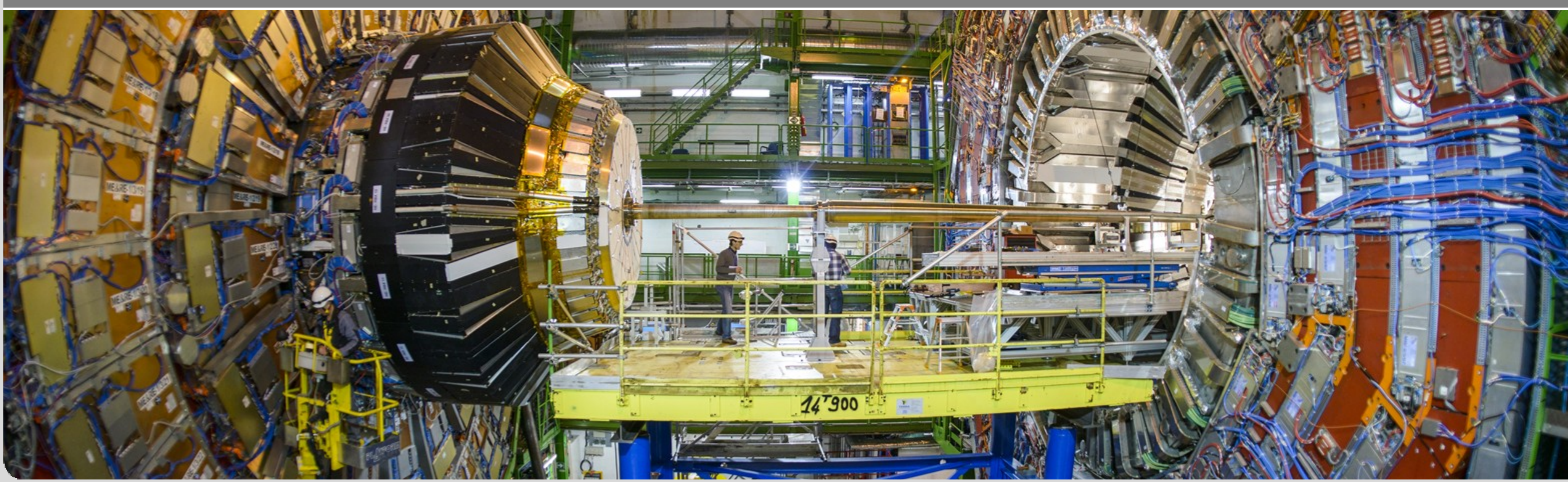
Karlsruhe Institute of Technology

Search for additional Higgs Bosons and BSM Higgs decays (E)

Roger Wolf

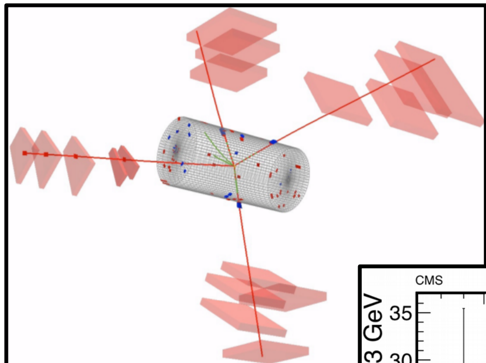
18. October 2016

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY

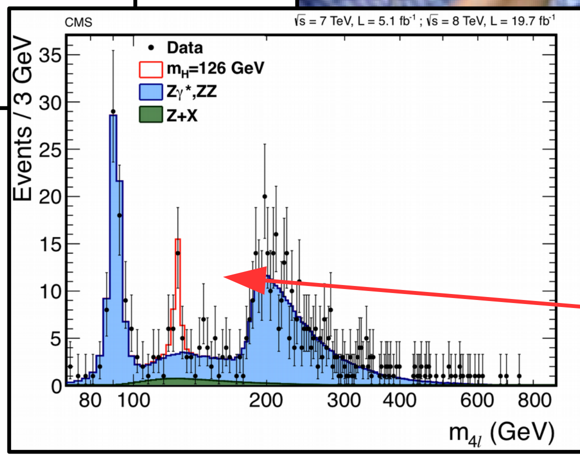


Discovery…

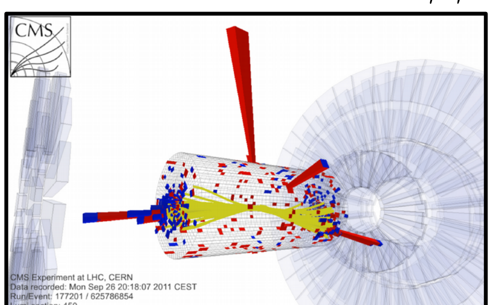
4th July 2012

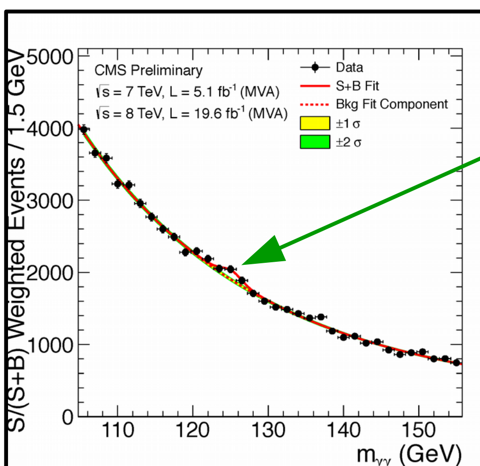


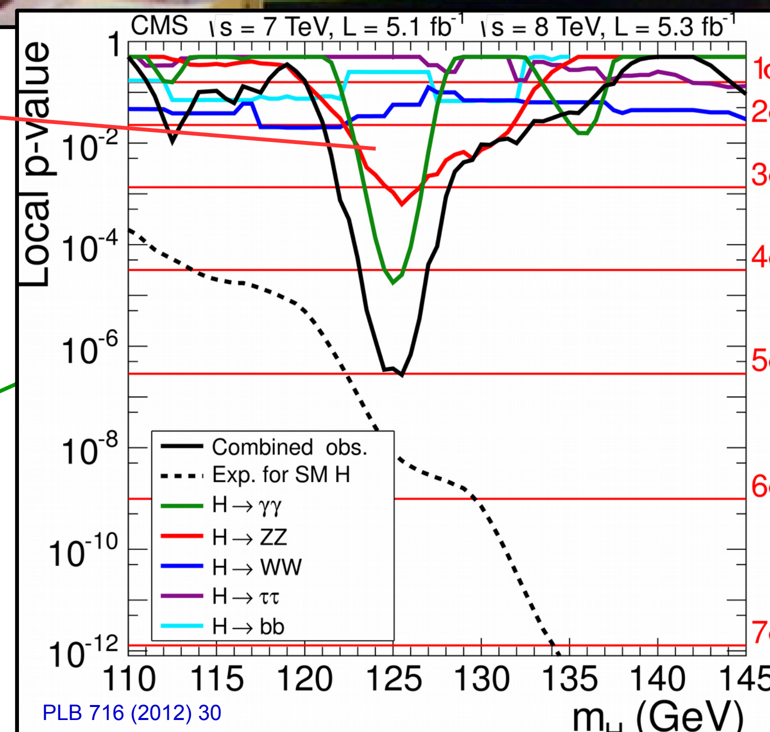
$H \to ZZ \to 4\ell$



$H \to \gamma\gamma$

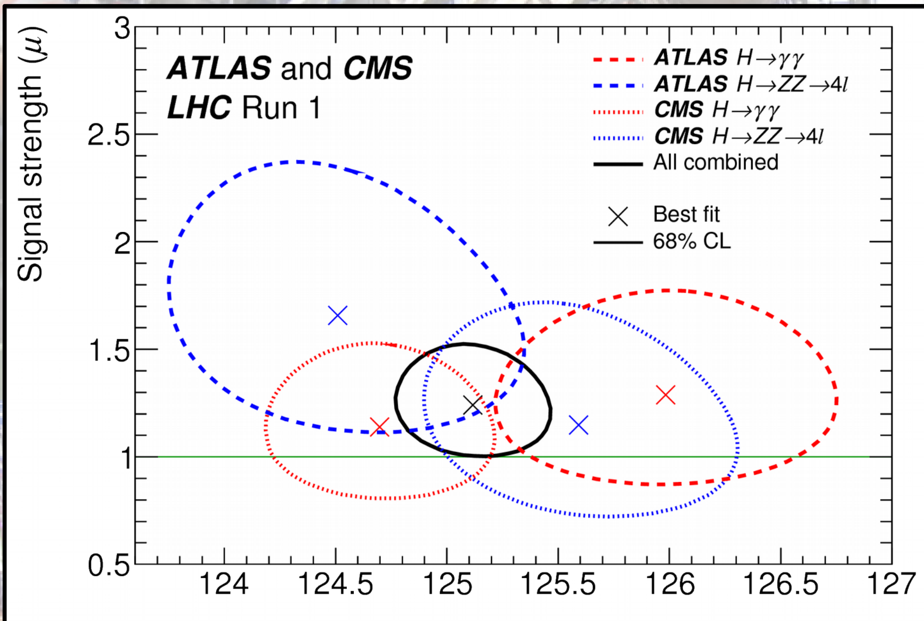




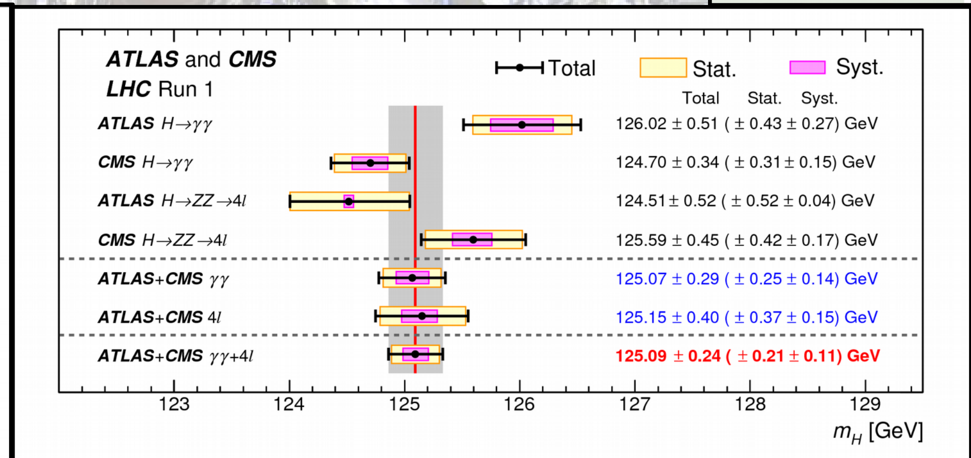


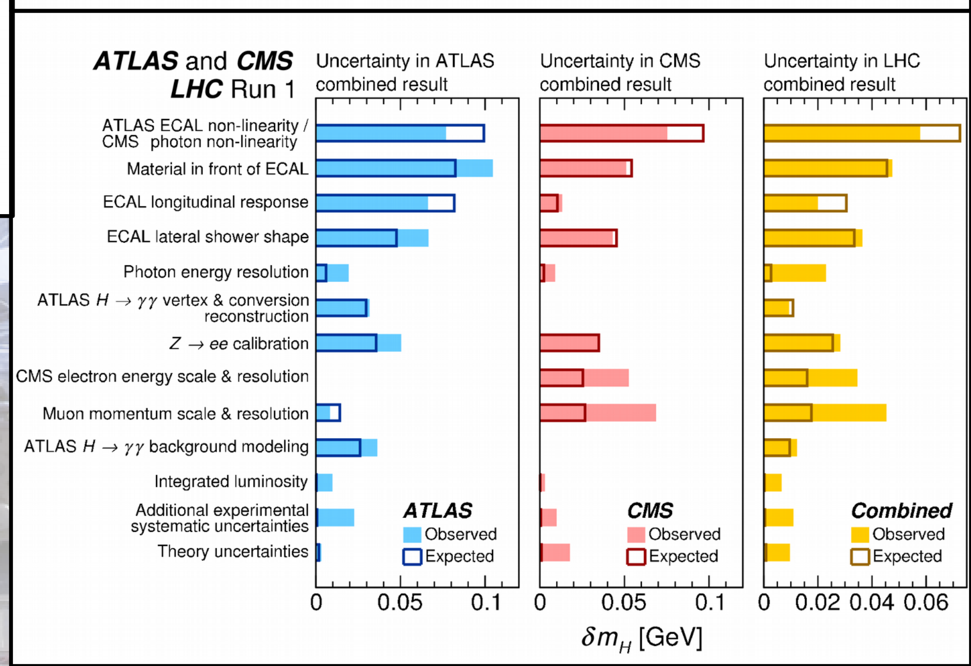
Higgs Boson mass

- ATLAS+CMS **LHC run-1 combination**:



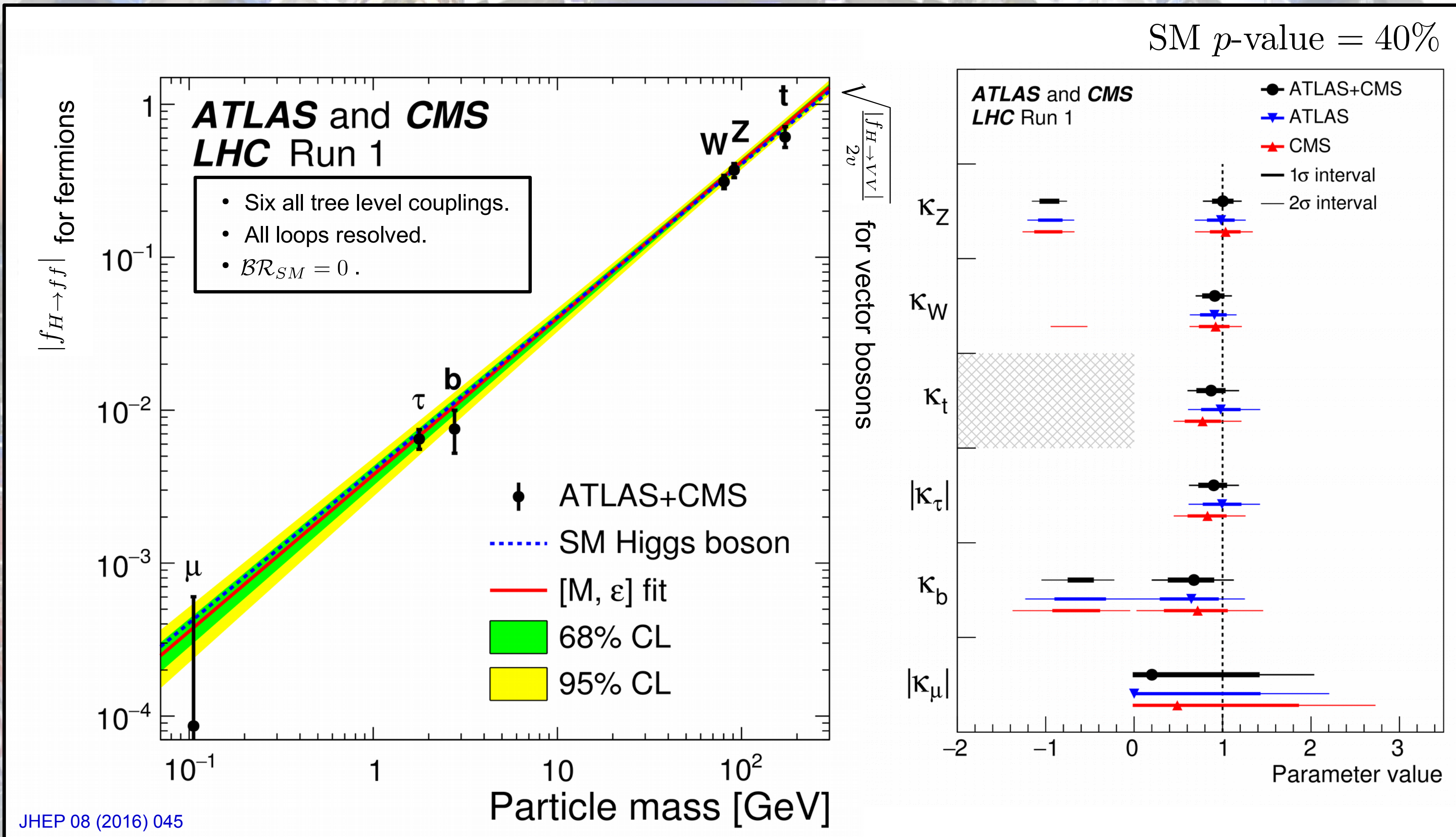
PRL 114 (2015) 191803





$$125.06 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})\ \text{GeV}$$

Higgs Boson couplings



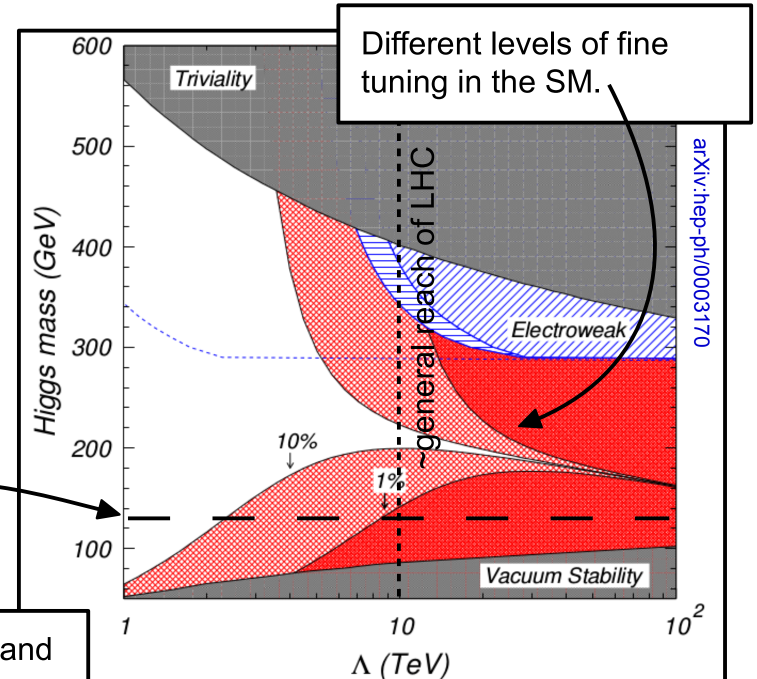
$$|f^{\rm obs}_{H\to ff}| = \kappa_f \cdot |f^{\rm SM}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

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

Within measurement accuracy unique scaling as expected within the SM.

Why the Higgs boson still is not THE *Higgs* boson [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 from the SM expectation in $a_\mu \equiv \frac{g_\mu - 2}{2}$ (3.6σ unresolved).

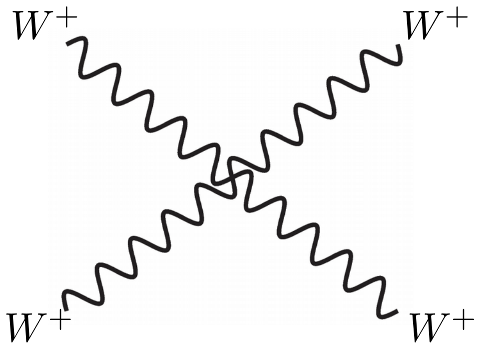


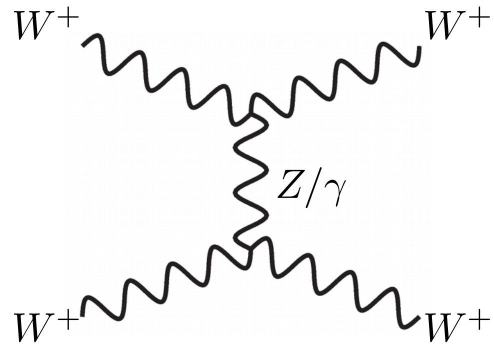
- There must be physics beyond the SM!
- At what scale does it set in?
- (How) Does it influence the Higgs sector?

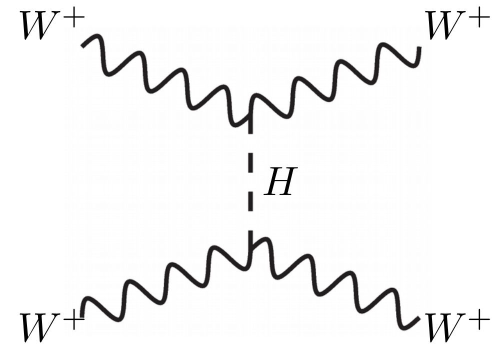
[1] Arguments taken from S. Heinemeyer (HH Higgs workshop 2014)

Higgs sector in the light of (tree-level) unitarity

- Unitarity problem demonstrated for $W^+W^+ \to W^+W^+$ scattering:







$$\mathcal{M}_{gauge} = -g^2 \frac{s}{4m_W^2} + \mathcal{O}(s^0)$$

constraint

$$\mathcal{M}_H = g_{HWW}^2 \frac{s}{m_W^4} + \mathcal{O}(s^0)$$

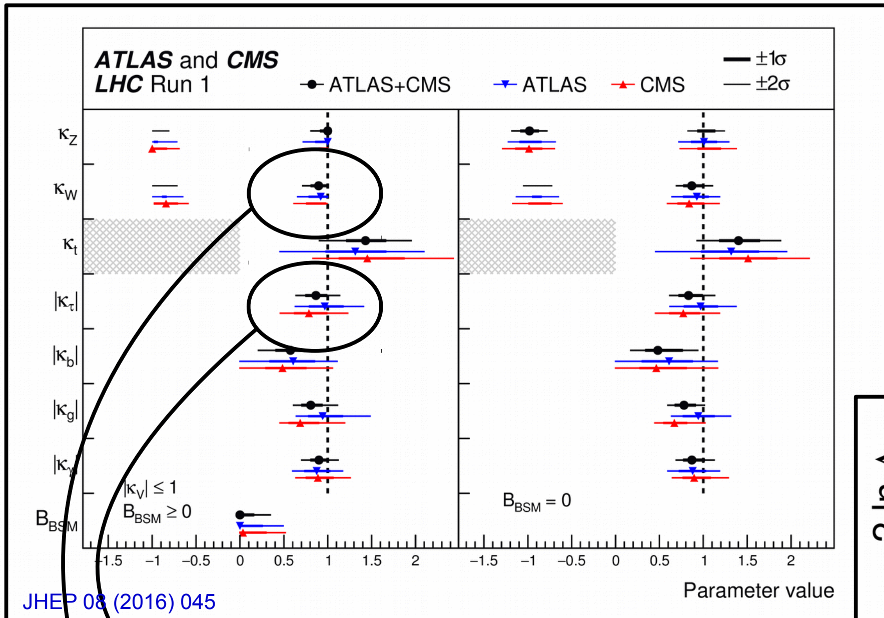
$$g_{HWW} = \frac{2m_W^2}{v} = g \cdot m_W$$

with: $v = \frac{2m_W}{g}$

> Exact cancellation of **divergent behavior** only if scalar exchange particle has coupling of type $\propto m_W^2$.

- Any additional contribution to this process should preserve this cancellation.

Space left for new physics in the Higgs sector



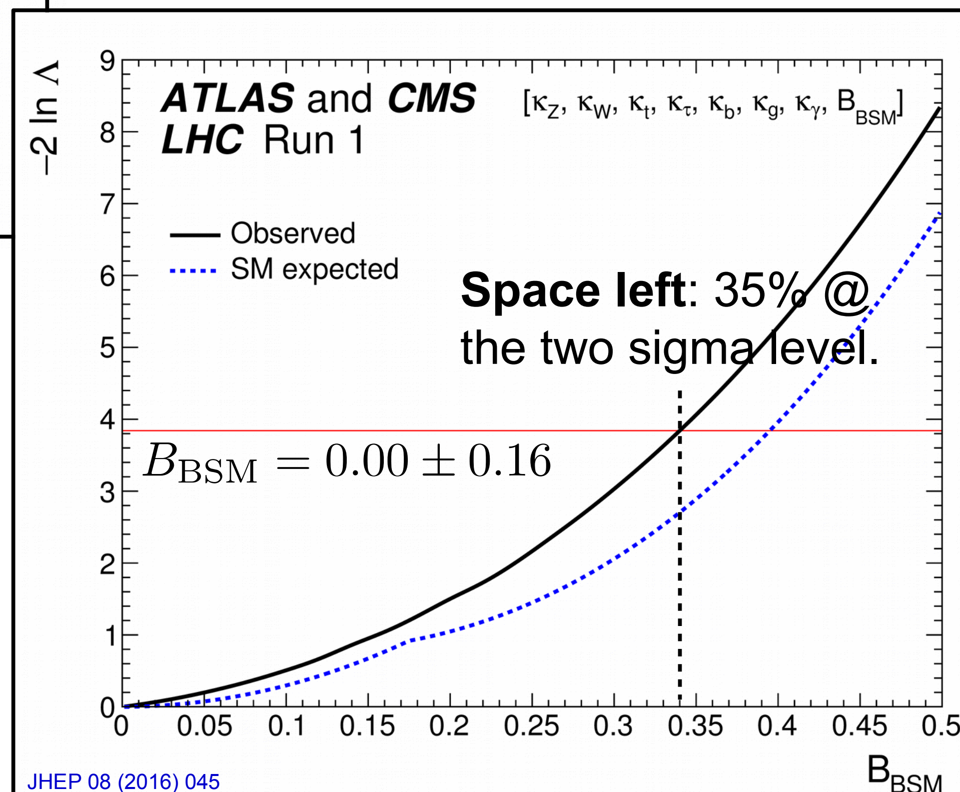
Two signatures of new physics in the Higgs sector:

- Find signal of new Higgs bosons directly.
- Presence of new Higgs bosons usually leads to modifications of h(125) couplings.

$$\kappa_\tau = 0.87 \pm^{0.12}_{0.11}$$

$$\kappa_W = 0.90 \pm 0.09$$

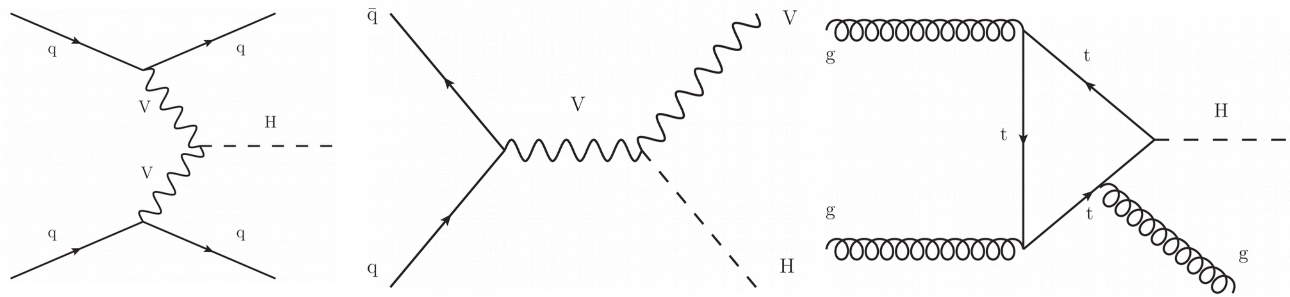
Space left: 20% @ the two sigma level.

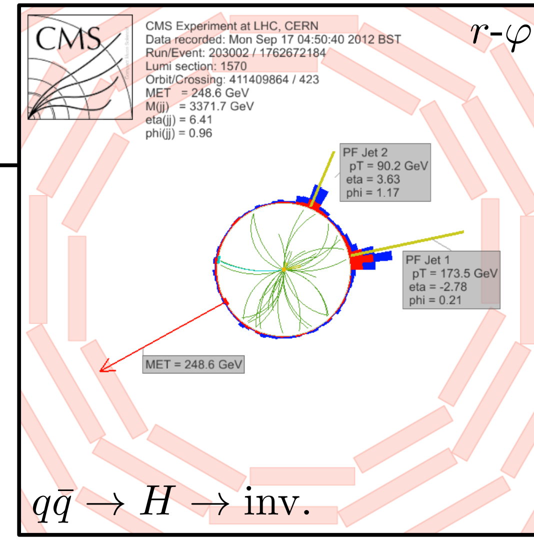


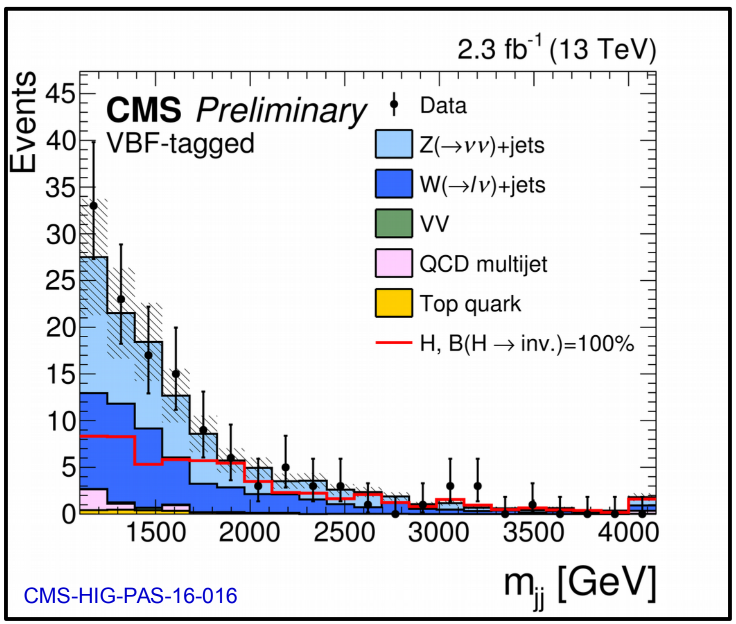
Space left: 35% @ the two sigma level.

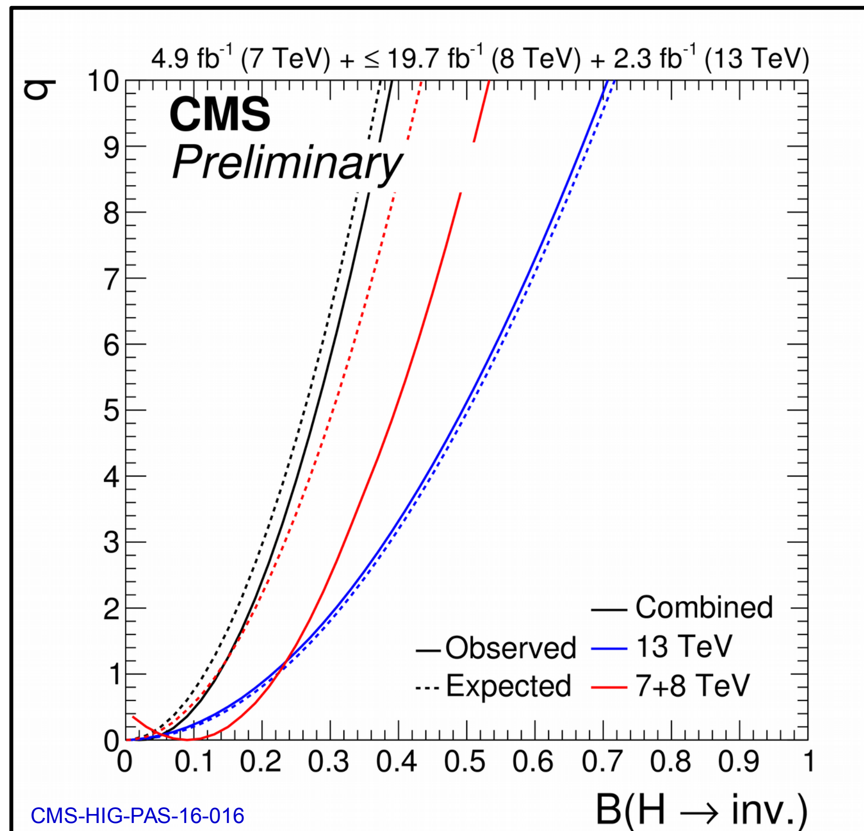
$$B_{\mathrm{BSM}} = 0.00 \pm 0.16$$

Direct searches for $H \to \text{invisible}$



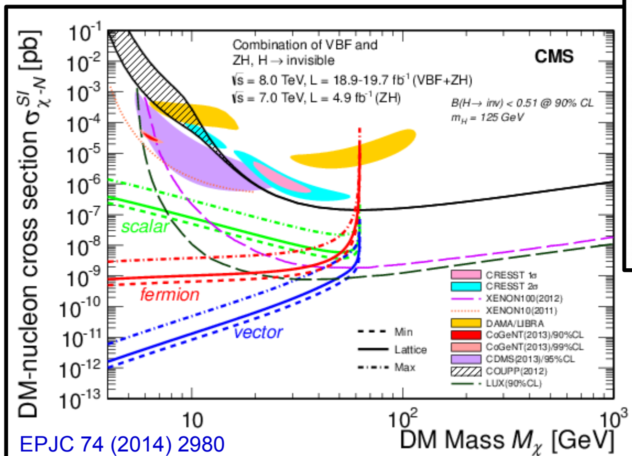


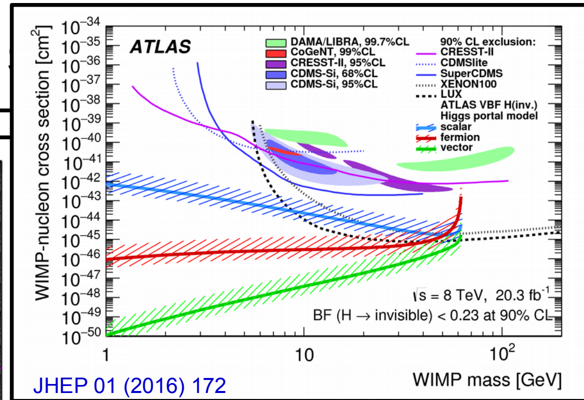


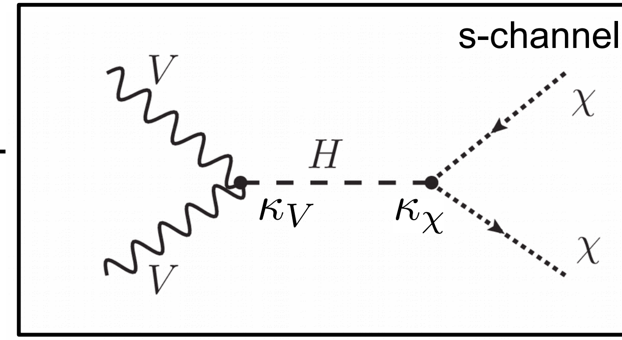


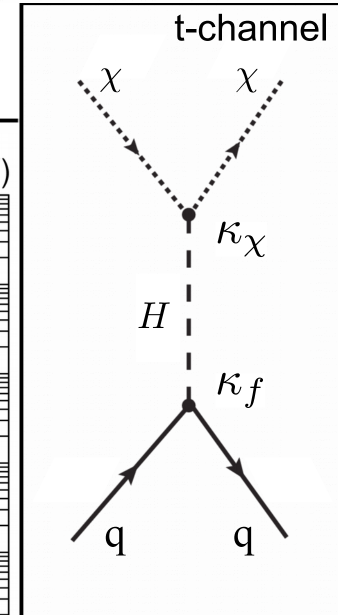
$$BR(H \to \text{inv}) \leq 0.24(0.23) \text{ @ } 95\% \text{ CL}$$

Higgs mediated DM



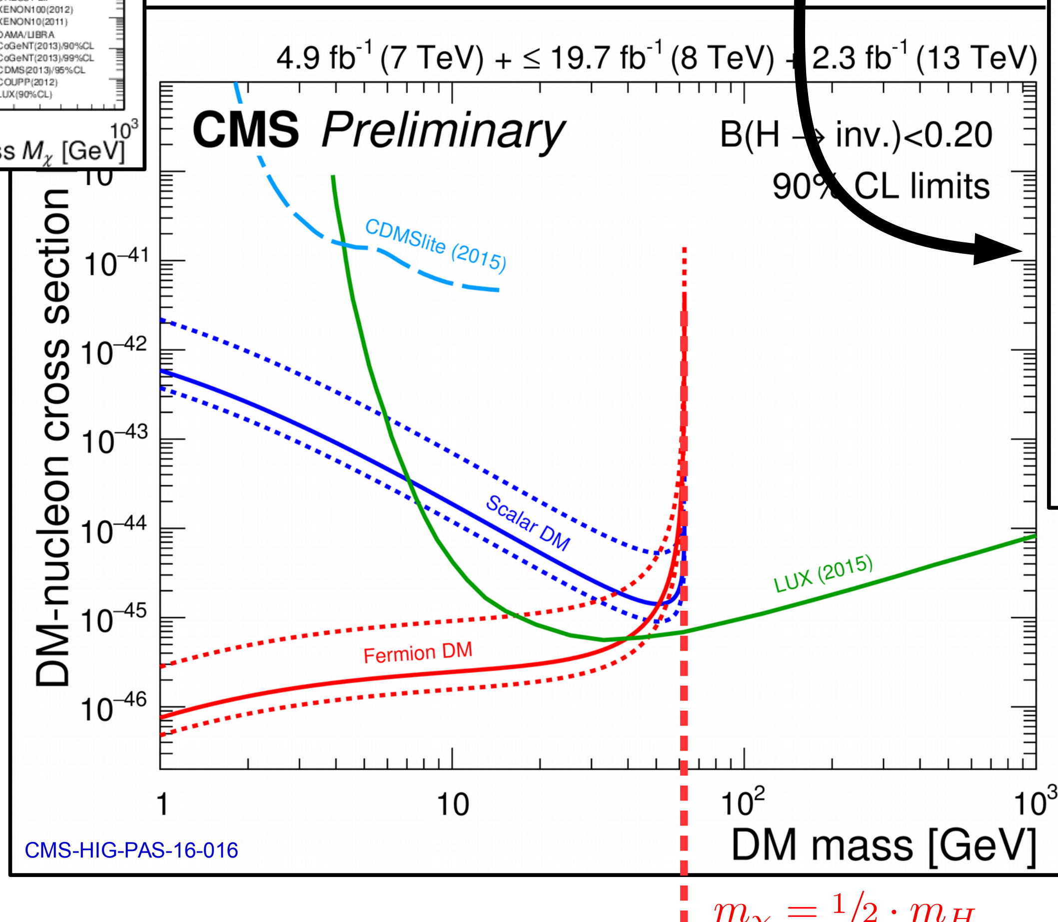






Reminder:

$10^{-46}\ \mathrm{cm}^2 = 10^{-10}\ \mathrm{pb}$



→ Pushing limits for direct DM searches.

Extensions of the Higgs sector

Additional $SU(2)_L$ singlets.

- Just one more Higgs boson.
- Mostly searched for in WW/ZZ final states.

Additional $SU(2)_L$ doublets.

- 5 additional Higgs bosons ($\rightarrow H^{+/-}$, A, H, h).
- 2HDM of four types (a priori 14 unconstrain-ed parameters).

NMSSM
(singlet + doublet)

MSSM

Additional $SU(2)_L$ triplets.

- Georgi-Machacek model (preserves custodial sym. of SM):

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^{+} \\ -\phi^{+*} & \phi^{0} \end{pmatrix}$$

$$X = \begin{pmatrix} \chi^{0*} & \xi^{+} & \chi^{++} \\ -\chi^{+*} & \xi^{0} & \chi^{+*} \\ \chi^{++*} & -\xi^{0*} & \chi^{0*} \end{pmatrix}$$

under global $SU(2)_L \times SU(2)_R$

- Two custodial singlets (m_h, m_H), one doublet (m_3), one fiveplet (m_5).

- All what is theoretically thinkable hosted/sorted by LHC HXSWG-3 (LHC HXSWG authority of CERN YR's).

Higgs Bosons in the 2HDM

- Any 2 Higgs Doublet Model (2HDM) predicts five Higgs bosons: [1]

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

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

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

[1] here shown for type-II.

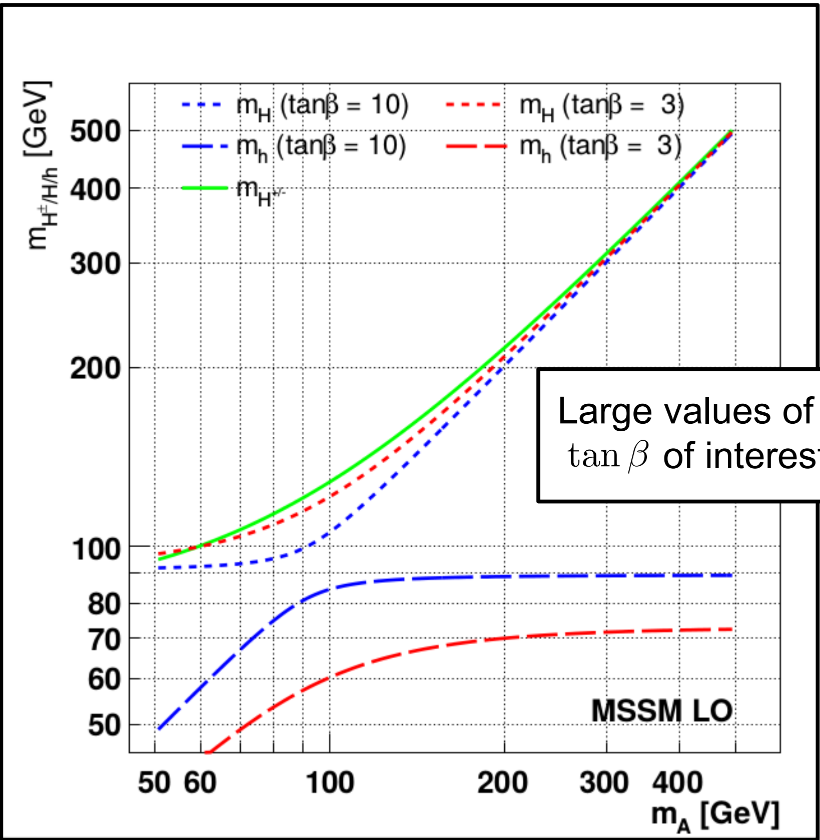
Higgs Bosons in the MSSM

- Any 2 Higgs Doublet Model (2HDM) predicts five Higgs bosons:

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

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

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



Large values of $\tan\beta$ of interest.

- Strict mass requirements at tree level:

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

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{H,\,h}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right)$$

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

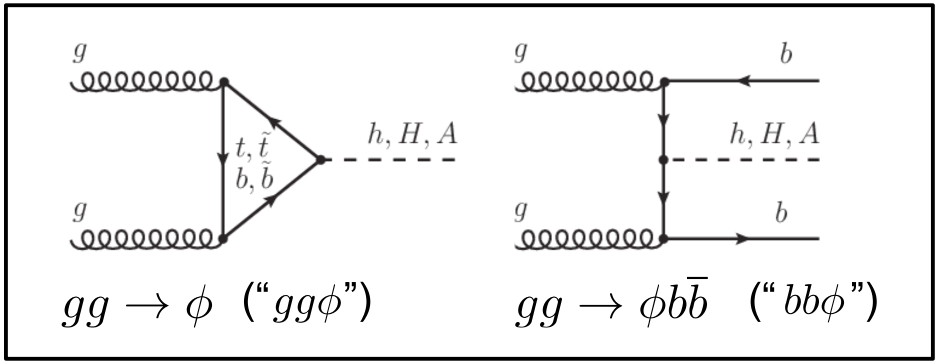
(angle btw. $\mathrm{v_u}$ & $\mathrm{v_d}$ in isospace)

The role of down-type fermions

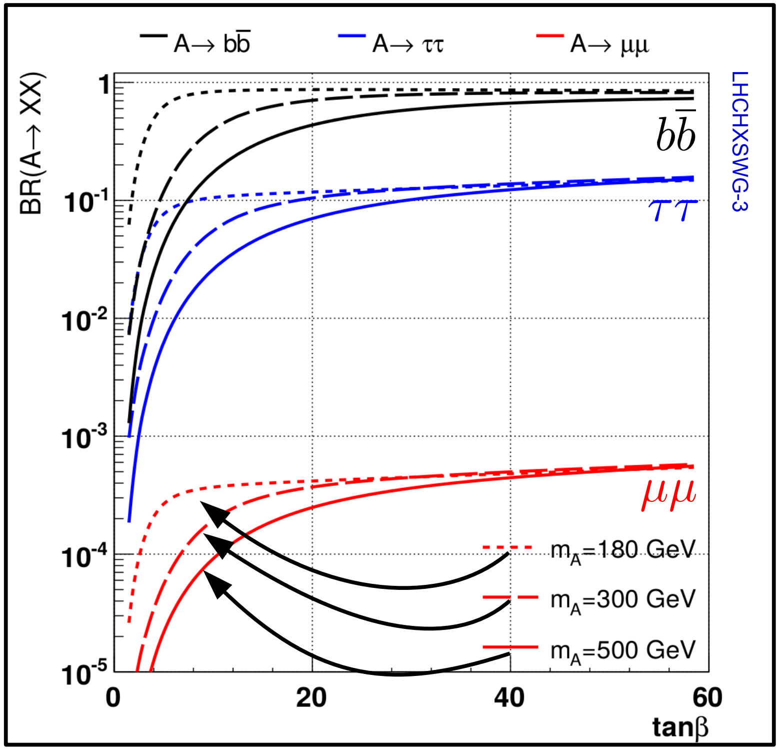
	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \rightarrow 0$	$\sin\alpha/\sin\beta \rightarrow \cot\beta$	$\cos\alpha/\cos\beta \rightarrow \tan\beta$
h	$\sin(\beta-\alpha) \rightarrow 1$	$\cos\alpha/\sin\beta \rightarrow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

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

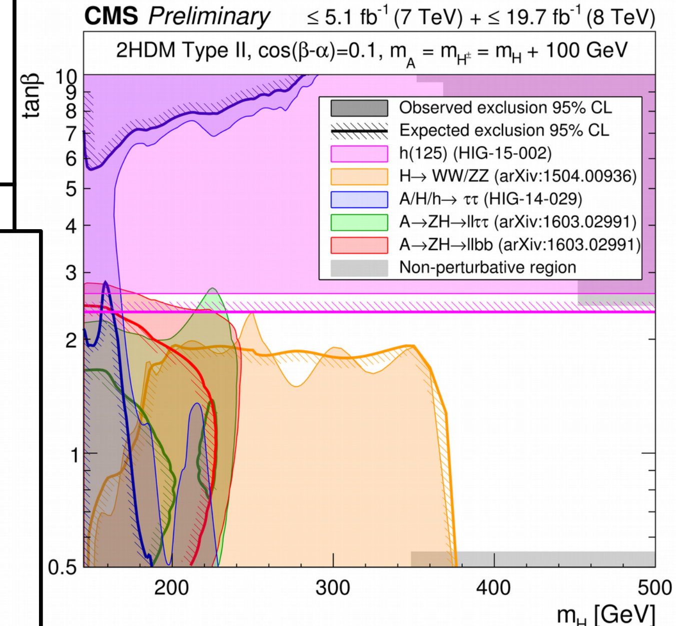
Interesting production modes:

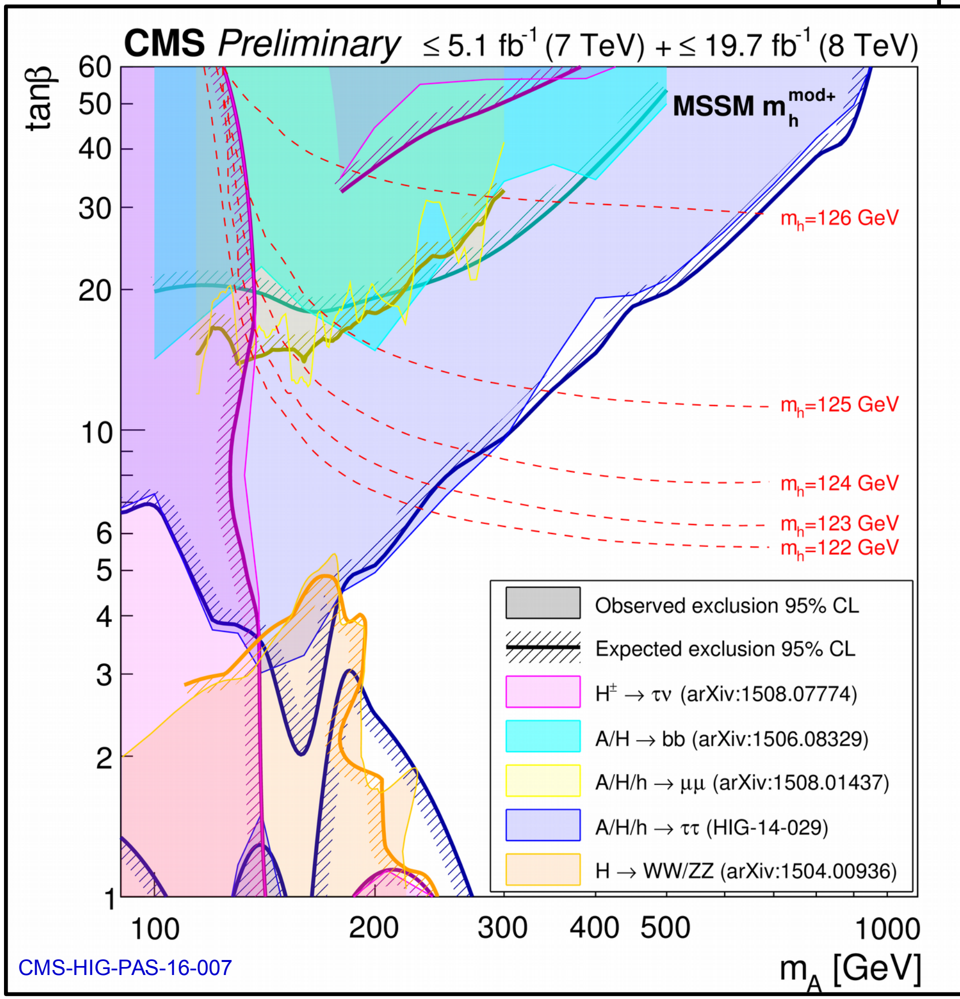


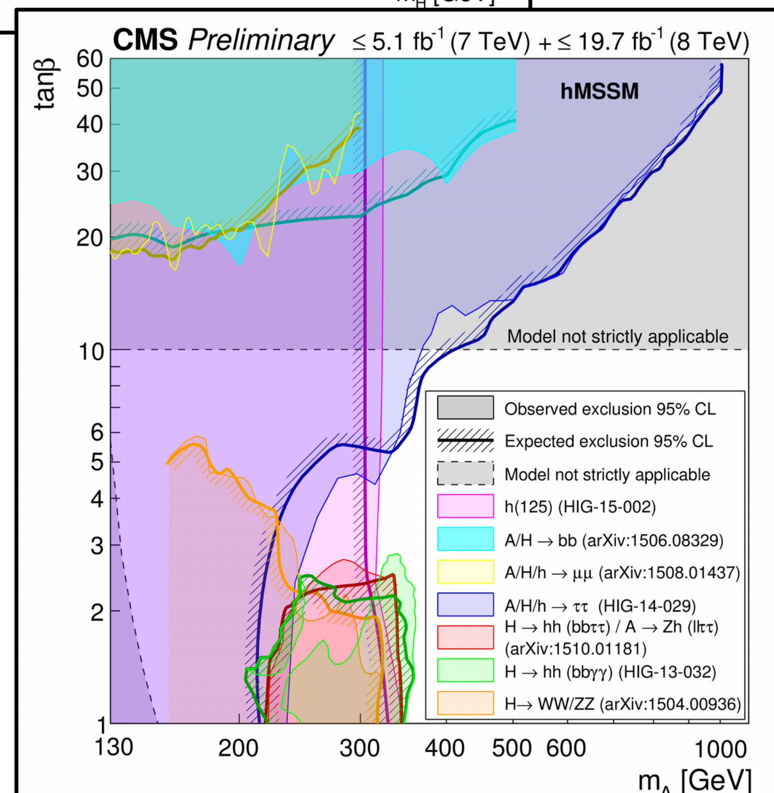
Interesting decay channels:



Upshot of LHC run-1:



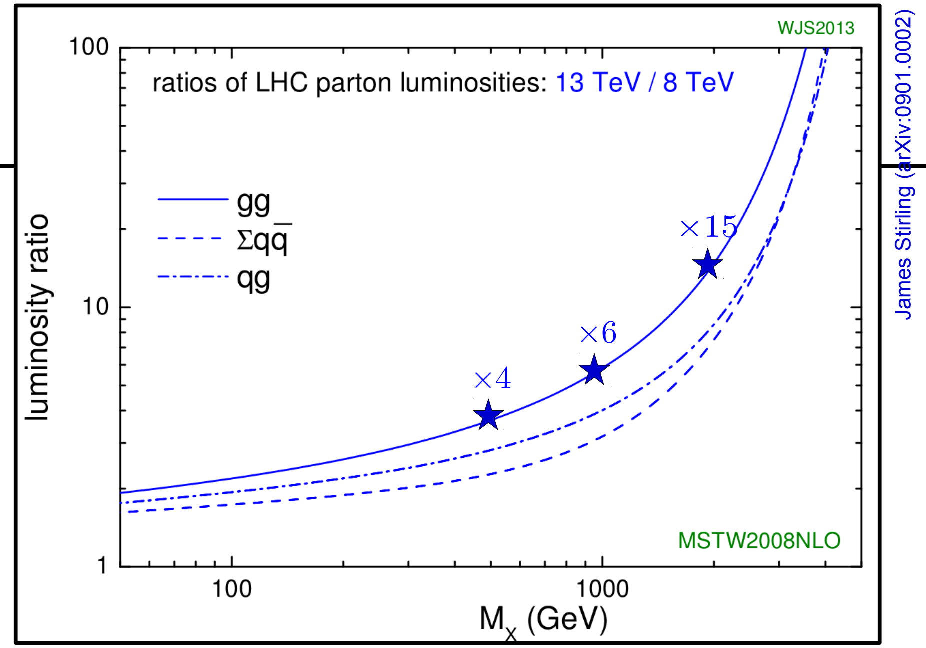


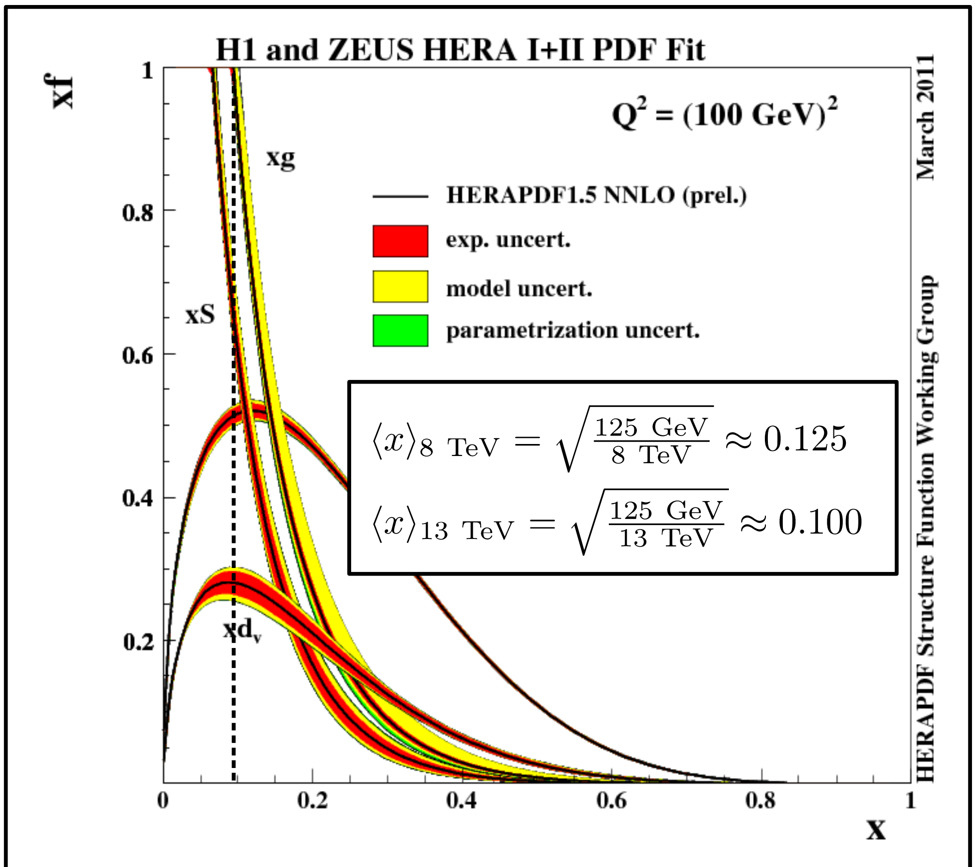


Similar results (only not in single plots) from ATLAS.

LHC run-1→ run-2

Process	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$	$\delta_X/\delta_{h(125)}$
$t\bar{t}$	3.3	1.43
W	1.6	0.70
Z	1.6	0.70
WW	2.0	0.87
$h(125)$	2.3	1.00



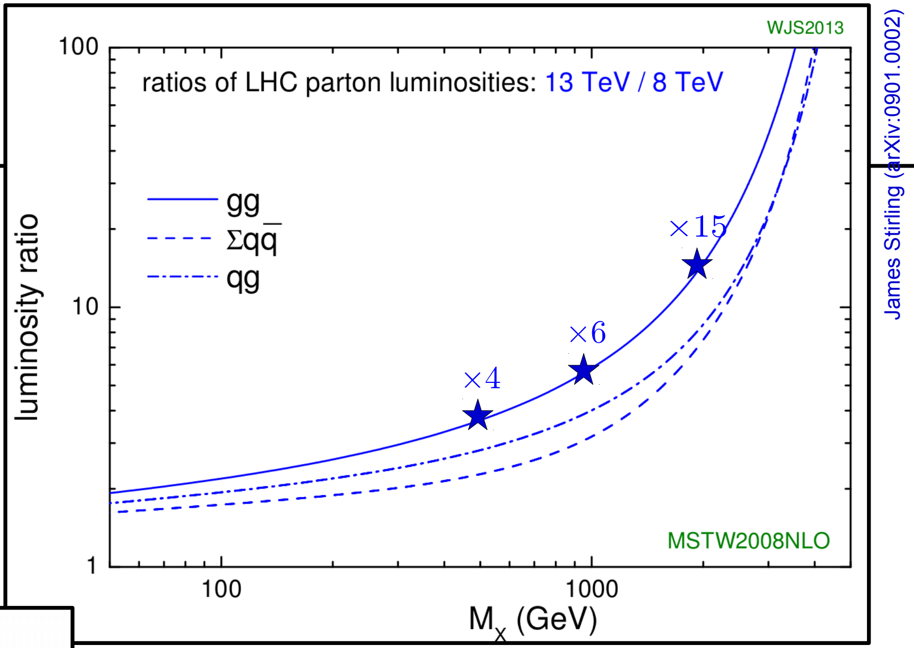


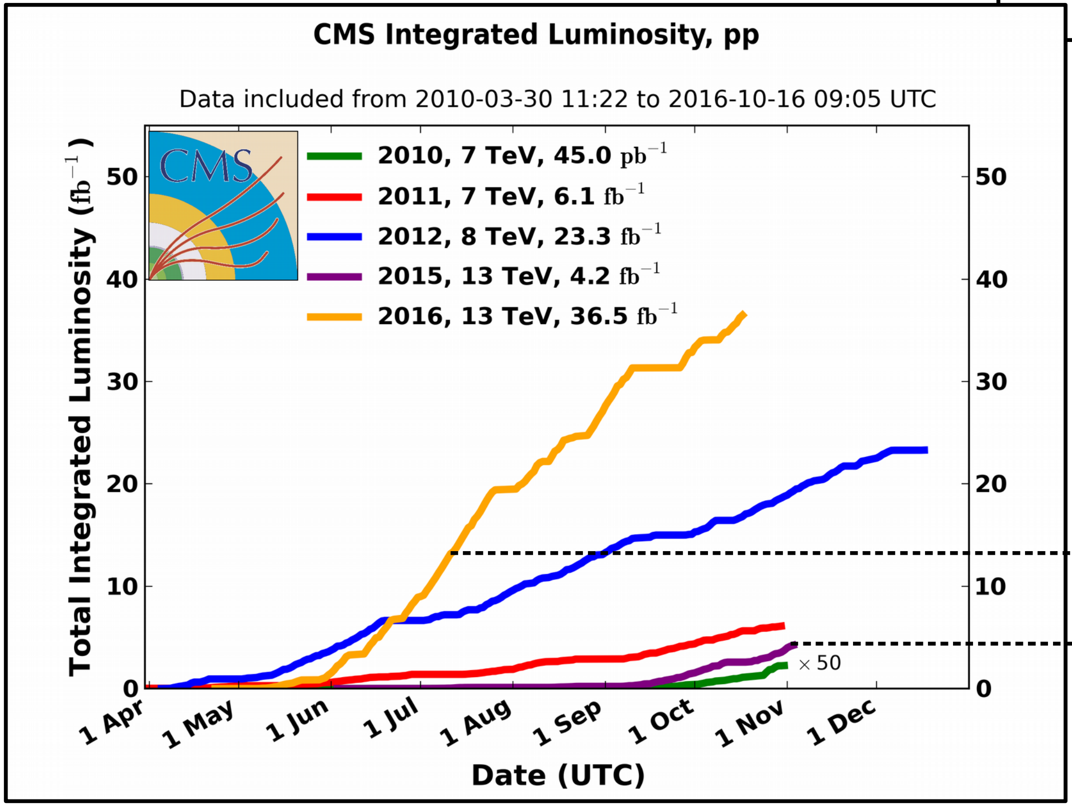
$$\langle x\rangle_{8\ \text{TeV}} = \sqrt{\frac{125\ \text{GeV}}{8\ \text{TeV}}} \approx 0.125$$

$$\langle x\rangle_{13\ \text{TeV}} = \sqrt{\frac{125\ \text{GeV}}{13\ \text{TeV}}} \approx 0.100$$

LHC run-1→ run-2

Process	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$	$\delta_X/\delta_{h(125)}$
$t\bar{t}$	3.3	1.43
W	1.6	0.70
Z	1.6	0.70
WW	2.0	0.87
$h(125)$	2.3	1.00





Results for ICHEP 2016:

13.2/fb (ATLAS)

12.9/fb (CMS)

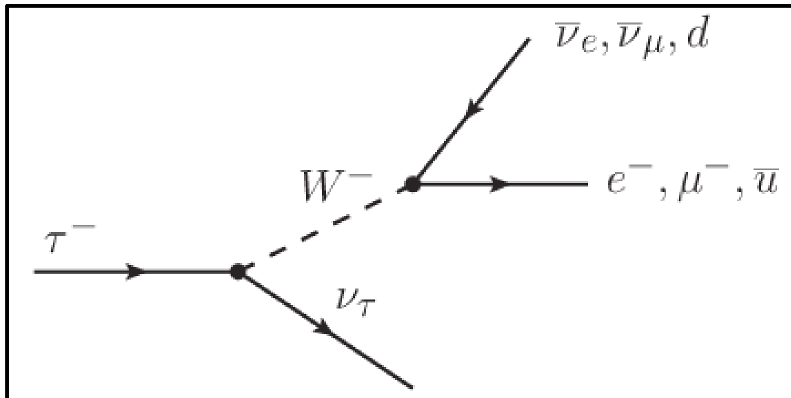
Results end of 2015:

3.2/fb (ATLAS)

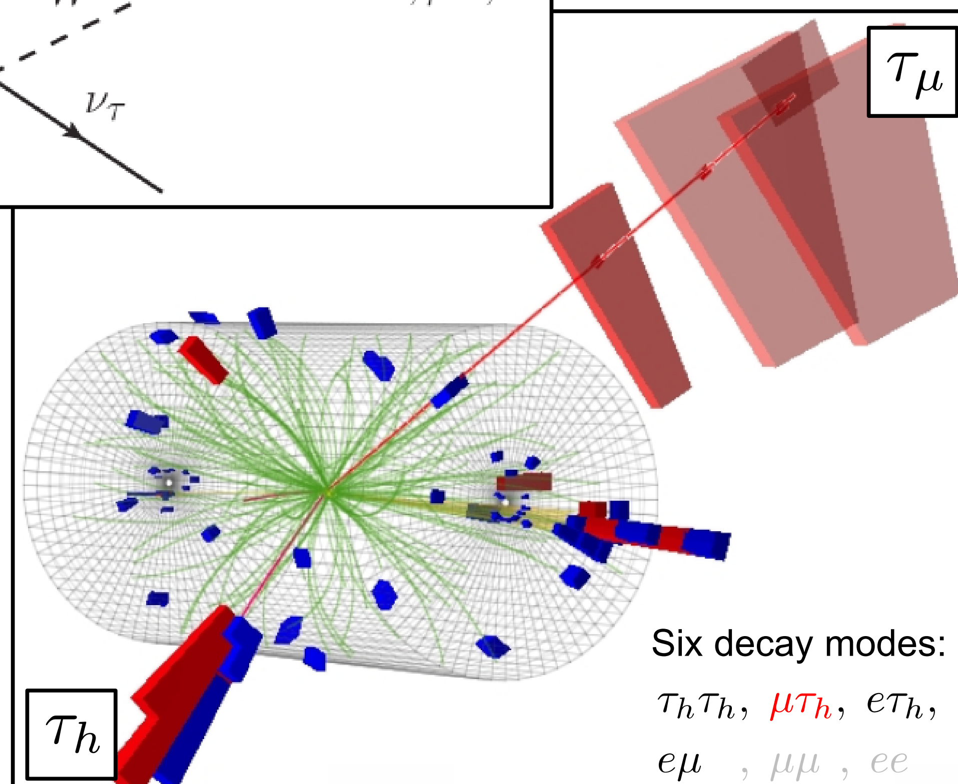
2.3/fb (CMS)

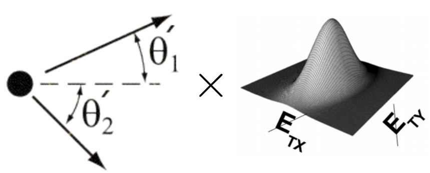
$H \to \tau\tau$ decay channel

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 .

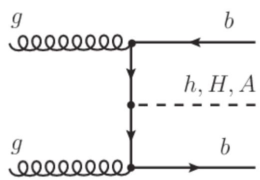
Search

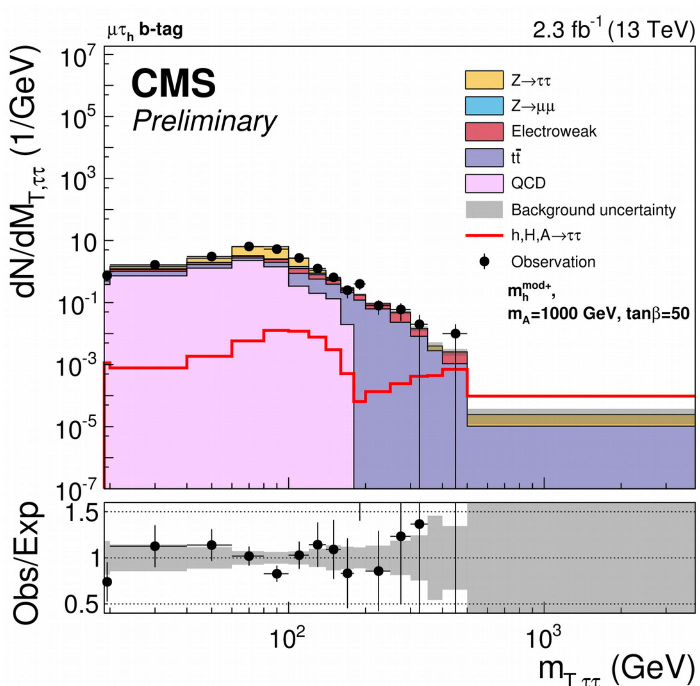
- Search for peak(s) e.g. in (transverse) $m_{\tau\tau}$ distribution.

b-tag category:

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

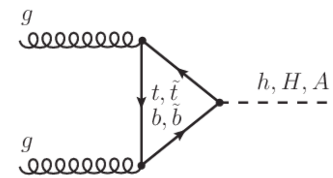
$\mathrm{N(Jet)} \quad \leq 1$

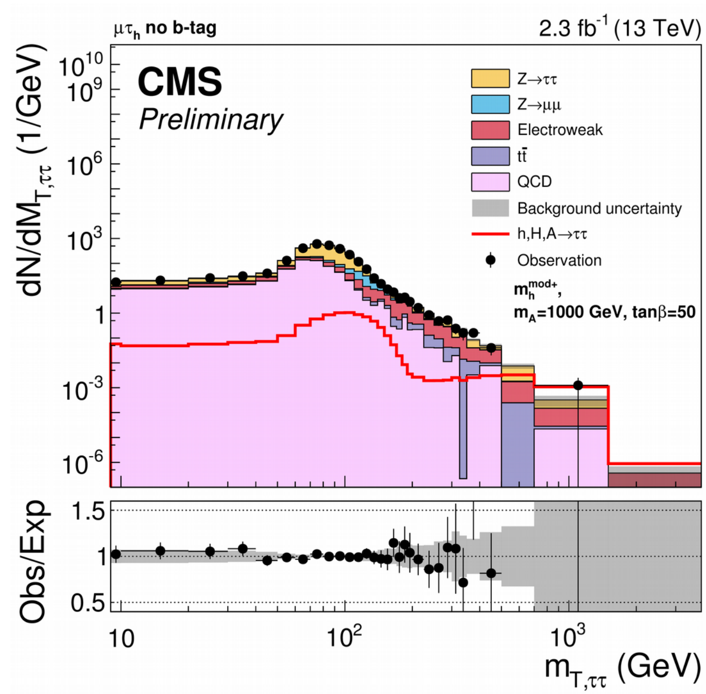




No b-tag category:

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

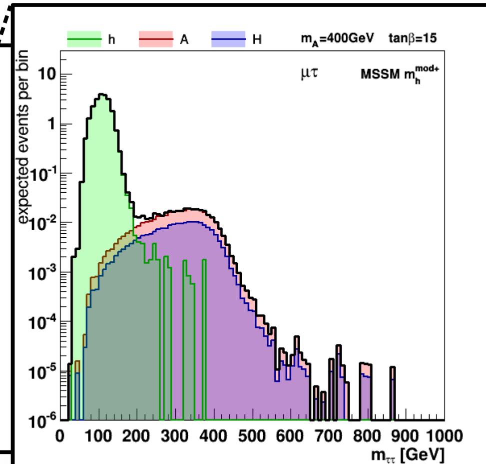


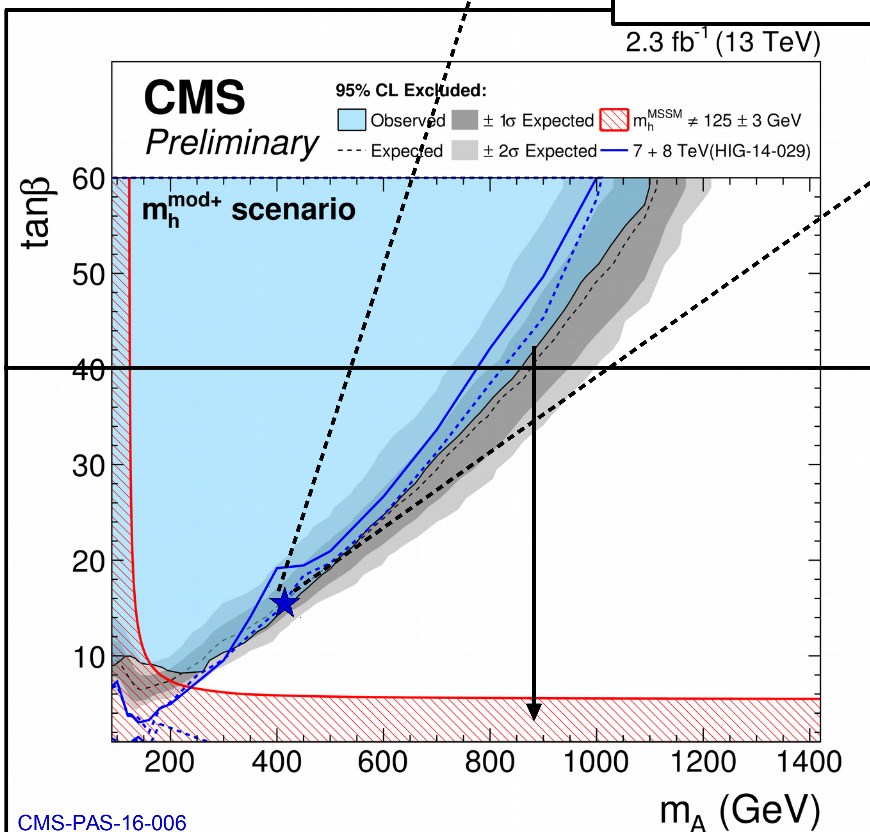


CMS-PAS-16-006

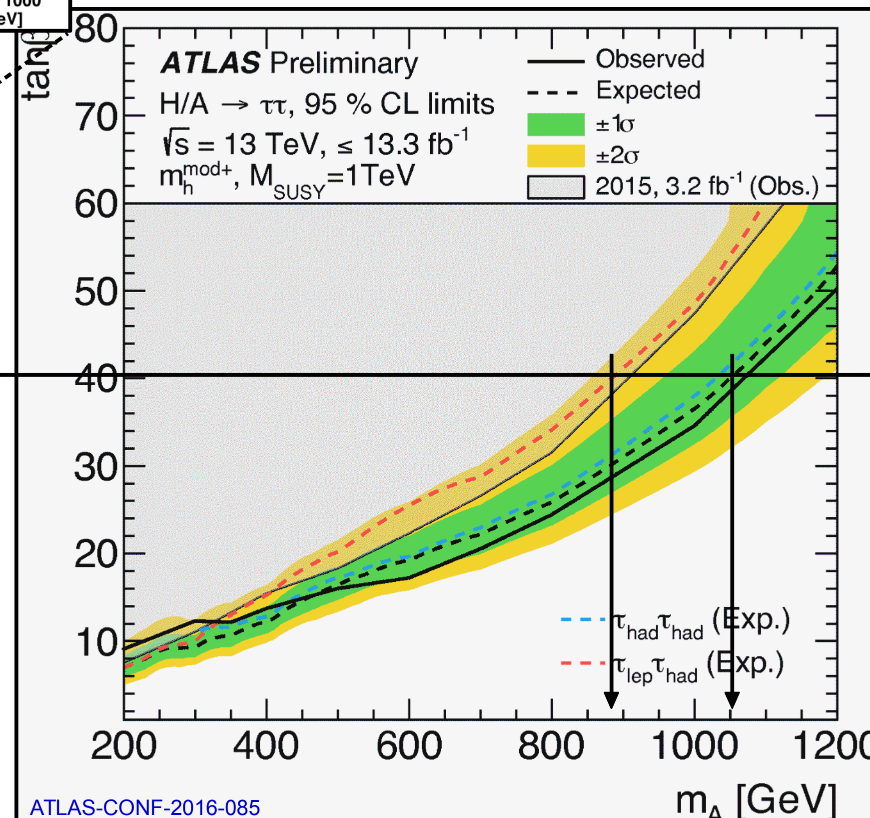
Exclusion

Both collaborations present their results also in form of maximally model independent limits on $\sigma \times BR$ or $\Delta\mathrm{NLL}$ values.



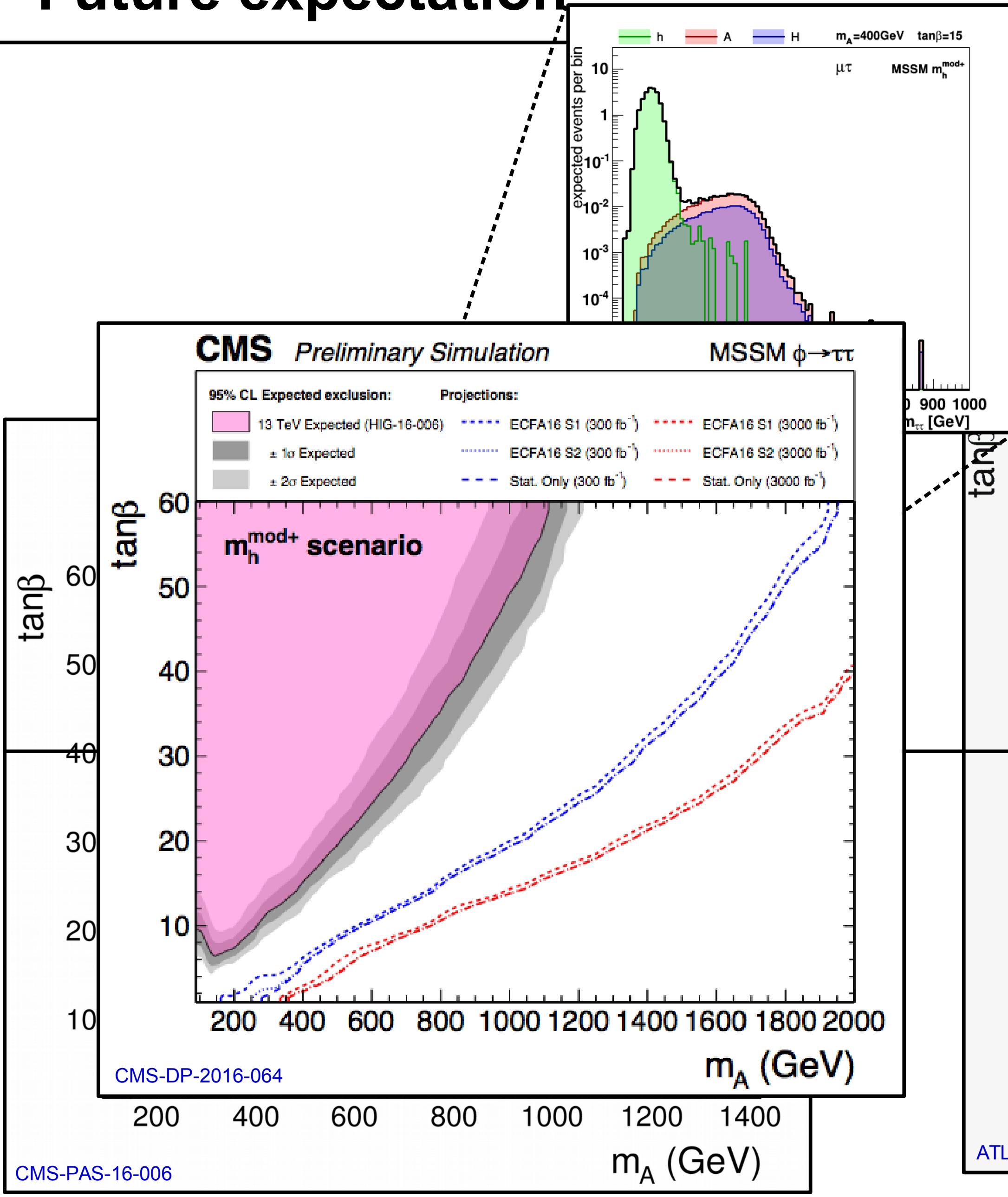


With slightly different event categories & different final discriminator.

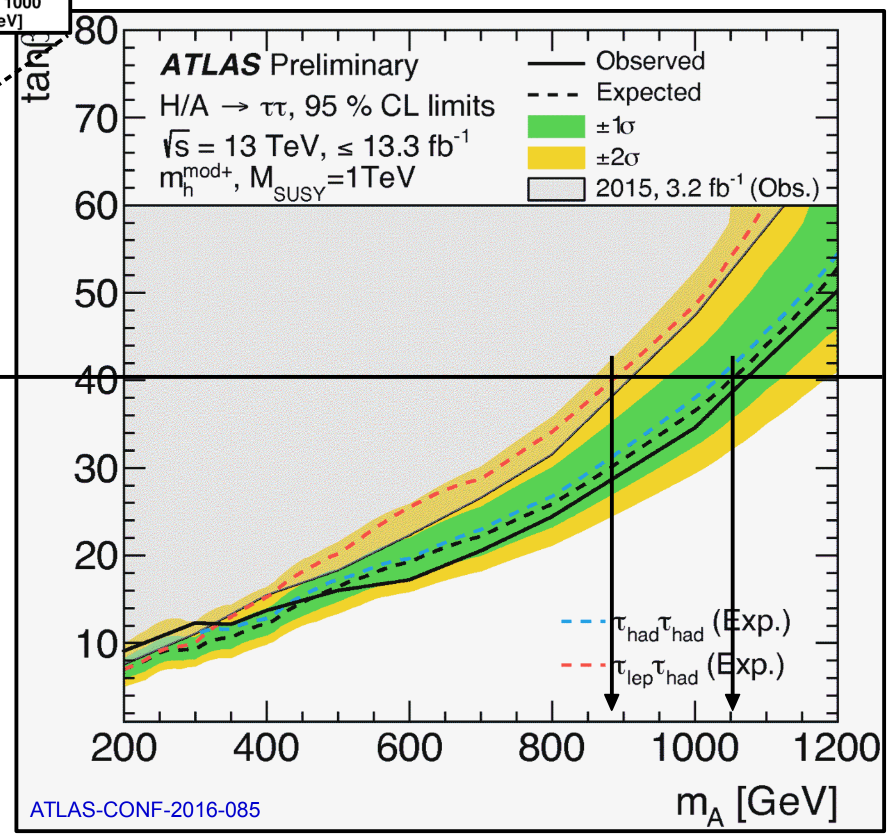


Future expectation

Both collaborations present their results also in form of maximally model independent limits on $\sigma \times BR$ or $\Delta\mathrm{NLL}$ values.

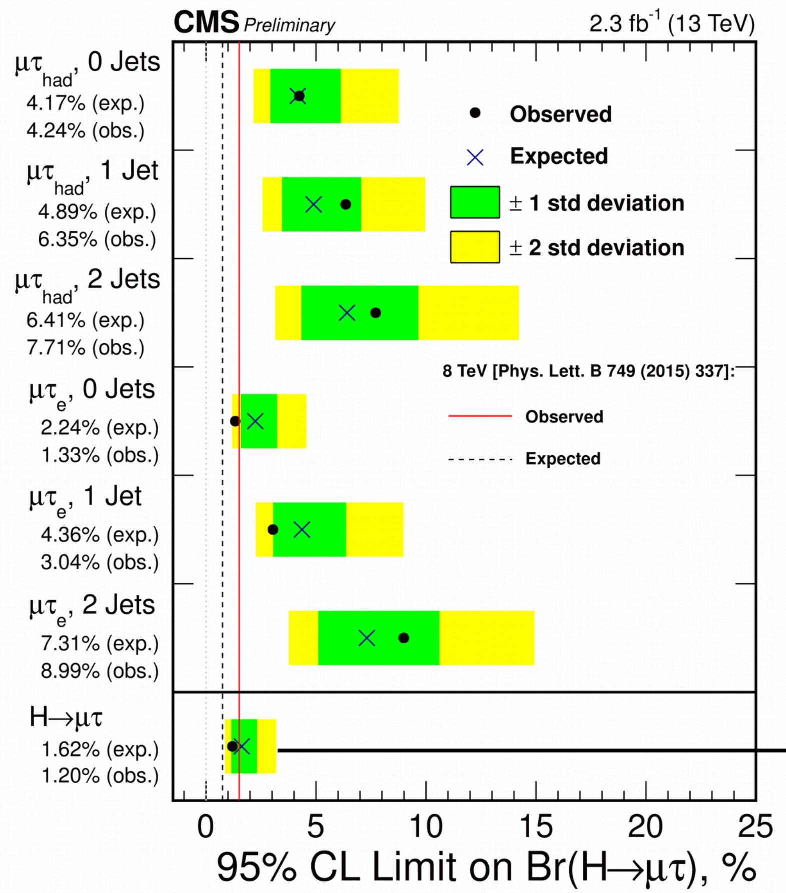


With slightly different event categories & different final discriminator.



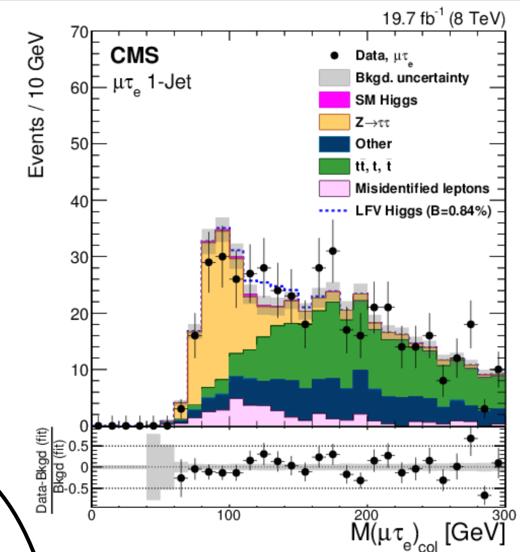
$H \to \mu\tau$ LFV Higgs couplings

- SM forbids LFV couplings at tree level.
- LVF could take place in Higgs sector.



CMS-PAS-16-005

LHC run-1 legacy:



$+2.5\sigma$

$+1\sigma$

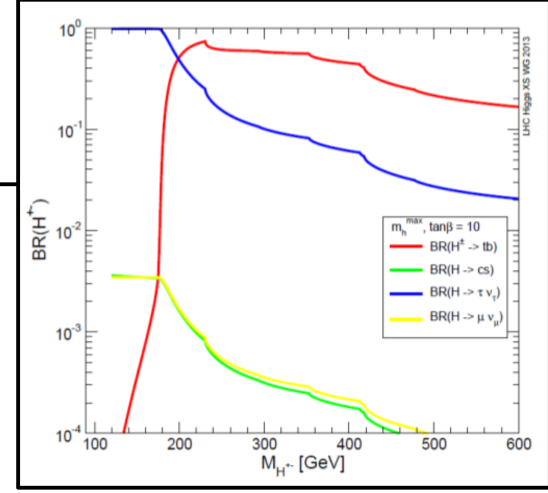
BR($H \to \mu\tau$) = 1.51 (0.75)% @ 95% CL (CMS)
PLB 749 (2015) 337

BR($H \to \mu\tau$) = 1.85 (1.24)% @ 95% CL (ATLAS)
JHEP 11 (2015) 211

- $H \to \mu\tau_h/\mu\tau_e$ with two specialties:
  - $p_T(\mu)$ harder ($\to$ less $\nu' s$ in decay).
  - ν more collinear.

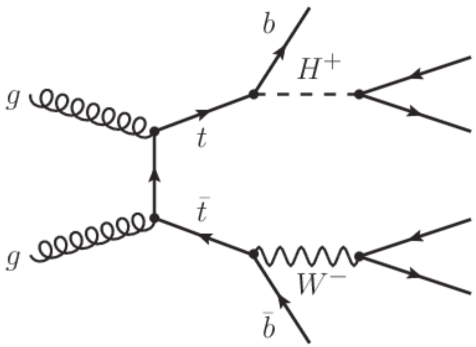
No excess, but also not same sensitivity reached, yet, as for LHC run-1.

Charged Higgs



- Expect signal in top sector:
- Most sensitive channels: $H^+ \to \tau\nu$, $H^+ \to tb$.

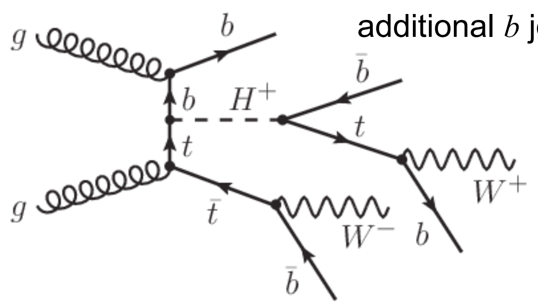
In decay ($m_{H^+} < m_t$):



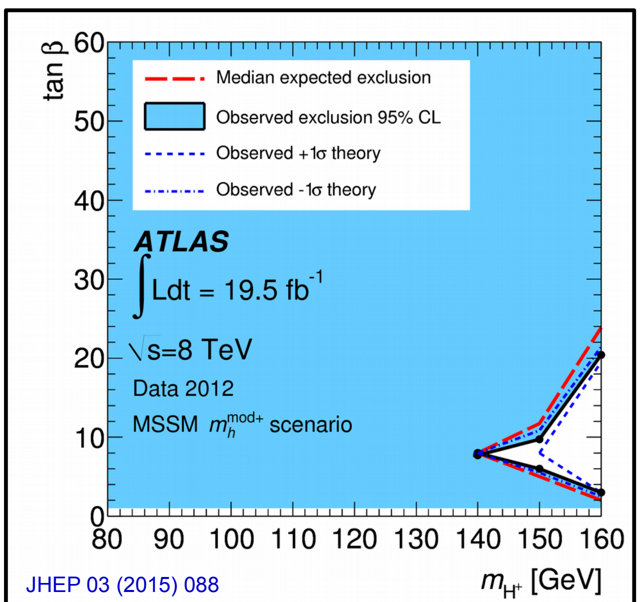
heavy flavors preferred

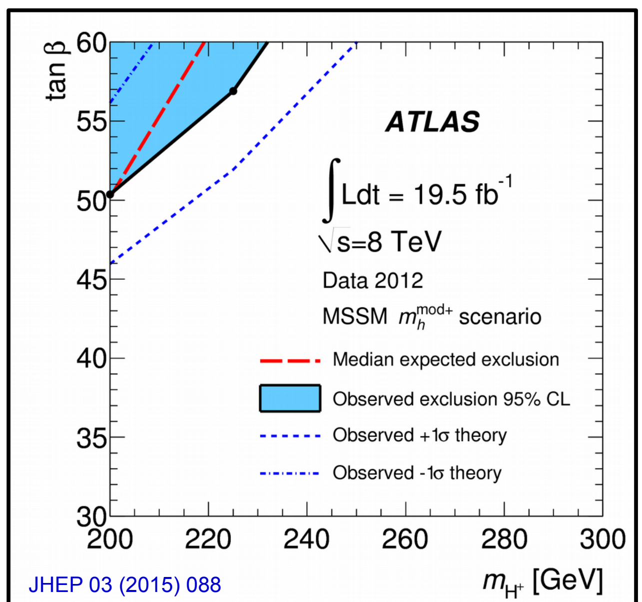
flavor democratic

In production ($m_t < m_{H^+}$):



additional b jets

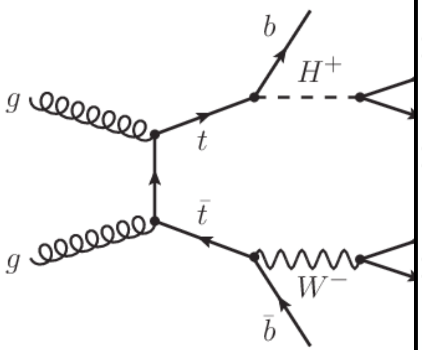


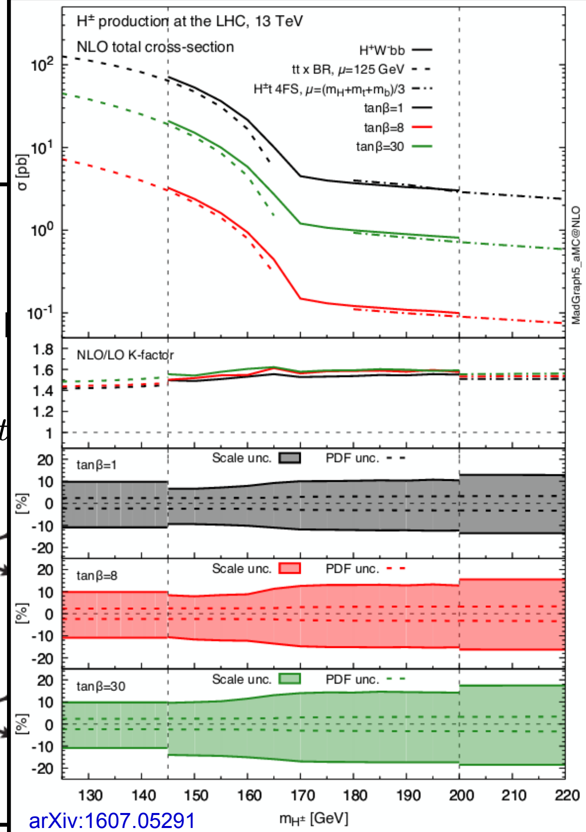


Charged Higgs

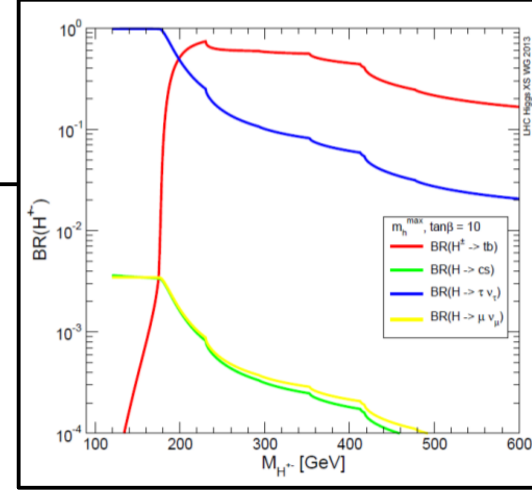
- Expect signal in top
- Most sensitive chan

In decay ($m_{H^+} < m_t$

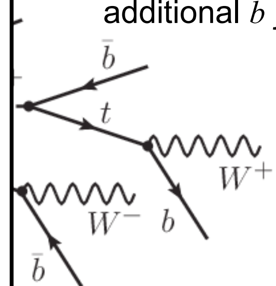


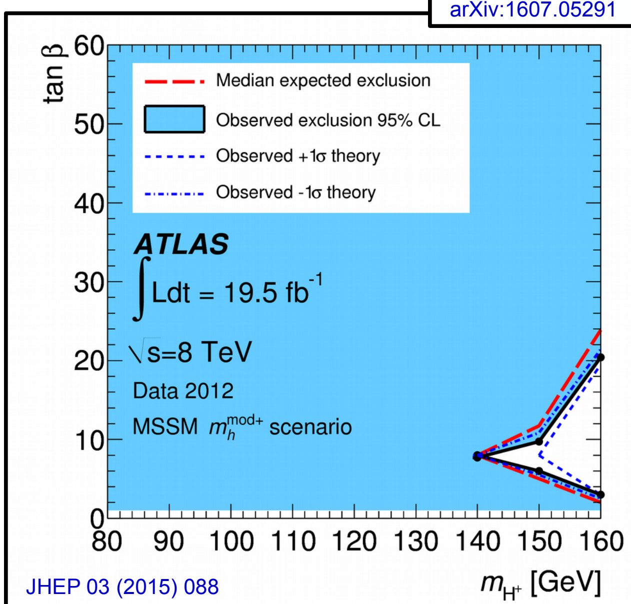


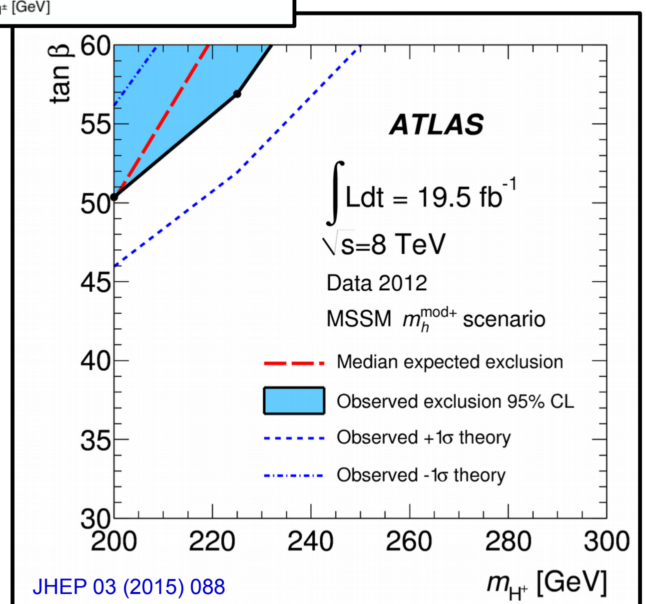
$(m_t < m_{H^+})$:



additional b jets

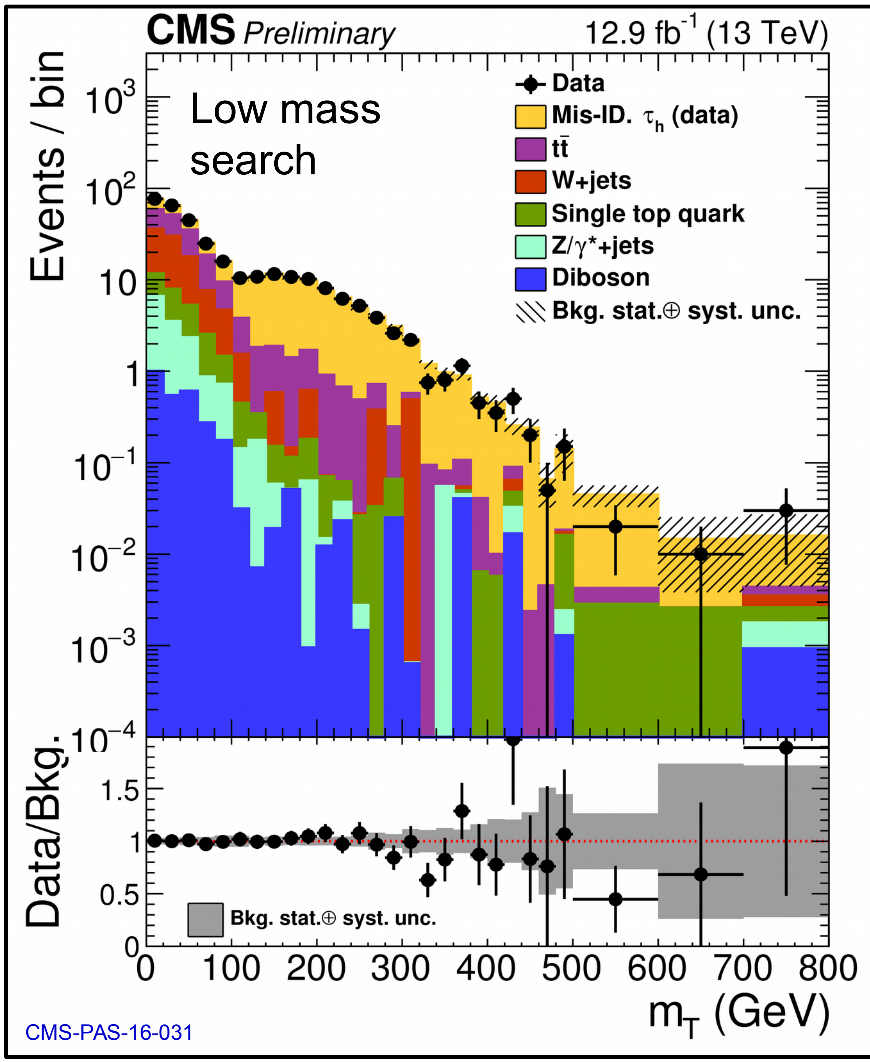




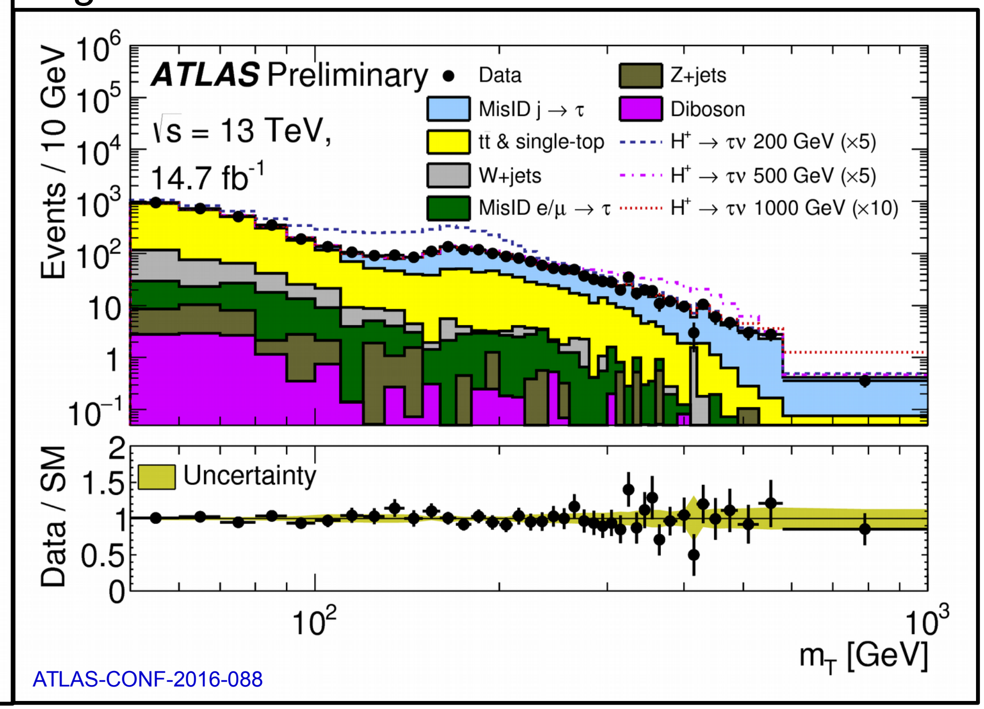


Charged Higgs ($H^+ \to \tau\nu$)

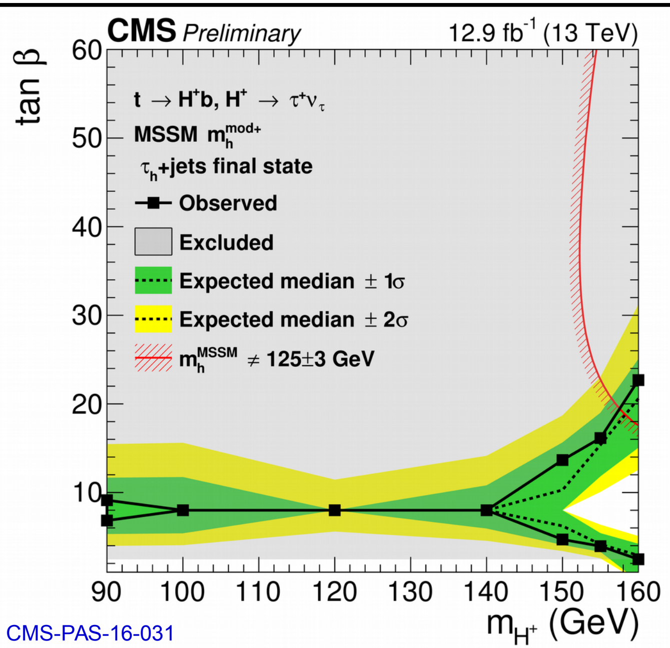
- Usually restrict to τ_h (1-prong), use $m_T(\tau_h, MET)$ as discriminating variable.

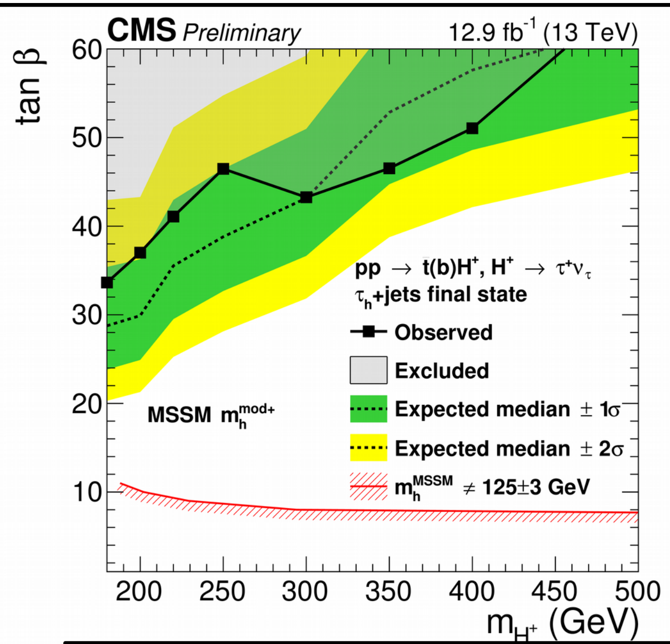


High mass search



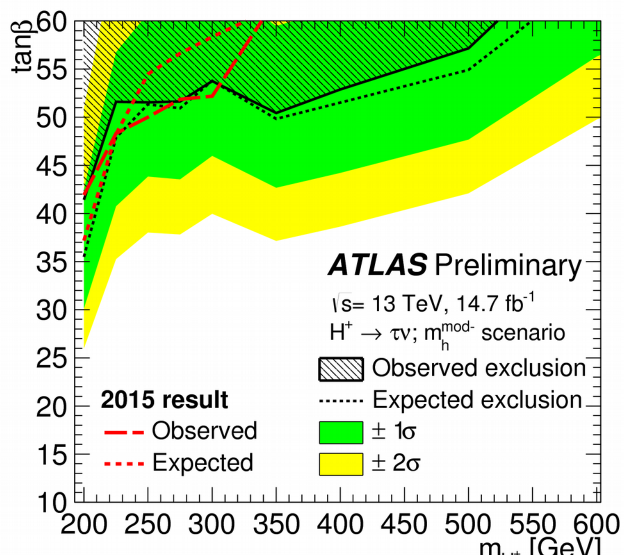
Exclusion





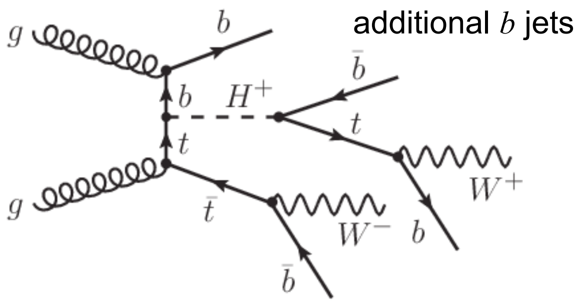
CMS-PAS-16-031

- Chapter of low mass region already closed by LHC run-1 results.
- About to surpass LHC run-1 sensitivity in high mass regime.

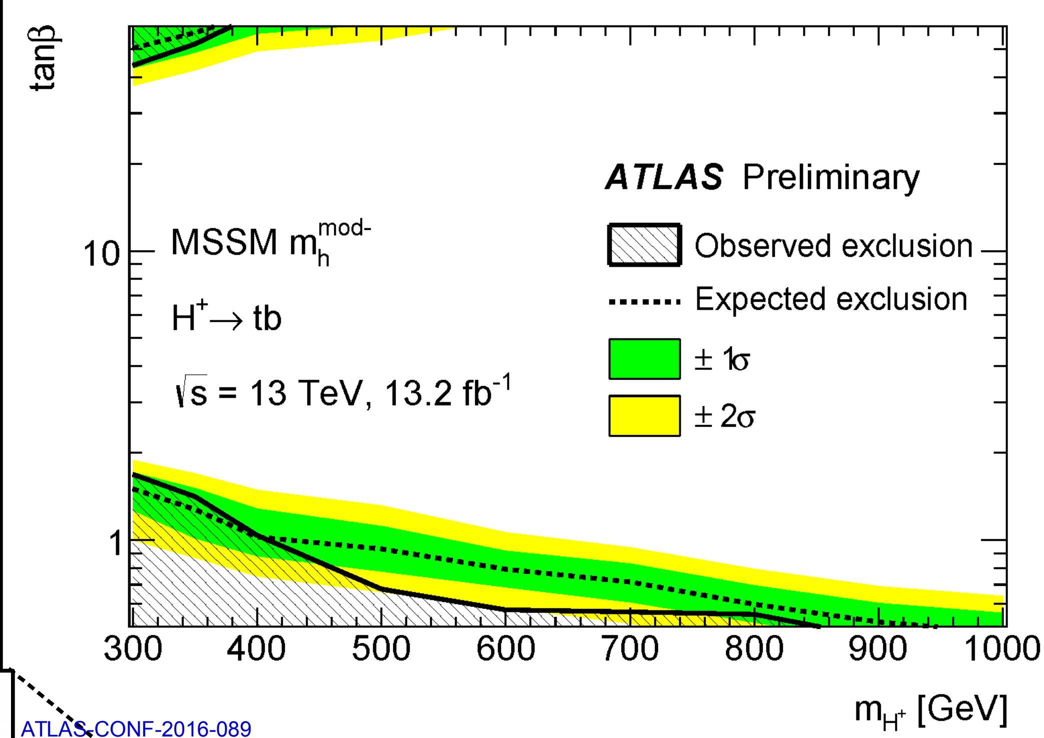


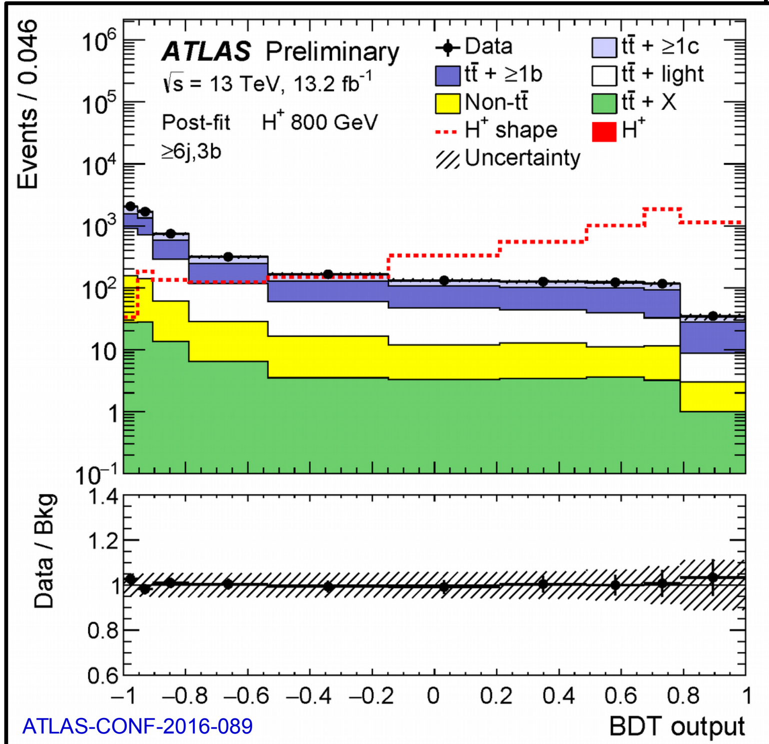
ATLAS-CONF-2016-088

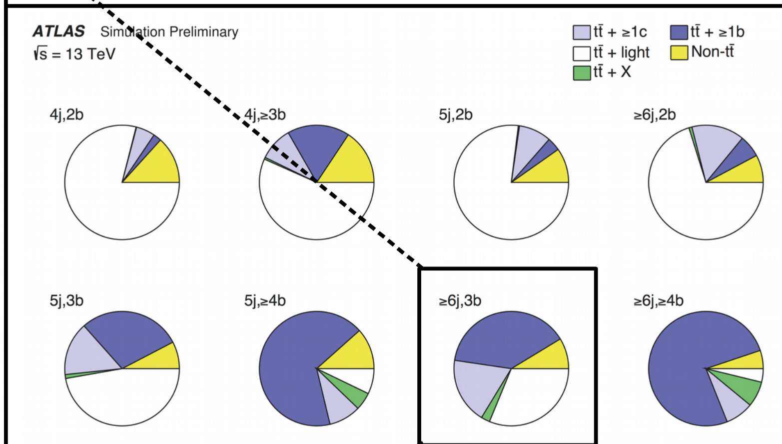
Charged Higgs ($H^+ \to tb$)



Select one leptonic and one hadronic W decay.

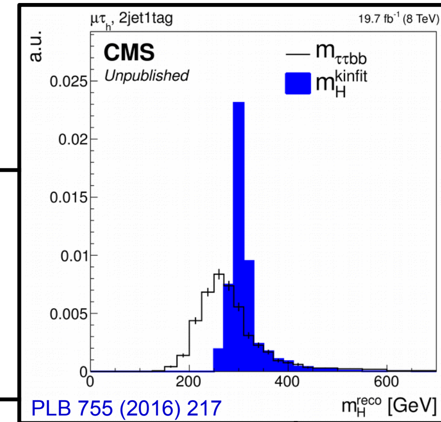




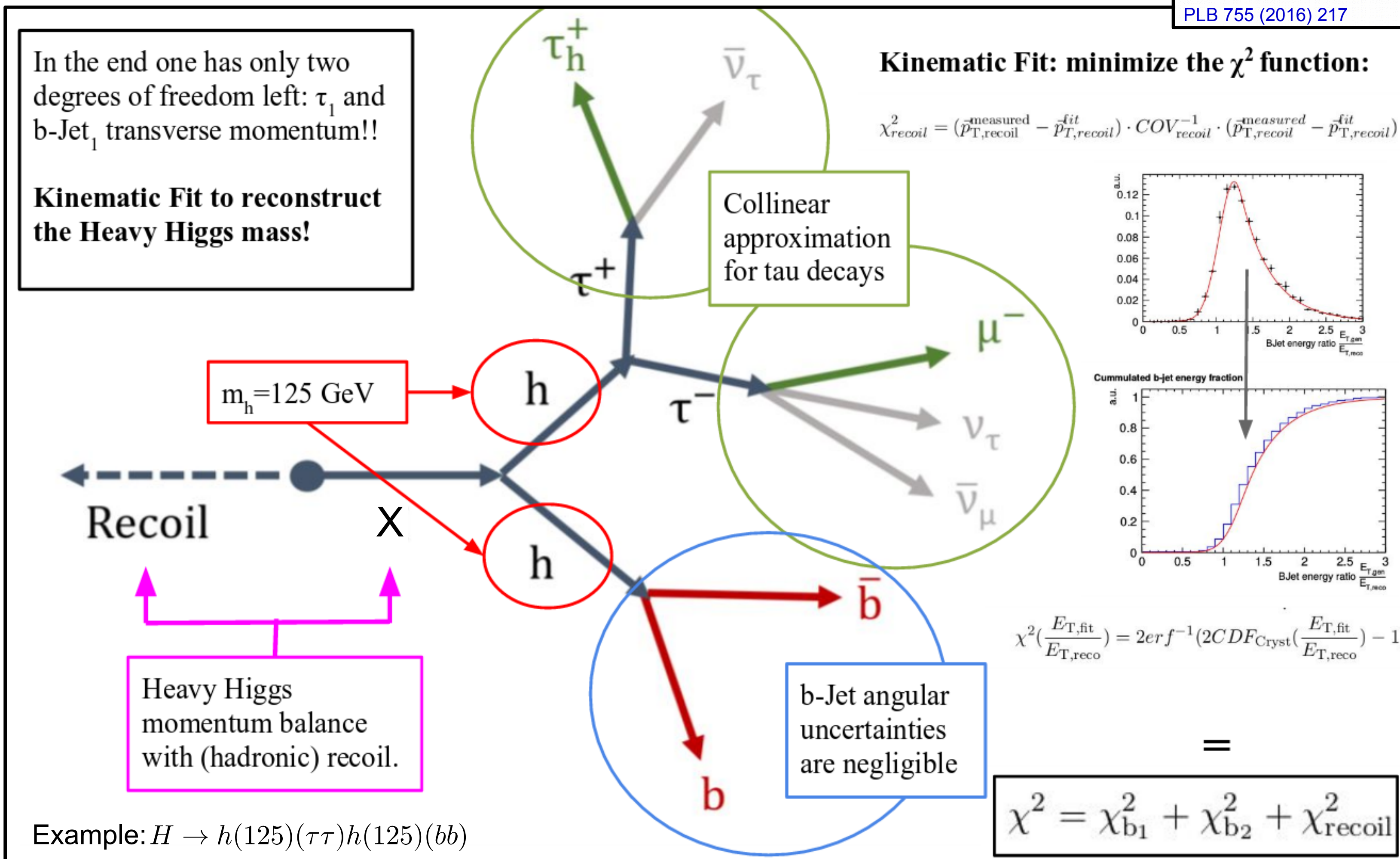


→ Gain sensitivity to low $\tan\beta$!

$X \rightarrow h(125)h(125)$

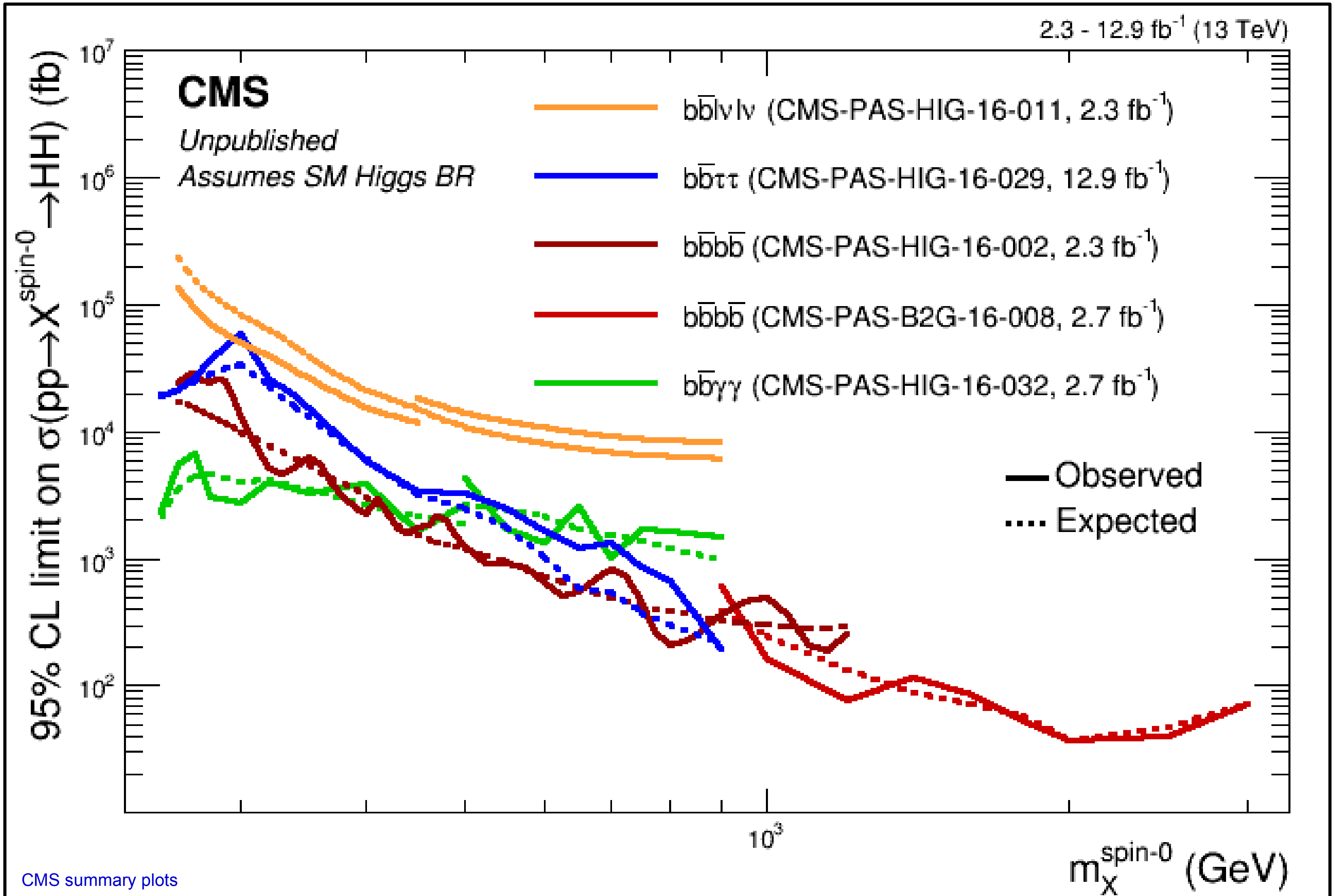


- In principle sensitive to $f_{h\rightarrow hh}$ (search (non-)resonant).
- Plenty of constraints due to “cascade”:

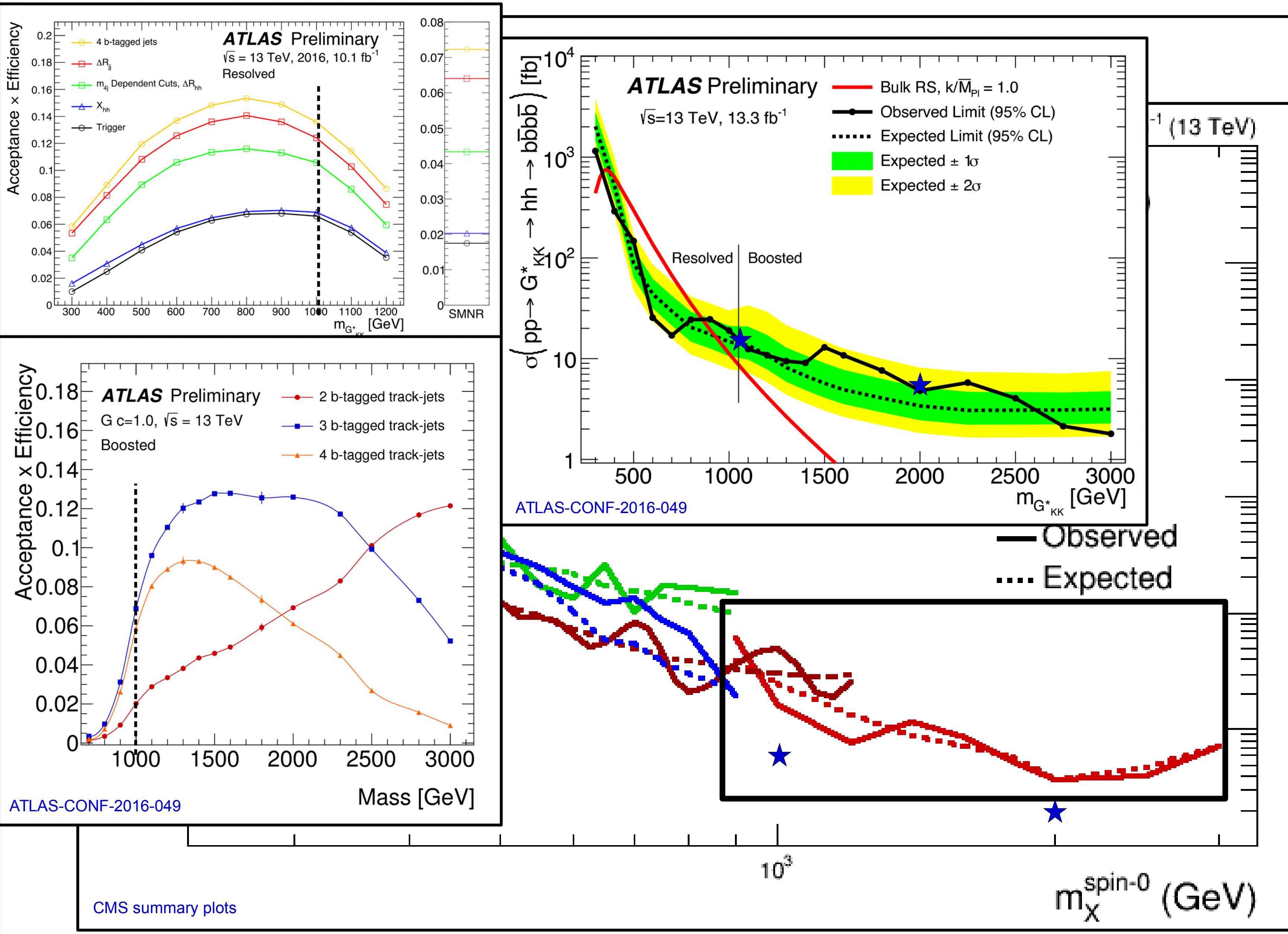


$X \to h(125)h(125)$

- Search channels according to $h(125)$ couplings:



$X \to h(125)h(125)$



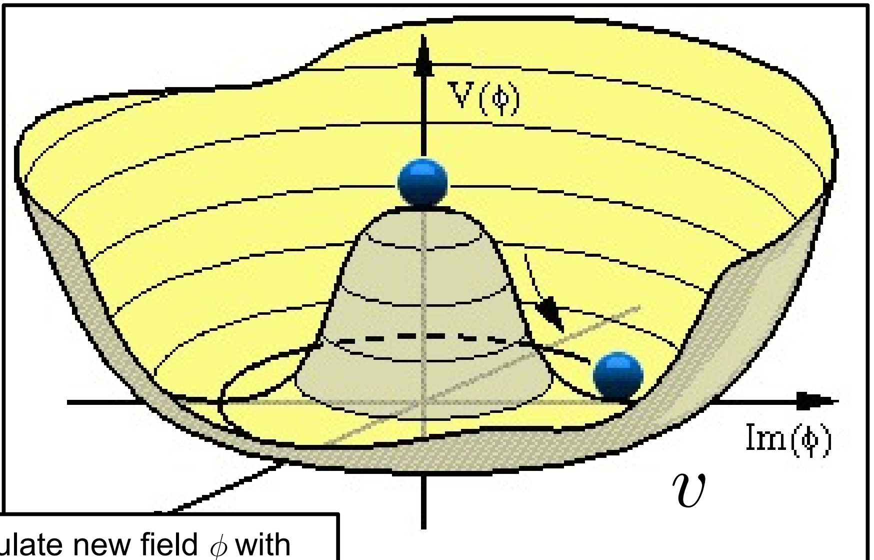
Conclusions

- Very rich LHC run-2 BSM Higgs program of both ATLAS & CMS.
- Impossible to cover all (even in 50min) → personal selection.
- Higgs physics requires high statistics → also and esp. in BSM Higgs the most interesting results are still to come.
- Looking forward to full “LHC 2016” and “LHC 2017” datasets!

Backup

How can $SU(2)_L$ symmetry be the source of weak interactions while at the same time all interacting particles with $m \neq 0$ explicitly break this symmetry?!?

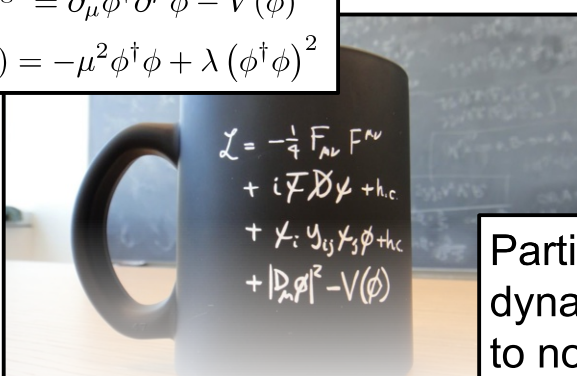
Spontaneous symmetry breaking:



Postulate new field ϕ with symmetry breaking vacuum:

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

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



Lagrangian Density of (baryonic)

Particle masses created dynamically by coupling to non-zero vacuum.

$$y_e \left(v + \frac{H}{\sqrt{2}}\right) \bar{e} e \quad m_e = y_e \cdot v$$

- Symmetry inherent to the system but not to its energy ground state (→ quantum vacuum).
- Excitation of vacuum ground state leads to existence of a new particle, characterized by very peculiar coupling structure, needed to preserve the symmetry of the system:

$$f_{H \to ff} = i \frac{m_f}{v} \qquad \text{(Fermions)}$$

$$f_{H \to VV} = i \frac{2m_V^2}{v} \qquad \text{(Heavy Bosons trilinear)}$$

$$f_{HH \to VV} = i \frac{2m_V^2}{v^2} \qquad \text{(Heavy Bosons quartic)}$$

$$f_{H \to HH} = i \frac{3m_H^2}{v} \qquad \text{(H Boson trilinear)}$$

$$f_{HH \to HH} = i \frac{3m_H^2}{v^2} \qquad \text{(H Boson quartic)}$$