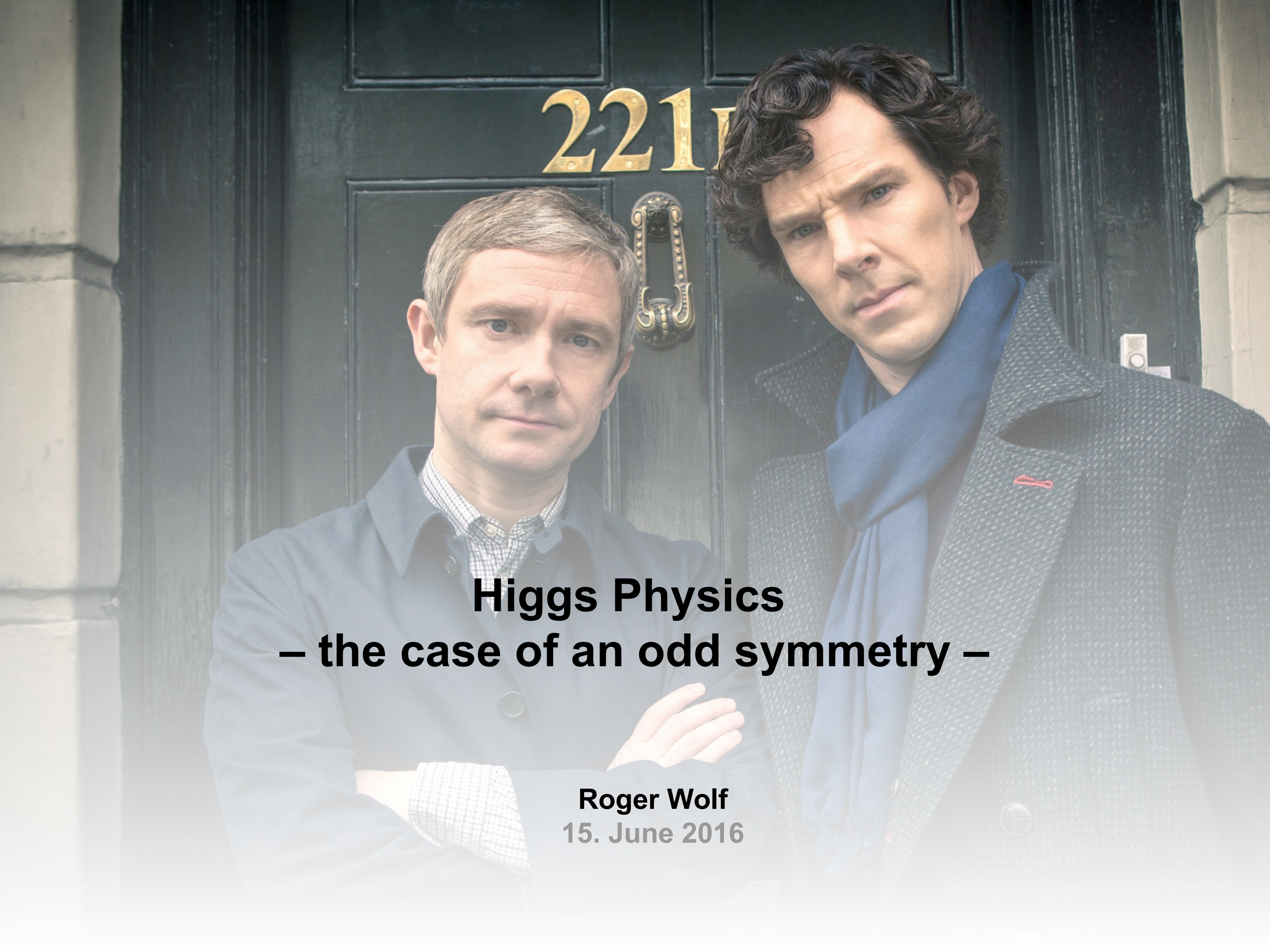


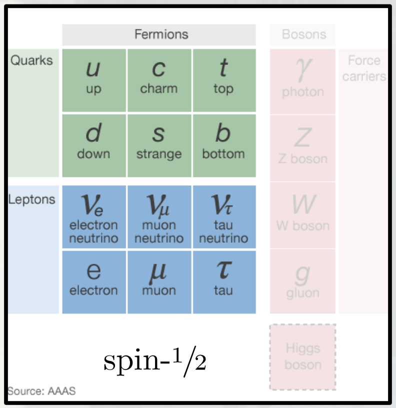
Higgs Physics
– the case of an odd symmetry –

Roger Wolf

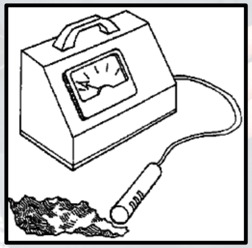
15. June 2016

The case of matter

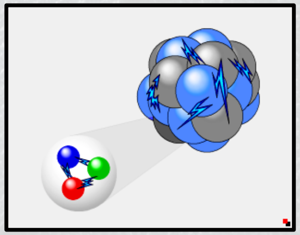
- All matter we know is made up of six quark flavors and six lepton flavors:



Electromagnetism



Weak force

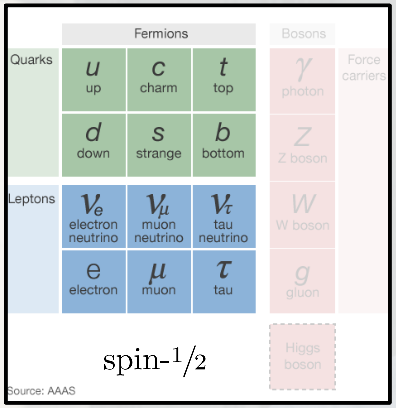


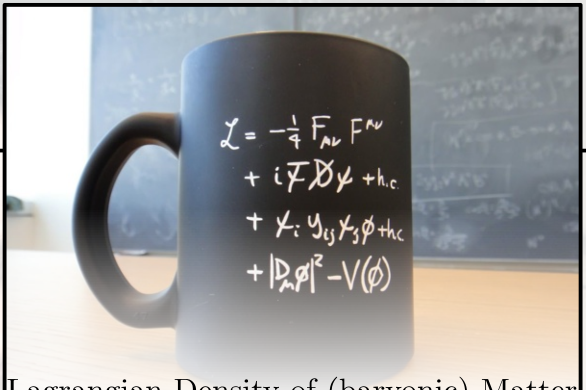
Strong force

- Four fundamental forces (three of importance for particle physics).

The case of matter

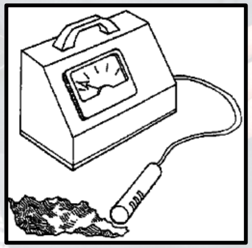
- All matter we know is made up of six quark flavors and six lepton flavors:

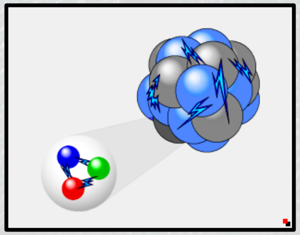




Lagrangian Density of (baryonic) Matter


Electromagnetism

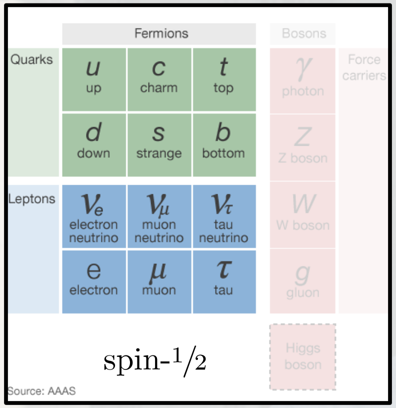

Weak force

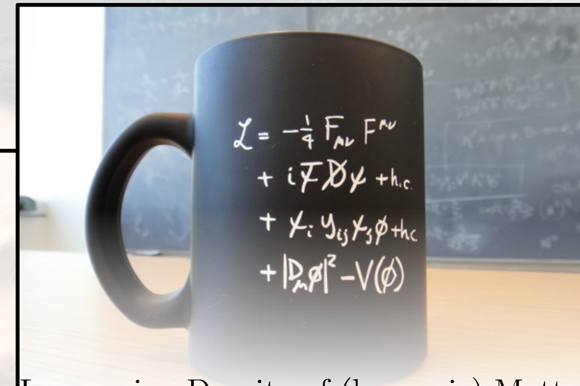

Strong force

- Formalize nature by Lagrangian density function.

The case of matter

- All matter we know is made up of six quark flavors and six lepton flavors:





Lagrangian Density of (baryonic) Matter

$$U(1)_Y \times SU(2)_L \times SU(3)_c$$

1d rotations

2d rotations

3d rotations

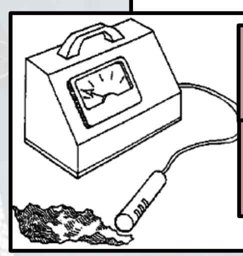
in a $\mathbb{C}(N)$ hyperspace (w/ $N \geq 5$)

$\psi \; e^{i\vartheta'}$

γ photon

Electromagnetism

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

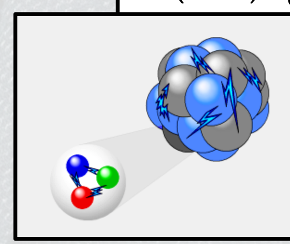


$W^\pm$ W boson

Z Z boson

Weak force

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



g gluon

Strong force

- "Simple" (local) symmetry requirements on $\mathcal{L}$ enforce complex interactions.

A wealth of structures

$$\mathcal{L}^{\rm SM} = \mathcal{L}^{\rm Lepton}_{\rm kin} + \mathcal{L}^{CC}_{\rm IA} + \mathcal{L}^{NC}_{\rm IA} + \mathcal{L}^{\rm Gauge}_{\rm kin} + \mathcal{L}^{\rm Higgs}_{kin} + \mathcal{L}^{\rm Higgs}_{V(\phi)} + \mathcal{L}^{\rm Higgs}_{\rm Yukawa}$$

$$\mathcal{L}^{\rm Lepton}_{\rm kin} = i\overline{e}\gamma^\mu\partial_\mu e + i\overline{\nu}\gamma^\mu\partial_\mu\nu$$

$$\mathcal{L}^{CC}_{\rm IA} = -\frac{e}{\sqrt{2}\sin\theta_W}\left[W^+_\mu\overline{\nu}\gamma_\mu e_L + W^-_\mu\overline{e}_L\gamma_\mu\nu\right]$$

$$\mathcal{L}^{NC}_{\rm IA} = -\frac{e}{2\sin\theta_W\cos\theta_W}Z_\mu\left[(\overline{\nu}\gamma_\mu\nu) + (\overline{e}_L\gamma_\mu e_L)\right] - e\left[A_\mu + \tan\theta_W Z_\mu\right](\overline{e}\gamma_\mu e)$$

$$\mathcal{L}^{\rm Gauge}_{\rm kin} = -\frac{1}{2}Tr\left(W^a_{\mu\nu}W^{a\mu\nu}\right) - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}\Big|_{\substack{B_\mu \to A_\mu \\ W^3_\mu \to Z_\mu}}$$

$$\mathcal{L}^{\rm Higgs}_{\rm kin} = \frac{1}{2}\partial_\mu H\partial^\mu H + \left(1 + \frac{1}{v}\frac{H}{\sqrt{2}}\right)^2 m_W^2 W^+_\mu W^{\mu-} + \left(1 + \frac{1}{v}\frac{H}{\sqrt{2}}\right)^2 m_Z^2 Z_\mu Z^\mu$$

$$\mathcal{L}^{\rm Higgs}_{V(\phi)} = -\frac{m_H^2 v^2}{4} + \frac{m_H^2}{2}\left(\frac{H}{\sqrt{2}}\right)^2 + \frac{m_H^2}{v}\left(\frac{H}{\sqrt{2}}\right)^3 + \frac{m_H^2}{4v^2}\left(\frac{H}{\sqrt{2}}\right)^4$$

$$\mathcal{L}^{\rm Higgs}_{\rm Yukawa} = -\left(1 + \frac{1}{v}\frac{H}{\sqrt{2}}\right)m_e\overline{e}e$$

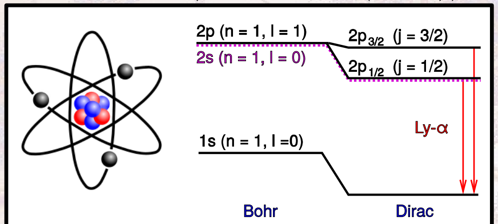
Full SM Lagrangian density (first lepton generation)

- "Simple" (local) symmetry requirements on $\mathcal{L}$ enforce complex interactions.

The standard model of particle physics (SM)

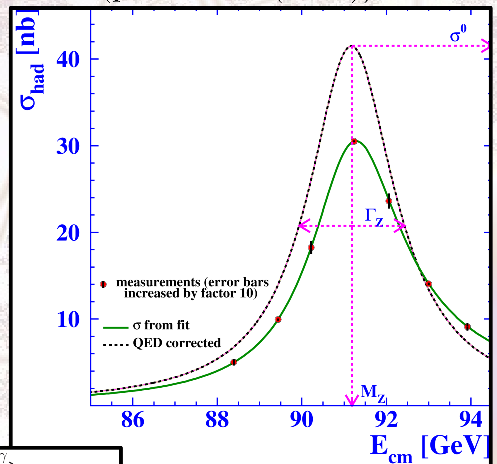
Precision observables:

Lamb shift: (precision $\mathcal{O}(10^{-7})$)



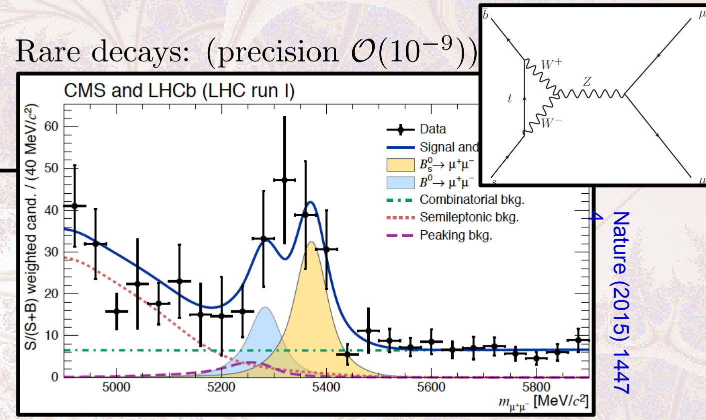
$\langle \Delta V \rangle \propto \alpha^5 m_e \ln(\pi\alpha) = \mathcal{O}(1\text{GHz})$

LEP: (precision $\mathcal{O}(10^{-5})$)



Phys. Rept 427 (2006)

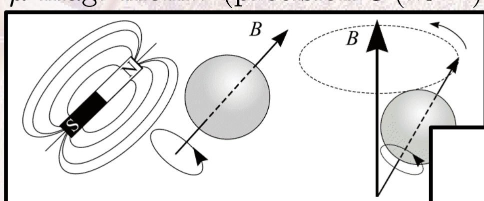
Rare decays: (precision $\mathcal{O}(10^{-9})$)

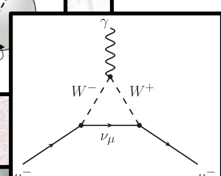


Nature (2015) 1447

$\mathcal{BR}(B_s \to \mu^+\mu^-)_{SM} = (3.66 \pm 0.23) \times 10^{-9}$

μ mag. mom.: (precision $\mathcal{O}(10^{-9})$)

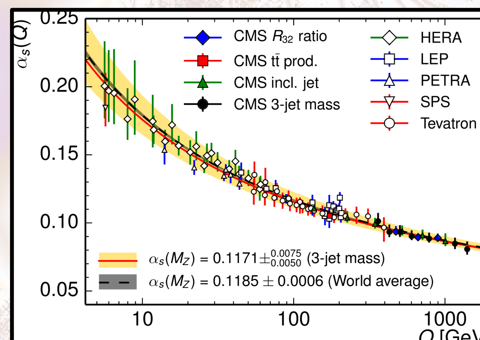




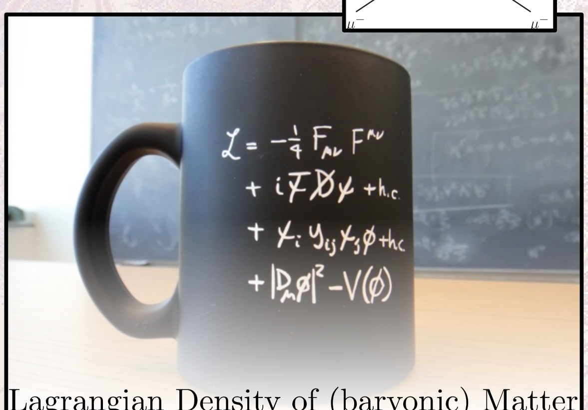
$\frac{(g-2)}{2} = 0.00115965218073(28)$

Striking features & global characteristics:

Asymptotic freedom:

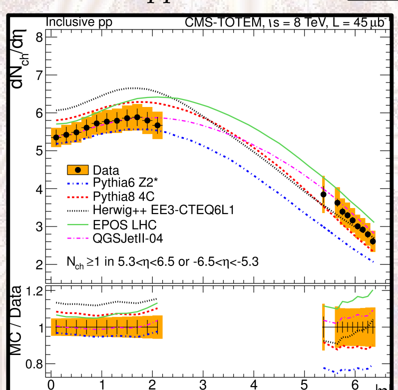


EPJC 75 (2015) 186



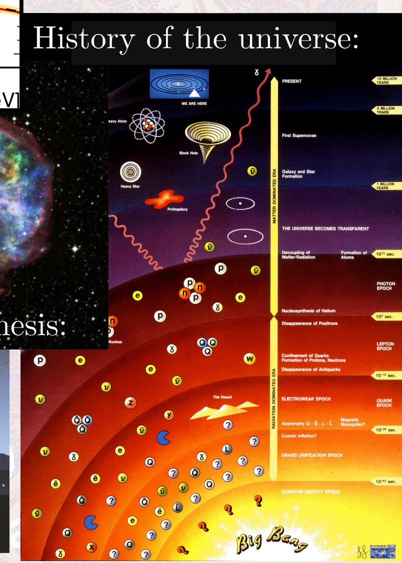
Lagrangian Density of (baryonic) Matter

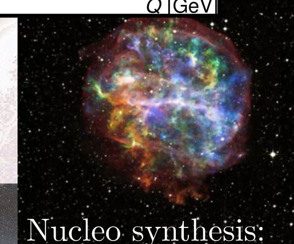
Inclusive pp collisions:



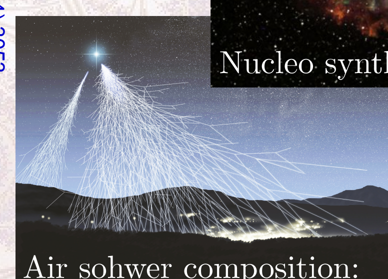
EPJC 74 (2014) 3053

History of the universe:





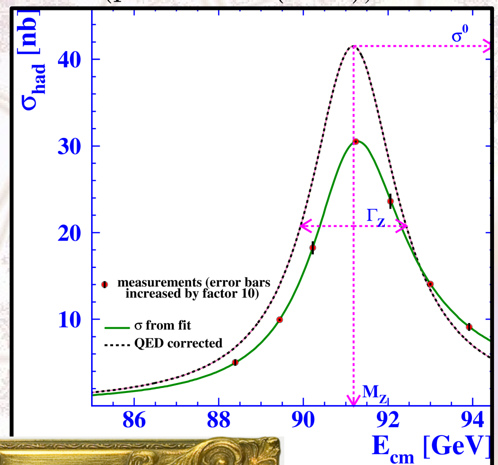
Nucleo synthesis:



Air sohwer composition:

Precision observables:

LEP: (precision $\mathcal{O}(10^{-5})$)



Phys. Rept 427 (2006)

Problem-1:

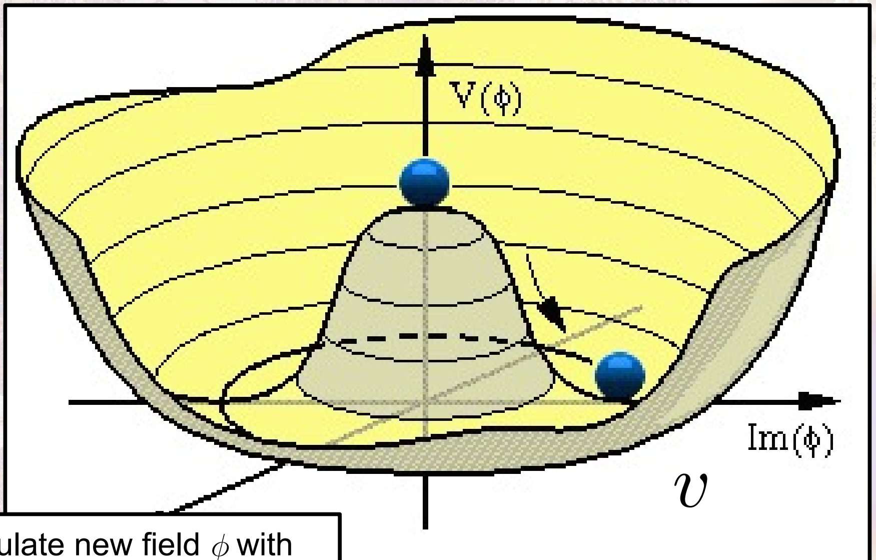
Symmetries strictly forbid **force mediators** to have mass $\neq 0$ (e.g. $M_Z^2 Z_\mu Z^{\mu *}$).

Problem-2:

Weak force distinguishes between left- and right-handed matter → breaks $SU(2)_L$ for **ALL** weakly interacting particles with mass $\neq 0$.

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?!?

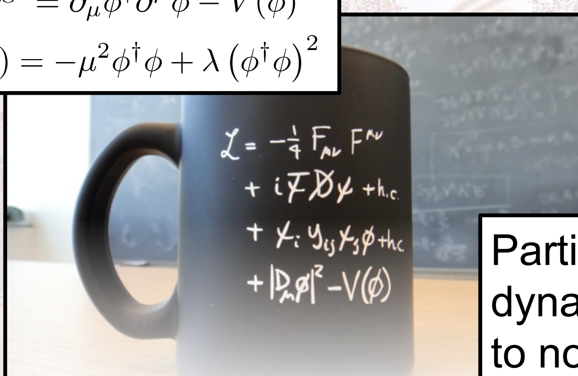
Spontaneous symmetry breaking:



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:

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

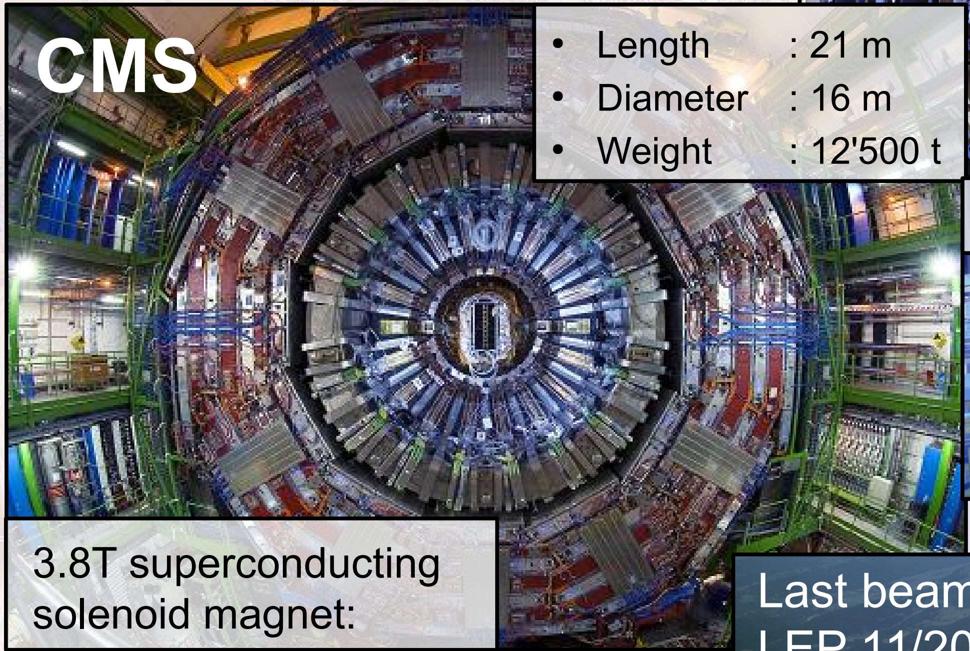
$$f_{H \to VV} = i\frac{2m_V^2}{v} \quad \text{(Heavy Bosons trilinear)}$$

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

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

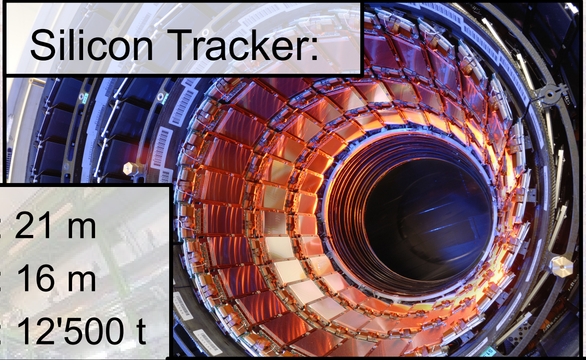
$$f_{HH \to HH} = i\frac{3m_H^2}{v^2} \quad \text{(H Boson quartic)}$$

The Higgs finder...



- Length : 21 m
- Diameter : 16 m
- Weight : 12'500 t

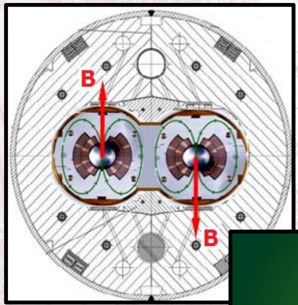
Silicon Tracker:



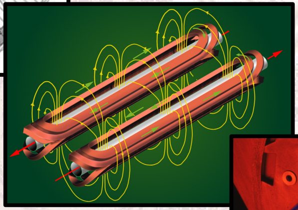
- Tracker: Si ($\delta p/p = 0.5\%$ for a 10 GeV track).
- ECAL: $\mathrm{PbWO_4}$($\delta E/E = 1\%$ for a 30 GeV e/γ).

Electromagnetic Calo:

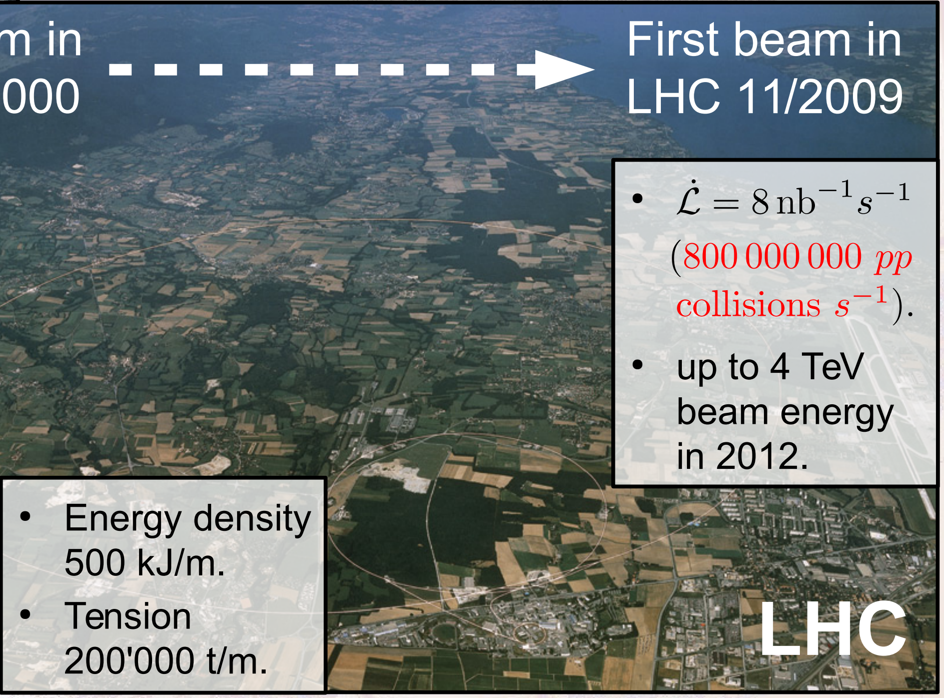
3.8T superconducting solenoid magnet:



- 8.3 T
- 11.8 kA
- 160 cyc



- Energy density 500 kJ/m.
- Tension 200'000 t/m.

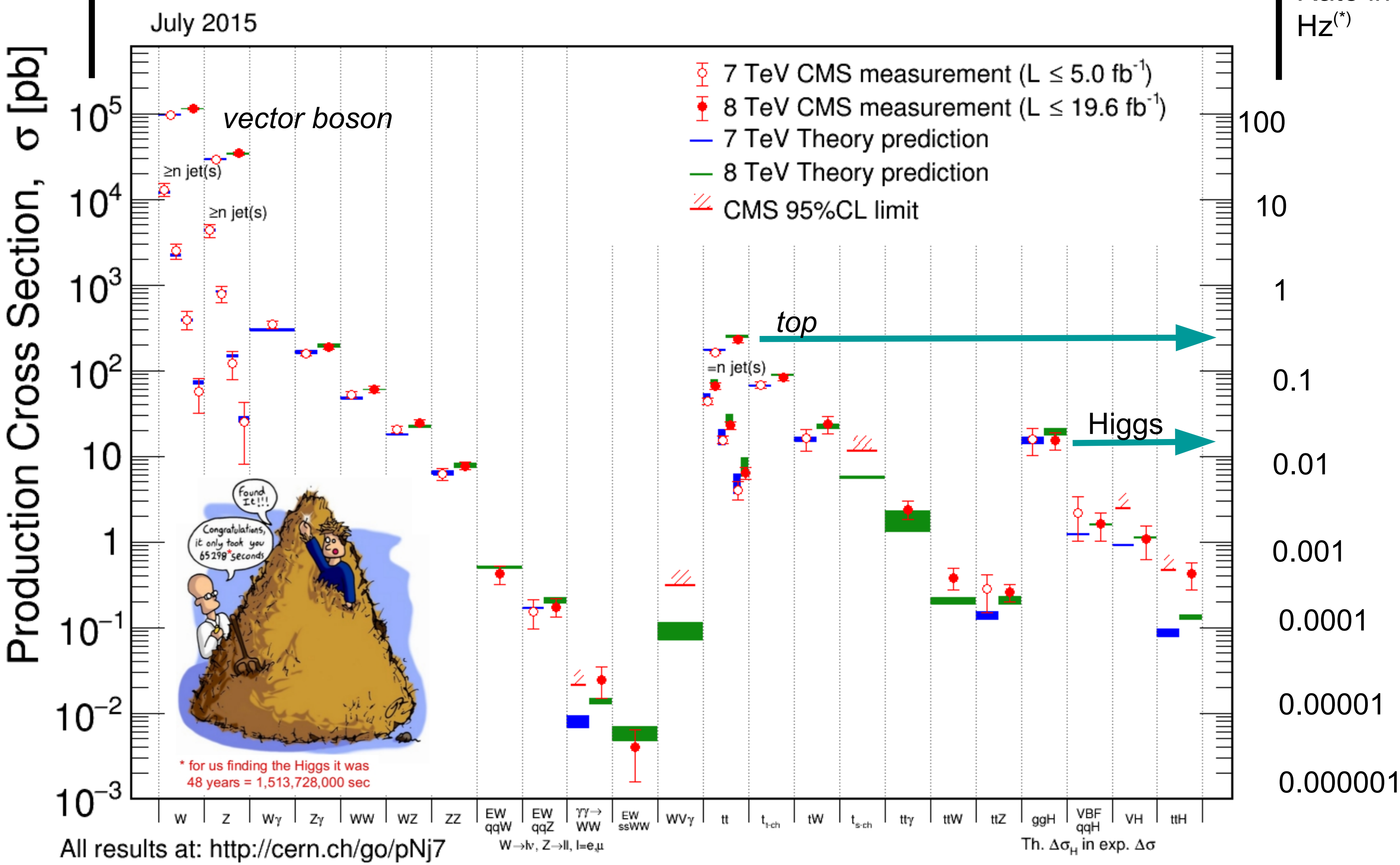


Last beam in LEP 11/2000 - - - - - - - - - → First beam in LHC 11/2009

- $\dot{\mathcal{L}} = 8\,\mathrm{nb}^{-1}s^{-1}$ (800 000 000 pp collisions s^{-1}).
- up to 4 TeV beam energy in 2012.

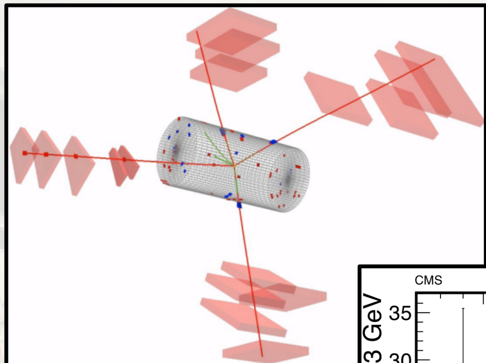
10^{11} $\sigma_{incl}(pp)$ 10^8

The challenge

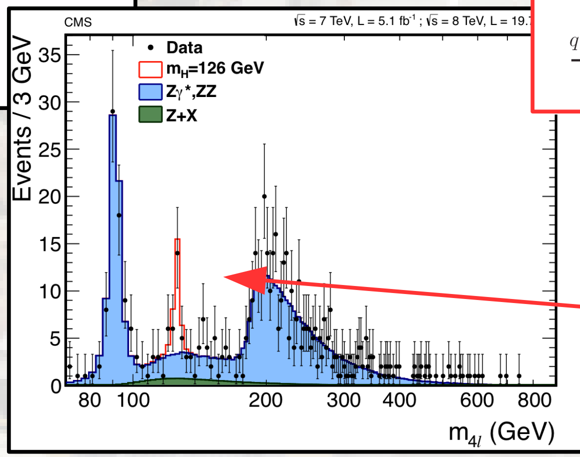


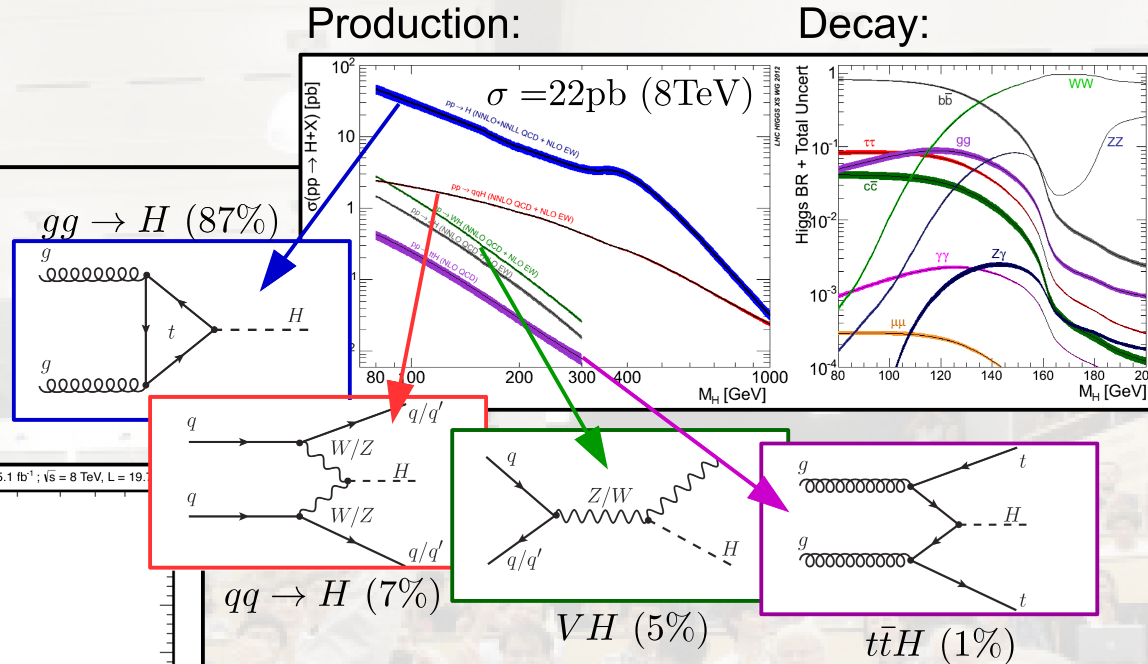
(*) for $\dot{\mathcal{L}} = 1\,\mathrm{nb}^{-1}s^{-1}$.

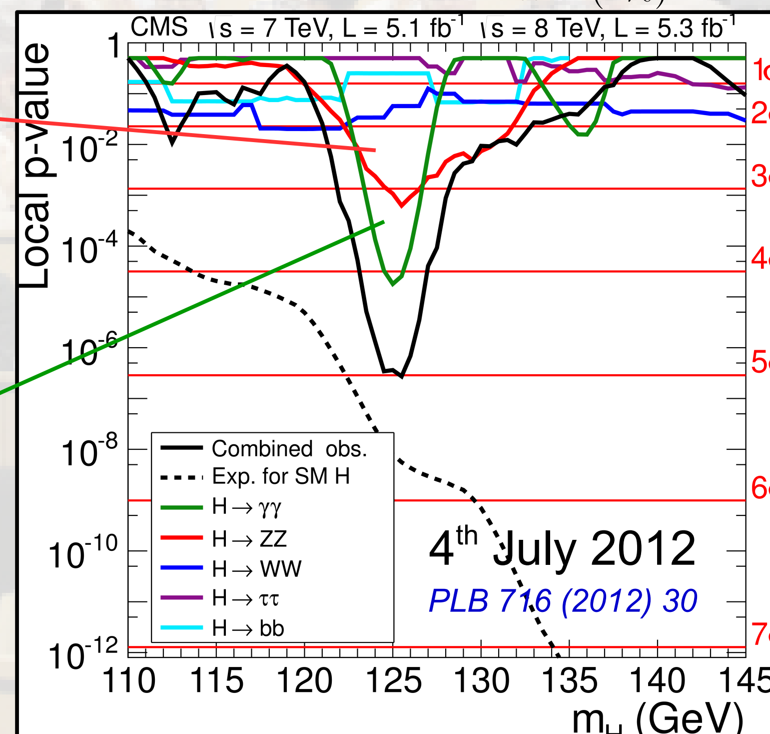
The discovery…



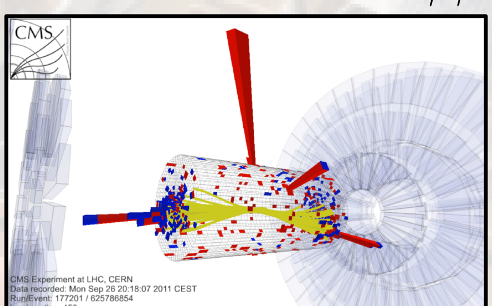
$H \to ZZ \to 4\ell$

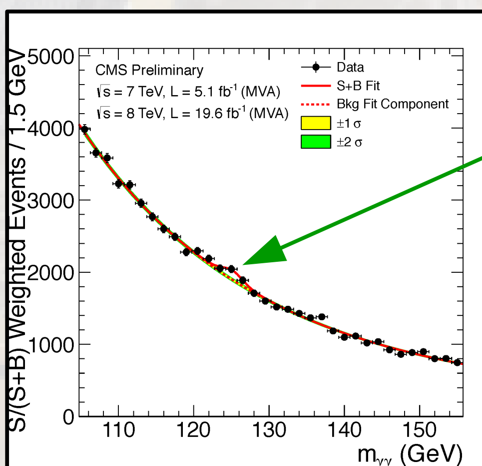






$H \to \gamma\gamma$





… and beyond

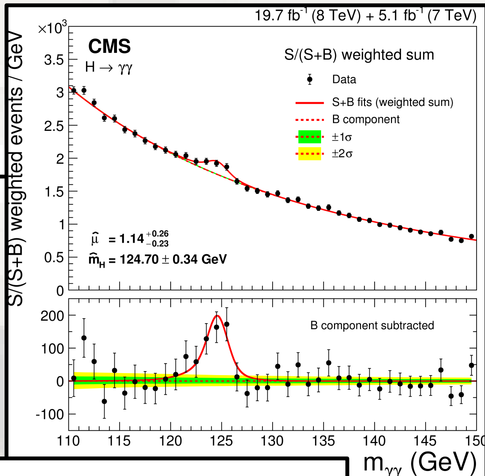
Impressive consolidation of discovery. Major LHC run-1 result!

"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

EPJ C 74 (2014) 3076

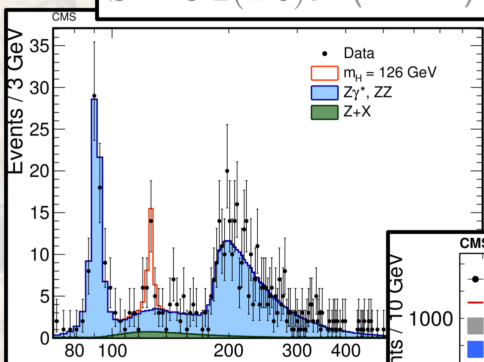


Significance:

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

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

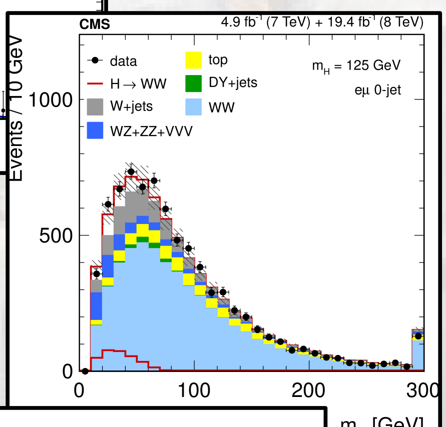
PRD 89 (2014) 092007



Significance:

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

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

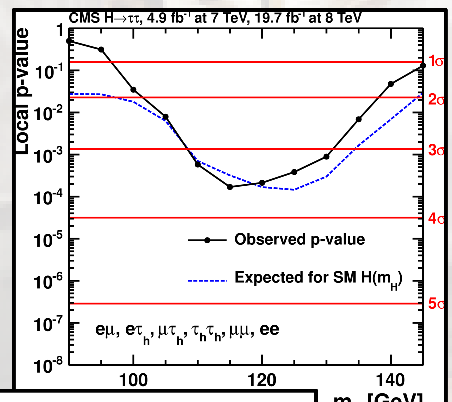


JHEP 01 (2014) 096

Significance:

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

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

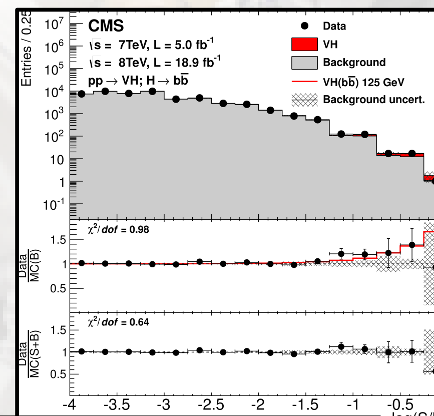


JHEP 05 (2014) 104

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

… the case of fermions

- Still lacking: convincing single channel observation of coupling to fermions.

- Branching ratios much higher but signature less distinct from SM backgrounds.

(→ experimentally interesting)

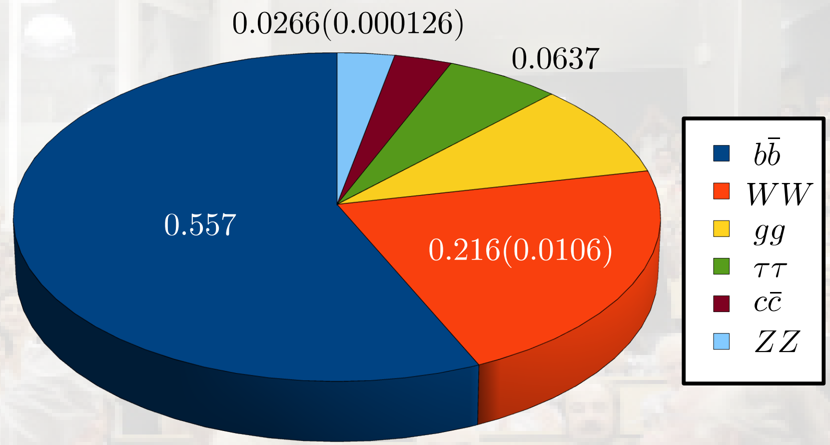
- Coupling to vector bosons w/o d.o.f. in SM (and protected):

$$D_\mu\phi^\dagger D^\mu\phi = \frac{1}{2}\partial_\mu H\partial^\mu H + \frac{g^2+g'^2}{4}\left(v+\frac{H}{\sqrt{2}}\right)^2 Z_\mu Z^\mu + \frac{g^2}{4}\left(v+\frac{H}{\sqrt{2}}\right)^2 W_\mu^+ W^{\mu -}$$

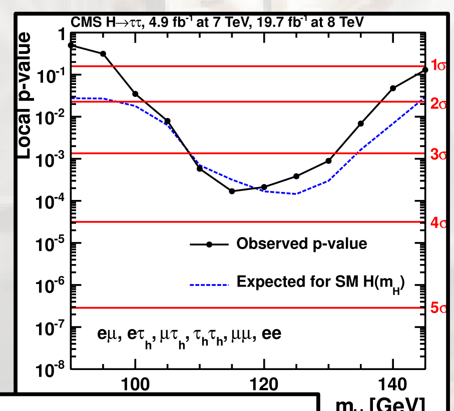
- Coupling to fermions introduced by hand as *Yukawa* couplings, thus theoretically least motivated.

$$\mathcal{L}^{\text{Yukawa}} = -f_e\left(\overline{e}_R\phi^\dagger\psi_L\right) - f_e^*\left(\overline{\psi}_L\phi e_R\right) = -\left(1+\frac{1}{v}\frac{H}{\sqrt{2}}\right)m_e\overline{e}e$$

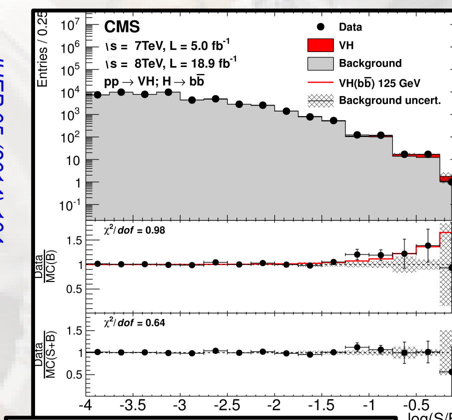
(→ theoretically interesting)



Values in braces correp. To final states of experimental interest.



JHEP 05 (2014) 104



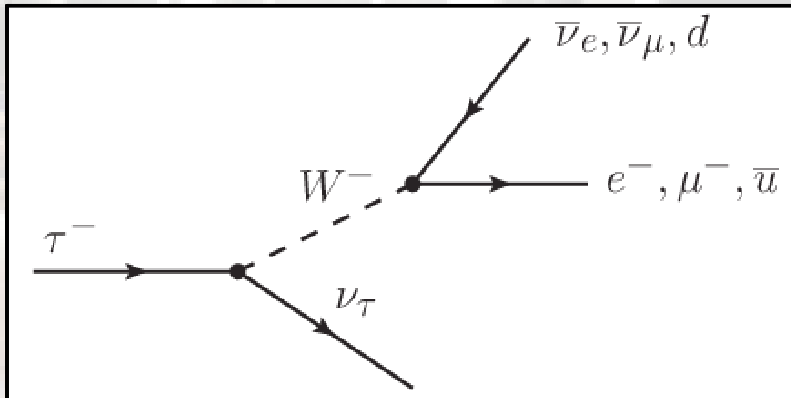
PRD 89 (2013) 012003

Significance:
$S = 3.2(3.7)\sigma$ (CMS)
$S = 4.5(3.4)\sigma$ (ATLAS)

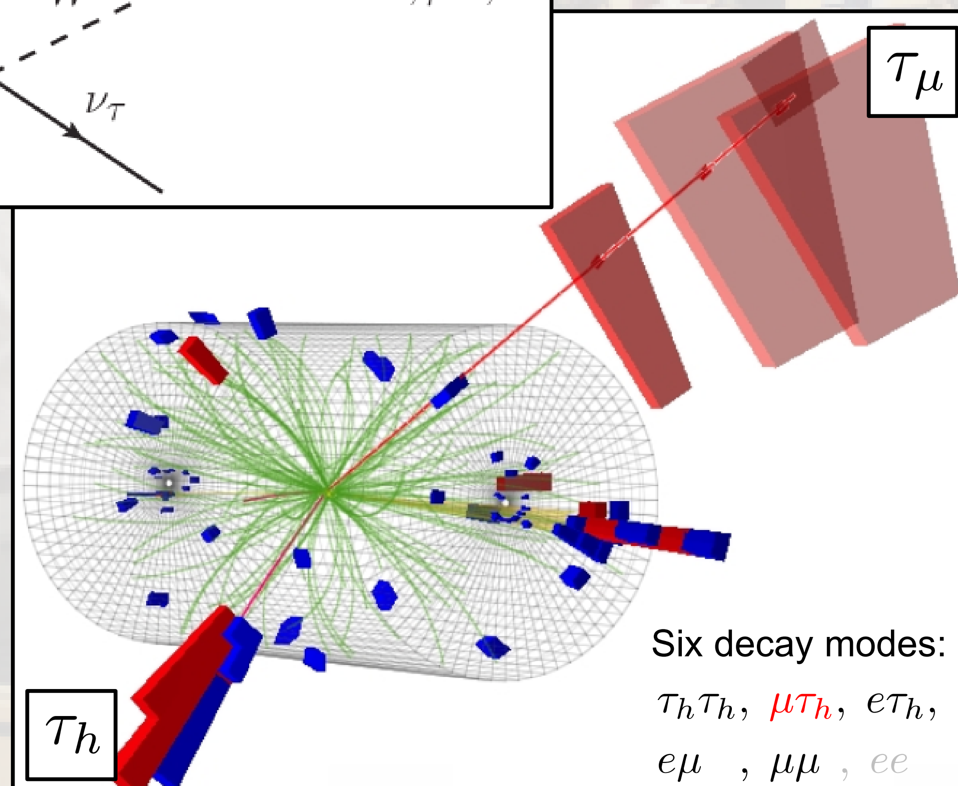
Significance:
$S = 2.1(2.5)\sigma$ (CMS)
$S = 1.4(2.6)\sigma$ (ATLAS)

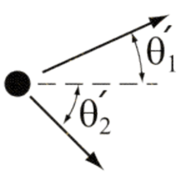
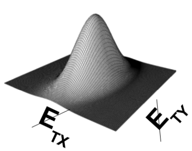
The $H \to \tau\tau$ decay channel

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 $m_{\tau\tau}$.



$\mathcal{L} =$  $\times$ 

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

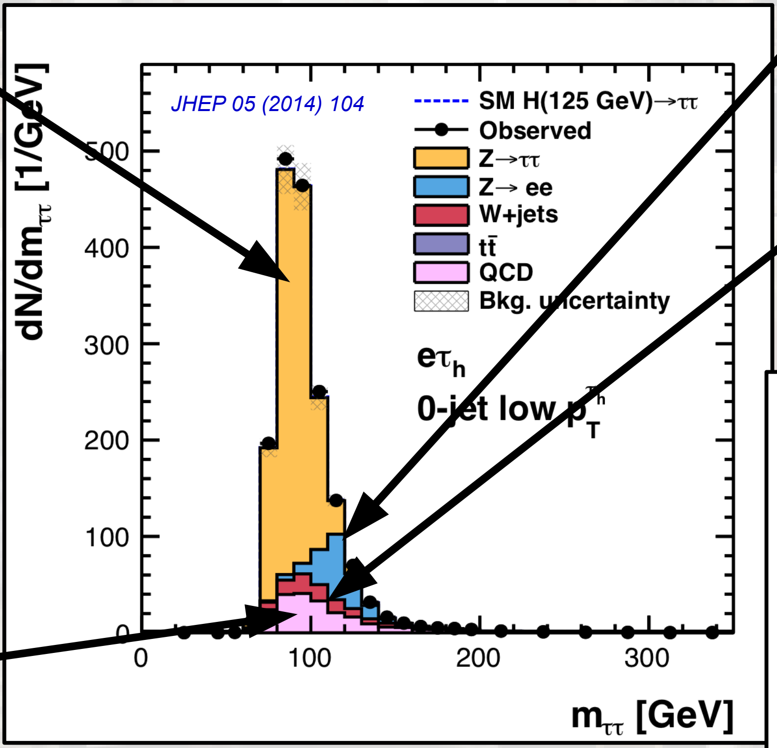
Control remaining backgrounds

$Z \to \tau\tau$

- 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

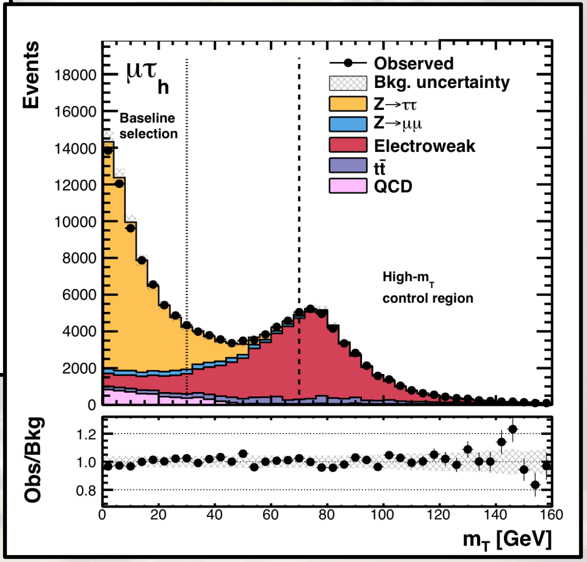
- From simulation
- Normalization from sidebands.

tt

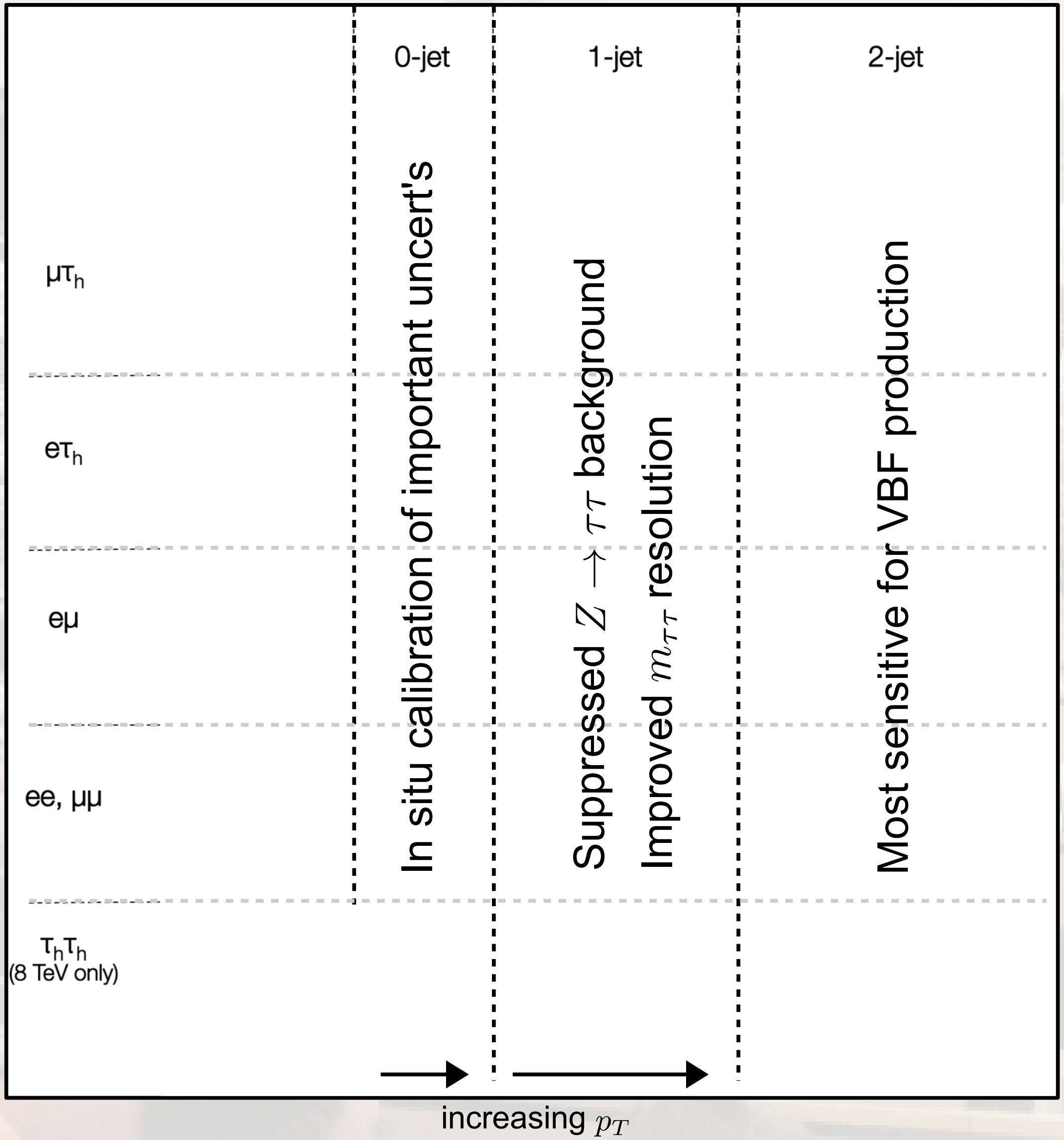
- From simulation.
- Normalization from sideband.

QCD multijet

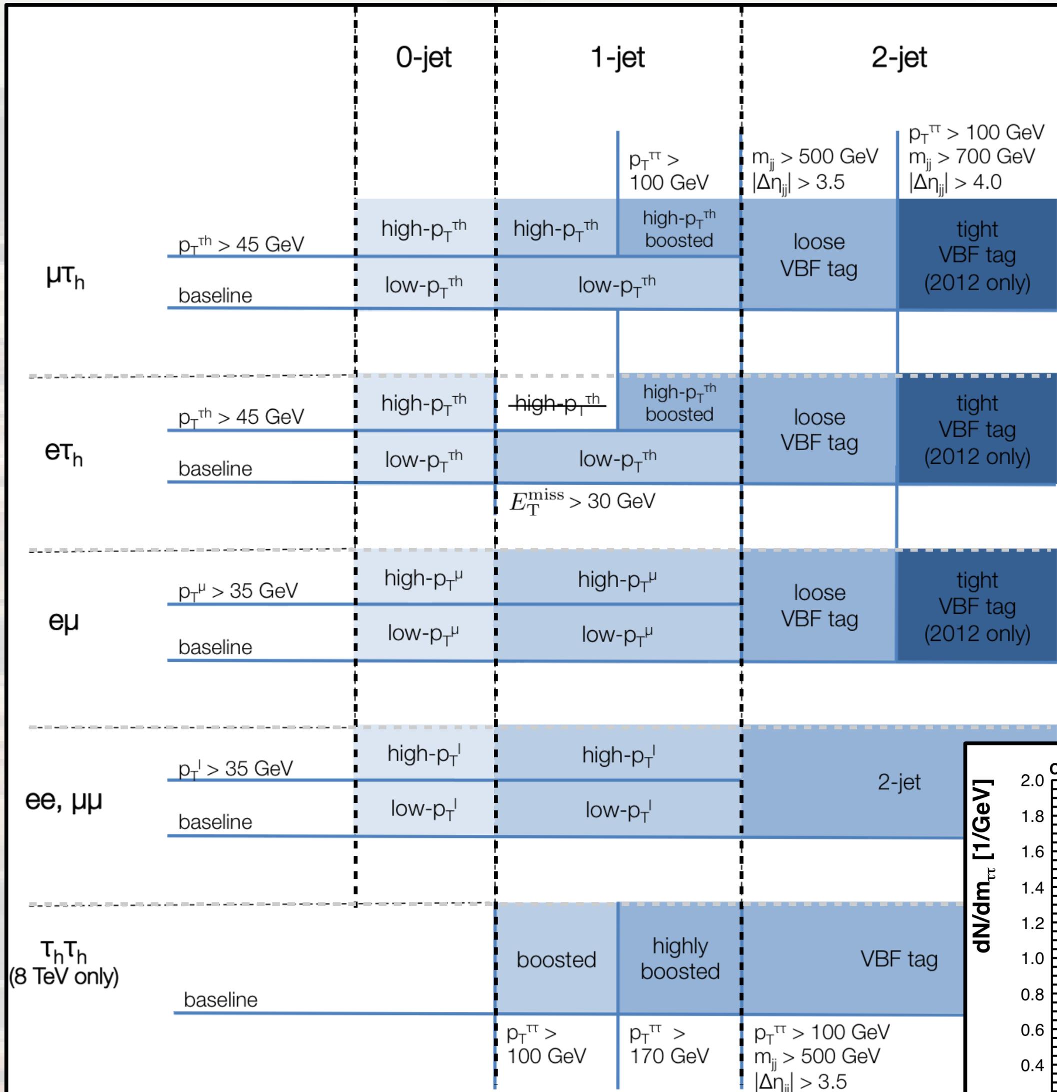
- Normalization & shape from data.



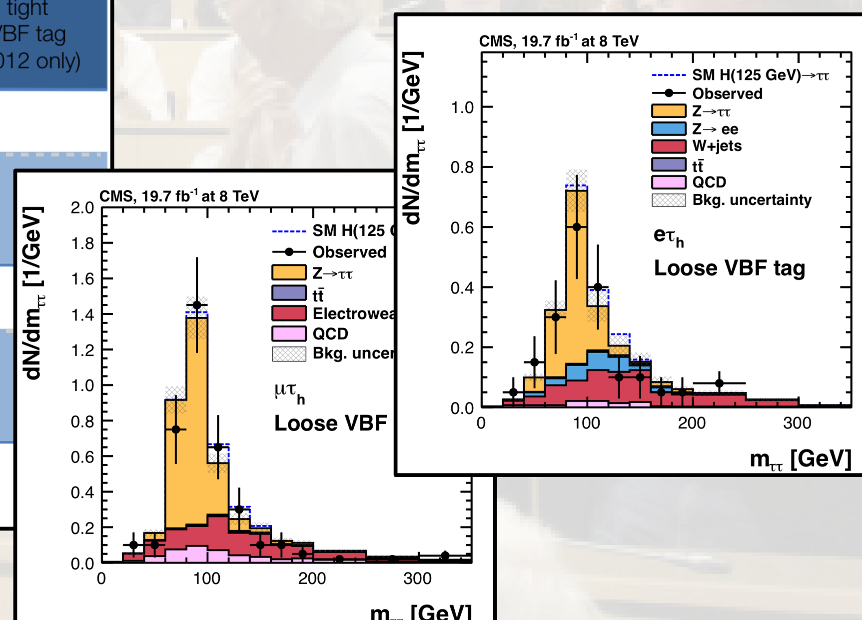
Further Event Categorization



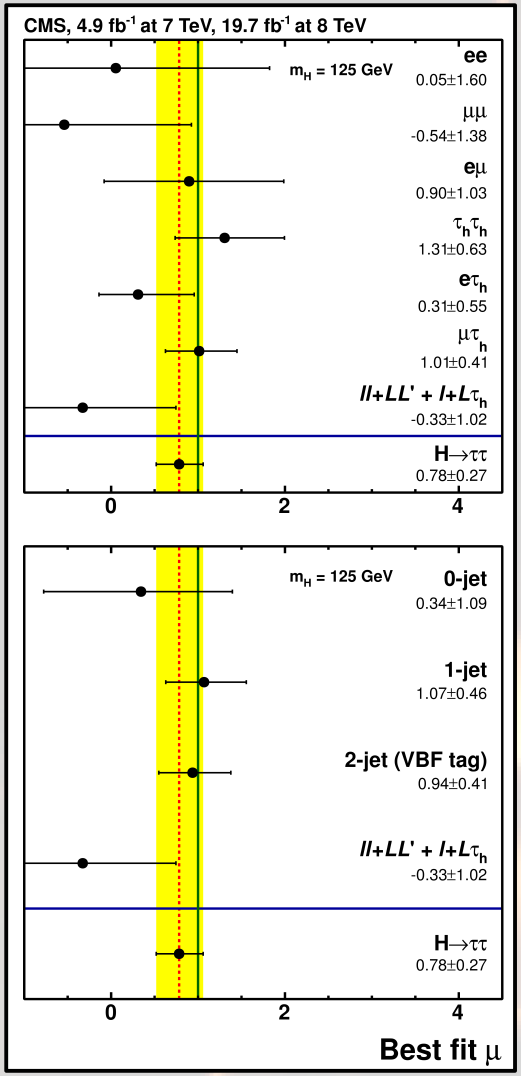
Further Event Categorization



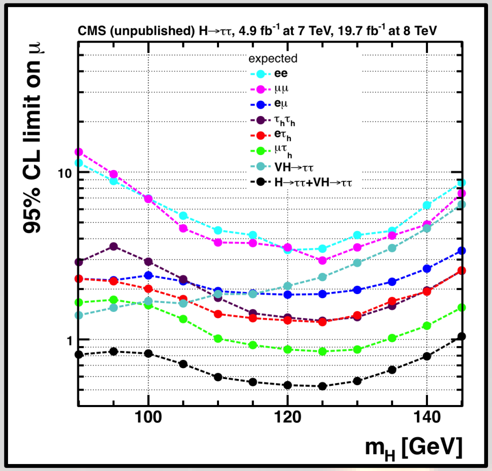
- 6 inclusive decay channels.
- Exclusive decay channels for production in association with W, Z bosons.
- Nearly 100 exclusive event categories (on 7+8 TeV dataset $\mathcal{O}(1200)$ single measurements, $\mathcal{O}(600)$ nuisance parameters).



Body of evidence

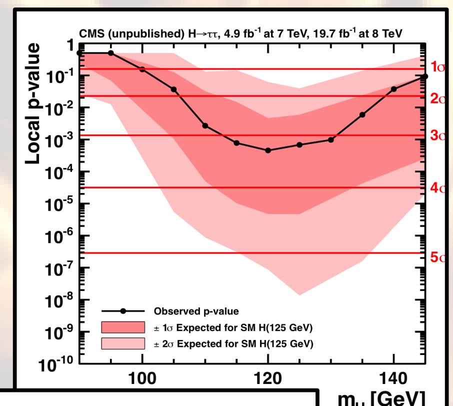


Consistent build-up of signal



Single channel sensitivity

p-value plot



Significance:
$S = 3.2(3.7)\sigma$ (CMS)
$S = 4.5(3.4)\sigma$ (ATLAS)

Homework left for LHC run-2:

- Convincingly establish observation of coupling to fermions.
- Turn observation into a measurement (→ cross section, fiducial/differential).
- Theoretically cleanest channel to measure CP of the Higgs.

JHEP 05 (2014) 104
NP 10 (2014) 557-560

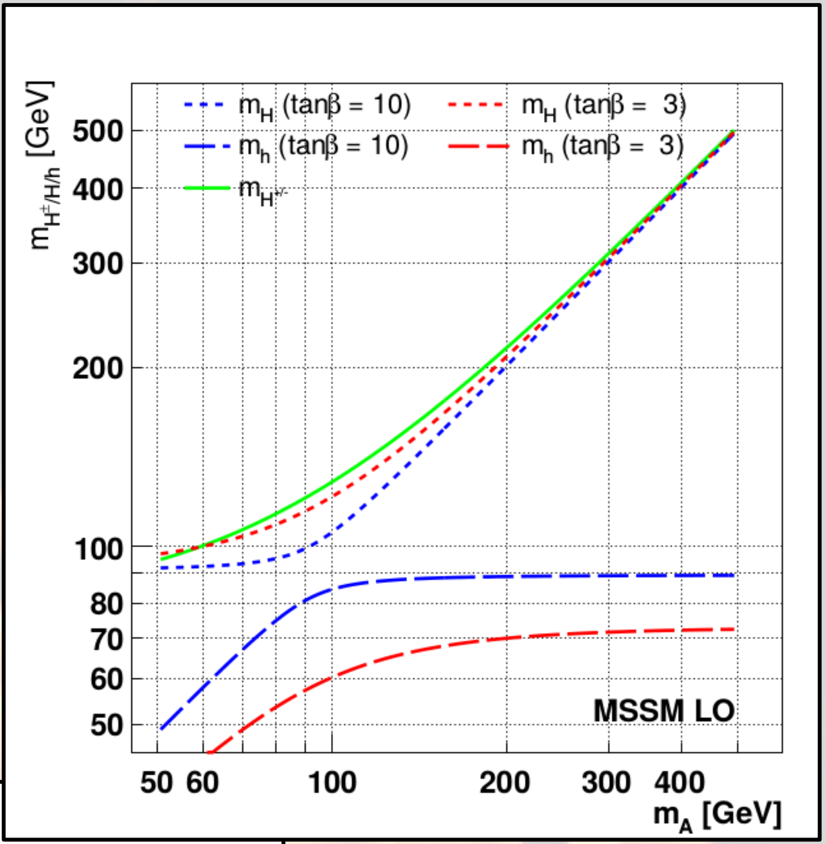
Extended Higgs sectors

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

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

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

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



- Strict mass requirements at tree level:

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

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

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

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

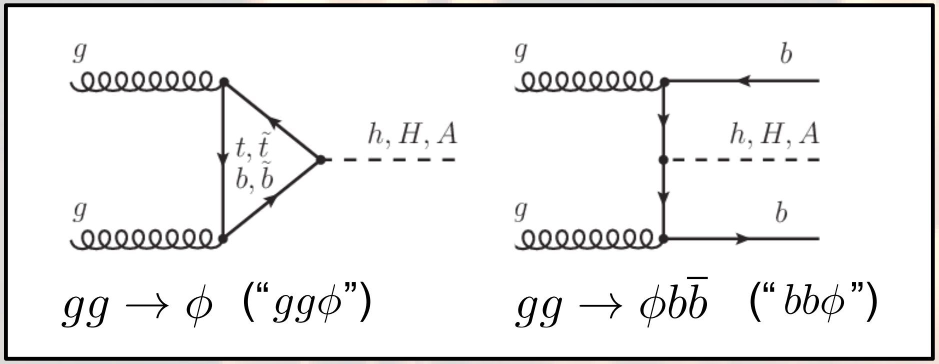
(angle btw. H_u & H_d in isospace)

The role of down-type fermions

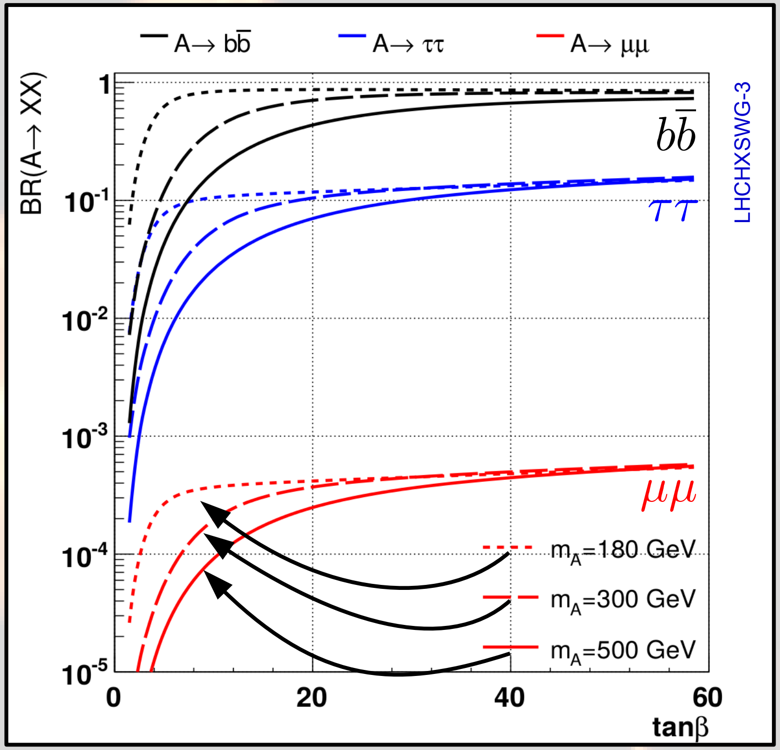
	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \to 0$	$\sin\alpha/\sin\beta \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \to 1$	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to 1$

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

Interesting production modes:



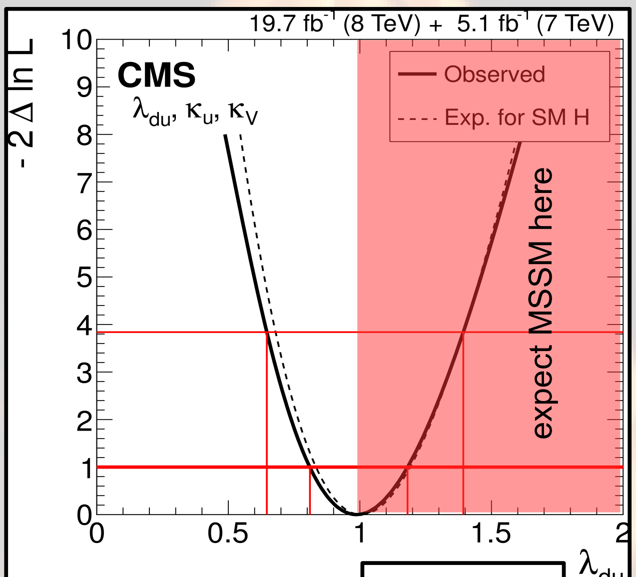
Interesting decay channels:



The role of down-type fermions

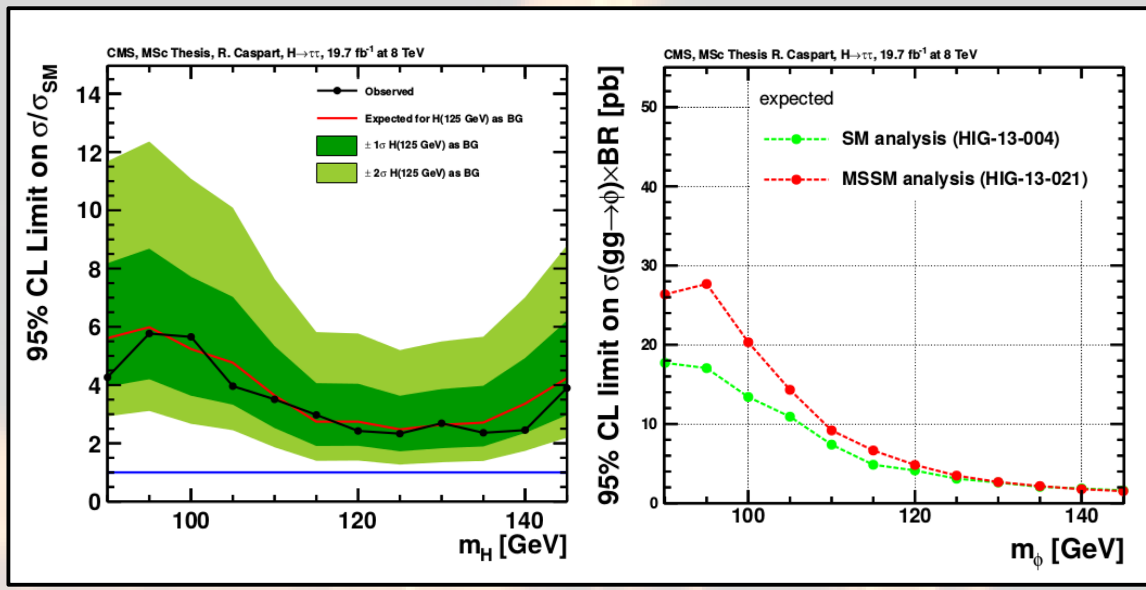
	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \to 0$	$\sin\alpha/\sin\beta \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \to 1$	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to 1$

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



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

EPJC 75 (2014) 212



IEKP-KA/2014-07

$H \to \tau\tau$: $\hat{\kappa}_\tau = 0.84^{+0.19}_{-0.18}$

$H \to bb$: $\hat{\kappa}_b = 0.74^{+0.33}_{-0.29}$

Modify SM $H \to \tau\tau$ analysis to scan for an additional *CP-odd* Higgs boson between 110 GeV and 145 GeV.

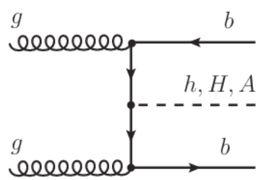
The search

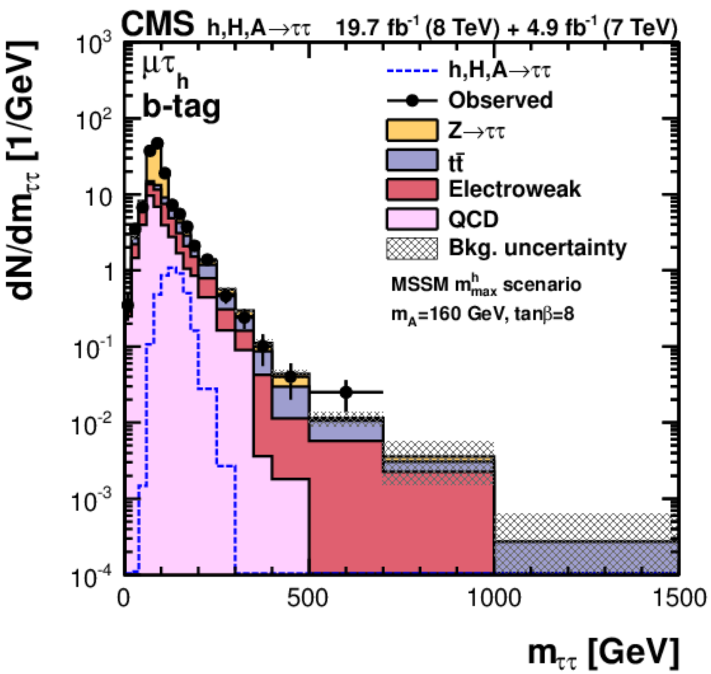
- Search for additional peak(s) in $m_{\tau\tau}$ distribution.

b-tag category:

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

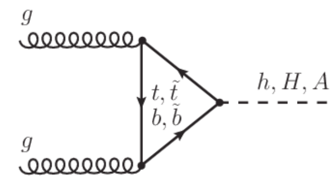
$N(\text{Jet}) \quad \leq 1$

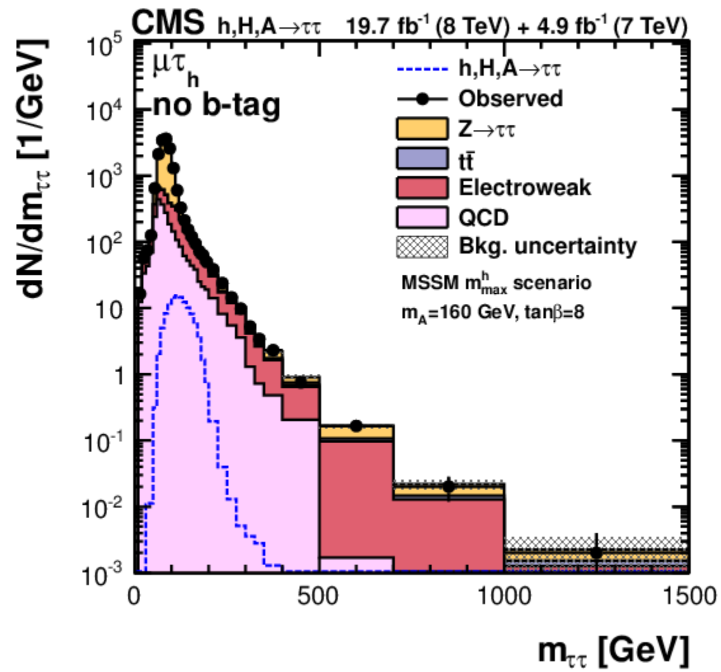




No b-tag category:

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

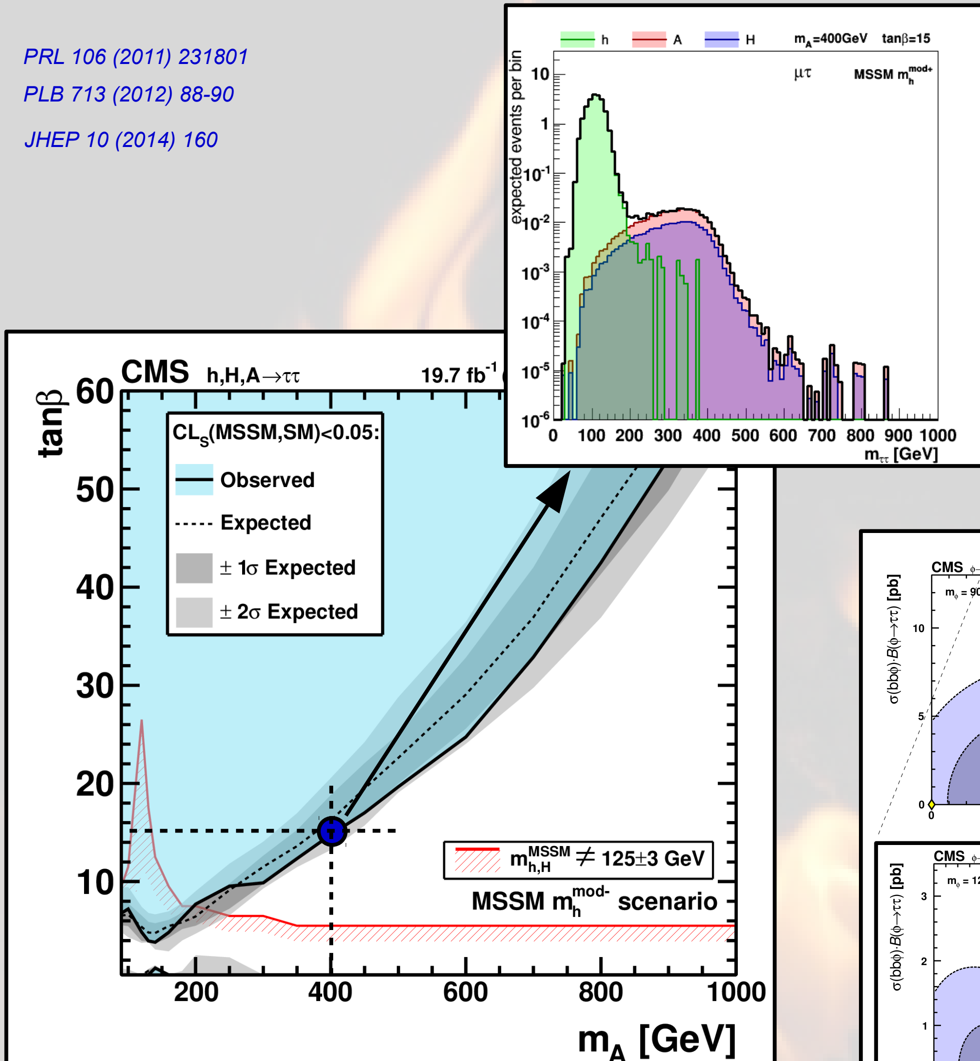


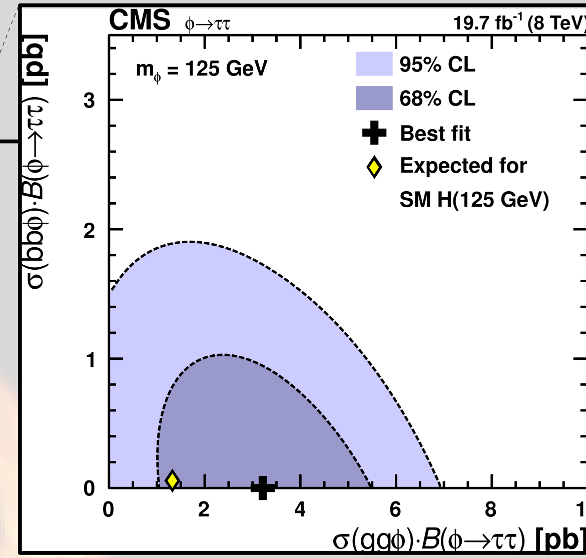


JHEP 10 (2014) 160

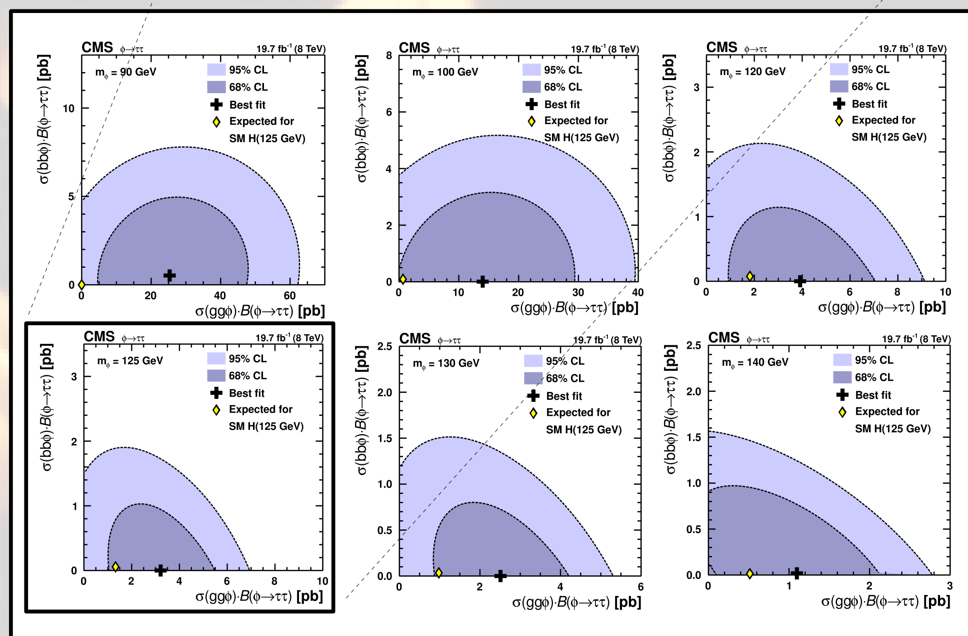
Presentation of outcome …

PRL 106 (2011) 231801
PLB 713 (2012) 88-90
JHEP 10 (2014) 160



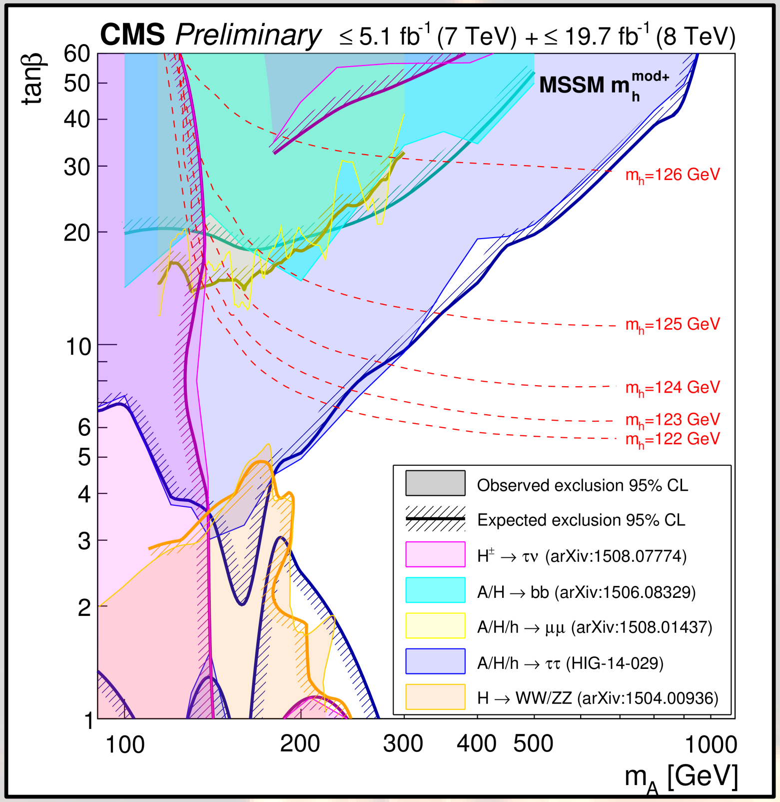


“Model independent” limits: single narrow resonance search in $gg\phi$ & $bb\phi$ mode.

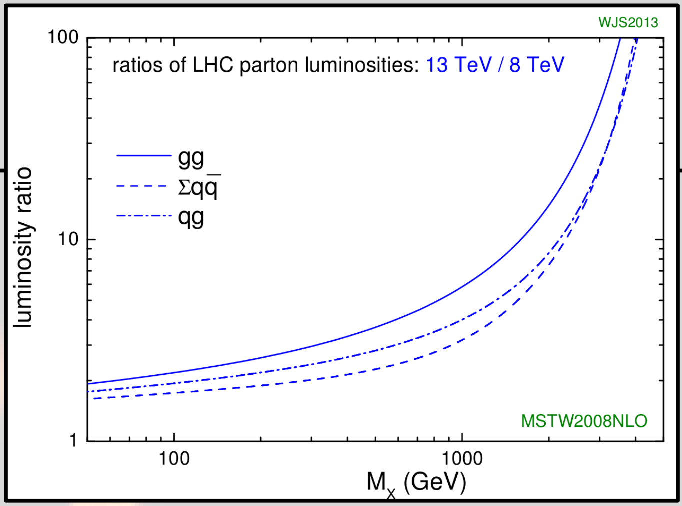


Full exclusion (here in m_h^{mod+} scenario).

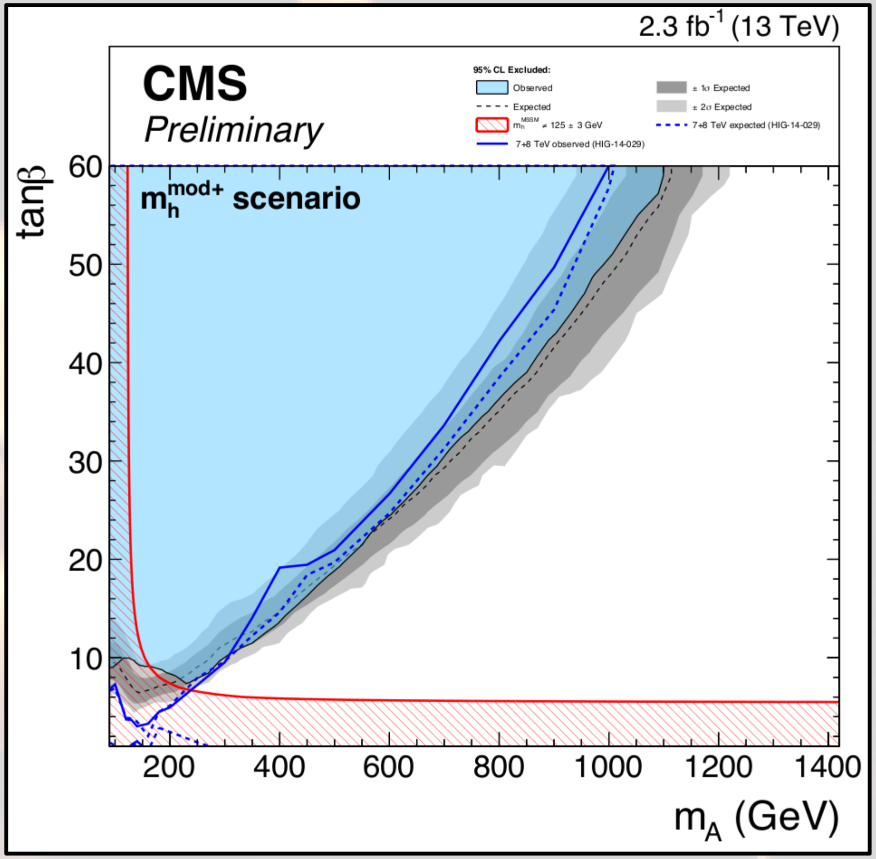
Latest greatest …



CMS-HIG-PAS-16-007



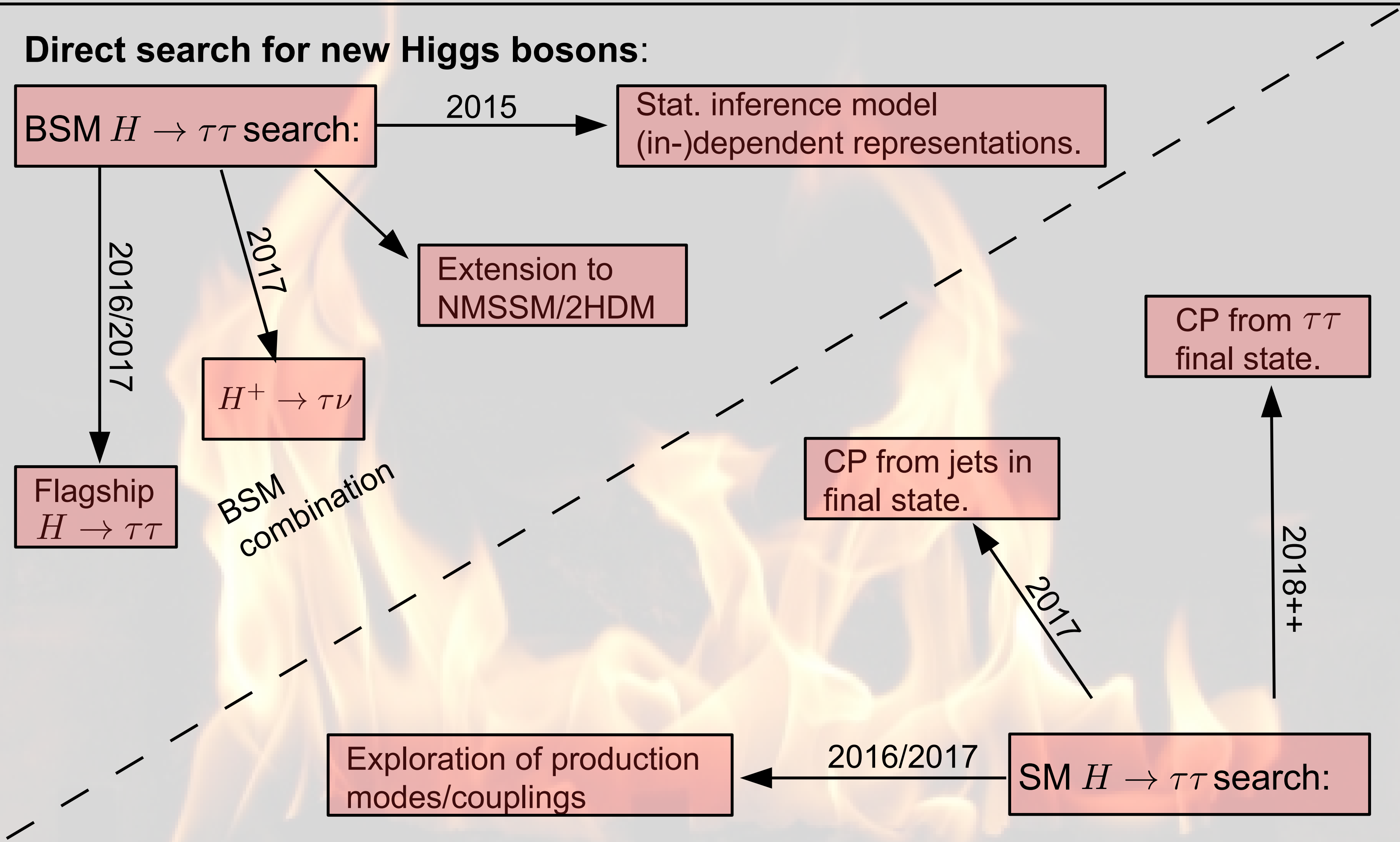
James Stirling (arXiv:0901.0002)



CMS-HIG-PAS-16-007

The Higgs pincer

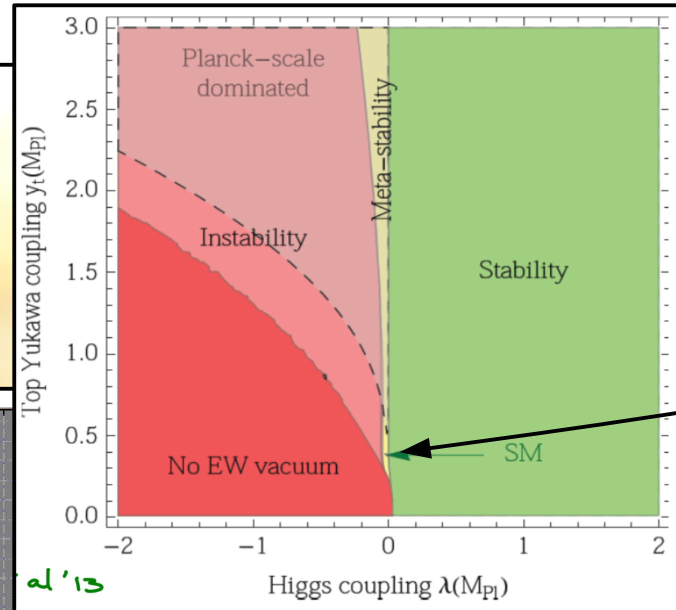
Direct search for new Higgs bosons:

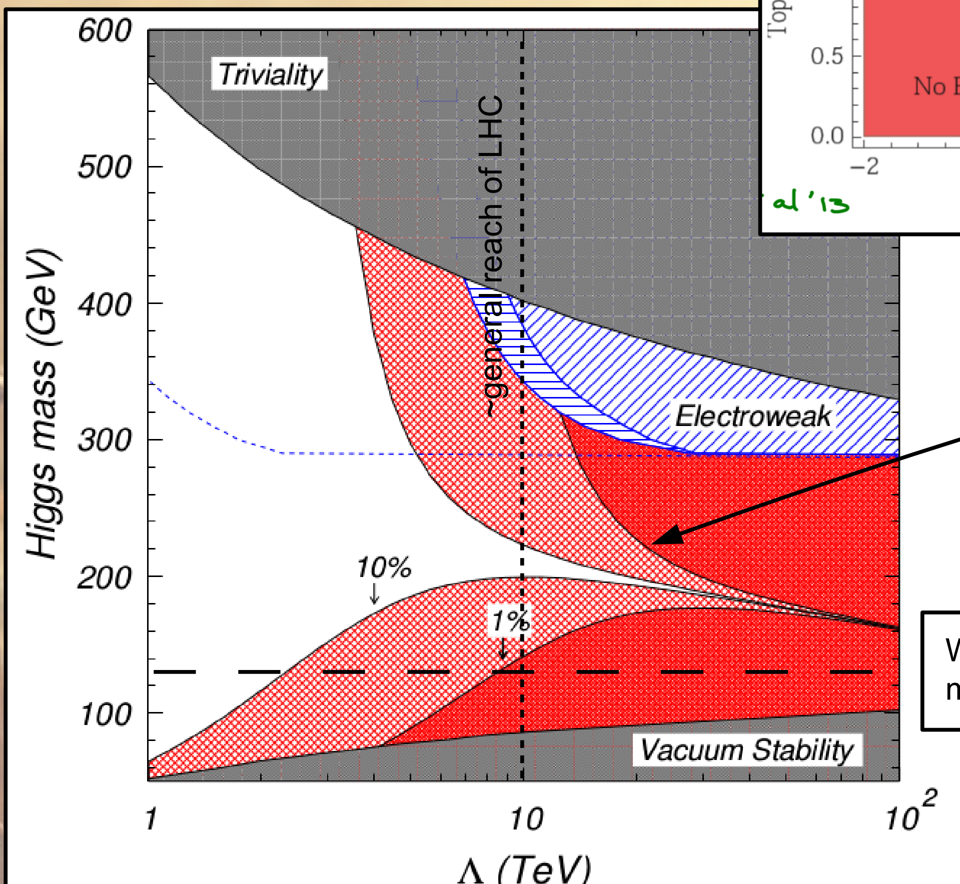


Deviations from SM expectation:

Closing in …

The SM in the stress field
of vacuum stability.





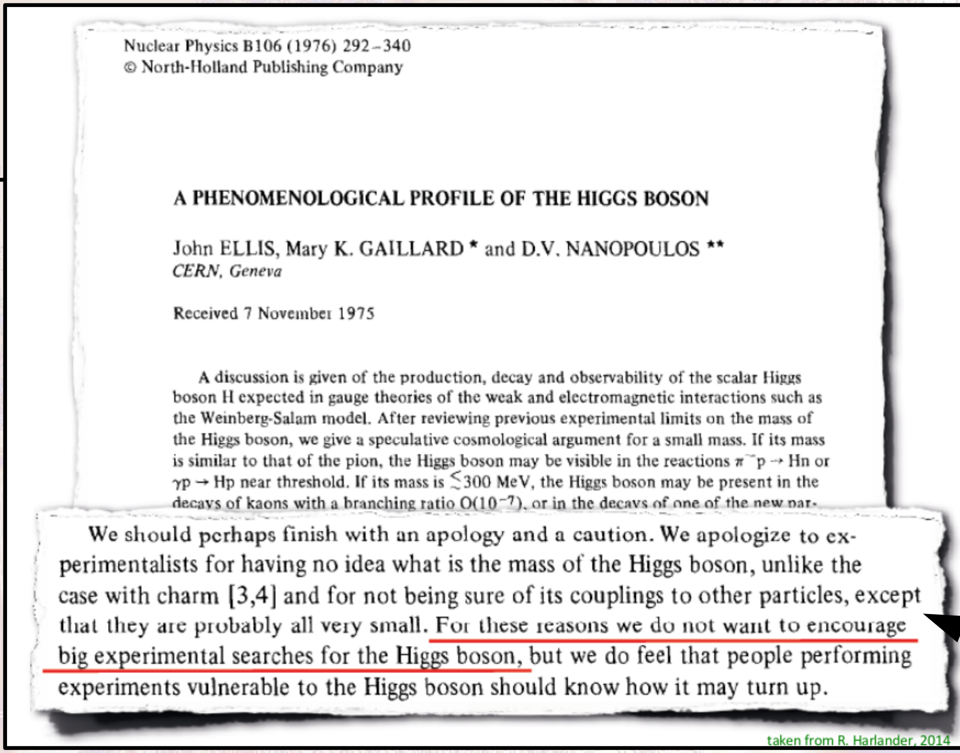
Different levels of fine tuning in the SM.

What we have found and measured for m_H.

Conclusion

- The Higgs (and more general electroweak) sector of the SM is mot exciting in HEP at the moment.
- Guaranteed new physics in reach (→ well motivated program of measurements & searches).
- In the SM Higgs sector fermion couplings are theoretically least understood and at the same time experimentally most difficult to study.
- This program can be linked up with several interesting corners of HEP (including the unexpected …).

Backup



Nuclear Physics B106 (1976) 292–340
© North-Holland Publishing Company

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim$300 MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new par-

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

taken from R. Harlander, 2014

1961: First formulation of a unification of electromagnetic and weak force.

1962: Spontaneous symmetry breaking in super conductivity.

1964: Higgs mechanism in particle physics.

1967: Formulation of electroweak SM.

1971: Proof of renormalizability.

1974-77: Discovery of *charm*, τ and *bottom*.

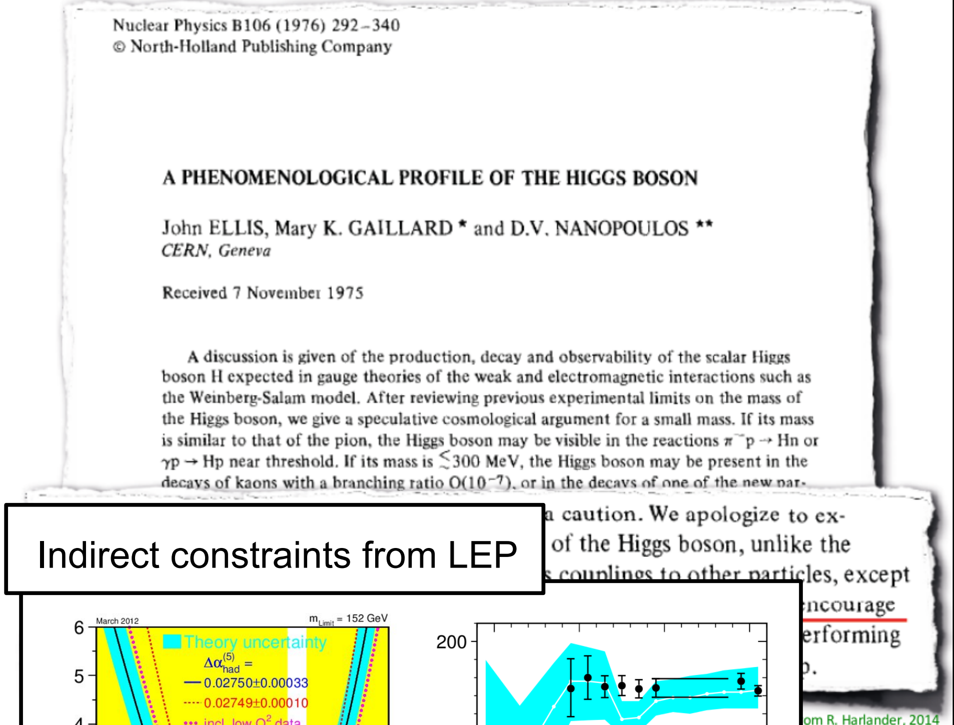
1983: Discovery of *W* and *Z*.

1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

2013: Nobel prize to Peter Higgs and Francois Englert.


Nuclear Physics B106 (1976) 292–340
© North-Holland Publishing Company

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

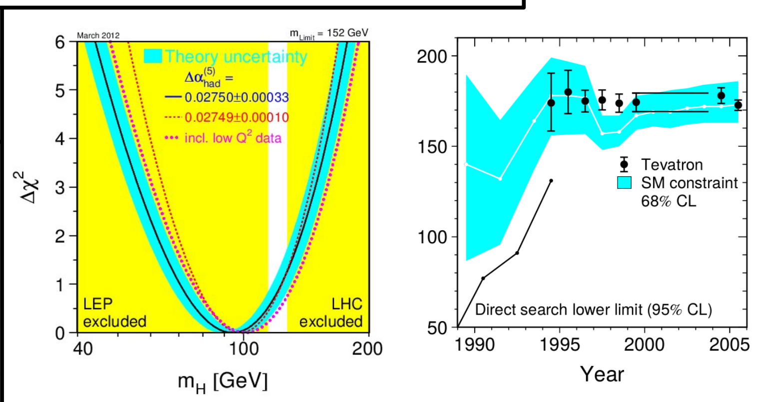
Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim 300$ MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new par-

...a caution. We apologize to ex-
...of the Higgs boson, unlike the
...s couplings to other particles, except
...ncourage
...erforming
...p.

...om R. Harlander, 2014

Indirect constraints from LEP



$m_H = 98 \pm^{25}_{21}$ GeV $m_t = 178.1 \pm^{10.9}_{7.8}$ GeV

1961: First formulation of a unification of electromagnetic and weak force.

1962: Spontaneous symmetry breaking in super conductivity.

1964: Higgs mechanism in particle physics.

1967: Formulation of electroweak SM.

1971: Proof of renormalizability.

1974-77: Discovery of *charm*, τ and *bottom*.

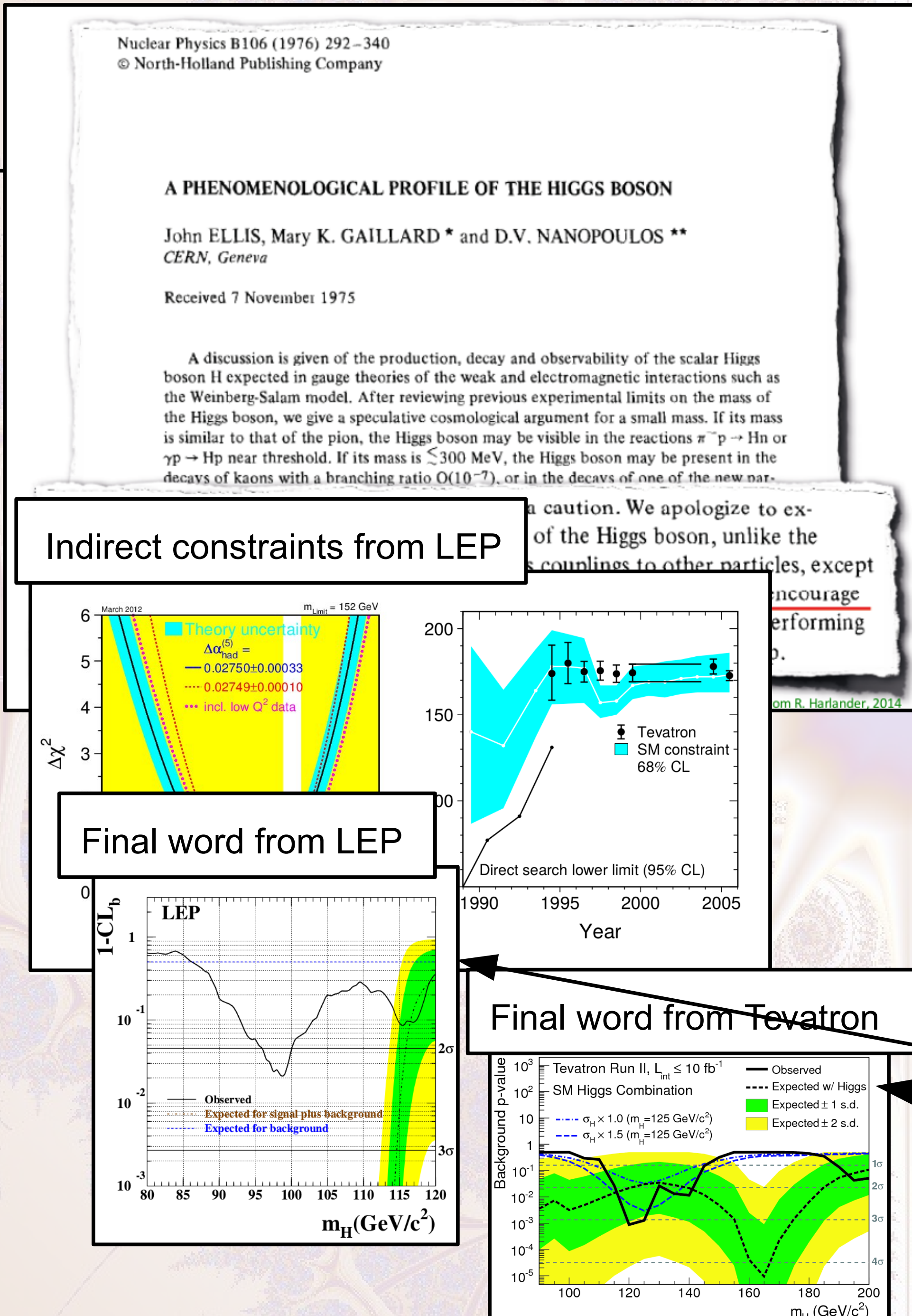
1983: Discovery of *W* and *Z*.

1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

2013: Nobel prize to Peter Higgs and Francois Englert.


Nuclear Physics B106 (1976) 292–340
© North-Holland Publishing Company

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of the Higgs boson, we give a speculative cosmological argument for a small mass. If its mass is similar to that of the pion, the Higgs boson may be visible in the reactions $\pi^- p \to Hn$ or $\gamma p \to Hp$ near threshold. If its mass is $\lesssim 300$ MeV, the Higgs boson may be present in the decays of kaons with a branching ratio $O(10^{-7})$, or in the decays of one of the new par-

... a caution. We apologize to ex- ... of the Higgs boson, unlike the ... s couplings to other particles, except ... ncourage ... erforming ... p.

1961: First formulation of a unification of electromagnetic and weak force.

1962: Spontaneous symmetry breaking in super conductivity.

1964: Higgs mechanism in particle physics.

1967: Formulation of electroweak SM.

1971: Proof of renormalizability.

1974-77: Discovery of *charm*, τ and *bottom*.

1983: Discovery of *W* and *Z*.

1995: Discovery of *top*.

2000: Discovery of ν_τ .

2012: Discovery of Higgs boson.

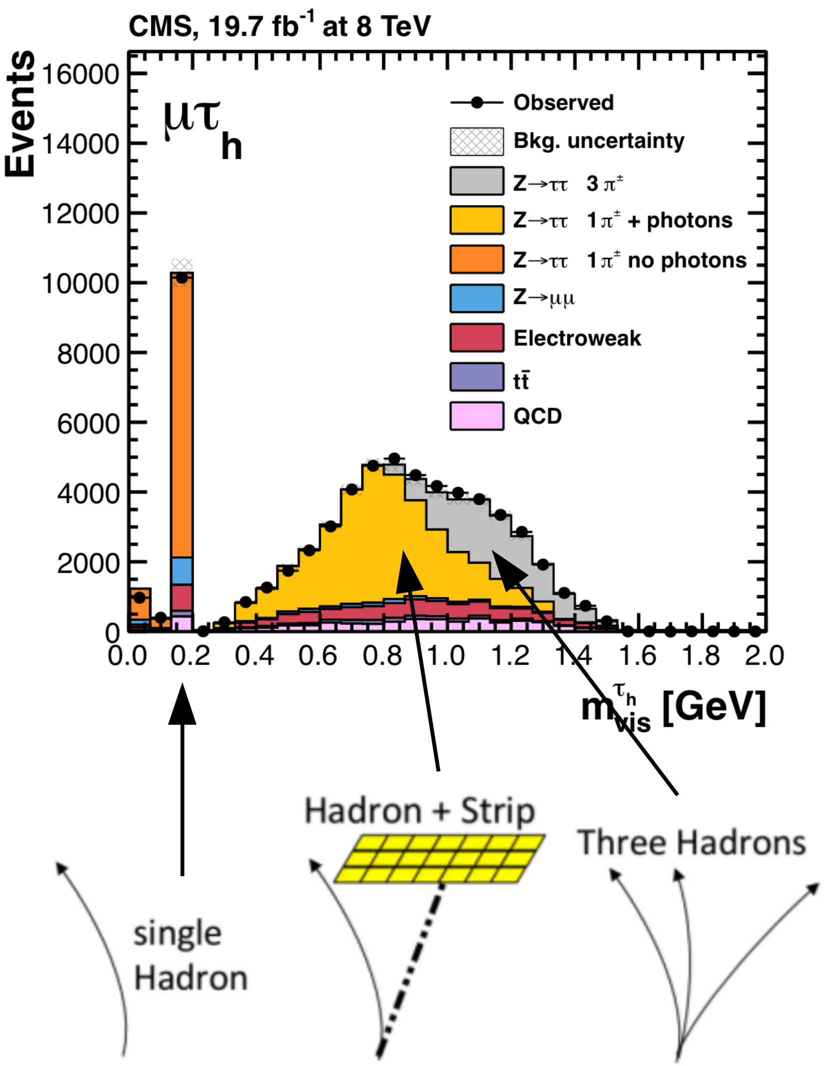
2013: Nobel prize to Peter Higgs and Francois Englert.

Event Estimates for LHC run-2

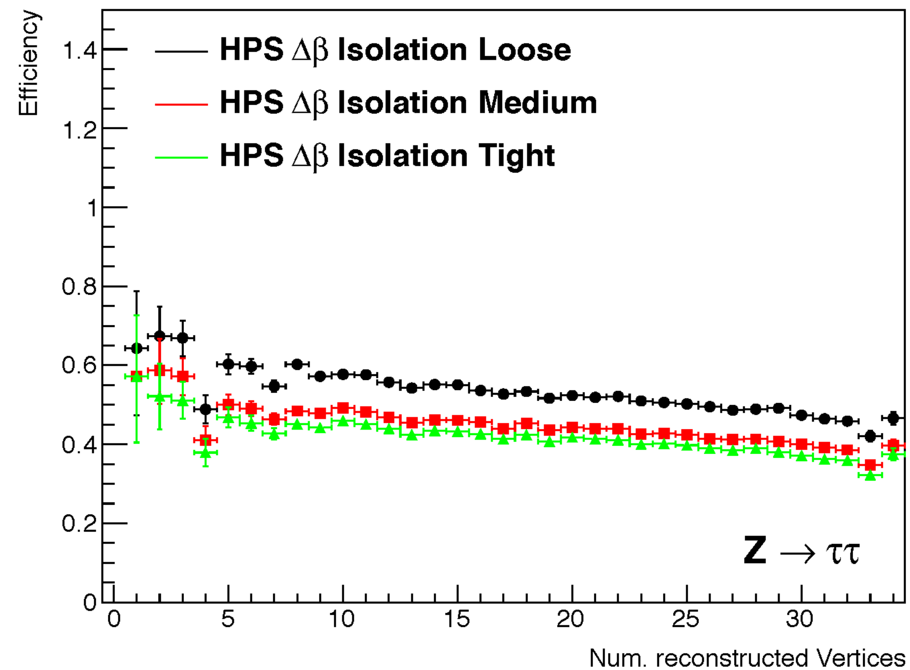
Decay	$\sqrt{s} = 8$ TeV, 20 fb^{-1}	$\sqrt{s} = 13$ TeV, 300 fb^{-1}					
Channel	inclusive	inclusive	$gg \to H$	$qq \to H$	WH	ZH	$t\bar{t}H$
$\gamma\gamma$	1 000	33 000	30 000	2 300	1 000	700	300
ZZ	50	1 500	1 300	100	50	30	15
WW	5 000	150 000	130 000	10 000	4 500	3 000	1 500
$b\bar{b}$	12 000	400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

Rough estimates of event yields before reconstruction and selection.

Performance of hadronic τ reconstruction

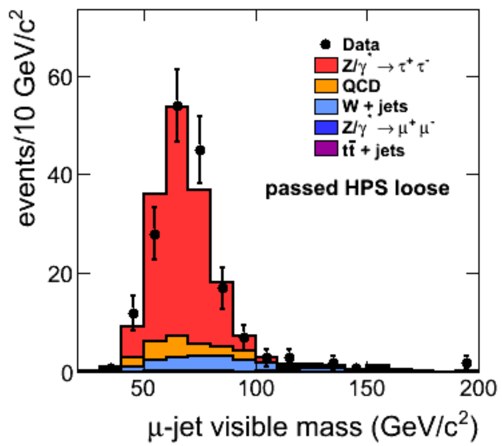


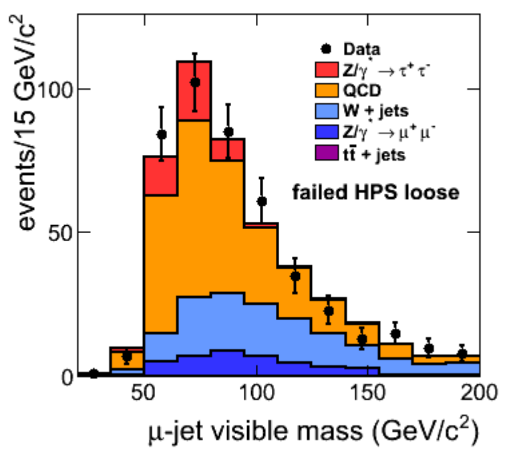
- Efficiency $\approx 60\%$ ($\approx 3\%$ fakerate), flat for $p_T(\tau) > 30$ GeV & independent from pileup events.



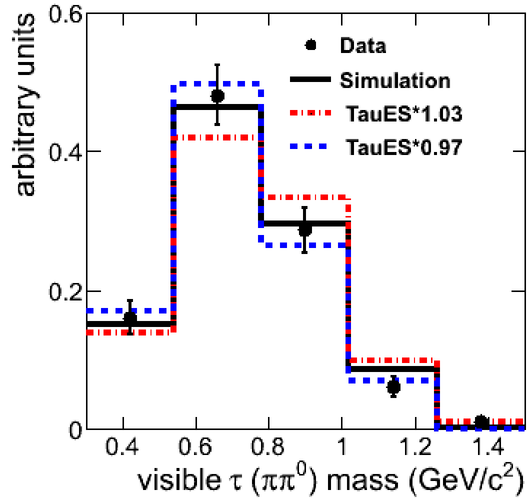
Performance of hadronic τ reconstruction

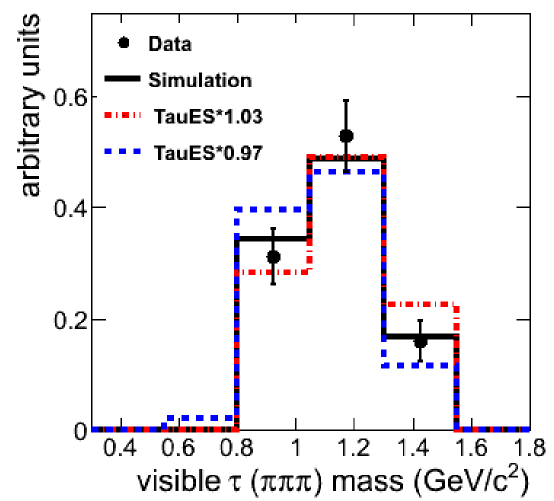
- Control efficiency within $\pm 7\%$ using tag & probe methods:





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

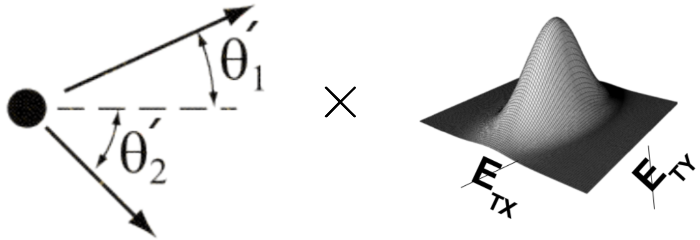


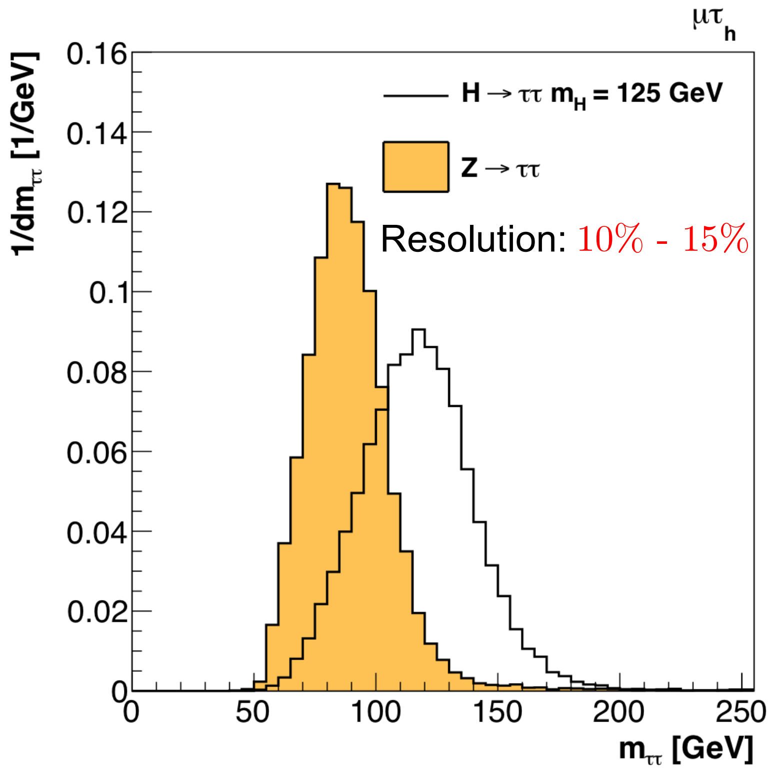


- Uncertainties further constrained by maximum likelihood fit in the statistical inference for signal extraction.

Analysis Strategy

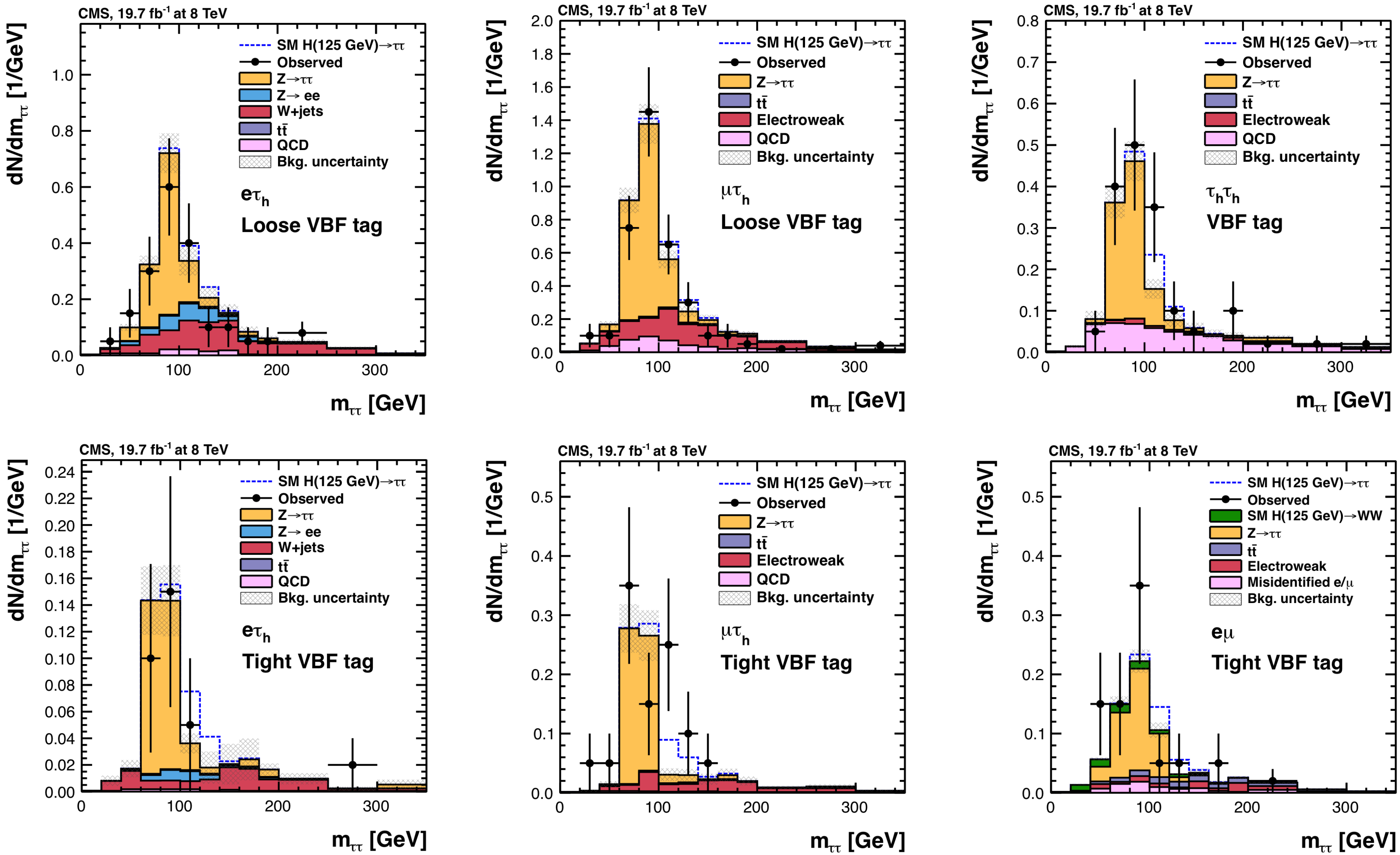
- Analyze all six inclusive decay channels ($\tau_h\tau_h,\ \mu\tau_h,\ e\tau_h,\ e\mu,\ \mu\mu,\ ee$) & many more exclusive decay channels for VH production ($Z \to \ell\ell,\ W \to \ell\nu$).
- Select two isolated leptons ($\tau_h,\ \mu,\ e$).
- Restrict $\not{E}_T$ to reduce background from $W + \mathrm{jets}$ events.
- Use fully reconstructed $m_{\tau\tau}$ as discriminating variable:

$\mathcal{L} =$ 



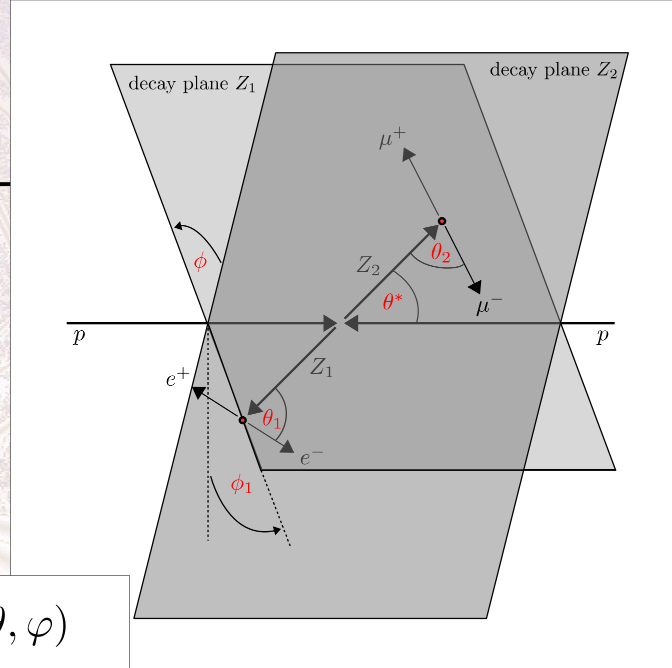
- Inputs: visible leptons, x-, y-component of $\not{E}_T$.
- Free parameters: φ, θ^*, ($m_{\nu\nu}$) per τ.

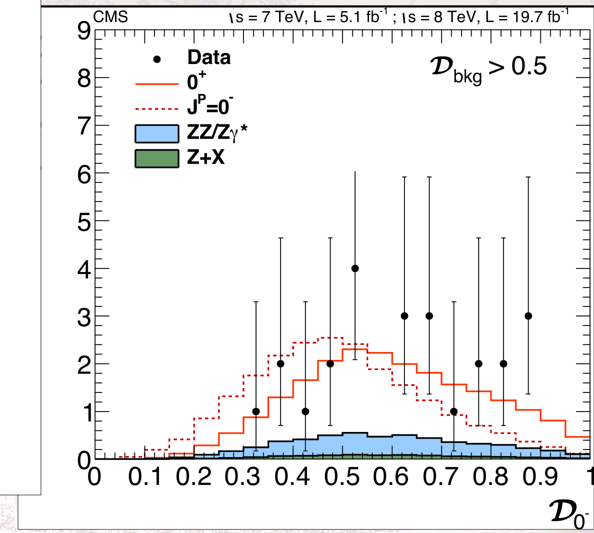
Distribution of $m_{\tau\tau}$



Spin & CP

- Golden decay channel:
  $H \to ZZ \to 4\ell$

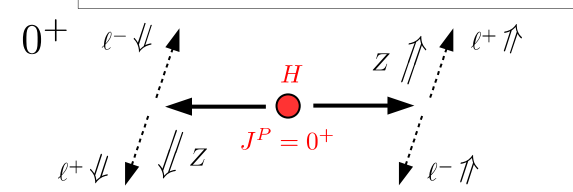




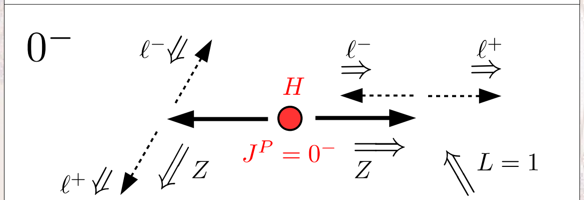
PRD 89 (2014) 092007

$$P(Y_L^m(\theta,\varphi)) = (-1)^L \cdot Y_L^m(\theta,\varphi)$$

$$P(4\ell) = (-1)^L(-1)^2(+1)^2 = (-1)^L$$

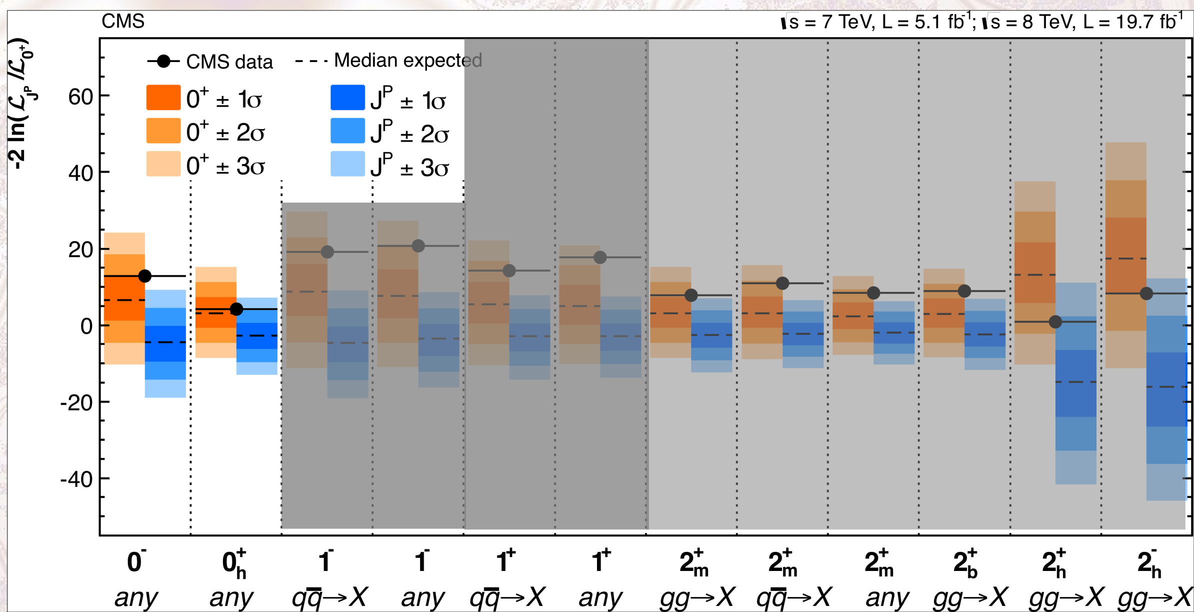


$$|0,0\rangle = \sqrt{\tfrac{1}{3}}|1,\ \ 1\rangle \otimes |1,-1\rangle - \sqrt{\tfrac{1}{3}}|1,0\rangle \otimes |1,0\rangle + \sqrt{\tfrac{1}{3}}|1,-1\rangle \otimes |1,\ \ 1\rangle$$



$$|1,\pm1\rangle = \sqrt{\tfrac{1}{2}}|1,\pm1\rangle \otimes |1,0\rangle - \sqrt{\tfrac{1}{2}}|1,0\rangle \otimes |1,\pm1\rangle$$

Test of pure spin hypotheses (based on $\mathcal{O}(50)$ evts):



CP admixtures

- General phenomenology of non-*CP* conserving HVV couplings:

$$A(HVV) \propto \left[a_1^{VV} + \kappa_1^{VV}\frac{q_{V1}^2}{\Lambda^2}\right] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* f_{\mu\nu} f^{*(2),\mu\nu} + a_3^{VV} f_{\mu\nu}^{(1)} \tilde{f}^{*(2),\mu\nu}$$

(LO-amplitude formalism)

Applied to: HWW, HZZ, $HZ\gamma$, $H\gamma\gamma$.

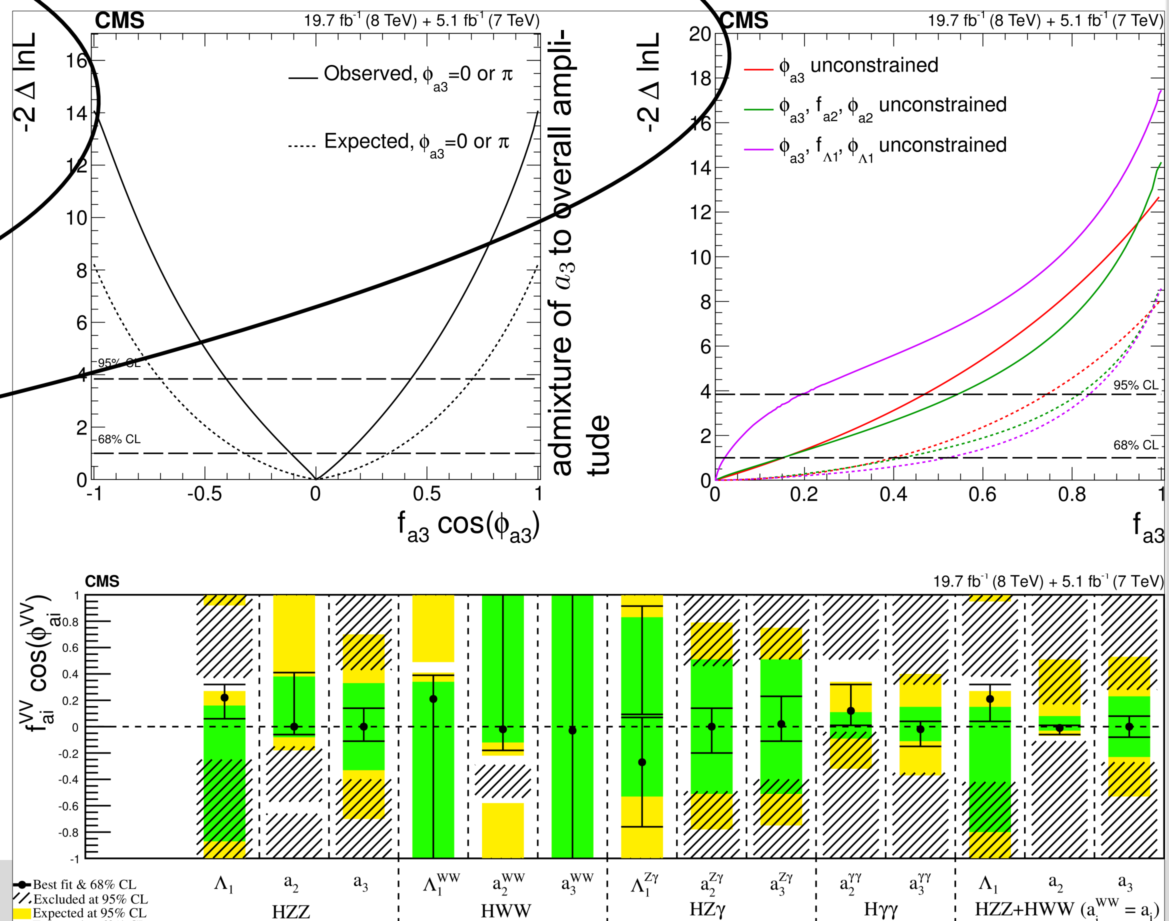
PRD 92 (2015) 012004

SM CP-even

CP-even "higher dimension"

CP-odd admixture.

admixture of a_3 to overall amplitude



$$f^{(i),\mu\nu} = \epsilon_{Vi}^{\mu} q_{Vi}^{\nu} - \epsilon_{Vi}^{\nu} q_{Vi}^{\mu}$$

$$\tilde{f}_{\mu\nu}^{(i)} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} \tilde{f}^{(i),\rho\sigma}$$

m_{V1}^2 (vector boson mass)

ϵ_{Vi} (polarization vector)

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

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

Orbital momentum:	$\times$	Intrinsic parity of fermions:
$P(Y_l^m(\theta,\varphi)) = (-1)^l \cdot Y_l^m(\theta,\varphi)$		$P(f) = (+1)\cdot f \qquad P(\bar{f}) = (-1)\cdot f$

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

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

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

- For two fermion system:

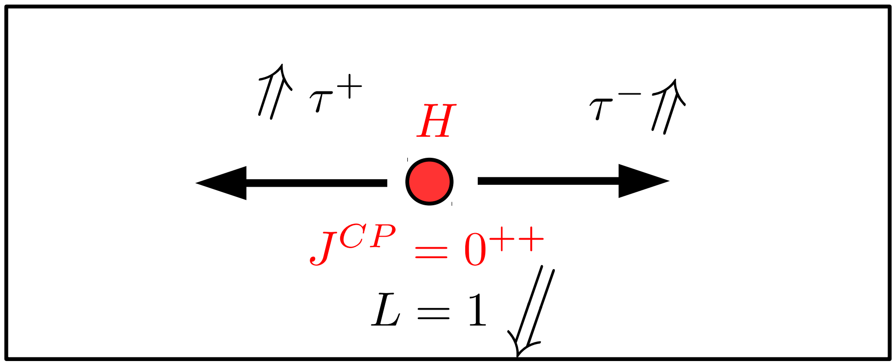
$$\begin{aligned} P &= (-1)^{L+1} \\ C &= (-1)^{L+S} \\ CP &= (-1)^{S+1} \end{aligned}$$

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

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

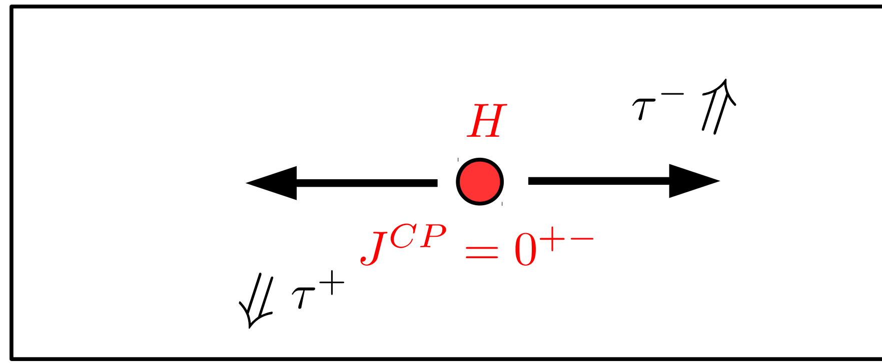
CP-even:

$L = 1 \quad S = 1$



CP-odd:

$L = 0 \quad S = 0$



- For two fermion system:

$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$
$$CP = (-1)^{S+1}$$

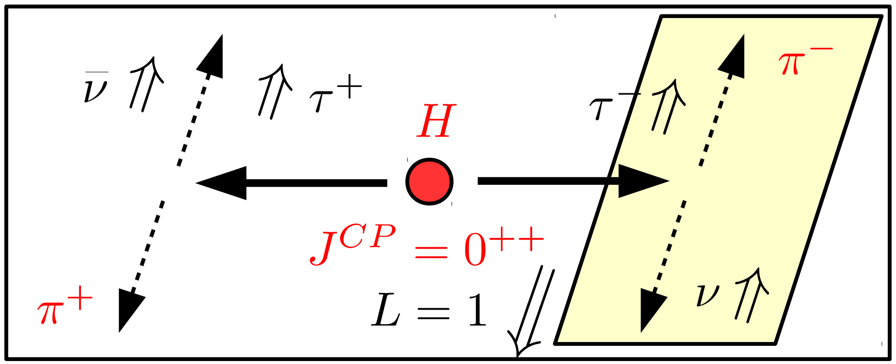
CP of parent particle translates into spin configuration of two fermion system.

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

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

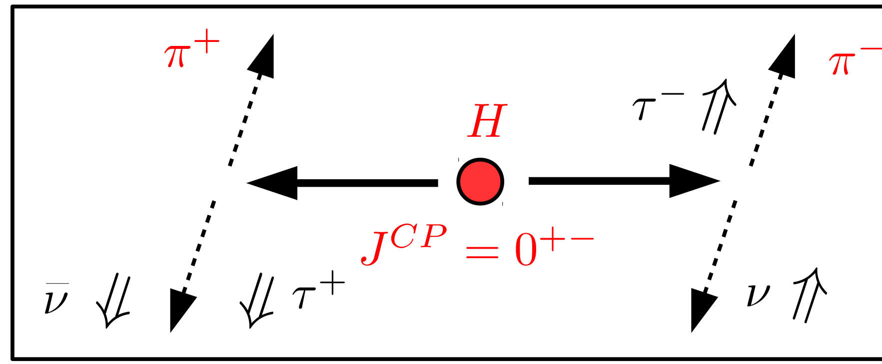
CP-even:

$L = 1 \quad S = 1$



CP-odd:

$L = 0 \quad S = 0$



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

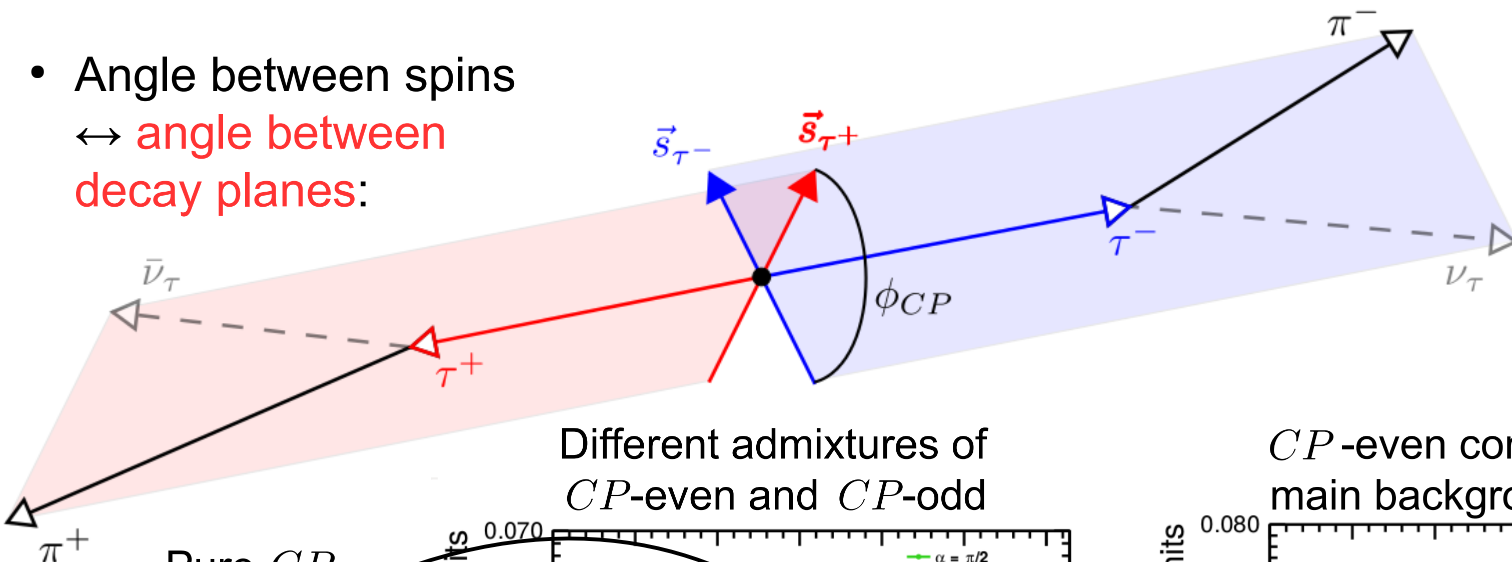
- For two fermion system:

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

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

Transverse spin polarization in the di-τ system

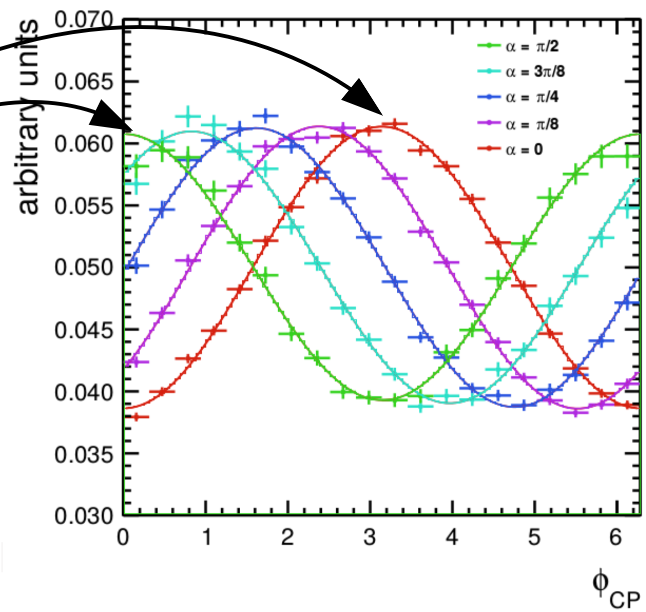
- Angle between spins $\leftrightarrow$ angle between decay planes:



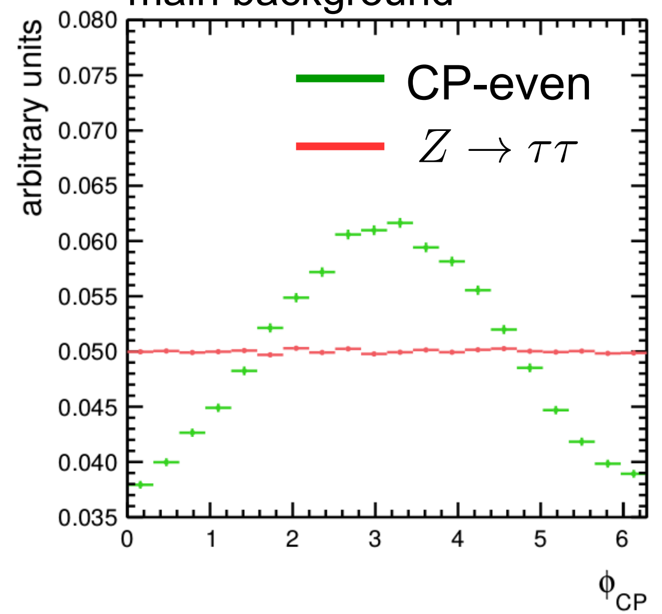
Pure CP-even

Pure CP-odd

Different admixtures of CP-even and CP-odd



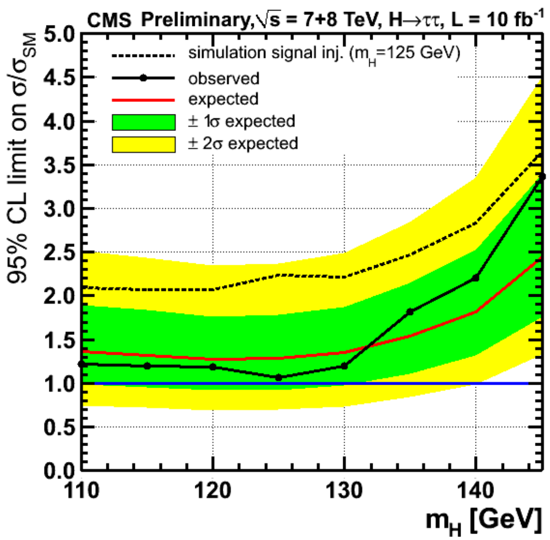
CP-even compared to main background



arXiv:0812.1910
arXiv:1108.0607
arXiv:1408.0798

$H \to \tau\tau$ Decay Channel

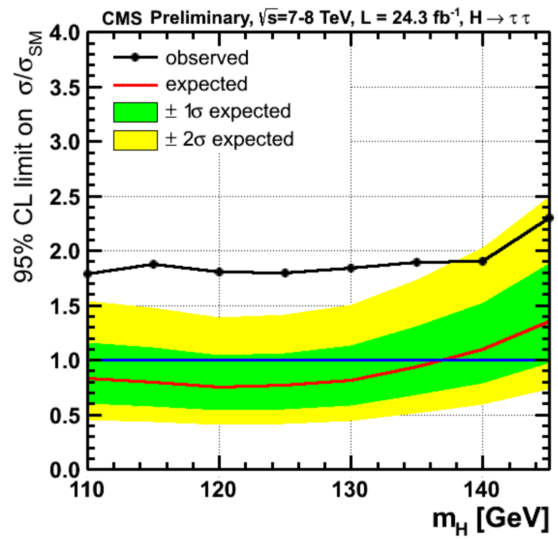
Status **July 2012**:



$$\mu = \text{N.A.}$$
$$\sigma = 0(\text{obs}) \;\; 1.4(\text{exp})$$

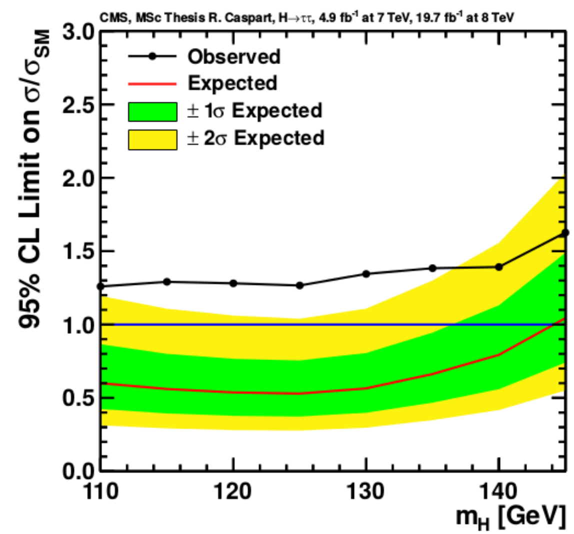
$@ \; m_H \approx 125$ GeV

Status **March 2013**:



$$\mu = 1.1 \pm 0.4$$
$$\sigma = 2.9(\text{obs}) \;\; 2.6(\text{exp})$$

Status **Summer 2014**:

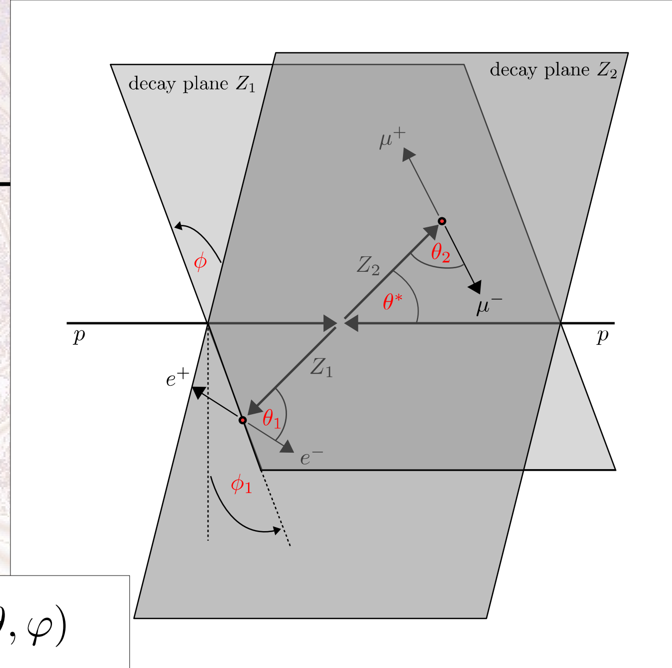


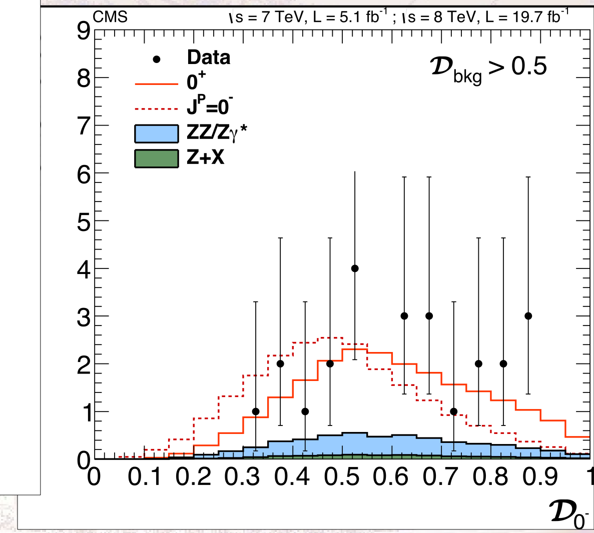
$$\mu = 0.8 \pm 0.3$$
$$\sigma = 3.2(\text{obs}) \;\; 3.7(\text{exp})$$

Treating contributions from $H \to WW$ as background.

Spin & CP

- Golden decay channel:
  $H \to ZZ \to 4\ell$

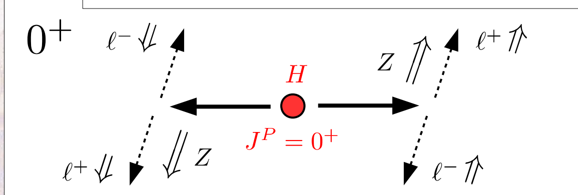




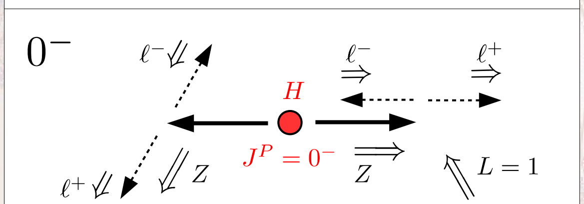
PRD 89 (2014) 092007

$$P(Y_L^m(\theta,\varphi)) = (-1)^L \cdot Y_L^m(\theta,\varphi)$$

$$P(4\ell) = (-1)^L(-1)^2(+1)^2 = (-1)^L$$

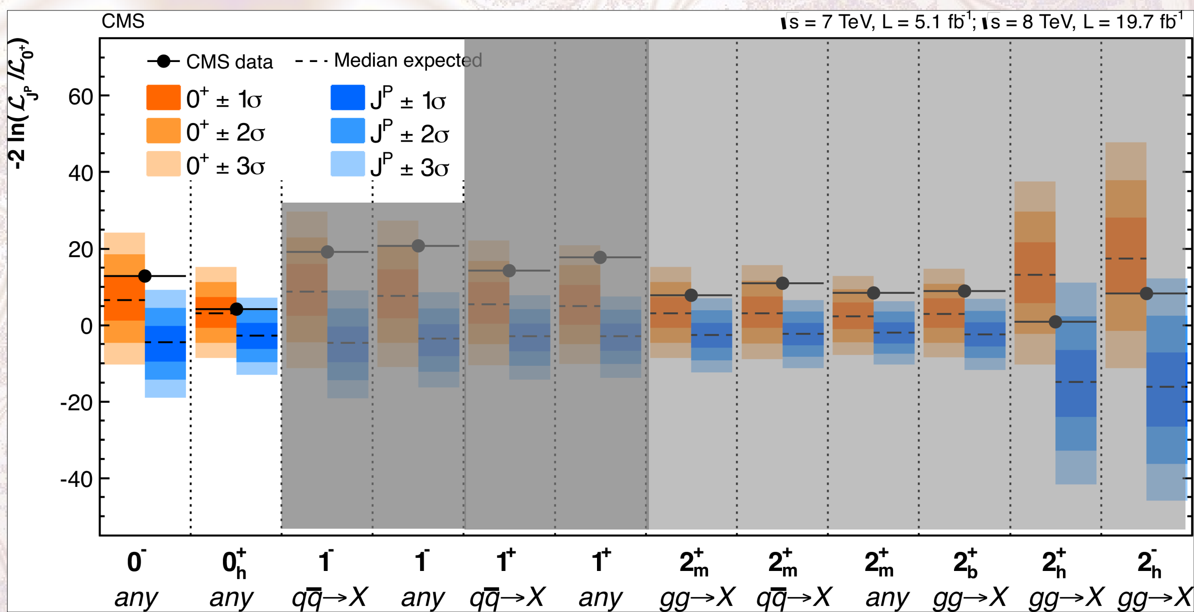


$$|0,0\rangle = \sqrt{\tfrac{1}{3}}|1,\ \ 1\rangle \otimes |1,-1\rangle - \sqrt{\tfrac{1}{3}}|1,0\rangle \otimes |1,0\rangle + \sqrt{\tfrac{1}{3}}|1,-1\rangle \otimes |1,\ \ 1\rangle$$



$$|1,\pm 1\rangle = \sqrt{\tfrac{1}{2}}|1,\pm 1\rangle \otimes |1,0\rangle - \sqrt{\tfrac{1}{2}}|1,0\rangle \otimes |1,\pm 1\rangle$$

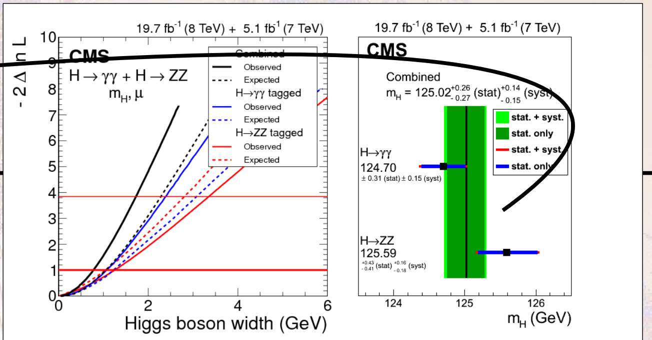
Test of pure spin hypotheses (based on $\mathcal{O}(50)$ evts):



Mass & decay width

- From high resolution channels:
  $H \to \gamma\gamma$ & $H \to ZZ \to 4\ell$

compatible within 1.6σ.



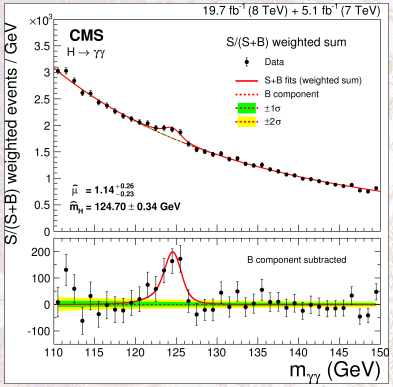
PRD 92 (2015) 012004

$\hat{m}_H = 125.02 \pm^{0.26}_{0.27}$ (stat.) $\pm^{0.14}_{0.15}$ (syst.) GeV

$\Gamma_H < 1.7\,(2.3)$ GeV (95% CL)

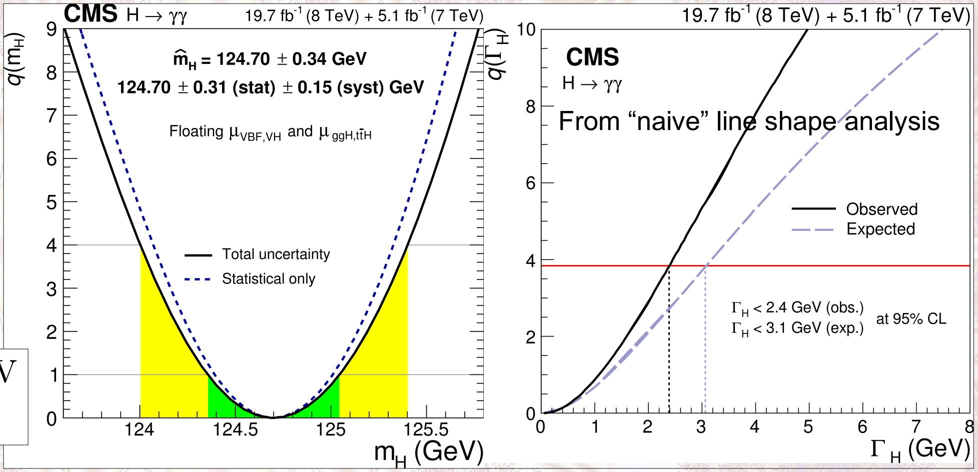
Expectation from SM:
$\Gamma_H(125\text{ GeV}) = 4.04$ MeV

EPJ C 74 (2014) 3076

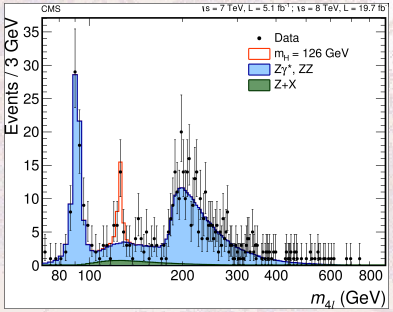


$\hat{m}_H = 124.7 \pm^{0.5}_{0.31}$ (stat.) $\pm\, 0.15$(syst.) GeV

$\Gamma_H < 2.4\,(3.1)$ GeV (95% CL)

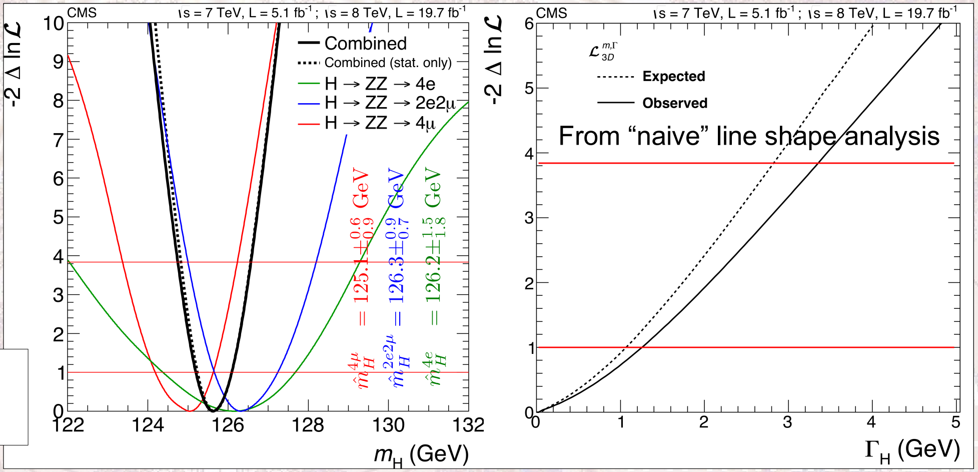


PRD 89 (2014) 092007

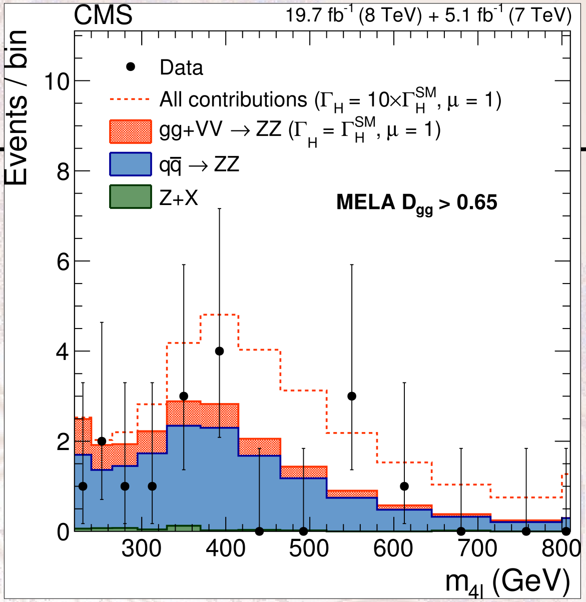


$\hat{m}_H = 125.6 \pm^{0.5}_{0.4}$ (stat.) $\pm\, 0.1$(syst.) GeV

$\Gamma_H < 3.4\,(2.8)$ GeV (95% CL)



Mass & decay width



$$\frac{d\sigma}{dm^2} \propto \frac{1}{(q^2-m^2)^2+m^2\Gamma^2} \xrightarrow{\Gamma\to 0} \frac{\pi}{m\Gamma}\delta\left(q^2-m^2\right)$$

$$\frac{d\sigma(gg\to ZZ\to 4\ell)}{dm^2_{4\ell}} \propto \frac{\kappa_g^2\kappa_Z^2}{\left(m^2_{4\ell}-m^2_H\right)^2+m^2_H\Gamma^2_H}$$

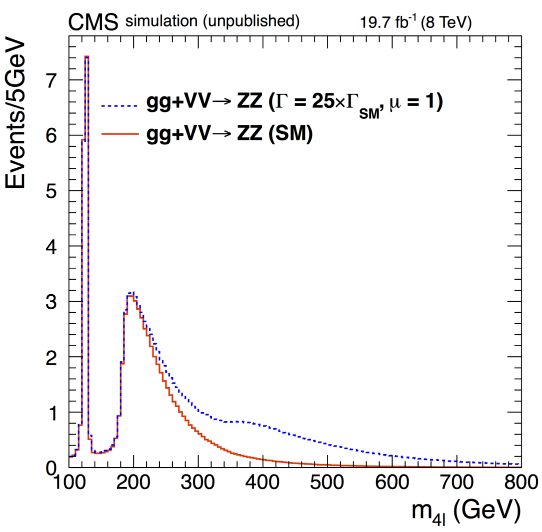
$$\propto \left.\frac{\kappa_g^2\kappa_Z^2}{m_H\Gamma_H}\right|_{m_{4\ell}\approx m_H}$$

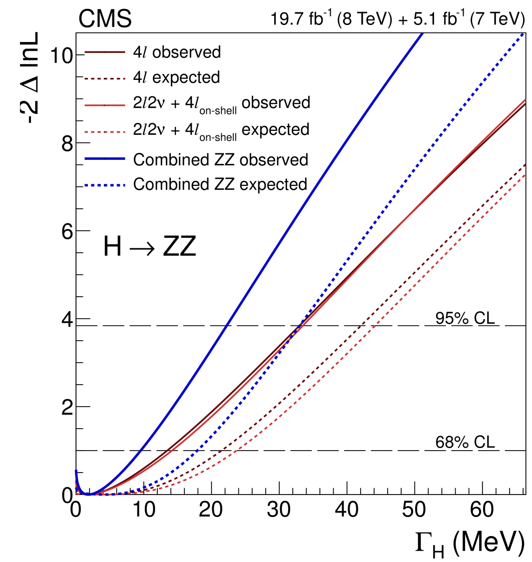
$$\propto \left.\frac{\kappa_g^2\kappa_Z^2}{m^4_{4\ell}}\right|_{m_{4\ell}\gg m_H}$$

From *offshell* cross section:
$\Gamma_H < 22(33)$ MeV (95% CL)

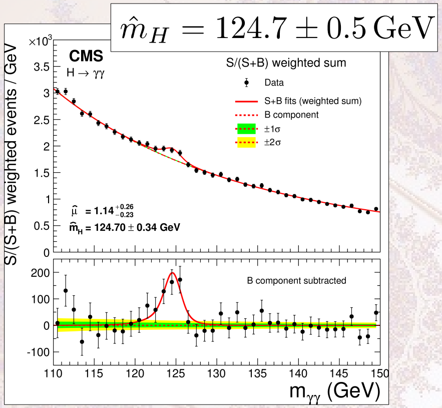
Expectation from SM:
$\Gamma_H(125\ \text{GeV}) = 4.04$ MeV

PLB 736 (2014) 64

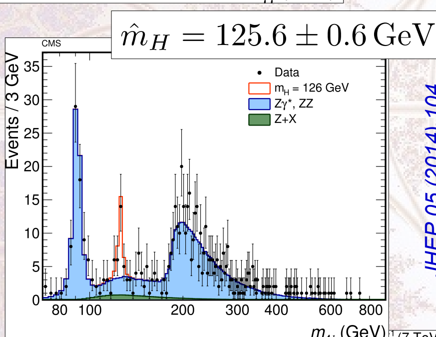




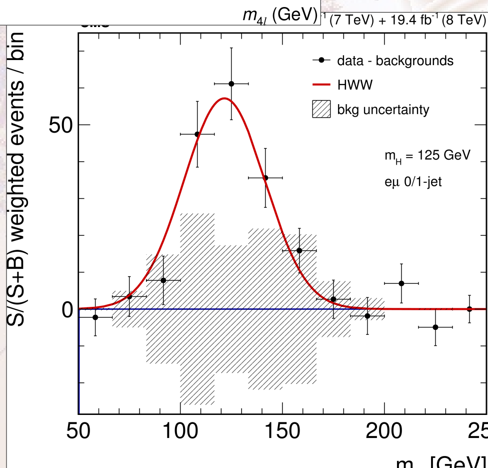
Compatibility

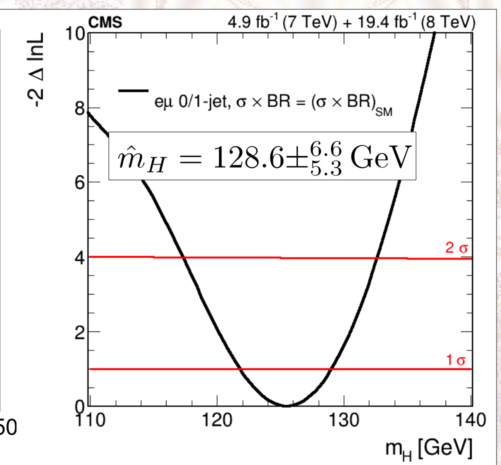


EPJ C 74 (2014) 3076



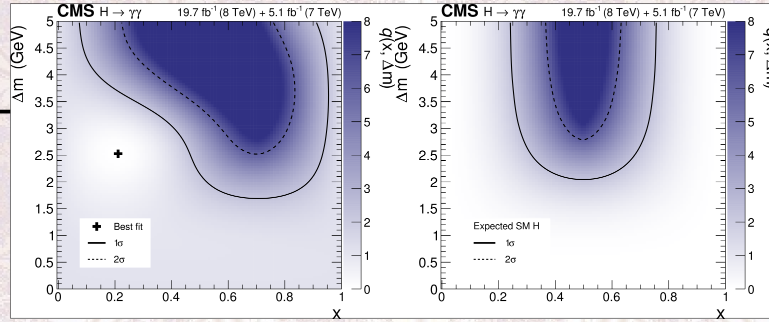
PRD 89 (2014) 092007



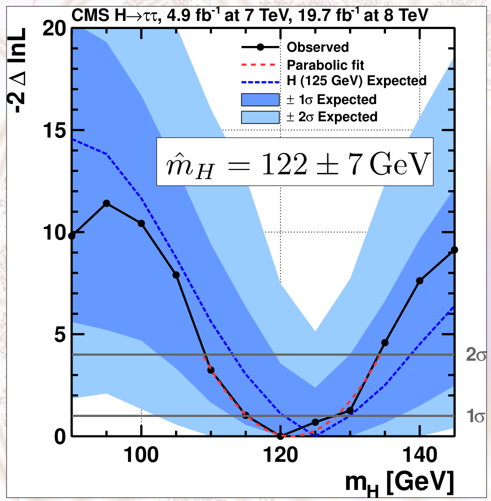


JHEP 01 (2014) 096

Second close-by resonance in $H \to \gamma\gamma$?

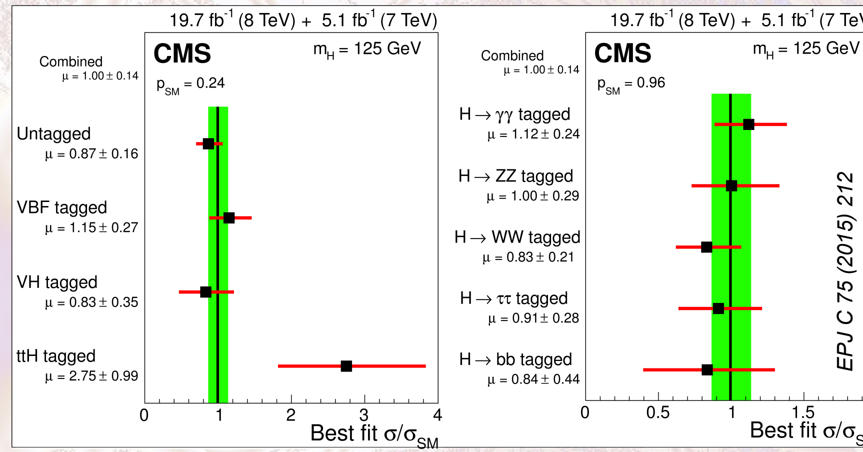


EPJ C 74 (2014) 3076



JHEP 05 (2014) 104

Coupling across production modes or decay channels:



EPJ C 75 (2015) 212

Overall coupling consistency:

- Event categories : 227
- Nuisance parameters: $\mathcal{O}(2500)$
- 16 MB binary file of stat. model (~145 MB in human readable form).

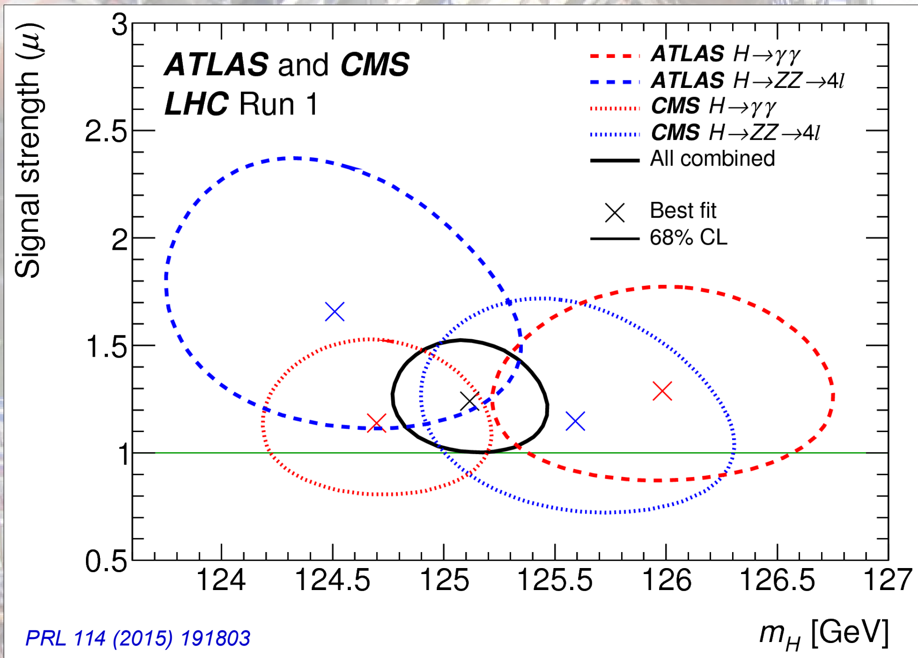
$\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.14$

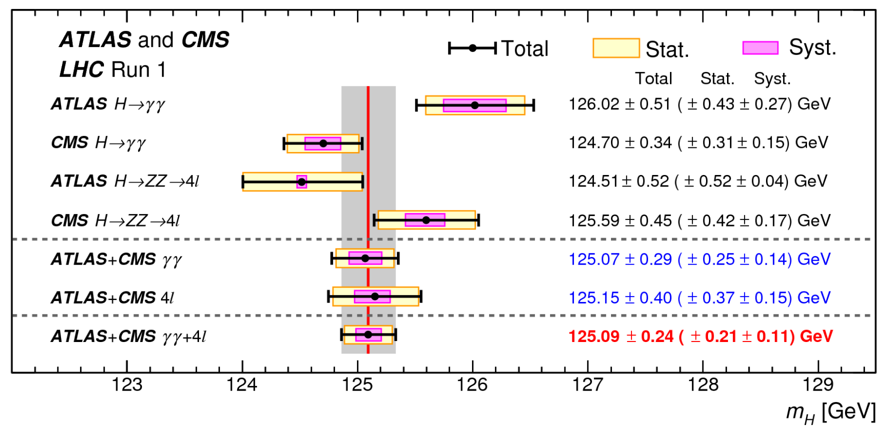
$p\text{-value} = 84\%$

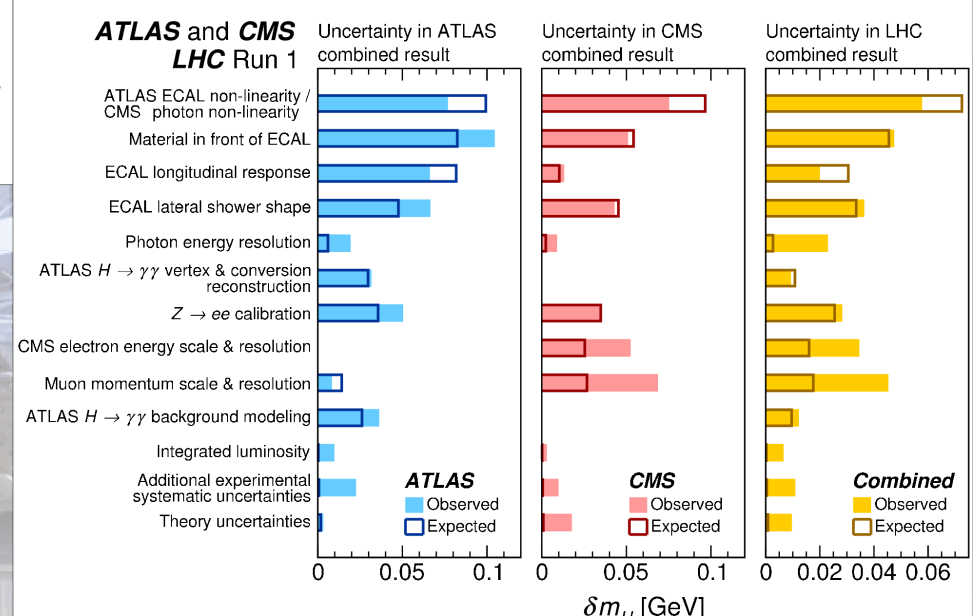
EPJ C 75 (2015) 212

Mass

- ATLAS+CMS LHC run-1 combination:







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

Coupling structure

CMS-PAS-HIG-15-002

- Event categories : 574
- Nuisance parameters: 4268

$\mu = \sigma/\sigma_{SM} = 1.09 \pm 0.11$

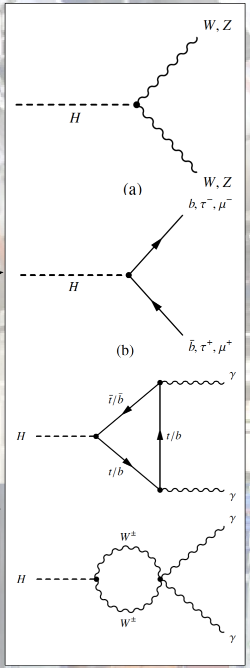
- ATLAS+CMS LHC run-1 combination:

Considered production modes:

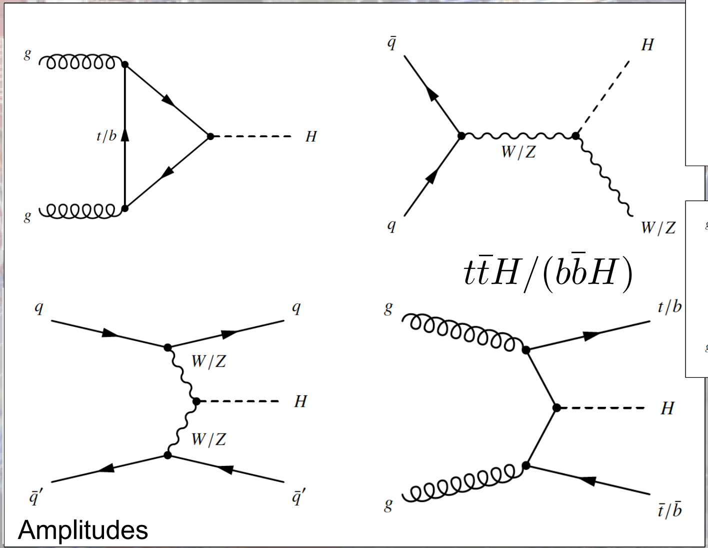
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

Considered decay channels:

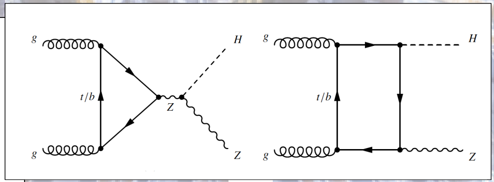
Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

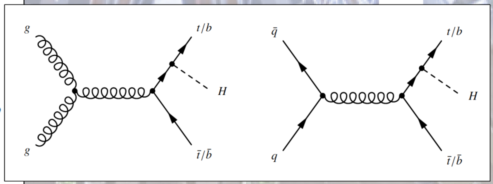


Main production modes:

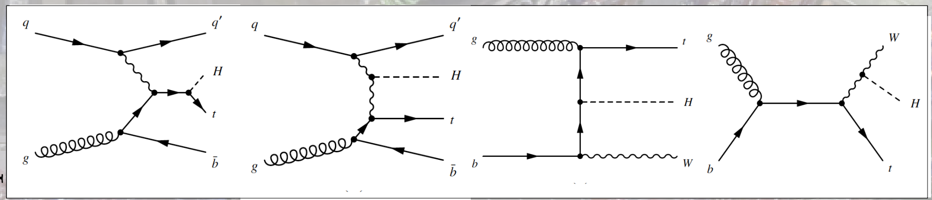


$gg \to ZH$ (10% to $ZHbb$)





$tqH + tHW$



The κ model

- Dress each coupling at tree-level with a scaling factor κ_i .
- Loops are resolved according to SM or treated as effective couplings.
- Comprise κ_i's to obtain simplified models.

Production	Loops	Interference	Multiplicative factor	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	κ_Z^2
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim$	$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim$	κ_t^2
$\sigma(gb \to WtH)$	–	$W-t$	$\sim$	$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim$	$3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim$	κ_b^2
Partial decay width				
Γ^{ZZ}	–	–	$\sim$	κ_Z^2
Γ^{WW}	–	–	$\sim$	κ_W^2
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim$	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim$	κ_τ^2
Γ^{bb}	–	–	$\sim$	κ_b^2
$\Gamma^{\mu\mu}$	–	–	$\sim$	κ_μ^2
Total width for $\mathrm{BR_{BSM}} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

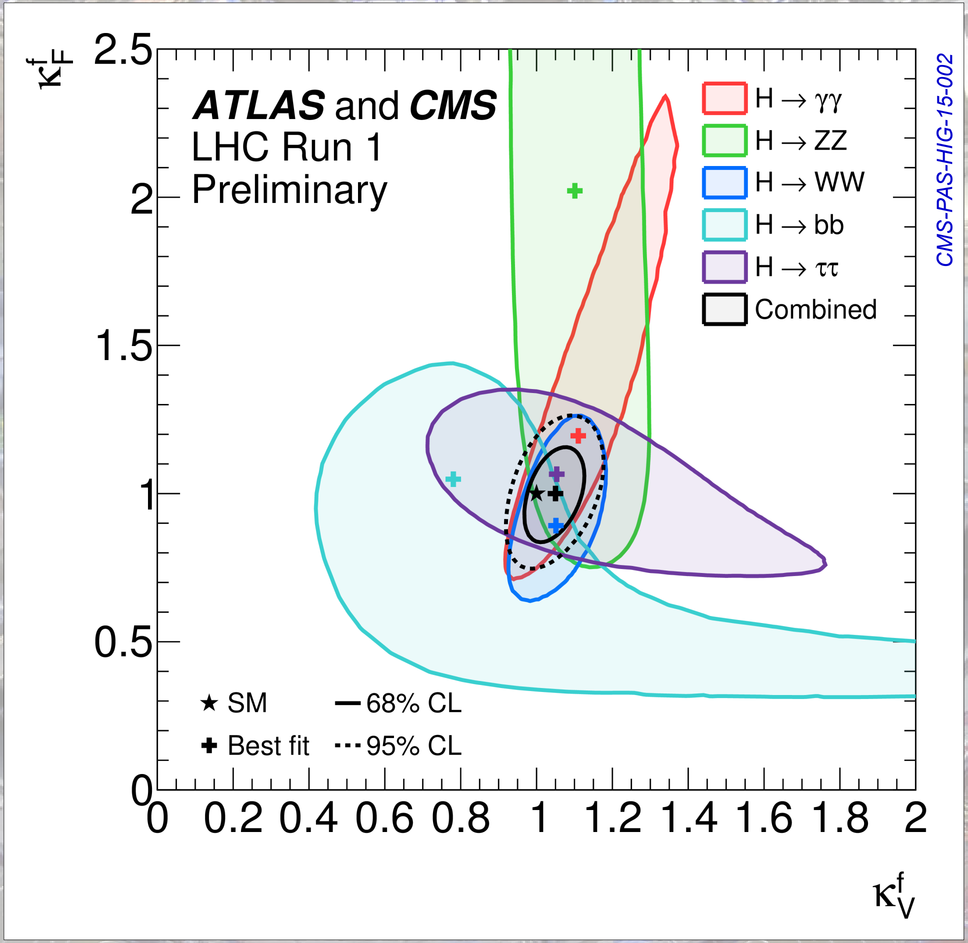
$\approx (1.26\kappa_W - 0.26\kappa_t)^2$

Non measurable couplings tied to measurable ones: $\kappa_c = \kappa_t$, $\kappa_\mu = \kappa_\tau$, $\kappa_s = \kappa_b$.

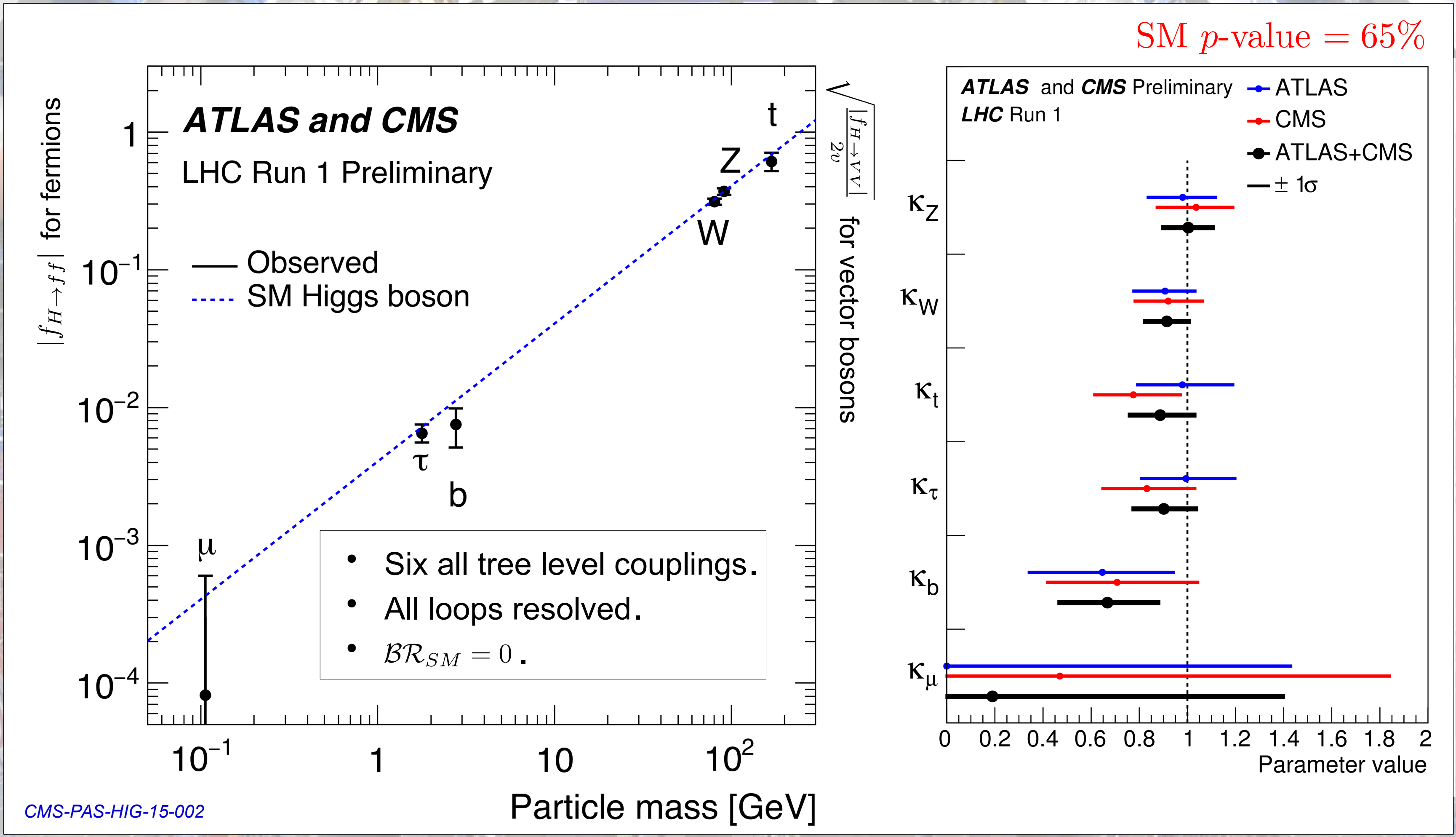
κ_V- κ_F model

- Resolve loops according to SM.
- Combine tree-level couplings into κ_V (coupling to *W* & *Z* boson) and κ_F (couping to fermions).

$\kappa_V \supset W, Z$ $\kappa_F \supset t, b, \tau, \ldots$



"Money plot"



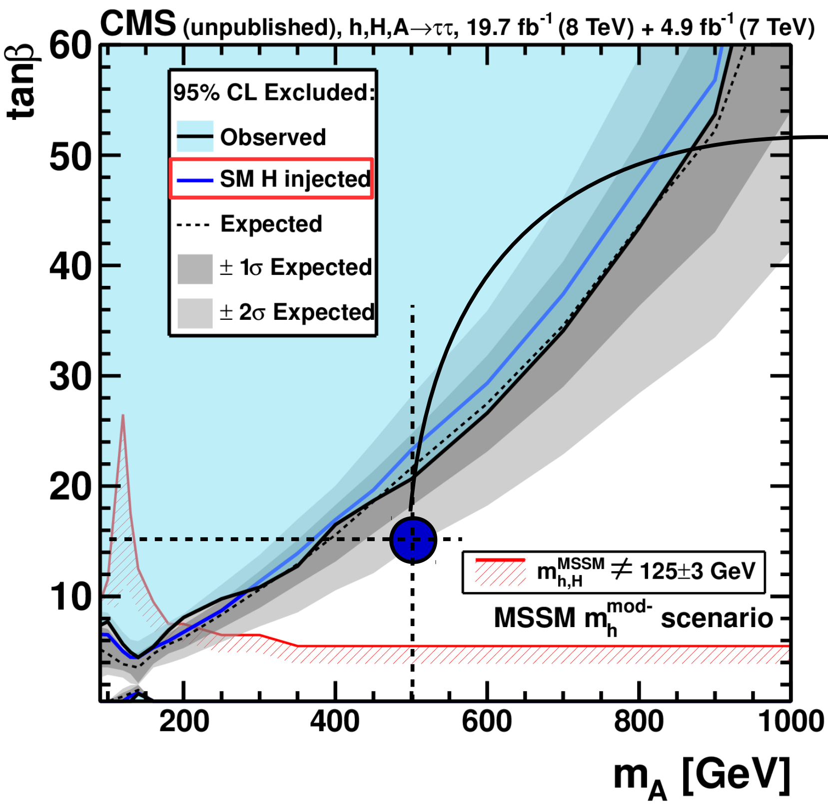
$$|f^{\mathrm{obs}}_{H\to ff}| = \kappa_f \cdot |f^{\mathrm{SM}}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

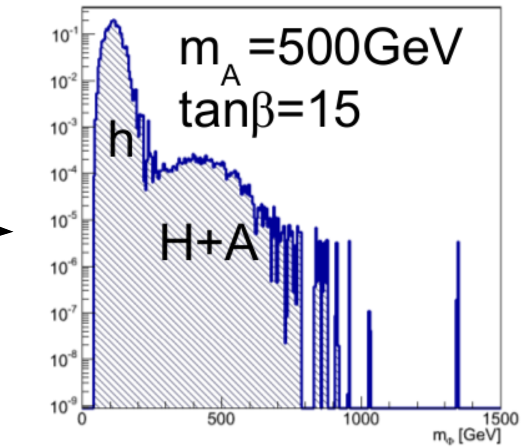
$$\sqrt{\frac{|f^{\mathrm{obs}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{|f^{\mathrm{SM}}_{H\to VV}|}{2v}} = \sqrt{\kappa_V} \cdot \frac{m_V}{v} \qquad V = W, Z$$

Within measurement accuracy unique scaling as expected within the SM.

Limits in dedicated MSSM Benchmark Scenarios

- Explicit prediction for three neutral Higgs bosons:





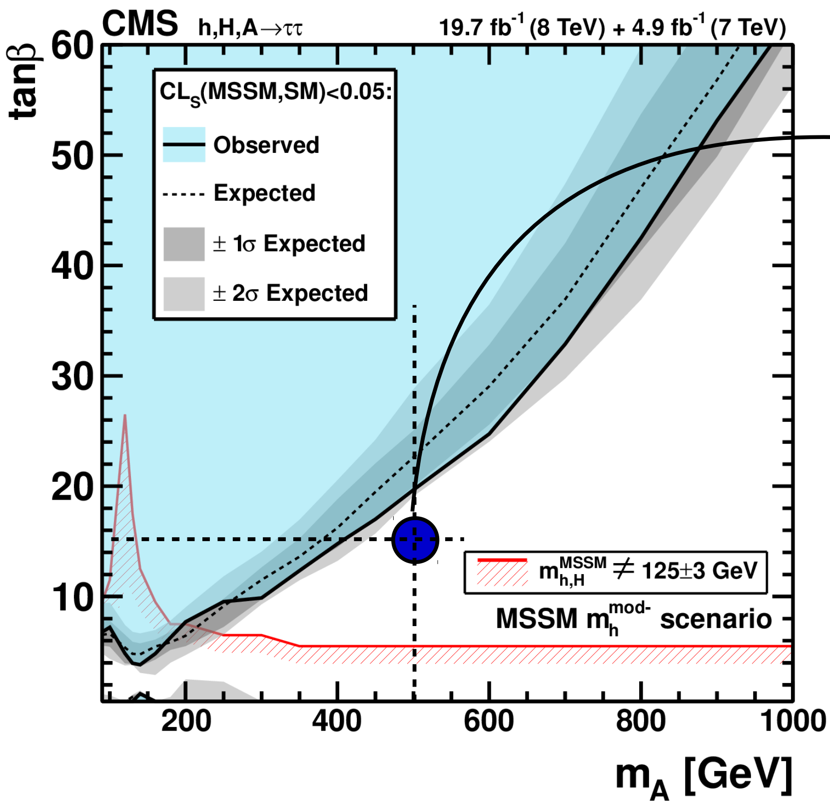
- Note: h(125) has been observed!
- With increasing sensitivity new statistical interpretation is needed: “1 Higgs vs 3 Higgses”.
- **Old method**: h(125) ignored in statistical inference:

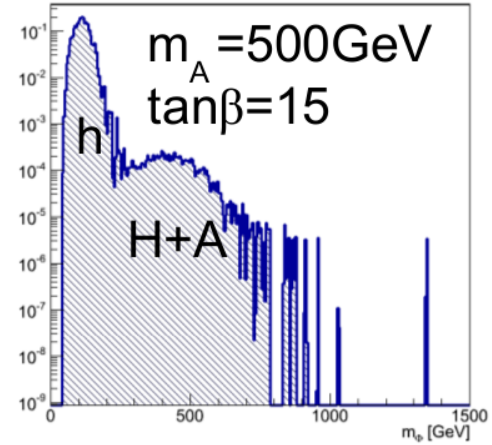
$$q_{\mathrm{MSSM/BG}} = \frac{\mathcal{L}\big((N|(S_{\mathrm{MSSM}}+B),\hat{\theta}_{MSSM}\big)}{\mathcal{L}\big(N|B,\hat{\theta}_B\big)}$$

arXiv:1408.3316

Limits in dedicated MSSM Benchmark Scenarios

- Explicit prediction for three neutral Higgs bosons:

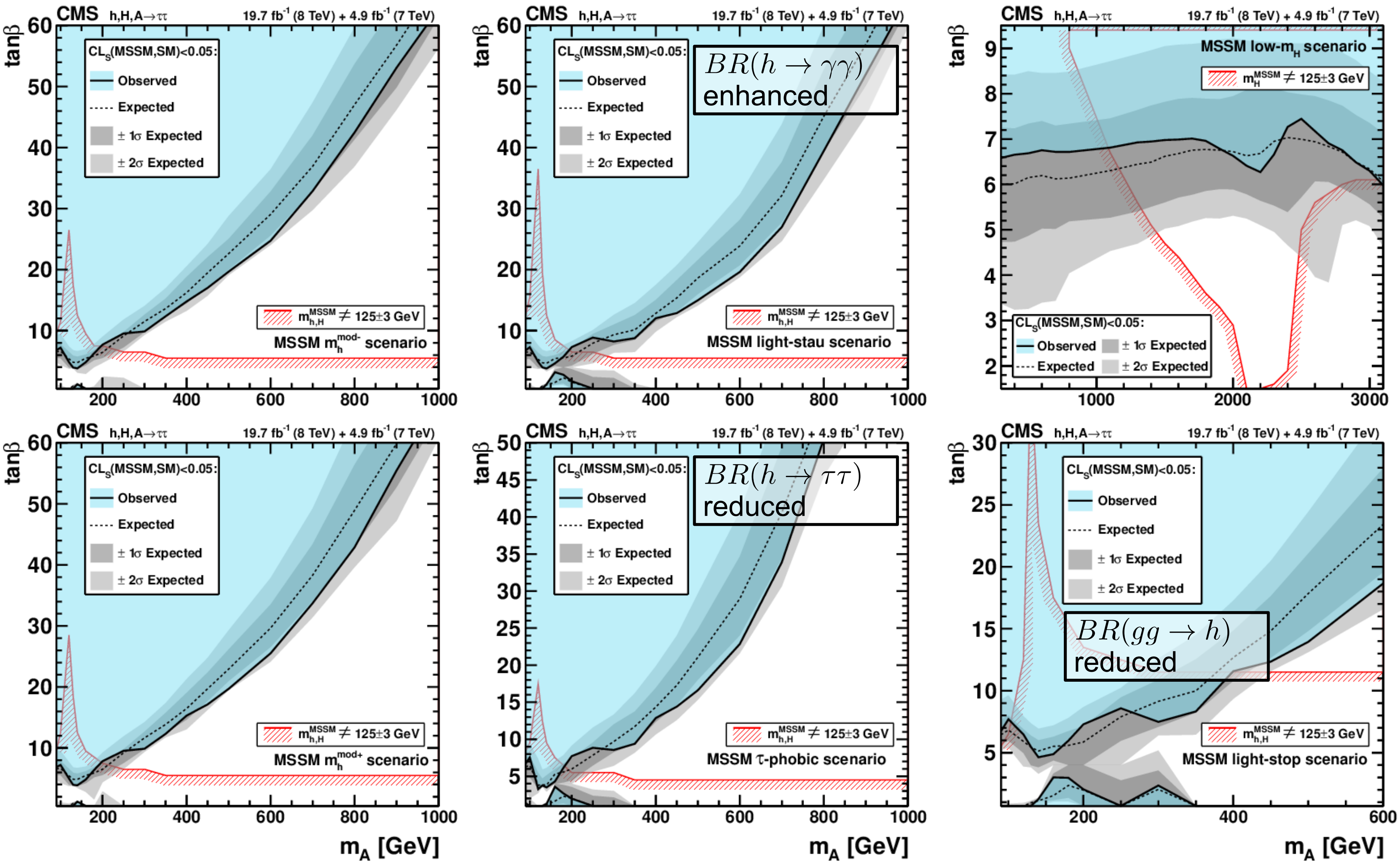




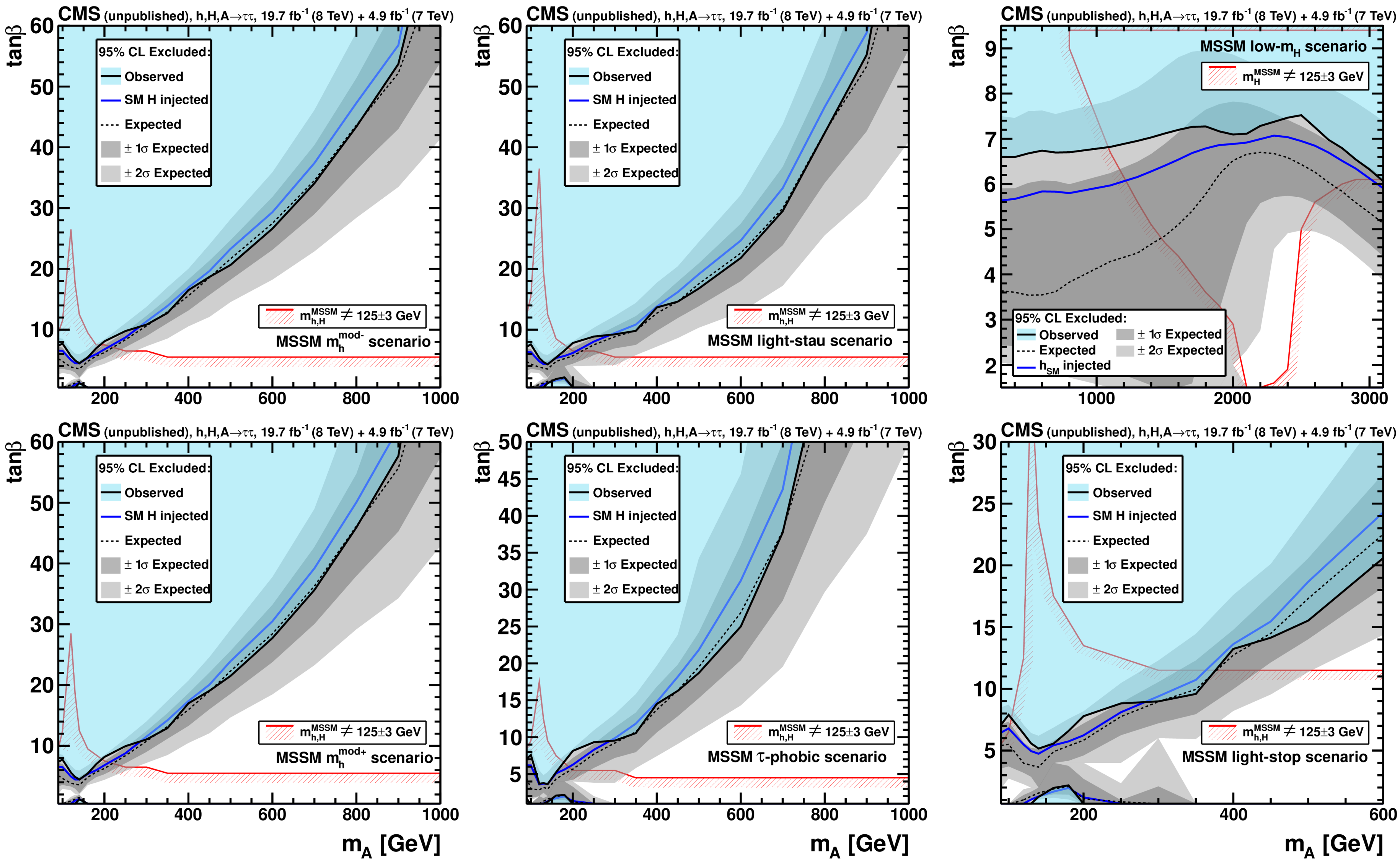
- Note: h(125) has been observed!
- With increasing sensitivity new statistical interpretation is needed: “1 Higgs vs 3 Higgses”.
- **New method**: h(125) taken into account in test statistic:

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

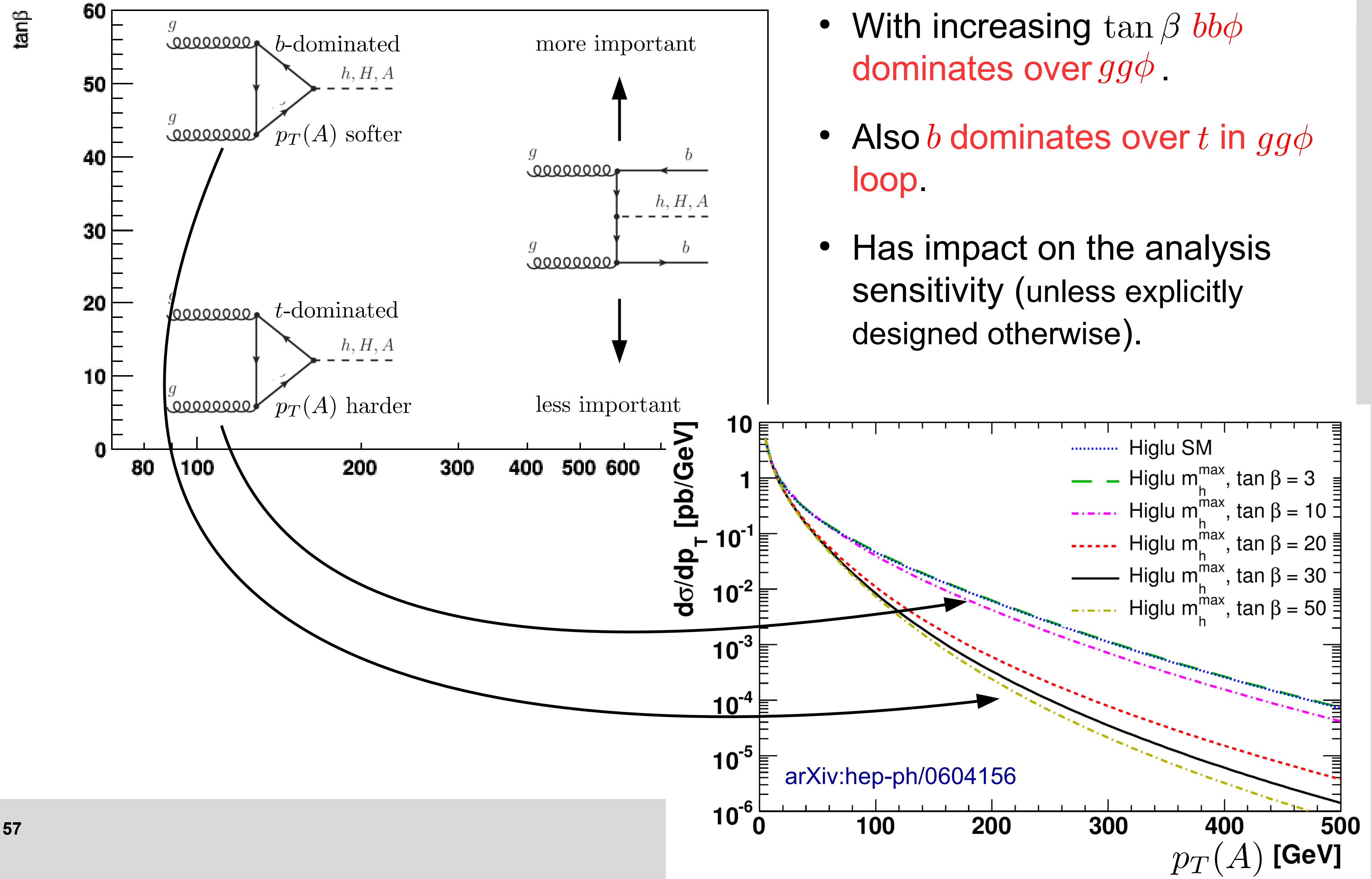
More benchmark scenarios (as defined by arXiv:1302.7033)



More benchmark scenarios... (old method)



Yukawa couplings for b and t vary with $\tan\beta$



- With increasing $\tan\beta$ $bb\phi$ dominates over $gg\phi$.
- Also b dominates over t in $gg\phi$ loop.
- Has impact on the analysis sensitivity (unless explicitly designed otherwise).

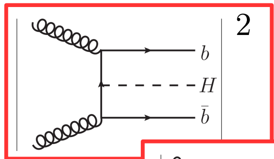
Mitigation of $p_T(A)$ dependence in $H \to \tau\tau$ analyses

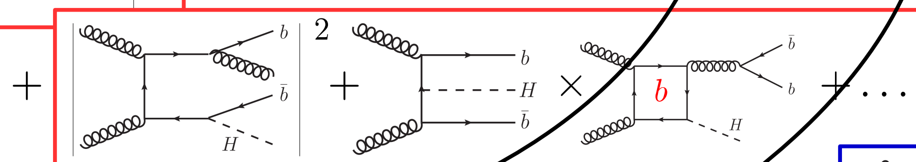
Karlsruhe Institute of Technology

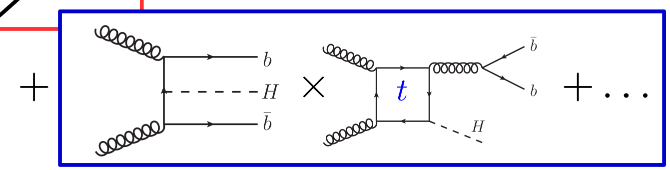
- MSSM $bb\phi$ (MG5_aMC@NLO):

Technically requires generation of 2 MC samples per mass point.

$$\sigma_{bb\phi}^{4FS}(m_A, \tan\beta) = \overbrace{\alpha_s^2 \tilde{y}_b^2 \Delta^{(0)}_{\tilde{y}_b^2} + \alpha_s^3 \tilde{y}_b^2 \Delta^{(1)}_{\tilde{y}_b^2}}^{\tilde{y}_b^2\text{-terms}} + \underbrace{\alpha_s^2 \tilde{y}_b \tilde{y}_t \Delta^{(0)}_{\tilde{y}_b \tilde{y}_t}}_{\tilde{y}_b \tilde{y}_t\text{-terms}}$$







- MSSM $gg\phi$ (Powheg NLO):

Technically requires generation of five MC samples @ three different scales per mass point.

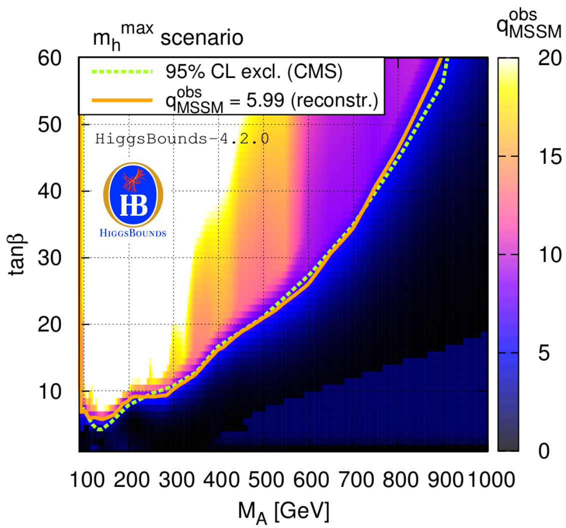
$$\sigma_{gg\phi}^{t+b}(m_A, \tan\beta) = \underbrace{\tilde{y}_b^2 \sigma_{SM}^b(Q_b)} + \underbrace{\tilde{y}_t^2 \sigma_{SM}^t(Q_t)} + \underbrace{\frac{\tilde{y}_b \tilde{y}_t}{\tilde{y}_b' \tilde{y}_t'} \left(\sigma_{MSSM}^{t+b}(Q_{tb}) - \tilde{y}_b'^2 \sigma_{SM}^b(Q_{tb}) \tilde{y}_t'^2 \sigma_{SM}^t(Q_{tb})\right)}$$

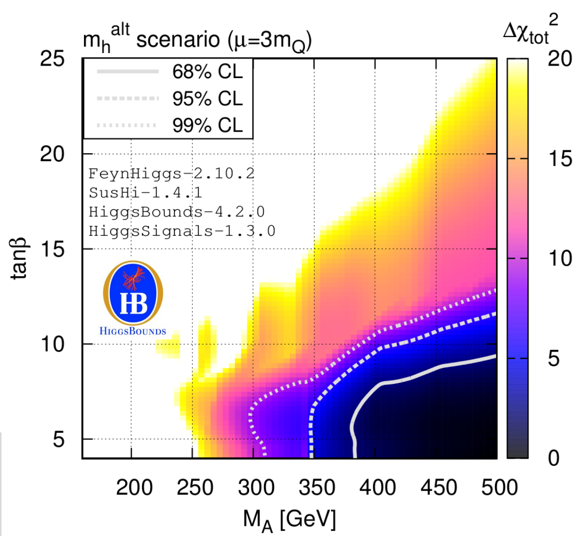
- In the process of thorough validation campaign to set up corresponding workflows.
- General procedures will be documented in YR4.

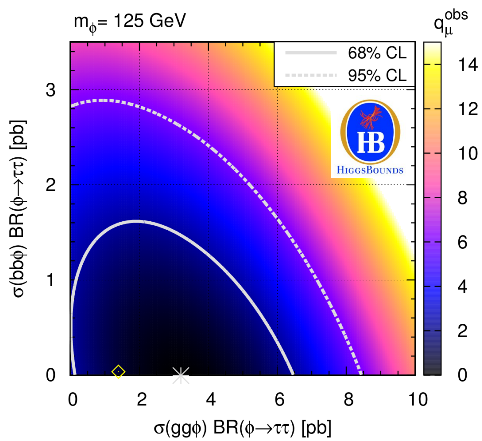
Sasha Nikitenko, Yuta Takahashi, Rene Caspart (on CMS side)

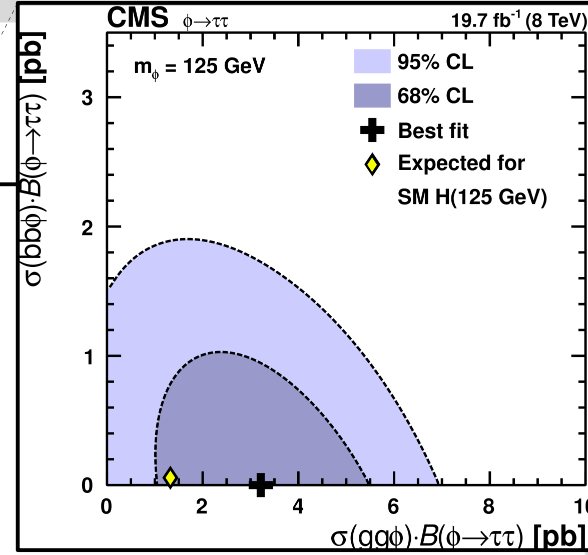
… picked up by theory

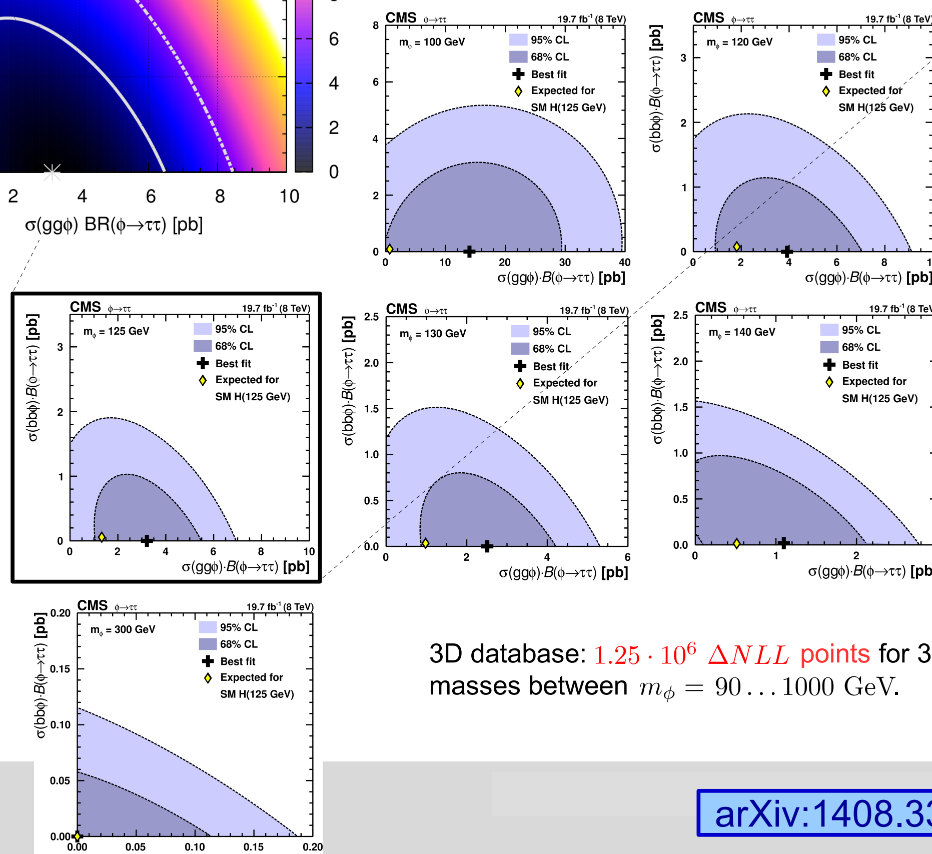
- First application to new models (using HiggsBounds): arXiv:1507.06706











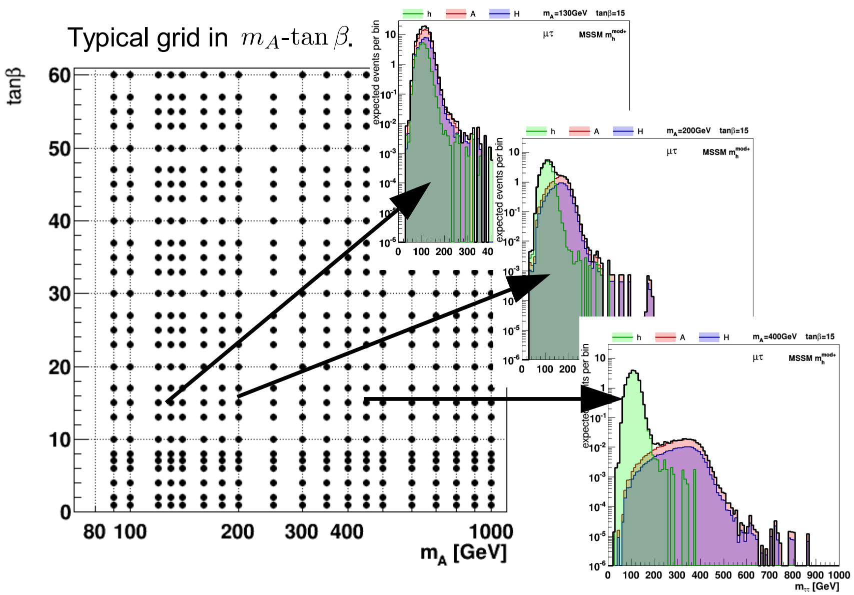
3D database: $1.25 \cdot 10^6$ ΔNLL points for 31 masses between $m_\phi = 90 \ldots 1000$ GeV.

arXiv:1408.3316

Recall: limit construction algorithms

Direct limit on full benchmark:

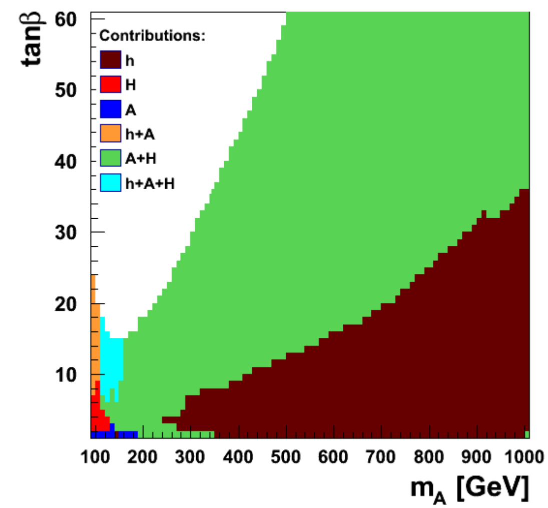
- For fixed values in $(m_A, \tan\beta)$ build templates composed of $h + H + A$ according to model.



- vary whole template (scaling factor μ).
- for fixed value of m_A find value of $\tan\beta$ where $CL_s(\mu = 1) = 0.05$.

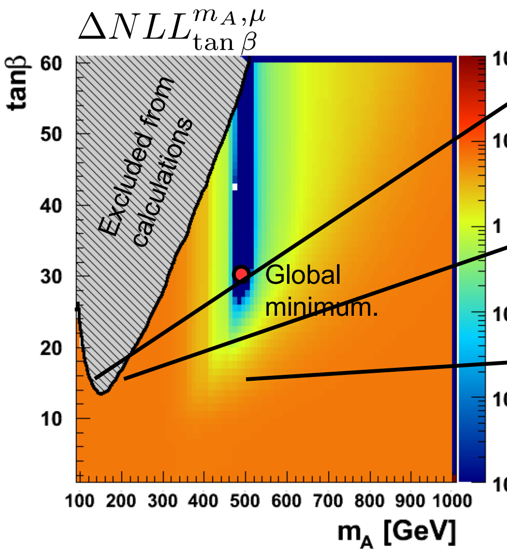
Re-interpretation from LH:

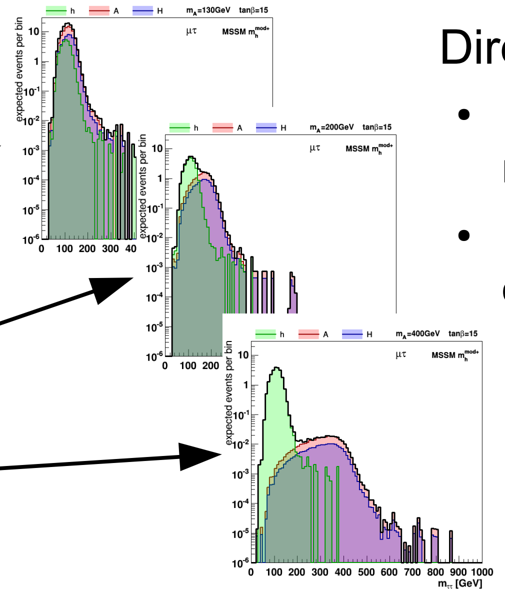
- Cluster Higgs bosons if they are close to each other (within exp. Resolution).
- Determine cluster with highest expected exclusion sensitivity (i.e. largest ΔNLL_{exp} from DB based on BG-only *Asimov* dataset).



- Read off ΔNLL_{obs} for each given point of $(m_A, \tan\beta)$ from DB based on data.

LH components

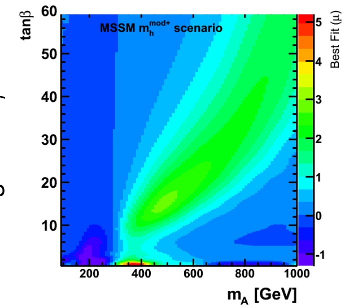




Direct limit:

- Fix template according to exact model point.
- Find best fit point. Allow for floating overall normalization ($\hat{\mu}$).

Profile of the overall scaling factor $\hat{\mu}$.



$$\Delta NLL^{m_A,\mu}_{\tan\beta} = \ln\left(\frac{\mathcal{L}\left(\hat{\mu},\hat{\theta}_{\hat{\mu}}\right)\Big|^{m_A}_{\tan\beta}}{\mathcal{L}\left(\hat{\hat{\mu}},\hat{\hat{\theta}}_{\hat{\hat{\mu}}}\right)}\right)$$

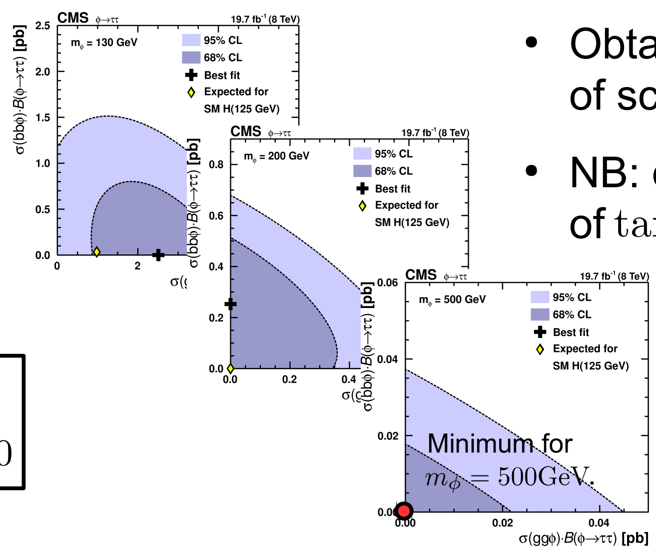
"$\Delta NLL\,(m_A, \tan\beta)$ w.r.t. global minimum with floating μ".

Pseudo-dataset (30/fb):

BG + m_h^{mod+} $m_A = 500,\ \tan\beta = 30$

Re-interpretation:

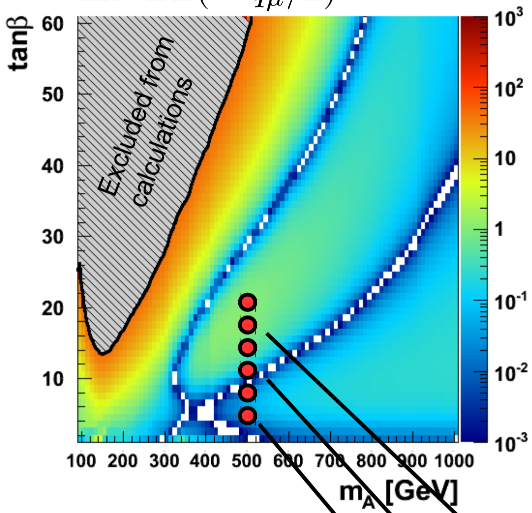
- Obtain ΔNLL from minimum of scan for given m_ϕ.
- NB: does not vary as function of $\tan\beta$.

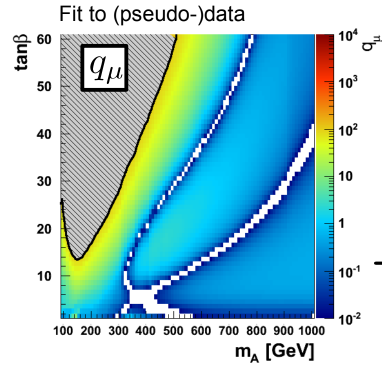


NB: plots do not corresp. to pseudo-dataset, but to CMS publication.

LH components

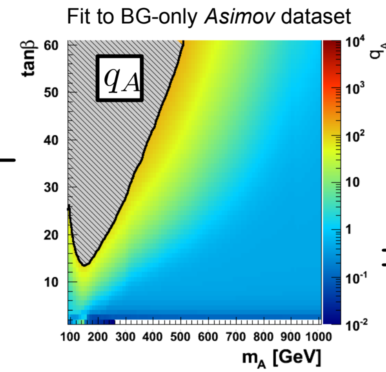
$\Delta NLL (= q_\mu/2)$



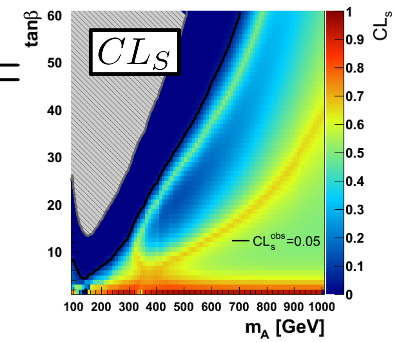


Direct limit:

+



=



$$\Delta NLL = \ln \left(\frac{\mathcal{L}(\mu=1, \hat{\theta}_{\mu=1})\big|^{m_A}_{\tan\beta}}{\mathcal{L}(\hat{\mu}, \hat{\theta}_{\hat{\mu}})\big|^{m_A}_{\tan\beta}} \right)$$

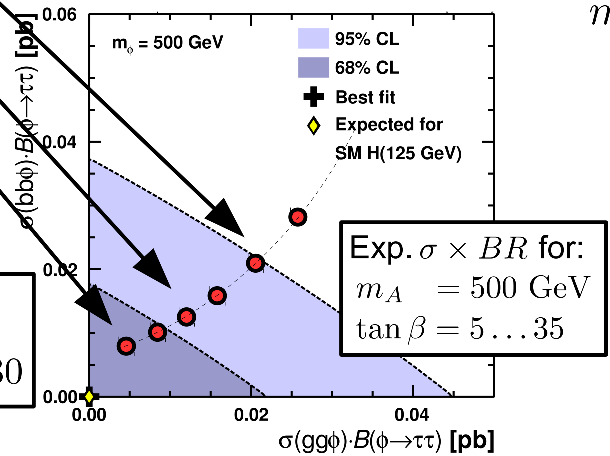
"$\Delta NLL\,(m_A, \tan\beta)$ for exact model point (with $\mu = 1$) w.r.t. floating μ".

Pseudo-dataset (30/fb):

BG + m_h^{mod+} $m_A = 500,\ \tan\beta = 30$

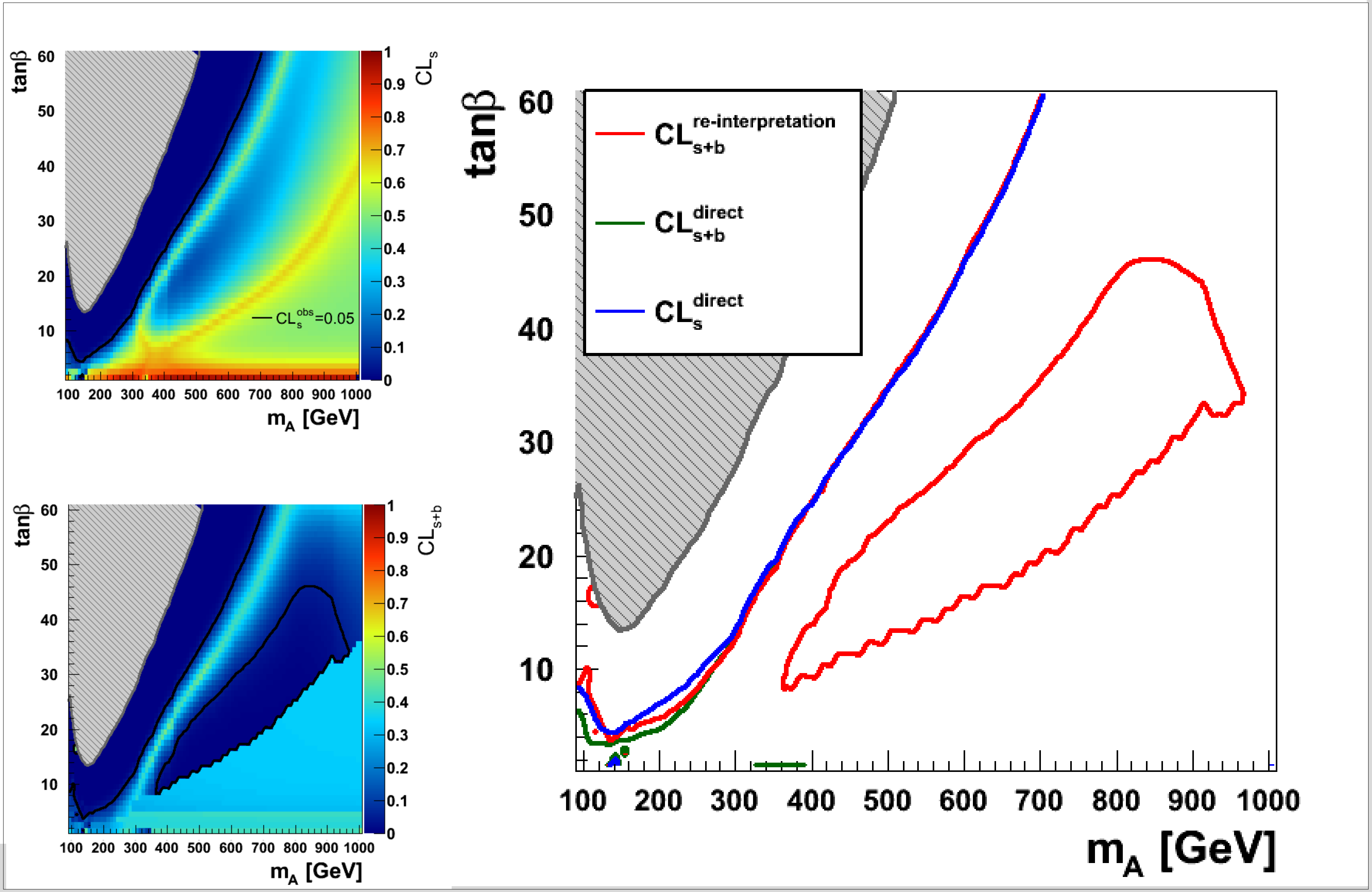
Re-interpretation:

- Read off ΔNLL and apply to m_A- $\tan\beta$ plot.

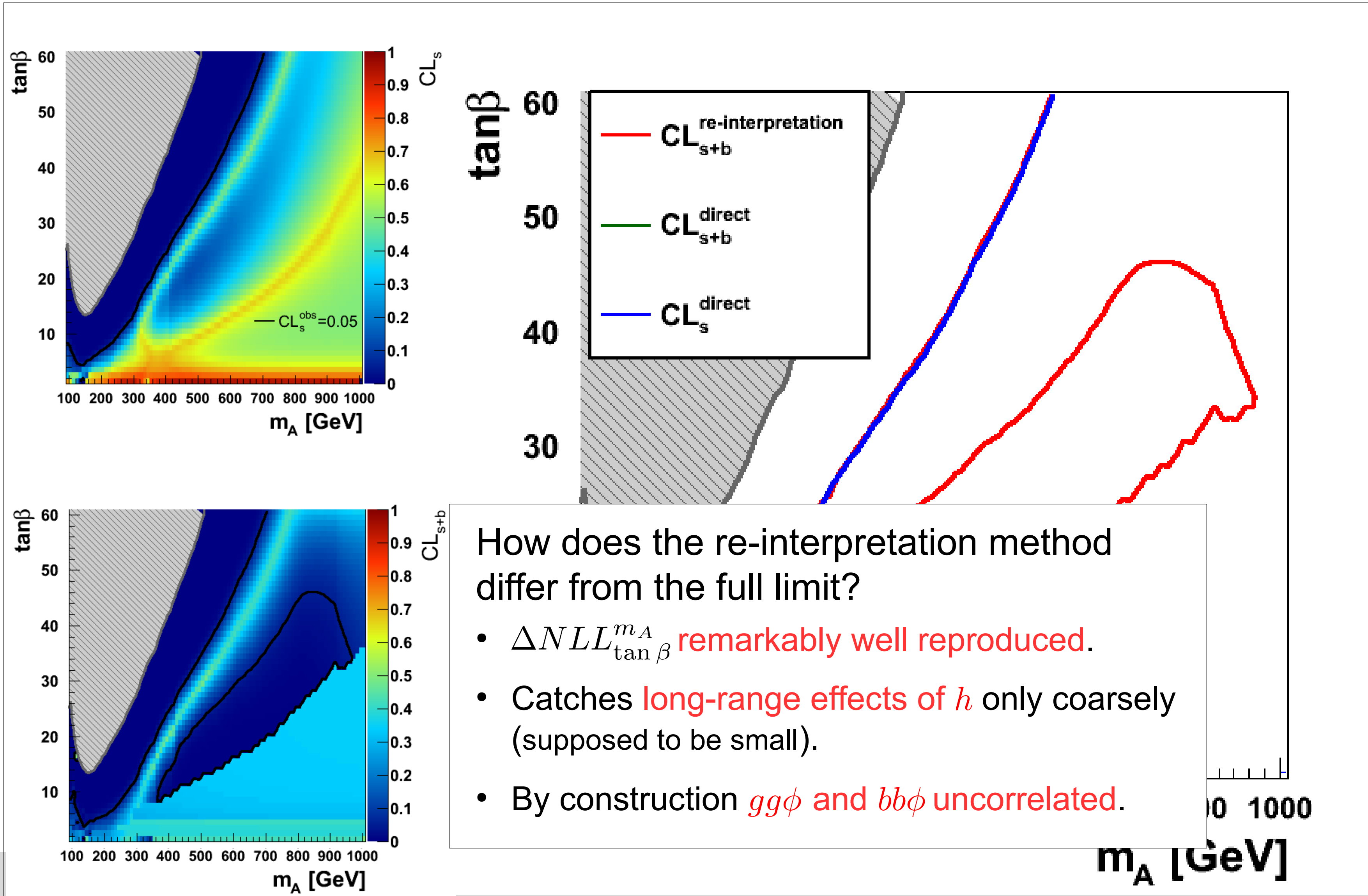


NB: plots do not corresp. to pseudo-dataset, but to CMS publication.

Method comparison (exclusion contour)



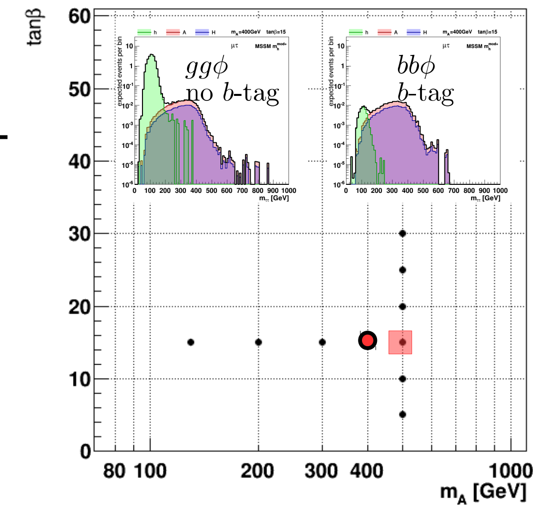
Method comparison (exclusion contour)



How does the re-interpretation method differ from the full limit?

- $\Delta NLL^{m_A}_{\tan\beta}$ remarkably well reproduced.
- Catches long-range effects of h only coarsely (supposed to be small).
- By construction $gg\phi$ and $bb\phi$ uncorrelated.

Walk across $(m_A, \tan\beta)$ plane

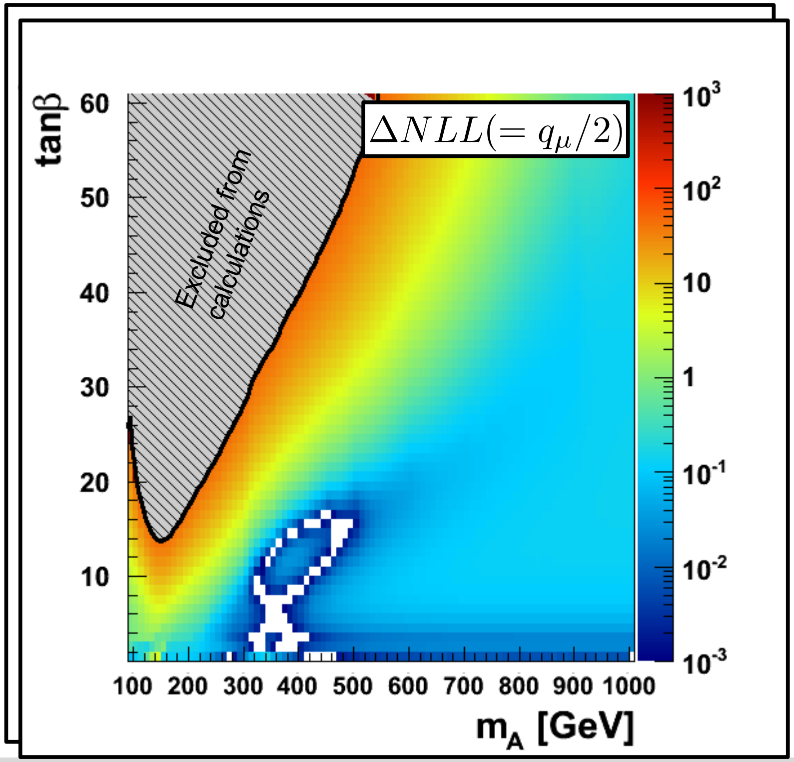


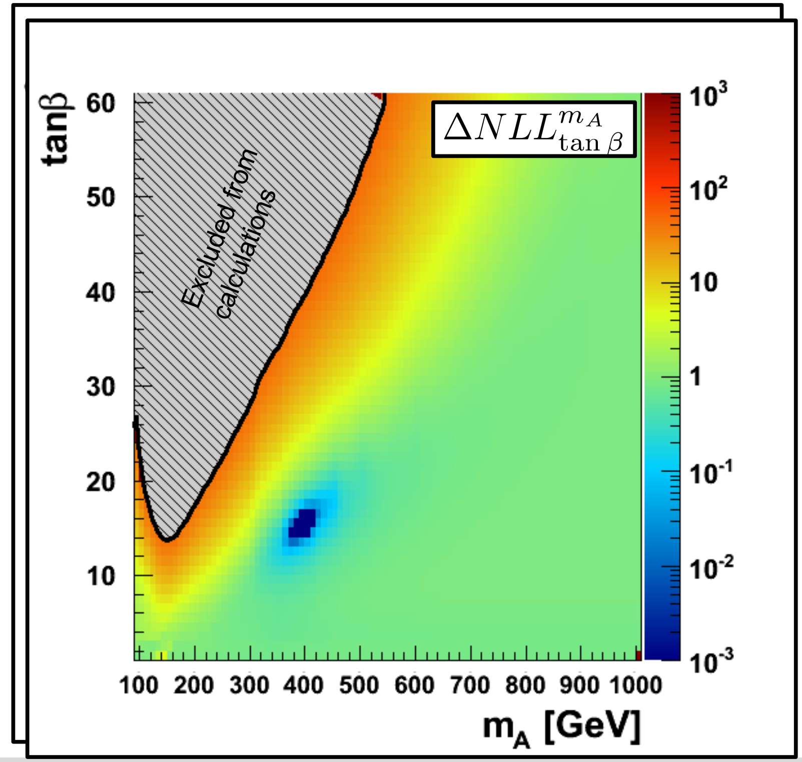
Direct limit

- Inject signal for decreasing values of m_A :

m_h^{mod+}	$m_A = 400$ GeV	$\tan\beta = 15$

- Investigate behavior of signal templates & likelihood.



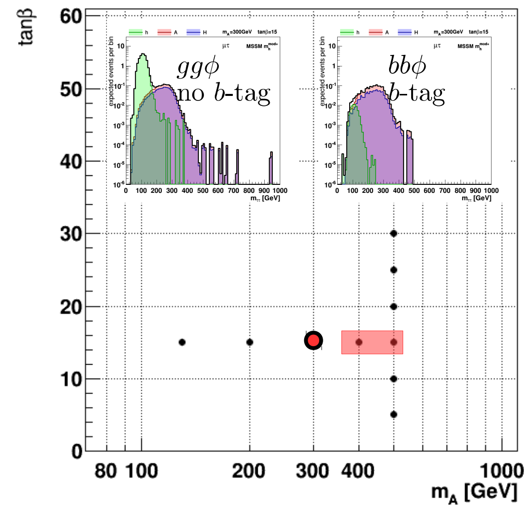


Walk across $(m_A, \tan\beta)$ plane

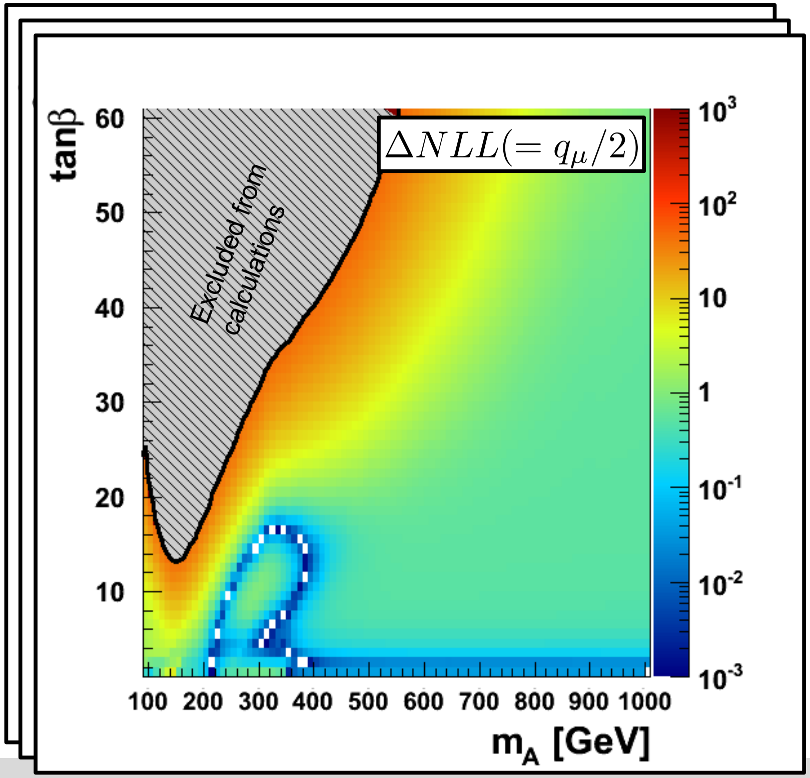
- Inject signal for decreasing values of m_A :

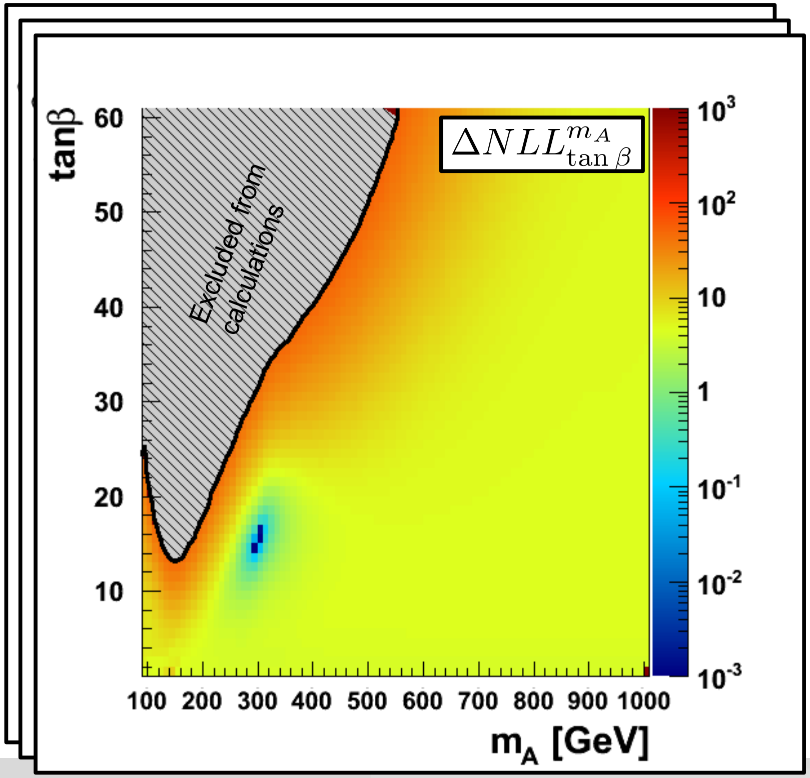
$$m_h^{mod+} \quad \color{red}{m_A = 300\ \mathrm{GeV}} \quad \tan\beta = 15$$

- Investigate behavior of signal templates & likelihood.



Direct limit



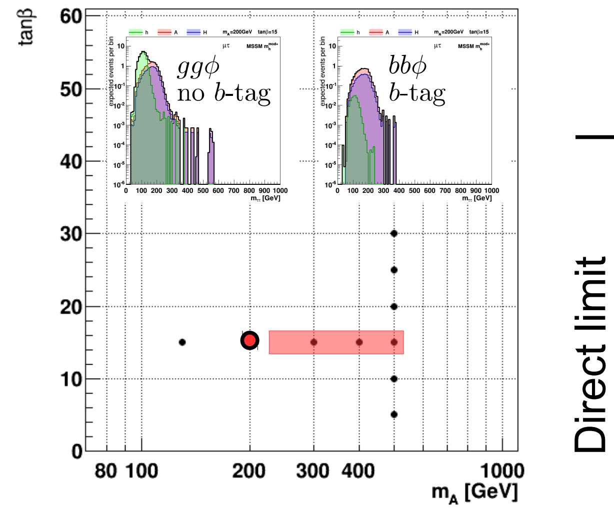


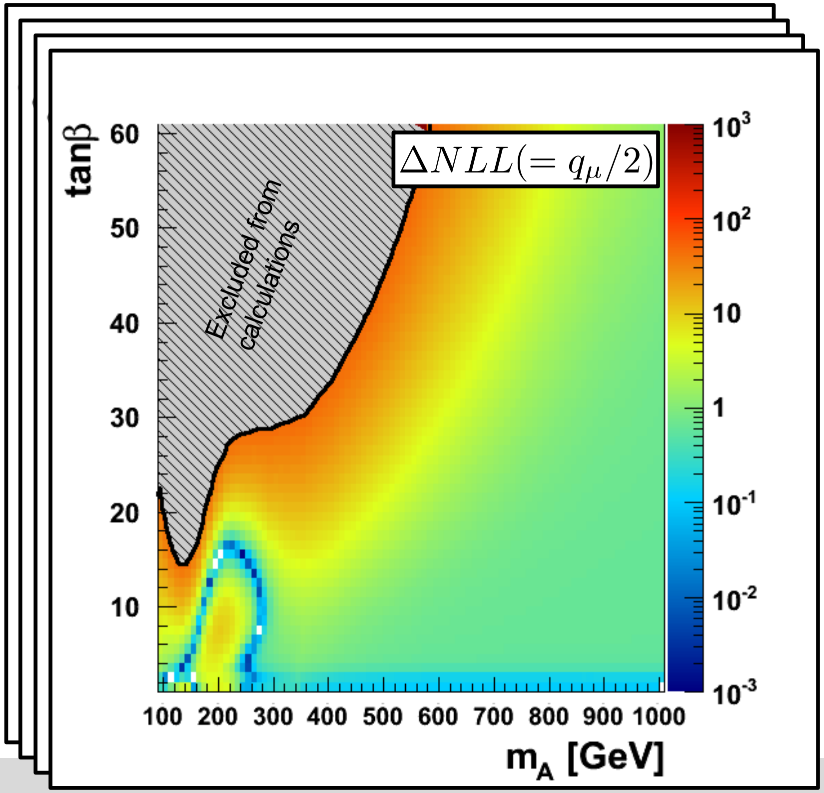
Walk across $(m_A, \tan\beta)$ plane

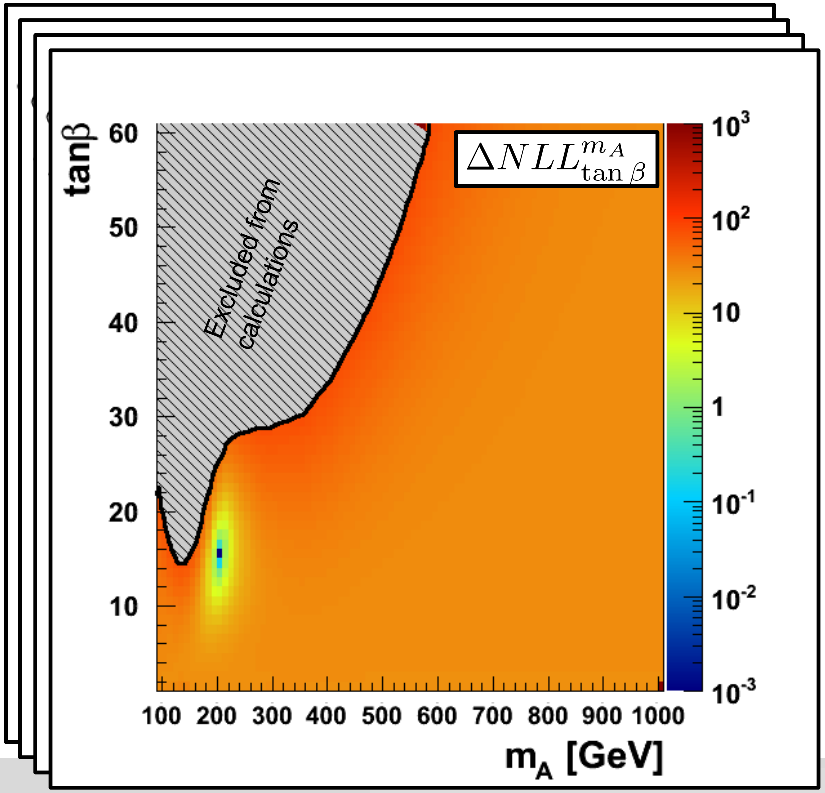
- Inject signal for decreasing values of m_A :

m_h^{mod+}	$m_A = 200$ GeV	$\tan\beta = 15$

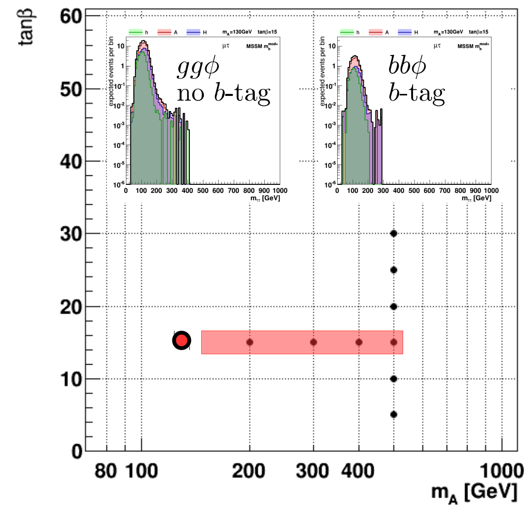
- Investigate behavior of signal templates & likelihood.







Walk across $(m_A, \tan\beta)$ plane

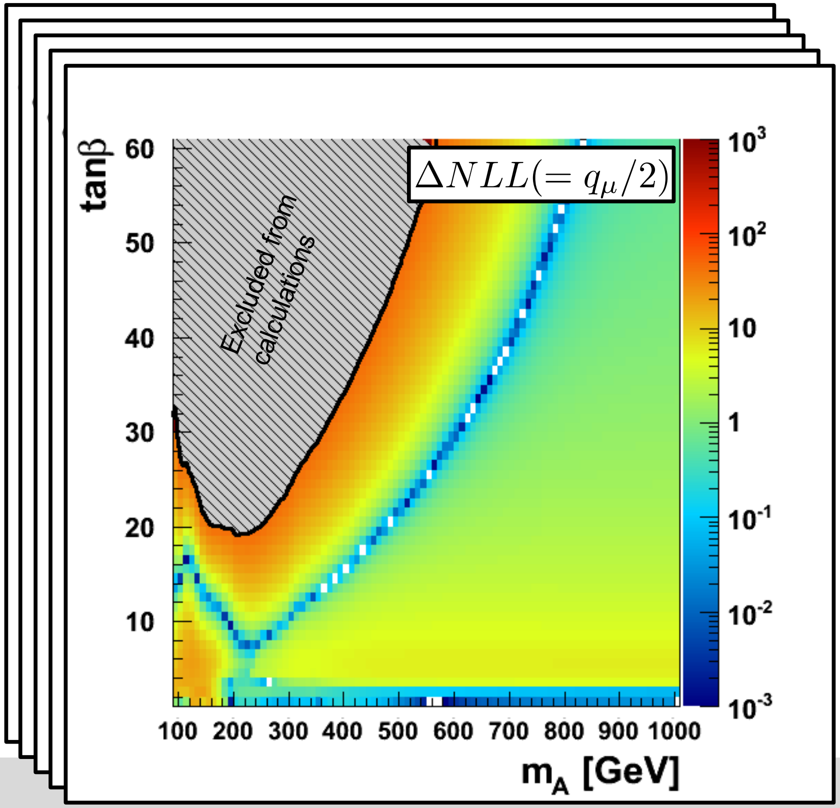


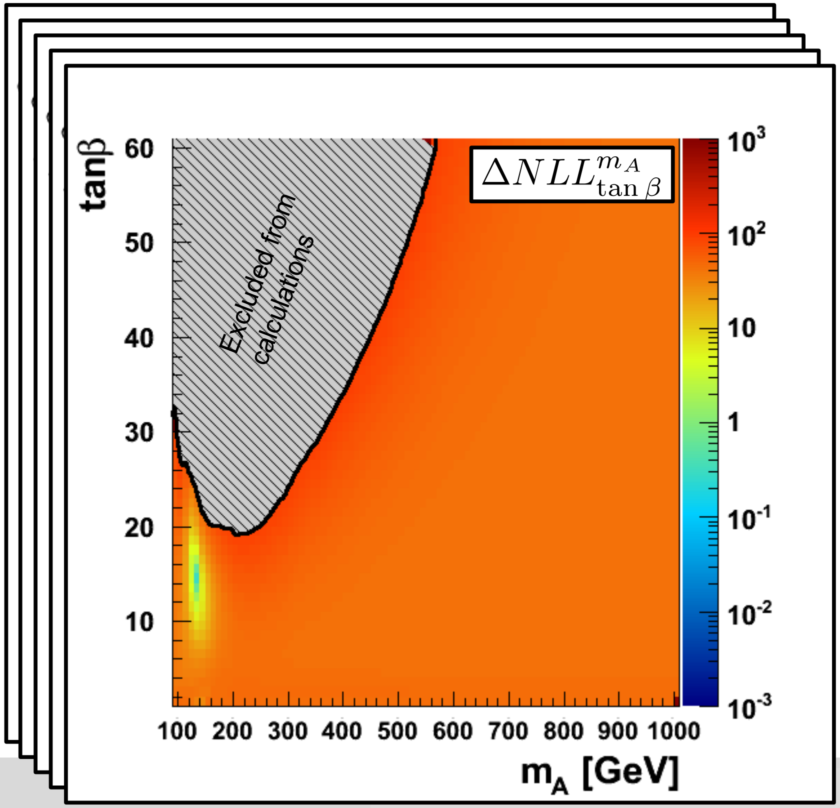
Direct limit

- Inject signal for decreasing values of m_A :

$$m_h^{mod+} \quad m_A = 130 \text{ GeV} \quad \tan\beta = 15$$

- Investigate behavior of signal templates & likelihood.



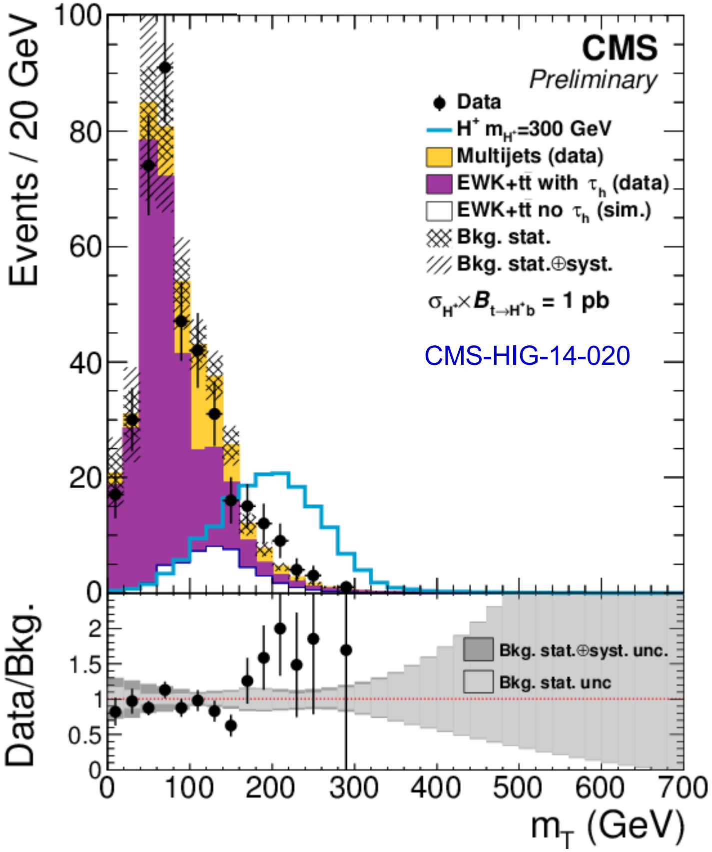


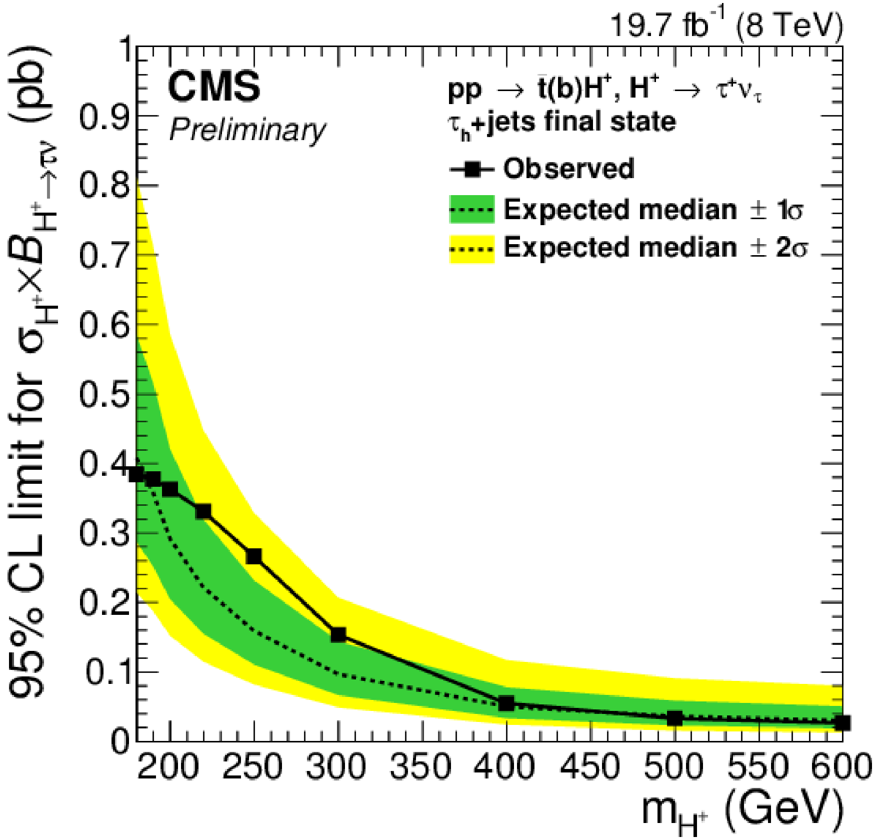
Charged Higgs boson search ($H^{+/-} \to \tau\nu$)

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

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

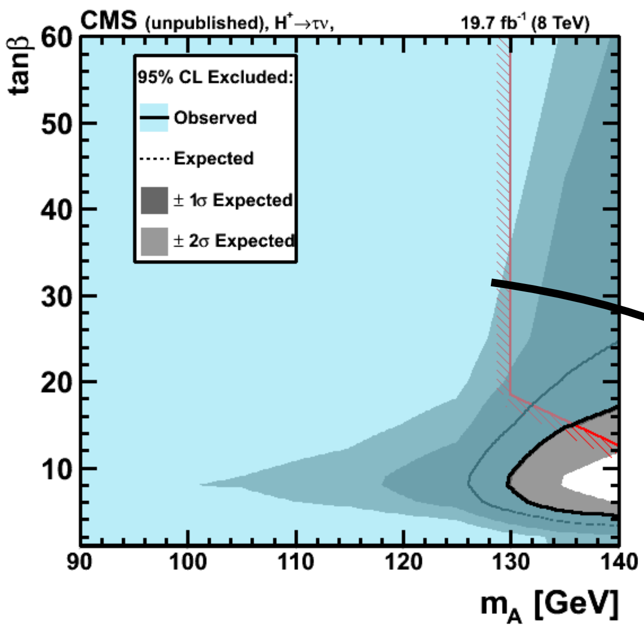
- Extending mass range of search by $180\ \text{GeV} \leq m_{H^{+/-}} \leq 600\ \text{GeV}$.

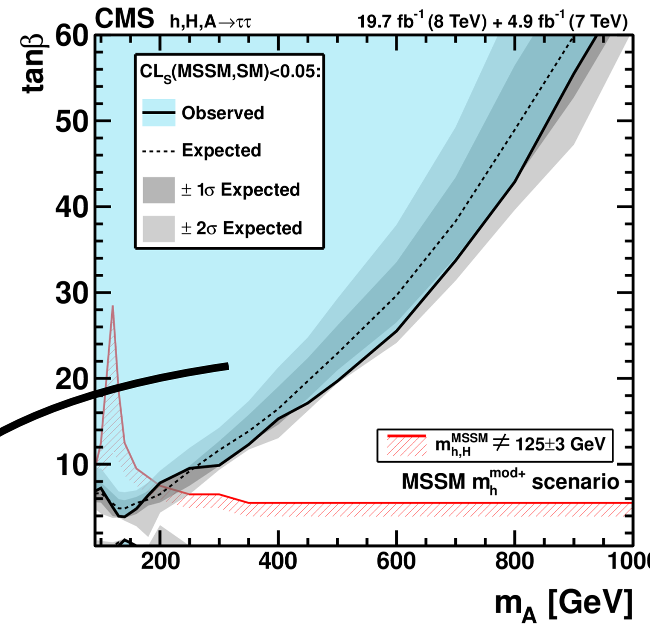


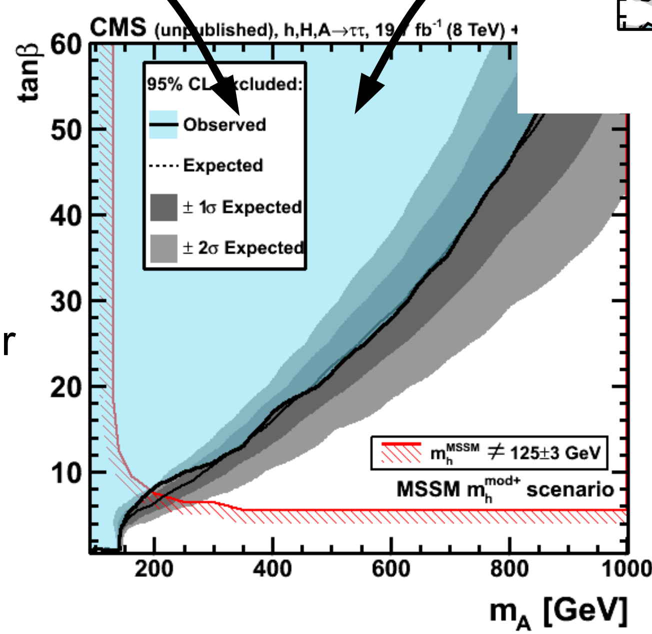


Combined MSSM $H \to \tau\tau$ & $H^+ \to \tau\nu$ Limits

- **Coherent search for all 5 MSSM Higgs bosons**:





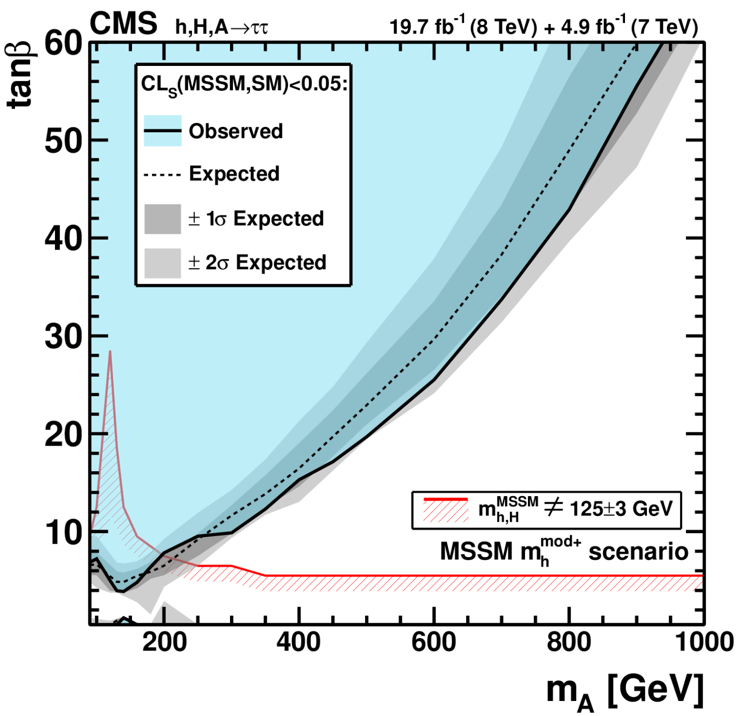


- Infrastructure already set up.
- Setting path for any kind of other combined model searches.
- **Extension by further channels** straight forward (e.g. $H \to b\bar{b}$, $H \to hh \to \tau\tau b\bar{b}$, $A \to Zh \to \ell\ell\tau\tau$).

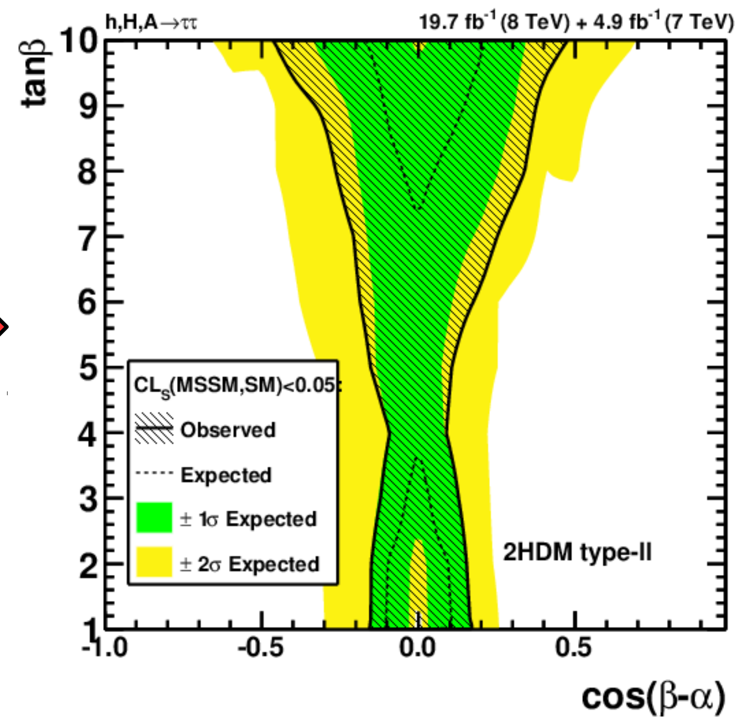
$H \to \tau\tau$ MSSM limits re-interpreted in Type-II 2HDM

Karlsruhe Institute of Technology

- **Infrastructure in place**. Incorporation in existing framework nearly trivial:



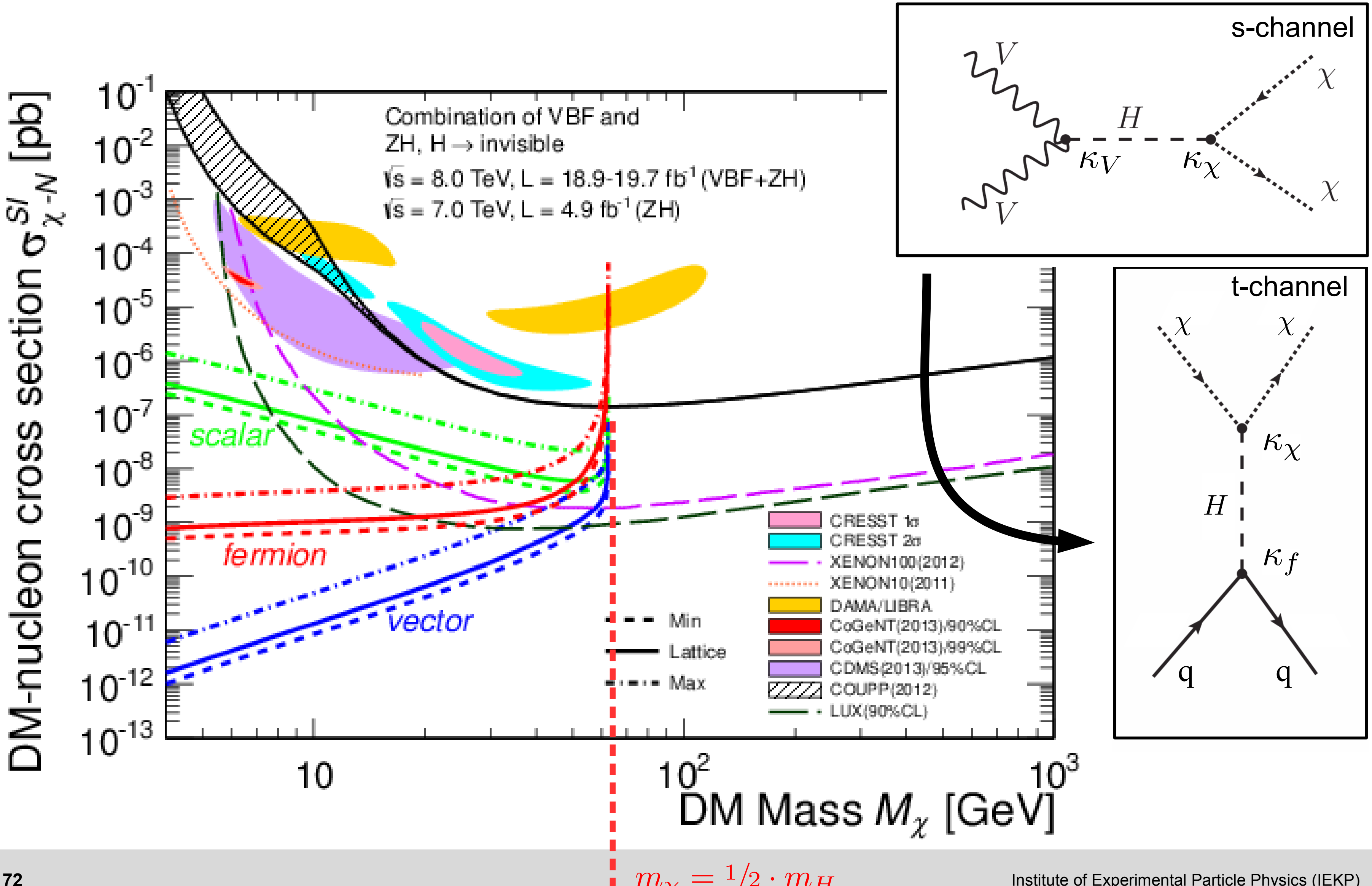
same data



Ph.D. thesis F. Frensch 05/2015

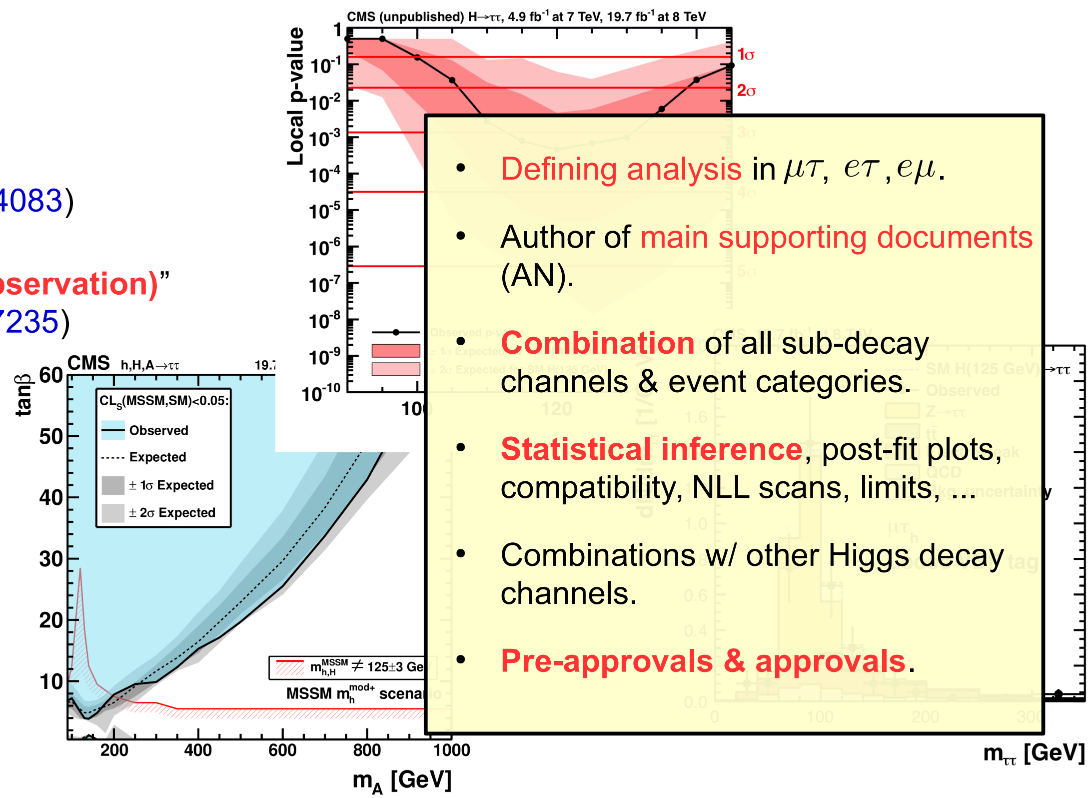
- Usually 7 free parameters on general 2HDM scenarios.
- Much more studies/understanding required.

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



Higgs Discovery Period (2011 – 2013)

- **Personal contributions to Higgs discovery** (& beyond): [Σ: 9 PASes, 5 papers!]
  - "First MSSM limits (for Moriond)" (03/2011, $36\mathrm{pb}^{-1}$) (HIG-10-002/arXiv:1104.1619)
  - "Update of MSSM limits (for EPS)" (07/2011, $1.1\mathrm{fb}^{-1}$) (HIG-11-009)
  - "Update of MSSM limits (for SUSY)" (08/2011, $1.6\mathrm{fb}^{-1}$) (HIG-11-020)
  - "**First SM & MSSM limits (for Jamboree)**" (12/2011, $4.6\mathrm{fb}^{-1}$) (HIG-11-029/arXiv:1202.4083)
  - "**Update of SM limits for ICHEP (Higgs observation)**" (07/2012, $10\mathrm{fb}^{-1}$) (HIG-12-018/arXiv:1207.7235)
  - "**Update of SM limits (for HCP)**" (11/2012, $17\mathrm{fb}^{-1}$) (HIG-12-043)
  - "Update of MSSM limits (for HCP)" (11/2012, $17\mathrm{fb}^{-1}$) (HIG-12-050)
  - "SM4 searches (direct publication)" (02/2013, $10\mathrm{fb}^{-1}$) (arXiv:1302.1764)
  - "**SM evidence (for Moriond)**" (03/2013, $25\mathrm{fb}^{-1}$) (HIG-13-004/arXiv:1401.5041)
  - "**MSSM limits on full dataset (for SUSY)**" (07/2013, $25\mathrm{fb}^{-1}$) (HIG-13-021/arXiv:1408.3316)



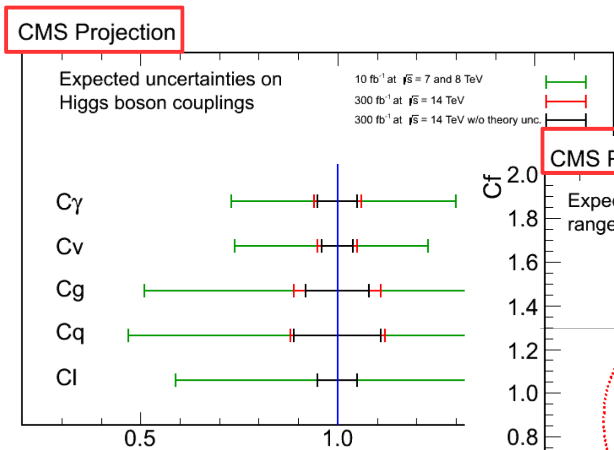
- Defining analysis in $\mu\tau$, $e\tau$, $e\mu$.
- Author of main supporting documents (AN).
- **Combination** of all sub-decay channels & event categories.
- **Statistical inference**, post-fit plots, compatibility, NLL scans, limits, ...
- Combinations w/ other Higgs decay channels.
- **Pre-approvals & approvals**.

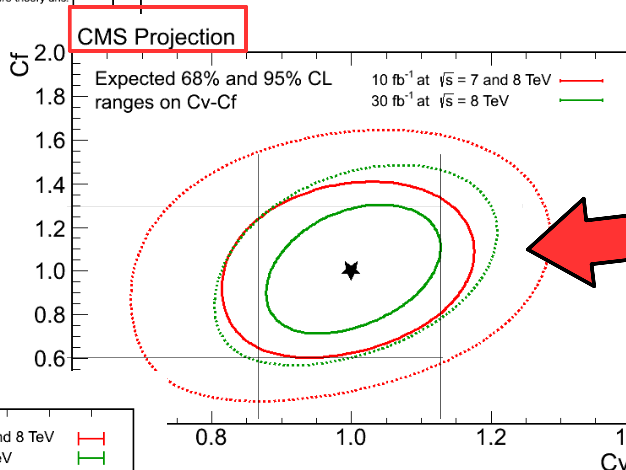
Mike Bachtis, Josh Swanson, Andrew Gilbert, Valentina Dutta, Aram Apyan, Riccardo Manzoni, Alexei Raspereza, Phil Harris, Markus Klute, RW...

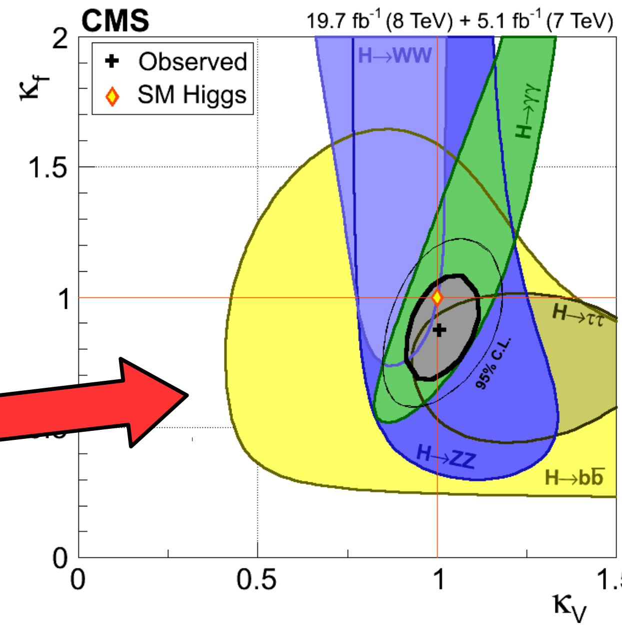
Higgs Future Projections (2011/2012)

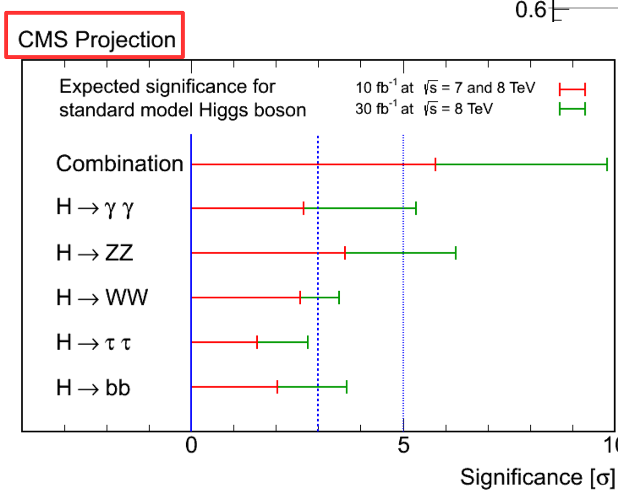
- ESG (CMS-NOTE-2012-006) & snowmass reports

Marco Zanetti, Markus Klute, RW.









obs	exp
5.7σ	(5.3σ)
6.8σ	(6.7σ)
4.3σ	(5.8σ)
3.2σ	(3.7σ)
2.1σ	(2.5σ)

as published

Projections for 30 / 300 / 3000 fb^{-1}

- **Basis for strategical decisions**.
- Preparation of datacards in all decay channels + calculation of significances.
- NB: Scenario for 30fb^{-1} compares quite well with reality.

Tools for $H \to \tau\tau$ Limit Calculation

TWiki > CMS Web > HiggsWG > SWGuideHiggsAnalysisCombinedLimit > SWGuideHiggs2TauLimits (2013-11-26, RogerWolf)

Edit Attach PDF

Calculating Limits for the Higgs2Tau Working Group

Contents

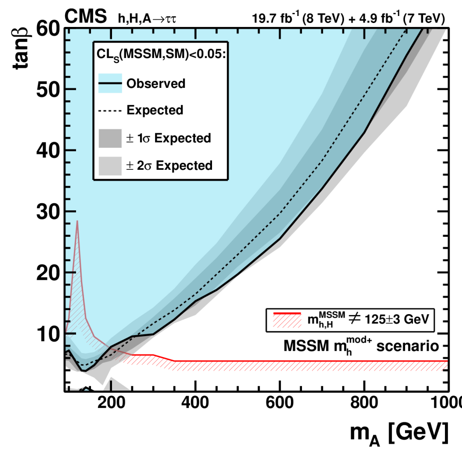
Introduction and Installation

The HiggsToTauTau subgroup has an official CMSSW package to centrally administrate a
the subsequent decay into tau leptons. On this TWiki you will find the relevant information
package as described below. The most important part of the package is the set of scripts
important scripts you might make use of are listed below with a short description:

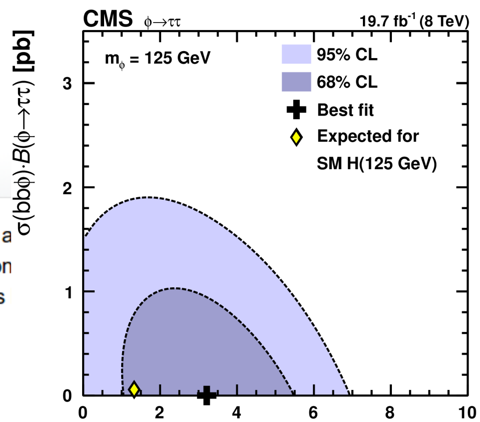
- *setup-datacards.py*: setup you
- *cvs2local.py*: copy officially su
- *setup-htt.py*: setup the directo
- *submit.py*: do the submission
- *limit.py*: do final signal strengt
- *plot*: initially create final plots i

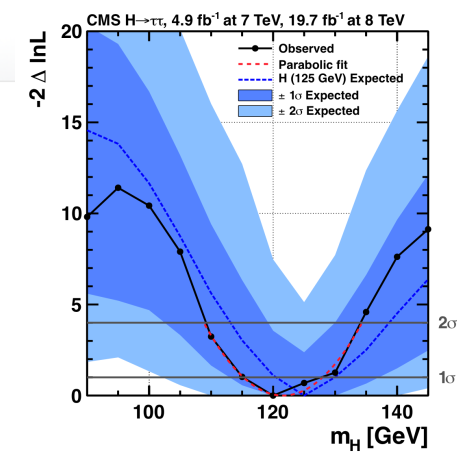
The package contains many more sc
does and what its scope is. To make
you with the information needed to s
dataset in Hig13004TWiki (for the SI

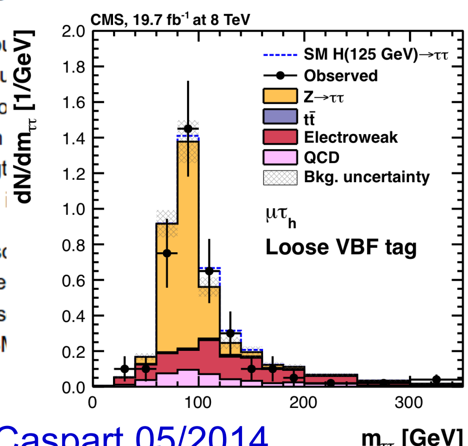
```
name                                               pre fit
CMS_eff_b_7TeV                              0.00 +/- 1.00     +0.18 +/- 0.59
CMS_eff_b_8TeV                              0.00 +/- 1.00     +0.44 +/- 0.55
CMS_eff_e                                   0.00 +/- 1.00    !-0.09 +/- 0.16
CMS_eff_m                                   0.00 +/- 1.00    !-0.28 +/- 0.14
CMS_eff_t_etau_7TeV                         0.00 +/- 1.00    !+0.21 +/- 0.19
CMS_eff_t_etau_8TeV                         0.00 +/- 1.00    !-0.36 +/- 0.12
CMS_eff_t_mssmHigh_etau_7TeV                0.00 +/- 0.99     +0.00 +/- 1.04
CMS_eff_t_mssmHigh_etau_8TeV                0.00 +/- 0.99     +0.00 +/- 1.04
CMS_eff_t_mssmHigh_mutau_7TeV               0.00 +/- 0.99     +0.00 +/- 1.04
CMS_eff_t_mssmHigh_mutau_8TeV               0.00 +/- 0.99     +0.00 +/- 1.04
CMS_eff_t_mssmHigh_tautau_8TeV        |     0.00 +/- 0.99     +0.00 +/- 1.04
CMS_eff_t_mutau_7TeV                        0.00 +/- 1.00    !+0.47 +/- 0.12
CMS_eff_t_mutau_8TeV                        0.00 +/- 1.00    !-0.21 +/- 0.07
CMS_eff_t_tautau_8TeV                       0.00 +/- 1.00    !+0.81 +/- 0.14
CMS_fake_b_7TeV                             0.00 +/- 1.00     +0.15 +/- 0.94
CMS_fake_b_8TeV                             0.00 +/- 1.00     +0.11 +/- 0.66
                                                             !-0.73 +/- 0.49
                                                             !+0.09 +/- 0.23
                                                              +0.03 +/- 1.09
                                                              +0.02 +/- 0.98
                                                              +0.01 +/- 1.01
                                                              -0.07 +/- 0.87
```

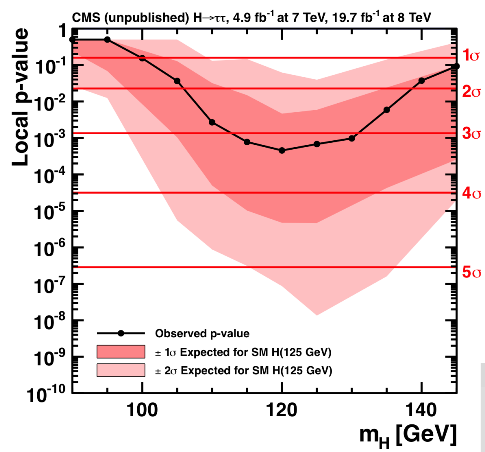


now:
Andrew Gilbert, Felix Frensch, Rene Caspart, Artur Akhmetshin, RW









Used for **all statistical inference** in $H \to \tau\tau$ up to now!

e.g.:
Master thesis Rene Caspart 05/2014.
under my responsible supervision.

Current Personal Situation

Karlsruhe Institute of Technology

- **Habilitation @ KIT/EKP** (Leader of KIT Higgs group, since 11/2013):

Lectures on Higgs physics (3x evaluated)

Convener of $H \to \tau\tau$ sub-group (2014/2015)

Convenor of LHCXSWG-3 (MSSM & BSM).

Baden-Württemberg Stiftung
WIR STIFTEN ZUKUNFT

Habilitation document published in Springer Tracts of Modern Physics ("The Higgs Boson Discovery at the Large Hadron Collider")

Fellow of the Baden-Württemberg Stiftung (supported with budget of 90k Euro for own group, since 01/2014).

- **Higgs Group @ KIT**: Dr. A. Gilbert, Dr. S. Wayand, 3 Ph.D., 4 Master, 1 Bachelor.
  - SM $H \to \tau\tau$ (5σ) and turning it into a CP measurement.
  - Continue/extend BSM searches in $H \to \tau\tau$ decay channel & statistical interpretation.
  - Extend searches towards H^+.