Karlsruhe Institute of Technology

The Case of τ Final States in Higgs Physics (at the LHC)

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Road map...

- **Front page:** Higgs why & what?
- The **discovery** and role of the di-τ final state.
- Search for **LFV** in the Higgs sector.
- Di-τ final states and **CP** measurements.
- Search for additional Higgs bosons in **extensions of the SM**.

Disclaimer:

- This is a personal choice of topics, which are strongly τ-lepton related.
- When discussing results and measurements I will mostly stick to CMS.
- Since all results are well known in the meantime I will stick to the principles/physics part more than the technical details of the analyses.

Higgs: why & what?

- **Question:** how can the $SU(2)_L \times U(1)_Y$ symmetry be the source of electroweak interactions and at the same time elementary particle masses $\neq 0$, which explicitly break this symmetry.

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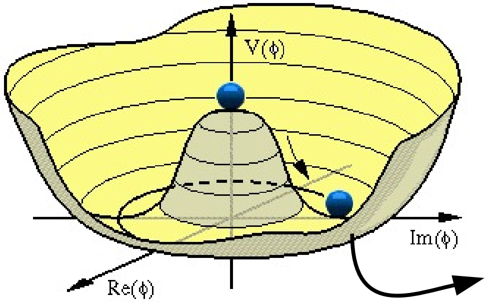
- **Answer :** Higgs-mechanism

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

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



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 lead to the existence of new physical particles (→ Higgs boson(s)).

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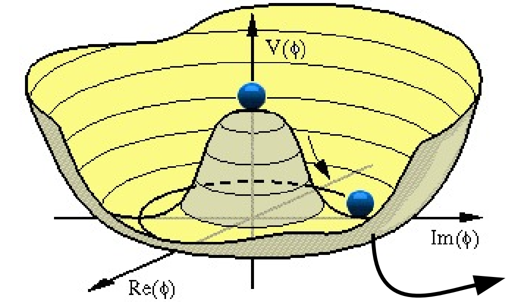

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- In a quantum field theory (QFT) this can lead to the existence of new physical particles (→ Higgs boson(s)).

- A Higgs boson has very a peculiar coupling structure, needed to preserve the symmetry of the system:

$f_{H\to ff} = i\frac{m_f}{v}$ (trilinear coupling to fermions)

$f_{H\to VV} = i\frac{2m_V^2}{v}$ (trilinear coupling to vector bosons)

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4th of July 2012

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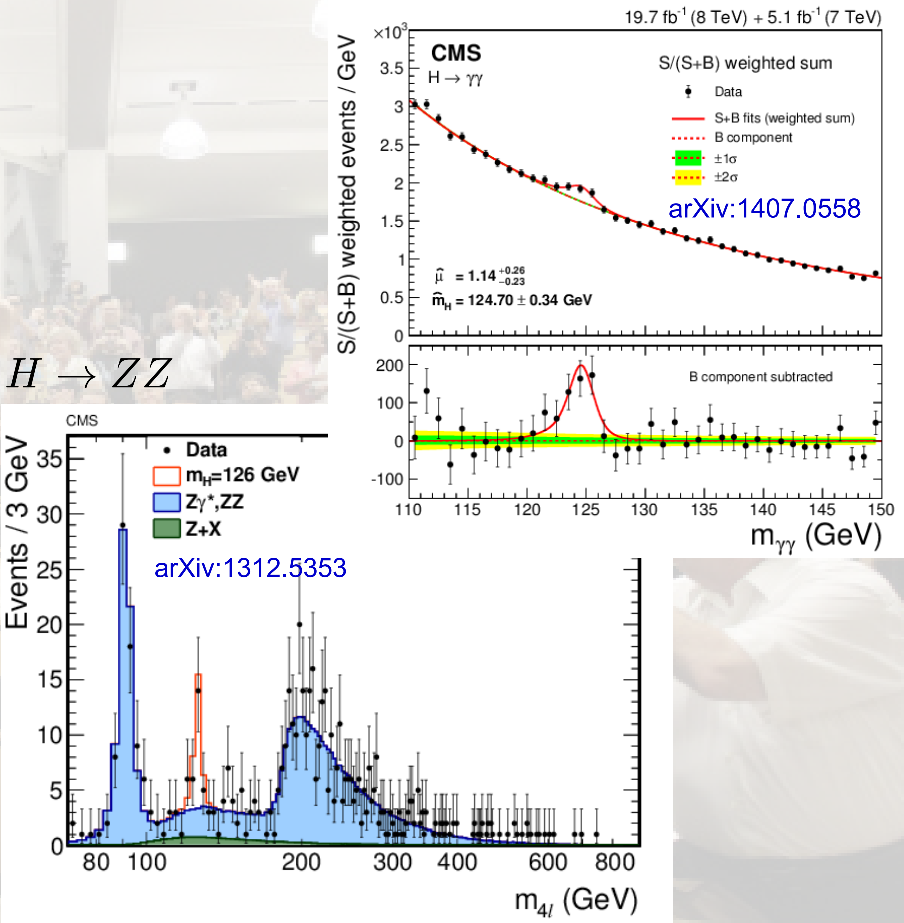
$H \to \gamma\gamma$

4th of July 2012

$H \to ZZ$

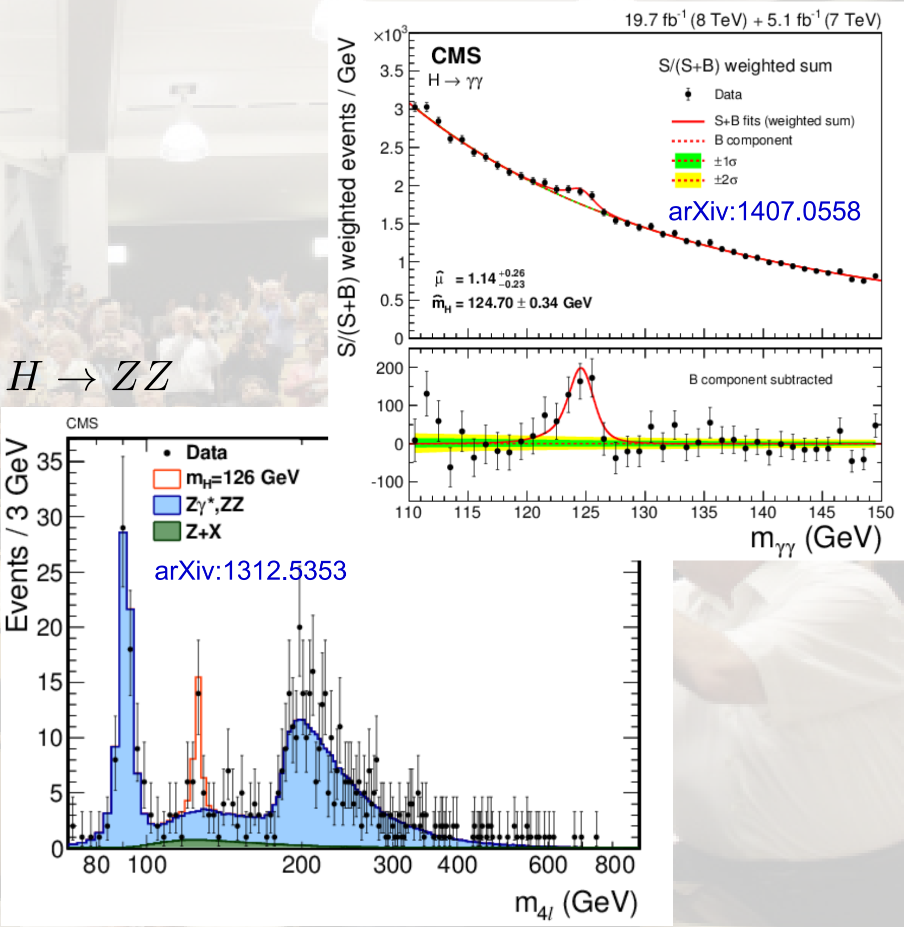


Higgs: a known suspect

- We know it exists (arXiv:1207.7235)!
- We know its a boson.
- We know its mass:

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\text{GeV}$$

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

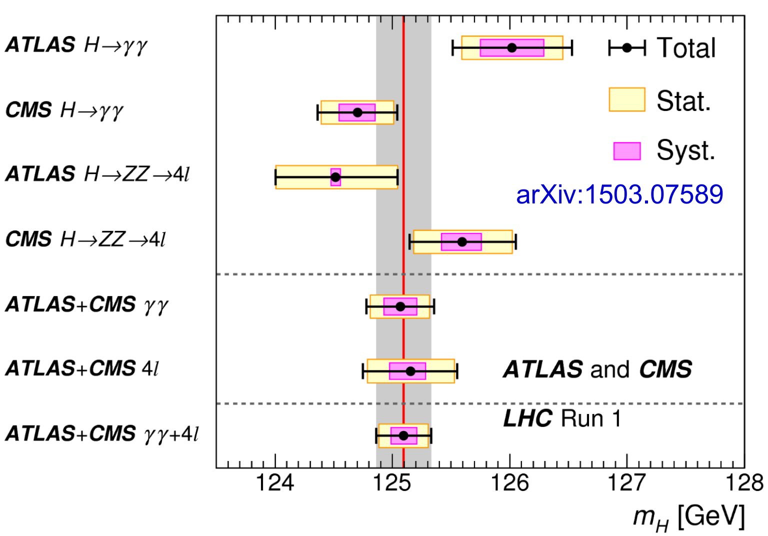


arXiv:1407.0558

$H \to ZZ$

arXiv:1312.5353

$H \to ZZ + H \to \gamma\gamma$



arXiv:1503.07589

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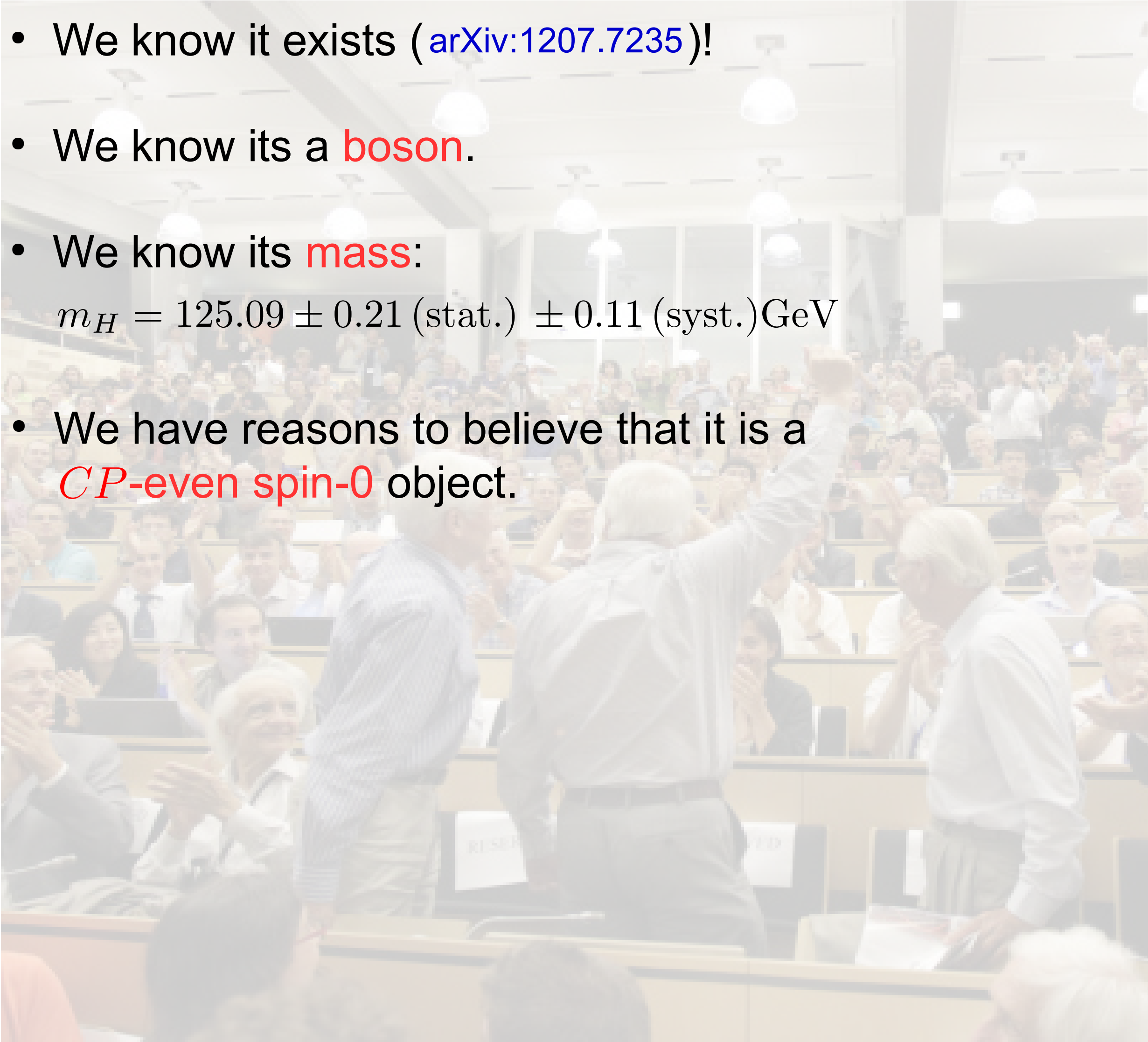

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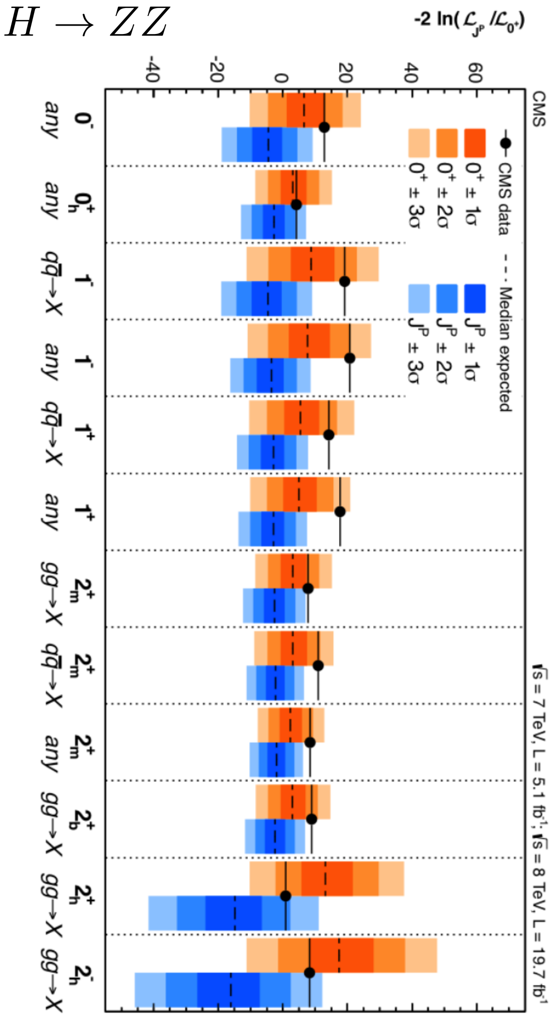
- We have reasons to believe that it is a CP-even spin-0 object.



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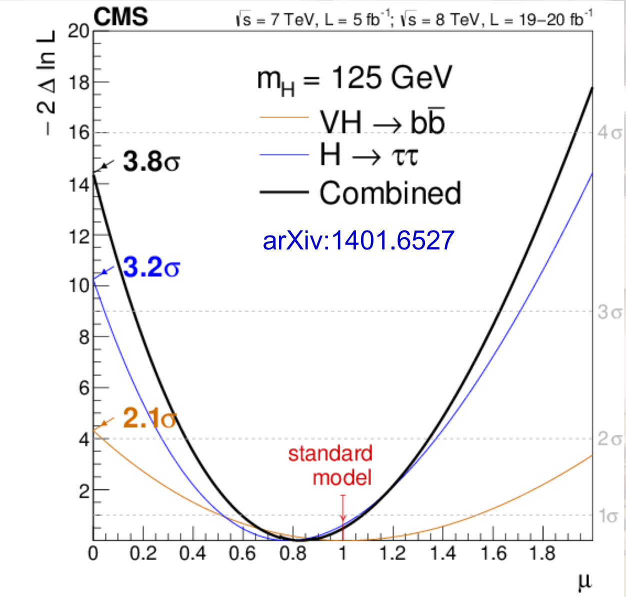
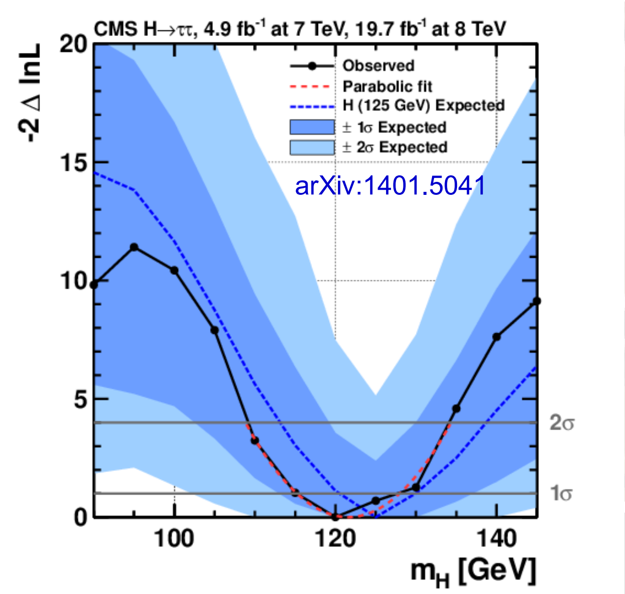


arXiv:1401.6527



arXiv:1401.5041

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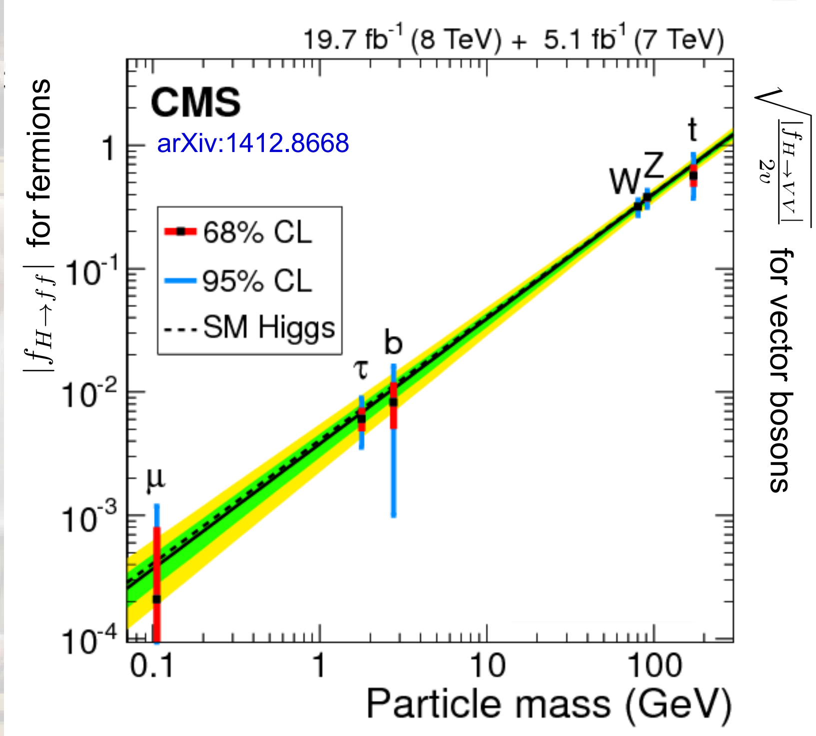
- We have strong evidence that it couples to fermions.
- We know it's a Higgs boson!

$$|f^{\text{obs}}_{H\to ff}| = \kappa_f \cdot |f^{\text{SM}}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

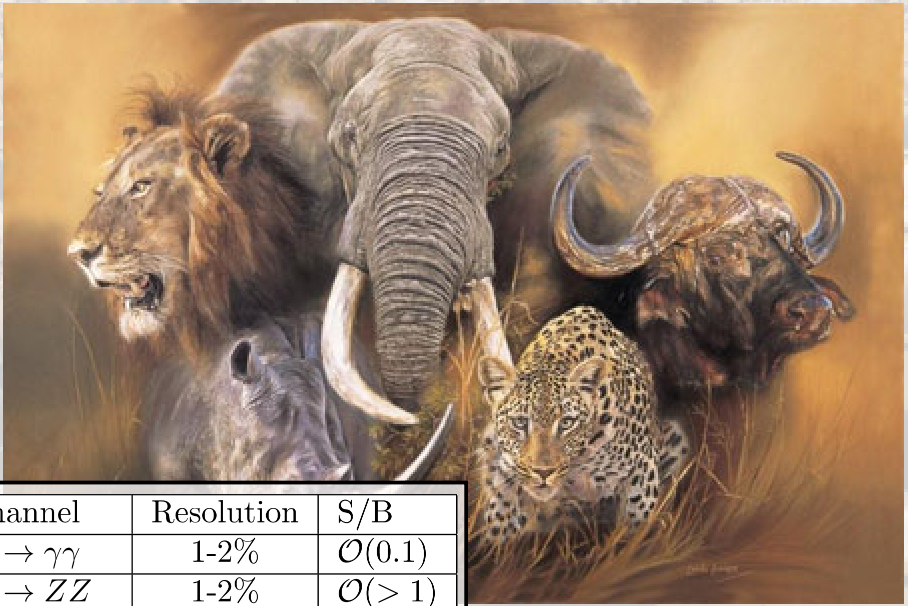
$$\sqrt{\frac{|f^{\text{obs}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{|f^{\text{SM}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \frac{m_V}{v} \qquad V = W, Z$$

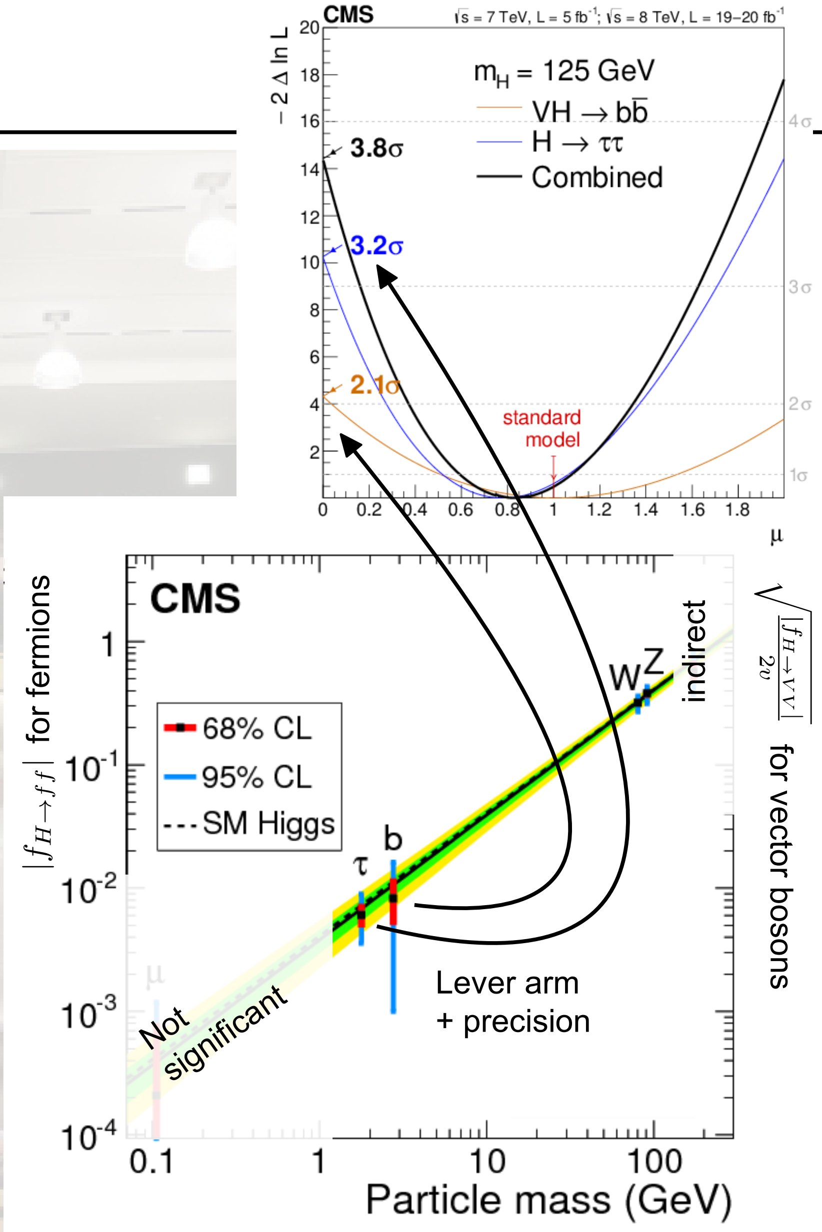


Higgs: the role of τ-leptons

- Most convincing part of evidence for Higgs boson like coupling to fermions comes from $H \rightarrow \tau\tau$.

- $H \rightarrow \tau\tau$ is a crucial part of our current understanding of the Higgs sector.





Channel	Resolution	S/B
$H \rightarrow \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
$H \rightarrow ZZ$	1-2%	$\mathcal{O}(>1)$
$H \rightarrow WW$	20%	$\mathcal{O}(1)$
$H \rightarrow b\bar{b}$	10%	$\mathcal{O}(0.1)$
$H \rightarrow \tau\tau$	15%	$\mathcal{O}(0.1)$

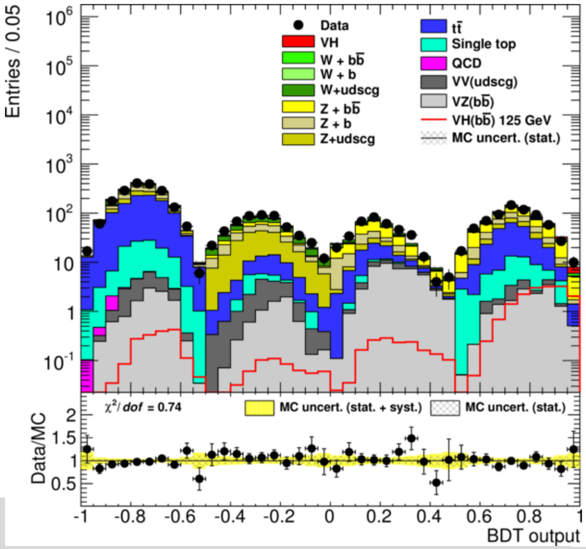
Higgs: the role of τ-leptons

- Event yields from pure $\sigma \times BR$ (i.e. before any reconstruction & selection):

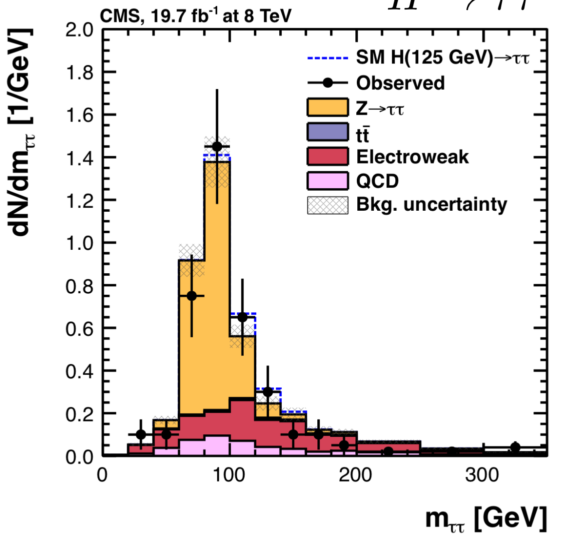
Decay Channel	$\sqrt{s} = 8$ TeV, 20 fb^{-1} inclusive	$\sqrt{s} = 13$ TeV, 300 fb^{-1} inclusive	$gg \to H$	$qq \to H$	WH	ZH	$t\bar{t}H$
$\gamma\gamma$	1 000	33 000	30 000	2 300	1 000	700	300
ZZ	50	1 500	1 300	100	50	30	15
WW	5 000	150 000	130 000	10 000	4 500	3 000	1 500
$b\bar{b}$	12 000 (*)	400 000	350 000	30 000	12 000	10 000	40 000
$\tau\tau$	30 000	1 000 000	900 000	70 000	30 000	20 000	10 000
$\mu\mu$	100	3 000	2 500	200	90	60	30

- Typical environment:
  - $H \to b\bar{b}$ subject to fierce environment.
  - Much cleaner selection in $H \to \tau\tau$.
  - Backgrounds easier to control.

$H \to b\bar{b}$



$H \to \tau\tau$

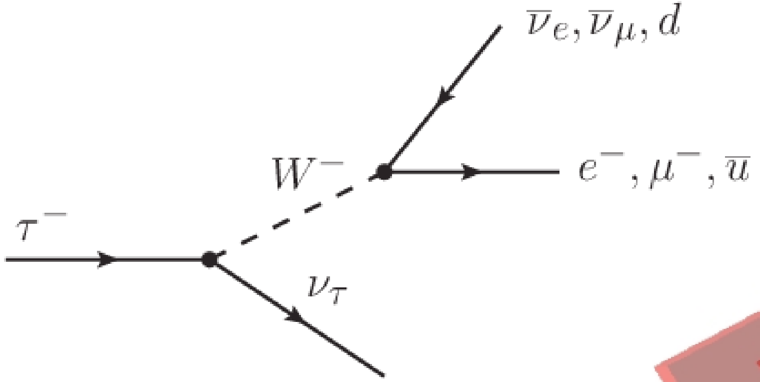


(*) in VH production mode.

Search for Higgs bosons in the di-τ final state

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%

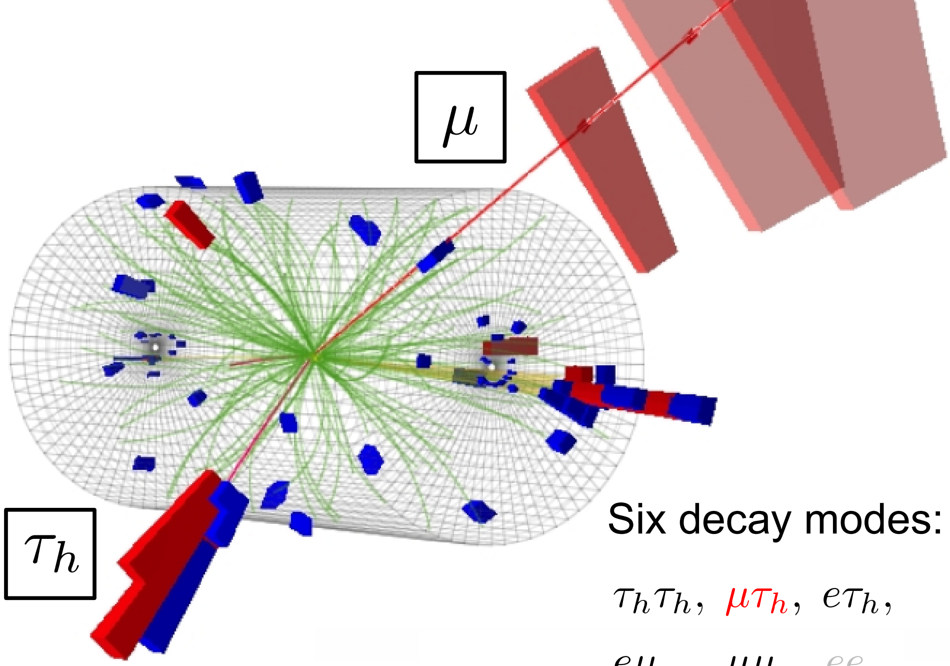
$> 50\%$ of all decay modes.



- 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.

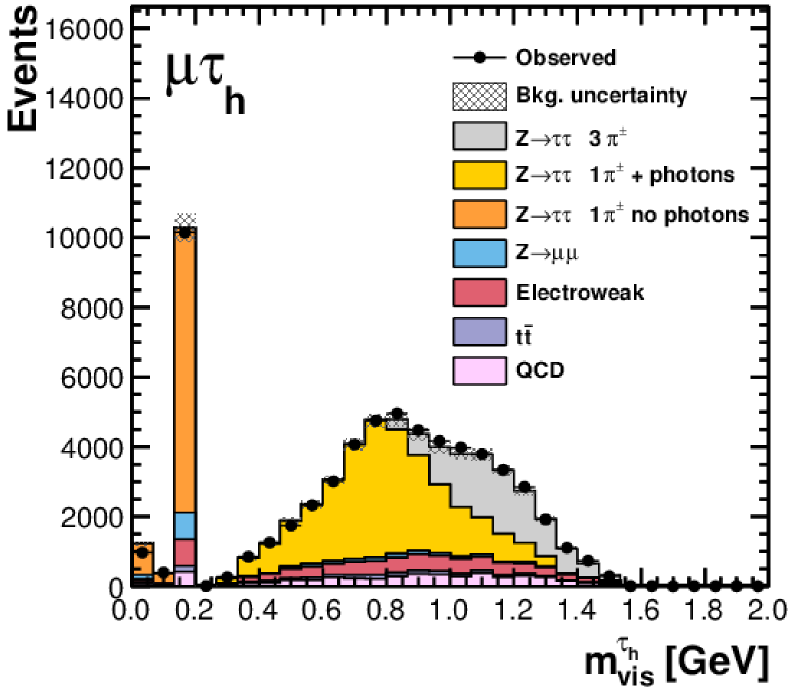


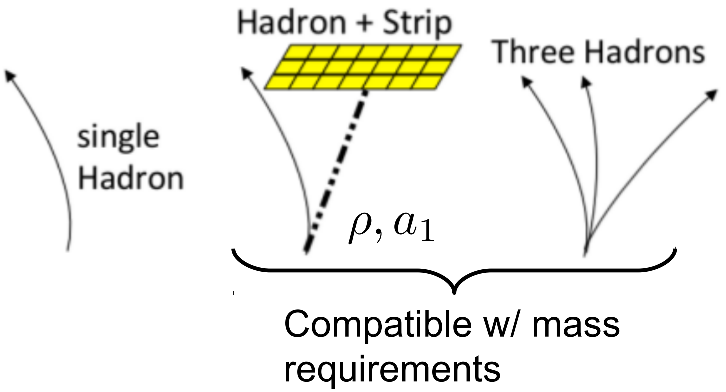
Six decay modes:

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

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

Reconstruction of hadronic τ-leptons

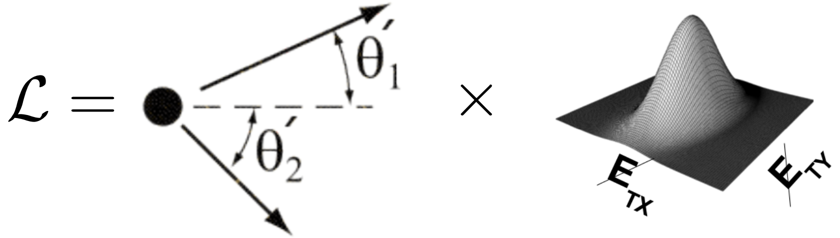




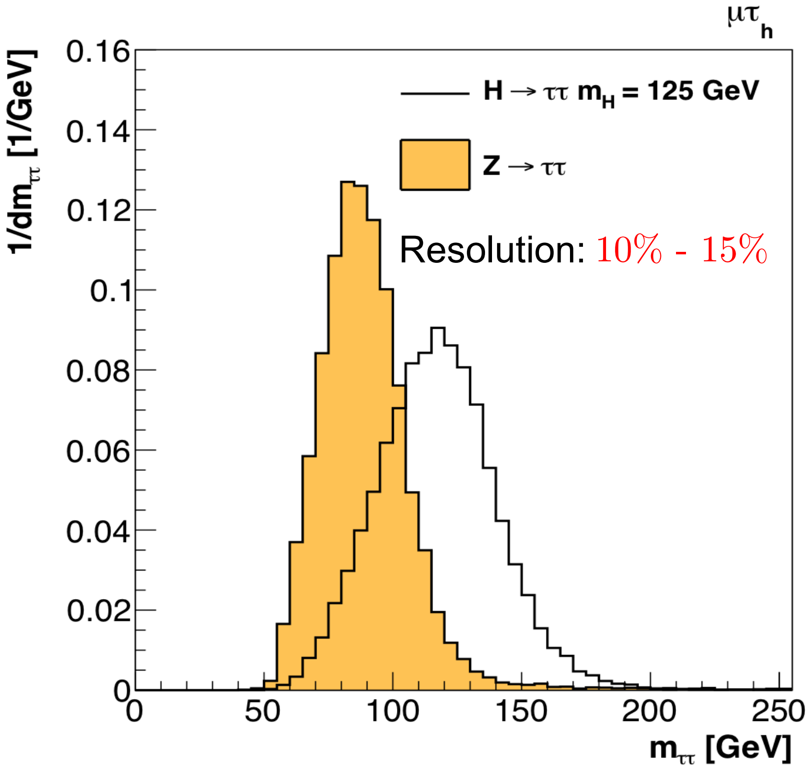
- Exploit particle flow algorithm: distinguish between γ, $\mathrm{neutral}$ and $\mathrm{charged\ hadron}$.
  - Isolation (based on energy deposits in vicinity of reconstructed τ_h candidate).
  - Discrimination against electrons (based on shower shape & E/p).
  - Discrimination against muons.
  - Allows 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.

$Z \rightarrow \tau\tau$

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

$Z \rightarrow \ell\ell$

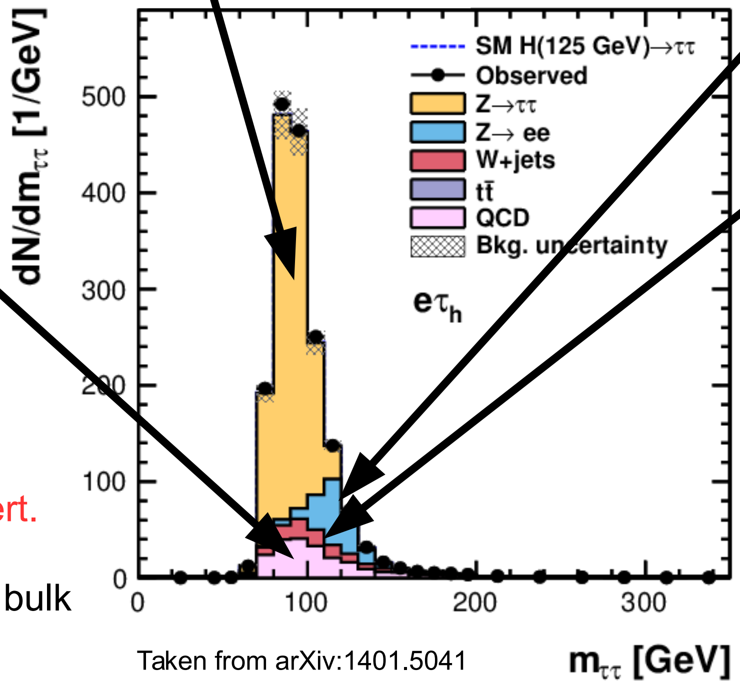
- From simulation
- Corrected for $jet \rightarrow \tau$ or $e/\mu \rightarrow \tau$ fakerate.

QCD multijet

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

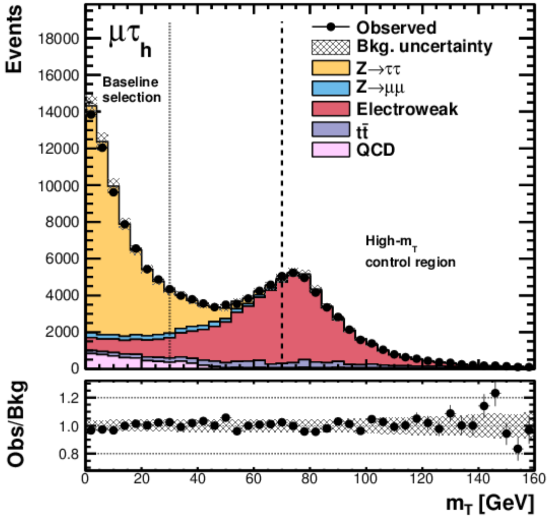
$W + jets$, Diboson

- From simulation
- Normalization from sidebands.



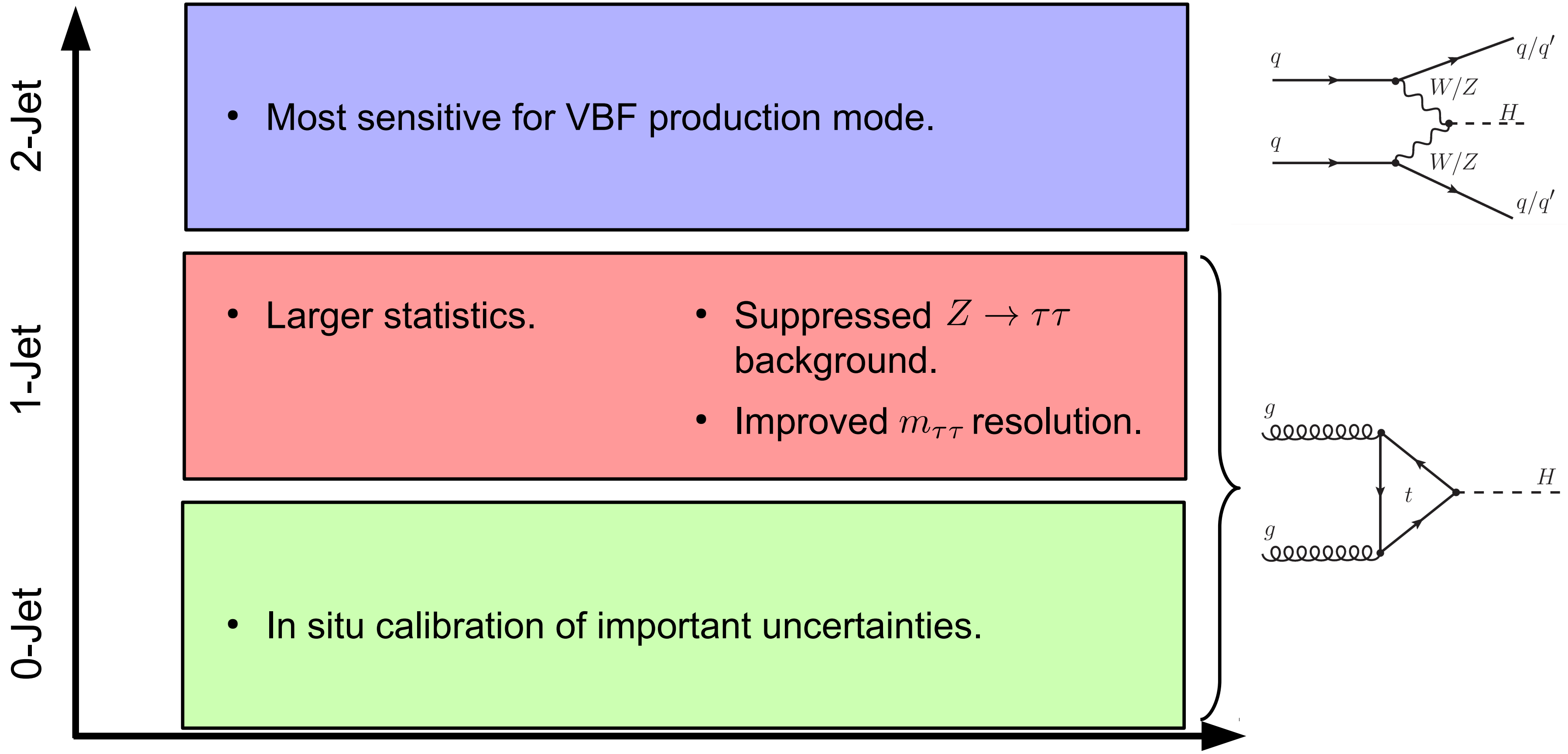
- Full consideration of uncert. due to limited statistics in control or MC samples in bulk of distributions.

Taken from arXiv:1401.5041



Further event categorization

- Further event categorization to increase sensitivity of the analysis:



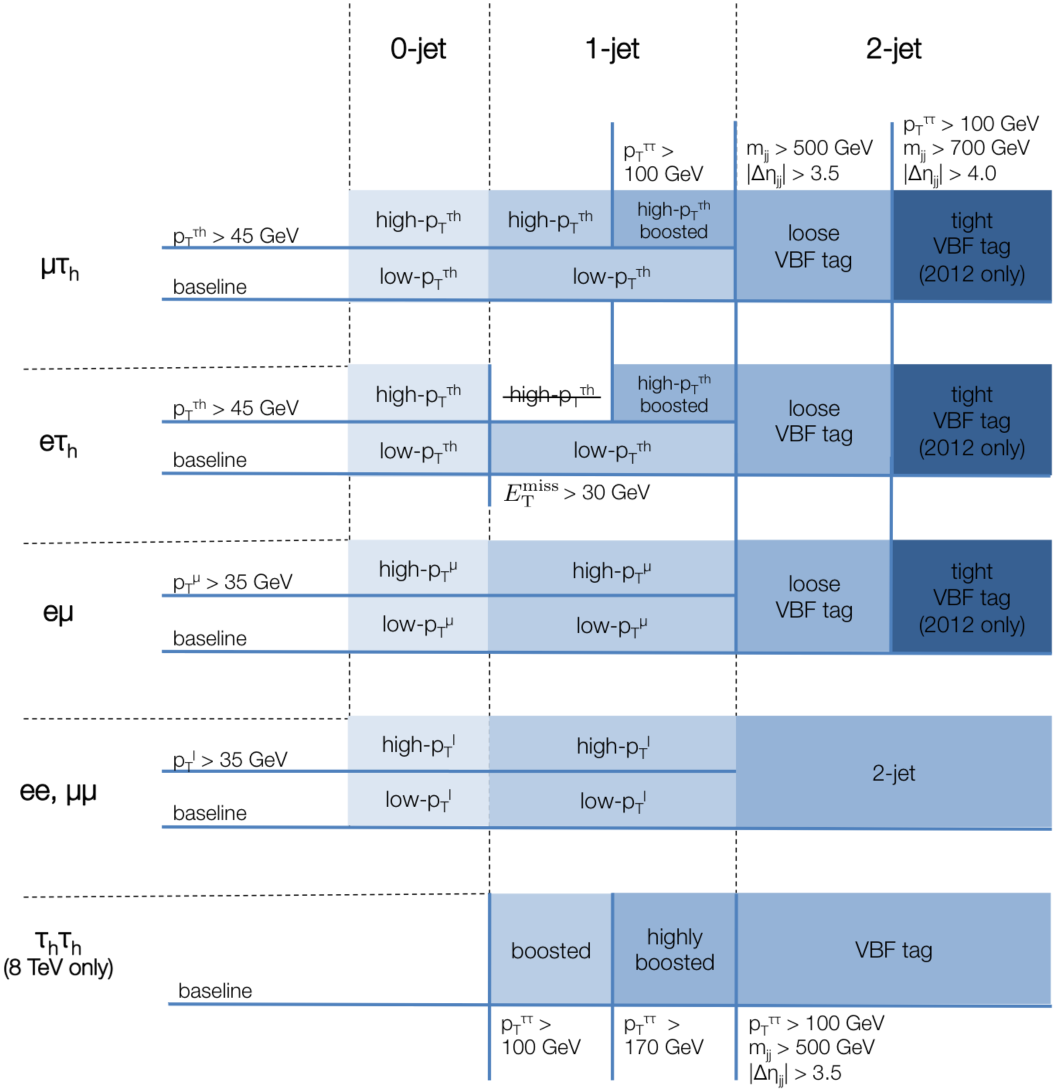
- Most sensitive for VBF production mode.

- Larger statistics.
- Suppressed $Z \rightarrow \tau\tau$ background.
- Improved $m_{\tau\tau}$ resolution.

- In situ calibration of important uncertainties.

Increasing p_T of τ or μ .

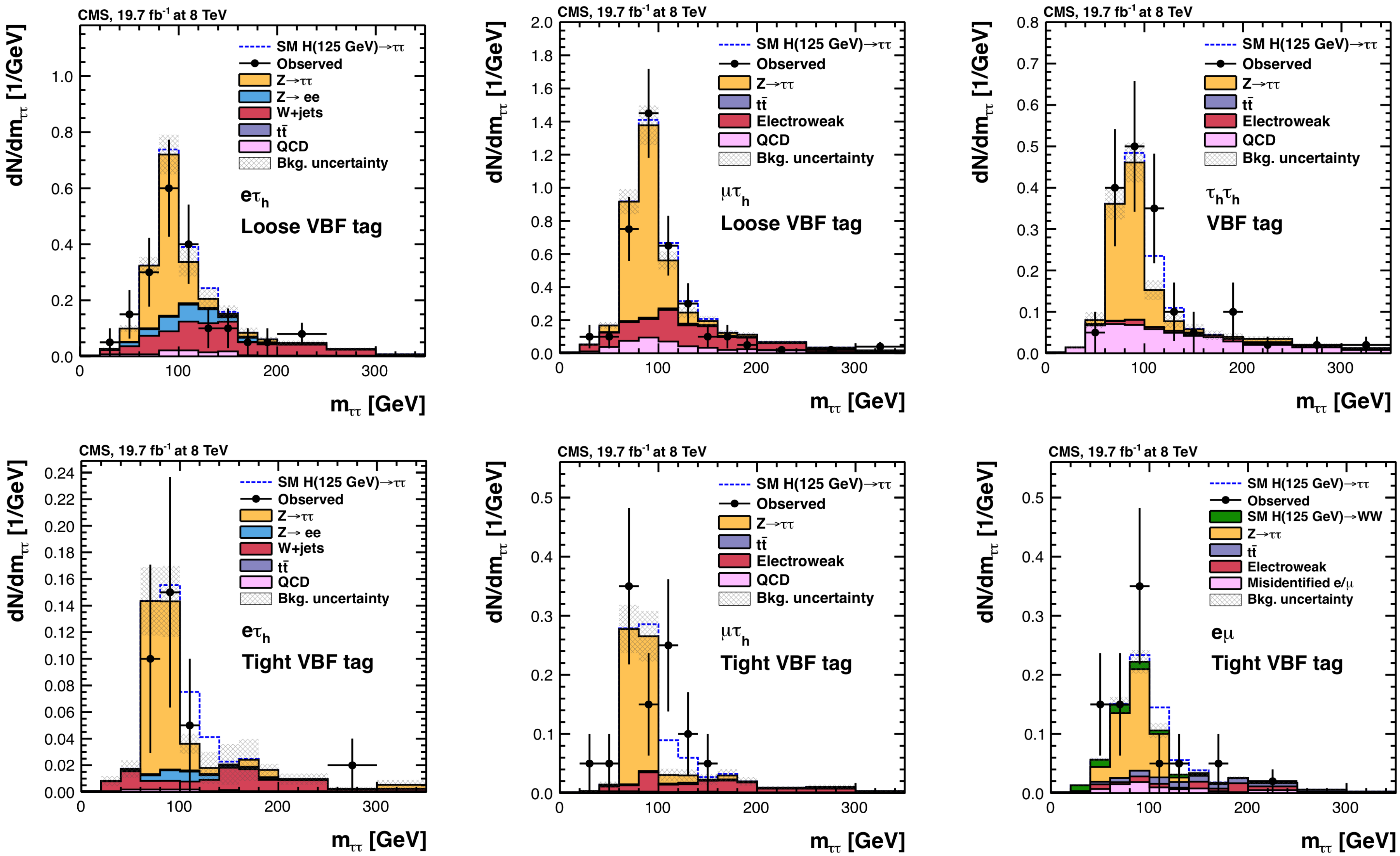
Further event categorization



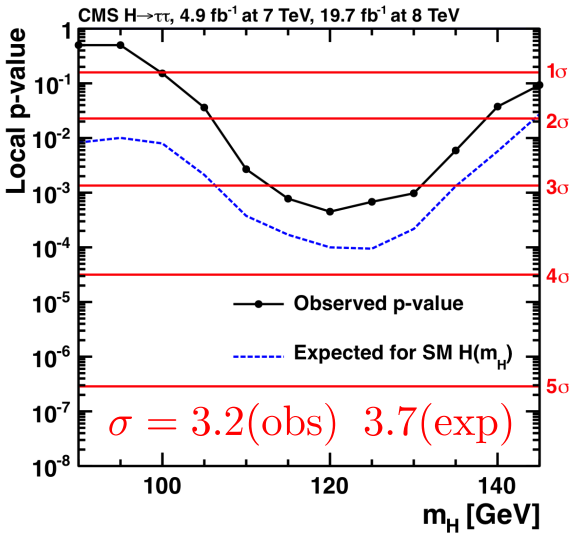
		0-jet	1-jet		2-jet	
				$p_T^{\tau\tau} >$ 100 GeV	$m_{jj} >$ 500 GeV $\lvert\Delta\eta_{jj}\rvert >$ 3.5	$p_T^{\tau\tau} >$ 100 GeV $m_{jj} >$ 700 GeV $\lvert\Delta\eta_{jj}\rvert >$ 4.0
$\mu\tau_h$	$p_T^{\tau h} >$ 45 GeV	high-$p_T^{\tau h}$	high-$p_T^{\tau h}$	high-$p_T^{\tau h}$ boosted	loose VBF tag	tight VBF tag (2012 only)
	baseline	low-$p_T^{\tau h}$	low-$p_T^{\tau h}$			
$e\tau_h$	$p_T^{\tau h} >$ 45 GeV	high-$p_T^{\tau h}$	~~high-$p_T^{\tau h}$~~	high-$p_T^{\tau h}$ boosted	loose VBF tag	tight VBF tag (2012 only)
	baseline	low-$p_T^{\tau h}$	low-$p_T^{\tau h}$ $E_T^{\text{miss}} >$ 30 GeV			
$e\mu$	$p_T^{\mu} >$ 35 GeV	high-p_T^{μ}	high-p_T^{μ}		loose VBF tag	tight VBF tag (2012 only)
	baseline	low-p_T^{μ}	low-p_T^{μ}			
ee, $\mu\mu$	$p_T^{l} >$ 35 GeV	high-p_T^{l}	high-p_T^{l}		2-jet	
	baseline	low-p_T^{l}	low-p_T^{l}			
$\tau_h\tau_h$ (8 TeV only)	baseline		boosted	highly boosted	VBF tag	
			$p_T^{\tau\tau} >$ 100 GeV	$p_T^{\tau\tau} >$ 170 GeV	$p_T^{\tau\tau} >$ 100 GeV $m_{jj} >$ 500 GeV $\lvert\Delta\eta_{jj}\rvert >$ 3.5	

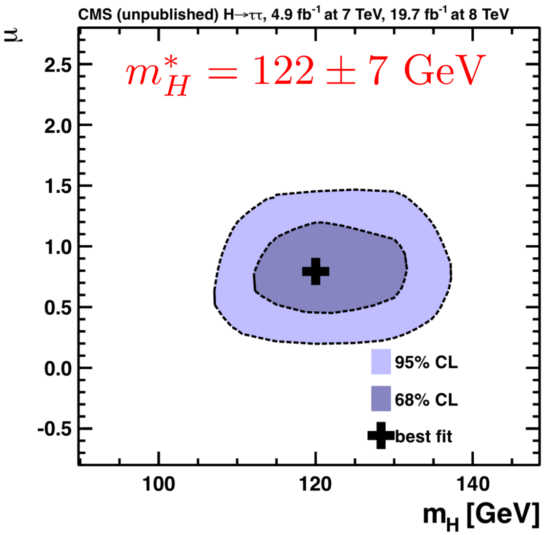
- ~80 exclusive event categories.
- 6 inclusive decay channels.
- Exclusive decay channels for production in association with W, Z bosons.
- On 7 TeV and 8 TeV dataset.
- $\mathcal{O}(700)$ nuisance parameters in ML fit for signal extraction.

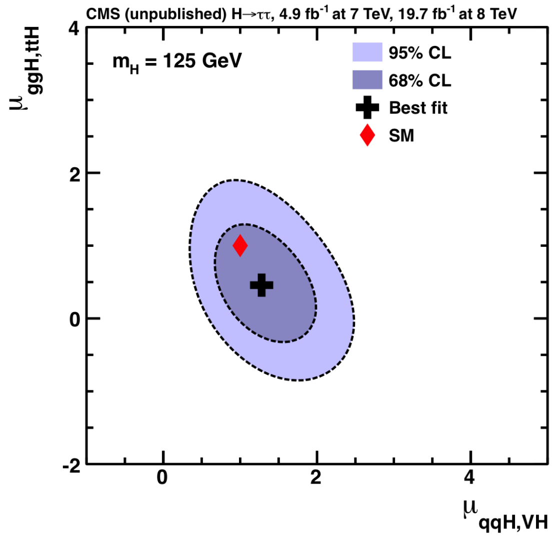
Distribution of $m_{\tau\tau}$ (arXiv:1401.5041)

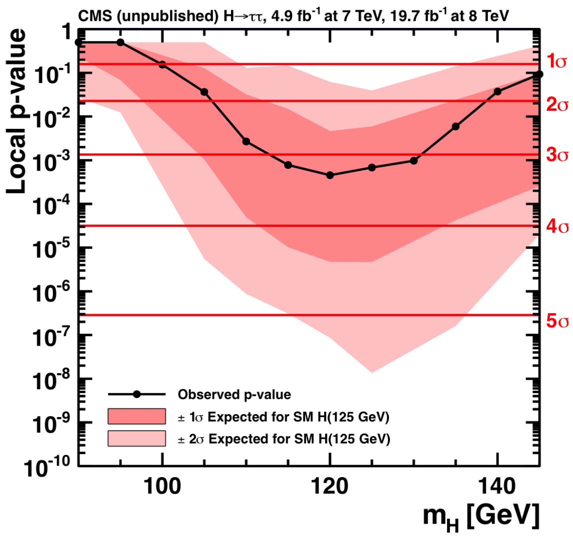


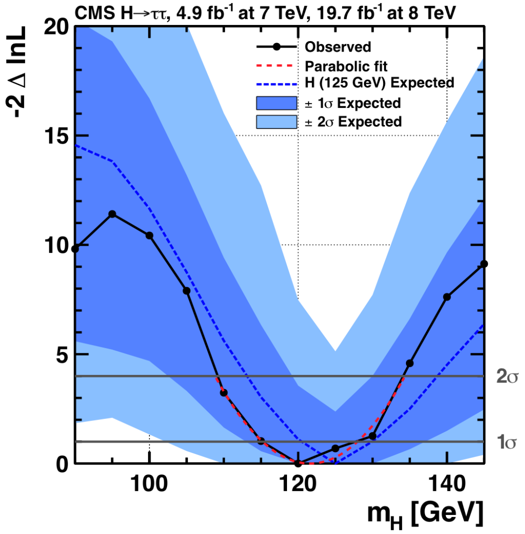
3σ Evidence of Higgs coupling to fermions

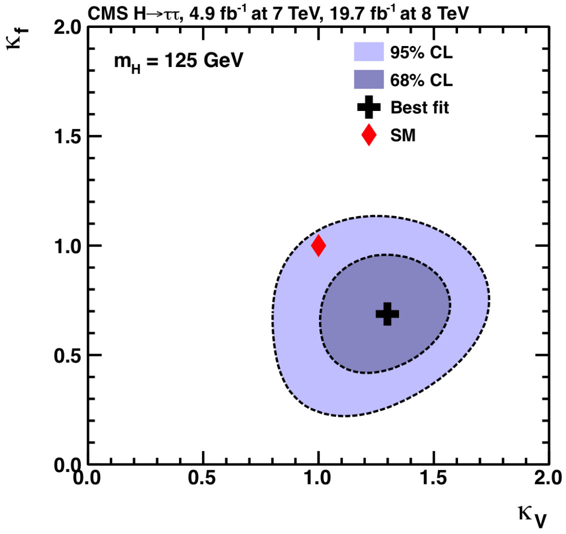






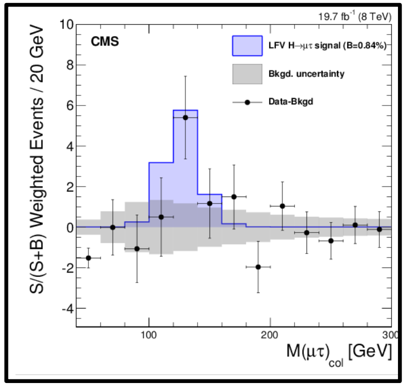


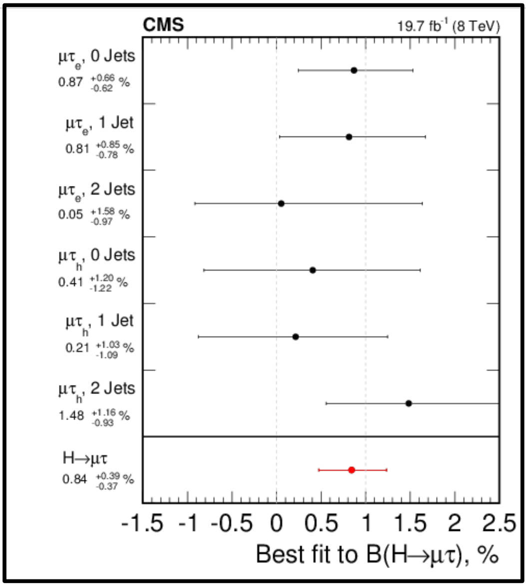


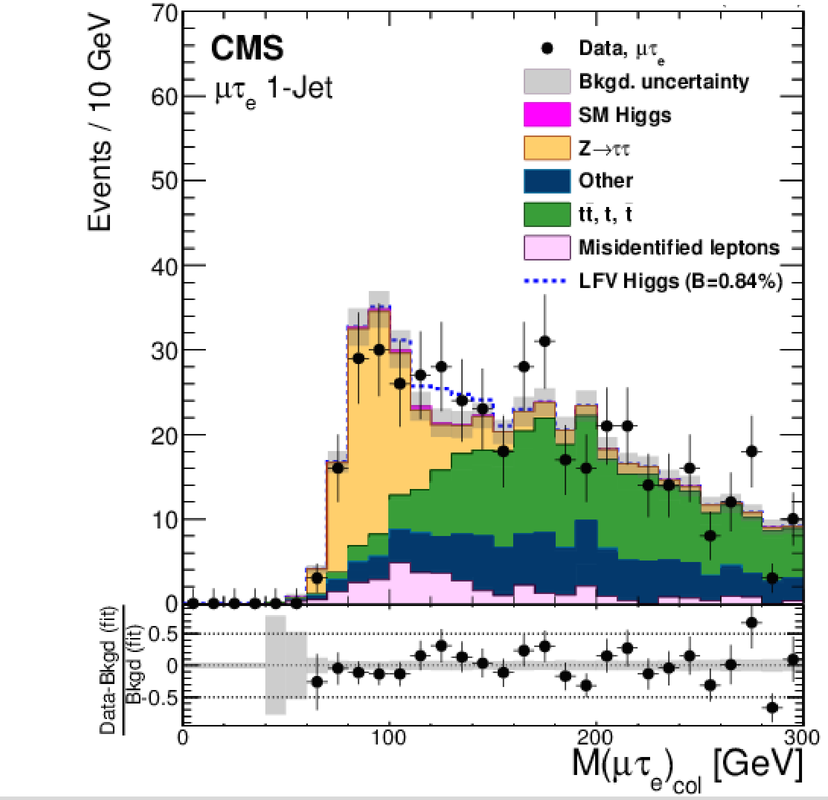


$H \to \mu\tau$ LFV Higgs couplings (arXiv:1502.07400)

- 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:
  - $BR(H \to e\mu) = \mathcal{O}(10^{-8})$.
  - $BR(H \to e\tau) = \mathcal{O}(0.1)$.
  - $BR(H \to \mu\tau) = \mathcal{O}(0.1)$.



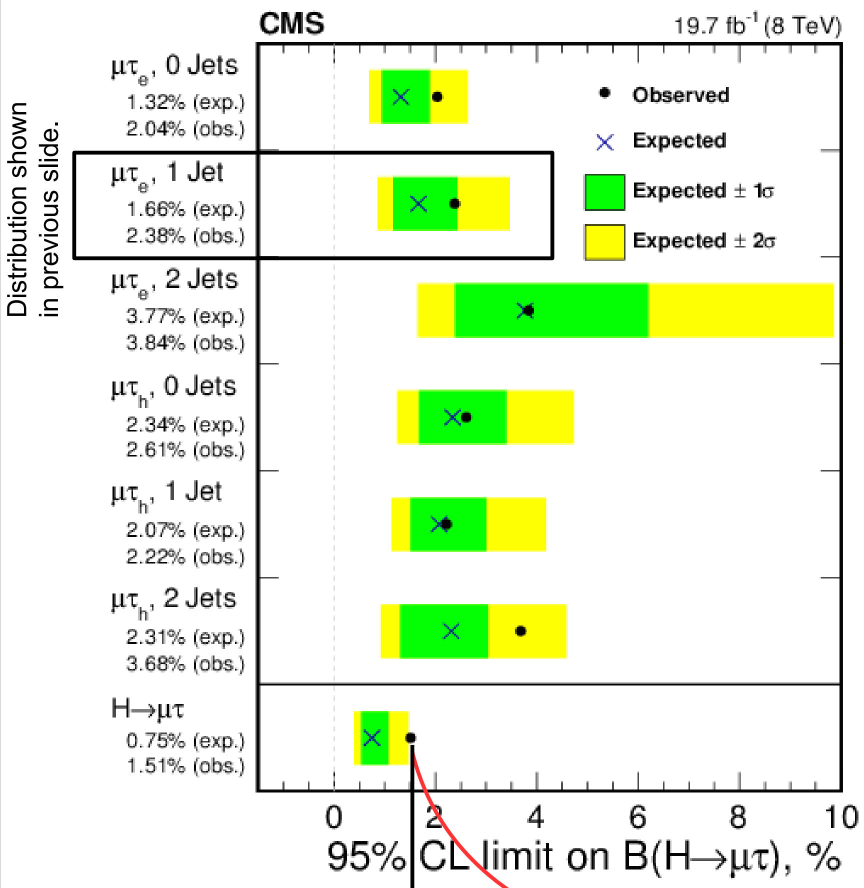


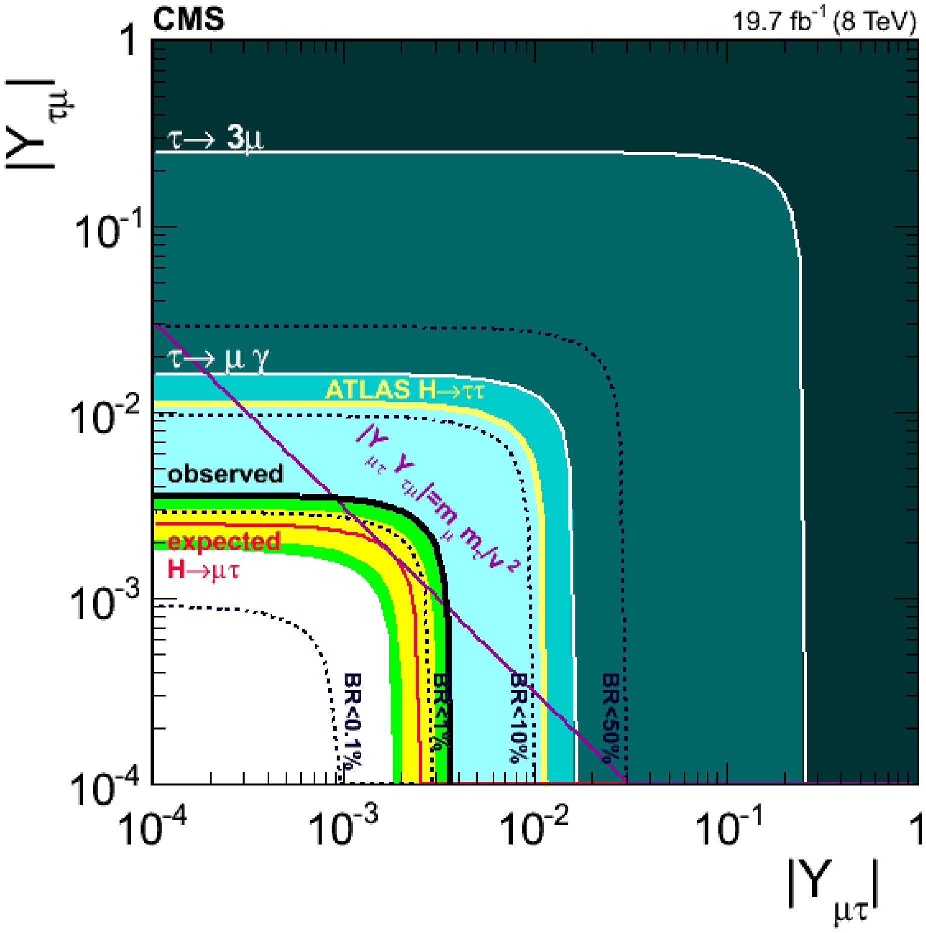


$H \to \mu\tau_h/\mu\tau_e$ analysis w/ two specialties:

- $p_T(\mu)$ is harder (→ 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





1.51% @ 95% CL

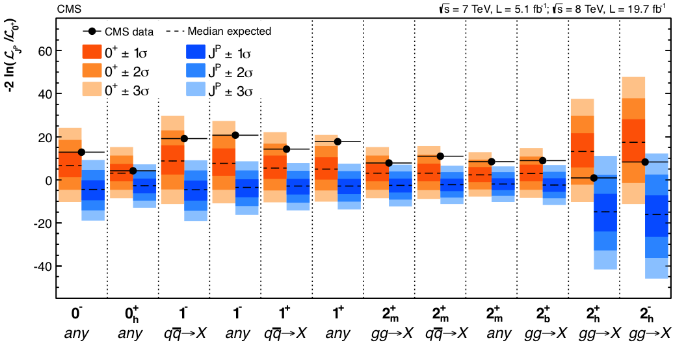
$\approx 2.5\sigma$ excess

Strongest limits on the market!

Higgs: CP properties (from $H \to ZZ$)

- Up to now CP could seriously only be studied from angular analyses in $H \to ZZ$ decays.

- From this we know: Higgs seems to be spin-0, CP-even.



BUT

- Both in the SM as well as in any extension that is being discussed at the moment a CP-odd Higgs boson (component) would not couple to vector bosons at tree level (→only know the expected)!

- In $H \to f\bar{f}$ a CP-odd coupling of the Higgs boson can easily be incorporated at tree level:

CP violating phase

$$\mathcal{L}_Y = -N\left(\cos\phi\,\bar{\tau}\tau + \sin\phi\,\bar{\tau}i\gamma_5\tau\right)H$$

CP-odd Yukawa coupling

Higgs: CP properties (from $H \rightarrow f\bar{f}$)

- Obtain P from an angular momentum analysis of the QM system:

Orbital momentum:

$P(Y_l^m(\theta,\varphi)) = (-1)^l \cdot Y_l^m(\theta,\varphi)$

×

Intrinsic parity of fermions:

$P(f) = (+1) \cdot f$ $P(\bar{f}) = (-1) \cdot f$

- Obtain C from $P \times (\pm 1)$ for permutations of objects (→spin statistics):

$$\left.\begin{aligned} |1,\pm1\rangle &= |{}^1\!/_2,\pm{}^1\!/_2\rangle \otimes |{}^1\!/_2,\pm{}^1\!/_2\rangle \\ |1,\quad 0\rangle &= \sqrt{\frac{1}{2}}\,(|{}^1\!/_2,+{}^1\!/_2\rangle \otimes |{}^1\!/_2,-{}^1\!/_2\rangle + (|{}^1\!/_2,-{}^1\!/_2\rangle \otimes |{}^1\!/_2,+{}^1\!/_2\rangle) \end{aligned}\right\} (+1) \text{ under permutations.}$$

$$|0,\quad 0\rangle = \sqrt{\frac{1}{2}}\,(|{}^1\!/_2,+{}^1\!/_2\rangle \otimes |{}^1\!/_2,-{}^1\!/_2\rangle - (|{}^1\!/_2,-{}^1\!/_2\rangle \otimes |{}^1\!/_2,+{}^1\!/_2\rangle) \quad (-1) \text{ under permutations.}$$

- For two fermion system:

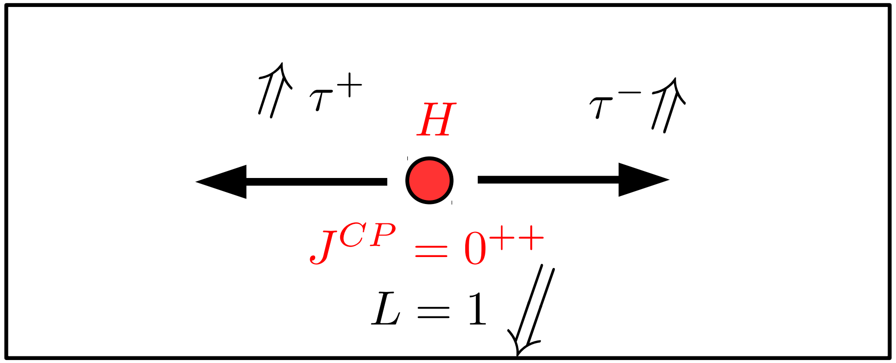
$$\begin{aligned} P &= (-1)^{L+1} \\ C &= (-1)^{L+S} \\ CP &= (-1)^{S+1} \end{aligned}$$

→ CP of parent particle translates into spin configuration of two fermion system.

Higgs: CP properties (from $H \to f\bar{f}$)

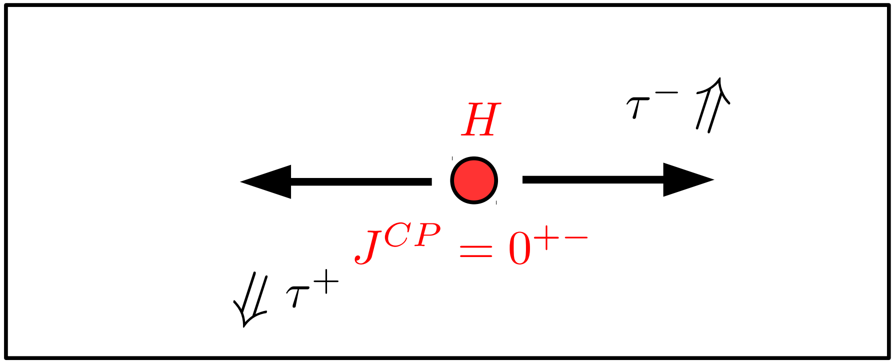
CP-even:

$L = 1 \qquad S = 1$



CP-odd:

$L = 0 \qquad S = 0$



- For two fermion system:

$$\boxed{\begin{aligned} P &= (-1)^{L+1} \\ C &= (-1)^{L+S} \\ CP &= (-1)^{S+1} \end{aligned}}$$

CP of parent particle translates into spin configuration of two fermion system.

Higgs: CP properties (from $H \to \tau\tau$)

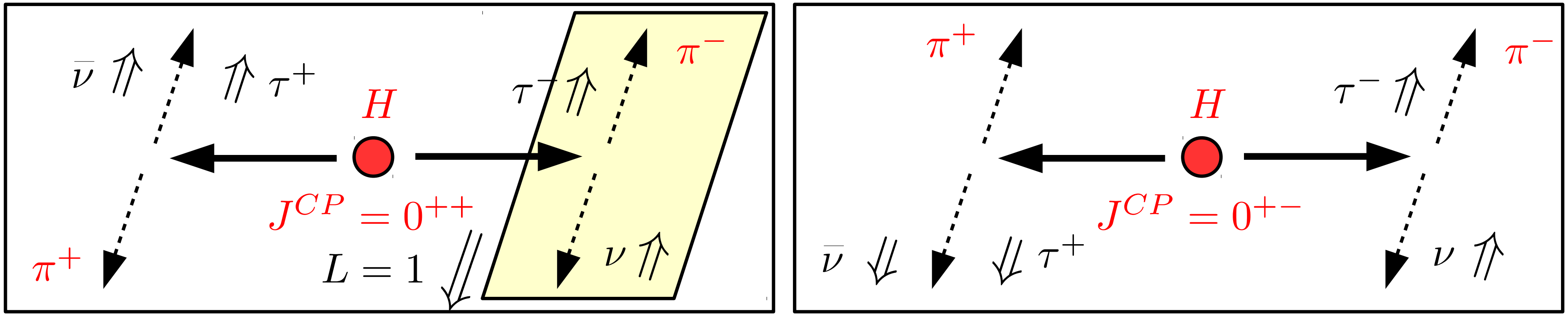
E.g. $\tau^- \to \pi^- \nu$ makes spin configuration detectable!

CP-even:

$L = 1 \quad S = 1$

CP-odd:

$L = 0 \quad S = 0$



Decay width: $\Gamma_{H\to\tau\tau} \propto 1 - \vec{s}_z^{\,-} \cdot \vec{s}_z^{\,+} + \underbrace{\cos(2\phi)\left(\vec{s}_T^{\,-} \cdot \vec{s}_T^{\,+}\right)}_{CP\text{-even}} - \underbrace{\sin(2\phi)\left[\left(\vec{s}_T^{\,-} \times \vec{s}_T^{\,+}\right) \cdot \hat{\vec{k}}^{-}\right]}_{CP\text{-odd}}$

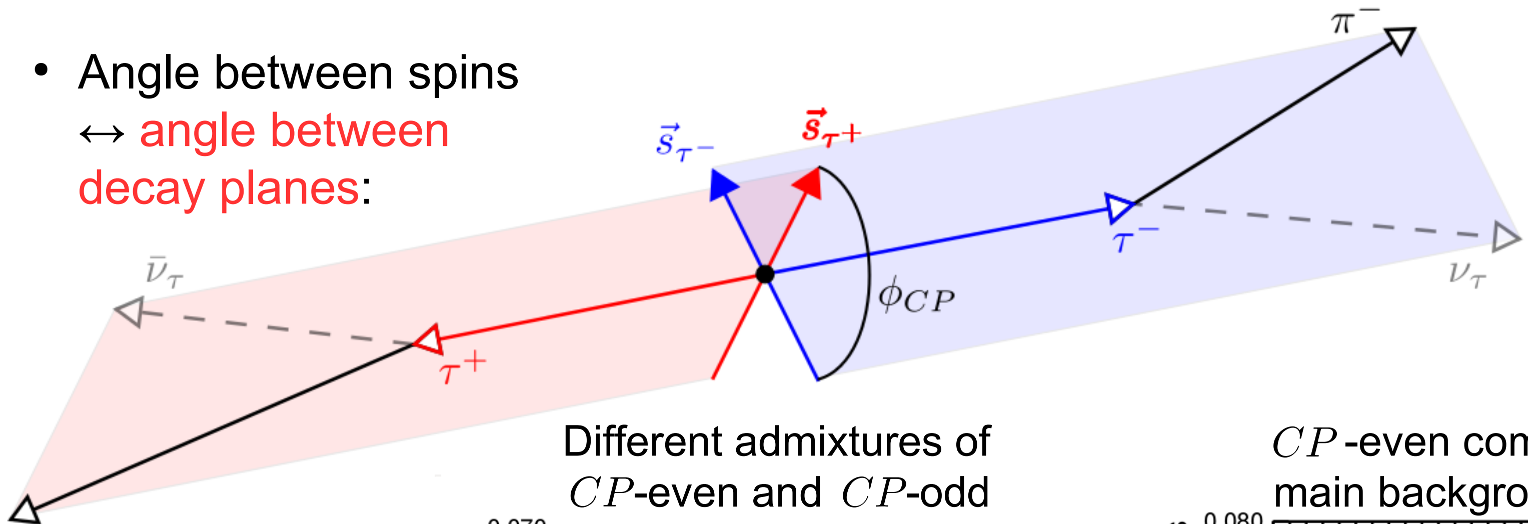
- For two fermion system:

$$\begin{aligned} P &= (-1)^{L+1} \\ C &= (-1)^{L+S} \\ CP &= (-1)^{S+1} \end{aligned}$$

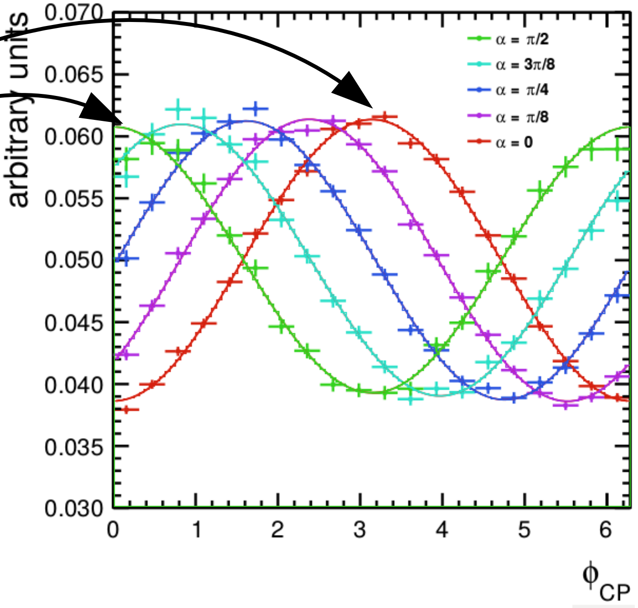
CP of parent particle translates into spin configuration of two fermion system.

Transverse spin polarization in the di-τ system

- Angle between spins ↔ angle between decay planes:



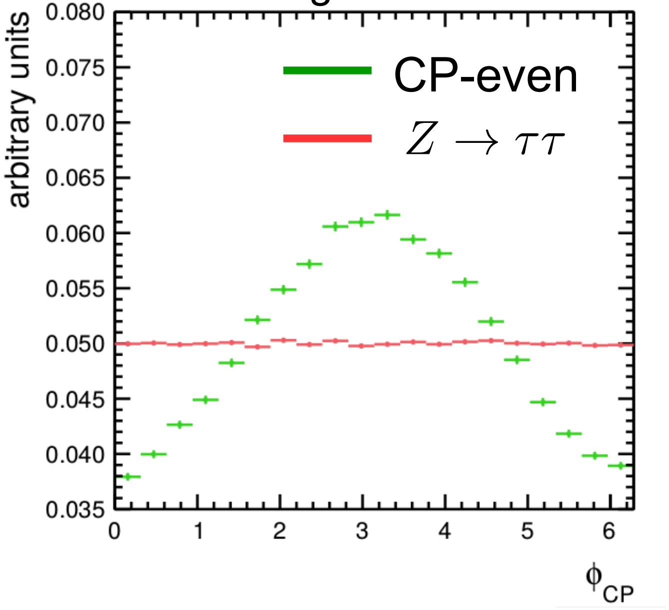
Different admixtures of CP-even and CP-odd



Pure CP-even

Pure CP-odd

CP-even compared to main background



arXiv:0812.1910

arXiv:1108.0607

arXiv:1408.0798

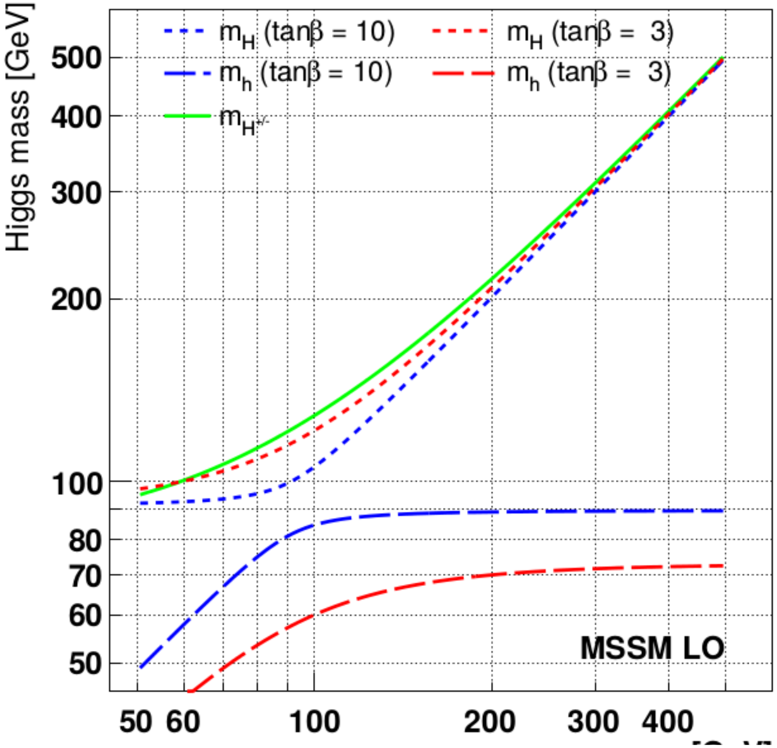
Higgs boson in the MSSM

- A CP-odd Higgs boson is indeed predicted in Two Higgs Doublet models (2HDM) like the MSSM:

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \quad Y_{H_d} = -1, \quad \mathrm{v_d} : \ \mathrm{VEV_d}$$

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad Y_{H_u} = +1, \quad \mathrm{v_u} : \ \mathrm{VEV_u}$$

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



- Strong mass requirements at tree level:

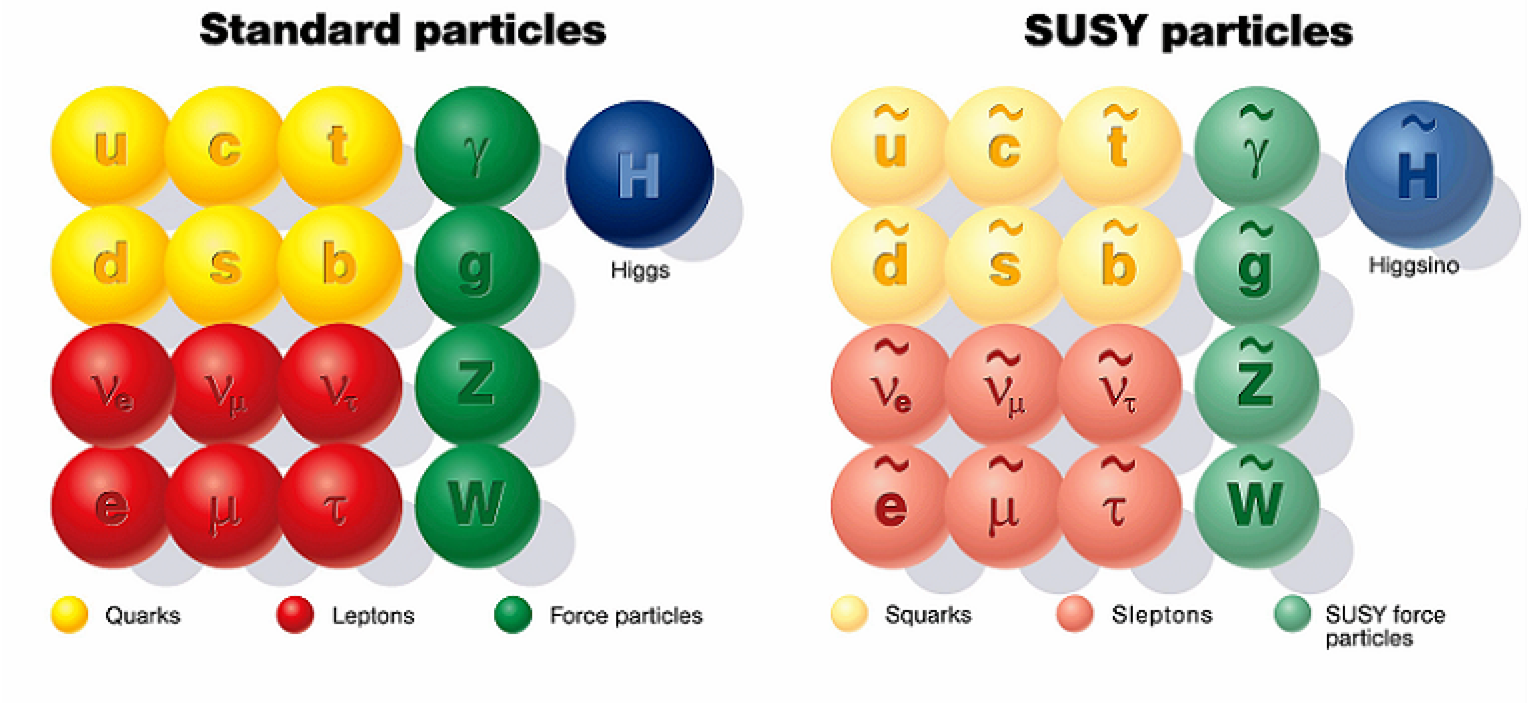
Two free parameters: m_A , $\tan\beta = \mathrm{v_u}/\mathrm{v_d}$

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

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

SUSY particles as *dark matter* candidates

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



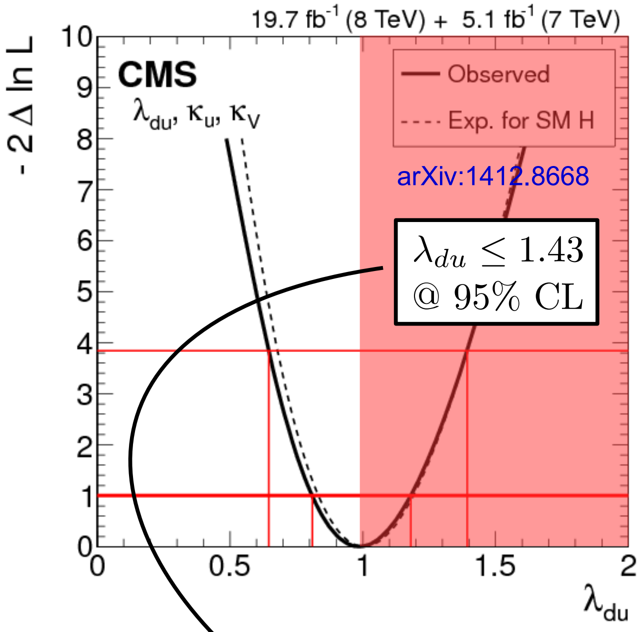
- E.g. lightest SUSY particle (LSP) perfect candidate for *dark matter* particle χ .
- **Problem:** SUSY itself is broken!

Enhancement of down-type couplings

- In the MSSM coupling to down-type fermions enhanced by $\tan\beta$ for $m_A \gg m_Z$ at LO (decoupling limit):

	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \to 0$	$\sin\alpha/\sin\beta \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \to 1$	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to -1$

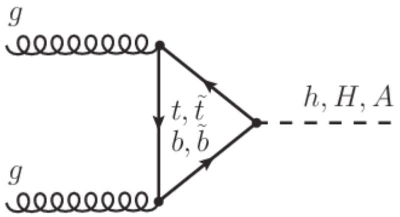
$$\alpha \to \beta - \pi/2$$



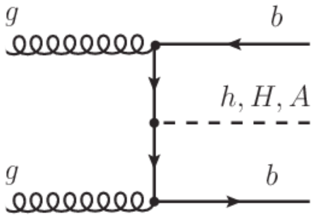
$\lambda_{du} \leq 1.43$
@ 95% CL

expect MSSM here!

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



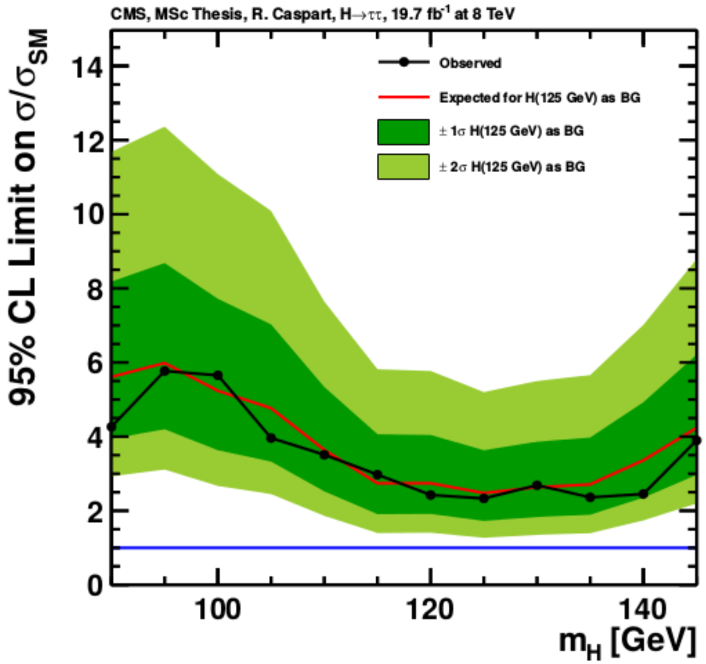
$gg \to H$ (“$gg\phi$”)

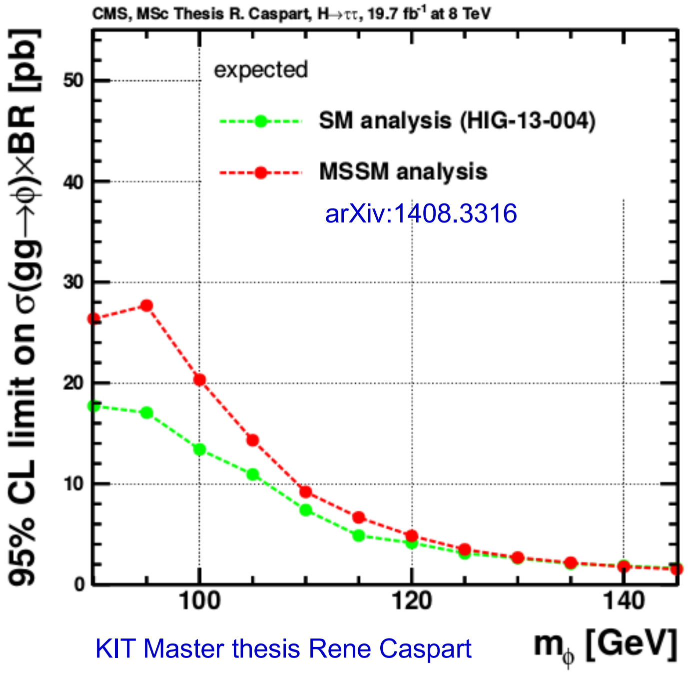


$gg \to Hb\bar{b}$ (“$bb\phi$”)

Simple check for CP-odd coupling in $H \rightarrow \tau\tau$

- Check for $gg \rightarrow H$ as only signal.
- Remove VBF sensitive categories from SM analysis.





KIT Master thesis Rene Caspart

- Scan for additional CP-odd Higgs boson between $90\ \mathrm{GeV}$ and $145\ \mathrm{GeV}$.

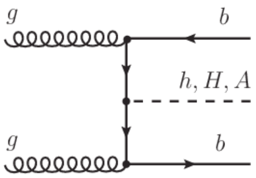
Dedicated MSSM analysis (arXiv:1408.3316)

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

b-tag category:

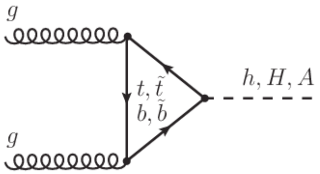
$\mathrm{N}(b\text{-tag}) \geq 1$

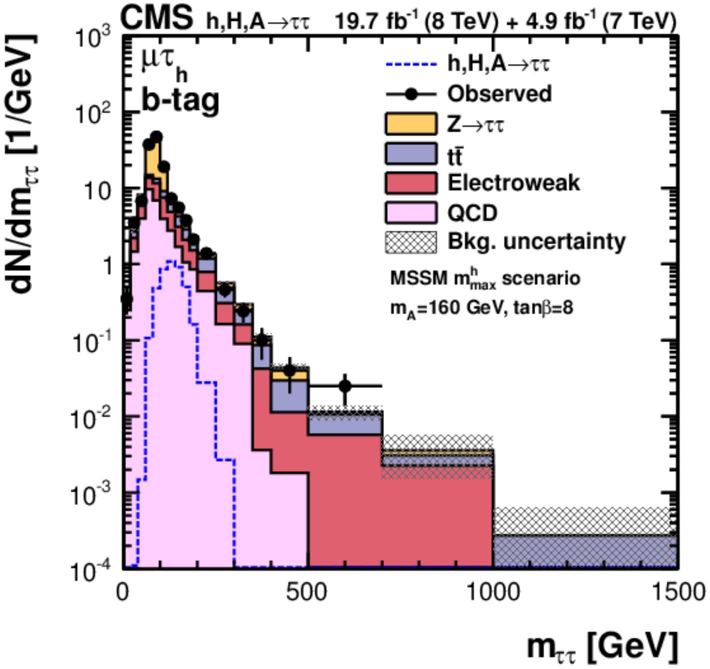
$\mathrm{N}(\mathrm{Jet}) \quad \leq 1$

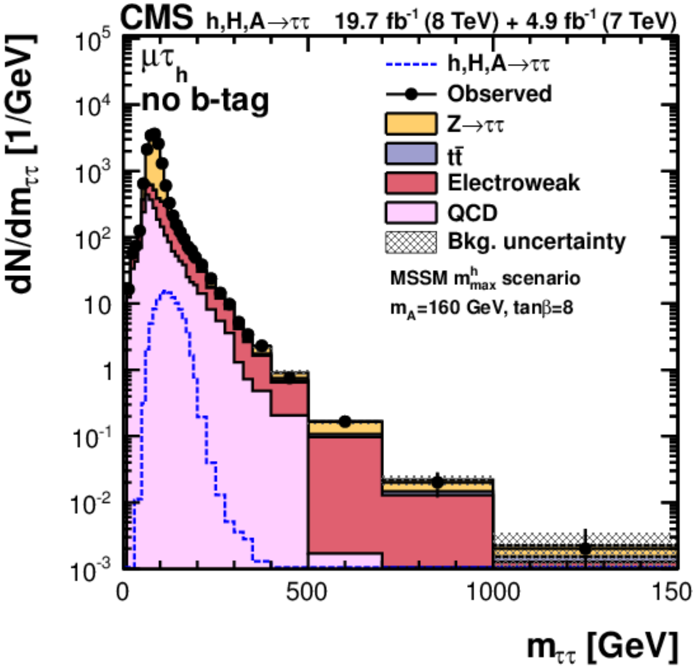


No b-tag category:

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



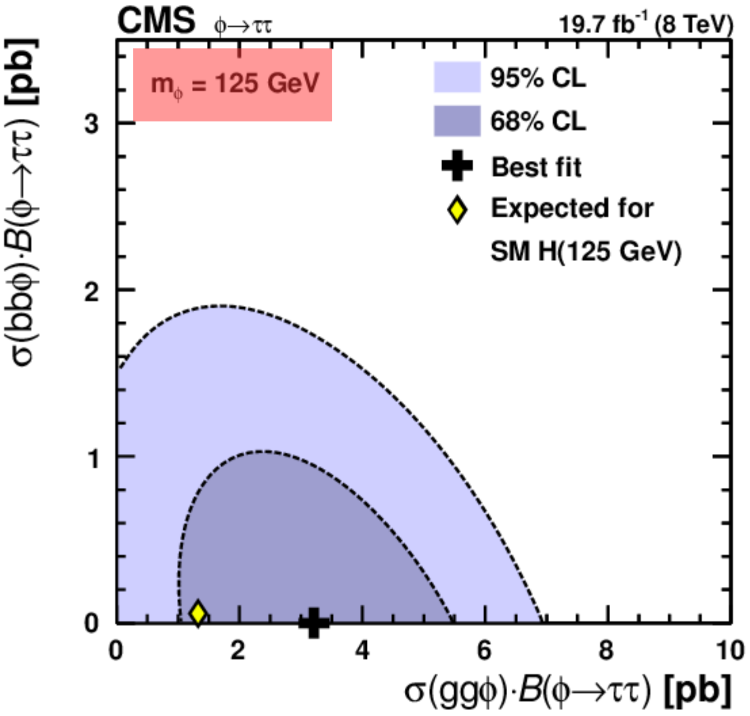


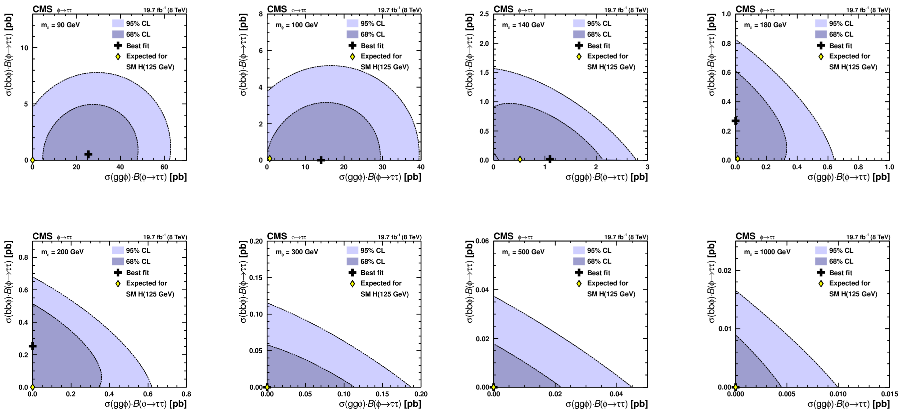


- Sensitive to both production modes!

Model independent limits (2D)

- Search for a narrow resonance in $gg\phi$ & $bb\phi$ production mode:





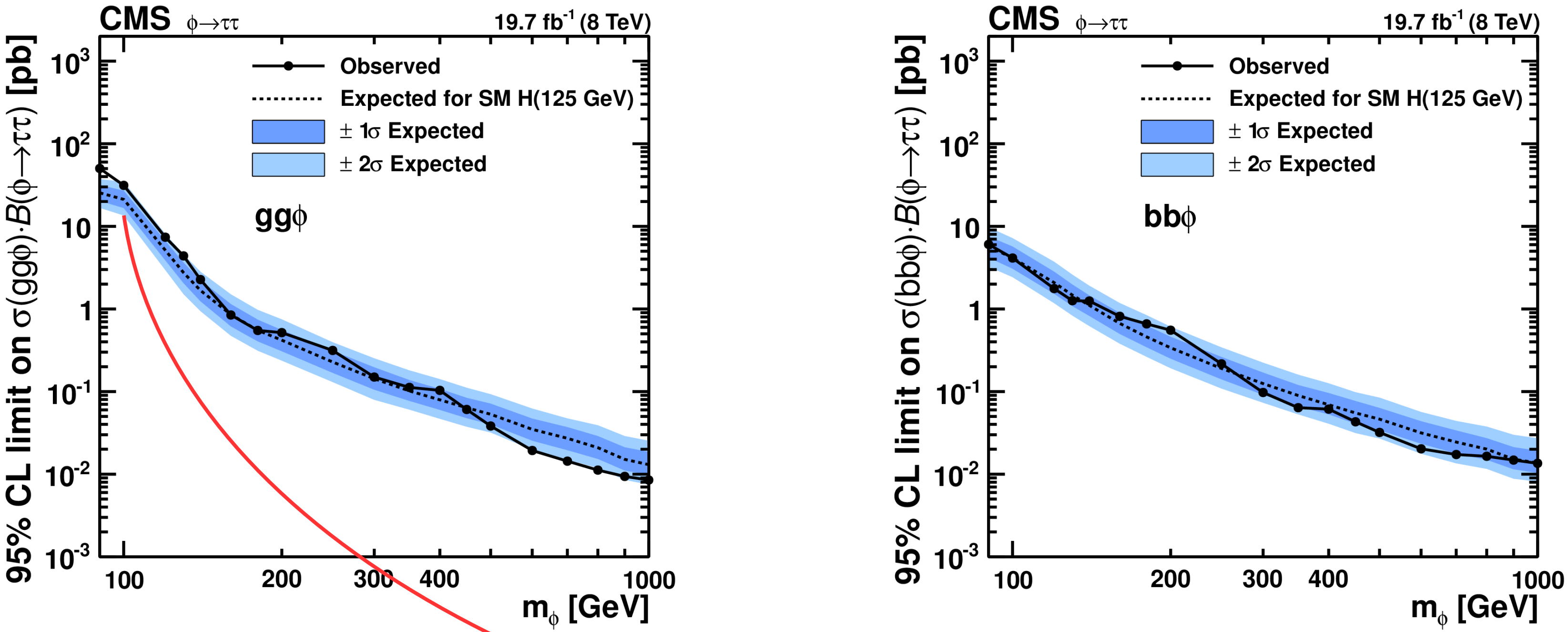
… (for 31 mass points btw. 90 and 1000 GeV, $\rightarrow 1.25 \times 10^6$ scan points).

- Most probable value and 2D limit contour from scan of likelihood function (200×200 NLL points).

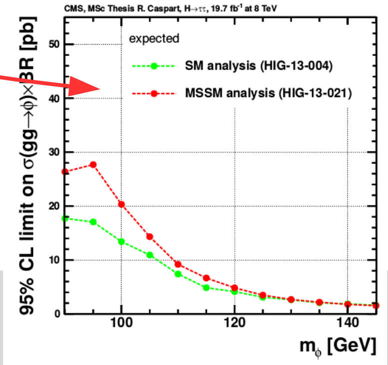
- Find DB of full likelihood scan in 3D ($gg\phi$, $bb\phi$, m_ϕ) on supporting TWiki for arXiv:1408.3316.

Model independent limits (1D)

- Search for a narrow resonance in $gg\phi$ & $bb\phi$ production mode:



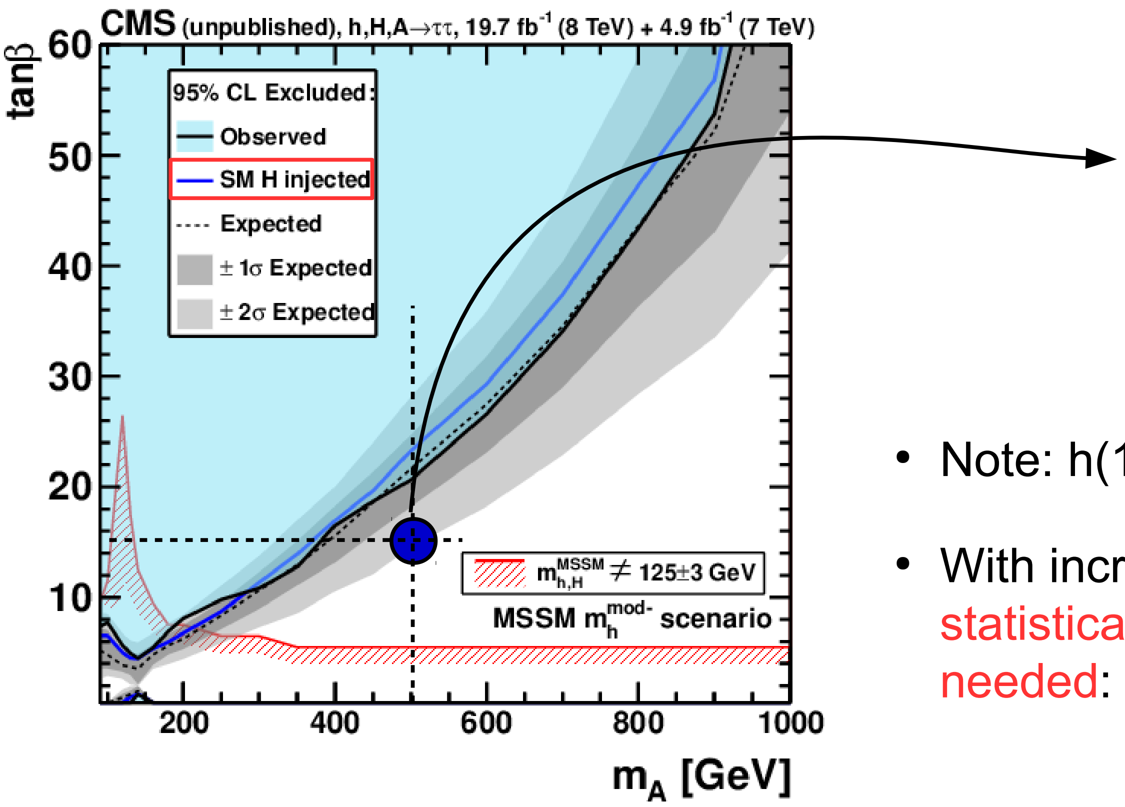
from two slides before

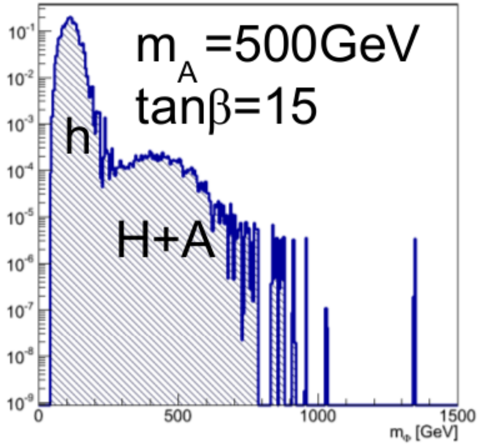


- 1D limit contours on $gg\phi$ & $bb\phi$ profiling corresponding other component.

Limits in full MSSM benchmark scenarios

- Explicit prediction for three neutral Higgs bosons:





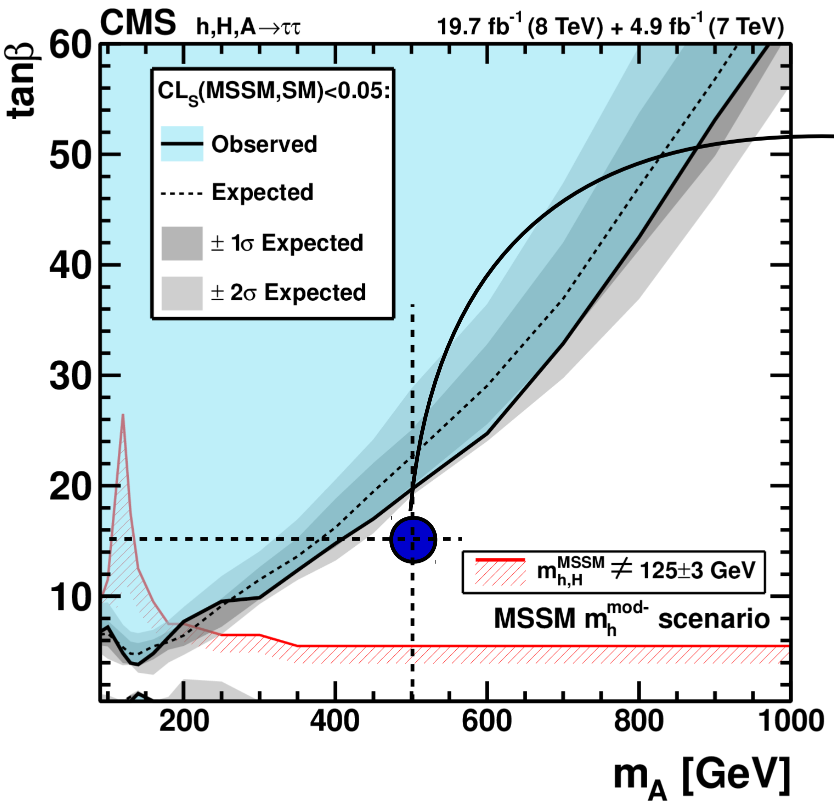
- Note: h(125) has been observed!
- With increasing sensitivity new statistical interpretation is needed: “1 Higgs vs 3 Higgses”.

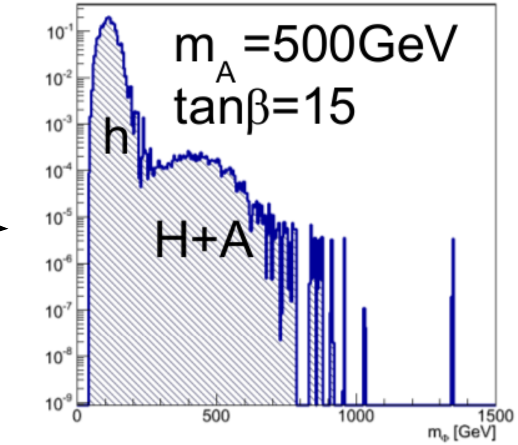
- **Old method**: h(125) ignored in statistical inference:

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

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”.

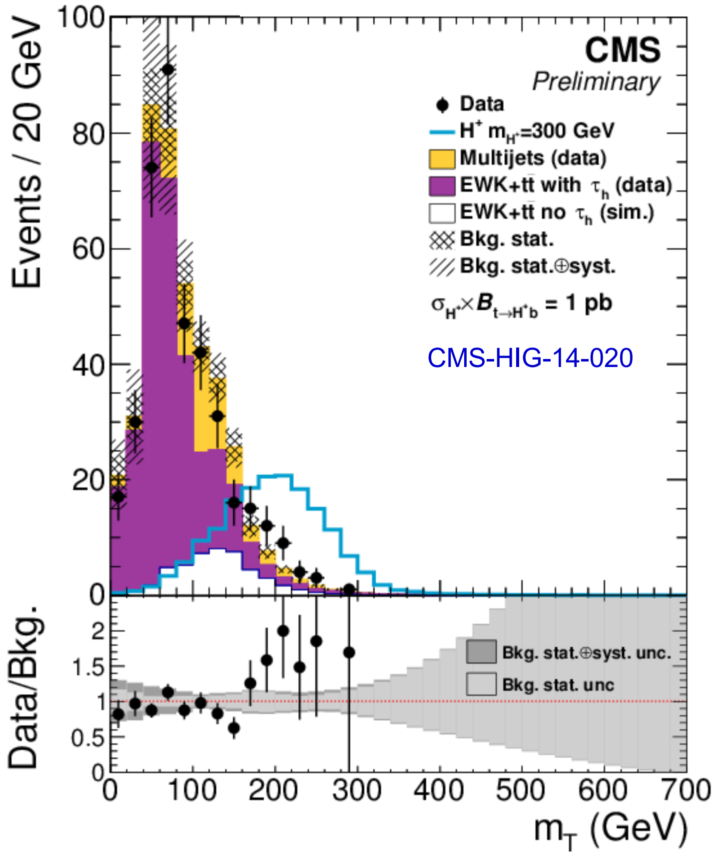
- **New method**: h(125) taken into account in test statistic:

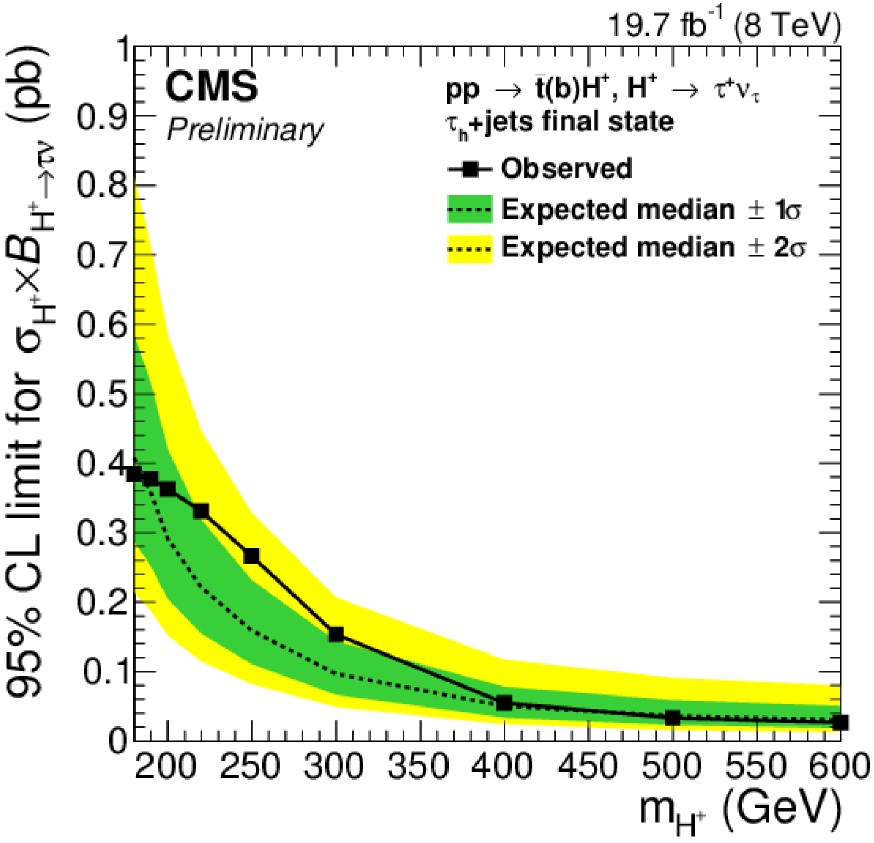
$$q_{\mathrm{MSSM/BG}} = \frac{\mathcal{L}\big(\,N|(S_{\mathrm{MSSM}}+B),\hat{\theta}_{MSSM}\big)}{\mathcal{L}\big(\,N|(S_{\mathrm{SM}}+B),\hat{\theta}_{SM}\big)}$$

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

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

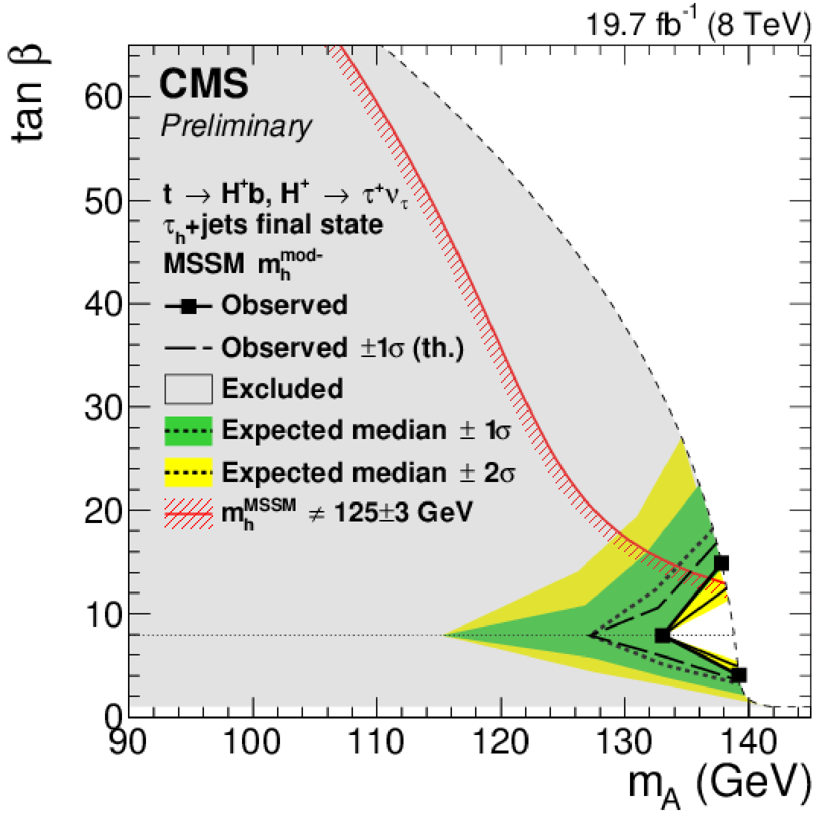
- Concentrate on hadronic decay of $W \to$ well defined use of m_T for sig extraction.
- Extending mass range of search by $180\ \mathrm{GeV} \leq m_{H^{+/-}} \leq 600\ \mathrm{GeV}$.

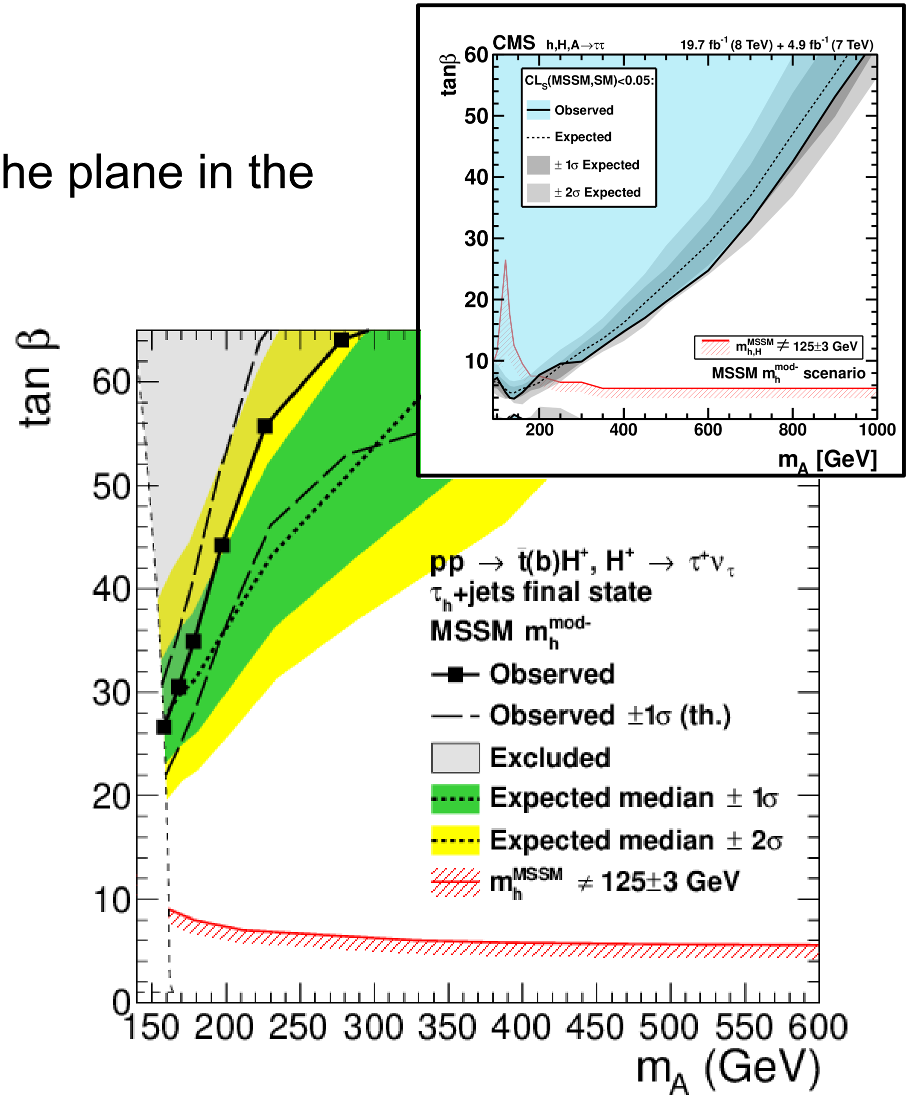




Charged Higgs boson search ($H^{+/-} \to \tau\nu$)

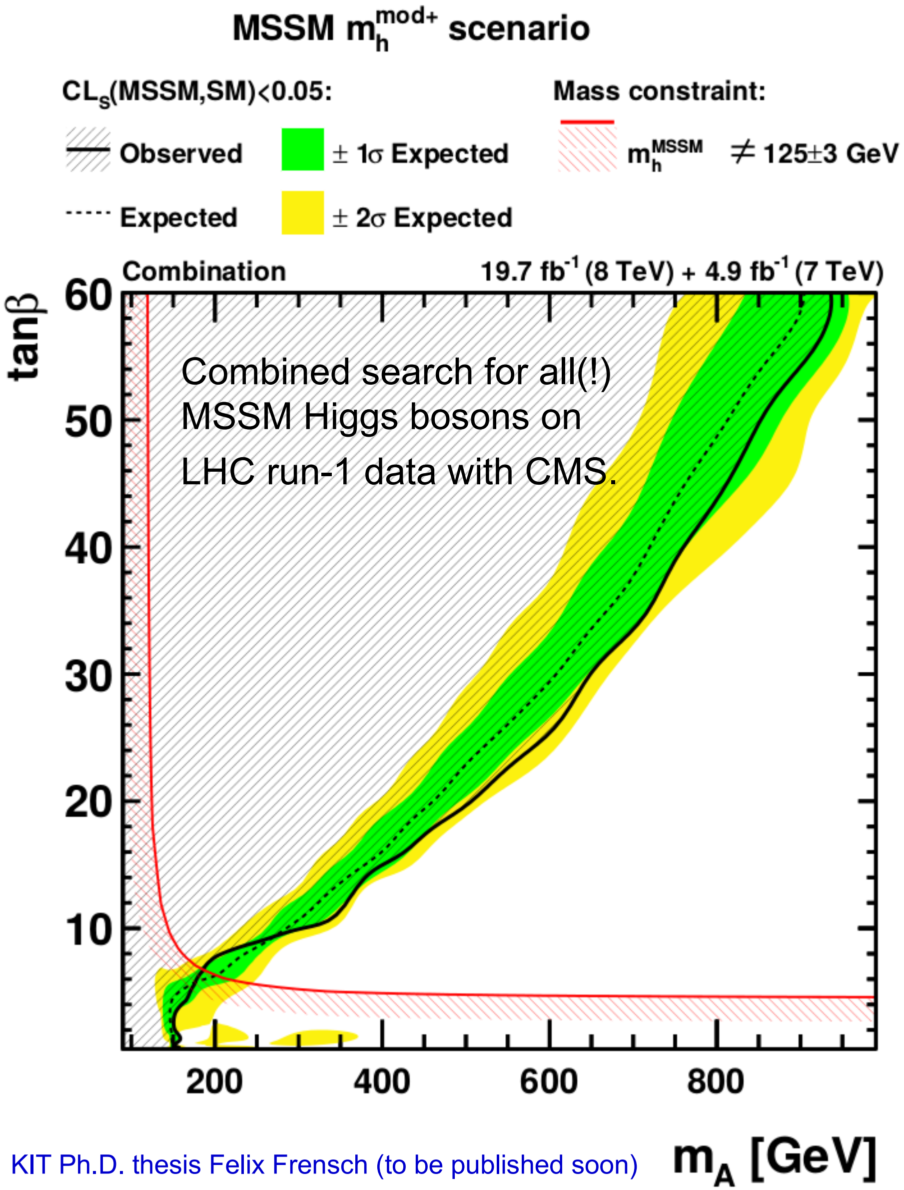
- Translated into m_A - $\tan\beta$ plane.
- Combining both measurement will close the plane in the range $90 \leq m_A \leq 140\ \mathrm{GeV}$.



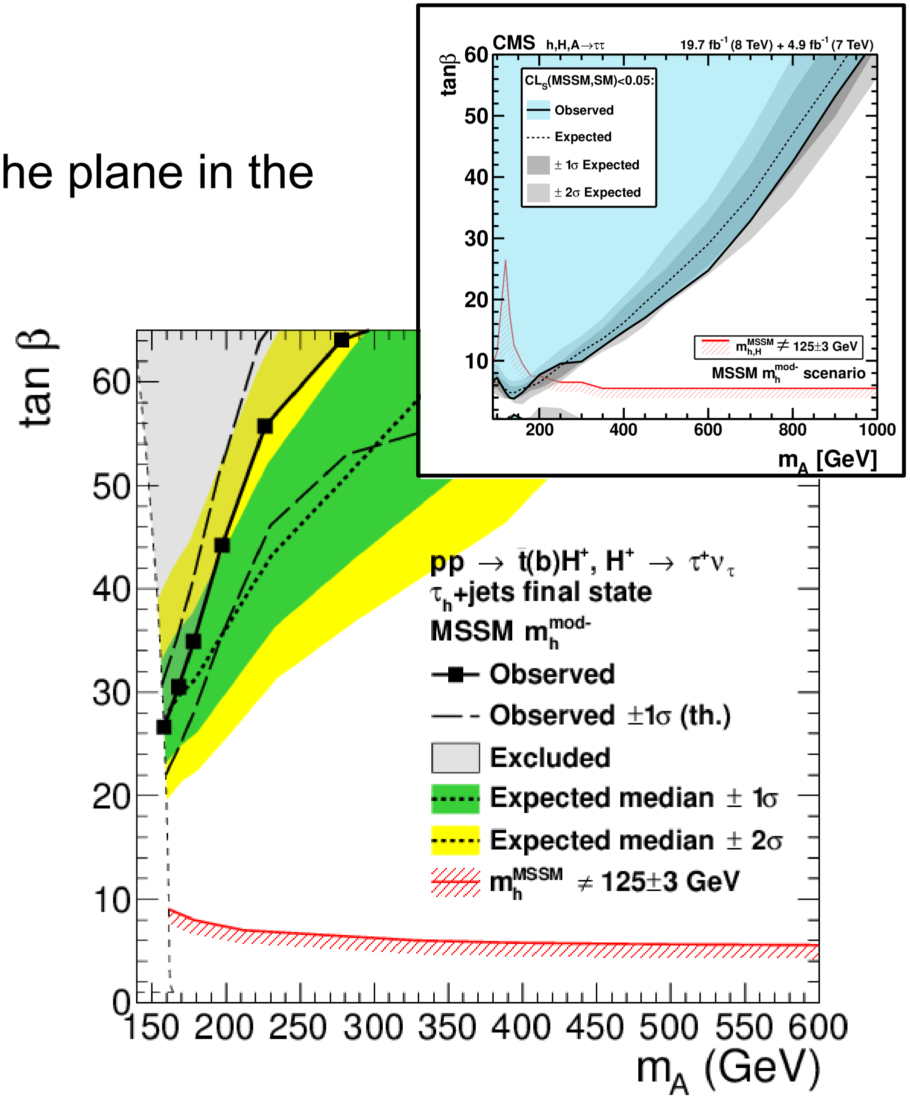


Charged Higgs boson search ($H^{+/-} \rightarrow \tau\nu$)

the plane in the



Combined search for all(!) MSSM Higgs bosons on LHC run-1 data with CMS.



KIT Ph.D. thesis Felix Frensch (to be published soon)

Conclusions

- Di-τ final states are rich and important in the Higgs sector.
- Importance originates from combination of high mass and relatively clean signature.
- **Implies:**
  - Large coupling to Higgs boson.
  - Decays into hadrons that can be used to make spin correlations and thus the CP measurable in 2-fermion final states.
  - Even enhanced couplings in large number of BSM models.
- This makes di-τ final states in Higgs physics (especially for LHC run-2) a very attractive area of research.

Backup

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).

---

(1) Arguments stolen from S. Heinemeyer (HH Higgs workshop 2014)

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

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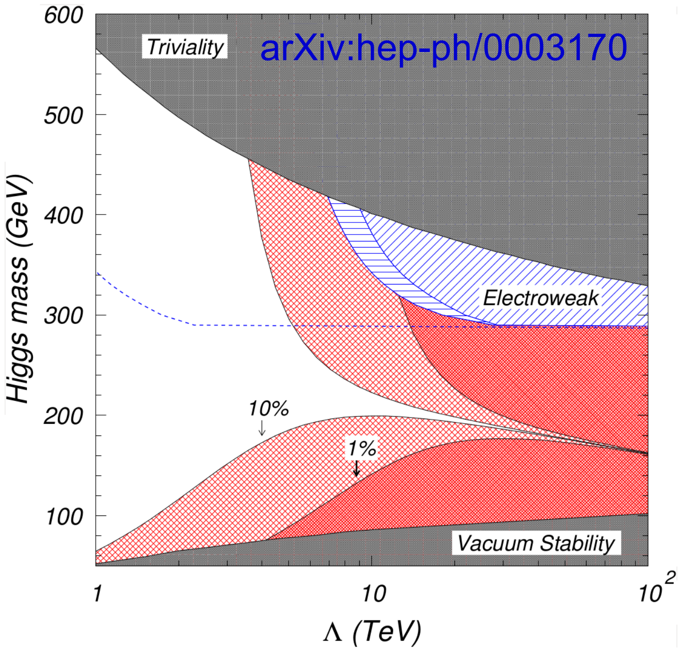


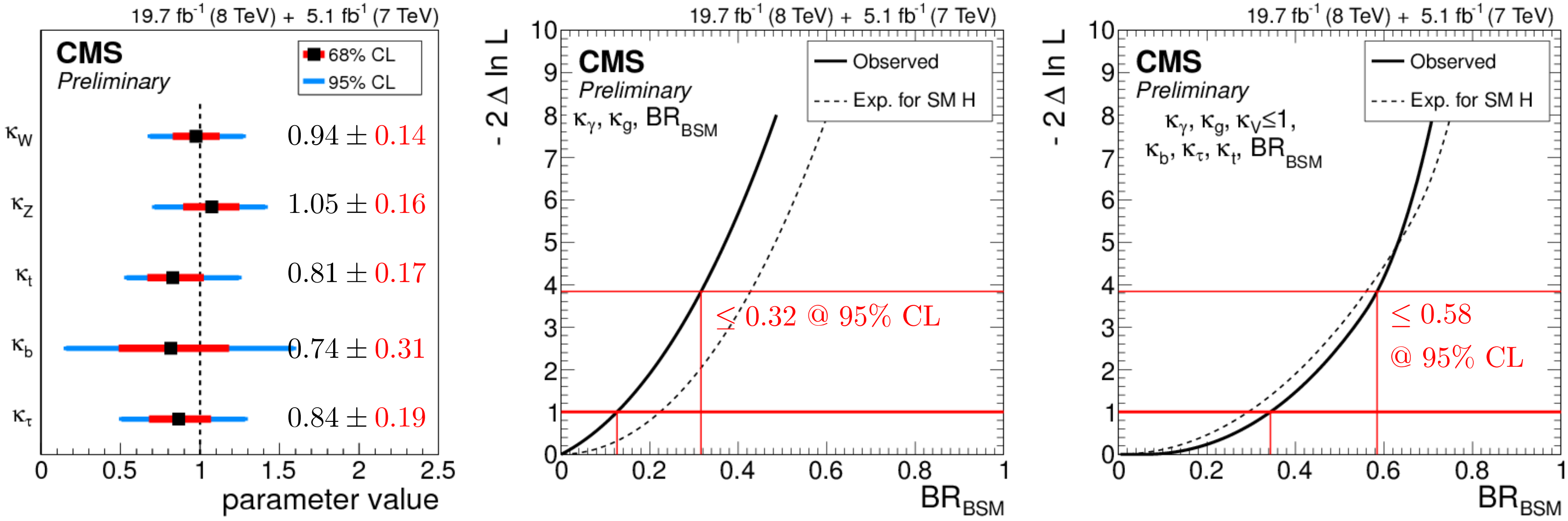
- There must be physics beyond the SM!
- At what scale does it set in?
- (How) Does it influence the Higgs sector?

---

(1) Arguments stolen from S. Heinemeyer (HH Higgs workshop 2014)

Space left for new physics in the Higgs sector

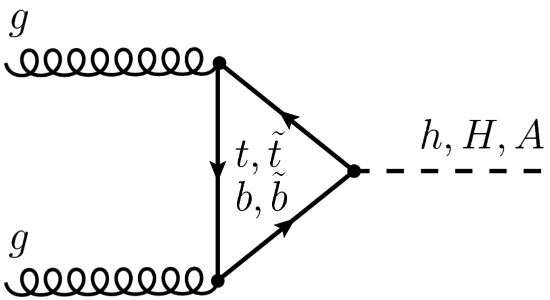
- Couplings are determined within $\pm 15\%$ to $\pm 20\%$ accuracy.
- Fixing all tree-level couplings to the SM ($\kappa_i,\ i = W, Z, \tau, b, t$) & introducing effective couplings for loop induced processes ($\kappa_g,\ \kappa_\gamma$) leaves room for $BR_{\mathrm{BSM}} \leq 0.32$ @ 95% CL.
- Adding maximal freedom to the fit leaves room for $BR_{\mathrm{BSM}} \leq 0.58$ @ 95% CL.



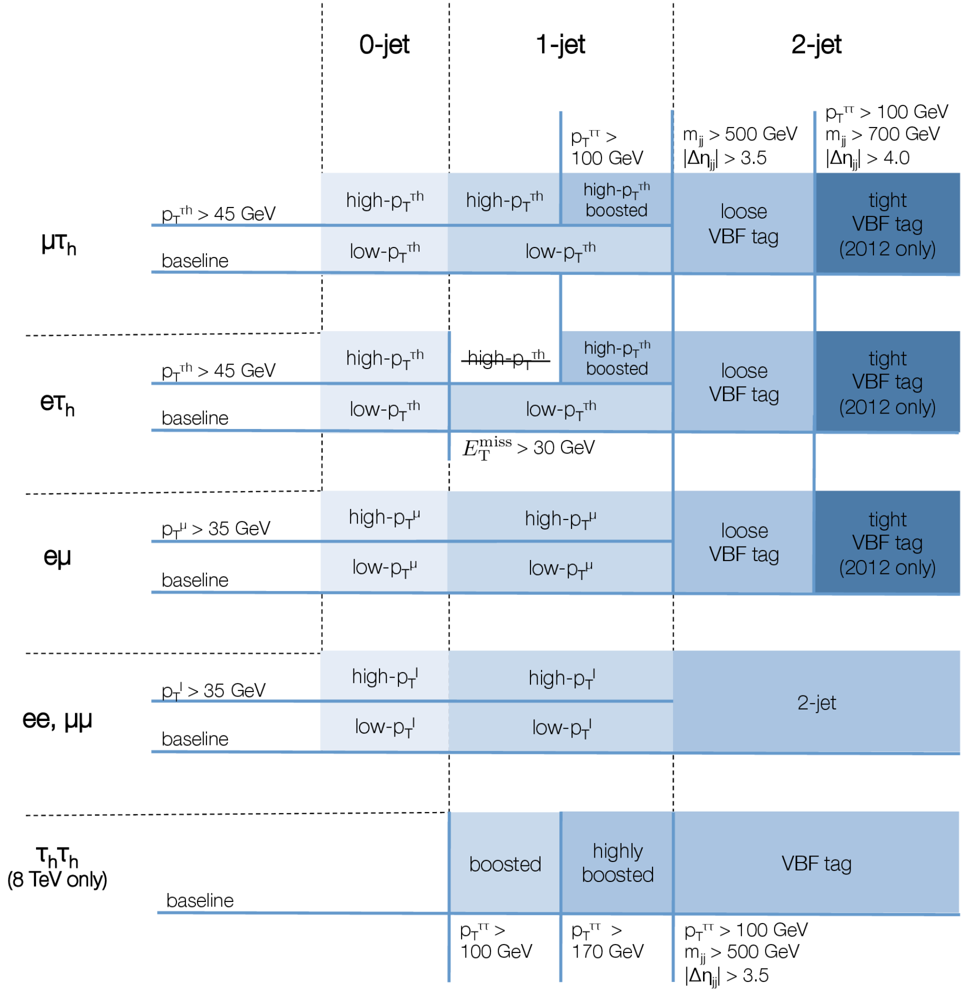
CMS-PAS-HIG-14-009

MSSM model dependency

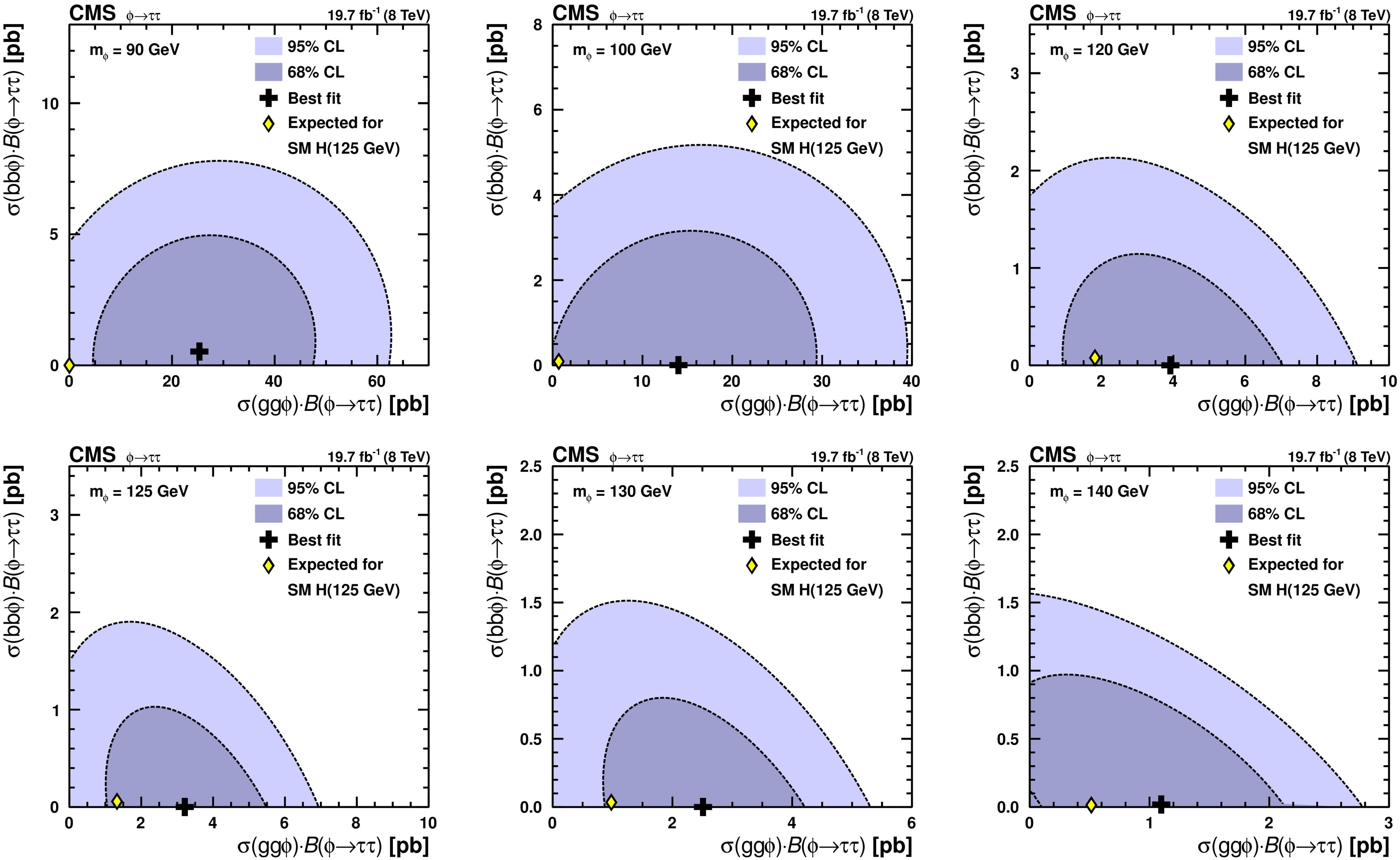
- In the SM analysis we chose nearly 100 different event categories. Why not choose more categories in MSSM analysis?
- In $gg\phi$ p_T spectra of Higgs bosons change with other particles in loop:



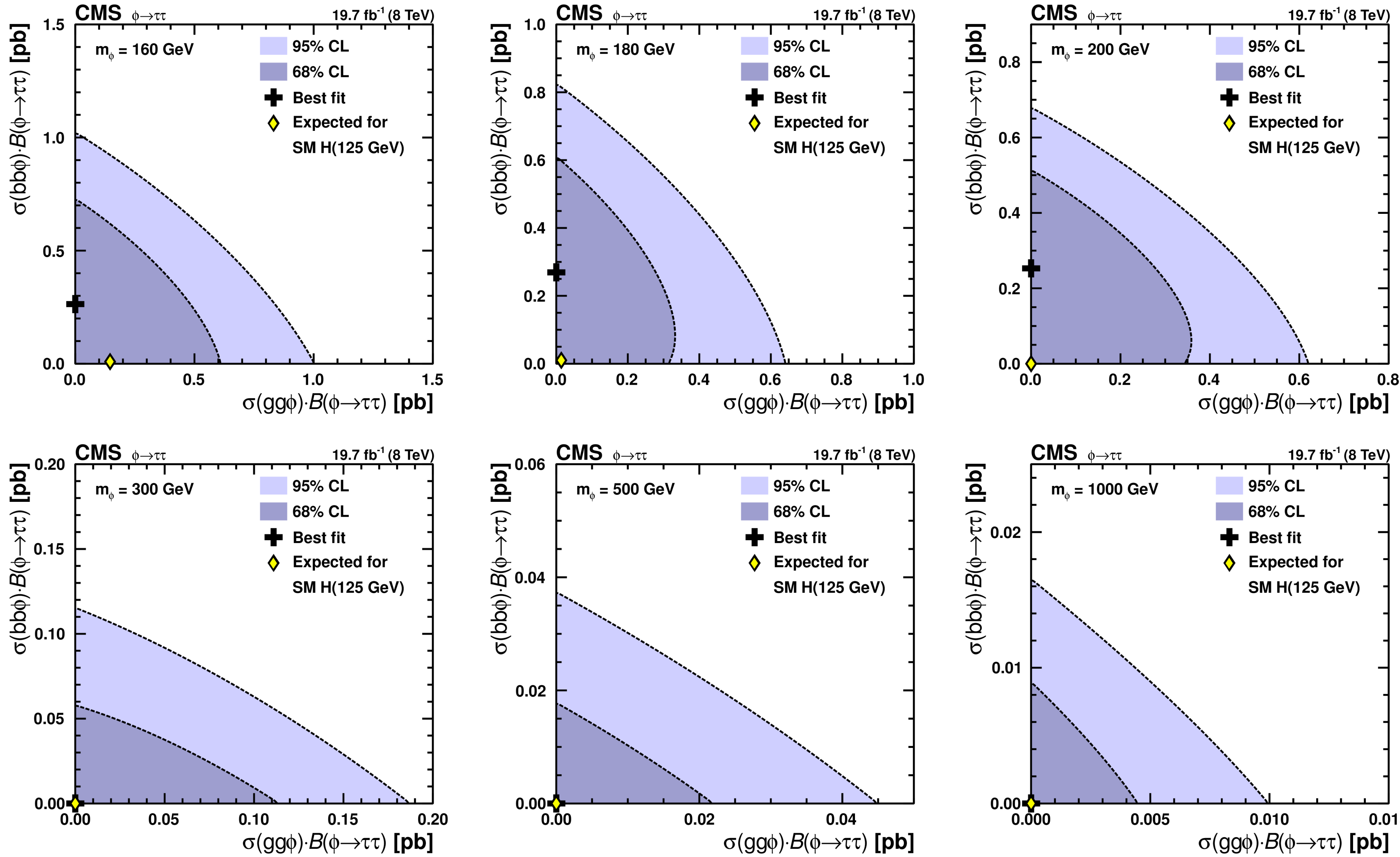
- Checked with pure b and pure t in loop from pythia that current categorization is not sensitive.
- Refrained from categorization that depends on Higgs p_T.



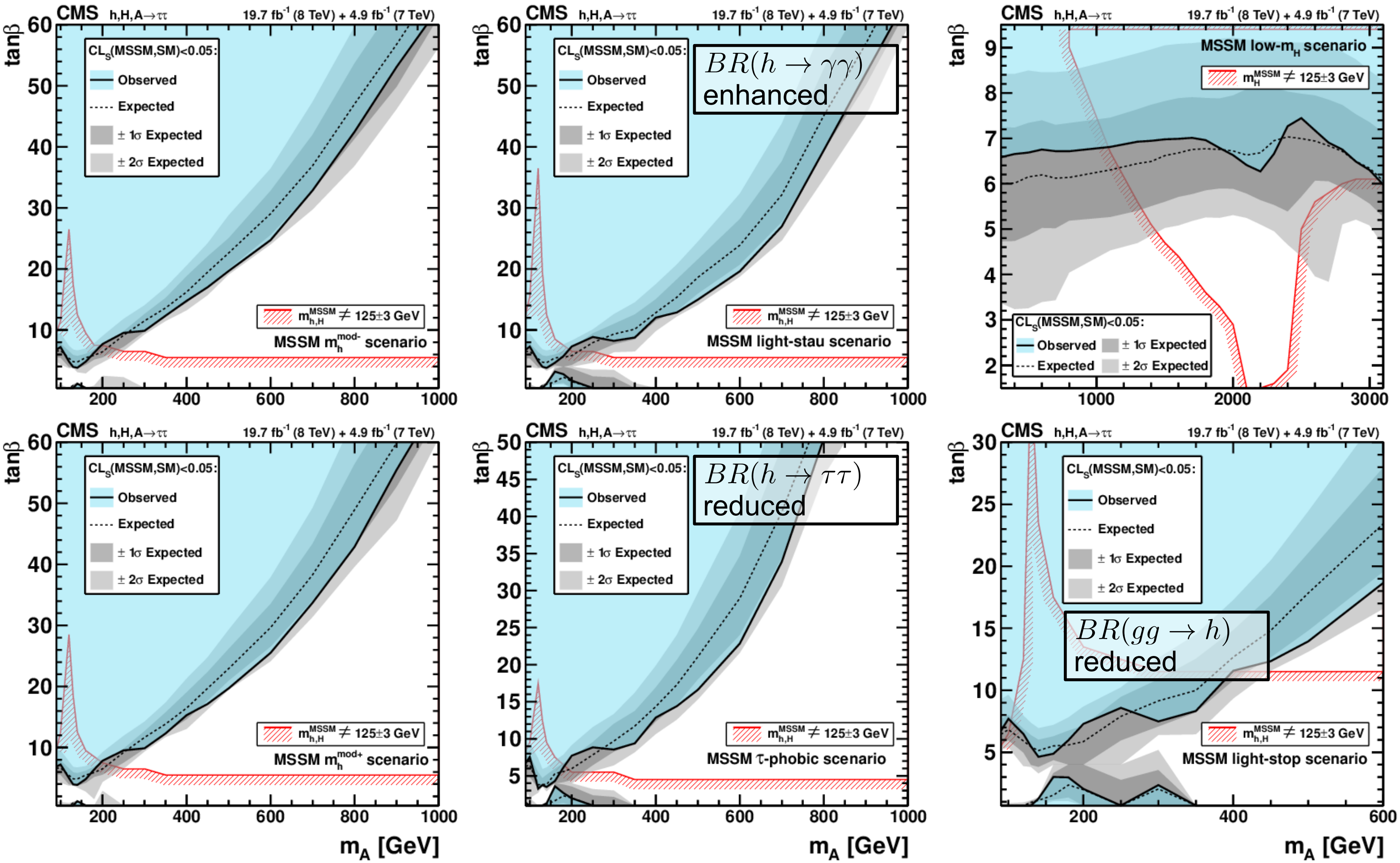
Model independent limits (2D)



Model independent limits (2D)



More benchmark scenarios (as defined by arXiv:1302.7033)

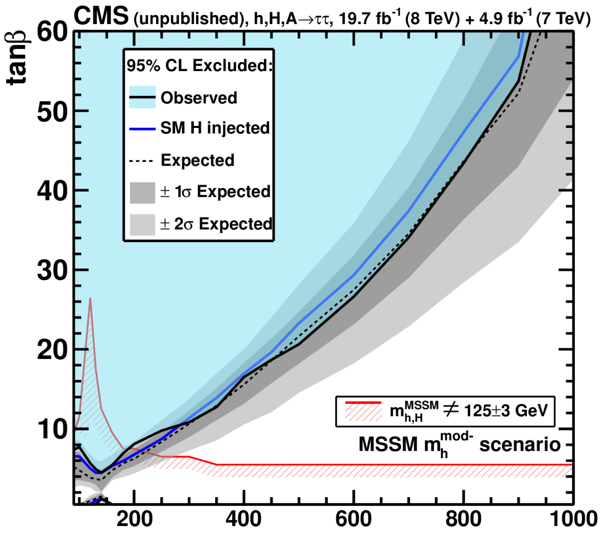


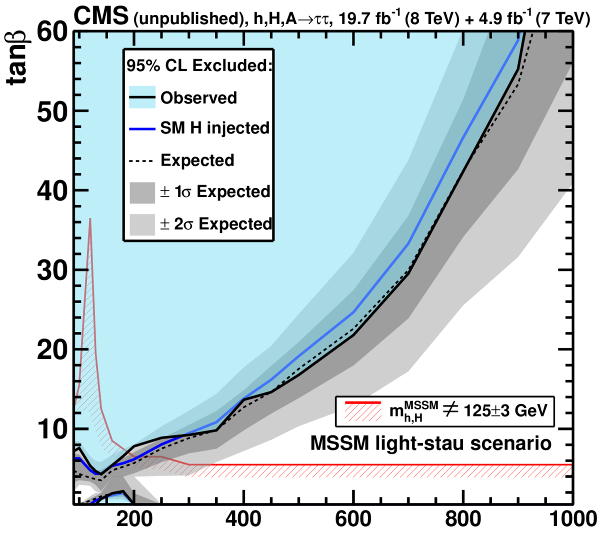
$BR(h \to \gamma\gamma)$ enhanced

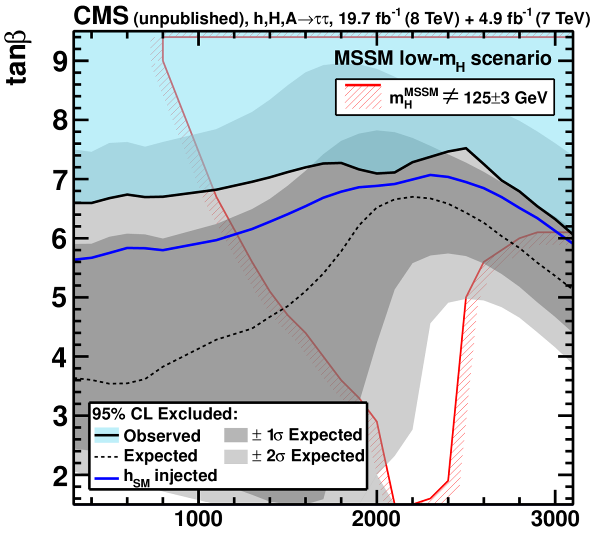
$BR(h \to \tau\tau)$ reduced

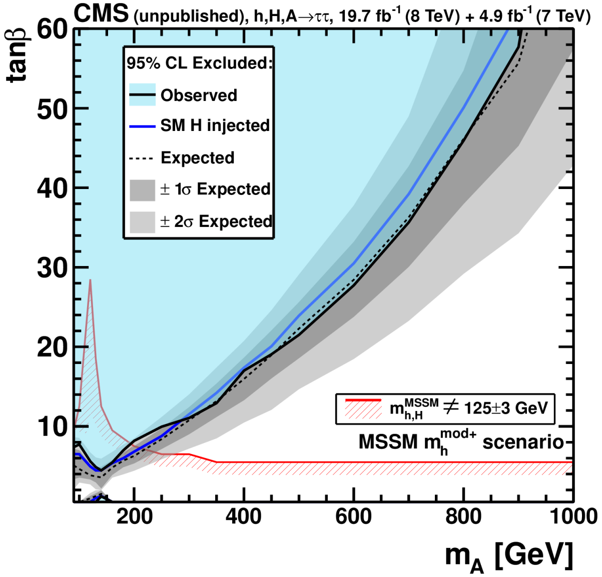
$BR(gg \to h)$ reduced

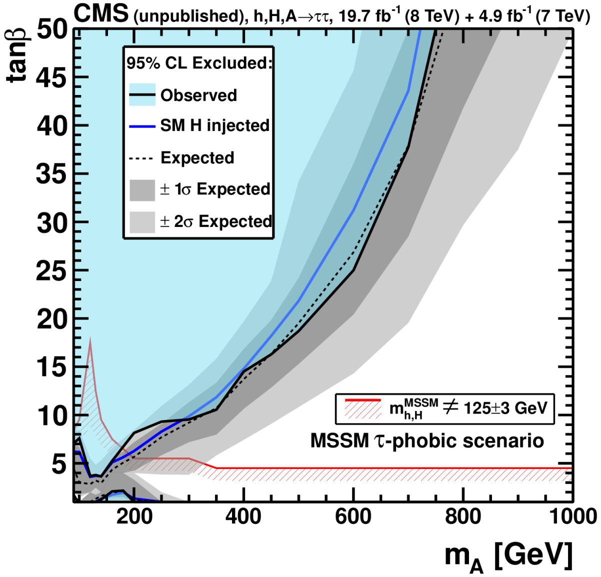
More benchmark scenarios... (old method)

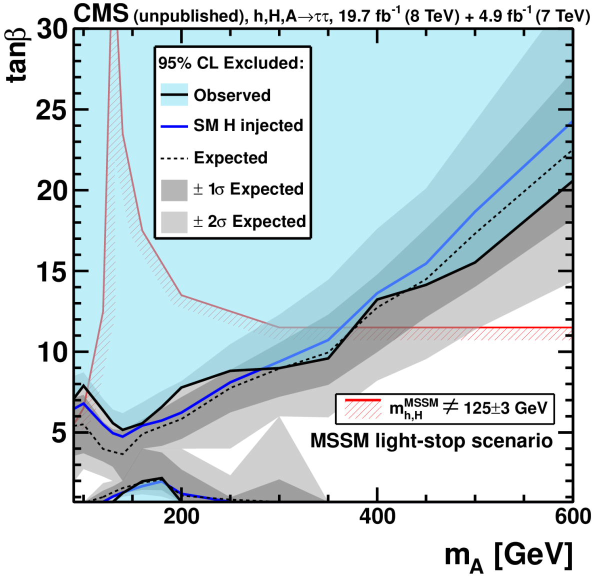








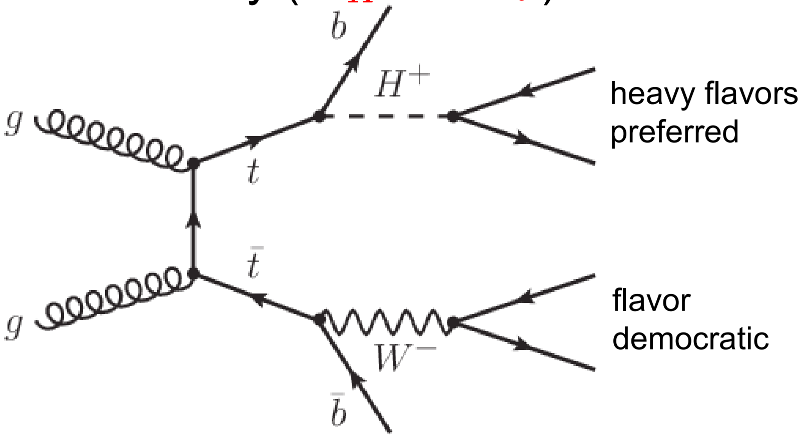




Charged Higgs in the MSSM

- Expect signal in *top* sector:

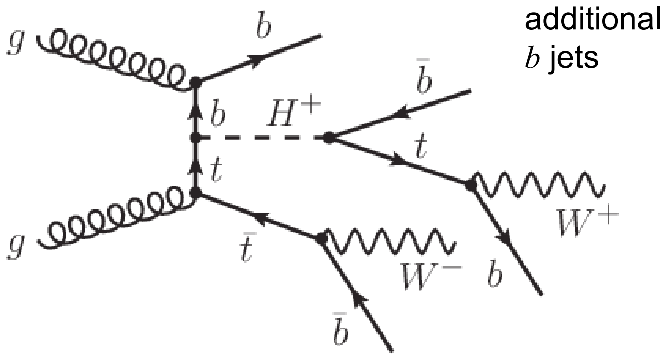
- In the decay ($m_{H^+} < m_t$):



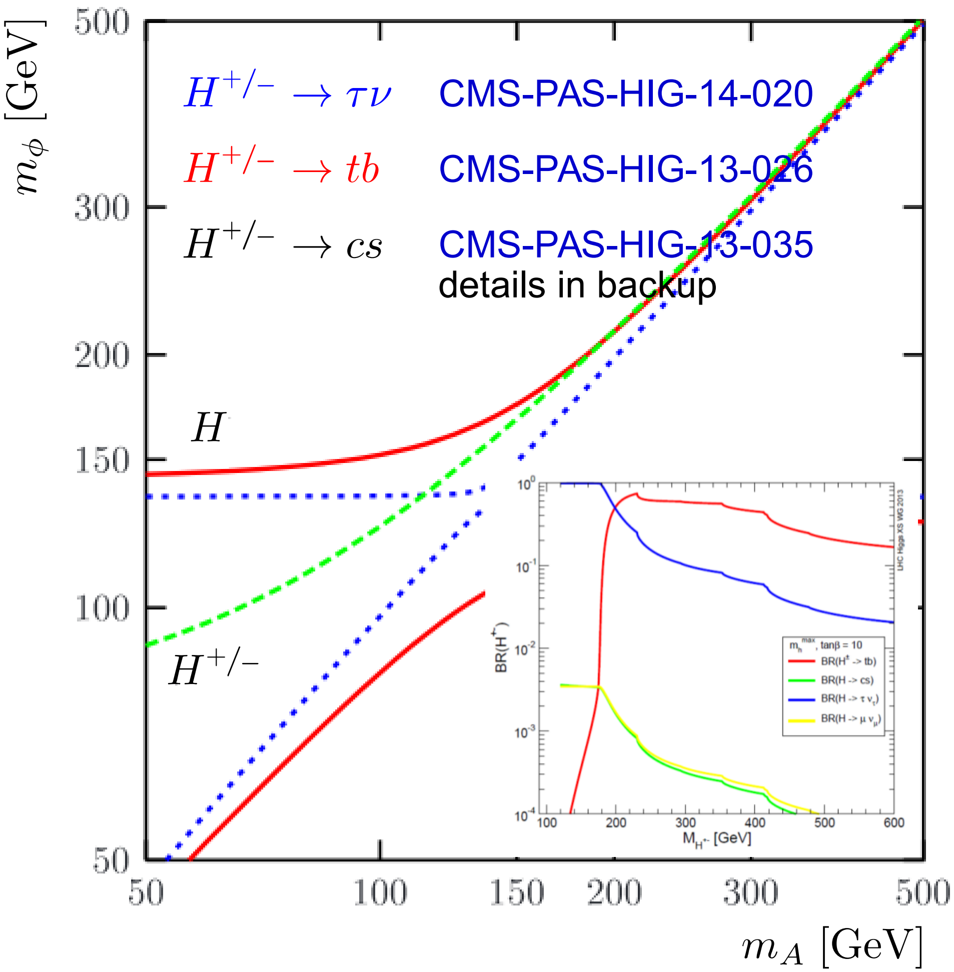
heavy flavors preferred

flavor democratic

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



additional b jets



$H^{+/-} \rightarrow \tau\nu$ CMS-PAS-HIG-14-020

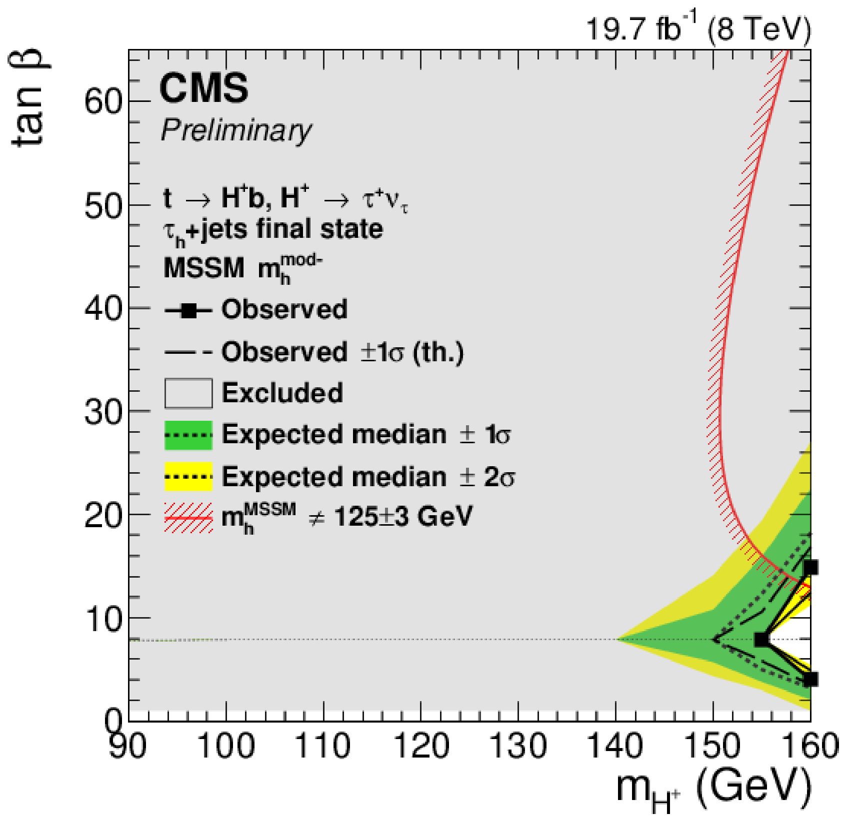
$H^{+/-} \rightarrow tb$ CMS-PAS-HIG-13-026

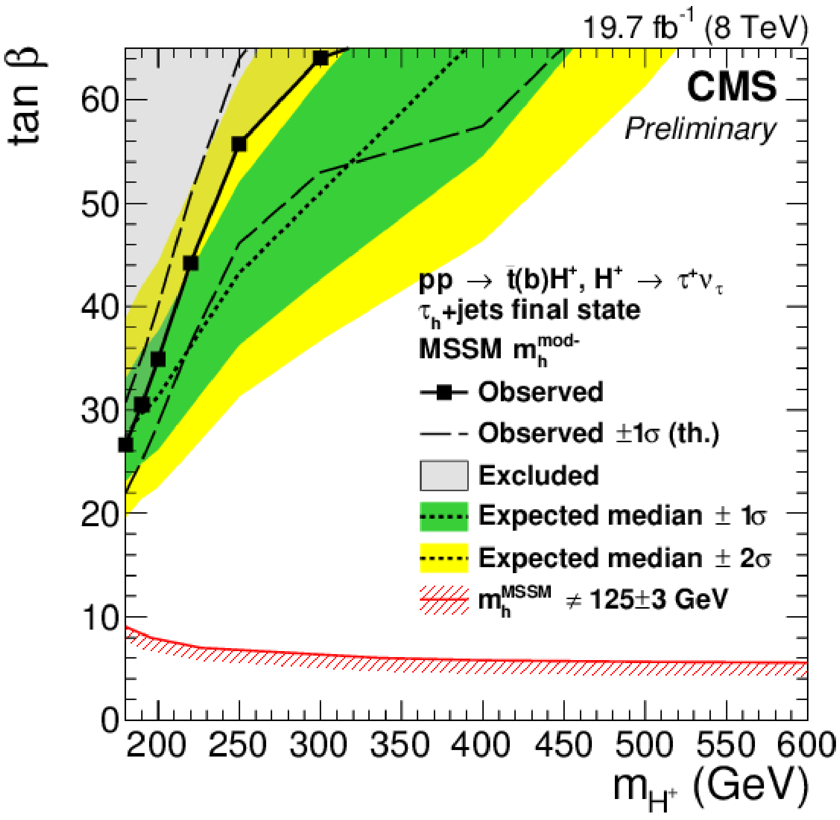
$H^{+/-} \rightarrow cs$ CMS-PAS-HIG-13-035

details in backup

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

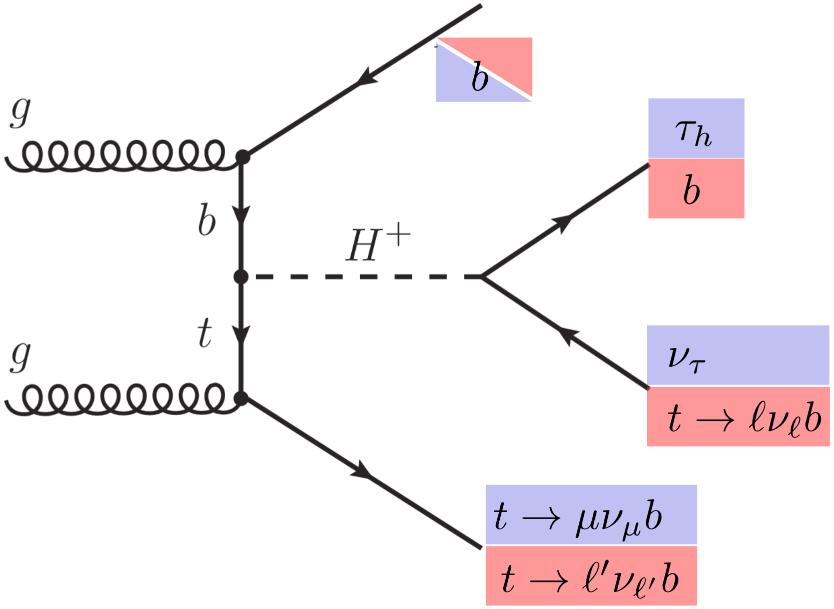
- Translated into m_{H^+} - $\tan\beta$ plane.

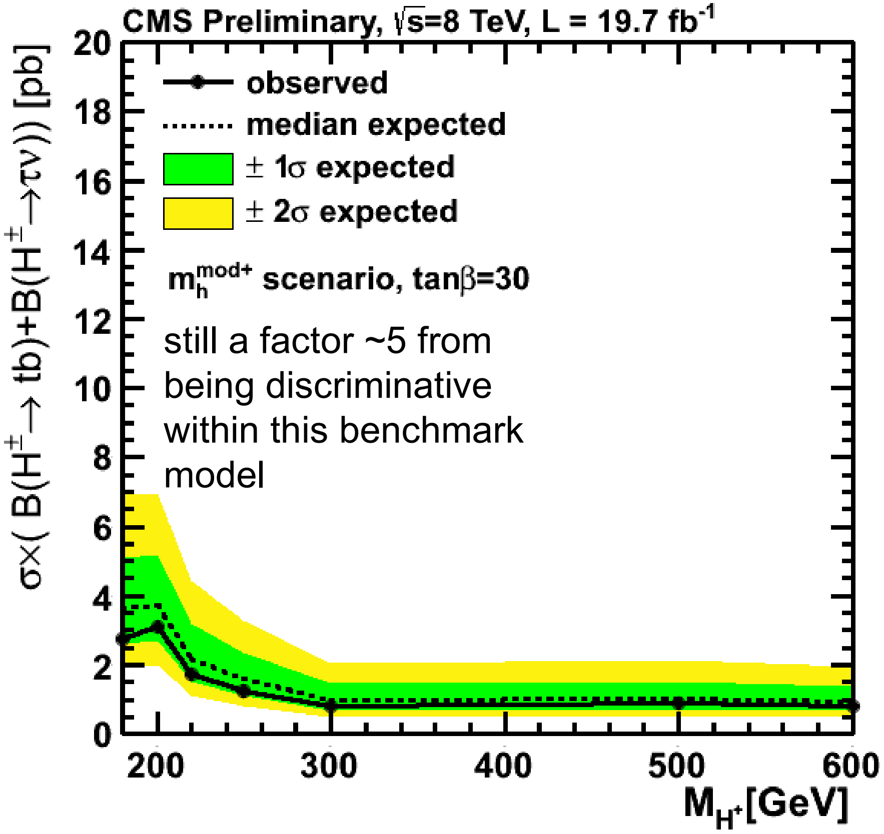




Charged Higgs boson search ($H^{+/-} \to tb$)

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





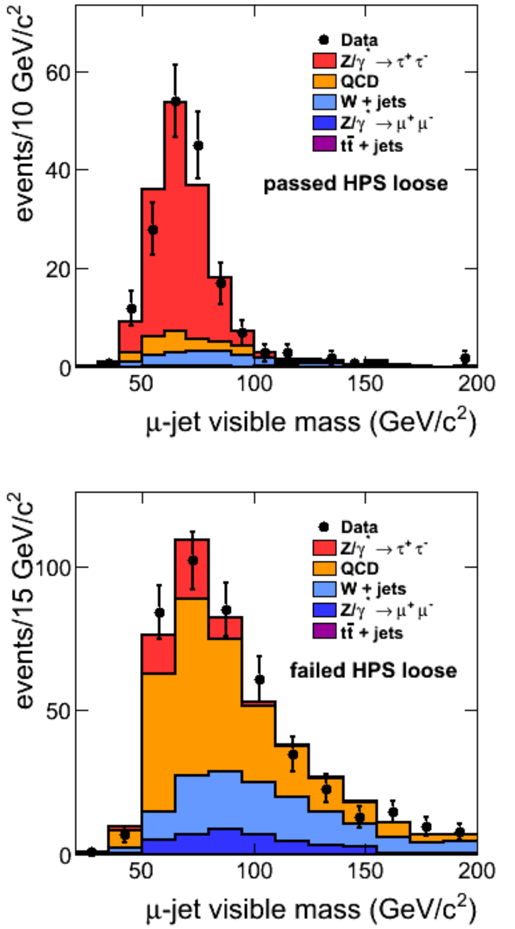
still a factor ~5 from being discriminative within this benchmark model

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

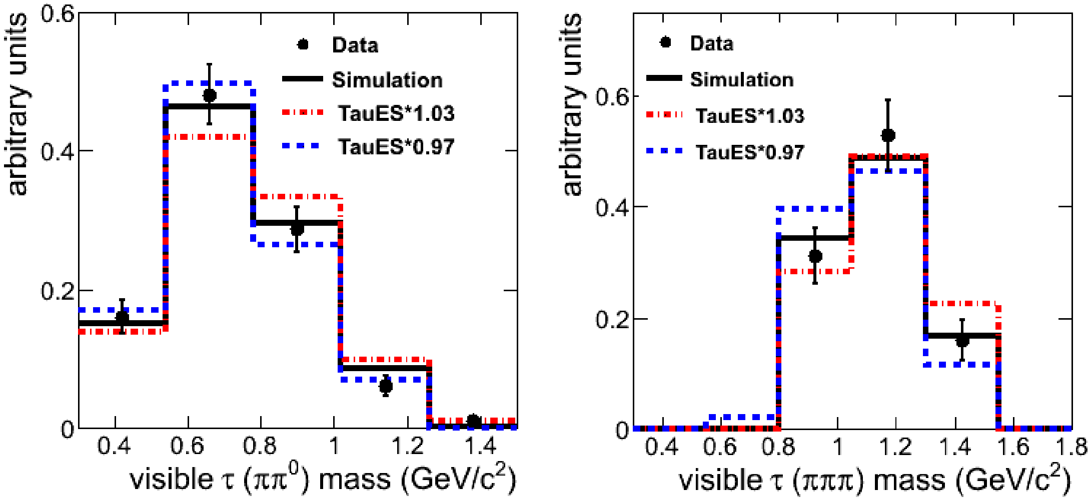
- Take into account signal in $H^{+/-} \to tb$ & in $H^{+/-} \to \tau\nu$.

Performance of hadronic τ reconstruction

- Control efficiency within $\pm7\%$ using tag & probe methods:



- Control τ_h energy scale within $\pm3\%$ from fits to $m_{\tau,\mathrm{vis}}$:



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

Performance of hadronic τ reconstruction

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