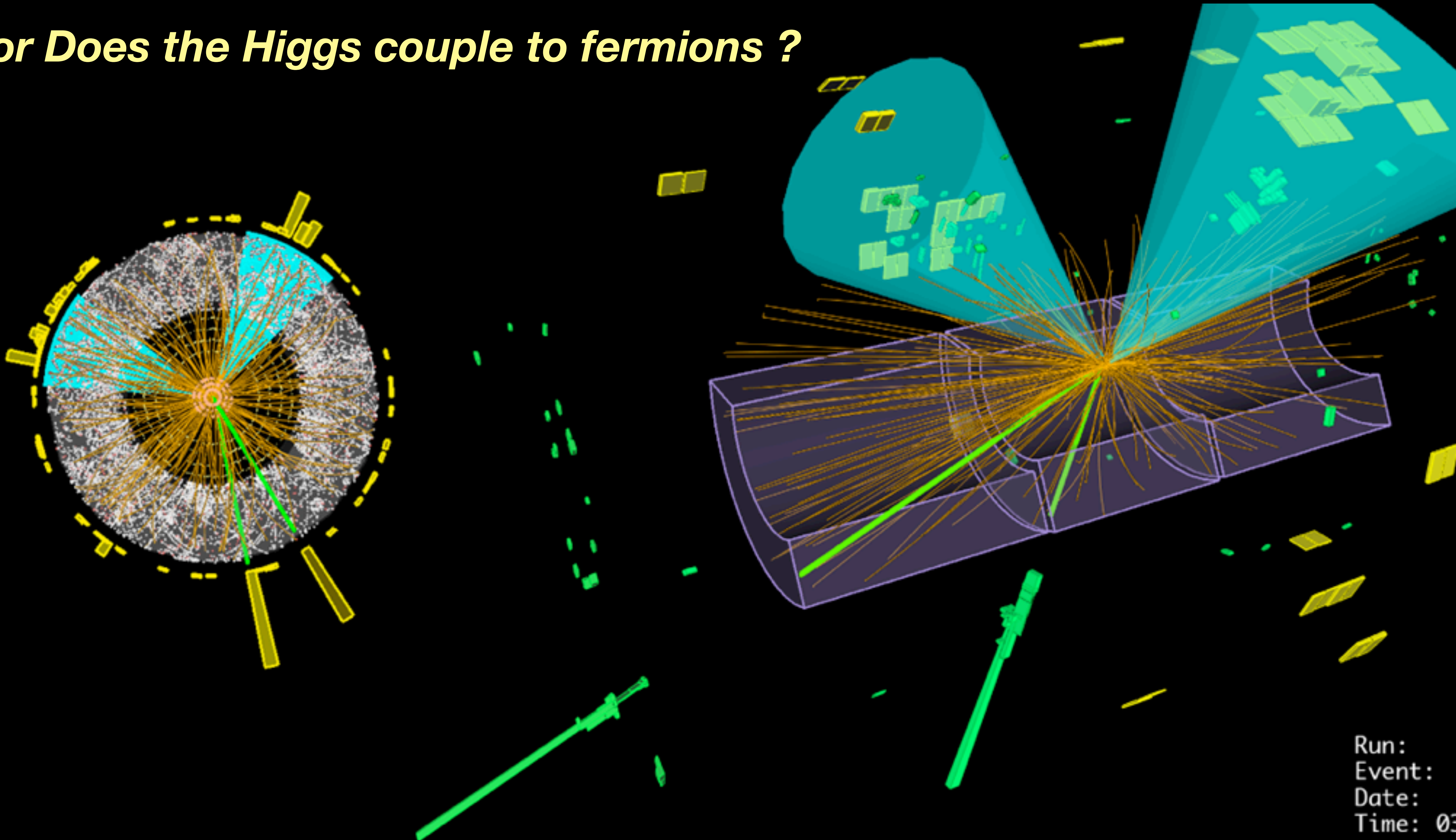
Study of Higgs Boson Production in Fermionic Decay Modes

or Does the Higgs couple to fermions ?

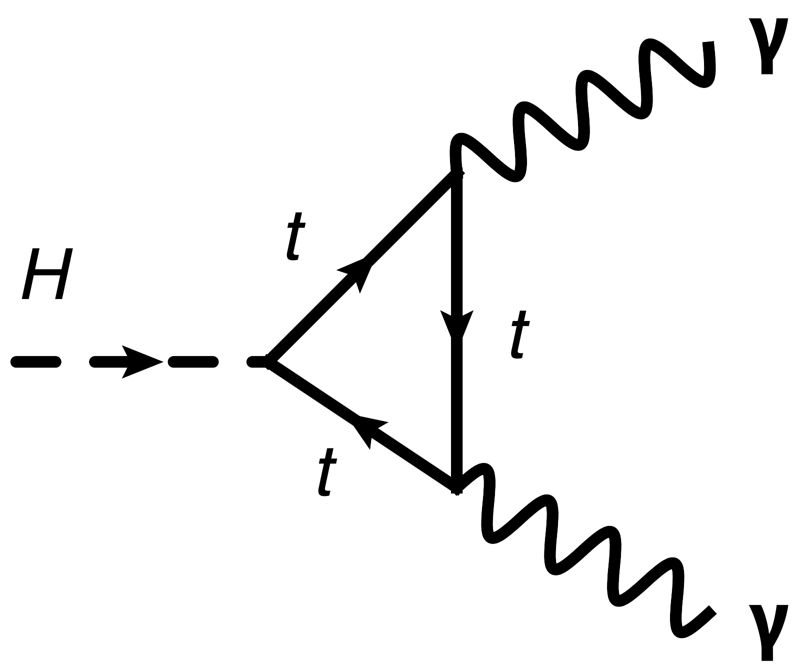


Heather M. Gray, CERN
on behalf of the ATLAS, CMS, CDF and D0 Collaborations

Introduction

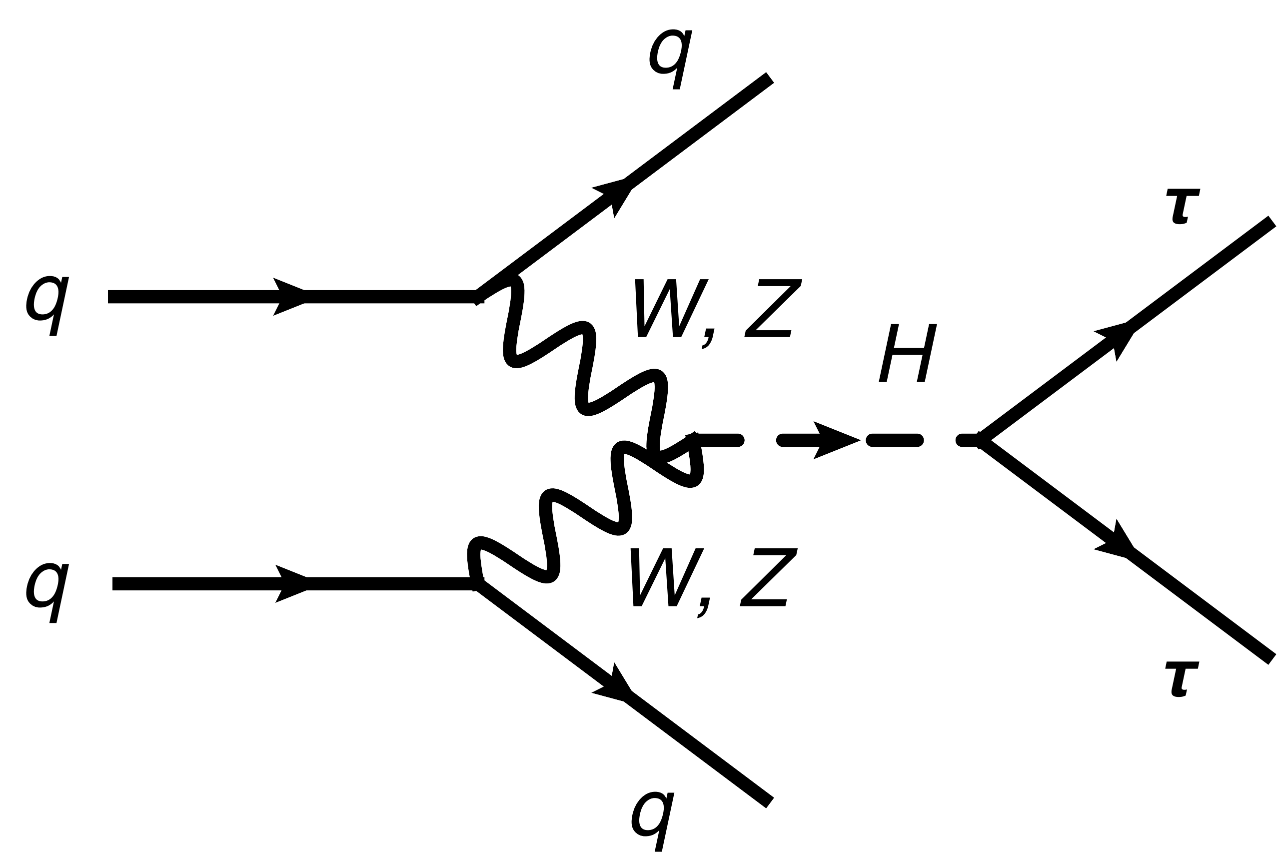
- **One year** after the discovery of a new boson with mass 125 GeV
  - This particle is a Higgs boson
- But is it really **the Standard Model Higgs boson** ?
  - Long-term program to study and measure **properties**
- Measuring the **coupling to fermions** is a key component
  - Are the fermionic couplings **consistent with SM** ?
  - Is there just **one particle** coupling to both fermions and bosons ?

Does the Higgs boson couple to Fermions ?



- Short answer: **Yes** !
- Photons are massless so cannot couple to the Higgs
- Observed decay to γγ
  - Dominant contribution from **top quark loop**

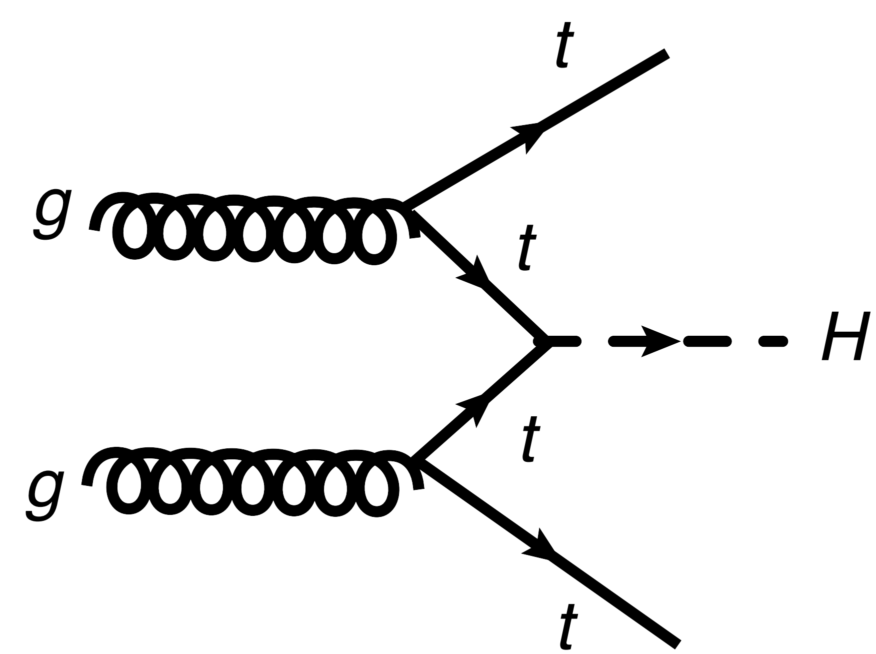
- More complete answer:
  - Not necessarily, **new particles** could contribute in the loop
- Need **direct measurement** of fermionic coupling



Direct Measurements of Fermionic Couplings

- Direct = measure fermions experimentally
- Two possibilities for direct measurement
  - **decays** to fermions (**ττ, bb or μμ**)
  - **produced** in association with fermions (**ttH**)
- Discuss **current status** and highlight **recent** Tevatron and LHC **results**

Associated ttH Production

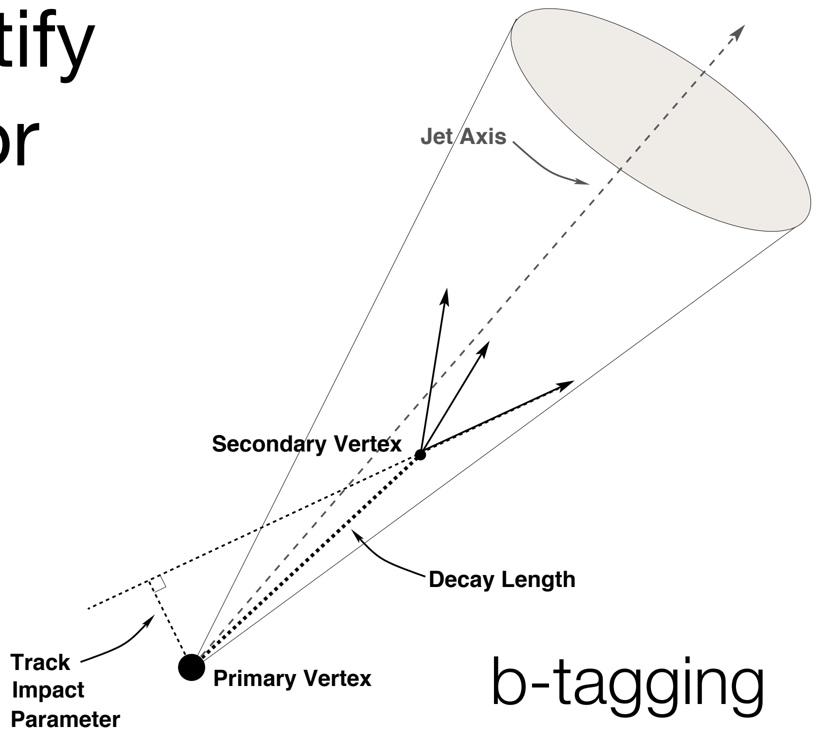


Higgs decays to fermions

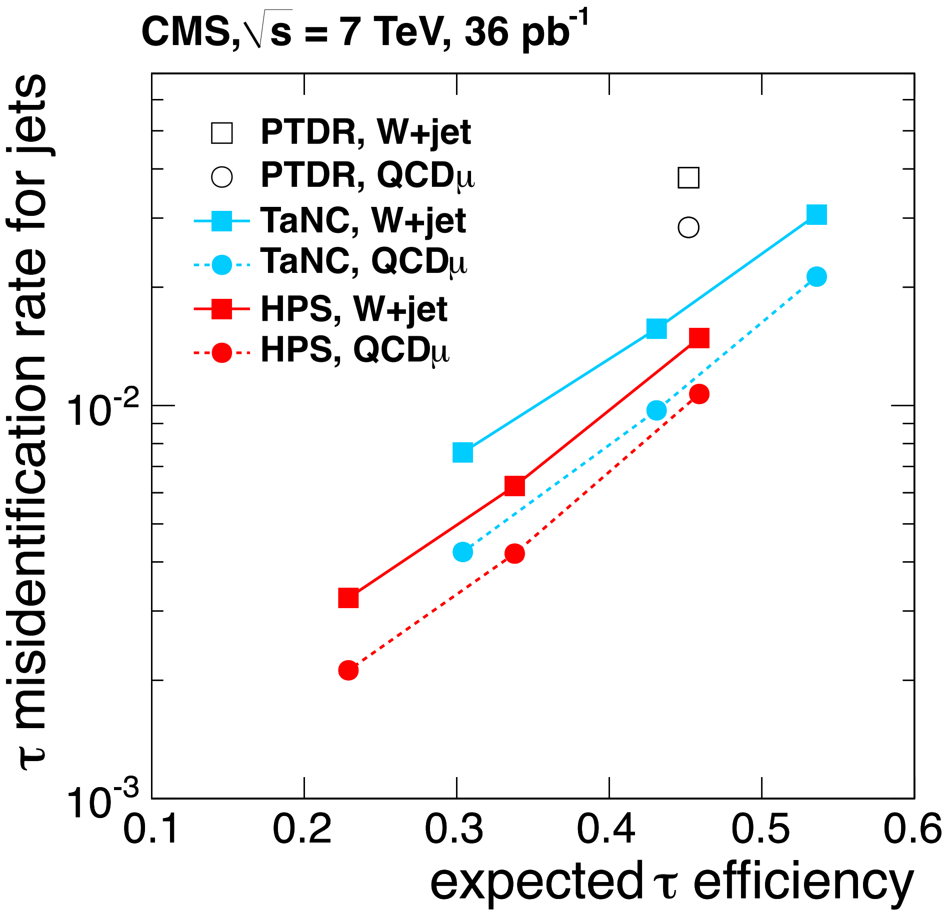
	BR@125 GeV	Resolution
bb	57%	10%
ττ	6%	15%
μμ	0.02%	2%

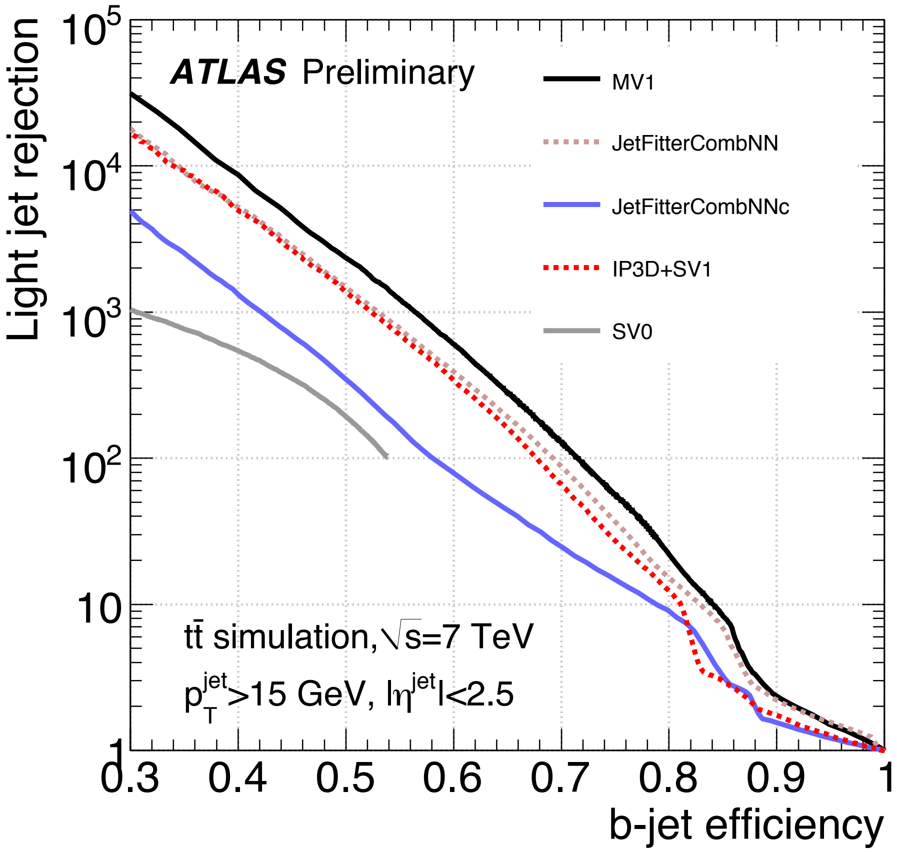
Reconstructing τ's and b-jets

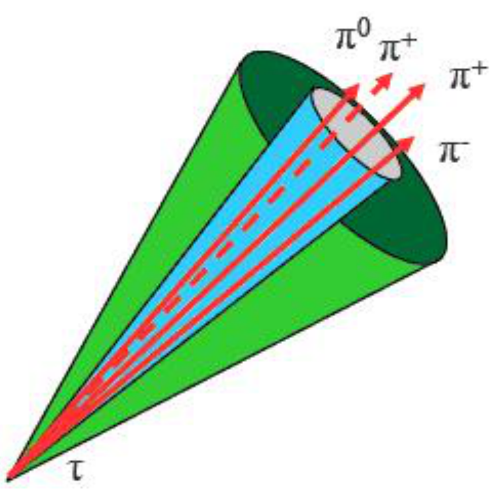
- **Sophisticated** (multivariate) algorithms to identify b-jets and τ's required to probe fermionic sector
- **b-tagging** algorithms mostly exploit b-quark **lifetime**
  - decay **displaced** from primary interaction
- **Hadronic taus** identified by decay to 1 or 3 collimated charged hadrons



b-tagging







τ-tagging

Probing Fermionic Couplings

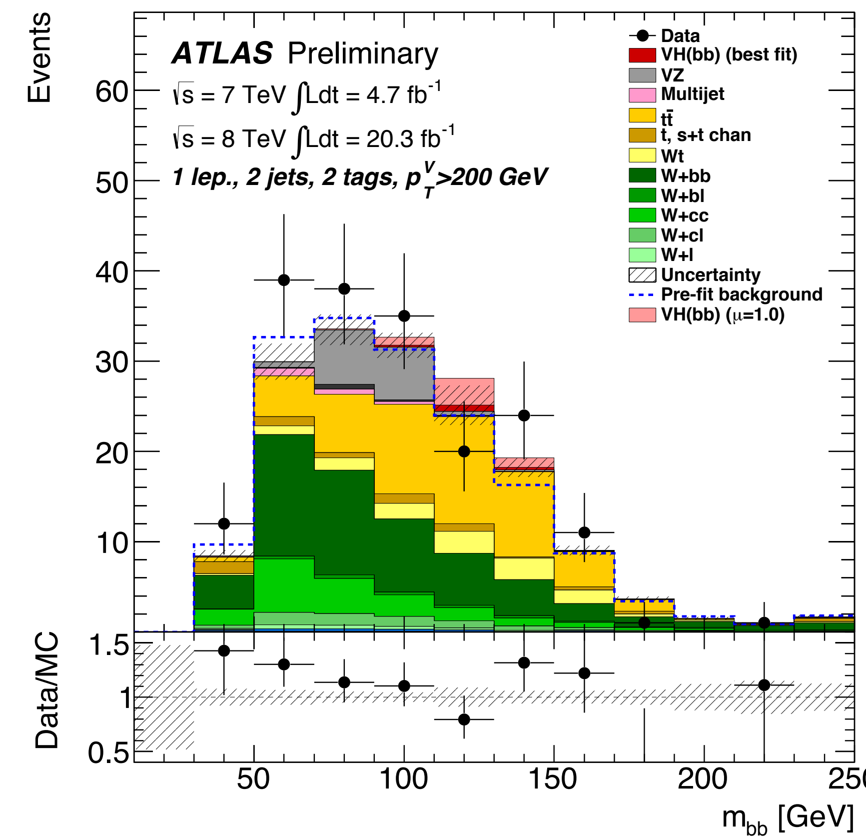
- Decays
  - bb
  - ττ
  - μμ
- Production
  - ttH

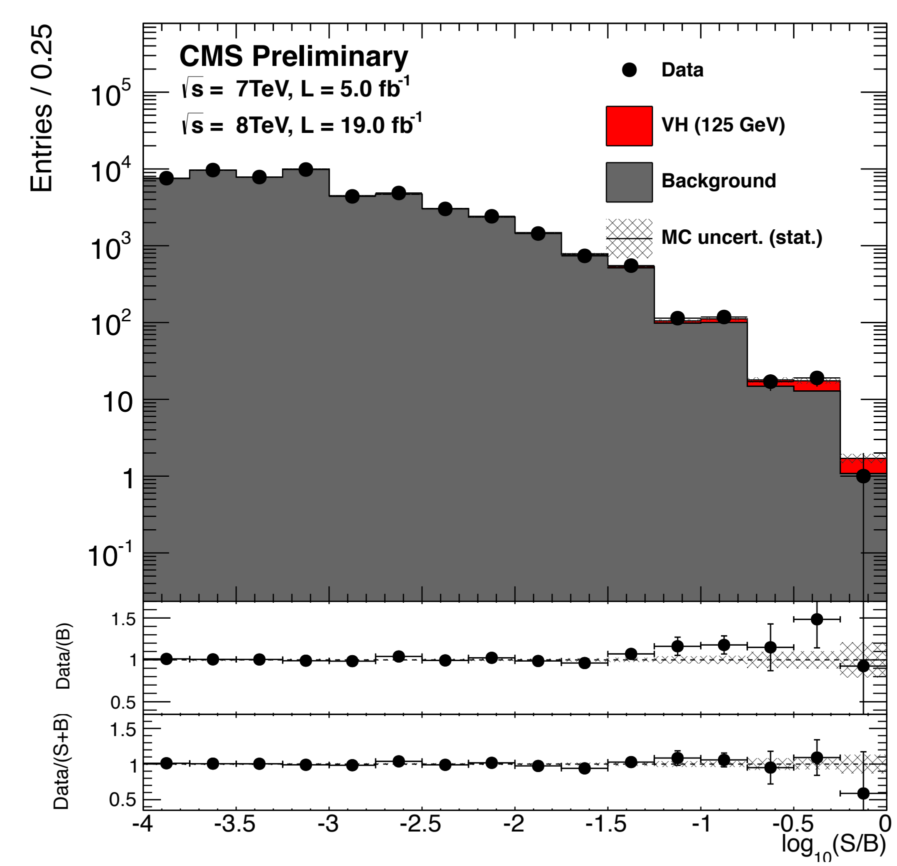
μ values quoted for m_H=125 GeV

Run 1 dataset = 5 fb^{-1} @ 7 TeV + 20-21 fb^{-1} @ 8 TeV

VH(bb)

- Production in **association** with a W/Z boson is the most powerful channel to search for decays to b-quarks
- Main challenges are **triggering** and large and uncertain **backgrounds**
  - Trigger using **leptonic** W/Z decays or MET
  - **Boost (V p_T)** to control backgrounds
- Select events containing **0, 1 or 2** leptons (W or Z decay)
- Search for **peak** in dijet invariant mass, **m_{bb}**, distribution
- **Categories** or **BDT discriminants** to increase **sensitivity**

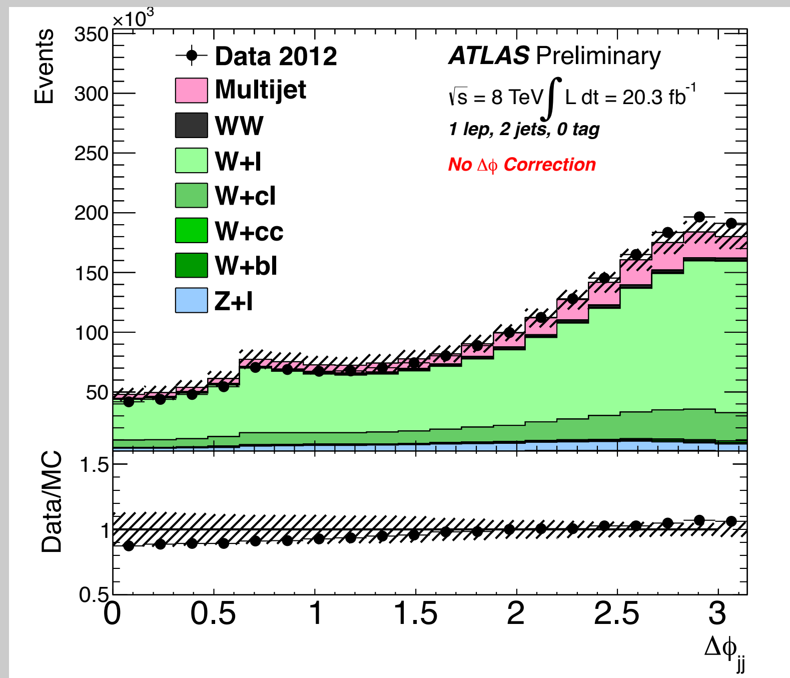


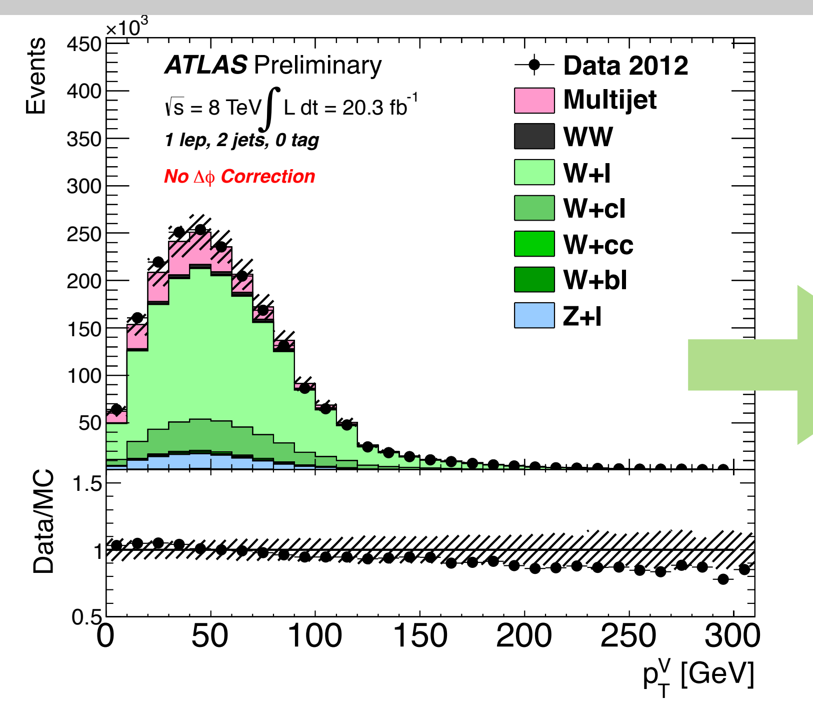


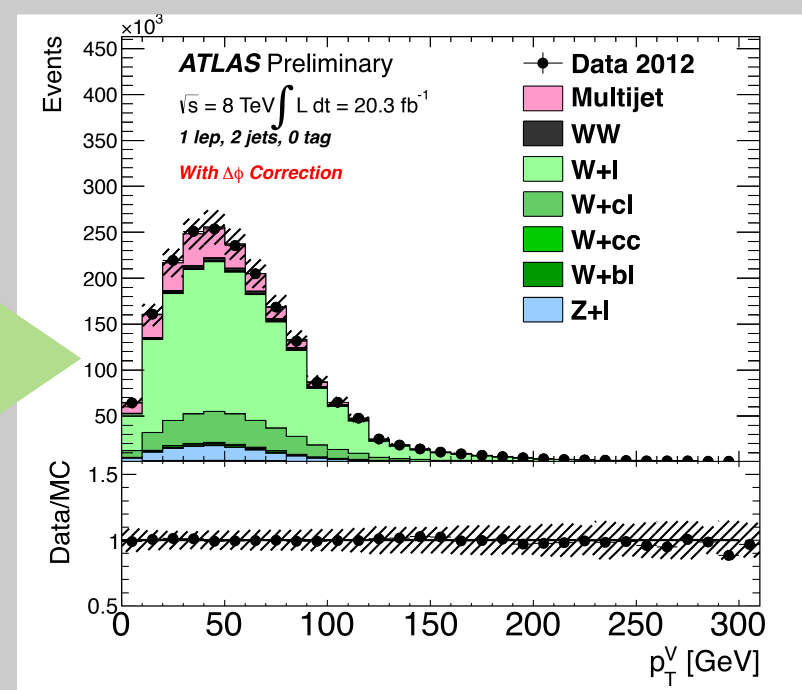
Background Modelling

Small signals require precise background control
→ *correct for observed discrepancies in current MCs*

ATLAS: mismodelling of **V+jets Δφ** in LO Sherpa
Derive **correction** from 0-tag control region
Also improves **p_T^V** distribution







CMS: **W+jet cross-section** vs **number of b-jets** in Madgraph
Corrected with separate scale factors

Process	$W(\ell\nu)H$	$Z(\nu\nu)H$
Low p_T		
W0b	$1.03 \pm 0.01 \pm 0.05$	$0.83 \pm 0.02 \pm 0.04$
W1b	$2.22 \pm 0.25 \pm 0.20$	$2.30 \pm 0.21 \pm 0.11$
W2b	$1.58 \pm 0.26 \pm 0.24$	$0.85 \pm 0.24 \pm 0.14$
Intermediate p_T		
W0b	$1.02 \pm 0.01 \pm 0.07$	$0.93 \pm 0.02 \pm 0.04$
W1b	$2.90 \pm 0.26 \pm 0.20$	$2.08 \pm 0.20 \pm 0.12$
W2b	$1.30 \pm 0.23 \pm 0.14$	$0.75 \pm 0.26 \pm 0.11$
High p_T		
W0b	$1.04 \pm 0.01 \pm 0.07$	$0.93 \pm 0.02 \pm 0.03$
W1b	$2.46 \pm 0.33 \pm 0.22$	$2.12 \pm 0.22 \pm 0.10$
W2b	$0.77 \pm 0.25 \pm 0.08$	$0.71 \pm 0.25 \pm 0.15$

Similar observation for Z+jets

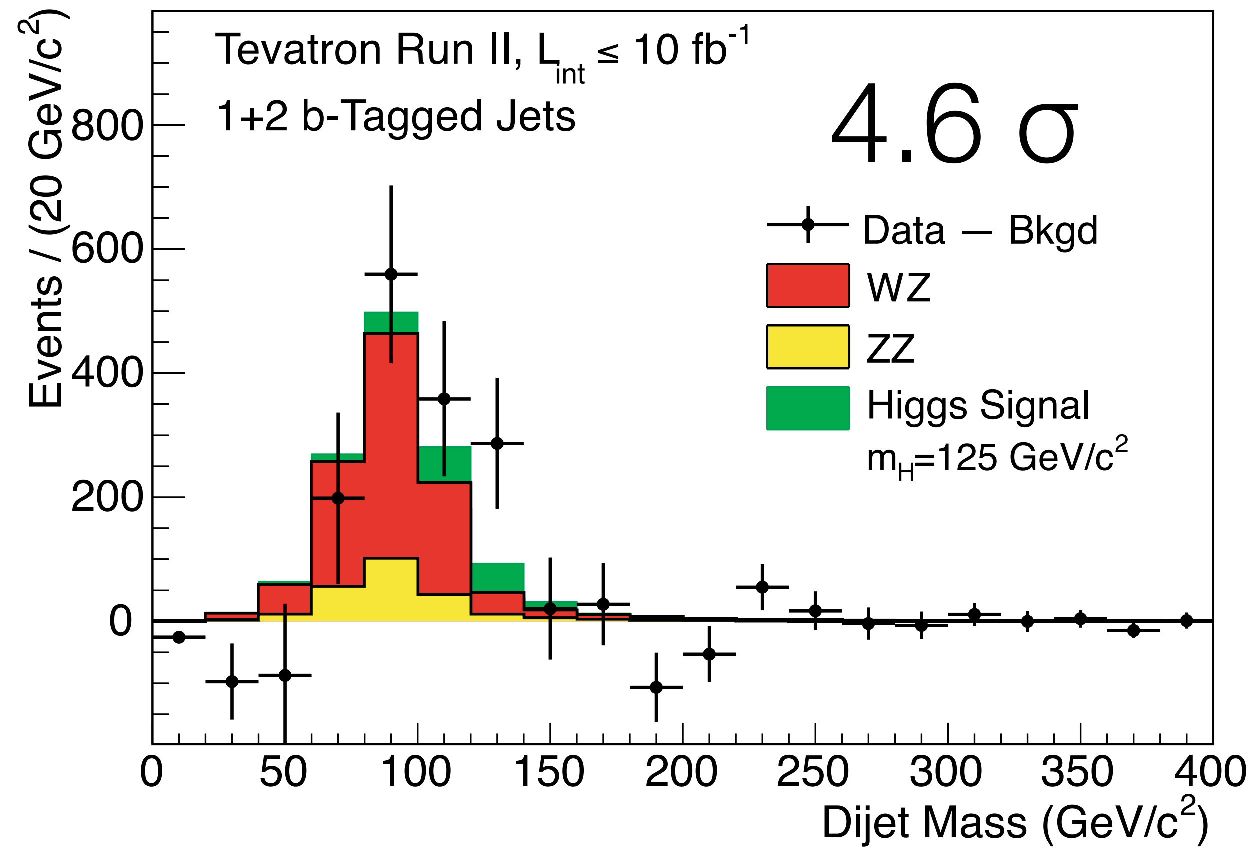
Diboson Validation

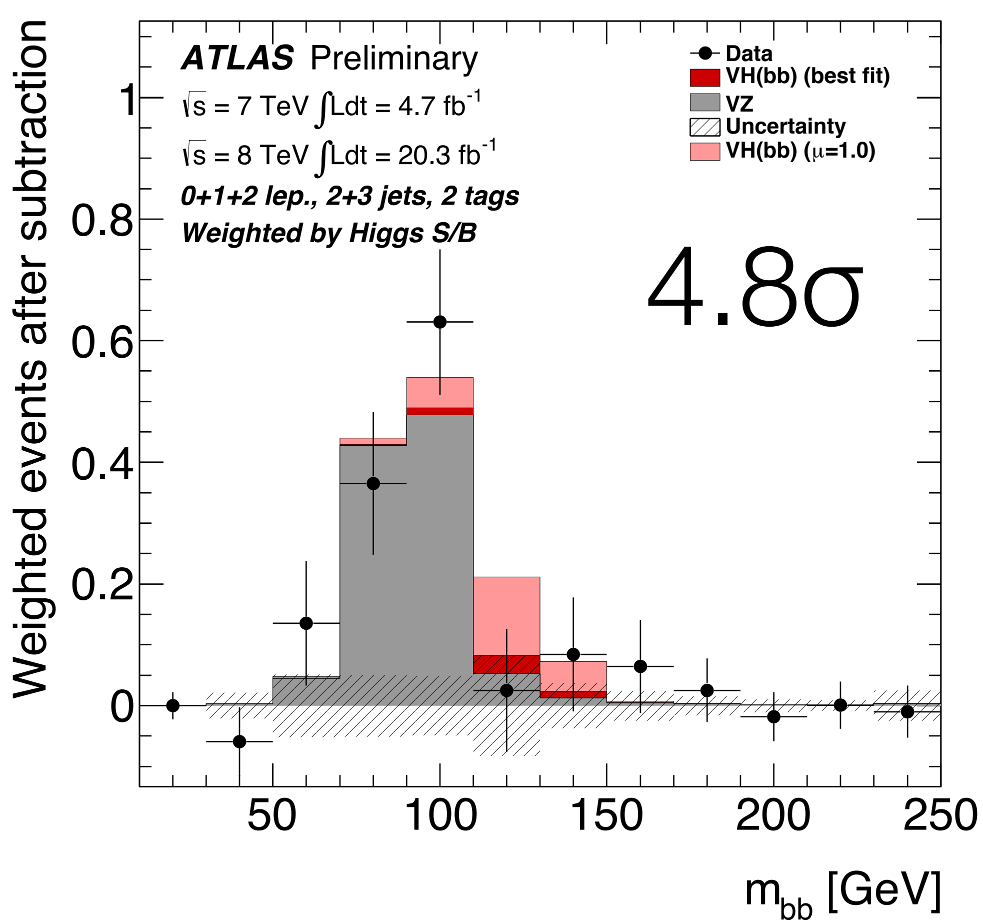
- Analysis techniques validated by **diboson** (WZ/ZZ) measurements

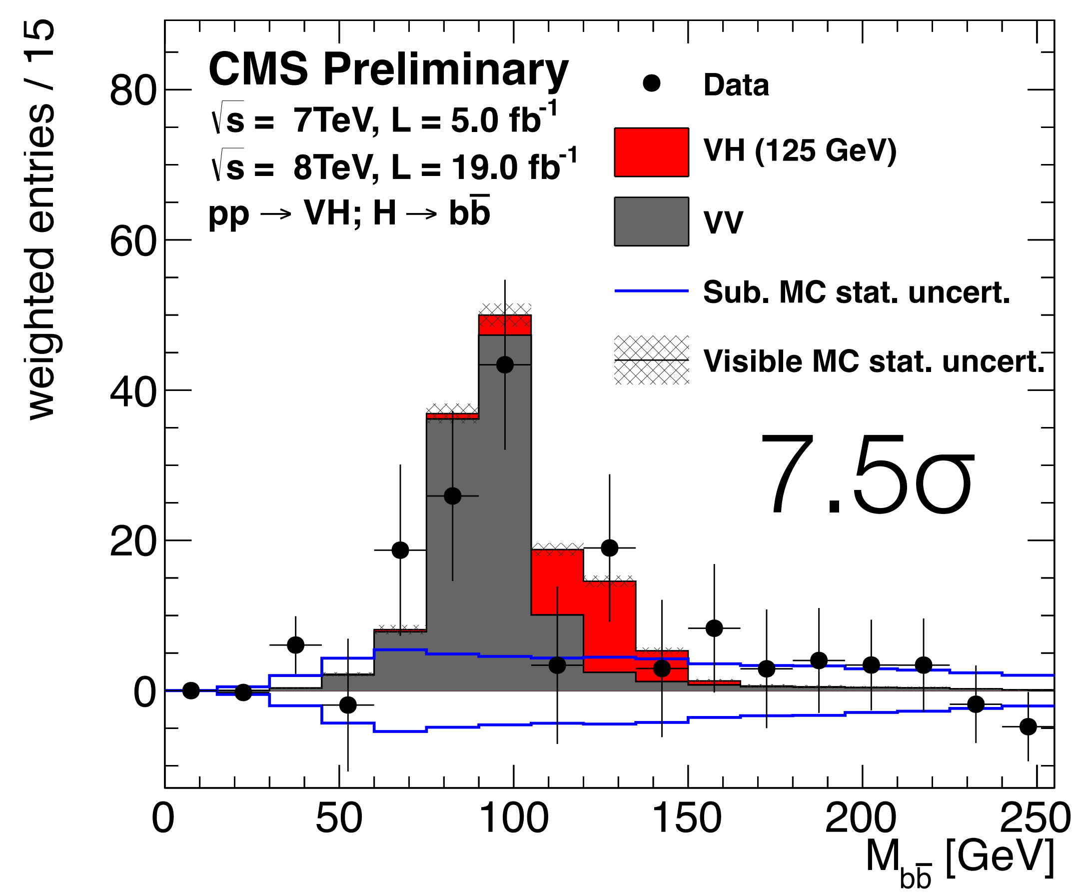
Tevatron: $\mu_{VZ} = 0.68 \pm 0.20$

ATLAS: $\mu_{VZ} = 0.9 \pm 0.2$

CMS: $\mu_{VZ} = 1.19^{+0.28}_{-0.23}$







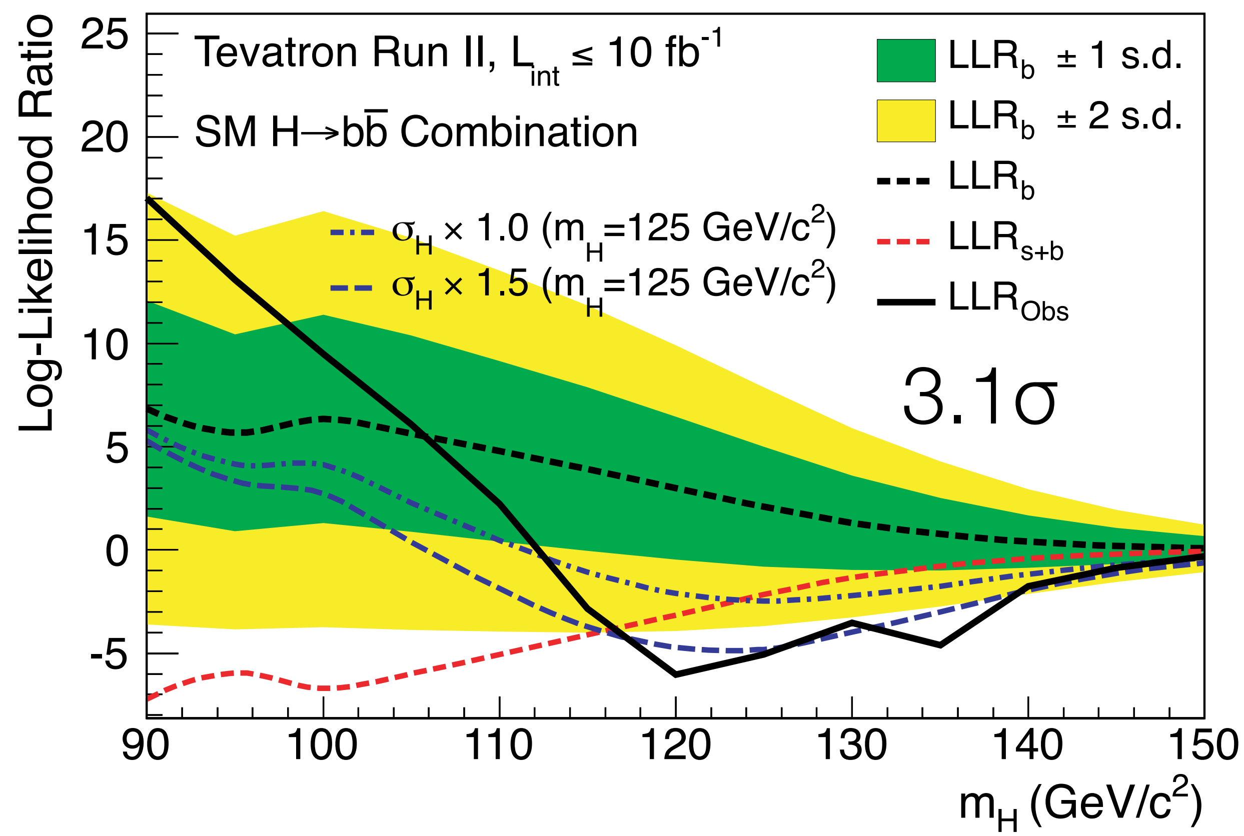
VH(bb) Results

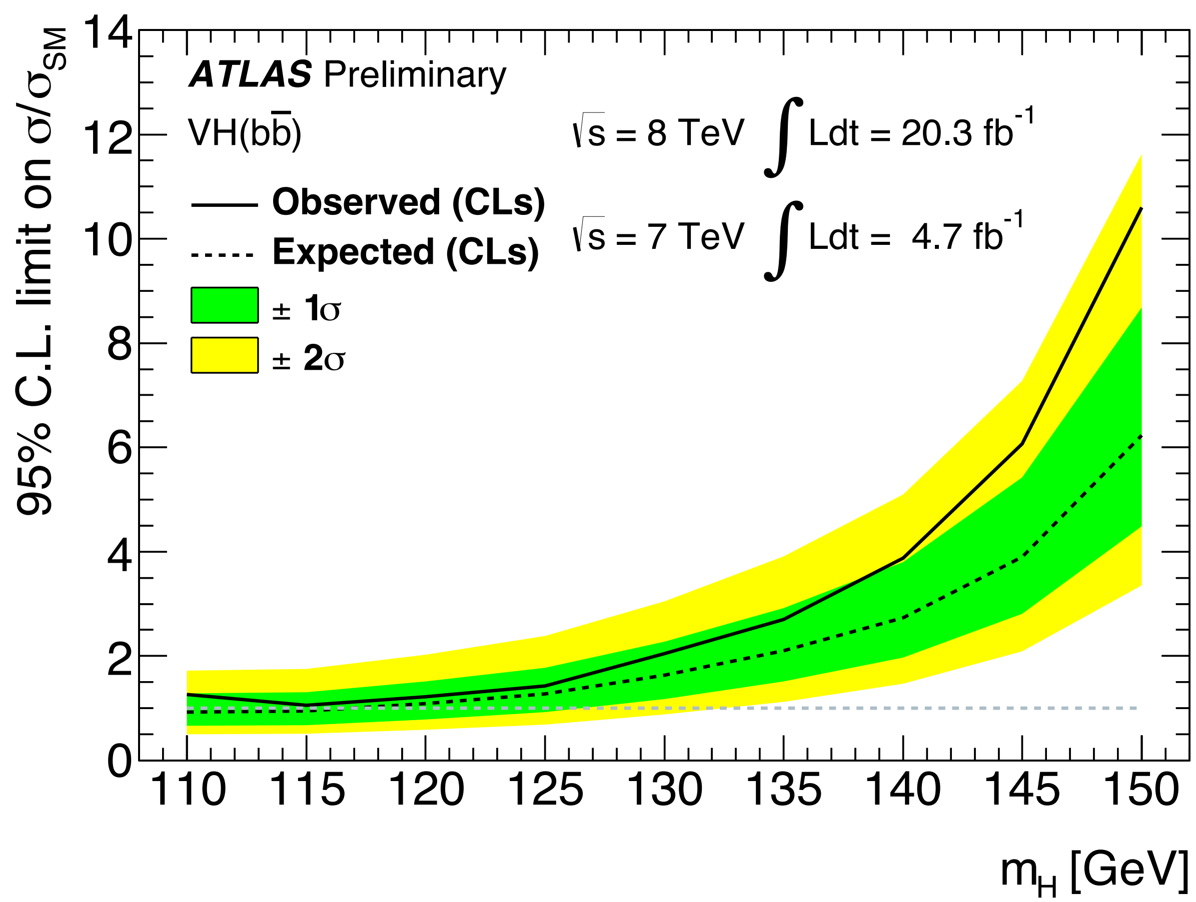
3.1σ observed significance
(Tevatron combination)

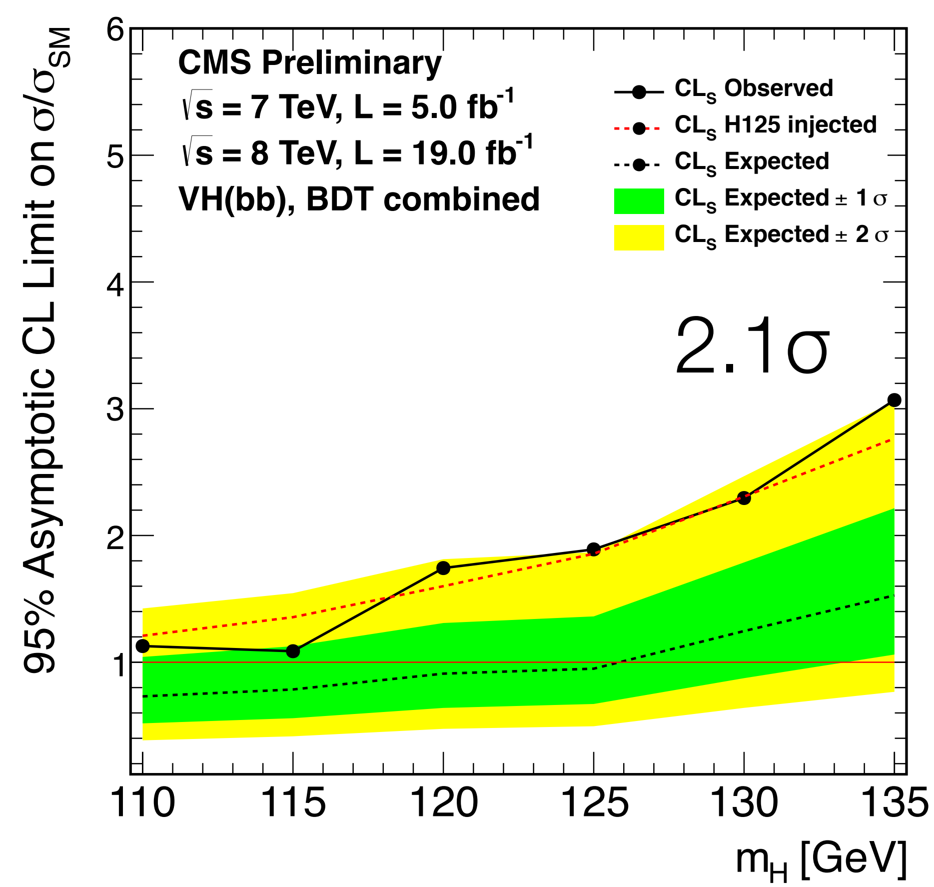
Tevatron: $\mu = 1.59^{+0.69}_{-0.72}$

ATLAS: $\mu = 0.2^{+0.7}_{-0.6}$

CMS: $\mu = 1.0 \pm 0.5$

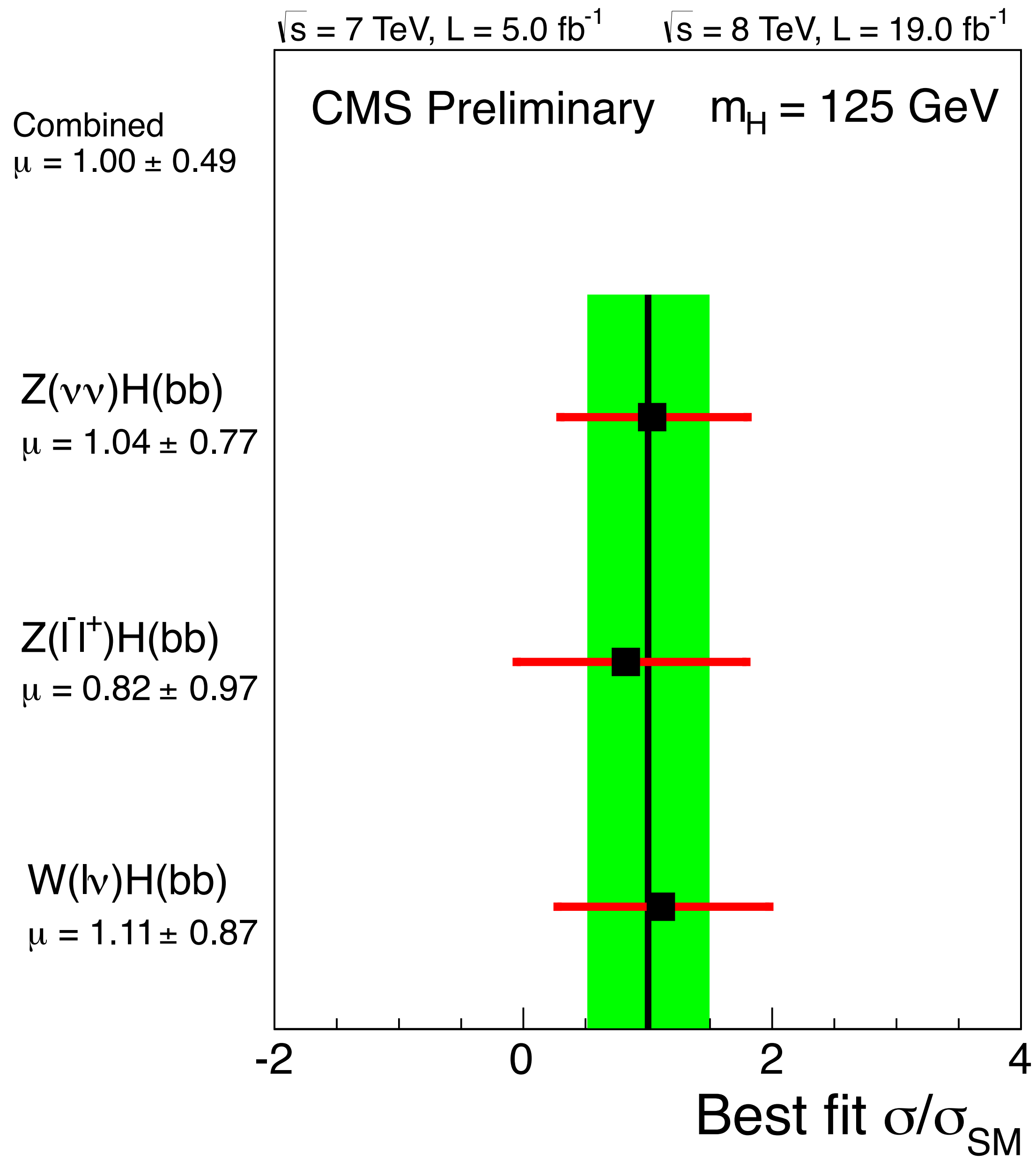


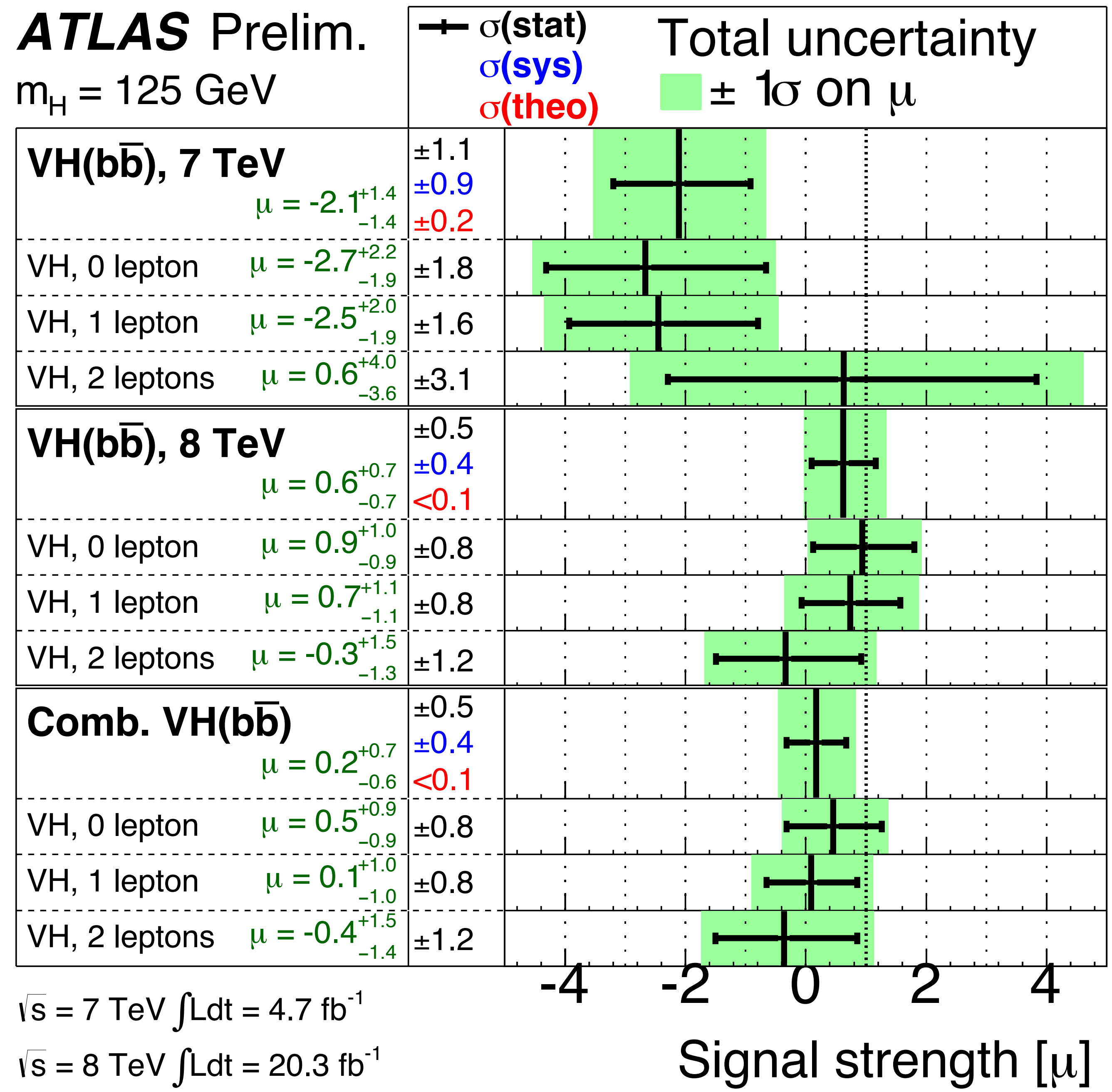




VH(bb) Results by Channel

Most powerful channel is Z(νν)bb



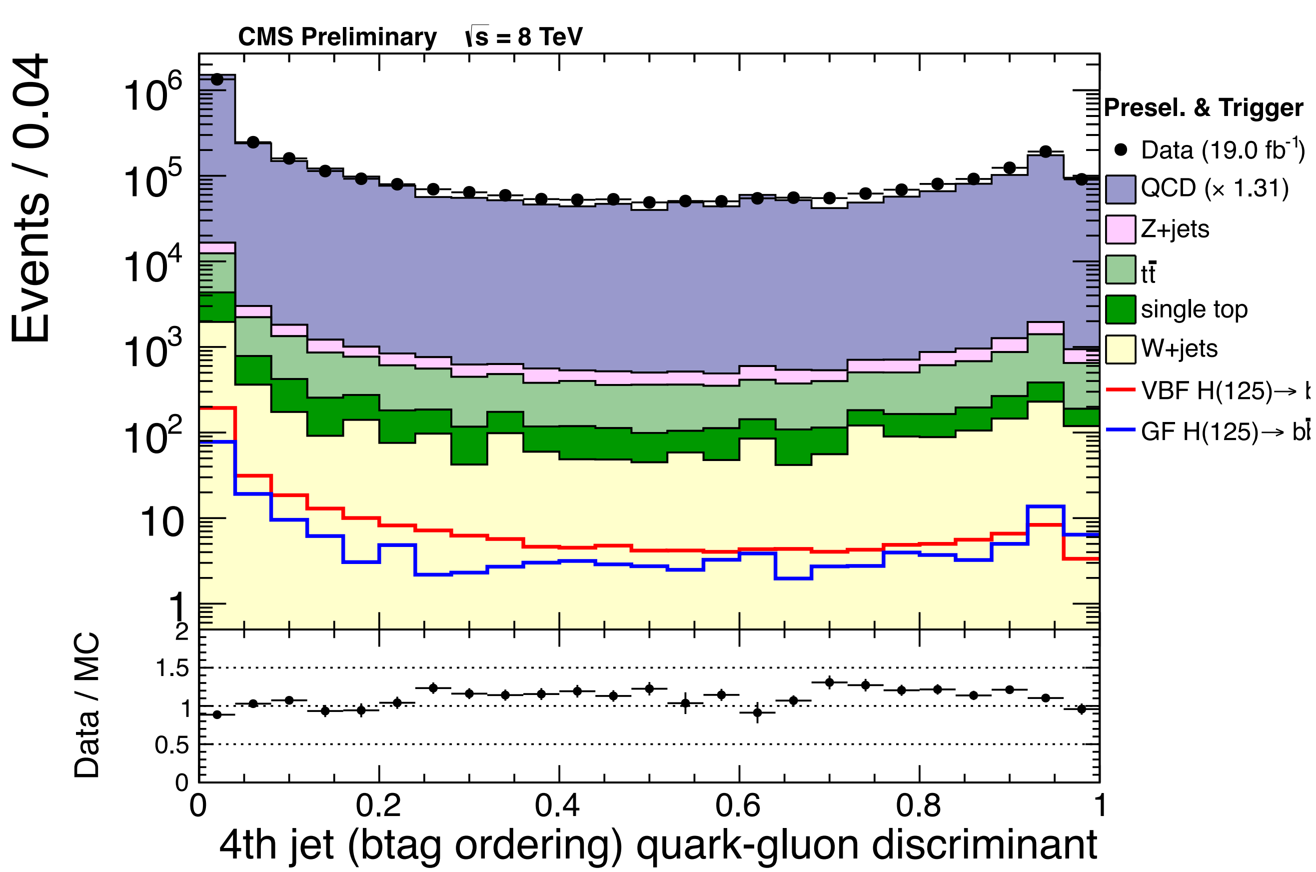


Small theory systematics for VH production

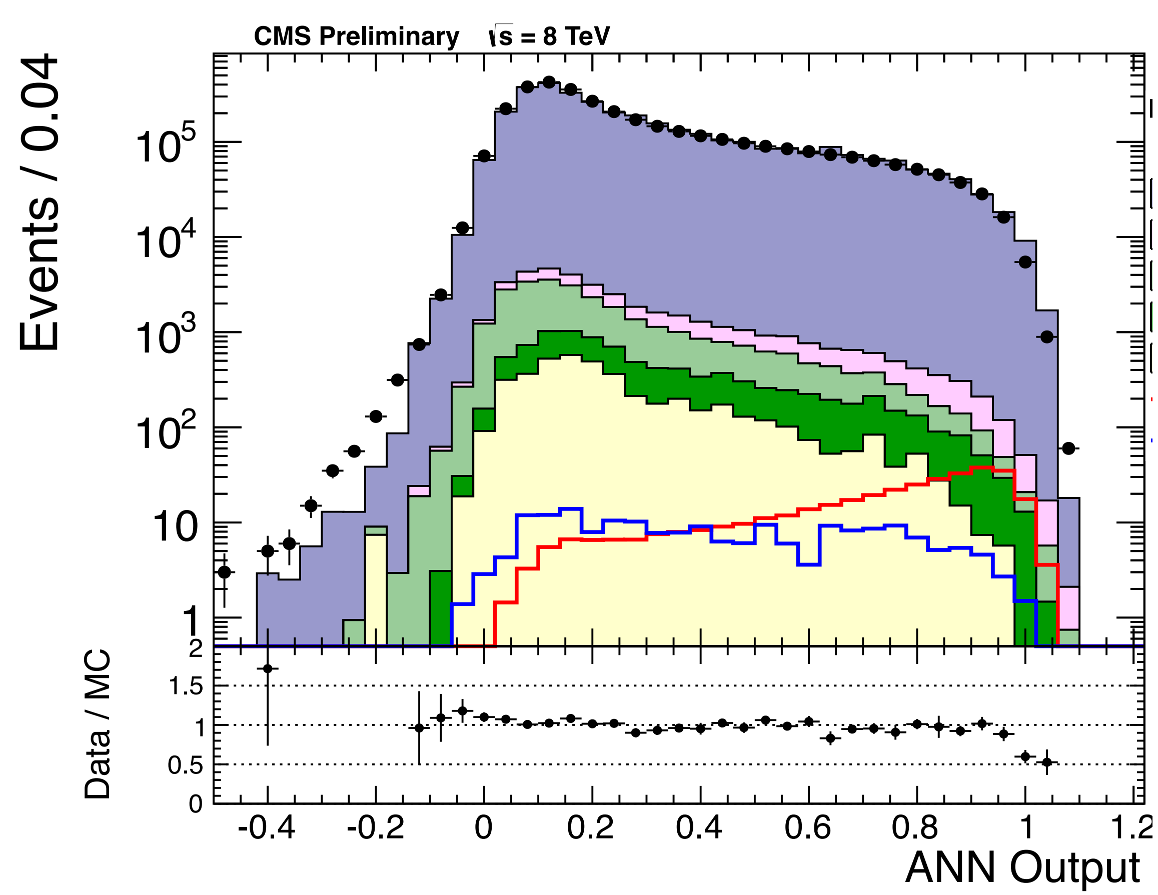
VBF H(bb)

- CMS VBF H(bb) analysis exploits **dedicated** bb **VBF trigger** and **event** selection
  - **quark-gluon discriminant** for non b-jets
  - reject events with **central hadronic activity**
- MVA discriminant defines 5 categories by **signal purity**

Quark-Gluon Discriminant

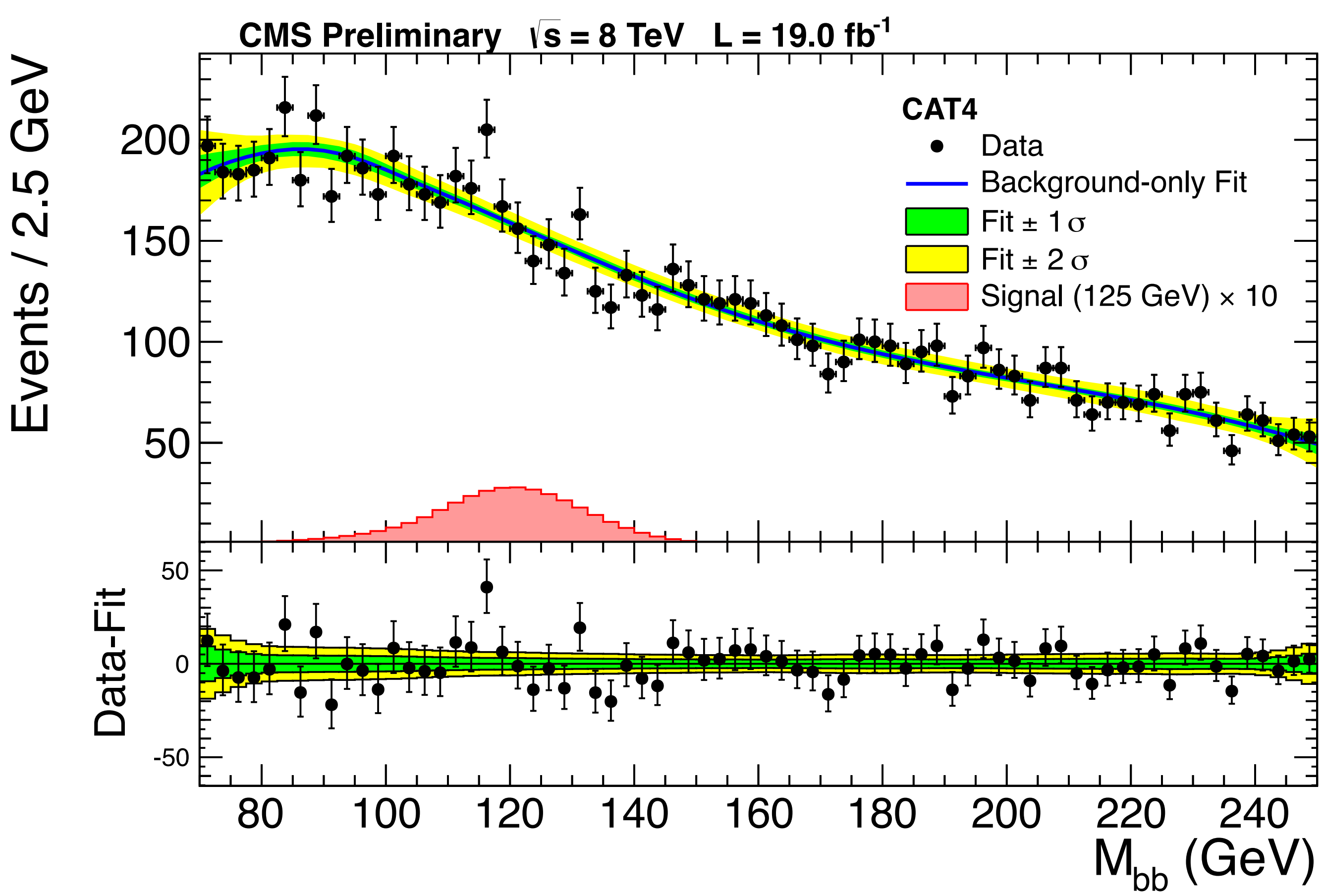


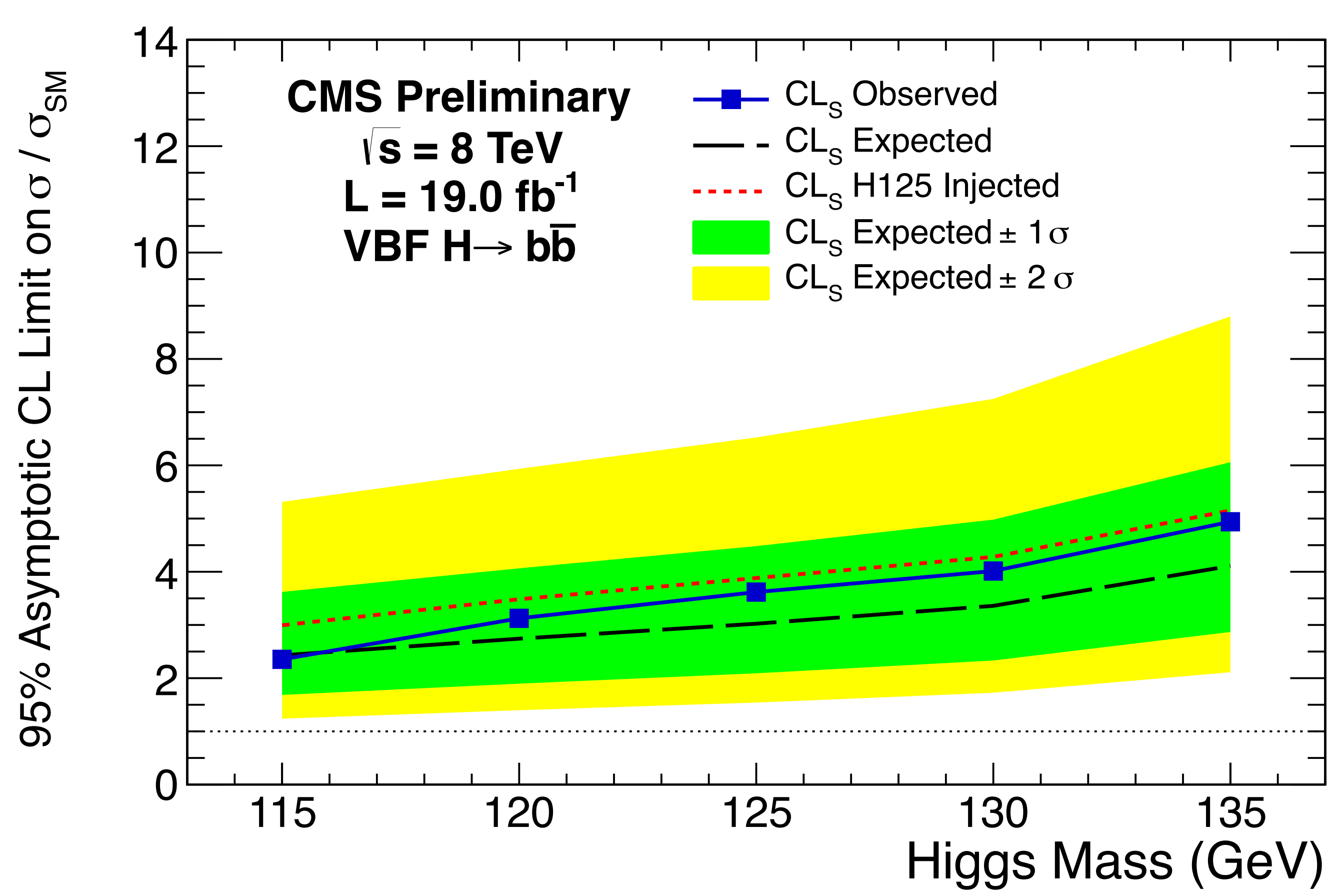
Category Discriminant



VBF H(bb) Results

- **Fit** to **m_{bb} distribution** in each category
  - Fifth degree Bernstein polynomial for QCD
  - Simulation templates for V+jets and top
- Limits:
  - **3.6 x SM (observed),** 3.0 x SM (expected)



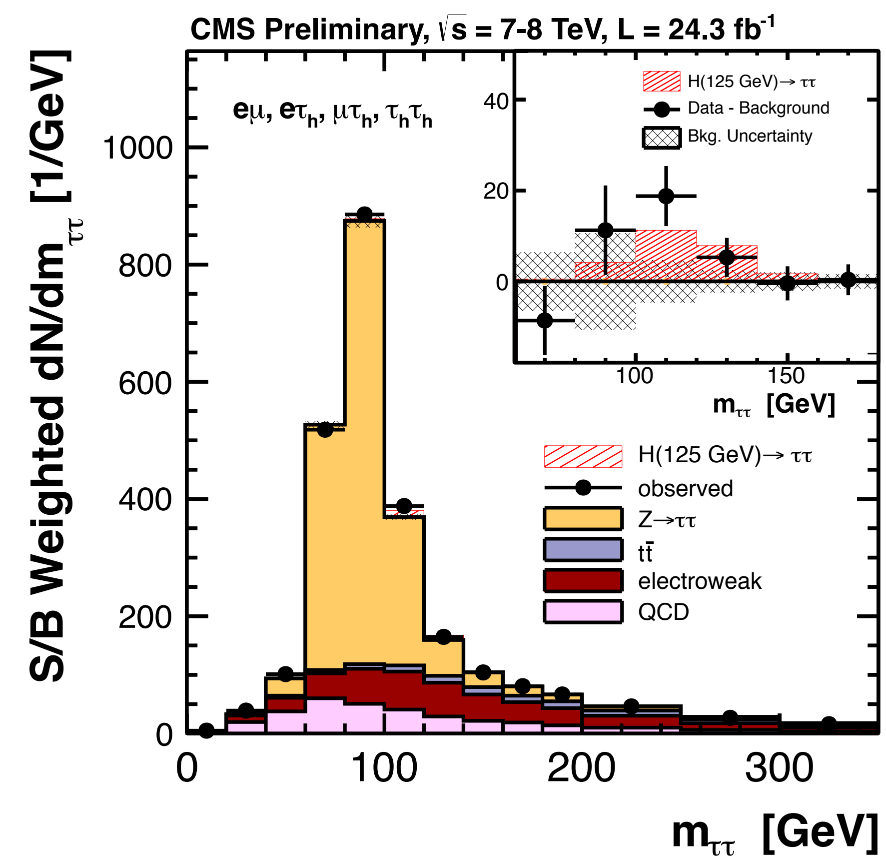


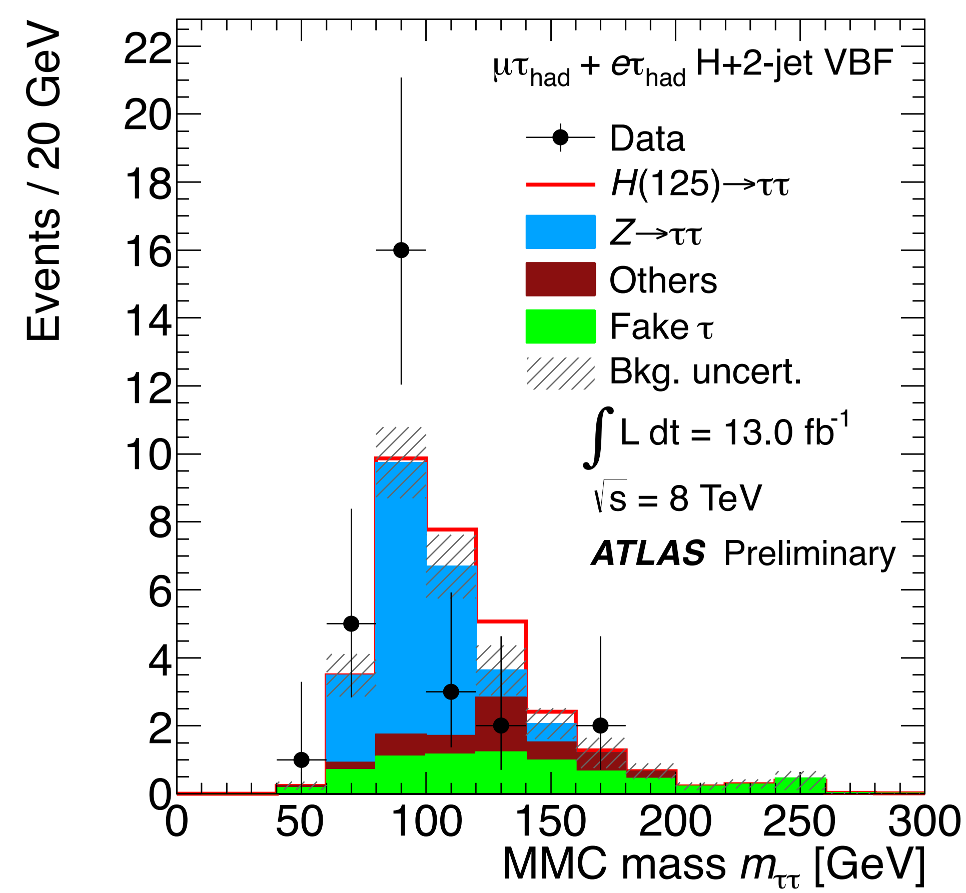
Probing Fermionic Couplings

- Decays
  - bb
  - ττ
  - μμ
- Production
  - ttH

H→ττ Categories

- Three **channels** by τ-decay
  - lep-lep (12%)
  - lep-had (46%)
  - had-had (42%)
- Analysis **categories**
  - **VBF**: 2 jets with large Δη & m_{jj}
  - **boosted Higgs p_T**
  - **1-jet**
  - **0-jet** (ATLAS, CMS for syst constraint)
  - **VH** (CMS only)
- Search for an excess in the invariant mass of the two τ candidates, $\mathbf{m_{\tau\tau}}$





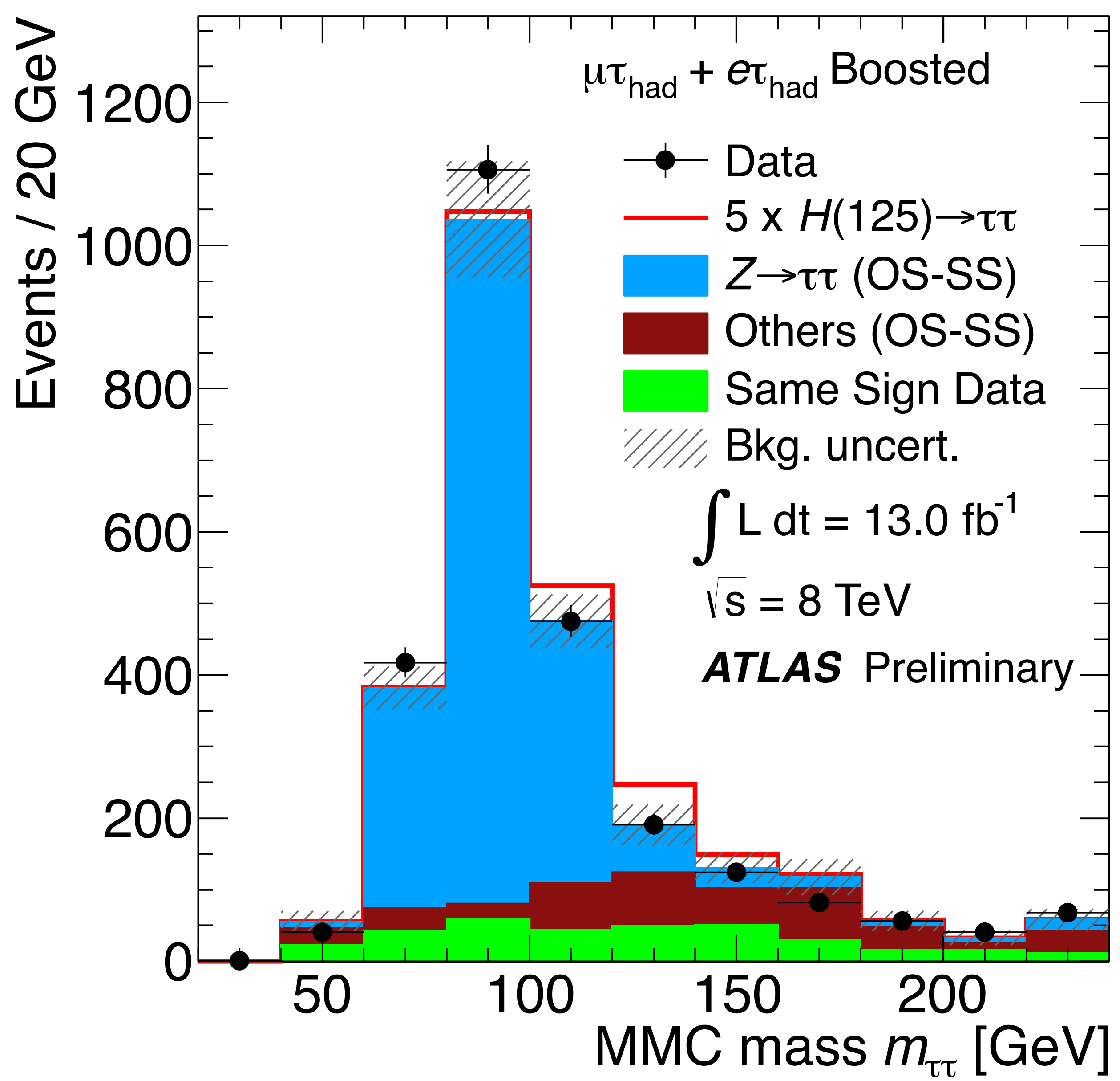
H→ττ Backgrounds

Embedding: **data** models all Z→ττ event properties except τ decays

Z→ττ: major background, special technique: **embedding**

Fakes: QCD, W+jets, top: data-driven

Diboson: MC



Data Z→μμ event

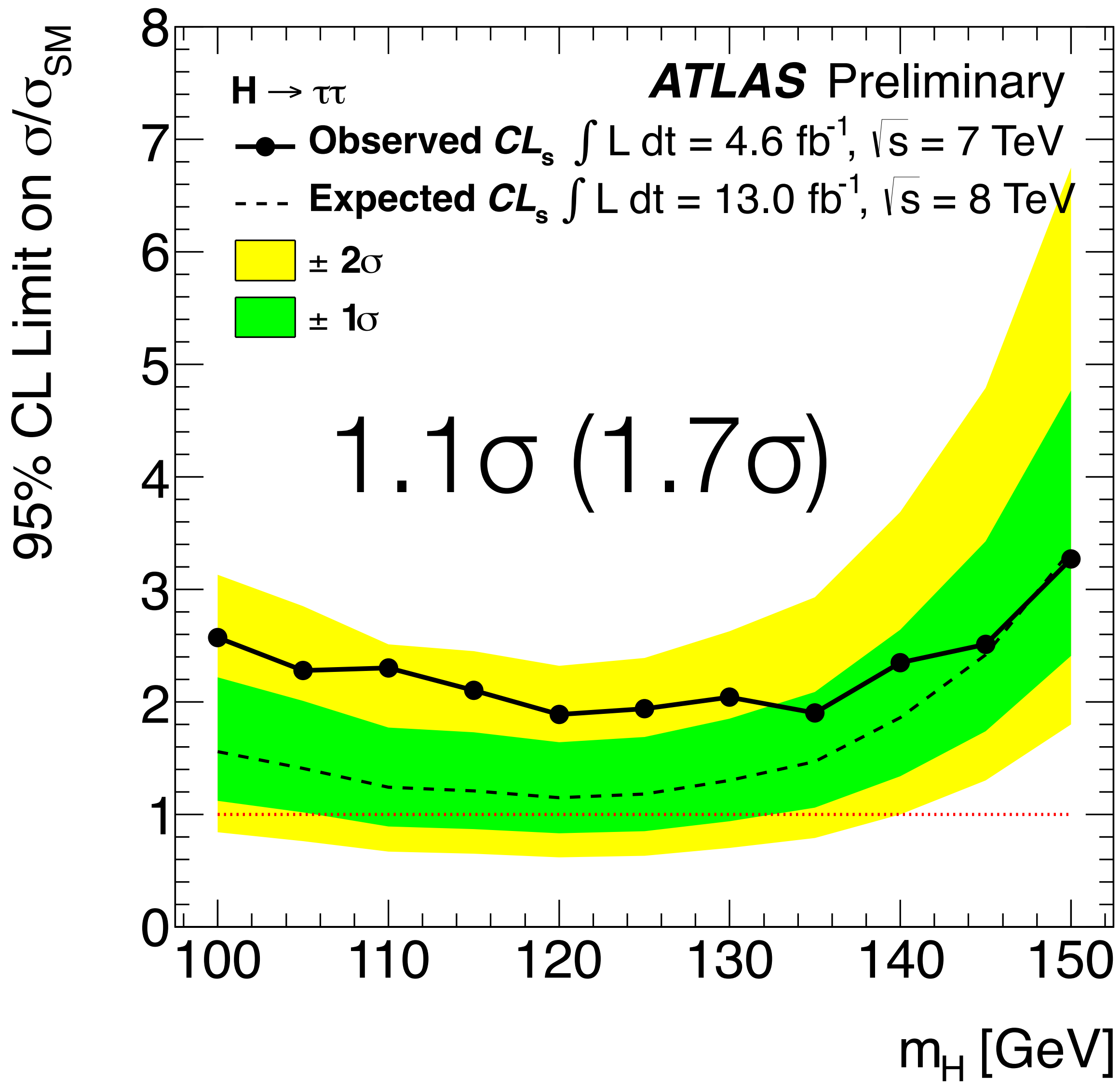
μμ→ττ

simulate τ decay

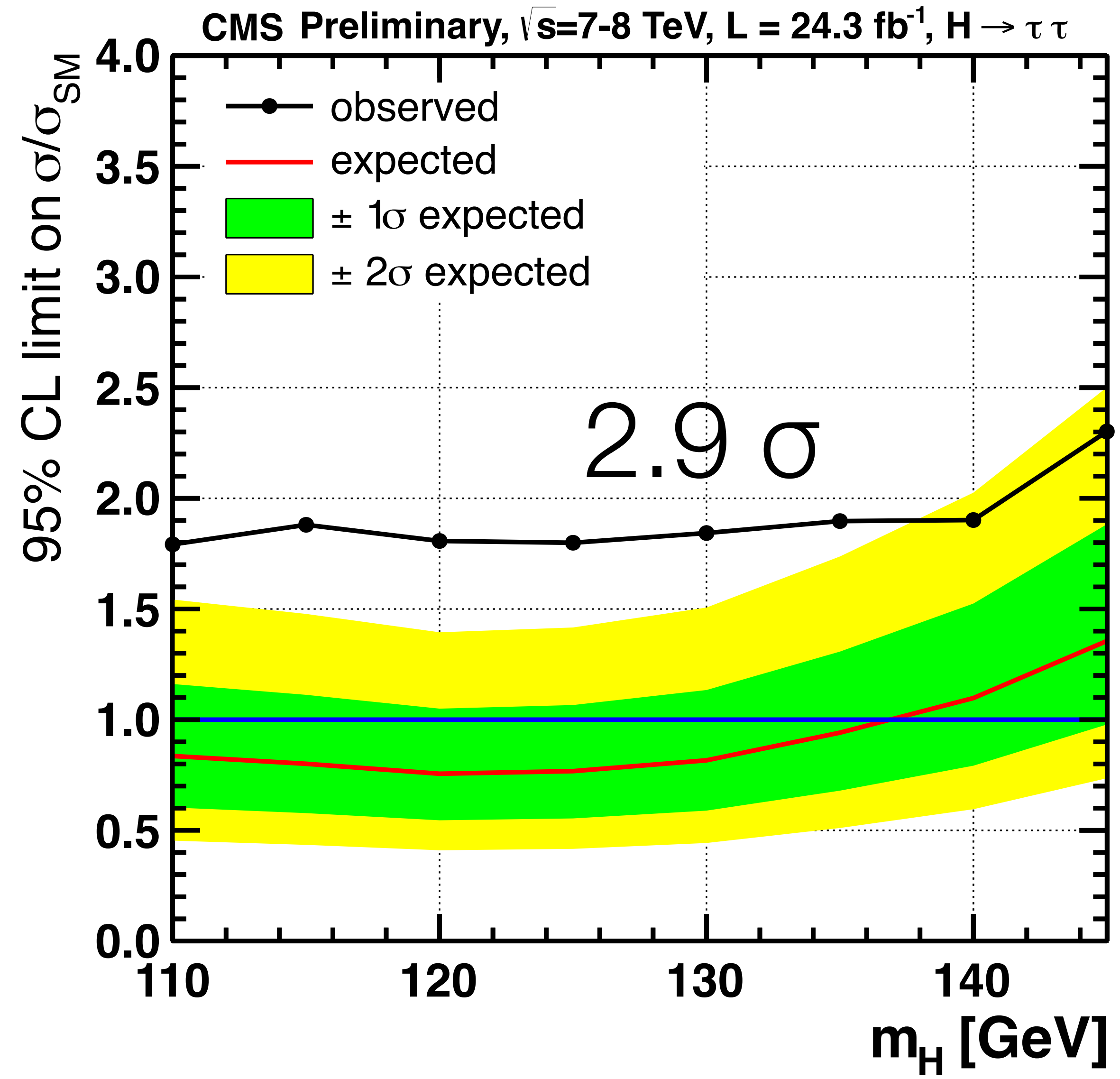
embed τ decay in Z data event

Hybrid Z→ττ event

H→ττ Results



CMS: ττ+bb* 3.4σ

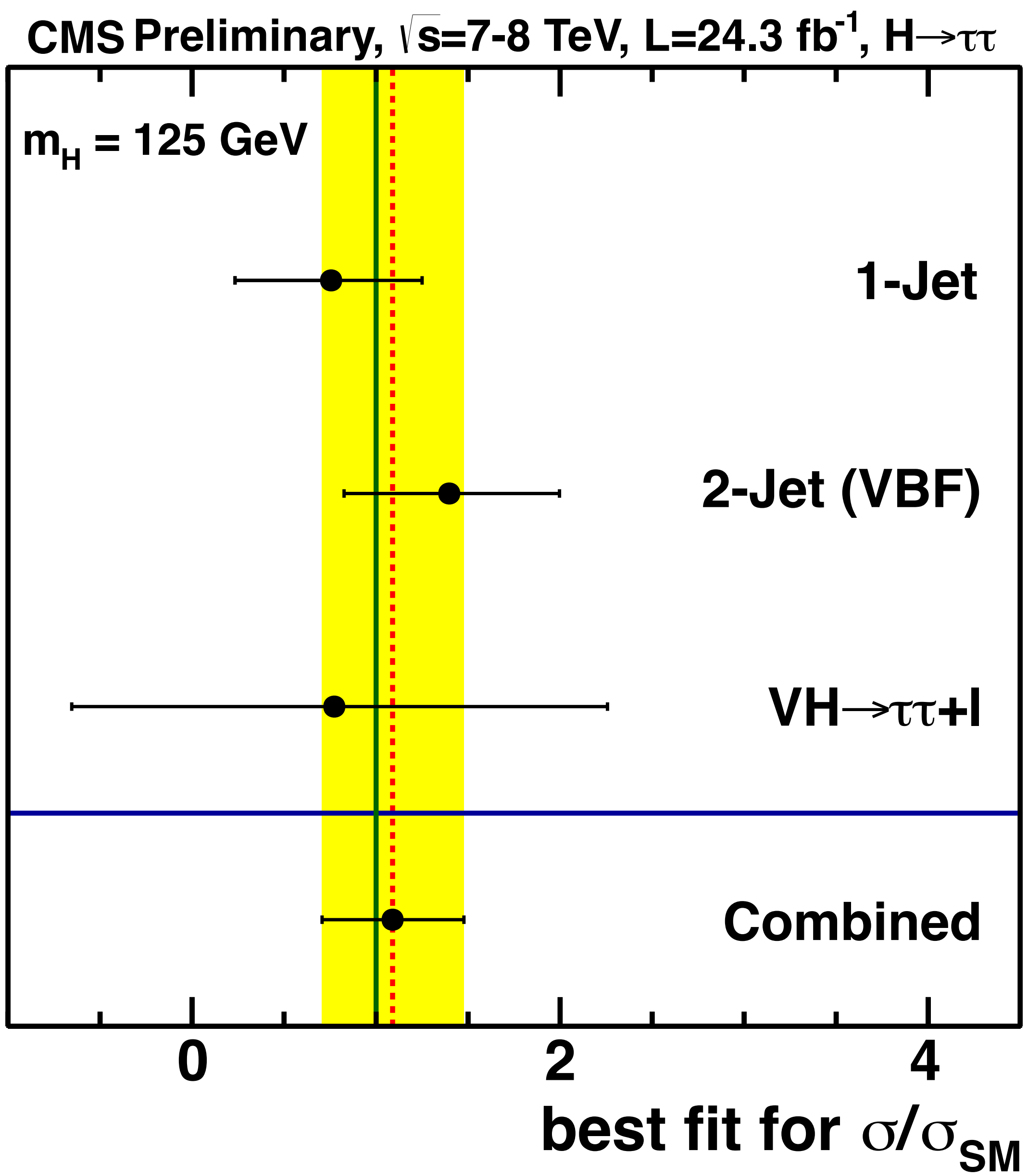


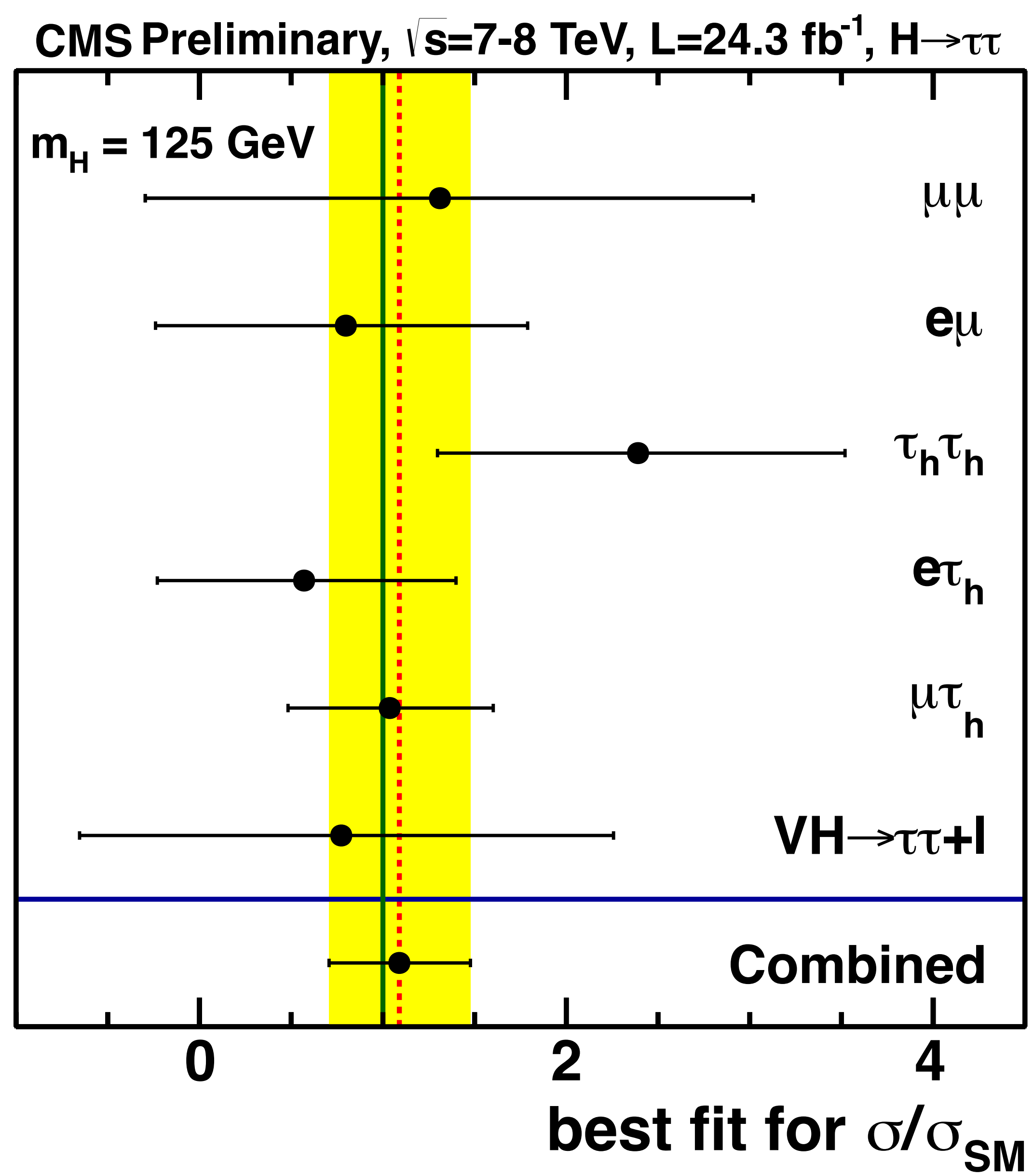
- ATLAS: $\mu = 0.7 \pm 0.7$ (4.6 + **13 fb^{-1}**)

*CMS-PAS-HIG-12-044

- CMS: $\mu = 1.1 \pm 0.4$ **(Run 1 dataset)**
- D0 Limit (9.7 fb^{-1}): 10.8 x SM (observed), 7.3 x SM (expected)
- CDF Limit (6 fb^{-1}): 16.4 x SM (observed), 16.9 x SM (expected)

H→ττ Results by Category





- Consistency between channels and categories
- Most powerful category is 1-jet
- VBF sensitivity from 2-jet category

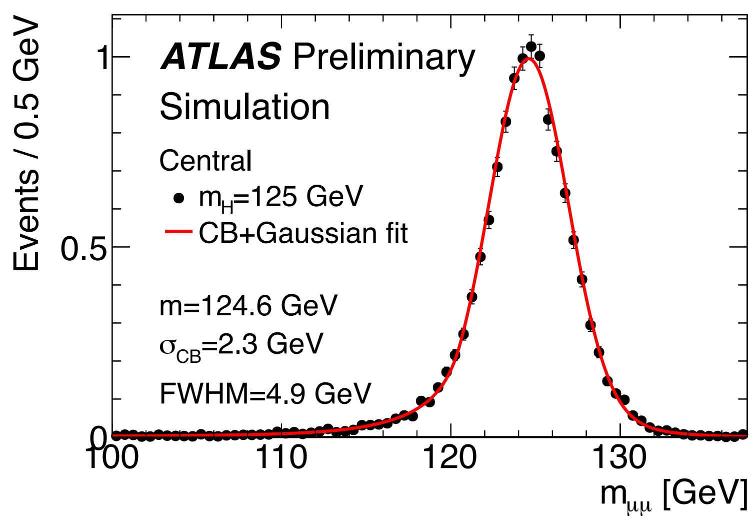
Probing Fermionic Couplings

- Decays
  - bb
  - ττ
  - μμ
- Production
  - ttH

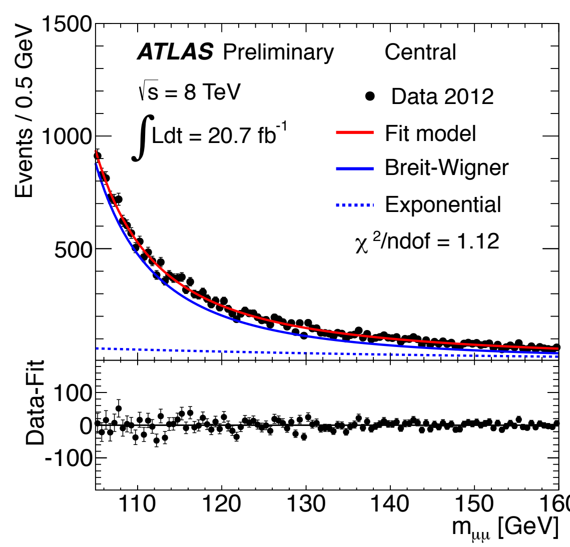
Search for H→μμ

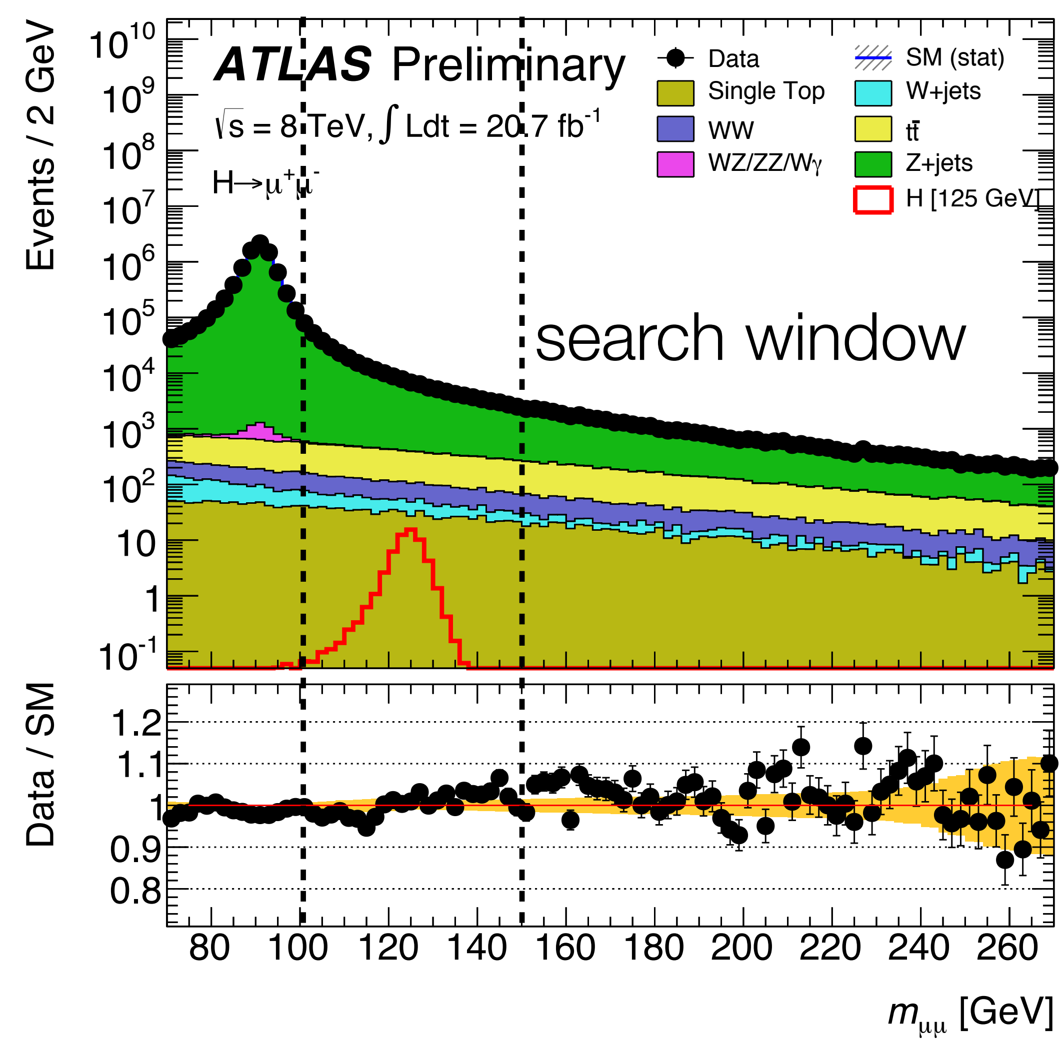
- Check **universality** of Higgs couplings: μμ vs ττ
- Tiny branching ratio, large background but excellent resolution
- **Two** isolated, opposite-sign **muons**, p_T > 25, 15 GeV
- Central (|η| < 1.0) and non-central **categories**
- Fit $m_{\mu\mu}$ with **analytical** signal and background **shapes**

Signal



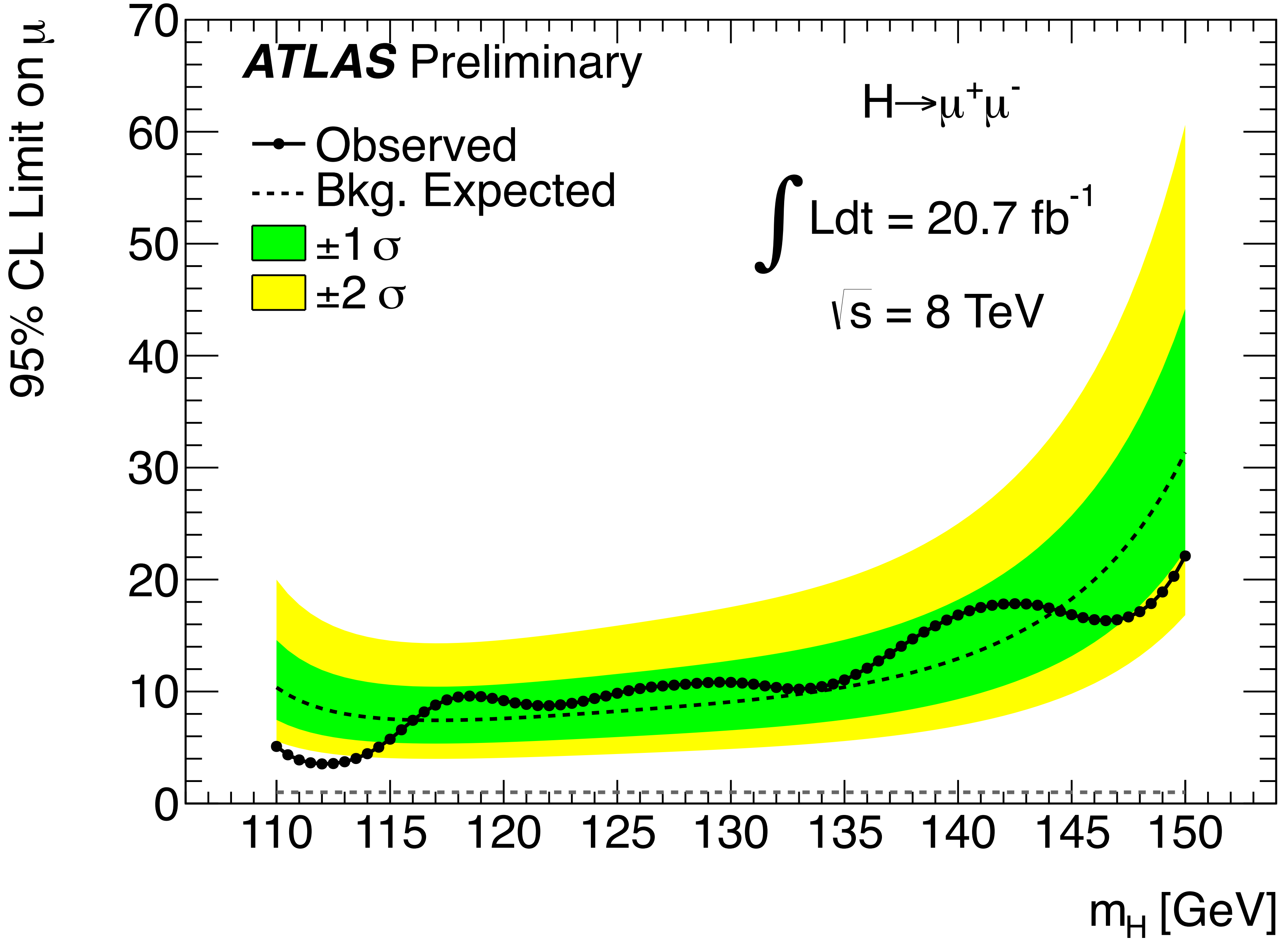
Background





H→μμ Results

- ATLAS (20.7 fb^{-1} of data)
  - Limits: **9.8 x SM (observed)**; 8.2 x SM (expected)
- Significantly more data needed to reach SM sensitivity

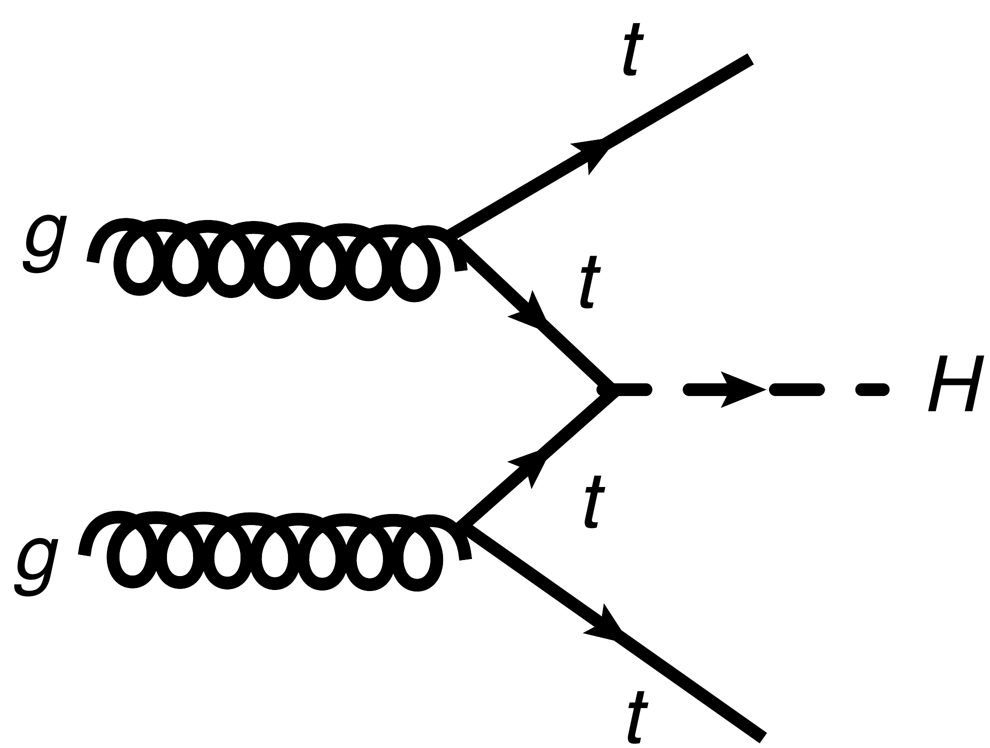


Probing Fermionic Couplings

- Decays
  - bb
  - ττ
  - μμ
- Production
  - ttH

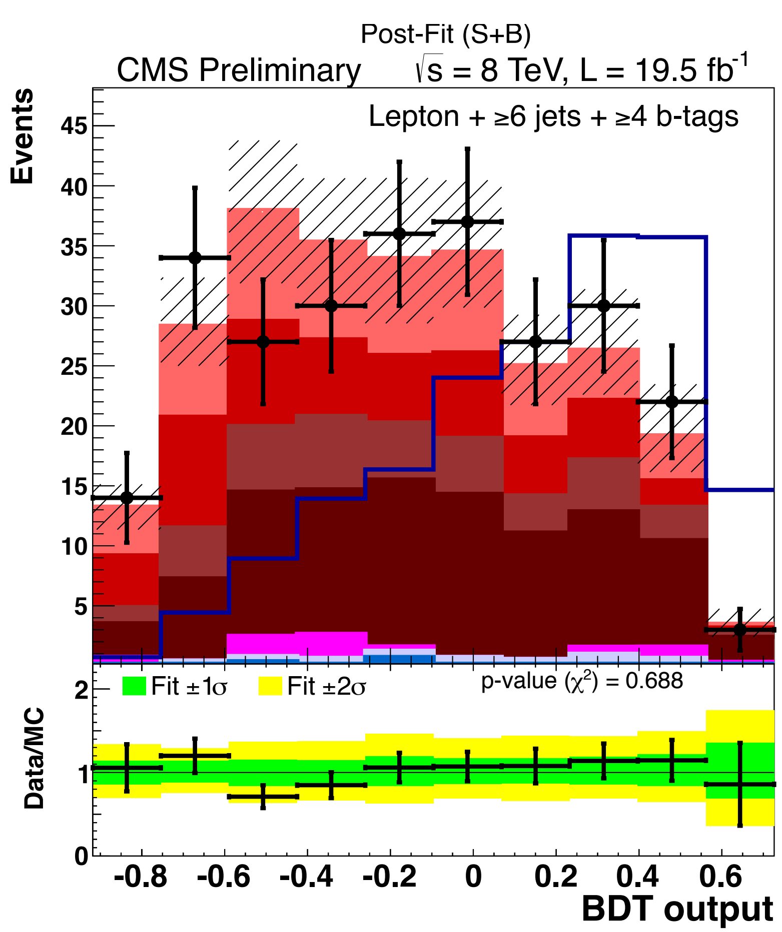
ttH

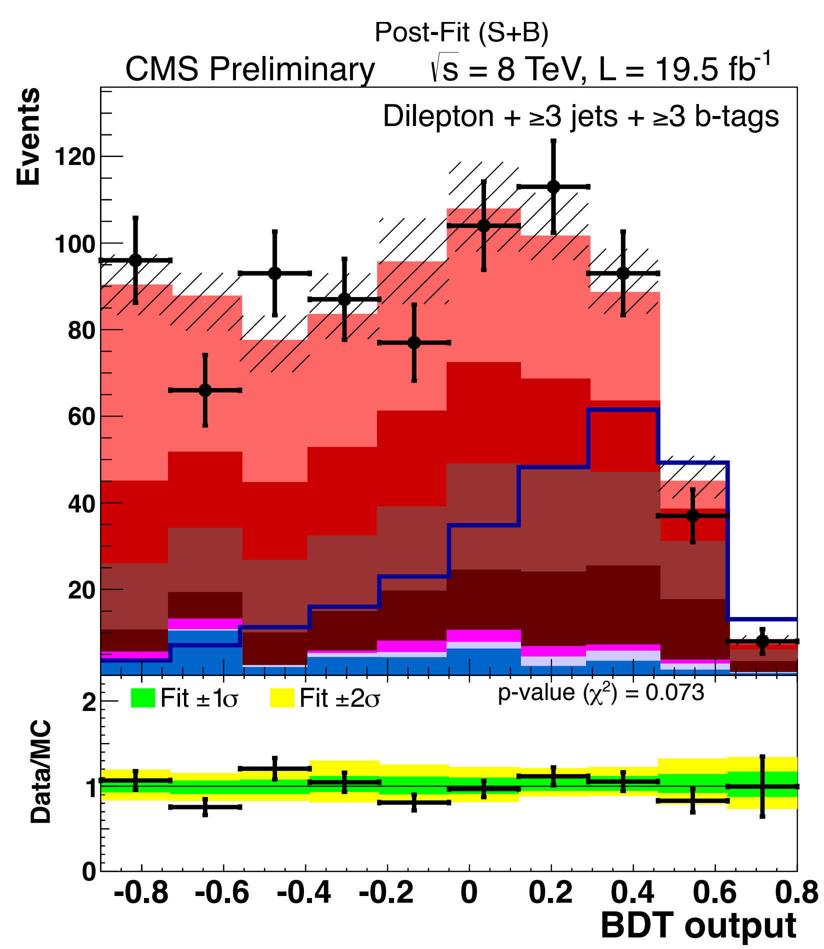
- Very **challenging** mode
  - Small cross-section, large backgrounds
  - Large theoretical uncertainties on key backgrounds
- Provides a **direct probe** of **Higgs-top coupling**
- Reconstruct top decays in lepton+jets and dilepton channels
- Boost sensitivity by including as **many decays** as possible
  - bb, ττ, γγ, leptons ...

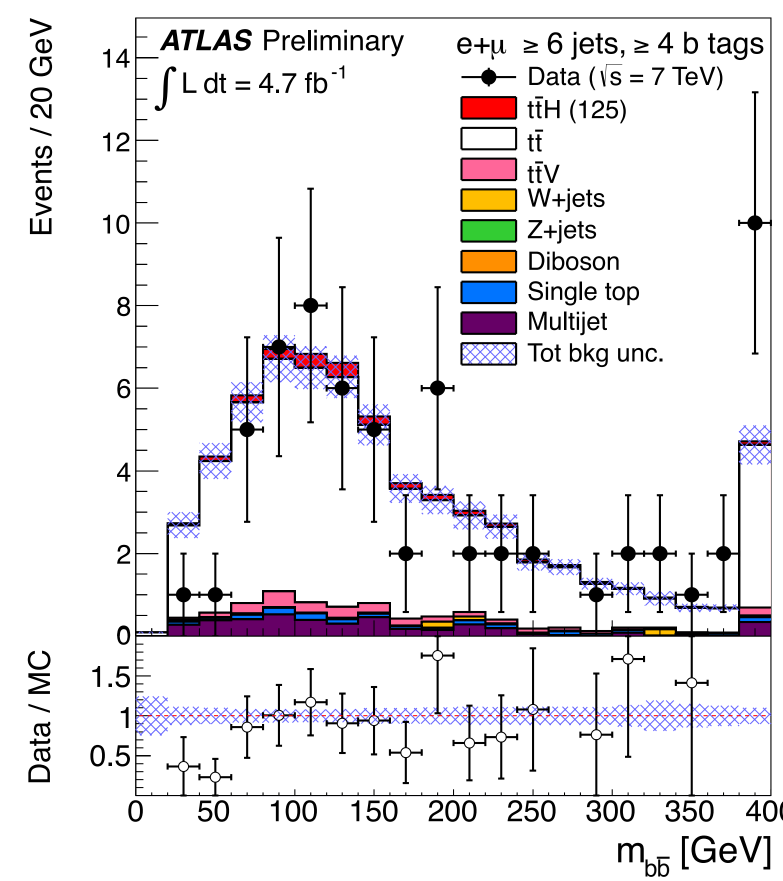


ttH(bb)

- **N$_{jet}$** and **N$_{b\text{-}jet}$** categories to constrain backgrounds and systematics and isolate signal
    - Most powerful category: 4 b-tagged jets + 2 additional jets
- Main challenge: **ttbb** background modelling
- Discriminating variables: BDT, H_T or m_{bb}

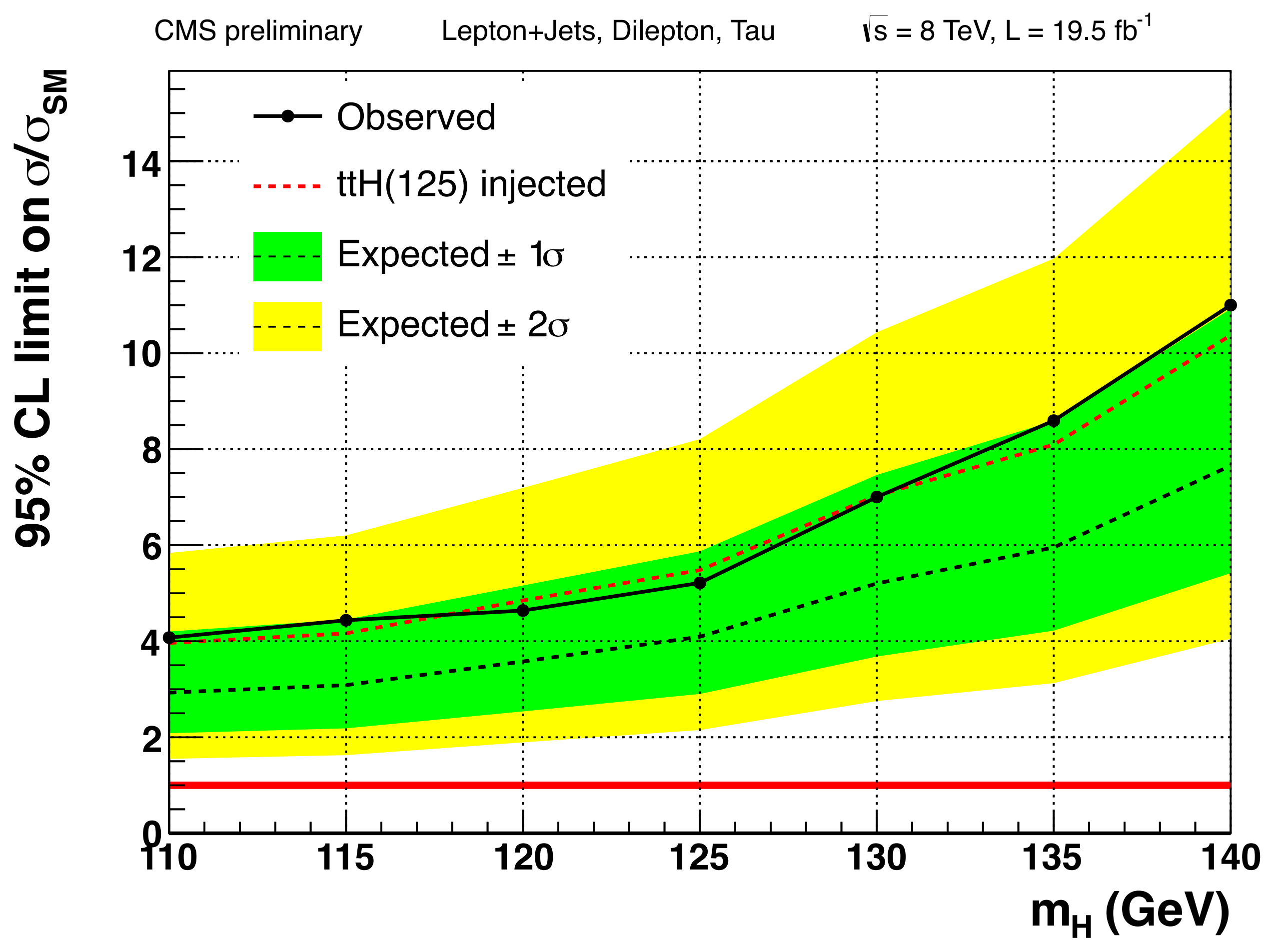


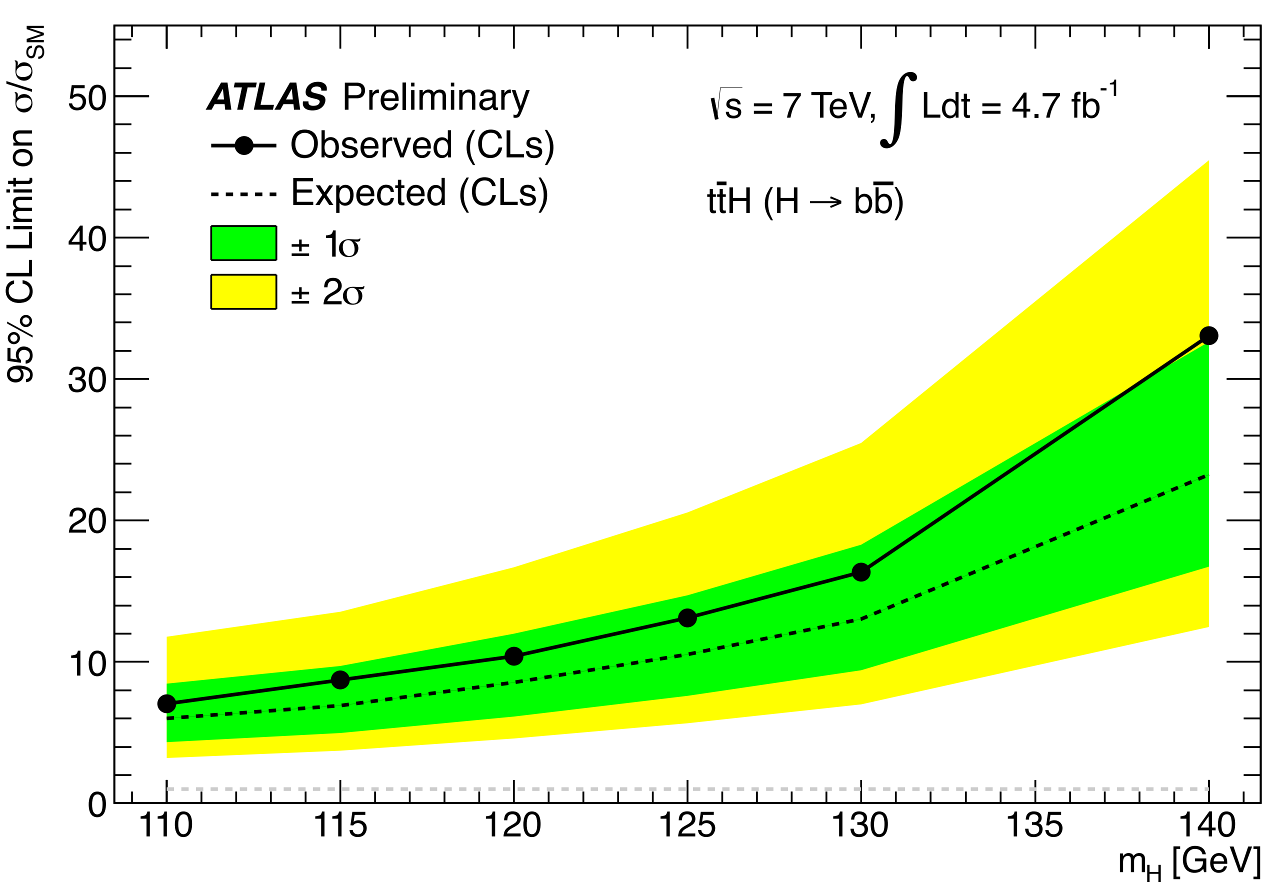




ttH(bb) Results

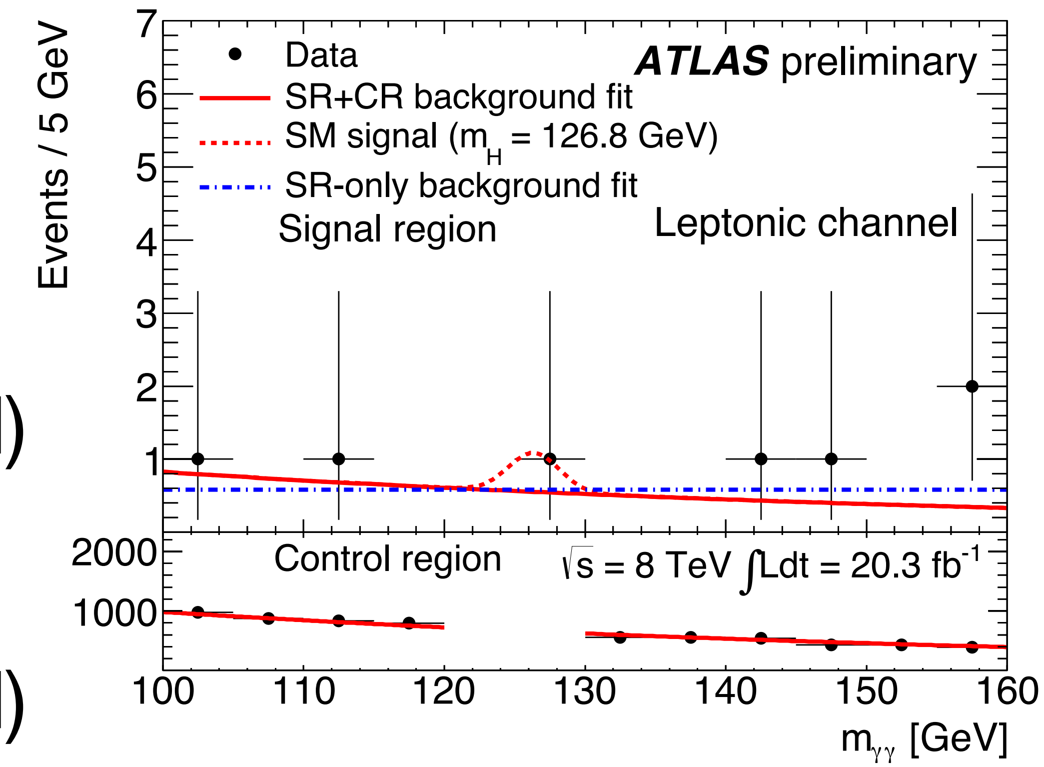
- ATLAS (4.7fb^{-1} @ 7 TeV)
  - Limits: **13.1 x SM (observed)**; 10.5 x SM (expected)
- CMS (full Run 1 dataset)
  - Limits: **5.2 x SM (observed)**; 4.1 x SM (expected)

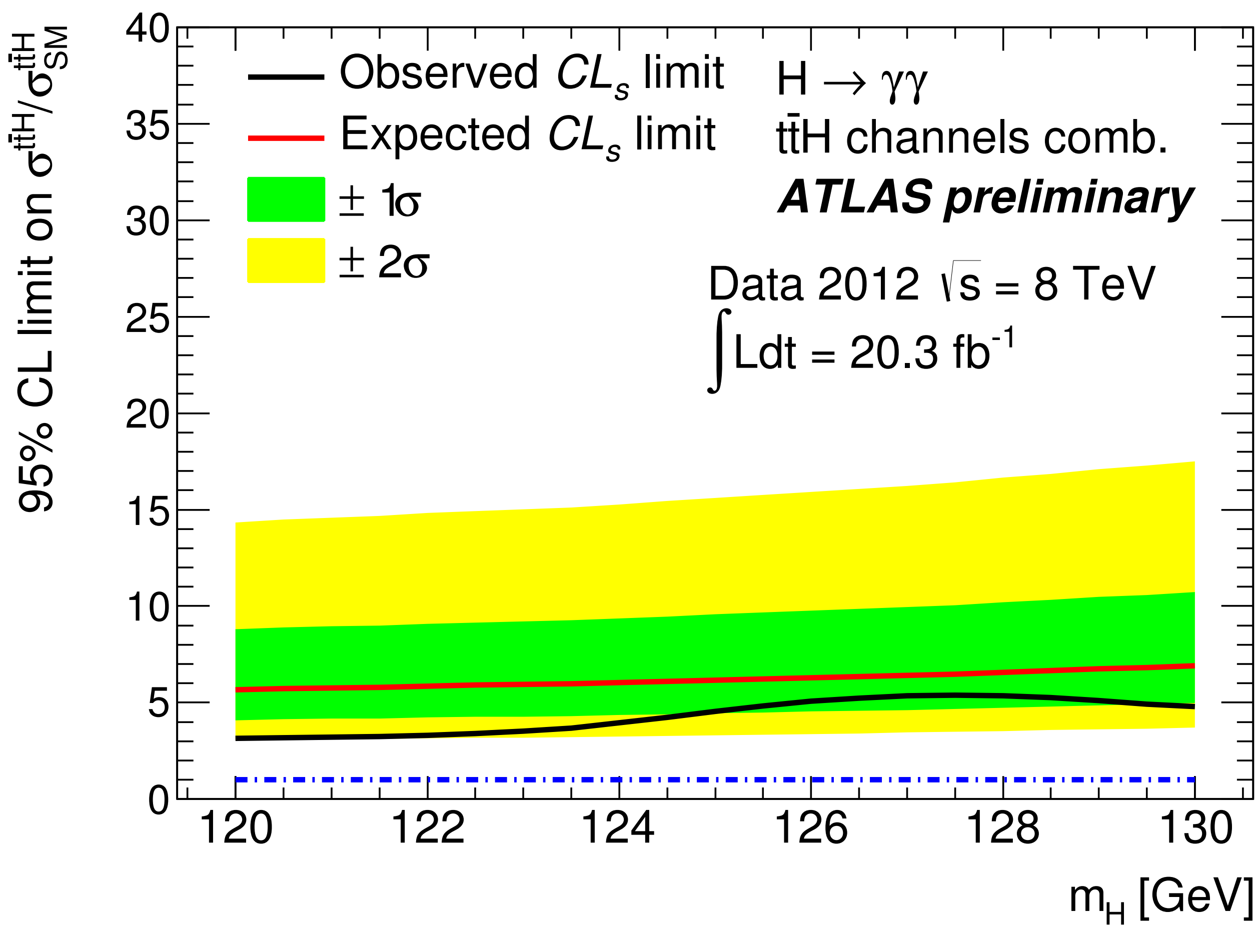


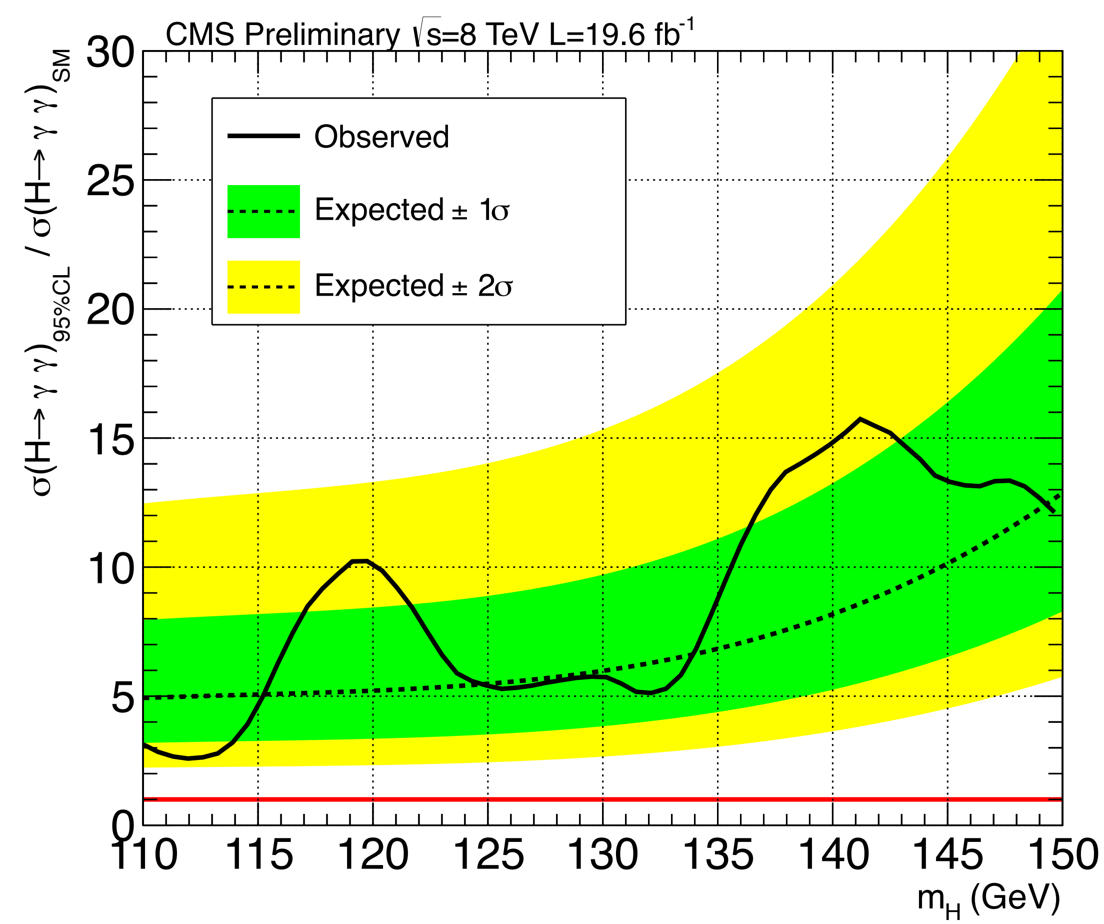


ttH(γγ)

- Select 2 top candidates; 2 photons
- **Parametric fit** to estimate backgrounds
- ATLAS (20.3 fb-1):
  - **5.3 x SM (observed)**; 6.4 x SM (expected)
- CMS (19.6 fb-1):
  - **5.4 x SM (observed);** 5.3 x SM (expected)

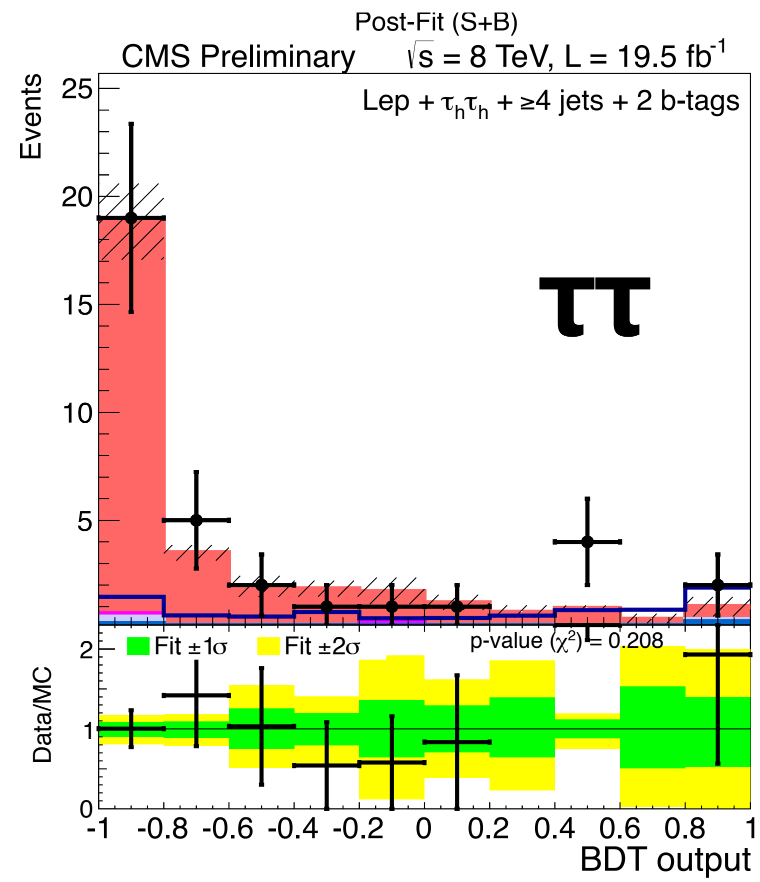


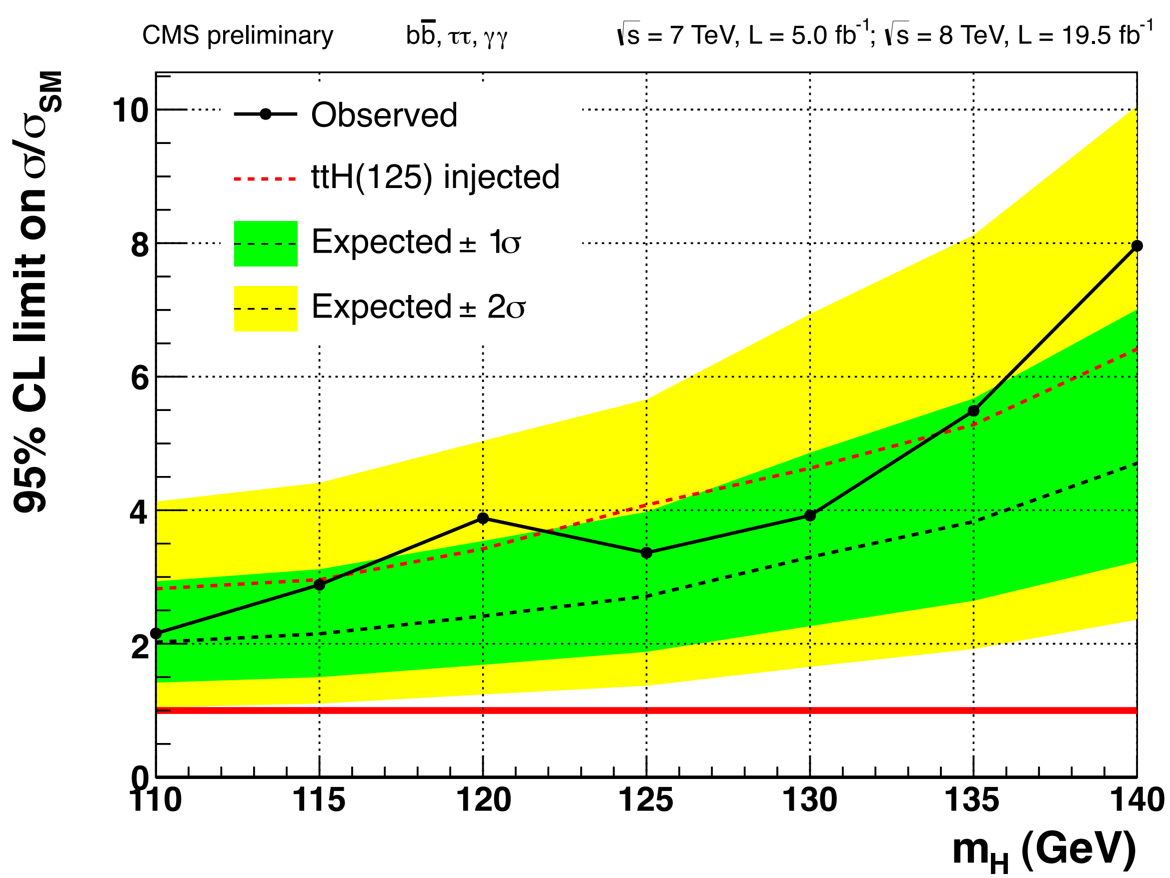


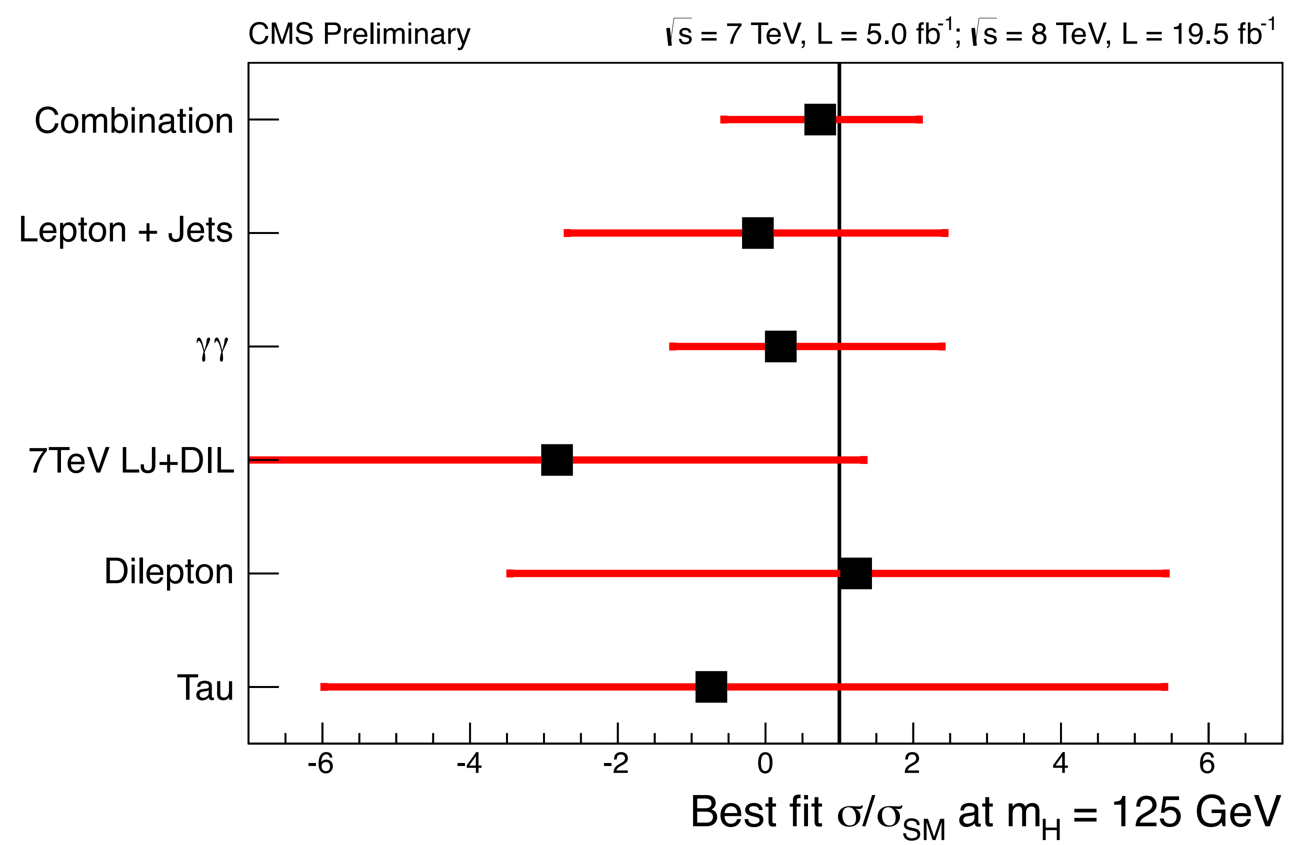


ttH Combination

- **Combine** ttH channels to maximise sensitivity
- Recent CMS γγ, bb and ττ **combination**
  - Limits: **3.4 x SM (observed)**, 2.7 x SM (expected)
- **Further improvements** from additional channels (e.g. leptons)
- Can the current dataset reach **SM sensitivity** ?

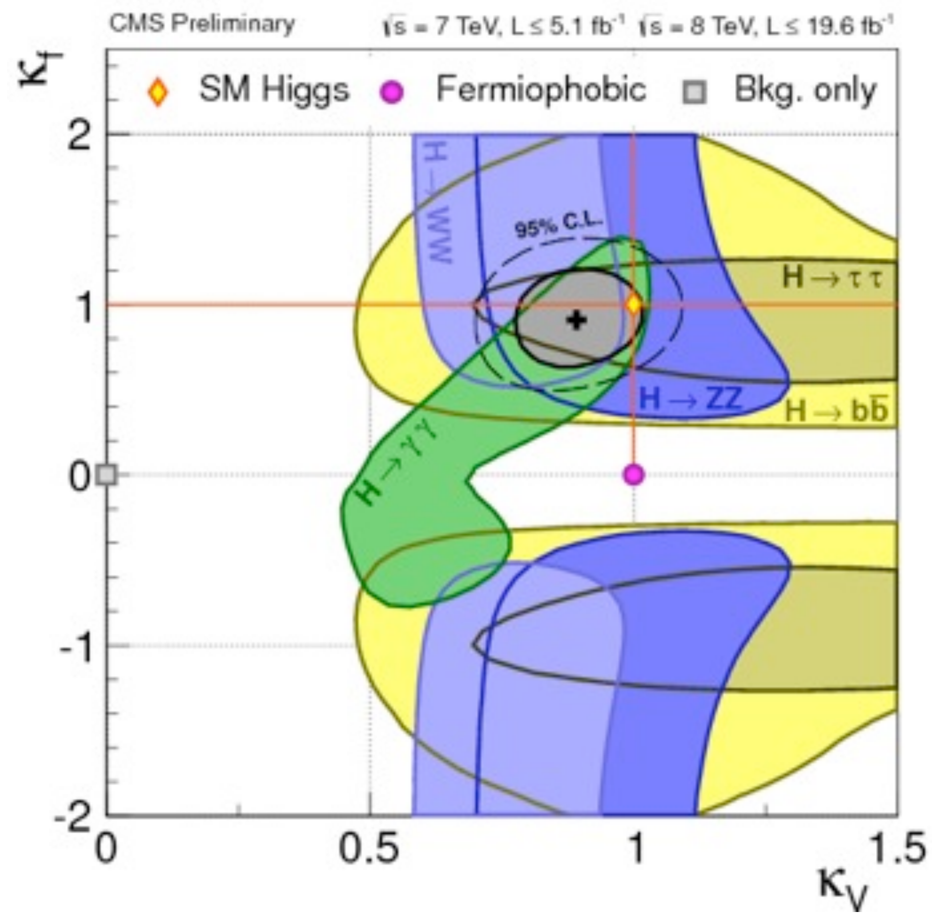


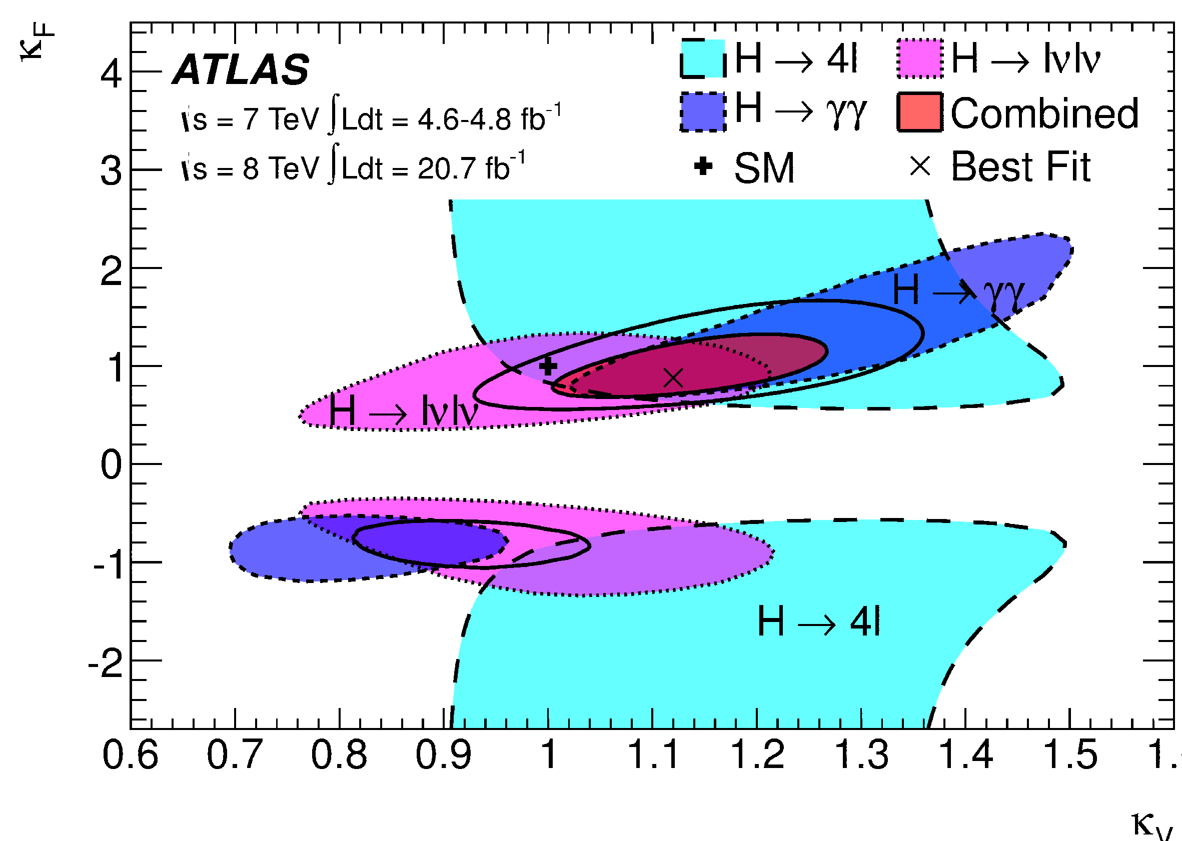




Indirect Evidence for Fermionic Coupling

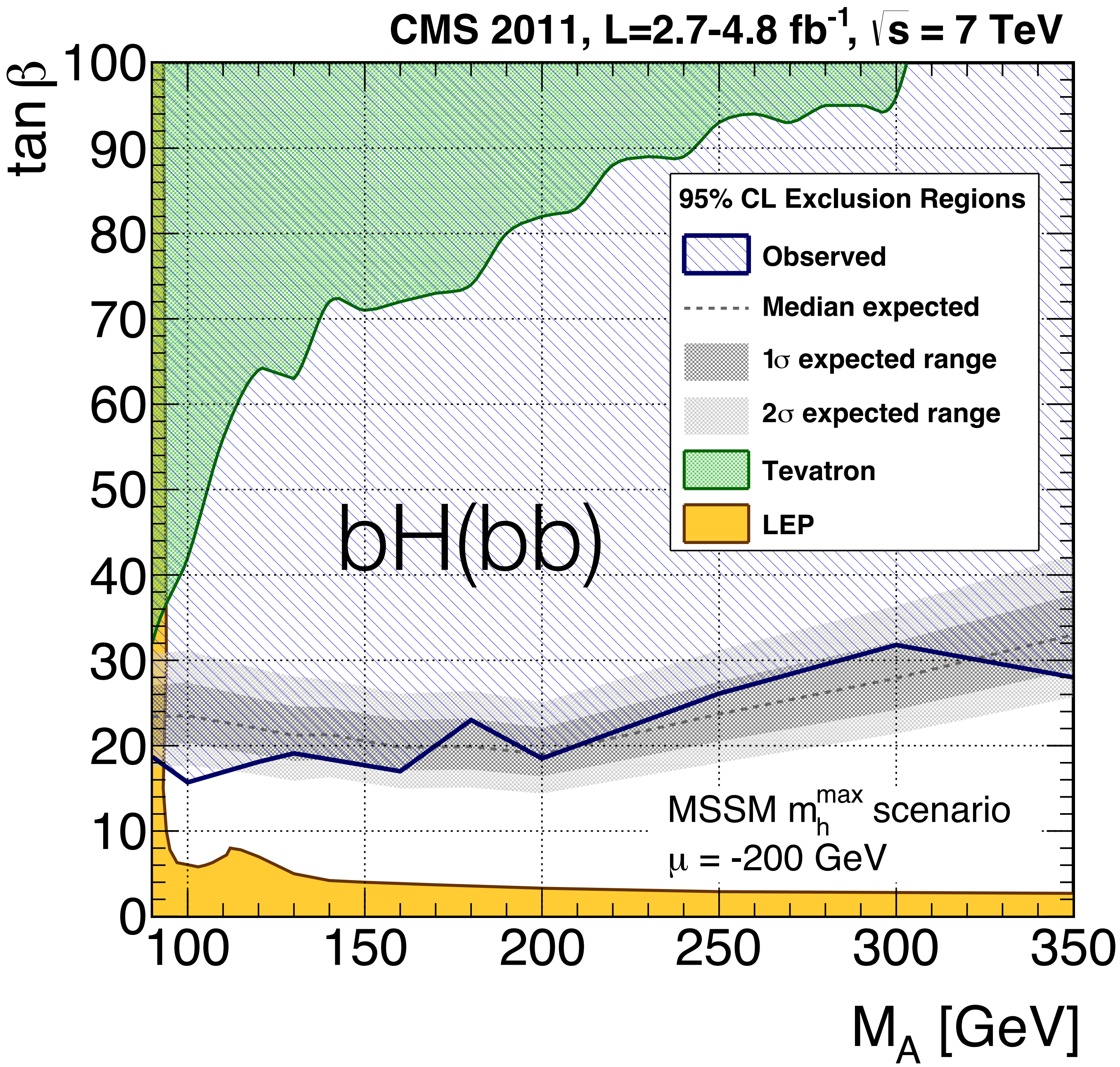
- Fits used to study Higgs properties provide **indirect** evidence for coupling to fermions
- Include most Higgs decay channels
- Assume **universal** fermionic and bosonic couplings and no additional non-SM particles
- Both ATLAS and CMS have **>5σ evidence** for coupling to fermions

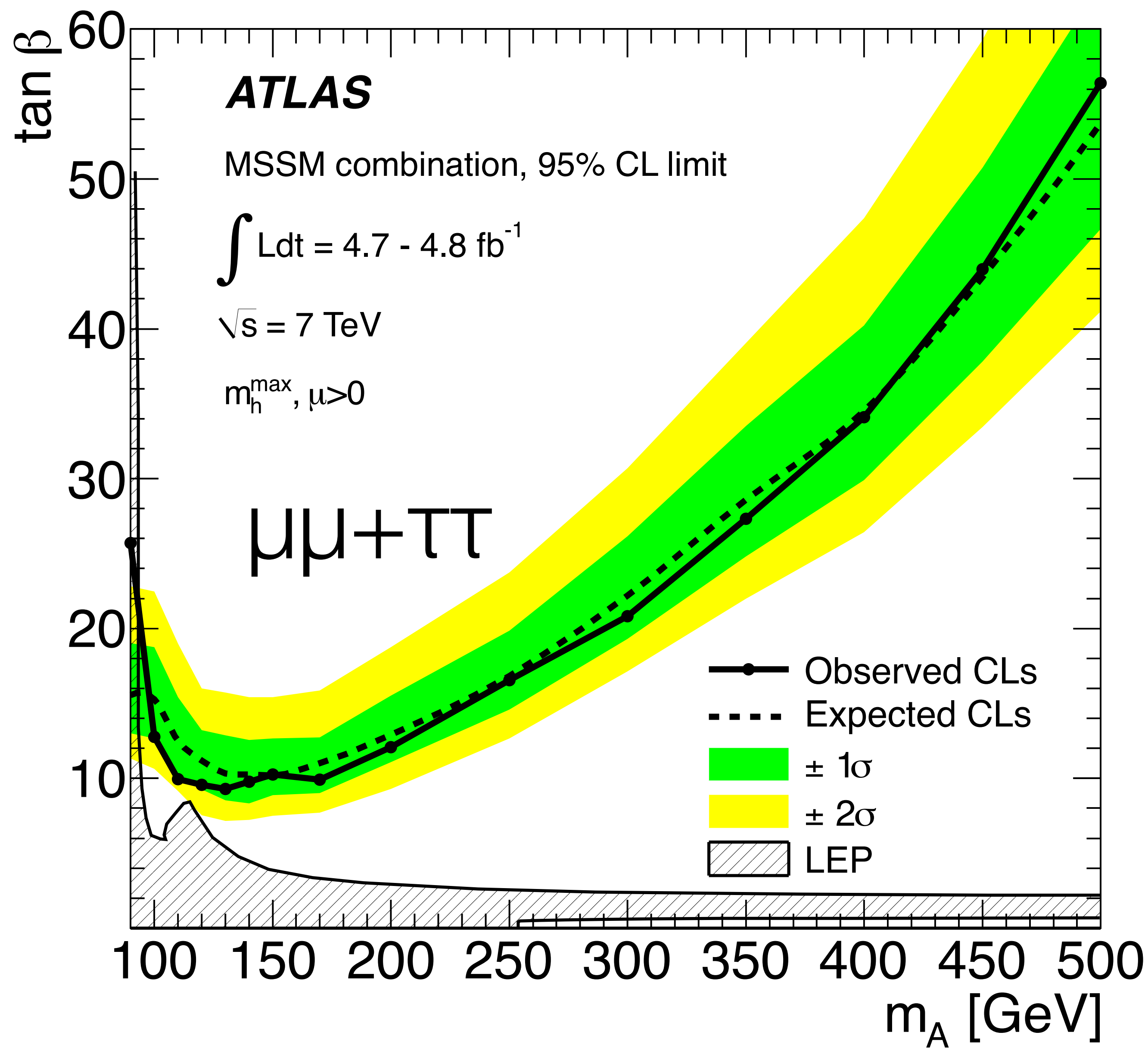




Searching beyond the SM

- Fermionic decays provide constraints on the MSSM in the context of 2 Higgs doublet models





Conclusion

- **Fermionic sector** currently an **exciting** and **active** part of the Higgs program
- Presented **recent results** from ATLAS, CMS, CDF and D0
  - VH(**bb**): ~2σ (LHC); ~3σ (Tevatron)
  - VBF(**bb**): < 3.6 x SM
  - **ττ**: ~3σ

  } CMS: ττ+bb 3.4σ
  - **μμ**: <10 x SM
  - **ttH** (bb, γγ and ττ): <3.4 x SM
- Summary: **direct > 3σ** (evidence); **indirect > 5σ** (observation)
- But more results still to come from ongoing Run 1 analyses
  - And 2015 is just around the corner...

Question: **Does the Higgs couple to fermions** ?

Answer: **Most likely**, but need to **wait** just a bit longer for conclusive evidence

Bibliography

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  - bb
    - VH(bb): ATLAS-CONF-2013-079, CMS-PAS-HIG-13-012, Phys. Rev. Lett. 109, 071804 (2012) (Tevatron)
    - WZ/ZZ: http://arxiv.org/abs/1203.3782 (Tevatron)
    - VBF(bb): CMS-PAS-HIG-13-011
  - ττ: ATLAS-CONF-2012-160, CMS-PAS-HIG-13-003
  - μμ: ATLAS-CONF-2012-010
  - MSSM: bH(bb): http://arxiv.org/pdf/1302.2892.pdf (CMS), ττ: http://arxiv.org/pdf/1104.1619.pdf (CMS), μμ+ττ: http://arxiv.org/abs/1211.6956 (ATLAS)
- Fermionic **Production**
  - ttH
    - ttH(bb): CMS-PAS-HIG-13-019, ATLAS-CONF-2012-135
    - ttH(γγ): ATLAS-CONF-2013-080, CMS-PAS-HIG-13-015