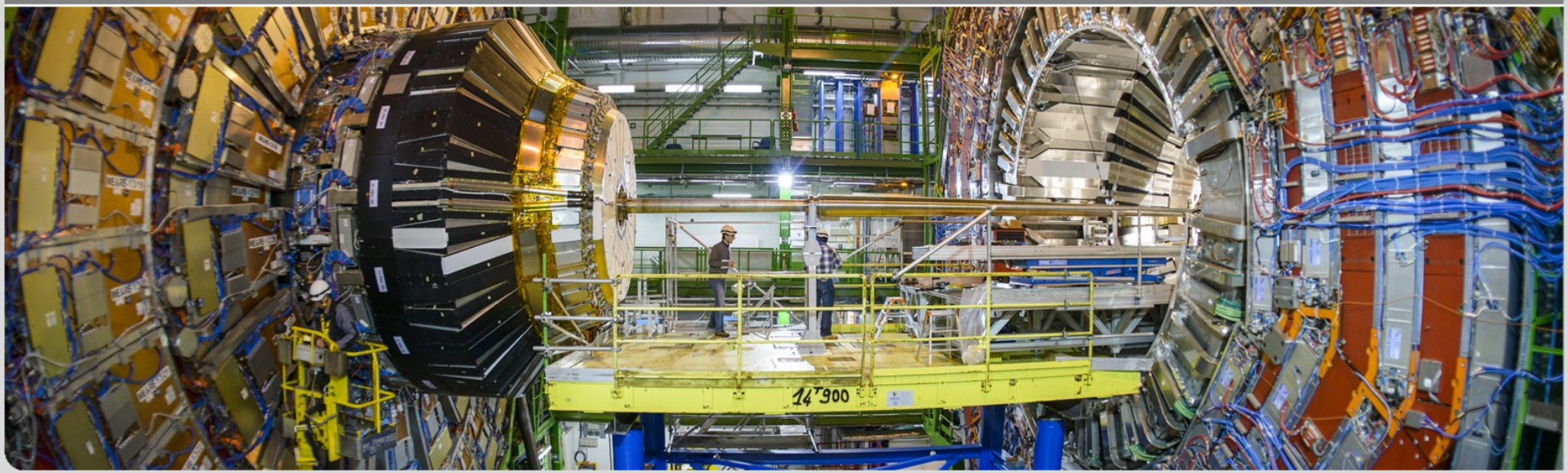
Karlsruhe Institute of Technology

Searches for the Higgs Boson Beyond the SM

Roger Wolf

07. July 2016

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



Schedule for today

- No more questions...

Bud Spencer 31. Okt. 1929 – 27. Jun. 2016

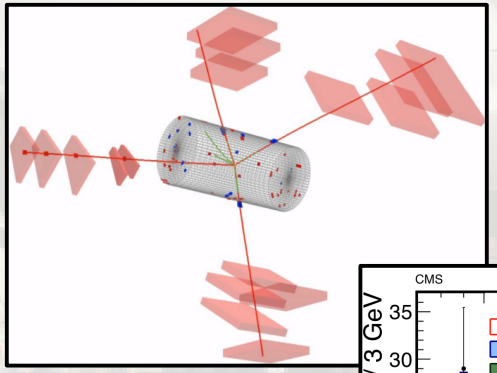
3 Searches in specific extensions of the SM Higgs sector

2 Generic searches

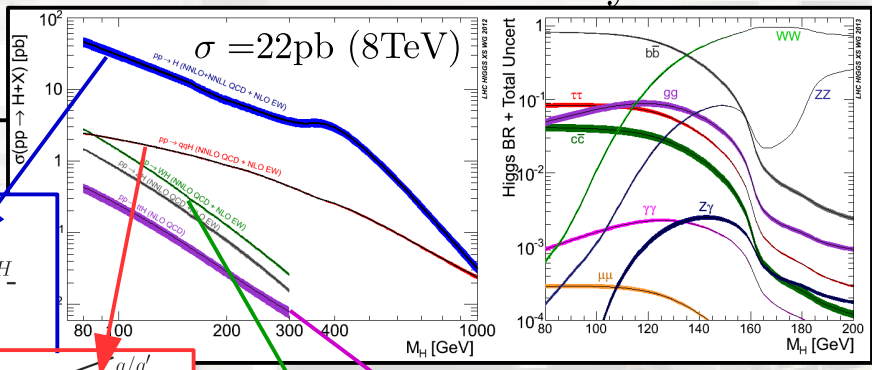
1 Higgs properties & implications

The discovery…

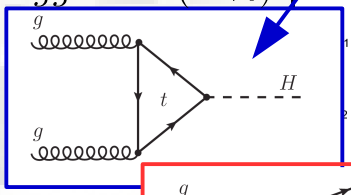
Production: Decay:

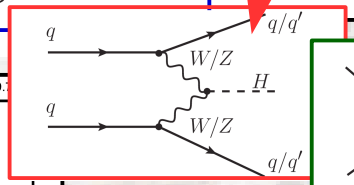


$H \to ZZ \to 4\ell$

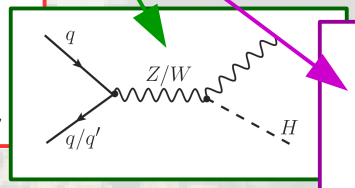


$gg \to H$ (87%)

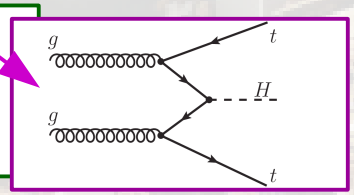




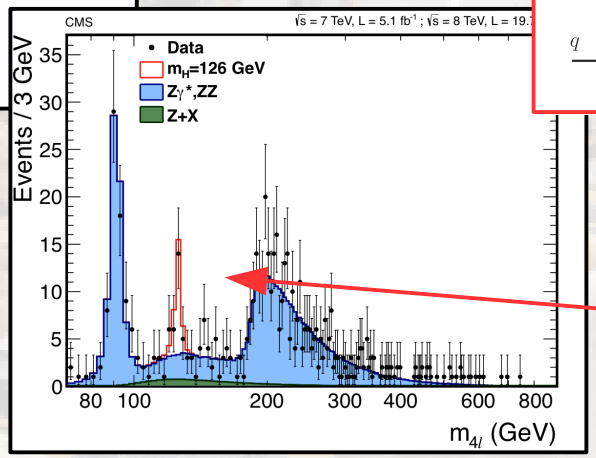
$qq \to H$ (7%)

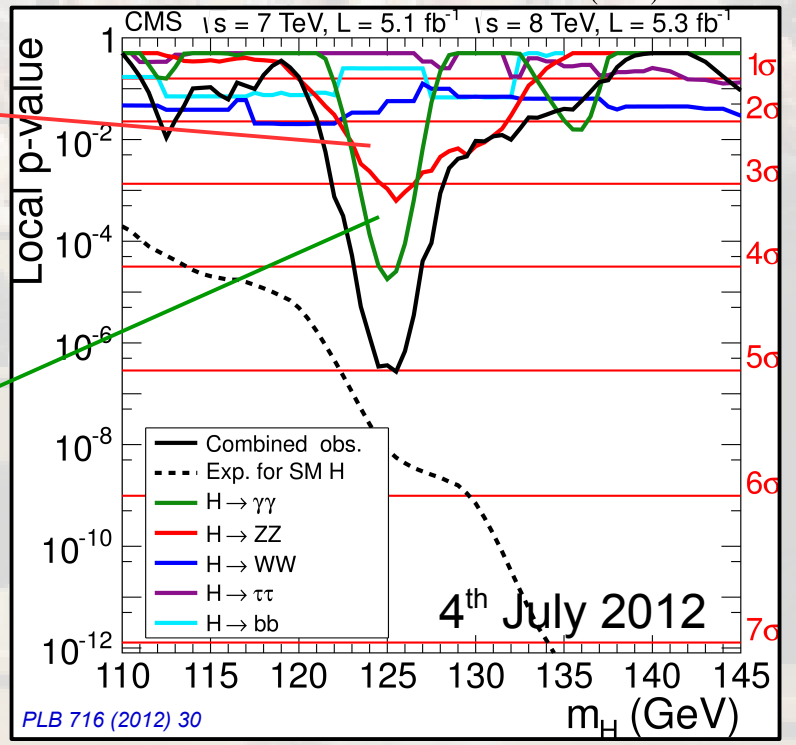


VH (5%)

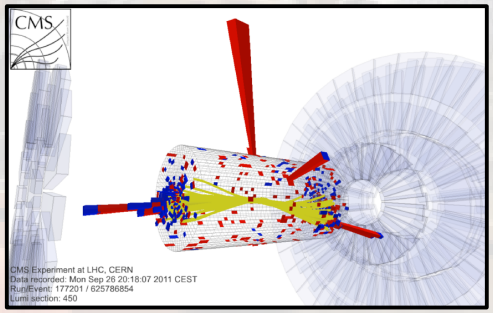


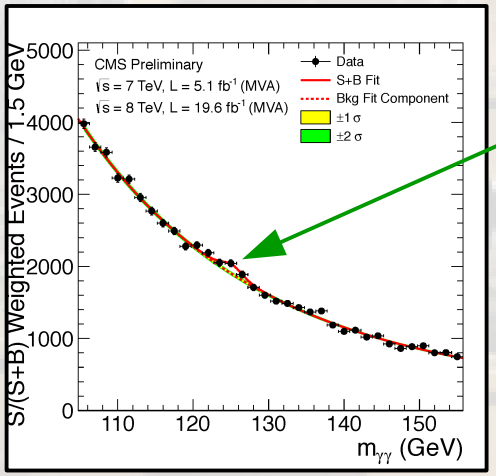
$t\bar{t}H$ (1%)





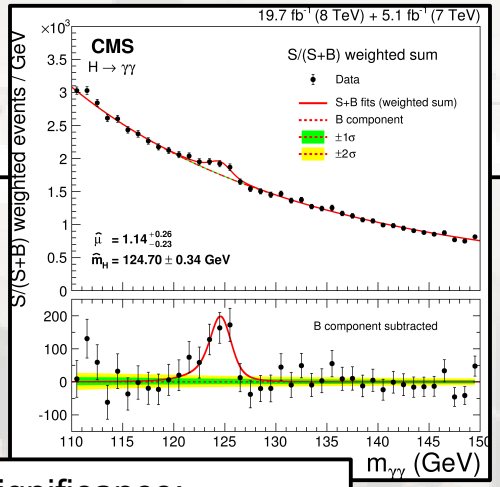
$H \to \gamma\gamma$





… and beyond

Impressive consolidation of discovery. Major LHC run-1 result!



EPJ C 74 (2014) 3076

Significance:

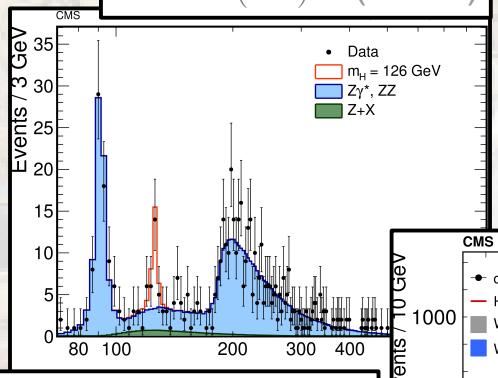
$S = 5.7(5.2)\sigma$ (CMS)

$S = 5.2(4.6)\sigma$ (ATLAS)

"untagged"

Decay / Prod	$gg \to H$ 87%	$qq \to H$ 7%	VH 5%	$t\bar{t}H$ 1%
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to ZZ$	✓	✓	✓	✓
$H \to WW$	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to b\bar{b}$		✓	✓	✓
$H \to \mu\mu$	✓	✓		

Part of discovery | After LHC run-1 | Not covered

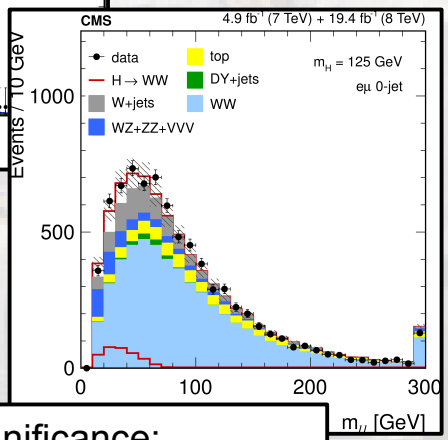


PRD 89 (2014) 092007

Significance:

$S = 6.8(6.7)\sigma$ (CMS)

$S = 8.1(6.2)\sigma$ (ATLAS)

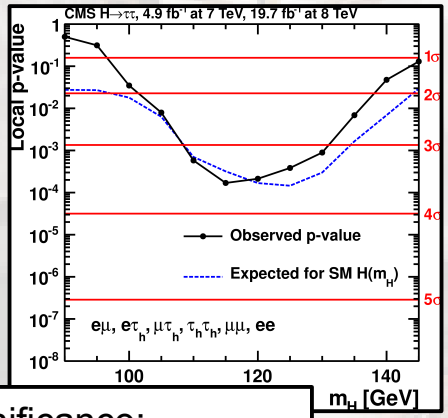


JHEP 01 (2014) 096

Significance:

$S = 4.3(5.8)\sigma$ (CMS)

$S = 6.1(5.8)\sigma$ (ATLAS)

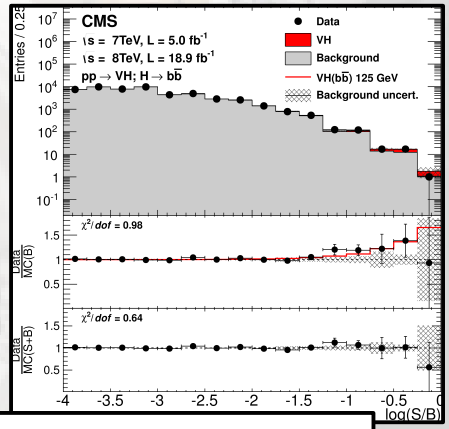


JHEP 05 (2014) 104

Significance:

$S = 3.2(3.7)\sigma$ (CMS)

$S = 4.5(3.4)\sigma$ (ATLAS)



PRD 89 (2013) 012003

Significance:

$S = 2.1(2.5)\sigma$ (CMS)

$S = 1.4(2.6)\sigma$ (ATLAS)

44 (peer reviewed) publications since discovery announcement

X(125) → H(125)

- A known suspect (within 10-30% accuracy):

Single particle? ✓
- checked mass
- checked couplings

Spin & CP? ✓
- Spin-1 and 2 excluded.
- CP-even.
- CP-odd admixture of up to 50% still possible.

Decay width? ✓
- $\Gamma_H < 22\,\mathrm{MeV}$ under SM assumptions.

Coupling structure? ✓
- Non-trivial coupling structure of a SM-like Higgs boson.
- No sign for deviations so far!

Mass? ✓
- $125.09\,\mathrm{GeV}$ one of the best known parameters in SM.

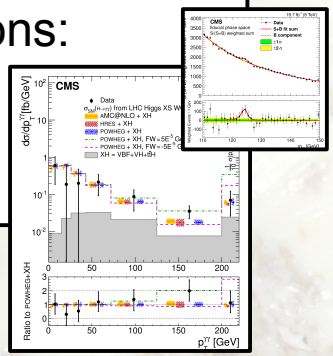
MISSION ACCOMPLISHED?

Directives for 2016++

- Explore what we have:
- Out for the unknown:

Pseudo-Observables/ Cross sections:

- fiducial
- simplified
- differential

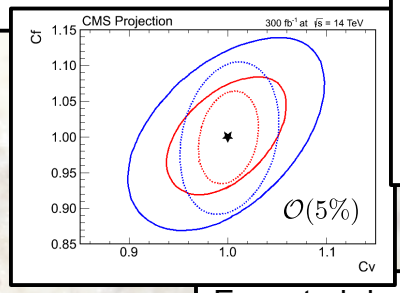


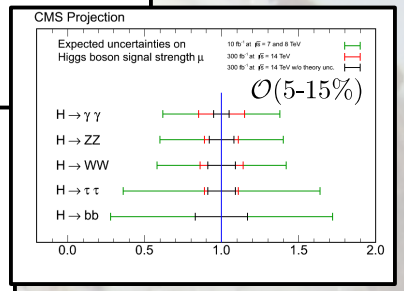
"up for 2016++"

EPJC 76 (2016) 13

Precision on couplings

- EFT approaches
- $\kappa++$





"expect lasting result ~2018/19"

Expected deviations in models:

	g_{VV}	g_{uu}	$g_{dd,\ell\ell}$	g_{hhh}
mixed-in singlet	6%	6%	6%	18%
composite Higgs	8%	$\mathcal{O}(10\%)$	$\mathcal{O}(10\%)$	$\mathcal{O}(10\%)$
MSSM	$< 1\%$	3%	$< 10\%$	2%

Heidi Rzehak (2013)

CP-measurement

- Hope for $H \to \tau\tau$
- Clear prospects.
- Still experimentally very challenging.

"endurance required (>2018)"

Higgs self-coupling

- LHC project for 3/at.
- Studies for upgrade proposals.

"beyond scope"

Find another Higgs boson

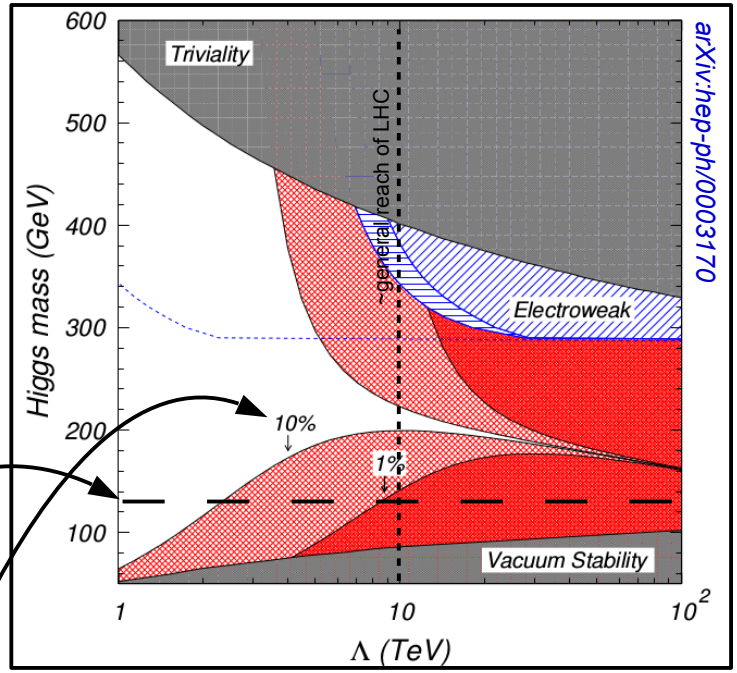
"on call for 2016++"

Extensions of the Higgs sector:

- additional singlet(s)
- additional doublet(s)
- additional triplet(s)
- …

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).



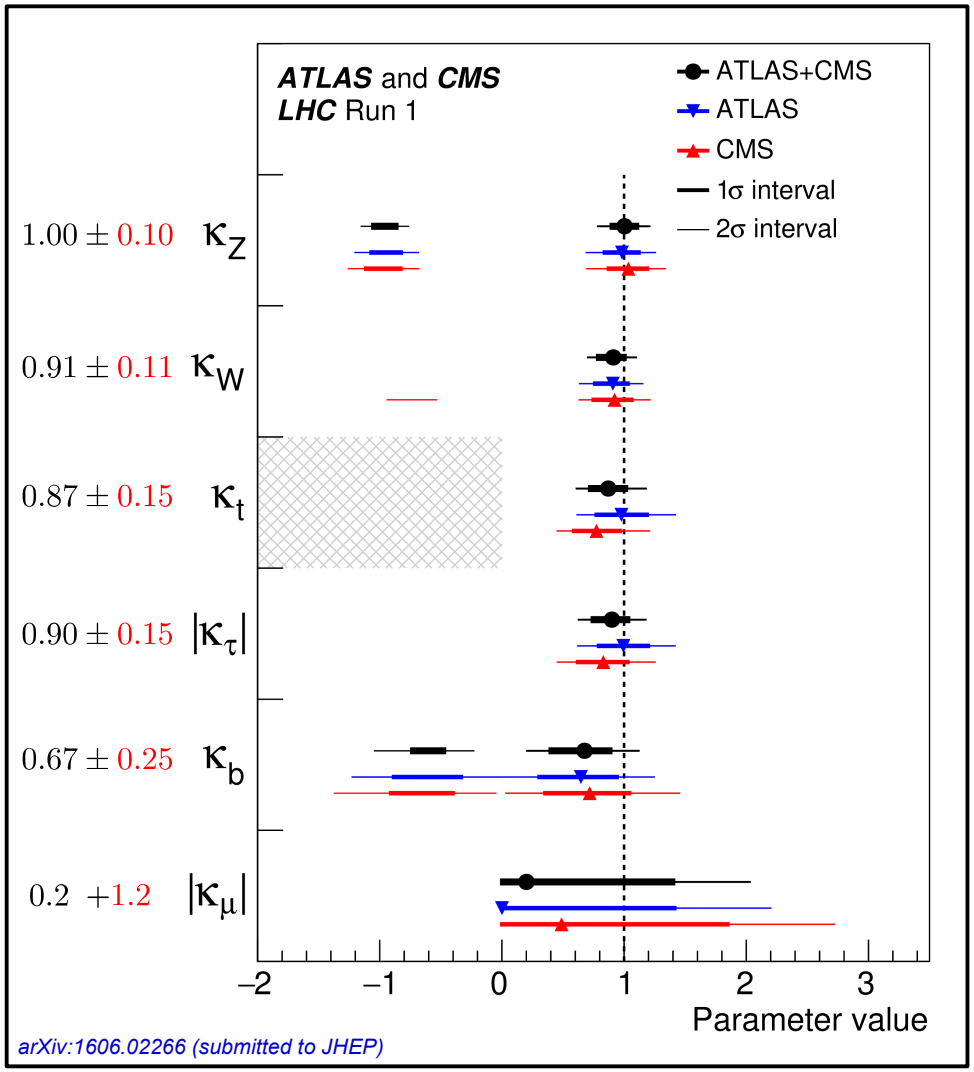
What we have found and measured for m_H.

Different levels of fine tuning in the SM.

- 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 $\pm 10 \ldots 30\%$ accuracy.
- Allows for contributions from additional Higgs bosons with couplings at this order.
- These can be searched for e.g. as simple additional $SU(2)_L$ singlets.

High mass Higgs boson search in WW and ZZ

- Search in mass range of $m_H = 145 \ldots 1000$ GeV.
- Combination of several channels in WW and ZZ ($\rightarrow$ 55 channels/categories).

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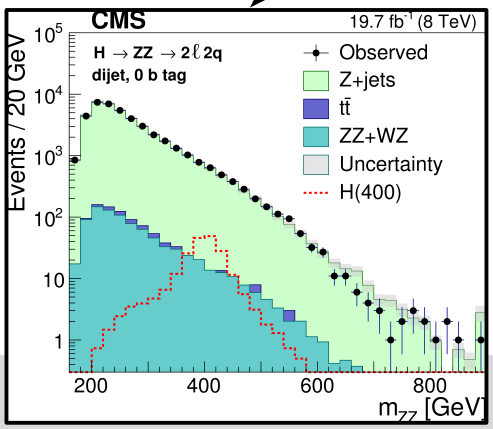
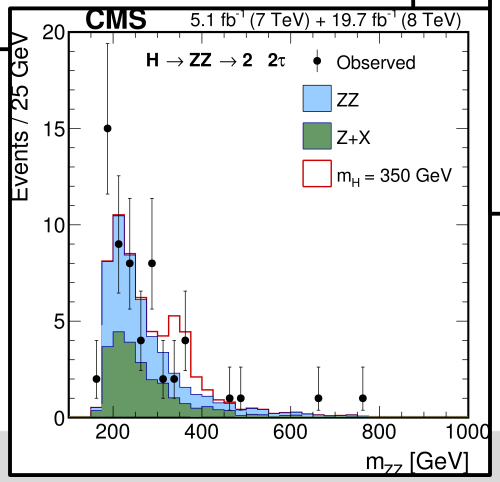
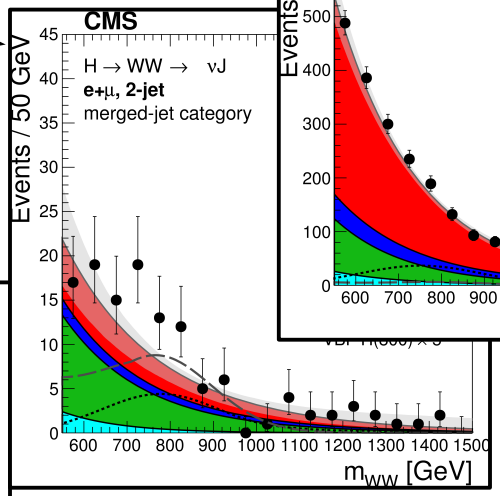
H decay mode	H production	Exclusive final states	No. of channels	m_H range [GeV]	m_H resolution
WW $\rightarrow \ell\nu\ell\nu$	untagged	((ee, $\mu\mu$), eμ) + (0 or 1 jets)	4	145–1000 [a,b]	20%
	VBF tag	((ee, $\mu\mu$), eμ) + $(jj)_{VBF}$	2	145–1000 [a,b]	20%
WW $\rightarrow \ell\nu$qq	untagged	(eν, $\mu\nu$) + $(J)_W$	2	180–600	5–15%
	untagged	(eν, $\mu\nu$) + $(J)_W$ + (0+1-jets)	2	600–1000 [b]	5–15%
	VBF tag	(eν, $\mu\nu$) + $(J)_W$ + $(jj)_{VBF}$	1	600–1000 [b]	5–15%
ZZ $\rightarrow 2\ell 2\ell'$	untagged	4e, 4μ, 2e2μ	3	145–1000	1–2%
	VBF tag	(4e, 4μ, 2e2μ) + $(jj)_{VBF}$	3	145–1000	1–2%
	untagged	(ee, $\mu\mu$) + ($\tau_h\tau_h$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_e\tau_\mu$)	8	200–1000	10–15%
ZZ $\rightarrow 2\ell 2\nu$	untagged	(ee, $\mu\mu$) + (0 or $\geq$ 1 jets)	4	200–1000	7%
	VBF tag	(ee, $\mu\mu$) + $(jj)_{VBF}$	2	200–1000	7%
ZZ $\rightarrow 2\ell$2q	untagged	(ee, $\mu\mu$) + $(jj)_Z^{0,1,2\,b\,tags}$	6	230–1000 [c]	3%
	untagged	(ee, $\mu\mu$) + $(J)_Z^{0,1,2\,b\,tags}$	6	230–1000 [c]	3%
	VBF tag	(ee, $\mu\mu$) + $(jj)_Z^{0,1,2\,b\,tags}$ + $(jj)_{VBF}$	6	230–1000 [c]	3%
	VBF tag	(ee, $\mu\mu$) + $(J)_Z^{0,1,2\,b\,tags}$ + $(jj)_{VBF}$	6	230–1000 [c]	3%

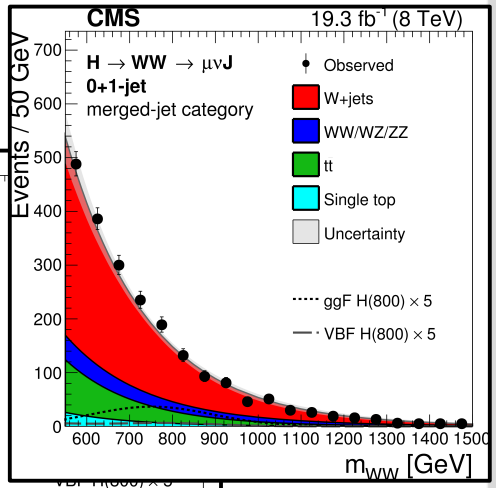
[a] EW singlet model interpretation starts at 200 GeV to avoid contamination from h(125).
[b] 600-1000 GeV for $\sqrt{s} = 8$ TeV only.
[c] For $\sqrt{s} = 8$ TeV only.

Merged jet event categories in WW:

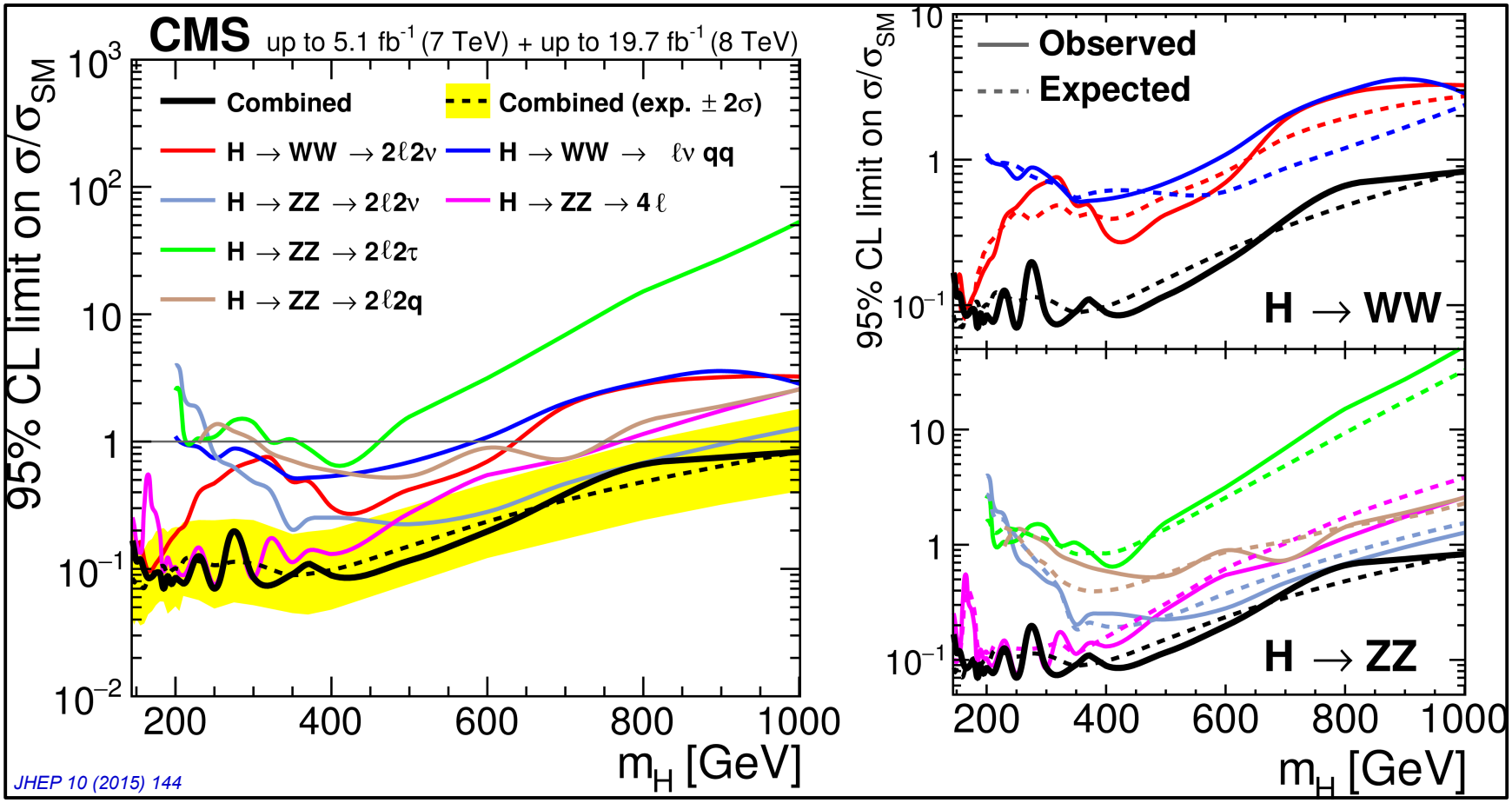








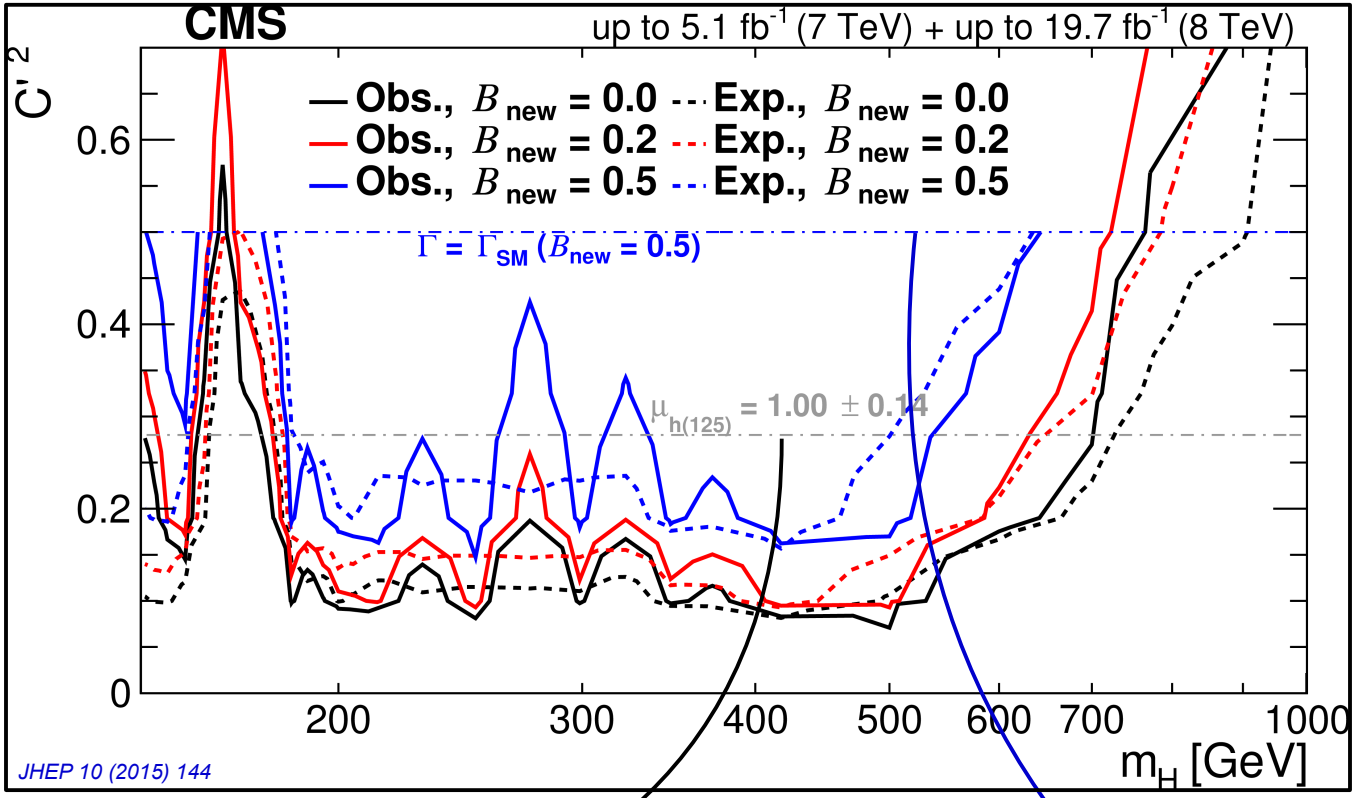
Additional SM-like Higgs boson?



- Additional Higgs boson with same production cross section and $\mathcal{BR}$ as expected for the SM (for given mass value).

EWK singlet admixtures?

Additional heavy Higgs (H) that mixes with $h(125)$.



- Unitarity constraint:
  C : coupling to h
  C': coupling to H
  $C'^2 + C^2 = 1$
  → couplings of h reduced by coupling to H.
- Allow additional $\mathcal{BR}$ for non-SM H decays:
  $\mu' = C'^2(1 - \mathcal{BR}_{new})$
  $\Gamma' = \frac{\Gamma_{SM}}{(1-\mathcal{BR}_{new})}$

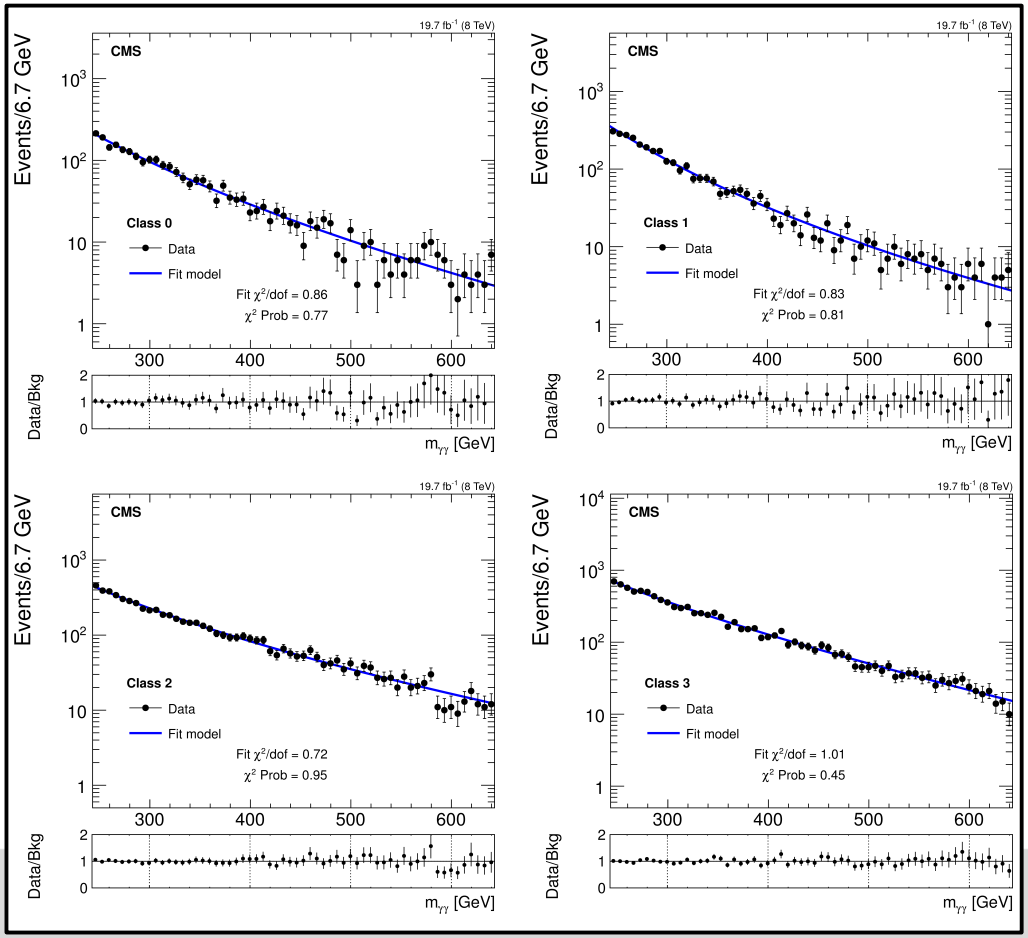
Unitarity bound for:
$\mu_{h(125)} = 1 \pm 0.14$
$-2\sigma \sim C'^2\big|_{B_{new}=0} \leq 0.28$

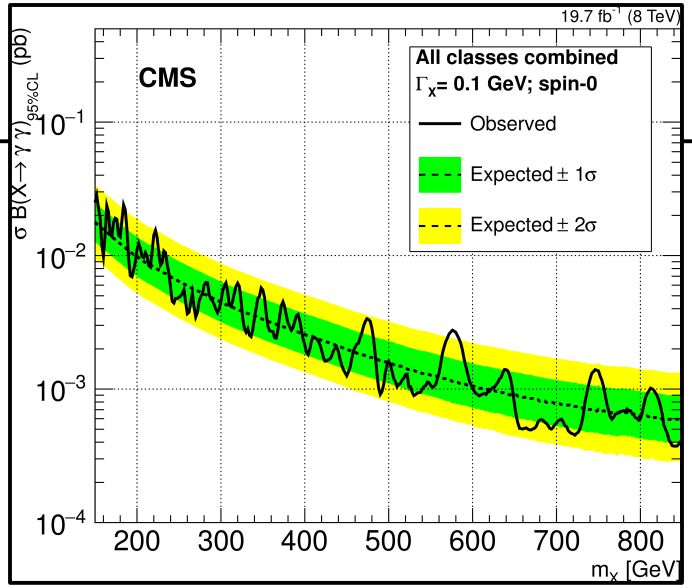
Boundary for main assumption of analysis:
$\Gamma' \leq \Gamma_{SM}$ (based on CMS limit on $\mathcal{BR}_{BSM} \lesssim 0.5(95\%CL)$ from couplings)

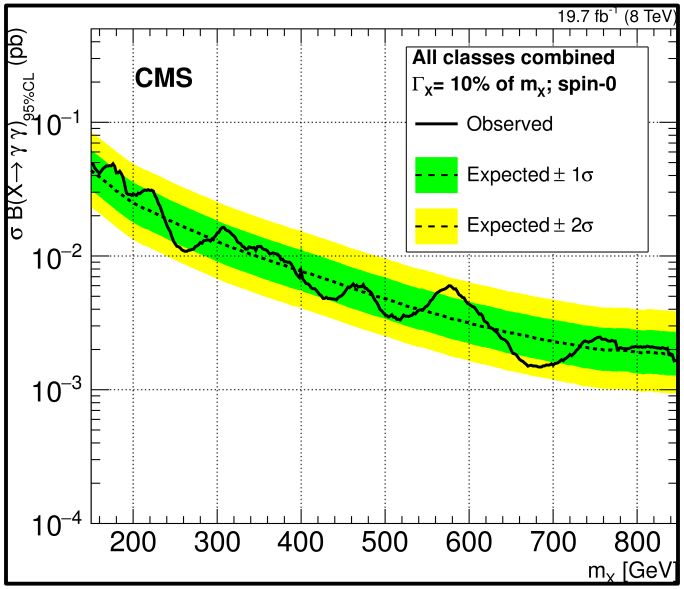
High mass Higgs boson search in $\gamma\gamma$

- Search in mass range of $m_H = 150 \ldots 850$ GeV.
- Combination of four sub-categories.
- Analysis strategy same as for SM Higgs search.

PLB 750 (2015) 494







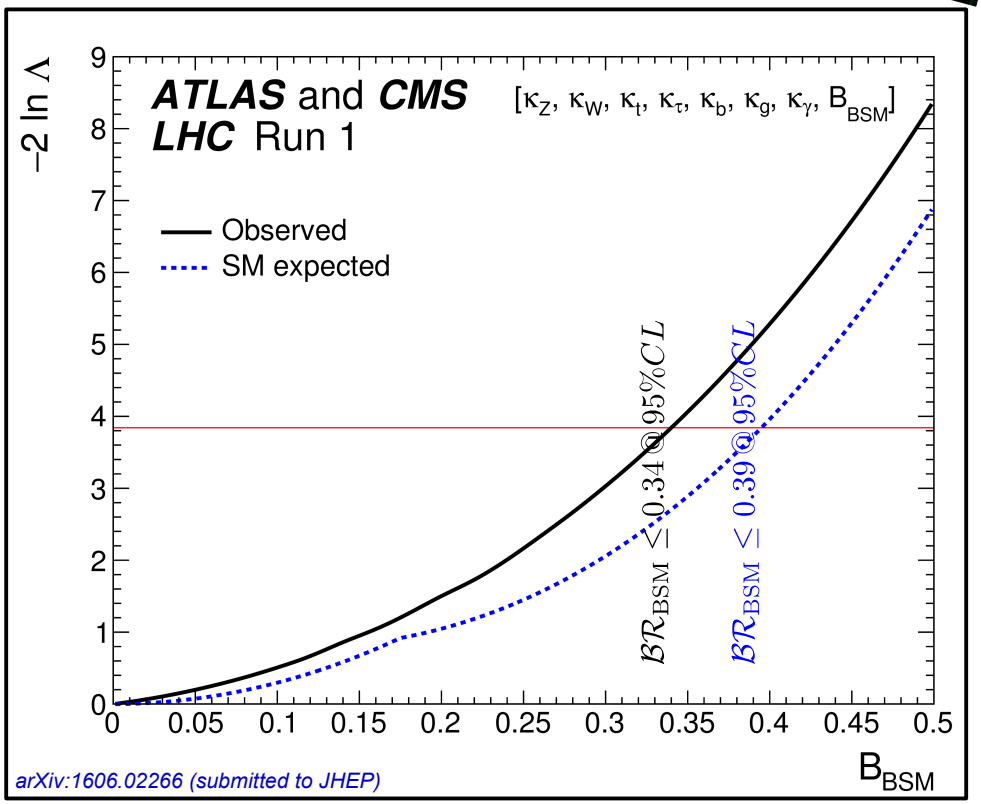
Space left for new physics in the Higgs sector

- Exotic decays of the observed Higgs boson.

- Estimate the space still left by the coupling measurement by adding $\mathcal{BR}_{\mathrm{BSM}}$ as a free parameter to the coupling estimate.

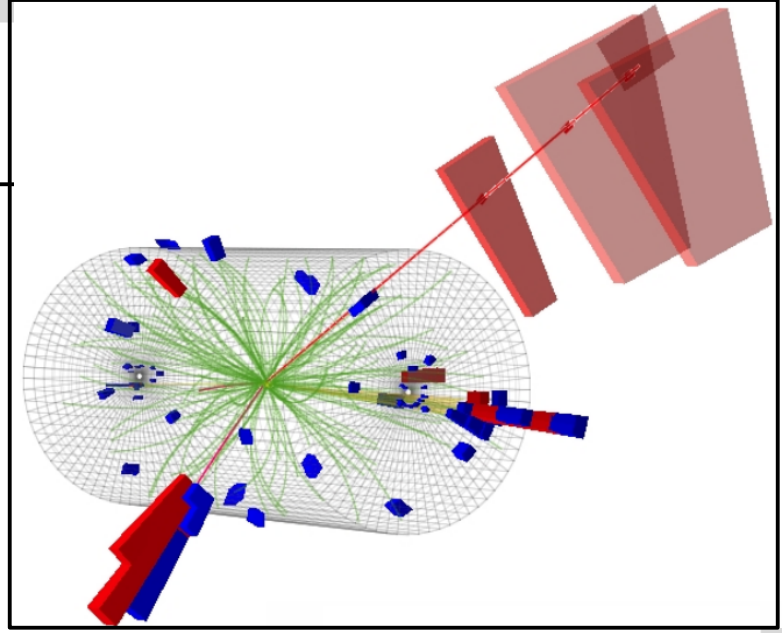
- Give maximal freedom to the fit: let all $\{\kappa_i\}$ float freely. Constrain $\kappa_V \leq 1$ ($\rightarrow$ which is a choice well motivated by theory).

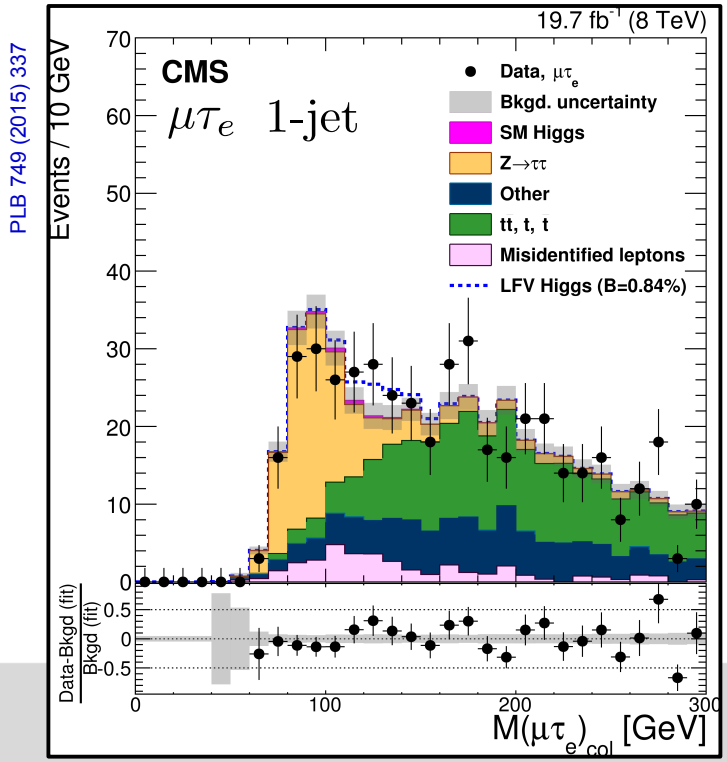
- $\mathcal{BR}_{\mathrm{BSM}} \approx 0.34$ still possible!



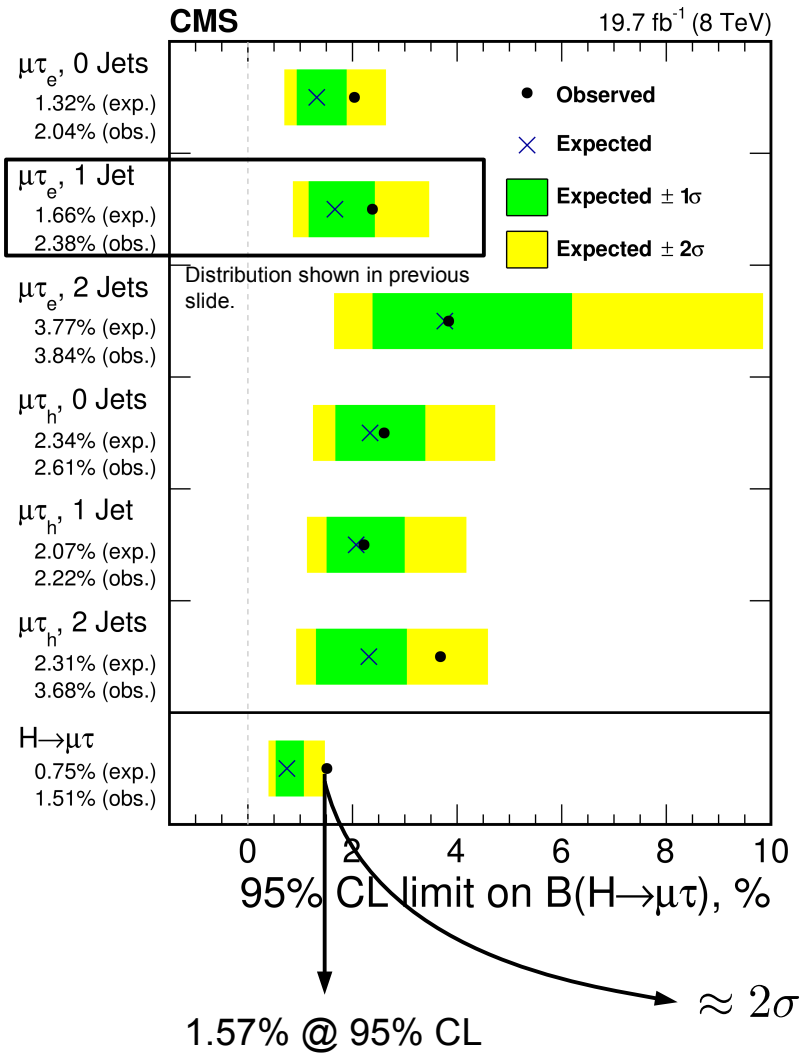
$H \to \mu\tau$ LFV Higgs couplings

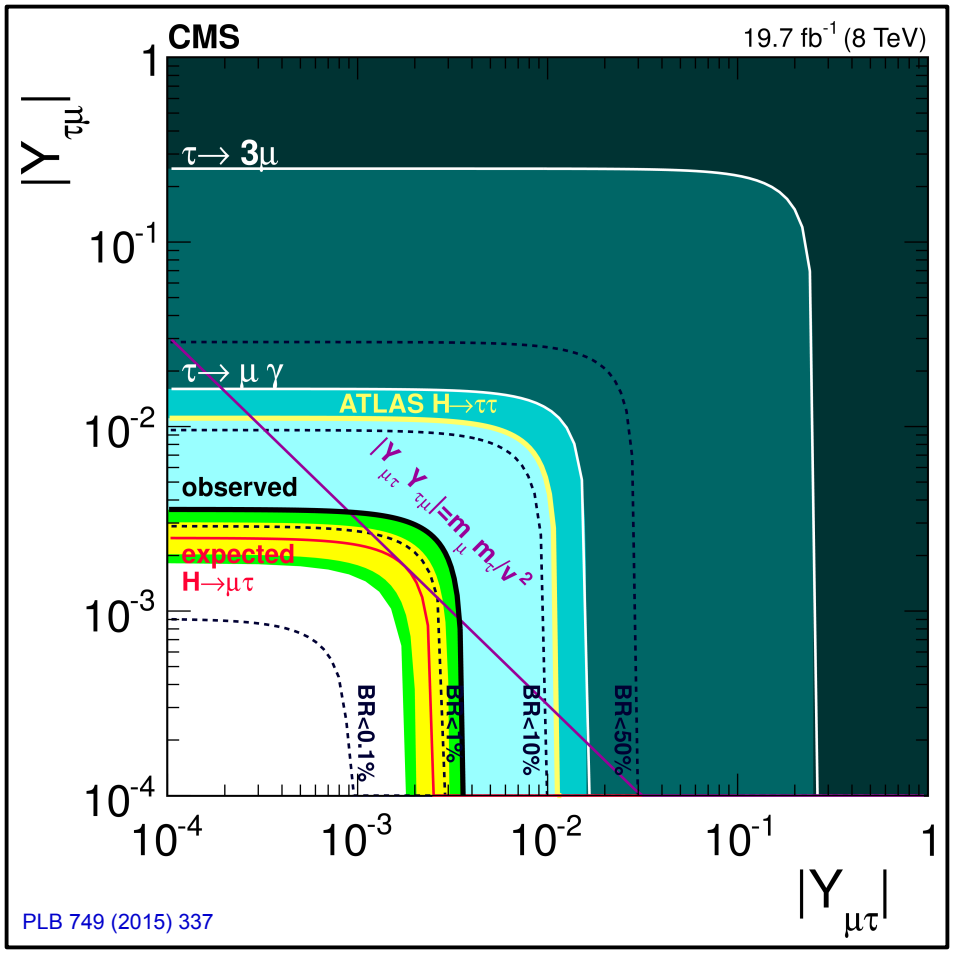
- SM forbids LFV couplings at tree level.
- Three couplings kinematically possible:
  $\tau \to e,\ \tau \to \mu,\ \mu \to e$.
- LVF in Higgs sector. Limits in literature:
  - $BR(H \to e\mu) = \mathcal{O}(10^{-8})$.
  - $BR(H \to e\tau) = \mathcal{O}(0.1)$.
  - $BR(H \to \mu\tau) = \mathcal{O}(0.1)$.
- $H \to \tau\tau_\mu/\mu\tau_e$ 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 $m_{\tau\tau}$.





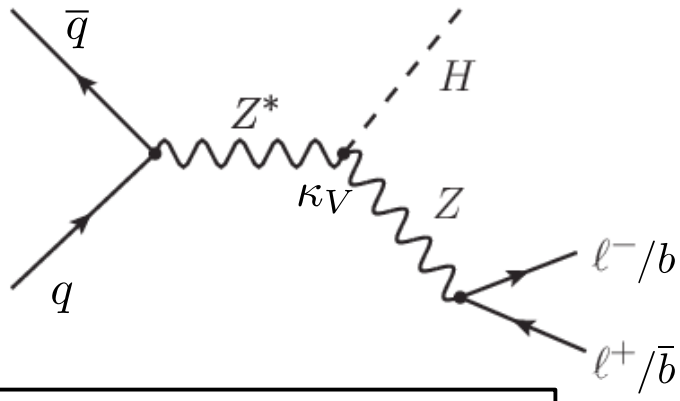
$H \to \mu\tau$ LFV Higgs couplings

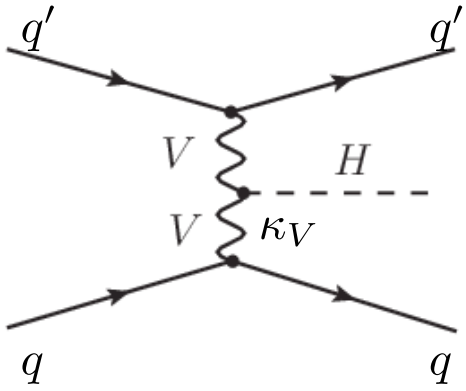


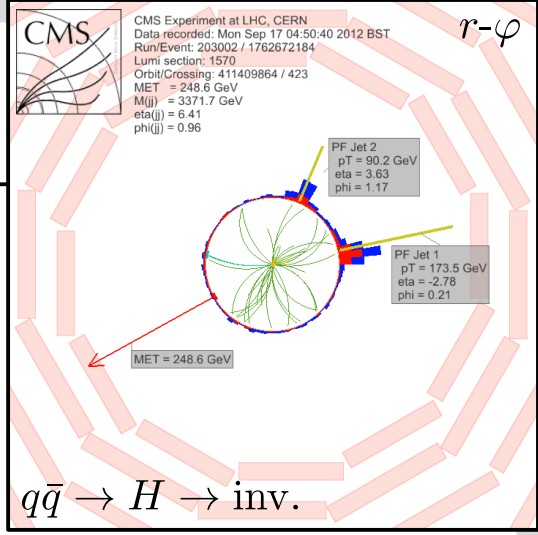


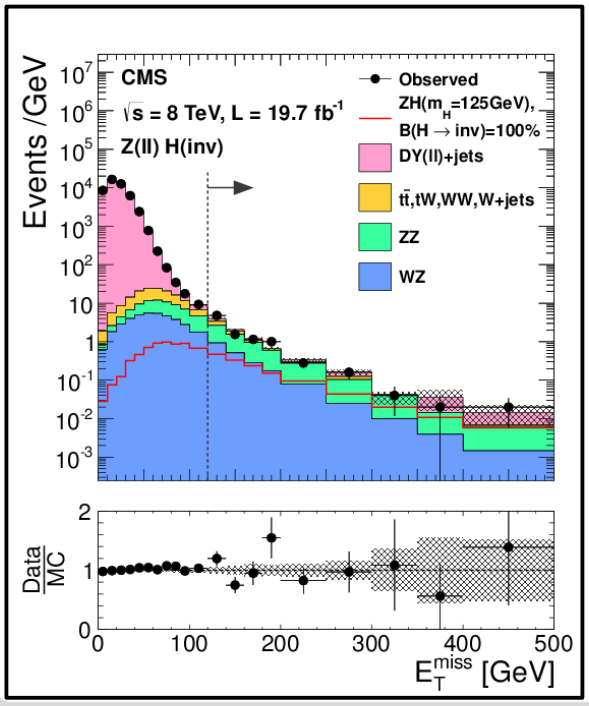
Strongest limits on the market!

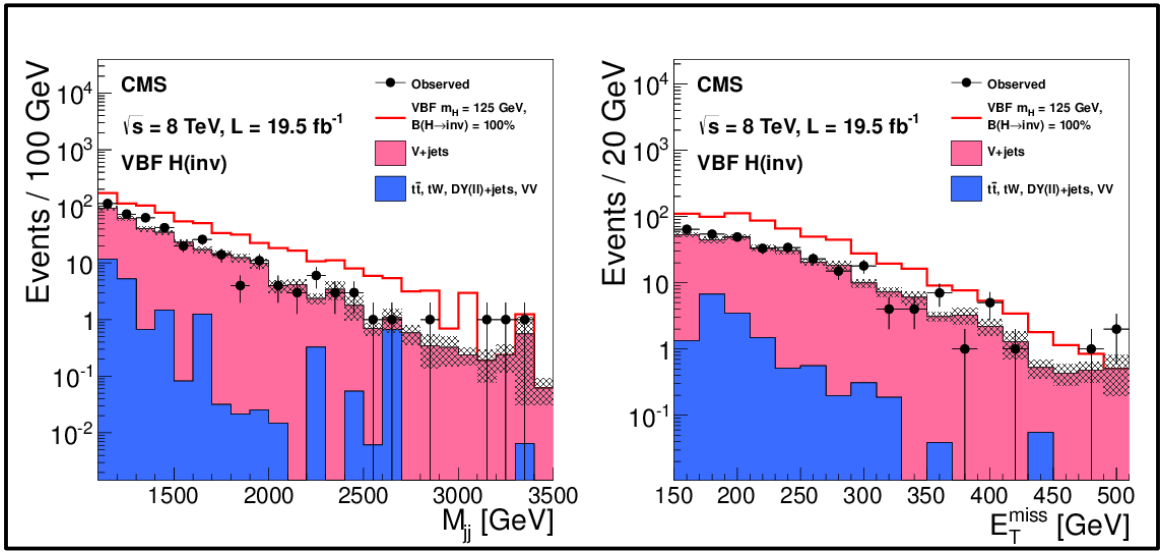
Direct searches for $H \rightarrow$ invisible





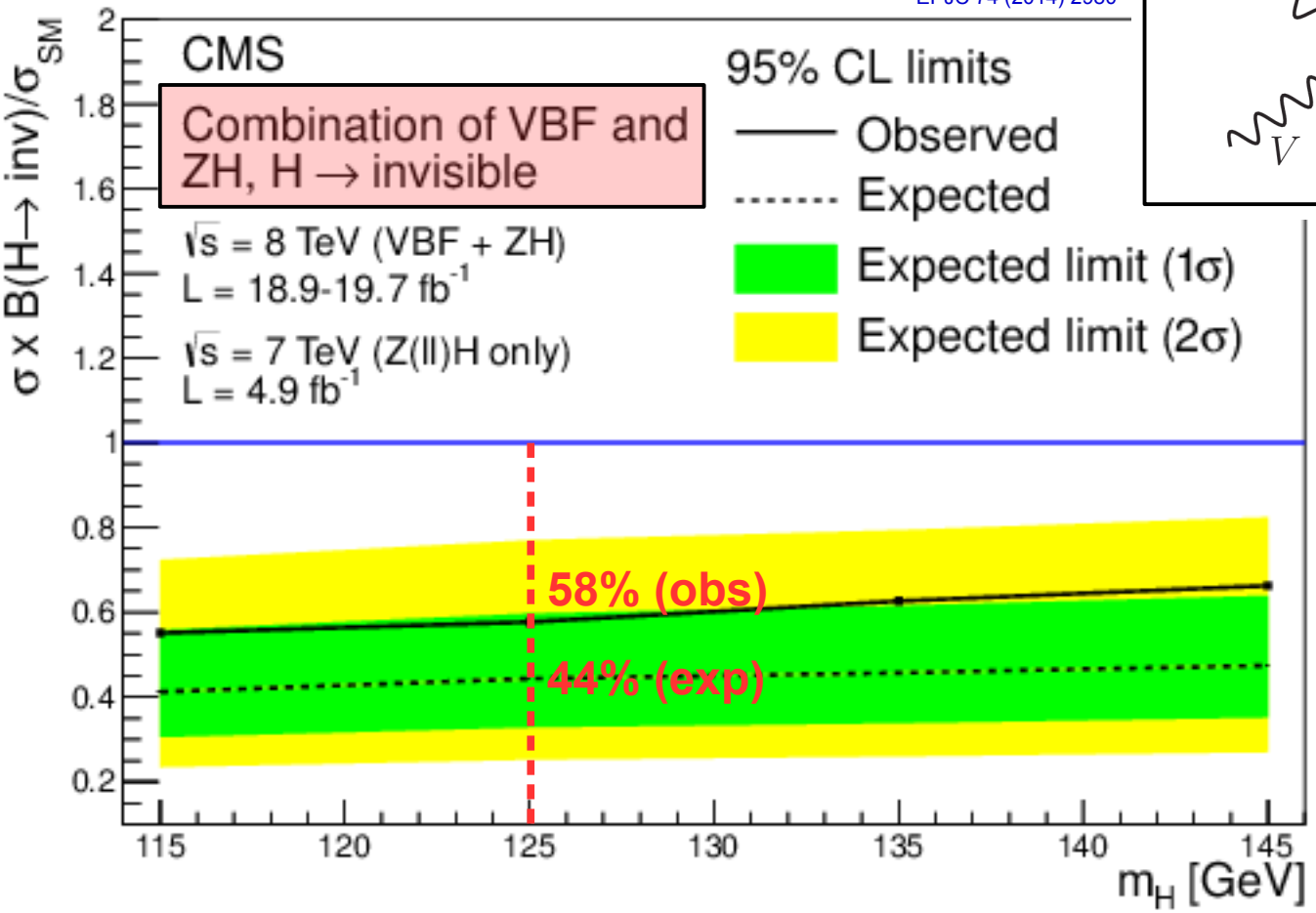


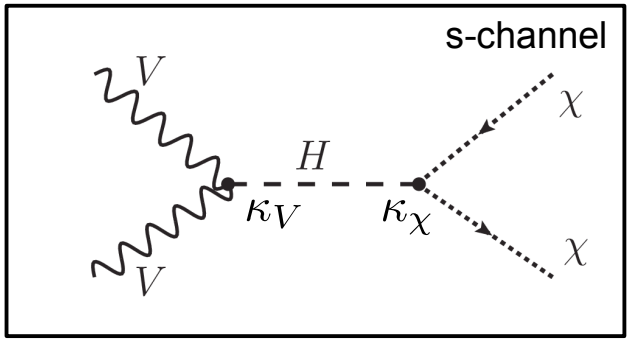




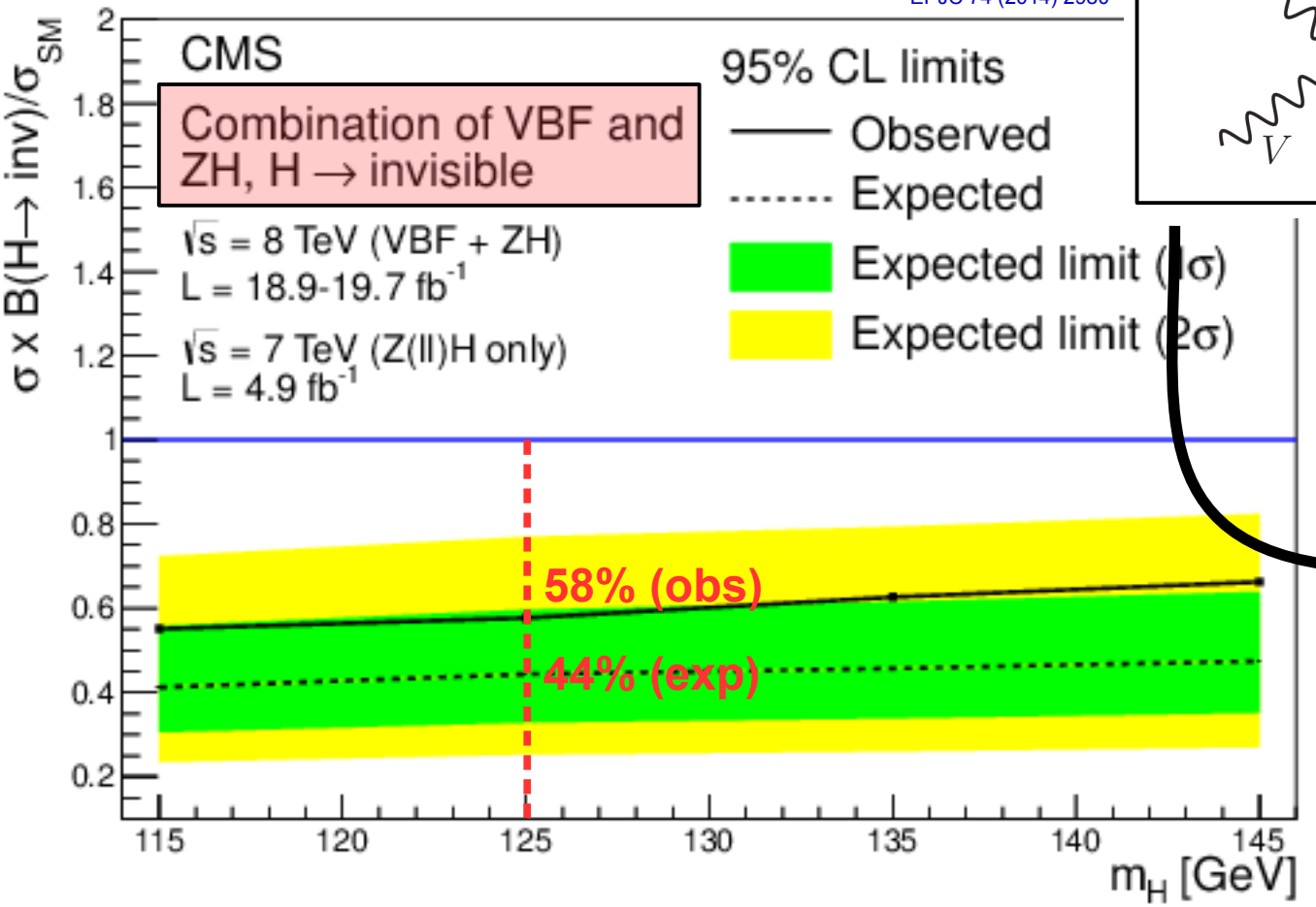
EPJC 74 (2014) 2980

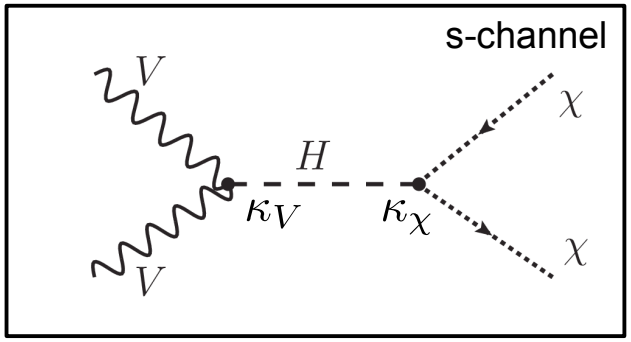
Direct searches for $H \rightarrow$ invisible

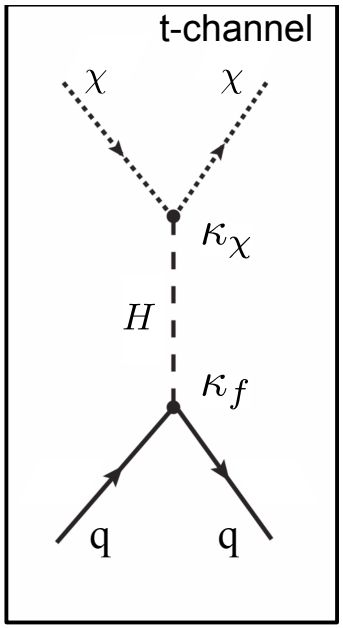




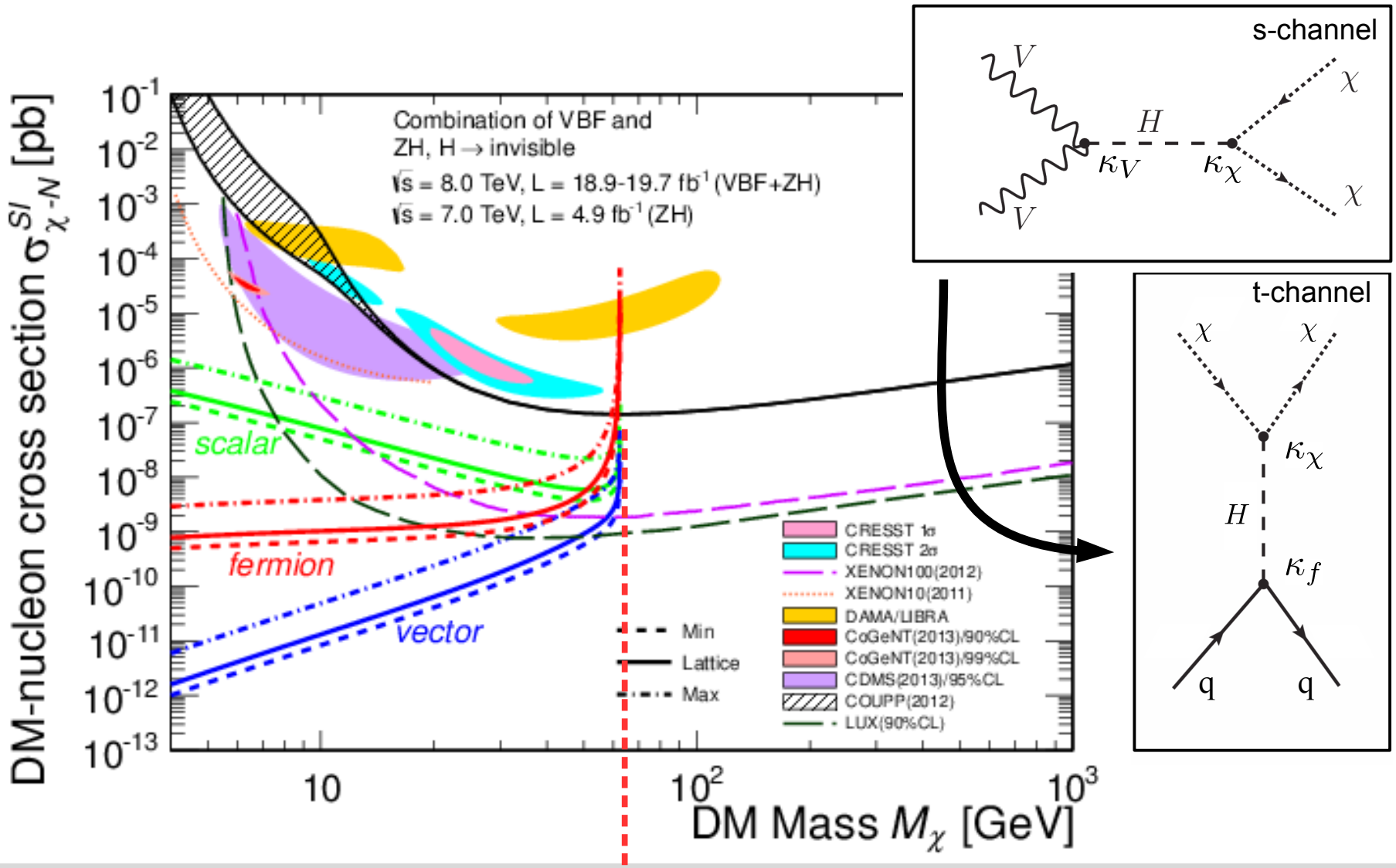
Direct searches for $H \rightarrow$ invisible





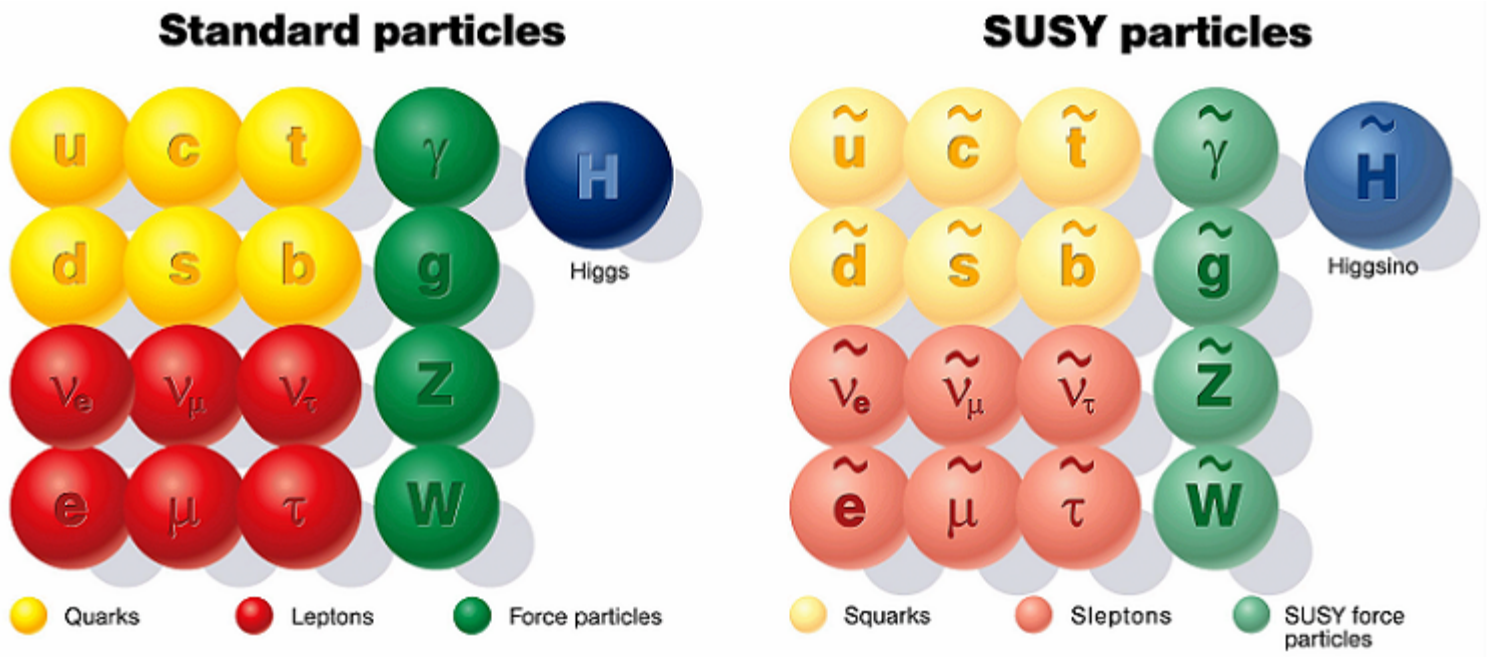


Direct searches for $H \rightarrow$ invisible



SUSY particles as DM 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 χ.
- **Problem:** SUSY itself is broken!

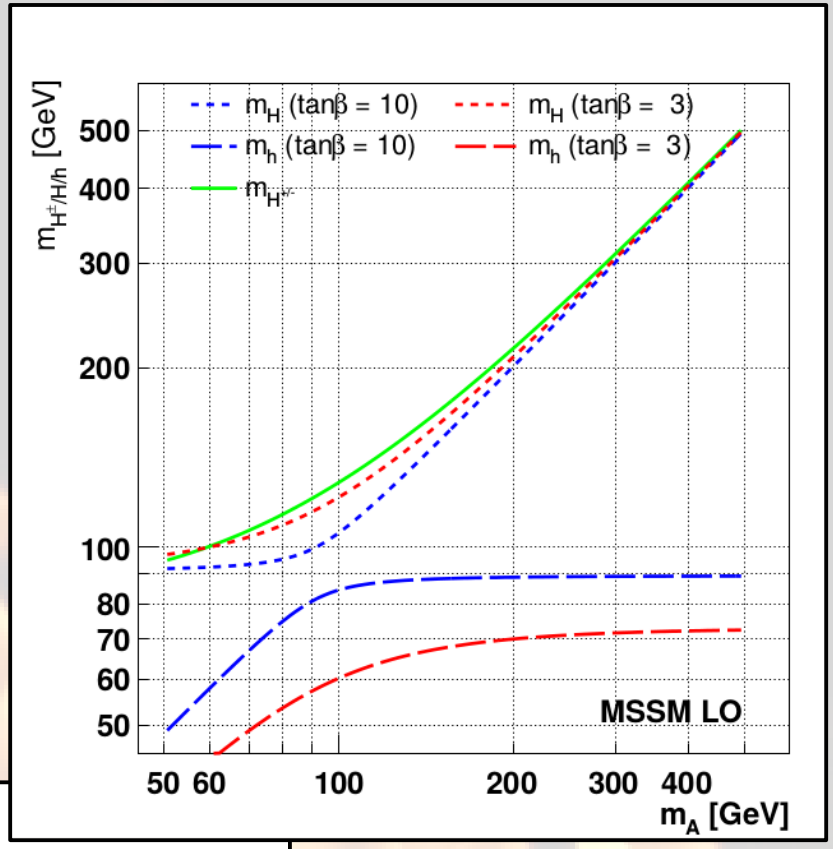
Extended Higgs sectors

- The MSSM, like any other Two Higgs Doublet Model (THDM) predicts five Higgs bosons:

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

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

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



- Strict mass requirements at tree level:

  two free parameters: m_A , $\tan\beta = {}^{\mathrm{v}_u}/_{\mathrm{v}_d}$

$$m^2_{H^\pm} = m^2_A + m^2_W$$

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

$$\tan\alpha = \frac{-(m^2_A + m^2_Z)\sin 2\beta}{(m^2_Z - m^2_A)\cos 2\beta + \sqrt{\left(m^2_A + m^2_Z\right)^2 - 4 m^2_A m^2_Z \cos^2 2\beta}}$$

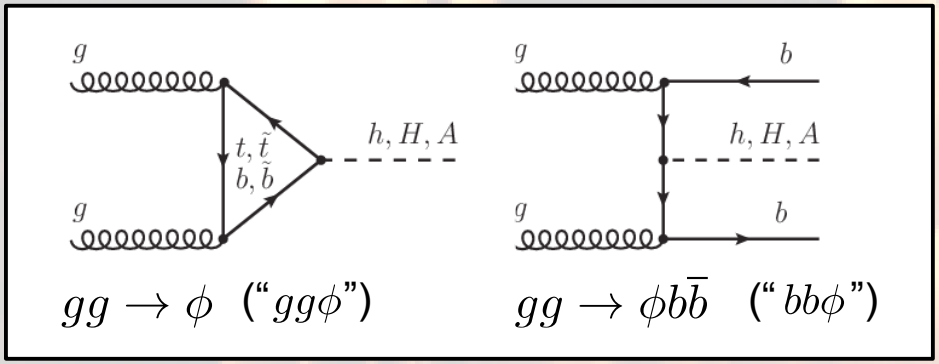
(angle btw. H_u & H_d in isospace)

The role of down-type fermions

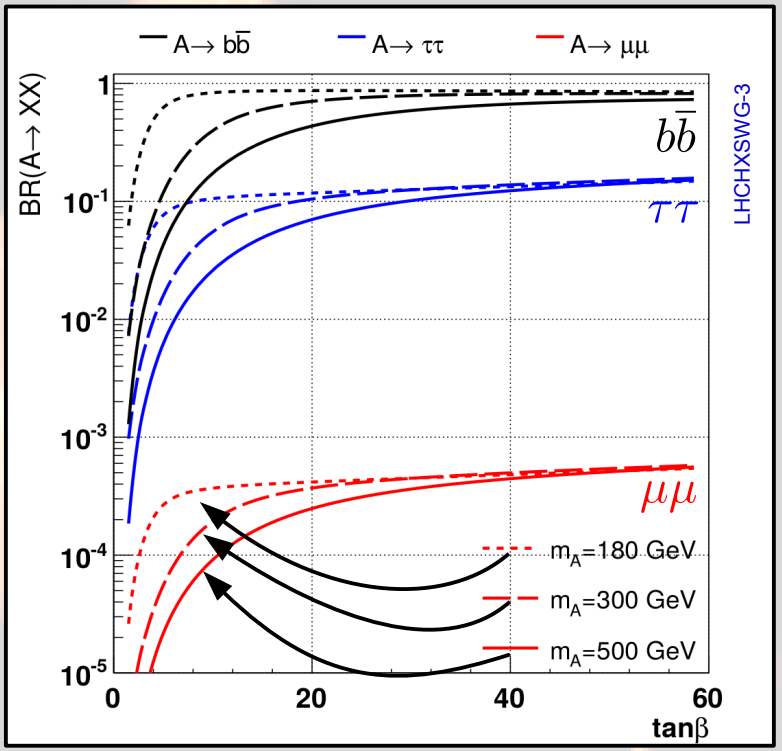
	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \to 0$	$\sin\alpha/\sin\beta \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \to 1$	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to 1$

For $m_A \gg m_Z$: $\alpha \to \beta - \pi/2$ (coupling to down-type fermions enhanced by $\tan\beta$).

Interesting production modes:

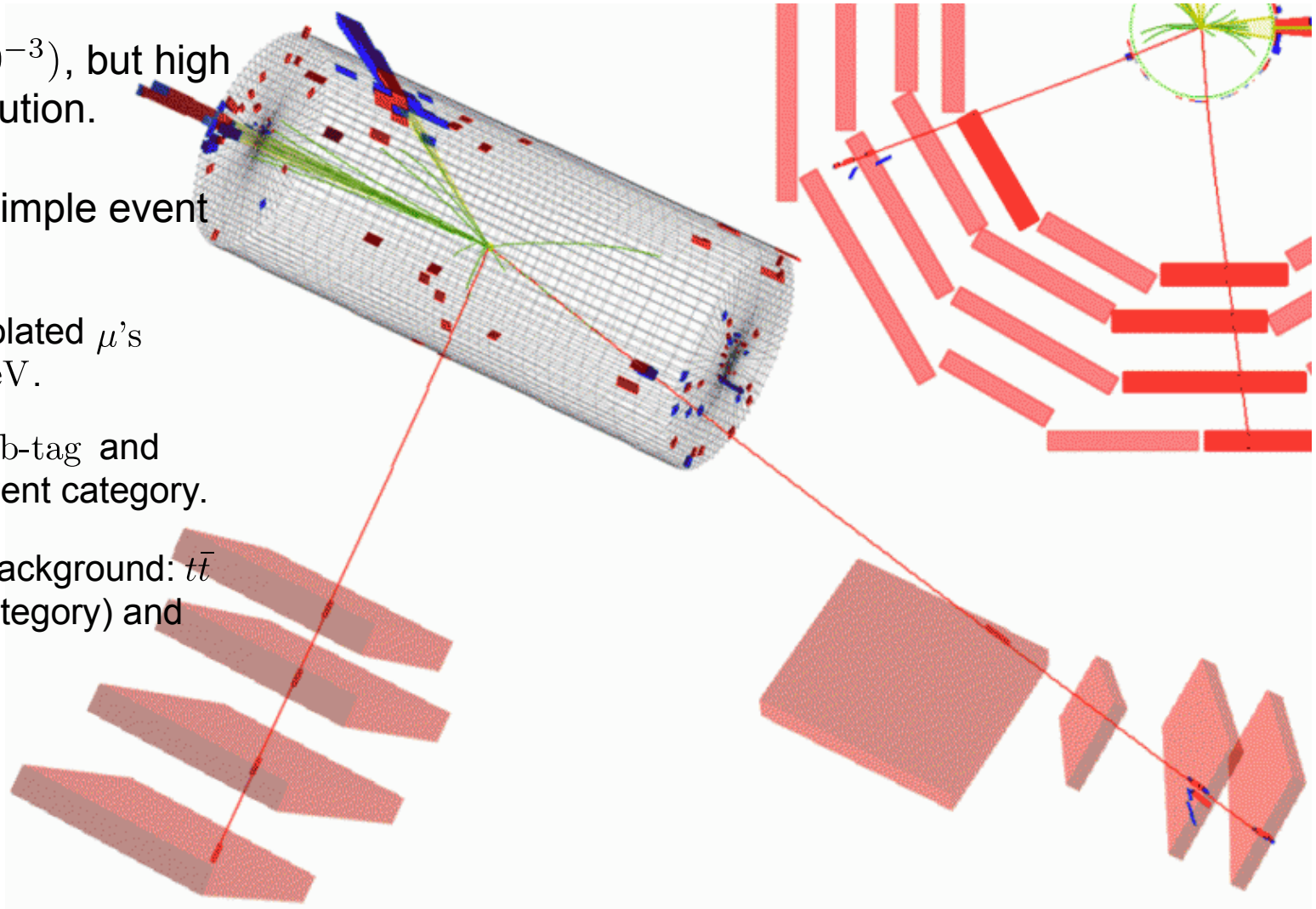


Interesting decay channels:



$H \to \mu\mu$ decay channel

- $BR \lesssim \mathcal{O}(10^{-3})$, but high mass resolution.
- Robust & simple event selection:
  - Two well isolated μ's $p_T > 25\ \mathrm{GeV}$.
  - Distinguish $\mathrm{b\text{-}tag}$ and $\mathrm{no\ b\text{-}tag}$ event category.
  - Dominant background: $t\bar{t}$ (in $\mathrm{b\text{-}tag}$ category) and $Z \to \mu\mu$.



$H \to \mu\mu$ decay channel

$\to$ 324 simulated signal samples

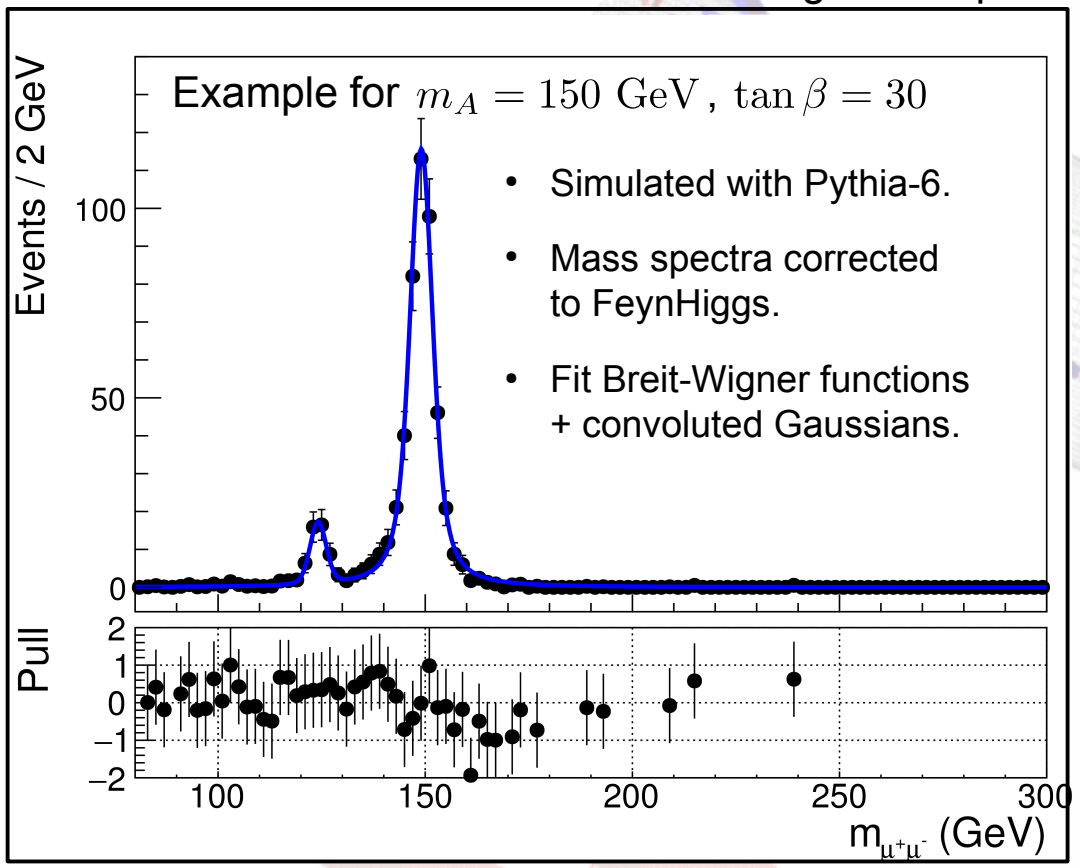
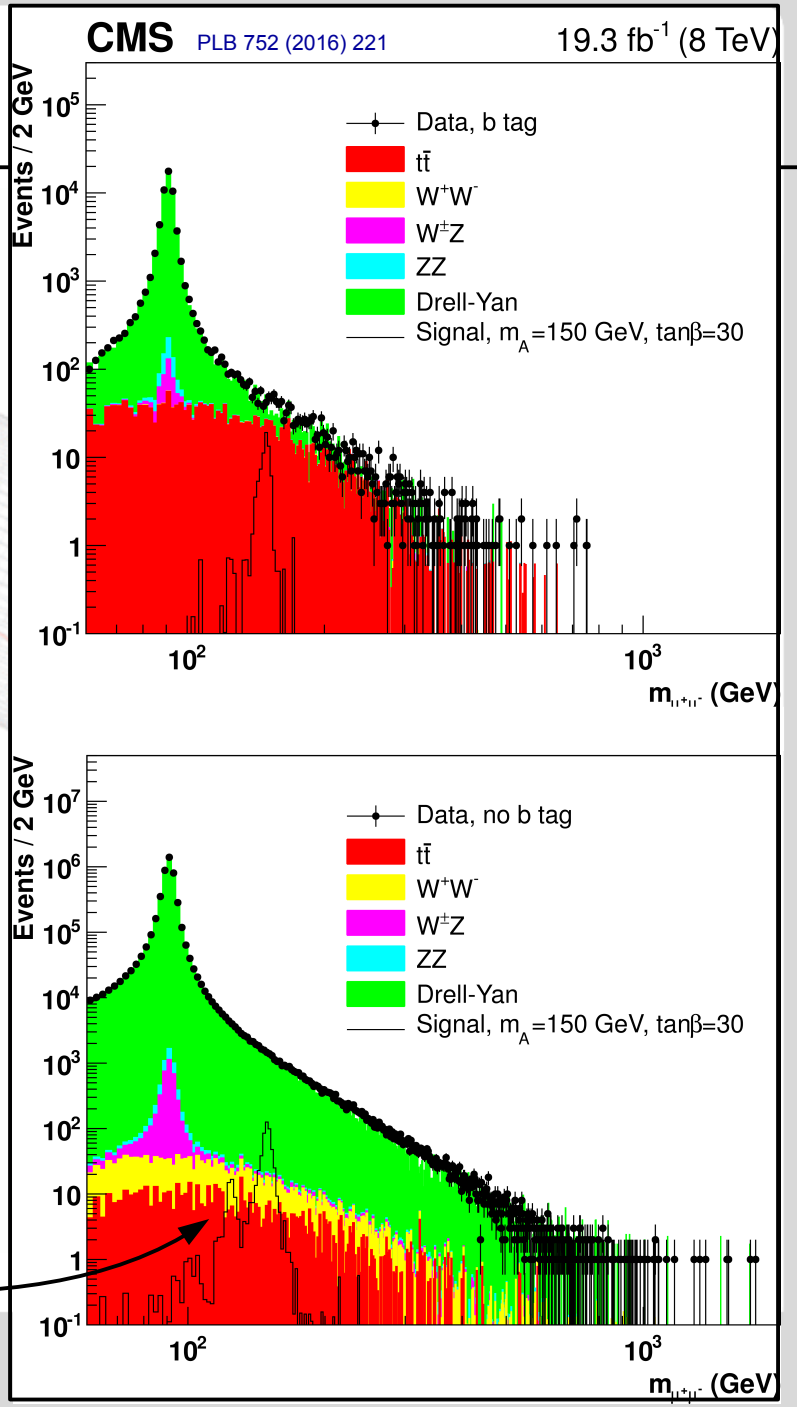
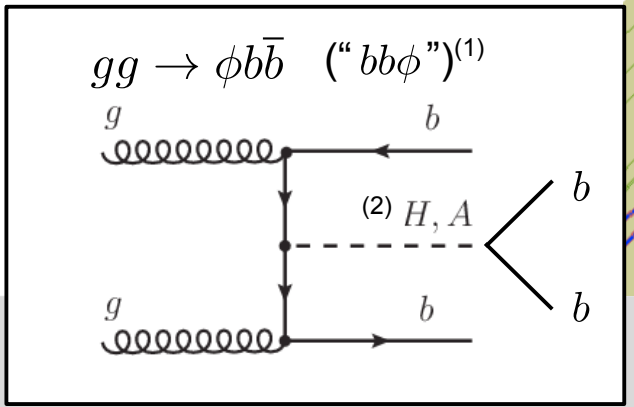


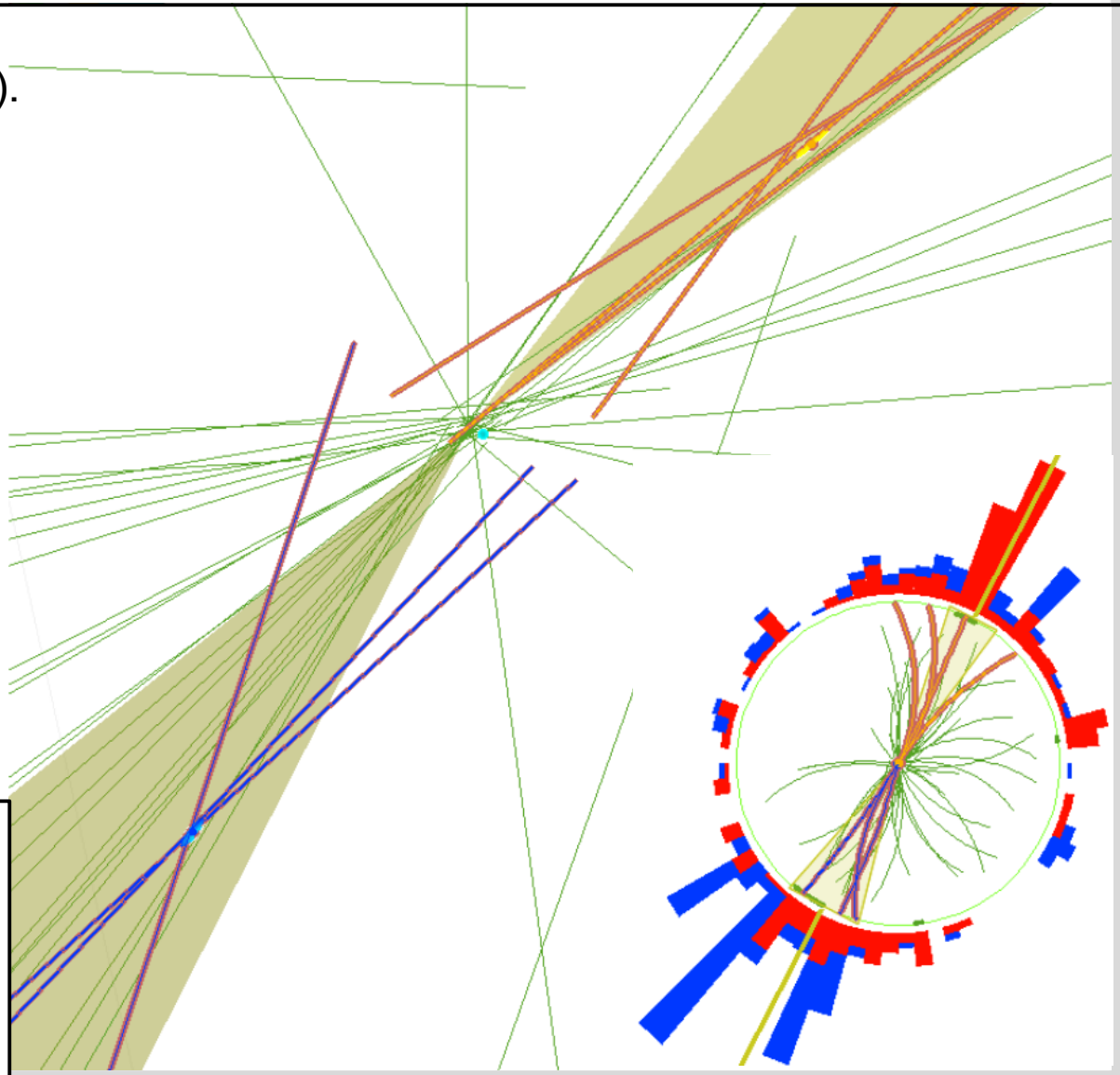
Table on cf 23 @ work:
h visible only in no b-tag category since couplings to b are not enhanced.



$H \to b\bar{b}$ decay channel

- Largest coupling (cf slide 23).
- Main challenge: background from QCD multi-jet prod.:
  - High rate:
    strict $\mathrm{b\text{-}tag}$ requirements during *online* selection.
  - Difficult to model
    model BG purely from control sample in data.
- Restrict search to associated production:





(1) usually one b-quark not within detector acceptance.

(2) h not included in this search.

$H \to b\bar{b}$ decay channel

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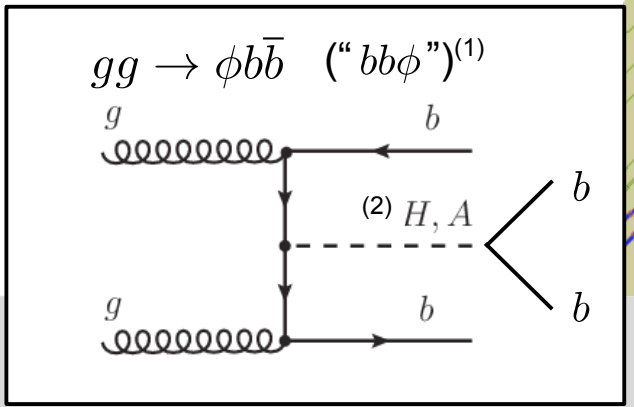
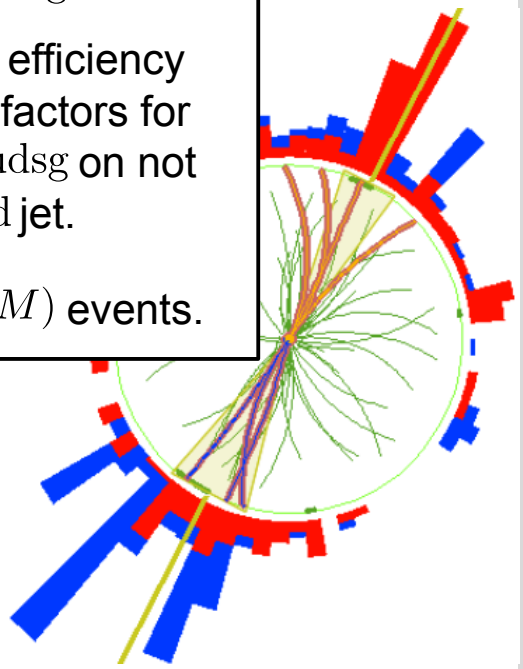


Signal region:

- $\gtrsim 3$ b-tags .
- Tightest $\mathrm{b\text{-}tag}$ requirement.
- $p_T > 80, 70, 20$ GeV .
- $\mathcal{O}(70k)$ events.

Control region:

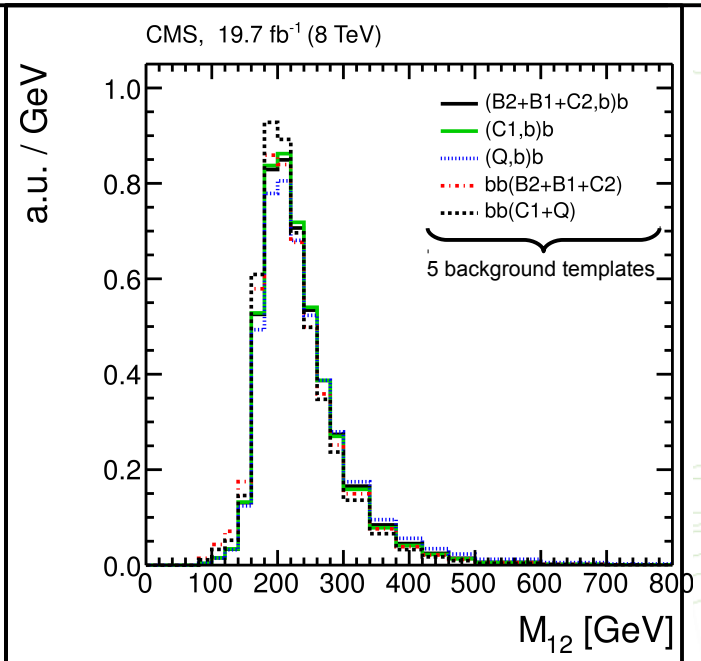
- $\gtrsim 2$ b-tags .
- Apply efficiency scale factors for $\mathrm{b},\ \mathrm{c},\ \mathrm{udsg}$ on not tagged jet.
- $\mathcal{O}(2.4M)$ events.

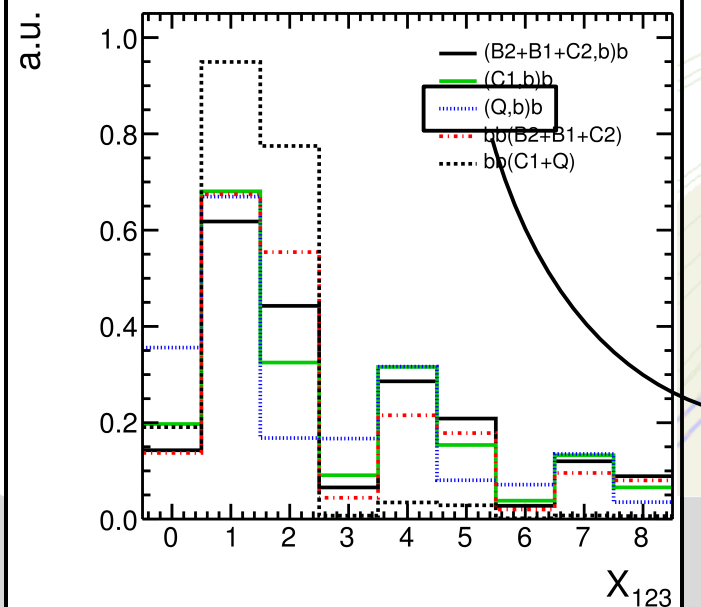


(1) usually one b-quark not within detector acceptance.

(2) h not included in this search.

$H \to b\bar{b}$ decay channel





2d signal extraction:

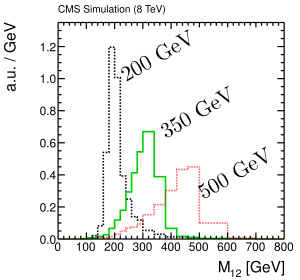
- Inv. mass of two leading b-tagged jets (M_{12}).
- Condensed event b-tag variable (X_{123}):

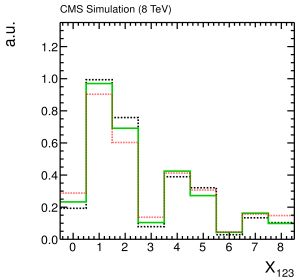
$\Sigma M_{SV,j}$ [GeV]	B_j
0–1	0
1–2	1
2–3	2
>3	3

B_3	$B_1 + B_2$		
	0–1	2–3	4–6
0–1	0	1	2
2	3	4	5
3	6	7	8

$\sum M_{SV,j}$: secondary vertex mass; B_j: j^{th} leading b-tagged jet.

- Signal:





Background model:

$(Q,b)b = Qbb + bQb$

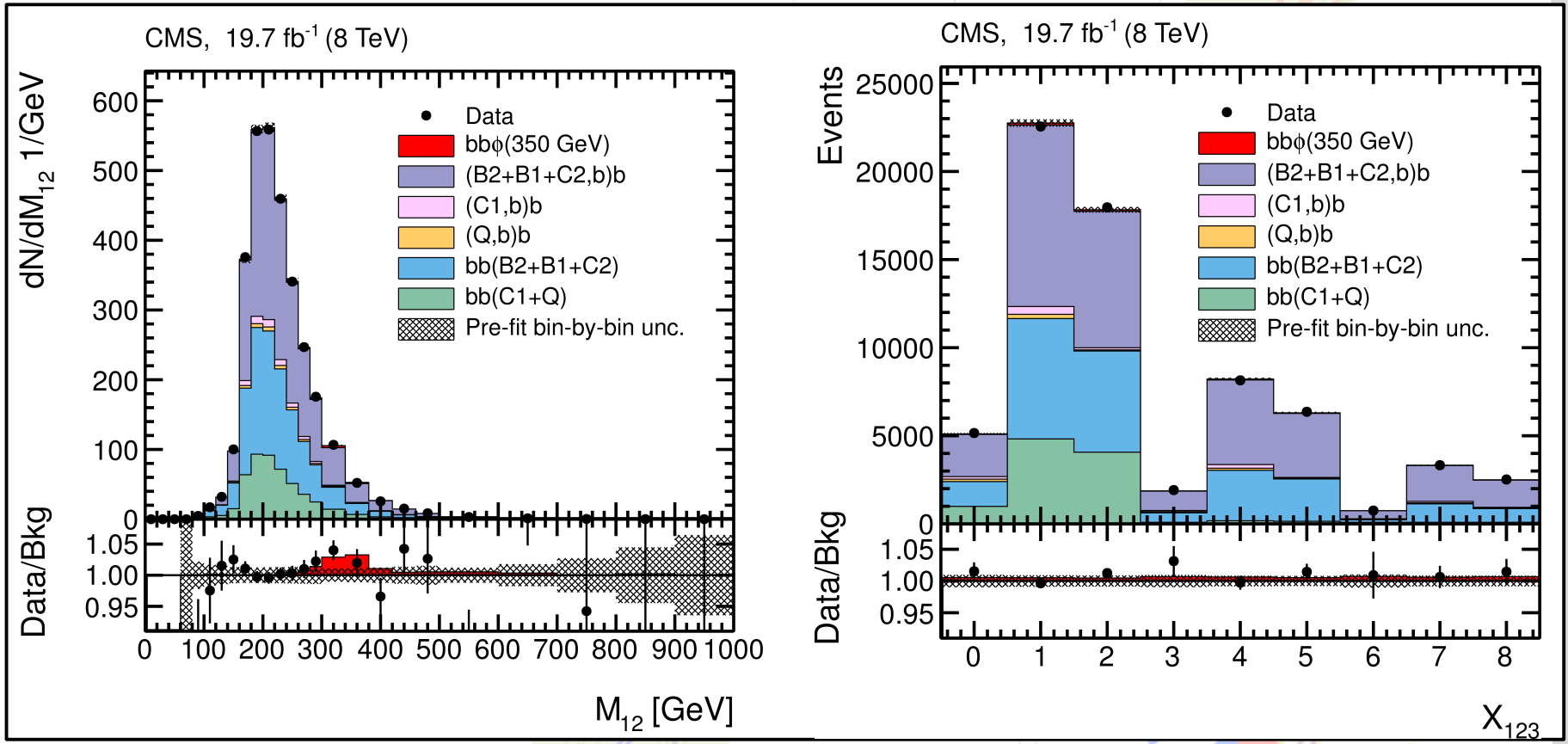
combine indistinguishable templates

- 3. leading (tagged)
- 2. leading (not tagged)
- 1. leading (tagged)

apply udsg efficiency

$H \to b\bar{b}$ decay channel

- Fit to data (signal model for $m_\phi = 350$ GeV, corresp. to 1.5σ significance)[3].



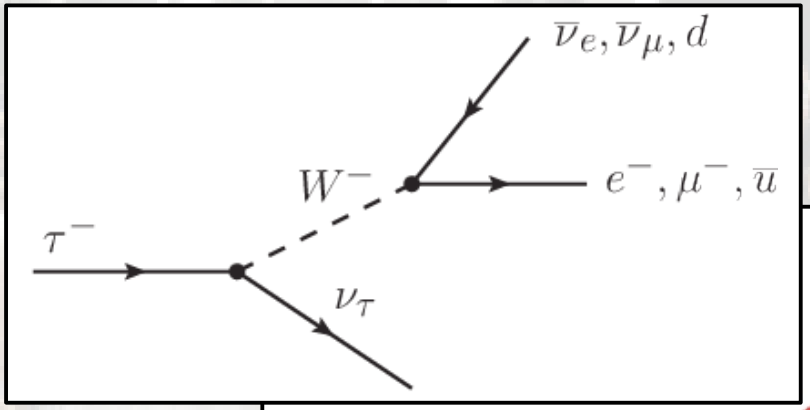
- $\chi^2/ndof = 205.2/208\ (207.9/209)$ for $s+b$ (b-only) fit. Dominated by triple $\mathrm{triple}\ b$ signatures ($\gtrsim 80\%$)[4].

[3] in $\sigma \times BR$ limit (see backup)

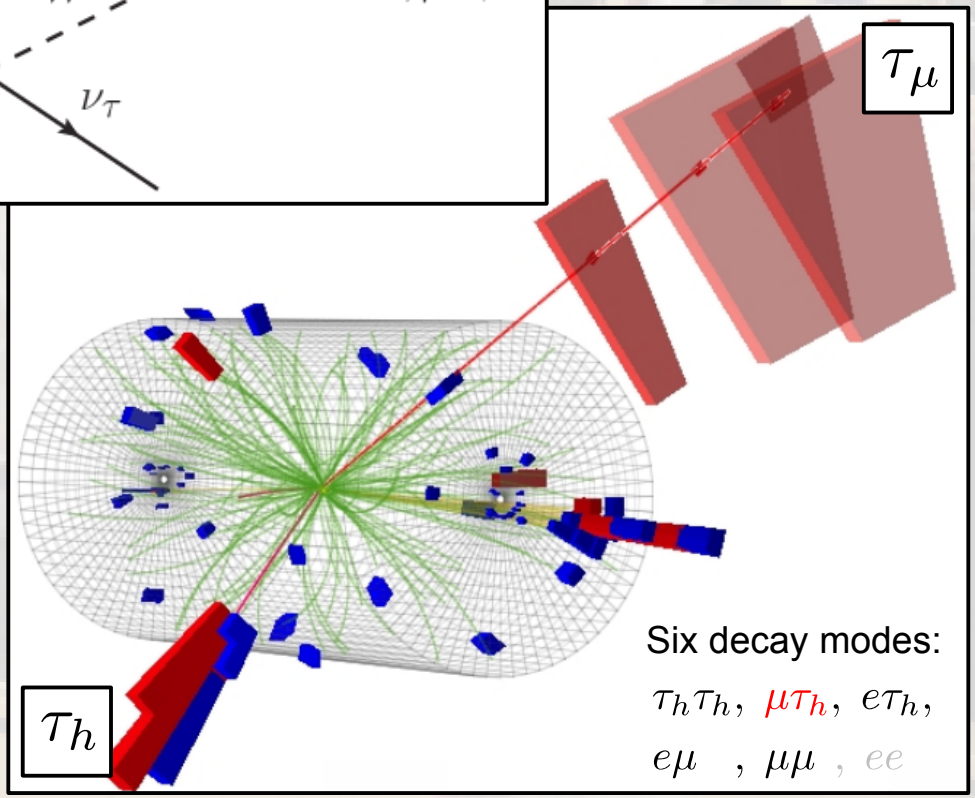
[4] $B, C_{1,2}$ means $1,2\ b,c$ quarks in jet

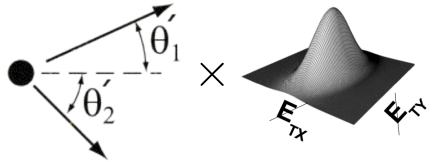
$H \to \tau\tau$ decay channel

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



- Search for 2 isolated high p_T leptons (e , μ , τ_h).
- Reduce obvious backgrounds (e.g. use $\not{E}_T$) & reconstruct $m_{\tau\tau}$.



$\mathcal{L} =$ 

- Inputs: visible leptons, x-, y-component of $\not{E}_T$.
- Free parameters: φ, θ^*, ($m_{\nu\nu}$) per τ.

$H \to \tau\tau$ decay channel

$Z \to \tau\tau$

- In $Z \to \mu\mu$ events replace μ by sim τ).
- Norm from $Z \to \mu\mu$.

$Z \to \ell\ell$

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

$W + jets$, Diboson

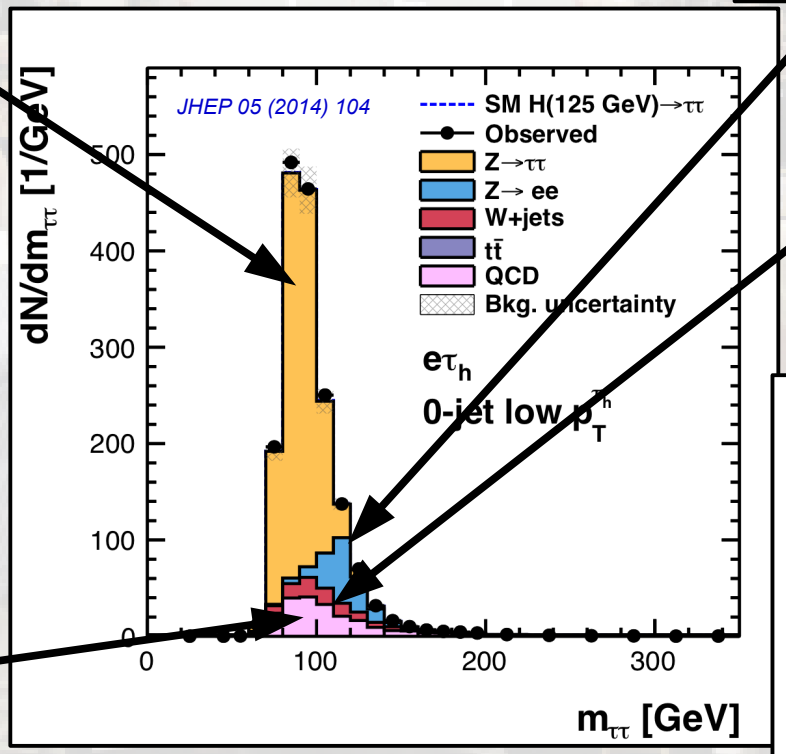
- From simulation
- Normalization from sidebands.

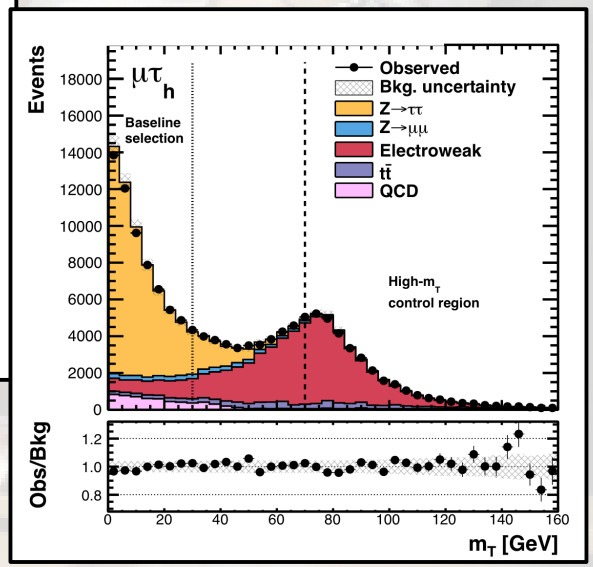
tt

- From simulation.
- Normalization from sideband.

QCD multijet

- Normalization & shape from data.





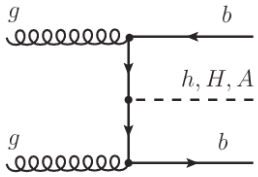
$H \to \tau\tau$ decay channel

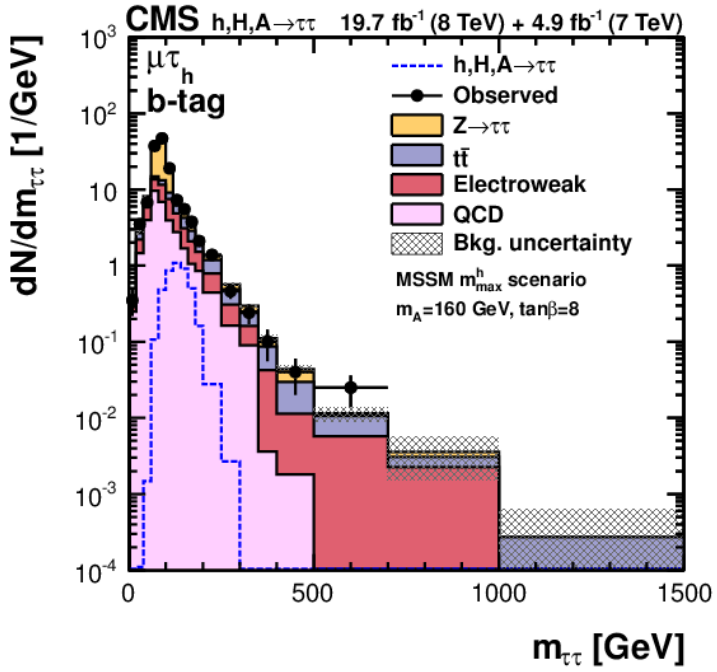
- Search for additional peak(s) in $m_{\tau\tau}$ distribution.

b-tag category:

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

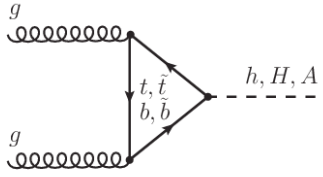
$\mathrm{N(Jet)} \leq 1$

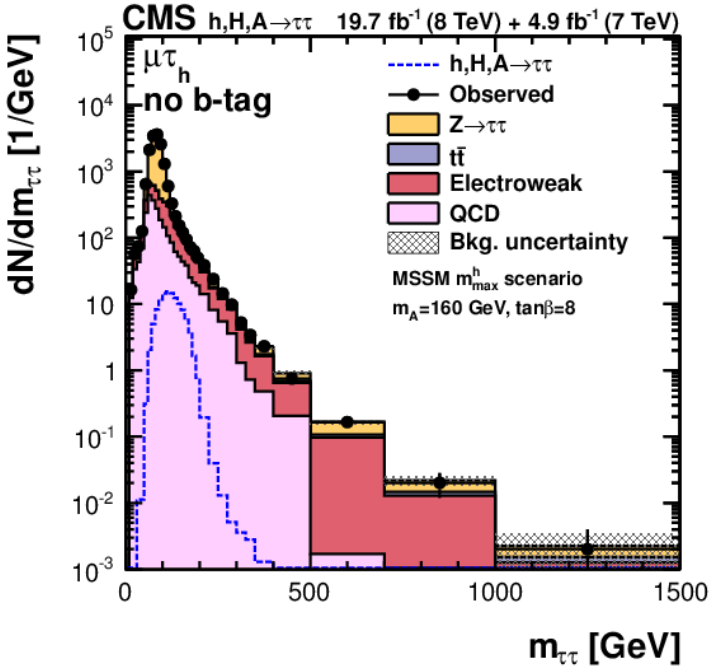




No b-tag category:

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





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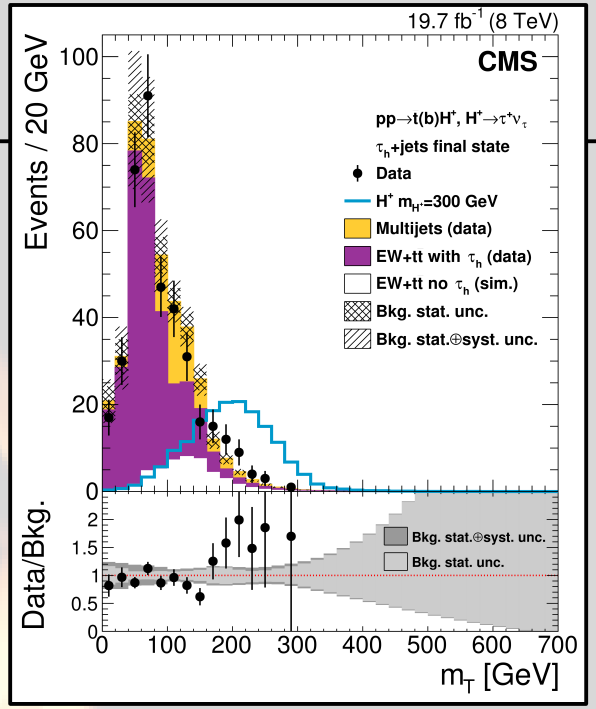
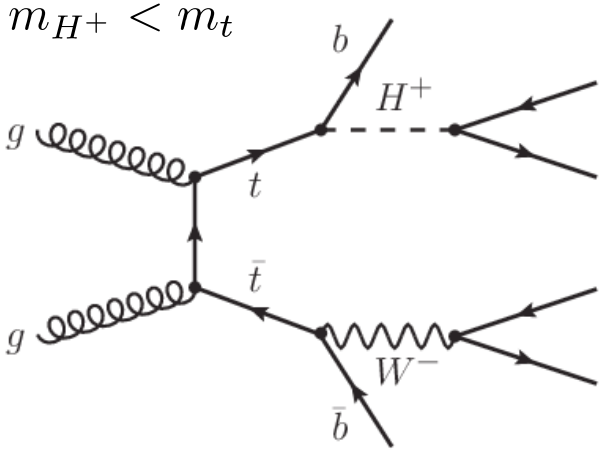
Charged Higgs in the MSSM

- Expect signal in *top* sector.
- Most sensitive decay channel: $\tau\nu$.
- Concentrate on hadronic decay of $W \rightarrow$ well defined use of m_T for signal extraction.



$m_{H^+} < m_t$

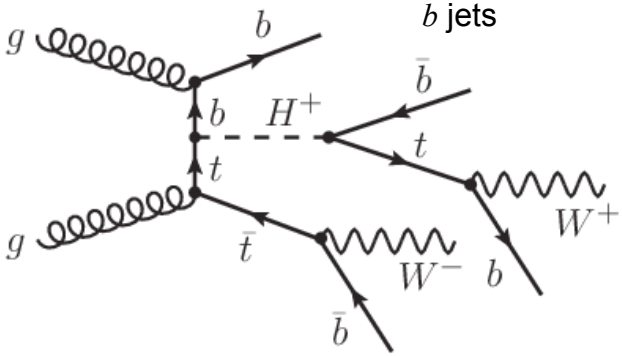


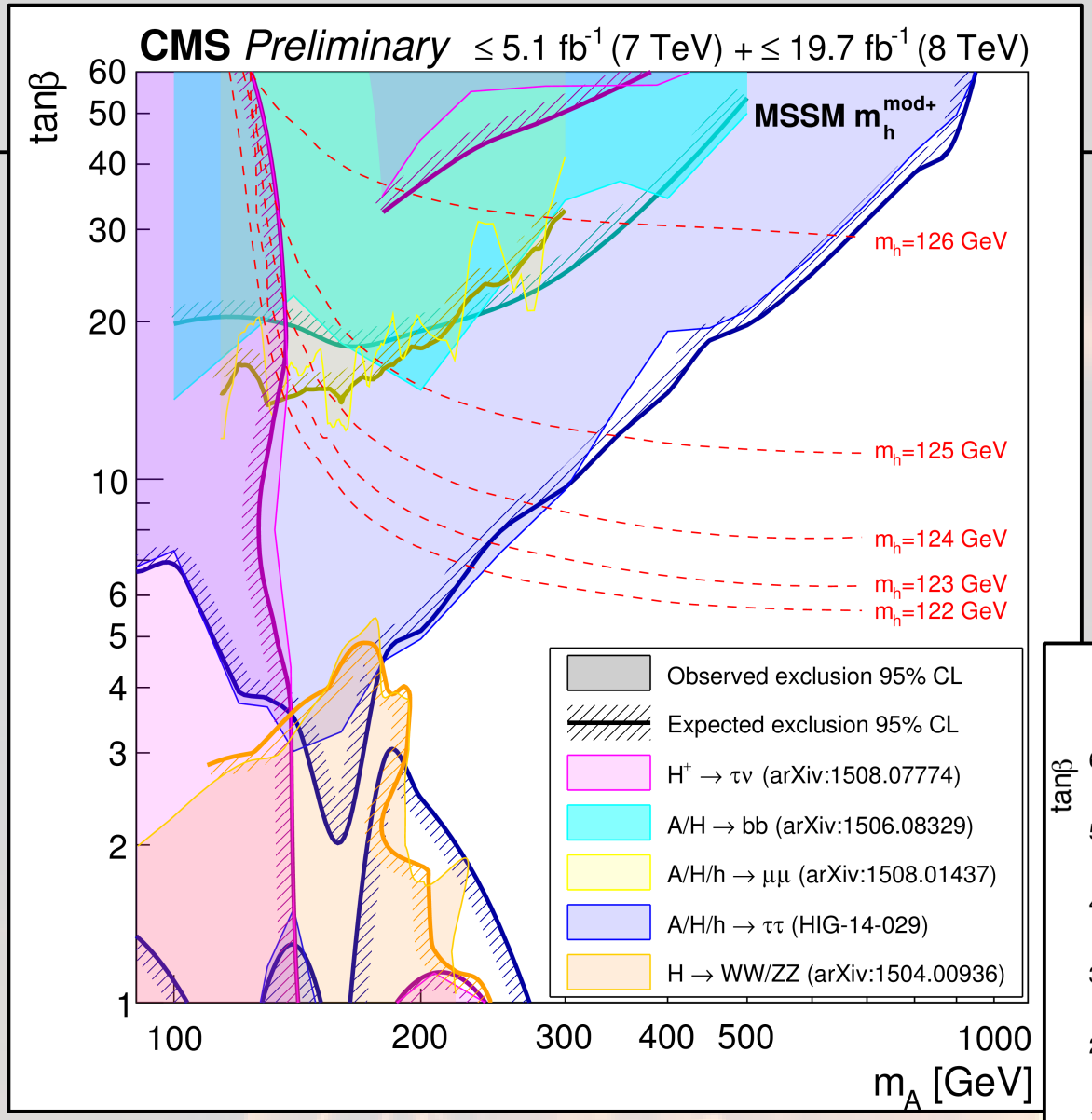
heavy flavors preferred

flavor democratic

$m_t < m_{H^+}$

additional b jets





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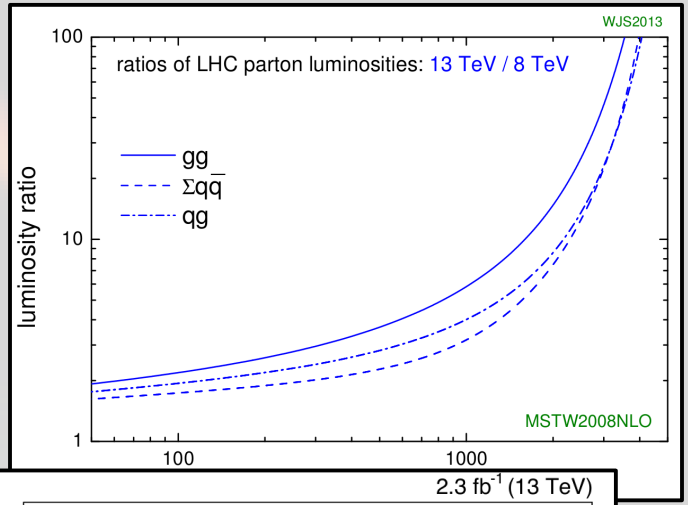
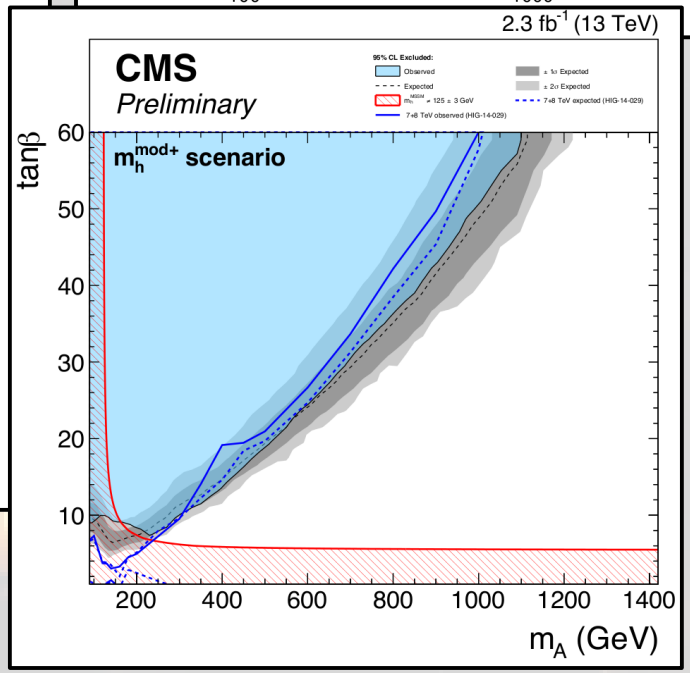


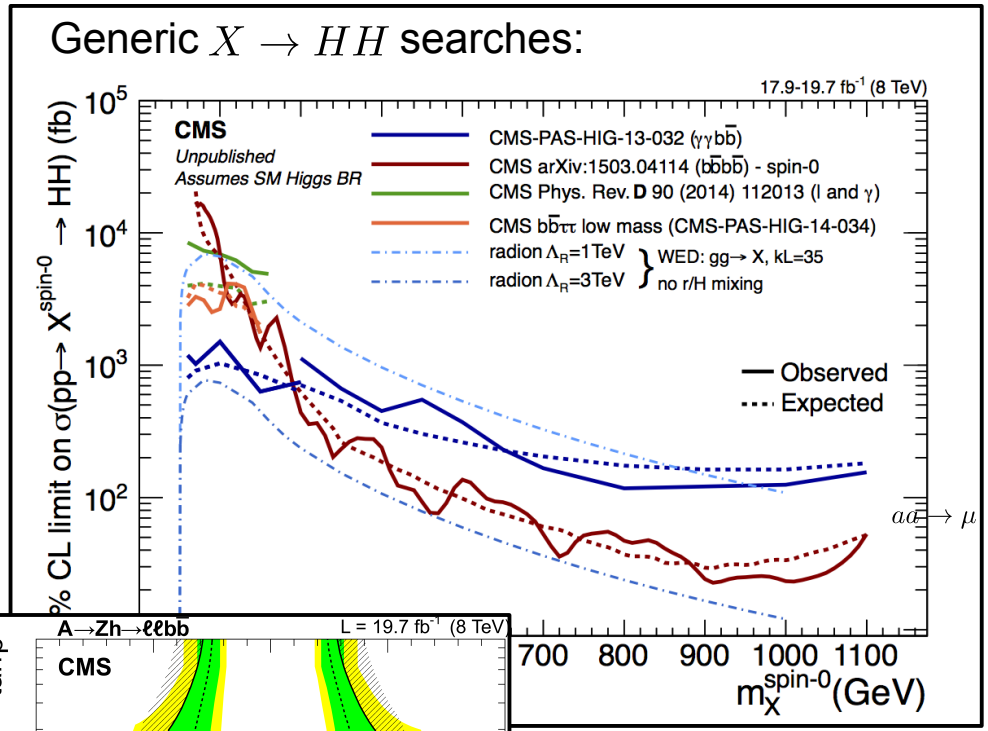
James Stirling (arXiv:0901.0002)

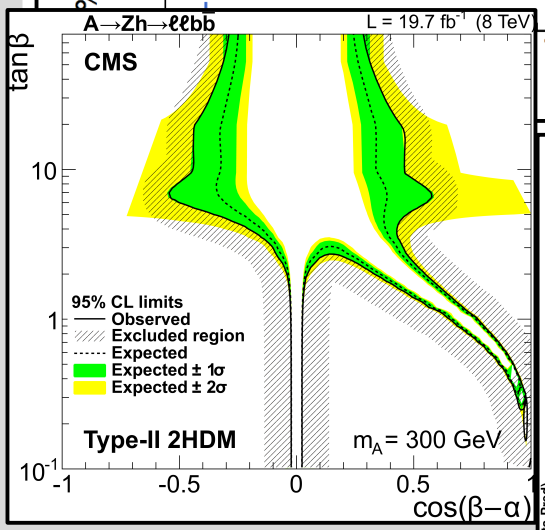


CMS-HIG-PAS-16-006

More searches!!!

Generic $X \to HH$ searches:





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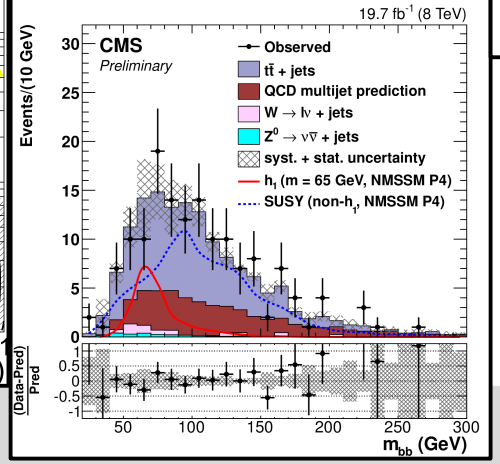
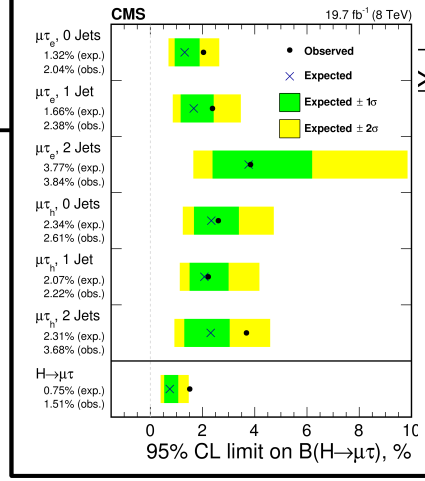
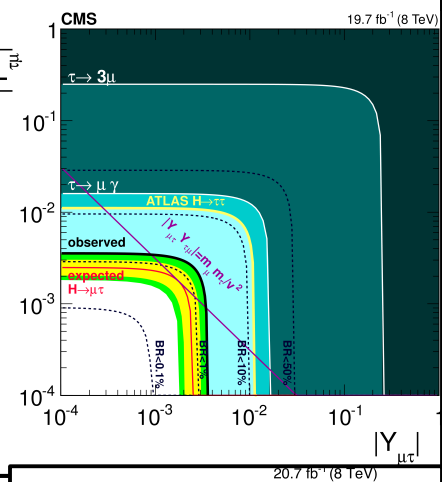


CMS-PAS-HIG-14-030

Lepton flavor violation in the Higgs sector





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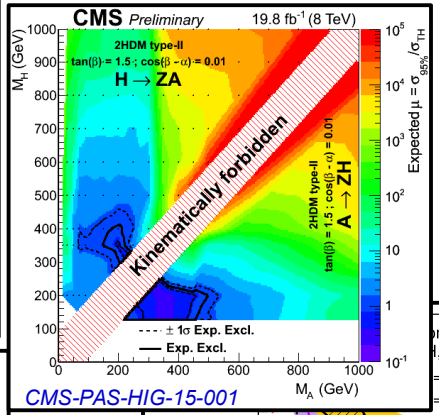
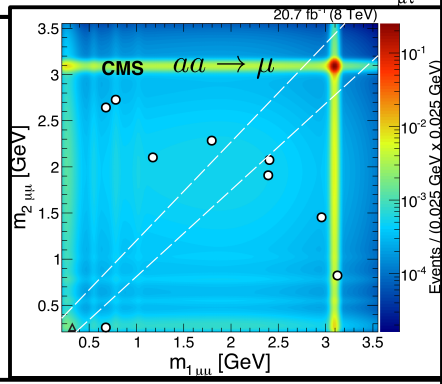
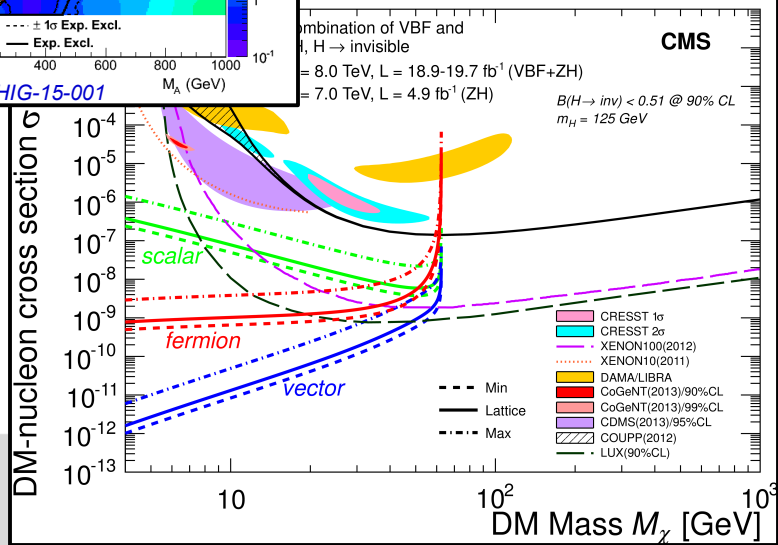


CMS-PAS-HIG-15-001

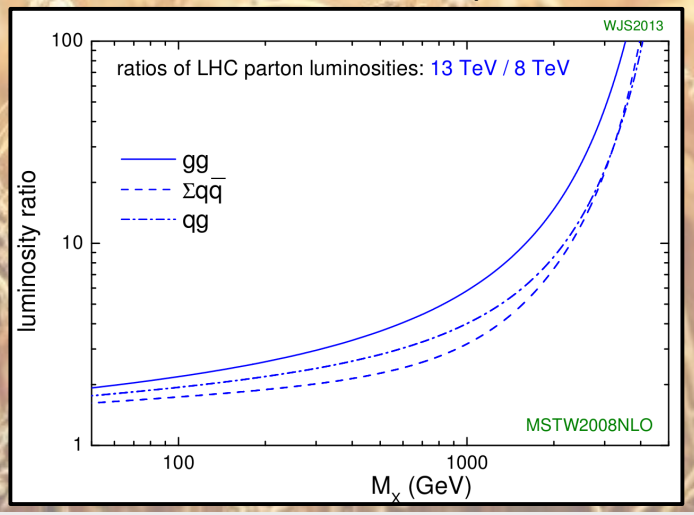
Subm. to PLB





Concluding remarks

- Discovered Higgs boson leaves still enough space for new physics beyond the SM. No reasons why Higgs sector should follow SM.
- Newly opened Higgs sector is a prime terrain to look out for new physics.
- New physics could show up in:
  - Deviations of coupling structure of observed Higgs from SM prediction.
  - Unexpected decays of the observed Higgs (→ link to DM searches).
  - Non-trivial extensions of the Higgs sector (→ link to DM & to CP violation).
  - Not discussed here: searches for new physics in form of resonant decays into the observed Higgs.
- BSM Higgs searches are the prime target for the LHC run-2.



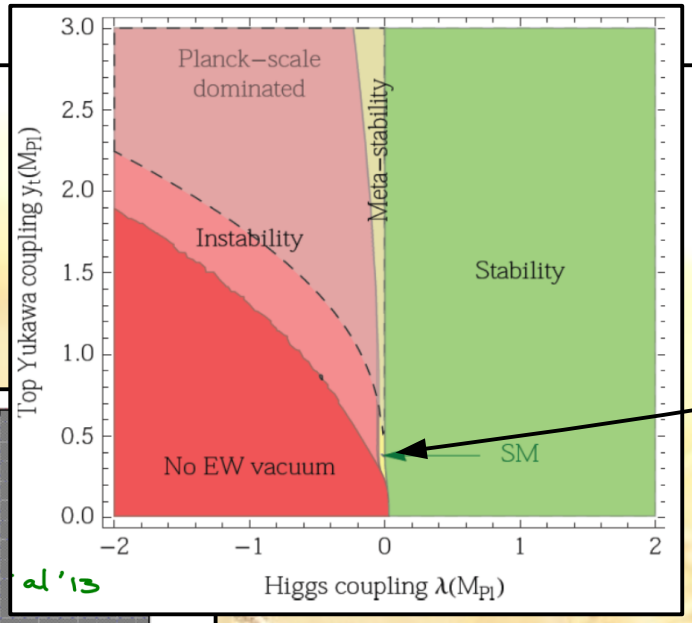
Backup

- Freitag 08/07: Fragestunde in SR 8-2.
- Donnerstag 14/07: Seminar kl. HS-B.
- Donnerstag 21/07: Kaffee & Eis (*tba*).

Schön war's...

Closing in …

The SM in the stress field of vacuum stability.



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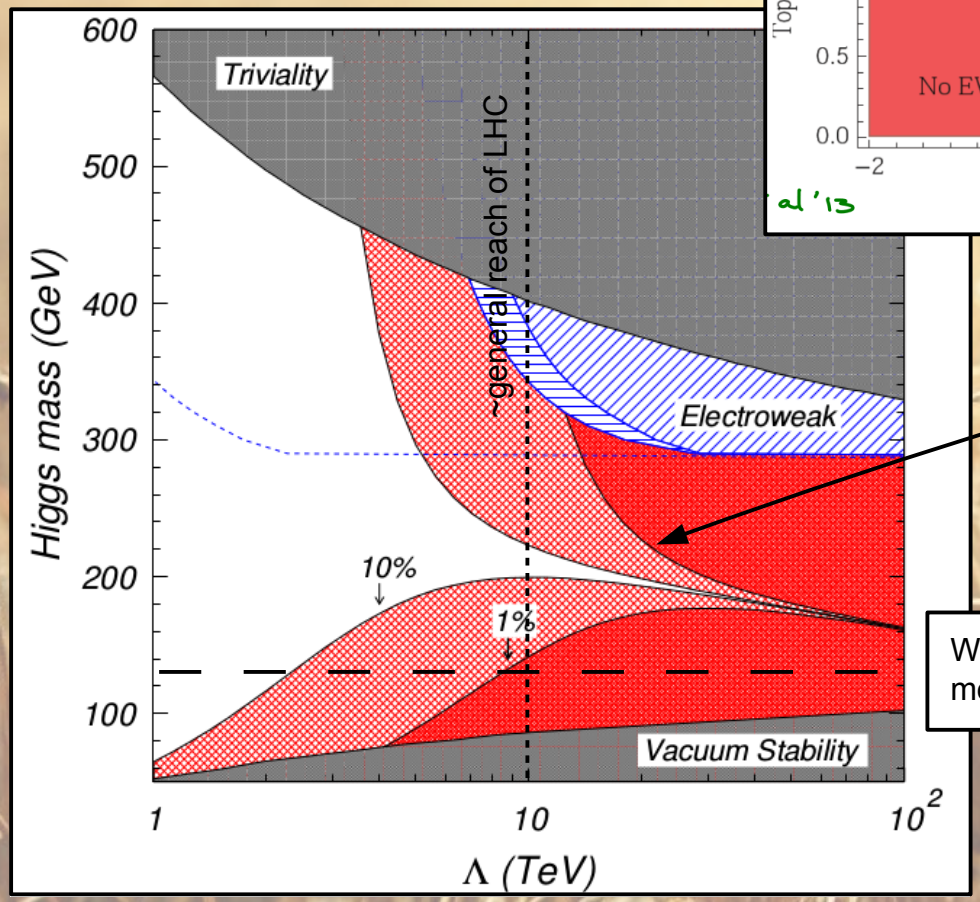

Different levels of fine tuning in the SM.

What we have found and measured for m_H.