Higgs decays to fermions in CMS ($H \to \tau\tau$, $H \to b\bar{b}$, $a \to \mu\mu$)

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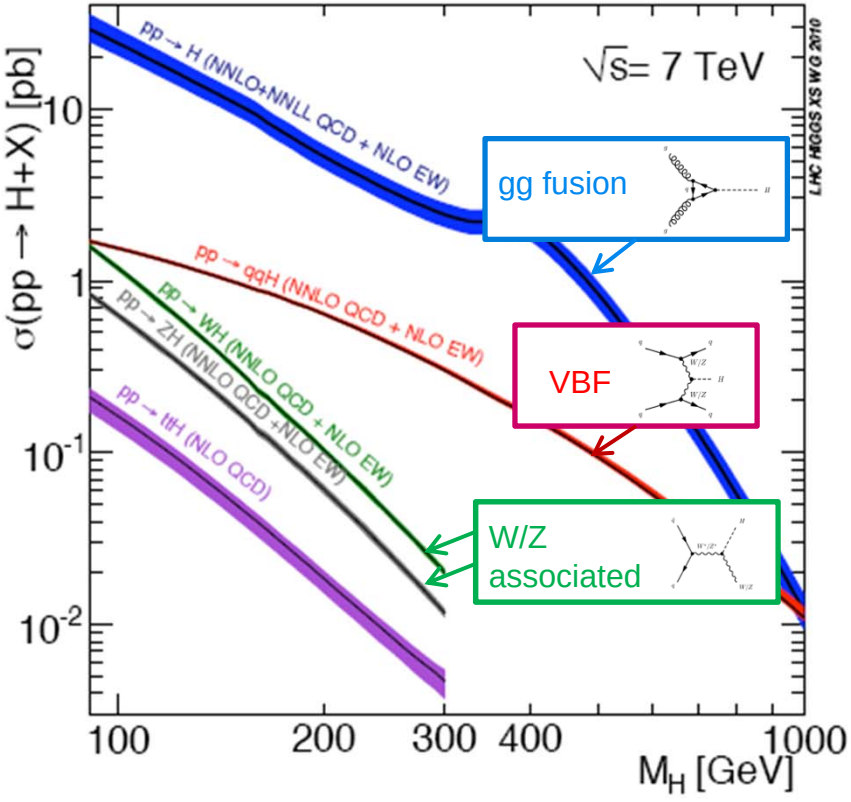
HELMHOLTZ ASSOCIATION

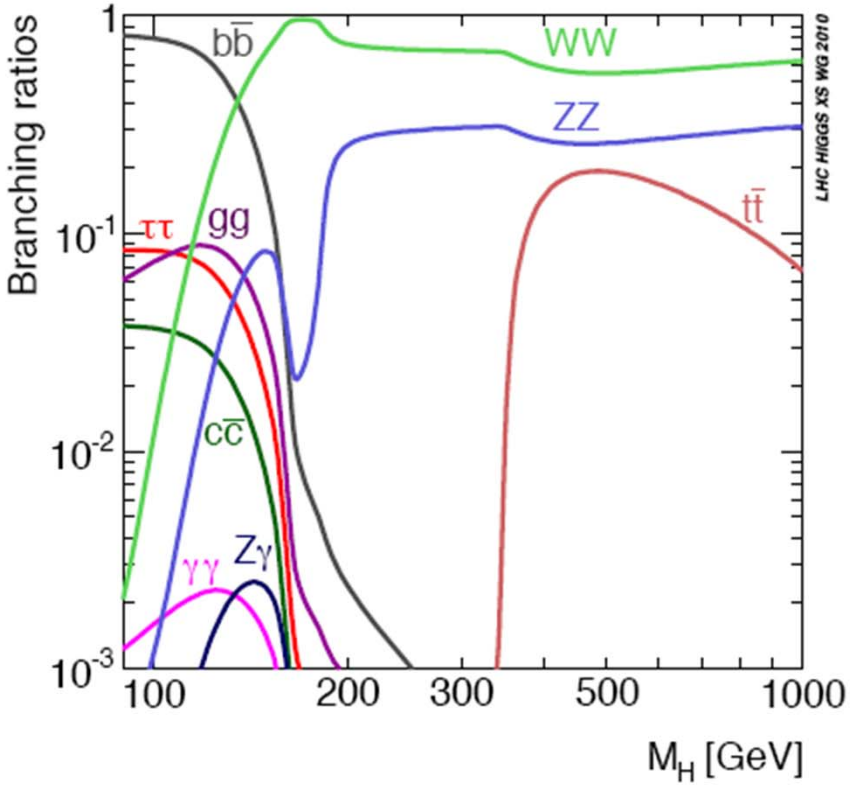
DESY

Introduction

- Standard model (SM) has been extremely successful in describing wide range of phenomena in particle physics
  - only remaining undiscovered SM particle: Higgs boson
  - comprehensive approach covering many different production mechanisms & decay channels
- Di-fermion final states:
  - below the thresholds for di-boson (W, Z) production, τ lepton and b quark offer relatively large masses for the Higgs to couple to
  - ➔ play important rôle in low-mass region
- Beyond a discovery, an essential goal is to investigate the detailed structure of the Higgs sector
  - ➔ di-fermion decays are an important probe distinguishing different structural options

SM Higgs Production & Decays





- For a Standard Model Higgs, di-fermion decay modes dominate for m_H<130 GeV

Higgs Sector: Structure?

Structure of the Higgs Sector

- Standard Model
  - one physical Higgs state (H)
  - quadratically divergent self-energy corrections at high energies

H→ $b\bar{b}$, ττ

- MSSM (=minimal supersymmetric extension)
  - two complex Higgs doublets
  - physical states: h, H, A, $H^{\pm}$ ⇔ (m_A, tan β)
    - "Φ"
  - avoids quadratic divergences
  - new mass scale parameter → "μ term problem"

Φ→ ττ

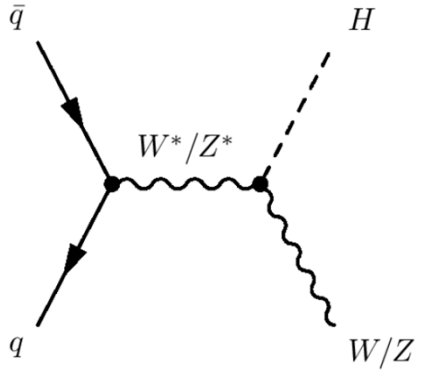
- NMSSM (=next to minimal supersymmetric extension)
  - avoids "μ term problem"
  - two complex Higgs doublets + additional singlet field
  - physical states are mixtures: h_1, h_2, h_3, a_1, a_2, $H^{\pm}$
    - CP-even: h_1, h_2, h_3
    - CP-odd: a_1, a_2

a→ μμ

H → $b\bar{b}$ Searches

VH→V(b$\bar{b}$)

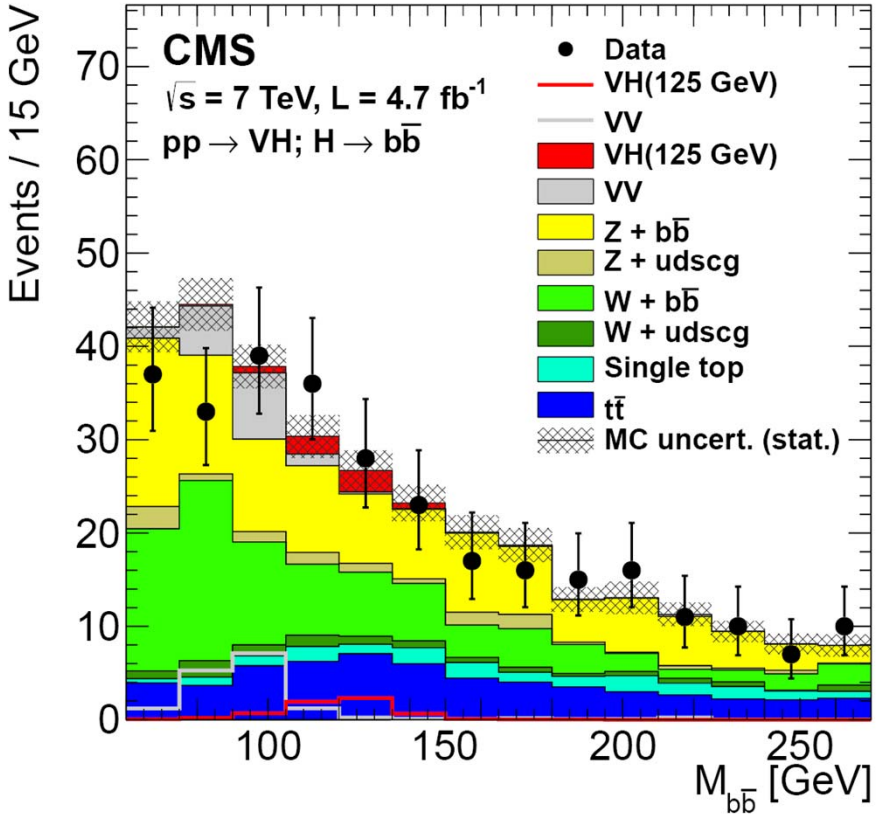
- For a light standard model Higgs, H→b$\bar{b}$ would be the predominant decay channel
  - → observation of H→b$\bar{b}$ decay is essential to determine nature of Higgs
- For gg→H (σ~17pb for m_H=120 GeV), QCD background is overwhelming
  - relation improves in association with W or Z boson → boosted analysis.
  - Five final states considered:
    - W(eν)H, W($\mu\nu$)H
    - Z(ee)H, Z($\mu\mu$)H, Z($\nu\nu$)H
- Main backgrounds:
  - Z/W + jets, t+X, t$\bar{t}$, VV, QCD multi-jet
  - background contributions normalized in control regions
  - mass-based and boosted decision tree-based (BDT) analyses



VH($b\bar{b}$) Analysis (cont'd)

(arXiv:1202.4195, submitted to P.L. B)

- Mass-based cut & count analysis
- $p_T(W)>160$ GeV
  - $p_T(Z_{\ell\ell})>100$ GeV
- $E_T^{miss}>160$ GeV for $Z(\nu\,\nu)H$
  - $E_T^{miss}>35$ GeV for $W(e\nu)H$
- Combined Secondary Vertex (CSV) algorithm used for b tagging
  - combines impact parameter and secondary vertex information in a discriminant
- No signal observed



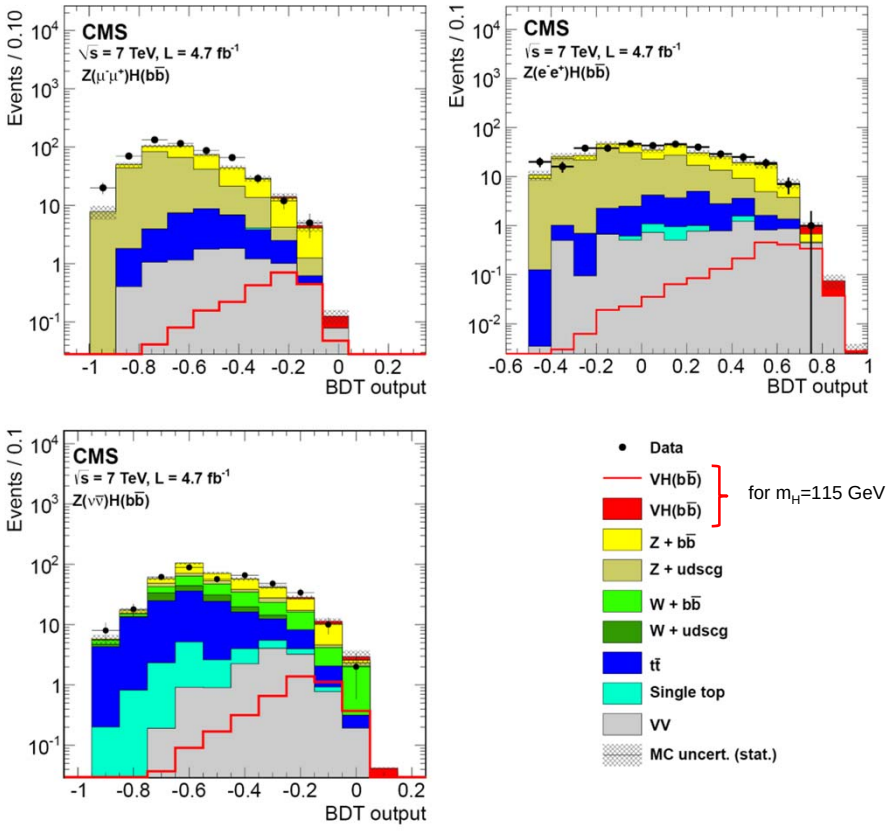
BDT Output (Selected Channels)

- Boosted decision tree technique used to improve separation of signal & background
- Variables for selection & training:

Variable	W(lν)H	Z(ll)H	Z(νν)H
$p_T(j_1)$	>30 GeV	>20 GeV	>80 GeV
$p_T(j_2)$	>30 GeV	>20 GeV	>20 GeV
$p_T(jj)$	>150 GeV	>100 GeV	>160 GeV
$p_T(V)$	>150 GeV	>100 GeV	-
E_T^{miss}	>35 GeV [W(eν)H]	-	>160 GeV
$\Delta\phi(V, H)$	-	-	-
CSV_{max}	>0.40	>0.244	>0.50
CSV_{min}	>0.40	>0.244	>0.50
N_{al}	=0	-	=0
N_{aj}	-	-	-
$\Delta\phi(E_T^{miss},jet)$	-	-	>0.5 rad

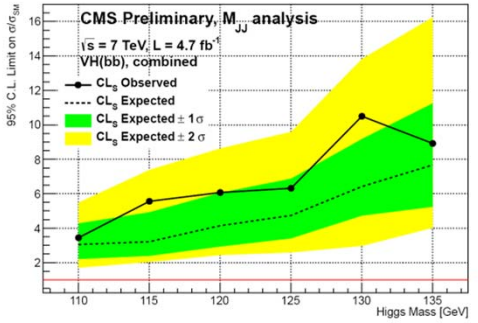
- For various variables relaxed selection cuts

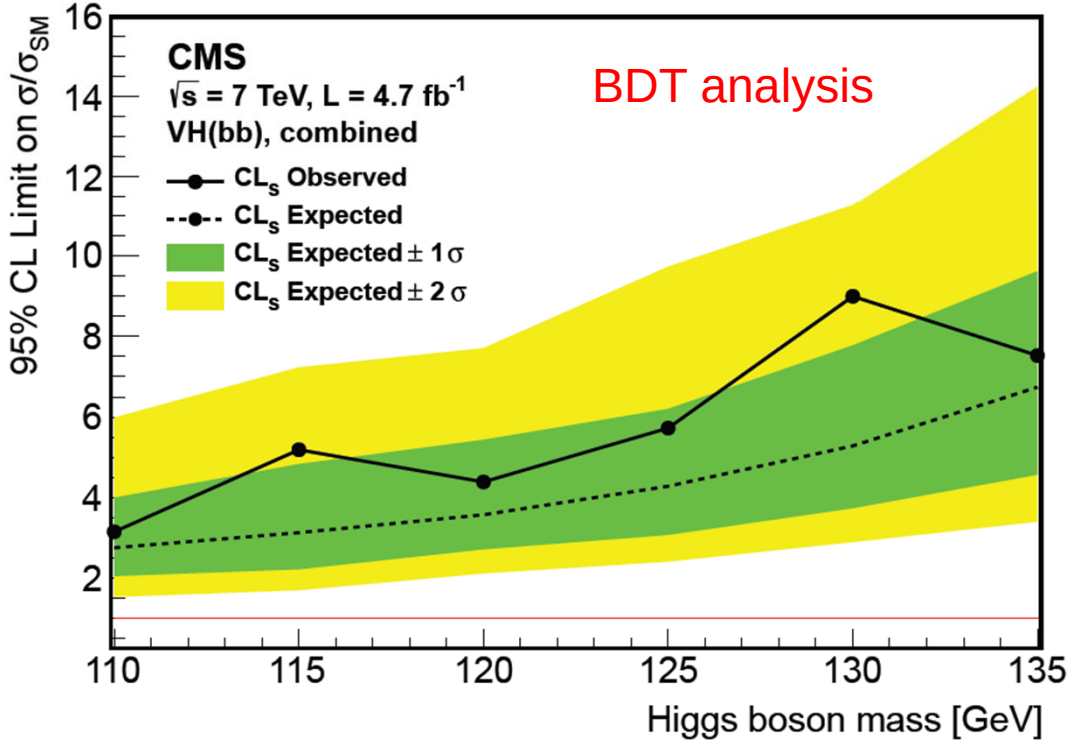
➔ BDT increases sensitivity by ~10% in each channel



VH→V(bb̄): Results

- No significant signal observed in any of the channels
- Total expected limit ~ 3x SM expectation (m_H=115 GeV)
- Observed limit from combination consistent with expectation
- BDT analysis (lower plot) performs 2-20% better than the mass-spectrum-based analysis (upper)

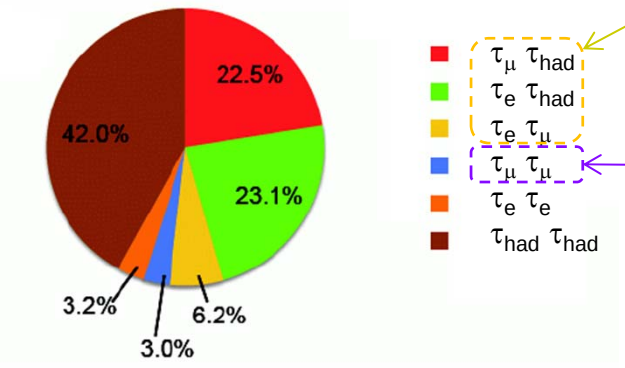




H → ττ Searches

H → τ τ

- At lowest masses 2nd strongest decay mode after H→b$\bar{b}$
- Final states:



$\tau_\mu\ \tau_{had}$
$\tau_e\ \tau_{had}$
$\tau_e\ \tau_\mu$
$\tau_\mu\ \tau_\mu$
$\tau_e\ \tau_e$
$\tau_{had}\ \tau_{had}$

(arXiv:1202.4083, submitted to P.L. B)

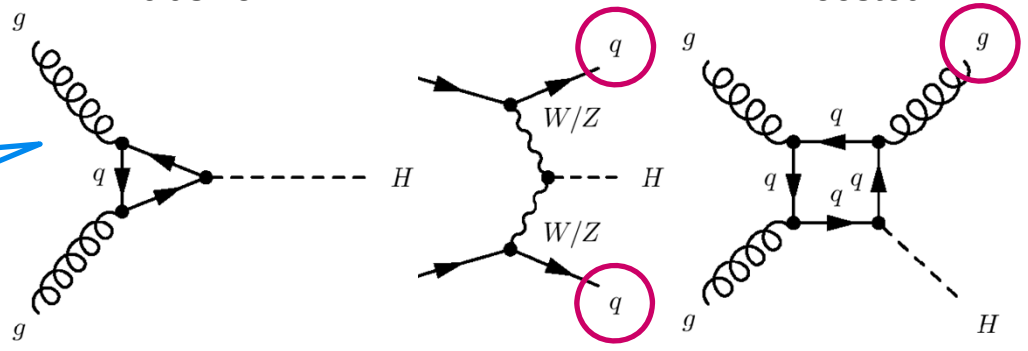
CMS PAS HIG-12-007

New!

- Standard Model search: event categories by production mechanisms:

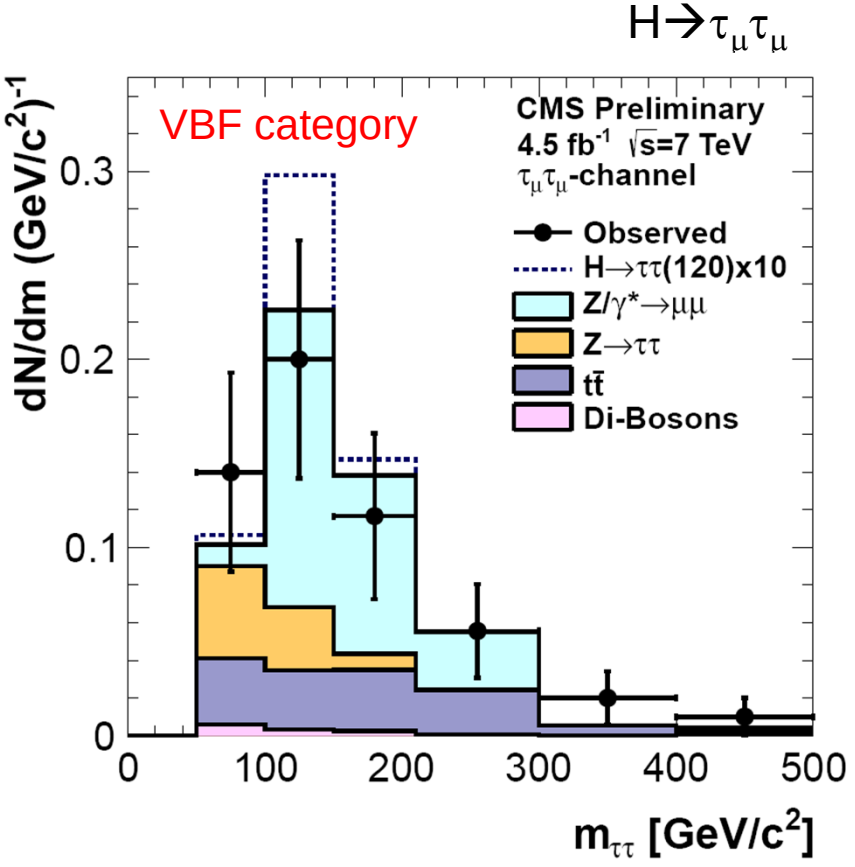
Inclusive | Vector Boson Fusion | Boosted

Little sensitivity due to background

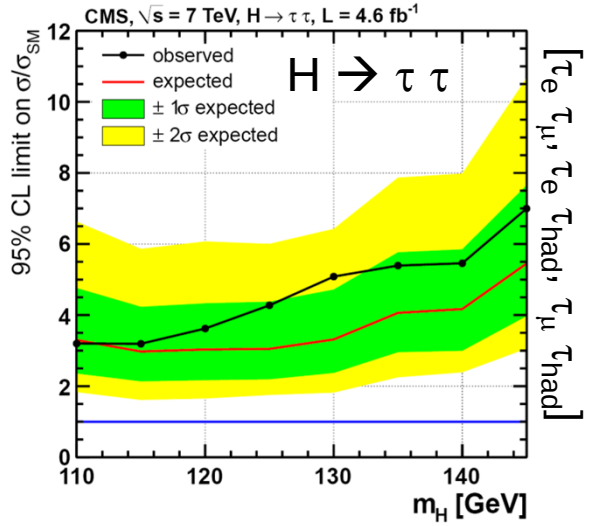


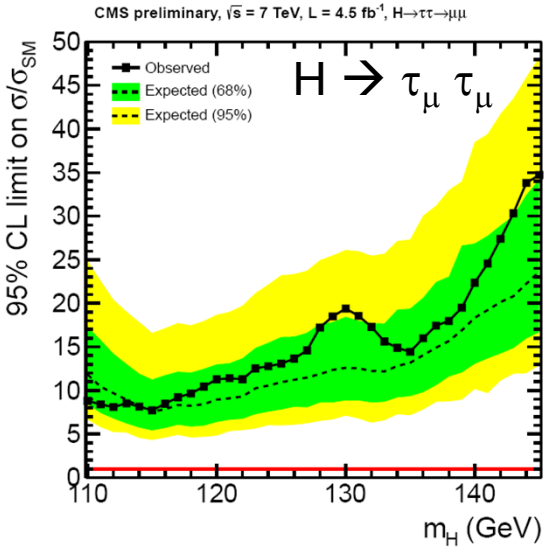
H → τ τ (cont'd)

- m(ττ) estimated by kinematic maximum likelihood fit
  - effective resolution ~21%
- Irreducible background from Z →ττ
  - addressed with "embedding method"
    - in Z→μμ events from real data, the μ's are replaced by simulated τ's
- New: H→$\tau_\mu\tau_\mu$
  - very challenging channel
  - irreducible background from Z →μμ
    - addressed by evaluating the distance of closest approach between μ's
  - signal enhancement with likelihood method



H → τ τ (cont'd)





- No significant excess over the expected standard model background contributions is observed
- Combination $\tau_e\,\tau_\mu$, $\tau_e\,\tau_{had}$, $\tau_\mu\,\tau_{had}$:
  - ➔ expected & observed 95% CL limit ~ 3x SM expectation (m_H=115 GeV)
  - ➔ observed limit consistent

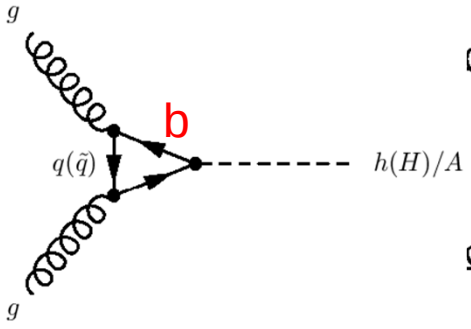
➔ Addition of H→$\tau_\mu\,\tau_\mu$ channel improves on combined limit from the other three decay

- combination result in preparation

Φ→ττ MSSM Search

- Mainly two processes contribute to pp→Φ+X
- Subsample with one btagged jet has increased sensitivity for MSSM Higgs boson search
  - ➔ smaller relative contribution from inclusive Z production

Non b-Tag:



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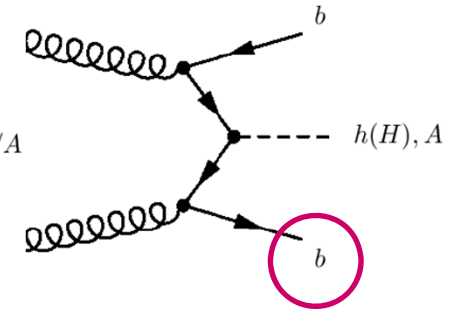
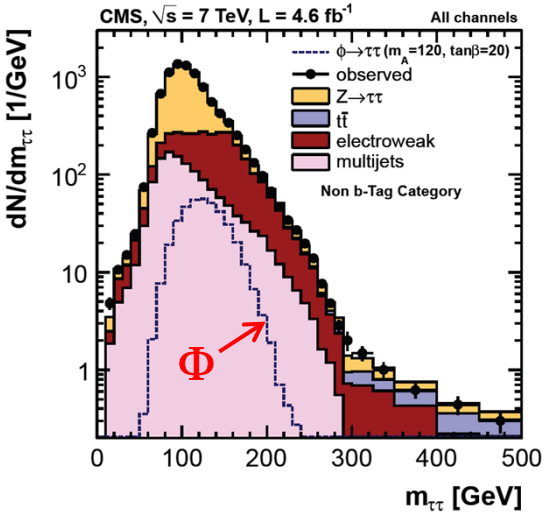


Non b-Tag:



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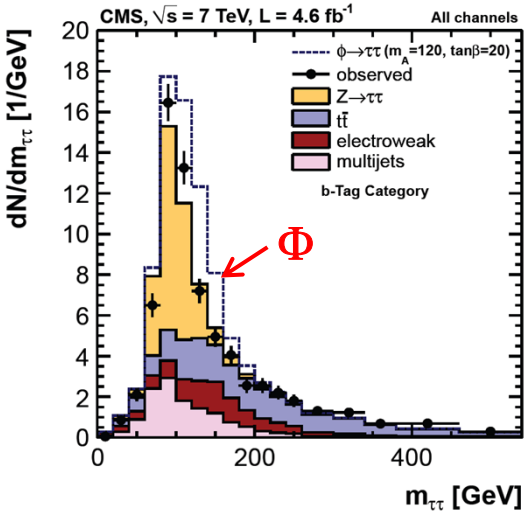
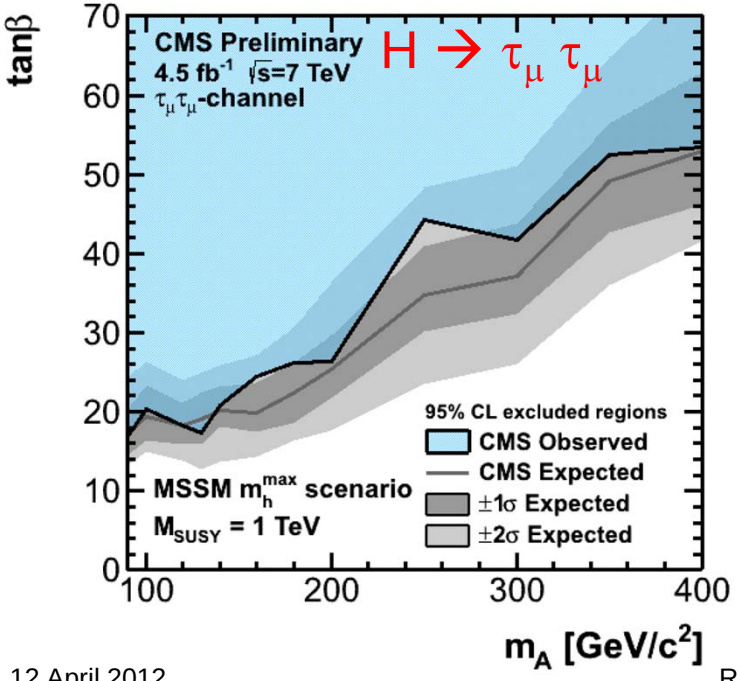
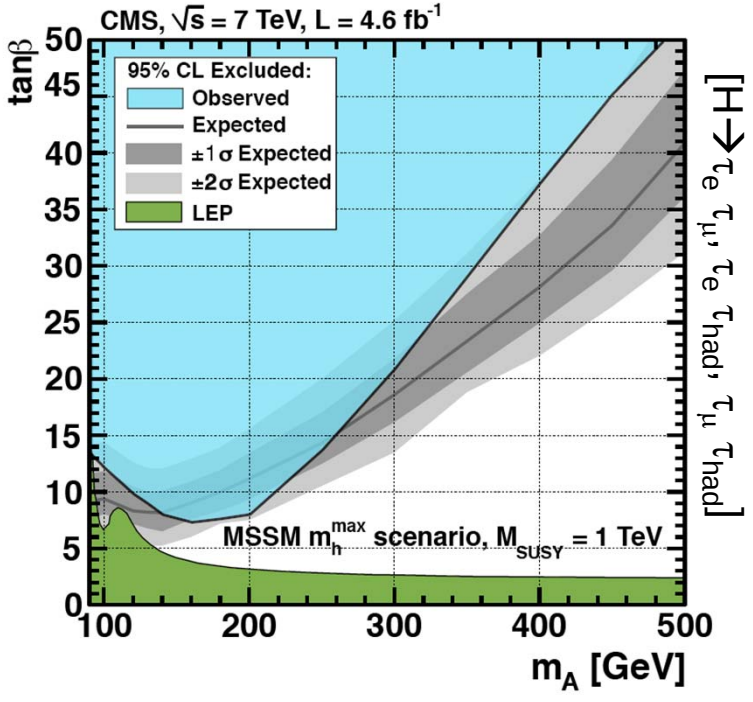


$\Phi \rightarrow \tau\tau$ MSSM Search

- Excludes previously unexplored territory
- 95% CL exclusion range for tan β extends down to 7.1 at m_A~160 GeV
  - ➔ narrowed parameter space at low m_A
- $\tau_\mu\ \tau_\mu$ channel alone fairly competitive with other measurements



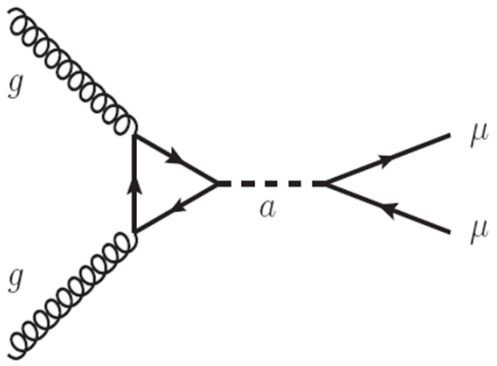


a → μμ Search

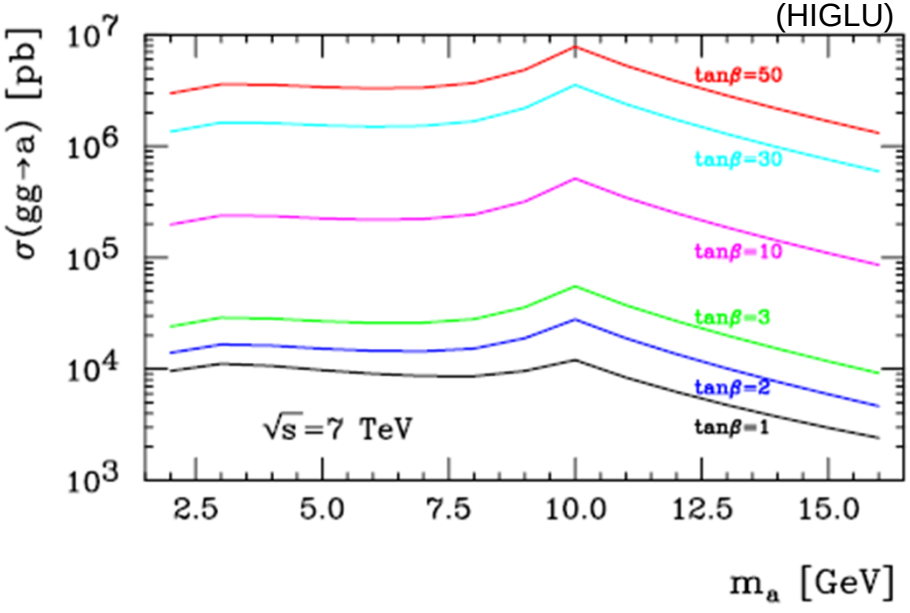
Search for a→μμ

CMS PAS HIG-12-004

- In the NMSSM, one of the two CP-odd scalars could be very light
  - superposition of CP-odd doublet scalar and the additional singlet scalar → mixing angle θ_A
  - → even m(a)<2 m_B thinkable
  - → sensitive to C_{abb} coupling
- Consider here:
  5.5 <m_a< 8.8 GeV,
  11.5 <m_a< 14 GeV
  - up to now, strongest constraints come from BaBar through $\Upsilon(3S)\rightarrow\gamma a$
- Cross section could be large

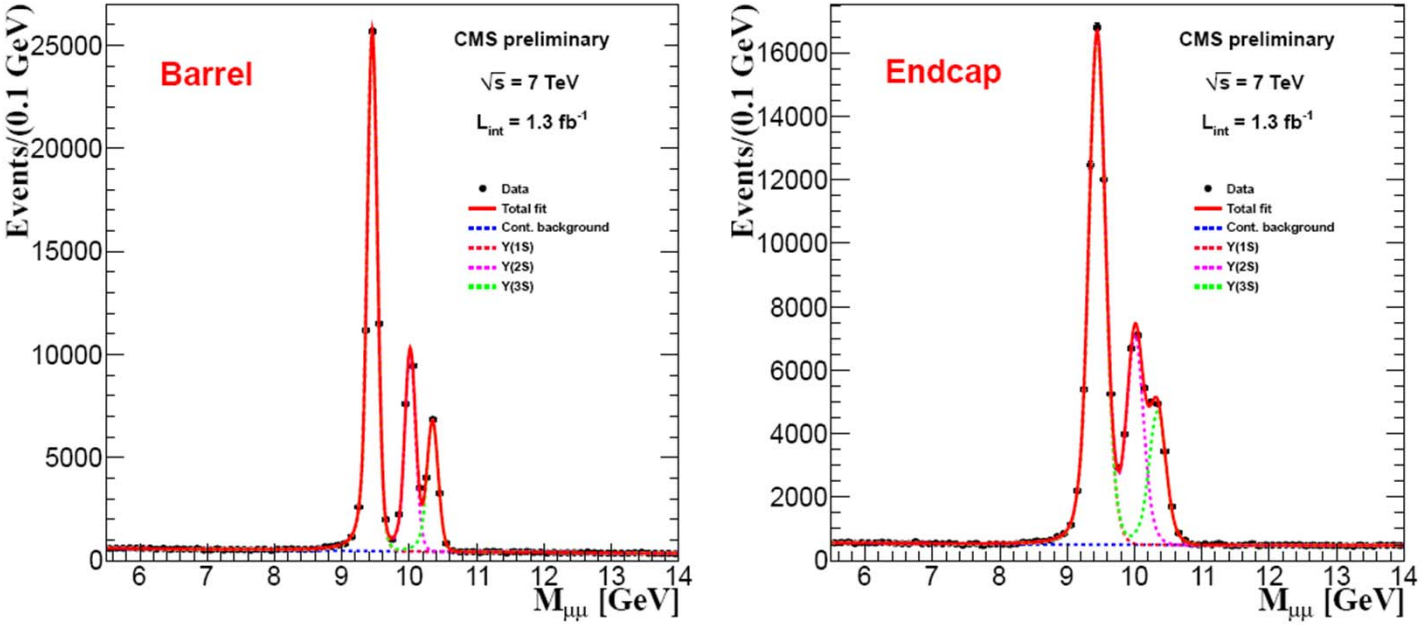


(HIGLU)



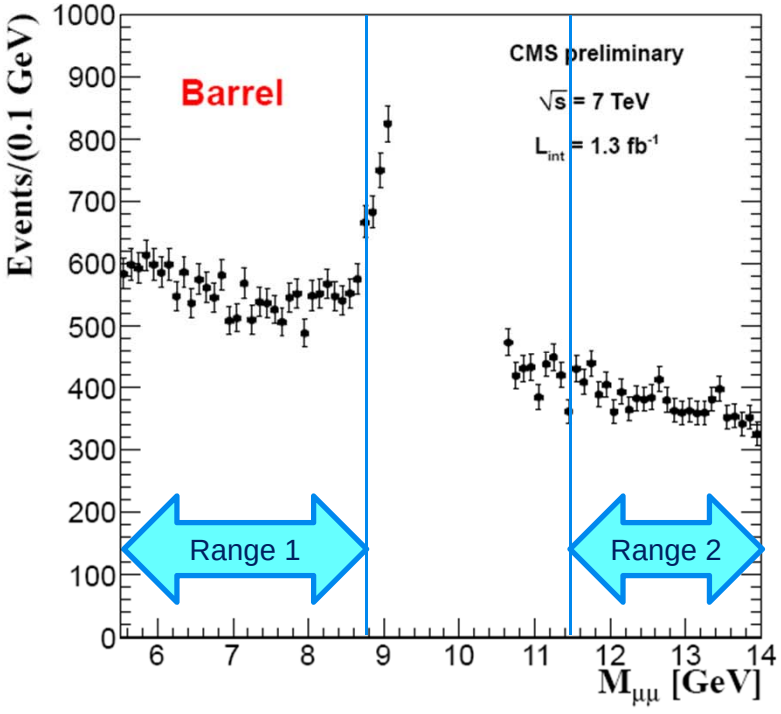
a→μμ (cont'd)

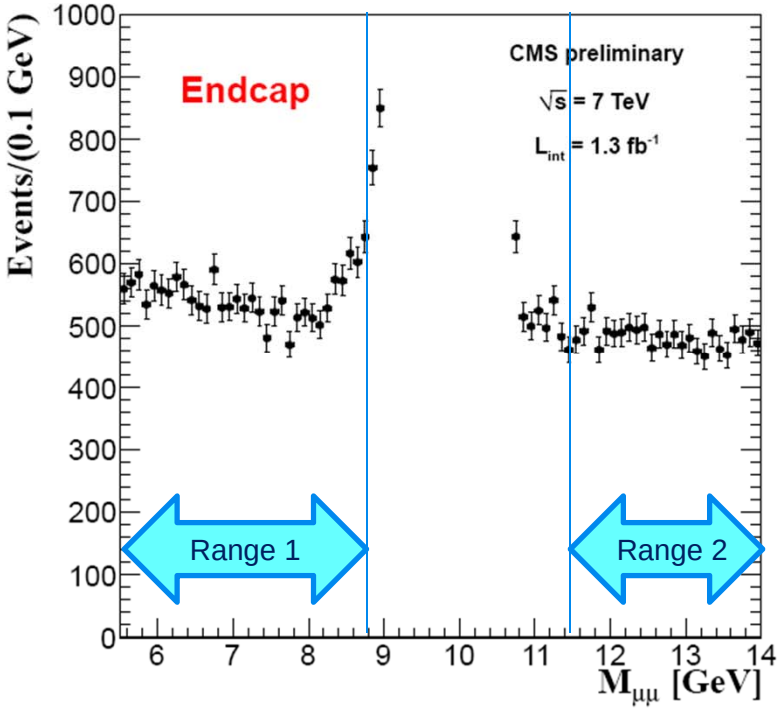
- Di-muon mass spectrum in ϒ mass region



- Main backgrounds:
  - Upsilon resonances → exclude mass region of 9-11 GeV
  - QCD continuum

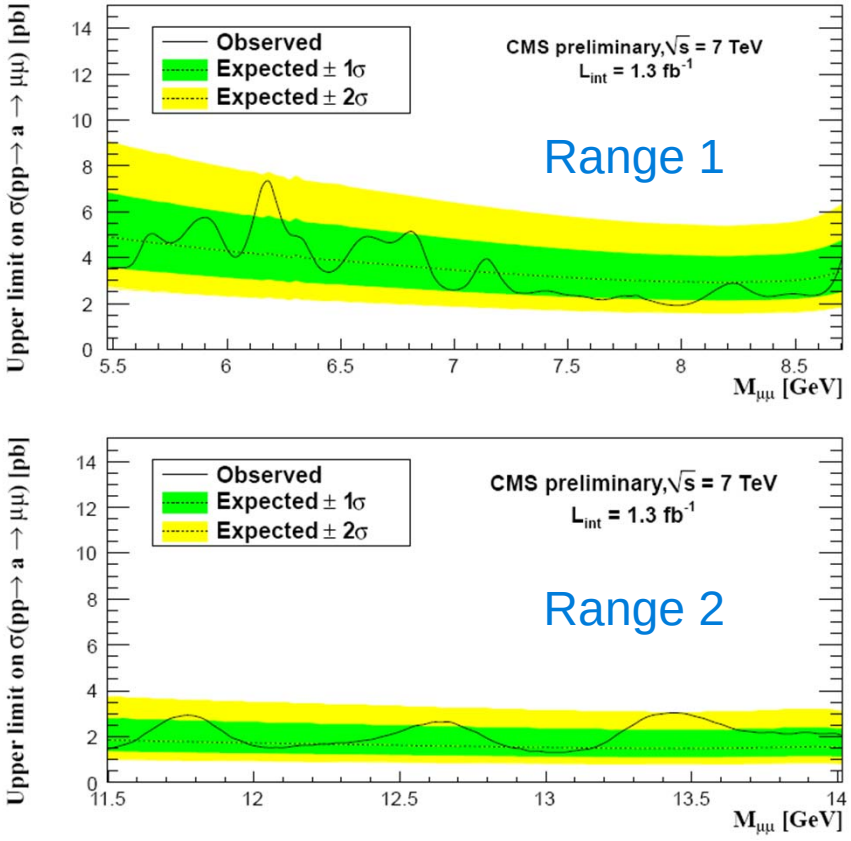
a→μμ (cont'd)

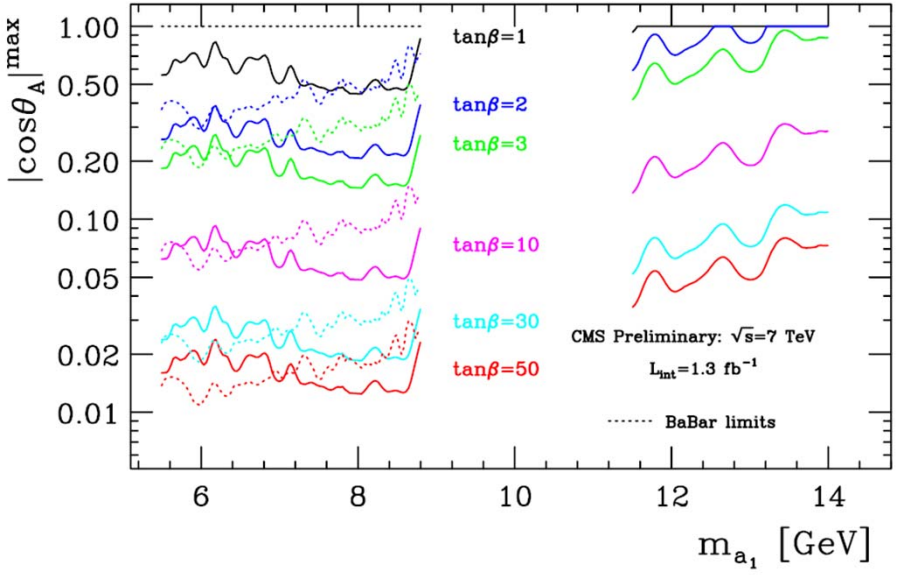




- Mass scan with Gaussian signal PDF
- Accounting for radiative tail of Υ(1S) in range 1

a→μμ (cont'd)



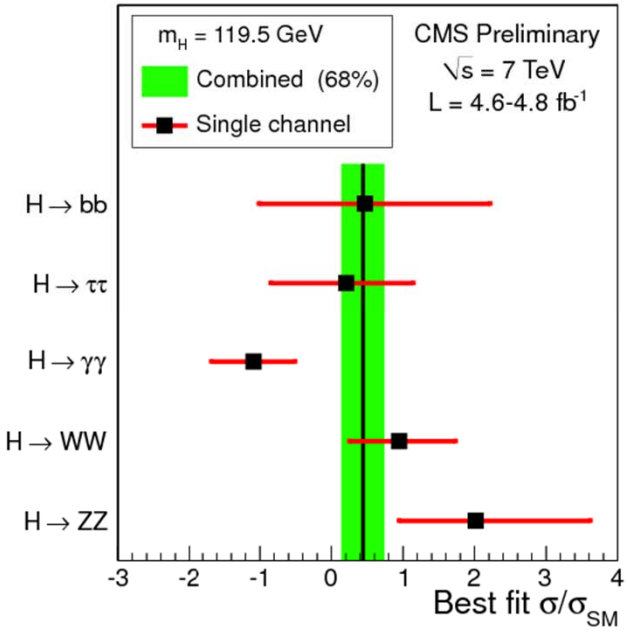


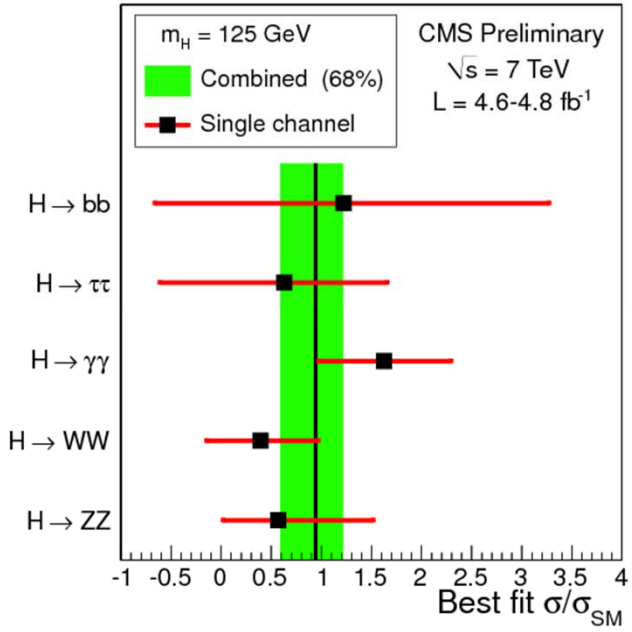
- Improvements on BaBar limits for NMSSM parameter $|\cos\theta_A|$ in lower mass range
- CDF published limits relative to Υ(1S) cross section (not shown)
- No BaBar or CDF limits in upper mass region

Di-Fermion Channels in SM Combination

SM Higgs Searches: Comparison Di-Fermion with Other Channels

(arXiv:1202.1488, submitted to P.L. B)



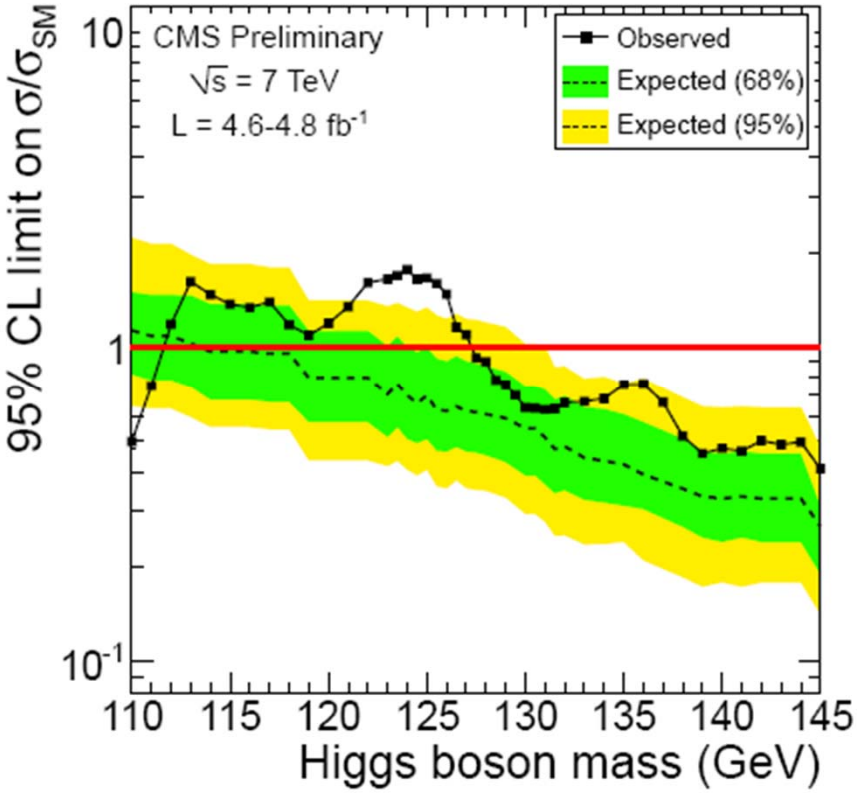


- Di-fermion channels show very good consistency with the di-boson channels
- At m_H=125 GeV, consistently see mild excess at level expected by standard model

CMS SM Higgs Searches Combined

- Showing low-mass region, where di-fermion decays contribute most
  - H→WW dominates in 125-200 GeV (H→ZZ beyond)
  - H→$\gamma\gamma$ dominates below 120 GeV
- Excluded mass ranges @ 95% CL:
  - expected 114.5-600 GeV
  - observed 127.5-600 GeV

➔ More data are required to assess nature of observed excess



Summary

- Di-fermion channels particularly important at low Higgs masses
  - also sensitive to detailed structure of Higgs sector
- Standard Model Higgs search:
  - ➔ in $b\bar{b}$ and $\tau\tau$ channels, 95% CL limits at low mass range near 3x SM
  - ➔ recent improvement due to $\tau_\mu\tau_\mu$ channel
- MSSM search:
  - ➔ $\tau\tau$ channel excludes wide area in (m_A, tan β) parameter space
- NMSSM search:
  - ➔ upper limits for very light pseudoscalar Higgs boson ($\mu\mu$ channel)

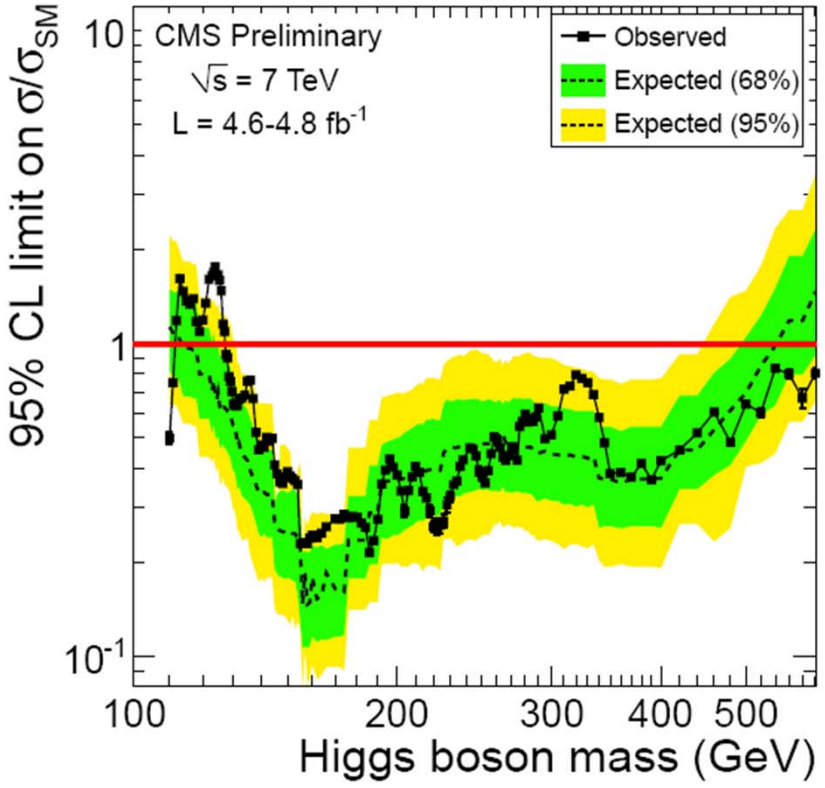
➔ Excellent prospects for 2012 LHC run (just started…)

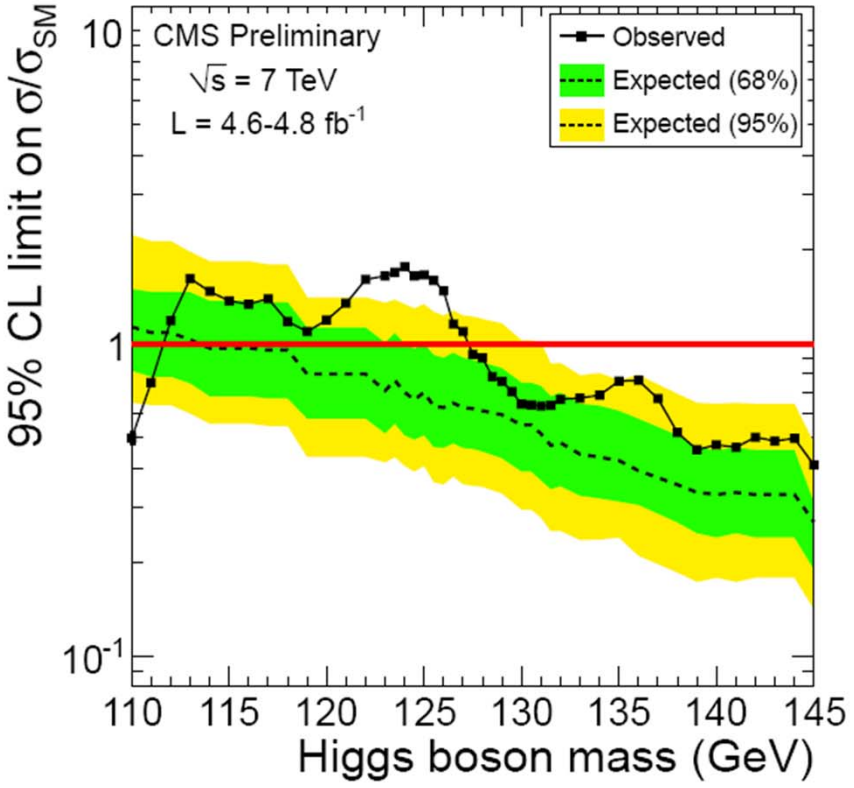
- More CMS results in fermion channels (not shown in this talk):
  - Search for doubly charged Higgs boson — CMS PAS HIG-12-005
  - Search for WH → e($\mu\tau$), μ($\mu\tau$) — CMS PAS HIG-12-006

Further information

SM Higgs Combination

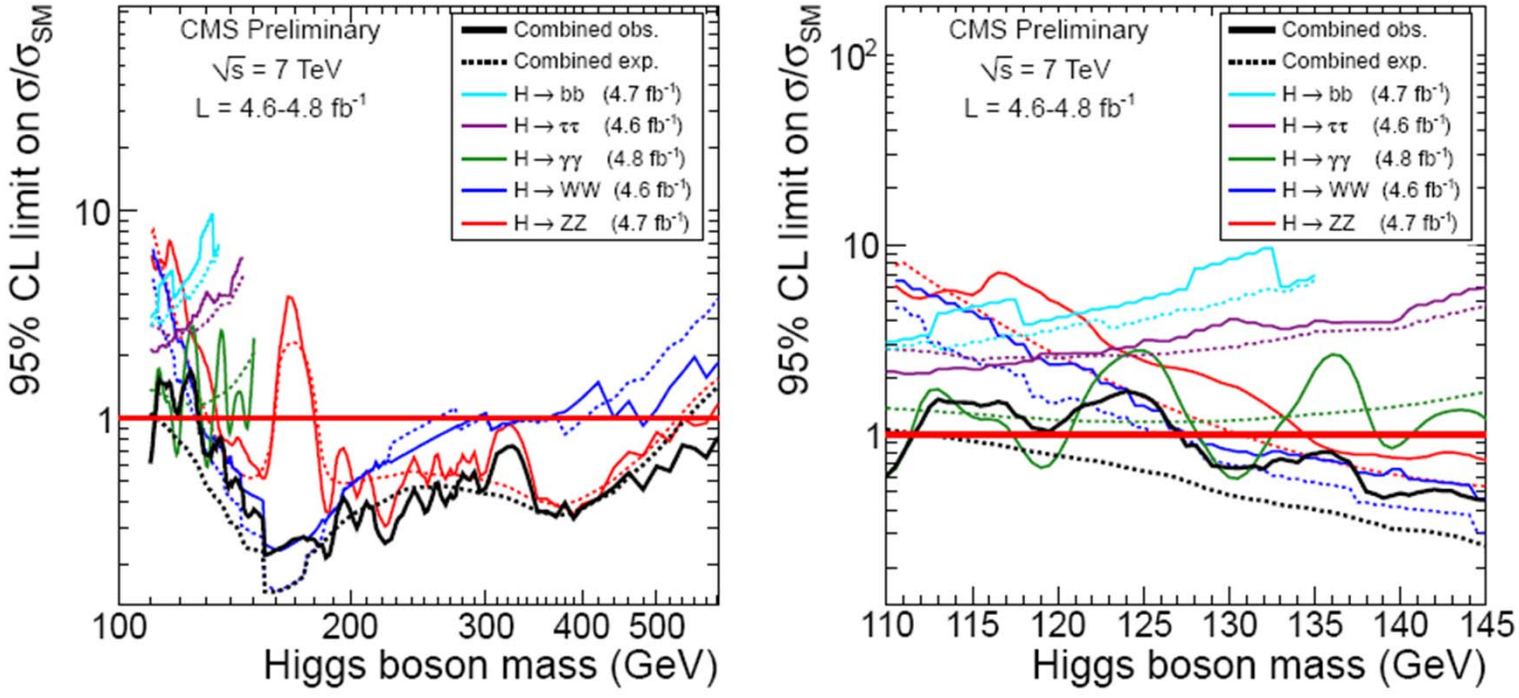
- Observed and expected 95% CL confidence limits on the signal strength parameter $\mu = \sigma / \sigma_{SM}$ for the SM Higgs boson hypothesis





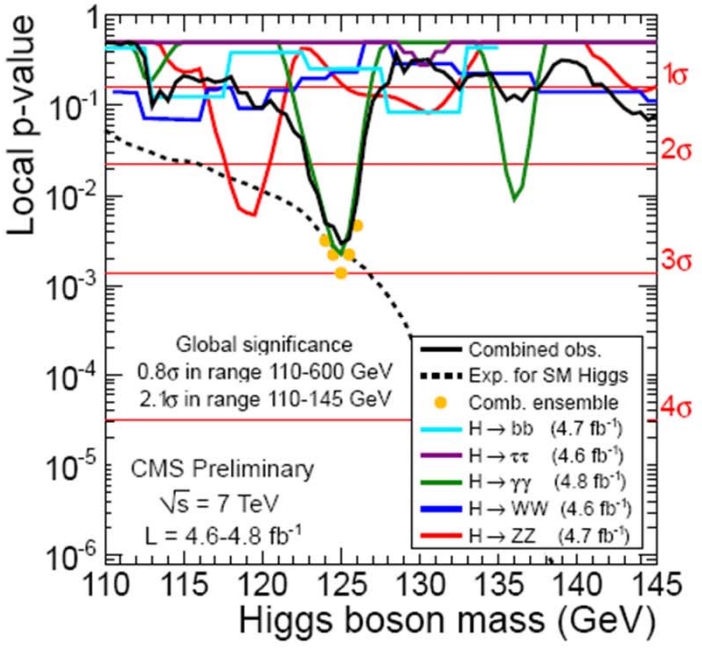
SM Higgs Combination

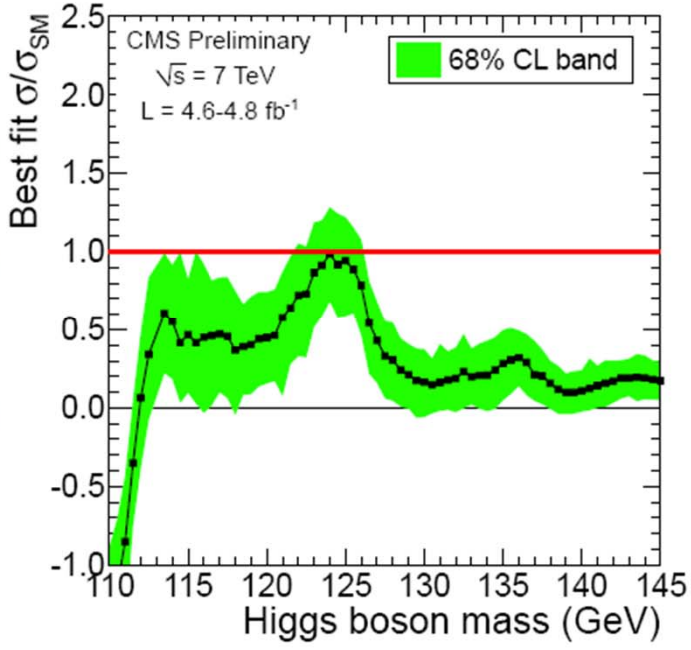
- Observed and expected 95% CL confidence limits on the signal strength parameter $\mu=\sigma/\sigma_{SM}$ for the SM Higgs boson hypothesis by decay channel



SM Higgs Combination

- Observed local p-value (p_0) and best-fit $\hat{\mu}=\sigma/\sigma_{SM}$





VH→V(bb̄): Example Control Regions

- Background-enhanced distributions
  - Wbb̄ enhanced for WH (top)
  - V+udscg enhanced for Z(νν)H (bottom, left)
  - tt̄ enhanced for Z(μμ)H (bottom, right)