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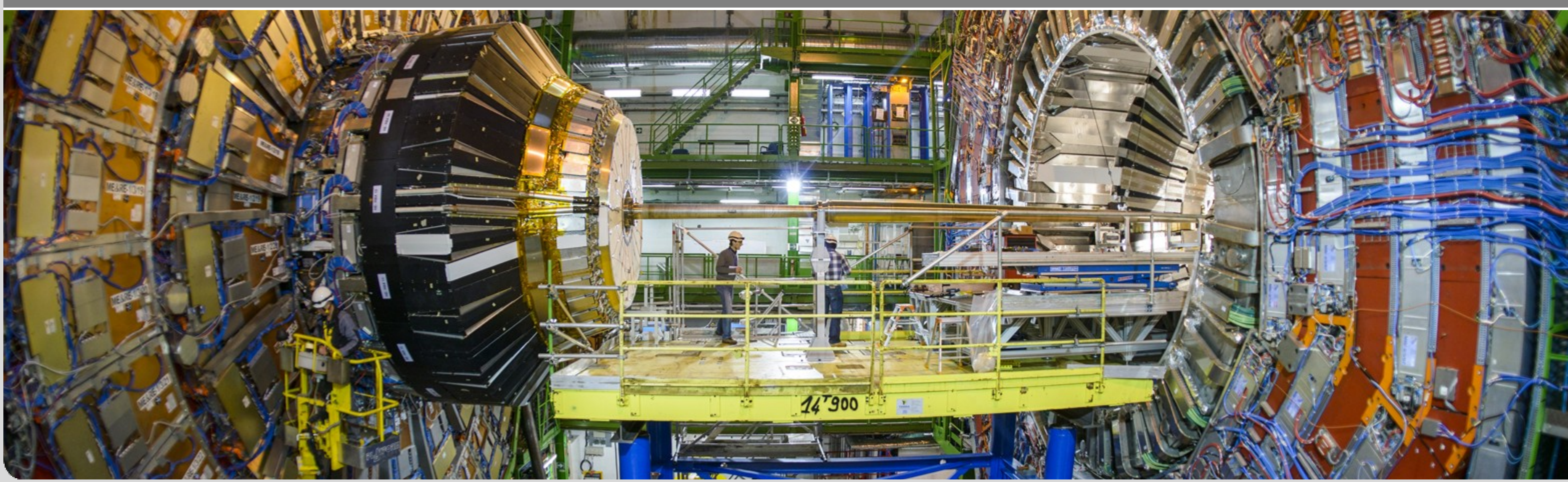
Searches for Higgs Bosons Beyond the Standard Model with the CMS Experiment at the LHC

Roger Wolf

18./19. November 2014

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



Road map...

- Short recap:
  - Higgs bosons – what it is about?
  - What do we know about the Higgs boson and how much space is still left for new physics in the Higgs sector?
- Higgs decays to invisible ($H \to \mathrm{inv.}$) and related statement on DM interactions.
- Search for additional supersymmetric Higgs bosons:
  - In the MSSM there are five Higgs bosons and we make strong statements on all of them!
  - There is one detour in this, on an analysis of LFV in the Higgs sector.

Disclaimer:
This is a personal choice and by no means complete.

About Higgs: a short recap...

- Need Higgs mechanism to explain how particles can have mass $\neq 0$ and at the same time $SU(2) \times U(1)$ symmetry can be source of electroweak interactions.

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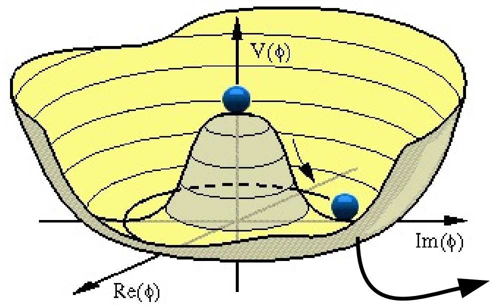
$$\mathcal{L}^{\mathrm{Higgs}} = \partial_\mu \phi^+ \partial^\mu \phi - V(\phi)$$

$$V(\phi) = -\mu^2 \phi^+ \phi + \lambda \left(\phi^+ \phi\right)^2$$



Non-zero vacuum expectation value v

- Symmetry inherent to a system but not to its energy ground state (→ quantum vacuum).
- In a quantum field theory (QFT) this can create new physical particles (→ Higgs boson(s)).

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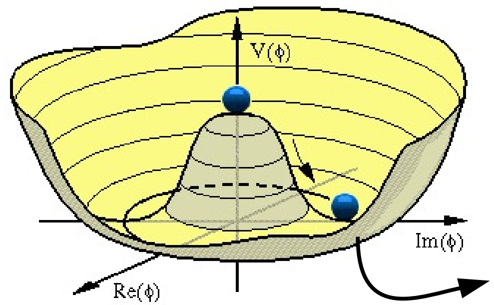

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- A Higgs boson has very a peculiar coupling structure, needed to fulfill the symmetry of the system (example for fermions):

$$\phi = \begin{pmatrix} 0 \\ \mathrm{v} + \frac{H}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L}^{\mathrm{Yukawa}} = -y_f \left(\mathrm{v} + \frac{H}{\sqrt{2}}\right) f\bar{f} = -\left(m_f + \frac{m_f}{\sqrt{2}\mathrm{v}} H\right) f\bar{f}$$

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$H \to \gamma\gamma$

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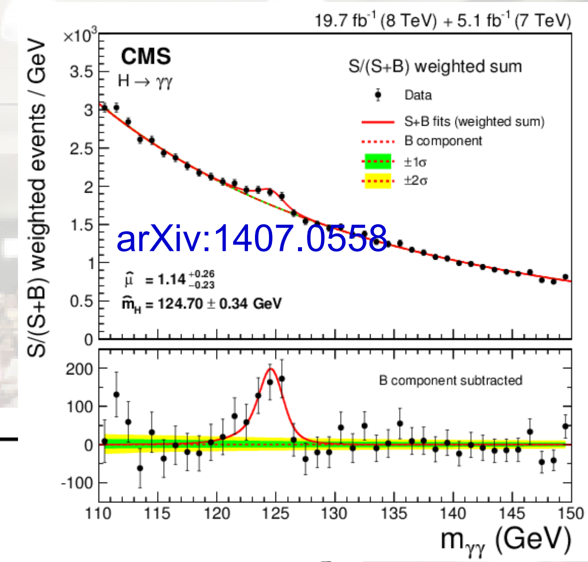

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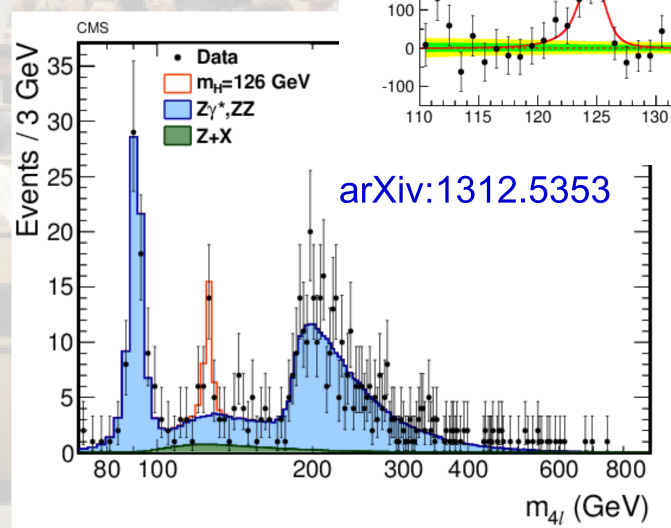
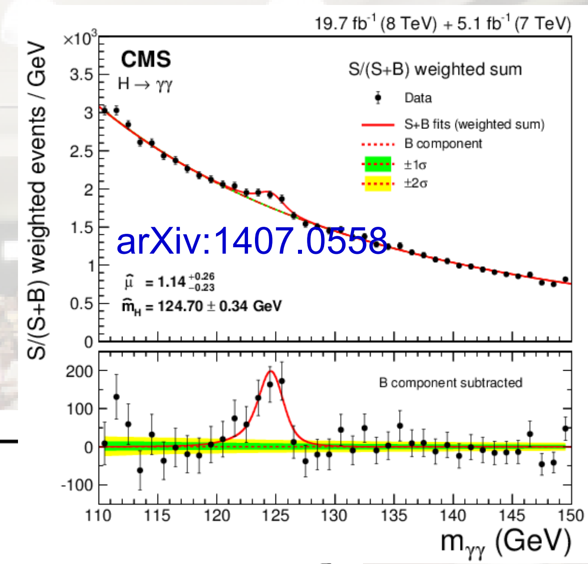


Higgs: a known suspect

- We know it exists (arXiv:1207.7235)!
- We know its a boson.
- We know its mass (CMS-PAS-HIG-14-009):

$$m_H = 125.03 \pm^{0.26}_{0.27}\ (\mathrm{stat.}) \pm^{0.13}_{0.15}\ (\mathrm{syst.})\mathrm{GeV}$$

$H \to \gamma\gamma$ 4th of July 2012



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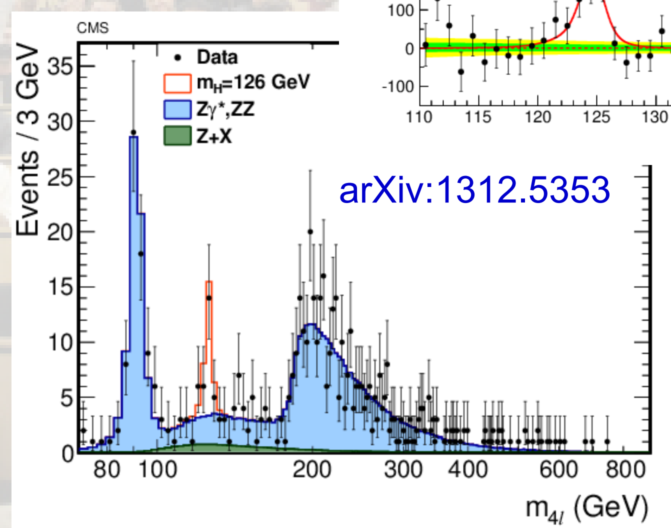

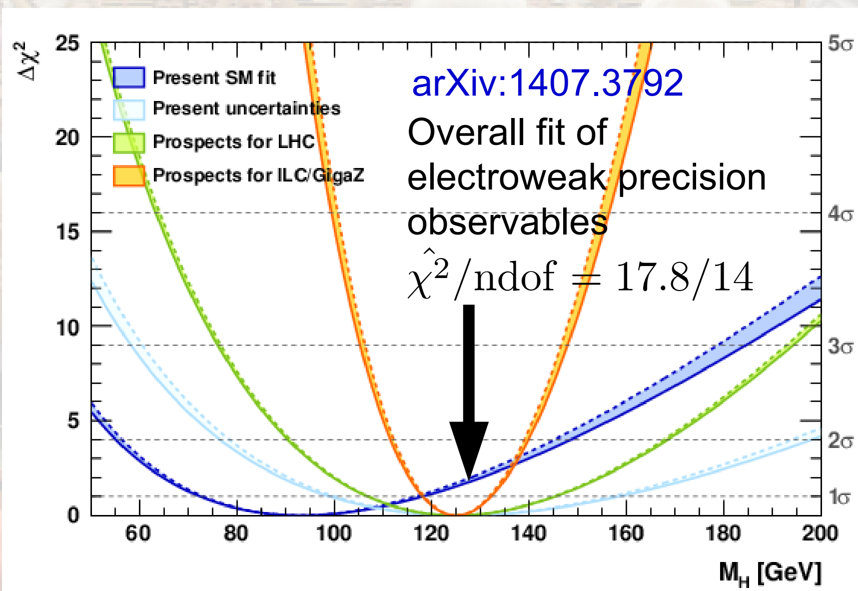

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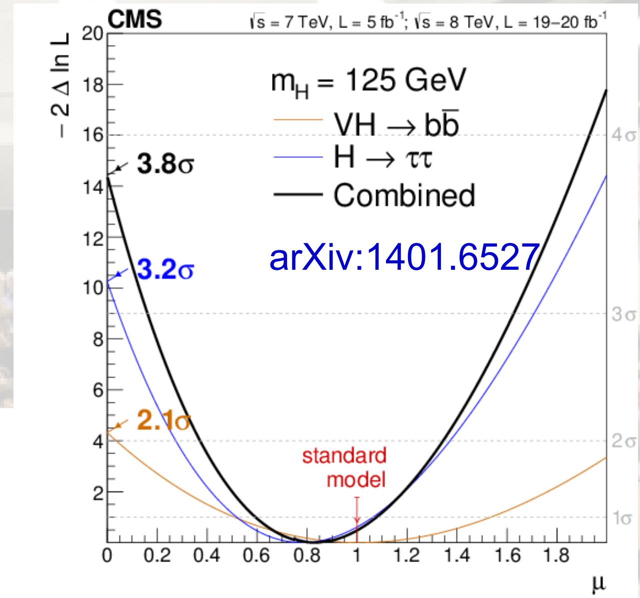

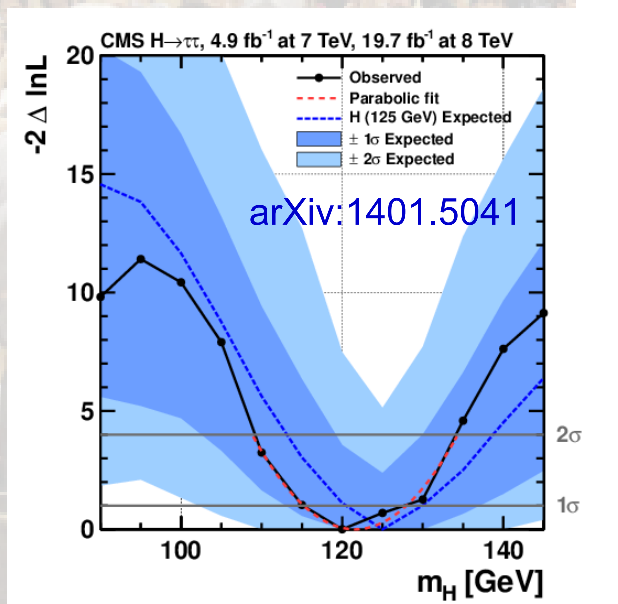

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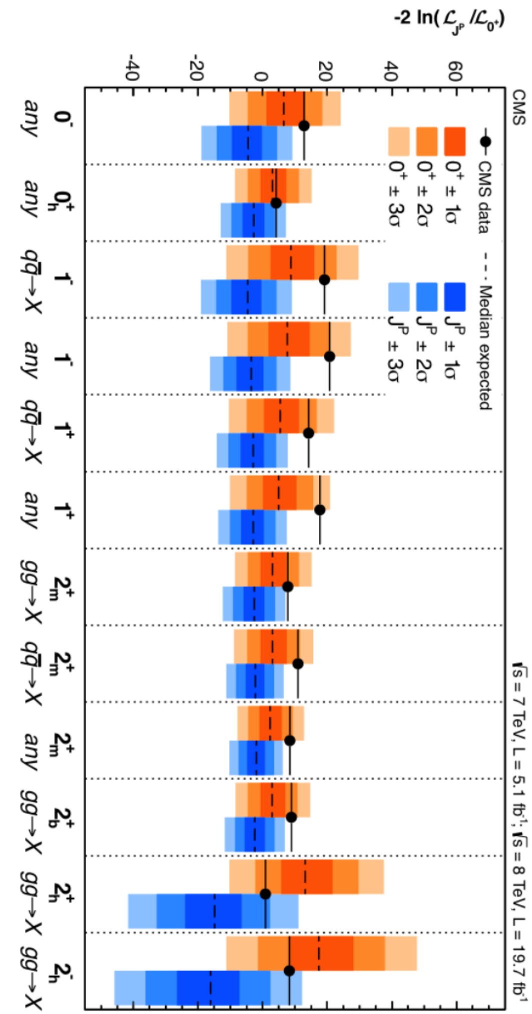
- We have reasons to believe that it is a spin 0 CP even object (arXiv:1312.5353).



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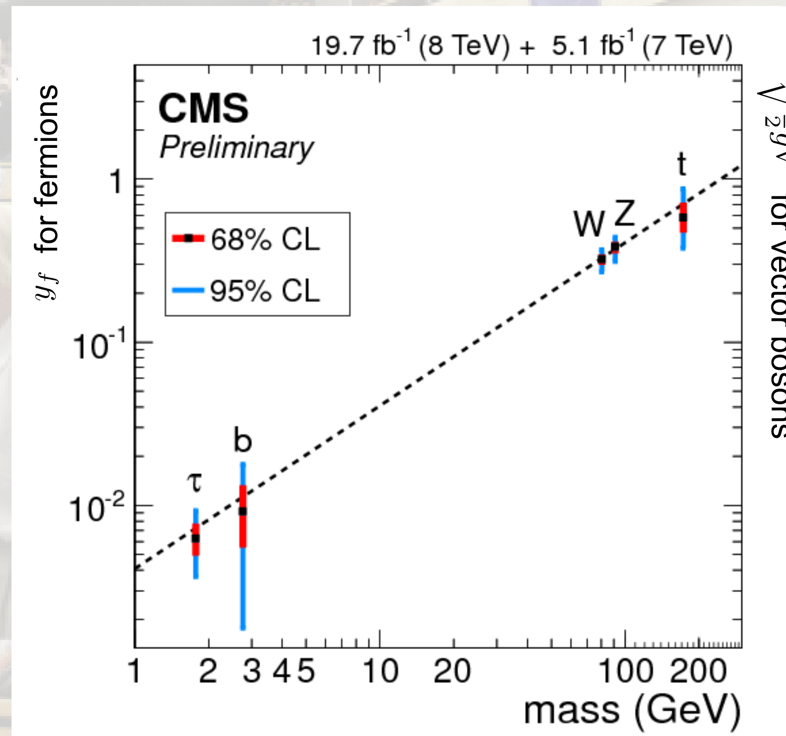

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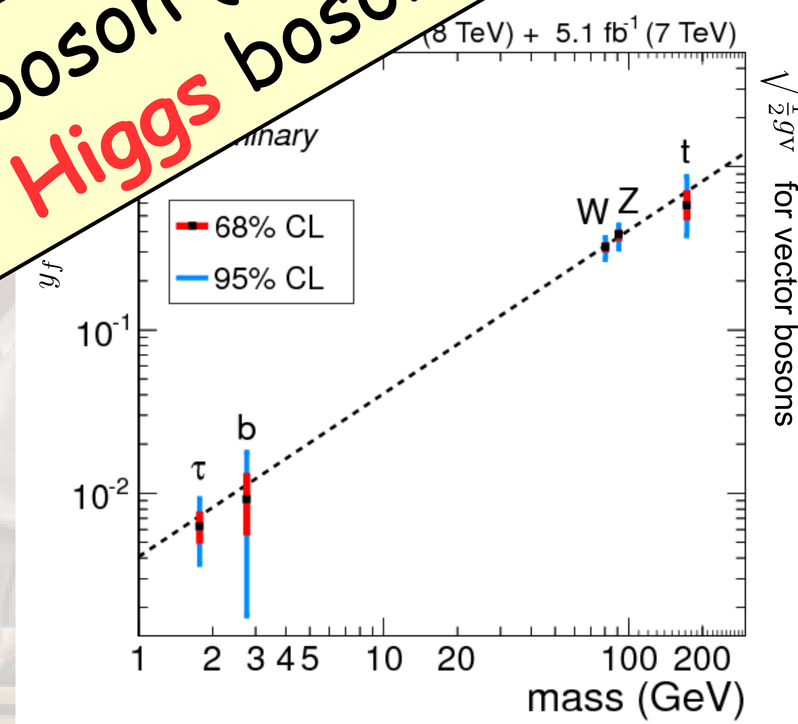
- We know…

Is this THE Higgs boson (of the SM) or is it just A Higgs boson?



Why it is not THE Higgs boson (of the SM) [1]

- Gravity is not included in the SM.
- The SM suffers from the hierarchy problem.
- Dark matter is not included in the SM.
- Neutrino masses are not included in the SM.
- There are known deviations in $a_\mu \equiv \frac{g_\mu - 2}{2}$ from the SM expectation (3.6σ unresolved).

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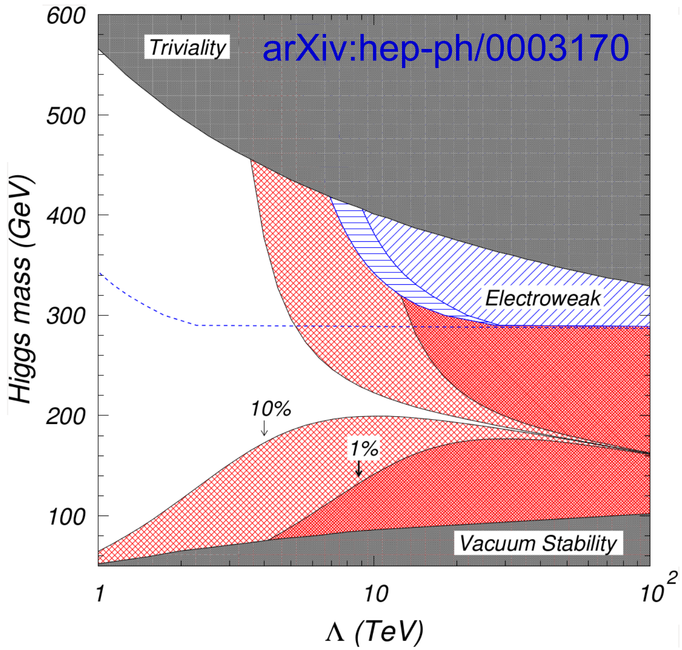

- There must be physics beyond the SM!
- At what scale does it set in?
- (How) Does it influence the Higgs sector?

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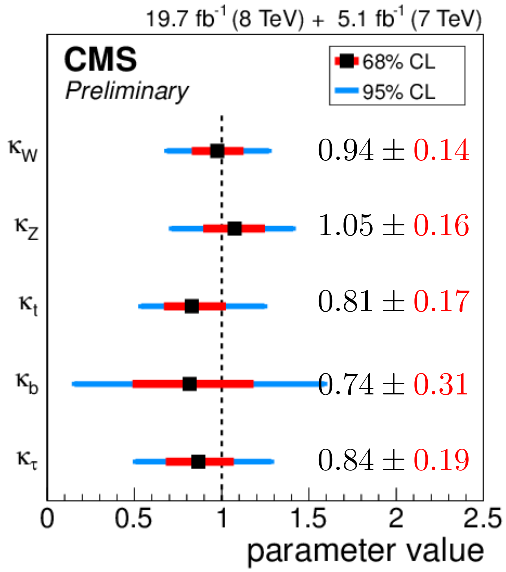
Space left for new physics in the Higgs sector

- Couplings are determined within $\pm 15\%$ to $\pm 20\%$ accuracy.



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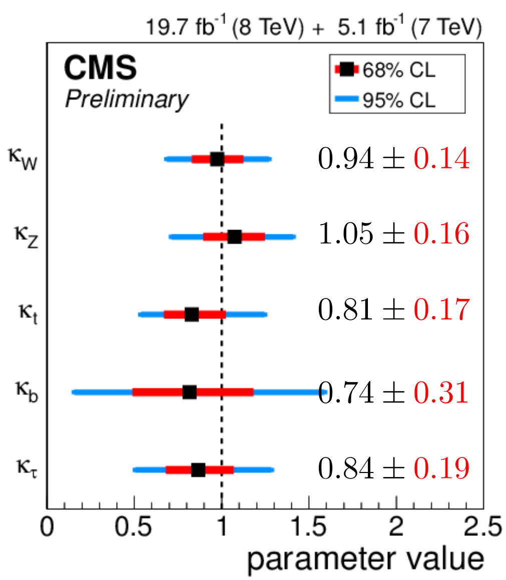

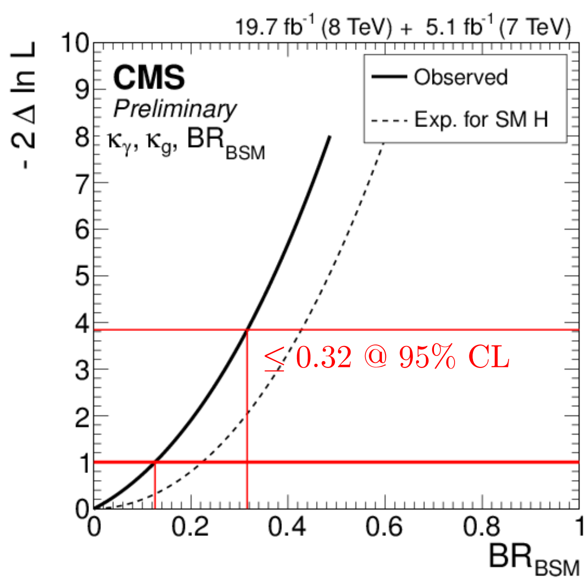

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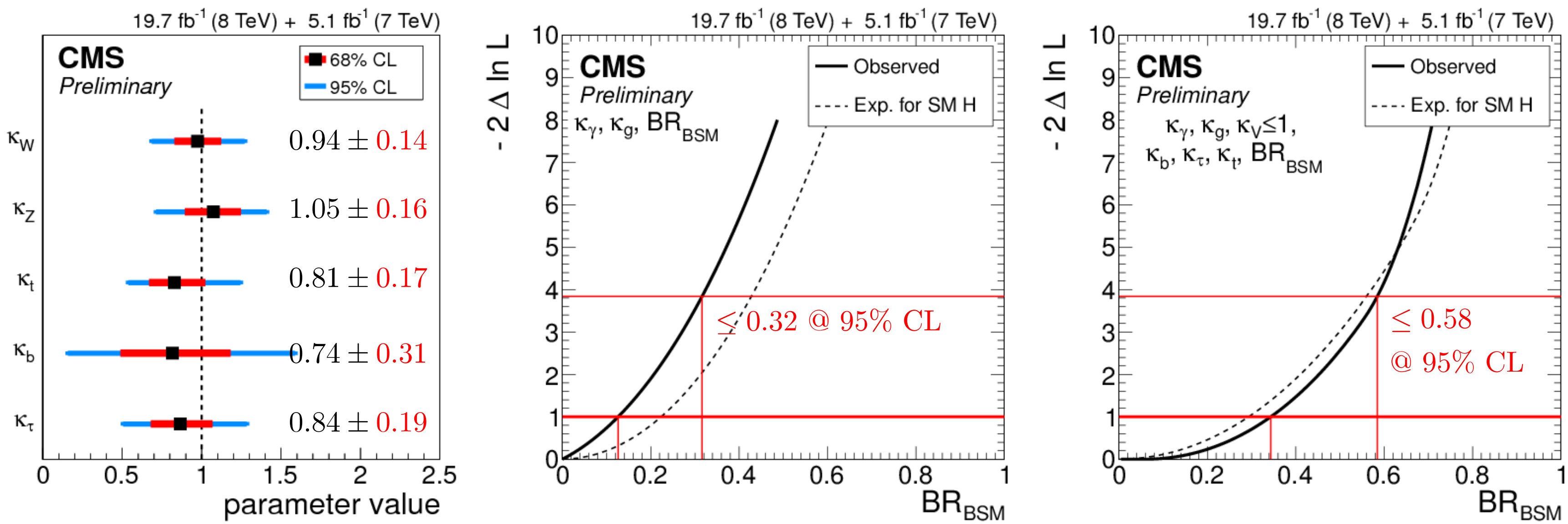
- Adding maximal freedom to the fit leaves room for $BR_{\mathrm{BSM}} \leq 0.58$ @ 95% CL.



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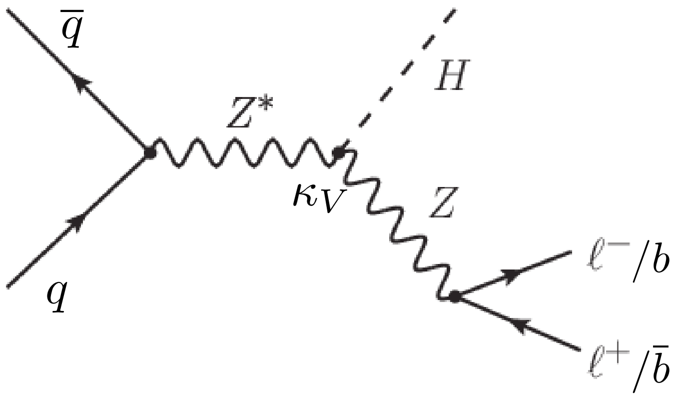
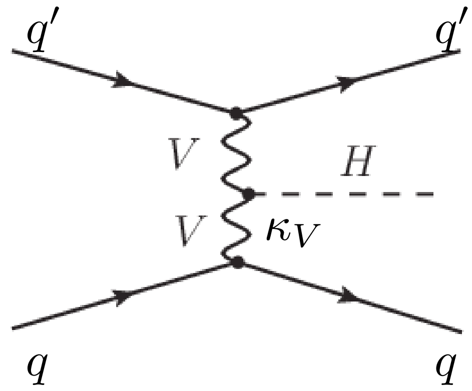
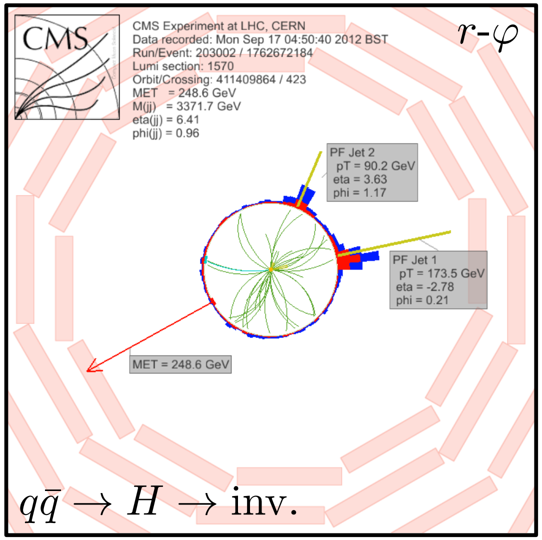
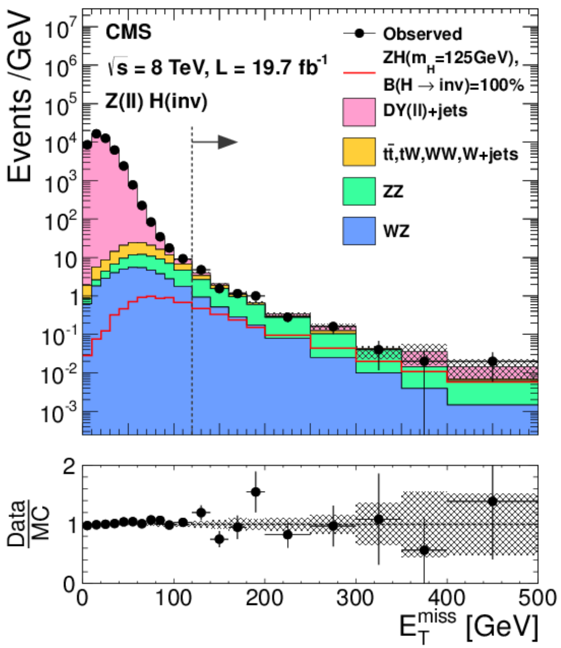
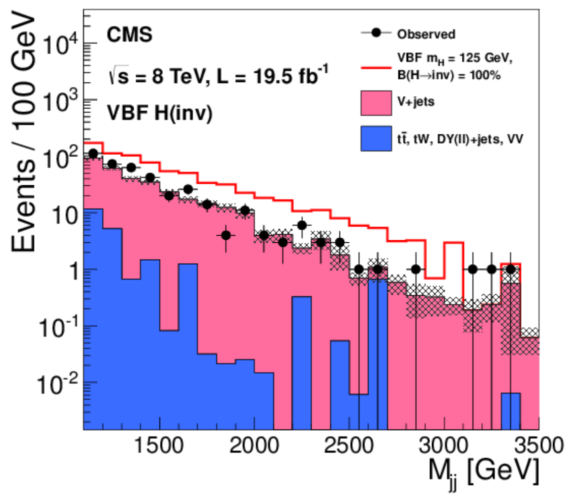
Direct searches for $H \to \text{invisible}$ (arXiv:1404.1344)

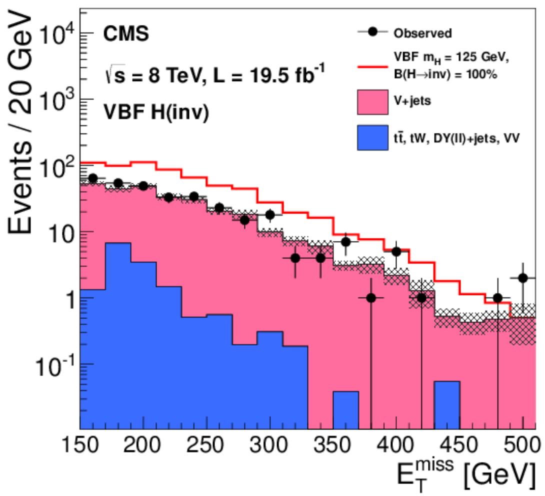












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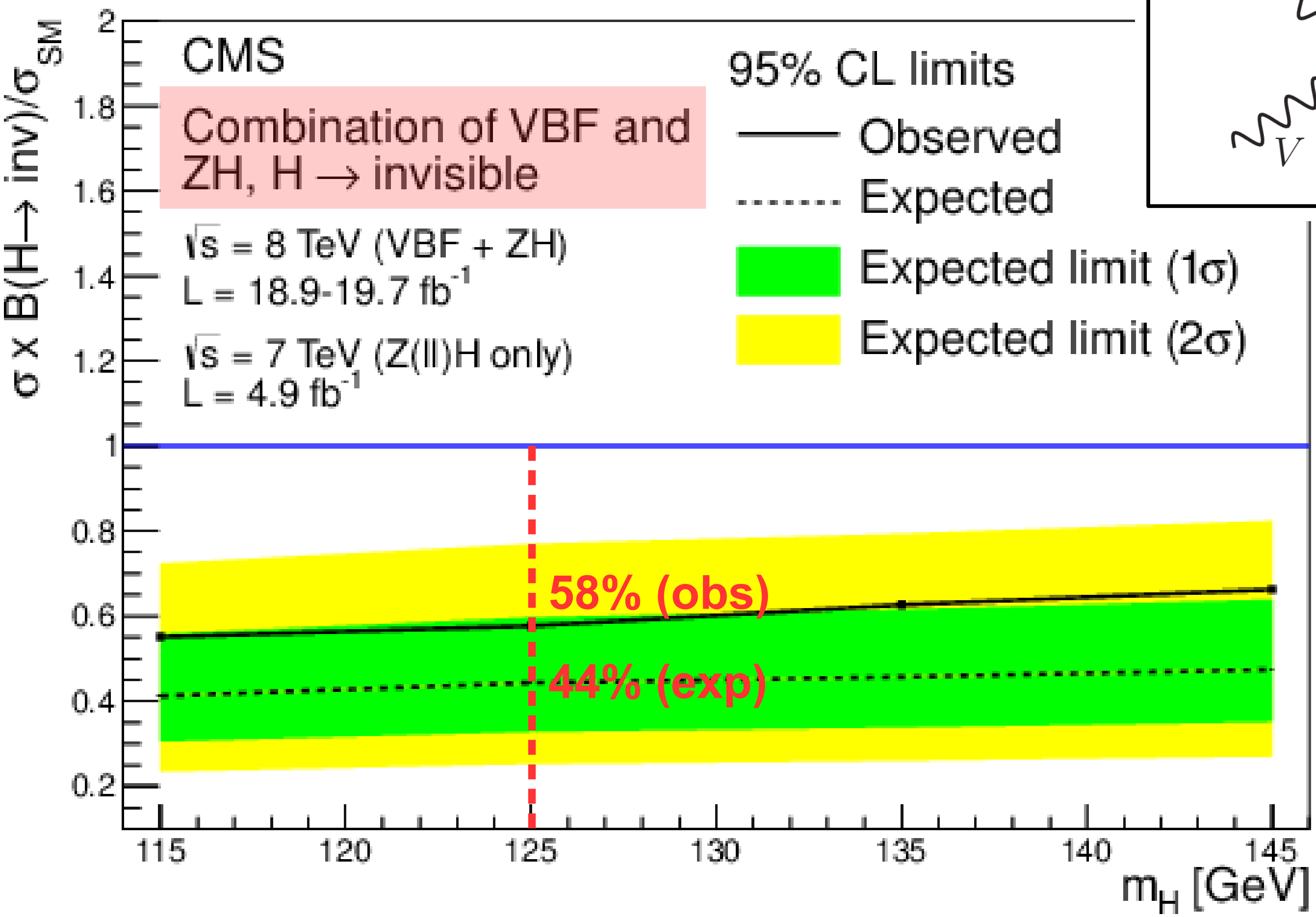

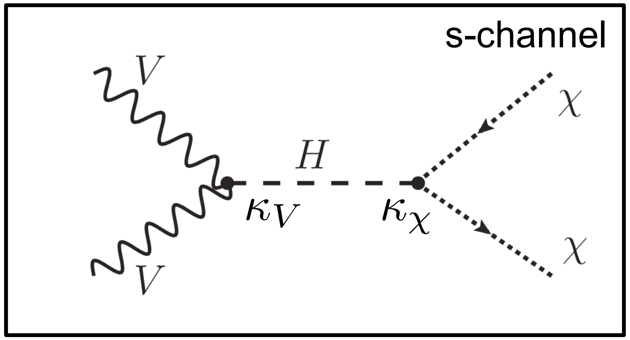

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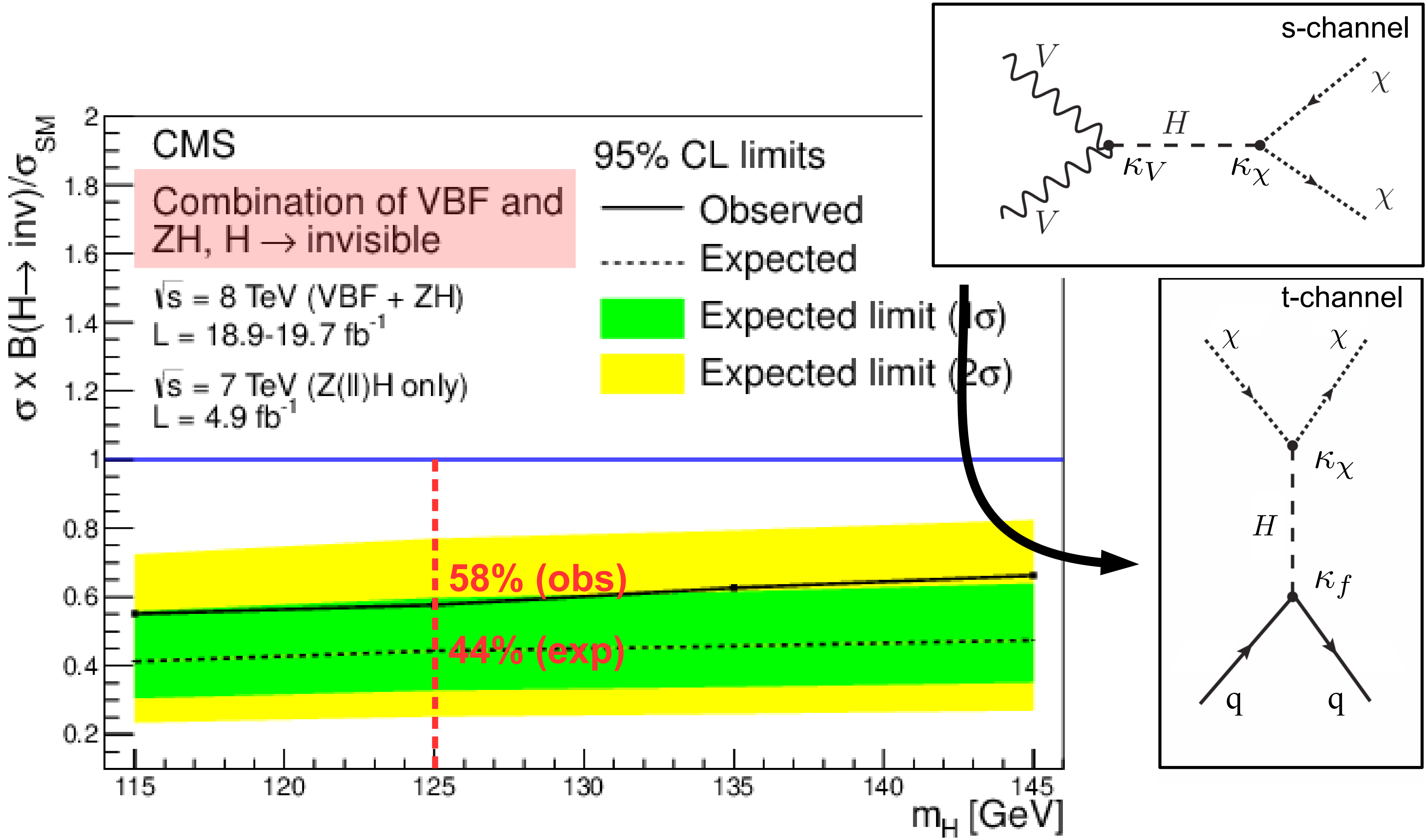

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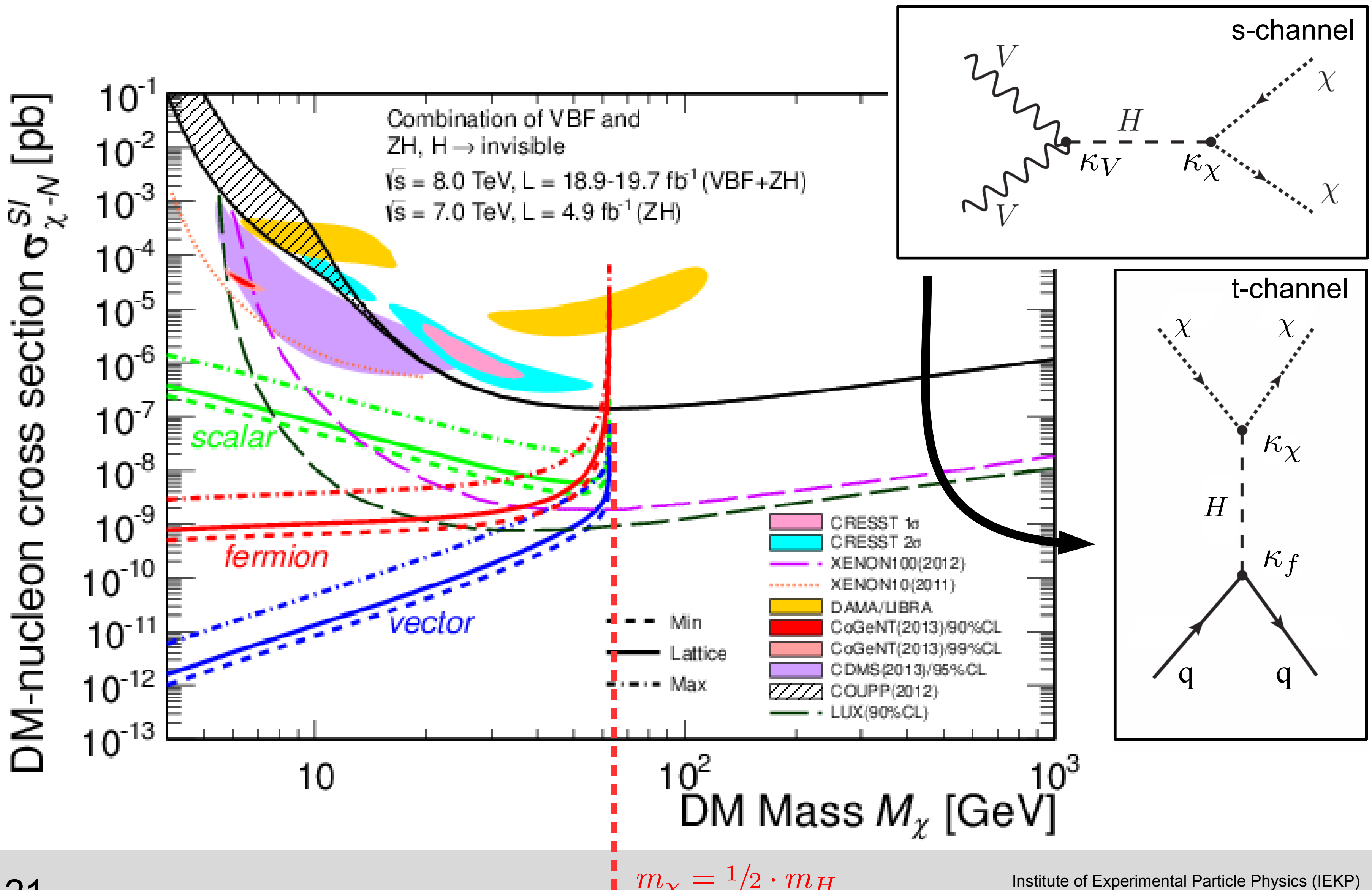
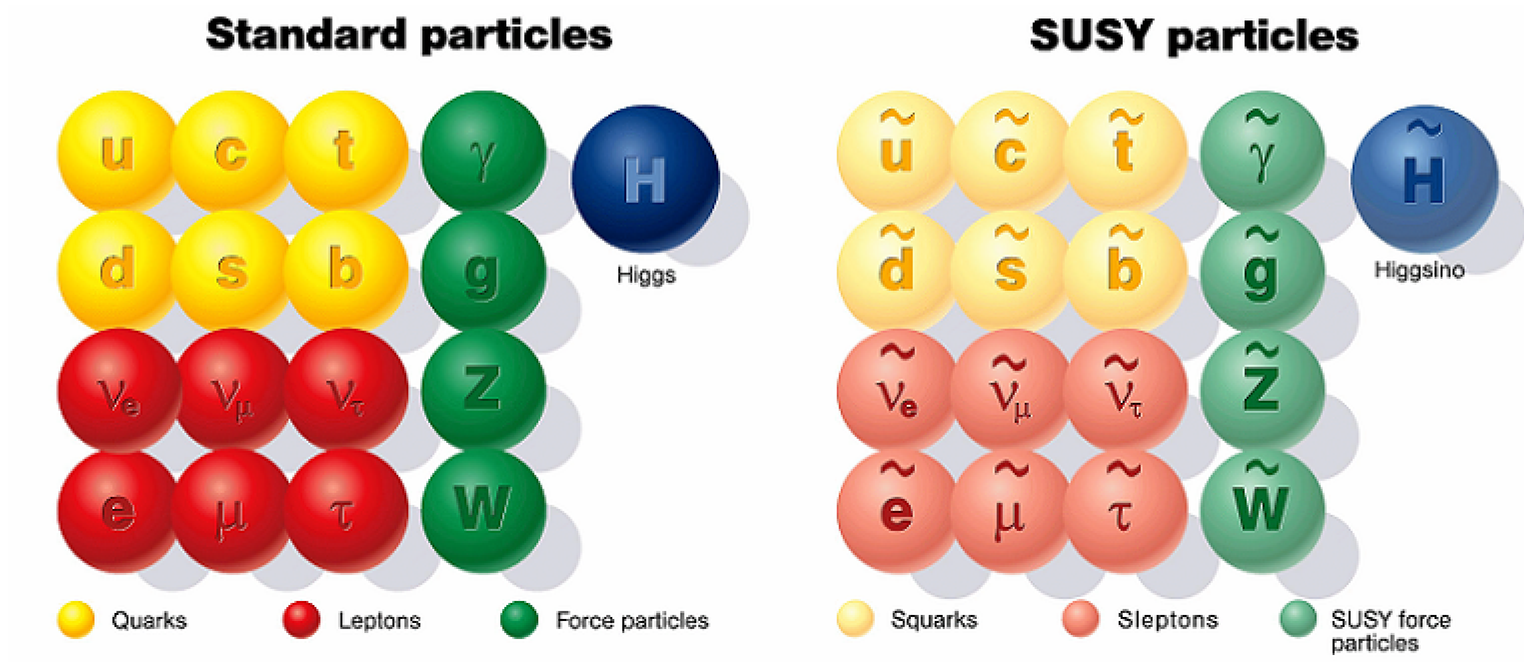


SUSY particles as DM candidates

- Extension of SM by a last remaining, non-trivial, symmetry operation (boson $\leftrightarrow$ fermion), SUSY, can cure many shortcomings of SM:



- E.g. lightest SUSY particle (LSP) perfect candidate for χ .
- **Problem:** SUSY itself is broken!

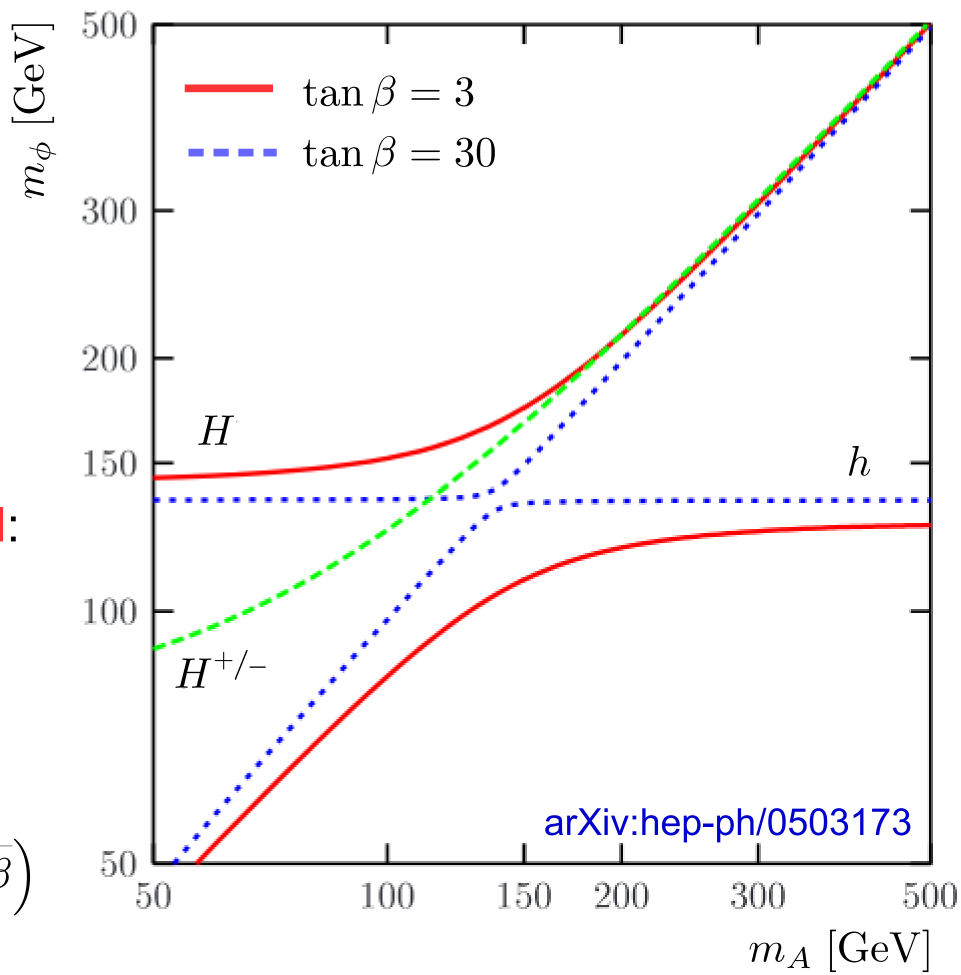
Higgs sector in the MSSM

- Five neutral Higgs bosons predicted:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}\,, \quad Y_{H_1} = -1\,, \quad \mathrm{v}_1 : \ \mathrm{VEV}_1$$

$$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}\,, \quad Y_{H_2} = +1\,, \quad \mathrm{v}_2 : \ \mathrm{VEV}_2$$

$$N_{\mathrm{ndof}} = 8 - \underbrace{3}_{W,\ Z} = \underbrace{5}_{H^{+/-},\ H,\ h,\ A}$$



- MSSM mass requirements at tree level:

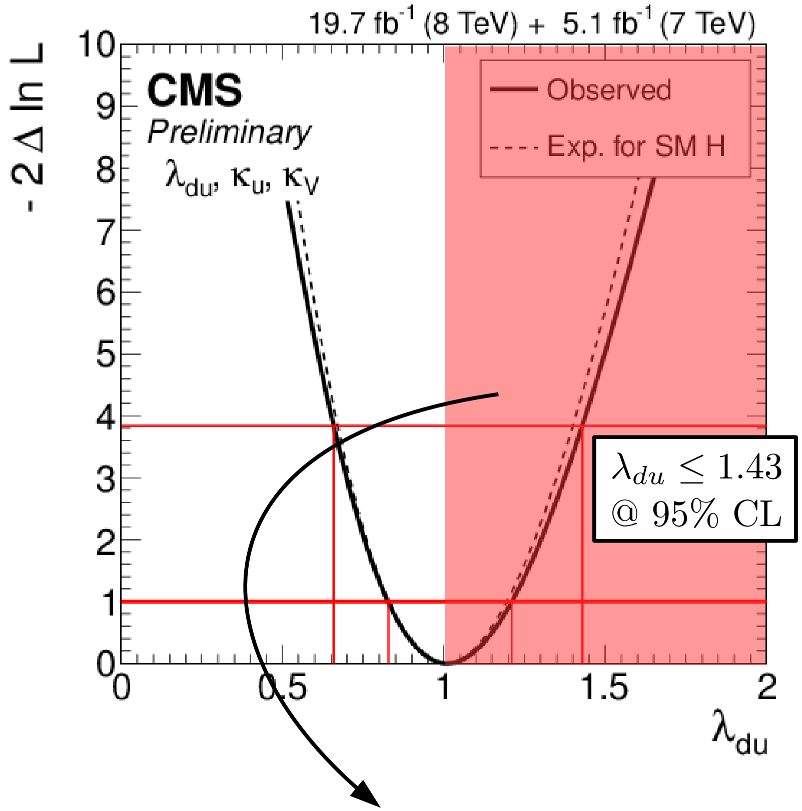
two free parameters: m_A , $\tan\beta = \mathrm{v}_1/\mathrm{v}_2$

$$m^2_{H+/-} = m^2_A + m^2_W$$

$$m^2_{H,\,h} = \frac{1}{2}\left(m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 \pm 4^2_A m^2_Z \cos^2 2\beta}\right)$$

Enhancement of down-type couplings

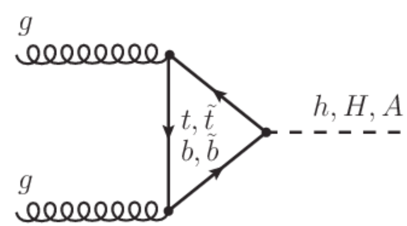
- In MSSM coupling to down-type fermions enhanced for $\tan\beta \gg 1$.



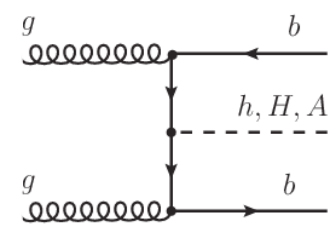
expect MSSM here!

- Interesting decay channels:
  - $H \to \tau\tau$ $\quad (\hat{\kappa}_\tau = 0.84 \pm^{0.19}_{0.18})$
  - $H \to bb$ $\quad (\hat{\kappa}_b = 0.74 \pm^{0.33}_{0.29})$

- Interesting production modes:



$gg \to H$ (“$gg\phi$”)



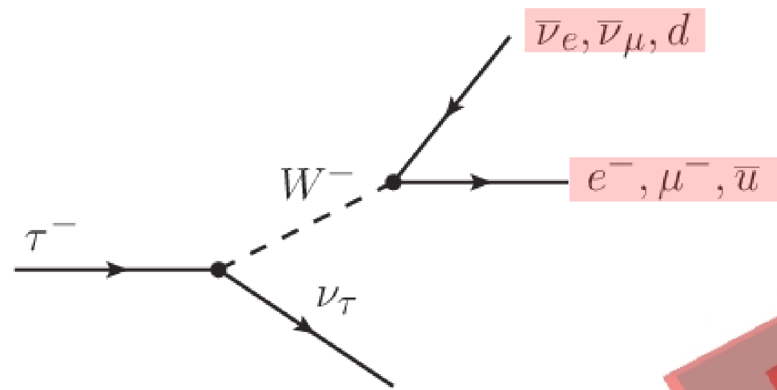
$gg \to Hb\bar{b}$ (“$bb\phi$”)

CMS-PAS-HIG-14-009

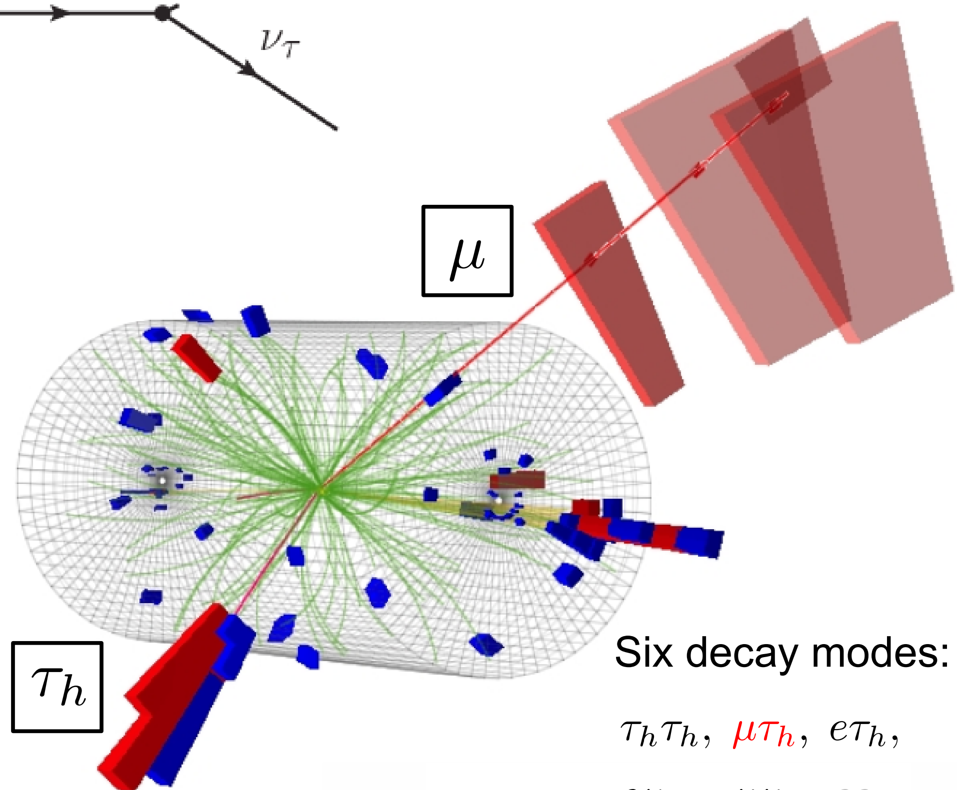
Search for $A/H/h \to \tau\tau$ (arXiv:1408.3316)

Decay Mode	BR
$\tau \to e\nu_e\nu_\tau$	17.83%
$\tau \to \mu\nu_\mu\nu_\tau$	17.41%
$\tau \to$1-prong ν_τ	37.10%
$\tau \to$3-prong ν_τ	15.20%

$> 50\%$ of all decay modes.



- Search for 2 isolated high p_T leptons (e , μ , τ_h).
- Reduce obvious backgrounds (use on $\not{E}_T$) & reconstruct $m_{\tau\tau}$.
- Exploit characteristics of production mode to increase sensitivity.

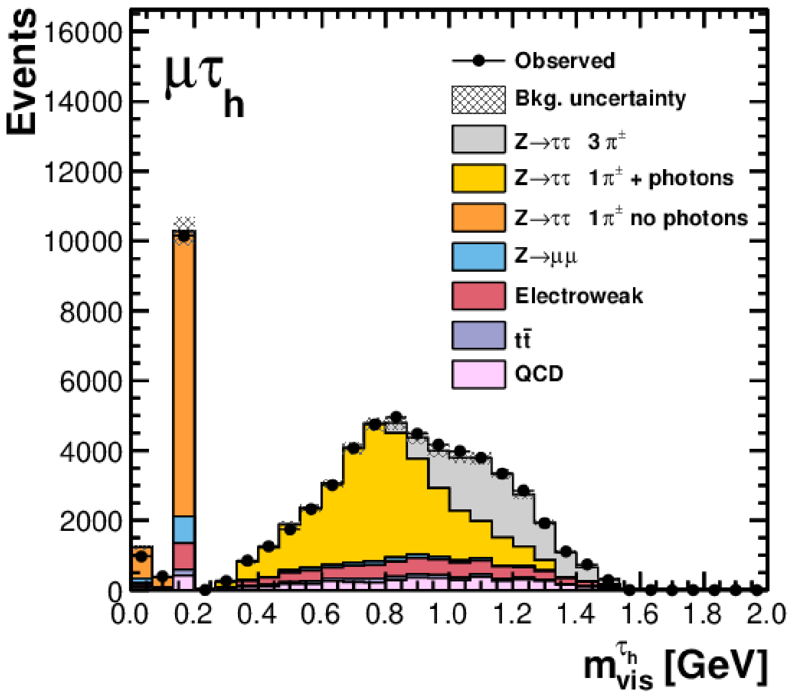


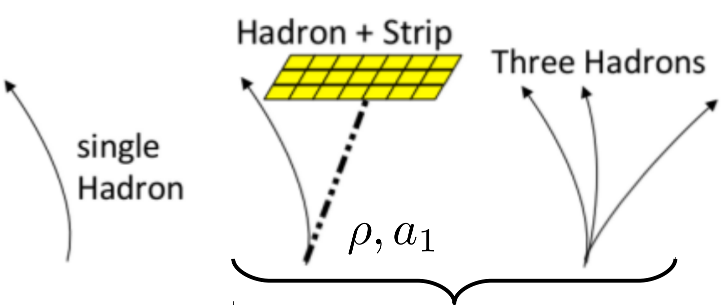
Six decay modes:

$\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$,

$e\mu$, $\mu\mu$, ee

Reconstruction of hadronic τ



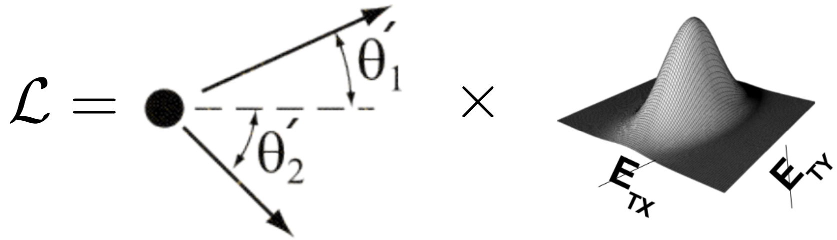


Compatible w/ mass requirements

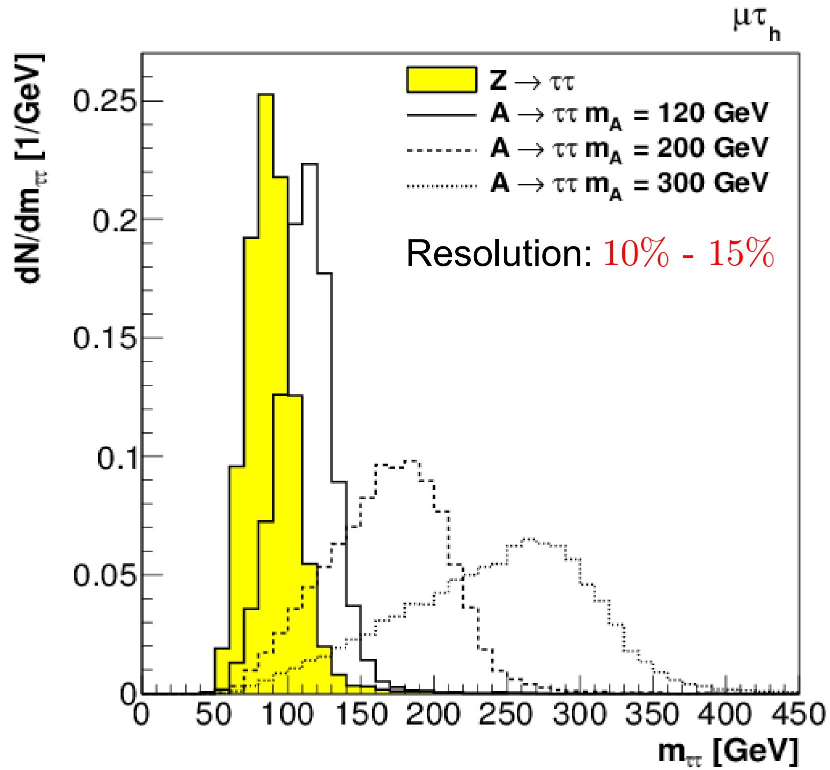
- Exploit particle flow algorithm: distinguish between γ, neutral and charged hadron .
  - Isolation (based on energy deposits in vicinity of reconstructed τ_h candidate).
  - Discrimination against electrons (based on shower shape & E/p).
  - Discrimination against muons.
  - Allows for independent cross check of τ_h energy calibration (use 3% uncert.).
  - Efficiency $\approx 60\%$ ($\approx 3\%$ fakerate), flat as function of $p_T(\tau_h)$ and $N(vtx)$.

Reconstruction of $m_{\tau\tau}$

- Likelihood approach:



- ME for leptonic τ decay or phase space kinematics of 2-body decay of τ_h .
- Estimate of expected $\not{E}_T$ resolution on event by event basis.
- Inputs: visible decay products, x-, y-component of $\not{E}_T$.
- Free parameters: φ , θ^*, ($m_{\nu\nu}$) per τ.



- Find minimum of $\mathcal{L}$ for given $m_{\tau\tau}$ and scan over all possible values of $m_{\tau\tau}$ to find global minimum.

Control of backgrounds

tt

- From simulation.
- Normalization from sideband.

QCD multijet

- Normalization & shape taken from LS/OS or fakerate.

$Z \to \tau\tau$

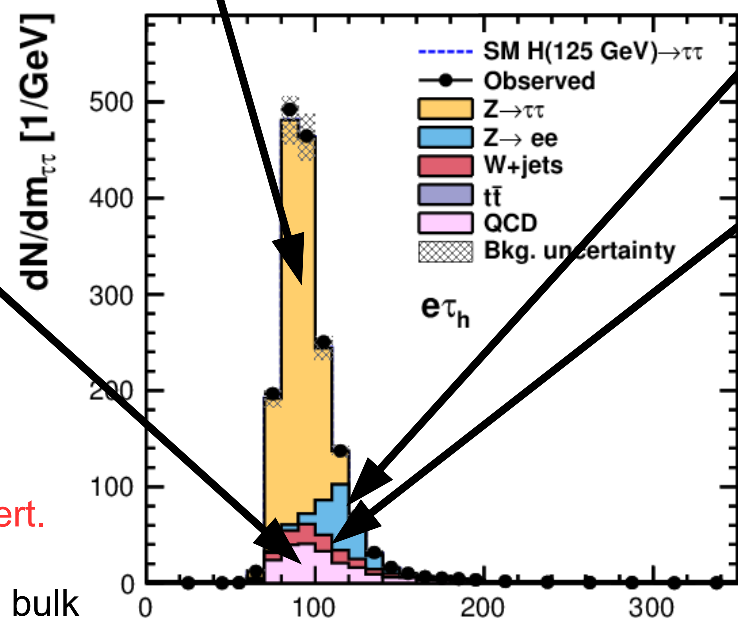
- Embedding (in $Z \to \mu\mu$ replace μ by sim τ).
- Norm from $Z \to \mu\mu$.

$Z \to \ell\ell$

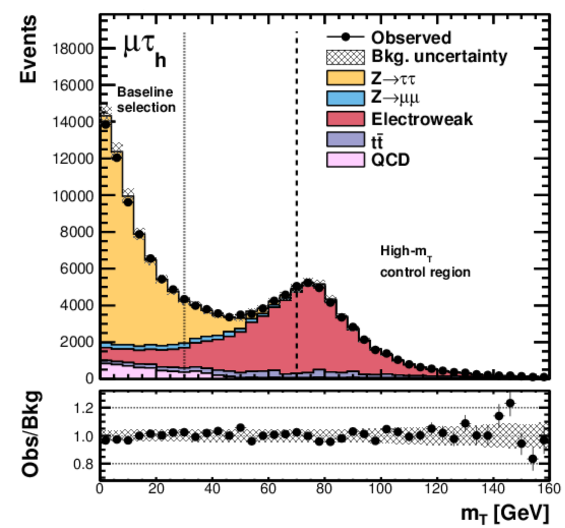
- From simulation
- Corrected for $jet \to \tau$ or $e/\mu \to \tau$ fakerate.

$W + jets$, Diboson

- From simulation
- Normalization from sidebands.



Taken from arXiv:1401.5041



- Full consideration of uncert. due to limited statistics in control or MC samples in bulk of distributions.
- Apply semi-analytic fits in tails.

Event categorization

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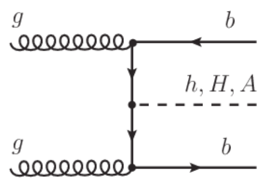
- Exploit enhancement of coupling to down-type fermions for initial state ($\rightarrow b$-quarks).

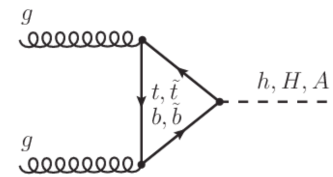
b-tag category:

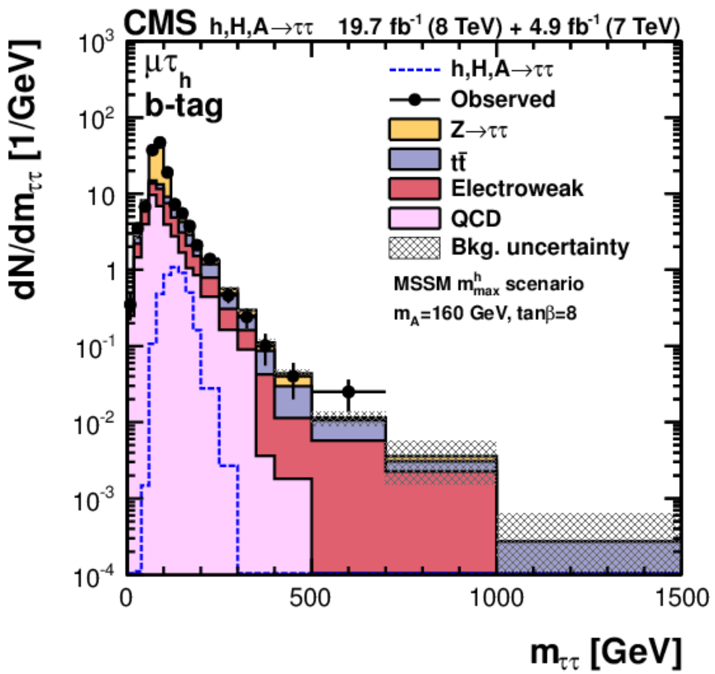
$N(\text{b-tag}) \geq 1$
$N(\text{Jet}) \quad \leq 1$

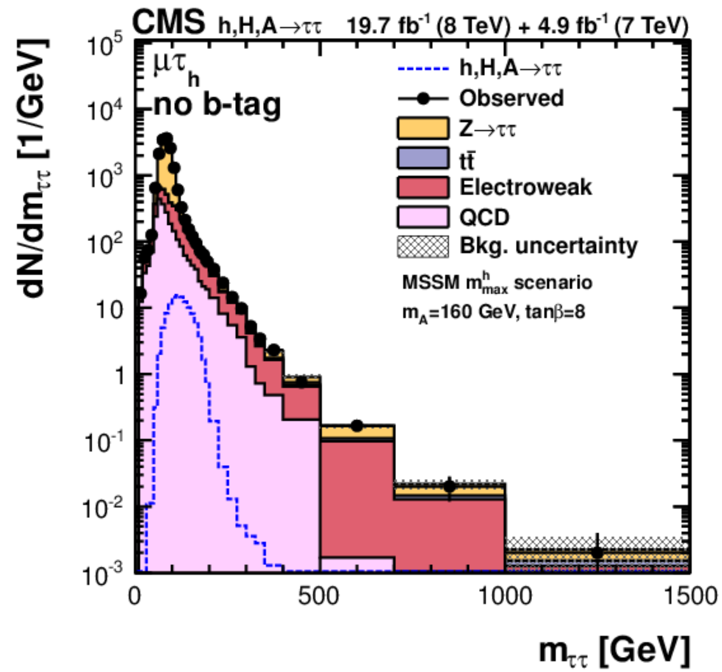


No b-tag category:

$N(\text{b-tag}) = 0$



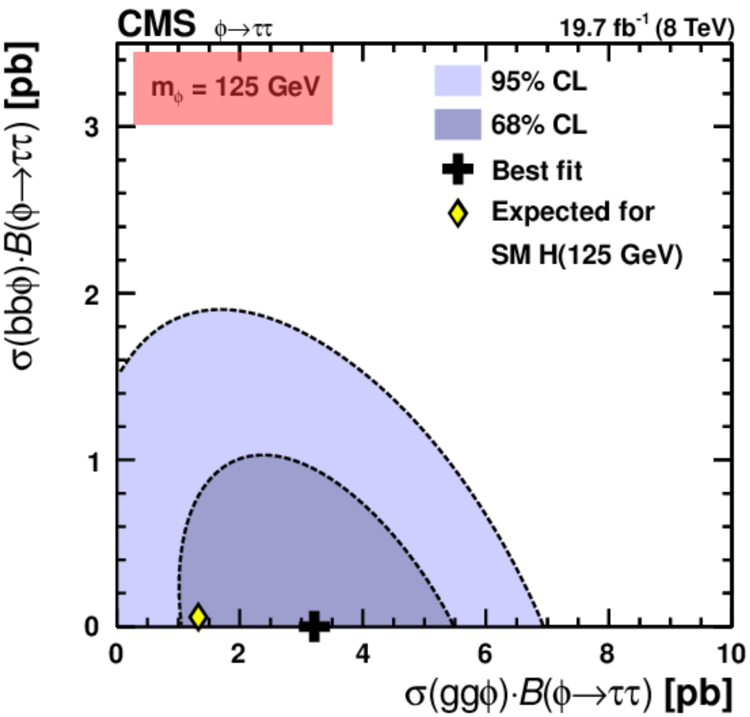


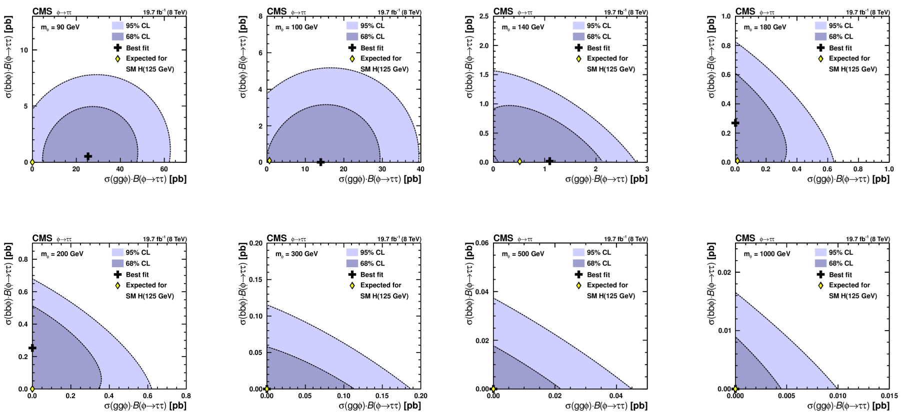


- Sensitive to both production modes!

Model independent limits (2D)

- Single narrow resonance search in $gg \rightarrow \phi\ (gg\phi)$ & $gg \rightarrow bb\phi\ (bb\phi)$ production mode:



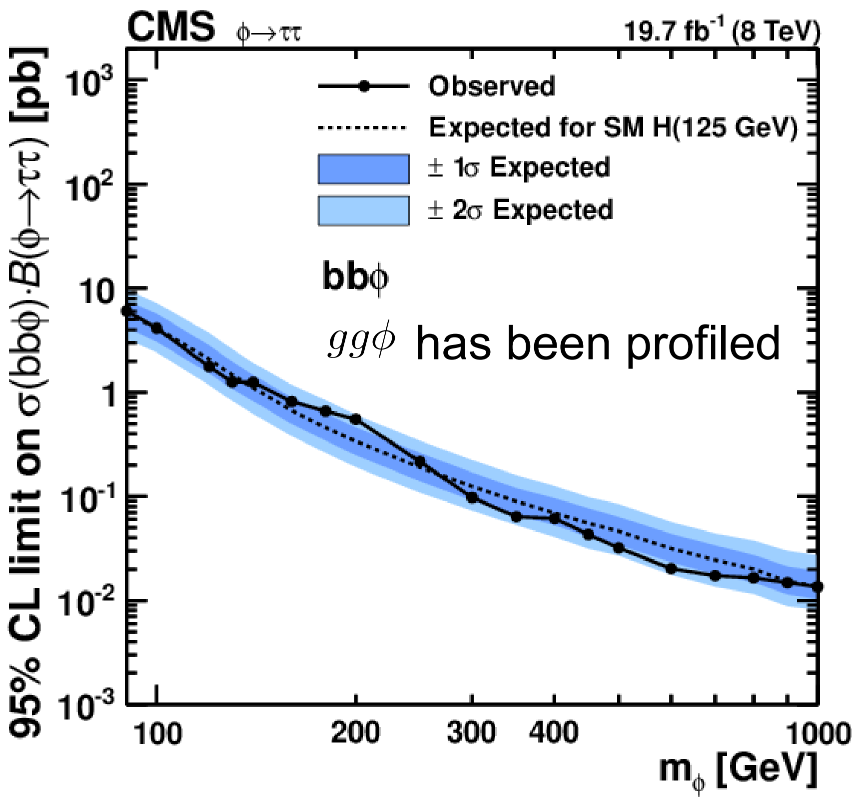


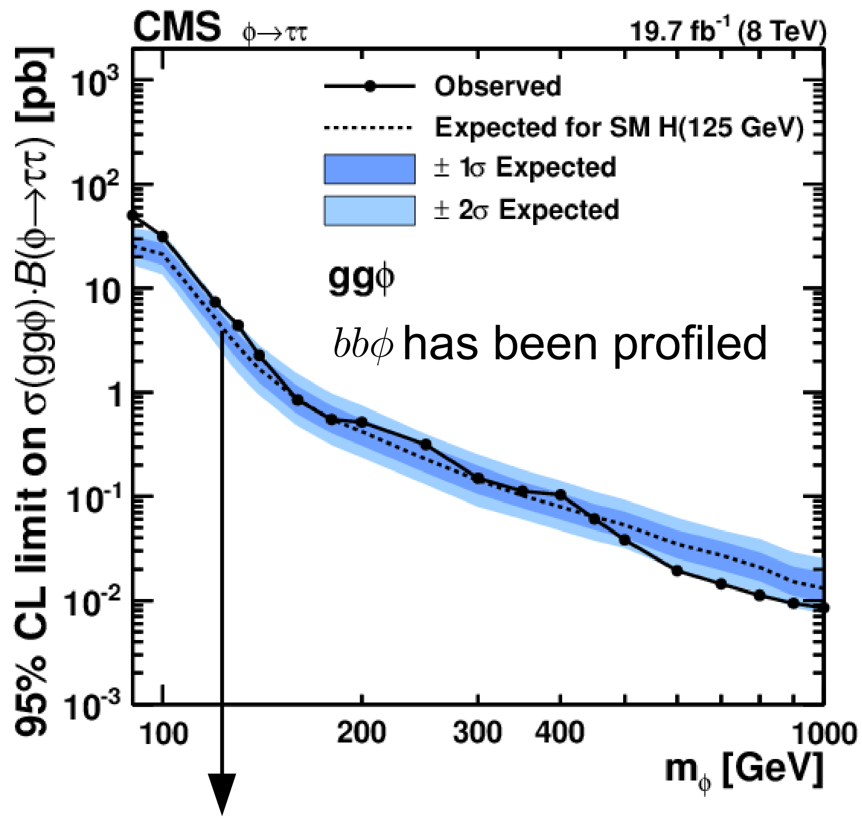
… (for 31 mass points btw. 90 and 1000 GeV, $\rightarrow 1.25 \times 10^6$ scan points).

- Most probable value and 2D limit contour from scan of likelihood function (200×200 NLL points).
- Find DB of full likelihood scan in 3D ($gg\phi$, $bb\phi$, m_ϕ) on supporting TWiki for arXiv:1408.3316.

Model independent limits (1D)

- 1D limit contours obtained from 2D by profiling non-observed component:

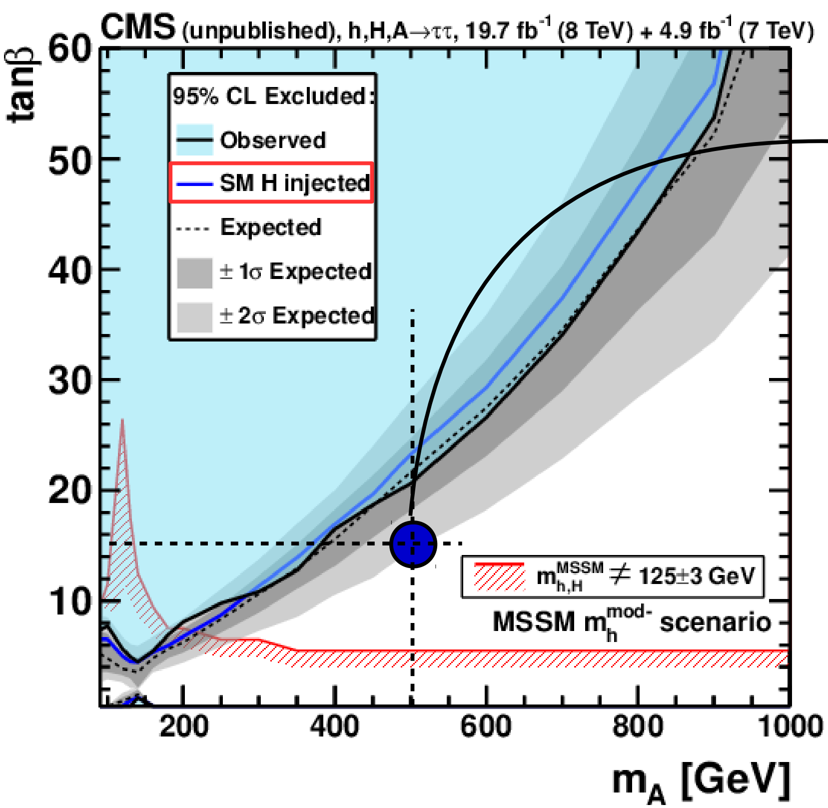


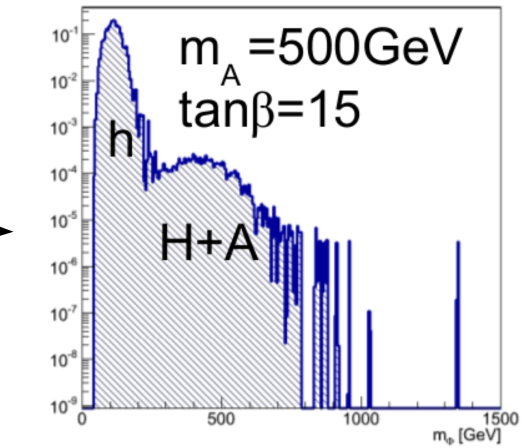


Sensitivity to h(125) of ~2.5 σ_{SM}.

Limits in full MSSM benchmark scenarios

- Explicit prediction for three neutral Higgs bosons:



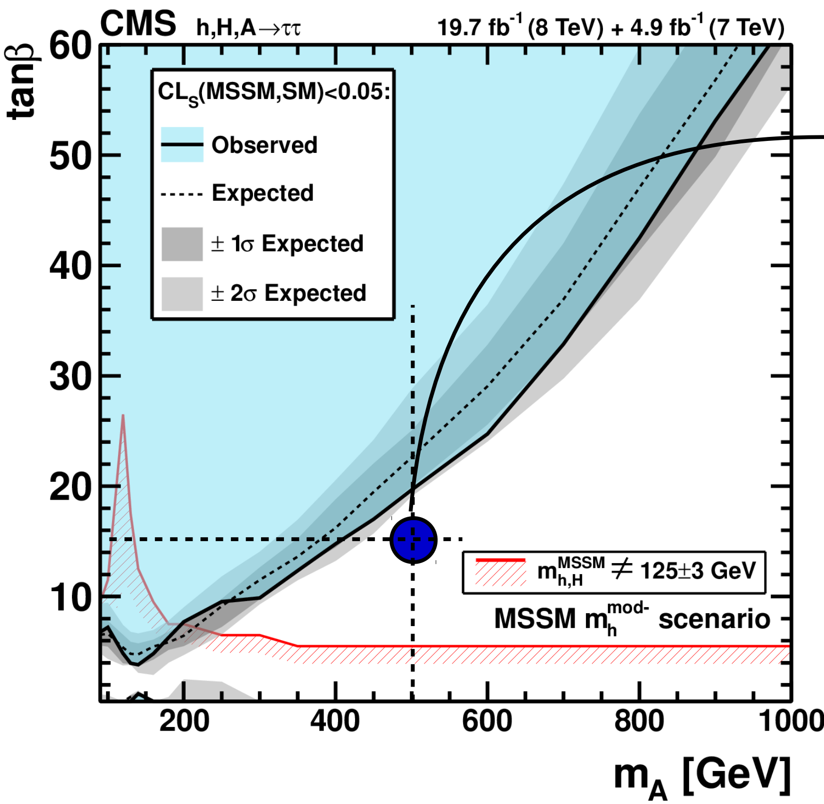


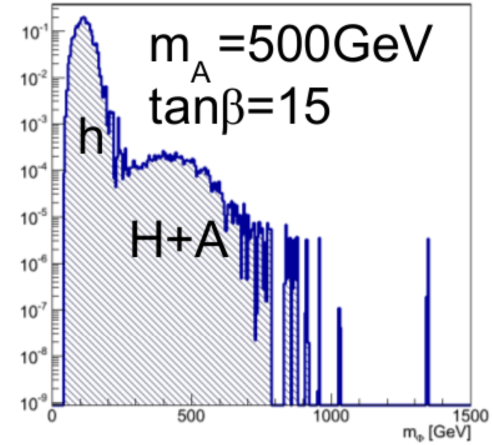
- Note: h(125) has been observed!
- With increasing sensitivity new statistical interpretation is needed: “1 Higgs vs 3 Higgses”.
- **Old method**: h(125) ignored in statistical inference:

$$q_{\mathrm{MSSM/BG}} = \frac{\mathcal{L}\big((N|(S_{\mathrm{MSSM}}+B),\hat{\theta}_{MSSM}\big)}{\mathcal{L}\big(N|B,\hat{\theta}_B\big)}$$

Limits in full MSSM benchmark scenarios

- Explicit prediction for three neutral Higgs bosons:



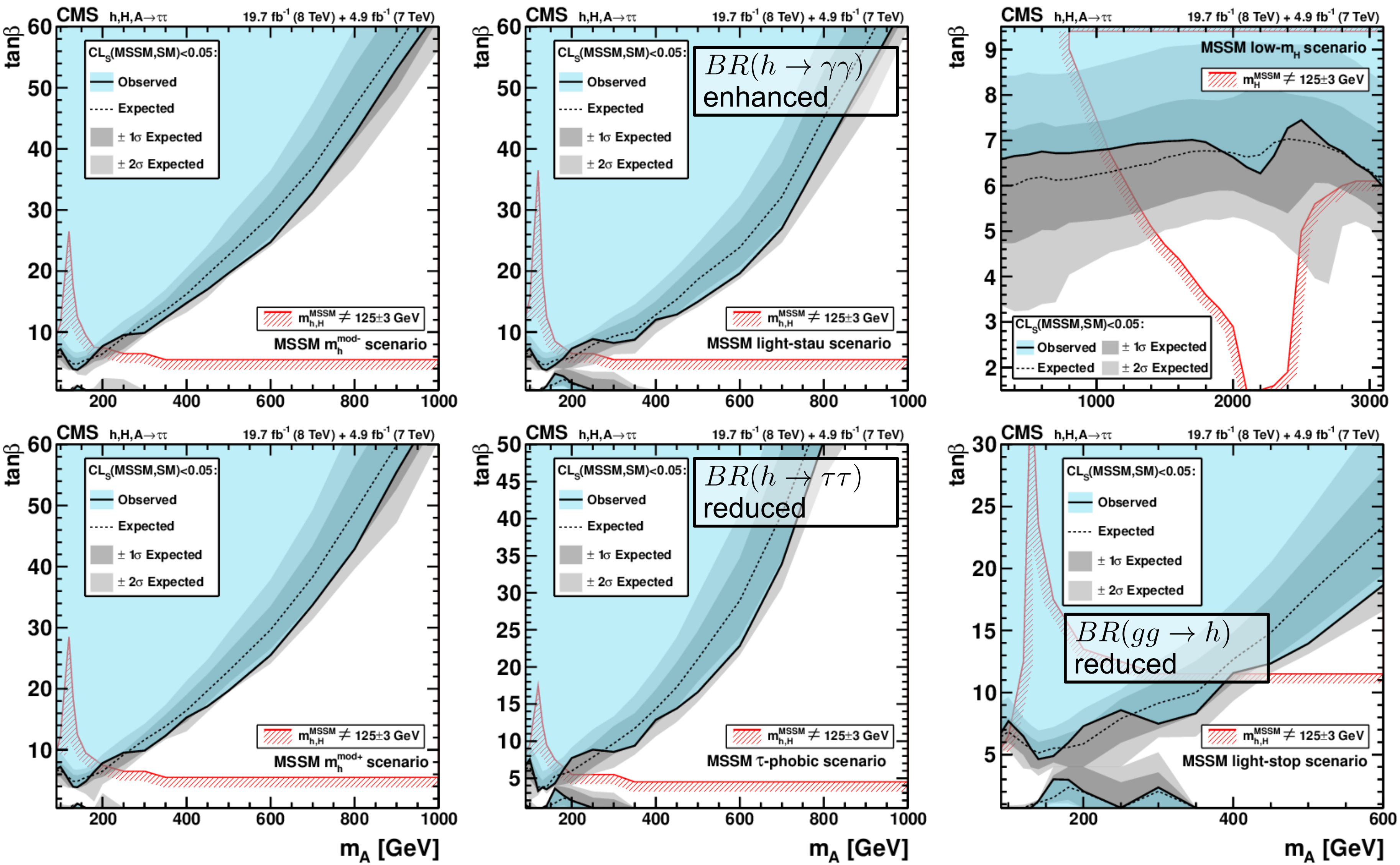


- Note: h(125) has been observed!
- With increasing sensitivity new statistical interpretation is needed: “1 Higgs vs 3 Higgses”.
- **New method**: h(125) taken into account in test statistic:

$$q_{\mathrm{MSSM/BG}} = \frac{\mathcal{L}\big((N|(S_{\mathrm{MSSM}}+B),\hat{\theta}_{MSSM}\big)}{\mathcal{L}\big(N|(S_{\mathrm{SM}}+B),\hat{\theta}_{SM}\big)}$$

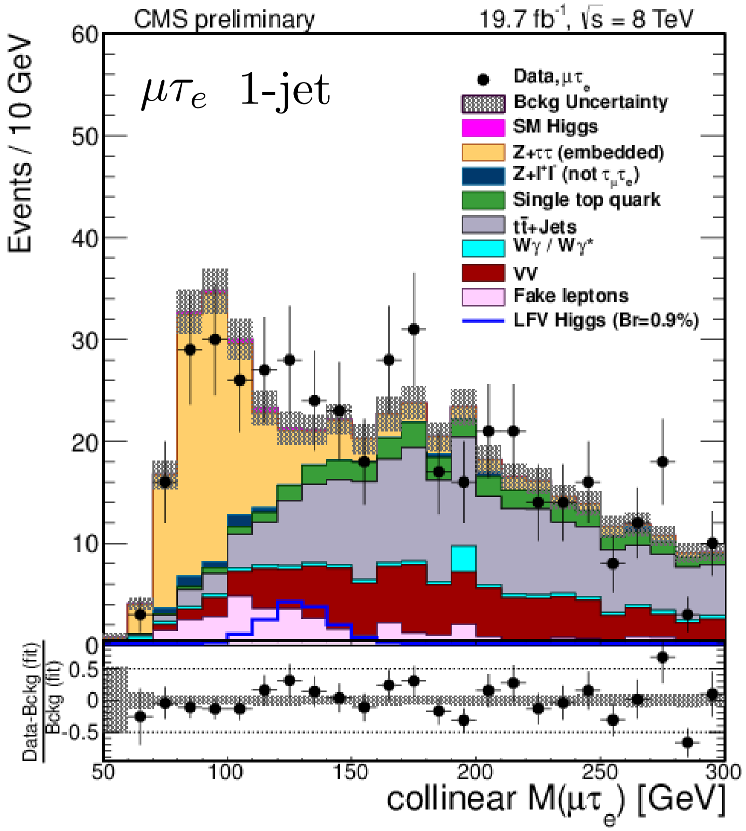
More benchmark scenarios...

(arXiv:1302.7033)

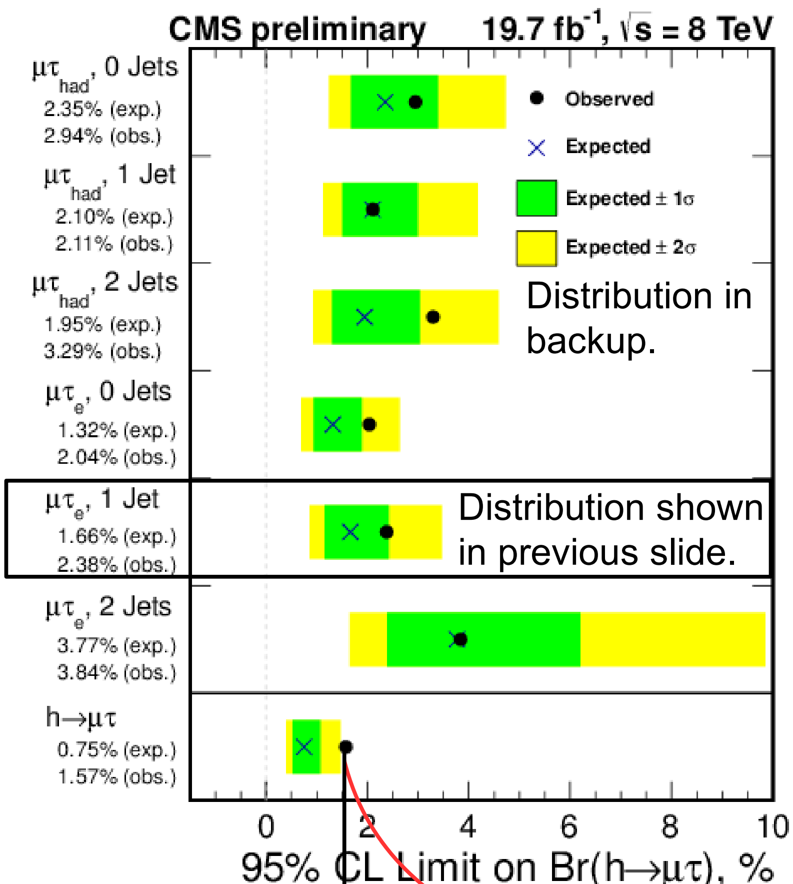


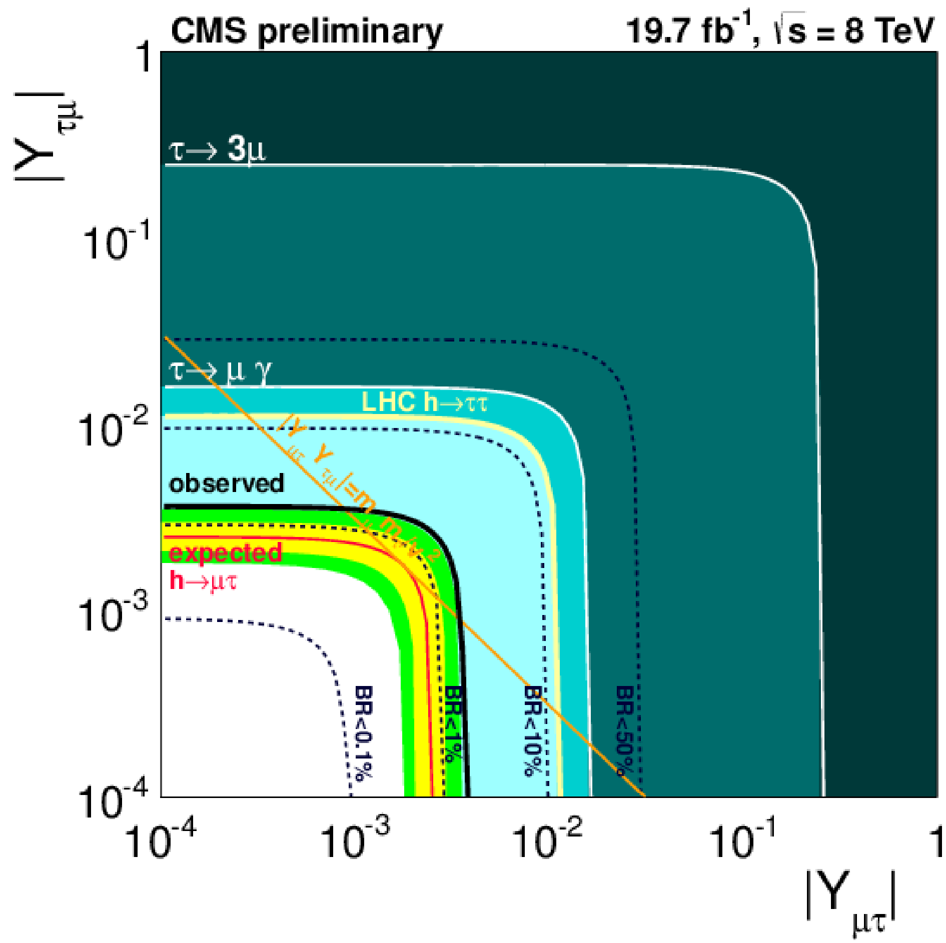
$H \to \mu\tau$ LFV Higgs couplings (CMS-PAS-HIG-14-005)

- SM forbids LFV couplings at tree level.
- Three couplings are possible: $\tau \to e$, $\tau \to \mu$, $\mu \to e$.
- LVF could take place in Higgs sector.
  Limits in literature:
  - $BR(H \to e\mu) = \mathcal{O}(10^{-8})$.
  - $BR(H \to e\tau) = \mathcal{O}(0.1)$.
  - $BR(H \to \mu\tau) = \mathcal{O}(0.1)$.
- $H \to \tau\tau_\mu/\mu\tau_e$ analysis w/ two specialties:
  - $p_T(\mu)$ is harder ($\to$ less $\nu's$ in the decay).
  - $\nu's$ are more collinear. Use of collinear approximation for $m_{\tau\tau}$.



$H \to \mu\tau$ LFV Higgs search results





1.57% @ 95% CL

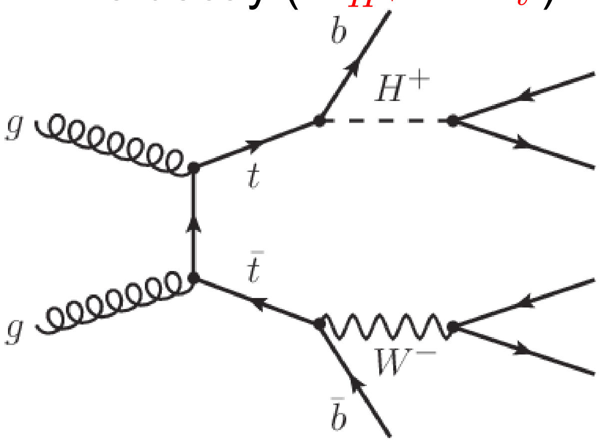
$\approx 2\sigma$ excess

Strongest limits on the market!

Charged Higgs in the MSSM

- Expect signal in *top* sector:

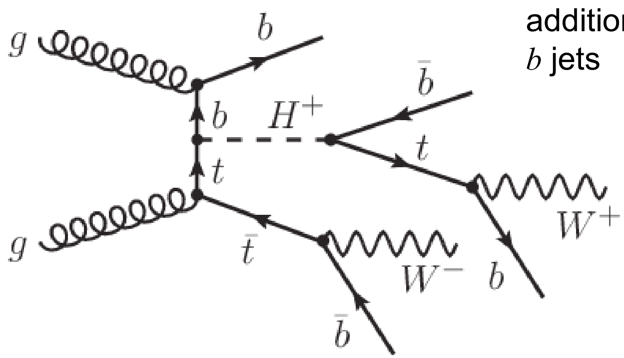
- In the decay ($m_{H^+} < m_t$):



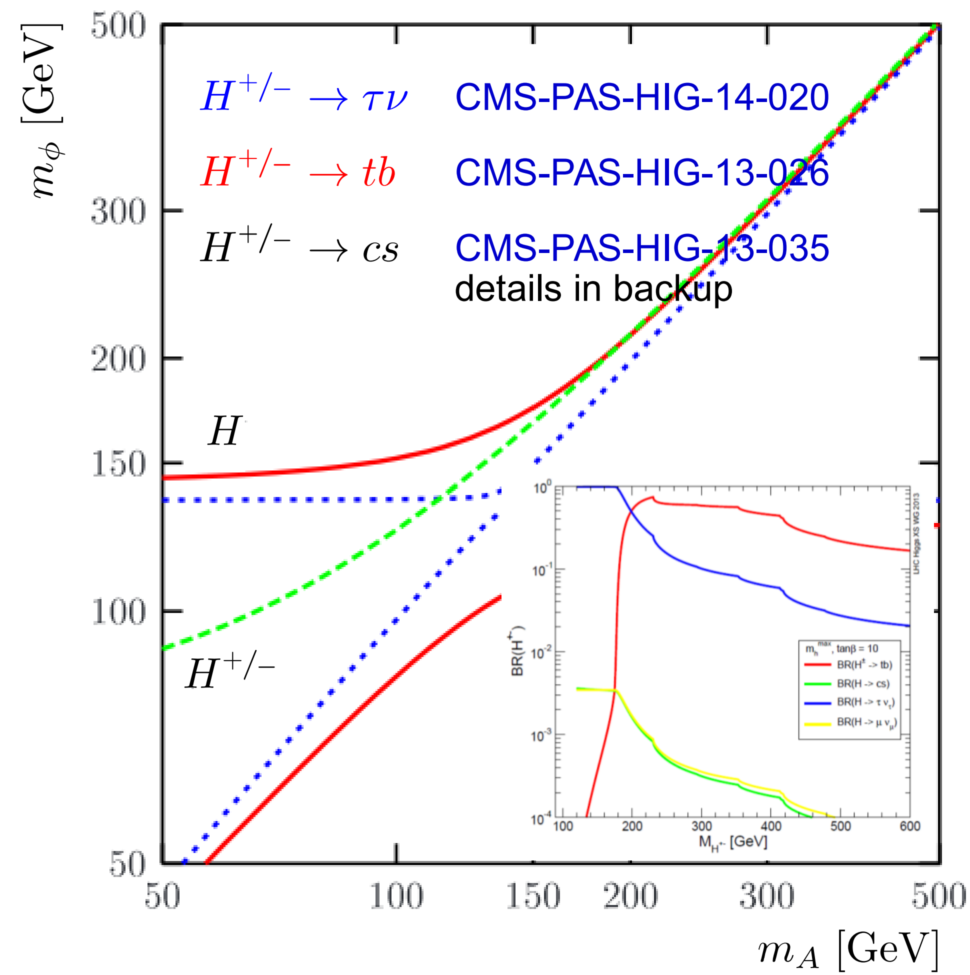
heavy flavors preferred

flavor democratic

- In the decay ($m_t < m_{H^+}$):



additional b jets

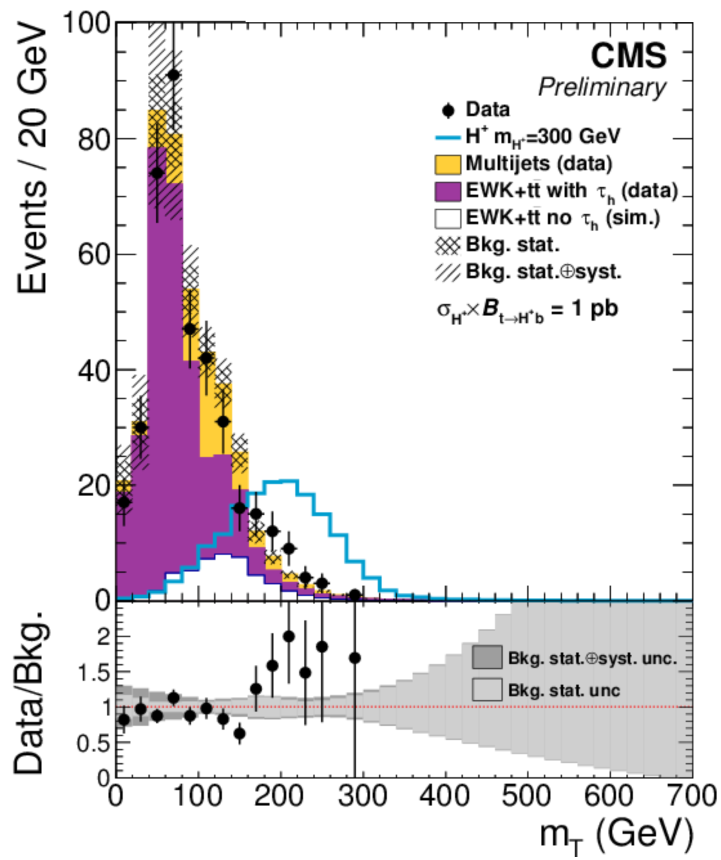


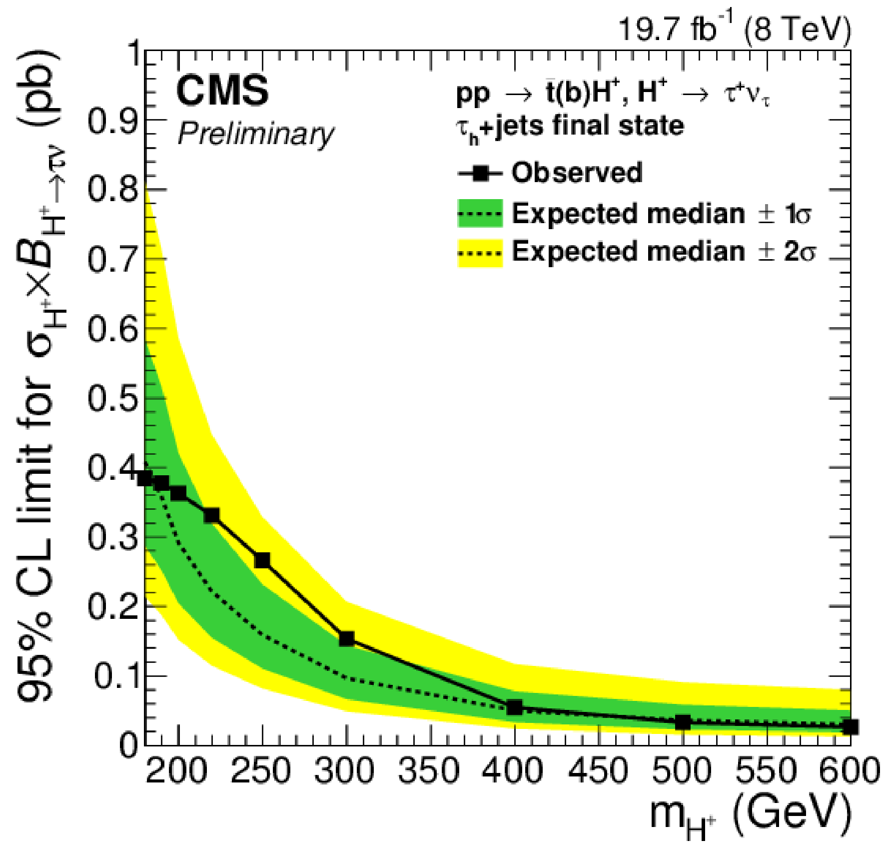
Charged Higgs boson search ($H^{+/-} \to \tau\nu$)

- Most sensitive decay channel (cf neutral Higgs searches).

- Concentrate on hadronic decay of $W \to$ well defined use of m_T for sig extraction.

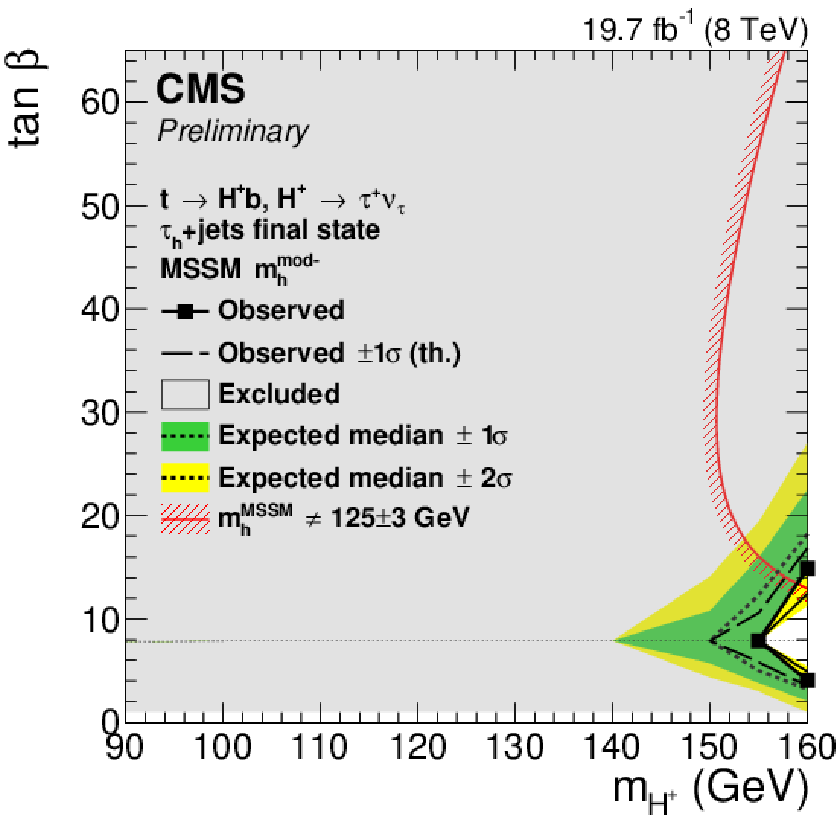
- Extending mass range of search by $180\ \mathrm{GeV} \leq m_{H^{+/-}} \leq 600\ \mathrm{GeV}$.

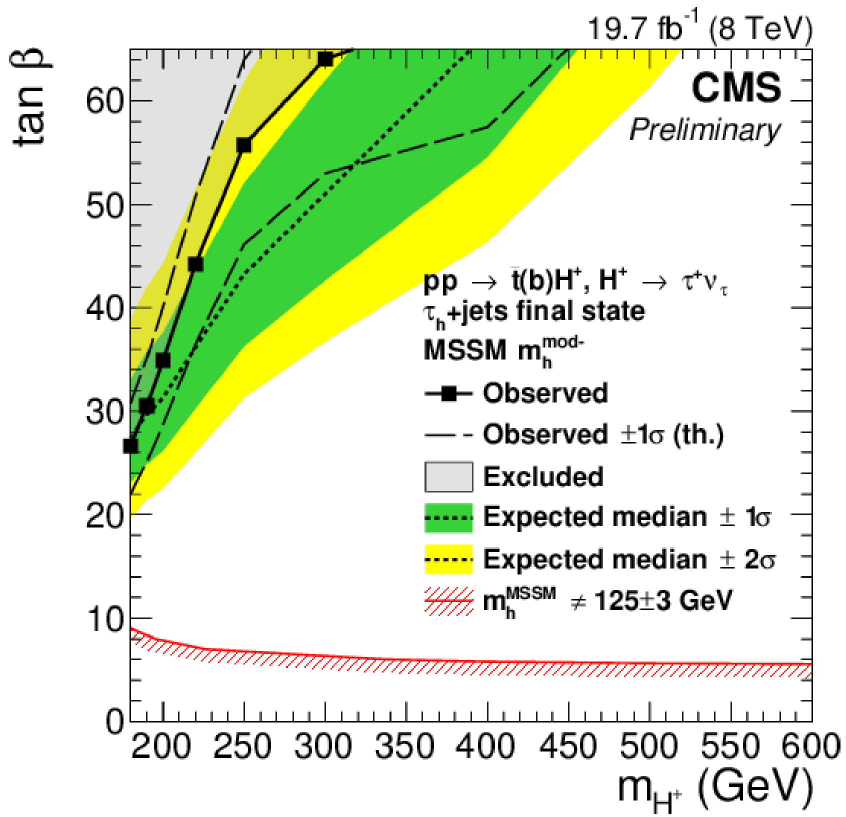




Charged Higgs boson search ($H^{+/-} \rightarrow \tau\nu$)

- Translated into m_{H^+} - $\tan\beta$ plane.





Charged Higgs boson search ($H^{+/-} \rightarrow \tau\nu$)

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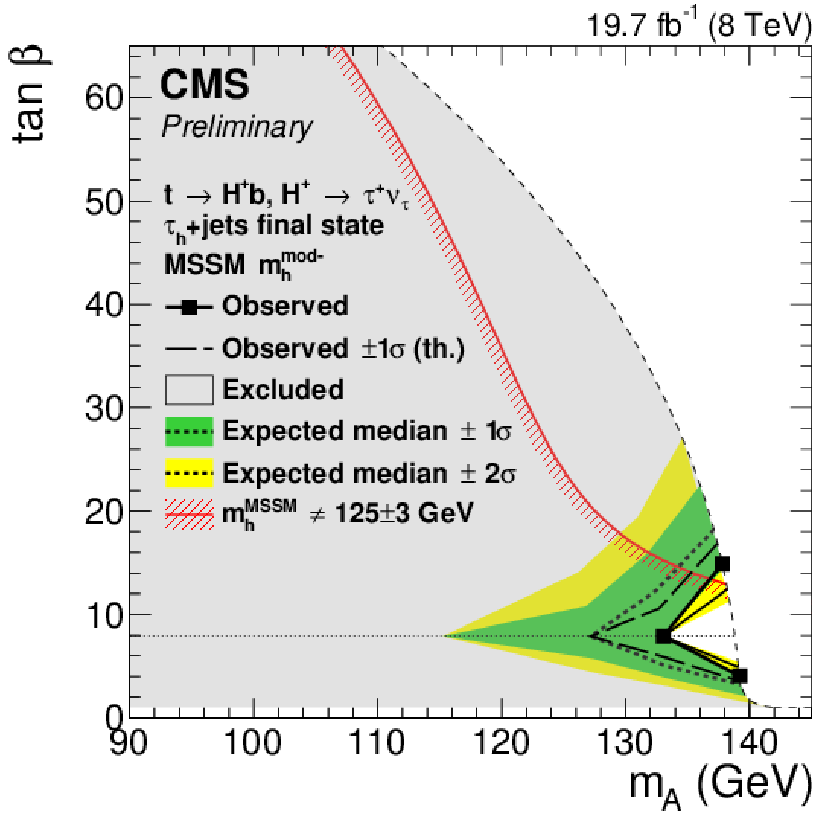
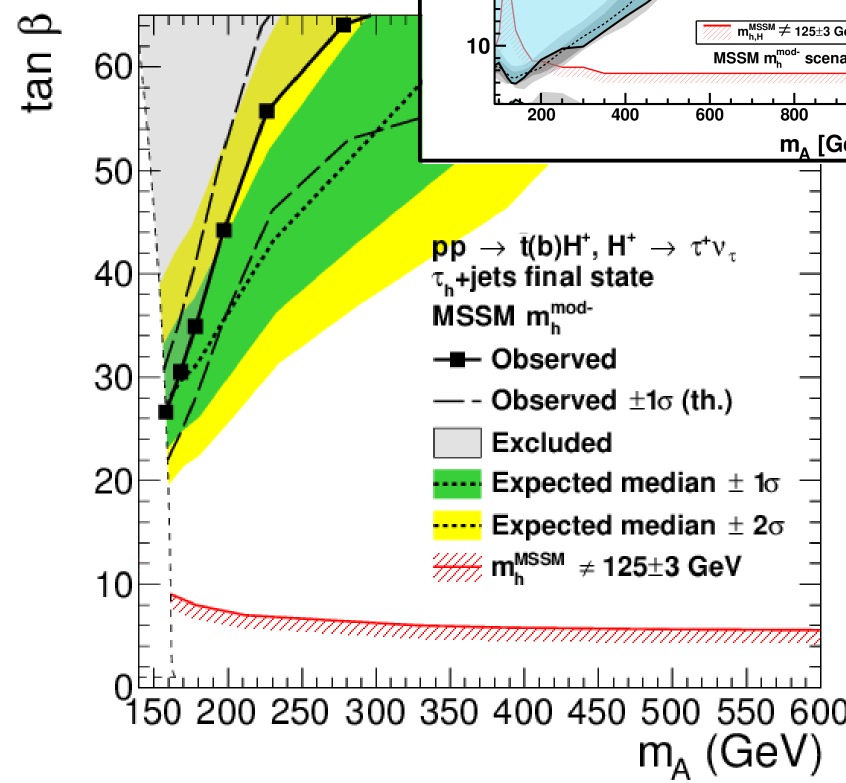
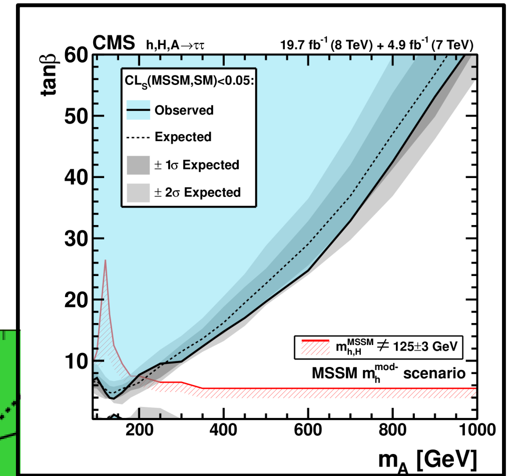
- Translated into m_A - $\tan\beta$ plane.
- Combining both measurement will close the plane in the range $90 \leq m_A \leq 140$ GeV.







Conclusions

- LHC had an extremely successful run-1 data taking period.
- **Greatest prey was the Higgs boson!**
- Unfortunately no further new physics discovered, yet. Good hunting grounds are the top and the Higgs sector, apart from conventional SUSY harvesting.
- CMS consolidating BSM Higgs searches on LHC-1 dataset by end of this year.

- Shown here only a very small and personal excerpt of most important results (others will be come more interesting from 2015 on):
  - $X \to HH$ searches (in $4b$ CMS-PAS-HIG-14-013 and $2b2\gamma$ CMS-PAS-HIG-13-032 final states).
  - $A \to Z(\ell\ell)h(bb)$ searches (CMS-PAS-HIG-14-011), w/ first interpretations in general 2HDMs.
  - … .

Conclusions

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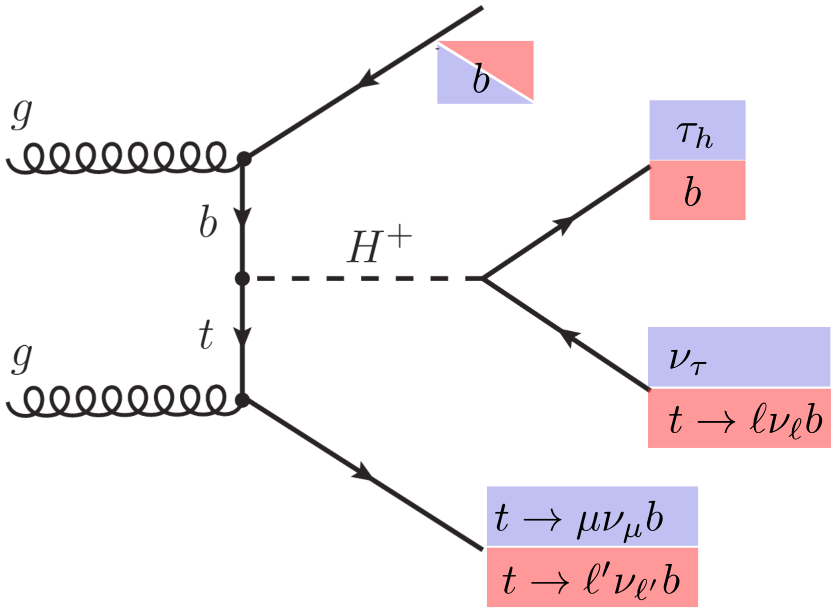
  - … .

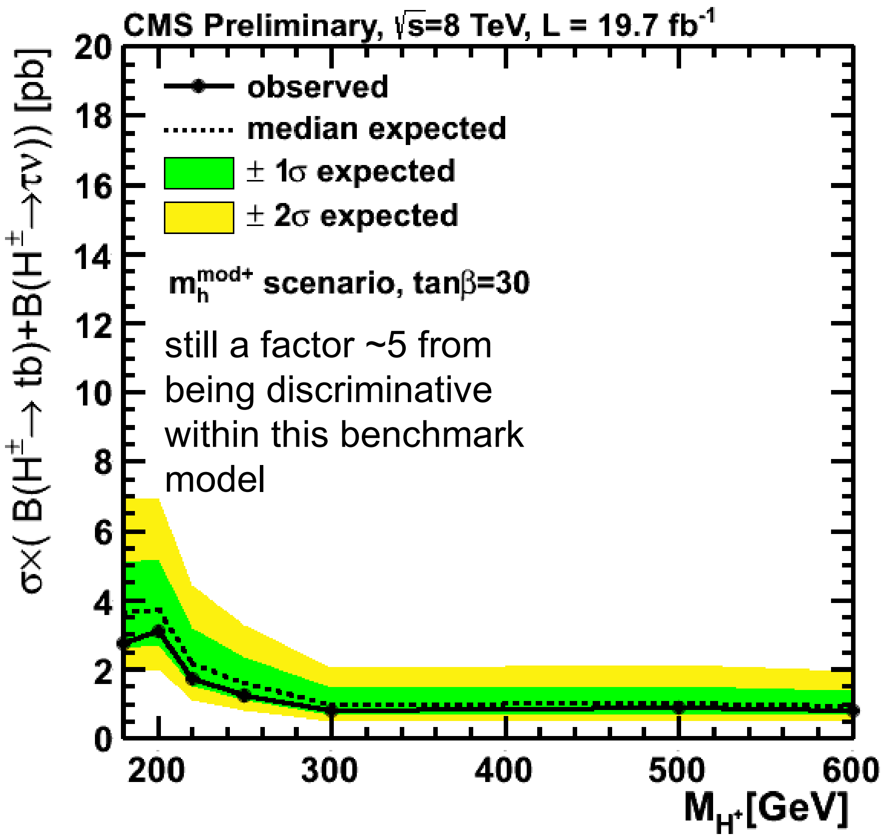
Looking forward to LHC run-2!

Backup

Charged Higgs boson search ($H^{+/-} \to tb$)

- Start off from regular $t\bar{t}$ analysis in the $\mu\tau_h$ and the $\ell\ell'$ channel ($\ell,\,\ell' = e,\,\mu$):

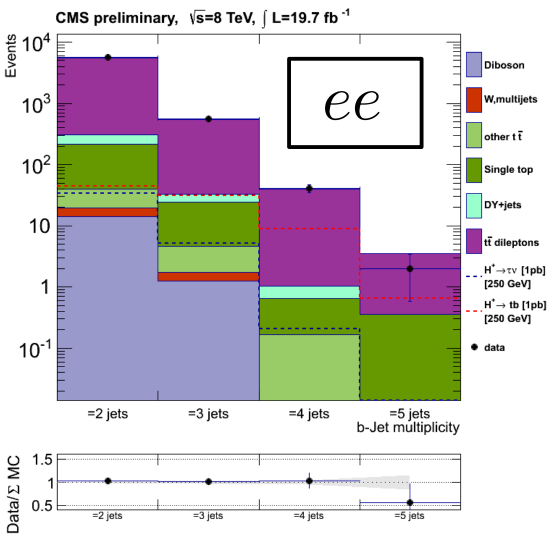


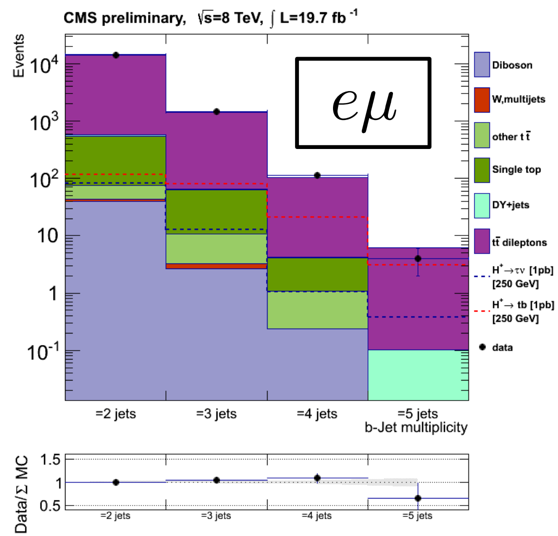


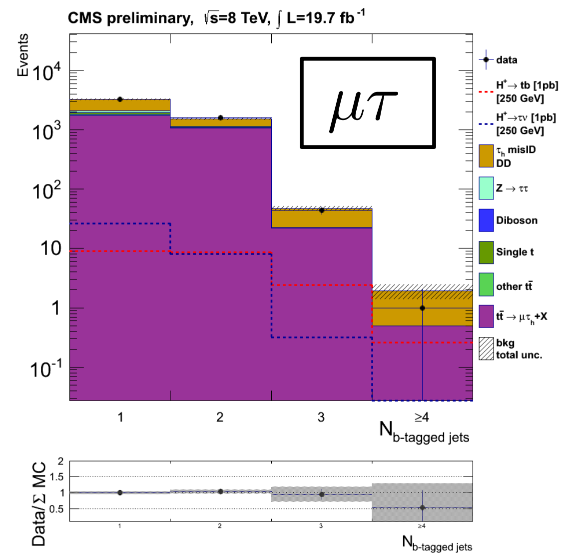
- Discriminate signal from background via N(b-tag).

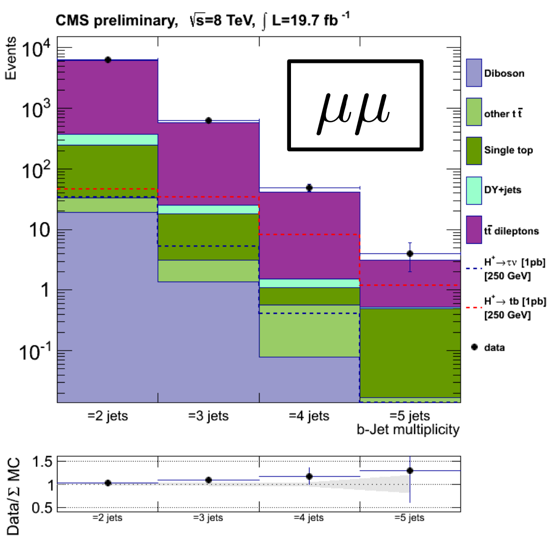
- Take into account signal in $H^{+/-} \to tb$ & in $H^{+/-} \to \tau\nu$.

Charged Higgs boson search ($H^{+/-} \to tb$)

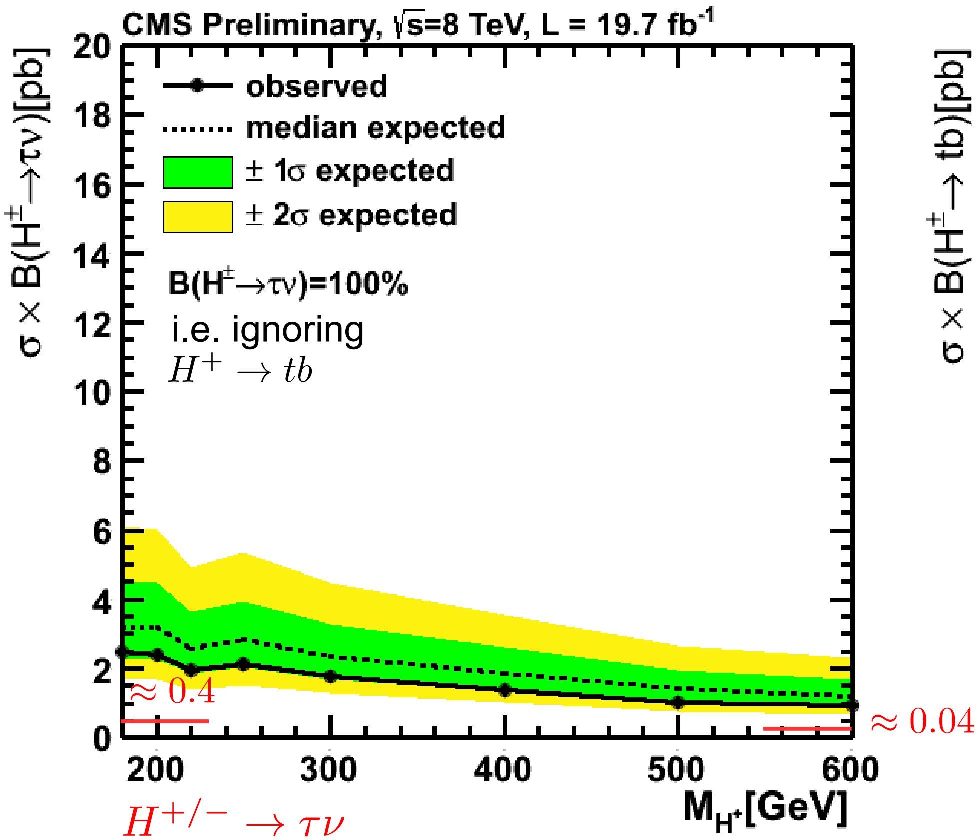


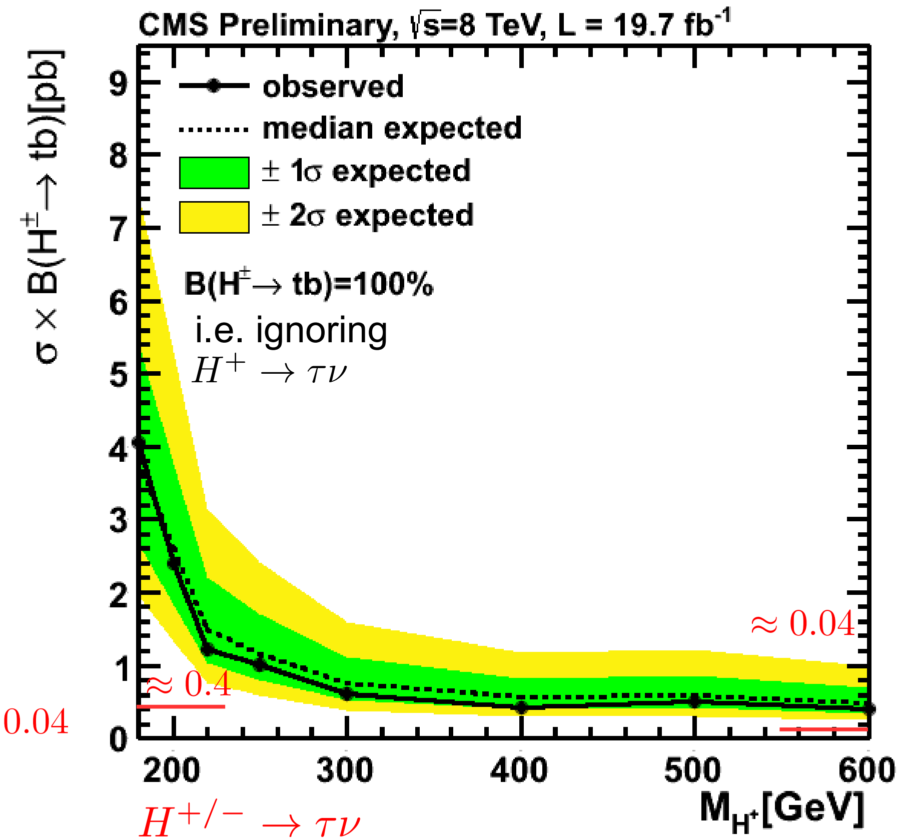






Charged Higgs boson search ($H^{+/-} \rightarrow tb$)

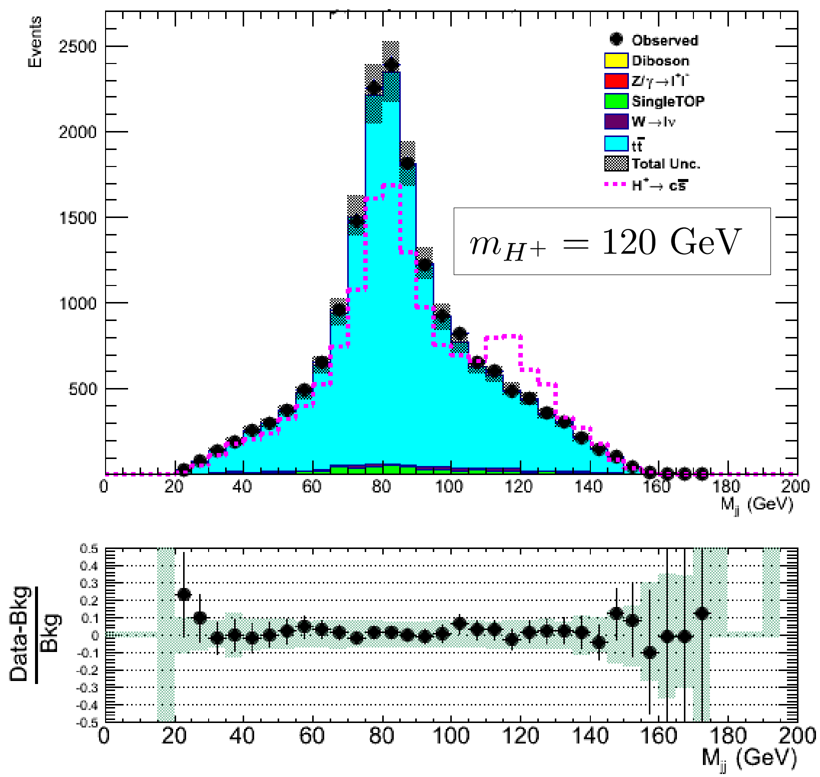




Charged Higgs boson search ($H^{+/-} \rightarrow cs$)

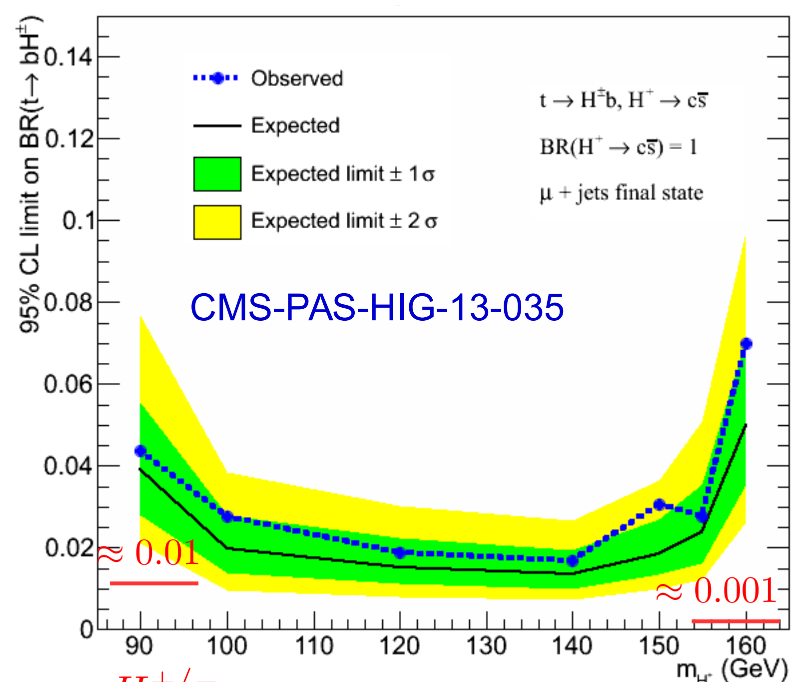
- Start off from regular $t\bar{t}$ analysis in $\mu + jet$ channel (based on 20fb^{-1} on 8 TeV).
- Reconstruct m_W from kinematic fit (using $m_t = 172.5$ GeV).

$BR(t \rightarrow H^+ b) = 0.2 \quad BR(H^+ \rightarrow cs) = 1.0$



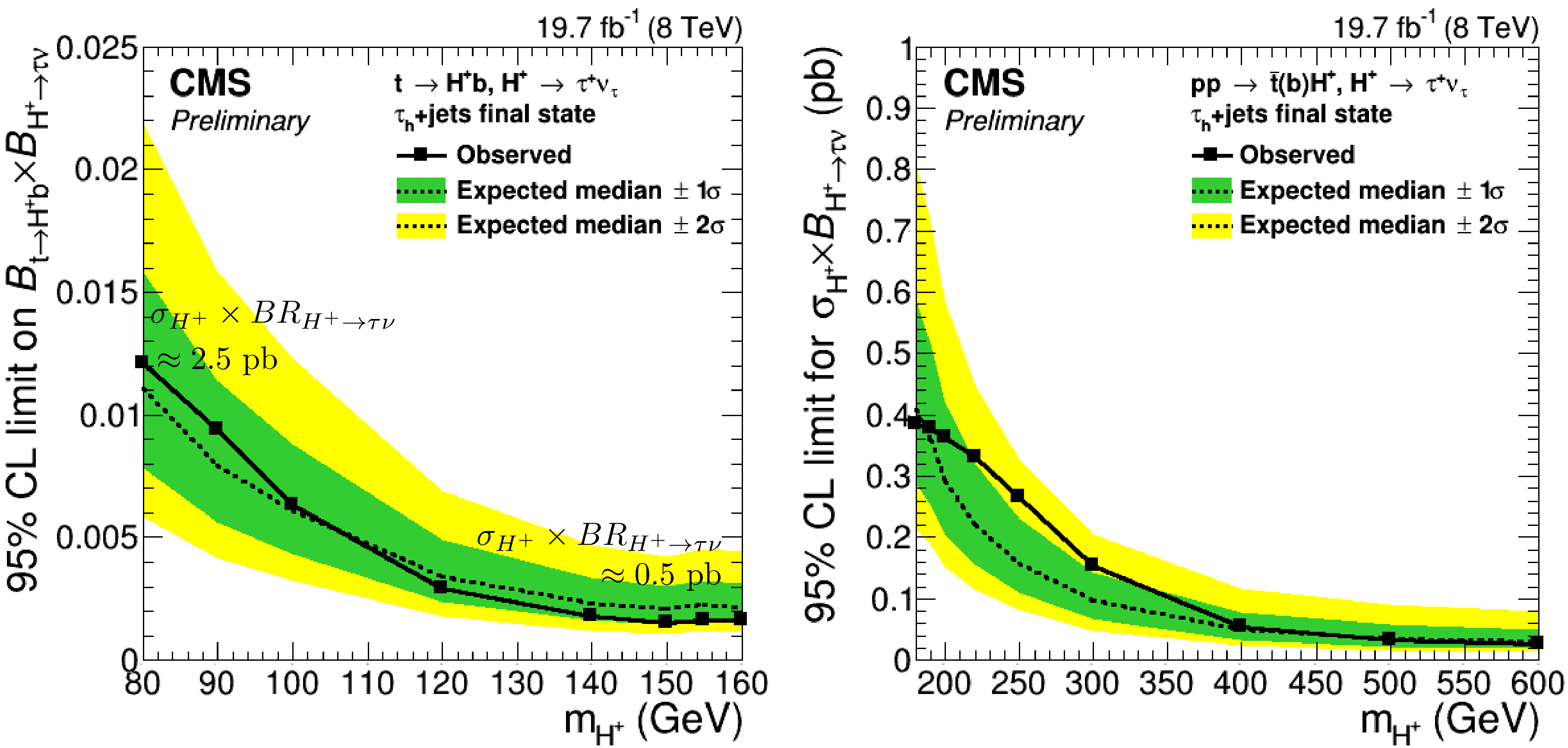
Limit on $BR = x$:

$$N_H^{BSM} = 2x(1-x)N_{H\pm}^{W\mp} + (1-x)^2 N_{SM}$$



$H^{+/-} \rightarrow \tau\nu$

Charged Higgs boson search ($H^{+/-} \to \tau\nu$)

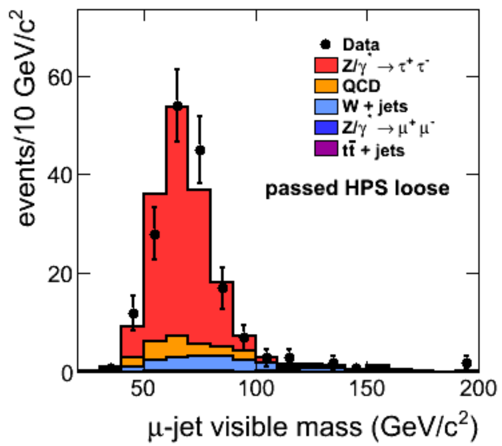


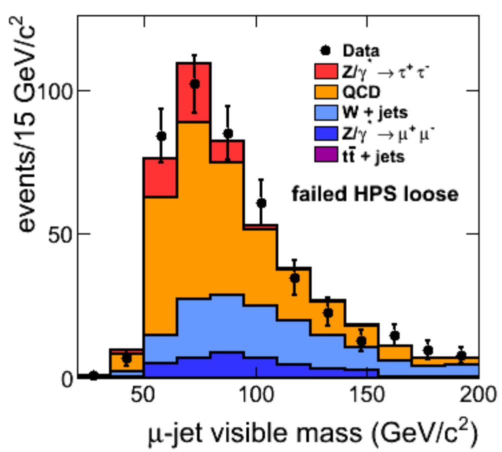
$\sigma(t\bar{t}, 8\ \mathrm{TeV}) = 257 \pm 25$ pb

arXiv:1407.6643

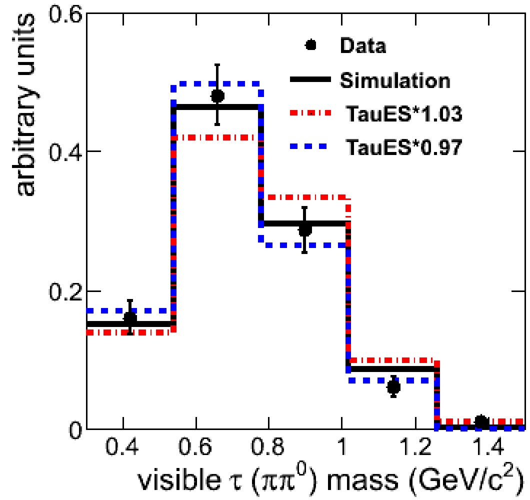
Performance of hadronic τ reconstruction

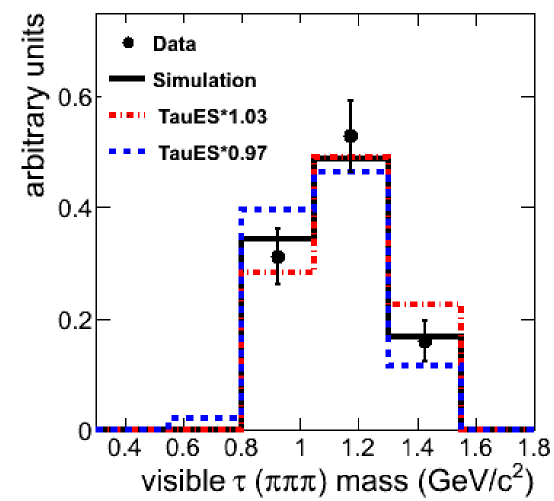
- Control efficiency within $\pm 7\%$ using tag & probe methods:





- Control τ_h energy scale within $\pm 3\%$ from fits to $m_{\tau,\text{vis}}$:



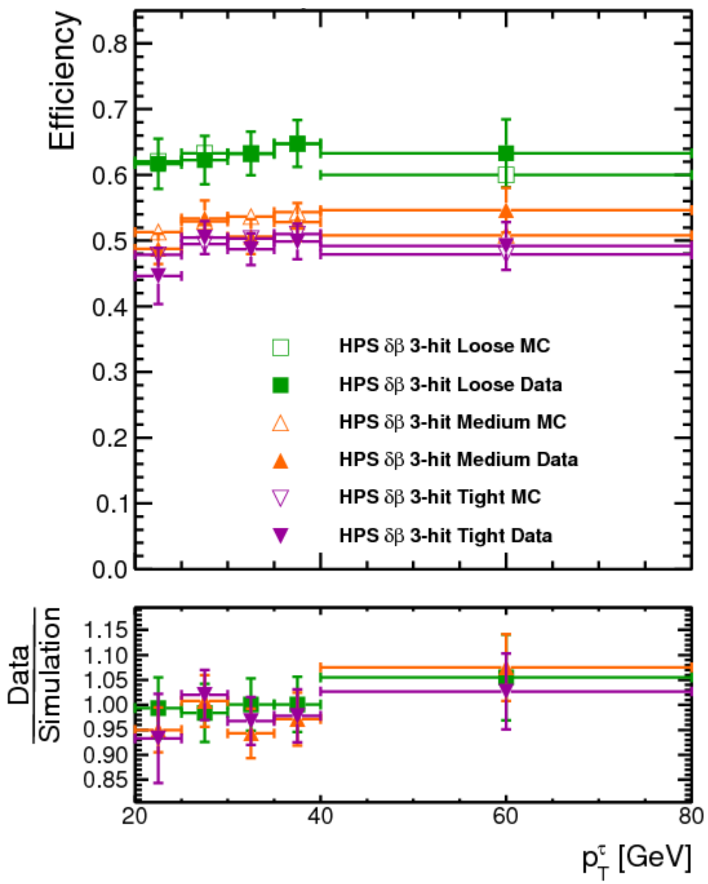


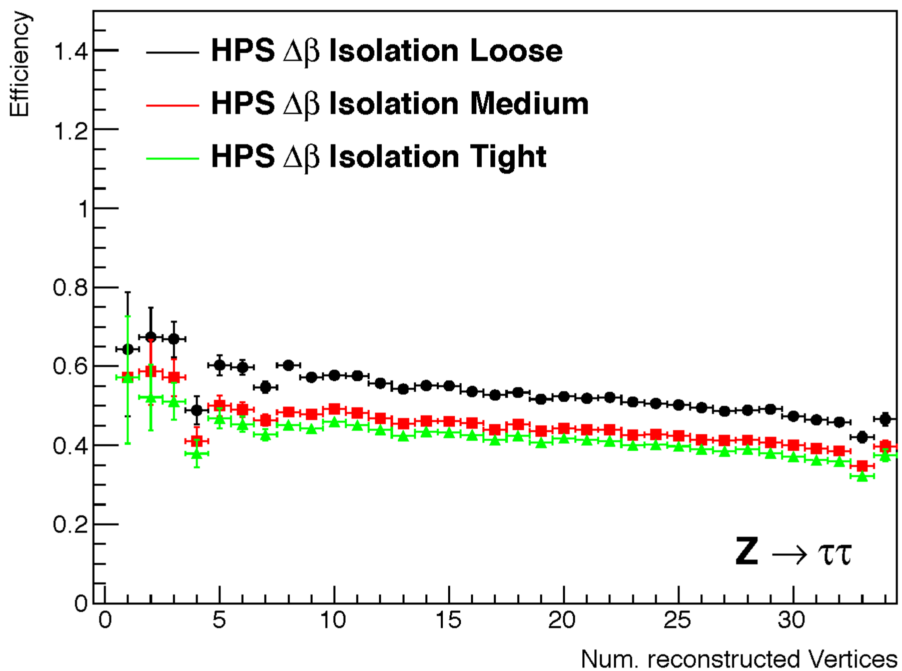
- Uncertainties further constrained by maximum likelihood fit in the statistical inference for signal extraction.

Performance of hadronic τ reconstruction

Karlsruhe Institute of Technology

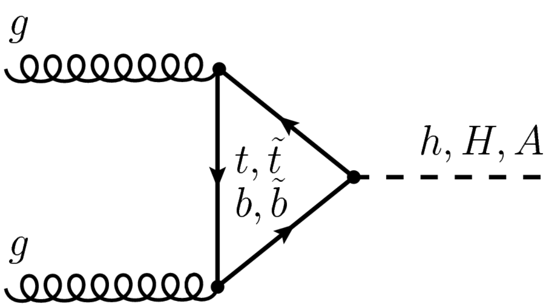
- Efficiency $\approx 60\%$ ($\approx 3\%$ fake rate), flat for $p_T(\tau) > 30\ \mathrm{GeV}$ & independent from PU.

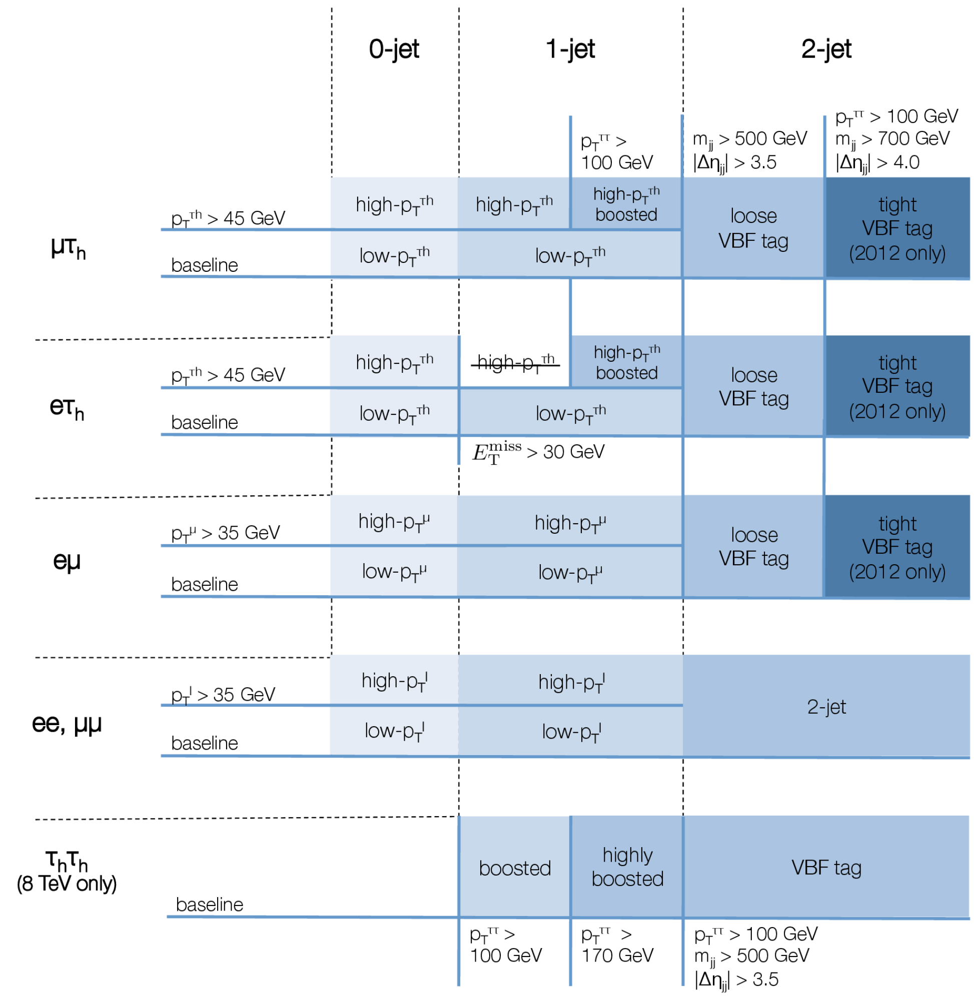




MSSM model dependency

- In the SM analysis we chose nearly 100 different event categories. Why not choose more categories in MSSM analysis?
- In $gg\phi$ p_T spectra of Higgs bosons change with other particles in loop:





- Checked with pure b and pure t in loop from pythia that current categorization is not sensitive.
- Refrained from categorization that depends on Higgs p_T .

Model independent limits (2D)

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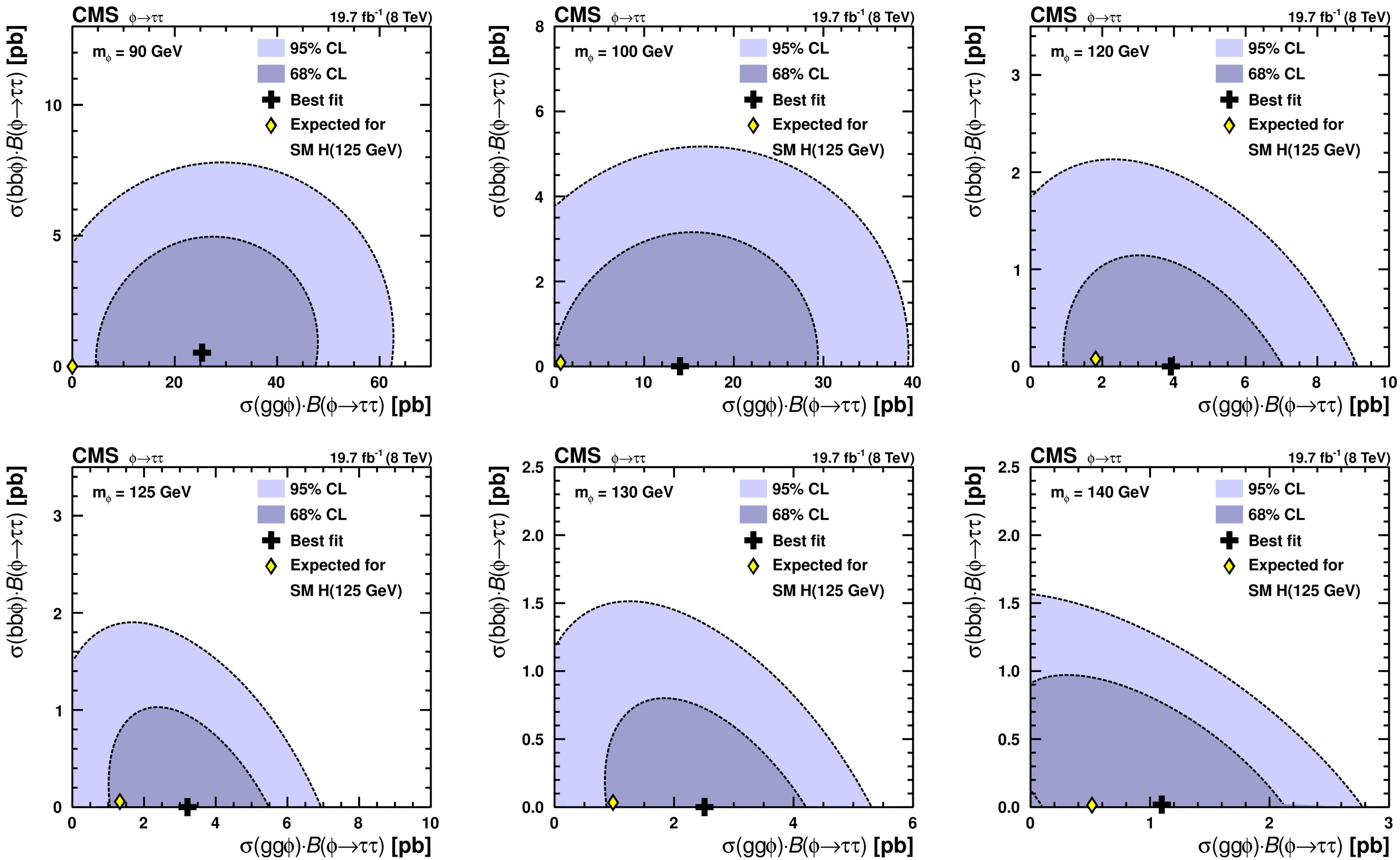
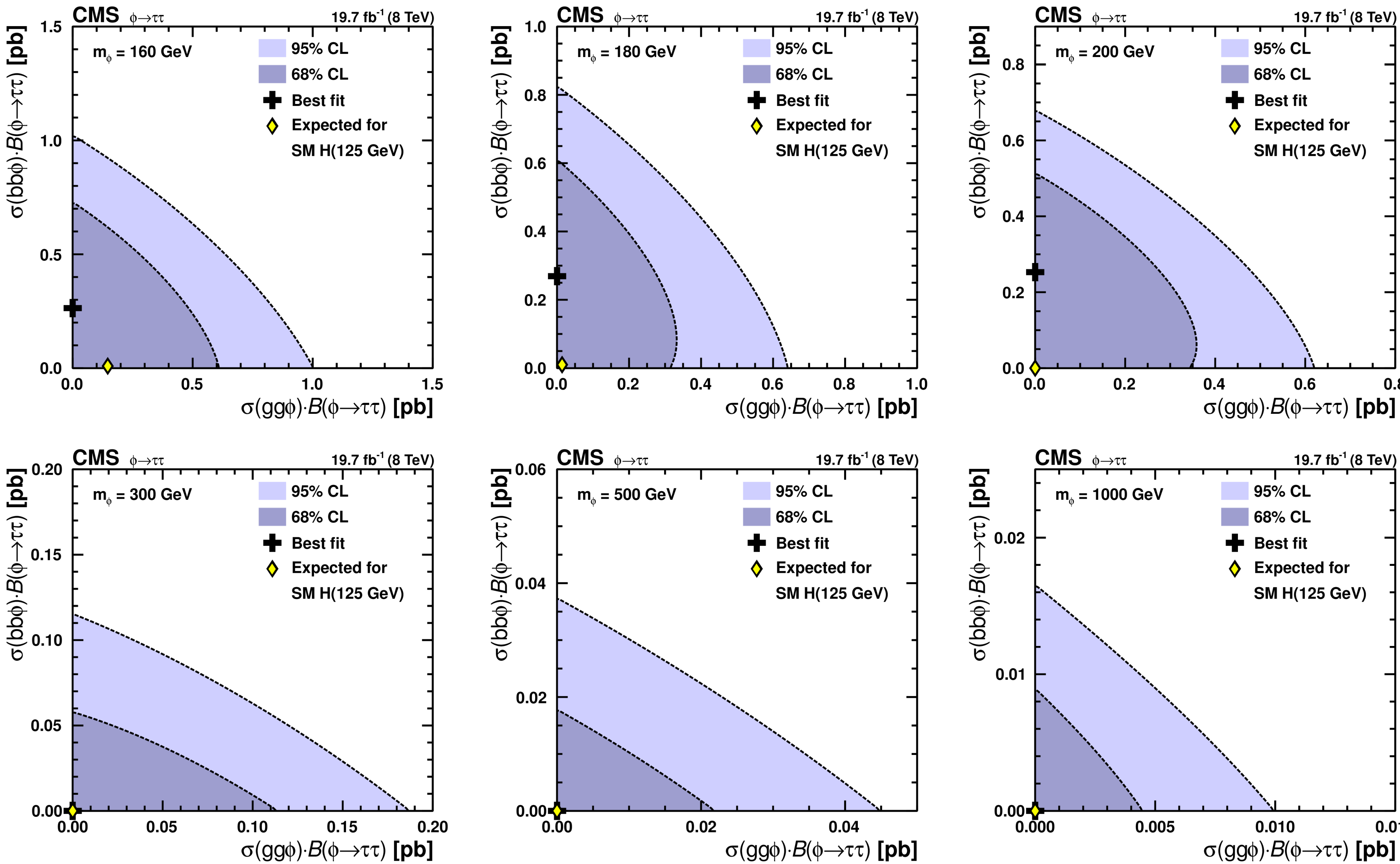
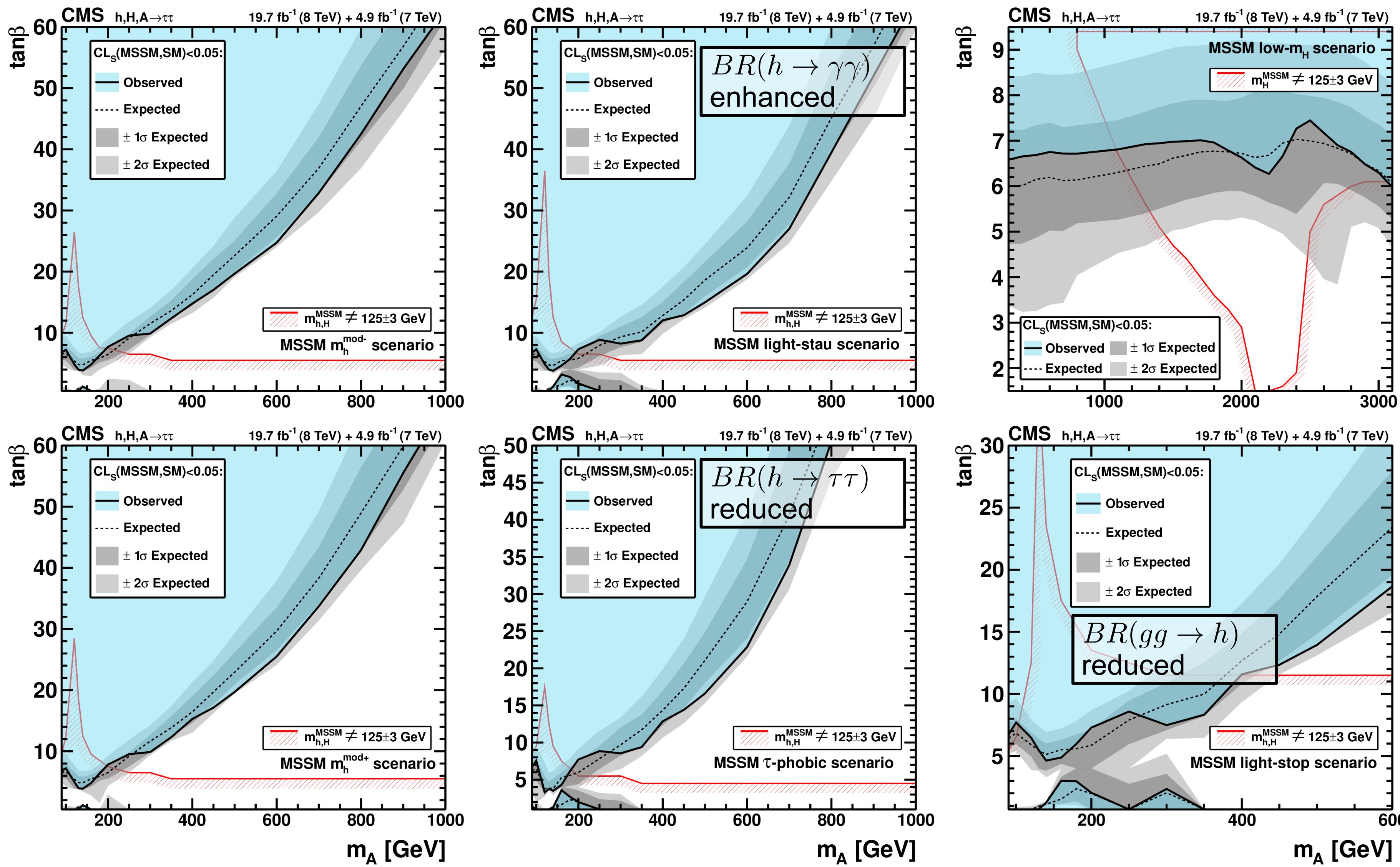


Model independent limits (2D)



More benchmark scenarios... (new method)



More benchmark scenarios... (old method)

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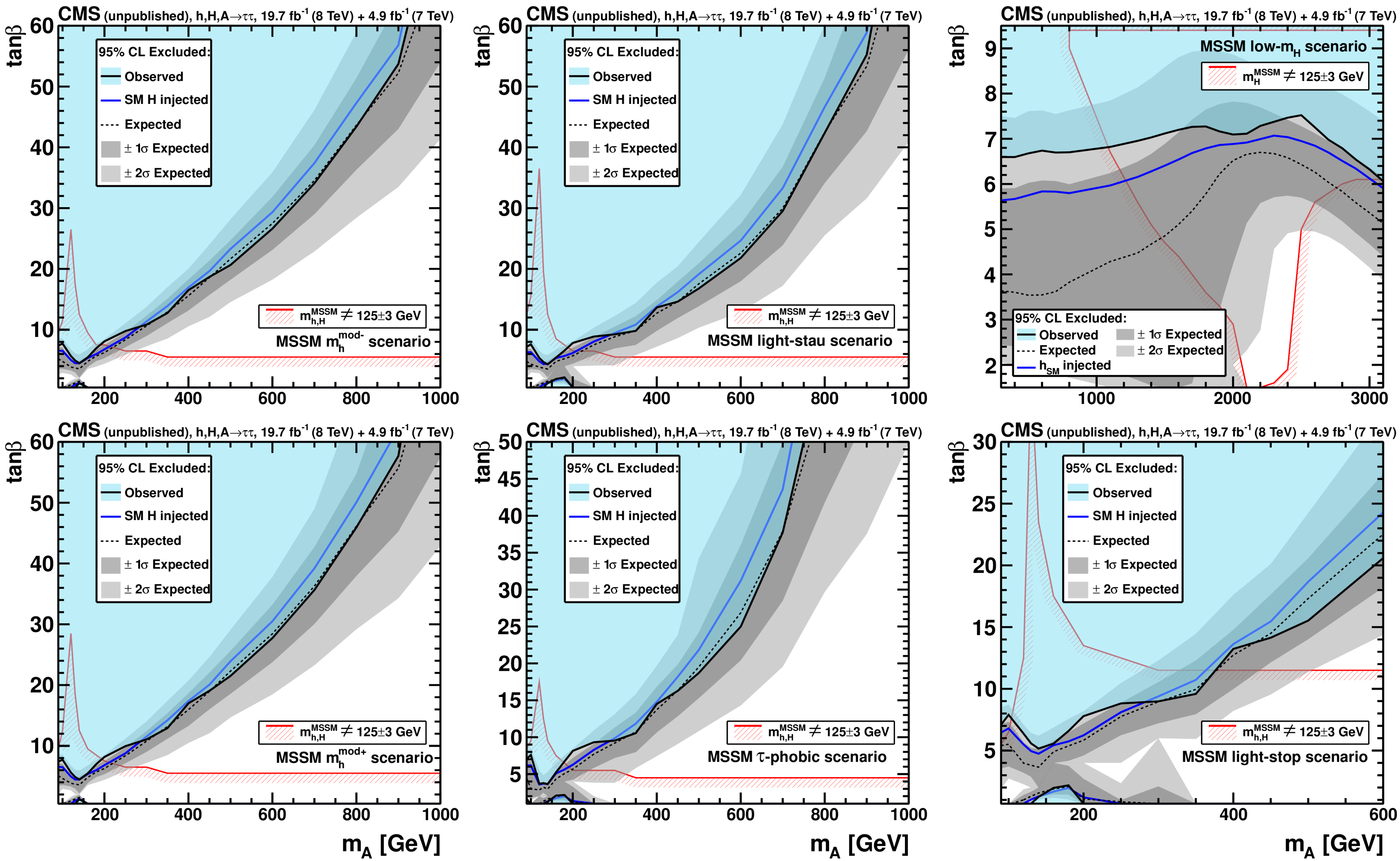
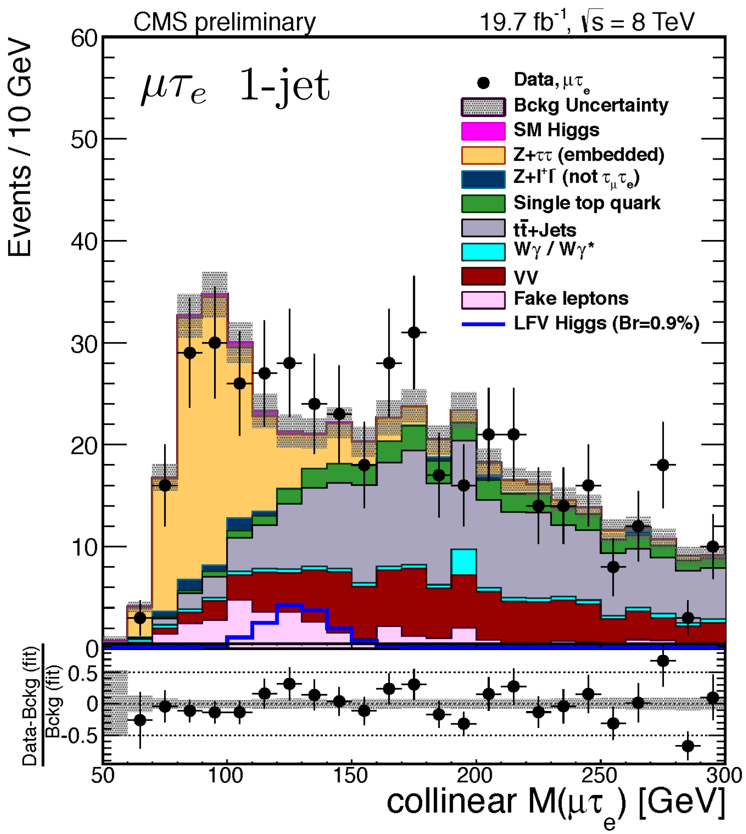
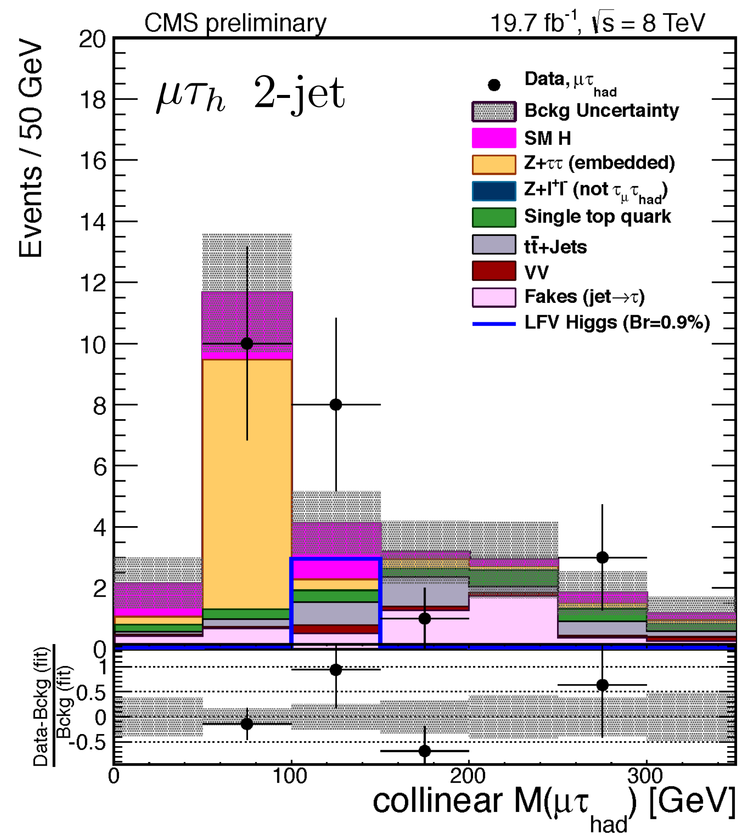


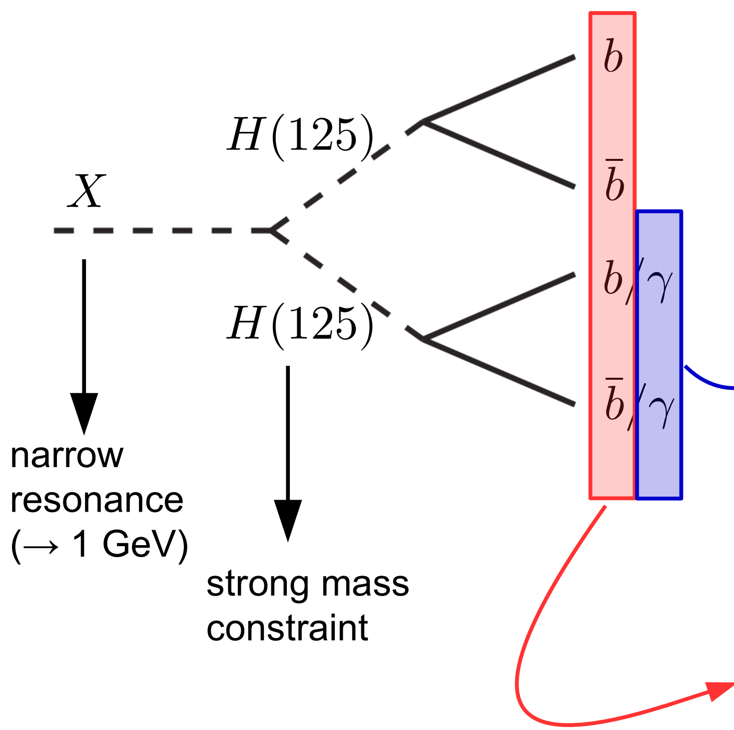
$H \to \mu\tau$ Input distributions





$X \to HH$

- Within the SM $\sigma(gg \to HH, 8\ \mathrm{TeV}) \approx 10\ \mathrm{fb}^{-1}$ is out of reach for current analyses.
- But in BSM models like Warped Extra Dimensions (WED) $\sigma(H \to HH)$ can be enhanced by several orders of magnitude.
- This motivates searches for resonant decay into ("SM") Higgs bosons:



$X \to H(\gamma\gamma)H(bb)$ CMS-PAS-HIG-13-032

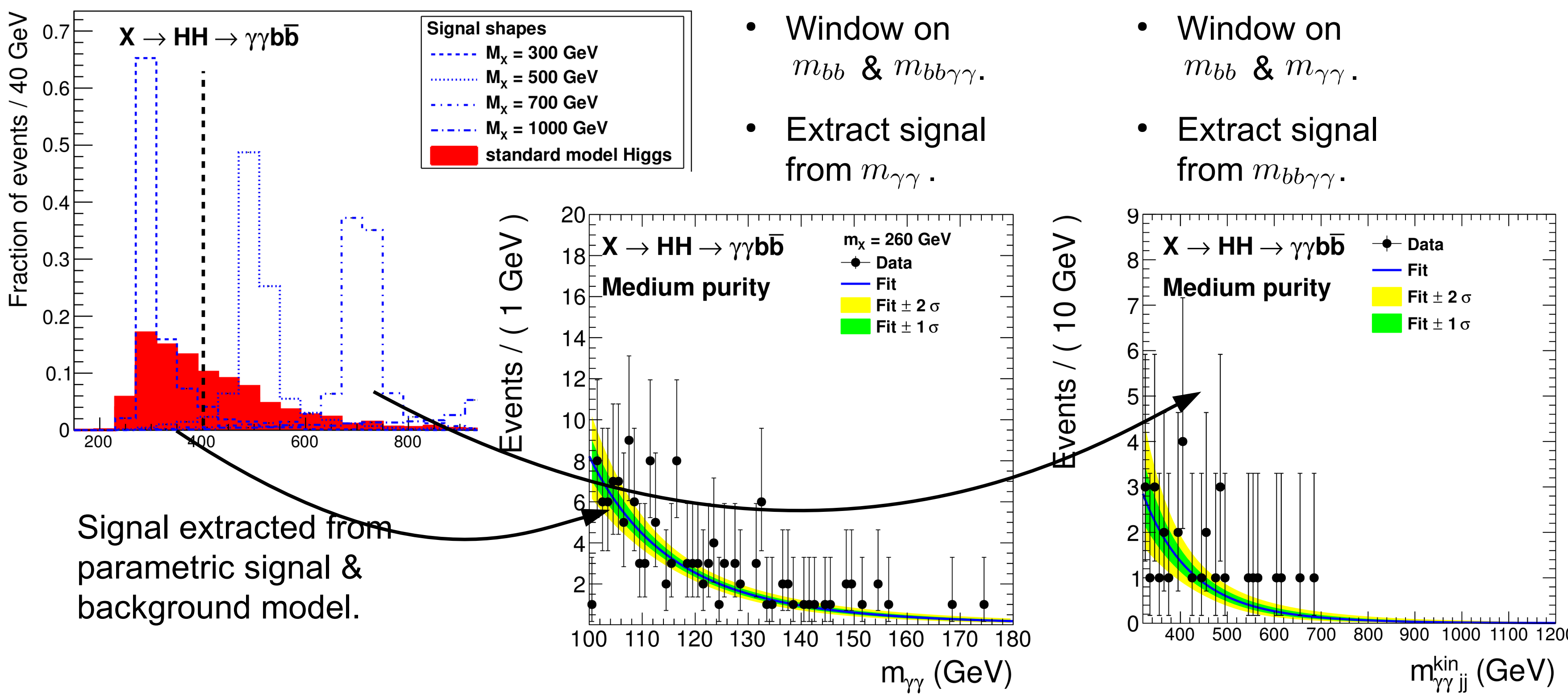
- High resolution of $m_{\gamma\gamma}$.
- High BR of $BR(H \to bb) = 0.57$.

$X \to H(bb)H(bb)$ CMS-PAS-HIG-14-013

- High BR of $BR(H \to bb) = 0.57$.

$X \to H(\gamma\gamma)H(bb)$

- Same γ reconstruction as for cut based $H \to \gamma\gamma$ SM cross check analysis.
- Two event categories: medium(high) purity $\to$ 1(2) b-tagged jets.
- Improved (b-)jet energy resolution by kinematic fit (cf. 4b analysis).



Signal extracted from parametric signal & background model.

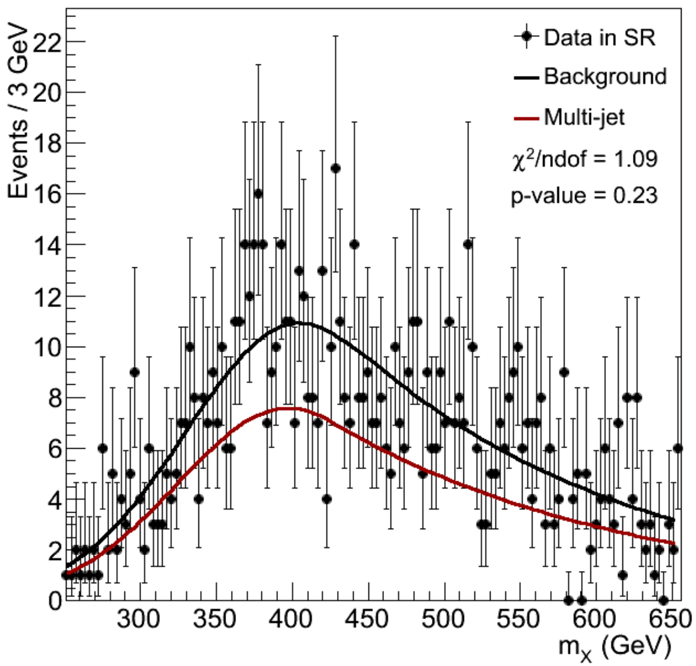
- Window on m_{bb} & $m_{bb\gamma\gamma}$.
- Extract signal from $m_{\gamma\gamma}$.

- Window on m_{bb} & $m_{\gamma\gamma}$.
- Extract signal from $m_{bb\gamma\gamma}$.

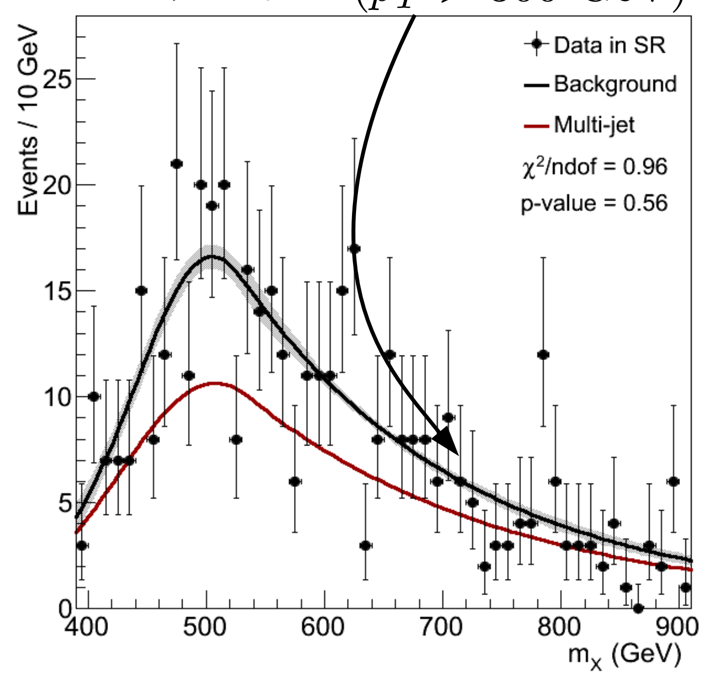
$X \to H(bb)H(bb)$

- Select 4 b-jets w/ highly efficient b-tagging algorithm (CVMVA $\epsilon = 75\%,\ f = 3.4\%$).
- Improved (b-)jet energy resolution by kinematic fit (20-40%).
- Distinguish high(low) mass region for association of b-jets to h(125) candidate.

$|m_H^{\text{rec}} - 125\ \text{GeV}| < 35\ \text{GeV}$

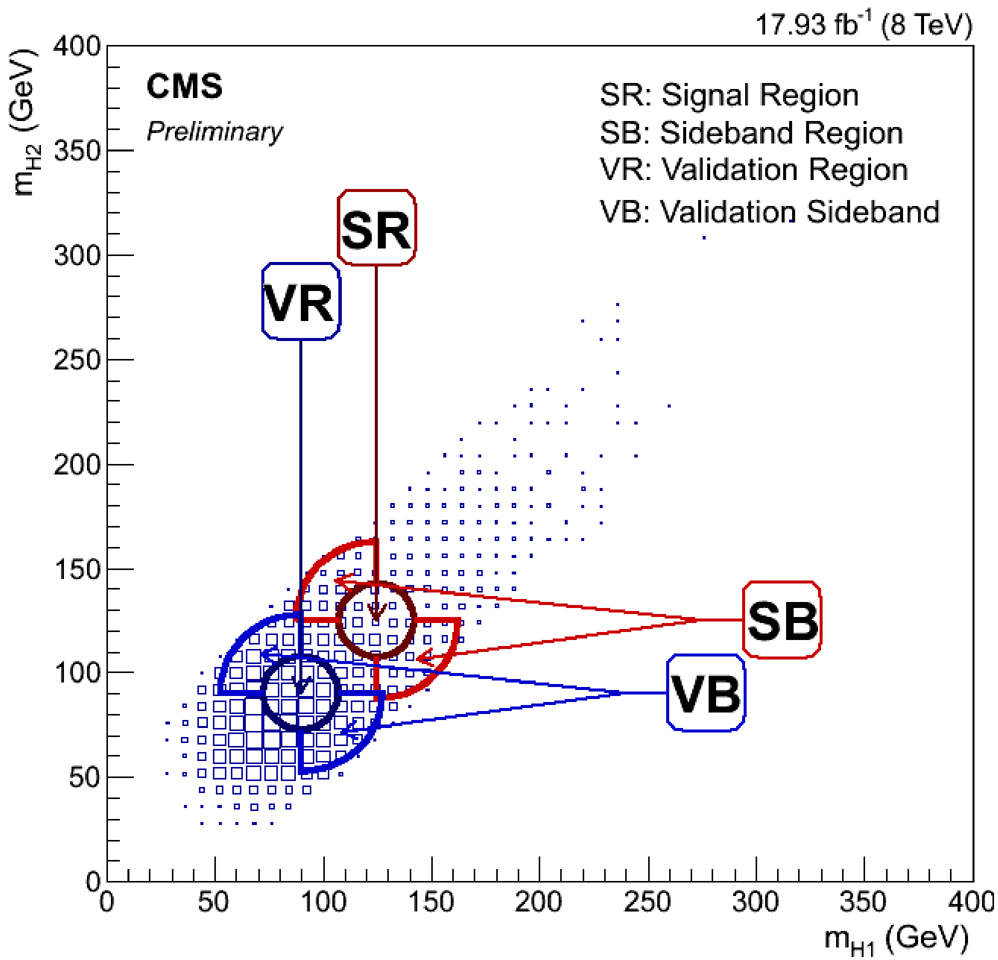


$\Delta R > 1.5 \qquad (p_T > 300\ \text{GeV})$

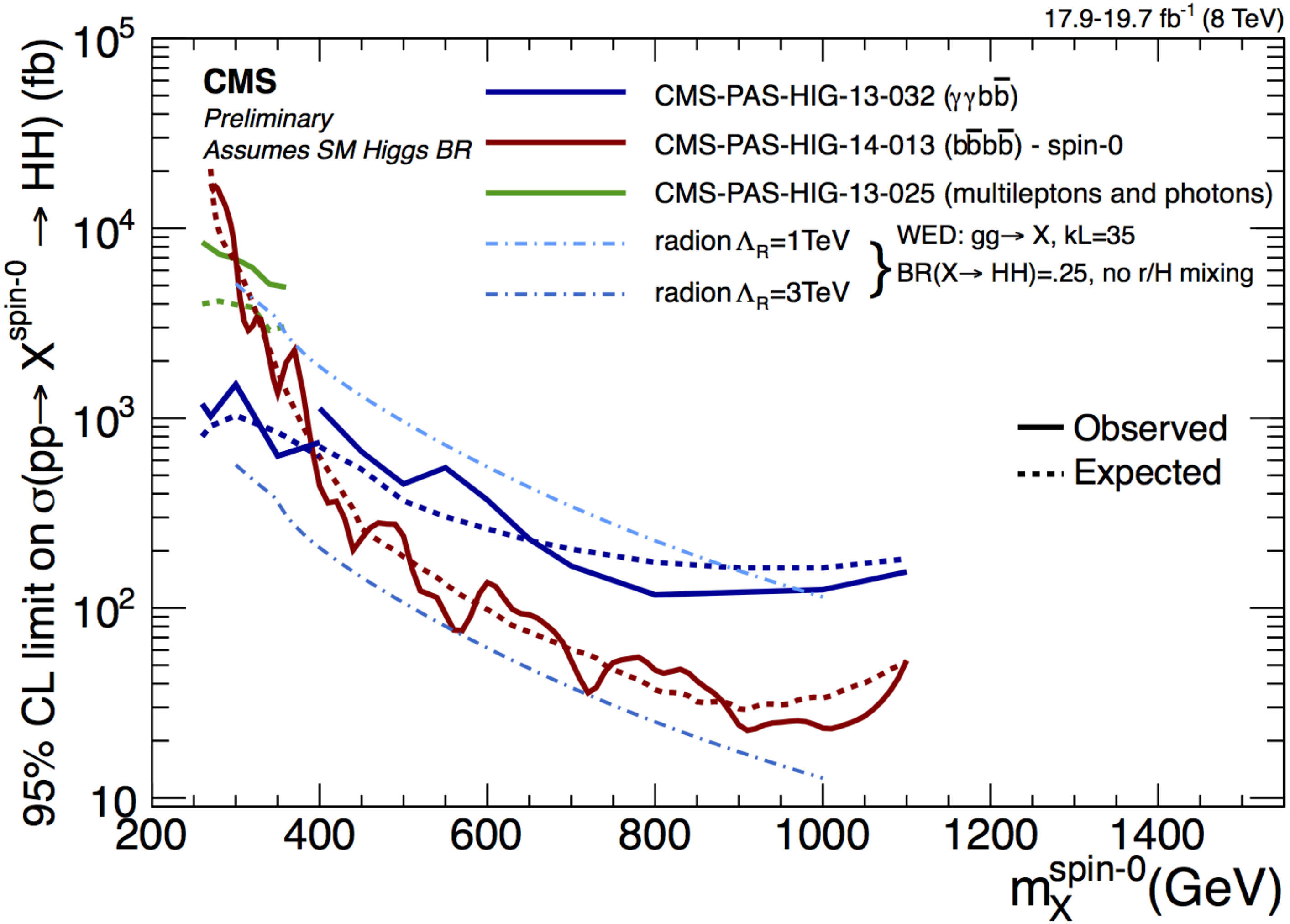


- Extract signal from parametric signal and BG model (→BG: 20% $t\bar{t}$, 80% QCD).

$X \to H(bb)H(bb)$: Template validation



$X \rightarrow HH$: Spin-0 result



$X \to HH$: Spin-2 result