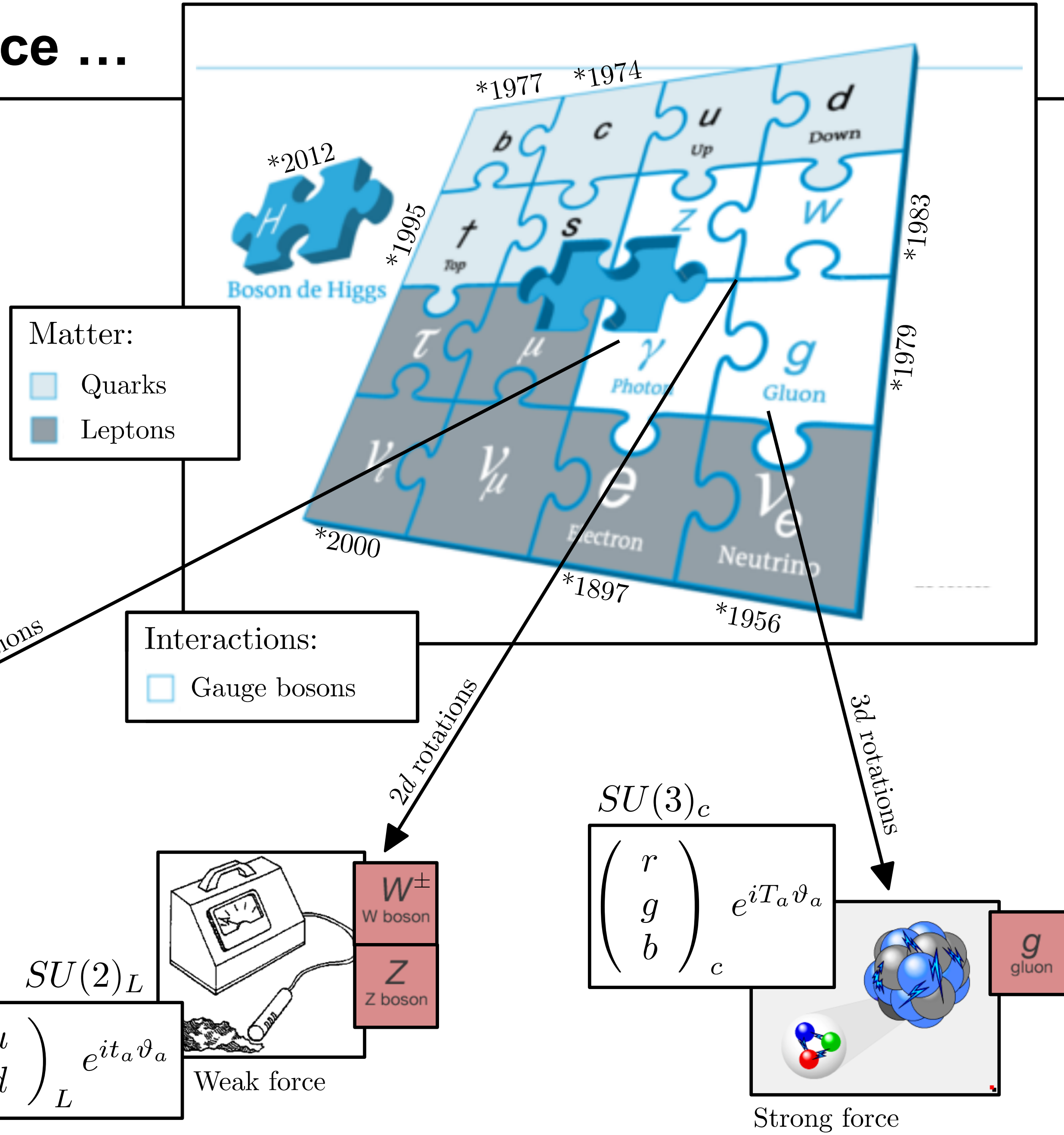
Die Akte Higgs
– fünf Jahre Higgsphysik am LHC –

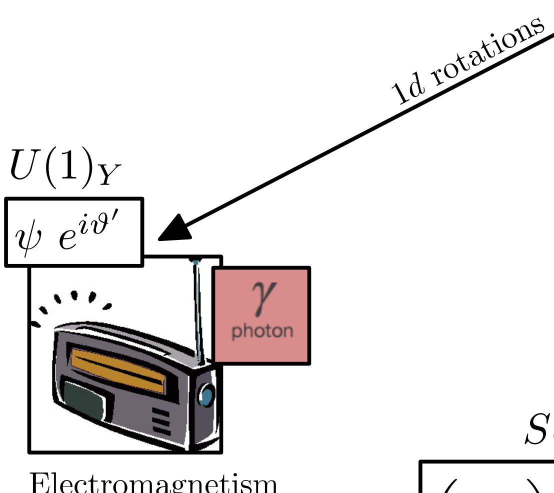
Roger Wolf (KIT)

Frühjahrstagung der DPG, 30. März 2017

The last missing piece …

- Matter made up of quarks and leptons.
- Interactions mediated by gauge bosons introduced via **local gauge symmetries**.
- ϟ particle masses break these symmetries!





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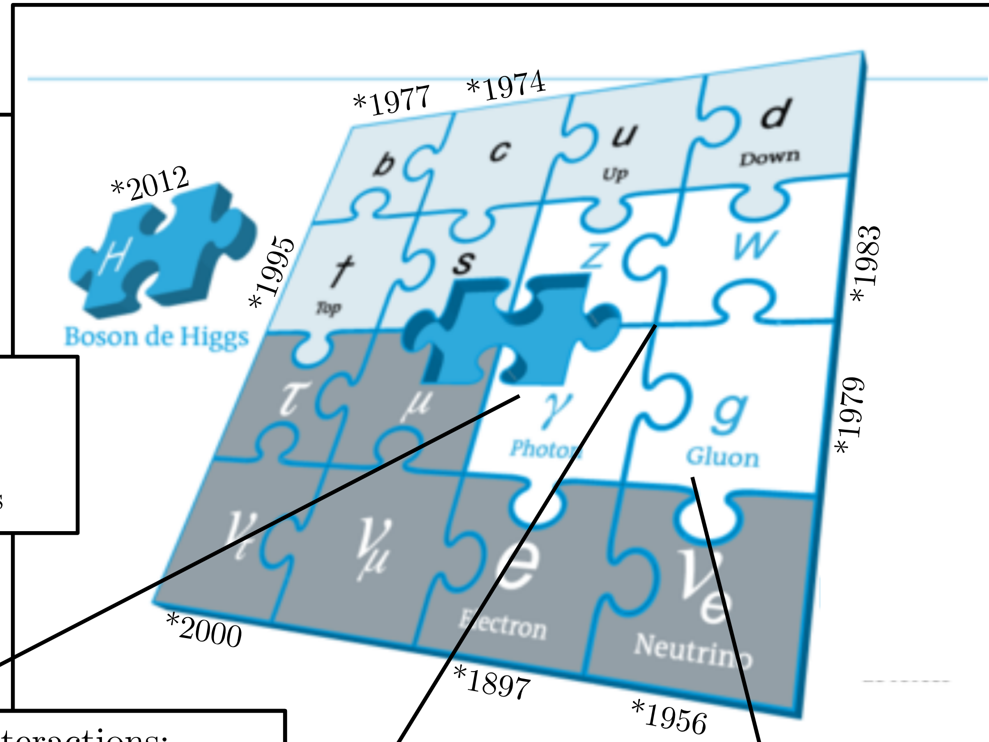


Matter:
- Quarks
- Leptons

Interactions:
- Gauge bosons

…tations

2d rotations

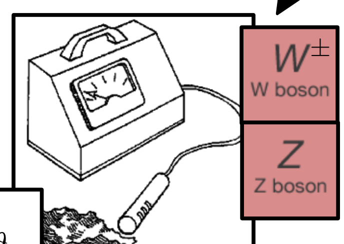
3d rotations

- Especially W & Z boson are very heavy.
- How can $SU(2)_L$ be realized & broken at the same time.

Electromagnetism

$SU(2)_L$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L e^{it_a \vartheta_a}$$

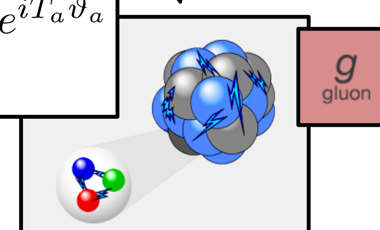


Weak force

$$m_W = 80.385 \pm 0.015 \text{ GeV}$$
$$m_Z = 91.187 \pm 0.002 \text{ GeV}$$

$SU(3)_c$

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix}_c e^{iT_a \vartheta_a}$$



Strong force

Giving mass to particles

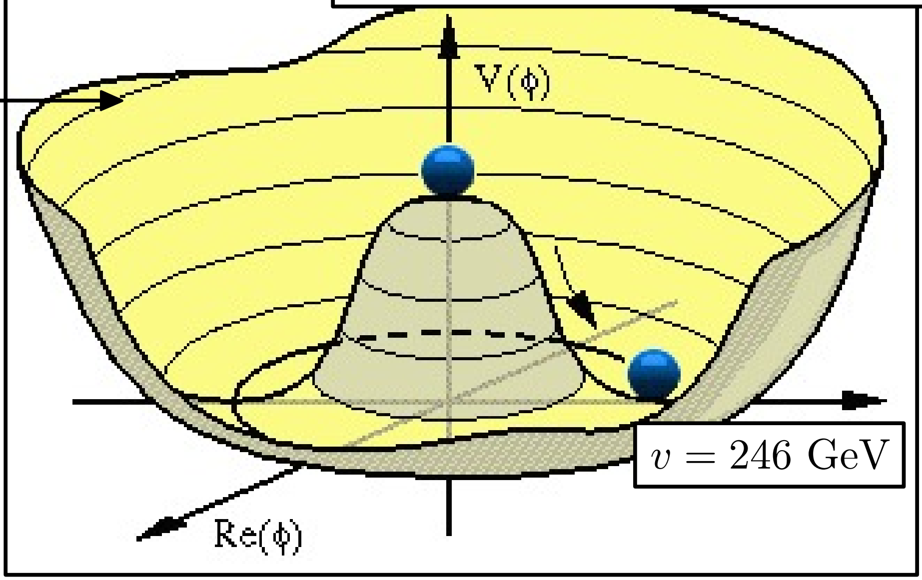
- Break $SU(2)_L$ symmetry not in Lagrangian itself but in the energy ground state.

- Postulate new $SU(2)_L$ doublet field ϕ in electroweak (EWK) sector of the theory w/ potential that breaks $SU(2)_L$.

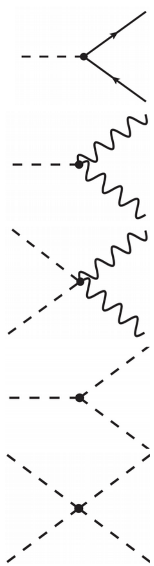
- Particle masses → coupling to vacuum.

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} \rightarrow \begin{pmatrix} 0 \\ v + \frac{H}{\sqrt{2}} \end{pmatrix}$$

$$N_{\mathrm{ndof}} = 4 - \underbrace{3}_{W^\pm,\ Z} = \underbrace{1}_{H}$$



Unique coupling structure:



$\propto \frac{m_f}{v}$ (Quarks & Leptons)

$\propto \frac{2m_V^2}{v}$, $\propto \frac{2m_V^2}{v^2}$ (Gauge bosons)

$\propto \frac{3m_H^2}{v}$, $\propto \frac{4m_H^2}{v^2}$ (Self coupling)

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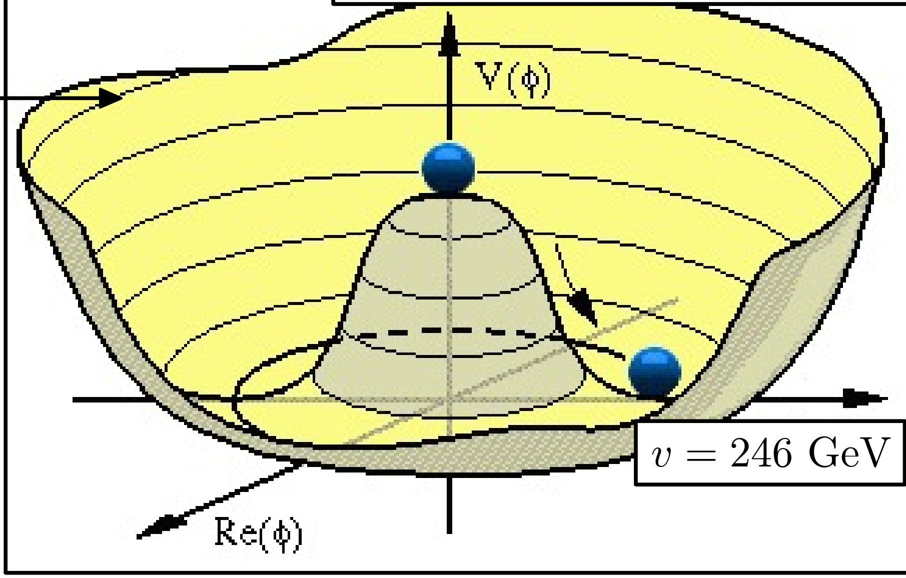

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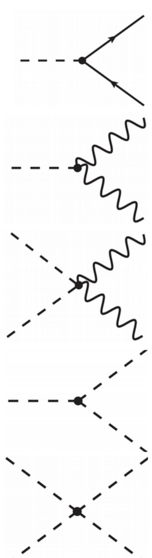

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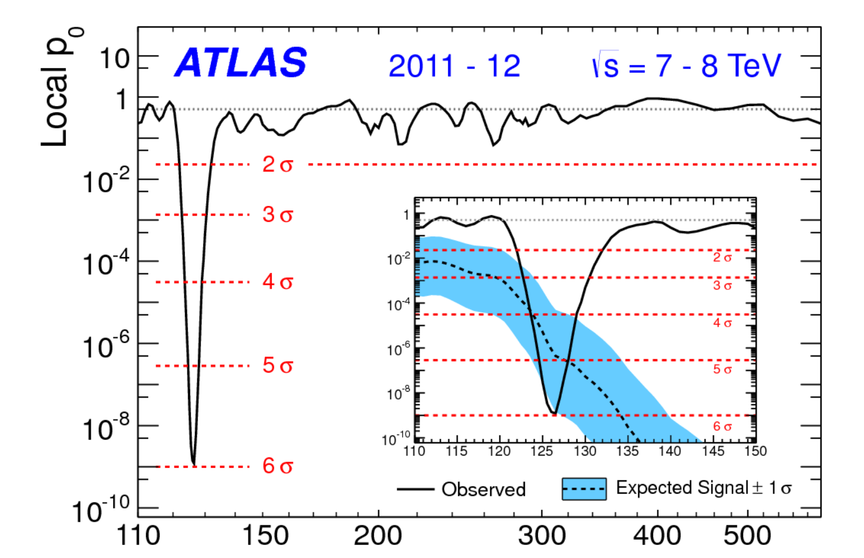
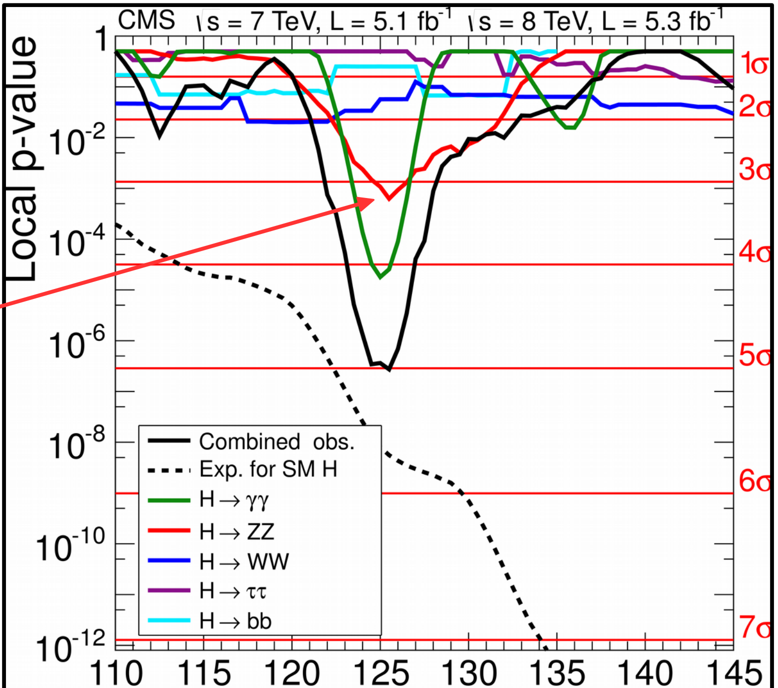
Till 2012 → mathematical trick to complete the SM. Since 4th July 2012 strong evidence that such a particle like a Higgs boson really exists.

The discovery (July 4th 2012)

- ATLAS and LHC with comparable sensitivity.
- Discovery made on only 40% of the full LHC run-1 dataset.
- **Is this a Higgs boson?** (→ check properties)
- **Is this the Higgs boson of the SM?**



PLB 716 (2012) 1 1000+ citations



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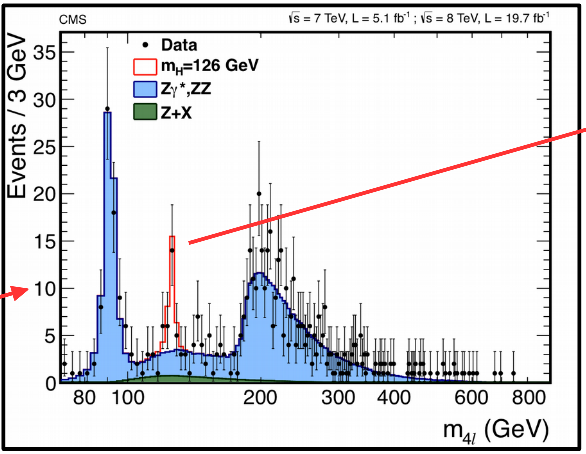
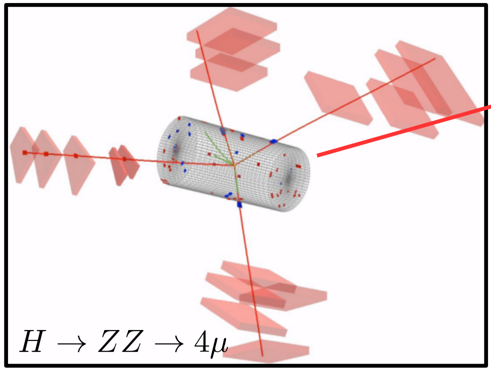
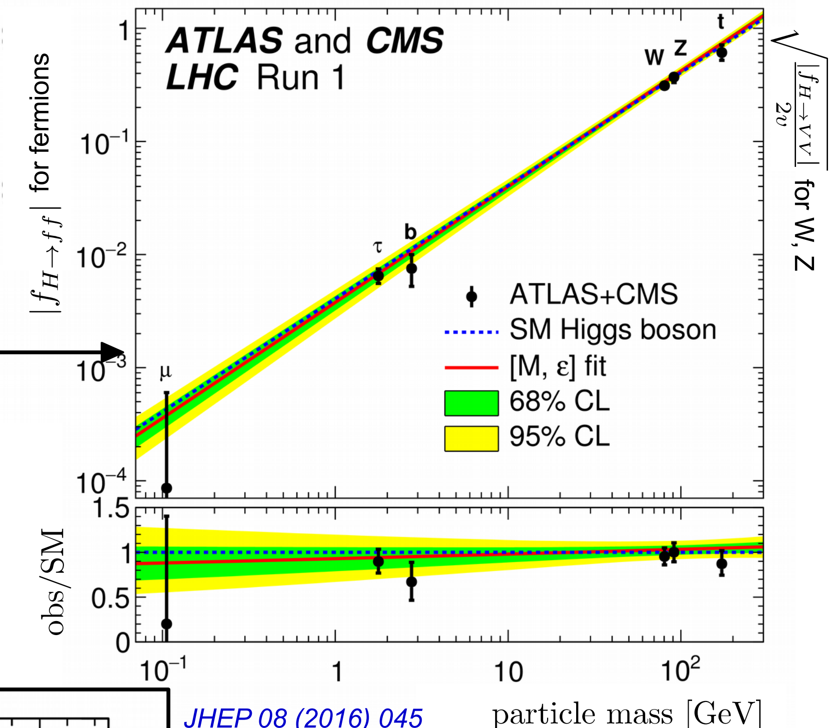




Higgs properties

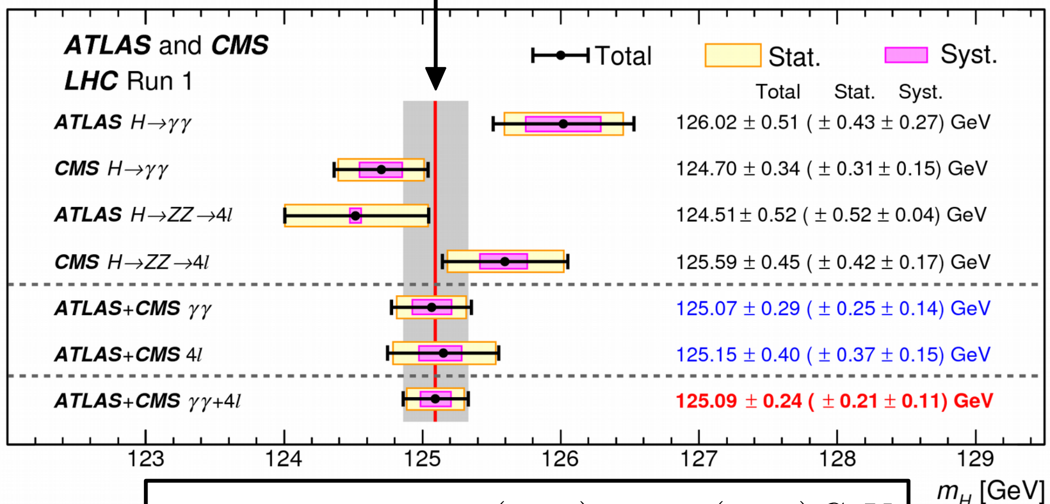
- Scalar particle with high probability (CP-odd admixtures still possible).
- Particle has the coupling structure of a Higgs boson (within 10-20% precision).
- m_H known with rel. precision of $3 \cdot 10^{-4}$ (to be compared with $\Delta m_Z / m_Z = \mathcal{O}(10^{-5})$ from LEP).

Coupling $\propto m_f, m_{W,Z}^2$ (Higgs-like)



JHEP 08 (2016) 045

PRL 114 (2015) 191803



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

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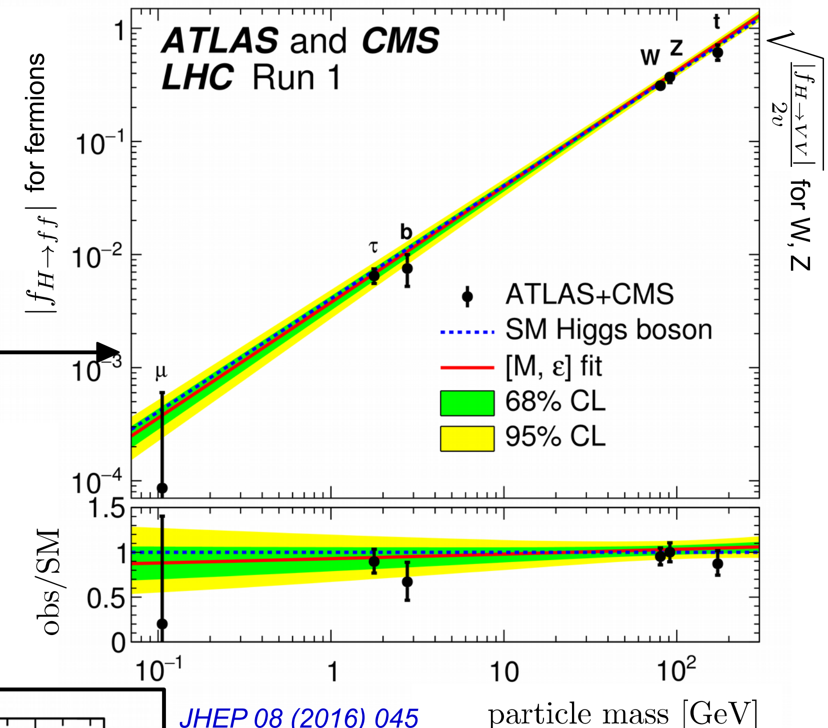

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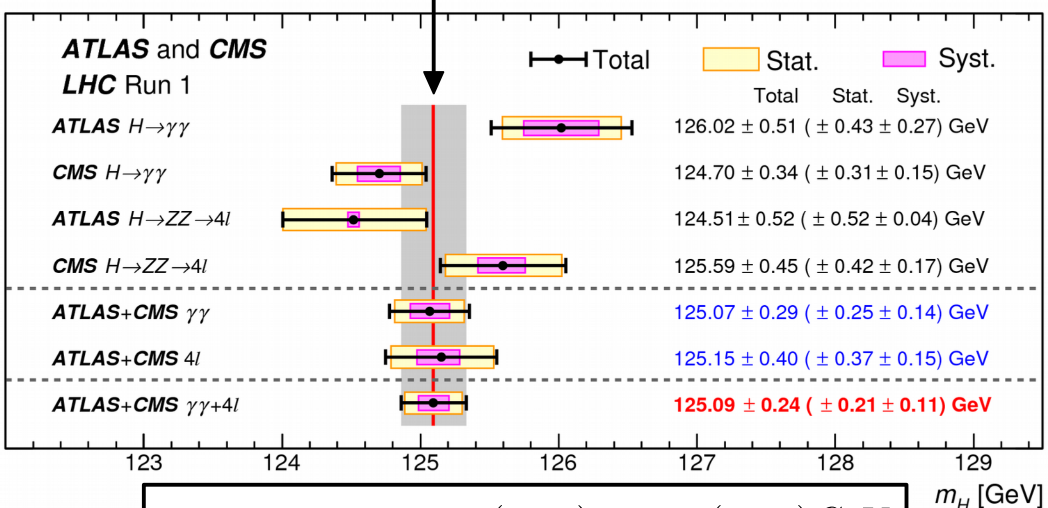


$$m_H = 125.06 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})\ \text{GeV}$$

Results of 3-4 years lasting **rich harvest** of run-1 data.

Higgs as input…

… particle lists of PDG Booklet (v 10/2016):

H^0 $J = 0$

Mass $m = 125.09 \pm 0.24$ GeV
Full width $\Gamma < 1.7$ GeV, CL = 95%

H^0 Signal Strengths in Different Channels

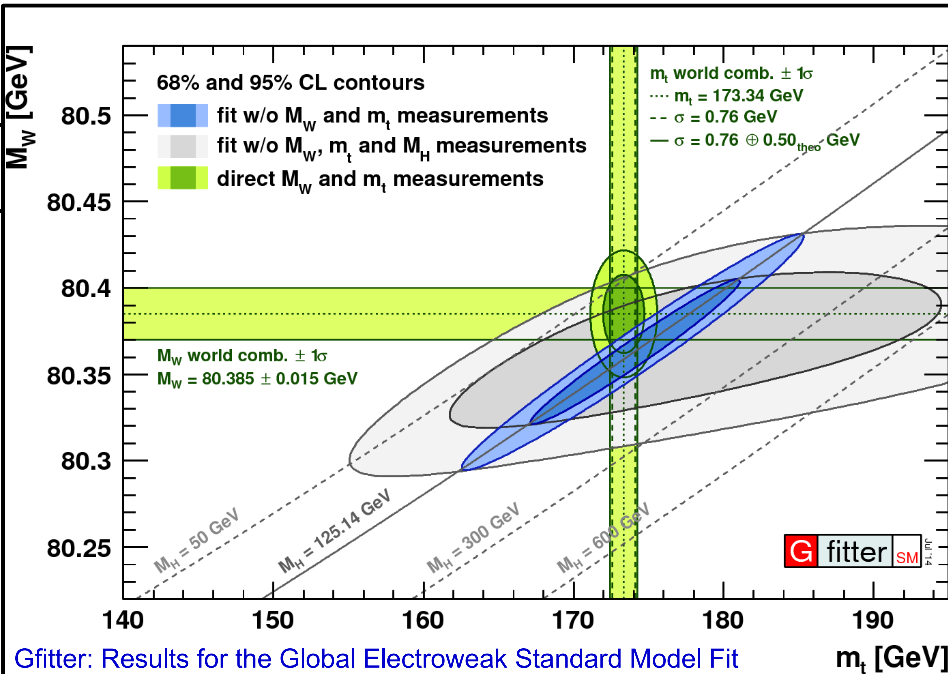
See Listings for the latest unpublished results.

Combined Final States = 1.10 ± 0.11
$WW^* = 1.08^{+0.18}_{-0.16}$
$ZZ^* = 1.29^{+0.26}_{-0.23}$
$\gamma\gamma = 1.16 \pm 0.18$
$b\overline{b} = 0.82 \pm 0.30$ (S = 1.1)
$\mu^+\mu^- < 7.0$, CL = 95%
$\tau^+\tau^- = 1.12 \pm 0.23$
$Z\gamma < 9.5$, CL = 95%
$t\overline{t}H^0$ Production = $2.3^{+0.7}_{-0.6}$

H^0 DECAY MODES	Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
e^+e^-	$< 1.9 \times 10^{-3}$	95%	62545
$J/\psi\gamma$	$< 1.5 \times 10^{-3}$	95%	62507
$\Upsilon(1S)\gamma$	$< 1.3 \times 10^{-3}$	95%	62187
$\Upsilon(2S)\gamma$	$< 1.9 \times 10^{-3}$	95%	62143
$\Upsilon(3S)\gamma$	$< 1.3 \times 10^{-3}$	95%	62116
$\mu\tau$	< 1.51 %	95%	62532
invisible	<58 %	95%	–

C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016)

… in global electroweak fits:



Gfitter: Results for the Global Electroweak Standard Model Fit

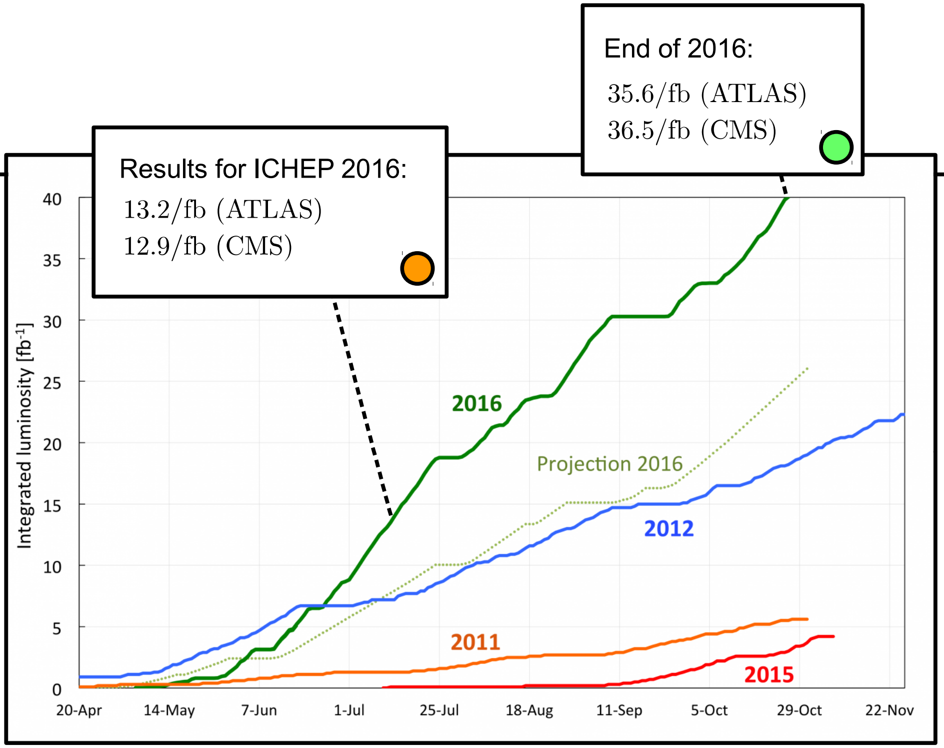
LHC run-1 → run-2

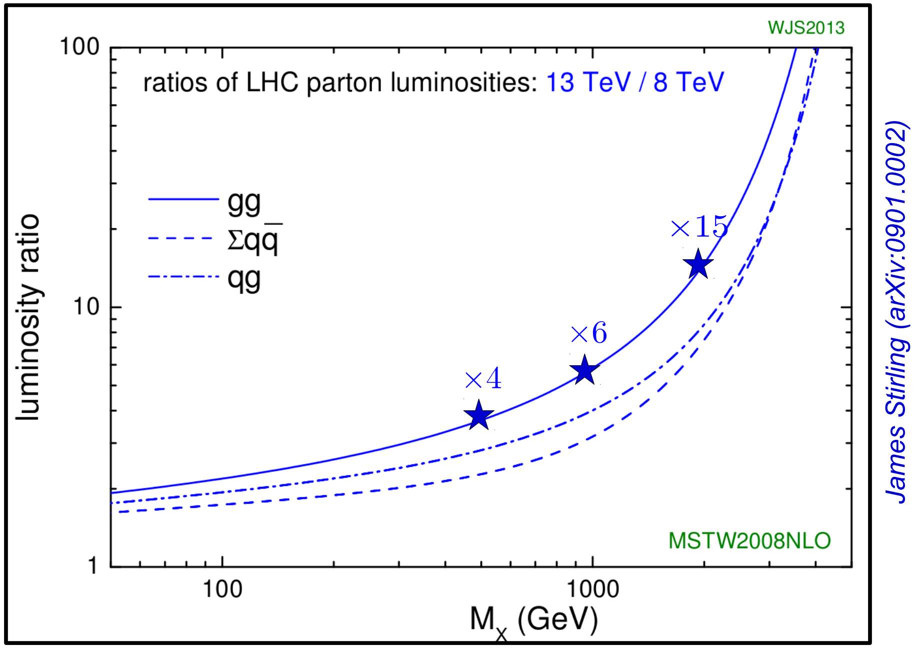
- **By end of 2016:** $\mathcal{L} = 1.4 \times \mathcal{L}_{run\text{-}1}$ + significant increase of parton luminosity depending on probed mass scale (M_X).

- For SM Higgs: see signal to BG gain in the table below

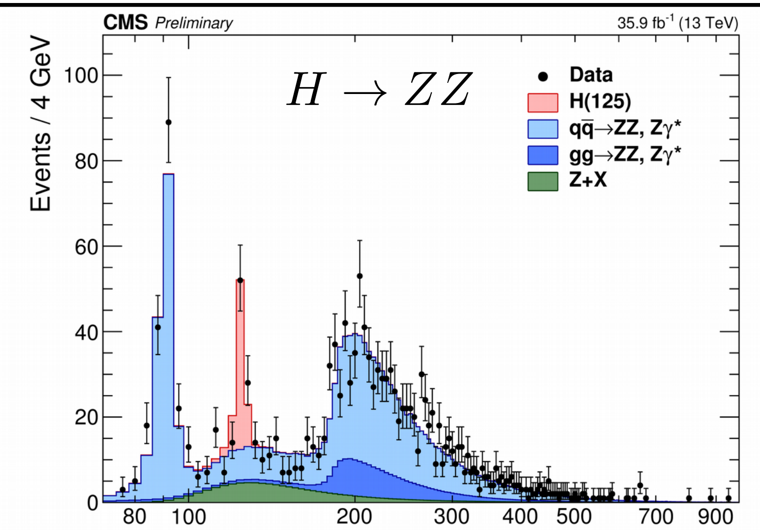
Process (X)	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$	$\Delta_X/\Delta_{h(125)}$
$t\bar{t}$	3.3	1.43
W	1.6	0.70
Z	1.6	0.70
WW	2.0	0.87
$h(125)$	2.3	1.00

- For BSM Higgs: **Golden age for classical searches** at the energy frontier. →

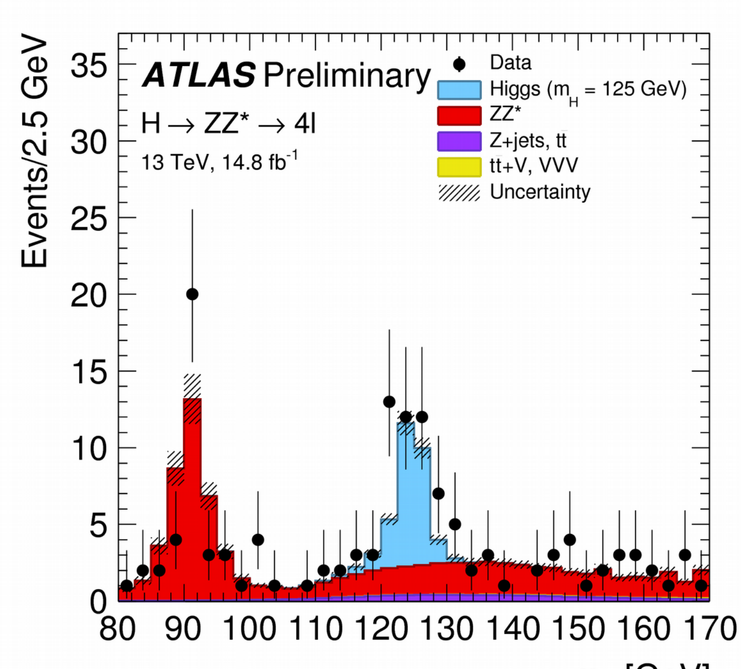




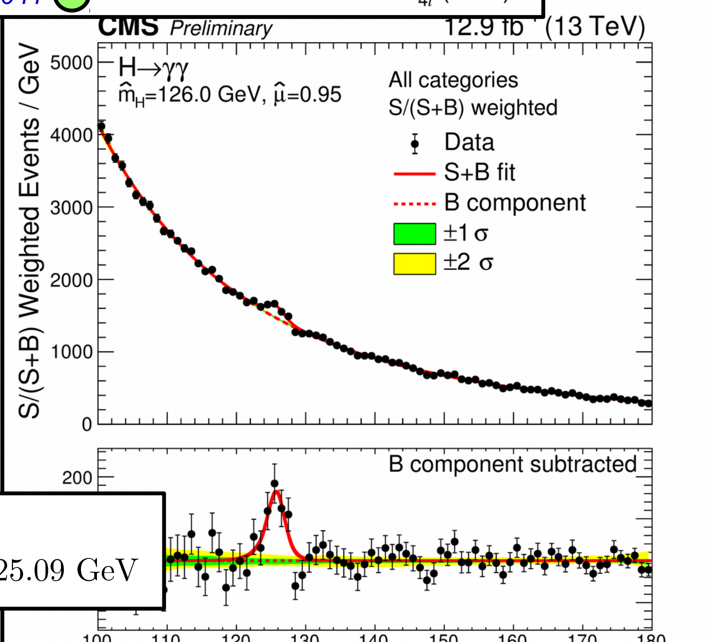
Higgs 2016: still there…



CMS-PAS-HIG-16-041

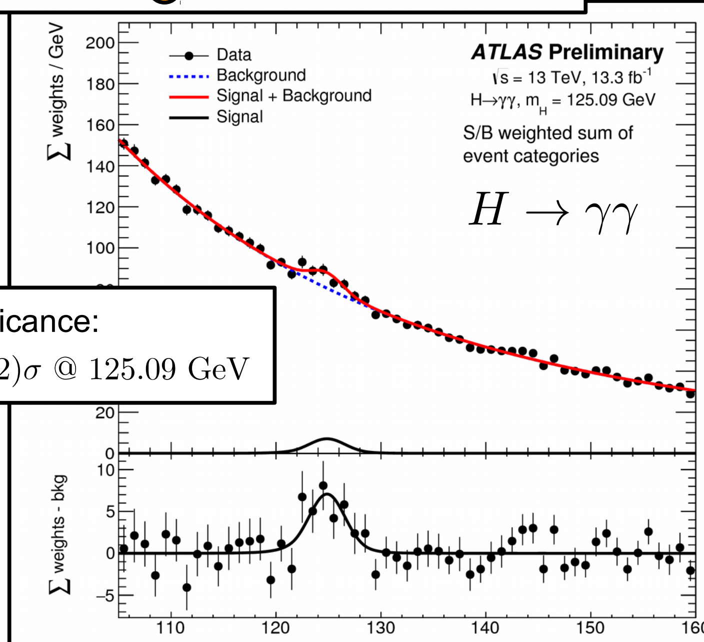


ATLAS-CONF-2016-079



Significance:
$5.6(6.2)\sigma$ @ 125.09 GeV

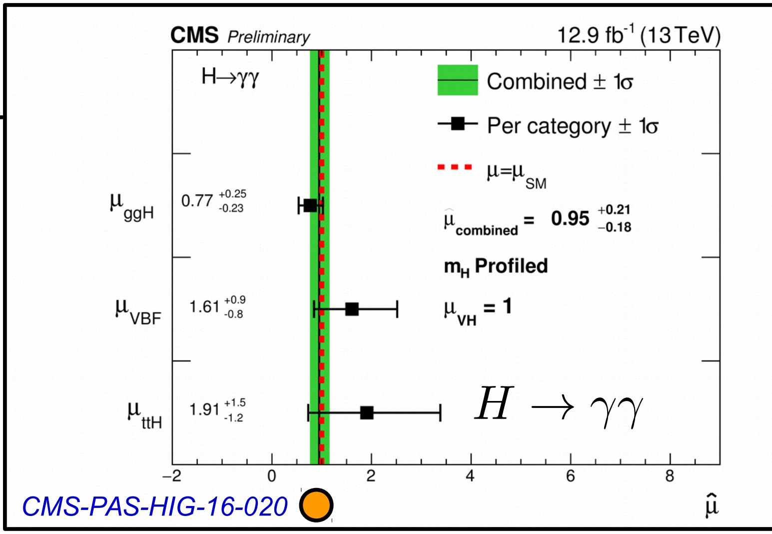
CMS-PAS-HIG-16-020



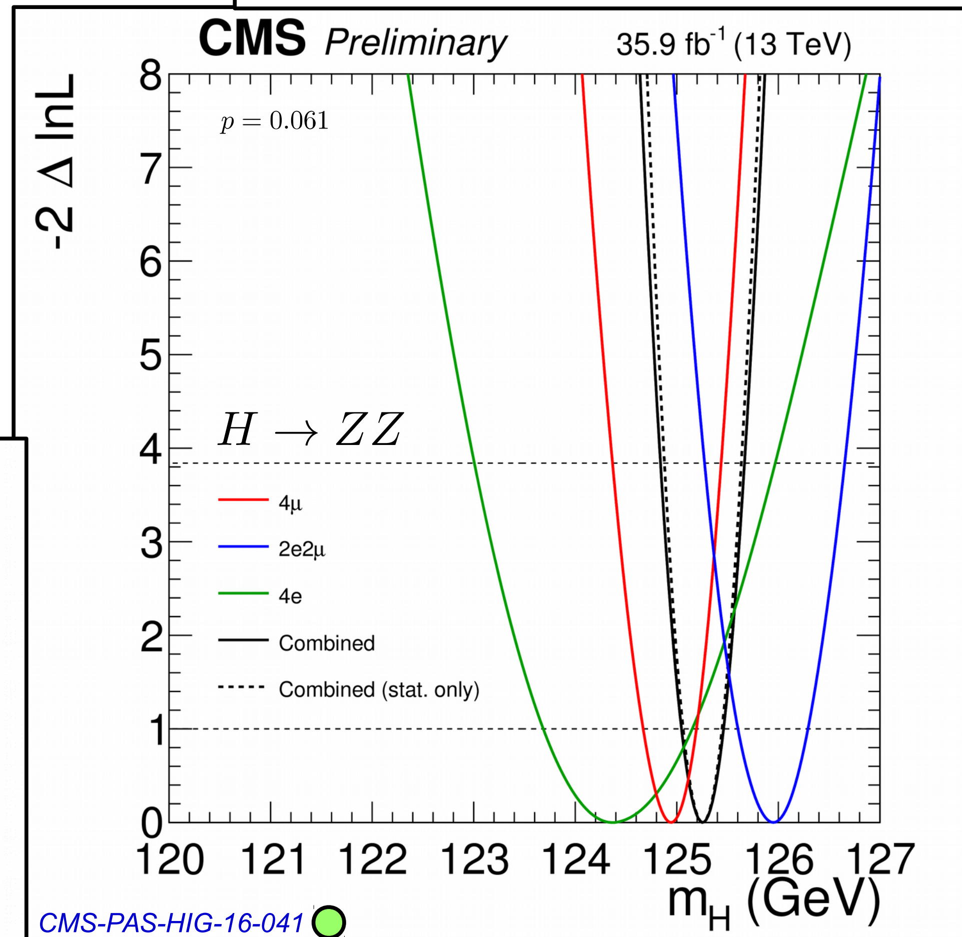
Significance:
$4.7(5.2)\sigma$ @ 125.09 GeV

ATLAS-CONF-2016-067

… and still with same properties

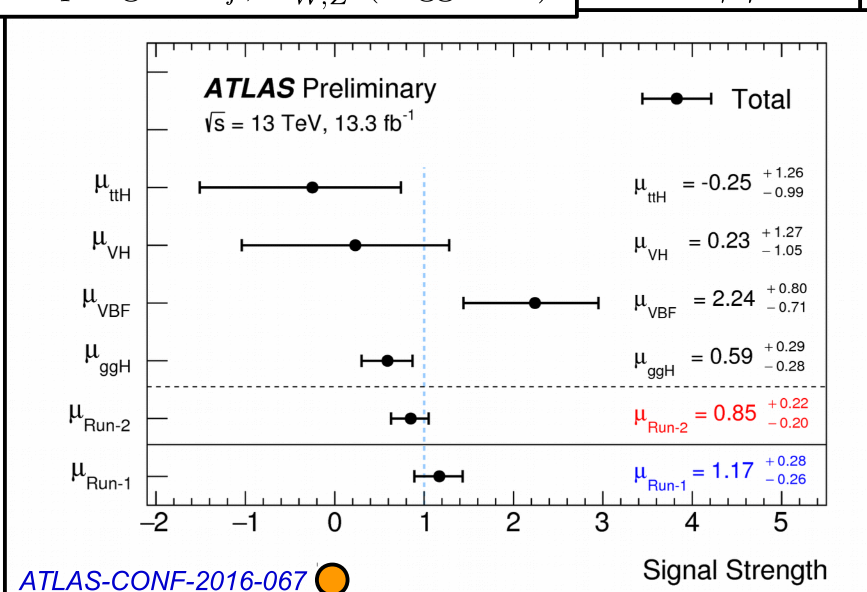


$m_H = 125.26 \pm 0.2\,(\text{stat.}) \pm 0.08\,(\text{syst.})$ GeV



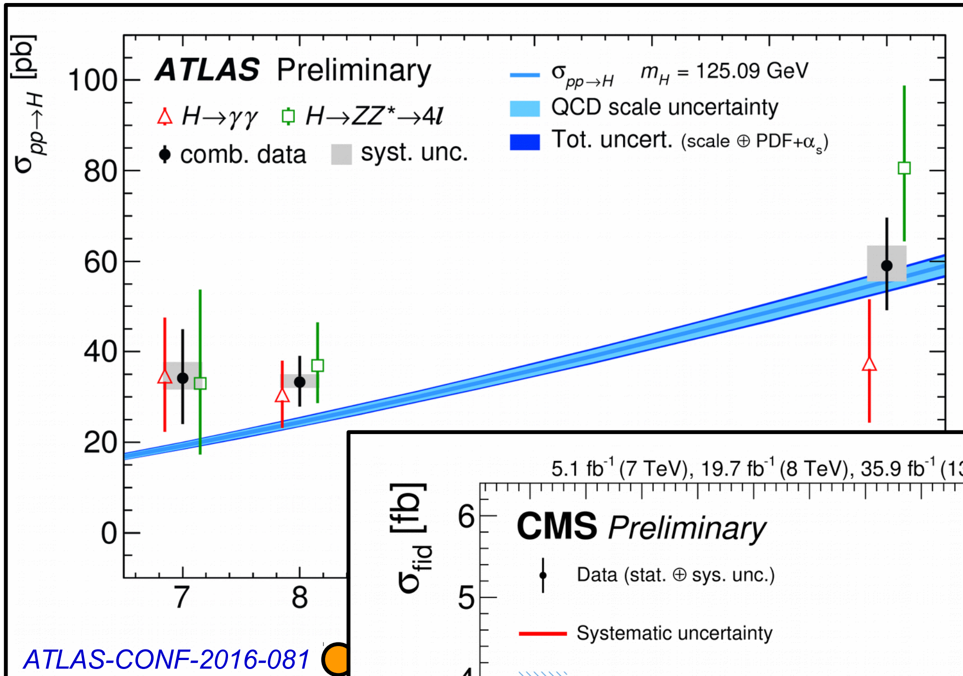
Coupling $\propto m_f, m_{W,Z}^2$ (Higgs-like)

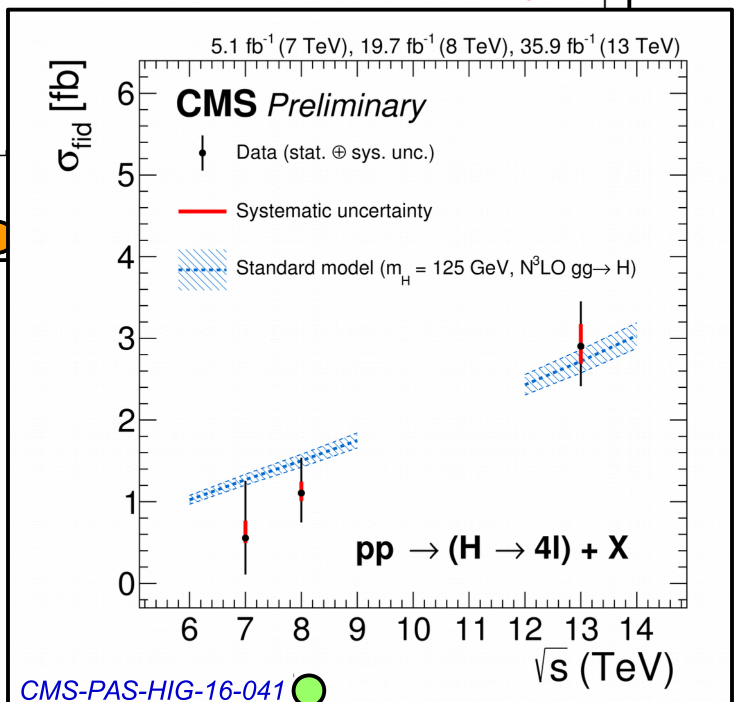
$H \to \gamma\gamma$



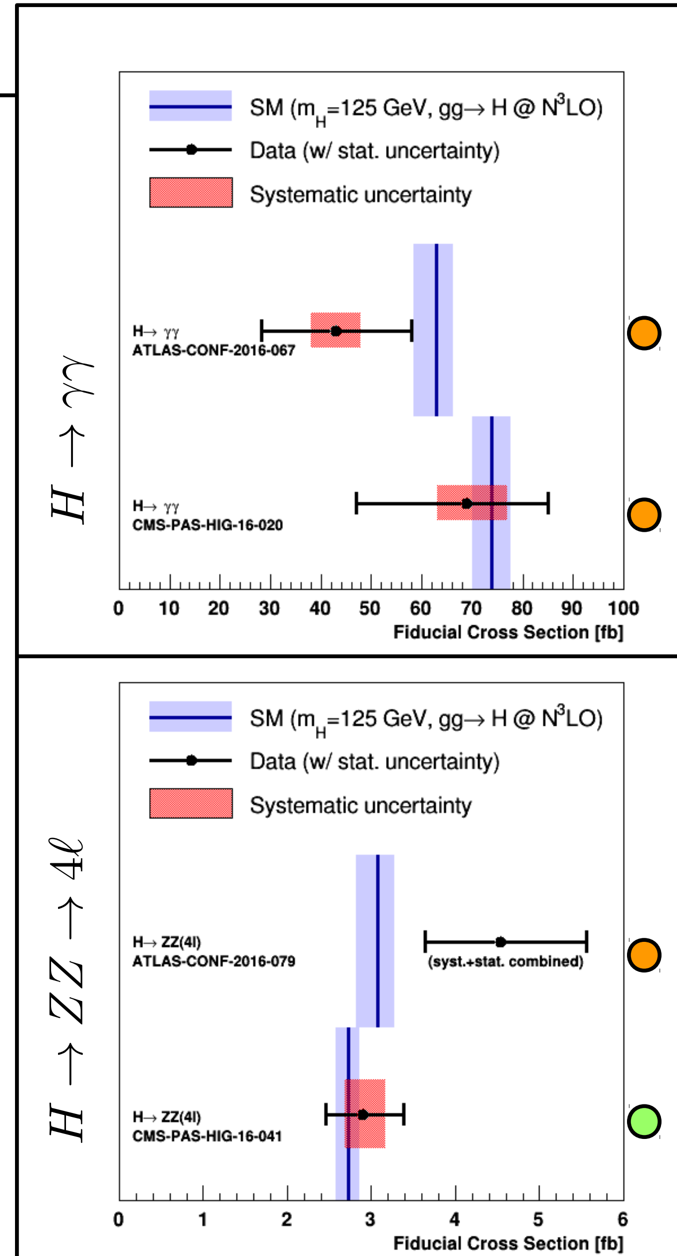
m_H single channel, single experiment already compatible with run-1 ATLAS+CMS combined.

Observation → measurement





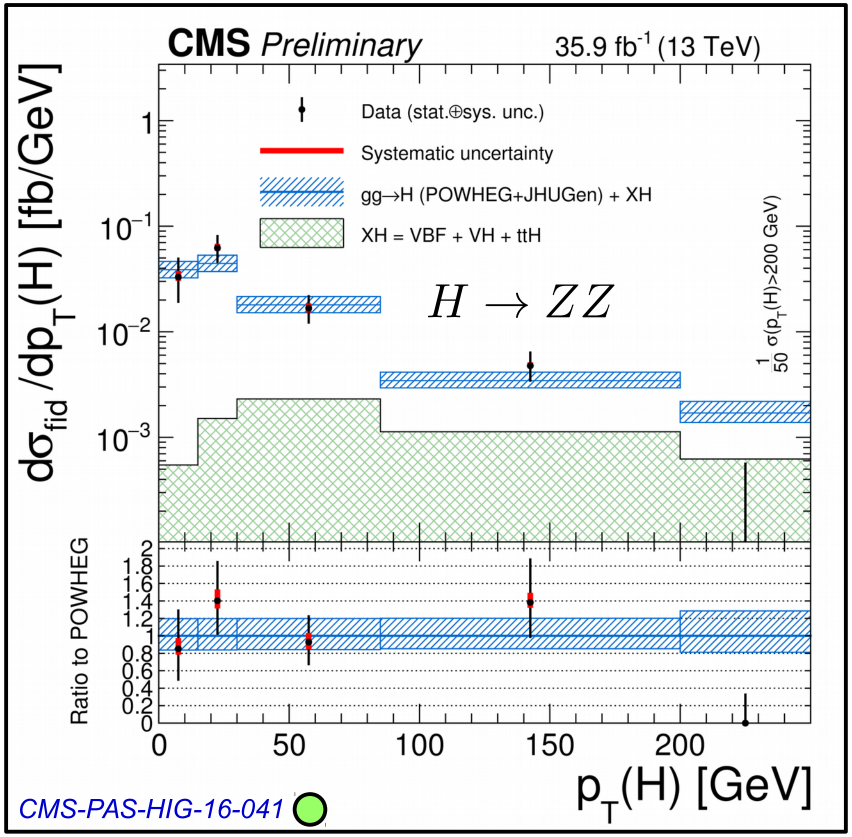
Fiducial cross sections:(*)

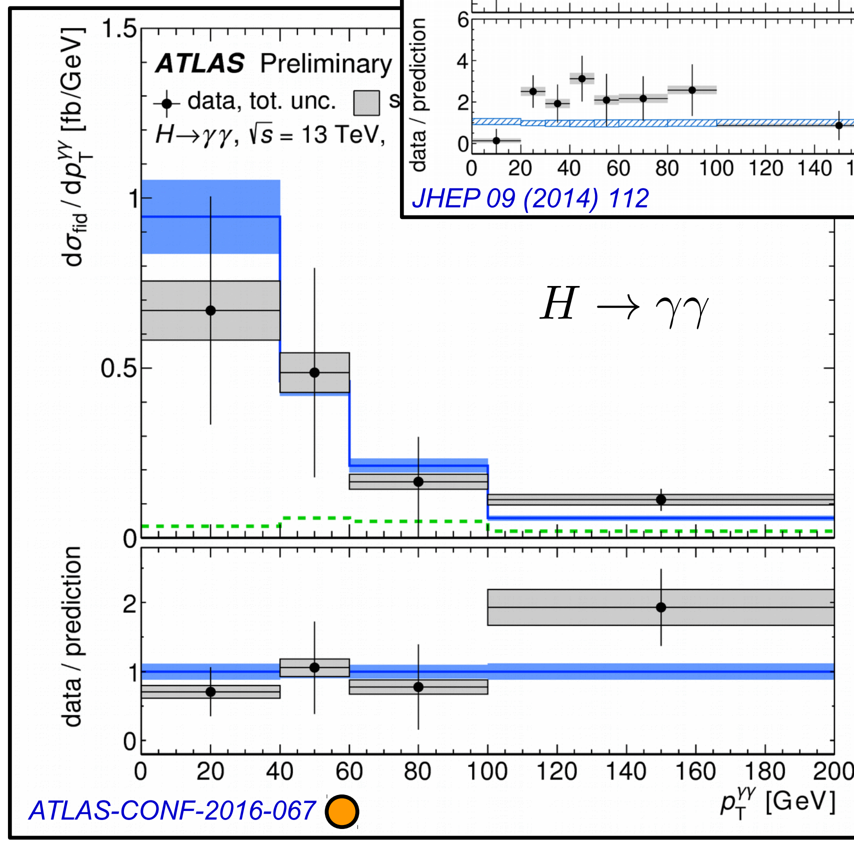


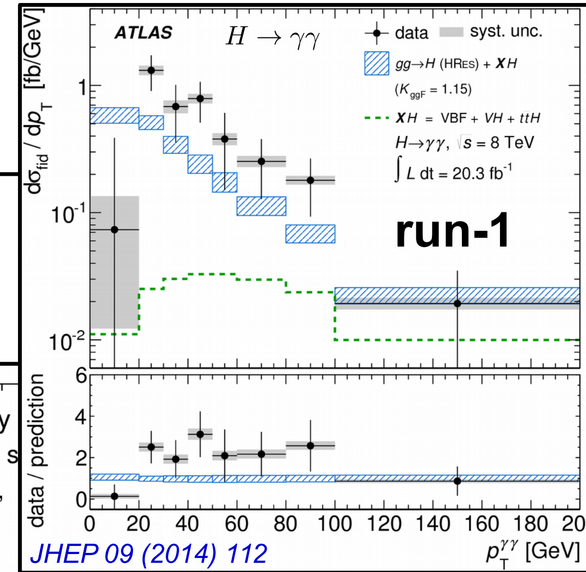
(*) definitions of fiducial volumes in backup.

Differential measurements

- Slight indications for harder spectrum in $p_T(H)$ in run-1.



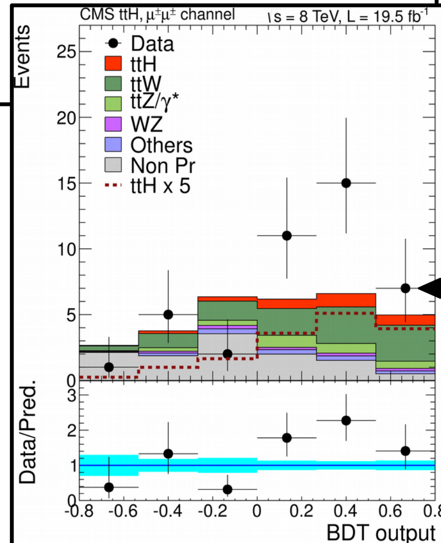


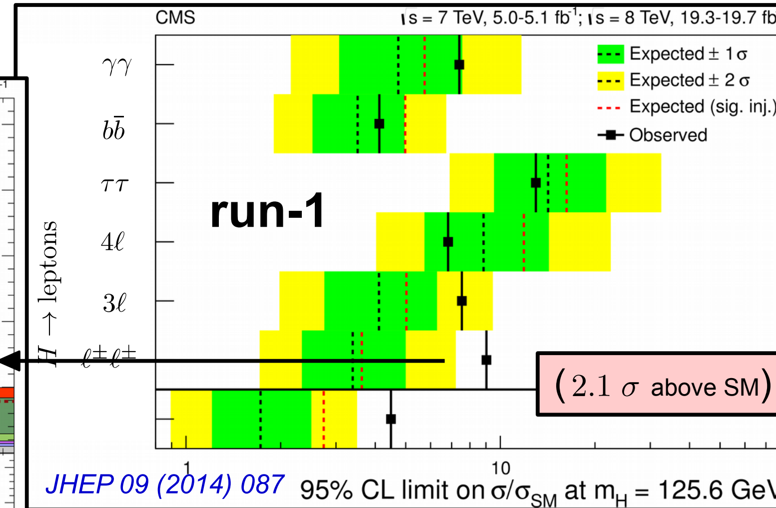


- Run-2 confirms that also differential distributions are well understood within experimental precision.

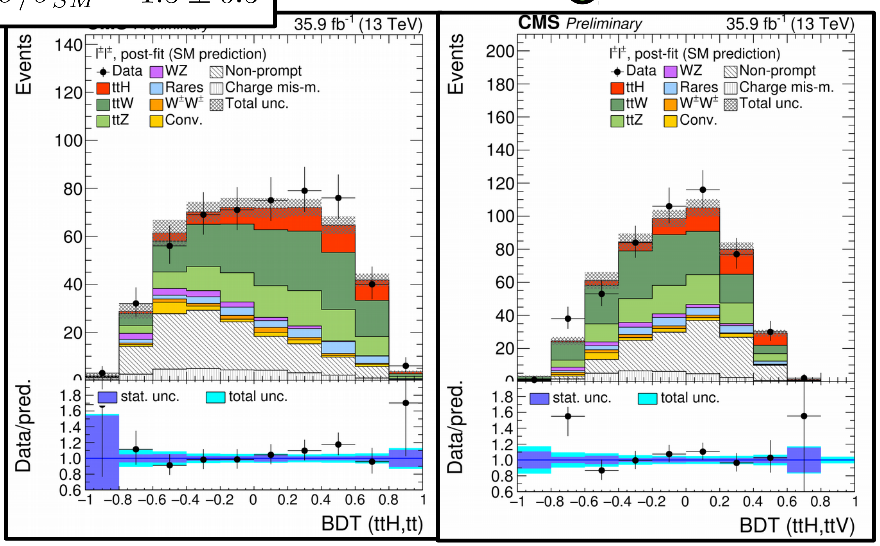
ttH

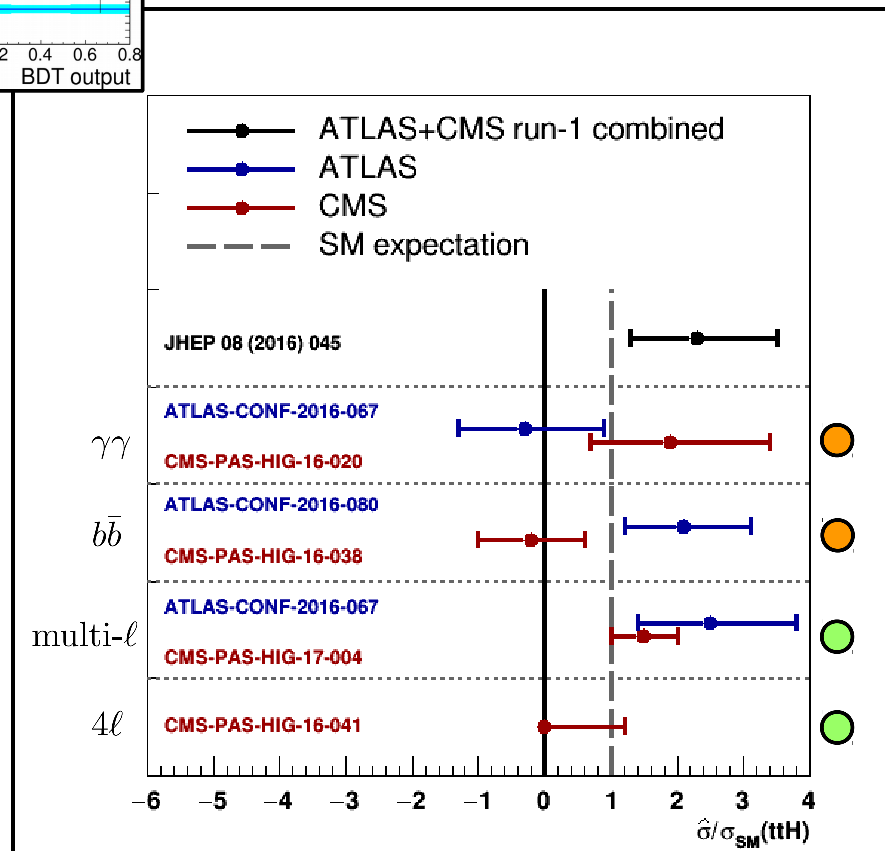
- Indications for slight excess seen in run-1 (both by ATLAS & CMS).
- Excess was most prominent in same-sign leptons.





$\hat{\sigma}/\sigma_{SM} = 1.5 \pm 0.5$ CMS-PAS-HIG-17-004





- Run-2 observations follow SM expectation.

- SM-like Higgs boson with $m_H = 125\ \mathrm{GeV}$established within experimental accuracy.
- Any extension of the SM should contain such a Higgs boson.

Extensions of the Higgs sector

Additional $SU(2)_L$ singlet(s).

Additional $SU(2)_L$ doublet(s).

Additional $SU(2)_L$ triplet(s).

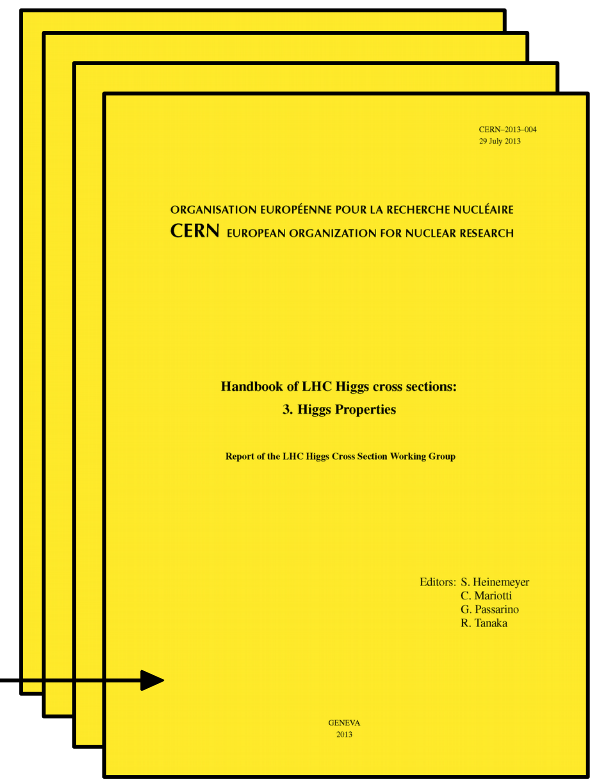
- Just one more Higgs boson.
- Mostly searched for in $WW/ZZ/\gamma\gamma$ final states.

General class of Two Higgs Doublet (2HDM) models.

MSSM

NMSSM
(singlet + doublet)

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



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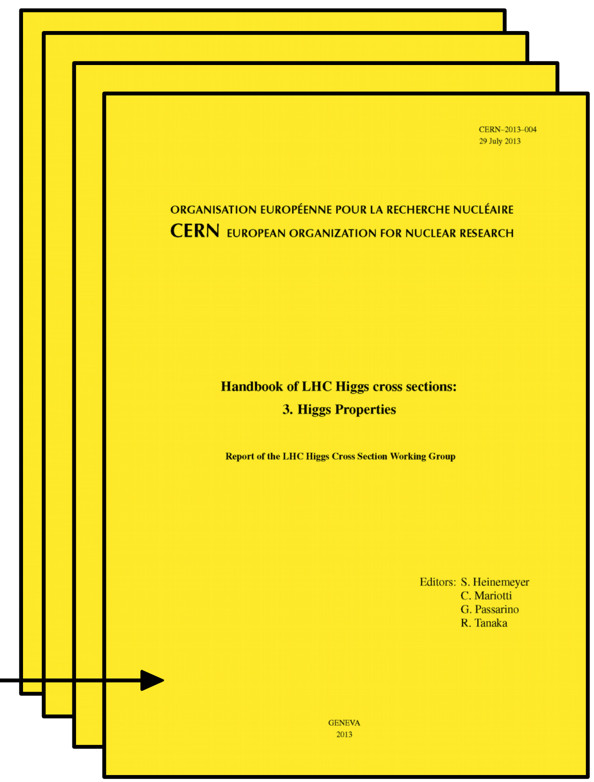
General class of Two Higgs Doublet (2HDM) models.

MSSM

Currently most intensively studied & most coherent set of searches.

NMSSM
(singlet + doublet)



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

Higgs Bosons in the MSSM

- As a 2 Higgs Doublet Model (2HDM) the MSSM predicts five Higgs bosons:

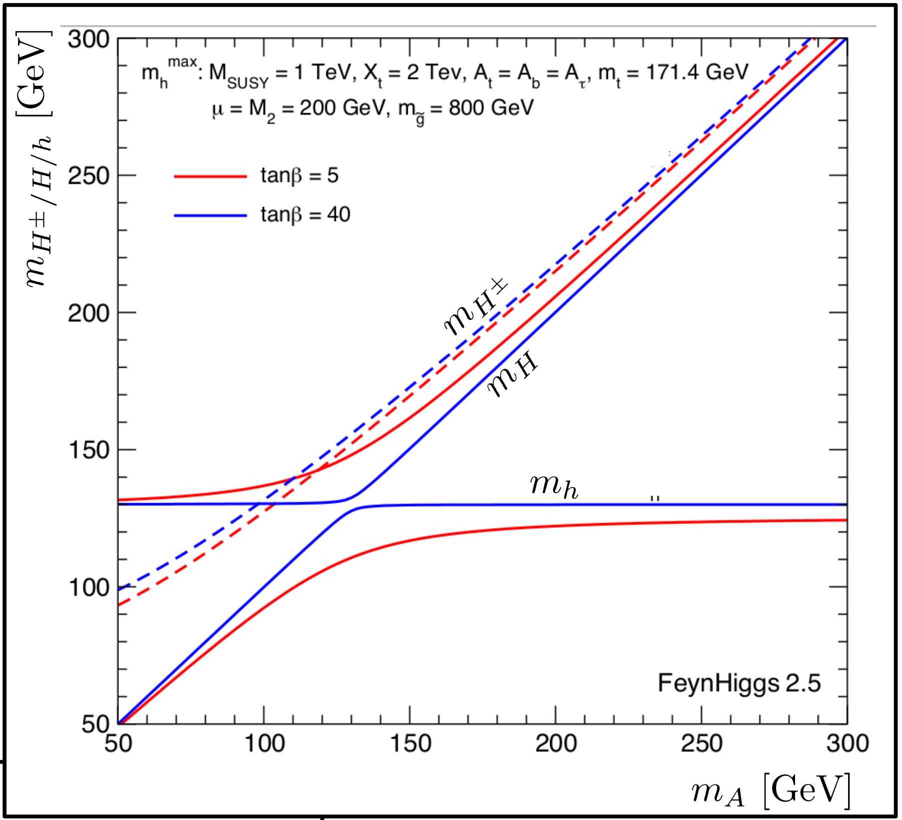
$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}, \quad Y_{\phi_u} = +1, \quad v_u : \ \mathrm{VEV}_u$$

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

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

H, h: CP-even

A: CP-odd



- Strict mass requirements at tree level. Two free parameters: $m_A\,,\ \tan\beta = {}^{v_u}/_{v_d}\,.$

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

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

$$\tan\alpha^{(1)} = \frac{-(m_A^2+m_Z^2)\sin 2\beta}{(m_Z^2-m_A^2)\cos 2\beta + \sqrt{\left(m_A^2+m_Z^2\right)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}}$$

→ Determines couplings @ LO.

(1) angle btw. v_u & v_d in isospace.

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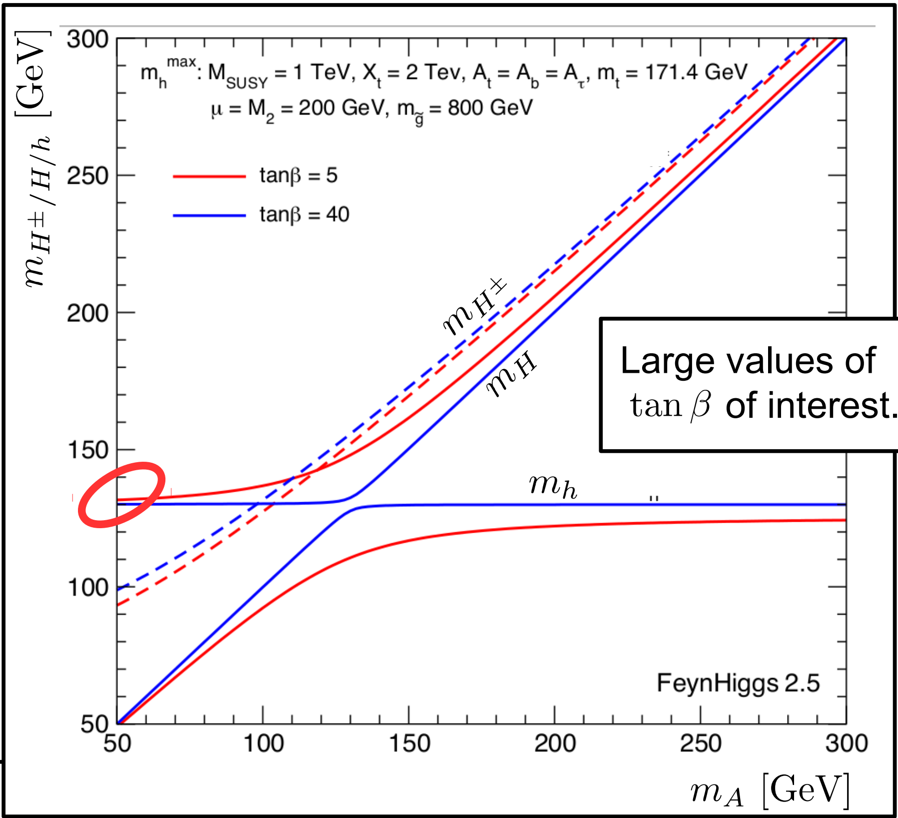
CP-even

CP-odd (A)



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

- Strict mass requirements at tree level. Two free parameters: m_A, $\tan\beta = {}^{v_u}/_{v_d}$.

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

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

$$\tan\alpha^{(1)} = \frac{-(m^2_A + m^2_Z)\sin 2\beta}{(m^2_Z - m^2_A)\cos 2\beta + \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_A m^2_Z \cos^2 2\beta}}$$

→ Determines couplings @ LO.

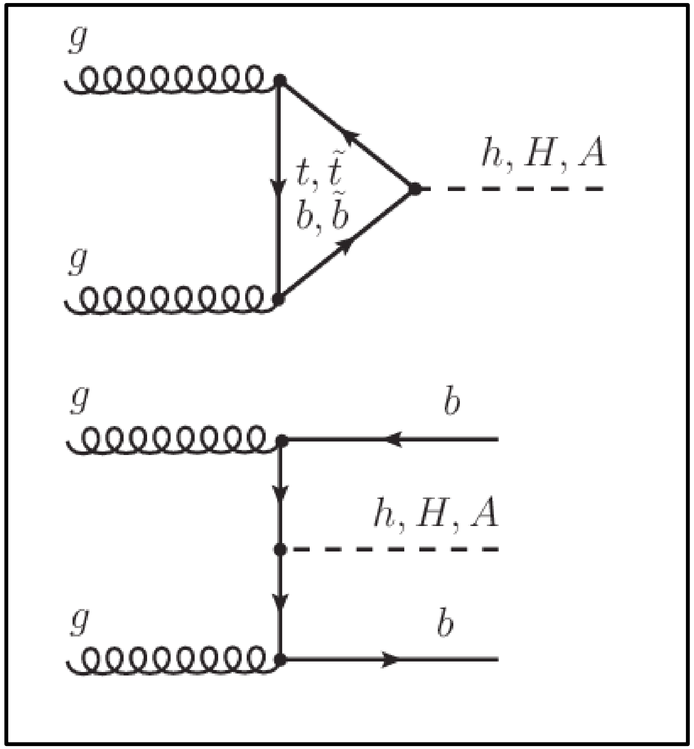
(1) angle btw. v_u & v_d in isospace.

The role of down-type fermions in the MSSM

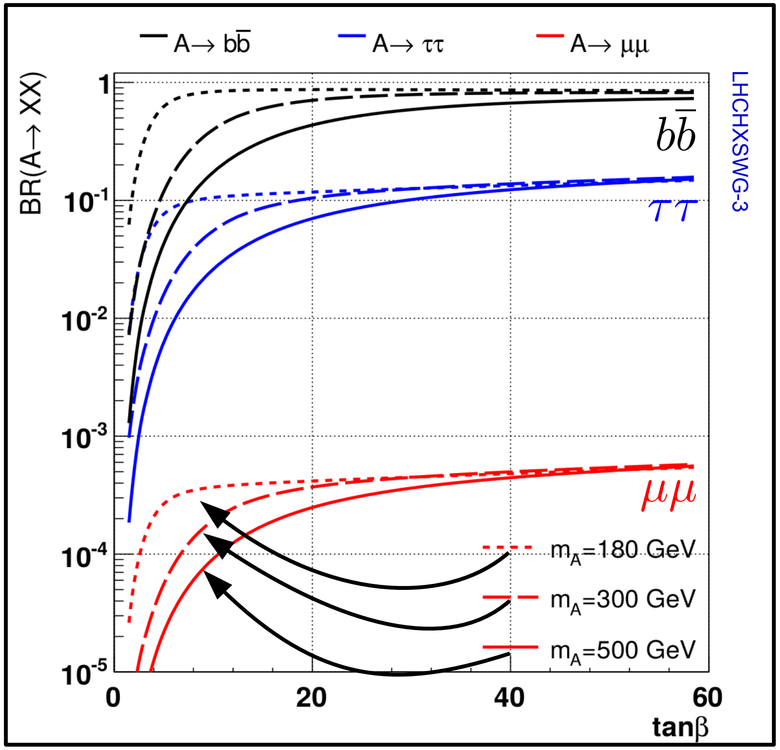
	g_{VV}/g_{VV}^{SM}	g_{dd}/g_{dd}^{SM}	g_{uu}/g_{uu}^{SM}
A	$-$	$\gamma_5 \tan\beta$	$\gamma_5 / \tan\beta$
H	$\cos(\beta-\alpha) \;\to 0$	$\cos\alpha/\cos\beta \to \tan\beta$	$\sin\alpha/\sin\beta \;\to 1/\tan\beta$
h	$\sin(\beta-\alpha) \;\to 1$	$-\sin\alpha/\cos\beta \to \;1$	$\cos\alpha/\sin\beta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

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

Interesting production modes:

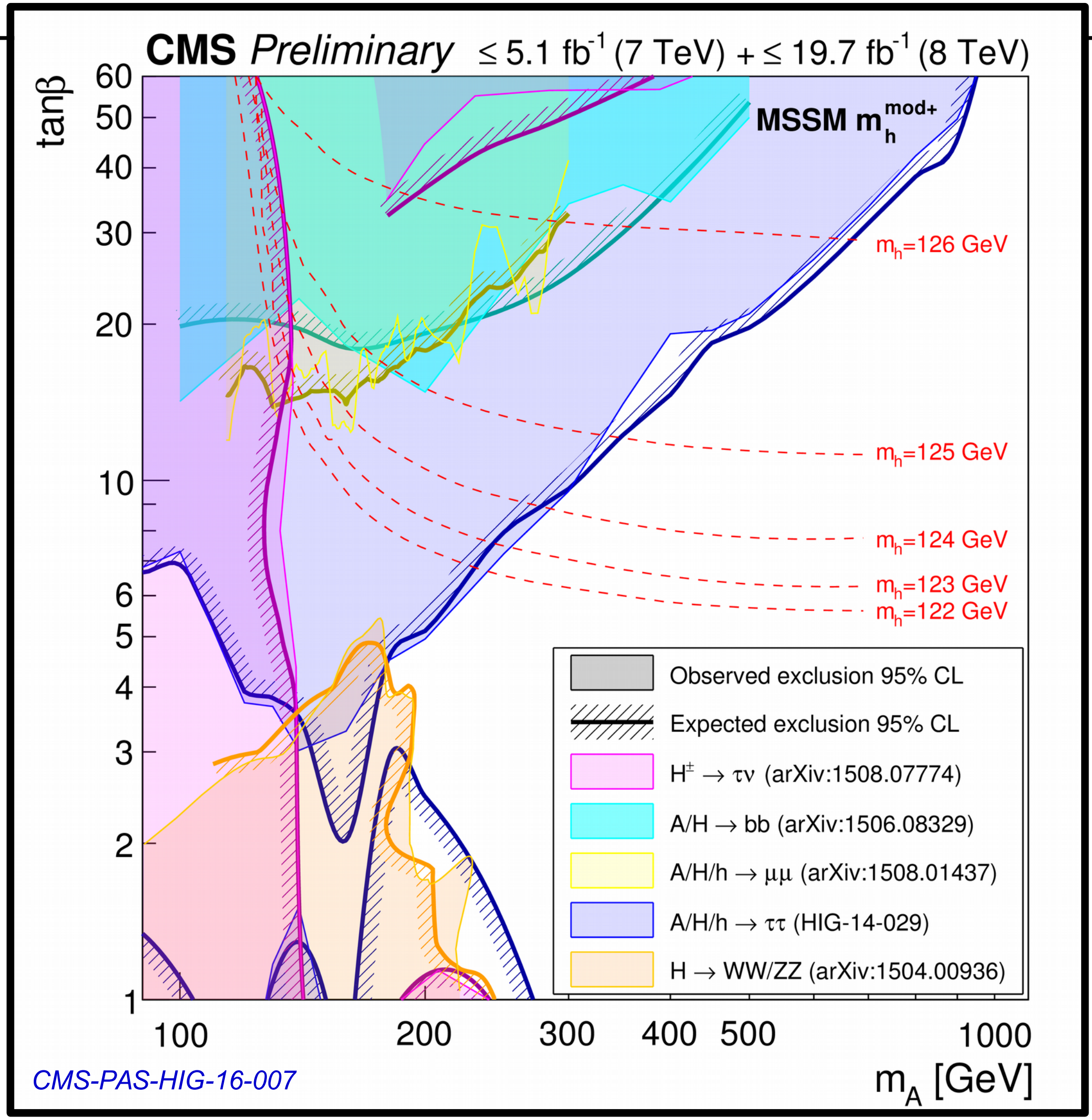


Interesting decay channels:



Upshot of run-1:

- $m_A \lesssim 200$ GeV excluded across whole $\tan\beta$ range.
- $m_A \lesssim 160$ GeV excluded by non-observation of “low mass” $H^{\pm}$.
- $A/H/h \to \tau\tau$ most sensitive channel for high m_A high $\tan\beta$.
- For low $\tan\beta$ vector boson channels gain importance.



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

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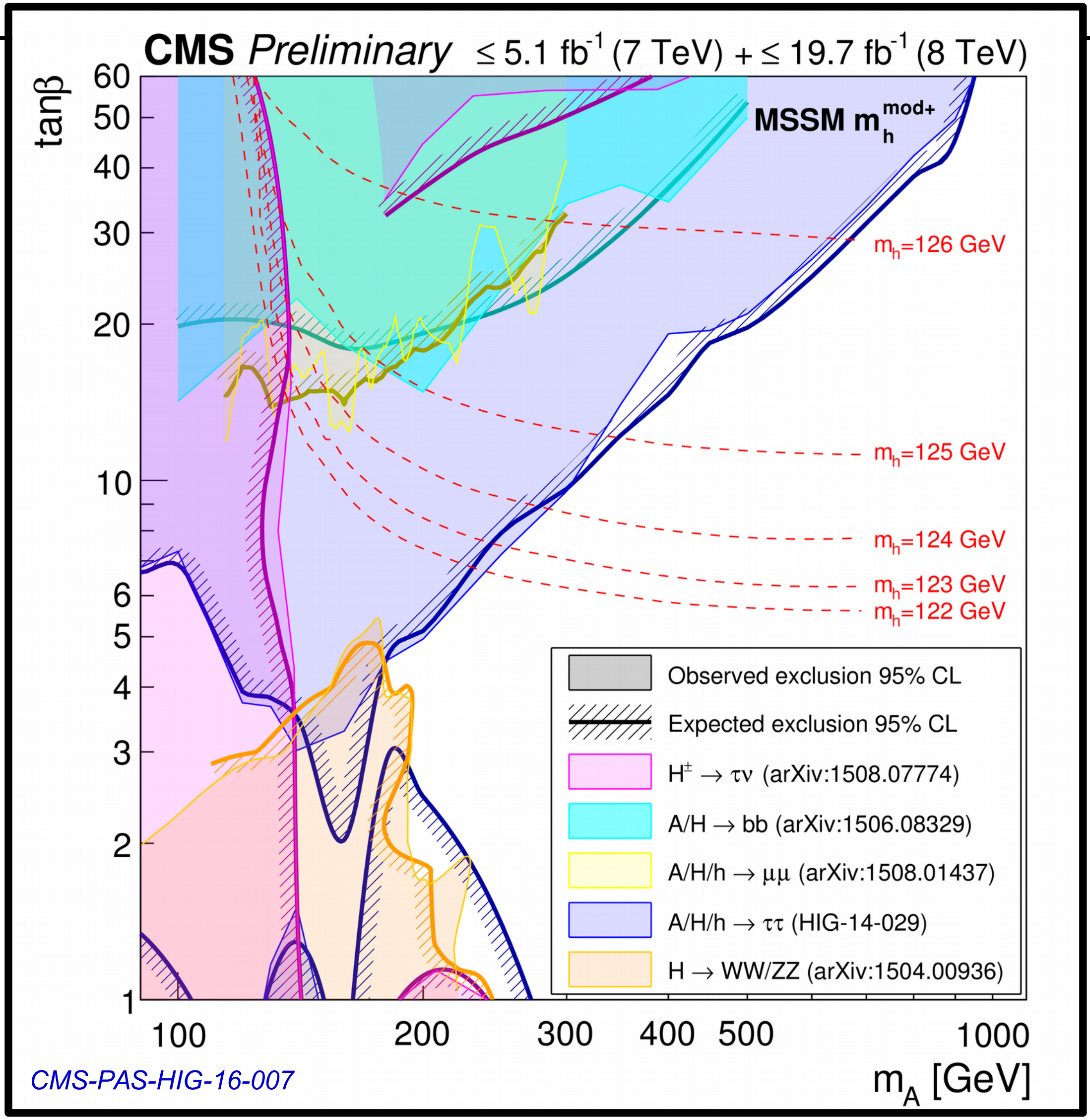
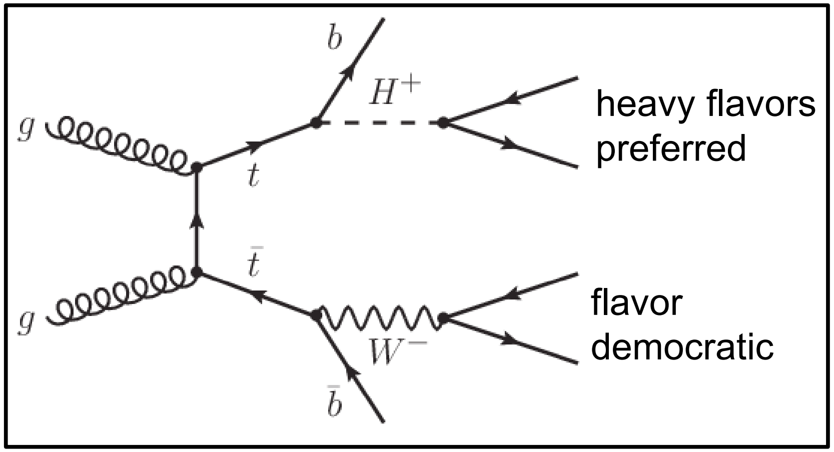


Similar results from ATLAS (only not in single plot).

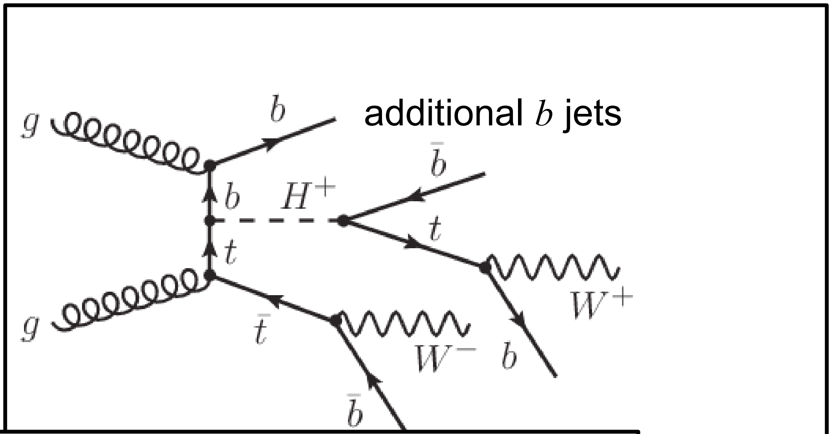
Charged Higgs

- Expect signal in top sector…

… in decay ($m_{H^+} < m_t$):



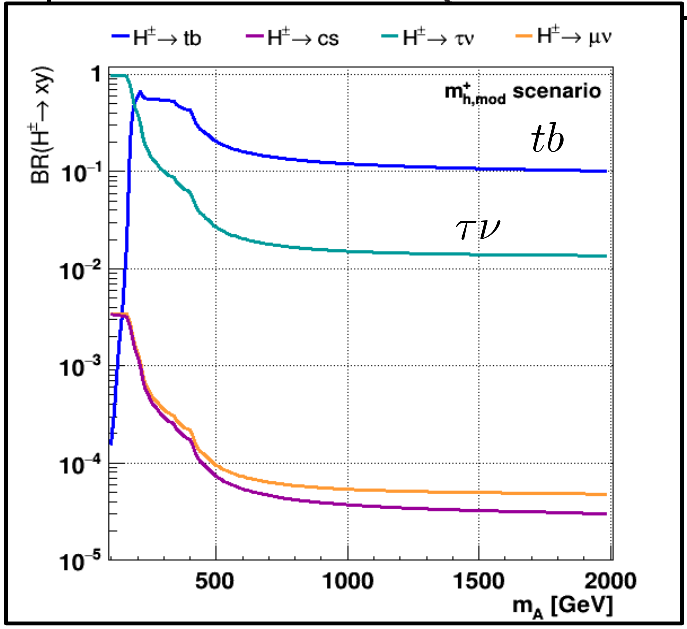
… in production ($m_t < m_{H^+}$):



- Covered channels:

channel	publication (run-2)
$\tau\nu$	ATLAS-CONF-2016-088 CMS-PAS-HIG-16-031
tb	ATLAS-CONF-2016-089
cs	run-1 only
WZ	CMS-PAS-HIG-16-027 (*)

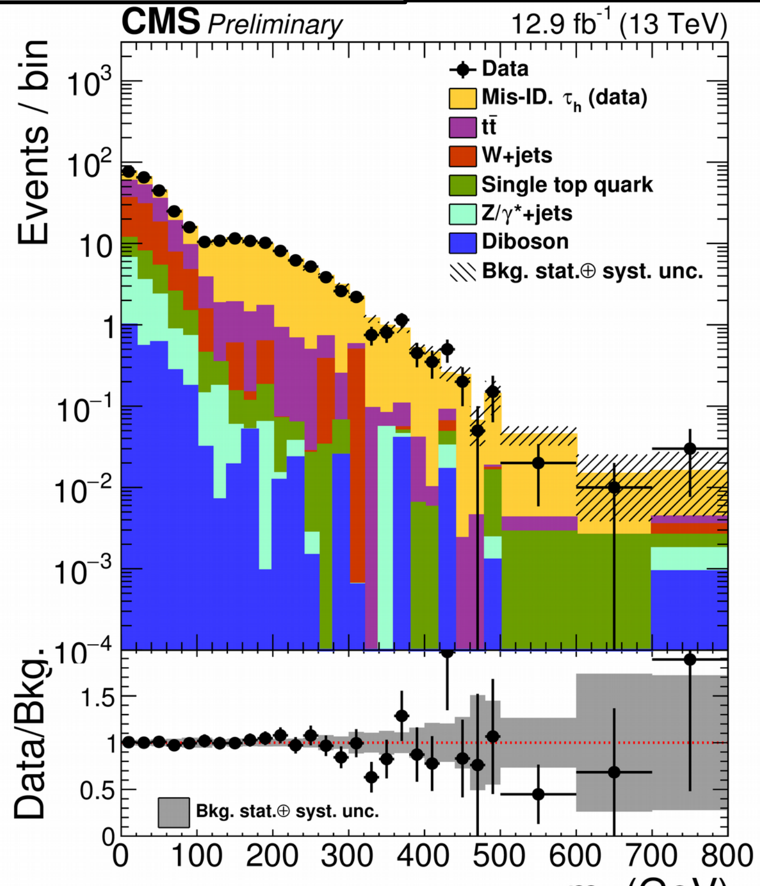
(*) in non-MSSM interpretations



$H^+ \to \tau\nu$

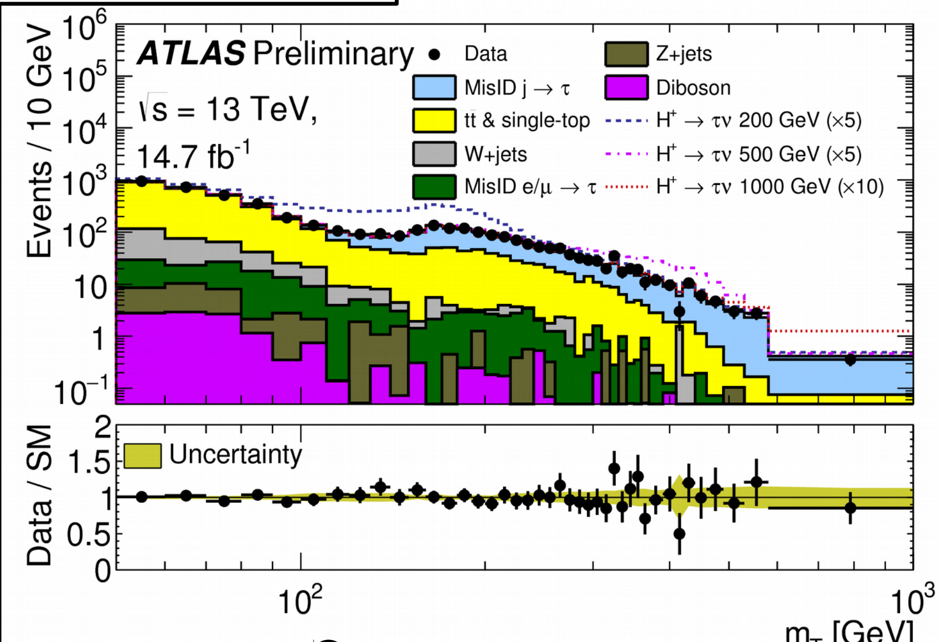
- Usually restrict to τ_h (1-prong), use $m_T(\tau_h, MET)$ as discriminating variable.

Low & high mass search



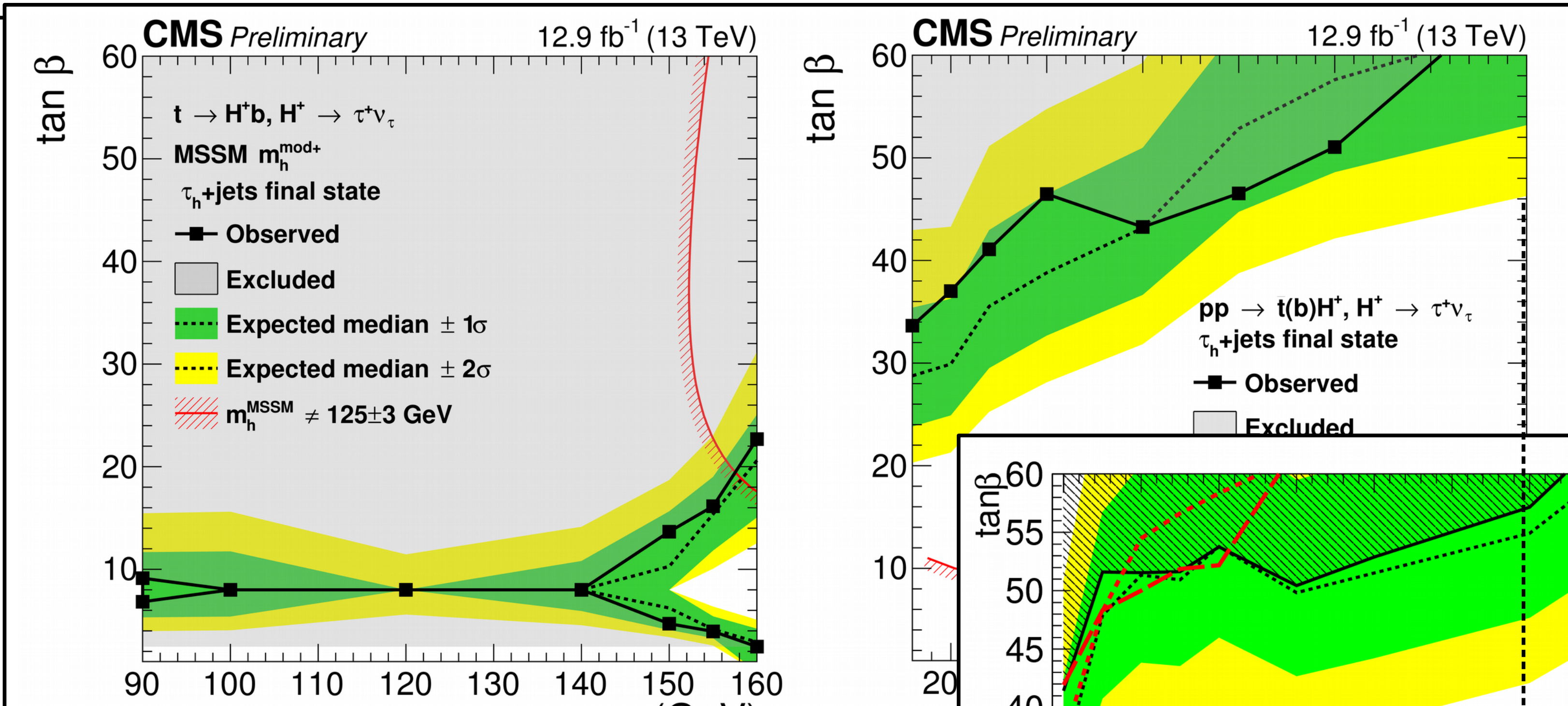
CMS-PAS-16-031

High mass search only

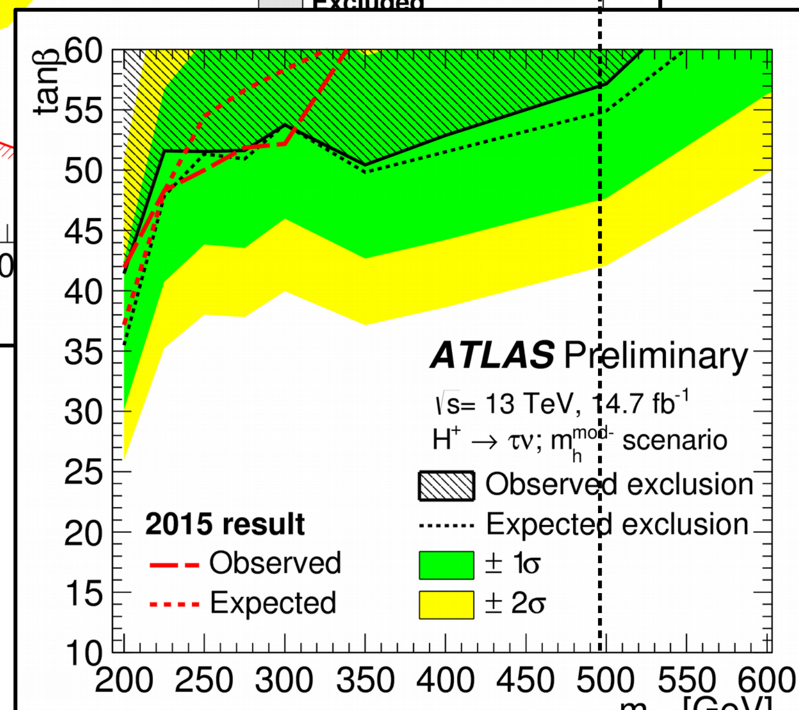


ATLAS-CONF-2016-088

Exclusion



CMS-PAS-HIG-16-031

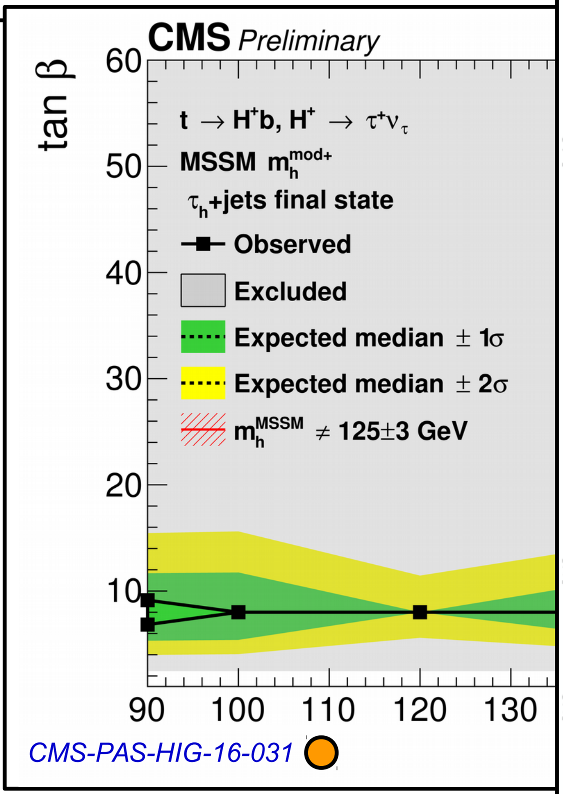


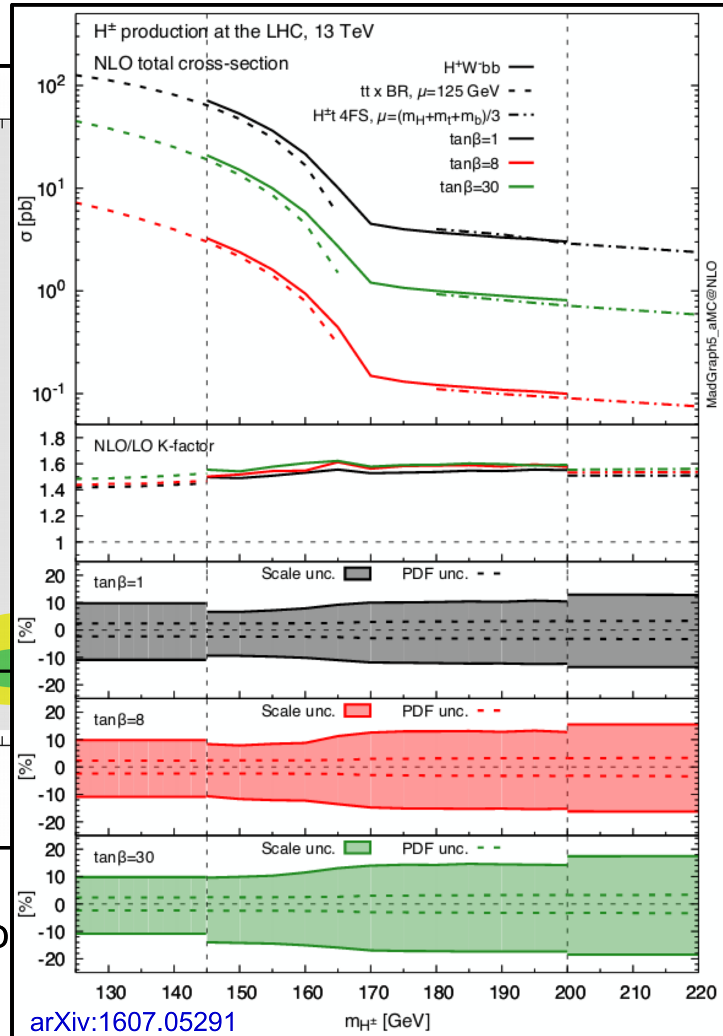
ATLAS-CONF-2016-088

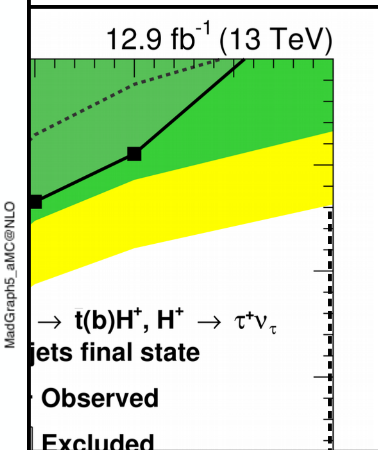
- Chapter of low mass region already closed by LHC run-1 results.
- Serious exploitation of high mass region only **about to start now!**

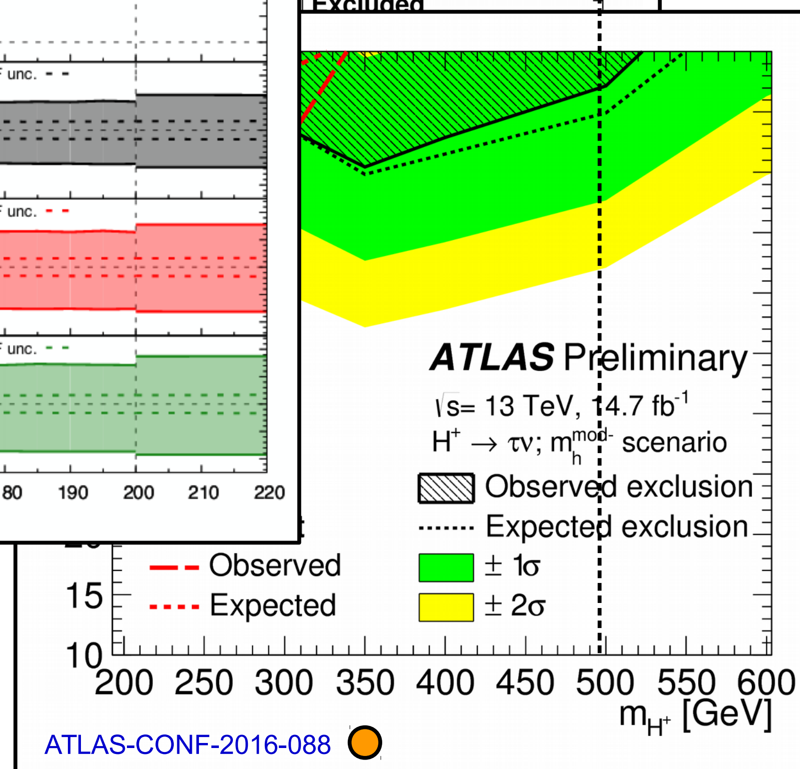
Exclusion

Intermediate mass region now accessible.



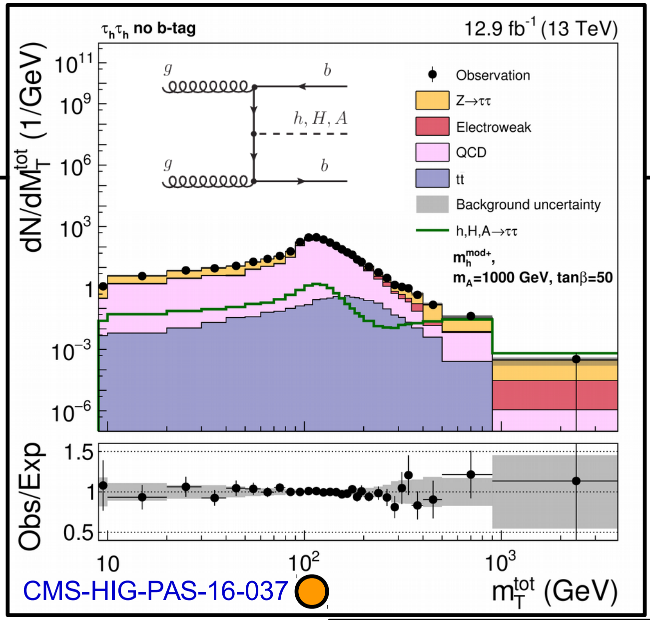


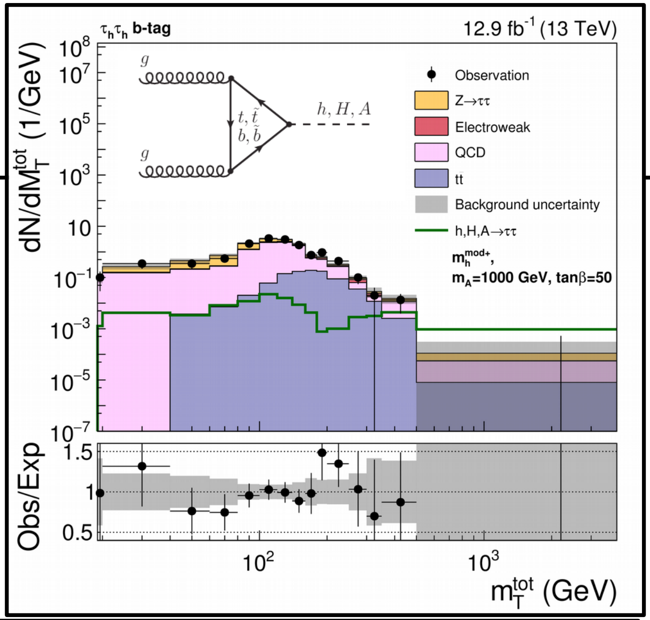




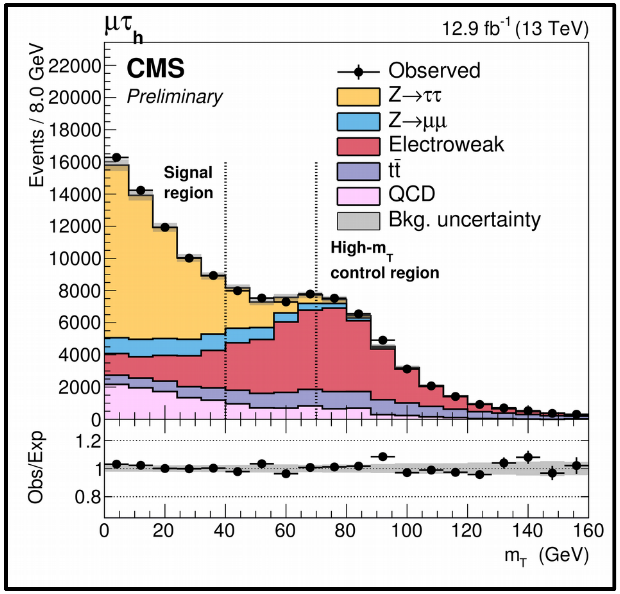
- Chapter of low mass regio[n] LHC run-1 results.
- Serious exploitation of high mass region only **about to start now!**

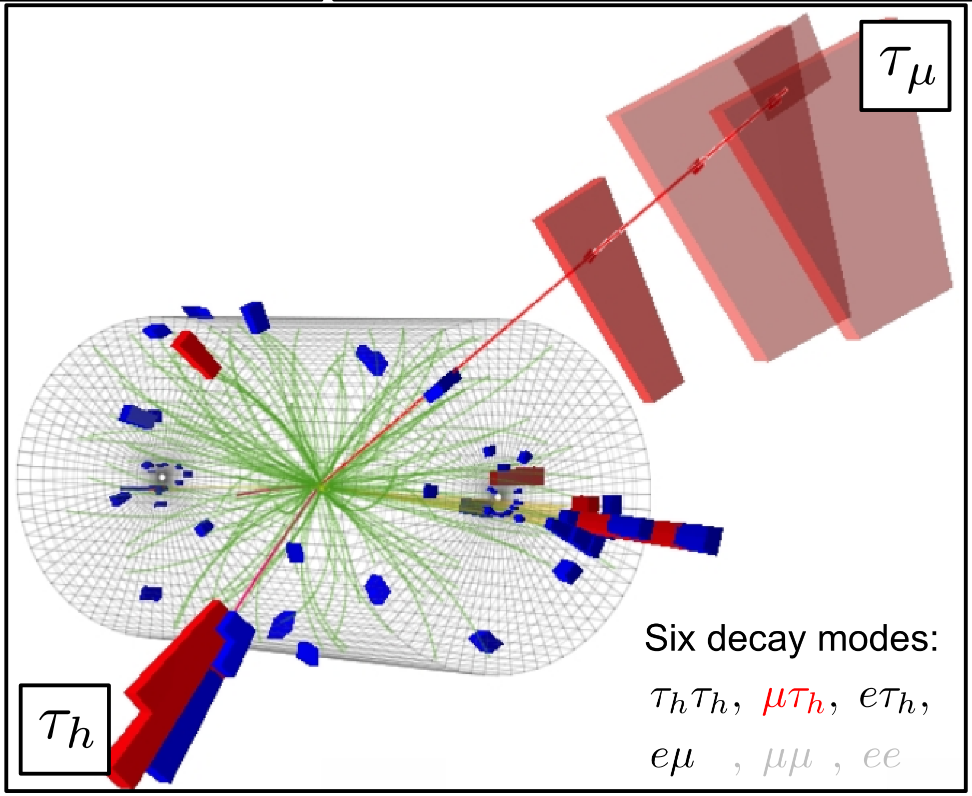
BSM $A/H/h \to \tau\tau$





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

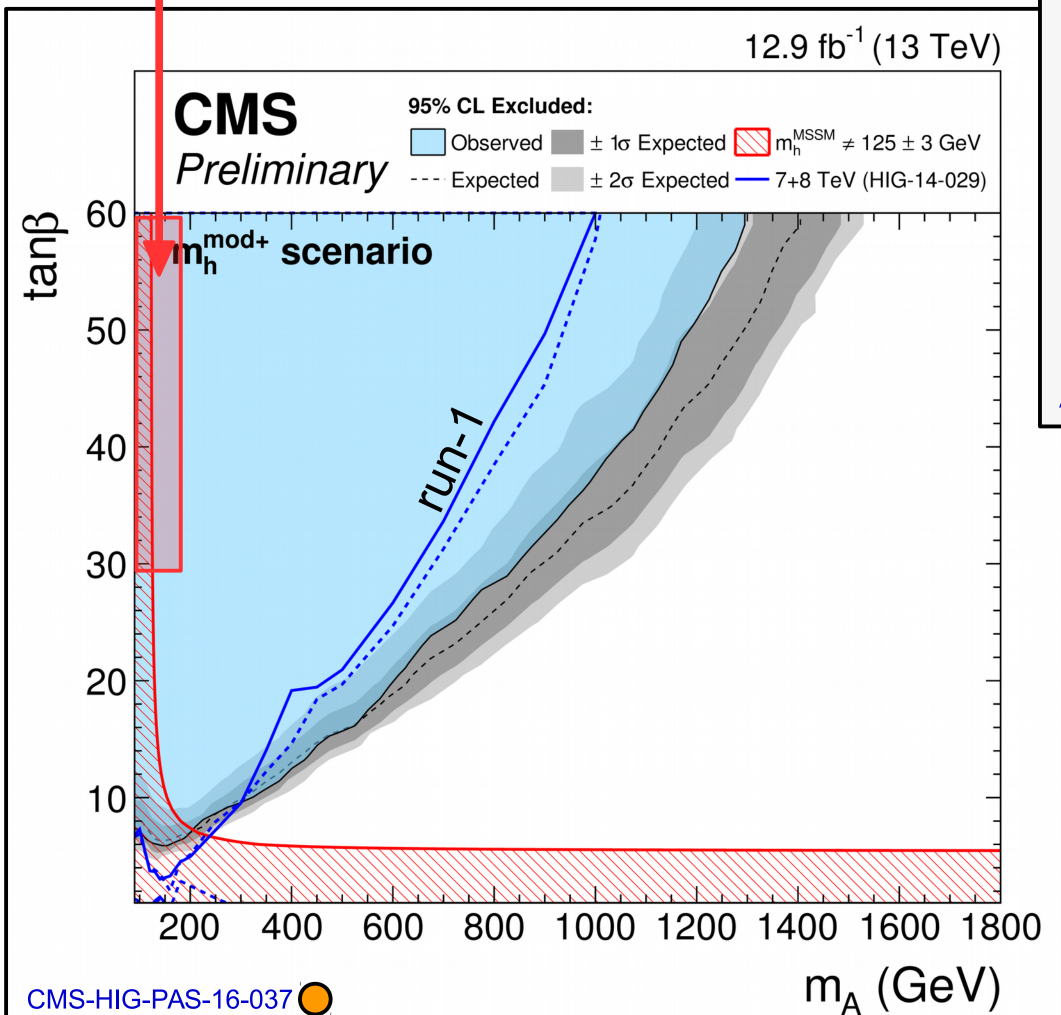


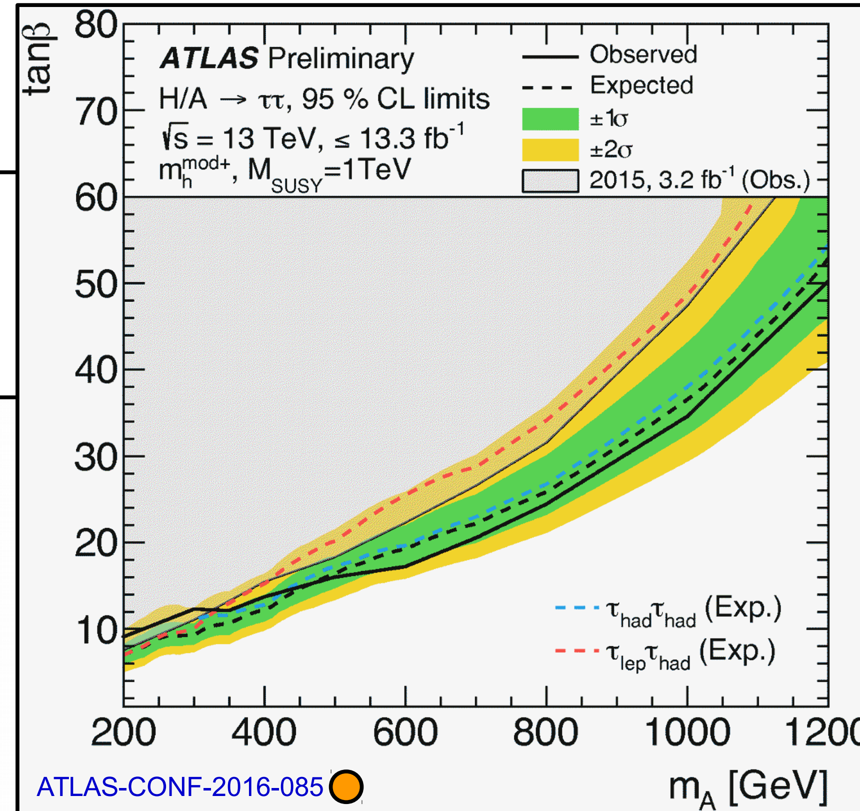


- Introduce event categorization to increase sensitivity.

Exclusion

Parameter space covered by Tevatron experiments before start of LHC.

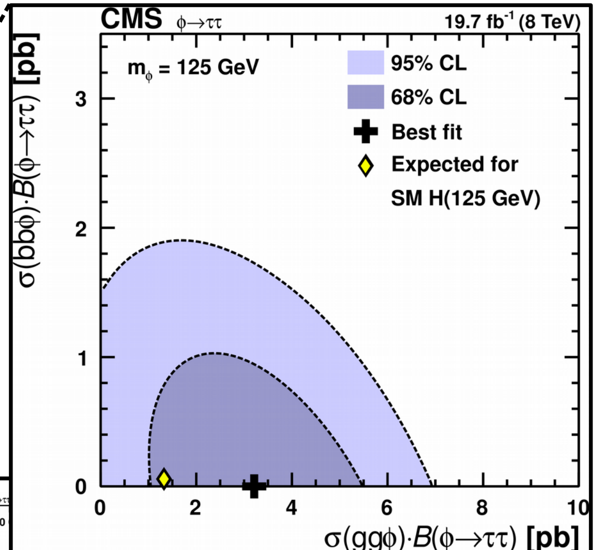




- Run-1 probed already an enormous region in m_A-$\tan\beta$.
- Run-2 extended this further with only **a fraction of data analyzed so far!**
- With full run-2 sample expect to reach out to 2TeV.

Link between experiment & theory

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



Database of 1.25 mio ΔNLL points for 31 points in m_A (e.g. as HEPdata).

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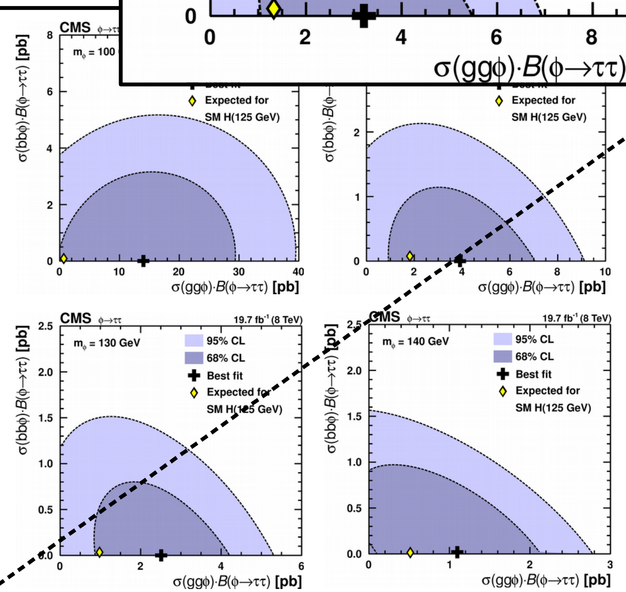
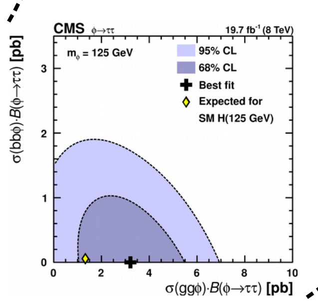
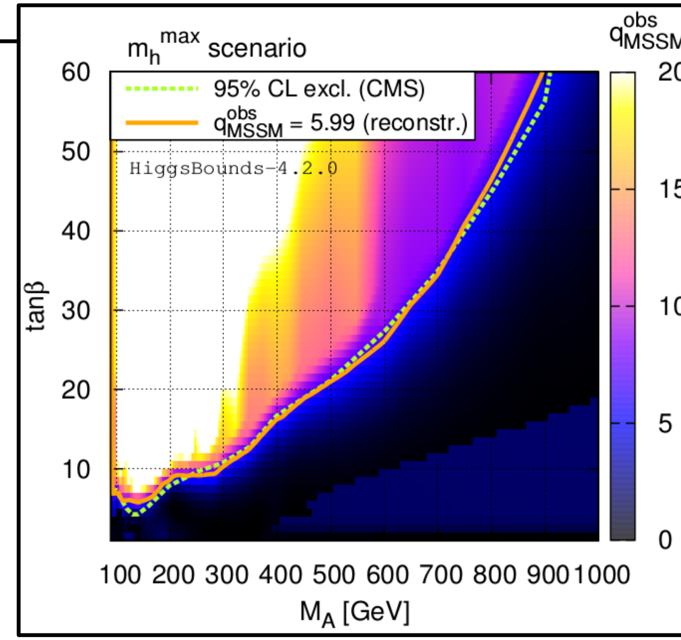
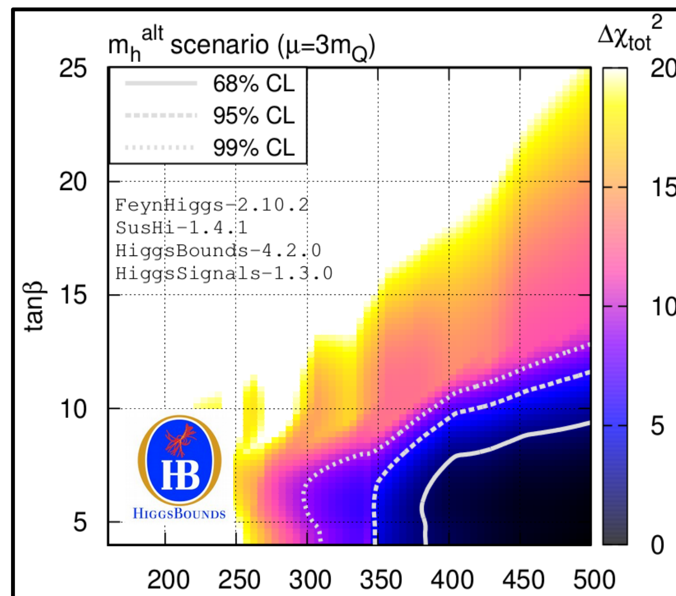




CMS limits picked up and applied to different model using HiggsBounds.





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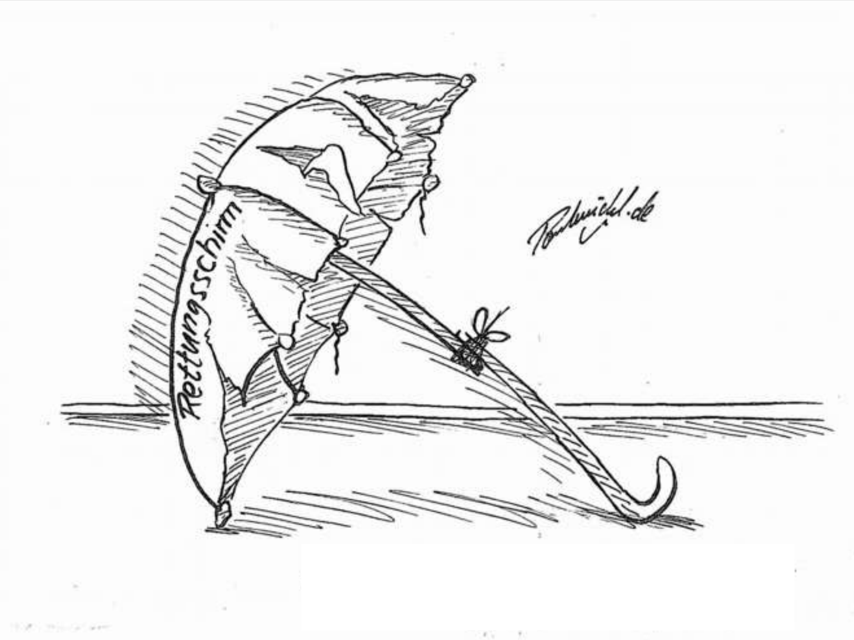
THE TRUTH IS OUT THERE

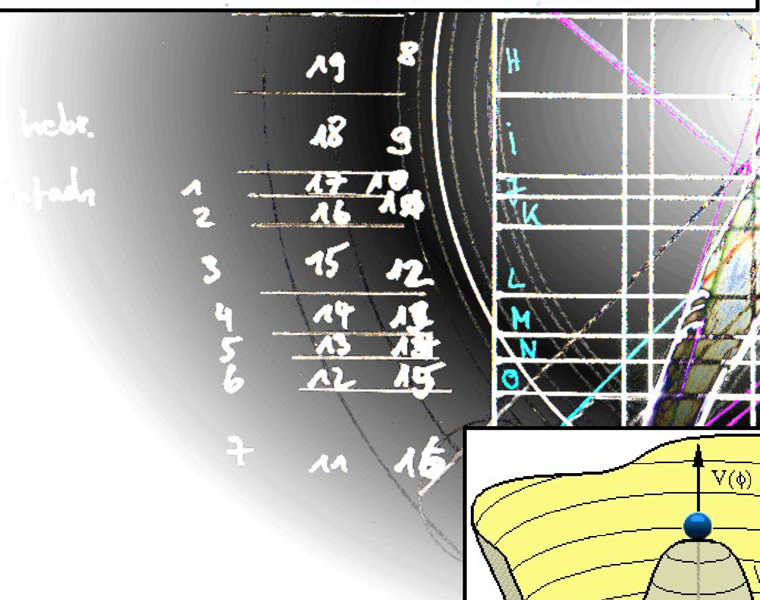
- Five years after Higgs discovery this new physics sector is better explored then we would ever have dreamed.
- **H established as SM-like Higgs boson** with mass of 125 GeV (→ Higgs mechanism reality; → BSM models have to be compliant with this finding).
- Discussion here concentrated on MSSM (2HDM) as well motivated and currently most intensively studied SM extension.
- In this field LHC experiments have demonstrated **enormous reach** and beside SM Higgs program opened a new era of BSM Higgs searches.
- Extensions of the SM alternative to the MSSM (e.g. NMSSM, general 2HDM, …) in process of being **systematically sorted** (in frame of LHC HXSWG).
- BSM Higgs searches have formed a major pillar of the LHC Higgs physics program so far and will **gain more and more importance** towards the end of run-2 an beyond.

Roger Wolf (KIT)
Frühjahrstagung der DPG, 30. März 2017

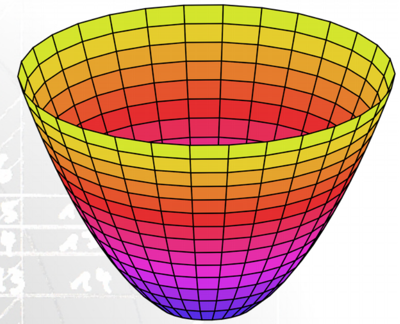
Backup



Wie kann eine Symmetrie zur gleichen Zeit erhalten und gebrochen sein?



Spontane Symmetrie-brechung:



$$f(x,y) = x^2 + y^2$$

$$x = r\cos\varphi$$

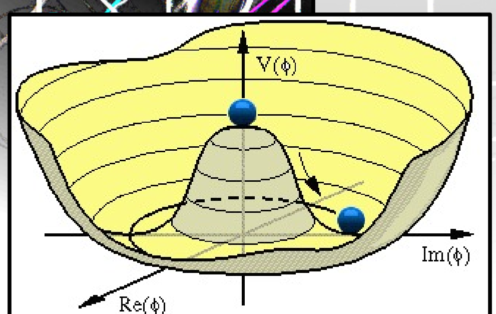
$$y = r\sin\varphi$$

$$f(x,y)\big|_{r,\varphi} = r^2\left(\cos\varphi^2 + \sin\varphi^2\right) = r^2$$

$$\tilde{f}(x,y) = (x-1)^2 + (y-1)^2$$

$$\tilde{f}(x,y)\Big|_{r,\varphi} = r^2 + 2\left(1 - r\left(\sin\varphi + \cos\varphi\right)\right)$$

("hidden symmetry")

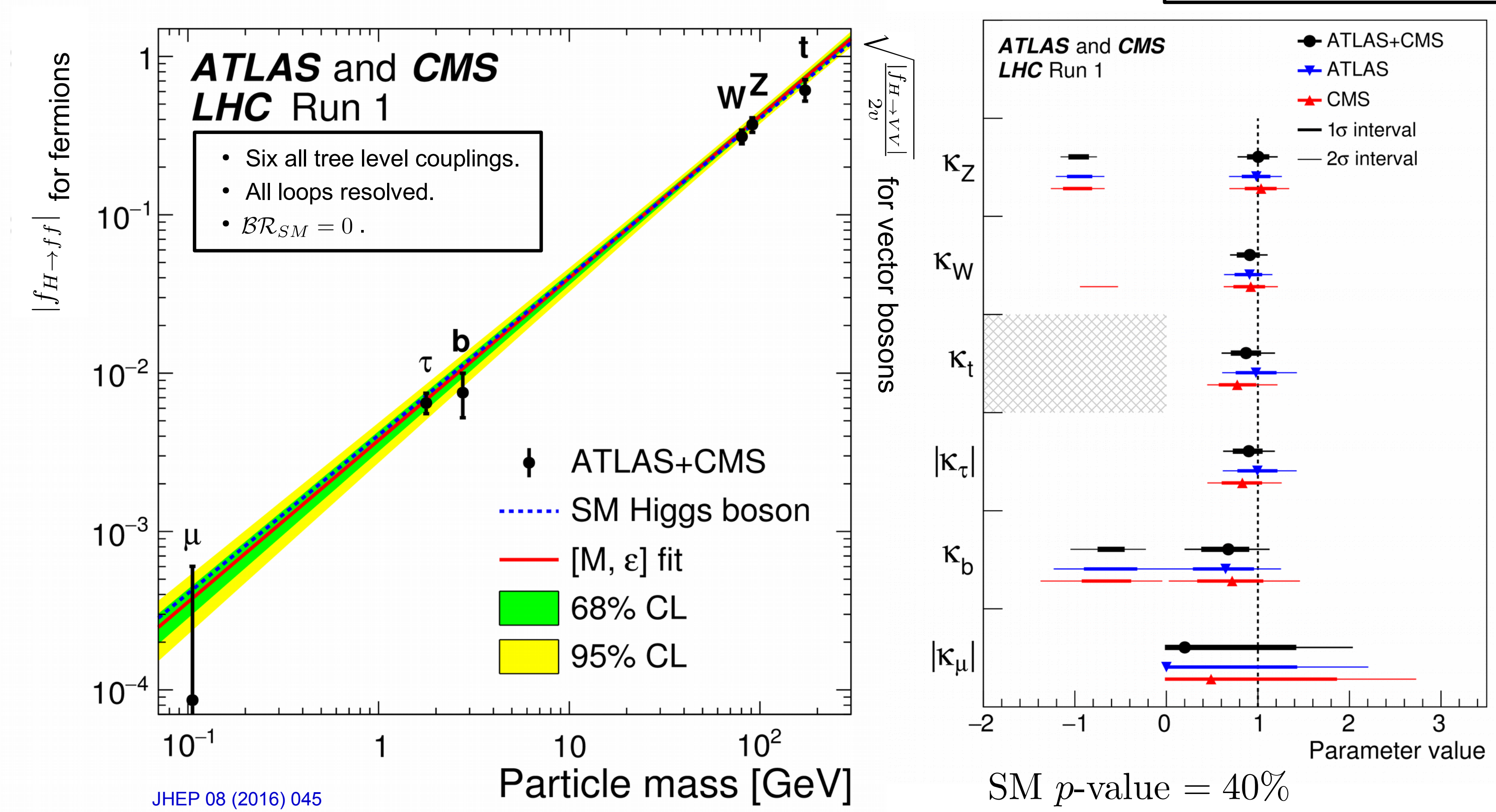


Führe Potential ein das den Grundzustand des Universums aus der Symmetrieachse der Bewegungsgleichungen zwingt.

→ Teilchenmasse als Kopplung an nicht verschwindenden Vakuumerwartungswert.

Higgs boson couplings

Within measurement accuracy unique scaling as expected within the SM.



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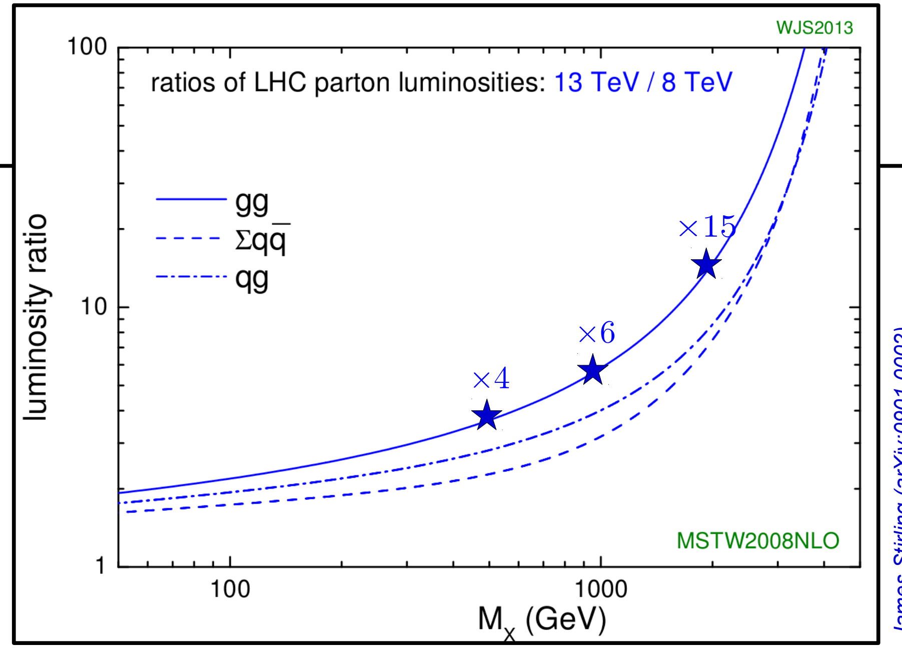
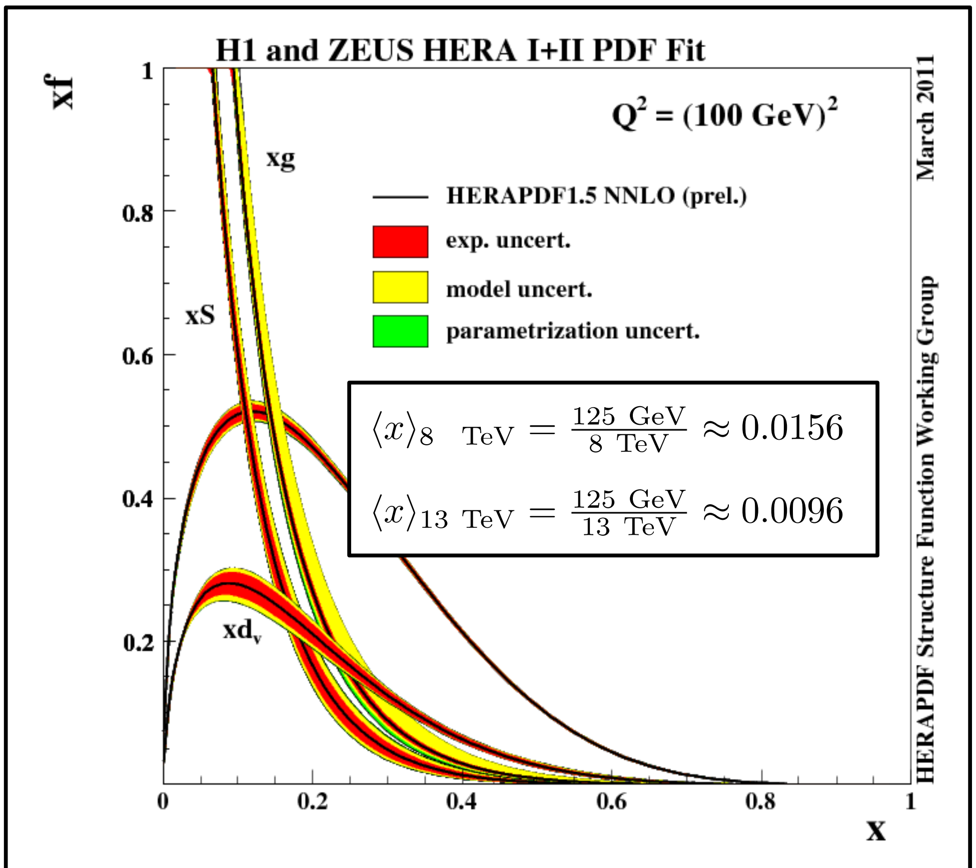
$$|f^{\text{obs}}_{H\to ff}| = \kappa_f \cdot |f^{\text{SM}}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

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

LHC run-1→ run-2

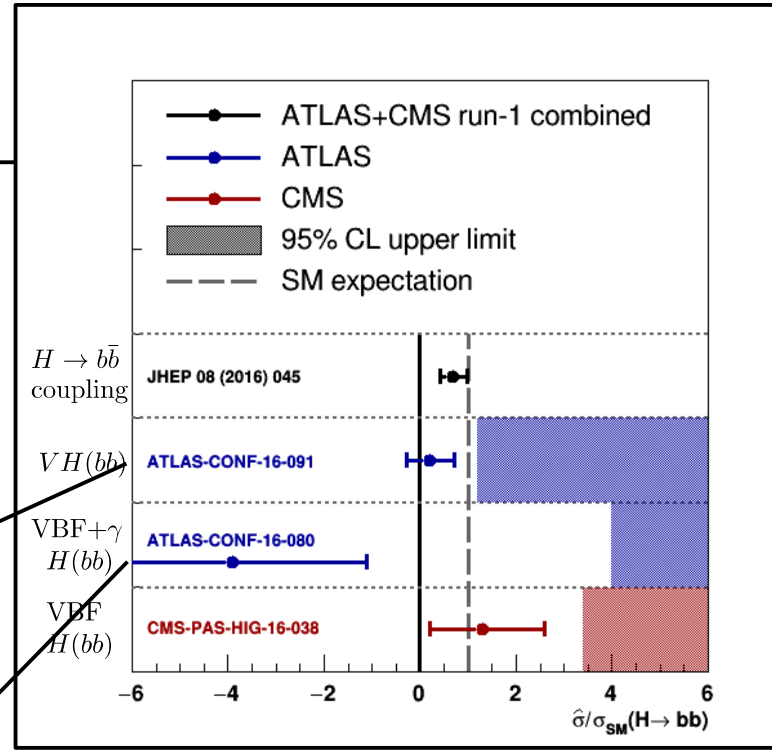
Process (X)	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$	$\Delta_X/\Delta_{h(125)}$
$t\bar{t}$	3.3	1.43
W	1.6	0.70
Z	1.6	0.70
WW	2.0	0.87
$h(125)$	2.3	1.00

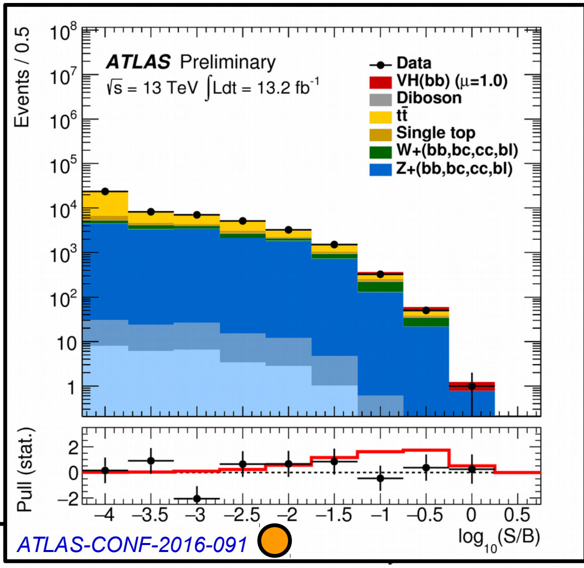


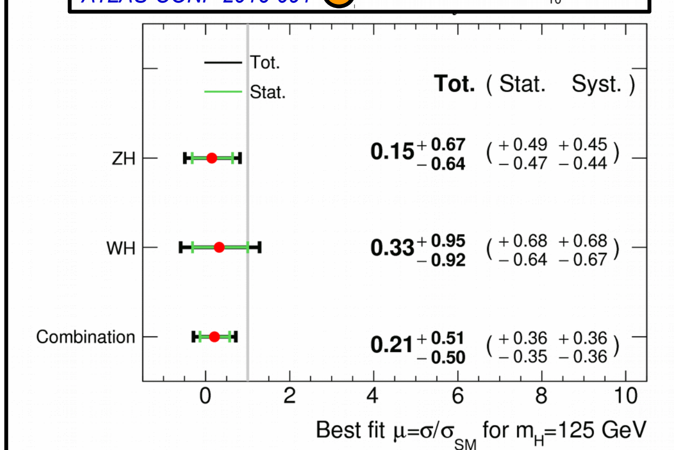


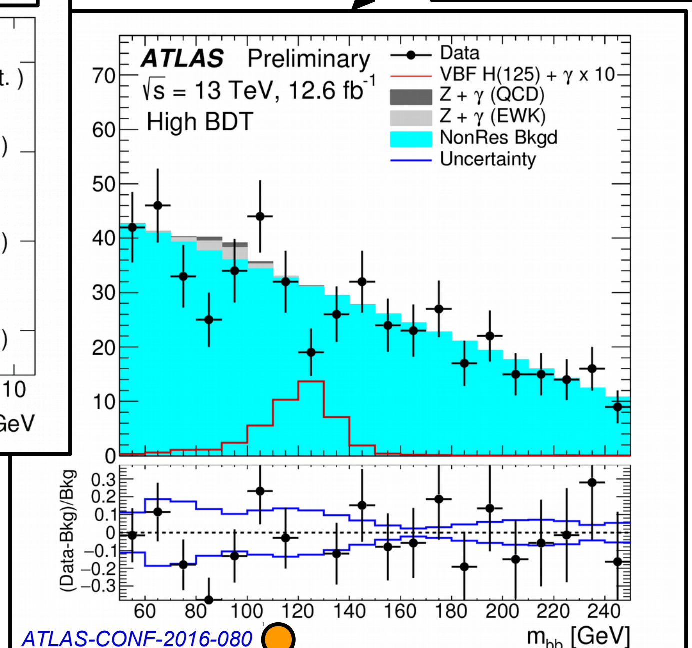
- Golden age for classical searches at the energy frontier.
- For SM Higgs the situation is mixed.

$H \to b\bar{b}$









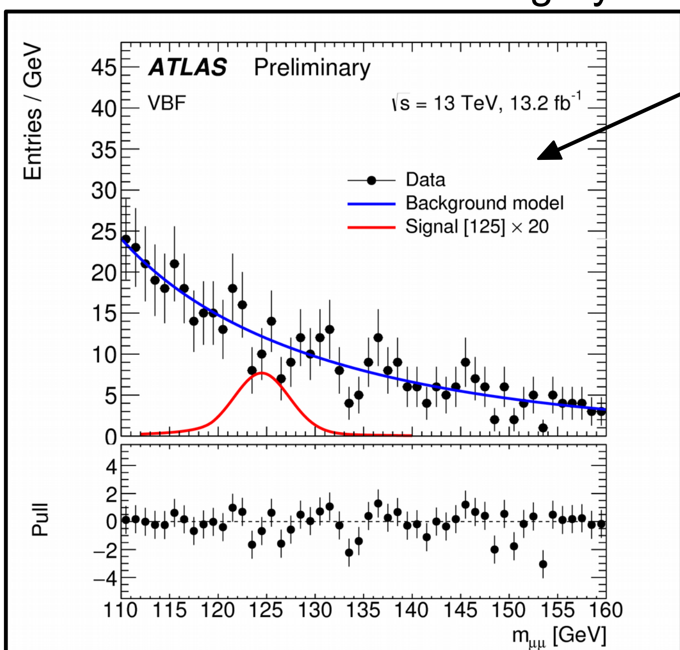
- Extra γ reduces non-Higgs background.
- Event classification using BDT, signal extraction based on m_{bb}.

Clear observation remains challenging.

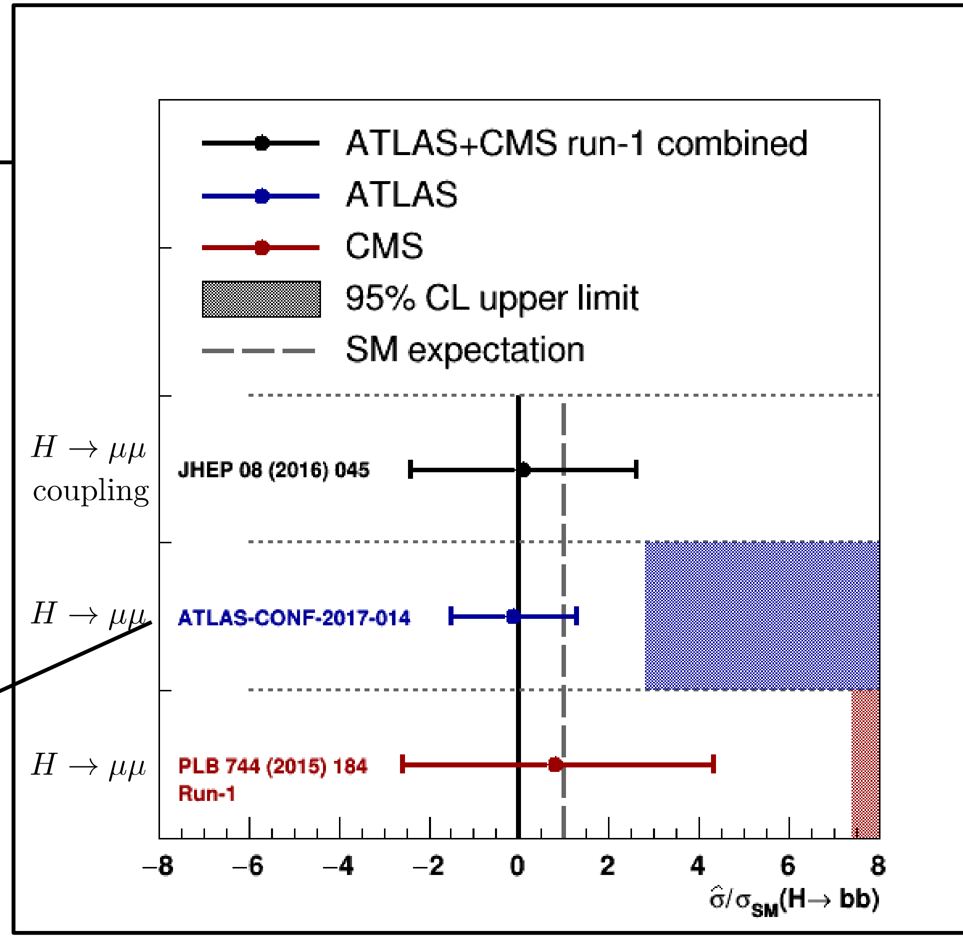
$H \to \mu\mu$

- Increase sensitivity by event classification by VBF topology, $p_T(\mu\mu)$ and $\eta(\mu)$ ($\to$ up to 8 event categories).
- Signal and background model based on analytic functions.

Most sensitive VBF category:



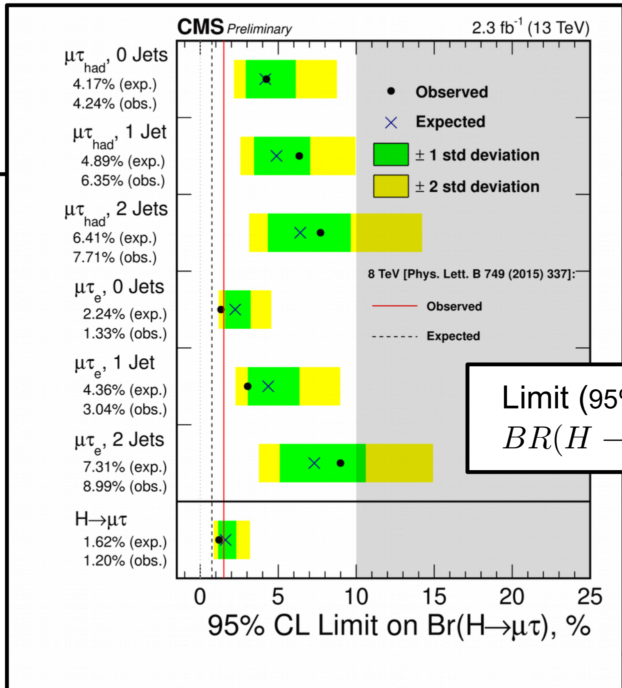
ATLAS-CONF-2016-041



- Second fermion generation in sight for LHC run-2.
- Another crucial test of the coupling structure of the new particle.

$H \rightarrow \mu\tau$

- Slight excess also observed in ATLAS run-1.
- Not (yet) confirmed by run-2.

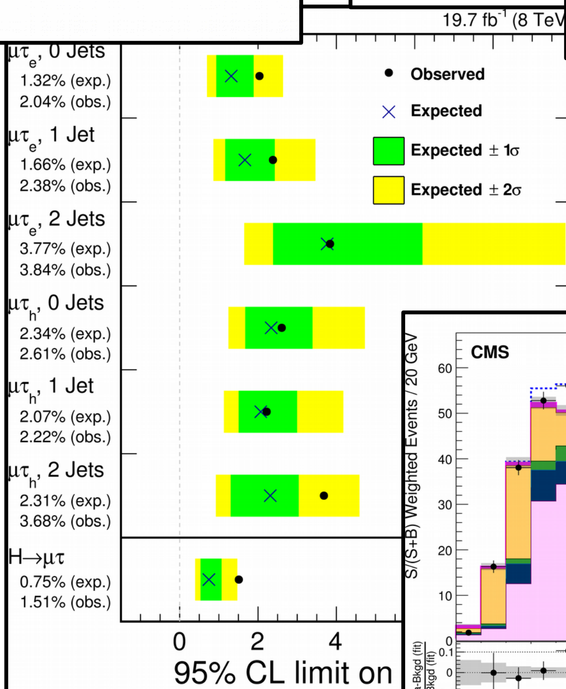


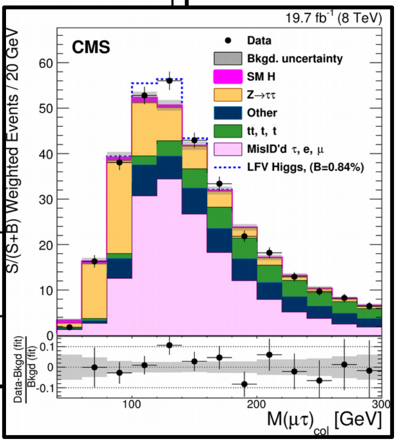
CMS-PAS-HIG-16-005

Limit (95% CL):
$BR(H \rightarrow \tau\mu) \leq 1.20(1.62)\%$

Limit (95% CL):
$BR(H \rightarrow \tau\mu) \leq 1.51(0.75)\%$

($2.4\ \sigma$ above zero)

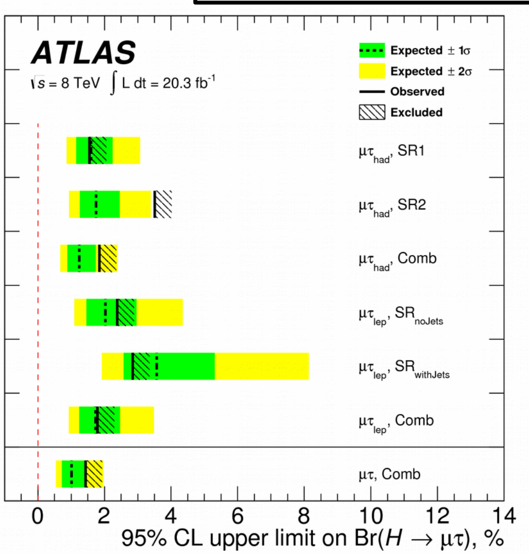




PLB 749 (2015) 337

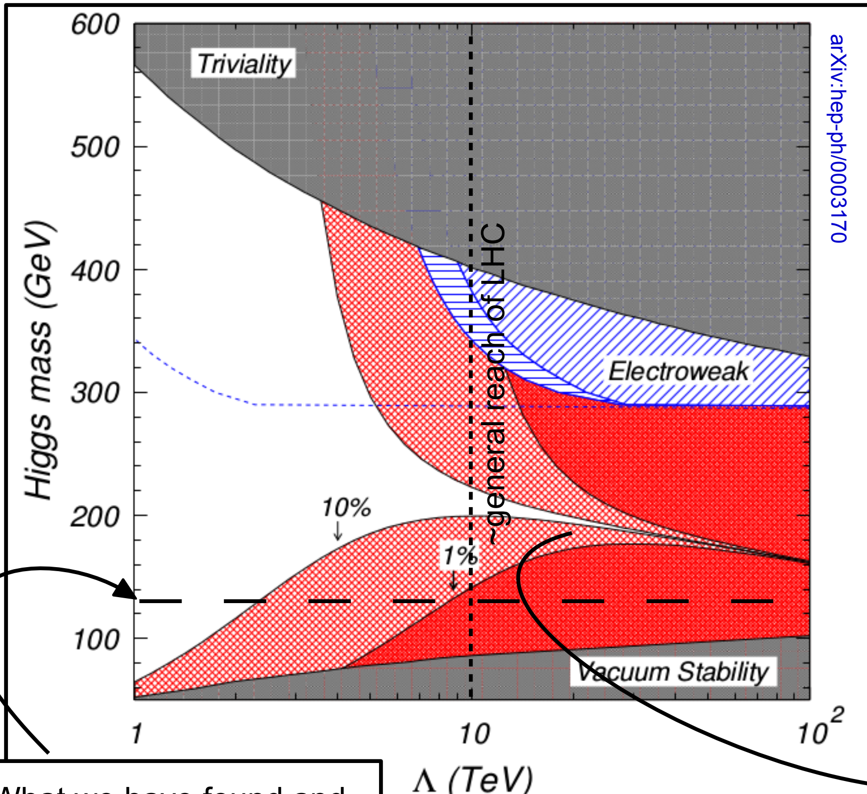
EPJ C 77 (2017) 70

Limit (95% CL):
$BR(H \rightarrow \tau\mu) \leq 1.43(1.01)\%$



RUN-1

Why the Higgs boson still is not THE *Higgs* boson [1]



What we have found and measured for m_H.

Relation to Higgs: why is m_H so small?

- SM does not contain gravity, which is of similar strength to other interactions latest at the Planck scale.
- SM → "low-energy limit" of (yet unknown) more complete theory.
- Question: is energy scale Λ at which new physics becomes observable accessible to us?

Different levels of fine tuning in the SM:

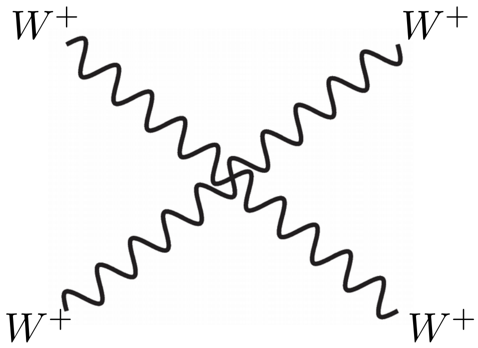
$$m_H^{obs} = m_{H,0} - \Delta m_H^{HO}(\Lambda) = 125\ \text{GeV}$$

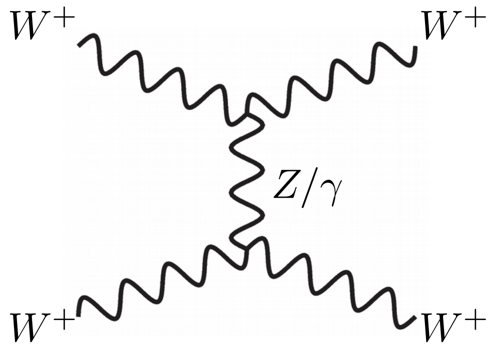
$$\frac{m_H^{obs}}{\Delta m_H^{HO}} = \frac{m_{H,0} - \Delta m_H^{HO}(\Lambda)}{\Delta m_H^{HO}} = 10\% \quad 1\%$$

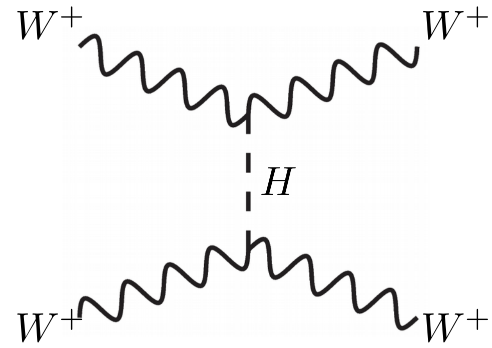
[1] Arguments taken from G. Weiglein (Higgs physics:where we are and what next? 01/2017)

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

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







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

constraint

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

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

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

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 (leading to sum rules).