CMS Experiment at the LHC, CERN

Data recorded: 2012-Nov-15 02:43:38.078227 GMT(03:43:38 CEST)

Run / Event: 207273 / 817836307

Higgs boson decay channels with fermions

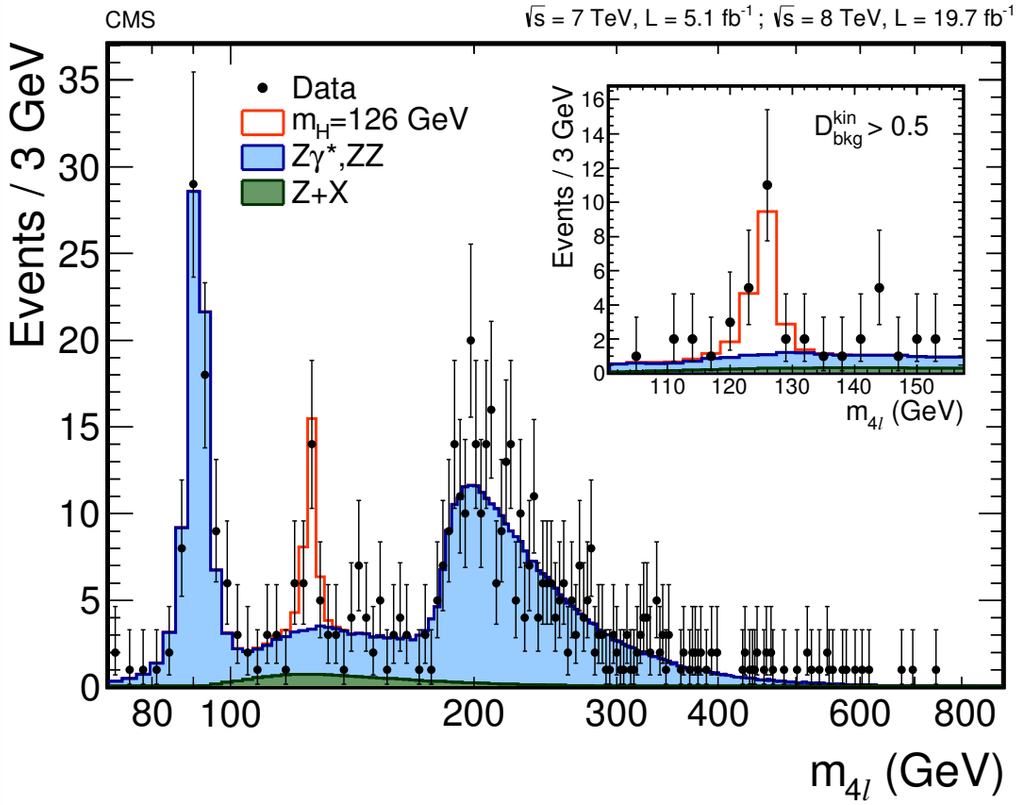
Mauro Verzetti - University of Zurich

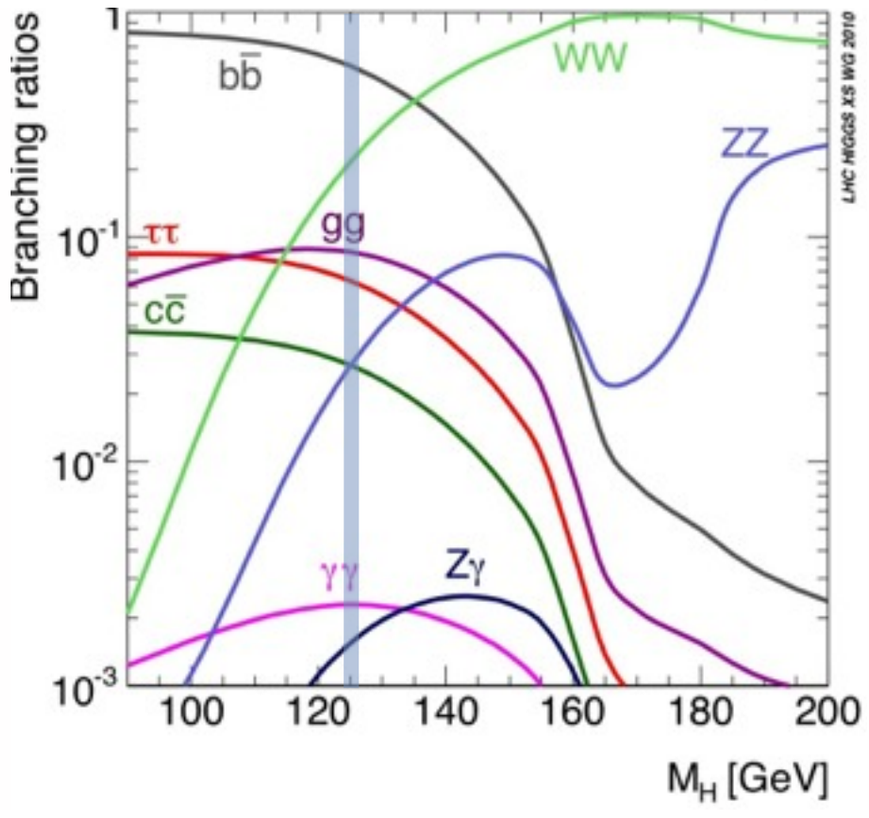
on behalf of the CMS collaboration

Higgs Hunting, Orsay, 21-23 July 2014

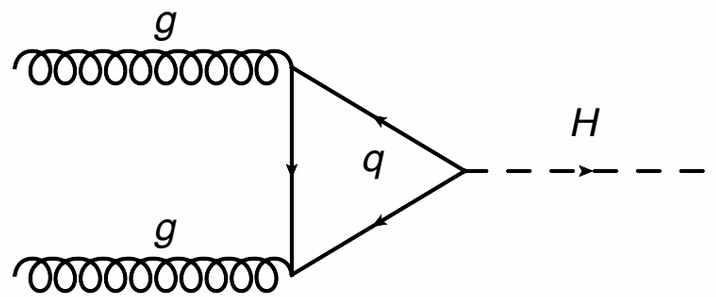
Higgs to Fermion searches at CMS

- Higgs found in decays to bosons:
  - Only indirect evidence of coupling to top.
  - Does it couple to fermions?
- SM Higgs couplings to fermions searches:
  - ttH
  - H→$\mu\mu$
  - H→bb
    - VBF
    - VH
  - H→$\tau\tau$
    - VBF + gg fusion
    - VH

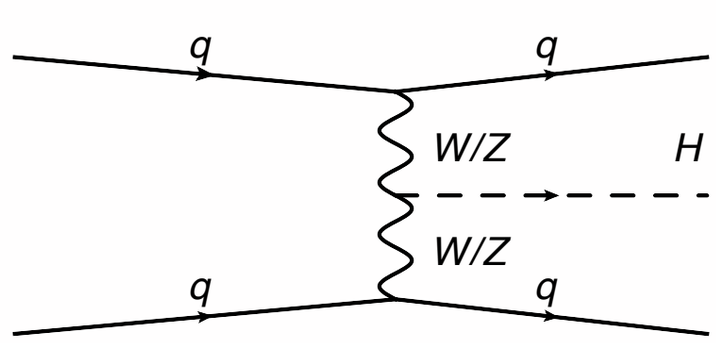


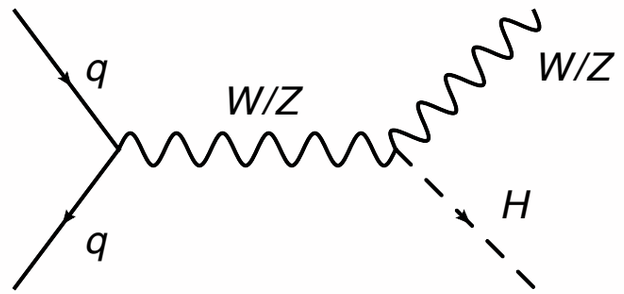


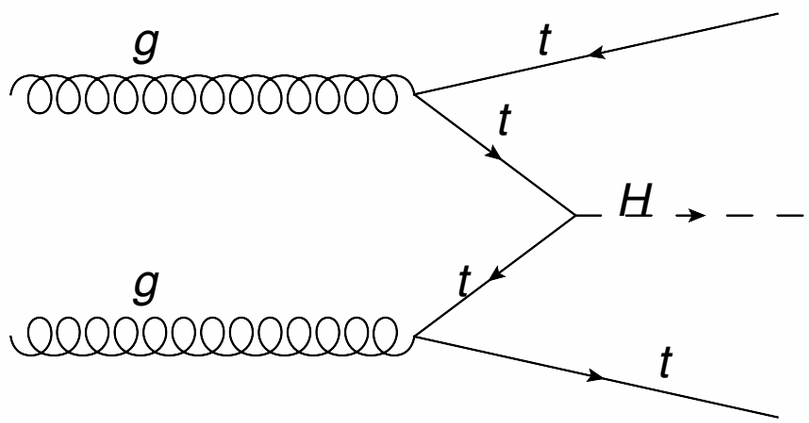
SM Higgs @ LHC



- Four main production processes:
  - Gluon fusion
  - **V**ector **B**oson **F**usion (VBF)
  - Associated production with a vector boson (VH)
  - ttH



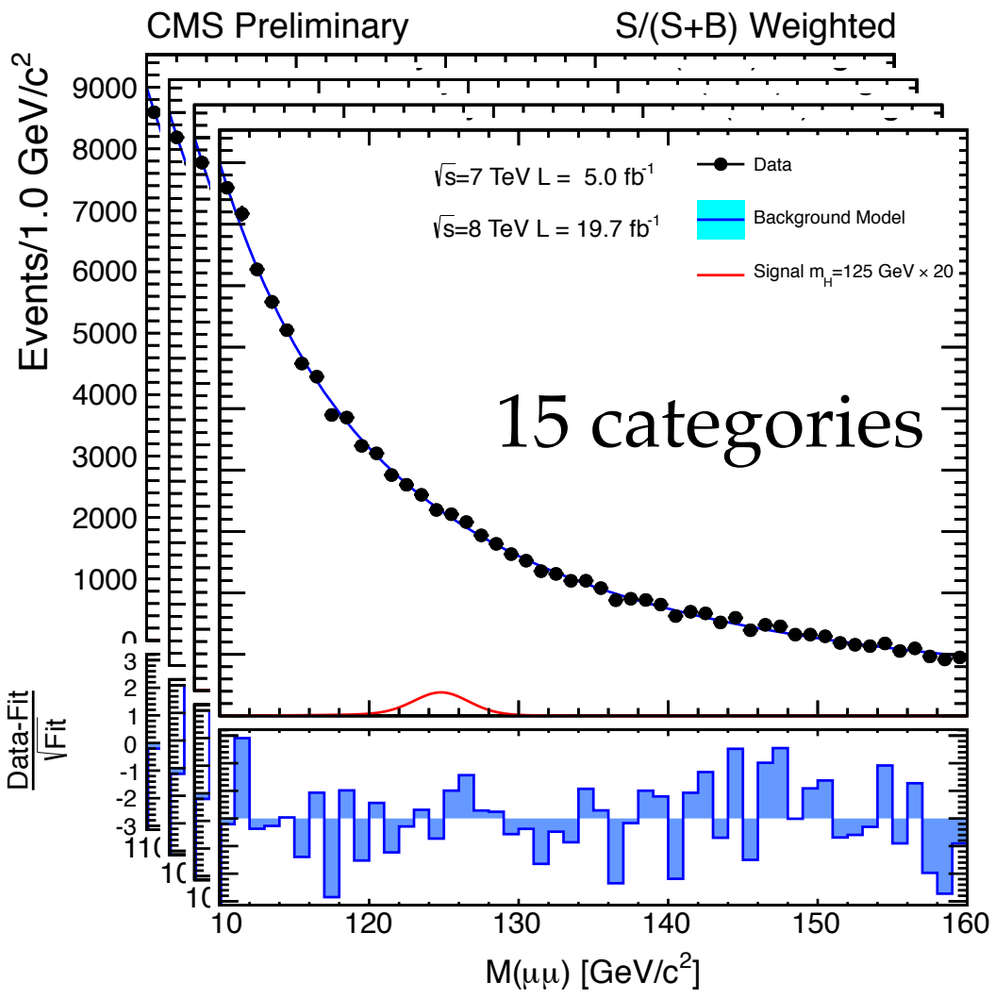


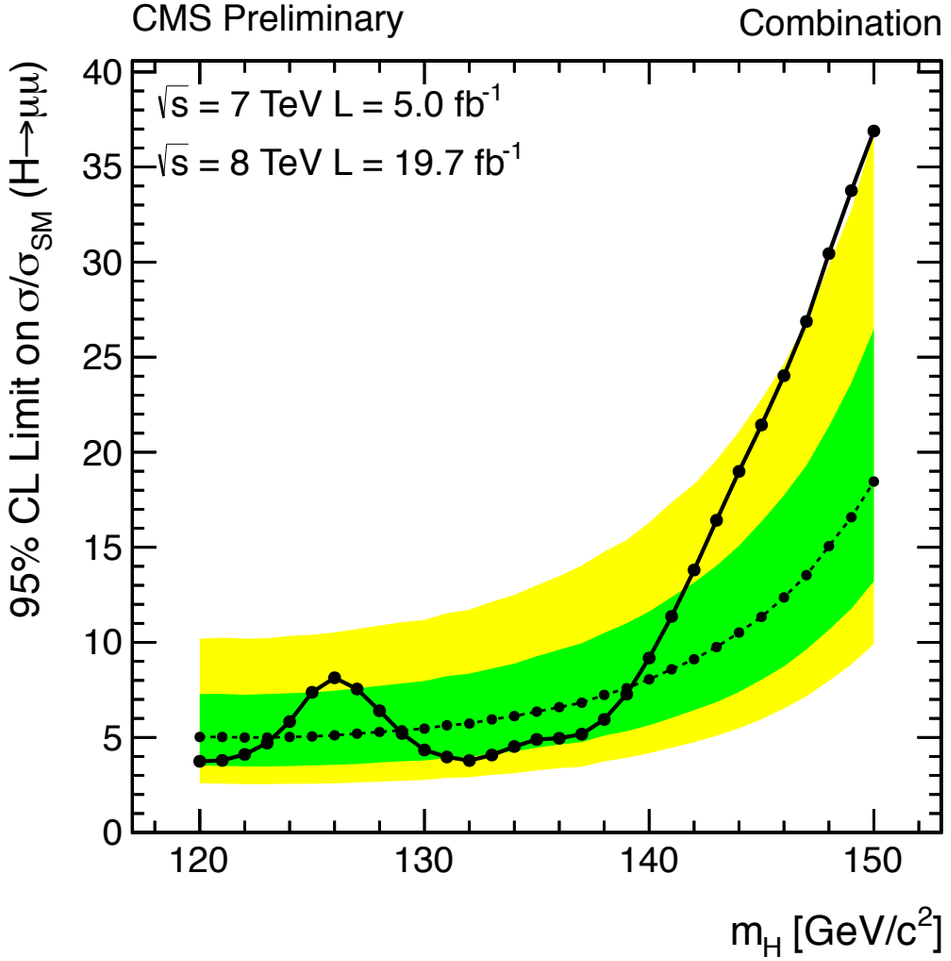


$H \rightarrow \mu\mu$

HIG-13-007

- Very high mass resolution: 1.6-2.5 GeV (FWHM @ 125 GeV)
- Event categorisation based on di-muon mass resolution and production process
- Background and signal modelled by parametric function
- No significant excess found
- $\sigma \times BR(H \rightarrow \mu\mu) < 3.4 \times 10^{-2}$pb, $\sigma \times BR(H \rightarrow ee) < 3.8 \times 10^{-2}$pb @ 95% CL



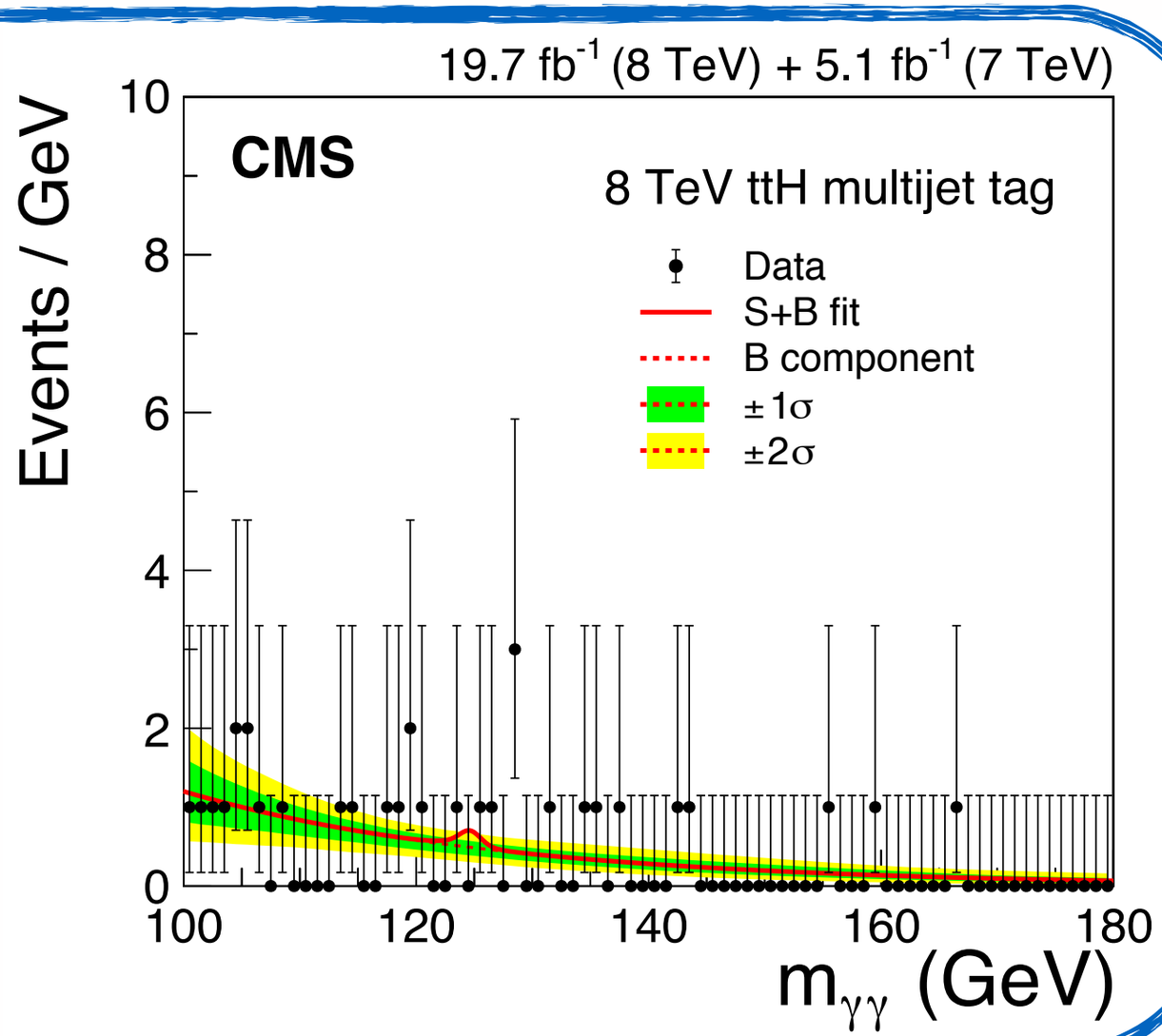


ttH

- Not a direct Higgs decay
- But is the only way to probe directly the Higgs coupling to top quarks
- **See Francesco Micheli's talk for more details**

H→γγ

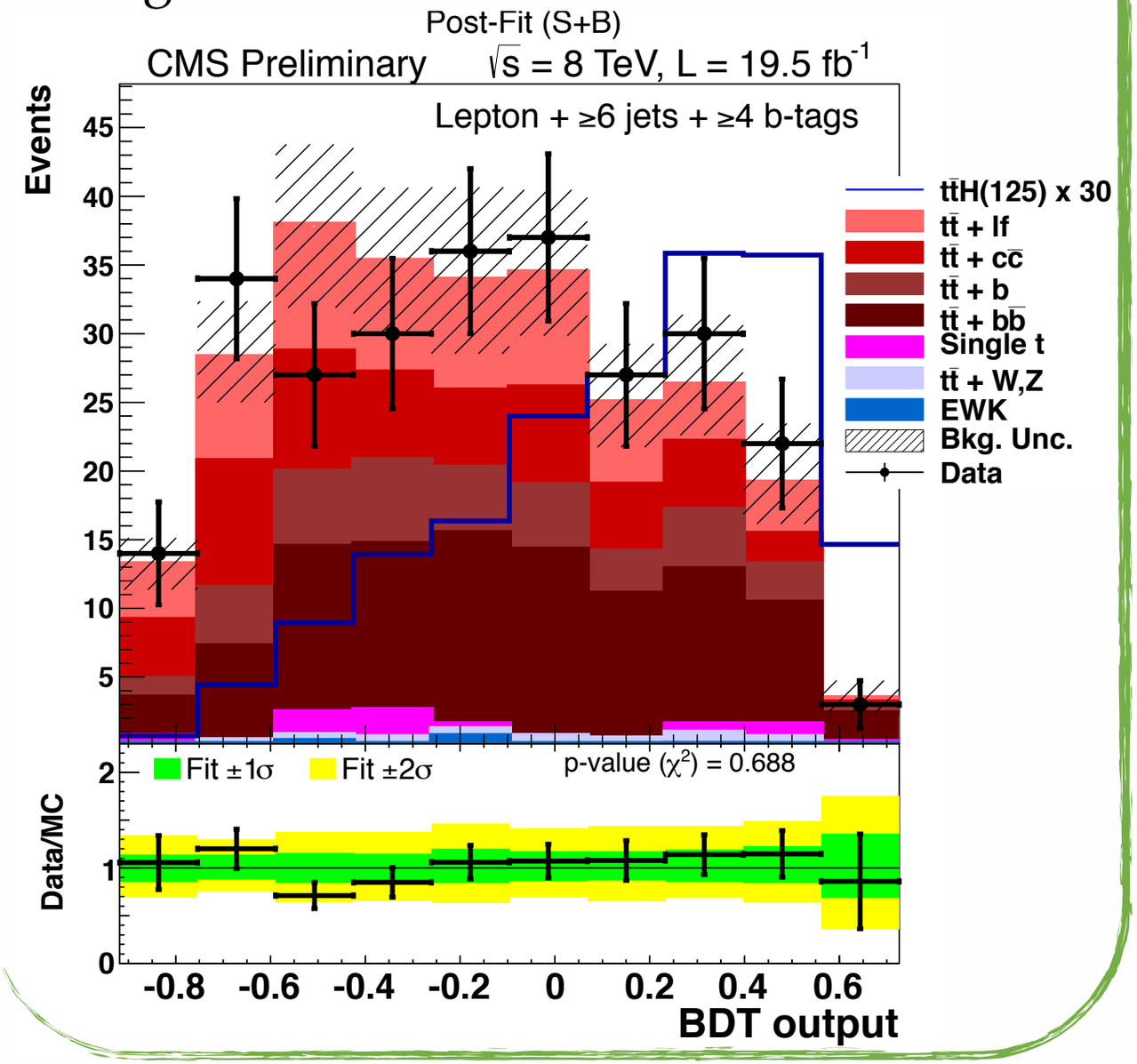
- Low rate, high purity
- Select events with 2γ, ≥2jets (≥ b-tagged)
- Two channels: for exclusive top decays
- Search for a peak in the di-photon mass spectrum



ttH

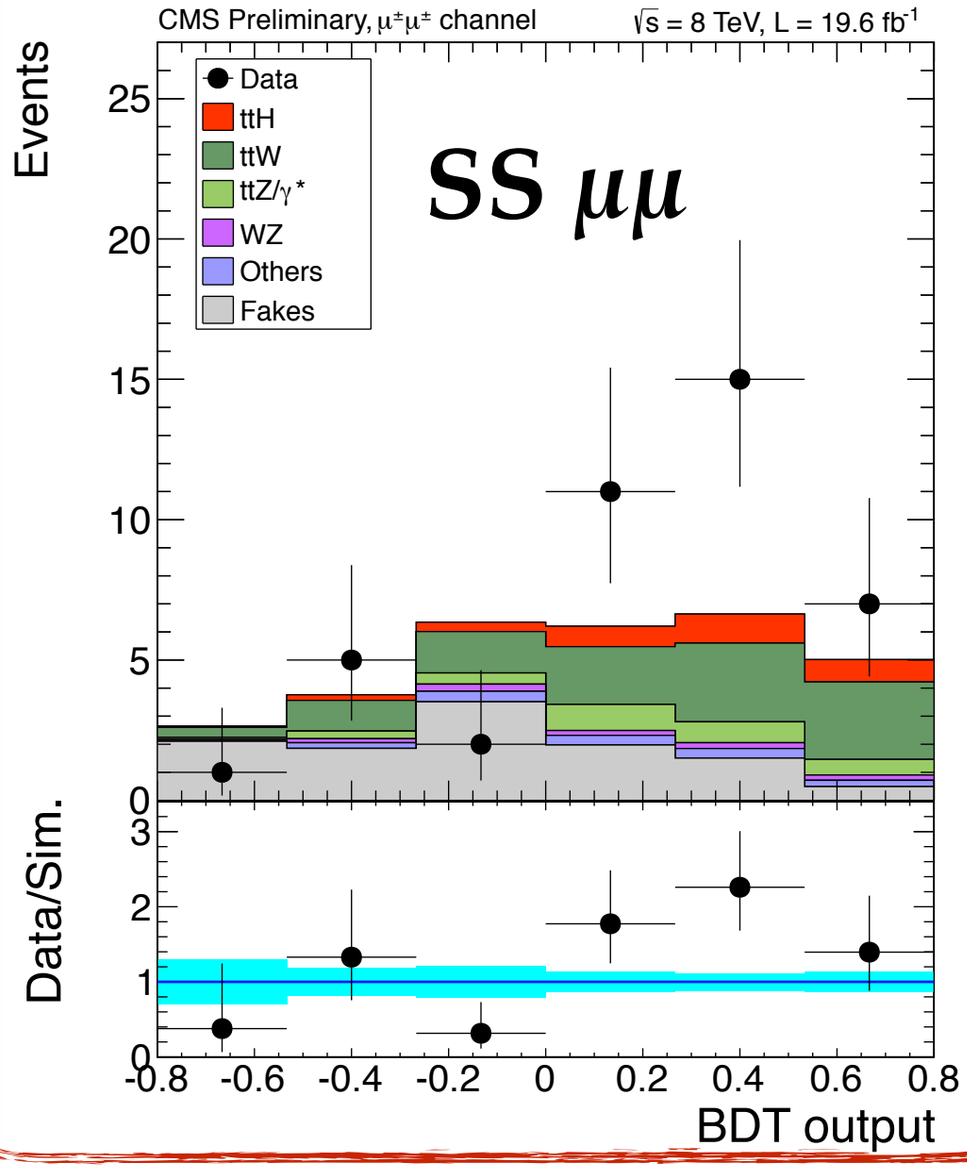
H→hadrons

- Categorisation according to N_{jets} and $N_{b\text{-}jets}$
- Purity enhanced in high jets regions
- MVA approach for background discrimination



H→leptons

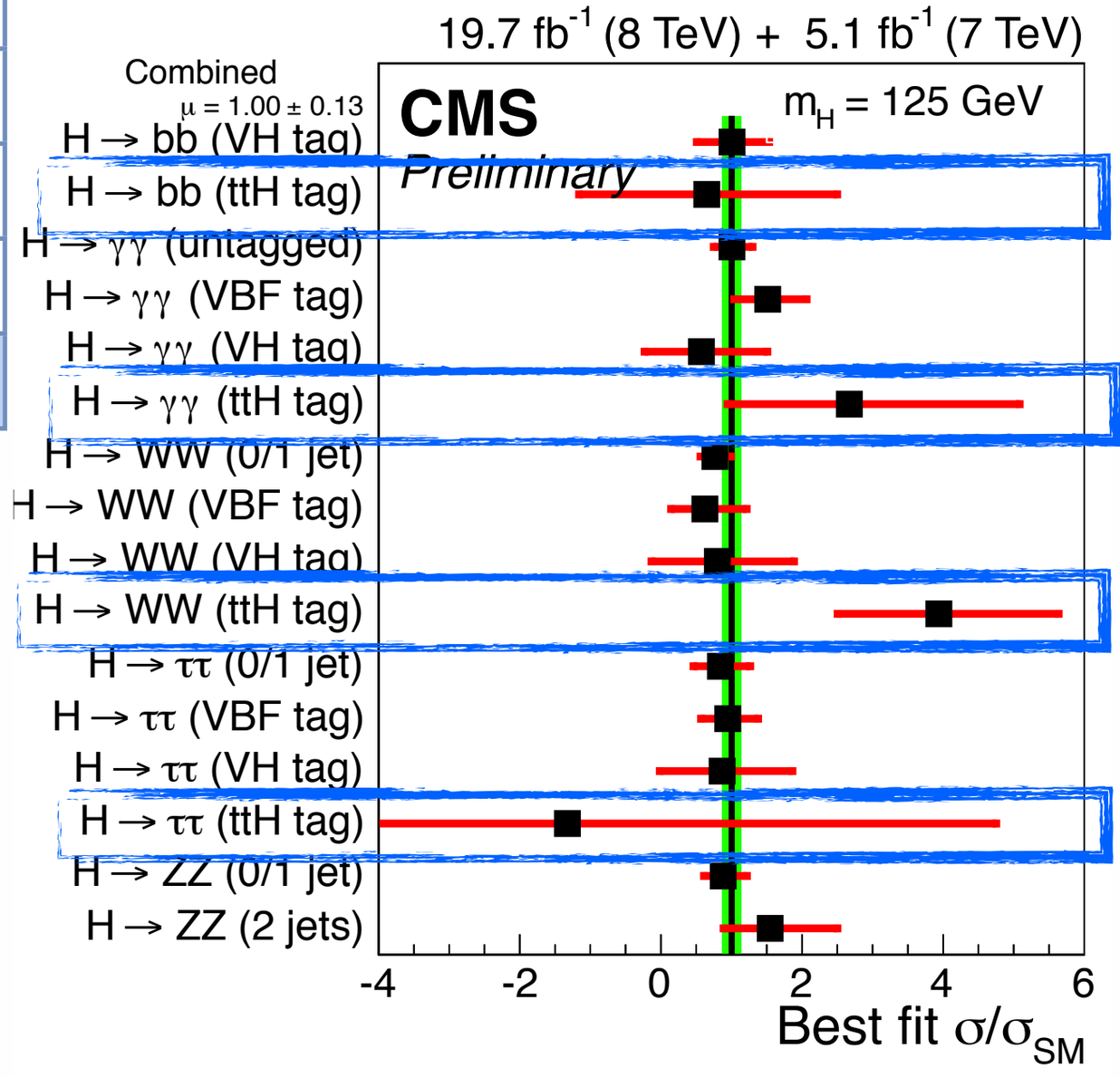
- Tag H→ττ,WW,ZZ to (>)1 leptons
- Only partial event reconstruction
- MVA approach
  - Jet activity used to reject backgrounds



ttH combination

Channel	μ_{Fit}
H→bb	0.7 ± 1.8
H→ττ	$-1.3^{+6.1}_{-3.6}$
H→leptons	$3.9^{+1.7}_{-1.4}$
H→γγ	$2.7^{+2.4}_{-1.7}$
Combination	$2.76^{+1.05}_{-0.92}$

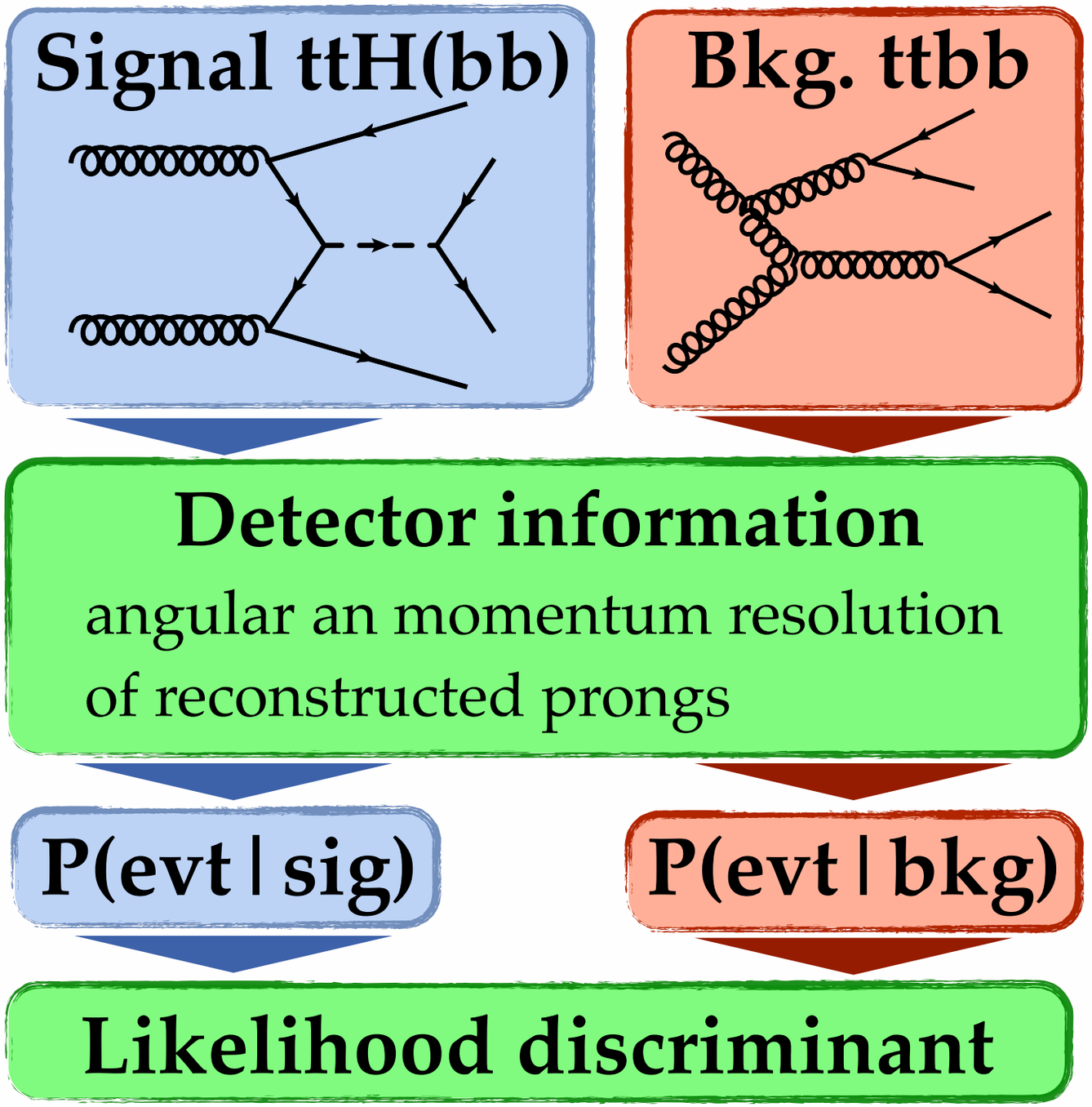
- Excess observed
- Compatible with SM (μ=1) at 2σ
- Compatible with Background only hypothesis at 3.5σ
- Excess driven by SS di-muon and H→γγ



ttH(bb) with MEM

HIG-14-010

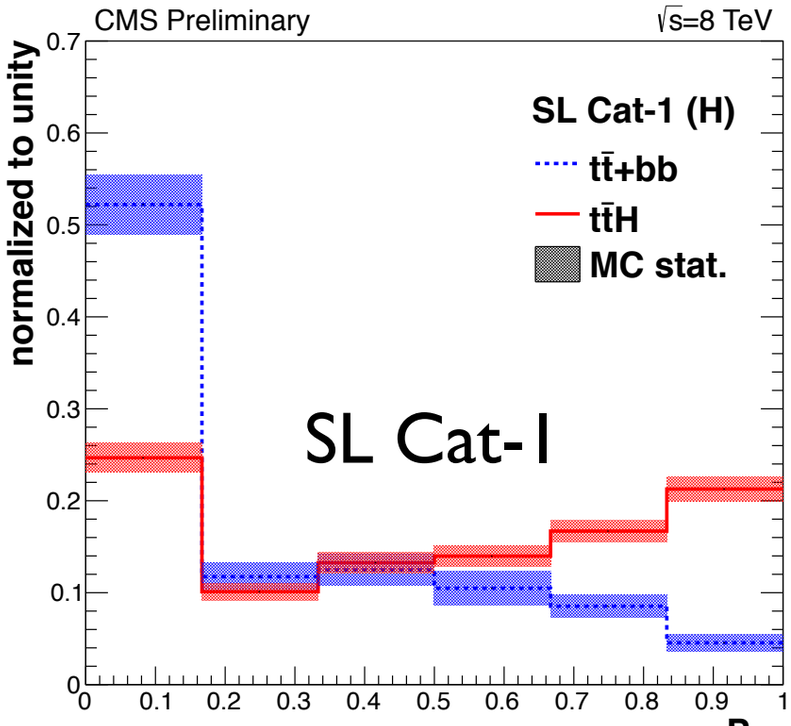
- Events with ≥1ℓ+≥4 jets
- Analytical Matrix Element Method:
  - Use theory information to separate tt+bb from ttH(bb)
    - Include detector resolution
    - Integrate over missing or poorly measured particles
    - Include jet b-tagging information
- Construct likelihood ratio discriminant to separate signal from irreducible backgrounds

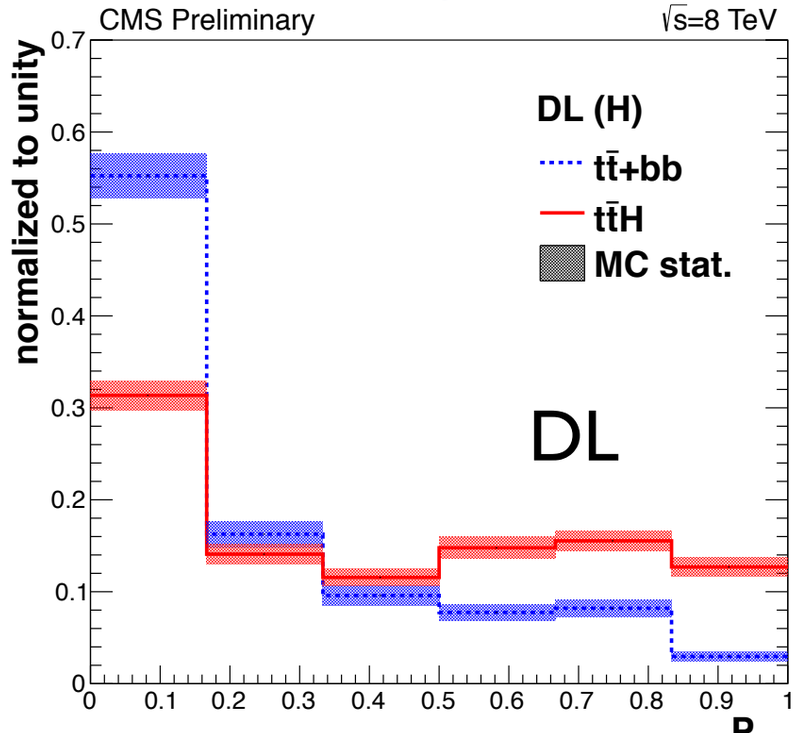


ttH(bb) with MEM

- Categorisation according to topology reconstructed
- Focus on (almost) complete reconstructed topology
- Use b-tagging and m(jj) to tag W reconstruction

Single Lepton (**SL**)			Double Lepton (**DL**)
1ℓ + ≥6 jets	1ℓ + 5 jets	1ℓ + ≥5 jets	2ℓ + ≥4 jets
Full topology reconstructed	One W-quark missing	One W-quark missing + guon(s)	Full topology reconstructed

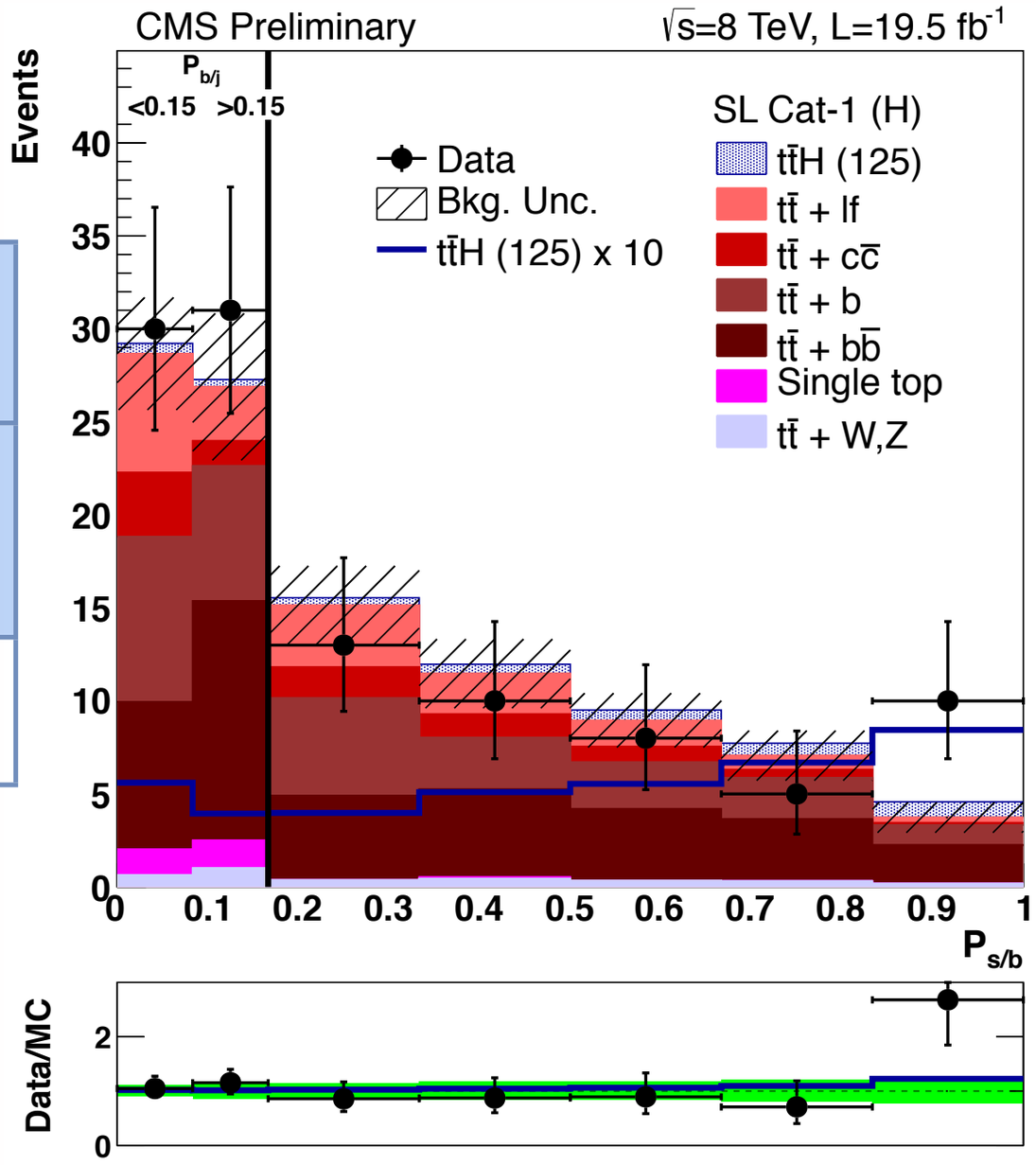




ttH(bb) with MEM

- Combined fit to ME discriminant

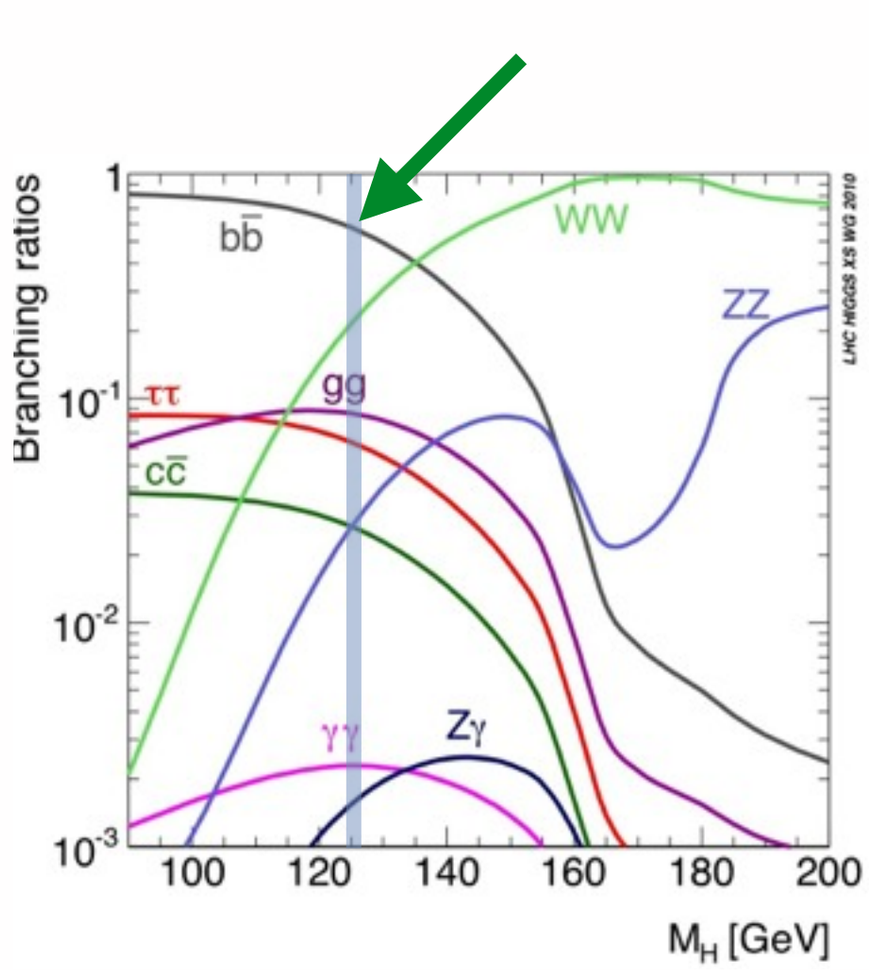
95% CL limits on μ		
Median exp.	Median exp. (Signal injected)	Observed
2.9	3.9	**3.3**



- **Best-fit $\mu = 0.7 \pm 1.4$** (prev.: 0.7±1.8)
- **30% improvement** from previous result

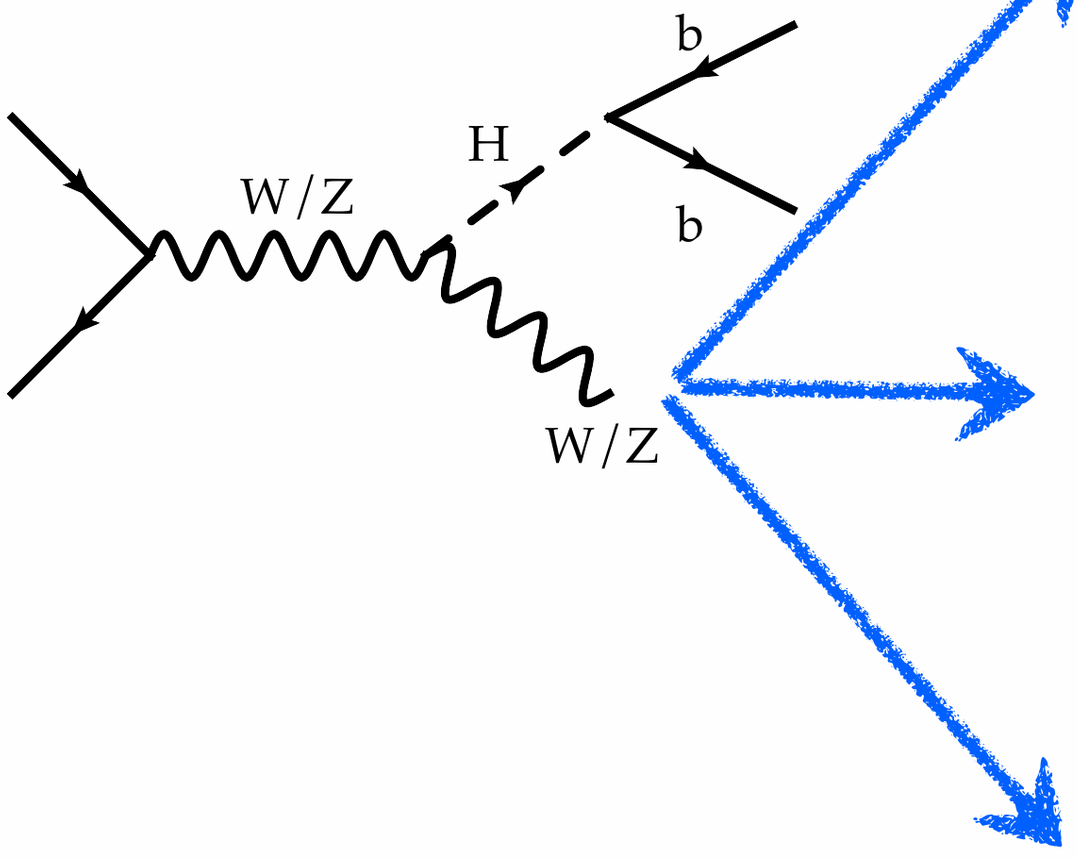
H→bb

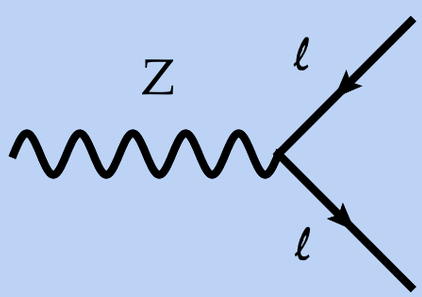
- Only feasible channel to measure down-type quark couplings
- **Highest branching fraction** for light Higgs
- Large QCD backgrounds, searches limited to:
  - **VH associated production**
  - **VBF**
  - ttH



VH→bb

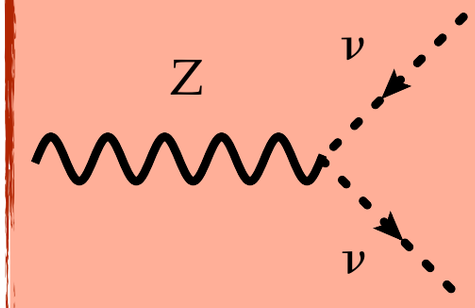
HIG-13-012



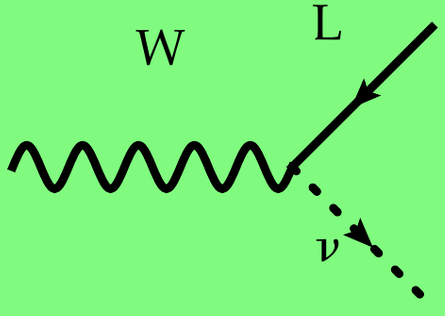


Opposite-Sign, same flavor light lepton (e,μ) pairs.

No intrinsic missing transverse energy



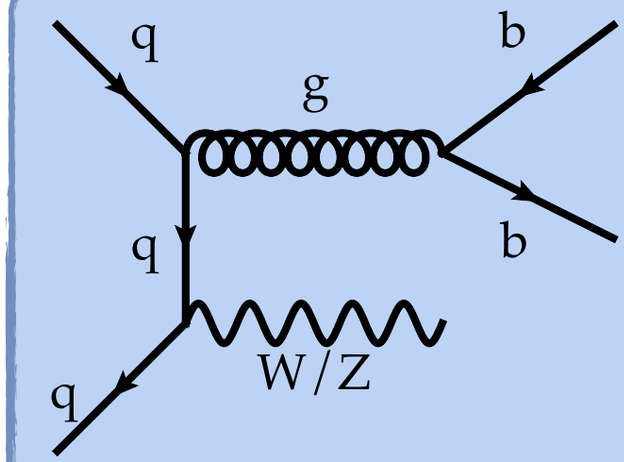
High missing transverse energy (MET)



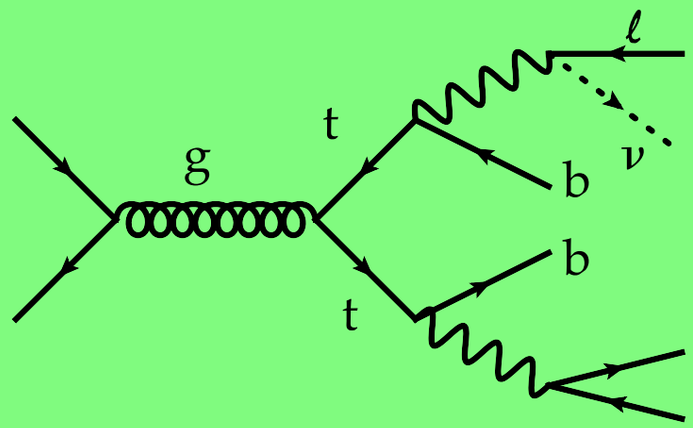
One lepton (e, μ, τ).

Missing transverse energy

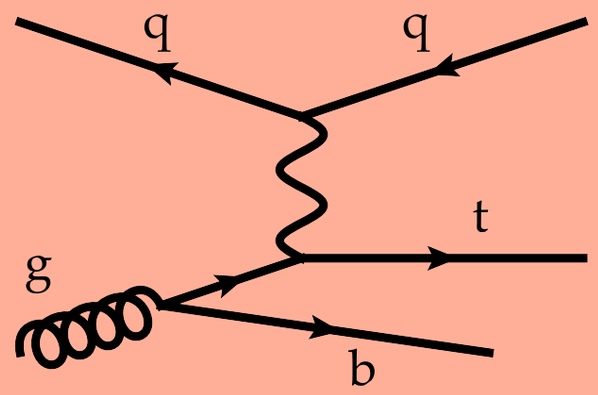
Backgrounds



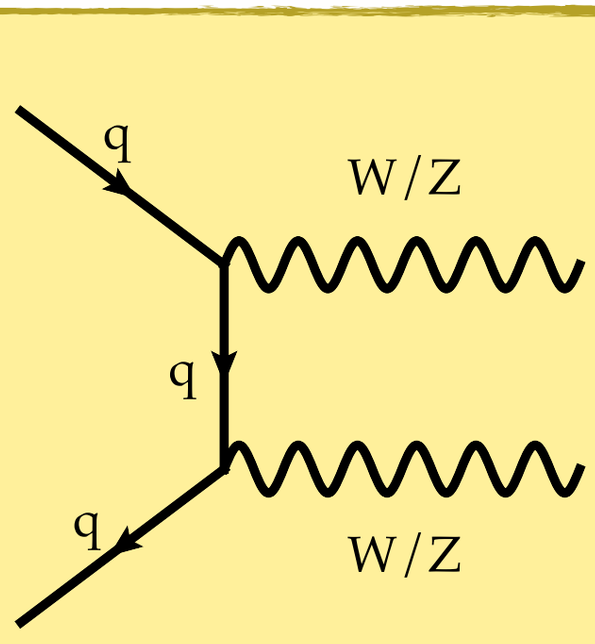
Vector boson
+ 2 b-Jets



Top quark pairs



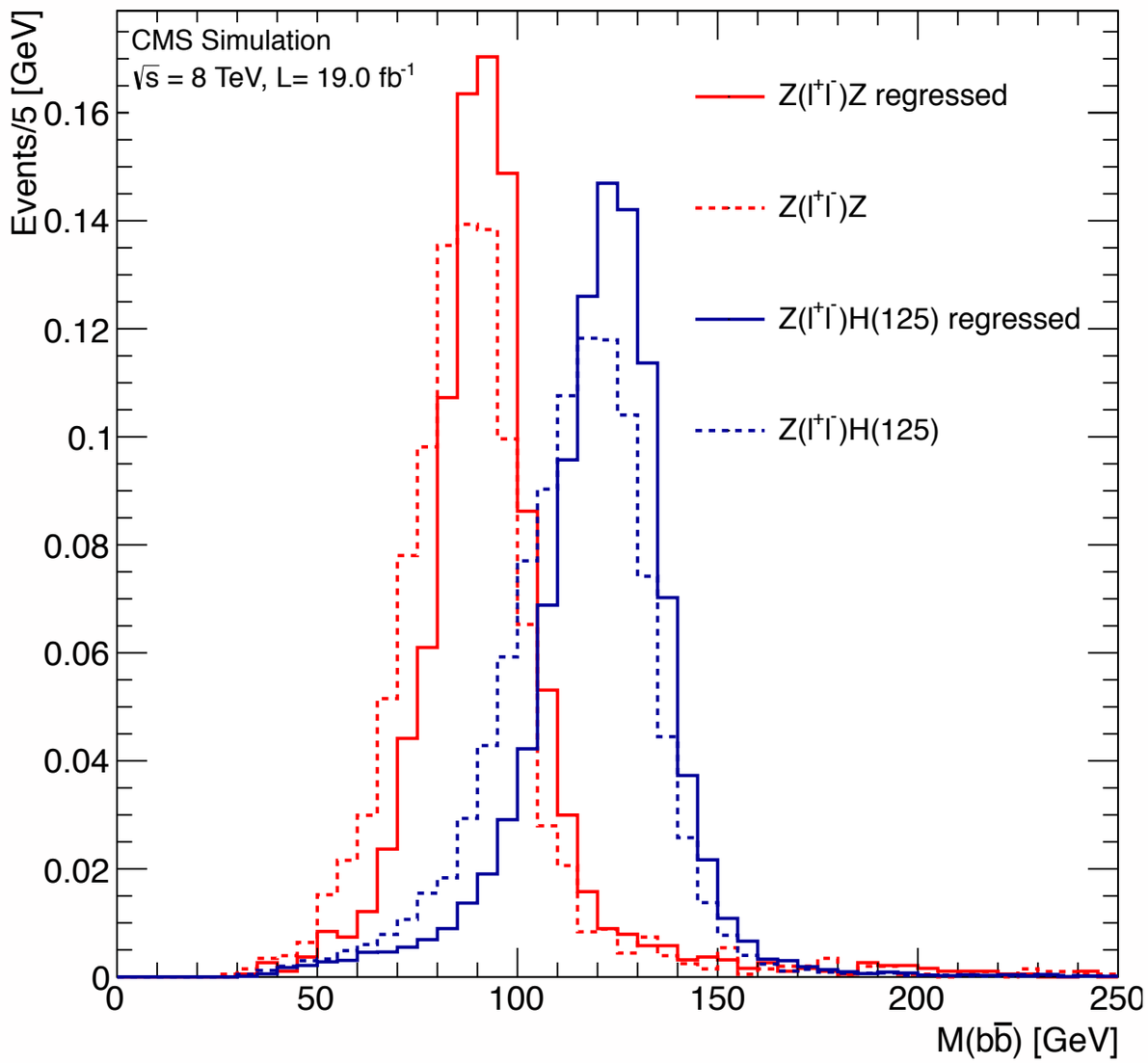
Single top



Diboson

Kinematic regression

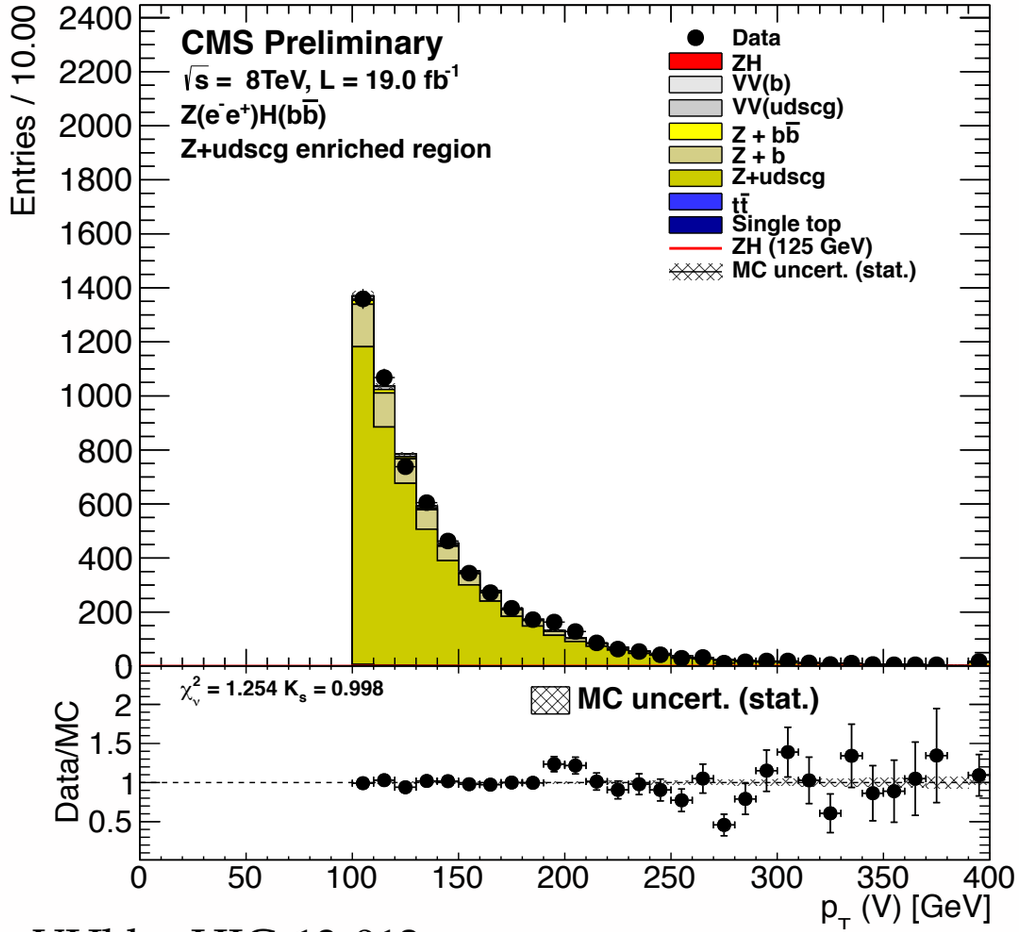
- Energy correction targeted on b-jets
- **MVA approach with BDT:**
  - Basic jet kinematic and shape information
  - Secondary vertex and soft lepton information
  - Missing transverse energy information: provides kinematic constraints and helps recover neutrinos from semi-leptonic decays
- **Mass resolution: 8-10%**
- Increase in Z/signal separation
- **10-20%** sensitivity improvement



Analysis strategy

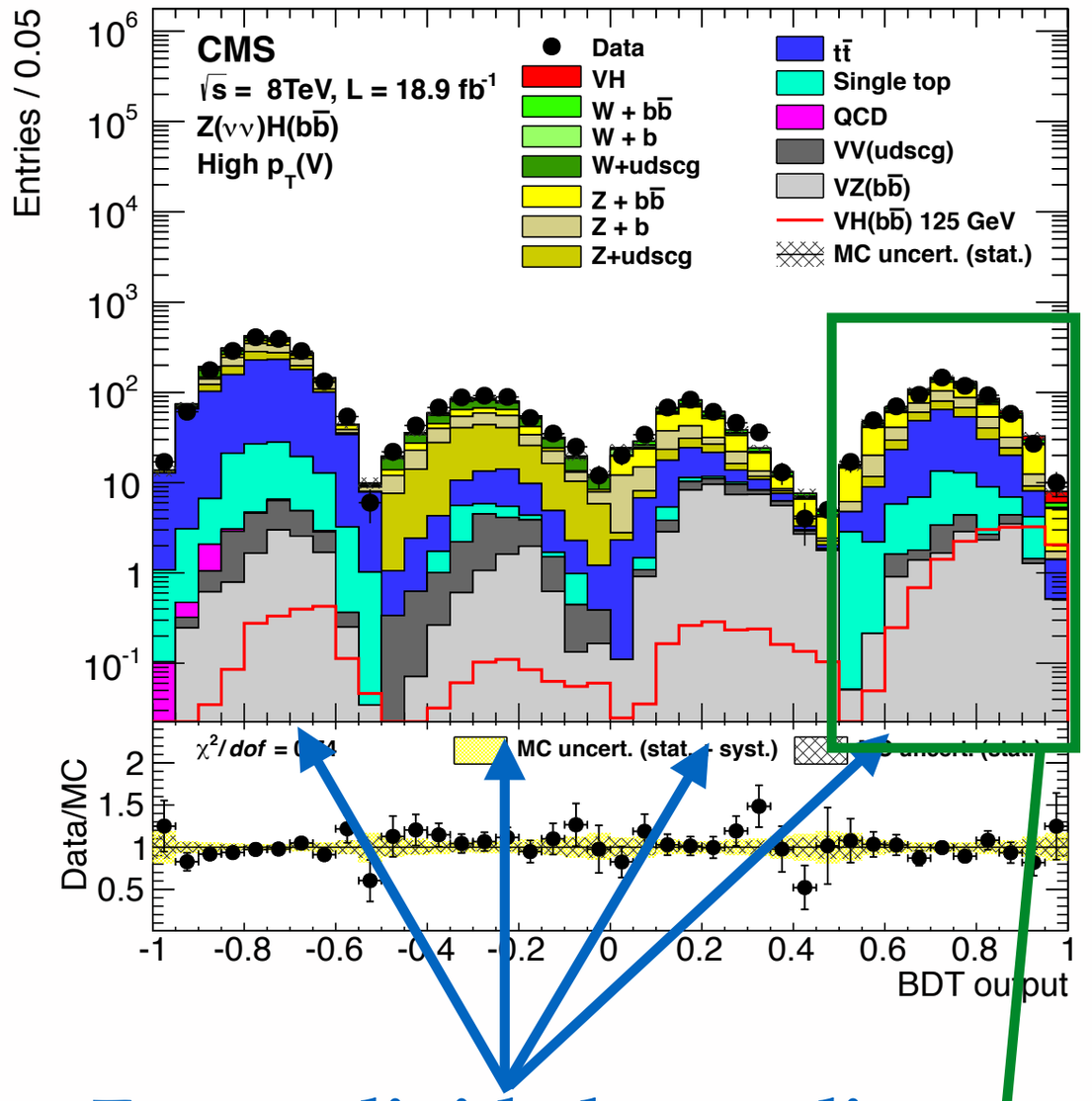
- **Require boosted vector boson**
  - **Large reduction of backgrounds**
  - Improves mass resolution
    - Separate categories according to channel and boost
- $Z \to \nu\nu$: additional requirements to reject mis-measured QCD events
- Good control of vector boson p_T distribution

	low	med	high
W($\ell\nu$)	[100,130]	[130,180]	>180
W($\tau\nu$)	>120	-	-
Z($\nu\nu$)	[100,130]	[130,170]	>170
Z($\ell\ell$)	[50,100]	-	>100



Analysis strategy

- Final signal to background discrimination performed with **BDT**
  - $p_T(V)$
  - $p_T(jj)$ and m(jj)
    - Separate training for each Higgs mass point
    - b-Tag values of jet candidates
- Dedicated BDT specialised on different backgrounds
- Separate training for the different channels and boost categories
- **BDT output is used as fitted observable for result extraction**
- **Cross check with M_{jj} performed**

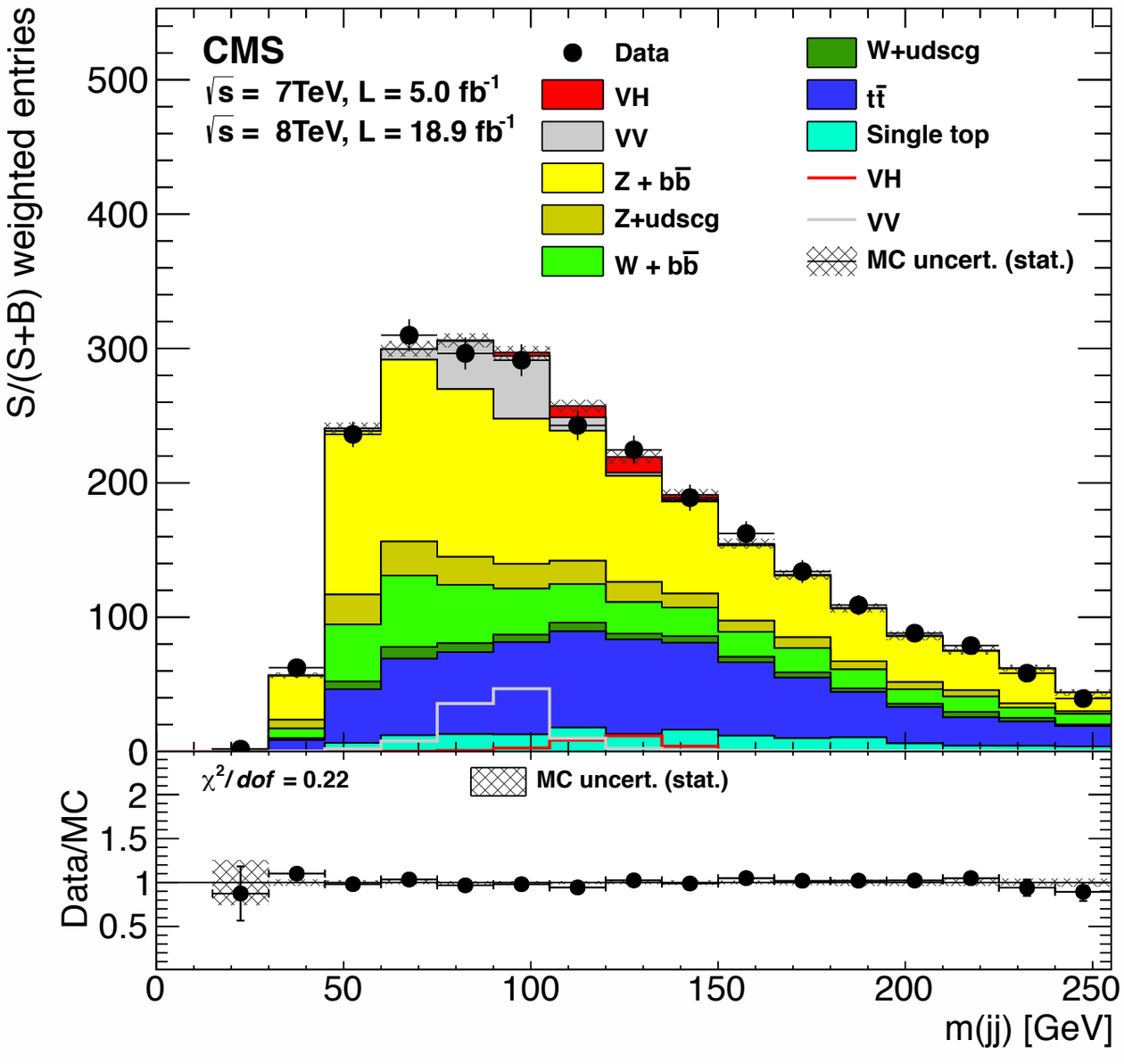


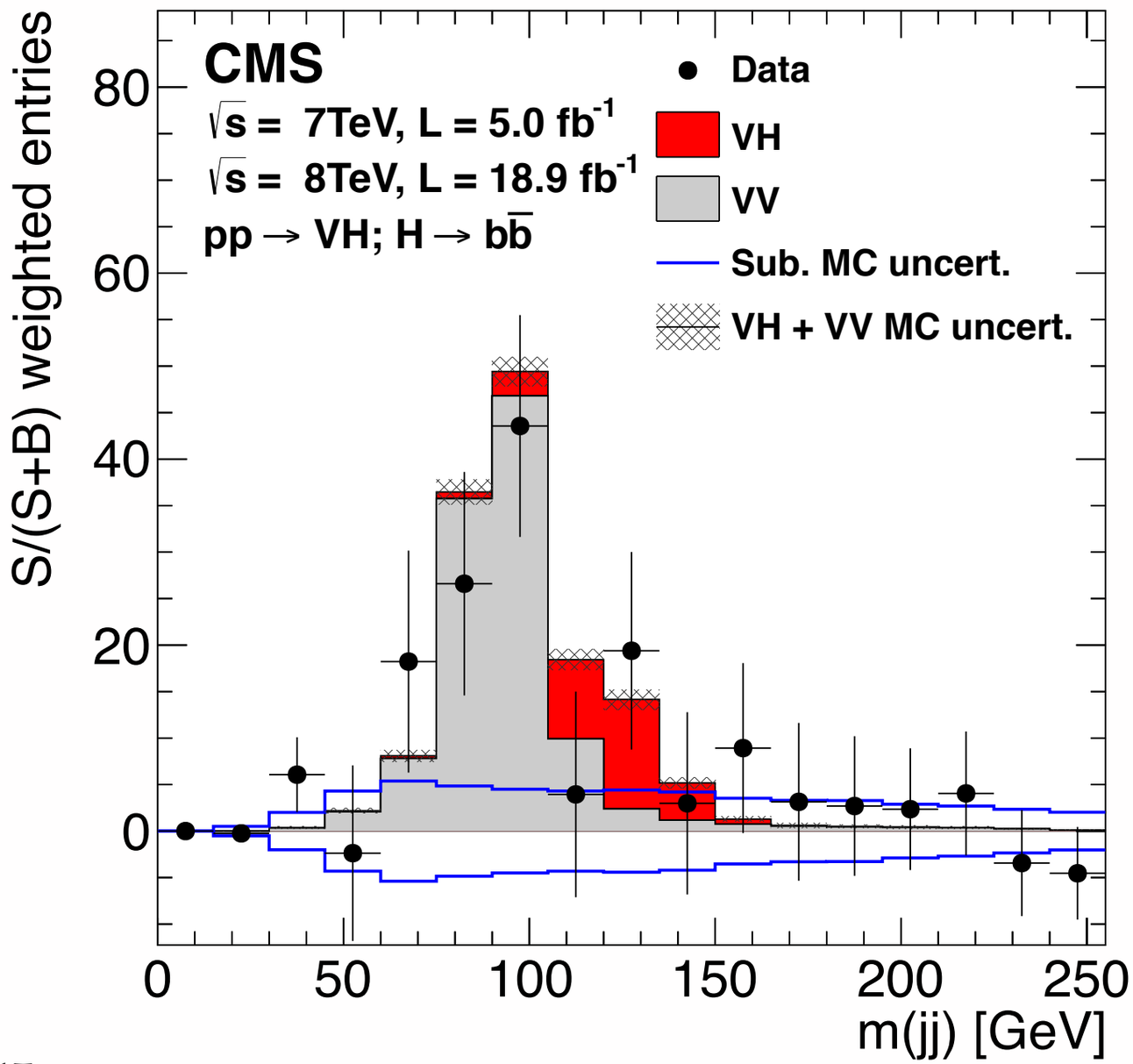
Events divided according to specialised BDT

General BDT output

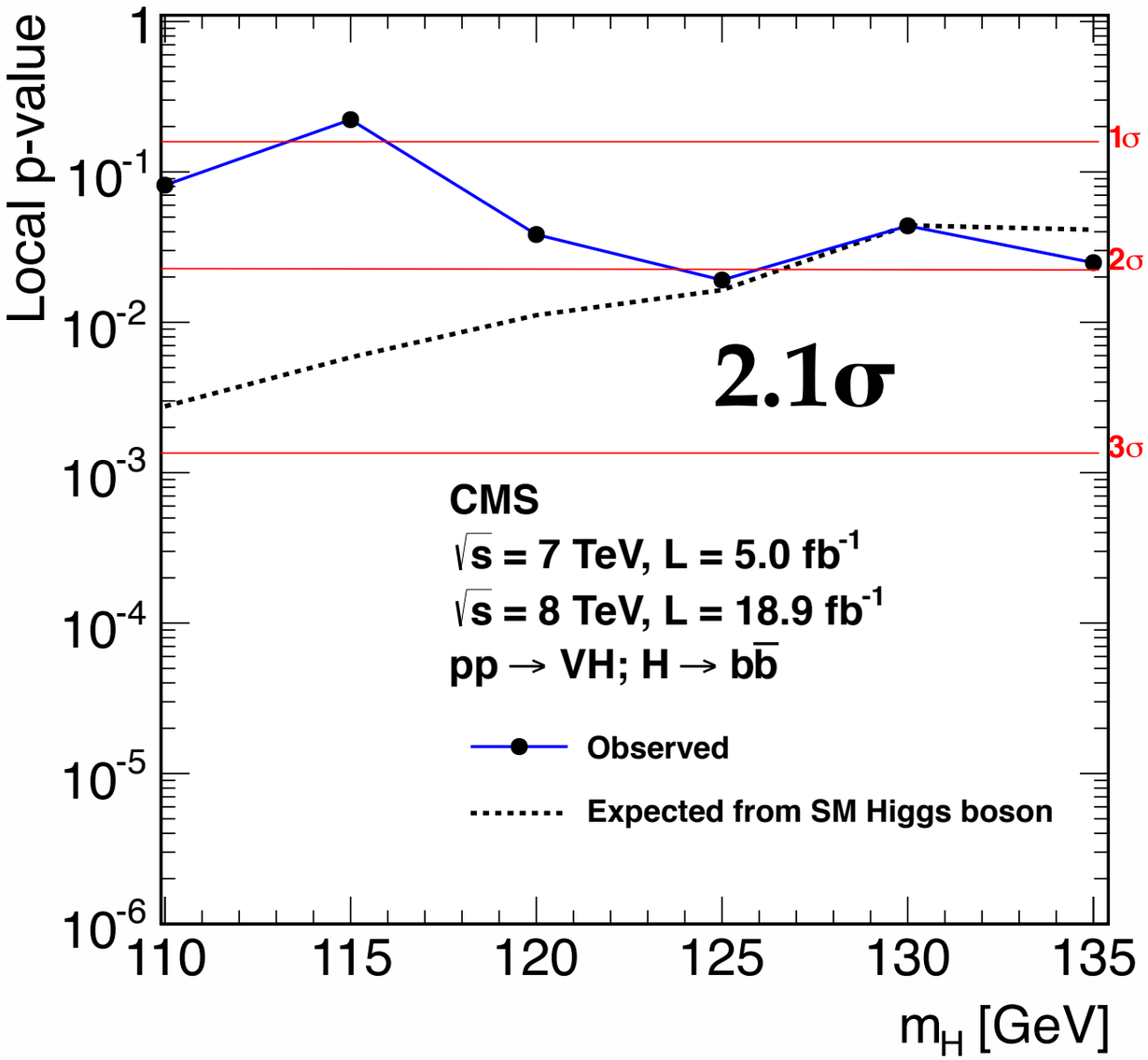
Results

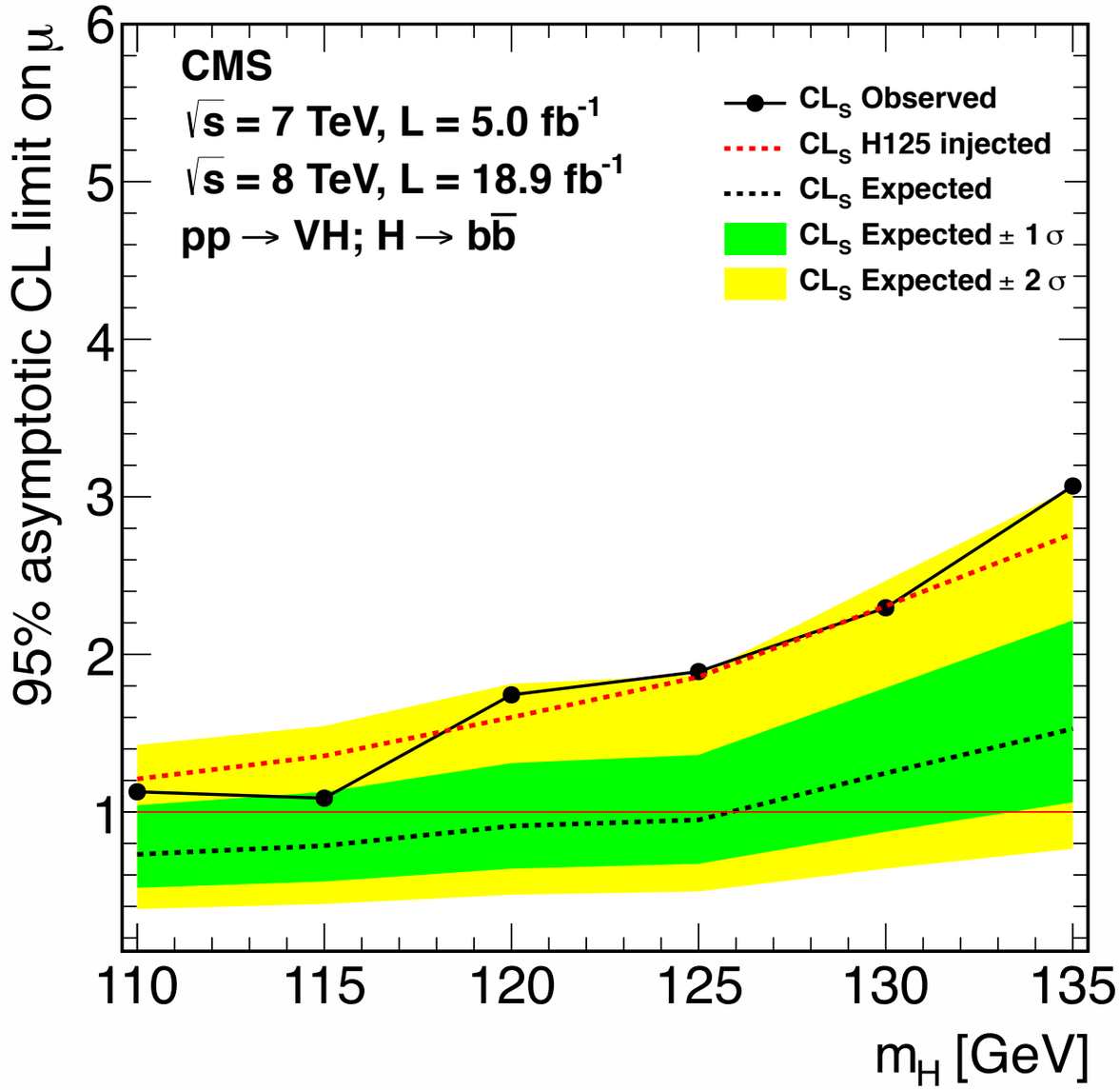
>6σ observation of VZ(bb)





Results


Local p-value
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1σ
2σ
3σ
2.1σ
CMS
$\sqrt{s}$ = 7 TeV, L = 5.0 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 18.9 fb^{-1}
pp → VH; H → bb̄
Observed
Expected from SM Higgs boson
110
115
120
125
130
135
m_H [GeV]


95% asymptotic CL limit on μ
6
5
4
3
2
1
CMS
$\sqrt{s}$ = 7 TeV, L = 5.0 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 18.9 fb^{-1}
pp → VH; H → bb̄
CL_s Observed
CL_s H125 injected
CL_s Expected
CL_s Expected ± 1 σ
CL_s Expected ± 2 σ
110
115
120
125
130
135
m_H [GeV]

$H \rightarrow \tau\tau$

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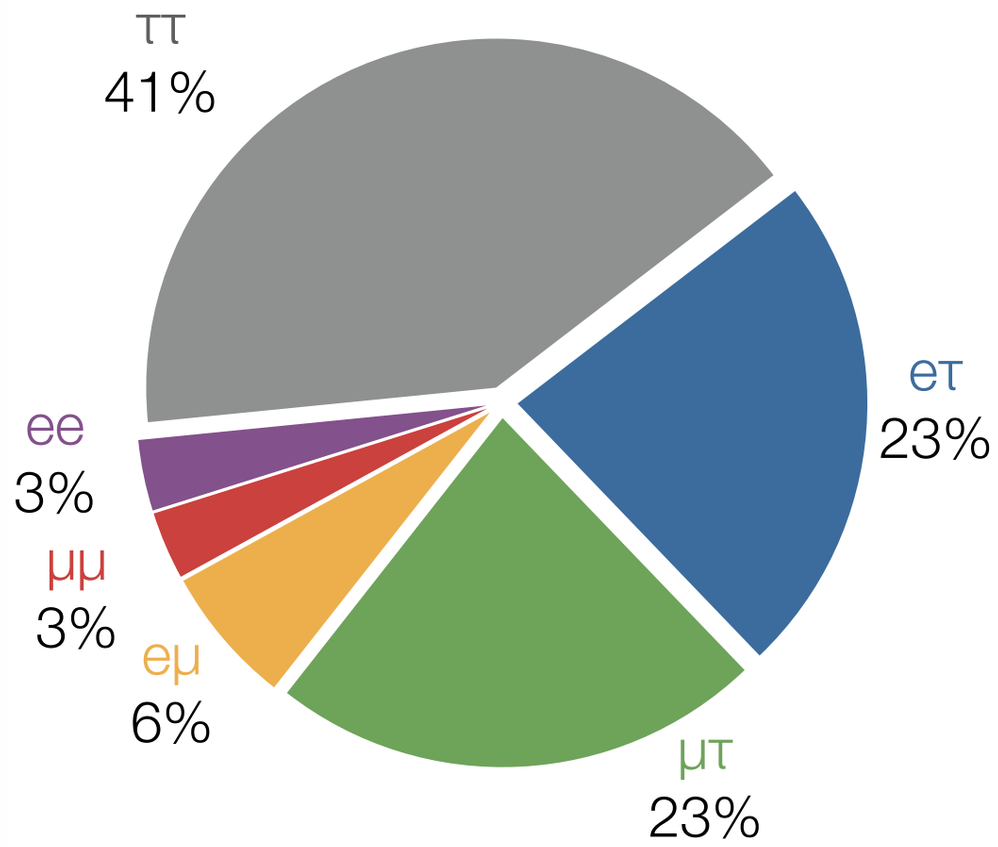
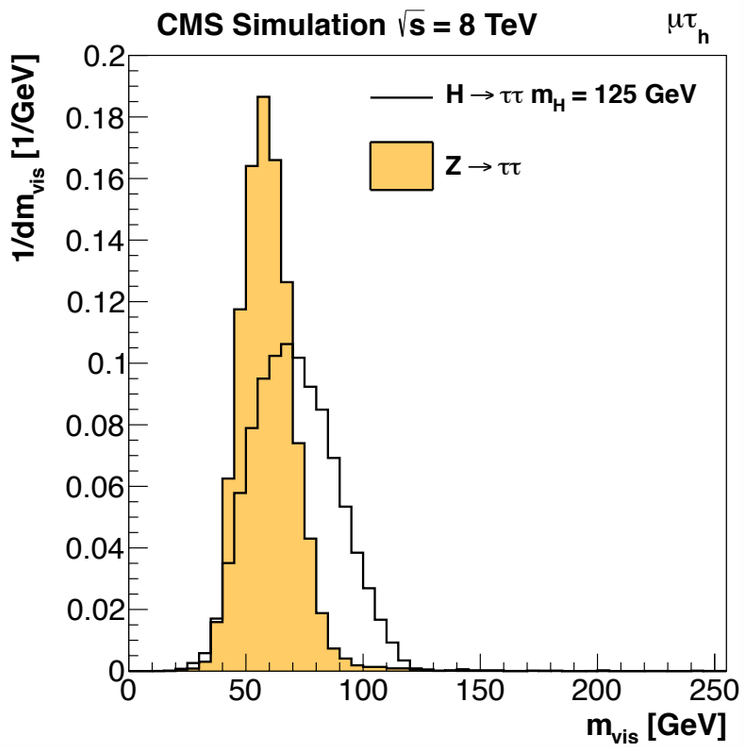
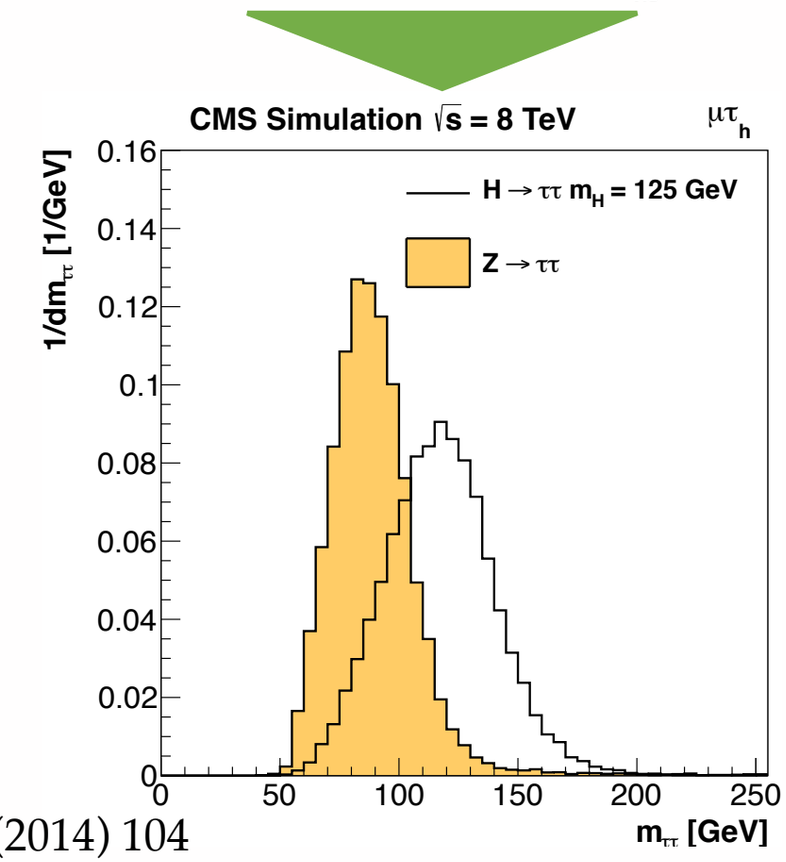
- Direct production:
  - All six possible final states analysed
- Associated production:
  - Most of the final states covered
    (see Armin Burgmeier's talk)



Mass reconstruction

- Neutrinos in tau decays smear invariant mass spectrum
- **numerical likelihood integration**
  - Includes MET information
- Mass resolution: **10-20%**
- Improves Z/H separation

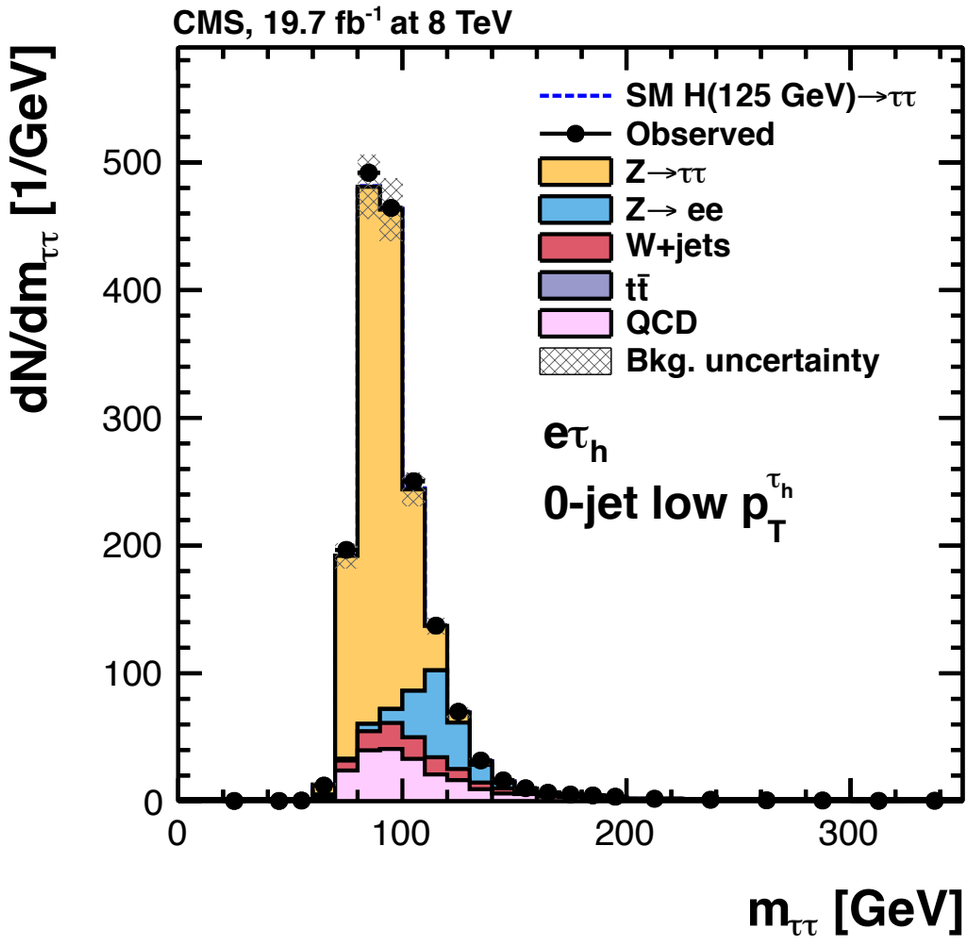




Backgrounds

Top pair

Shape taken from MC simulation, normalization from dedicated sideband



Z→ℓℓ

Shape taken from simulation. Yield corrected with dedicated sideband or T&P studies

Uncertainties:
20-74% for lepton faking tau. 2% on mass scale

W+Jets

Shape taken from MC simulation,
normalization from high $M_T(\mu,MET)$ sideband

Uncertainties:
10-100% normalization

Z→ττ

Embedded MC:
real Z→$\mu\mu$ events with a simulated tau replacing the muon. Normalization from Z→$\mu\mu$ data.

Uncertainties:
8-19% Tau ID and trigger efficiency,
3% Tau energy scale

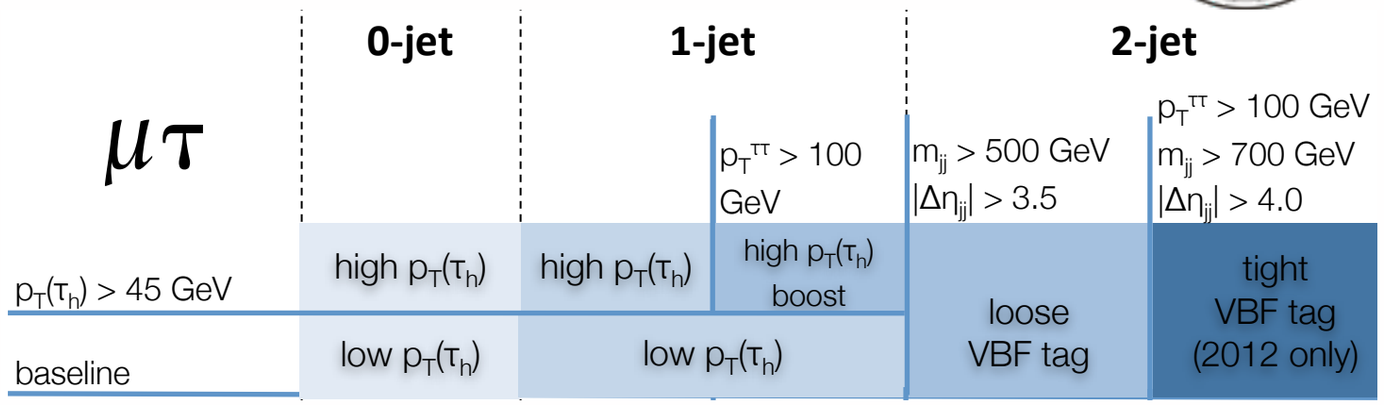
QCD

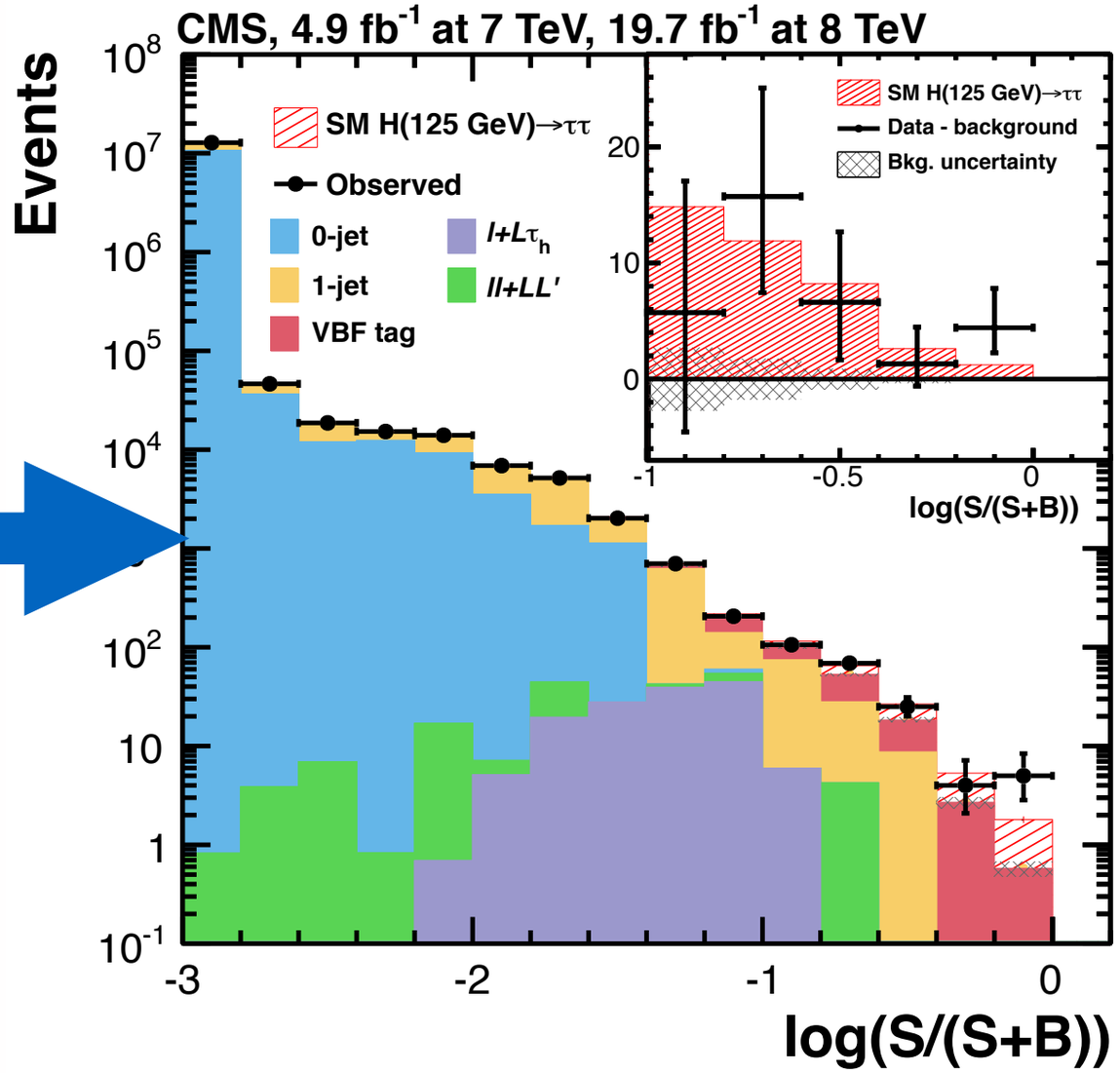
Jets identified as lepton/tau.
Dedicated control region with **SS** objects or relaxed isolation

Uncertainties:
6-70% Normalization

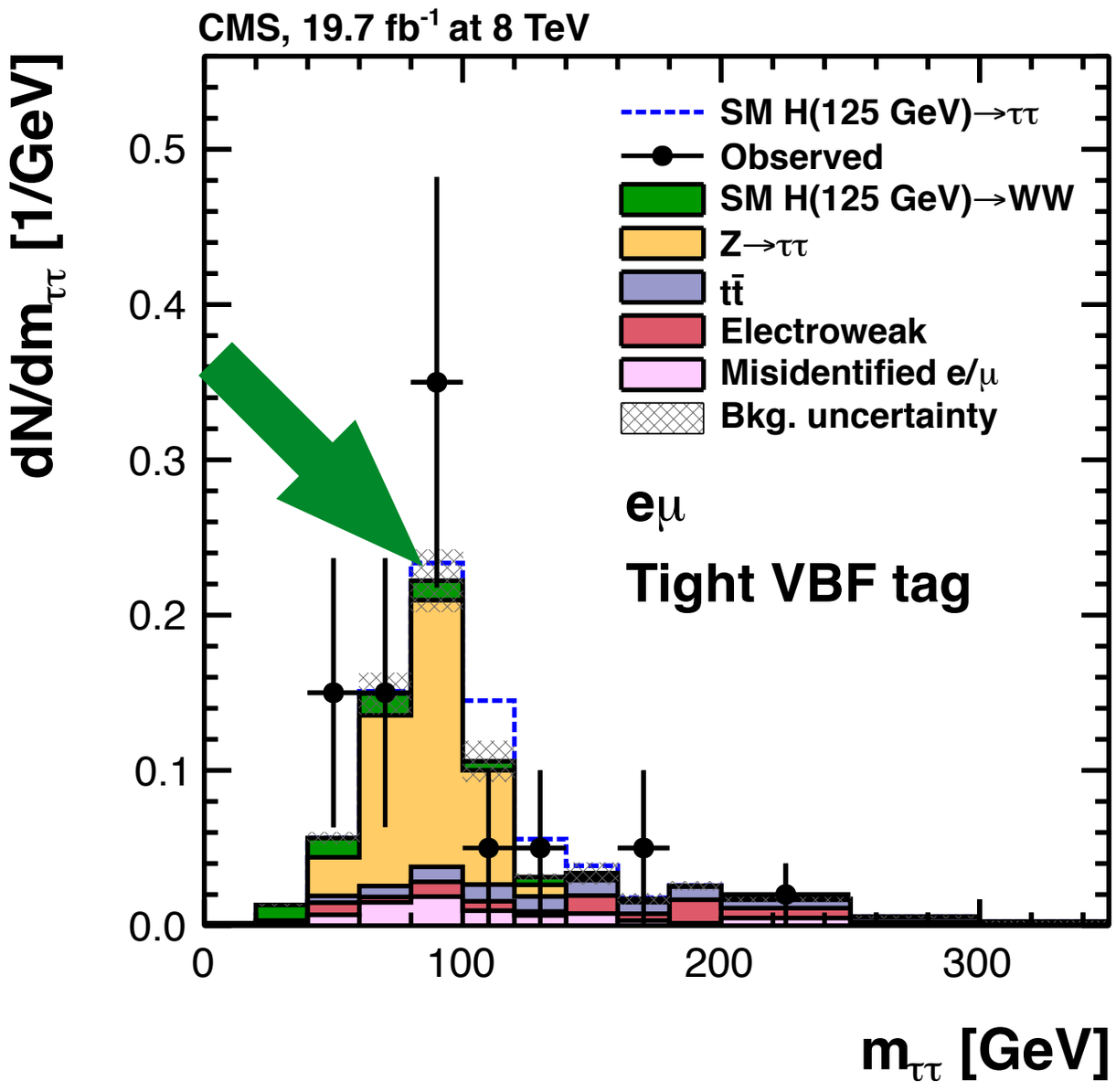
Analysis strategy

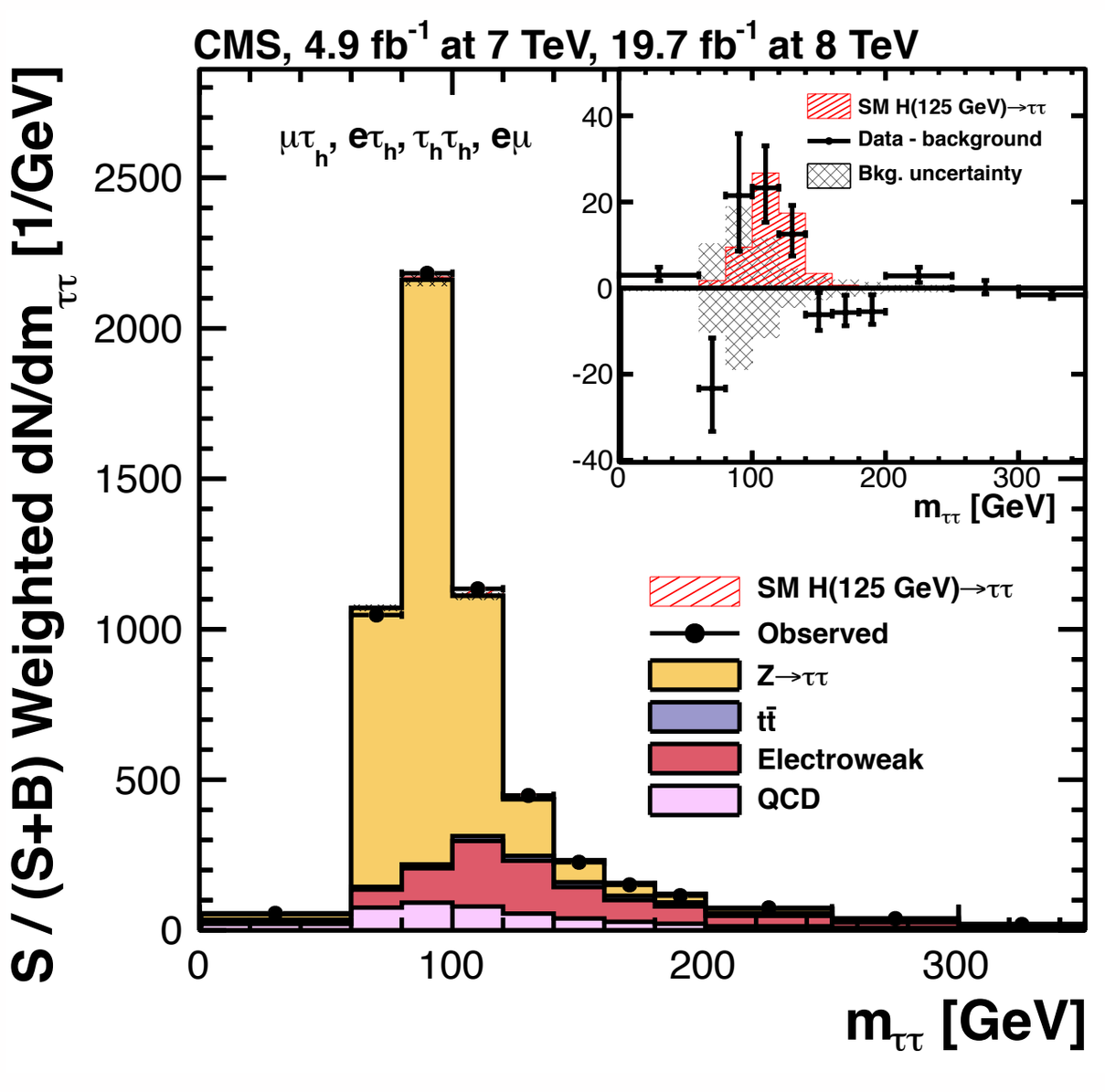
- Fine segmentation in categories
- Mass resolution improved with likelihood integration
- Exploit peculiar topologies or improved resolution
- **High stats categories help constraining systematics**
  - e.g. tau ID efficiency and energy scale
- Improves sensitivity





Analysis strategy



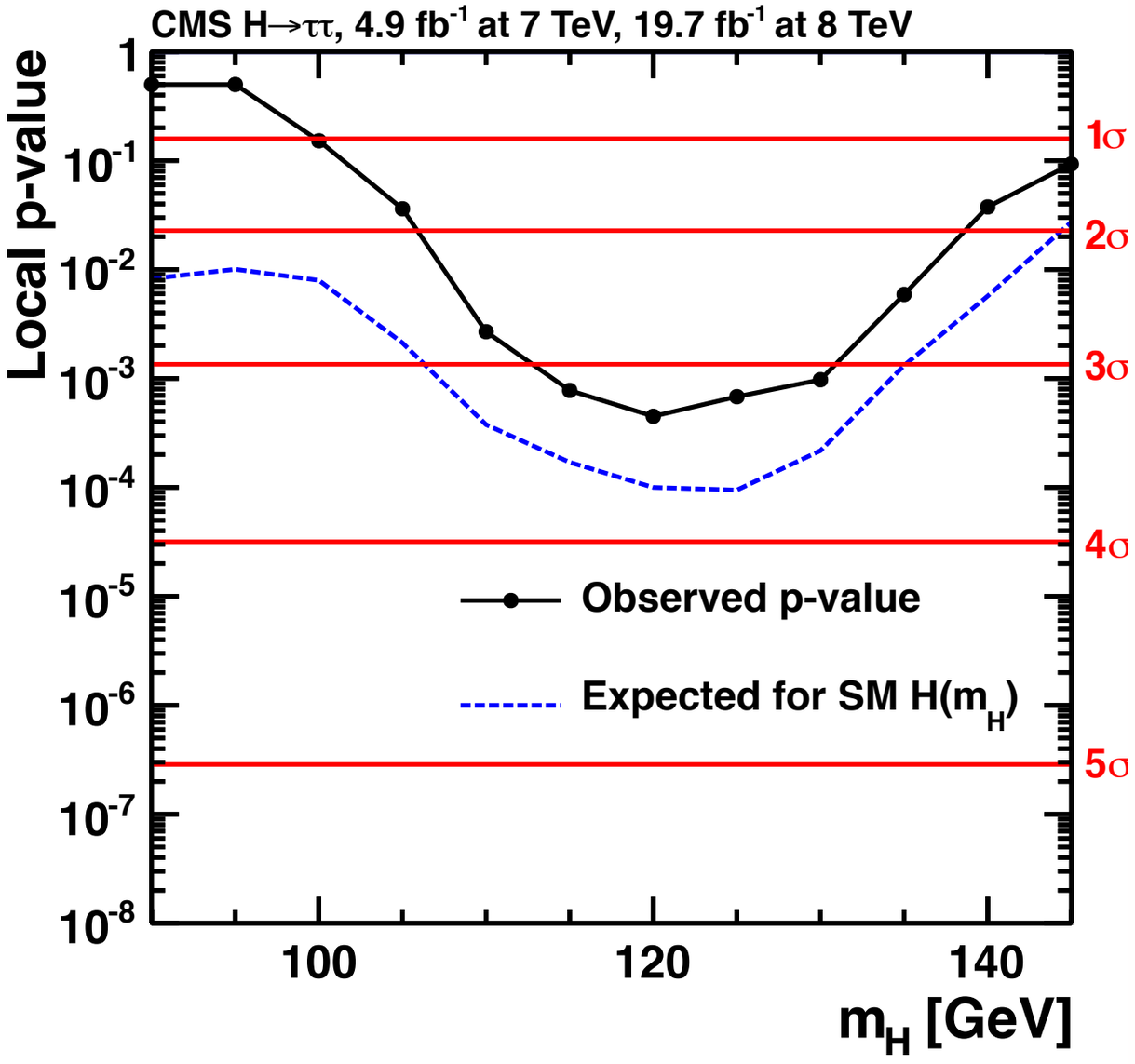


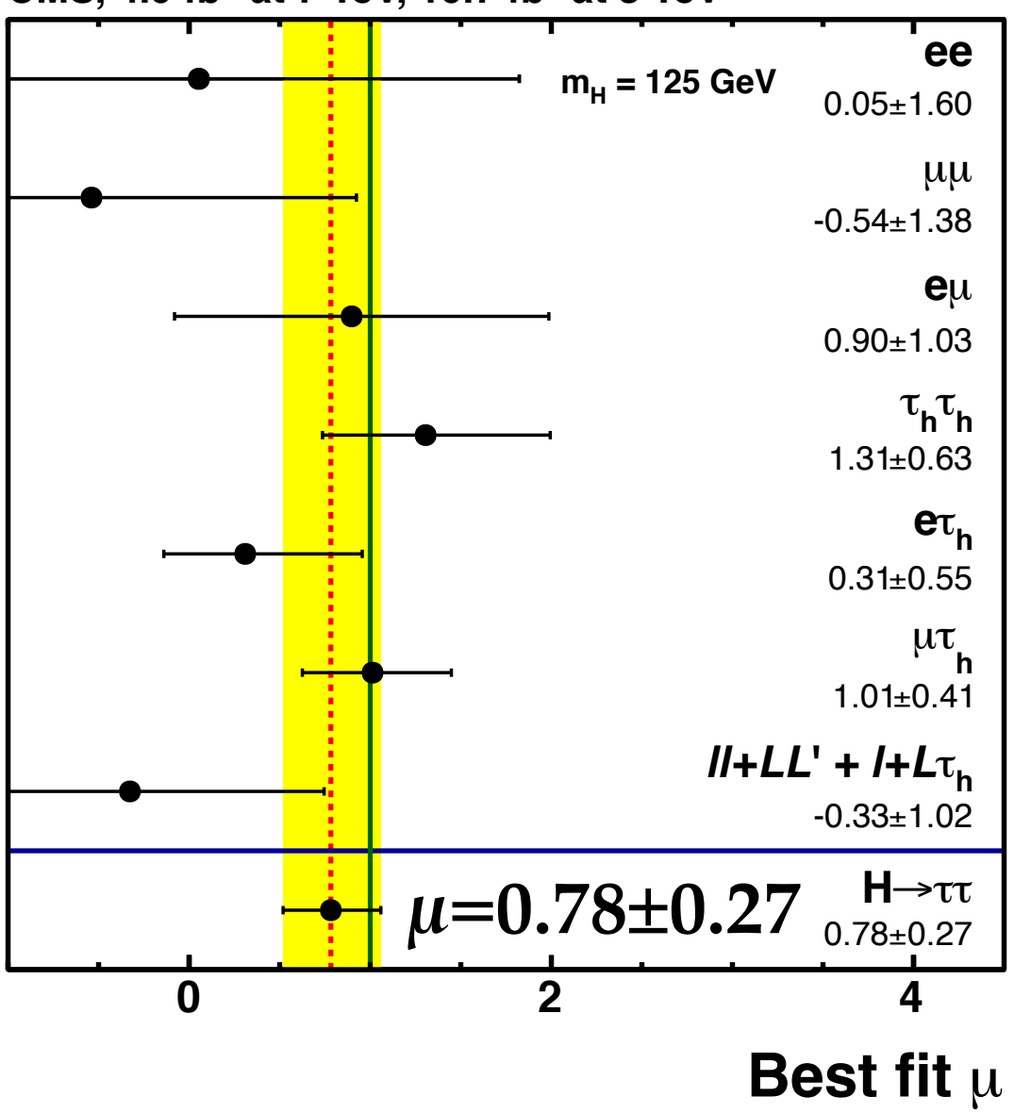
H→WW treated as background

Results

3.2σ significance.

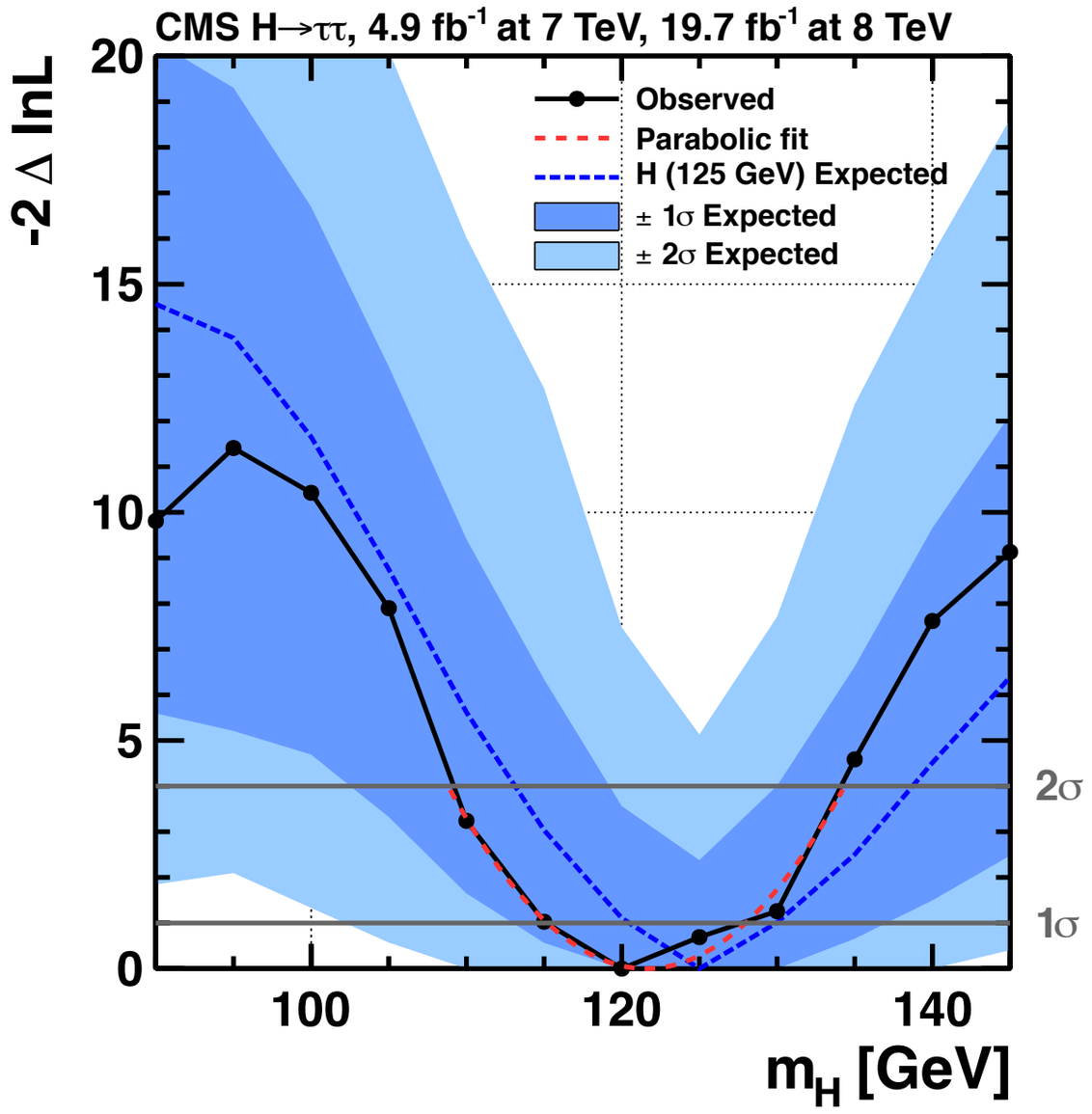
First evidence of H→ττ at CMS

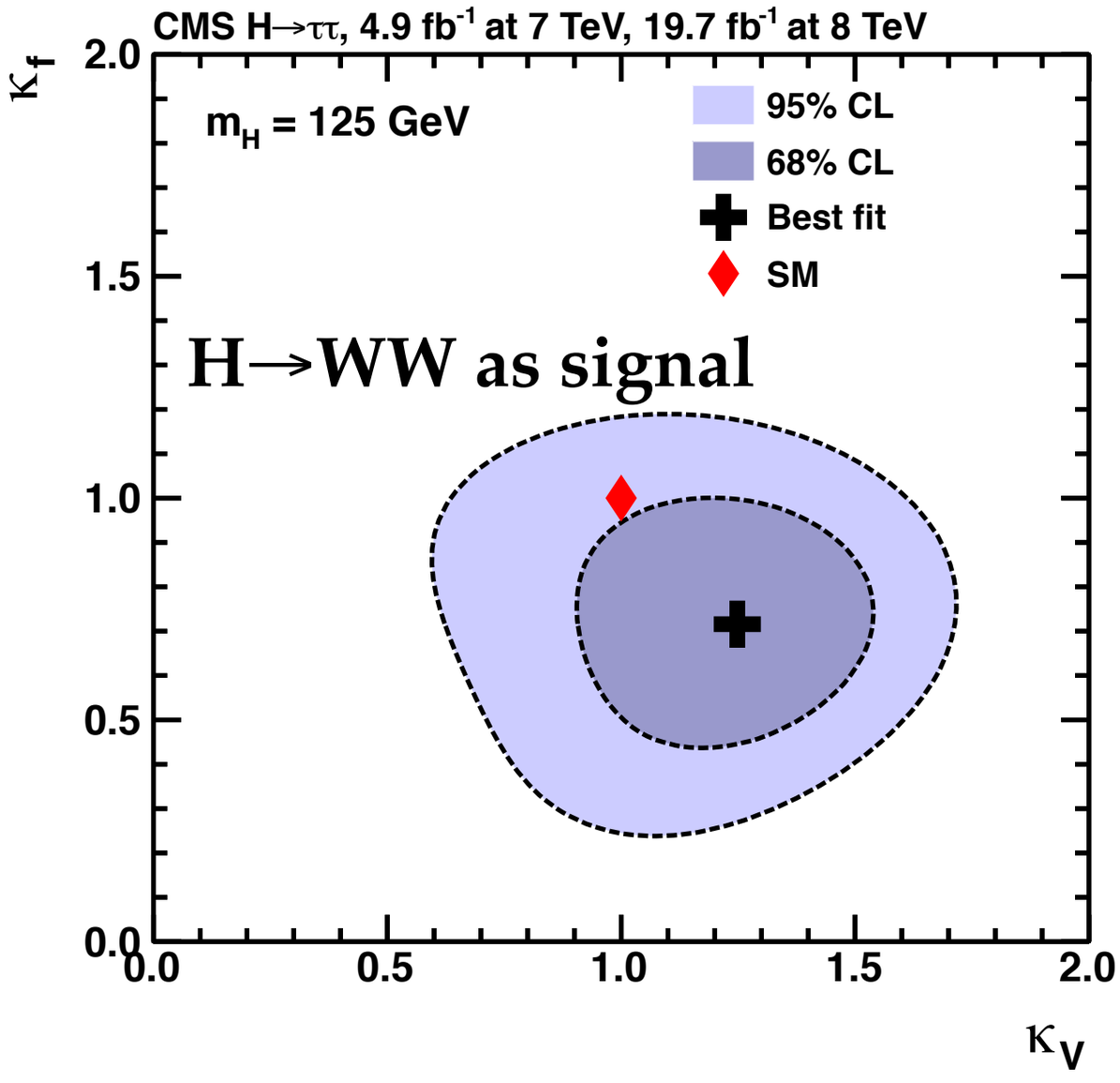




Results

Mass: 122 ± 7 GeV

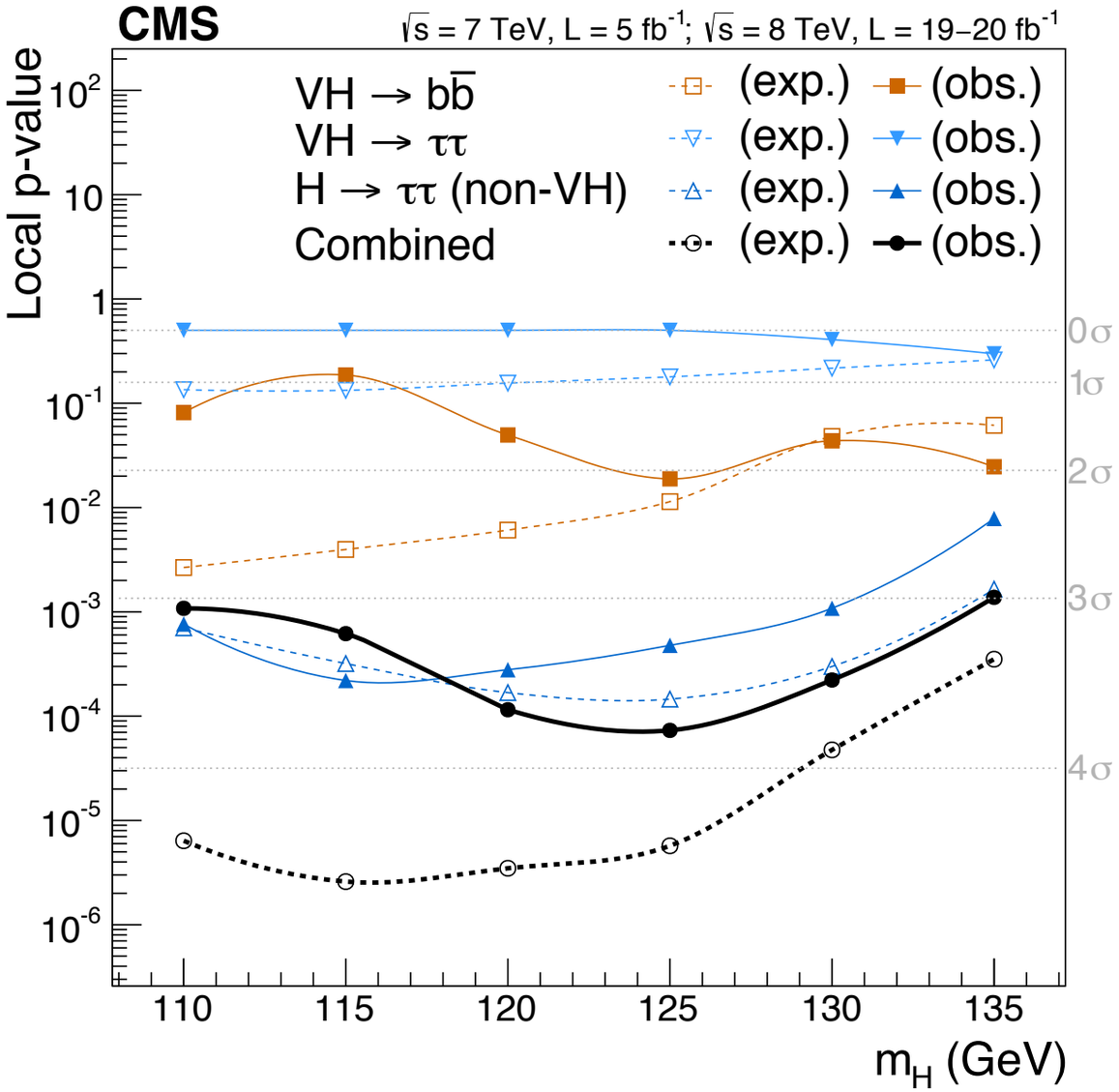


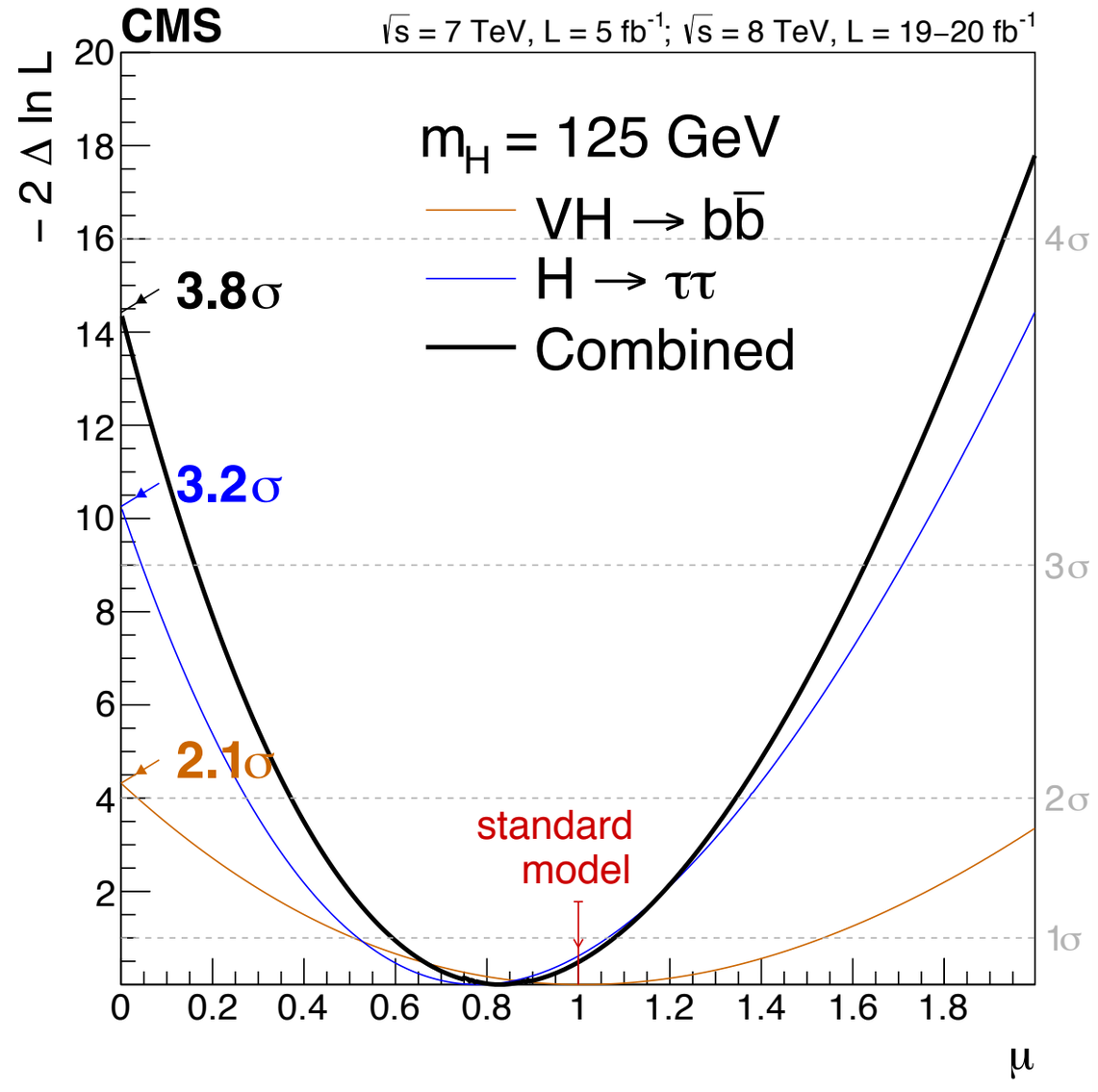


Combination

Nature Phys. 10 (2014)

Evidence of Higgs coupling to "down" type fermions





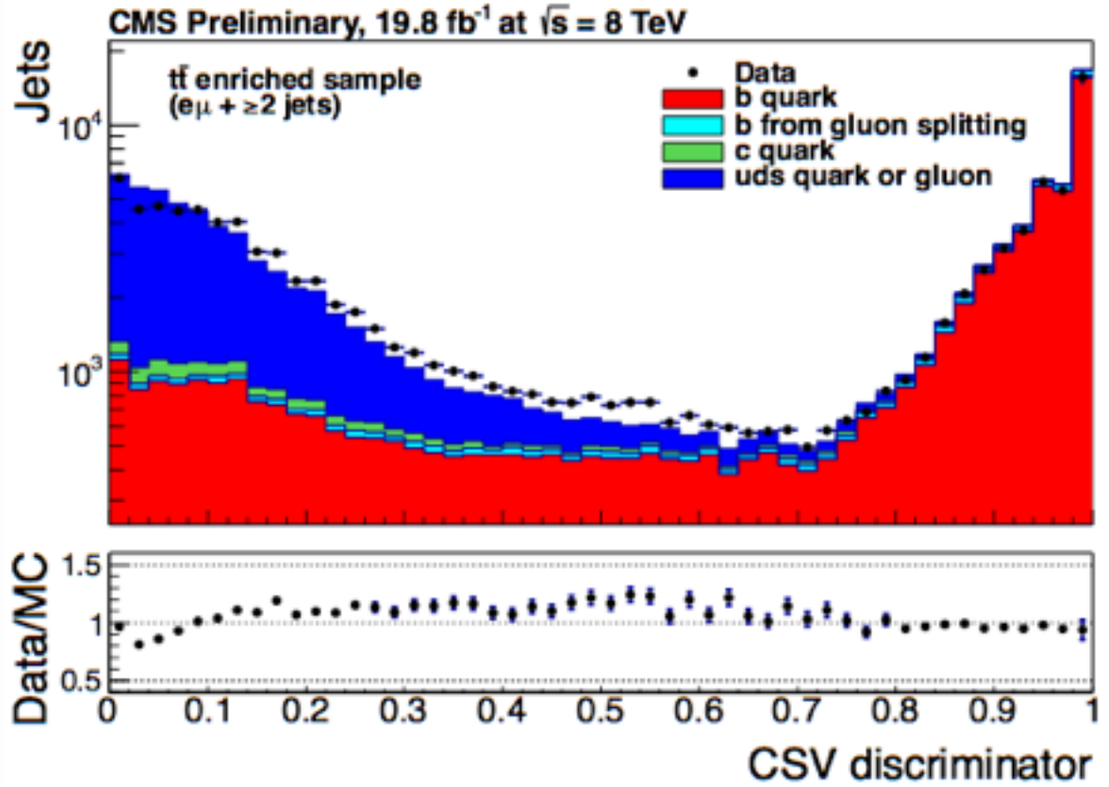
Conclusions

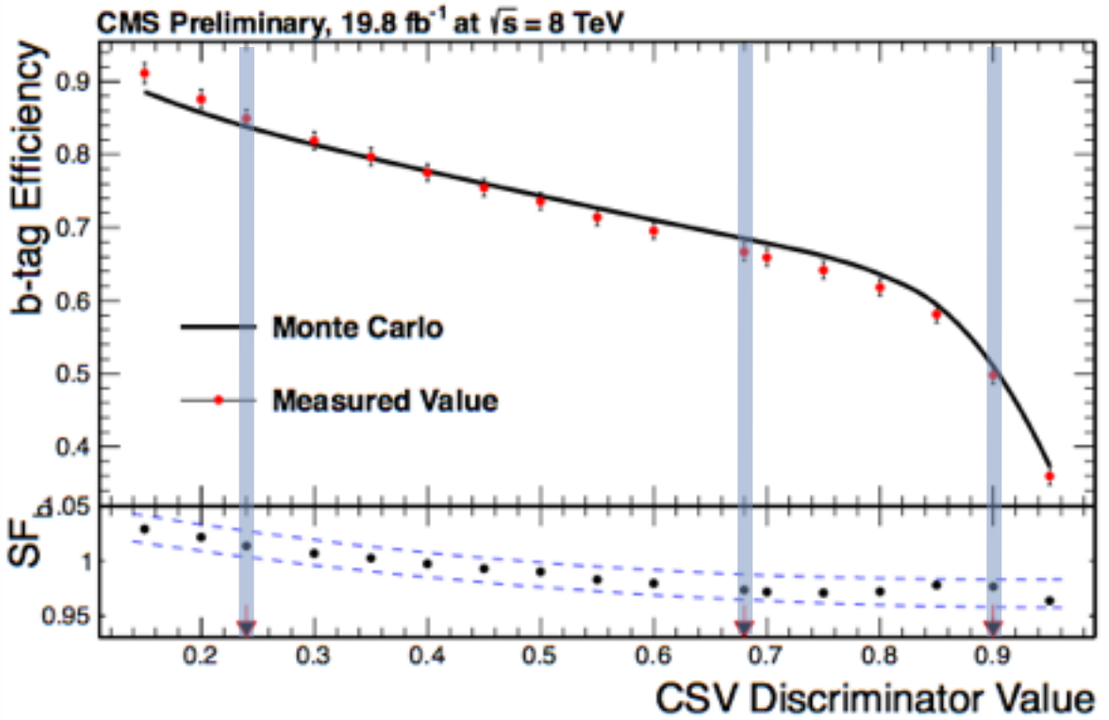
- Combined evidence of Higgs decay to fermions
  - **3.2σ** in H→ττ
  - **3.8σ** combined H→ττ + VH(bb)
- Couplings of Higgs to bosons and fermions compatible with SM predictions
- Excess in ttH worth some future attention

Back-up

b-Tagging

- b-Tagging performed by **C**ombined **S**econdary **V**ertex discriminator
- Multivariate approach to get maximum background rejection
- Track information: impact parameters of leading tracks in the jet
- Vertex information from secondary vertices inside the jet (if any)

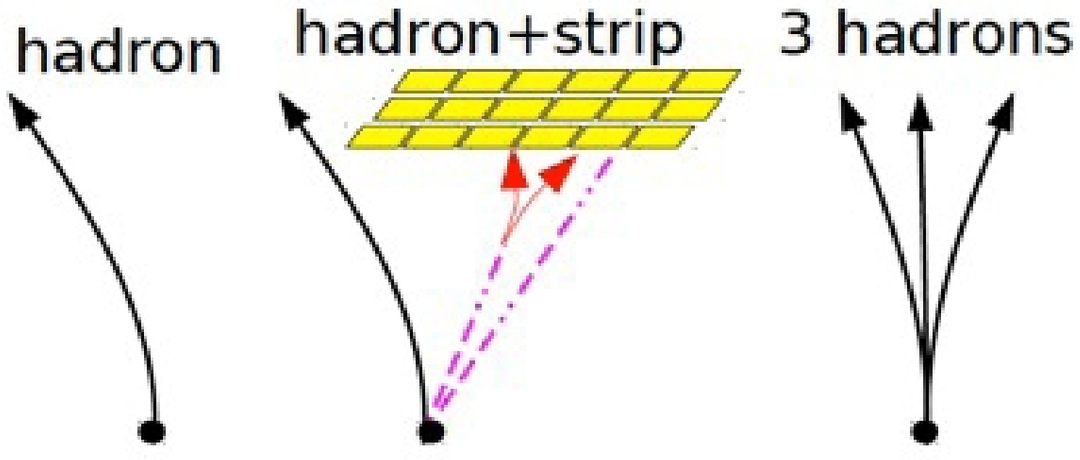




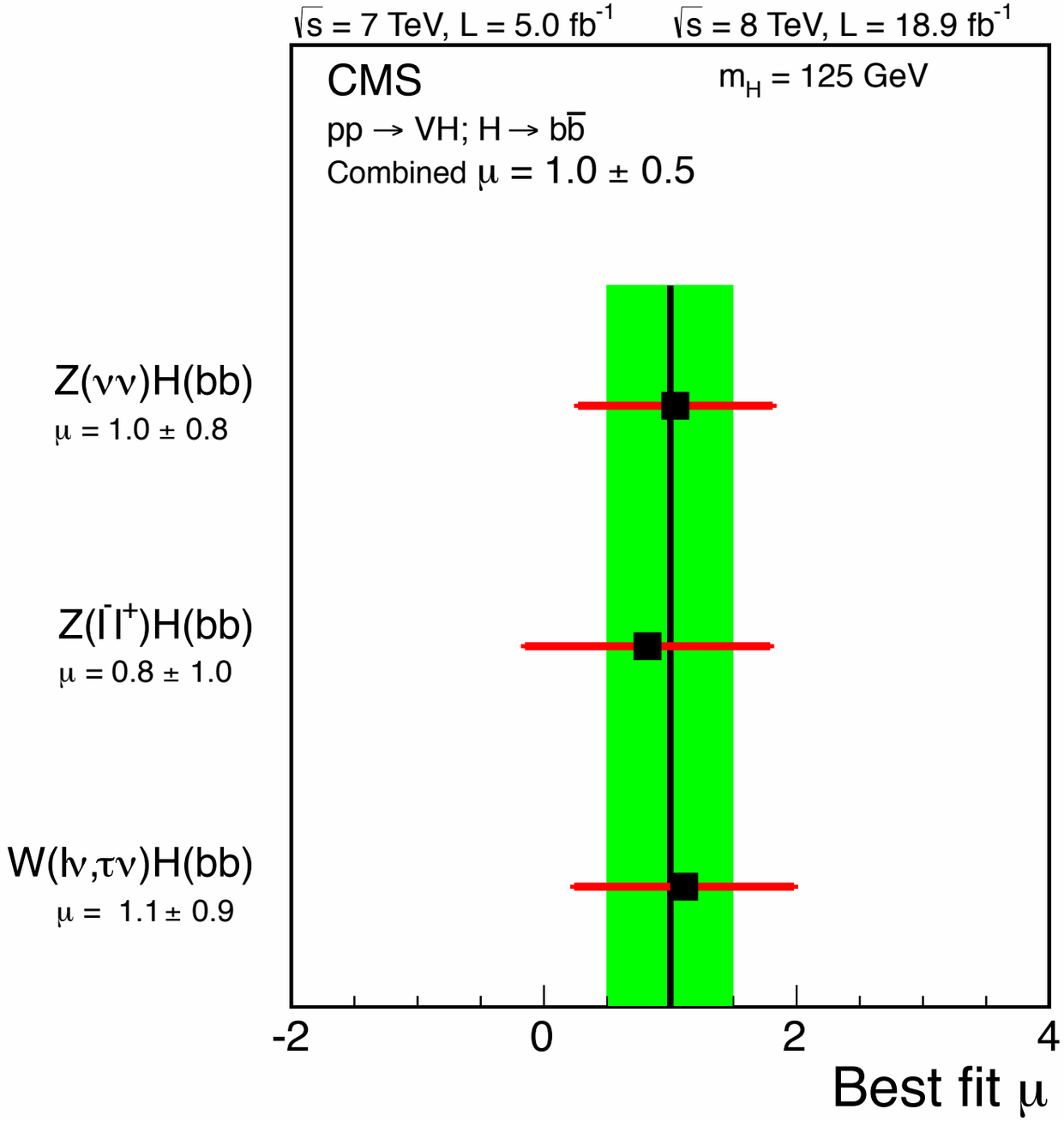
- b-tagging
- Tau Identification
- VHbb
- Htt
- LVF Htμ

Tau identification

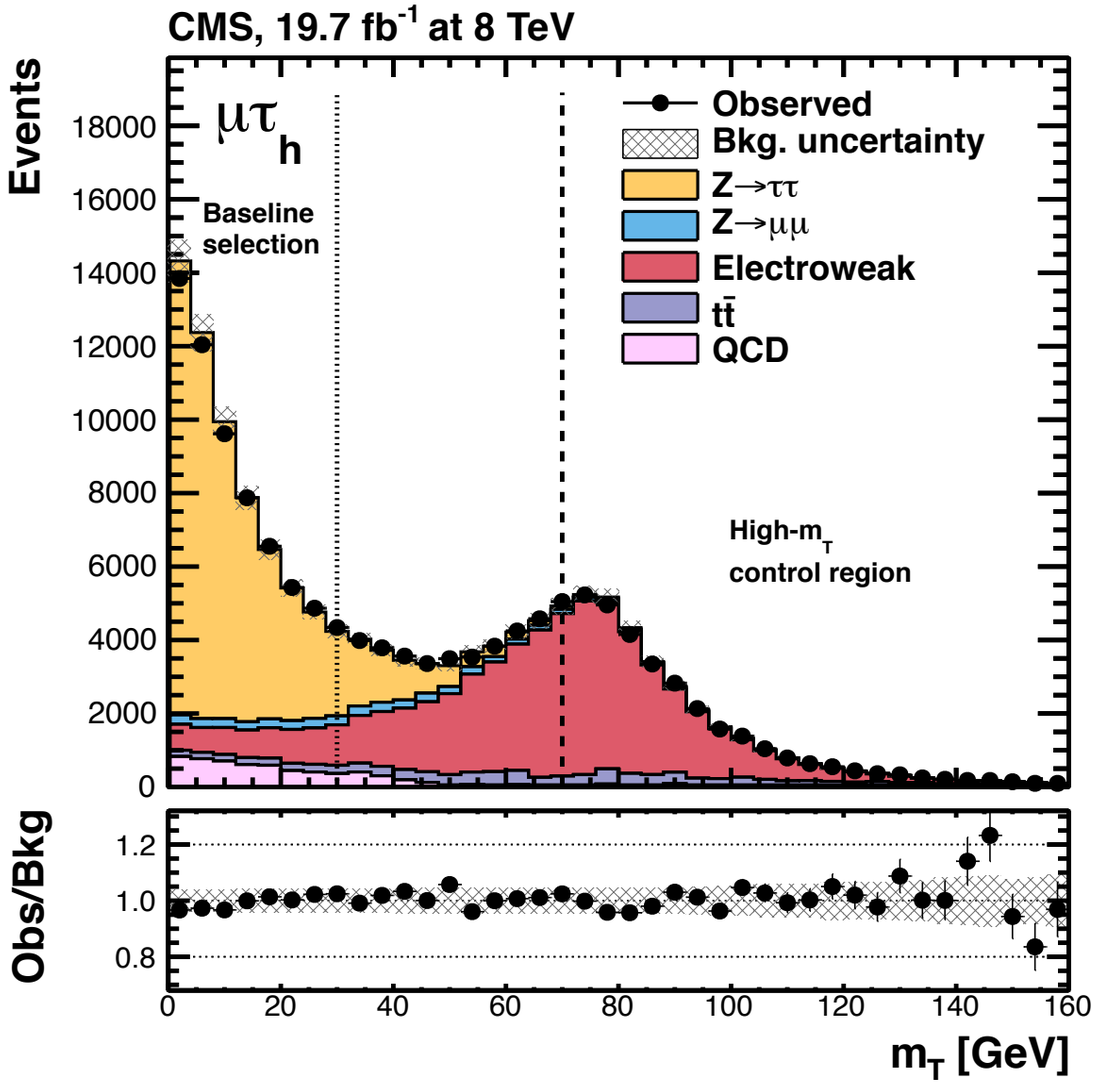
- **Identification:**
  - Based on **P**article **F**low objects
  - Reconstructs the decay modes starting from charged hadrons and ECAL strips
- **Additional discriminators to reject light leptons**
- **Isolation:**
  - PF-based isolation
  - Pile-Up correction using $\Delta\beta$
- **Identification also available at trigger level**

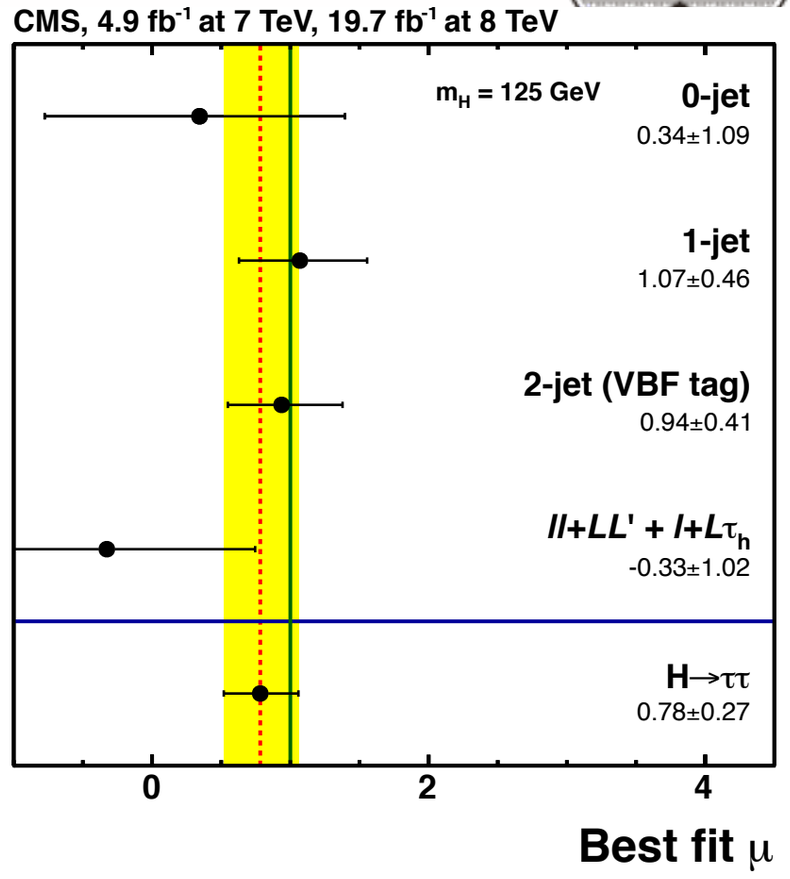


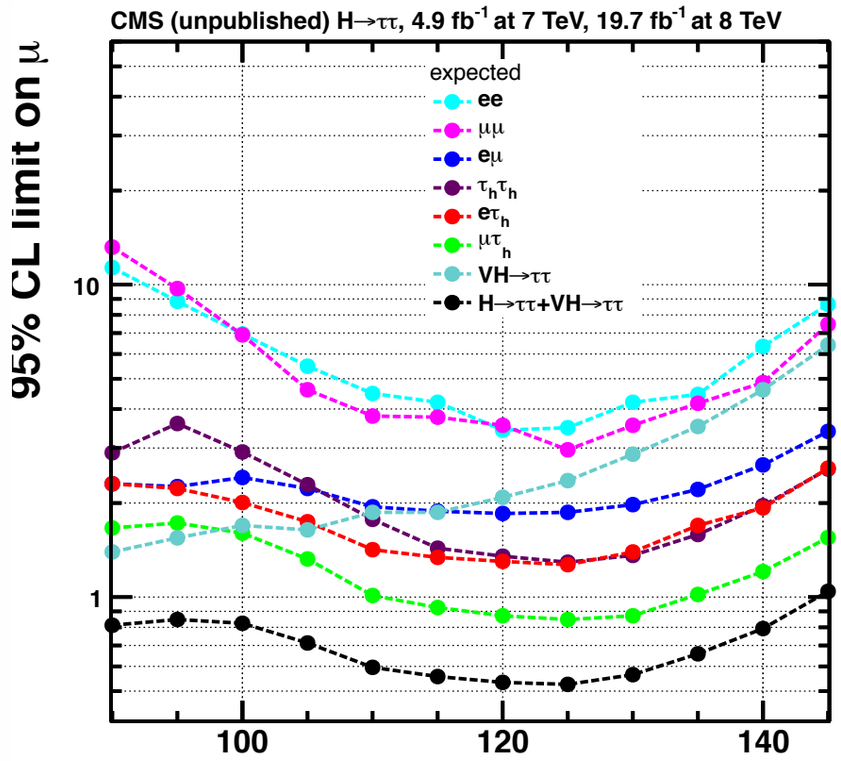
VH(bb)


√s = 7 TeV, L = 5.0 fb-1
√s = 8 TeV, L = 18.9 fb-1
CMS
mH = 125 GeV
pp → VH; H → bb̄
Combined μ = 1.0 ± 0.5
Z(νν)H(bb)
μ = 1.0 ± 0.8
Z(l⁻l⁺)H(bb)
μ = 0.8 ± 1.0
W(lν,τν)H(bb)
μ = 1.1 ± 0.9
-2
0
2
4
Best fit μ

Hττ


CMS, 19.7 fb-1 at 8 TeV
μτh
Baseline selection
High-mT control region
Observed
Bkg. uncertainty
Z→ττ
Z→μμ
Electroweak
tt̄
QCD
Events
Obs/Bkg
mT [GeV]

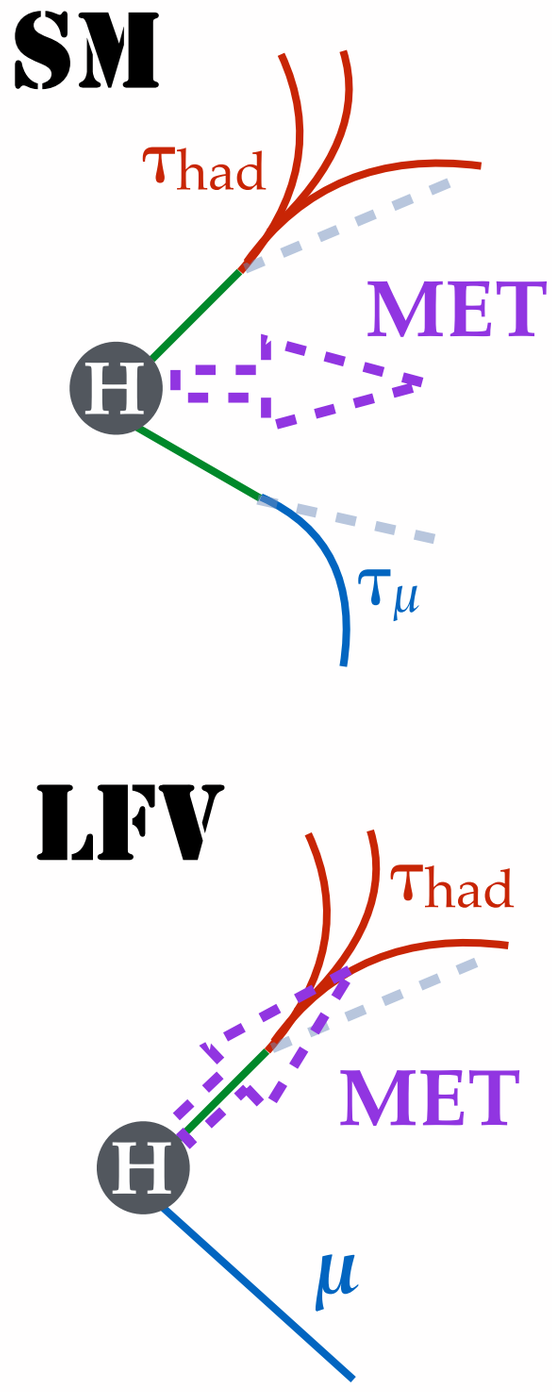

CMS, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
mH = 125 GeV
0-jet
0.34±1.09
1-jet
1.07±0.46
2-jet (VBF tag)
0.94±0.41
ll+LL' + l+Lτh
-0.33±1.02
H→ττ
0.78±0.27
Best fit μ


CMS (unpublished) H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
expected
ee
μμ
eμ
τhτh
eτh
μτh
VH→ττ
H→ττ+VH→ττ
95% CL limit on μ
mH [GeV]

Search for H→$\mu\tau$

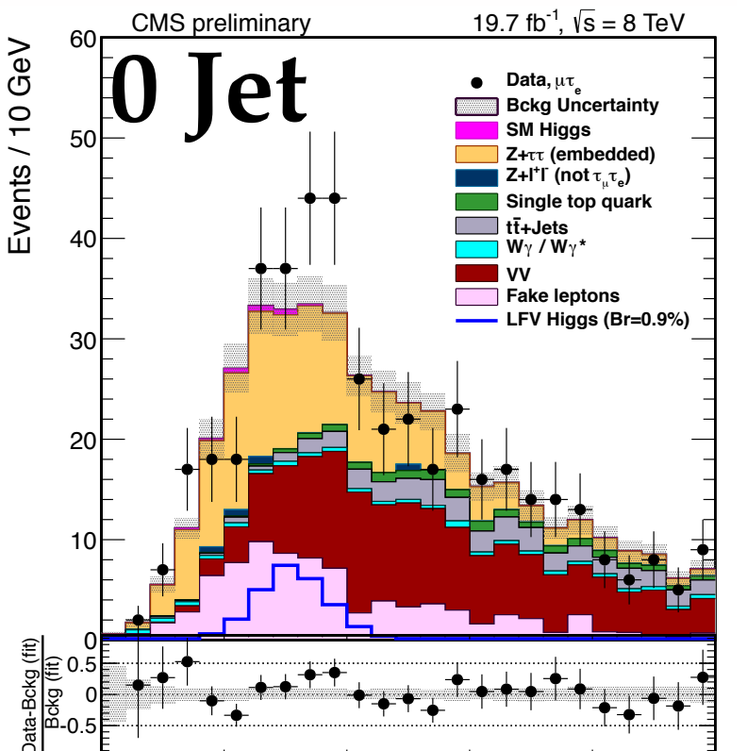
HIG-14-005

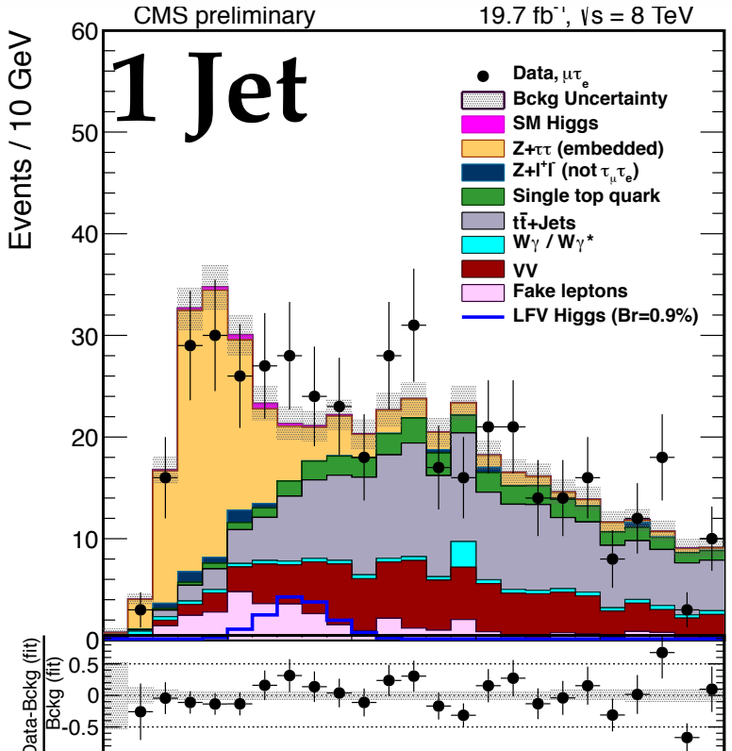
- Lepton flavour violation (LFV) is allowed in many models
  - Higgs doublet models
  - Randall-Sundrum models
- Previous best limit **B(H→$\mu\tau$) < ~10%** from LHC H→$\tau\tau$ and $\tau\to\mu\gamma$
  - Can be improved with dedicated search
- $\mu\tau_h$ $\mu\tau_e$ considered so far
- **Similar categorisation as in H→$\tau\tau$**
- Slightly different topology:
  - Harder muon p_T spectrum
  - Only one MET source
    - MET pointing towards τ
    - Collinear approximation for invariant mass

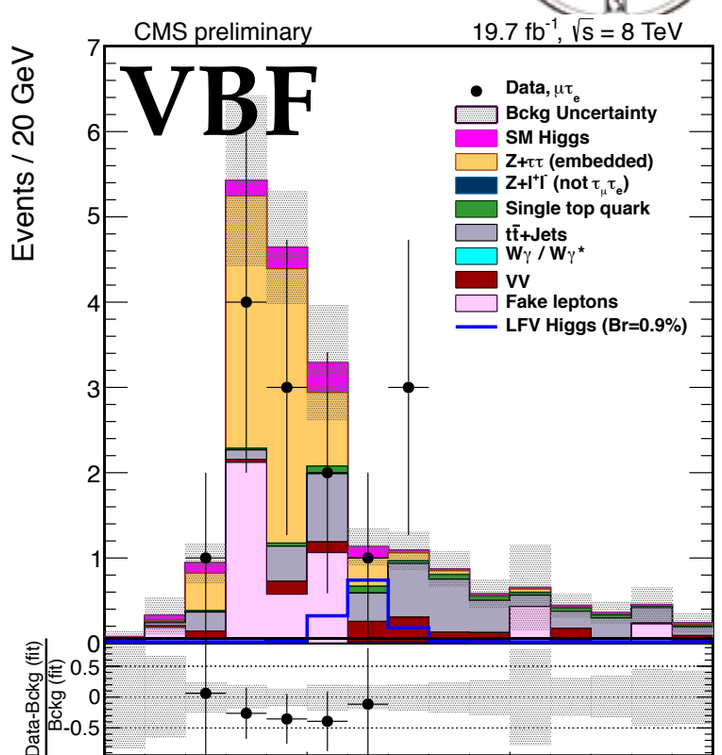


LFV

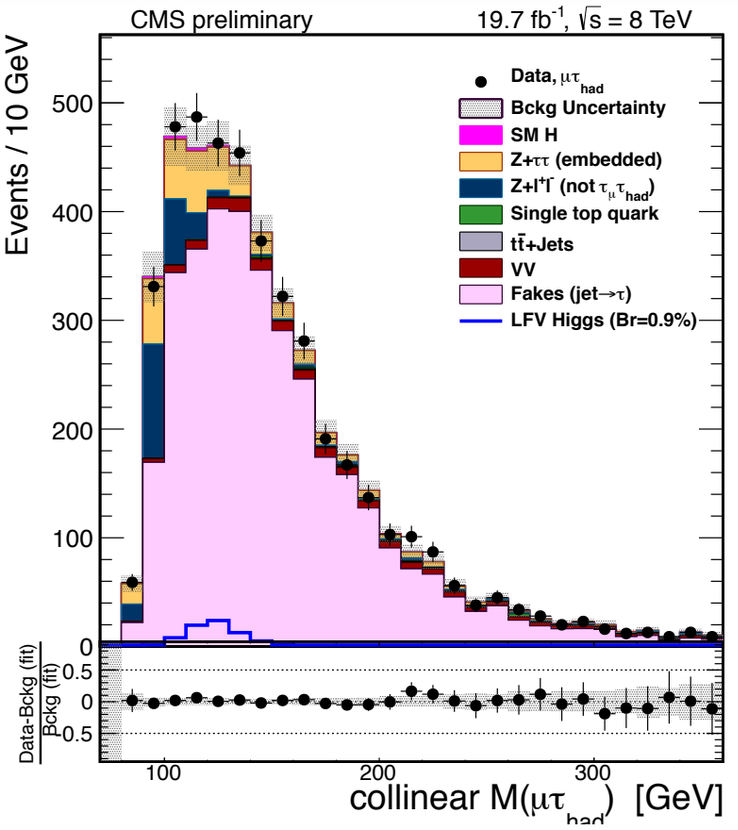
$e\mu$

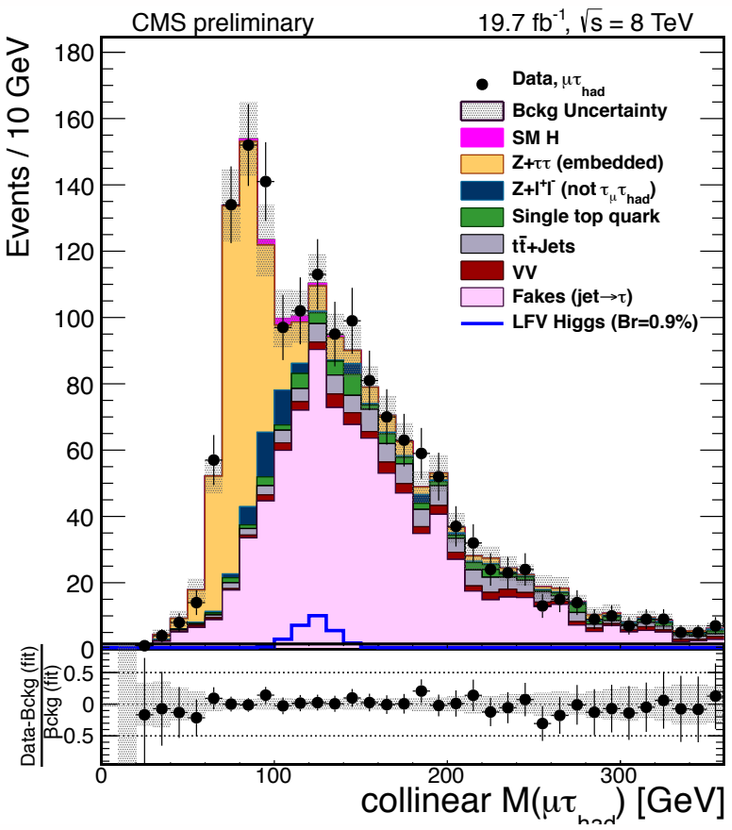


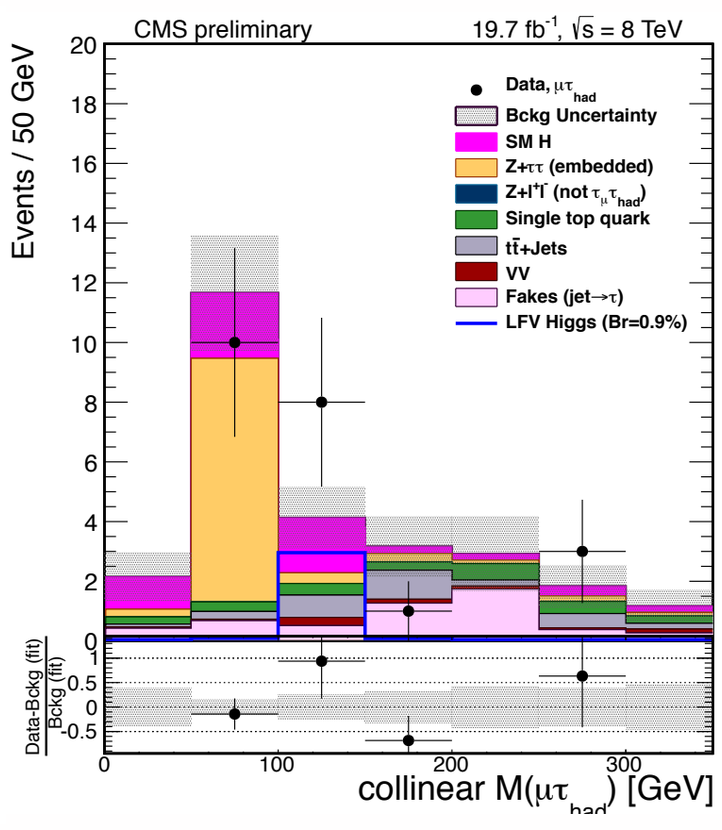




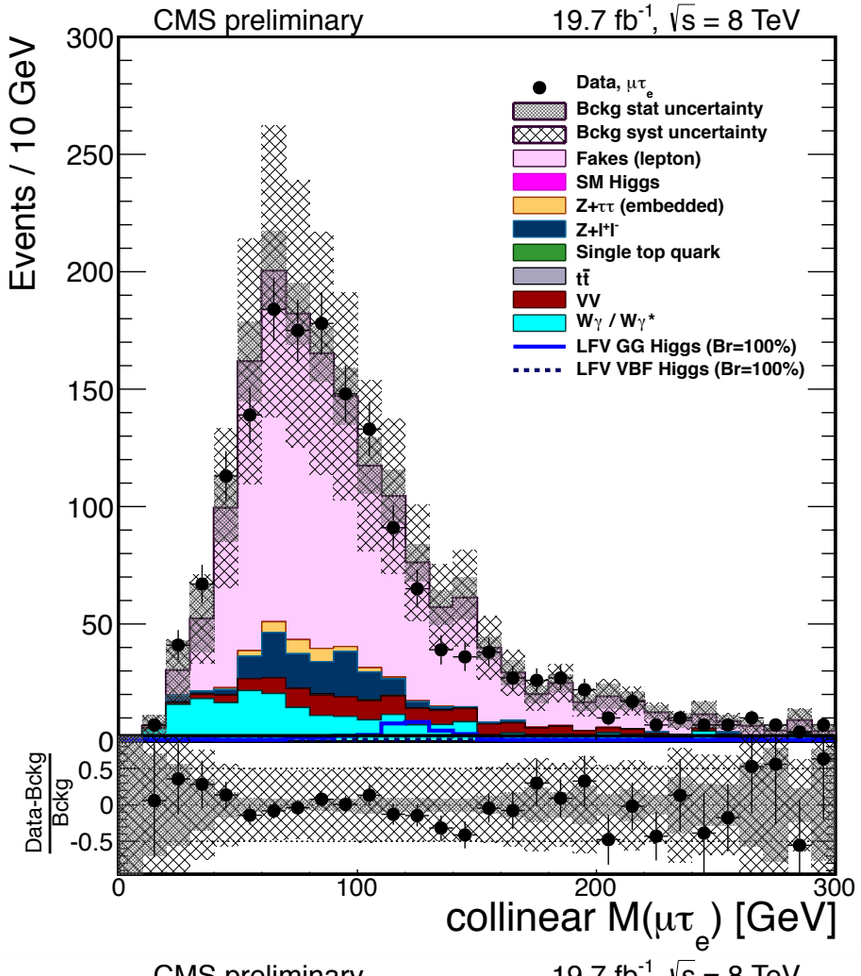
$\mu\tau$

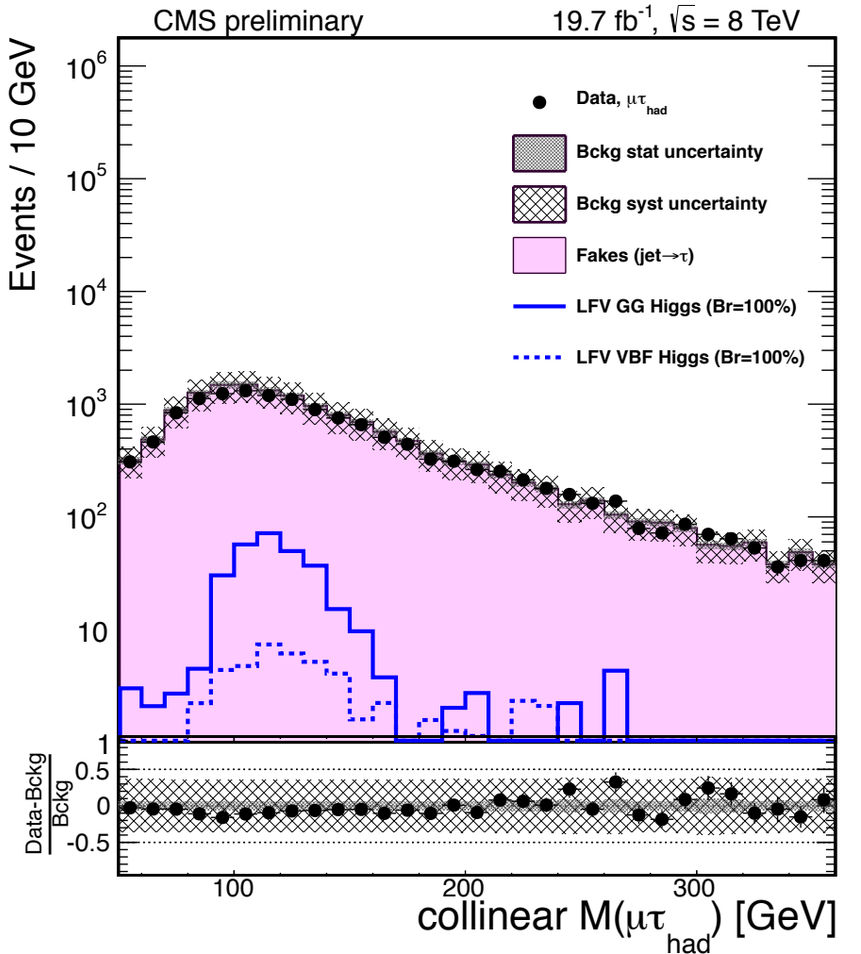


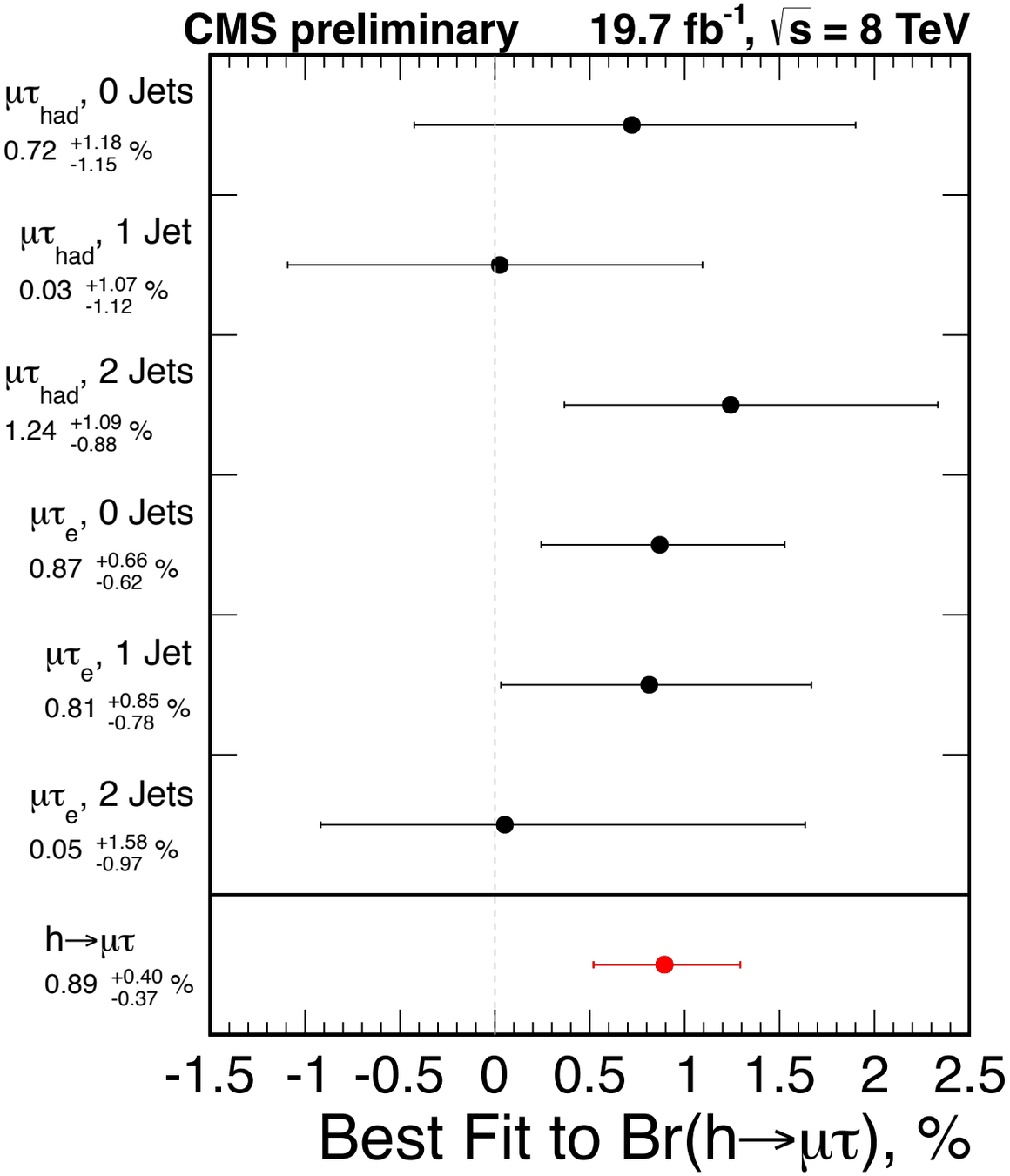




LFV


CMS preliminary
19.7 fb-1, √s = 8 TeV
Events / 10 GeV
Data, μτe
Bckg stat uncertainty
Bckg syst uncertainty
Fakes (lepton)
SM Higgs
Z+ττ (embedded)
Z+l+l-
Single top quark
tt̄
VV
Wγ / Wγ*
LFV GG Higgs (Br=100%)
LFV VBF Higgs (Br=100%)
Data-Bckg / Bckg
collinear M(μτe) [GeV]


CMS preliminary
19.7 fb-1, √s = 8 TeV
Events / 10 GeV
Data, μτhad
Bckg stat uncertainty
Bckg syst uncertainty
Fakes (jet→τ)
LFV GG Higgs (Br=100%)
LFV VBF Higgs (Br=100%)
Data-Bckg / Bckg
collinear M(μτhad) [GeV]

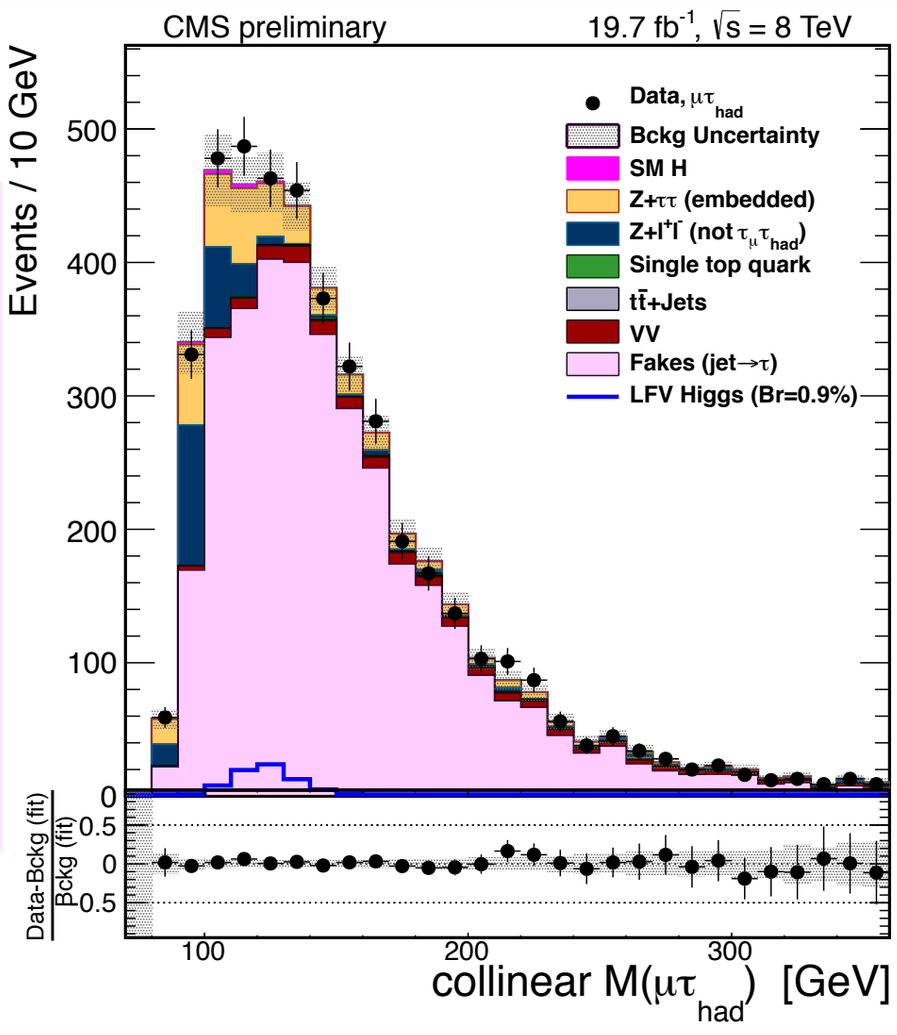

CMS preliminary
19.7 fb-1, √s = 8 TeV
μτhad, 0 Jets
0.72 +1.18 -1.15 %
μτhad, 1 Jet
0.03 +1.07 -1.12 %
μτhad, 2 Jets
1.24 +1.09 -0.88 %
μτe, 0 Jets
0.87 +0.66 -0.62 %
μτe, 1 Jet
0.81 +0.85 -0.78 %
μτe, 2 Jets
0.05 +1.58 -0.97 %
h→μτ
0.89 +0.40 -0.37 %
Best Fit to Br(h→μτ), %

Results

HIG-13-033

"Fake" background estimation fully data-driven (as in VH)

Large correlated uncertainties, mostly constrained by the fit

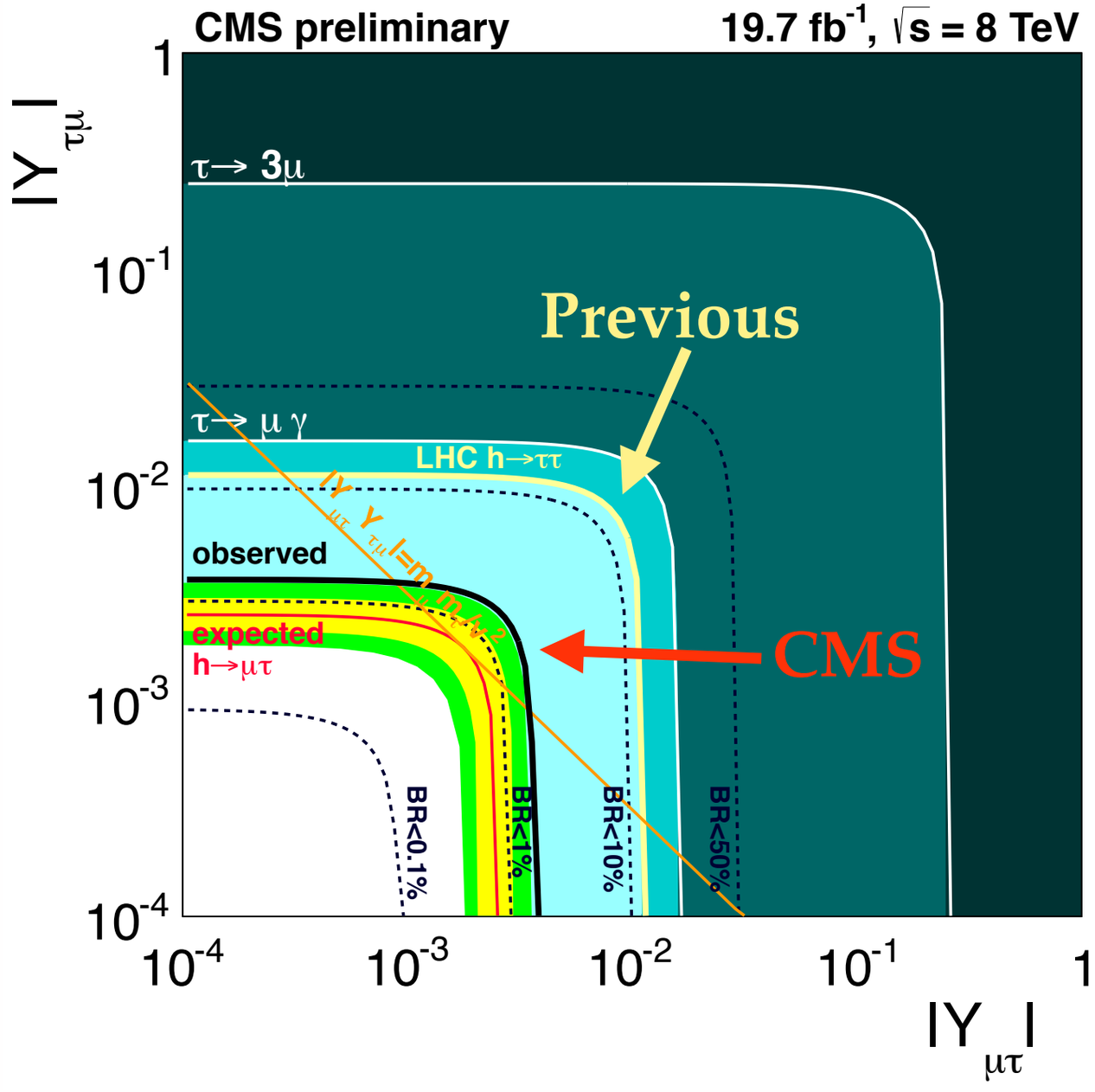


- **New best limit: 1.57%** (0.75% expected)
- 2.46σ above background only hypothesis
- Best fit $B(H\to\mu\tau) = 0.89^{+0.40}_{-0.37}\%$

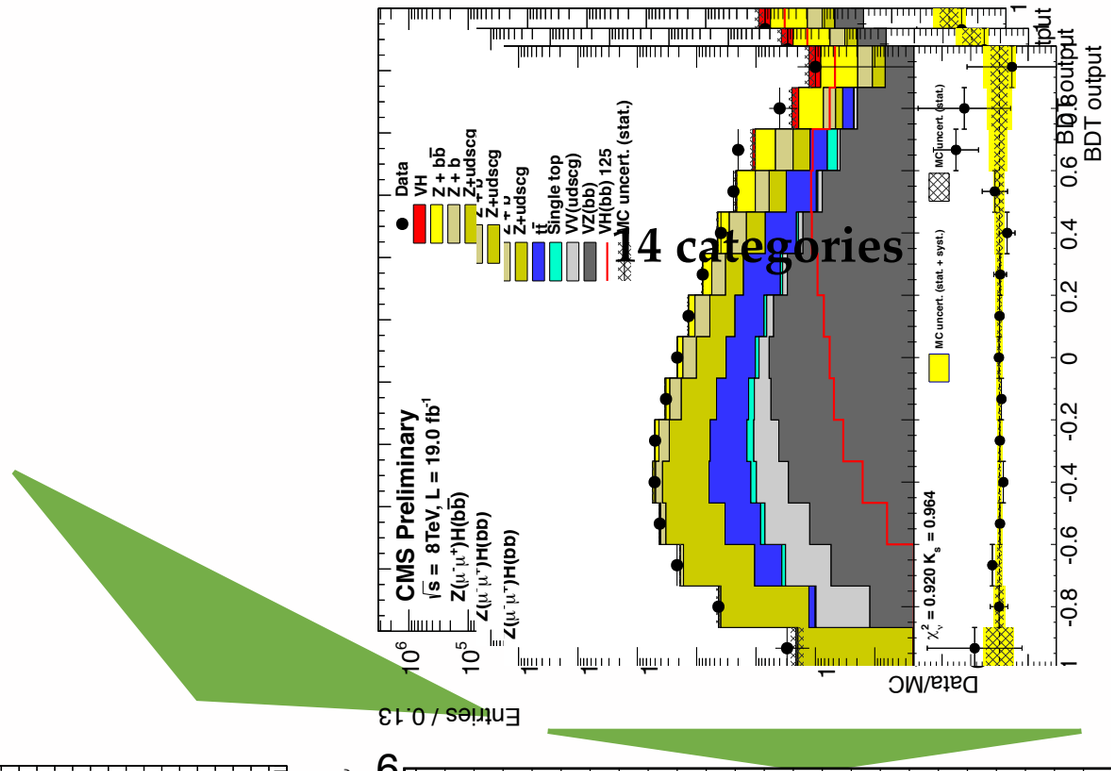
Yukawa coupling interpretation

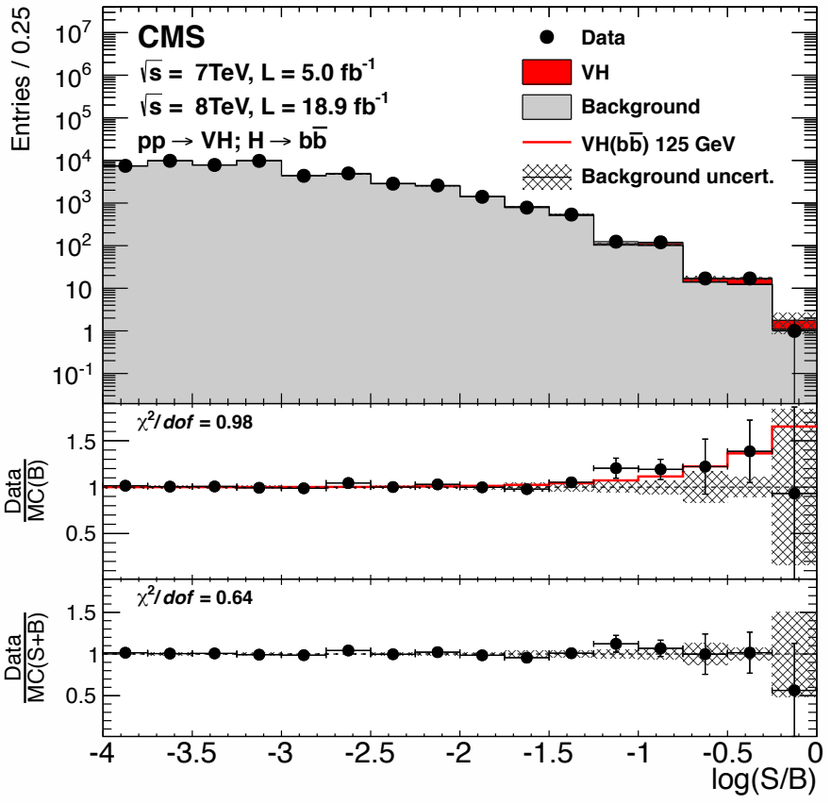
Translate branching ratio into Yukawa coupling limits:

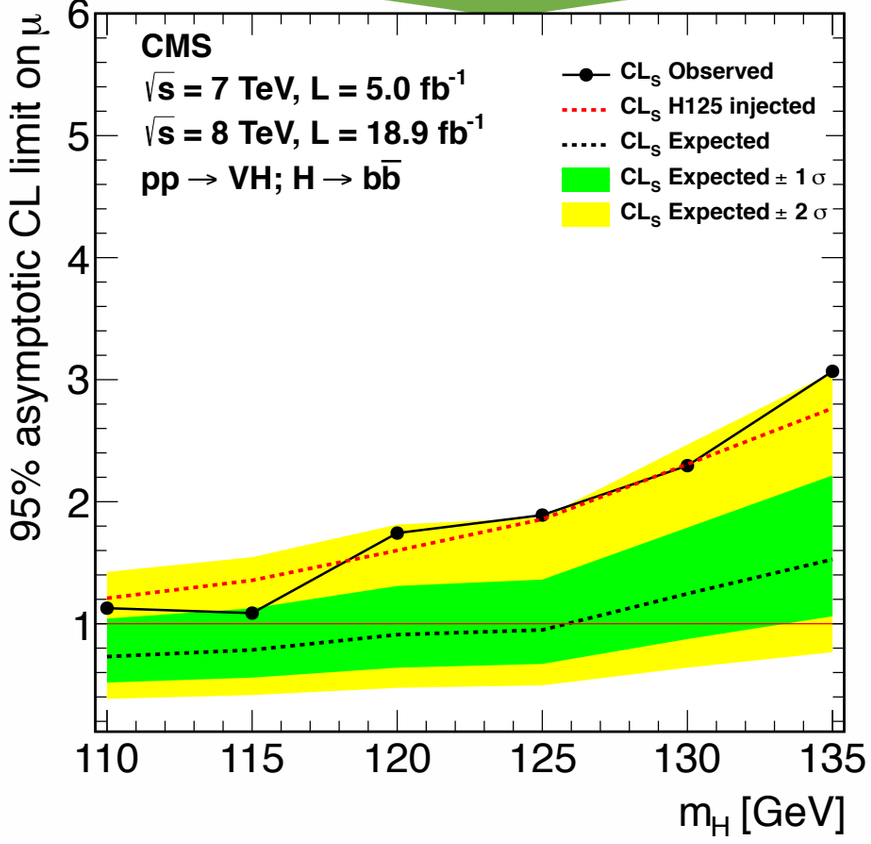
$$\sqrt{|\mathbf{Y}_{\mu\tau}|^2 + |\mathbf{Y}_{\tau\mu}|^2} < \mathbf{3.6 \times 10^{-3}}$$

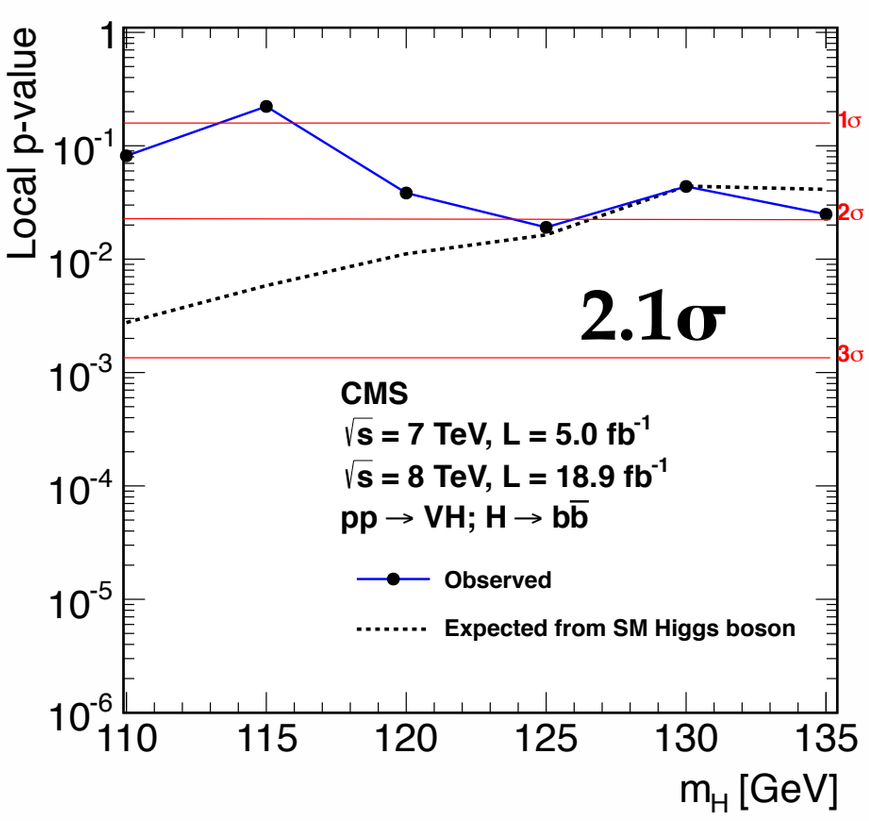


Results


14 categories
CMS Preliminary
$\sqrt{s}$ = 8TeV, L = 19.0 fb^{-1}
Z(μ⁻μ⁺)H(bb̄)
Z(μ⁻μ⁻)H(bb̄)
Z(μ⁺μ⁺)H(bb̄)
Data
VH
Z + bb̄
Z + b
Z+udscg
Z+udscg
Z+udscg
tt̄
Single top
VV(udscg)
VZ(bb̄)
VH(bb̄) 125
MC uncert. (stat.)
MC uncert. (stat. + syst.)
χ^2_ν = 0.920 K_s = 0.964
Entries / 0.13
Data/MC
BDT output


CMS
$\sqrt{s}$ = 7TeV, L = 5.0 fb^{-1}
$\sqrt{s}$ = 8TeV, L = 18.9 fb^{-1}
pp → VH; H → bb̄
Data
VH
Background
VH(bb̄) 125 GeV
Background uncert.
Entries / 0.25
χ^2/dof = 0.98
χ^2/dof = 0.64
Data/MC(B)
Data/MC(S+B)
log(S/B)


CMS
$\sqrt{s}$ = 7 TeV, L = 5.0 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 18.9 fb^{-1}
pp → VH; H → bb̄
CL$_s$ Observed
CL$_s$ H125 injected
CL$_s$ Expected
CL$_s$ Expected ± 1 σ
CL$_s$ Expected ± 2 σ
95% asymptotic CL limit on μ
m$_H$ [GeV]


2.1σ
CMS
$\sqrt{s}$ = 7 TeV, L = 5.0 fb^{-1}
$\sqrt{s}$ = 8 TeV, L = 18.9 fb^{-1}
pp → VH; H → bb̄
Observed
Expected from SM Higgs boson
Local p-value
1σ
2σ
3σ
m$_H$ [GeV]