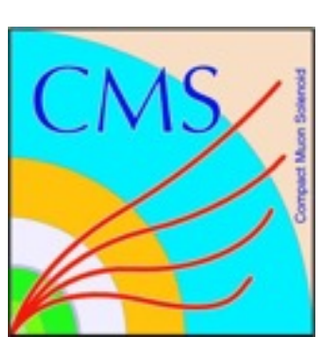
BSM Higgs searches @CMS



Li Yuan
Beihang University
On Behalf of CMS Collaboration

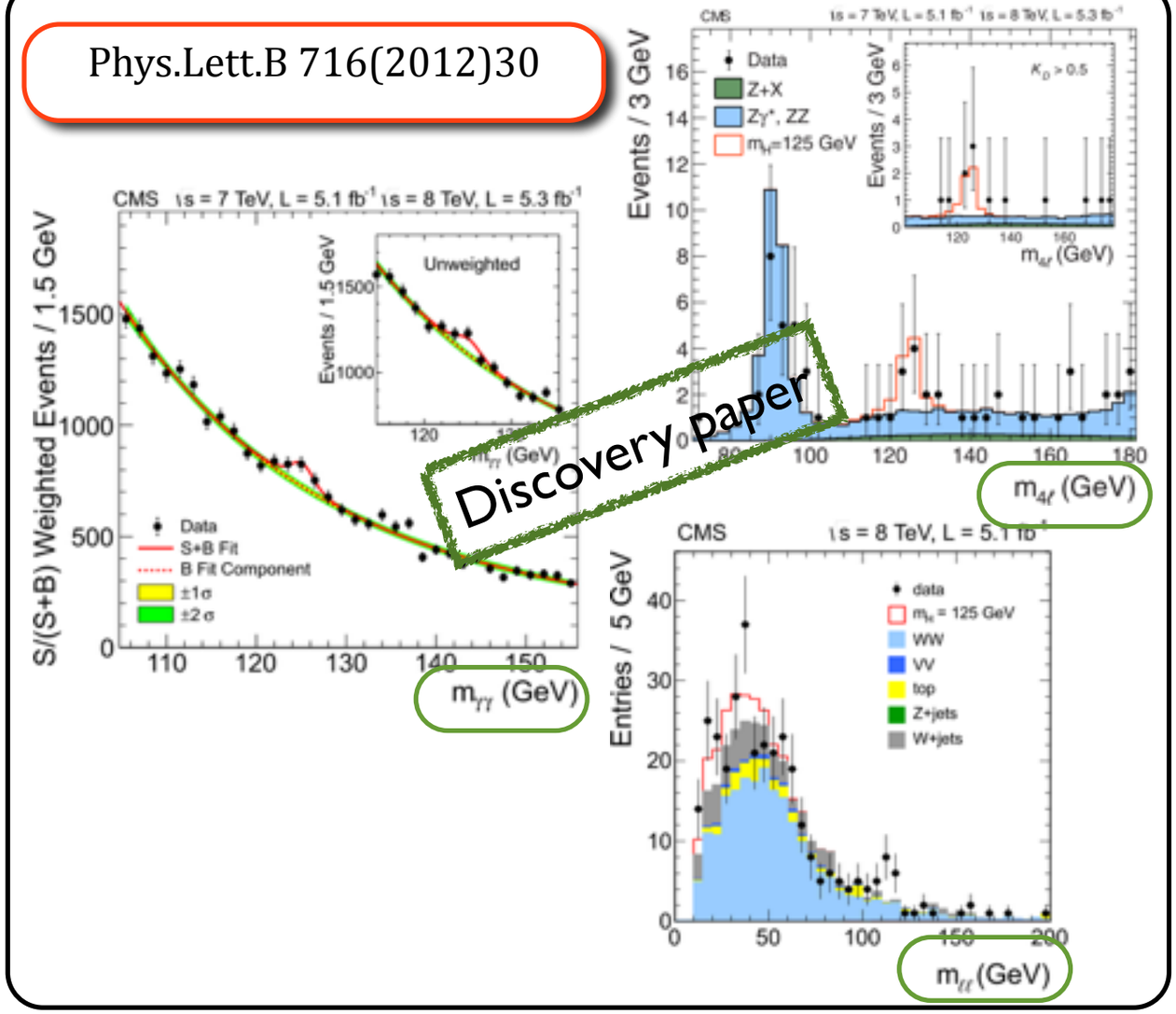
ISHBSM, Weihai, Shandong
August 16, 2016

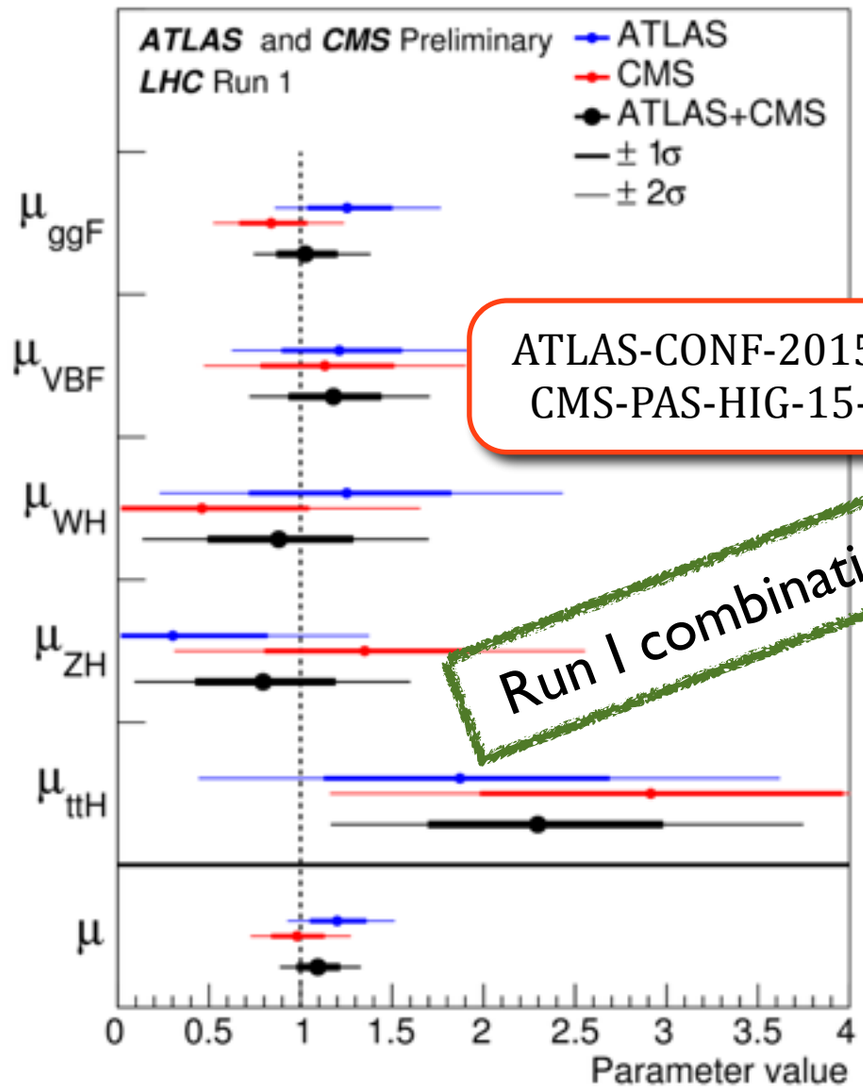
Outline

- Introduction
- Overview BSM Higgs
- BSM Higgs searches
  - Constraints via Higgs coupling measurement
  - Exotic Higgs decays searches
  - High mass Higgs searches
  - Low mass Higgs searches
  - Charged Higgs searches
- Conclusion

The "new" scalar boson

Phys.Lett.B 716(2012)30

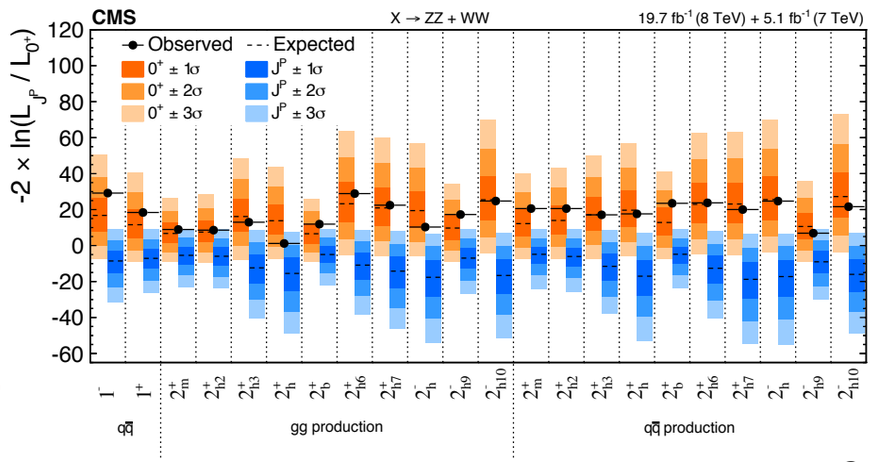




- **This scalar boson consistent with SM Higgs 0^+**

- $m_H \sim 125.09 \pm 0.24$ GeV

$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}(\text{stat})^{+0.04}_{-0.04}(\text{expt})^{+0.03}_{-0.03}(\text{thbgd})^{+0.07}_{-0.06}(\text{thsig})$



Introduction

- **Discovery of a scalar boson consistent with SM Higgs**
  - Is it SM Higgs or something else ?
  - new window for physics beyond SM

- **Non-SM interpretation**
  - the observed boson: part of an extended scalar sector
  - large variety of models: 2HDM, MSSM...

- **Search strategies:**
  - direct searches: additional charged or neutral Higgs bosons
  - indirect searches: measurement of properties of Higgs boson at 125GeV, constraints to be in-compatible with the SM

BSM Higgs Models

- **Additional EW Singlet: h, H**

- **Two Higgs Doublet Model (2HDM)**
  - an additional doublet
  - four types based on coupling structure

- **Minimal Supersymmetric Standard Model (MSSM)**
  - symmetry between boson and fermion, two Higgs Doublets in Higgs sector
  - search for neutral and charged Higgs bosons

- **Next-to-Minimal SUSY (NMSSM)**
- **……**
- **2HDM and MSSM have a rich phenomenology, compatible with SM-like Higgs boson. Focus in this talk**

Constraints on BSM via Higgs Couplings

- **Light Higgs couplings measured by combination of various channels (7+8 TeV)**
- **Using SM Higgs boson masses $m_H \sim 125.0$ GeV**
- **In 2HDM, the couplings of neutral Higgs to up-type and down-type modified, we test e.g $\lambda_{du}=\kappa_d/\kappa_u$, $\lambda_{lq}=\kappa_l/\kappa_q$**
- **Directly test the 125GeV higgs coupling with BSM particles**

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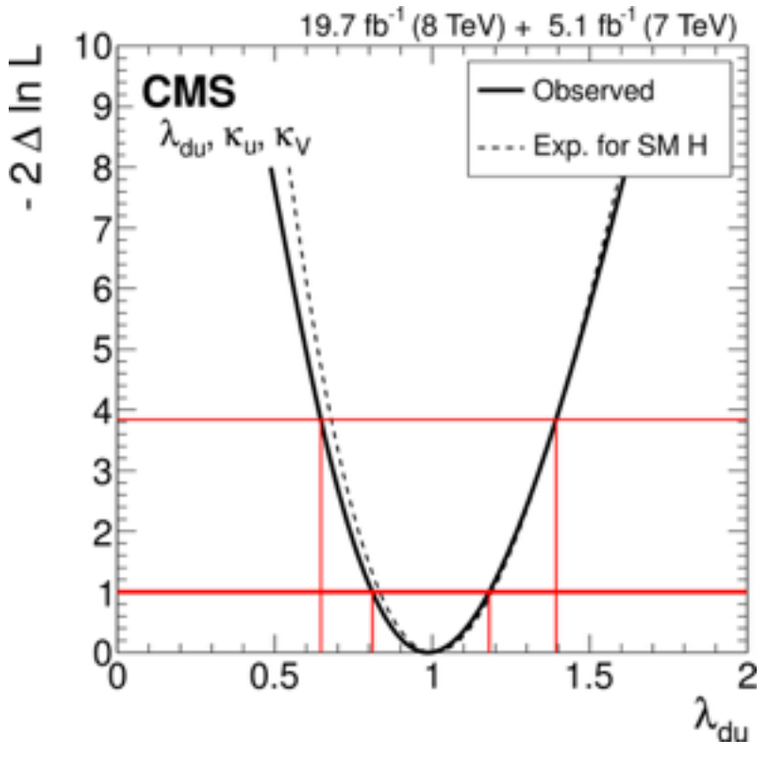
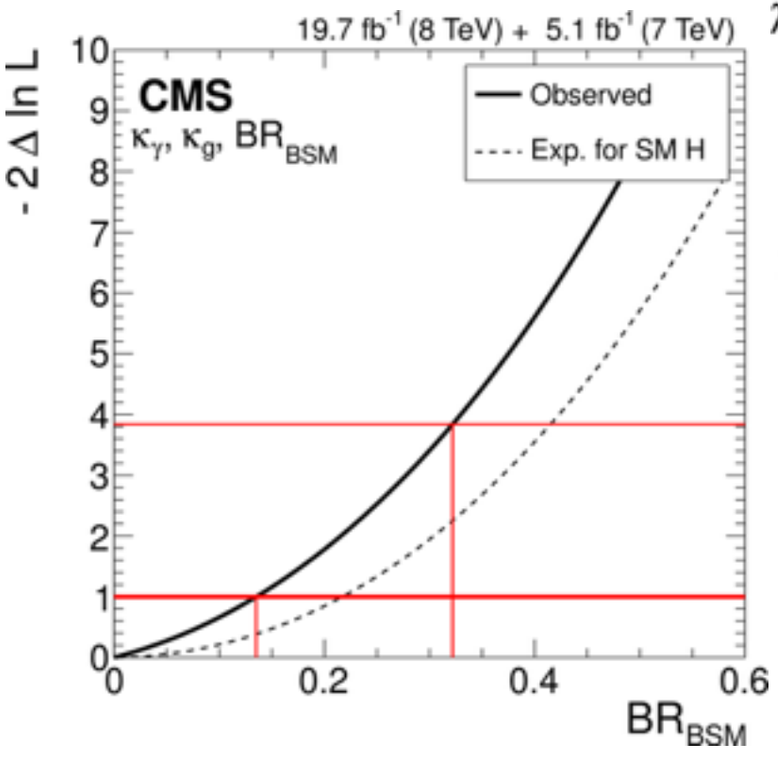
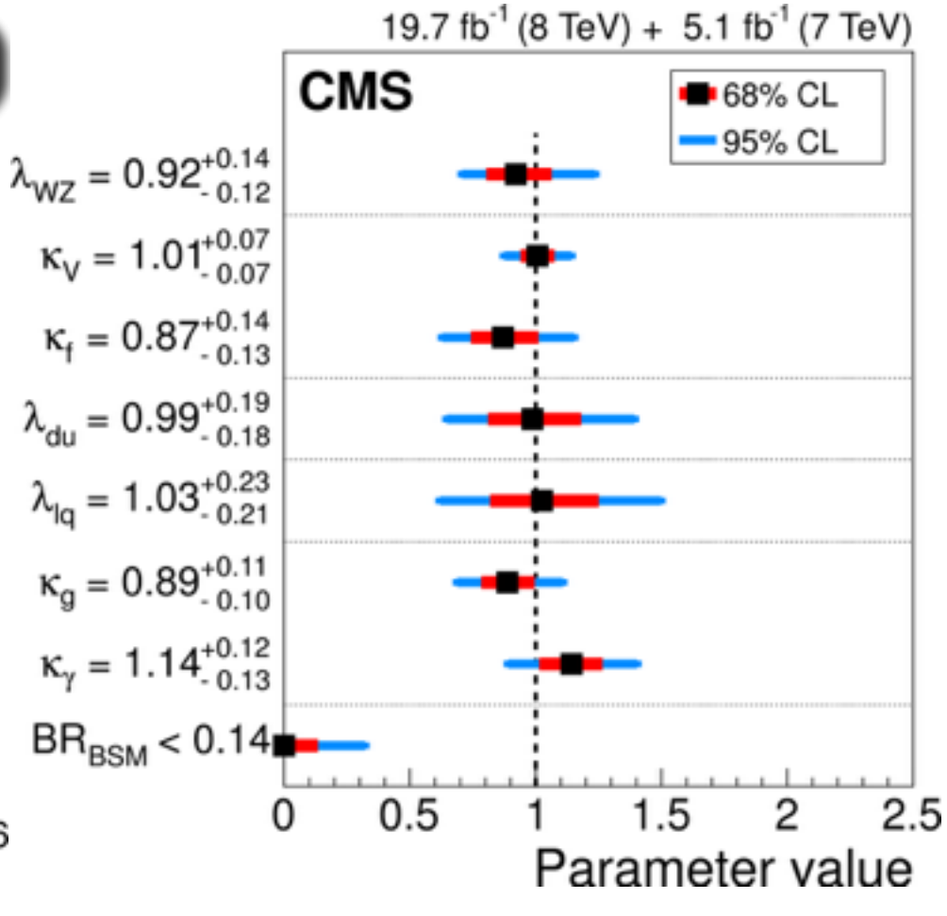
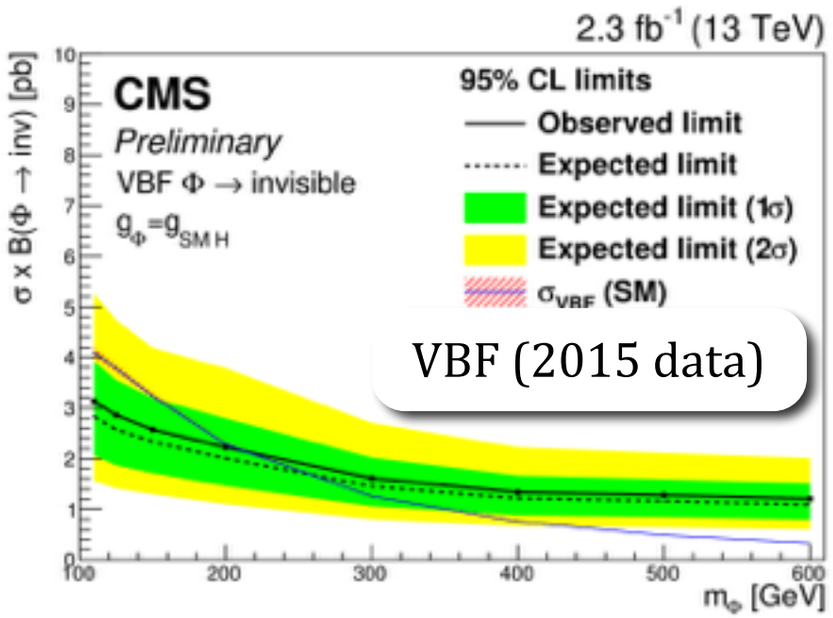






Invisible decay (1)

- **Search for evidence of invisible Higgs decay mode**
  - extensions of the SM allow Higgs decay into stable or long-lived particles
    - e.g dark matter candidate as Weak Interacting Massive Particle (WIMP)
  - event characteristic: large missing energy
- **Using the Higgs production in association with boson or jets (used for tagging events)**
  - VBF (most sensitive channel)
  - $Z(\rightarrow ll)$ H ($\rightarrow$inv.) or $Z(\rightarrow jj)$ H ($\rightarrow$inv.)
  - Mono-jet (ggF-tag)



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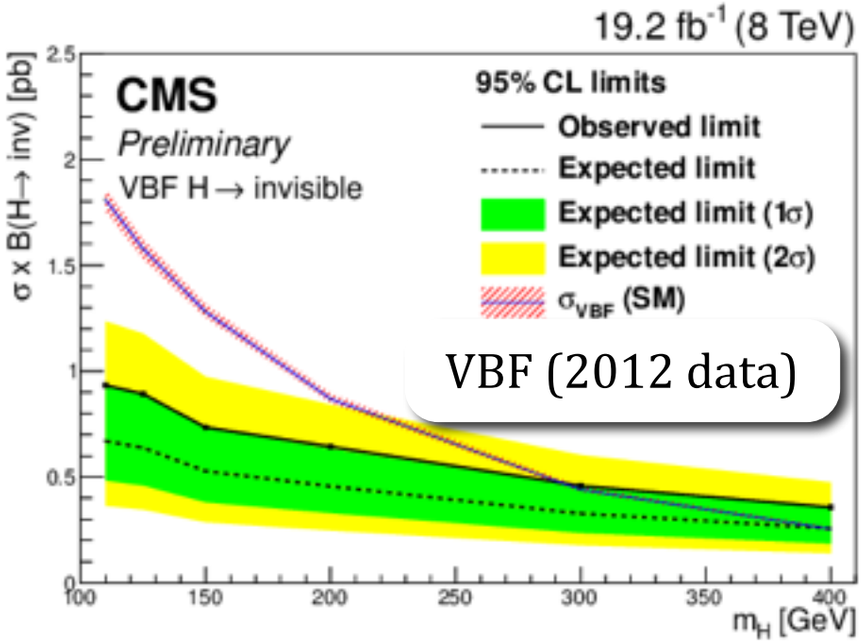
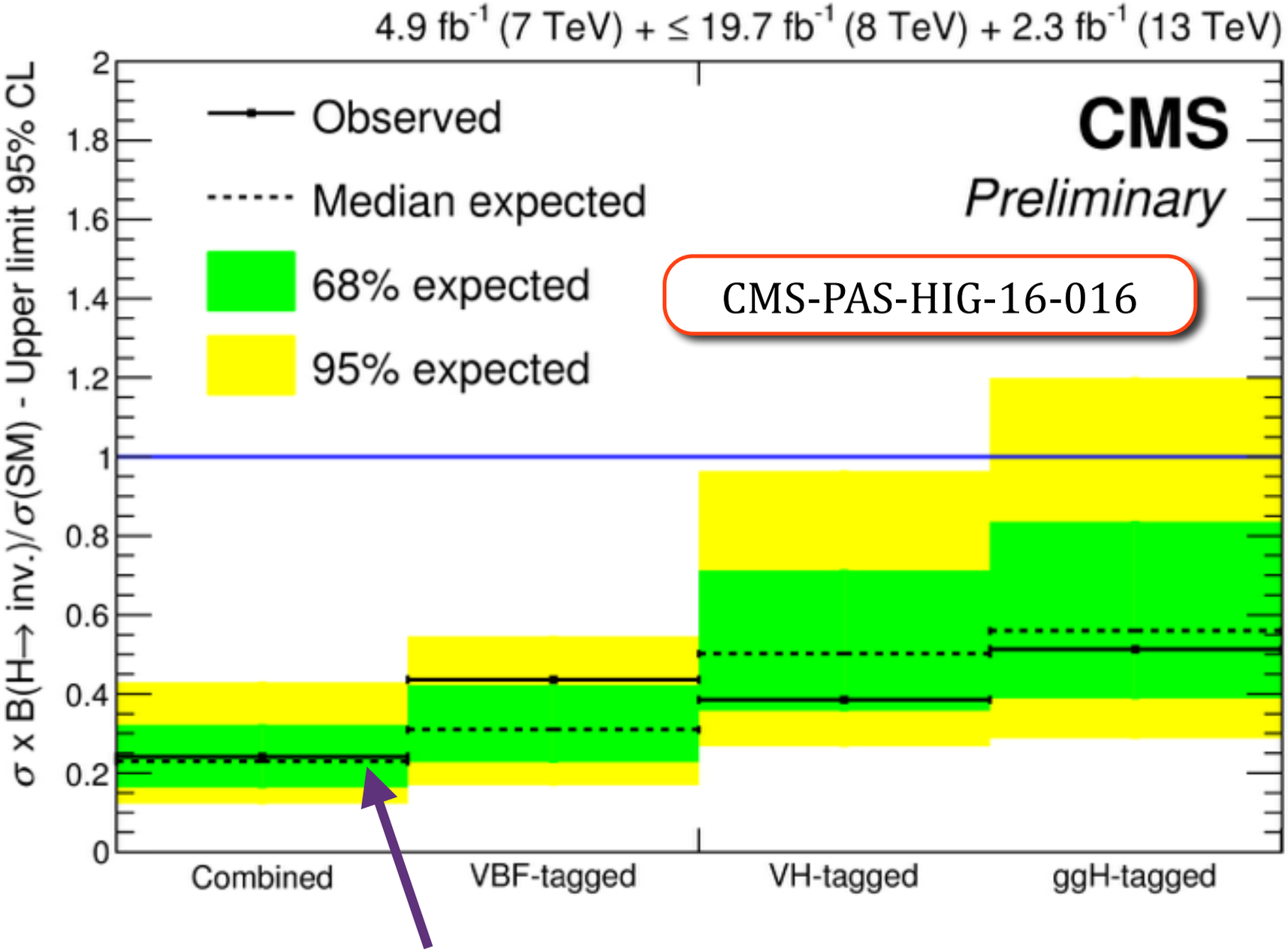


CMS-PAS-HIG-14-038

Observed Limit with VBF only: : BRinv < 0.69 (2015 data) , BRinv < 0.57 (2012 data)

Invisible decay (2)

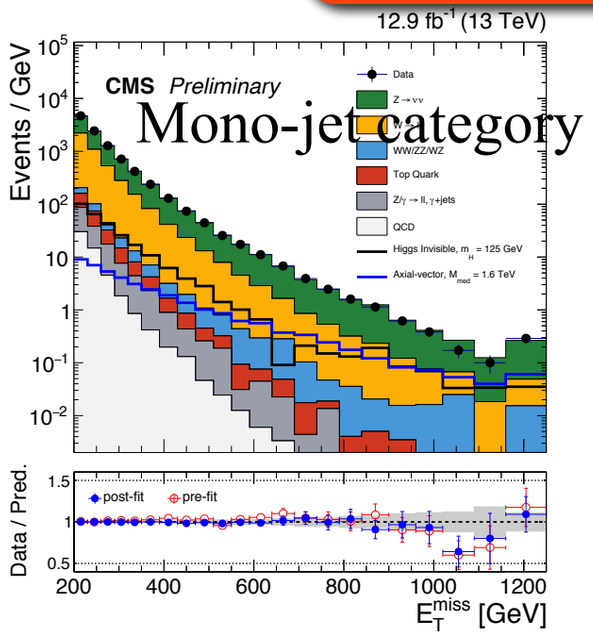
Combination of VBF, VH and ggH-tagged events with 2011, 2012 and 2015 data.

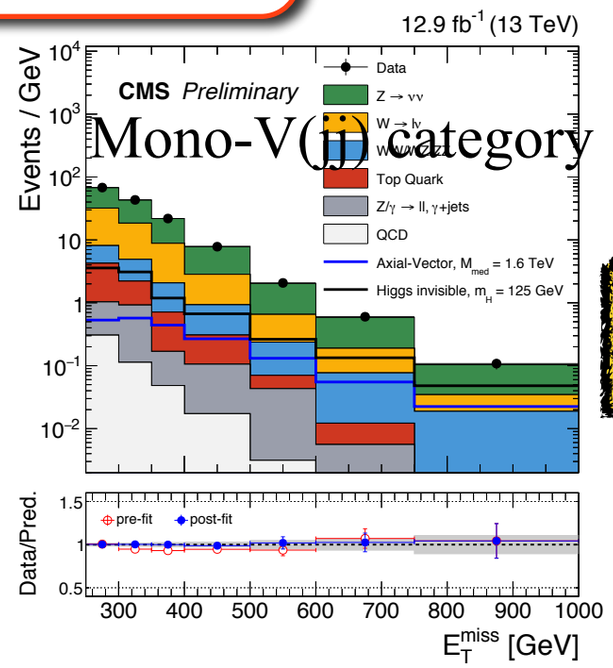


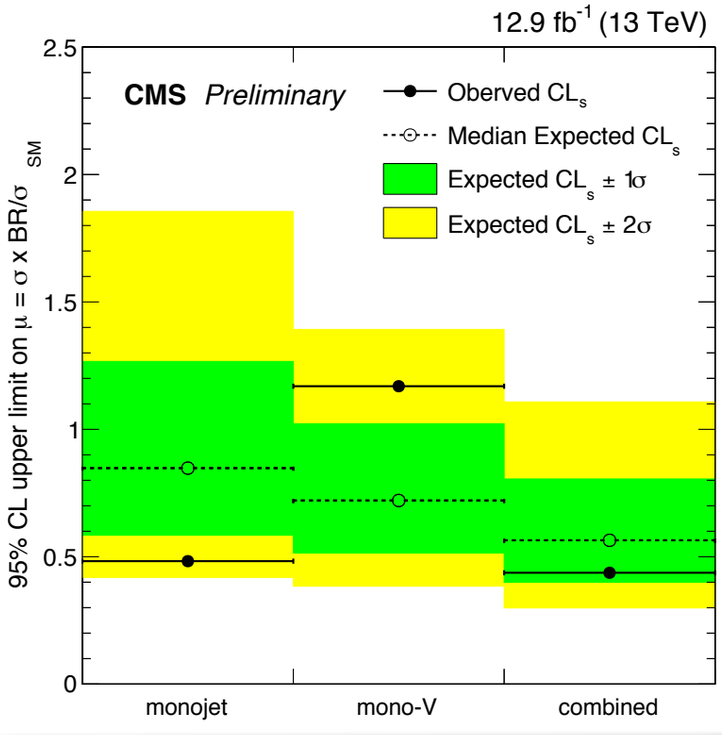
Combined Limit at 95% CL: BRinv < 0.24 (expected 0.23)

Invisible decay — 2016 data

CMS-PAS-EXO-16-037



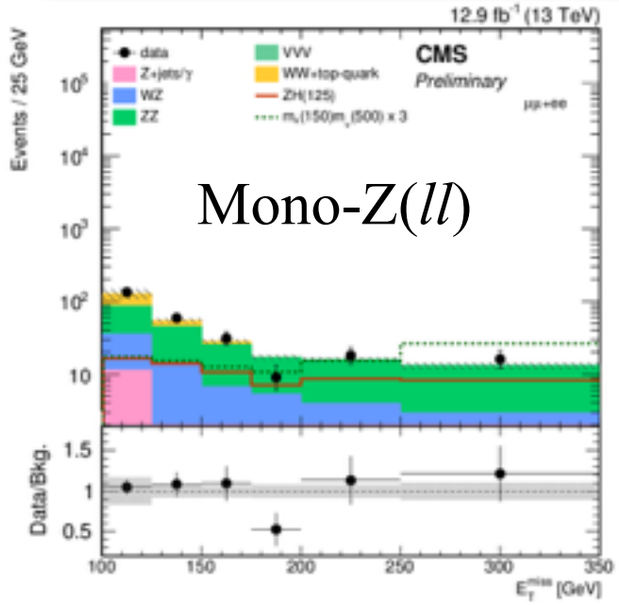




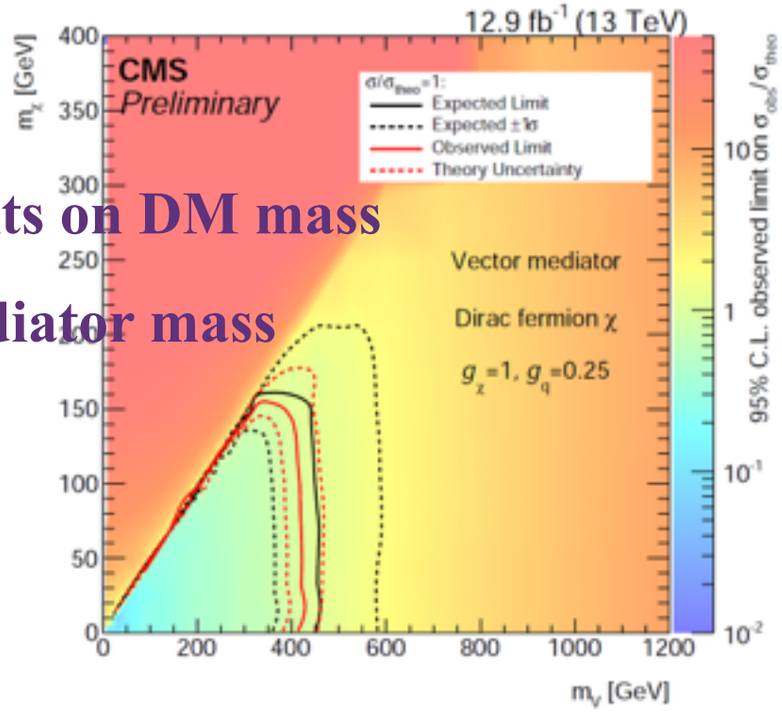
BR(H→inv) < 0.44 (expected 0.56)

Fit on E_T^{miss}

CMS-PAS-EXO-16-038



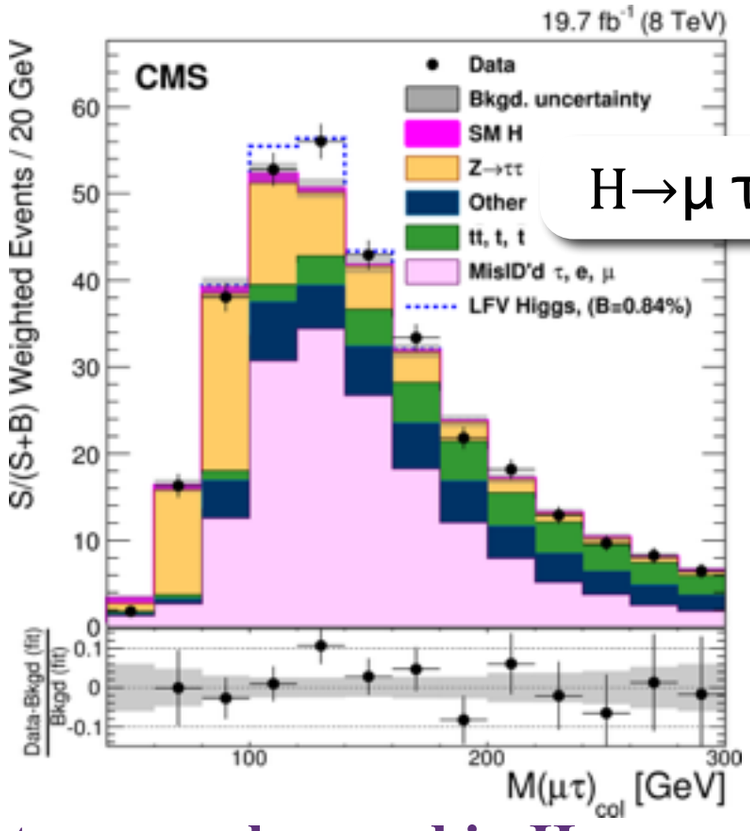
2D Limits on DM mass and mediator mass

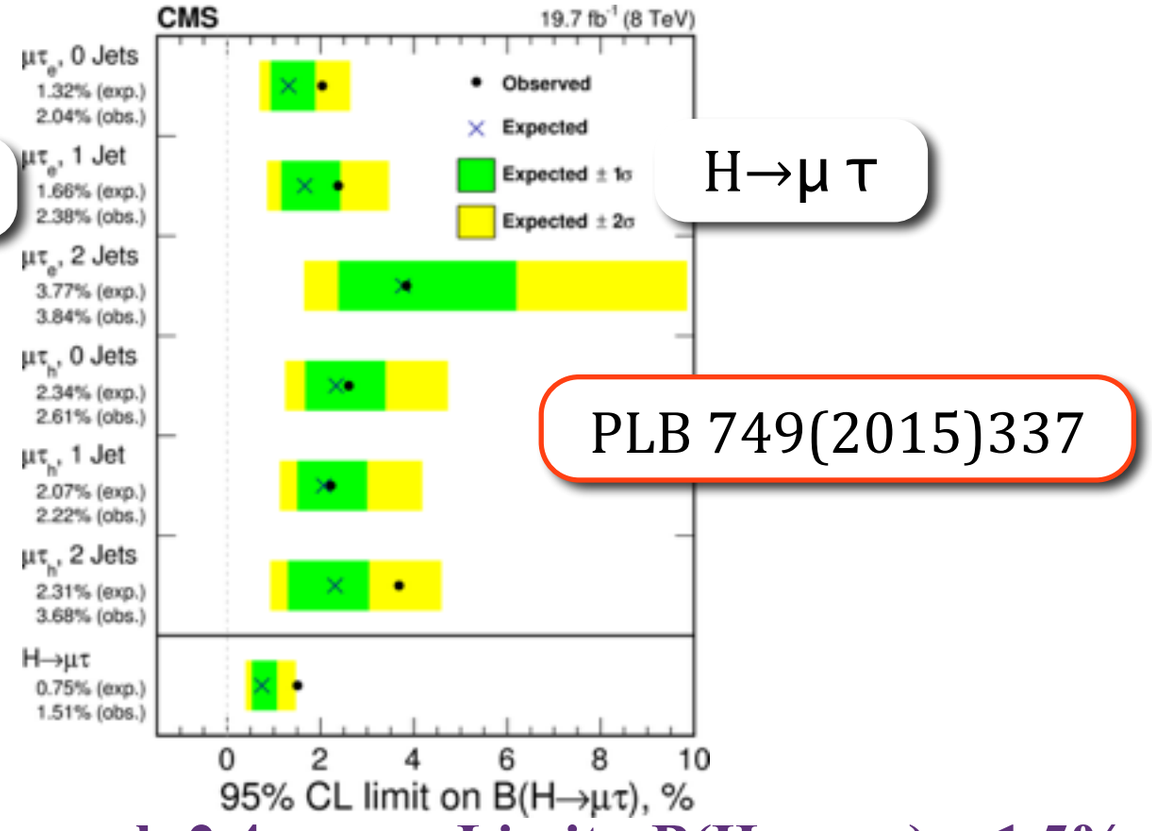


BR(H→inv) < 0.86 (expected 0.70)

Lepton Flavour Violating Decay

- **Allowed in many BSM models**
  - Higgs doublet, composite Higgs, Randall-Sundrum models
- **Search with 2012 data: H→μ τ, H→e τ, H→e μ**
  - H→μ τ, H→e τ analyses similar to SM H → τ τ, but more boost for e, μ in LFV





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Slight excess observed in H→μ τ channel: 2.4σ . Limit: B(H→μ τ) = 1.5%

No excess in H→e τ and H→e μ channels. CMS-PAS-HIG-14-040

Observed limits: B(H→e τ) = 0.7% B(H→e μ) = 0.036%

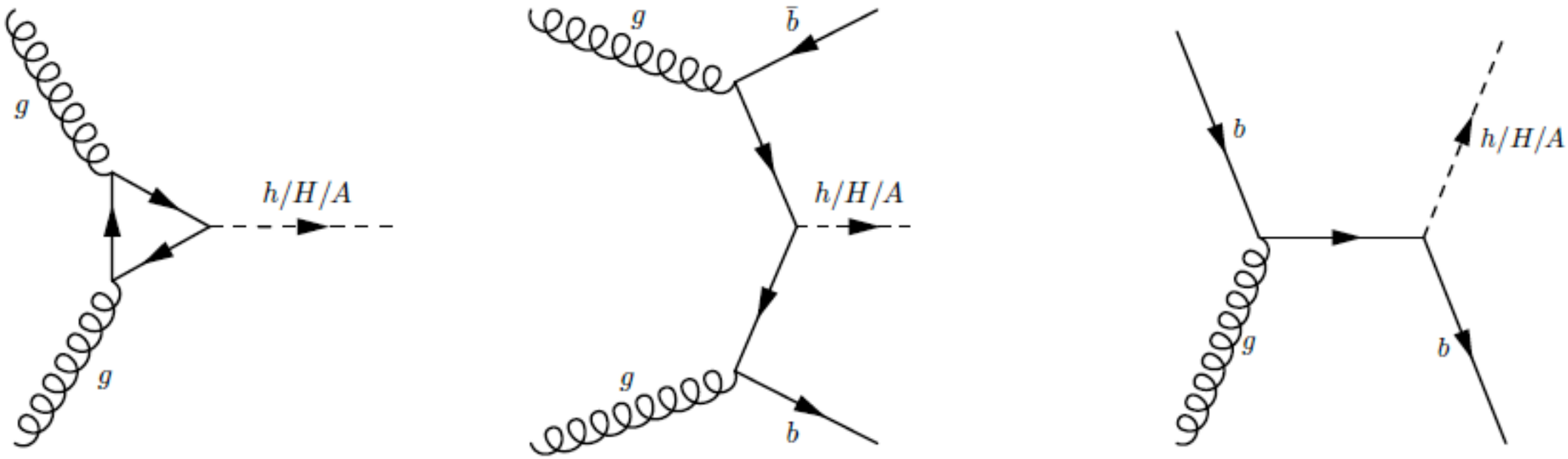
High Mass Higgs Searches

This talk show results based on Fermionic channels.

Searches with bosonic channels covered by Tongguang's talk in this conference..

Neutral Higgs bosons searches

- **The couplings of MSSM Higgs bosons to down-type fermions enhanced**
  - especially for large **tan β value (**ratio of vacuum expectation values of the doublets**)**
  - enhanced production mode with associated b-quarks
  - increased branching fraction to τ leptons and b-quarks
    - 3 neutral: h^0(CP even), H^0(CP even), A^0 (CP odd)
    - the ττ decay mode sensitive to neutral higgs boson searches



Neutral Higgs boson searches — ττ

- **Search through ττ decay mode with 2015 data, using the following channels**
  - $\tau_e\,\tau_\mu$ (6%), $\tau_e\tau_{had}$ (23%), $\tau_\mu\,\tau_{had}$ (23%), $\tau_{had}\tau_{had}$ (42%)
  - discriminating variable: transverse invariant mass of tau pair $m_{T,\,\tau\tau}$

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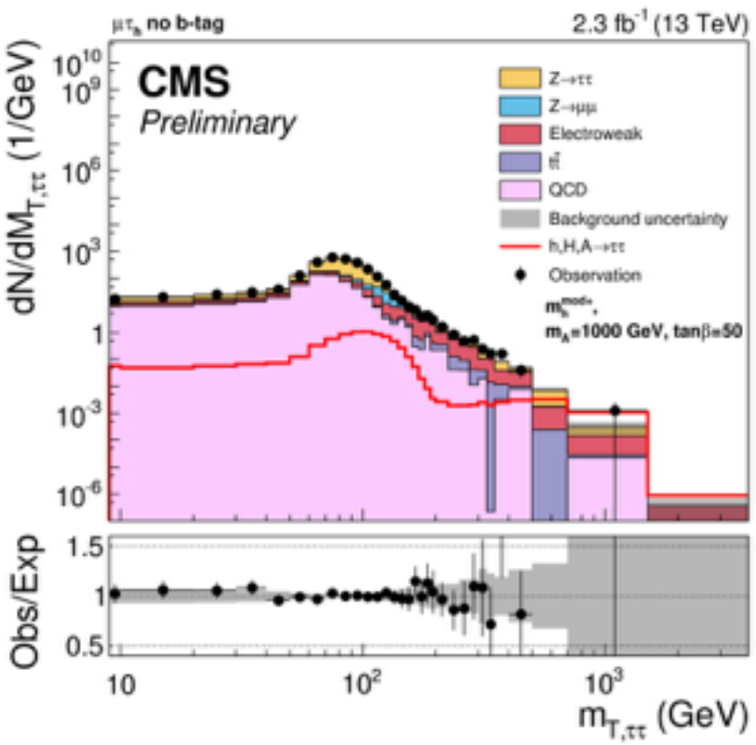
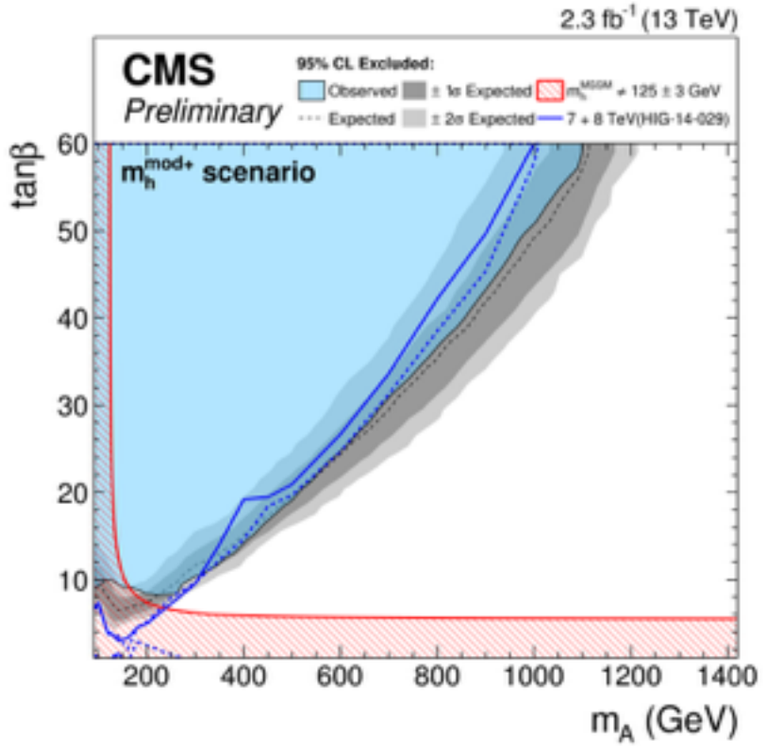
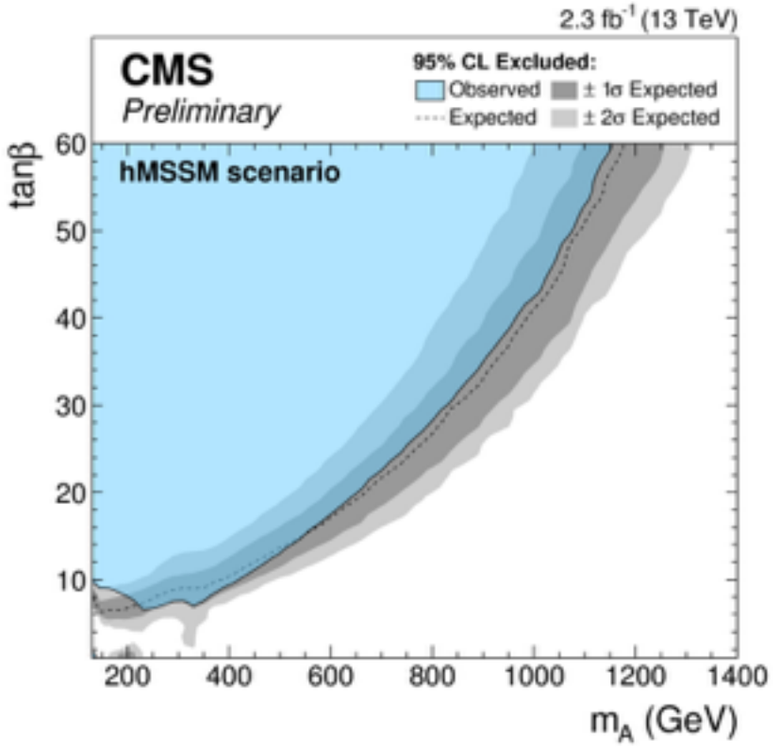
$m_{T,\,\tau\tau}$ in $\tau_\mu\,\tau_{had}$ no btag category



exclusion limits in m_h^{mod+} scenario



exclusion limits in hMSSM scenario



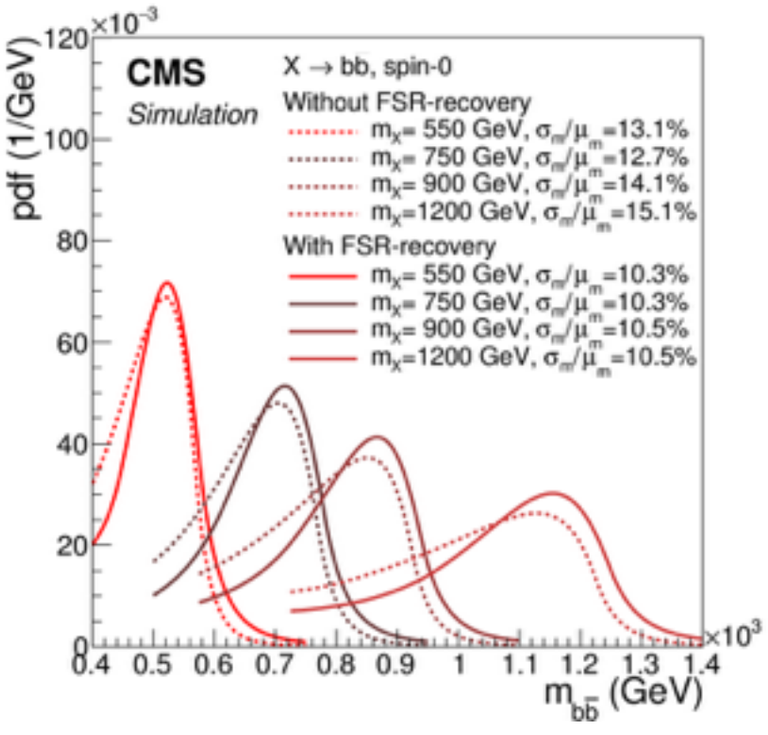
No excess beyond the SM expectation.

Neutral Higgs boson searches — bb

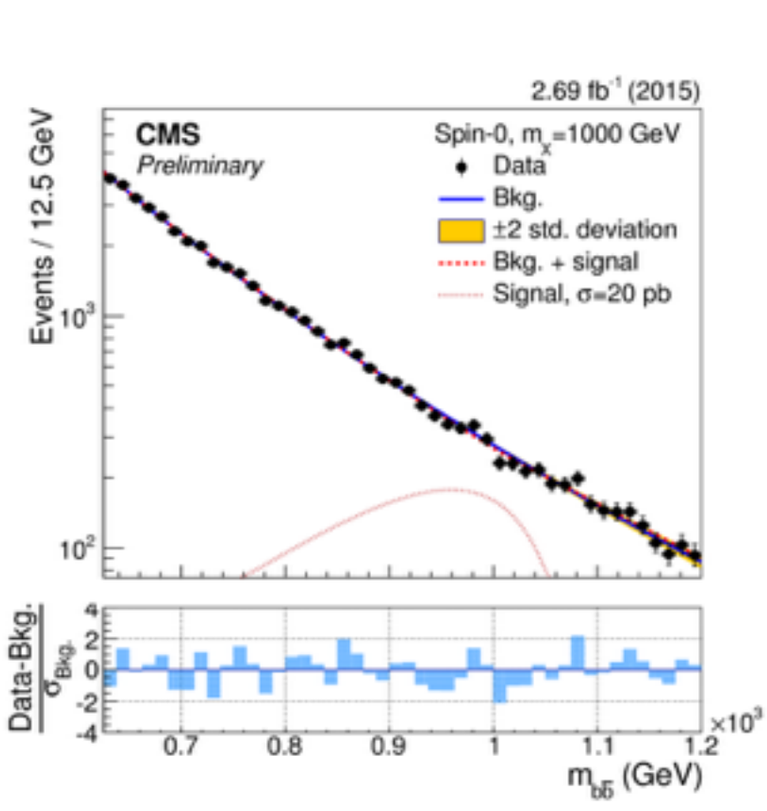
- **Search through bb decay mode with 2015 data using the following selections**
  - at least two jets pass the btagging medium operating point, and one pass tight
  - the two jets with the highest b-tagging weights with $p_T > 100$GeV, and $\Delta\eta < 1.6$
  - lepton veto

CMS-PAS-HIG-16-025

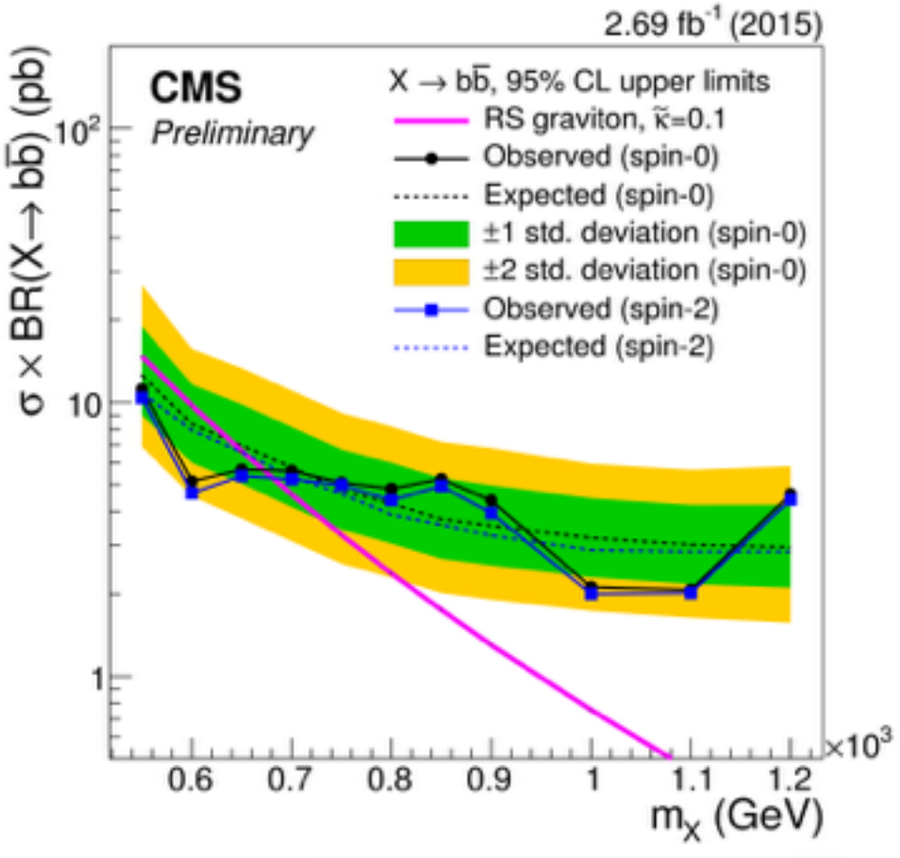
m_{bb} probability density function for different m_X



m_{bb} distribution in data



cross section exclusion limits



Neutral Higgs boson searches — $\mu^+ \mu^-$

- **Main production modes: gluon fusion, association production with bb**
- **Branching fraction to μ μ is 3 orders smaller than ττ, but with good mass resolution**

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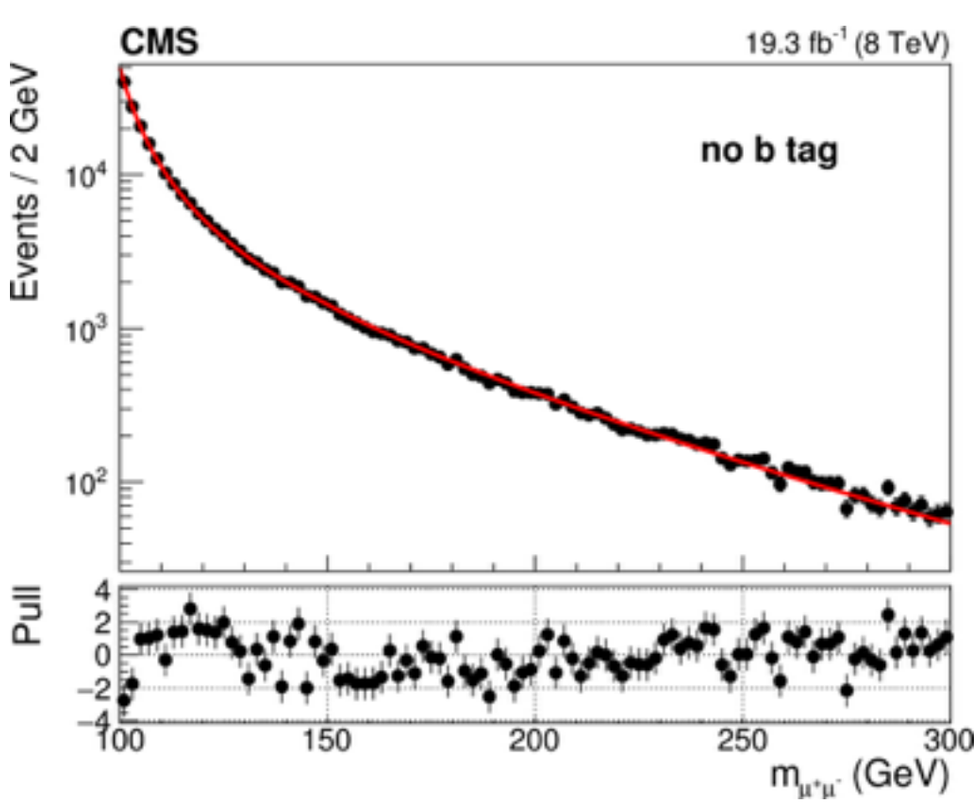
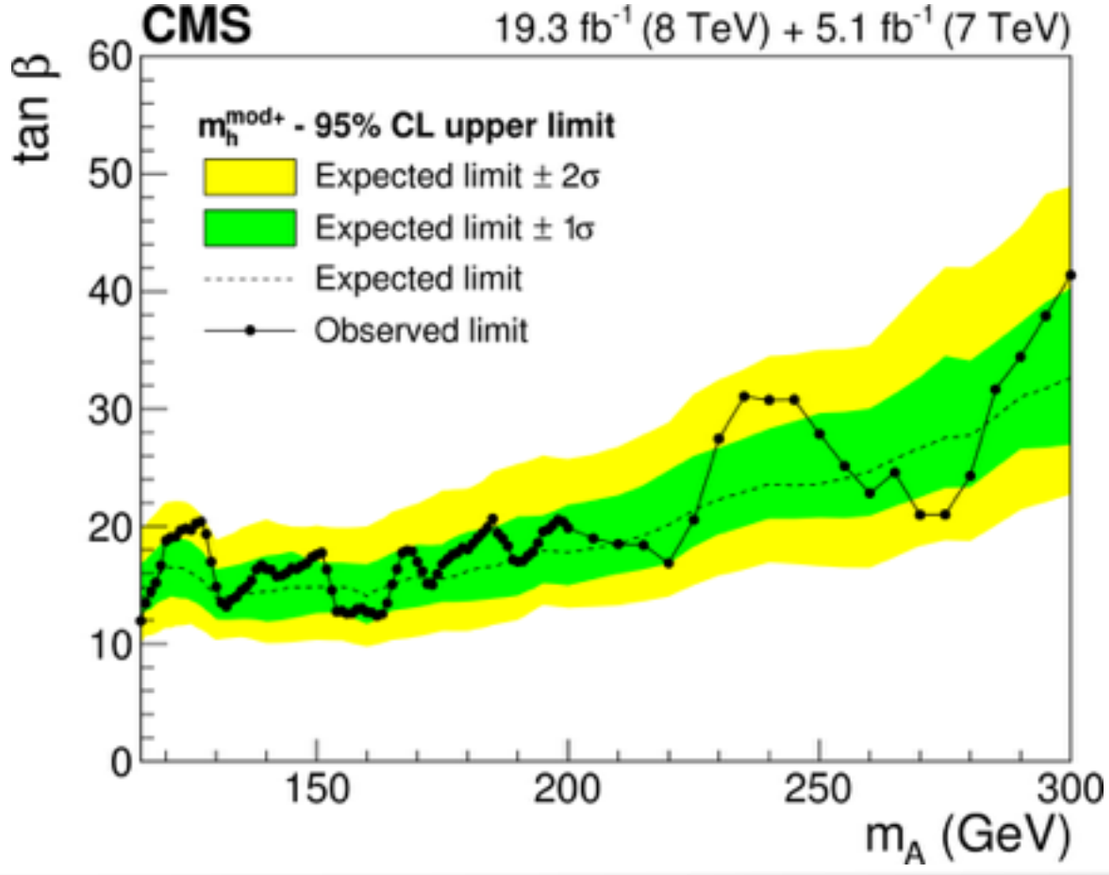


exclusion limits in m_h^{mod+} scenario



Low Mass Higgs Searches

H→γγ

- **NMSSM: σXBR(H→γγ) is ~3.5 higher compared to SM**
- **Range: [80, 110] GeV**
- **4 event categories based on diphoton event MVA**
- **Background model: diphoton continuum +Z peak contamination**

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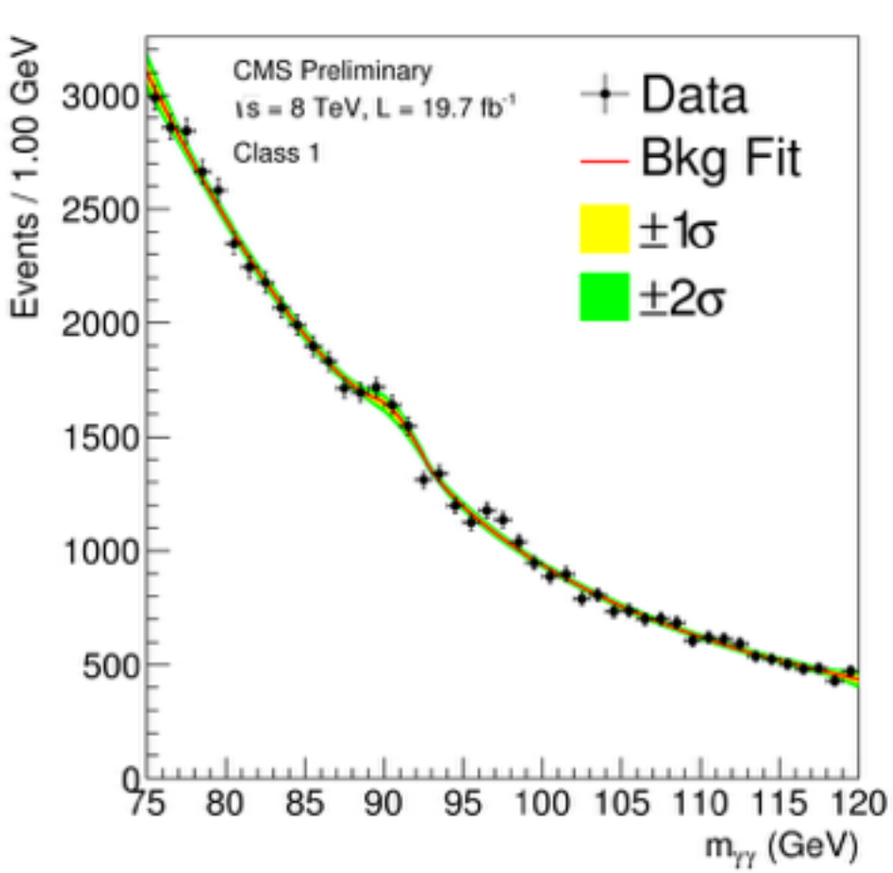
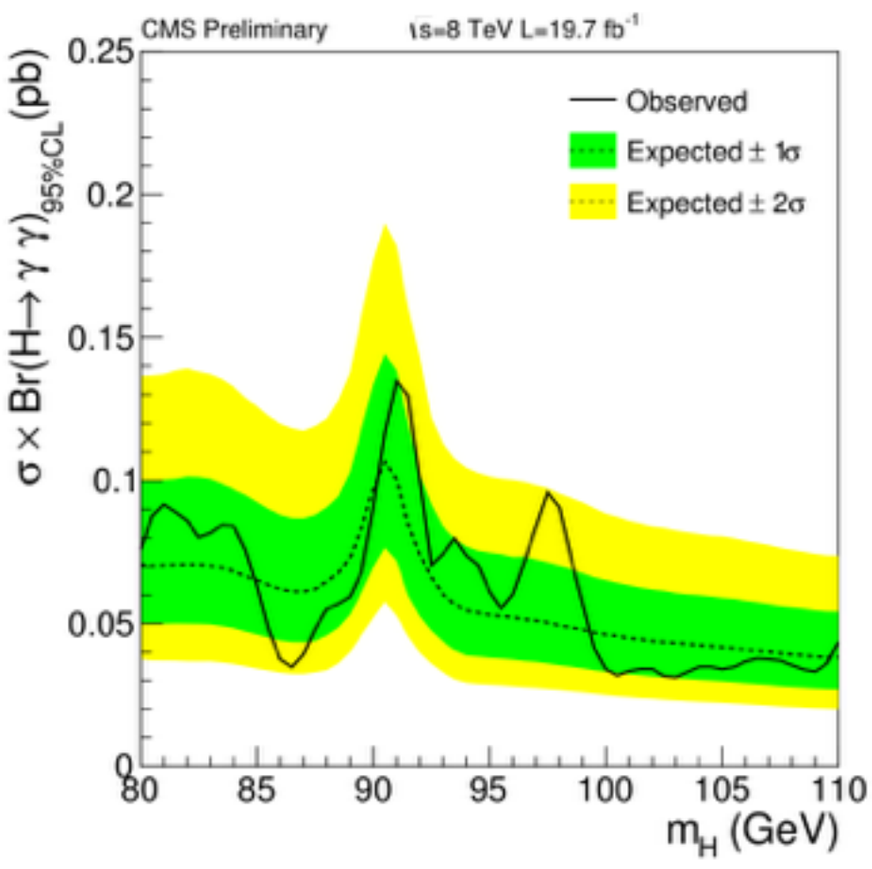


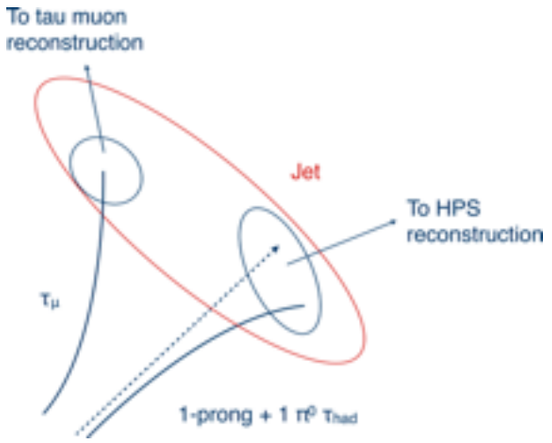


Exclude scalars with σXBR from 0.8 to 3 times the SM.

Search for light Higgs in H(125)→aa(hh)

- **Many BSM models allows H(125)→aa or H(125)→hh**
  - 2HDM, NMSSM, EWS
- **BR(a/h→ ττ) dominant if m(h) < 11 GeV, but still sizeable if m(h) > 11 GeV**
  - use 4τ final states, two different searches

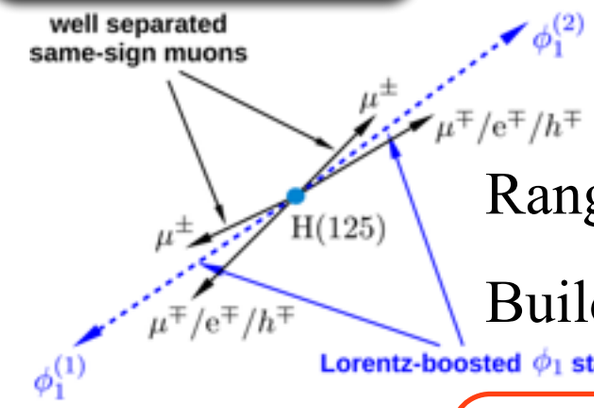
2012 data



Range: [5, 15] GeV

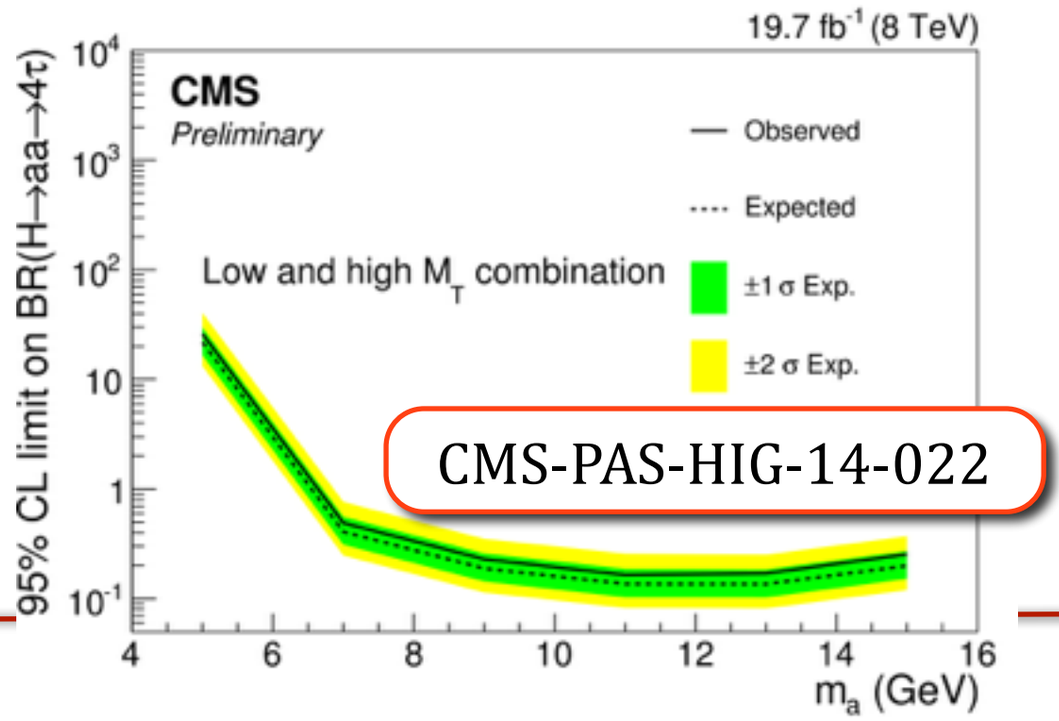
Triggered by single muon
$p_T > 25$GeV

Build a(h) with τ_μ + HPS
(Hadron Plus Strip algo.)



Range: [4, 8] GeV

Build a(h) with τ_μ + 1track



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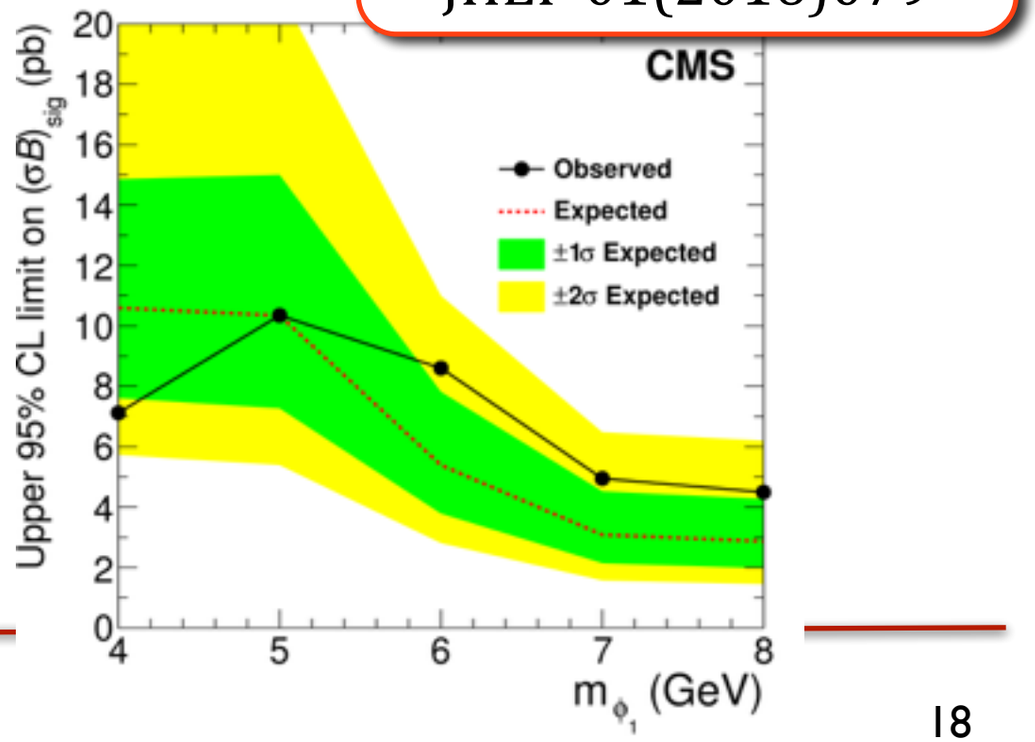

Light pseudoscalar Higgs A in association of bb

- **In the context of 2HDM Type-II, allows production of A(→ ττ)+bb**
- **Range: [25, 80] GeV**
- **Analyses based on 2012 data, include three sub-channels: $\tau_e\,\tau_\mu$, $\tau_e\tau_{had}$, $\tau_\mu\,\tau_{had}$**

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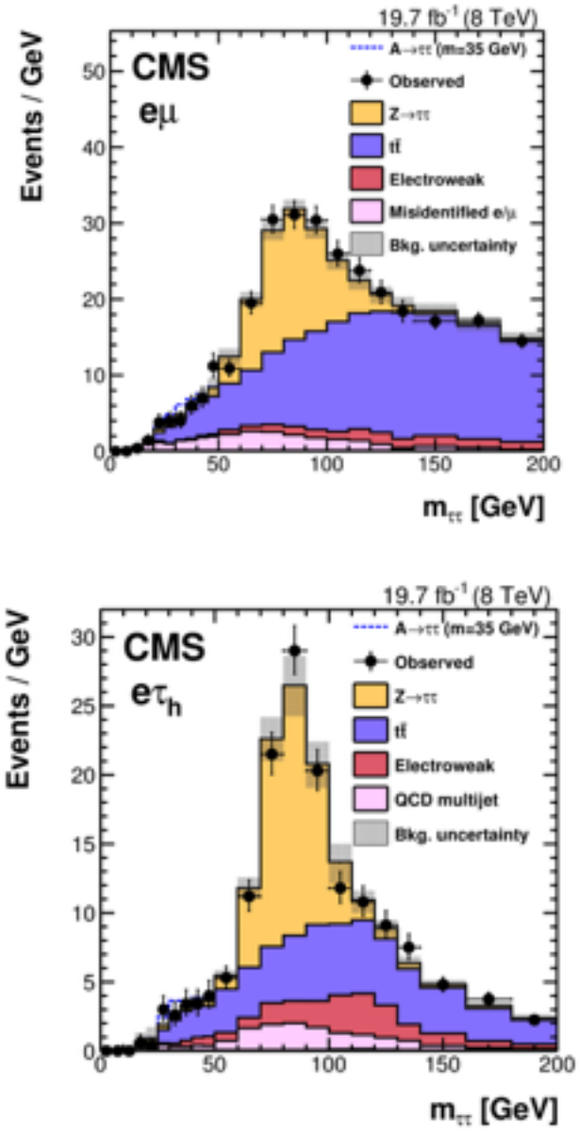
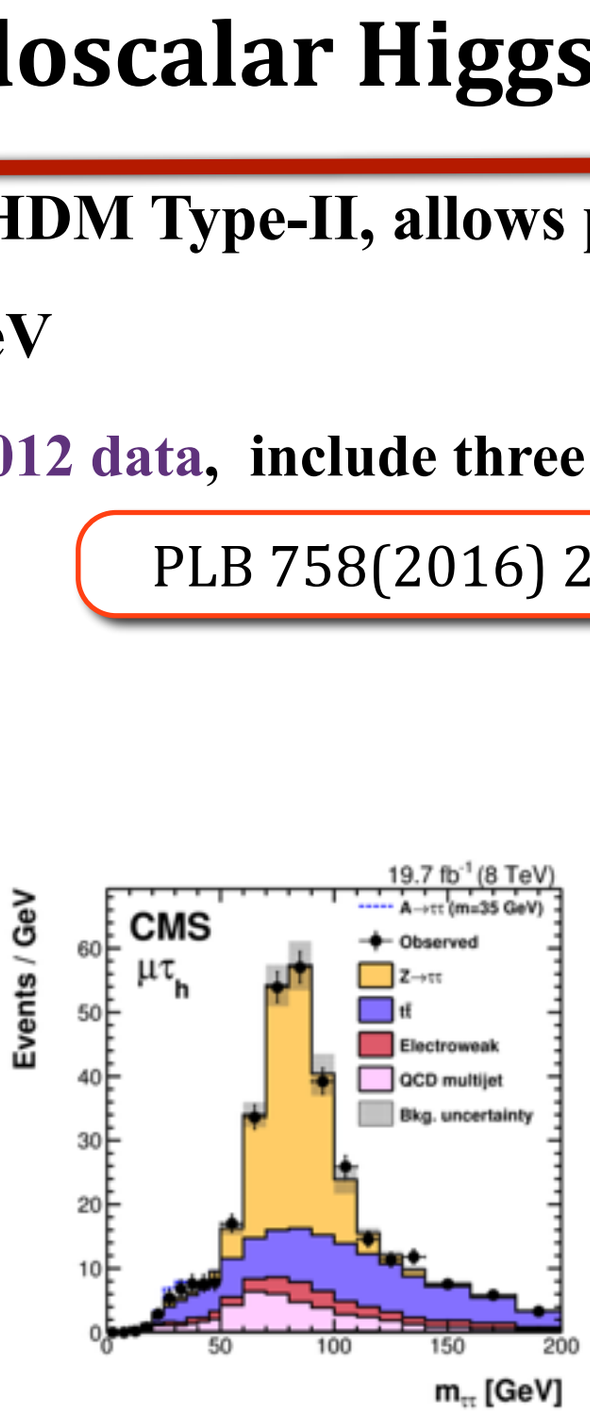
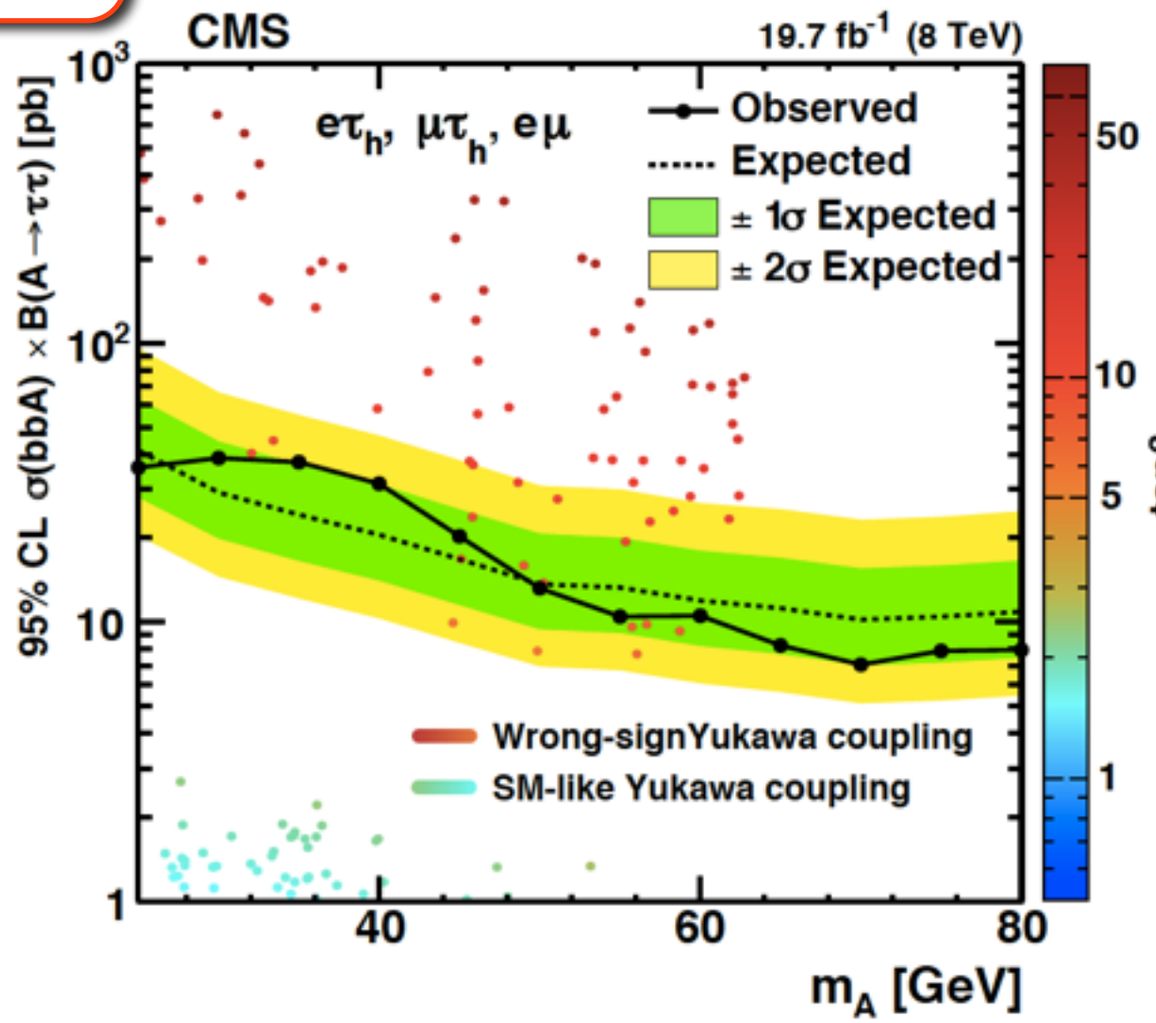






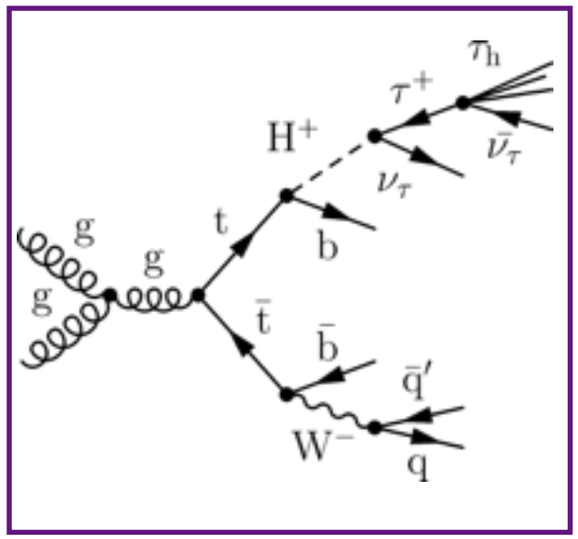
Exclude wrong-sign Yukawa coupling and large tanβ for 2HDM type II.

Charged Higgs Searches

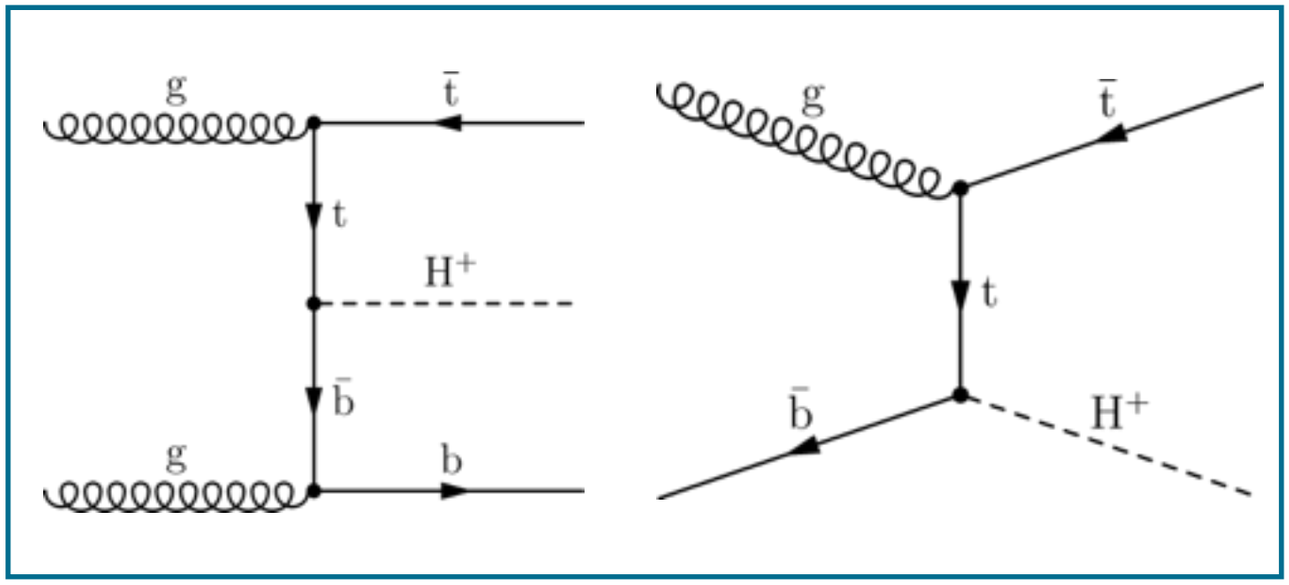
Charged Higgs searches

- **Charged Higgs production involves top-quarks**
  - Production mode depending on m(H+) relative to m(top)

m(H+) < m(t) - m(b)



m(H+) > m(t) - m(b)



- **Decay via H+→τυ/cs/tb, branching ratio depending on m(H+) and tan β**
  - light charged Higgs: tan β < 1, H+→cs dominant; tan β > 1, H+→τυ dominant
  - heavy charged Higgs: H+→τυ still sizeable, H+→tb become large

Charged Higgs searches — τυ, tb

- **Using the following channels**

Decay mode	Signatures for $m_{H^+} < m_t - m_b$	Signatures for $m_{H^+} > m_t - m_b$
	$pp \to t\bar{t} \to bH^+\bar{b}H^- / bH^+\bar{b}W^-$	$pp \to \bar{t}(b)H^+$
$H^+ \to \tau^+\nu_\tau$	τ_h+jets[5]	τ_h+jets[5], $\mu\tau_h$[6], $\ell\ell'$[7]
$H^+ \to t\bar{b}$	—	$\mu\tau_h$[6], $\ell\ell'$[7], ℓ+jets[8]

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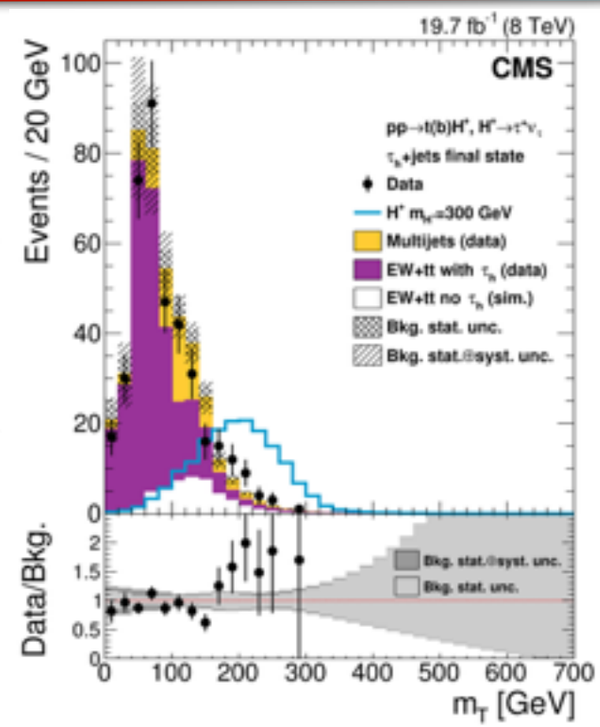
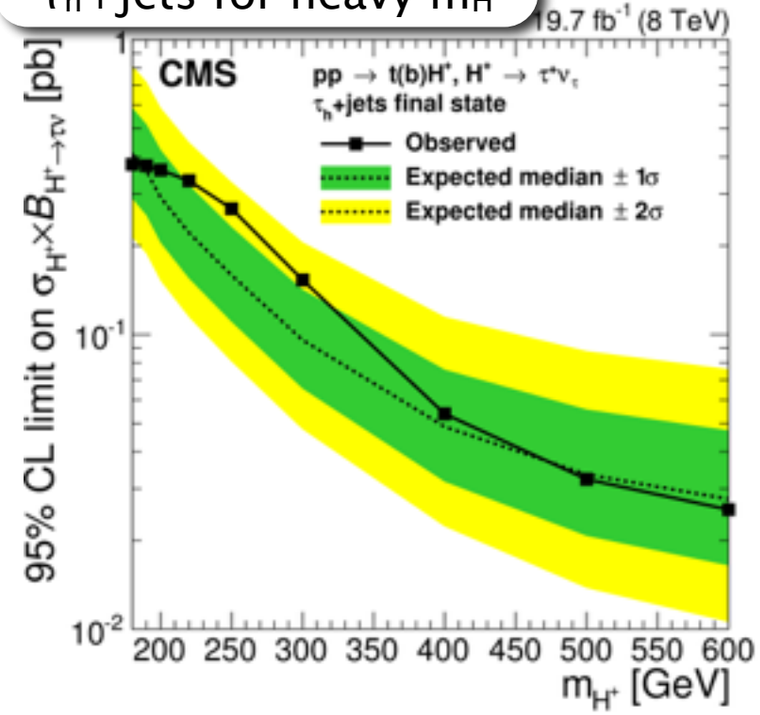
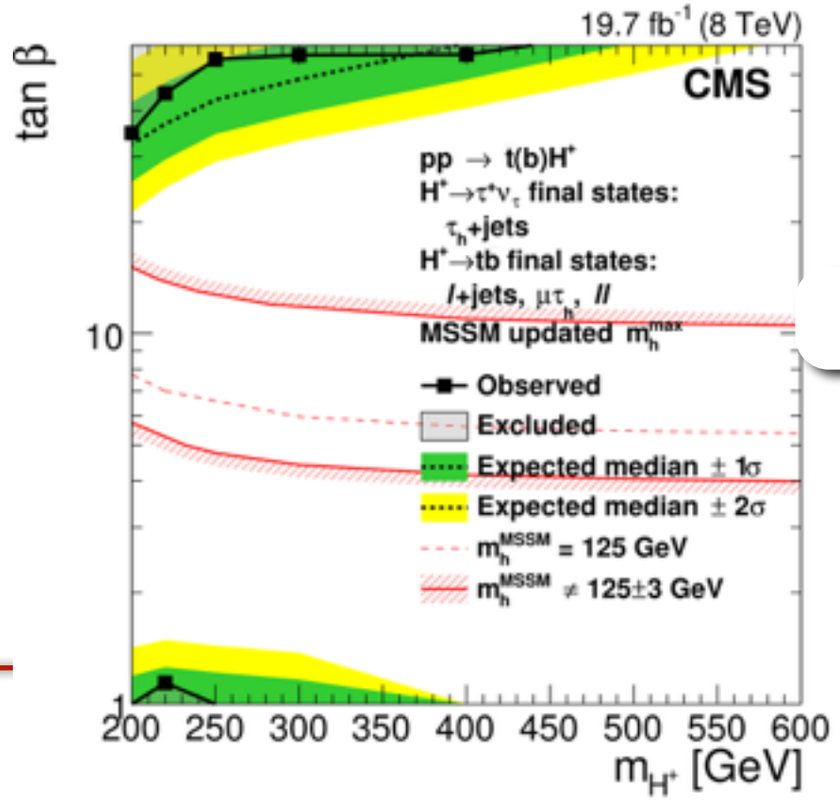


τh+jets for heavy m_H

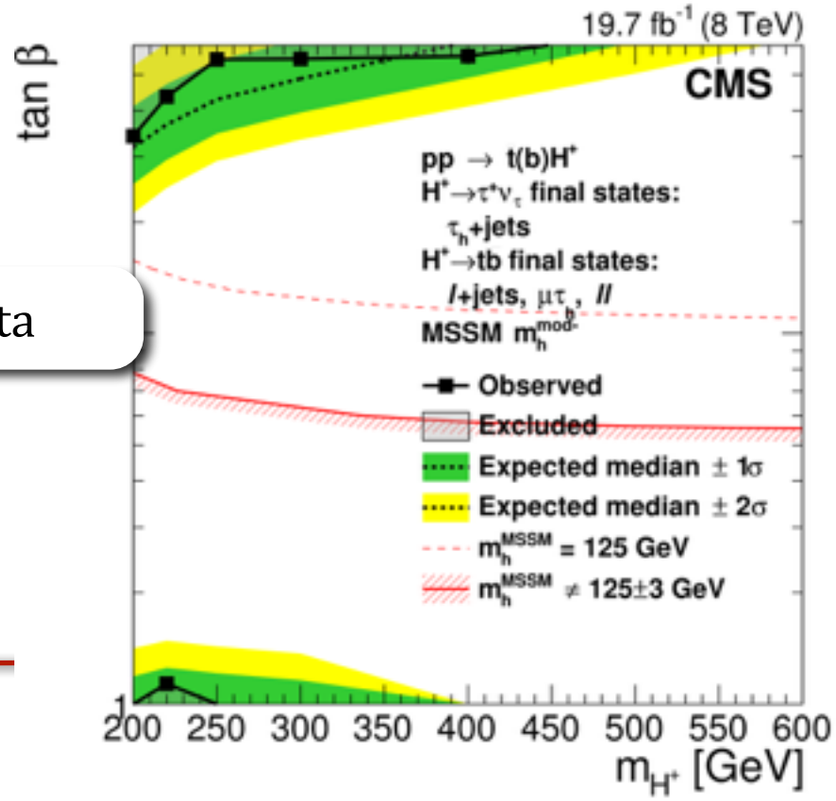


exclusion limits in m_h^{max} scenario



2012 data

exclusion limits in m_h^{mod-} scenario



Charged Higgs searches — cs

- **Light charged Higgs search through channel**
  ttbar→bW(→l**υ**)bH$^+$(→cs)
  - very similar final states as SM
    ttbar→bW(→l**υ**)bW(→jj), discriminate on m_{jj}
  - limit set on BR(t→ bH+) assuming BR(H$^+$→cs)=100%

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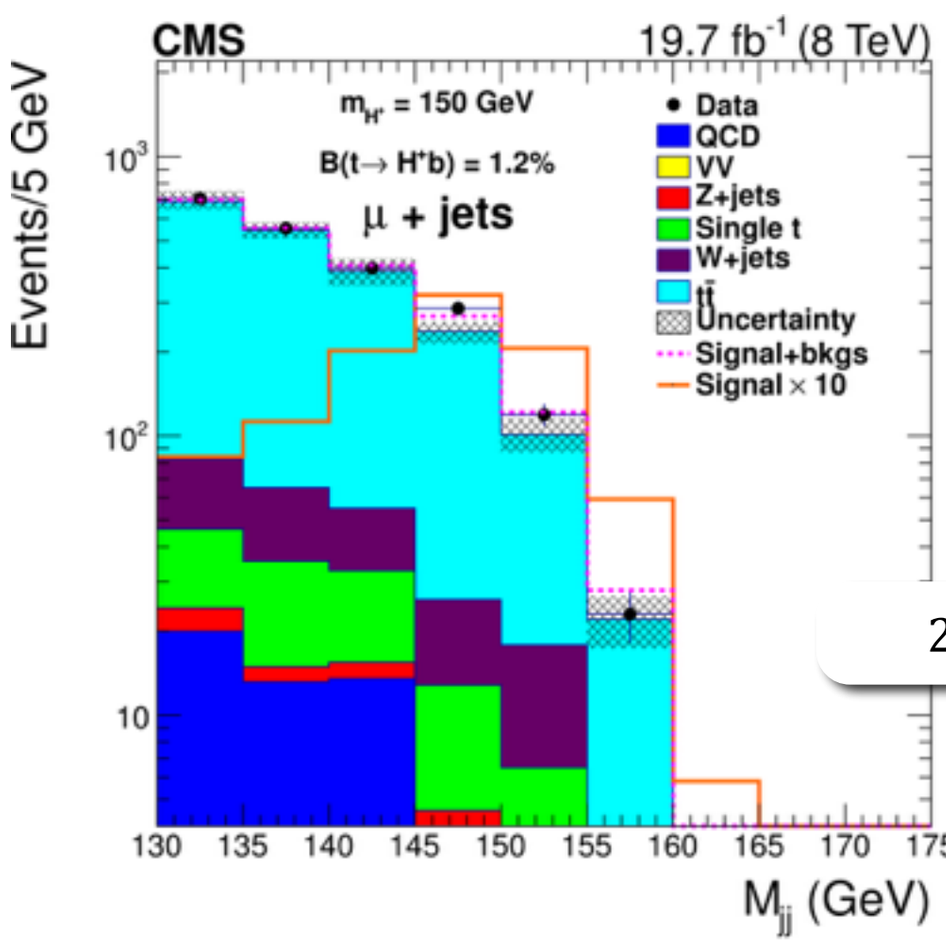
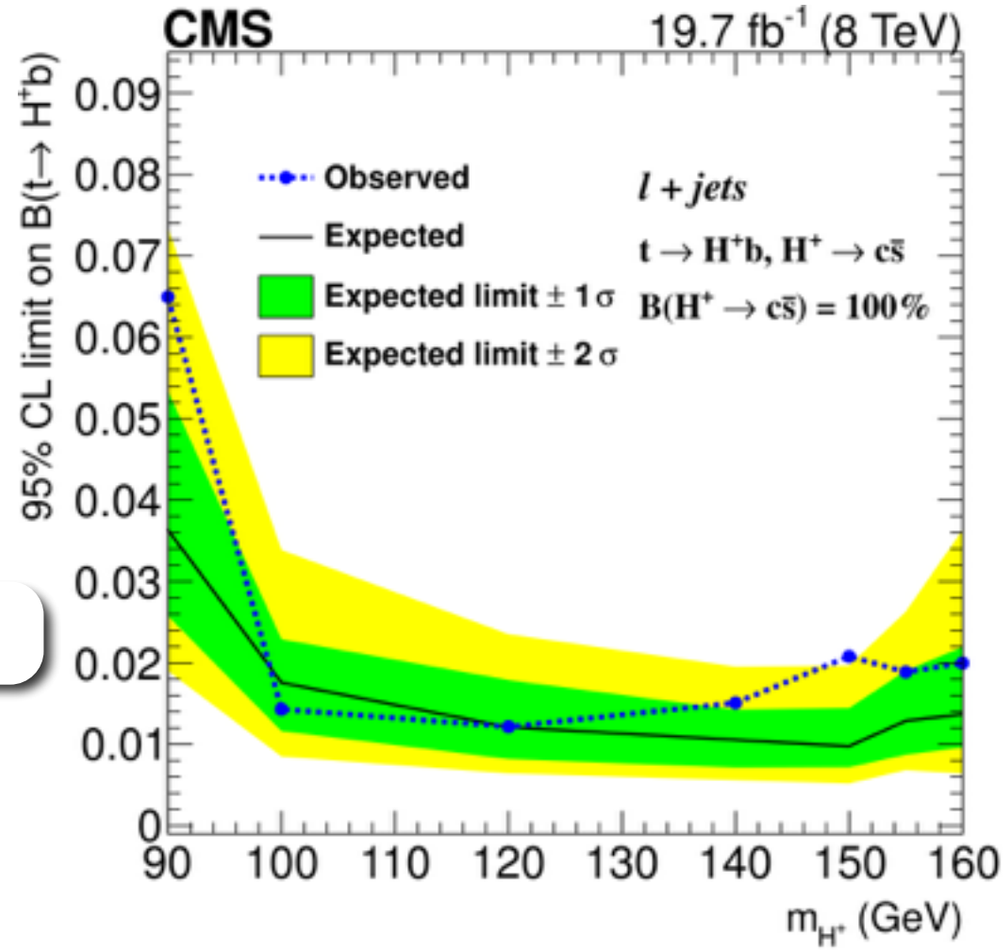


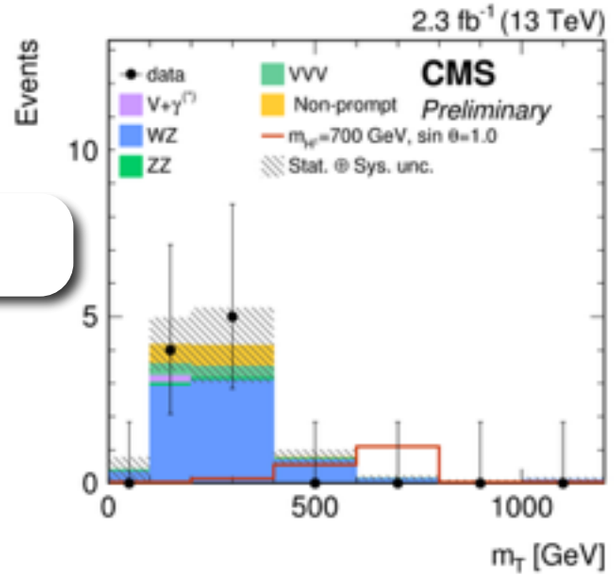
2012 data



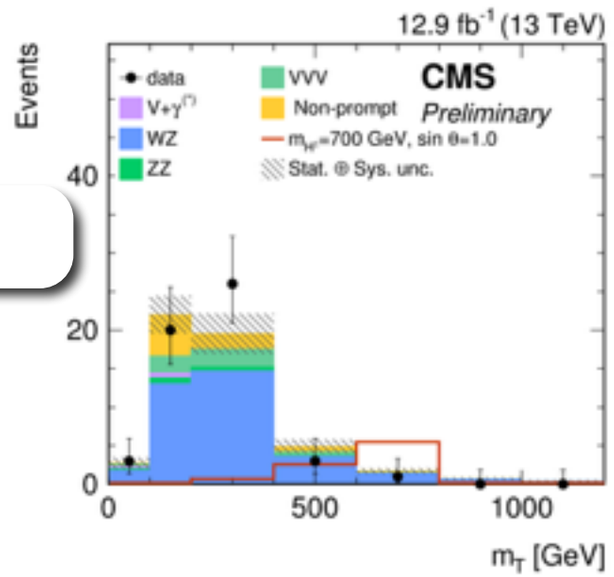
Charged Higgs searches — WZ

- **Probing Georgi-Machacek Higgs Triplet Model in mass range of [200, 1000] GeV**
  - Both W and Z decays leptonically
  - Vector Boson Scattering topology (Two jets with large rapidity separation and high dijet mass)

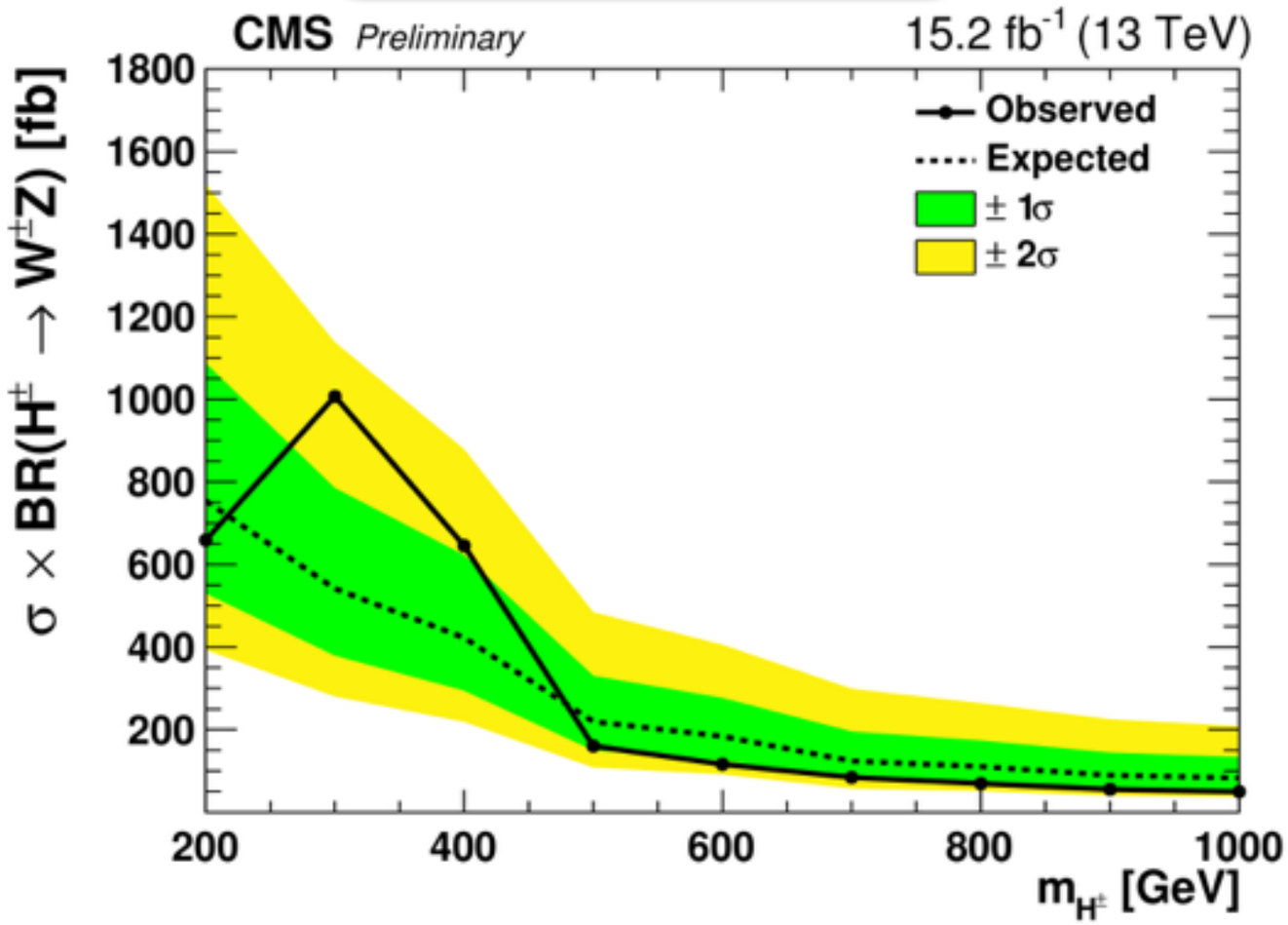
2015 data



2016 data



CMS-PAS-HIG-16-027



No significant excess!

Conclusion

- **BSM Higgs search very active field**
  - large variety of analyses
  - large potential to make a discovery
- **Rich results are produced**
  - only a small fraction of results shown in this talk
  - tight constraints to neutral and charged Higgs
  - limits on exotic decays
- **No sign for new physics found yet!**
- **Still lots of analyses ongoing based on 13 TeV data. Looking forward to more exciting results!**

- backup

Two Higgs Doublet Models

- **2HDM: one of the simplest extensions of the SM**
  - adding a second EW doublet to the Higgs sector
  - predicted 5 Higgs bosons:
    - 3 neutral: h^0(CP even), H^0(CP even), A^0 (CP odd)
    - 2 charged: $H^{\pm}$
- **Described by:**
  - 4 Higgs boson masses
  - tan β (ratio of vacuum expectation values of the doublets)
  - mixing parameter α (between two neutral CP even Higgs: h^0 H^0)
- **Four types: based on coupling structure**

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

- **MSSM: 2HDM type II + SUSY sector**

Standard Model Couplings

$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 - 0.66 \cdot \kappa_W \kappa_t + 0.07 \cdot \kappa_t^2 \quad (2)$$

$$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 - 0.07 \cdot \kappa_t \kappa_b + 0.01 \cdot \kappa_b^2 \quad (3)$$

$$\kappa_{VBF}^2 \sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2 \quad (4)$$

$$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2. \quad (5)$$