categories
  - Parametric fit
    - 5th degree polynomial



H→ bb, VBF

- **Released 16 May 2013**
- Full hadronic state:
  - QCD dominated (4jets)
  - b-tagging, VBF selection
- Mass of b-jets to extract signal:
  - Resolution improvement with regression
  - Jets up to $|\eta| < 4.7$
  - Categories using Neural Network:
    - 4 categories
  - Parametric fit
    - 5th degree polynomial

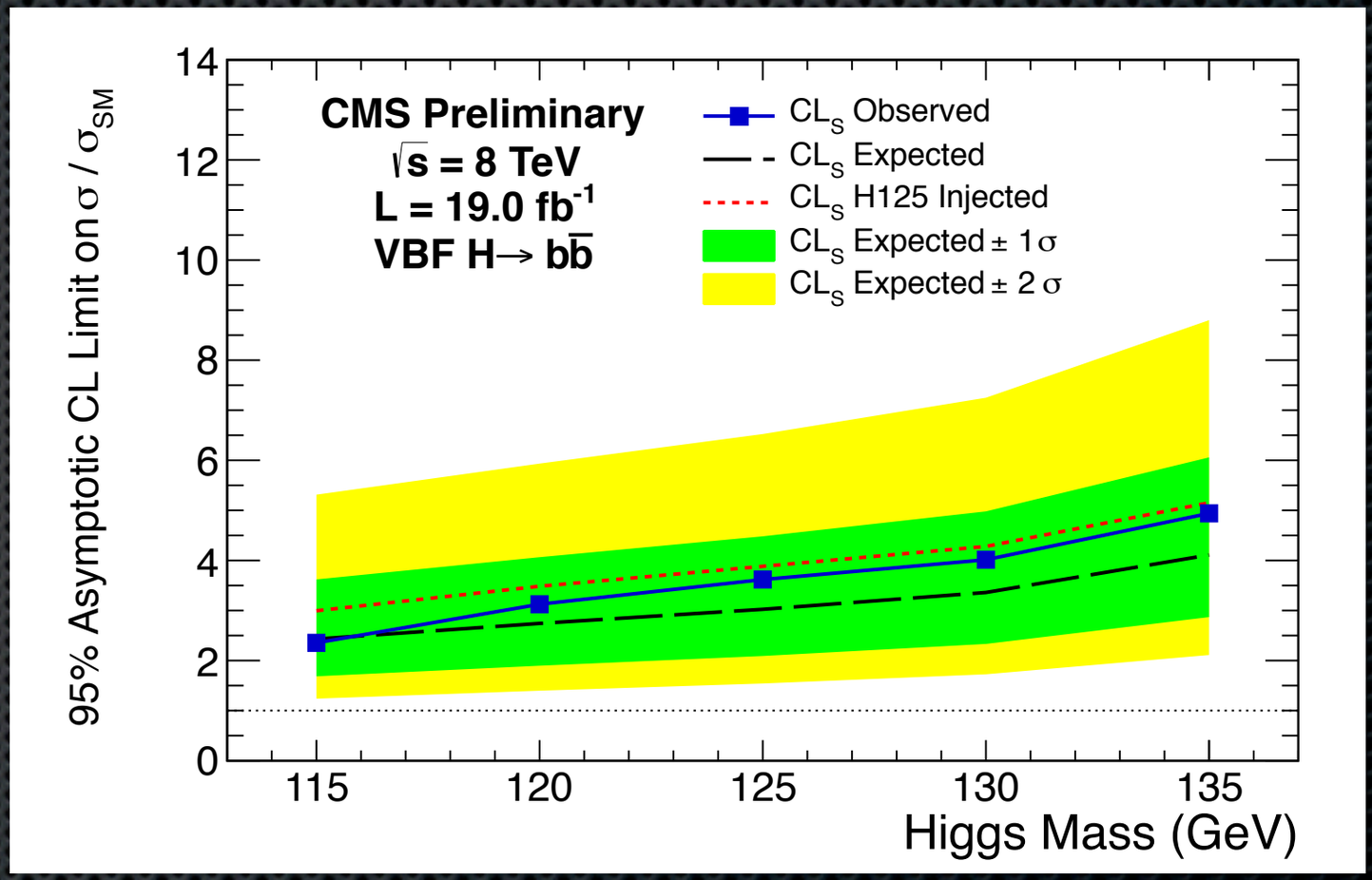




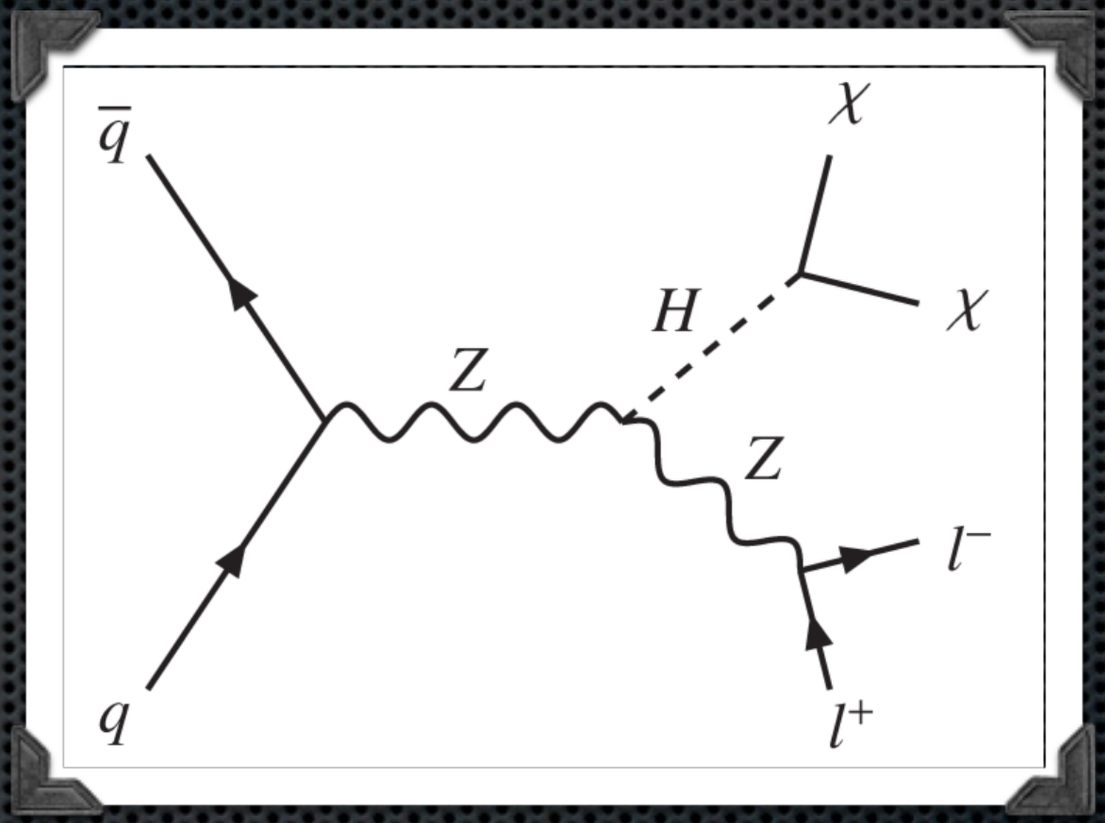
H→ bb, VBF Results

Agreement with SM

- Limit:
  - Observed 3.6xSM
  - Expected 3.0xSM
- Significance:
  - Observed 0.5 σ
  - Expected 0.7 σ
- Best Fit:
  - μ = 0.7 ± 1.4

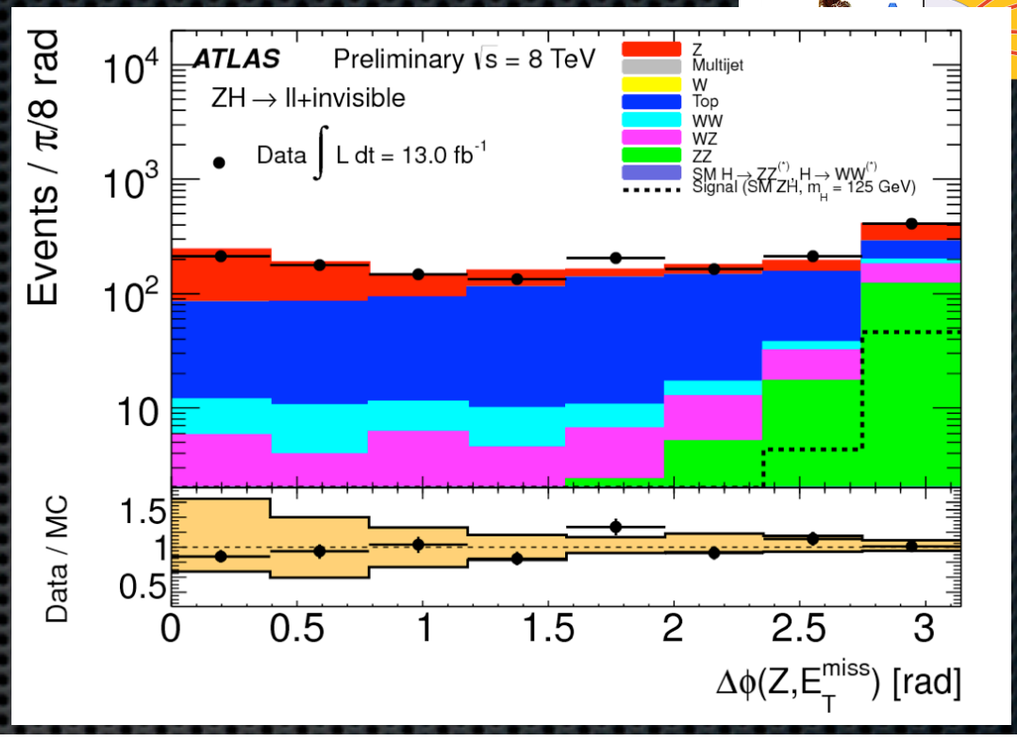


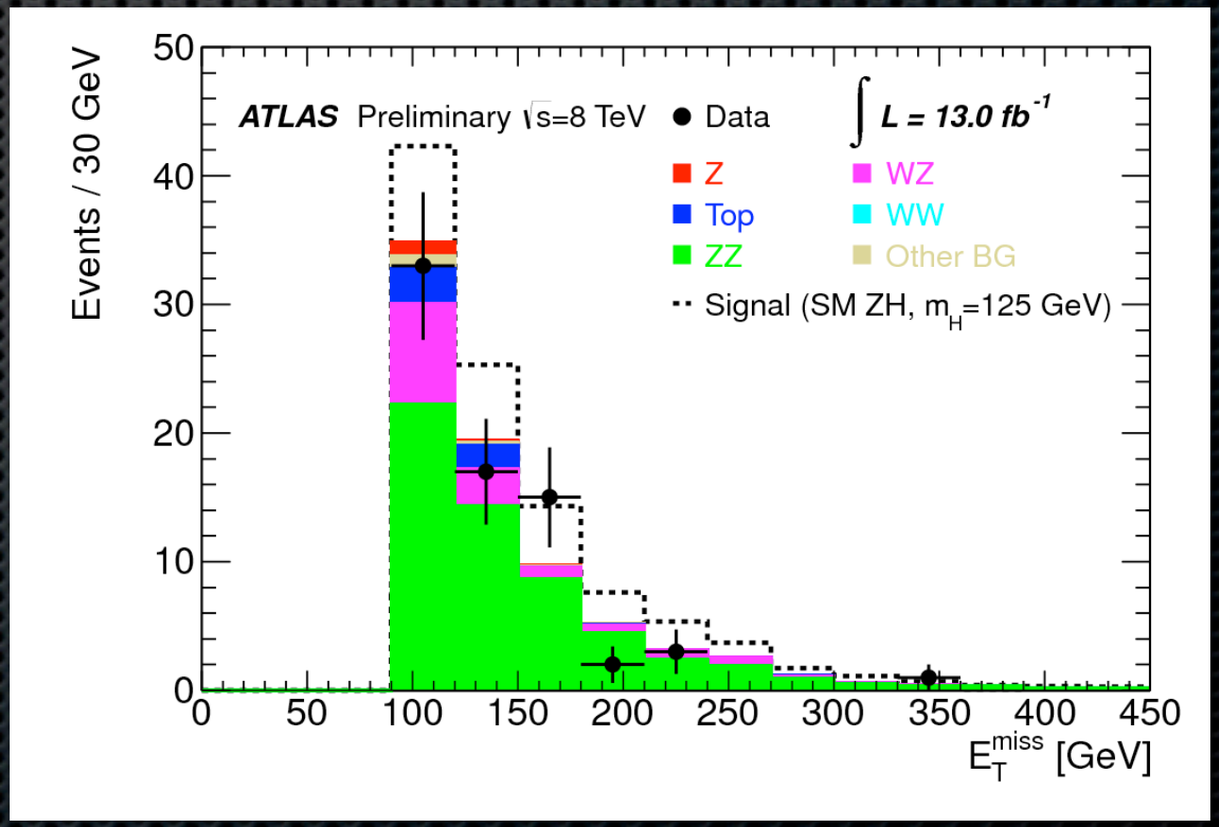
ZH, H → invisible



ZH, H → invisible

- **MODEL:**
  Higgs decay predominantly to invisible particles
  - Lep excluded up to $m_H < 114.4$ GeV
- Diboson is the main background
  - ZZ (70%) irreducible
  - WZ (20%) One lepton escaping detection
  - WW (5%)
- Signature:
  - $Z \rightarrow ee$, $Z \rightarrow \mu\mu$
  - Large $E_T^{miss} > 90$ GeV
  - ϕ angle between E_T^{miss} *and* $P_T^{miss} \sim 0$
  - ϕ angle between *Z and* $E_T^{miss} \sim \pi$

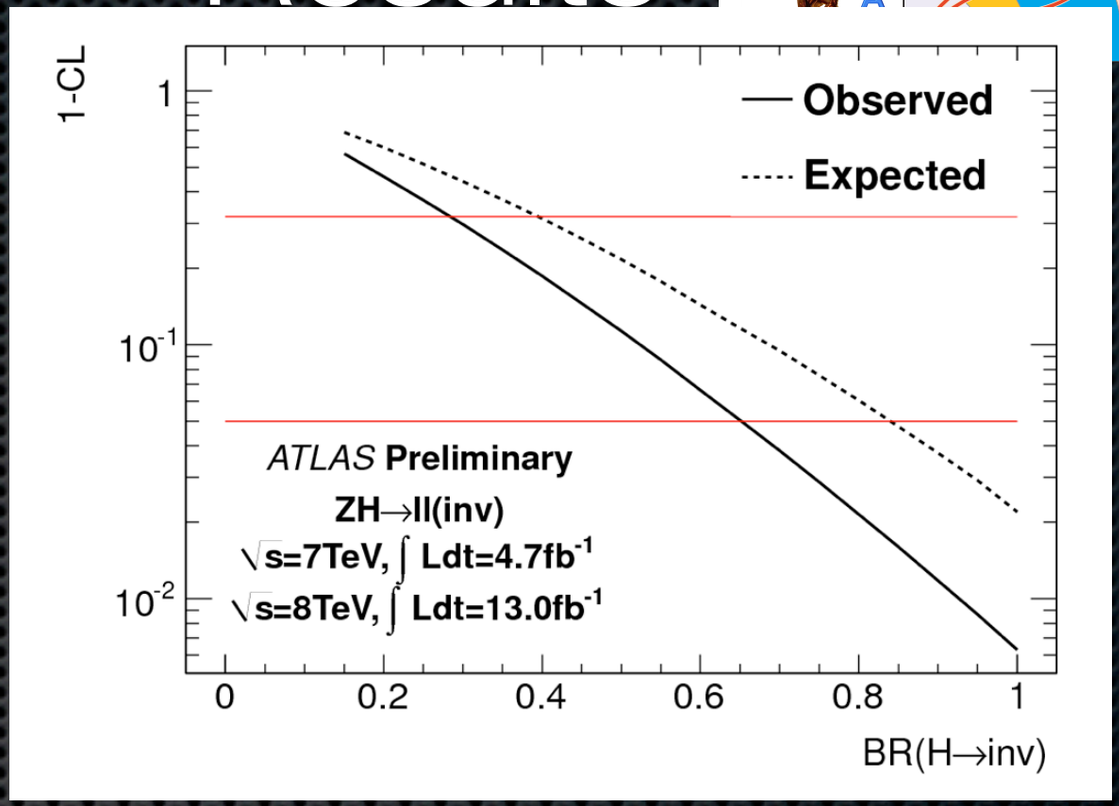




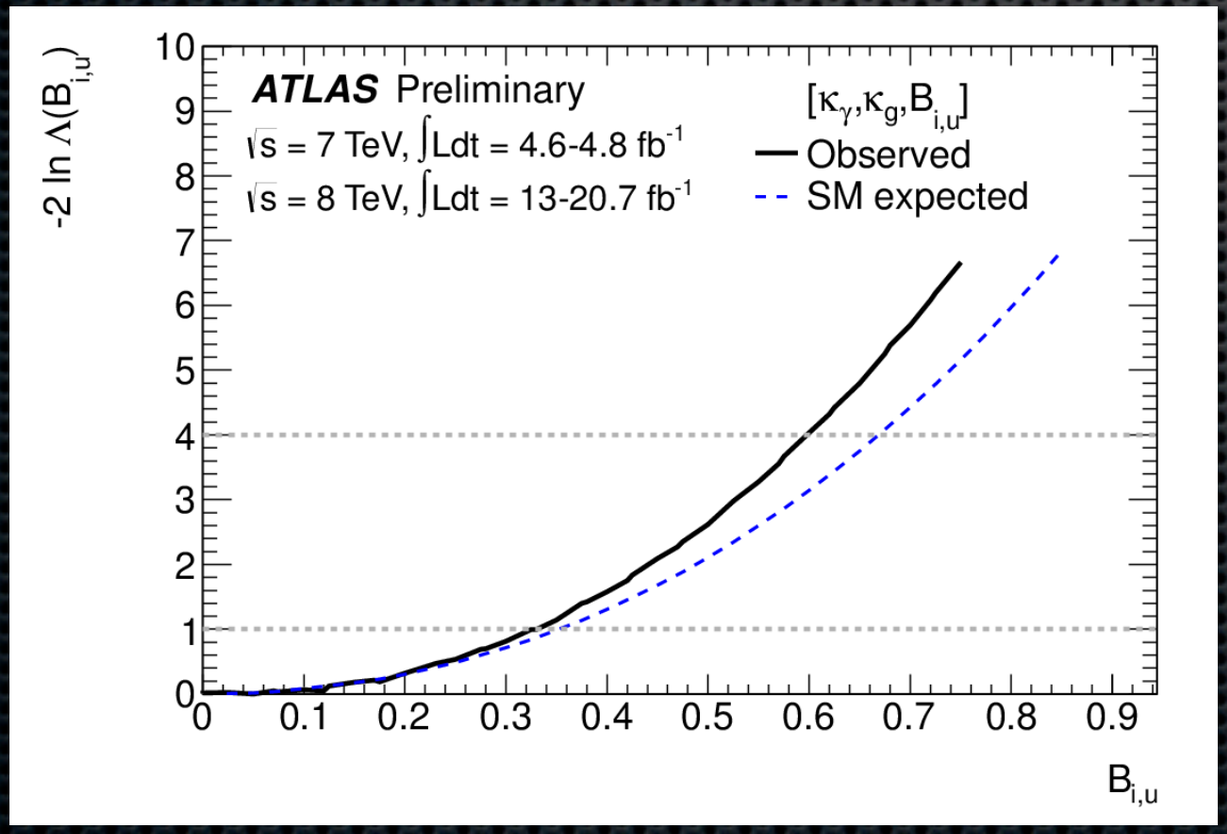
Signal model assumes 100% BR(H → invisible)

ZH, H → invisible Results

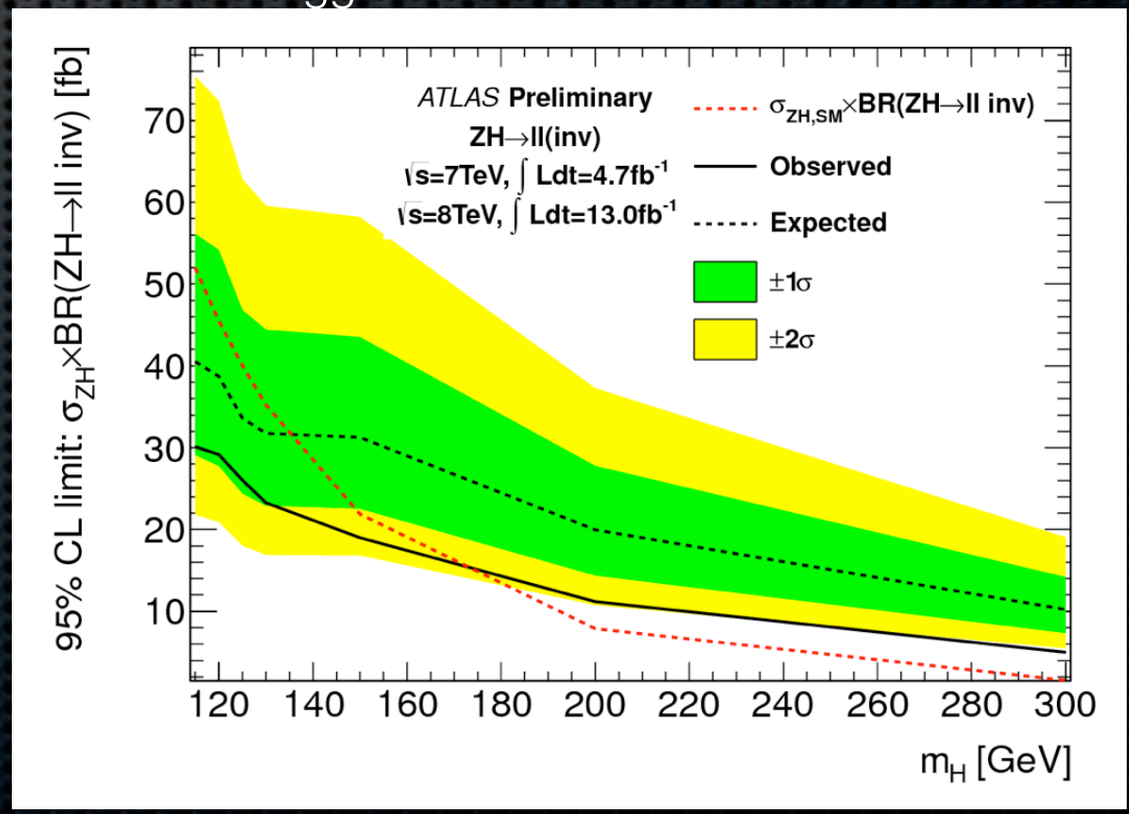
- Limit on BR (H → invisible) for SM Higgs of mass 125 GeV:
  - Observed <65%, expected <84%



In agreement with the indirect limit from the ATLAS Higgs combination



- Limit on σ(ZH) x BR (H → invisible) for SM Higgs of mass between 115 and 300 GeV



Summary

Summary

		CMS			ATLAS		
		data	Observed	Expected	data	Observed	Expected
H → bb	VH	2011 2012, 20 fb	1.8 **(2.1 σ)**	0.98 **(2.1 σ)**	2011 **2012, 13fb** *	1.8	1.9
	VBF	2011 2012, 20 fb	3.6	3.0	---	---	---
	ttH	2011 **2012, 5.0 fb** *	5.8	5.2	**2011** *	13.1	10.5
H → ττ		2011 2012, 20 fb	1.8 **(2.9 σ)**	0.98 **(2.5 σ)**	2011 **2012, 13fb** *	1.9	1.2
H → μμ		---	---	---	2012. 20.7fb	9.8	8.2
Combination		**VH → Vbb H → ττ**	**3.4 σ**	**3.4 σ**	---	---	---

***) Will be updated soon with full 2012 dataset**

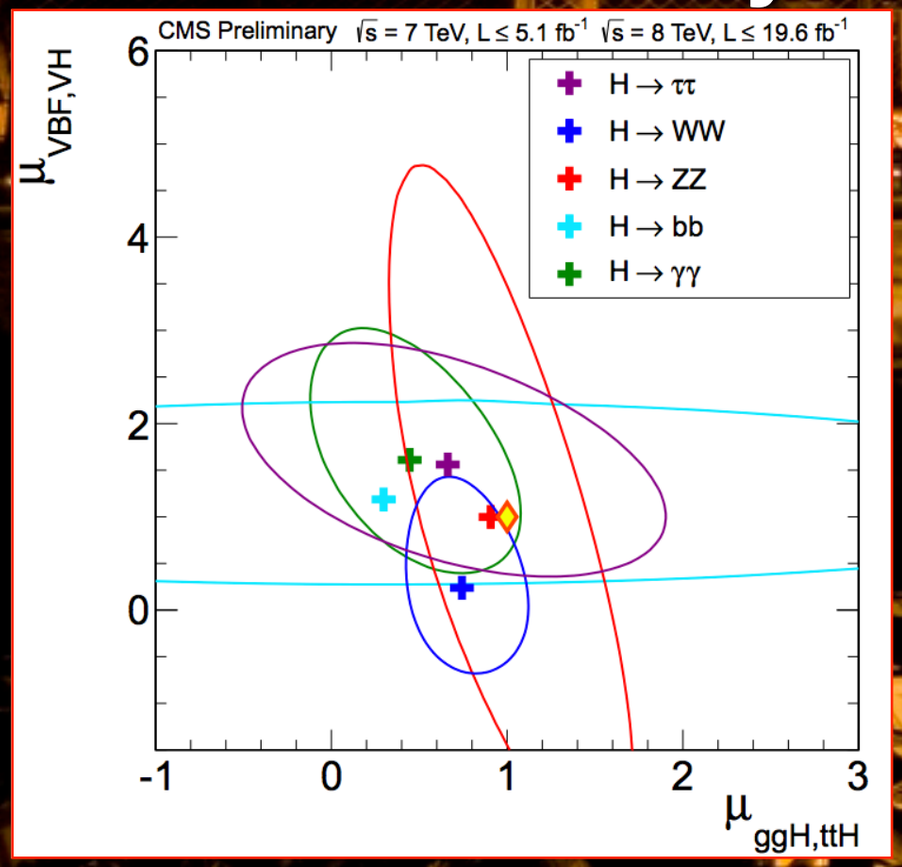
Summary

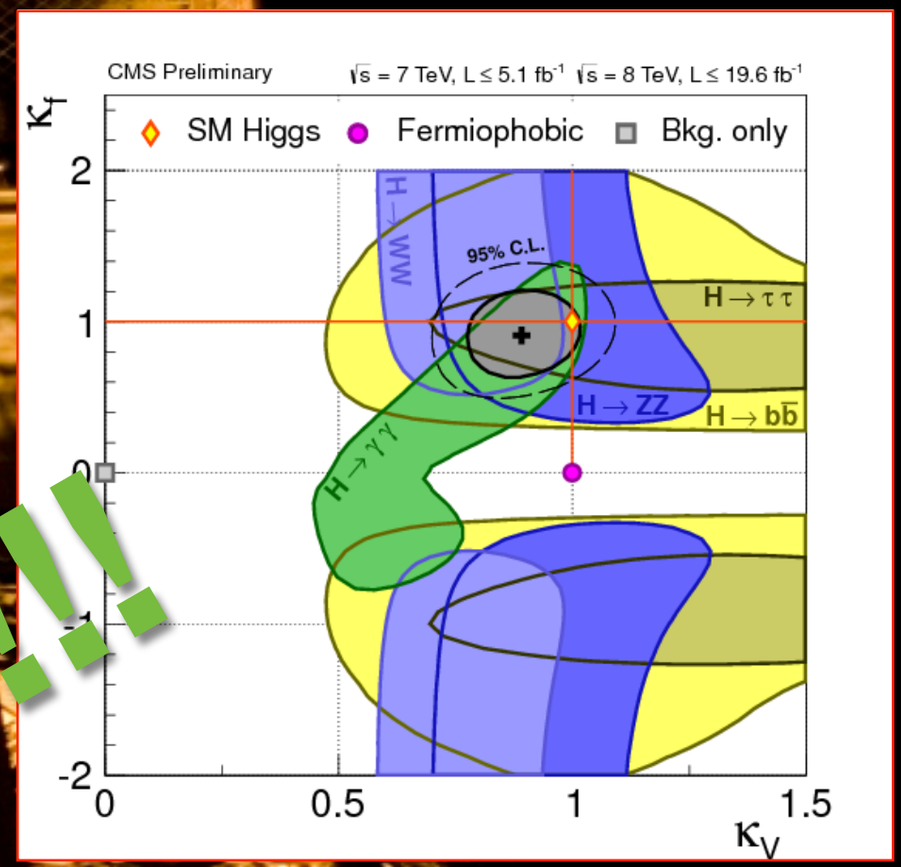
		CMS			ATLAS		
		data	Observed	Expected	data	Observed	Expected
H →	VH	2011 2012, 20 fb	1.8 **(2.1 σ)**	0.98 **(2.1 σ)**	2011 **2012, 13fb** *	1.8	1.9
Combination	**VH → Vbb H → ττ**	**3.4 σ**	**3.4 σ**	---	---	---	---

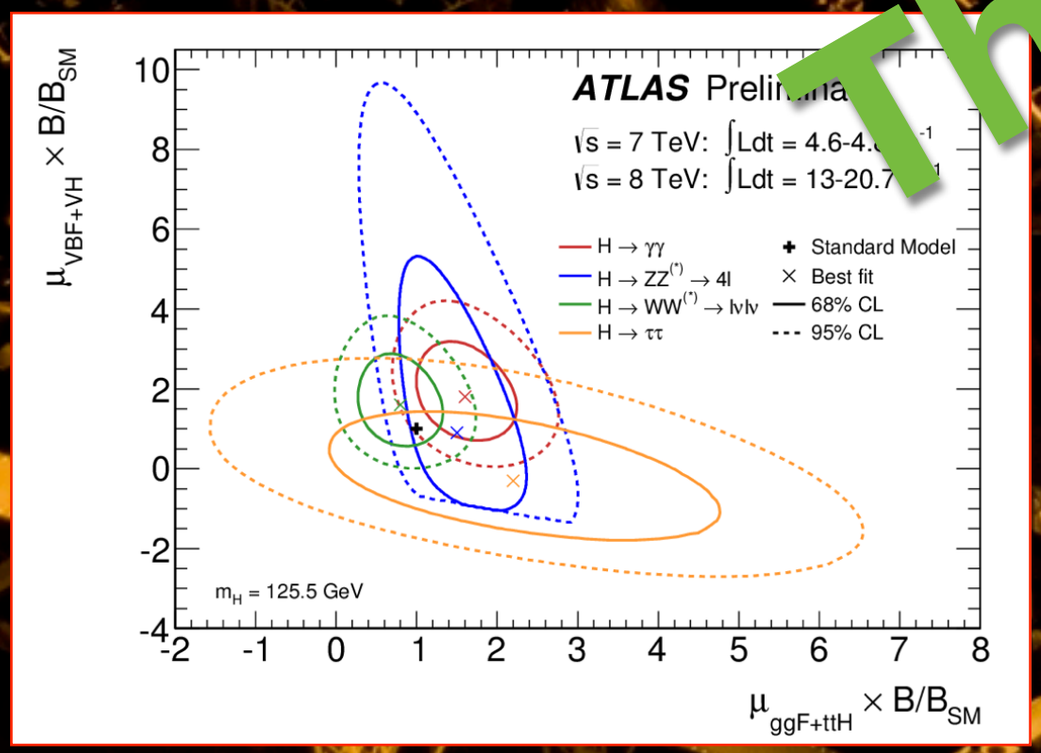
- **Several searches performed in LHC for SM Higgs decaying into fermions**
- **Very challenging analyses**: complex final states and large backgrounds
- **CMS sees evidence** when combining VH (H → bb) and H → ττ
- ATLAS does not observe evidence, but not expected with current data analyzed
- More data will be need to check each channel individually
- So far, **everything in fermionic channels looks like SM like**
- Sophisticated techniques under development and preparation for LHC run2

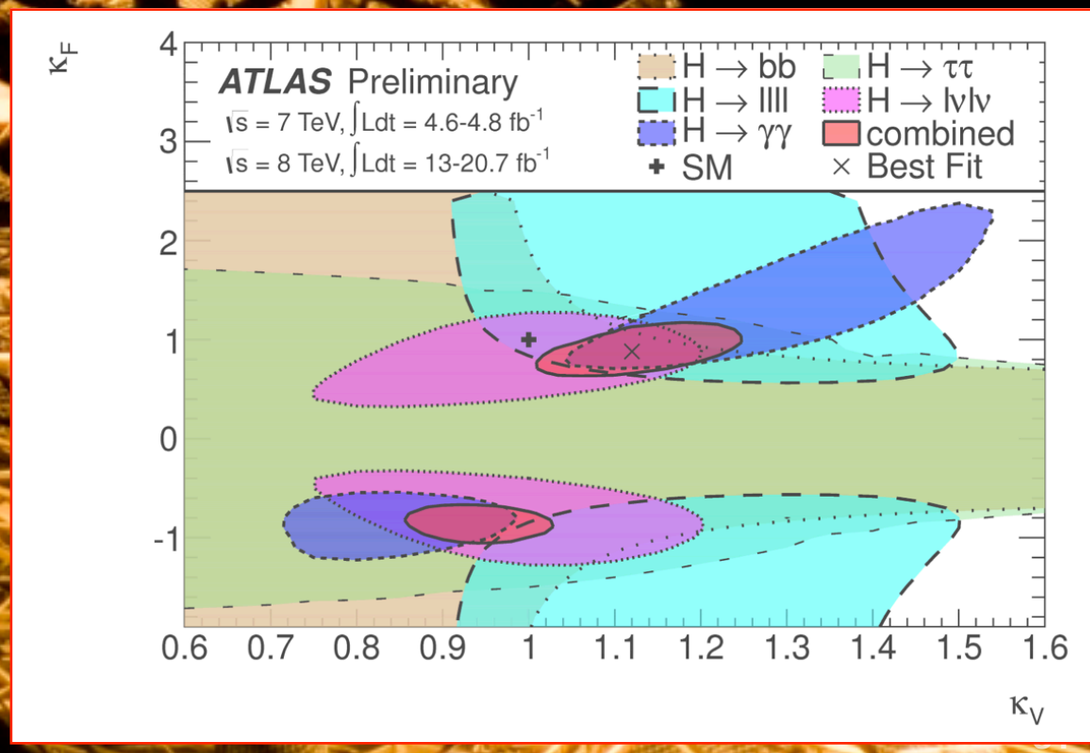
***) Will be updated soon with full 2012 dataset**

Summary









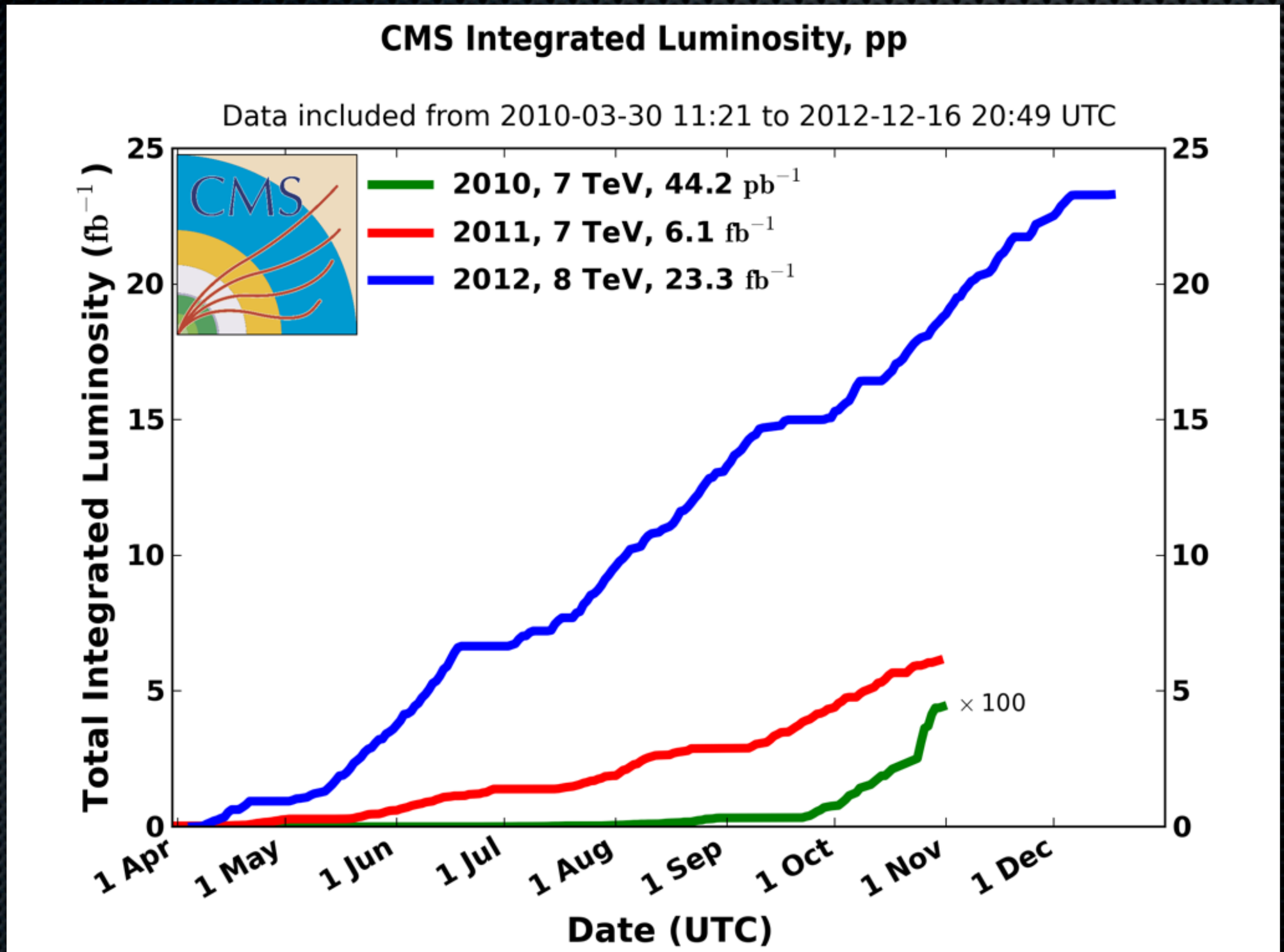
CMS

ATLAS

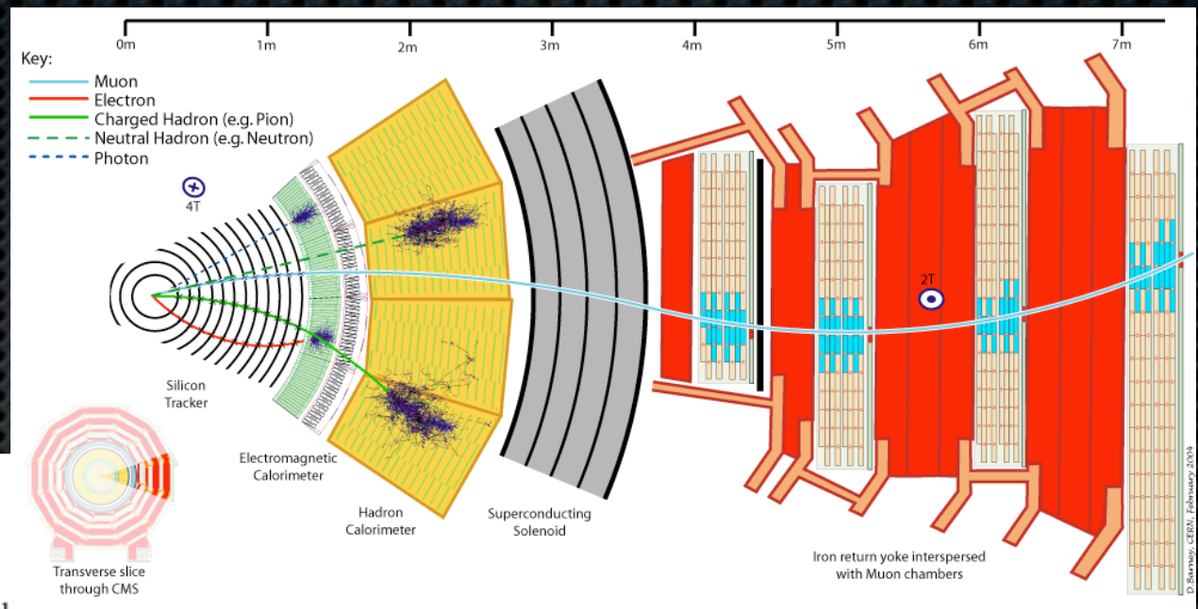
Thanks!!!

BACKUP

Luminosity


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
CMS
2010, 7 TeV, 44.2 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
× 100
Total Integrated Luminosity (fb^{-1})
0
5
10
15
20
25
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

CMS detector



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

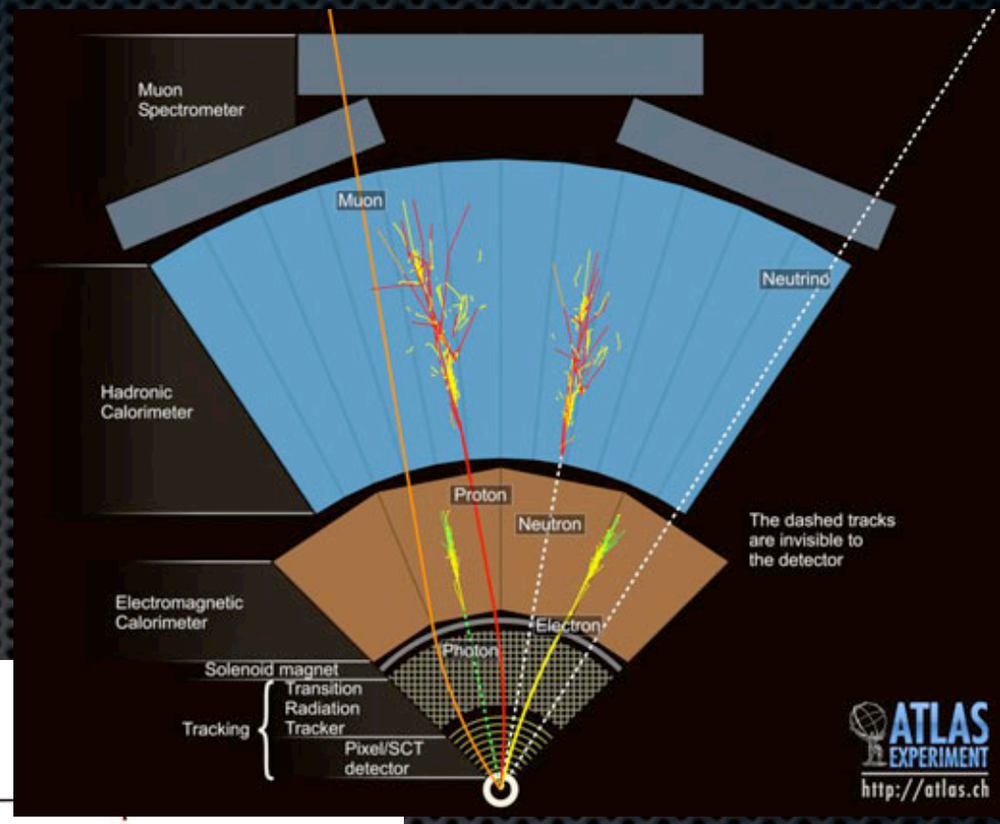
PRESHOWER
Silicon strips ~16m² ~137,000 channels

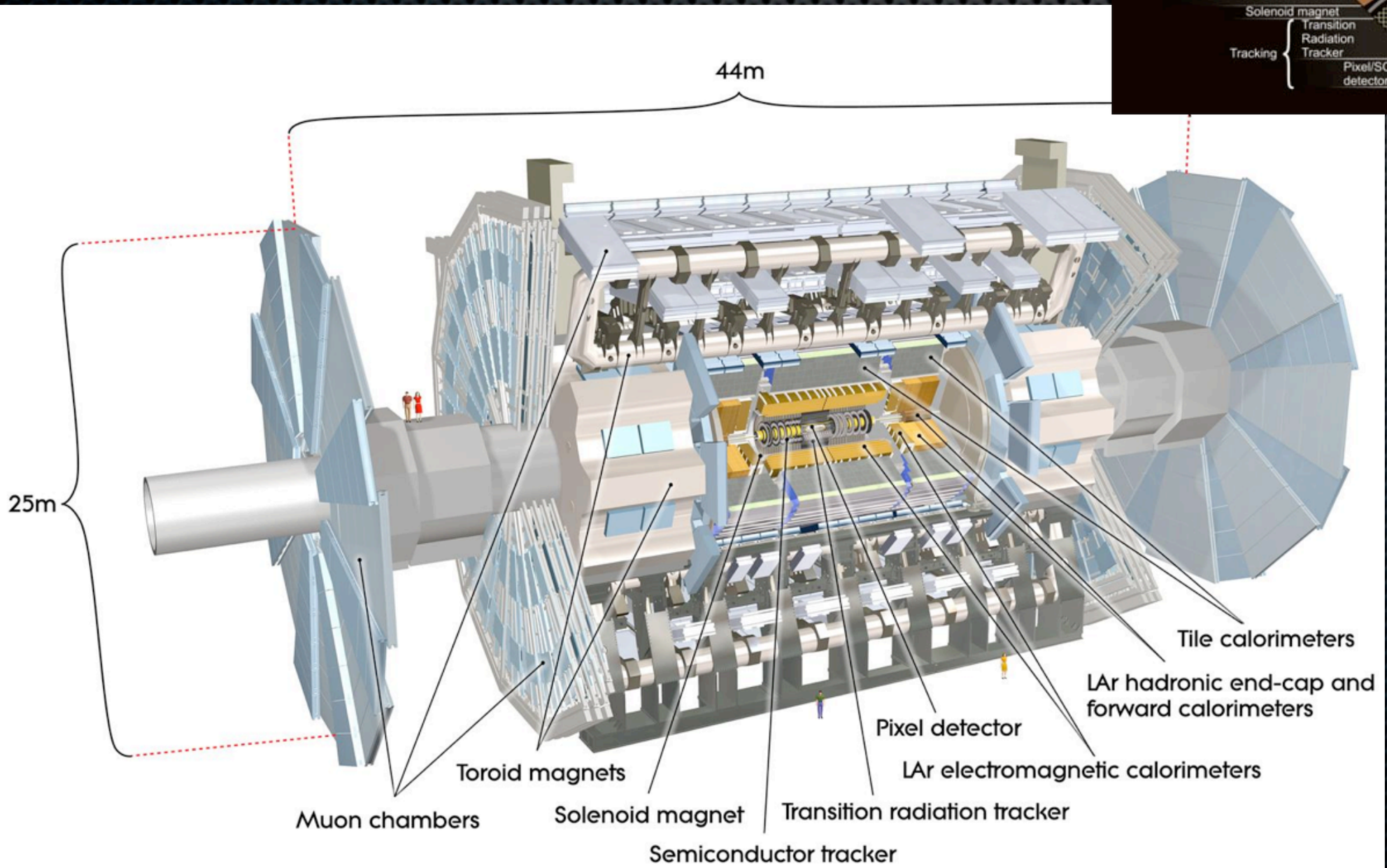
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

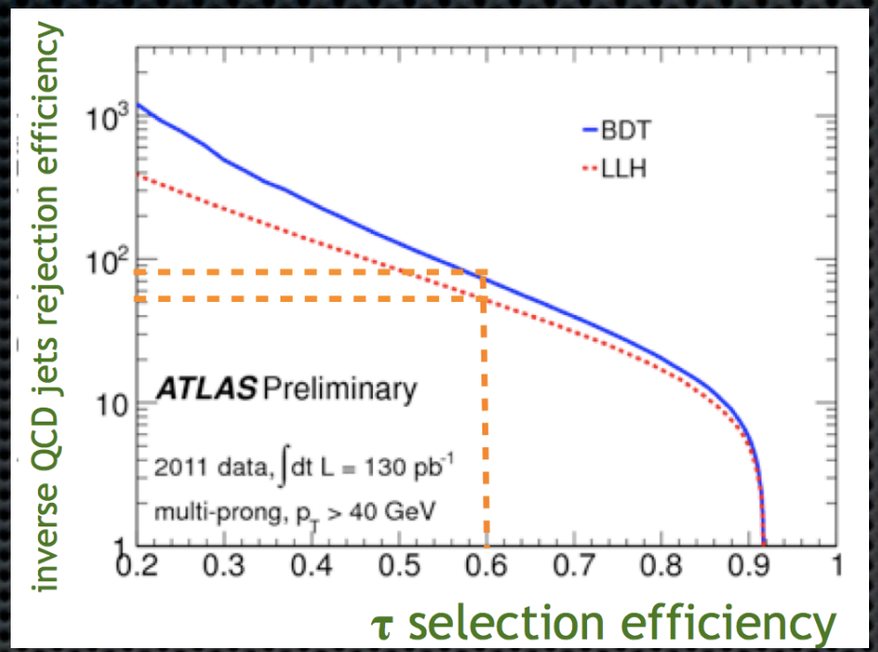
ATLAS detector



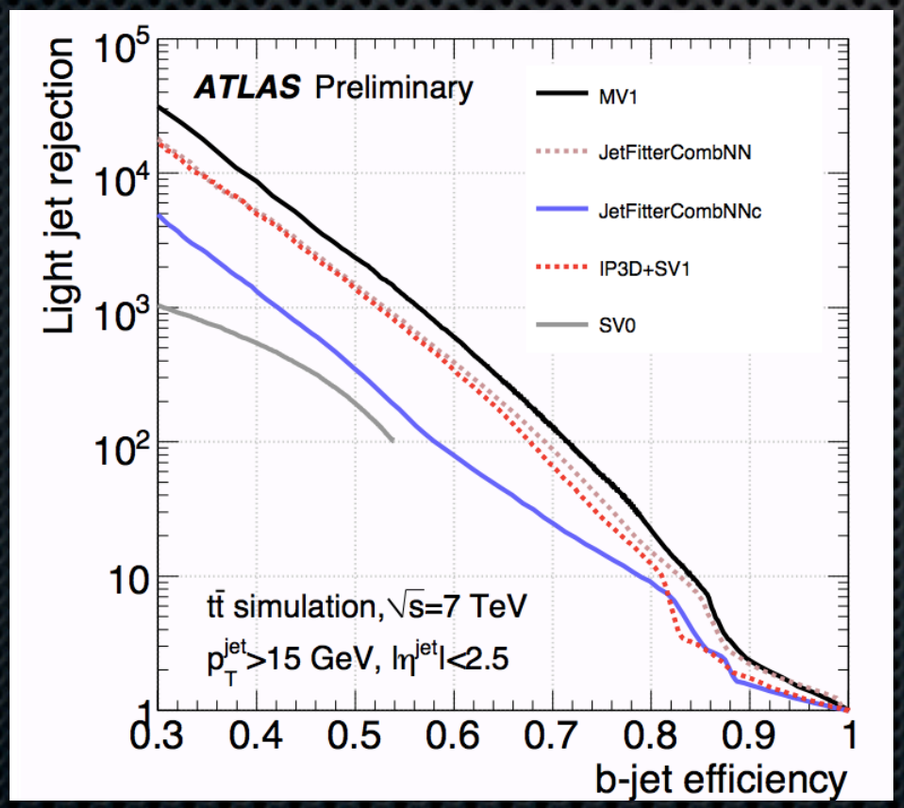


Object Reco in ATLAS

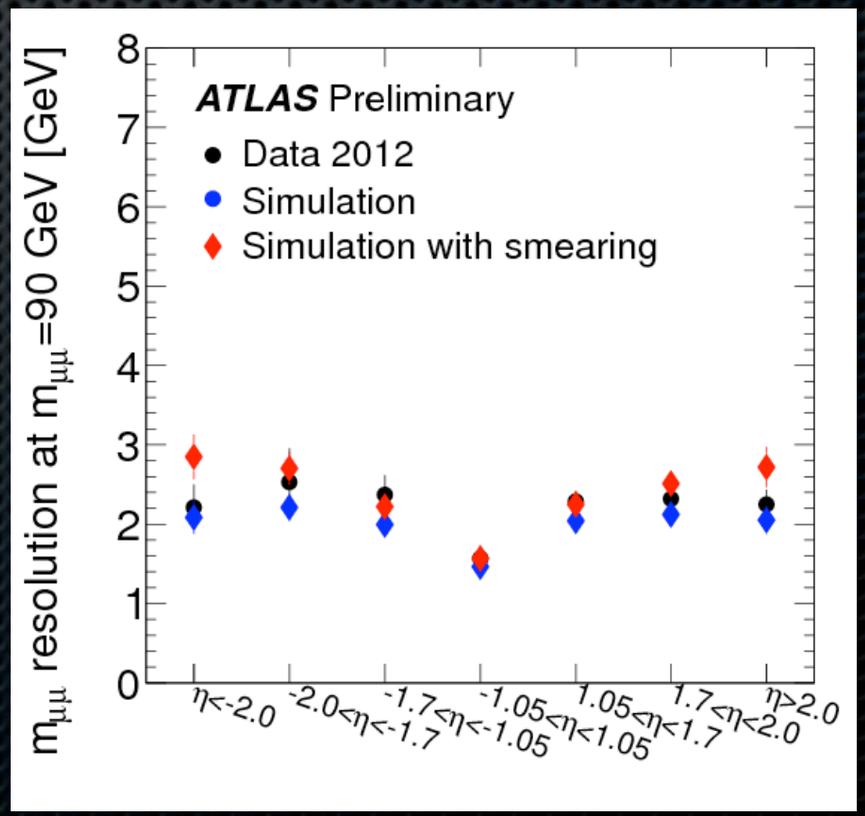
τ efficiency



b-jet tagging



Muon Resolution



H → μμ: Uncertainties

- **Theoretical:**
  - Production cross-sections: ~ 15 %
  - Branching-ratio: ~ 3-7 %

m_H[GeV]	gluon fusion σ[pb]	gluon fusion uncertainty [%] up	gluon fusion uncertainty [%] down	vector boson fusion σ[pb]	vector boson fusion uncertainty [%] up	vector boson fusion uncertainty [%] down	BR BR($H \to \mu^+\mu^-$)	BR uncertainty [%] up	BR uncertainty [%] down
110	25.04	+15.3	-14.9	1.809	+2.7	-3.0	2.76×10^{-4}	+7.0	-6.8
115	22.96	+15.0	-14.9	1.729	+2.7	-3.0	2.63×10^{-4}	+6.7	-6.6
120	21.13	+14.8	-14.8	1.649	+2.8	-3.0	2.44×10^{-4}	+6.4	-6.3
125	19.52	+14.7	-14.7	1.578	+2.8	-3.0	2.20×10^{-4}	+6.0	-5.9
130	18.07	+14.6	-14.6	1.511	+2.8	-2.9	1.90×10^{-4}	+5.5	-5.4
135	16.79	+14.4	-14.7	1.448	+2.8	-2.9	1.55×10^{-4}	+5.0	-4.9
140	15.63	+14.3	-14.5	1.389	+2.7	-2.9	1.22×10^{-4}	+3.7	-3.8
145	14.59	+14.1	-14.4	1.333	+2.8	-2.8	9.06×10^{-5}	+3.4	-3.4
150	13.65	+14.1	-14.4	1.280	+2.8	-2.9	6.19×10^{-5}	+3.1	-3.2

- **Signal Acceptance uncertainty**

Difference between nominal acceptance and acceptance under different variations:

- Renormalization and factorization scale cut off
- Uncertainties due to ISR and FSR
- PDF set used

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

- **Detector Related:**
  - Luminosity uncertainty is the dominant

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%

H-> bb, VH CMS

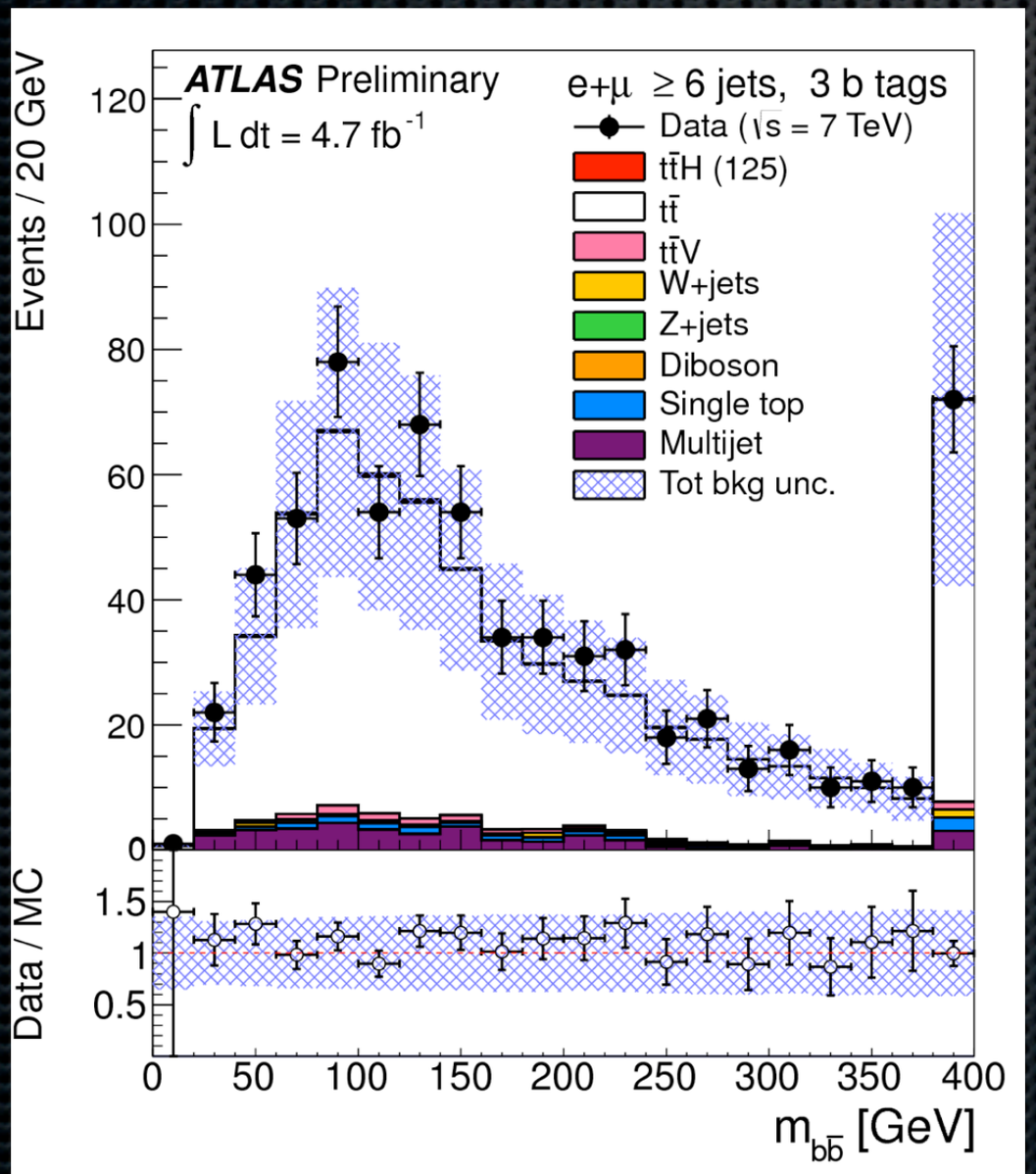
Table 1: Variables used in the BDT training.

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
ΔR(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)

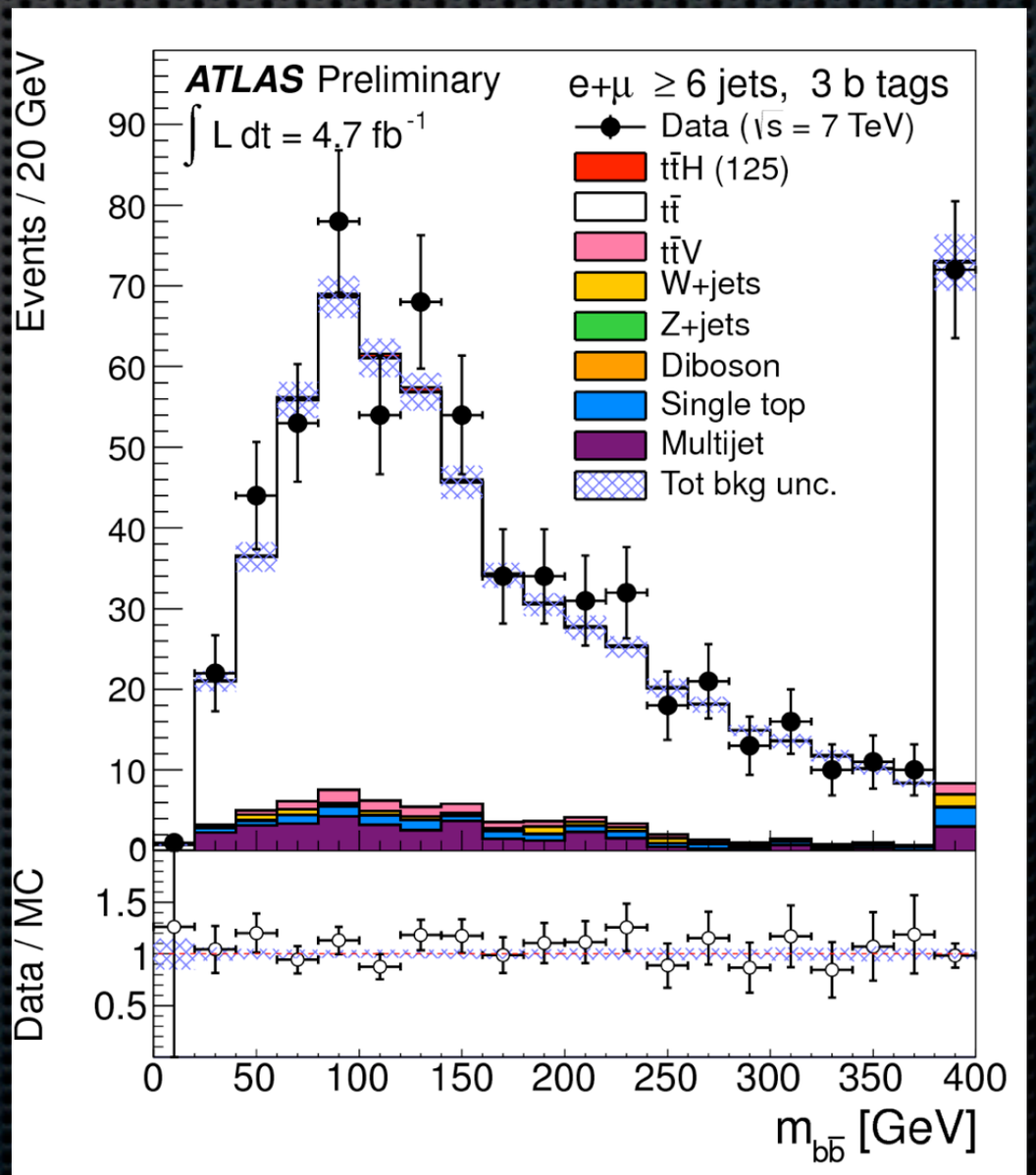
ttH, H→ bb

Main systematic due to b tagging uncertainties. Sistematics are constrained by fitting the distributions from data.

Before fit

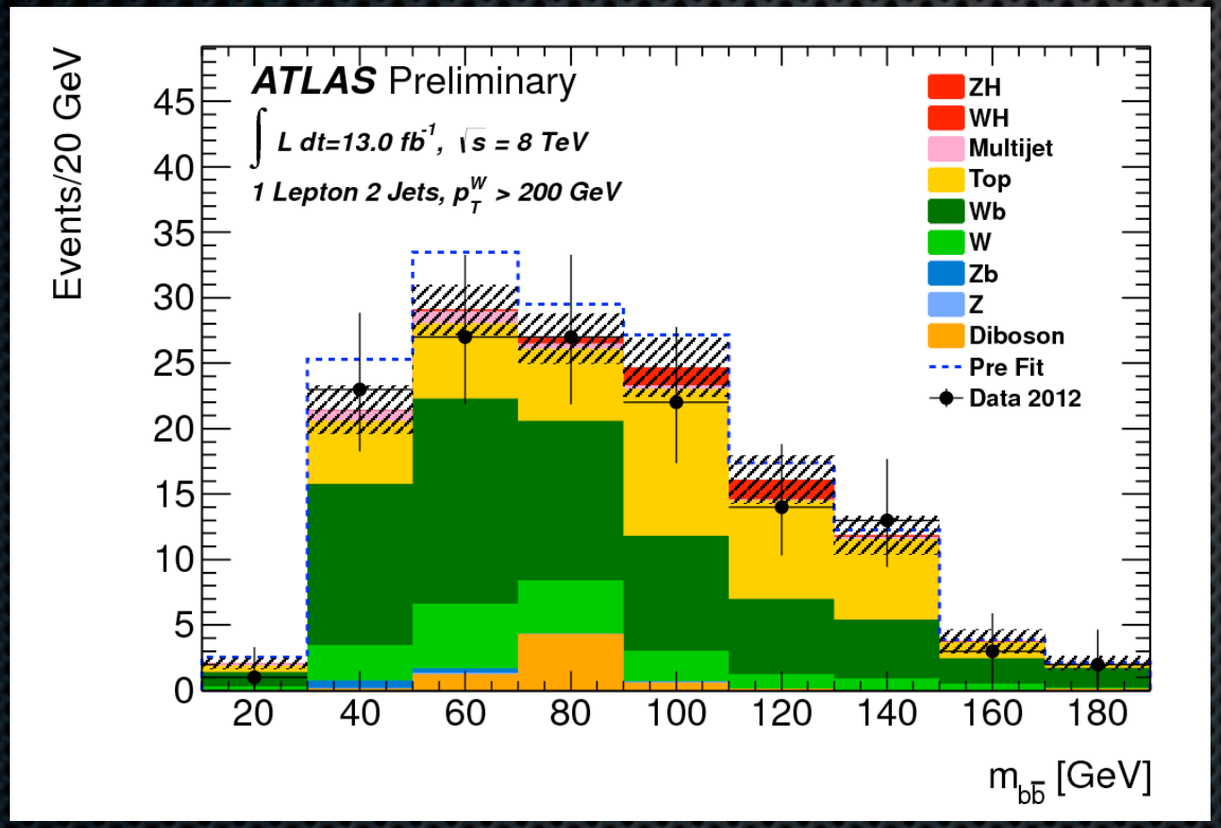


After fit

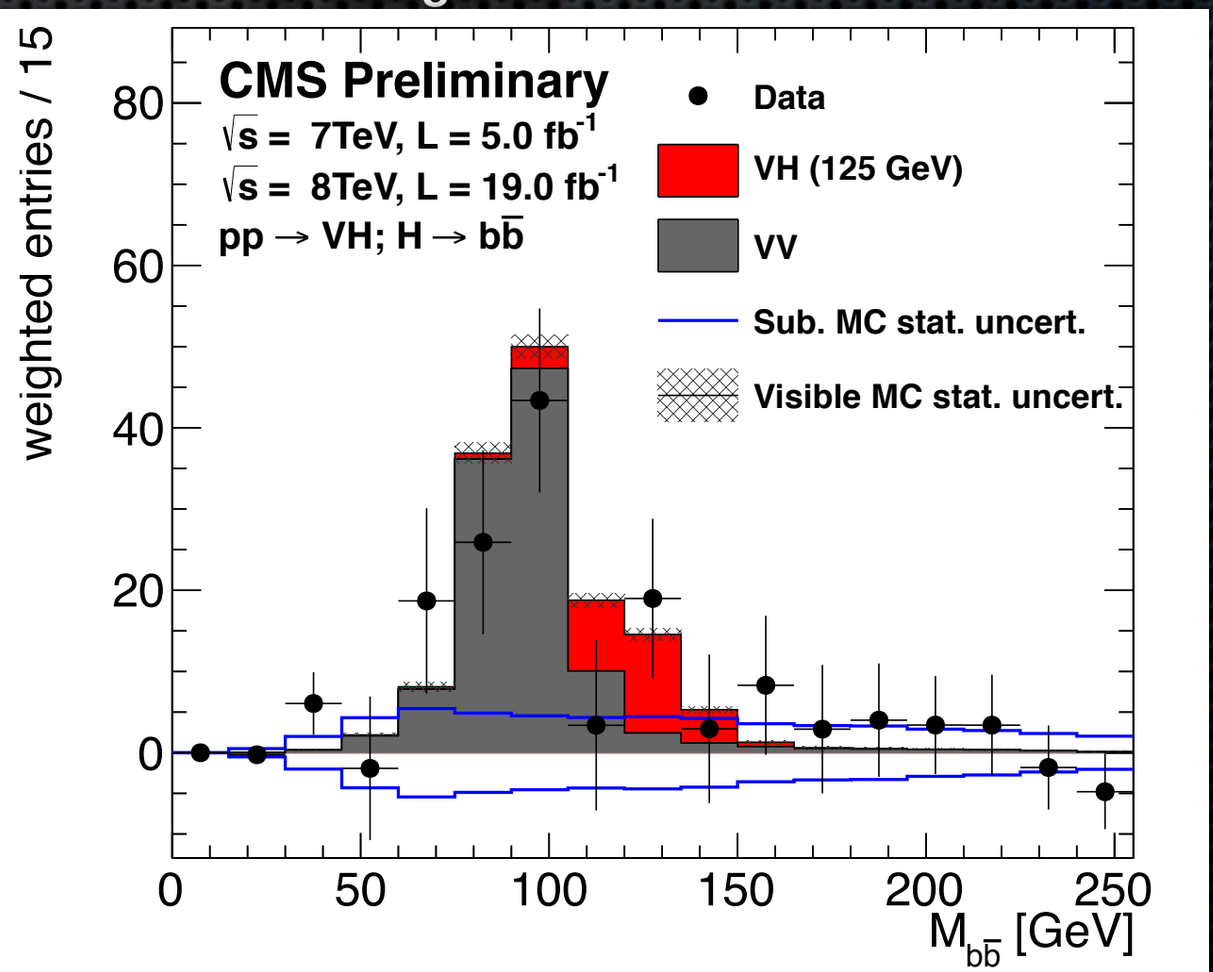


H→ bb, VH

- p_T (W,Z) > 200 GeV



- All backgrounds (no dibosons) extracted
- All categories



- Observation of VZ
- 5 times VH cross-section
- Validate the analysis!

H -> $\tau\tau$, mass reconstruction

- **Visible mass:**
  Uses the Momentum of measure objects

- **Transverse mass:**
  Momentum and MET

$$M^2(\tau_{\mathrm{vis}_1}, \tau_{\mathrm{vis}_2}, \not{E}_{\mathrm{T}}) = m^2_{\mathrm{vis}_1} + m^2_{\mathrm{vis}_2} +$$
$$2 \times \left(\sqrt{m^2_{\mathrm{vis}_1} + p^2_{\mathrm{vis}_1}} \sqrt{m^2_{\mathrm{vis}_2} + p^2_{\mathrm{vis}_2}} + \not{E}_{\mathrm{T}} \sqrt{m^2_{\mathrm{vis}_1} + p^2_{\mathrm{vis}_1}} + \not{E}_{\mathrm{T}} \sqrt{m^2_{\mathrm{vis}_2} + p^2_{\mathrm{vis}_2}} \right) -$$
$$2 \times (\vec{p}_{\mathrm{vis}_1} \cdot \vec{p}_{\mathrm{vis}_2} + \vec{p}_{\mathrm{vis}_1} \cdot \vec{\not{E}}_{\mathrm{T}} + \vec{p}_{\mathrm{vis}_2} \cdot \vec{\not{E}}_{\mathrm{T}}),$$

- **Collinear mass:**
  Assumes neutrinos in the decay are collinear to solve the origin of the MET. Long tails and sometimes no solution

$$\not{E}_{\mathrm{T}x} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{vis}_1} \cos\phi_{\mathrm{vis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{vis}_2} \cos\phi_{\mathrm{vis}_2}$$
$$\not{E}_{\mathrm{T}y} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{vis}_1} \sin\phi_{\mathrm{vis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{vis}_2} \sin\phi_{\mathrm{vis}_2},$$

$$M_{\tau\tau} = m_{\mathrm{vis}} / \sqrt{x_1 x_2}$$

$$x_{1,2} = p_{\mathrm{vis}_{1,2}} / (p_{\mathrm{vis}_{1,2}} + p_{\mathrm{mis}_{1,2}})$$

H -> $\tau\tau$, mass reconstruction

- ATLAS : MMC (Missing Mass Calculator)

$$\not{E}_{\mathrm{T}\,x} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{mis}_1} \cos\phi_{\mathrm{mis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{mis}_2} \cos\phi_{\mathrm{mis}_2}$$

$$\not{E}_{\mathrm{T}\,y} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{mis}_1} \sin\phi_{\mathrm{mis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{mis}_2} \sin\phi_{\mathrm{mis}_2}$$

$$M_{\tau_1}^2 = m_{\mathrm{mis}_1}^2 + m_{\mathrm{vis}_1}^2 + 2\sqrt{p_{\mathrm{vis}_1}^2 + m_{\mathrm{vis}_1}^2}\sqrt{p_{\mathrm{mis}_1}^2 + m_{\mathrm{mis}_1}^2} - 2p_{\mathrm{vis}_1}p_{\mathrm{mis}_1}\cos\Delta\theta_{vm_1}$$

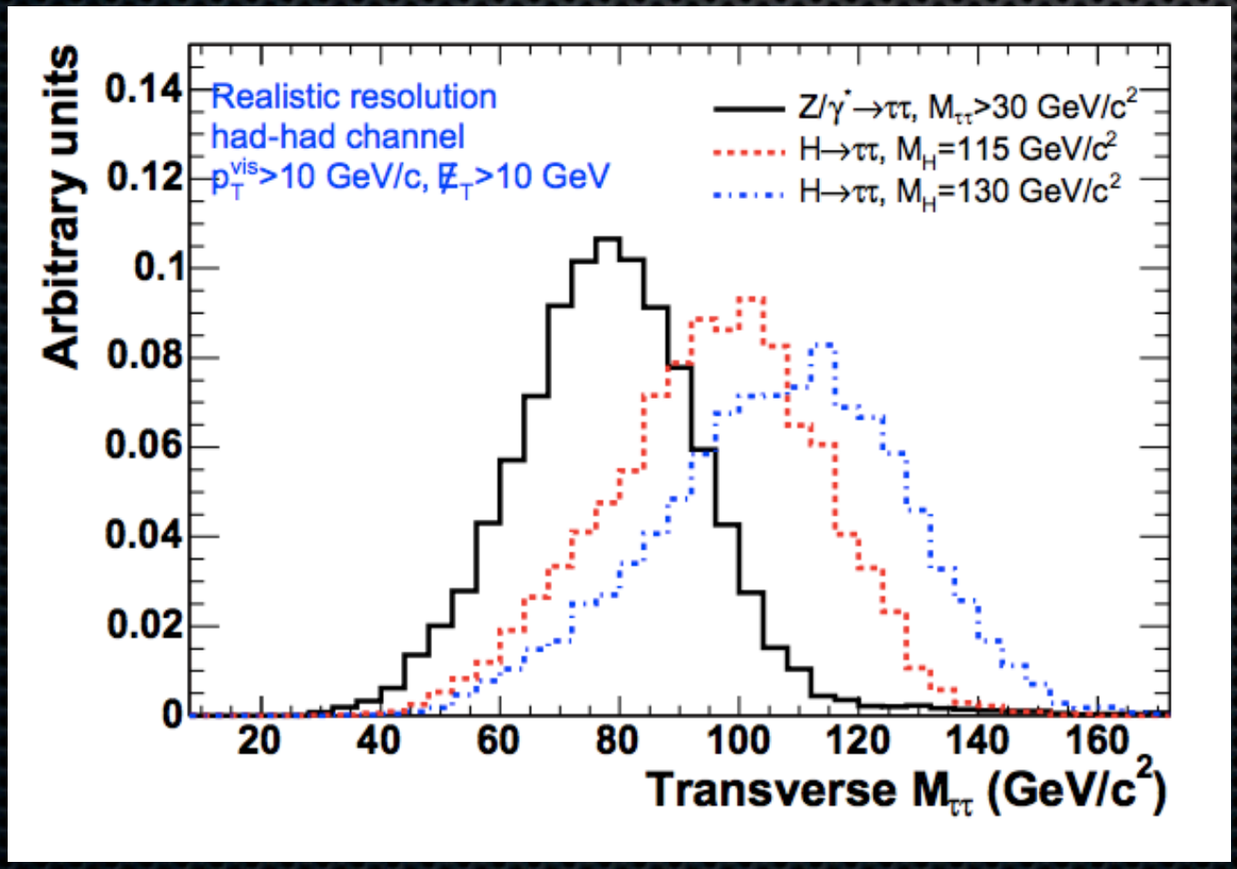
$$M_{\tau_2}^2 = m_{\mathrm{mis}_2}^2 + m_{\mathrm{vis}_2}^2 + 2\sqrt{p_{\mathrm{vis}_2}^2 + m_{\mathrm{vis}_2}^2}\sqrt{p_{\mathrm{mis}_2}^2 + m_{\mathrm{mis}_2}^2} - 2p_{\mathrm{vis}_2}p_{\mathrm{mis}_2}\cos\Delta\theta_{vm_2}$$

4 equation, 6-8 unknowns:

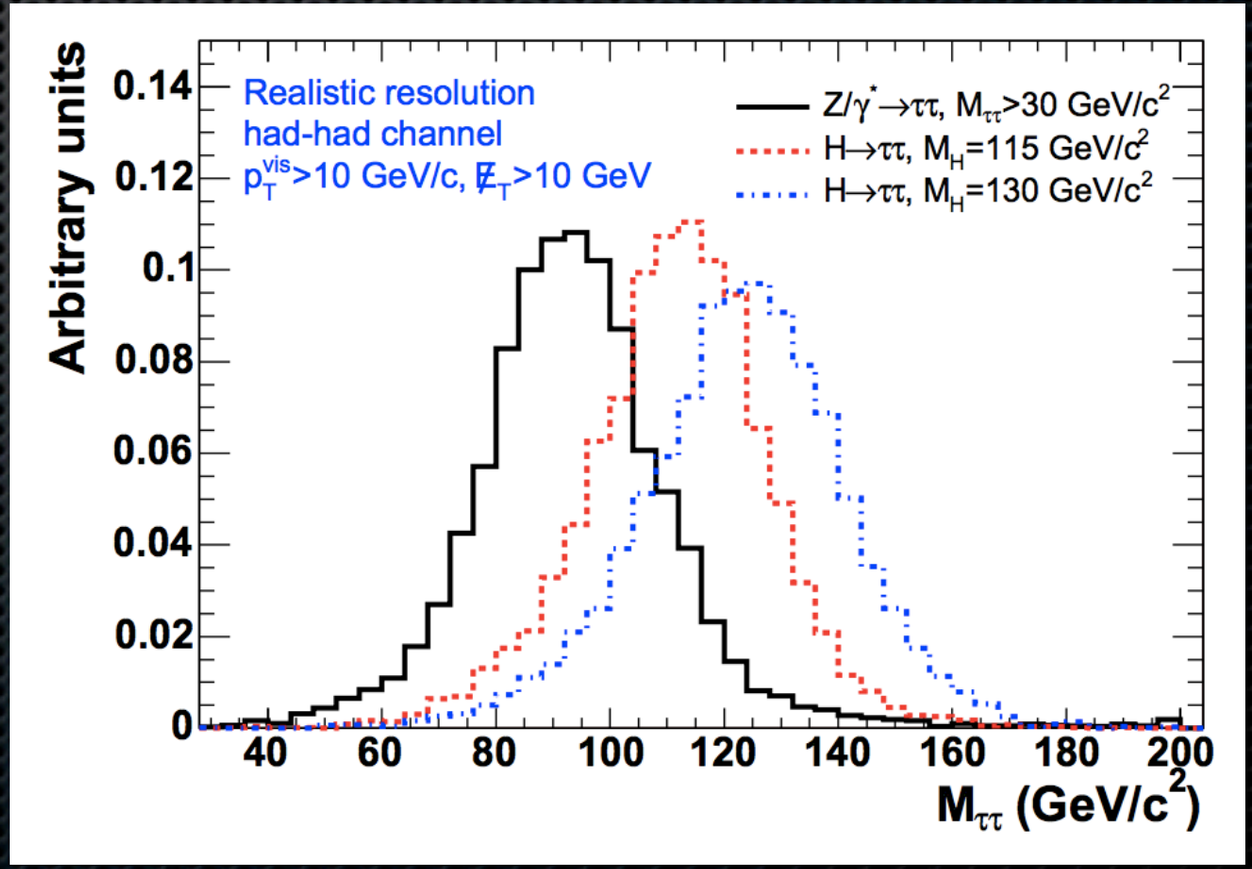
Scan the phase space

for **the most likely solution**

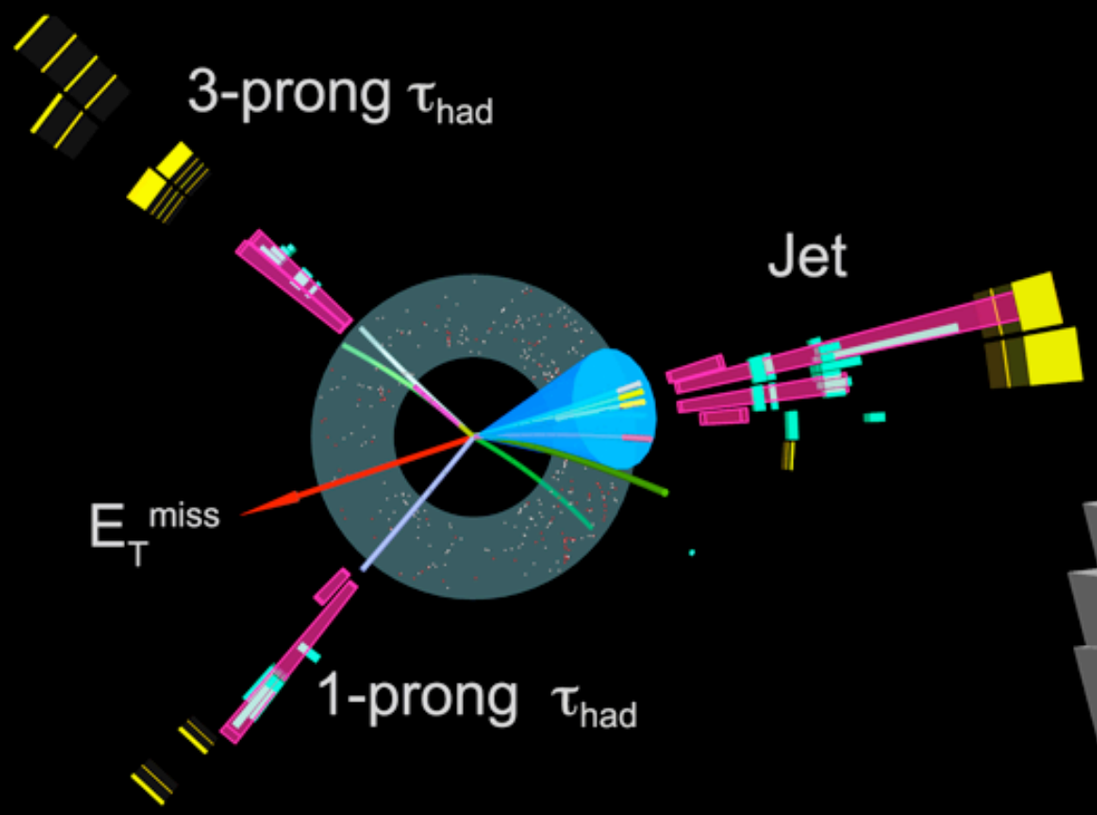
Transverse mass

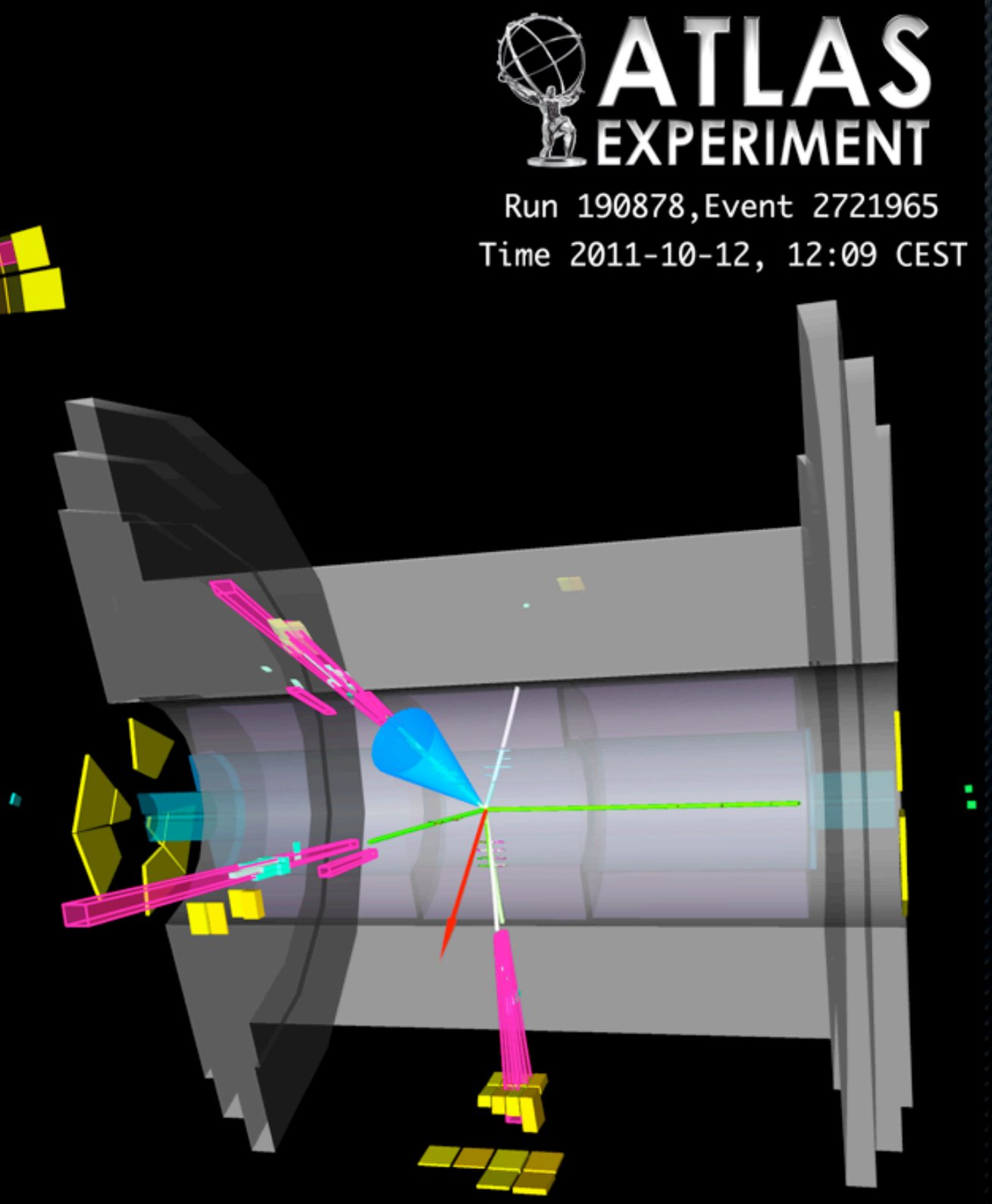


MMC



H -> $\tau\tau$. Event Candidate





$p_T(\tau_{had}^{3\text{-prong}})$ = 72 GeV
$p_T(\tau_{had}^{1\text{-prong}})$ = 45 GeV
E_T^{miss} = 28 GeV
p_T(jet) = 107 GeV
Coll. mass = 121 GeV

ZH -> ee bb. Event