Search for Higgs Bosons Beyond the Standard Model with the CMS Detector

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on behalf of the CMS Collaboration

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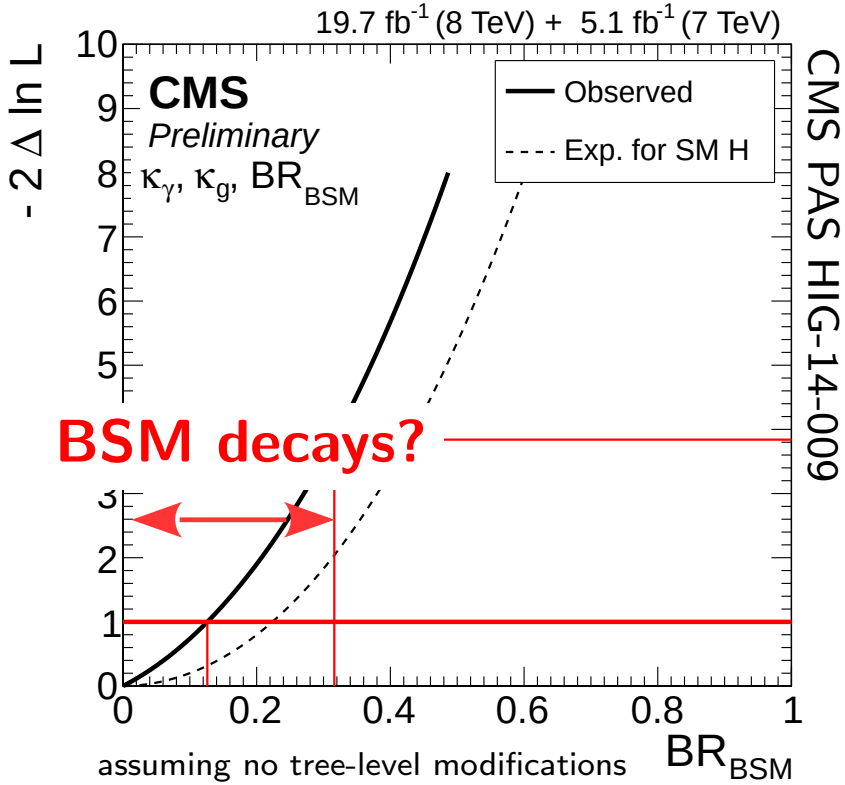
Did We Discover the Standard-Model Higgs?

- General indications of physics beyond the Standard Model
  - Dark matter
  - Fine-tuning problem
- Observed boson compatible with Standard-Model Higgs
- But from couplings analysis[1]: **plenty of room for BSM Higgs decays!**



What are the properties of the new boson?
Are there any additional Higgs bosons?

[1] presented on Monday by Shivali Malhotra

Examples of Models with Extended Higgs Sector

Supersymmetry

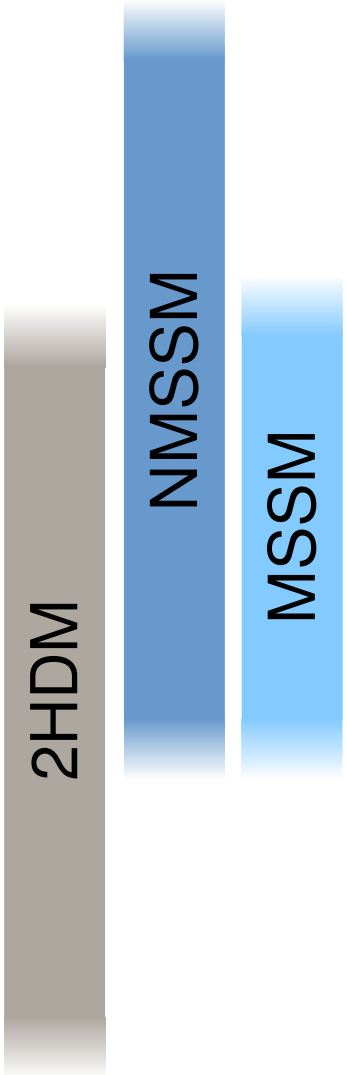
- Well-motivated extension of Standard Model
  - ✓ Provides dark-matter candidates
  - ✓ Solves fine-tuning problem
- Minimal supersymmetric extension (MSSM)
  - 2 Higgs doublets $\rightarrow$ **5 physical bosons**
    h, H, A $\equiv \Phi$ (neutral)
    H^+, H^- (charged)
  - 2 tree-level parameters m_A and $\tan\beta$
  - h usually identified with 125 GeV boson
- Next-to-Minimal model (NMSSM)
  - 2 doublets + 1 singlet = 7 physical bosons

Generic 2 Higgs-Doublet Models (2HDM)

- Effective extension of Standard Model
- Allows flavour-changing Yukawa couplings

MSSM predicts
$m_h \lesssim 135$ GeV!

Examples of BSM-Higgs Searches at CMS



additional Higgs bosons

$h \to 2a_1 \to 4\mu$

$a_1 \to 2\mu$

$\Phi \to \tau\tau$

$\Phi \to bb$

$\Phi \to \mu\mu$

$H^{\pm} \to cs$

$H^{\pm} \to \tau\nu$

H(125)-pair production

high-mass $H \to \gamma\gamma$

non-SM decays

invisible decays

anomalous HVV couplings

lepton-flavour violating decays

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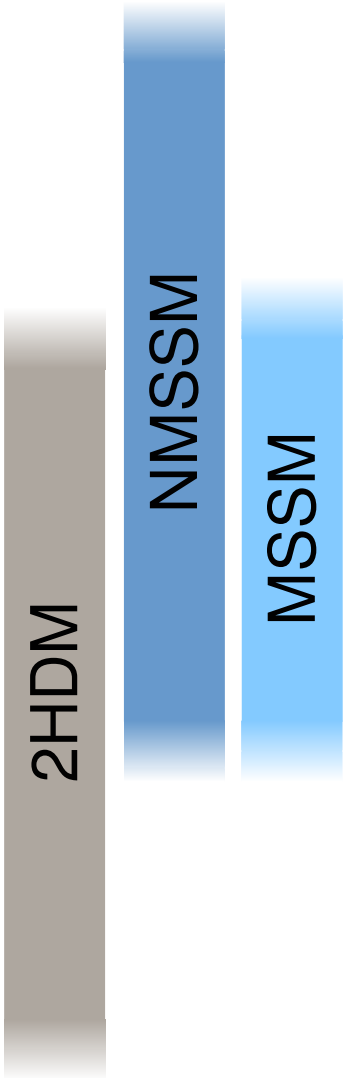

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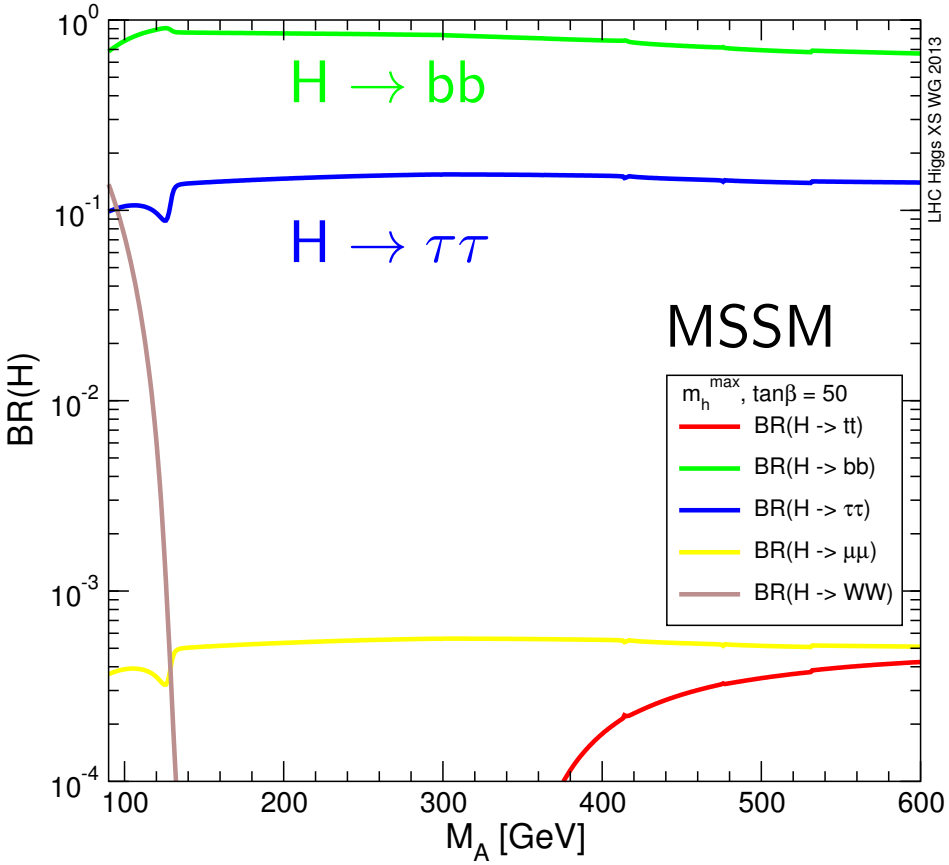
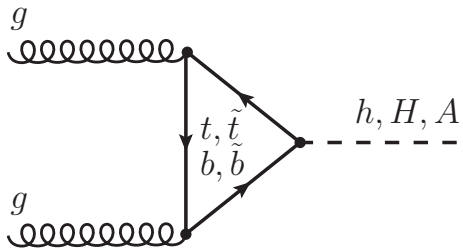
Search for a Heavy Neutral Higgs: $\Phi \to \tau\tau$



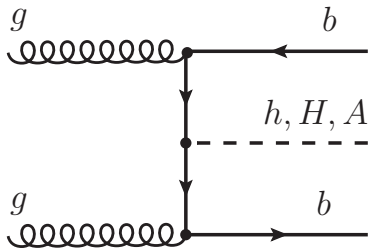
- $\Phi \to \tau\tau$ channel
  - Relatively large BR
  - Manageable backgrounds

- **no b-tagged jet**



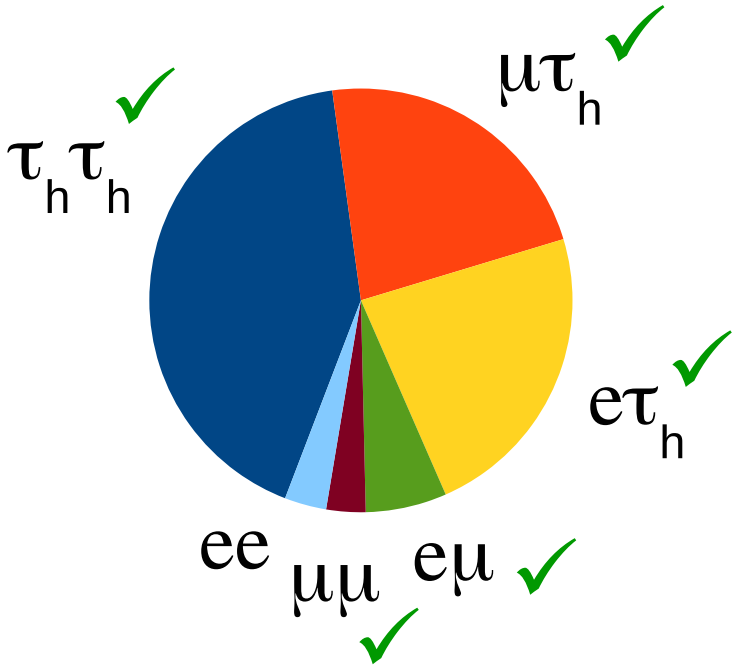
  - gg-fusion production
  - Dominant at small tan β

- ≥ 1 **b-tagged jets**



  - Associated production
  - Dominant at larger tan β

Analysis Strategy



5 of 6 $\tau\tau$ decay-channels
(= 97%) covered

Event selection

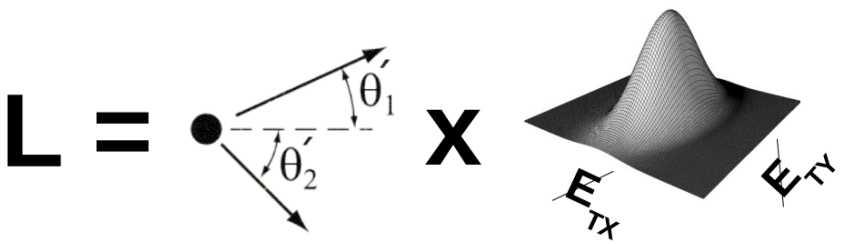
- 2 oppositely charged, isolated leptons
  - dedicated τ_h reconstruction
- + channel-dependent selections
  - e. g. $m_T(\mu, \not{E}_T) < 30$ GeV in $\mu\tau_h$ to suppress W + jets background

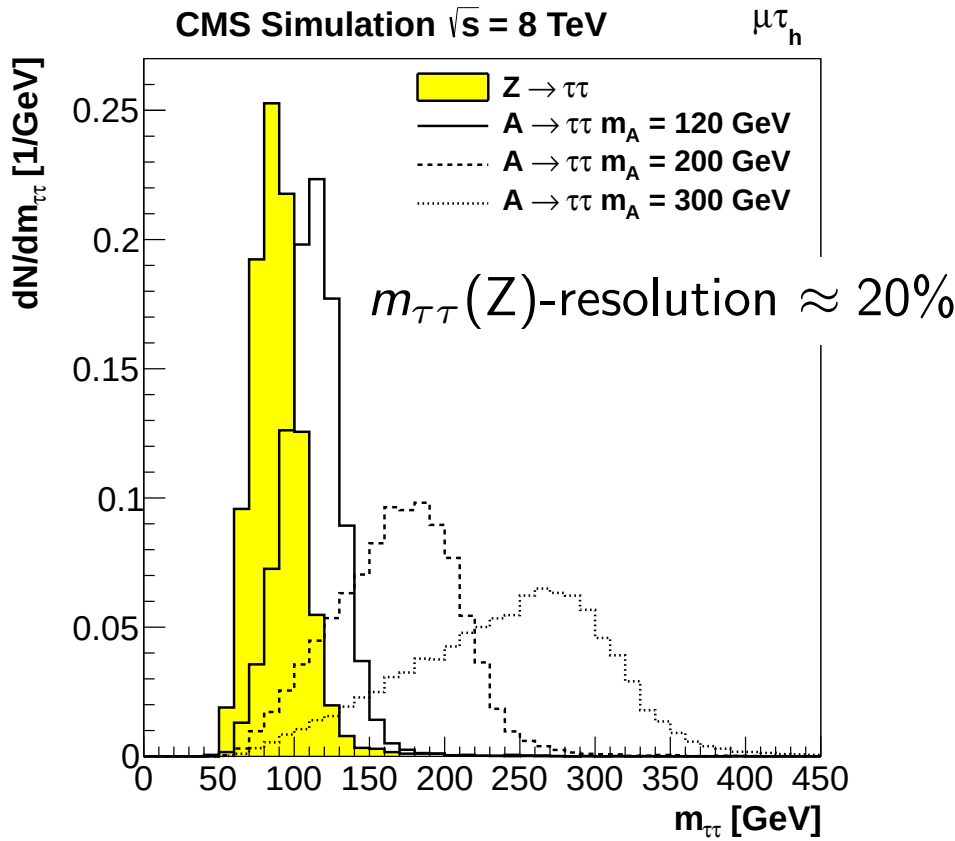
Search for peak in di-τ invariant mass distribution

Di-τ Invariant Mass Reconstruction

- $m_{\tau\tau}$ reconstruction from visible τ decay products and $\not{E}_T$
- Based on maximum-likelihood technique

$$L = \text{phasespace of } \tau \text{ decay} \times \text{expected } \not{E}_T \text{ resolution}$$

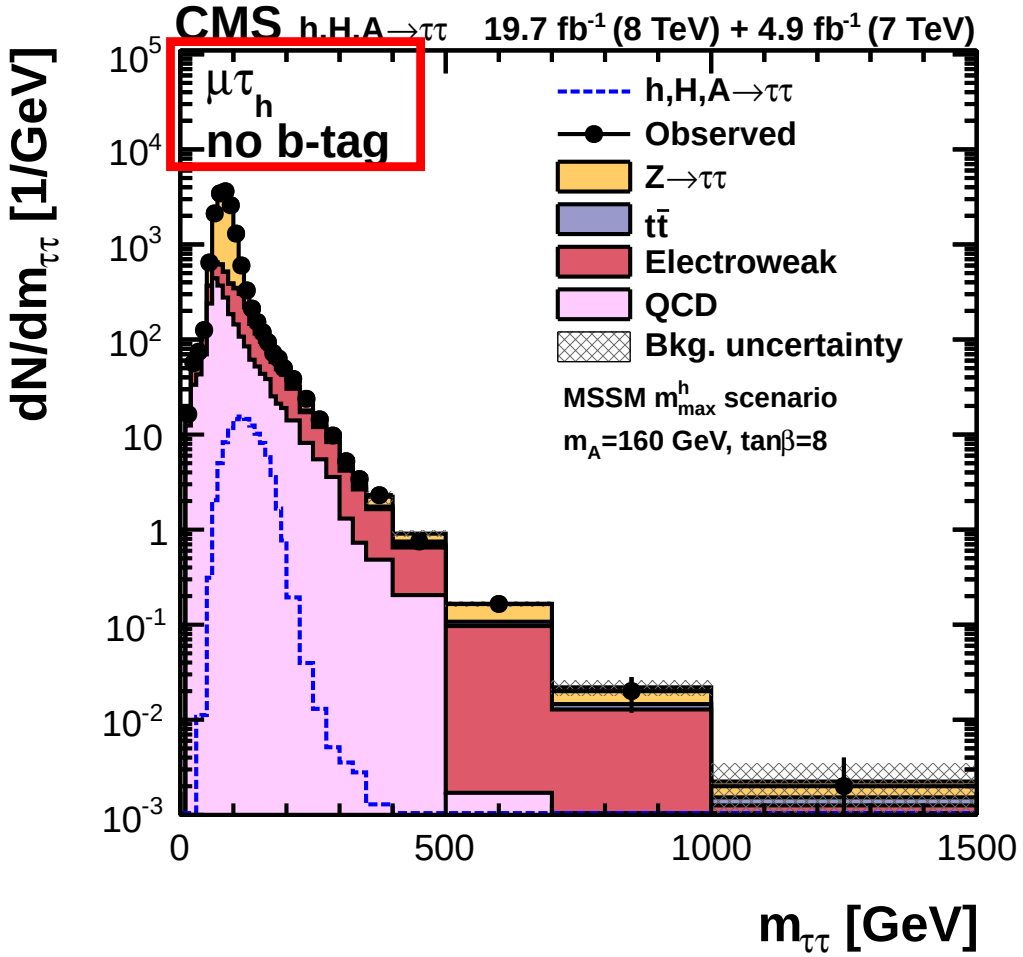




$m_{\tau\tau}$(Z)-resolution $\approx$ 20%

Enhanced separation of signal and dominant Z $\to \tau\tau$ background

Background Prediction



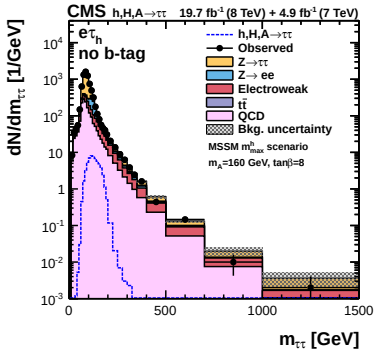
- $Z \to \tau\tau$: embedding technique
  - $Z \to \mu\mu$ events
  - μ replaced by simulated τ decay products
- $W + jets$
  - From sideband of events with large $m_T(\mu, \not{E}_T)$
- QCD-multijets
  - From rate of same-charge τ-pair events

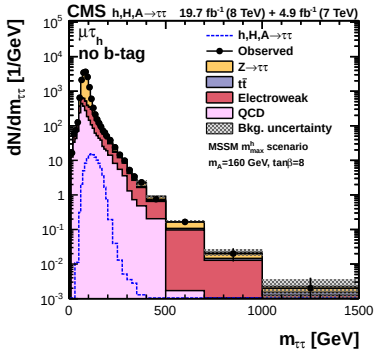
- Background composition varies across channels

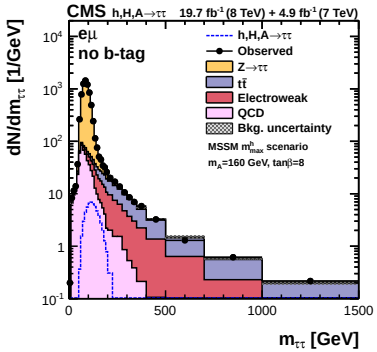
Results: Di-τ Invariant Mass Distributions

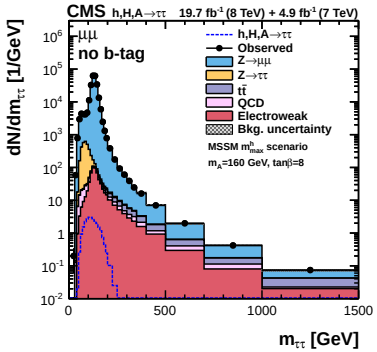
$e\tau_h$ | $\mu\tau_h$ | $e\mu$ | $\mu\mu$ | $\tau_h\tau_h$

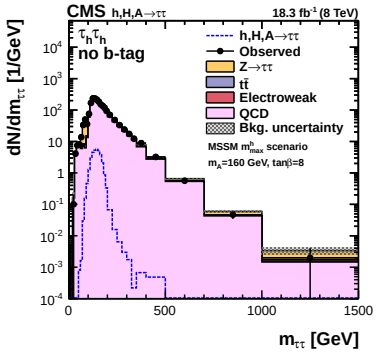
no b-tag



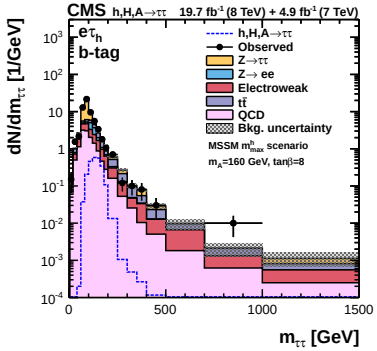


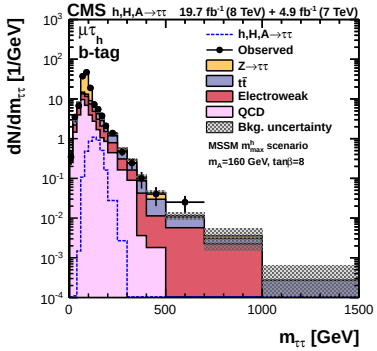


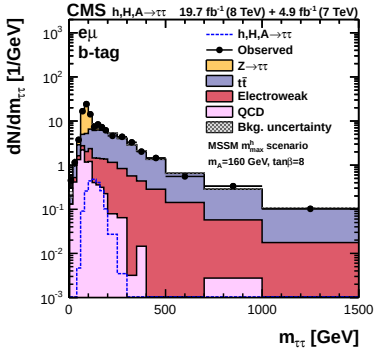


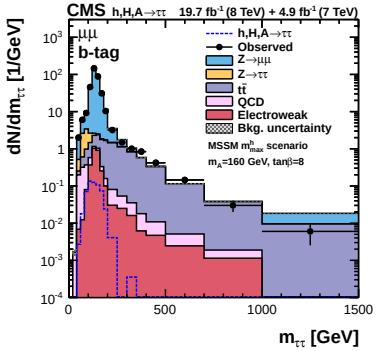


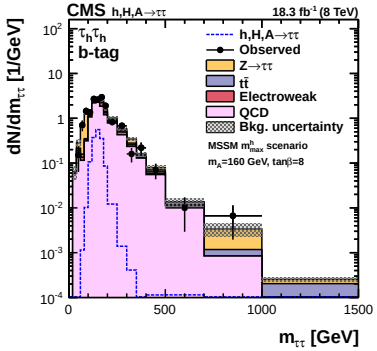
b-tag





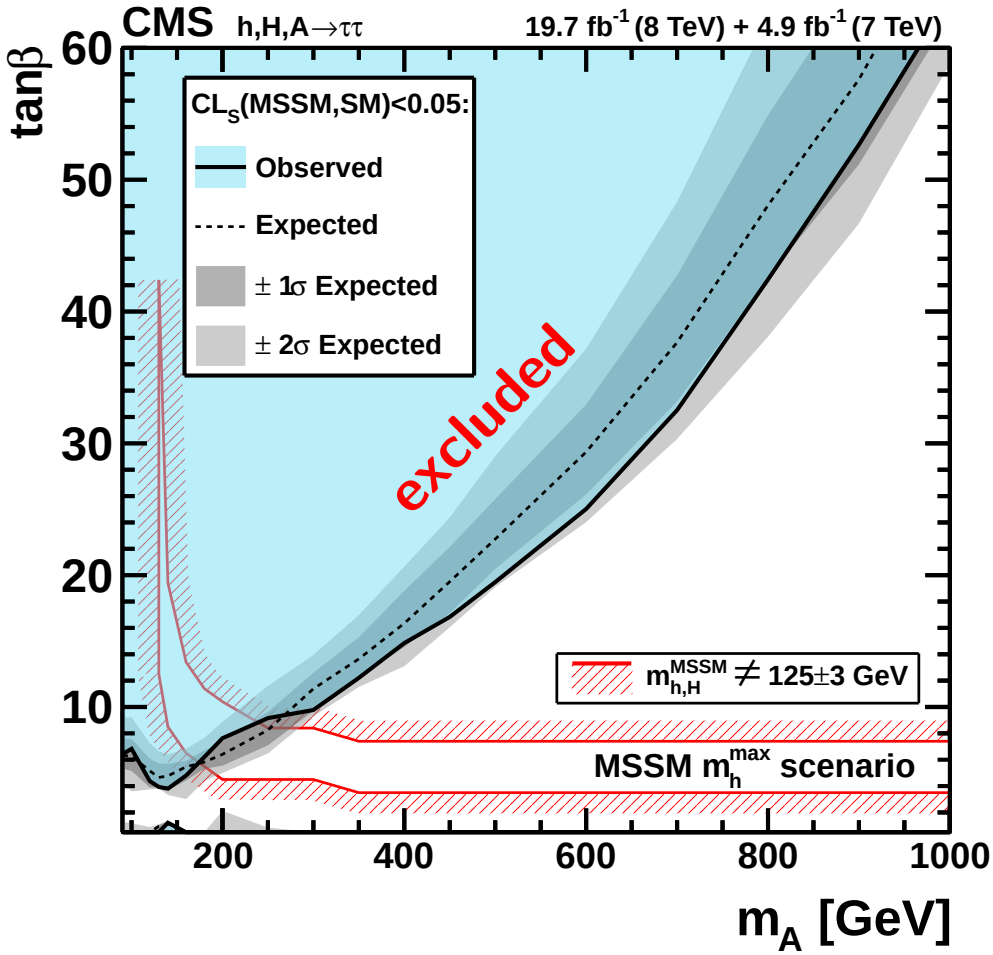






All distributions well described by background-only hypothesis

Interpretation of $\Phi \to \tau\tau$-Search Results



Limits in MSSM parameter space up to $m_A = 1$ TeV

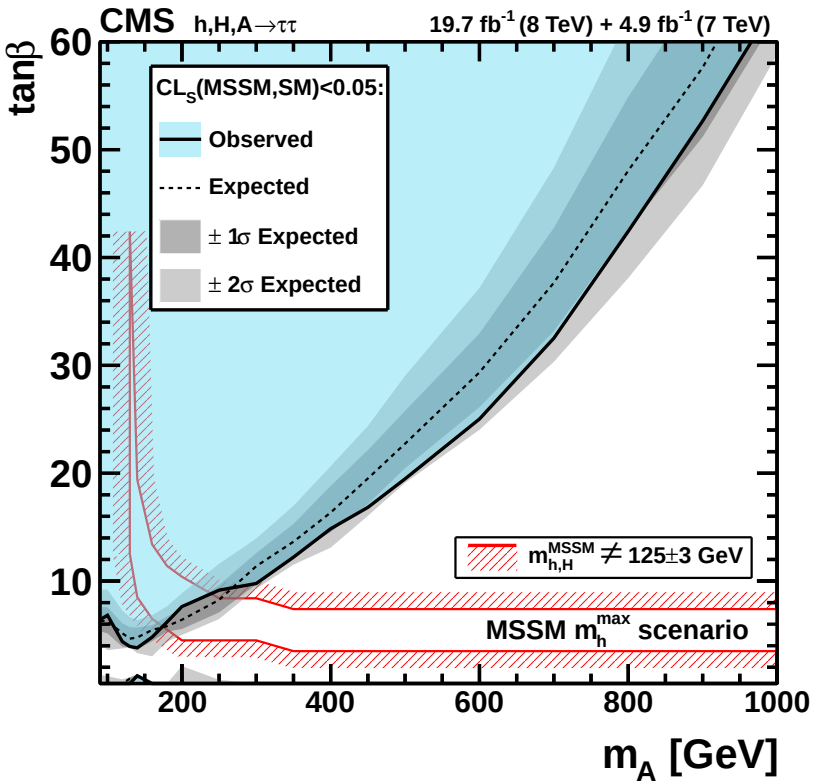
Excluding $\tan\beta \gtrsim 5$ at low m_A

Interpretation of $\Phi \to \tau\tau$-Search Results

new approach

Testing MSSM vs Standard Model

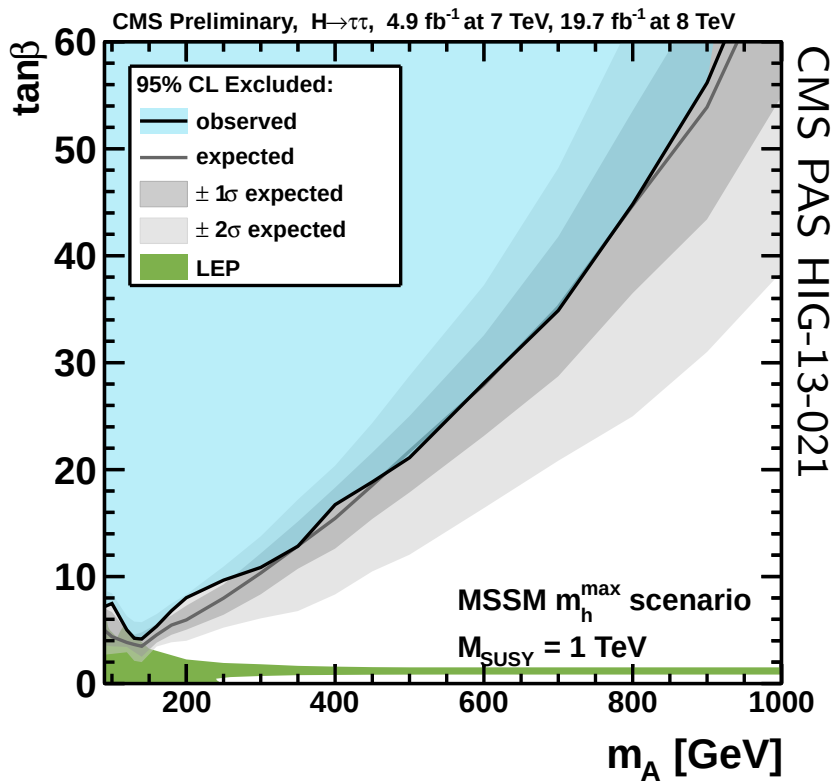
h + H + A + bkg vs h_{SM} + bkg



old approach

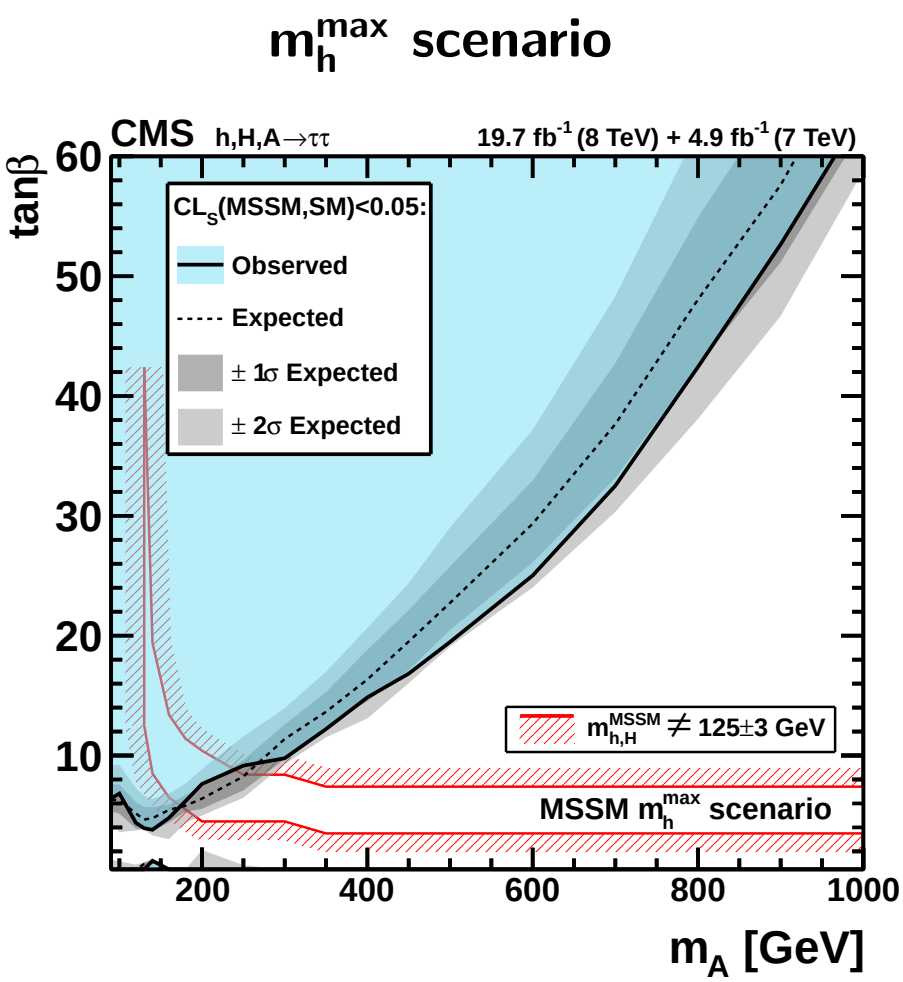
Testing MSSM vs background-only

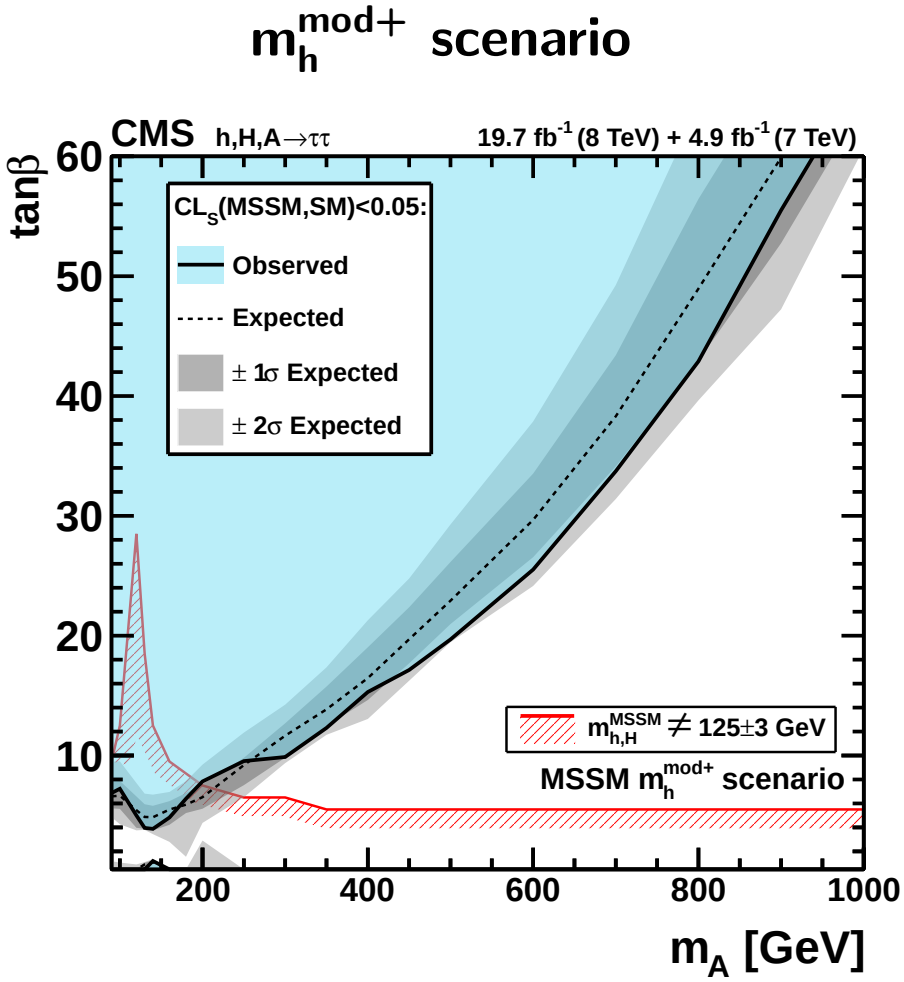
h + H + A + bkg vs bkg



Latest results take 125 GeV boson explicitly into account

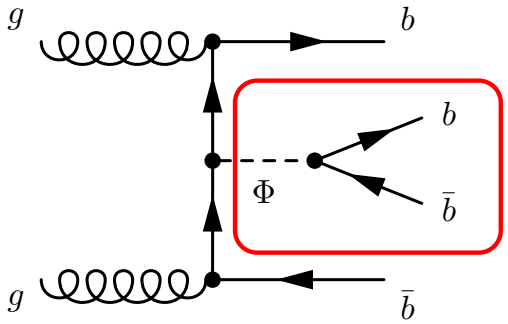
Interpretation of $\Phi \to \tau\tau$-Search Results



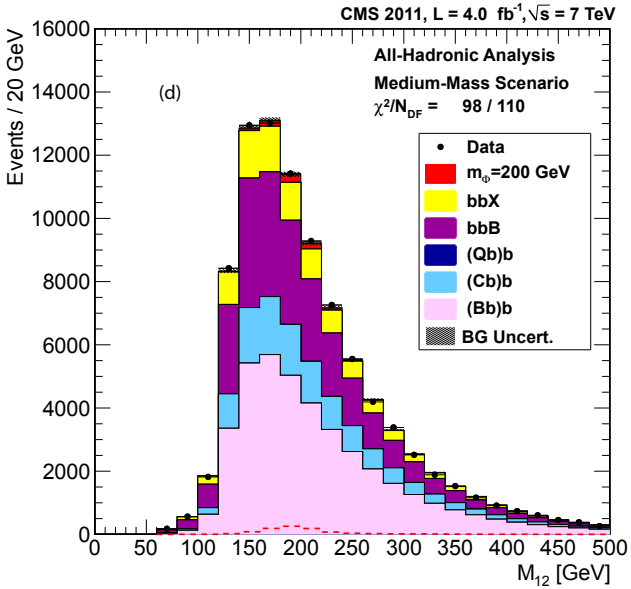


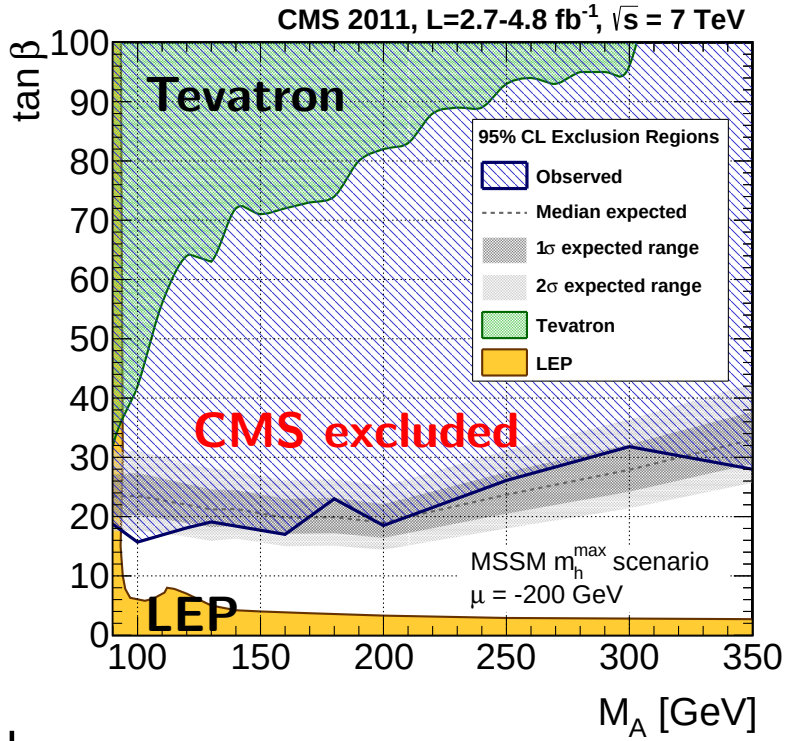
Interpretation in new benchmark scenarios

Search for a Heavy Neutral Higgs: $\Phi \to bb$



- $\mathcal{B}(\Phi \to bb)$ typically large ($\lesssim 90\%$) in MSSM
- Search for peak in bb invariant-mass distribution



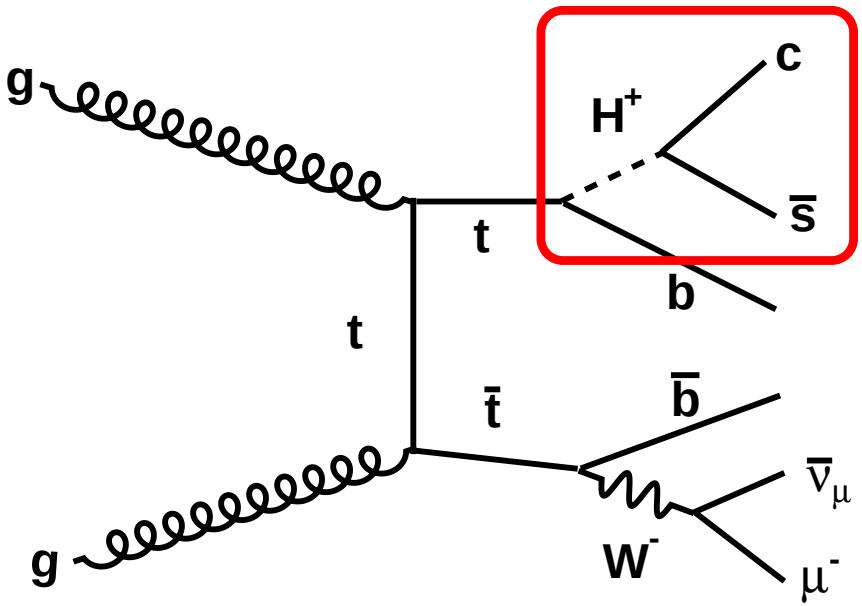


- Data-driven background model based on precise understanding of b-jet tag efficiency and mis-tag rate

Best sensitivity in this channel to date

Search for a Light Charged Higgs: $H^+ \to c\bar{s}$

- In MSSM
  - $H^+ \to c\bar{s}$ dominant decay mode for $\tan\beta < 1$
  - Production via t-quark decay for $m_{H^+} < m_t$

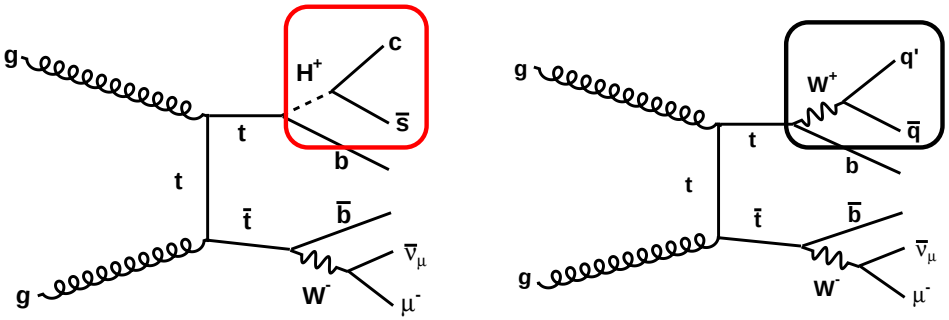


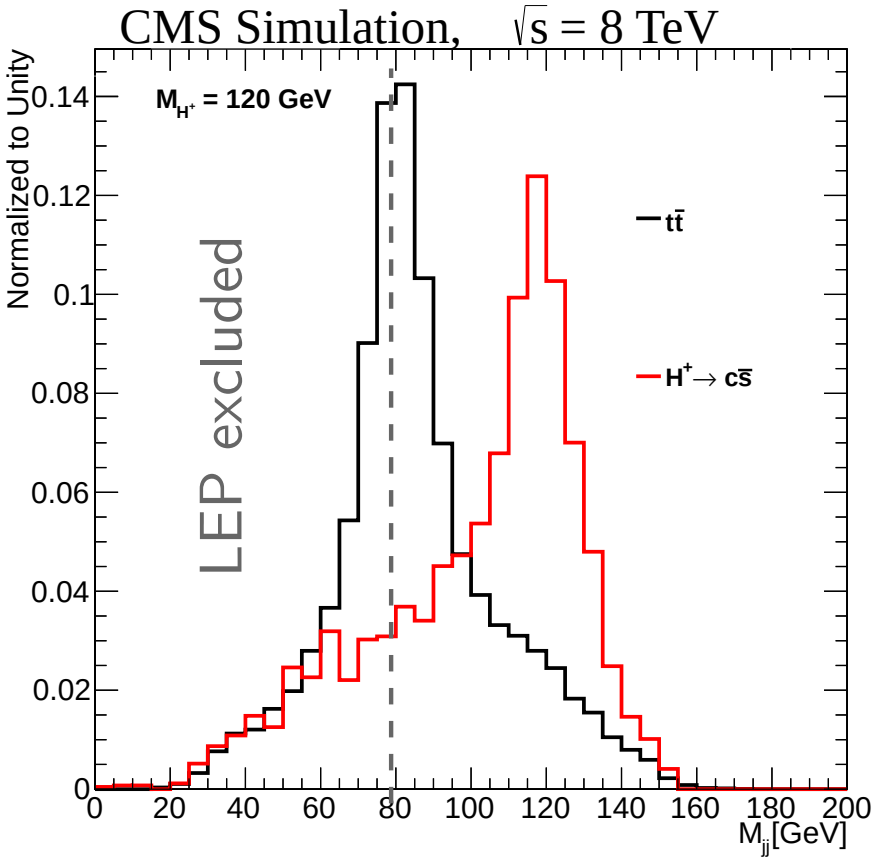
- Event selection
  - ≥ 4 central jets
  - ≥ 2 jets b-tagged
  - $= 1$ isolated μ
  - $\not{E}_T > 20$ GeV

Search for peak in invariant mass M_{jj} of non-b-tagged jets

H^+ Reconstruction

- Primary background from $t\bar{t}$ events in semi-leptonic channel
  - Peaks at $M_{jj} = m_W$



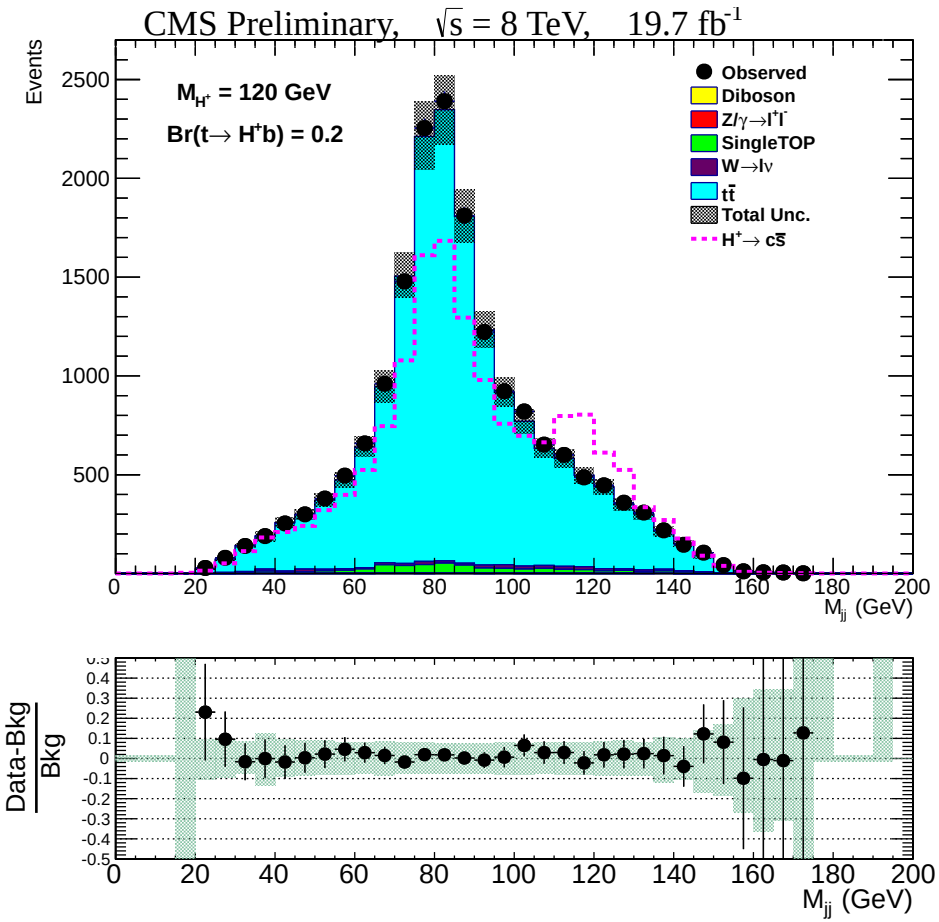


- M_{jj} reconstruction using constrained kinematic fit

$$m(\mathrm{b} + q + q') = m_\mathrm{t}$$
$$m(\mathrm{b} + \mu + \not{E}_\mathrm{T}) = m_\mathrm{t}$$

- Improved mass resolution of H^+ candidate
  - Good separation from SM $t\bar{t}$ decays

H^+ Signal Extraction

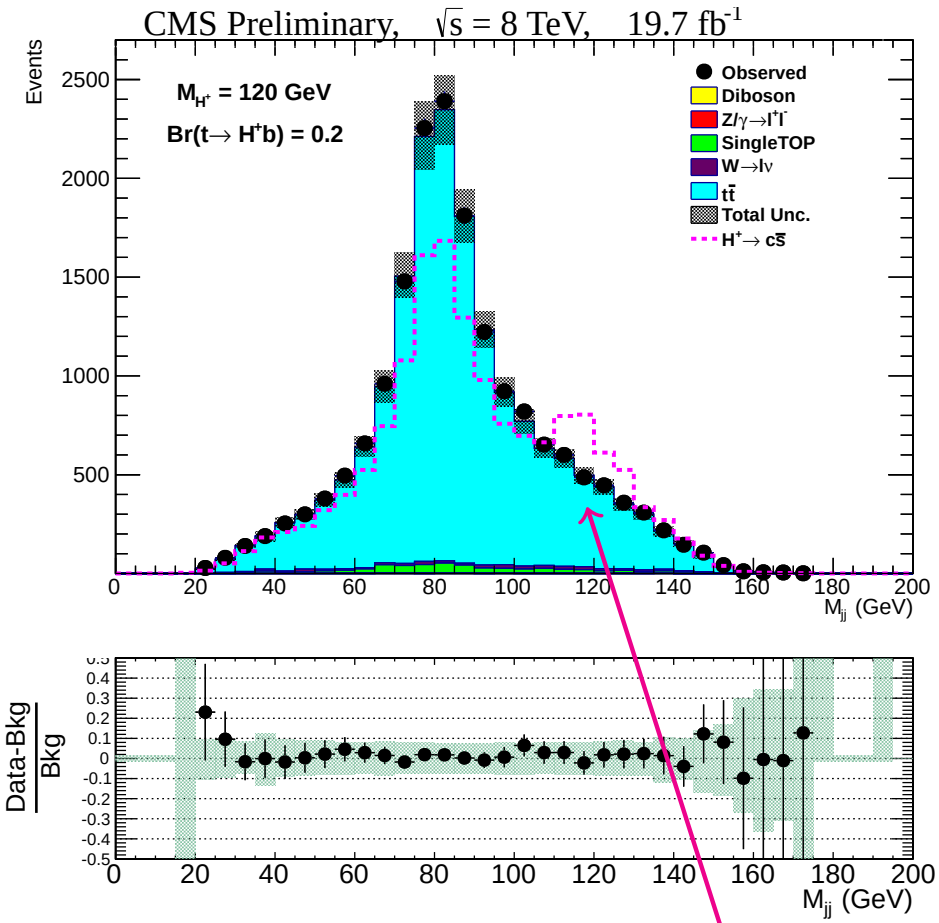


- Assuming Standard-Model $t\bar{t}$-production cross-section
- In case of signal
  - Excess at m_{H^+}
  - Deficit at m_W

No significant deviation from SM-only hypothesis observed

$$N_{\text{data}} = \left[\mathcal{B}(t \to Wb) + \mathcal{B}(t \to H^+ b)\right] \cdot \sigma_{t\bar{t}}$$

H^+ Signal Extraction



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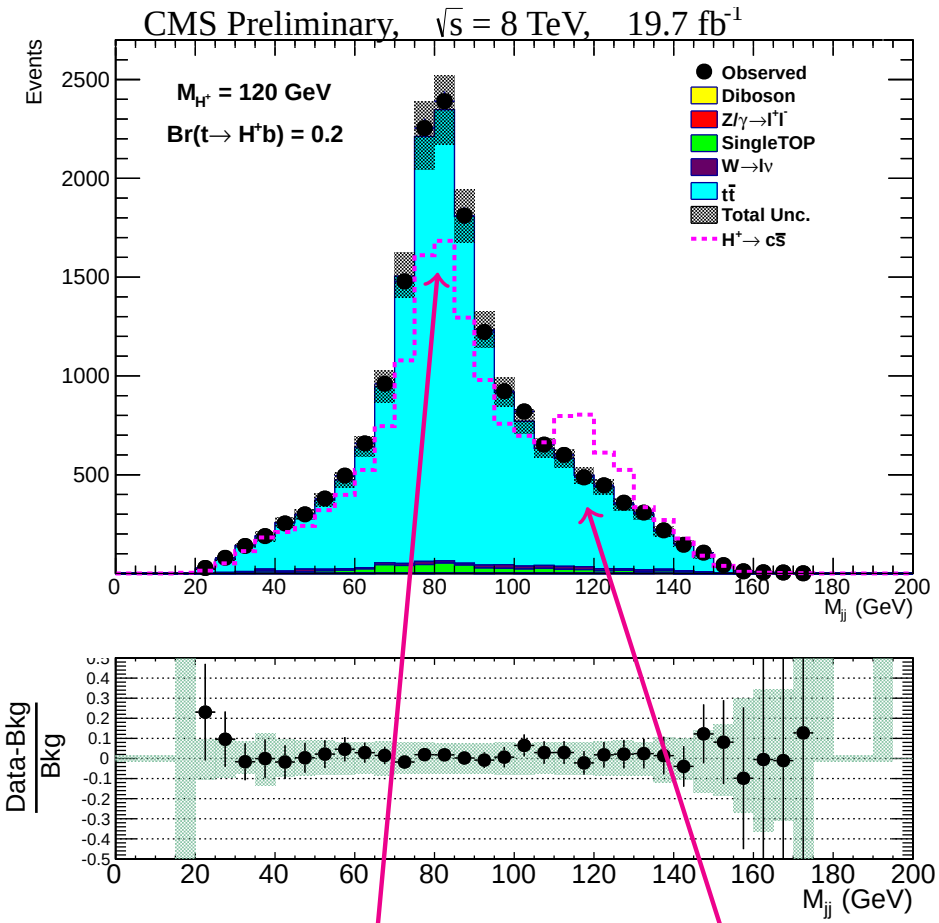

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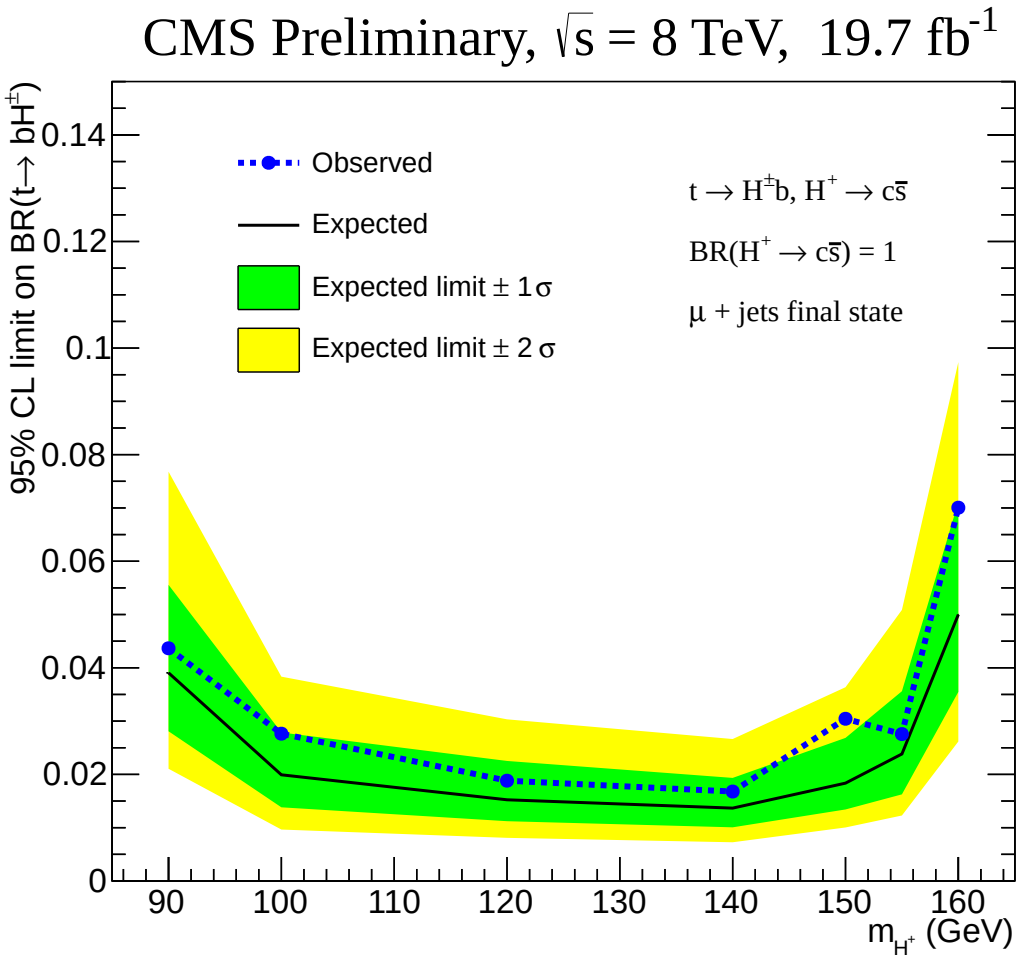
Interpretation of $H^+ \to c\bar{s}$-Search Results



$\mathcal{B}(H^+ \to c\bar{s}) = 100\%$ assumed

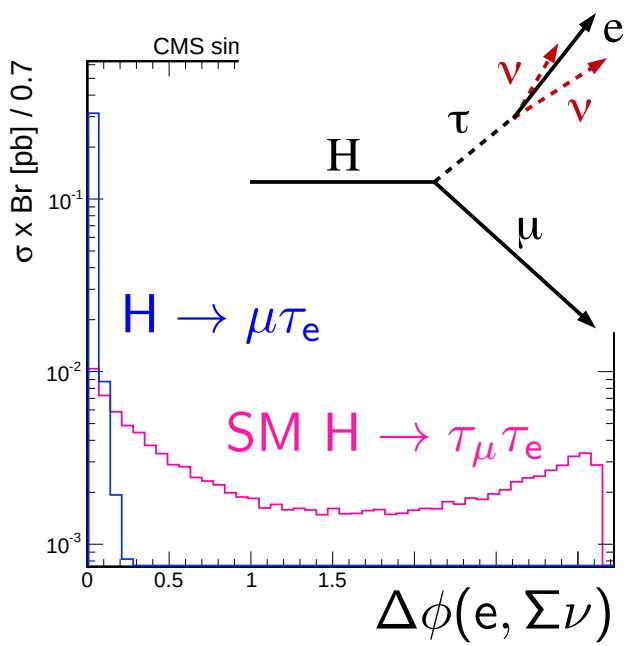
Model-independent upper limit of $\mathcal{B}(t \to H^+ b)$ of 2–7% for $90 < m_{H^+} < 160$ GeV

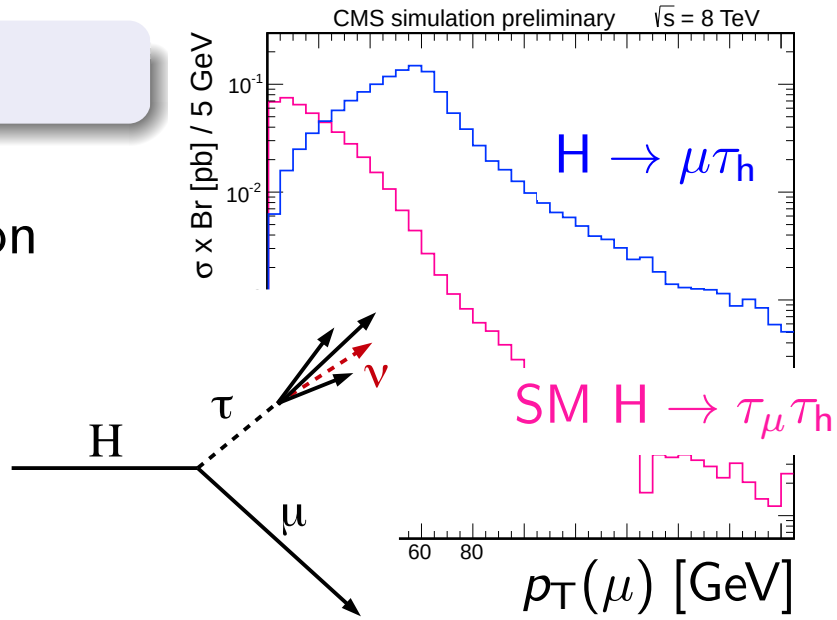
Lepton-Flavour Violating Higgs-Decays

- Possible e. g. in 2HDMs
- This search:
  H(125) $\rightarrow \mu\tau$ in $\mu\tau_e$ and $\mu\tau_h$ channels
  - Oppositely charged isolated μ and e
  - Oppositely charged isolated μ and τ_h candidate

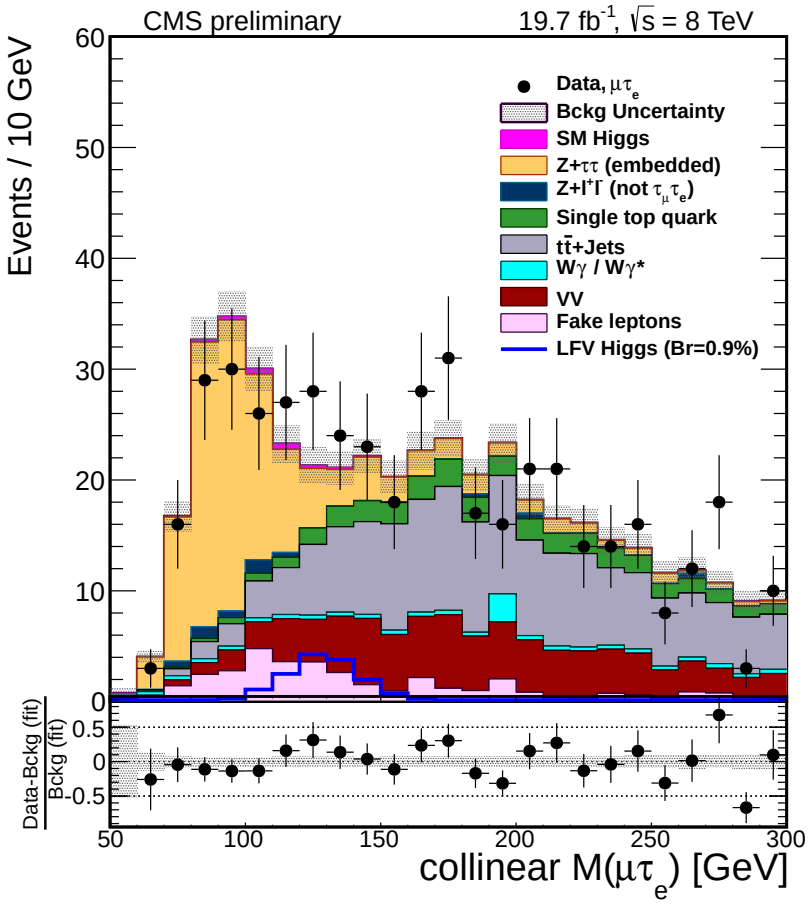
Search for $\mu\tau$-mass resonance

- Additional $\Delta\phi(\mathrm{e},\not{E}_\mathrm{T})$ and μ-p_T selection
- Exclusive 0,1,2-jets categories to enhance different production modes

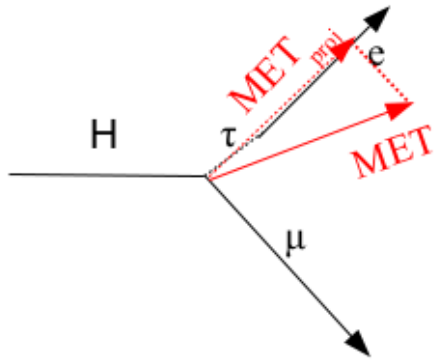




Invariant $\mu\tau$-Mass Reconstruction



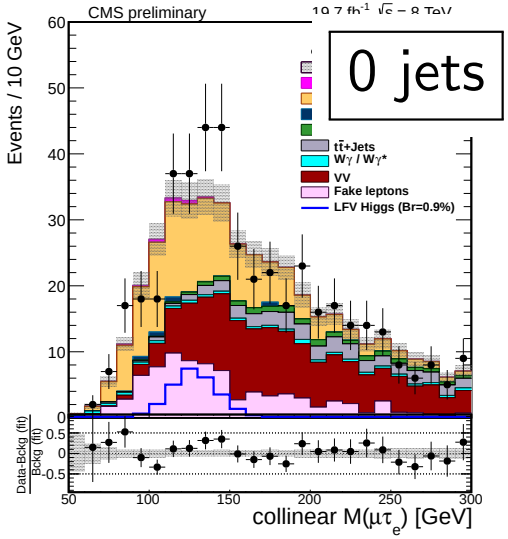
- Collinear-mass approximation
  - Assumption: τ decay products (visible and νs) collinear

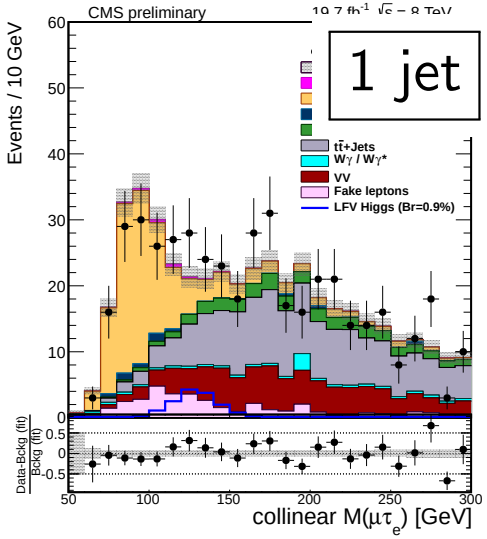


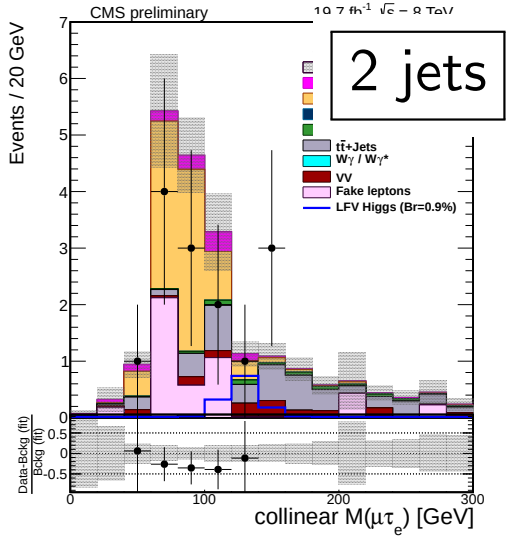
- Background composition varies across channels, e. g.
- $Z \rightarrow \tau\tau$ background
  - With embedding technique in $Z \rightarrow \mu\mu$ events

Results of $H \to \mu\tau$ Search

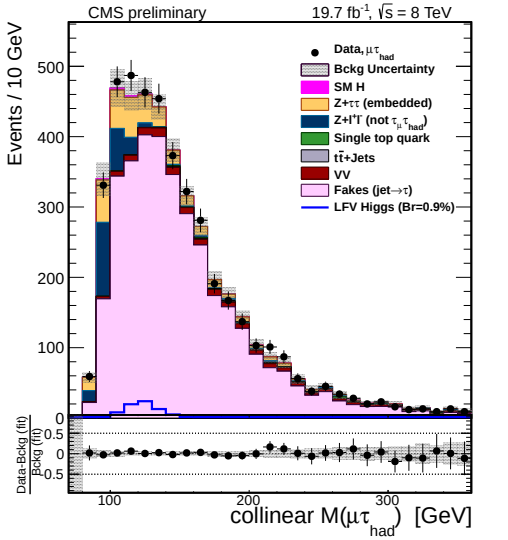
$H \to \mu\tau_e$

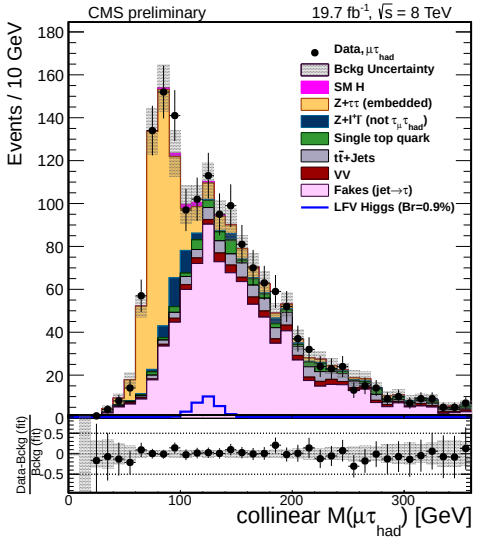


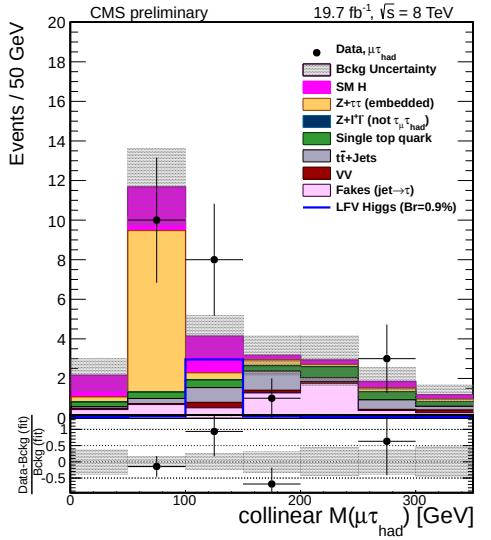




$H \to \mu\tau_h$

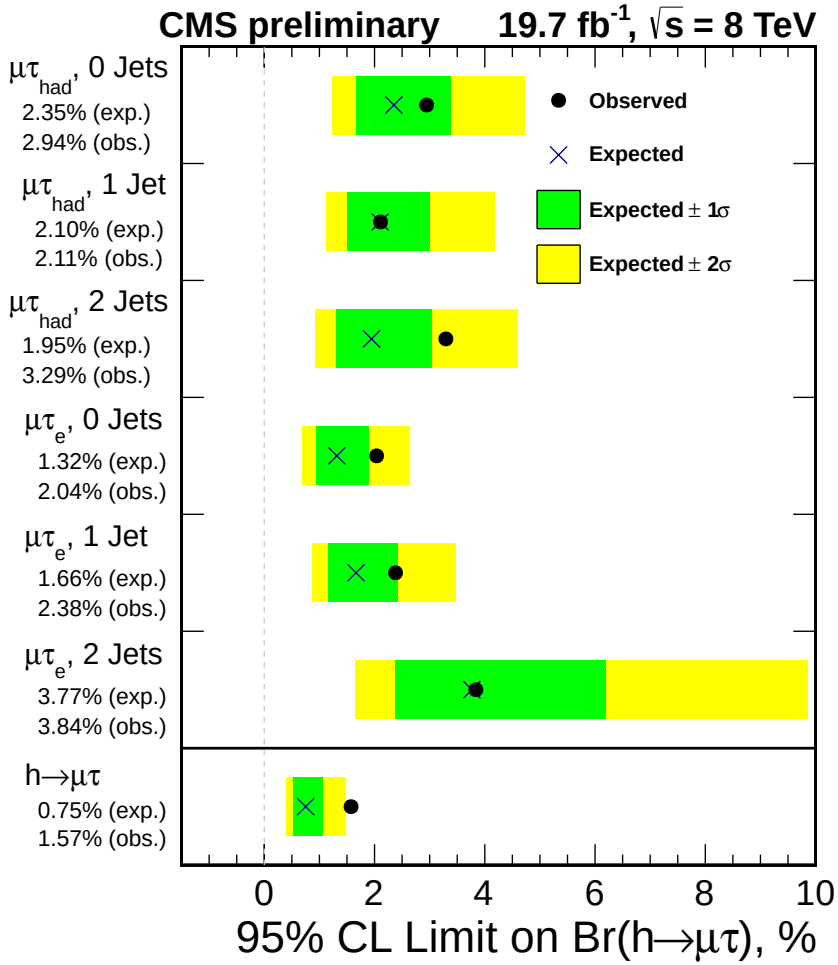






Observation compatible with SM expectation in all channels

Interpretation of the H $\to \mu\tau$-Search Results



Upper limit of $\mathcal{B}(\mathrm{H} \to \mu\tau)$: 1.57% obs. vs 0.75% exp.

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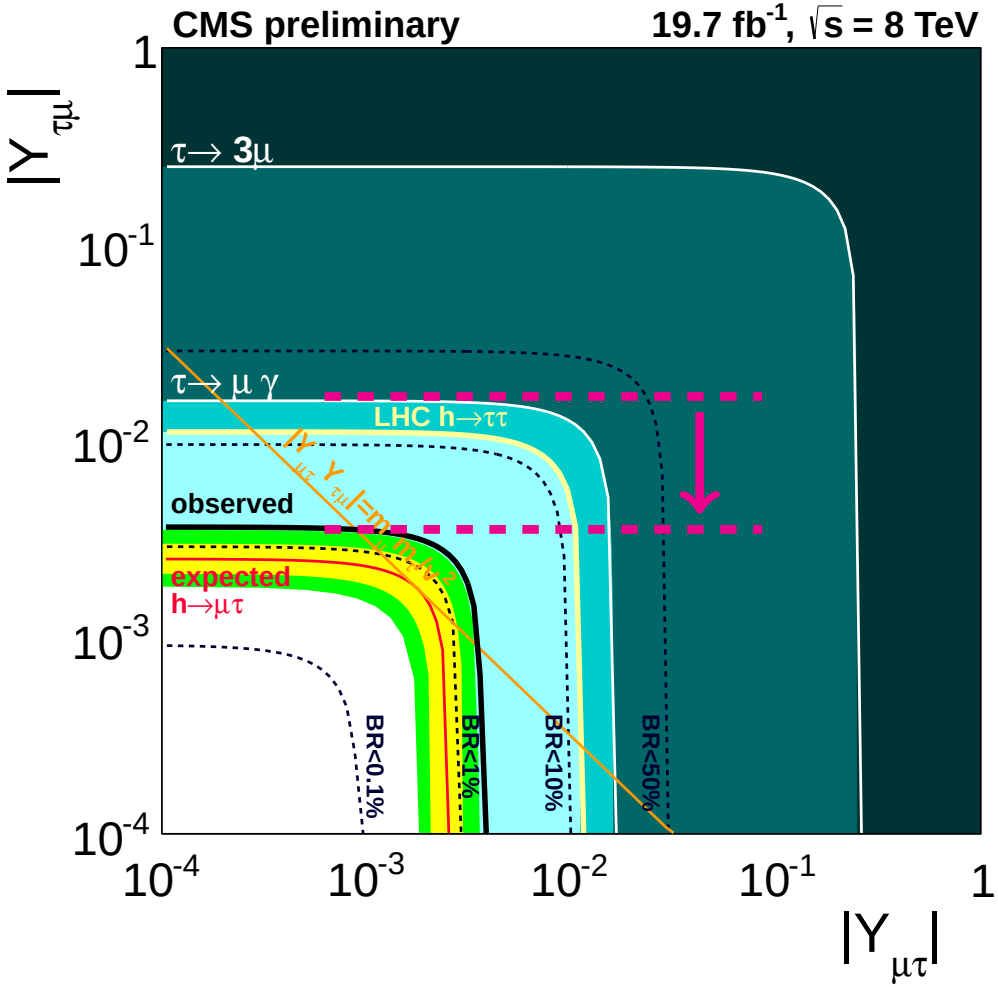


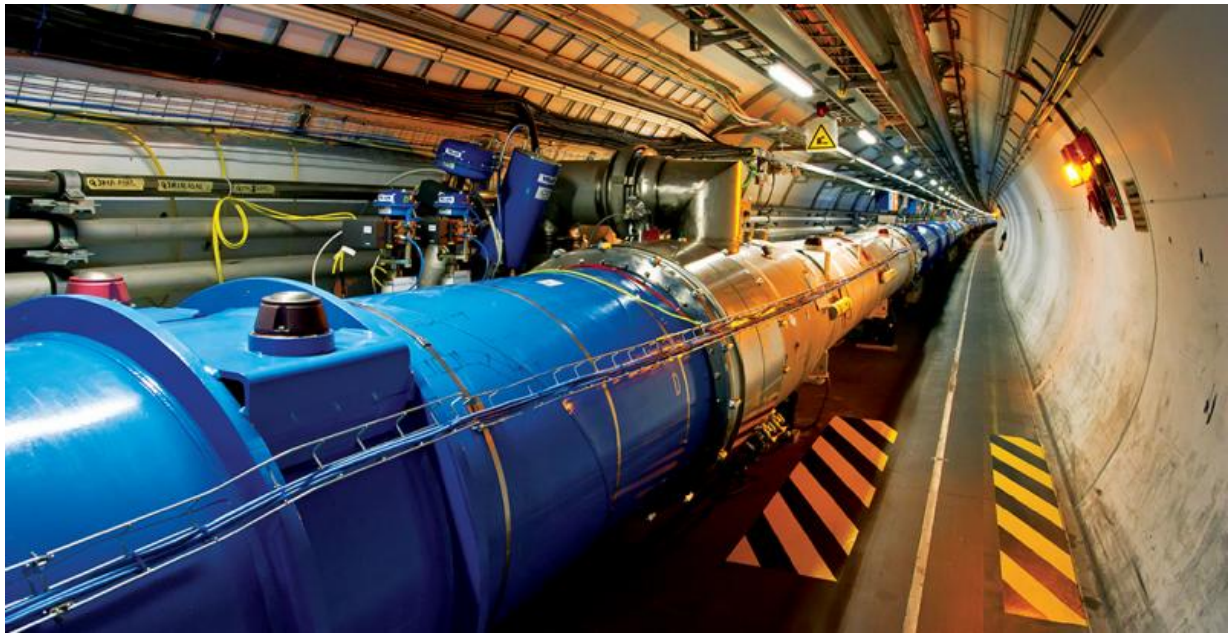
Upper limits of flavour-violating $\mu\tau$-Yukawa couplings
Best limits to-date, significant improvement on previous measurements

Summary

- After the Higgs boson discovery
  - Does it have the Standard-Model Higgs properties?
  - Are there any further Higgs bosons?
- Many new results targeting these questions, e. g.
  - Neutral heavy Higgs bosons $\Phi \to \tau\tau$
  - Charged light Higgs bosons $H^+ \to c\bar{s}$
  - Lepton-flavour violating Higgs decays $H \to \mu\tau$

Significantly improved constraints on 'BSM-Higgs parameter space'
e. g. closing lower m_A-region in MSSM

A new LHC-run at $\sqrt{s} = 13$ TeV Lies Ahead...



- Greatly enhanced sensitivity especially for high-mass signals
- CMS has developed the tools to explore this new territory

Many more exciting results expected

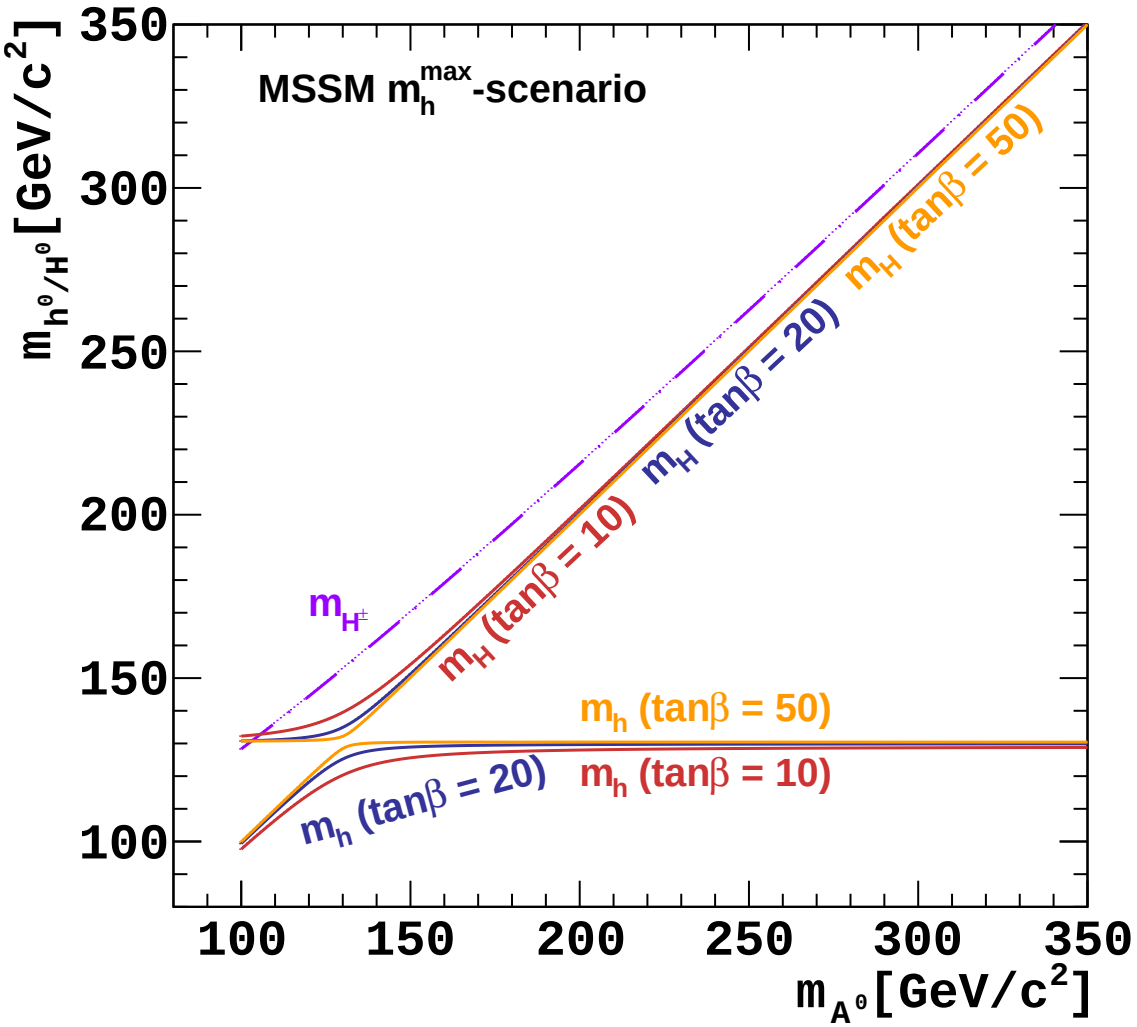
Additional Material

Examples of BSM-Higgs Searches at CMS

- MSSM
  - $\Phi \to \tau\tau$, submitted to JHEP (arXiv:1408.3316)
  - $\Phi \to$ bb, Phys. Lett. B 722 (2013) 207
  - $\Phi \to \mu\mu$, CMS PAS HIG-12-011
  - $H^+ \to c\bar{s}$, CMS PAS HIG-13-035
  - $H^+ \to \tau^+\nu_\tau$, CMS PAS HIG-12-052
- NMSSM
  - $h \to 2a_1 \to 4\mu$, CMS PAS HIG-13-010
  - $a_1 \to 2\mu$, Phys. Rev. Lett. 109, 121801
- Other
  - Lepton-flavour violating Higgs-decays, CMS PAS HIG-14-005
  - Invisible Higgs-decays, Euro. Phys. J. C 74 (2014) 2980
  - Resonant H(125)-pair production, CMS PAS HIG-14-013, HIG-13-032, HIG-13-025
  - High-mass $H \to \gamma\gamma$, CMS PAS HIG-14-006
  - Anomalous HVV couplings, CMS PAS HIG-14-012, HIG-14-014
  - Higgs properties, CMS PAS HIG-14-009

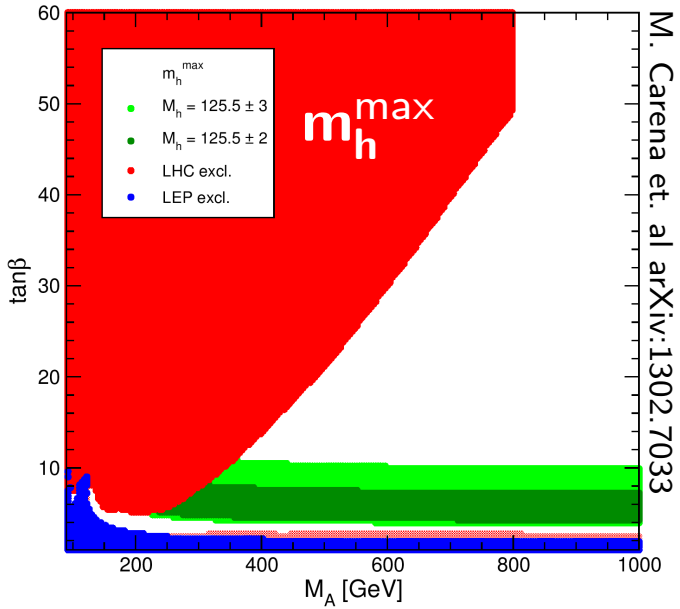
Neutral MSSM Higgs-Boson Masses in m_h^{max} Scenario

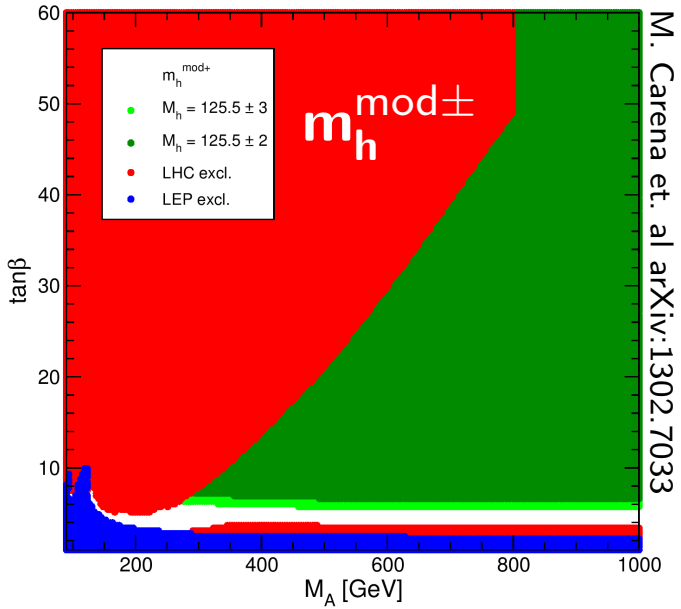
CMS-PAS-HIG-12-011



The 125 GeV-Higgs-Observation and the MSSM

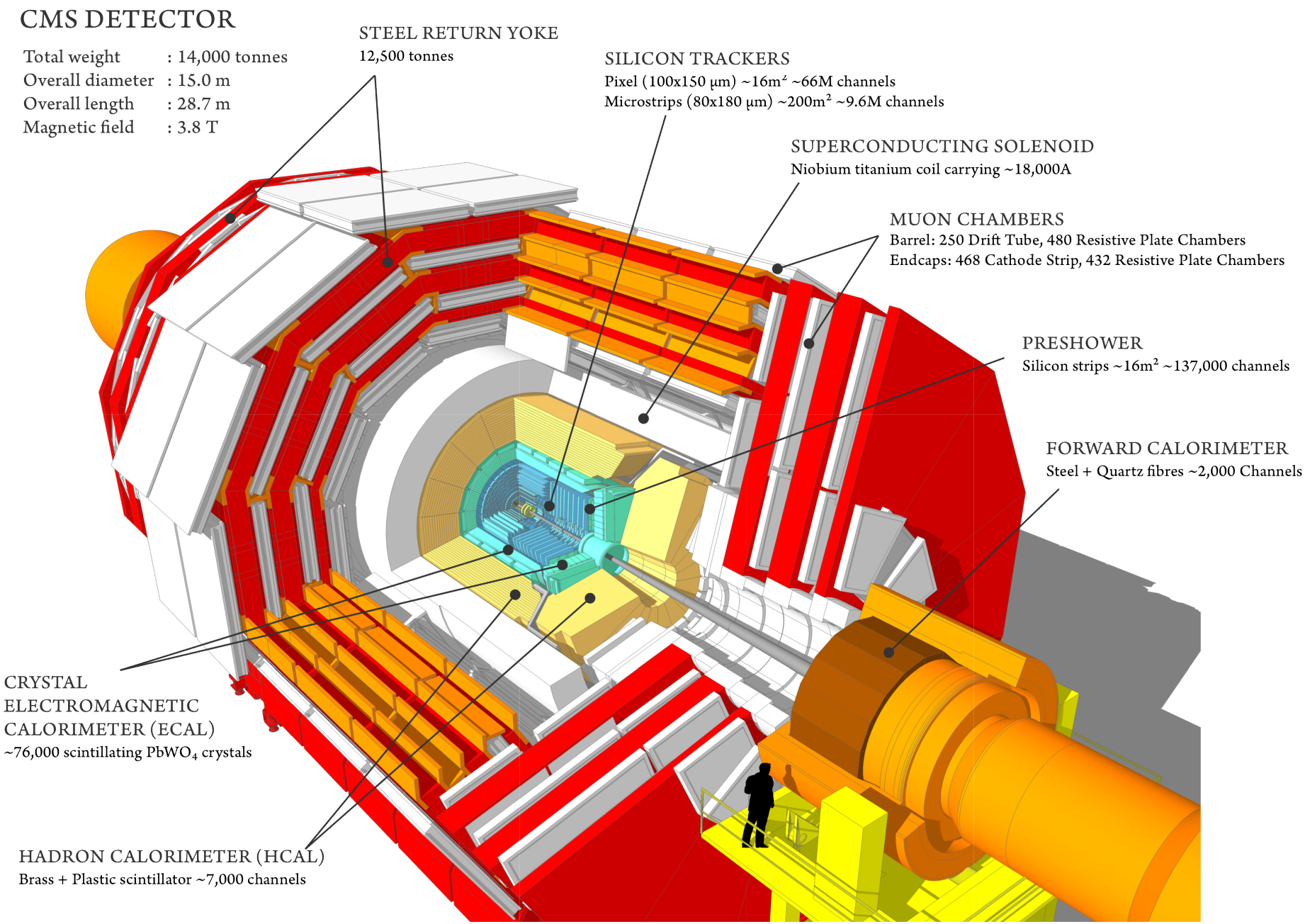
- Updated benchmark scenario $m_h^{\text{mod}\pm}$: Smaller stop-mass mixing parameter X_t to account for measured Higgs mass



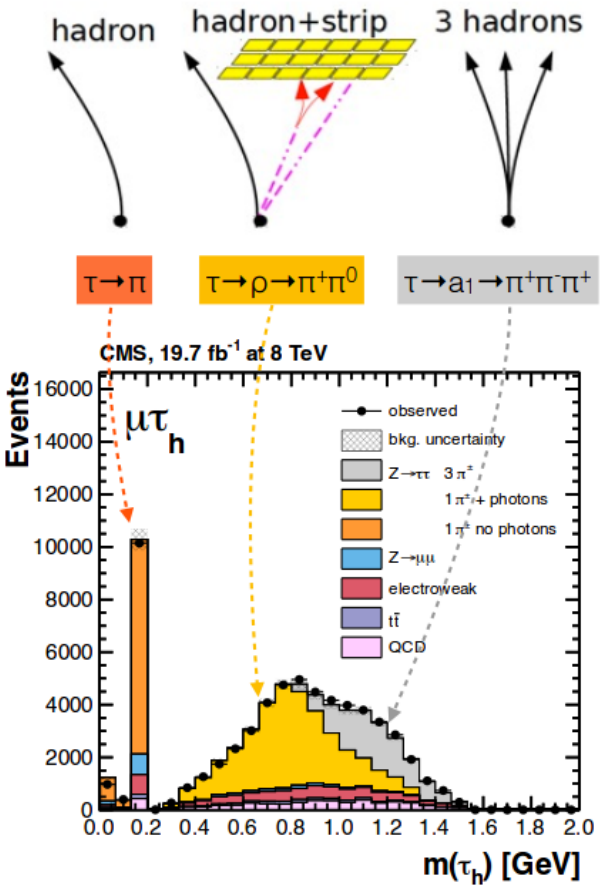


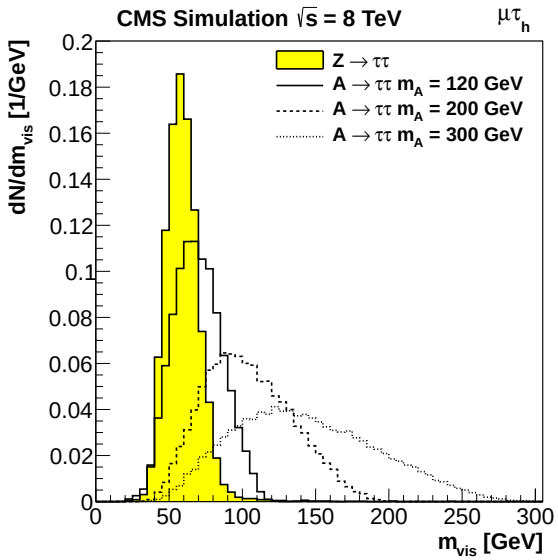
- 125 GeV-Higgs observation does not exclude a heavy MSSM Higgs-boson in wide range of tan β
- Decoupling limit ($m_A >> m_Z$): light CP-even Higgs becomes SM-like

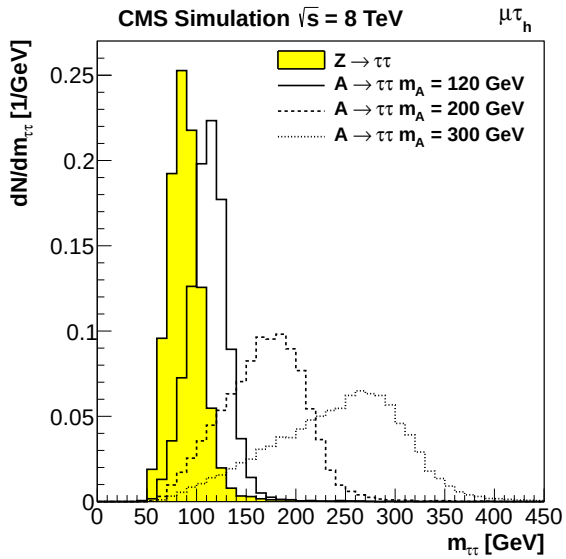
Both SM and MSSM fit current H(125) measurements equally well


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

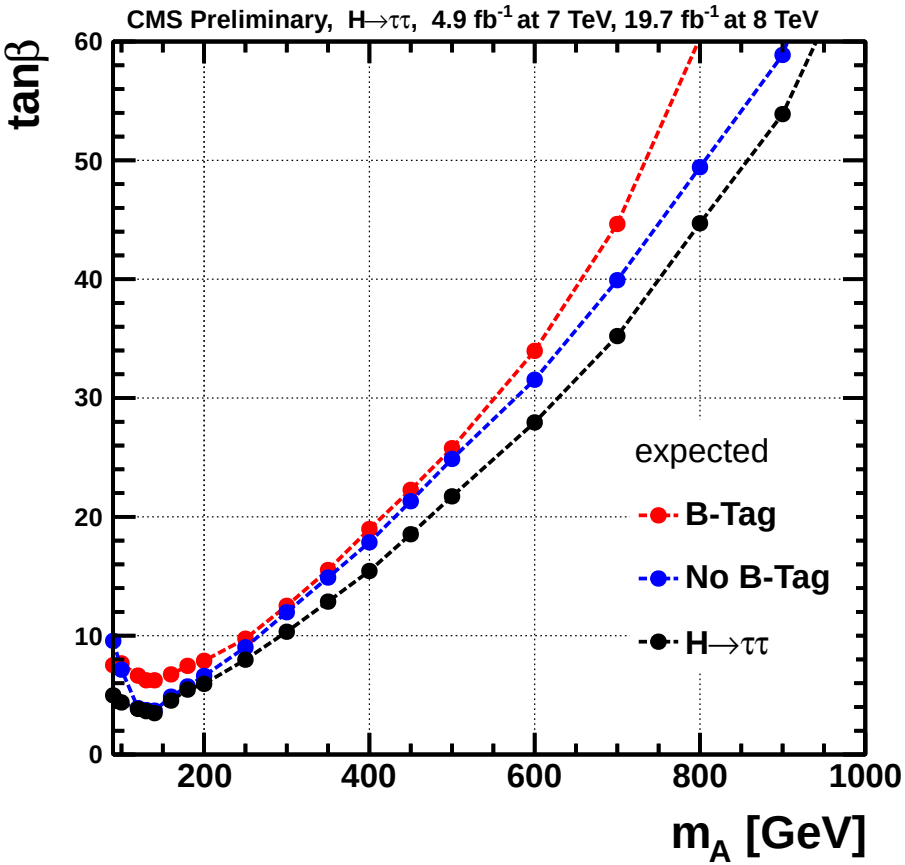
$m_{\tau\tau}$ Reconstruction

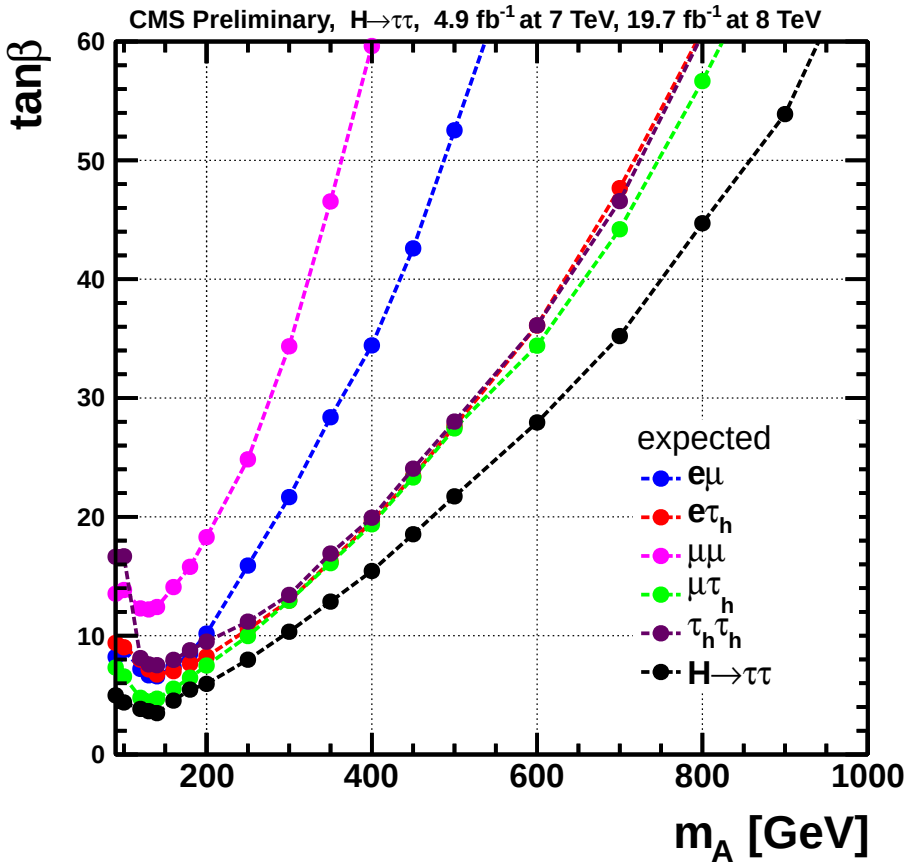




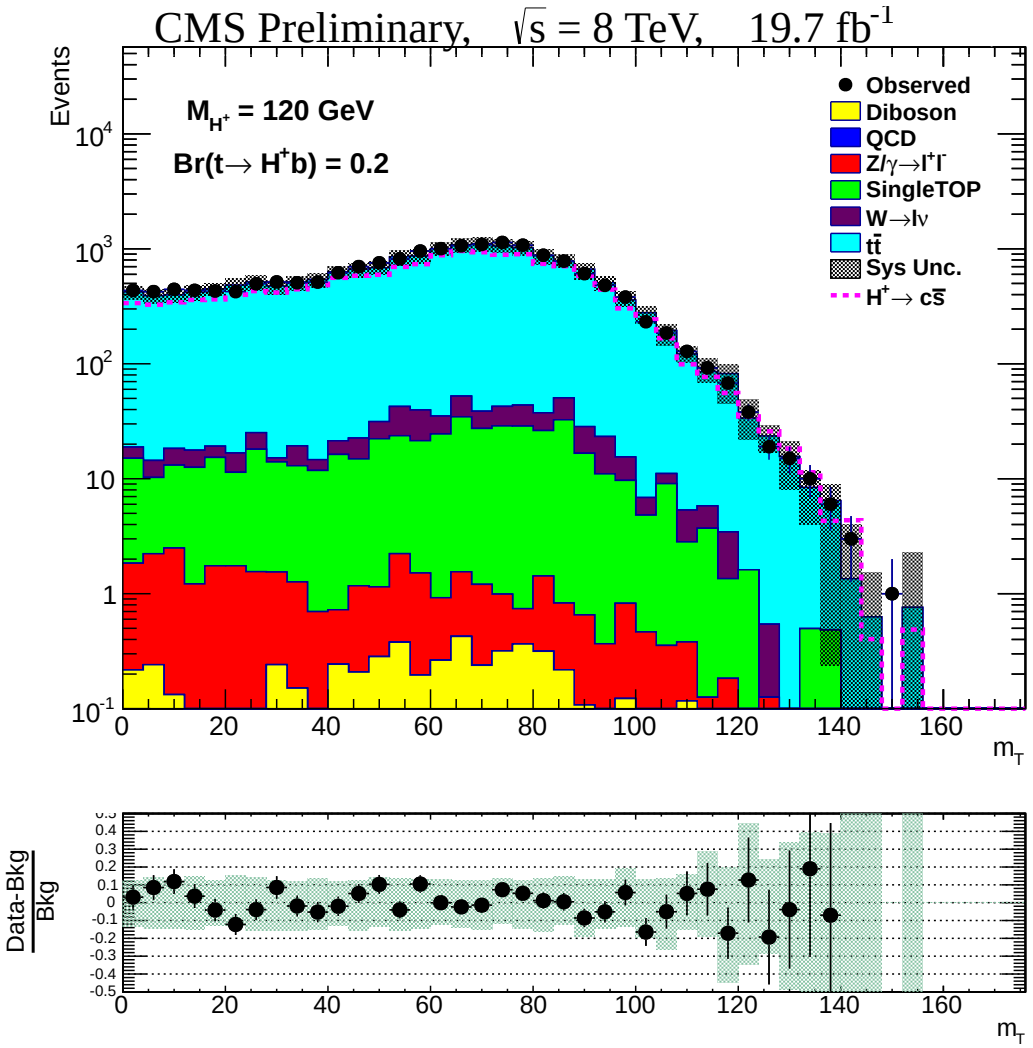


$\Phi \to \tau\tau$: Contributions

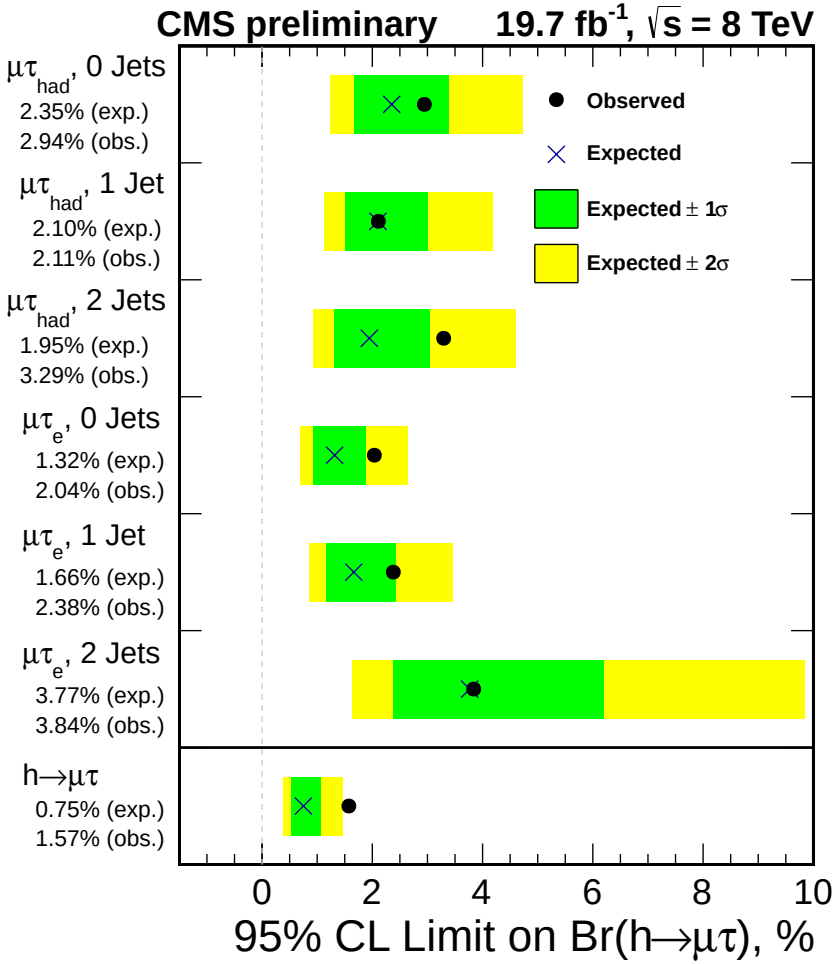


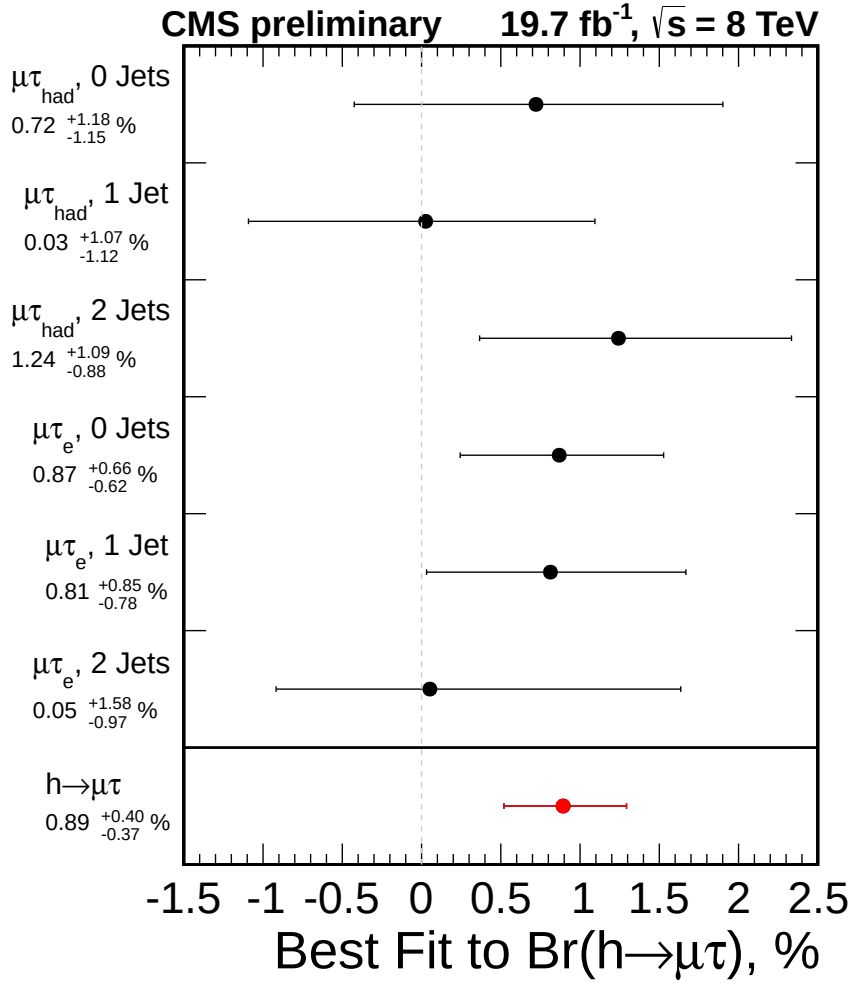


$H^+ \to c\bar{s}$: Control Distribution



H → μτ Results





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