

# Higgs boson discovery & properties

**Roger Wolf**  
17. July 2019

# Historical context

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*,  $\tau$  and *bottom*.

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

1995: Discovery of *top*.

2000: Discovery of  $\nu_\tau$ .

2012: Discovery of **Higgs** boson.

2013: Nobel prize to Peter Higgs and Francois Englert.

## 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  $\pi^- p \rightarrow Hn$  or  $\gamma p \rightarrow Hp$  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

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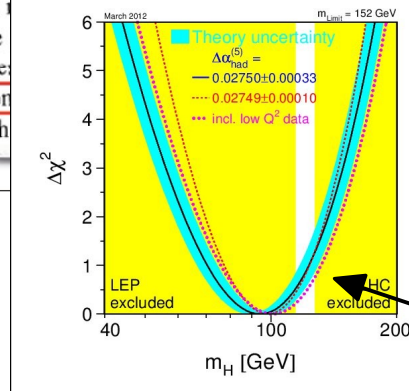
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## Indirect constraints from LEP

We should perhaps finish with an appeal to the experimentalists for having no idea what is the case with charm [3,4] and for not being sure that they are probably all very small. For the big experimental searches for the Higgs boson, the experiments vulnerable to the Higgs boson should be given priority.



$$m_H = 98 \pm_{21}^{25} \text{ GeV}$$

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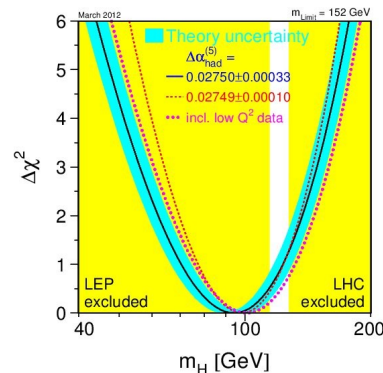
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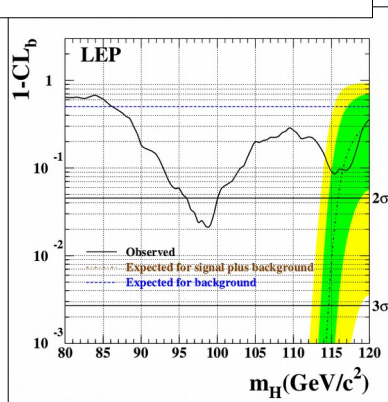
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## Final word from LEP



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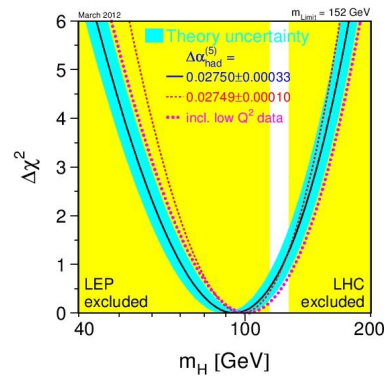
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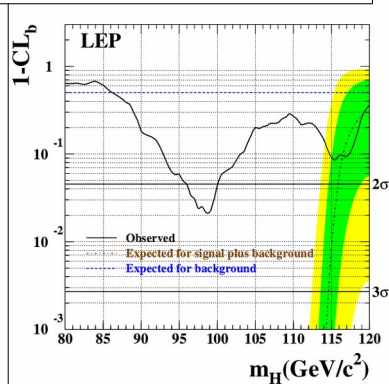
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## Indirect constraints from LEP

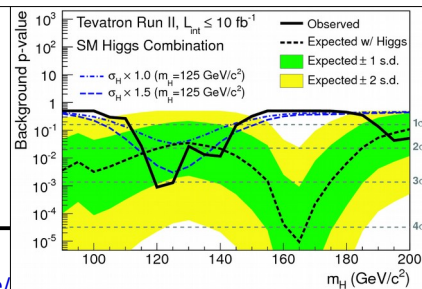


$$m_H = 98 \pm_{21}^{25} \text{ GeV}$$

## Final word from LEP



## Final word from Tevatron



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# Direct Higgs boson searches today ...

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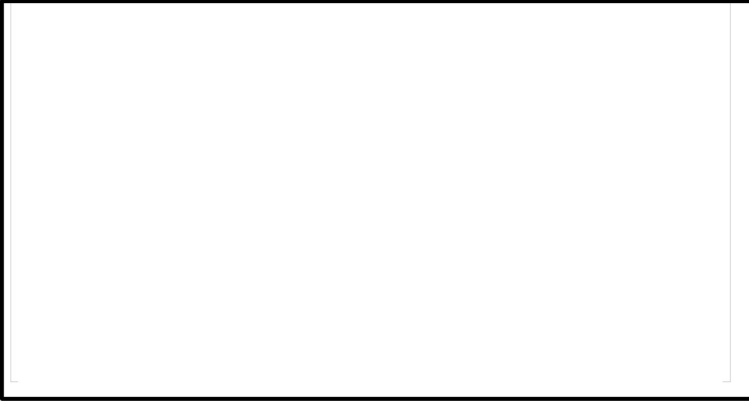


Google.de angeboten auf: [English](#)

# Direct Higgs boson searches @ LEP

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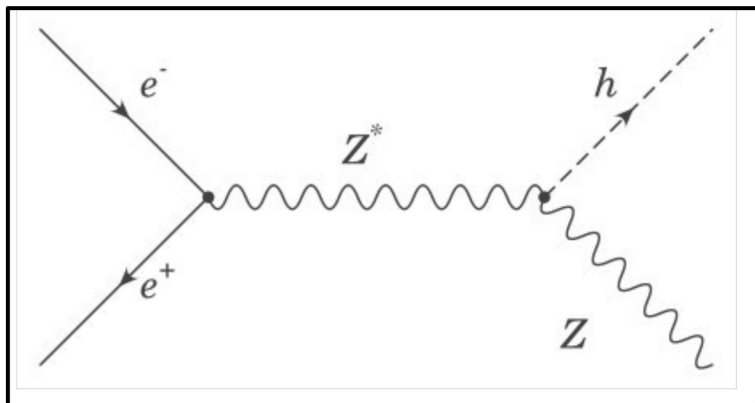
- Main production mode in  $e^+e^-$ :



- Higgs boson couples to mass.
- Strongest coupling to heaviest objects.

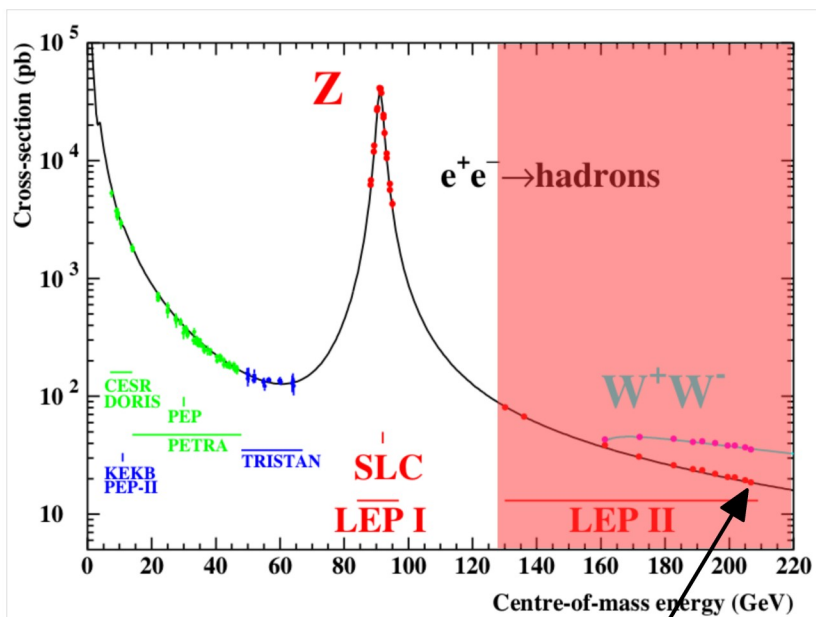
# Direct Higgs boson searches @ LEP

- Main production mode in  $e^+e^-$ :



- Higgs boson couples to mass.
- Strongest coupling to heaviest objects.

Integrated luminosities in $\text{pb}^{-1}$					
	ALEPH	DELPHI	L3	OPAL	LEP
$\sqrt{s} \geq 189 \text{ GeV}$	629	608	627	596	2461
$\sqrt{s} \geq 206 \text{ GeV}$	130	138	139	129	536

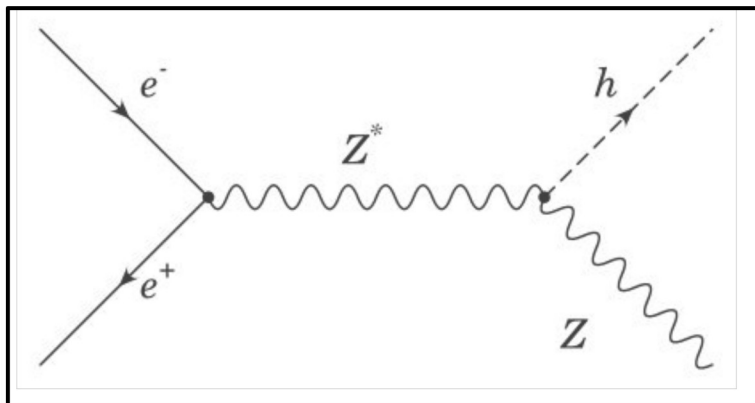


Year	1996		1997	1998	1999				2000	
$E_{\text{CM}}$ nominal [GeV]	161	172	183	189	192	196	200	202	205	207

What was the maximal reach on  $m_H$  at LEP?

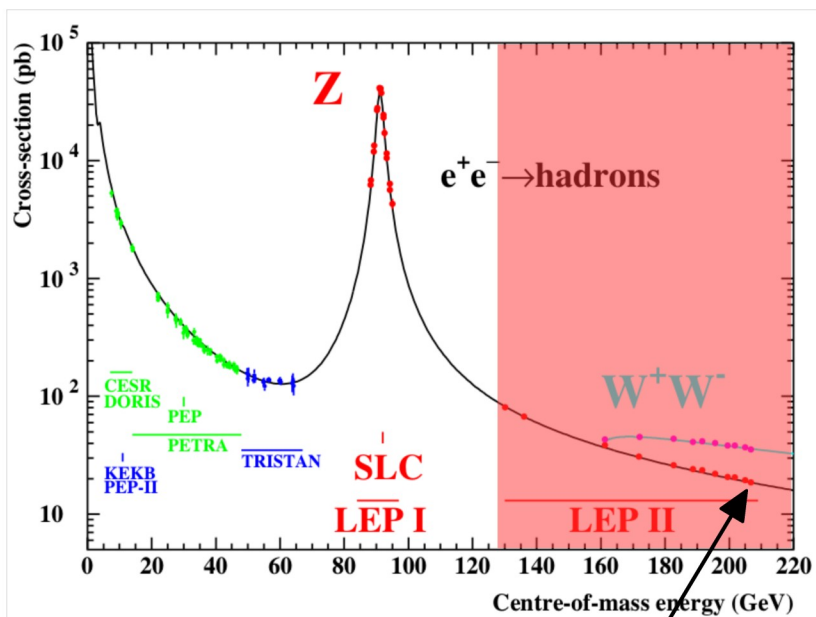
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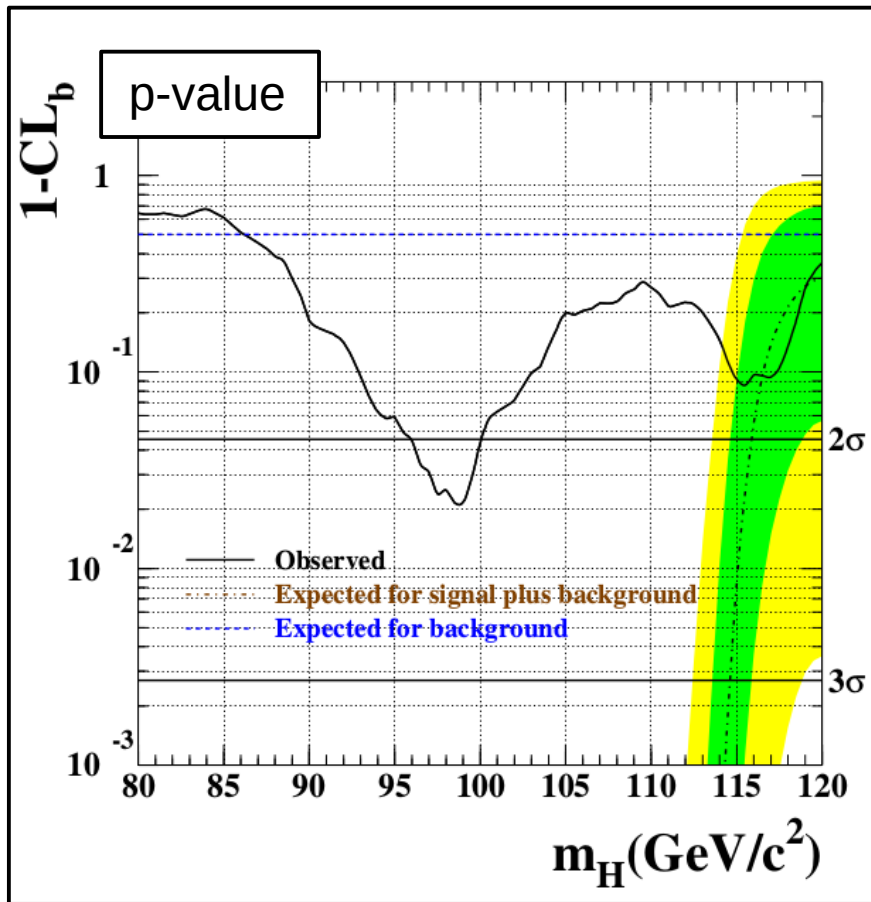


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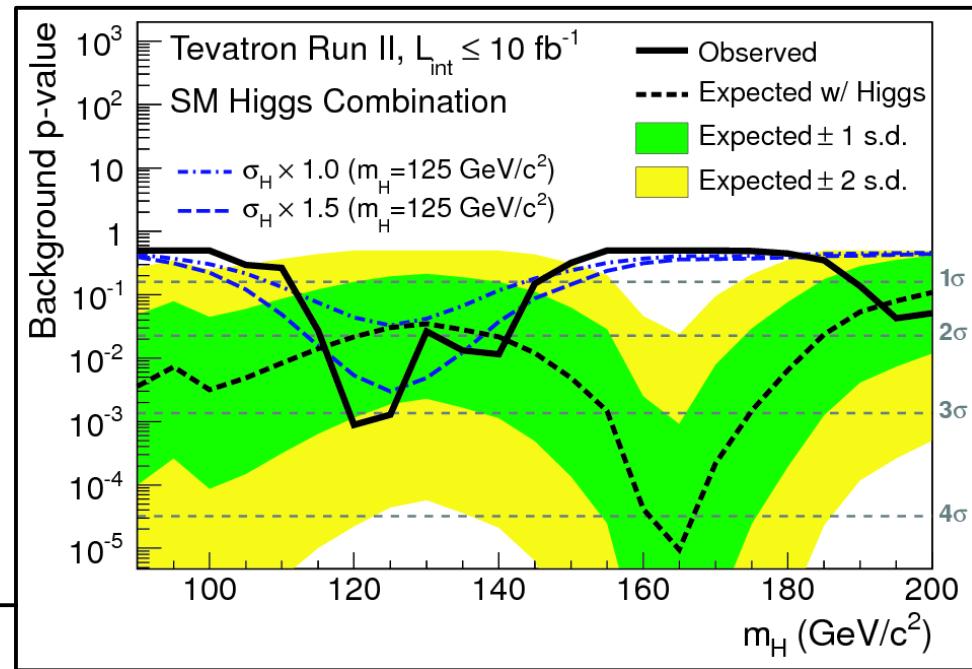
What was the maximal reach on  $m_H$  at LEP?  $m_H \approx 117 \text{ GeV}$



# LEP result (2000)



# Tevatron result (2012)



3.8T superconducting solenoid magnet:

# The LHC

Silicon Tracker:

- Tracker: Si ( $\delta p/p = 0.5\%$  for a 10 GeV track).

- ECAL:  $\text{PbWO}_4$  ( $\delta E/E = 1\%$  for a 30 GeV  $e/\gamma$ ).

## CMS

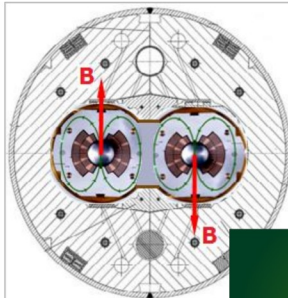
- Length : 21 m
- Diameter : 16 m
- Weight : 12'500 t

### Electromagnetic Calo:

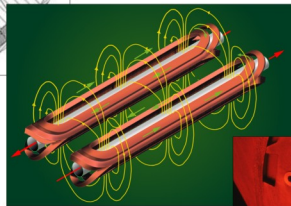


Last beam in LEP 11/2000

First beam in LHC 11/2009



- 8.3 T
- 11.8 kA
- 160 cyc

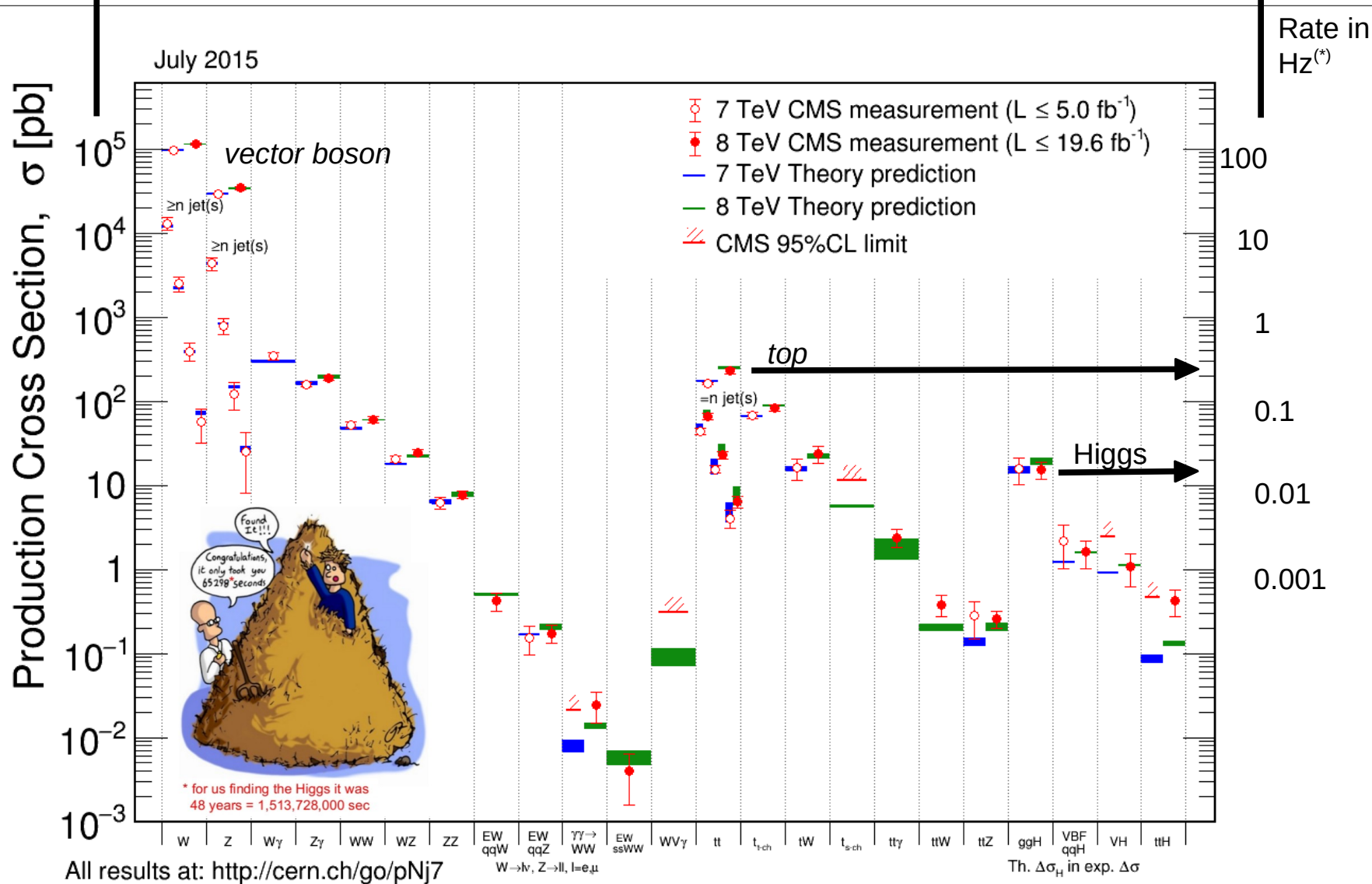


- Energy density 500 kJ/m.
- Tension 200'000 t/m.

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

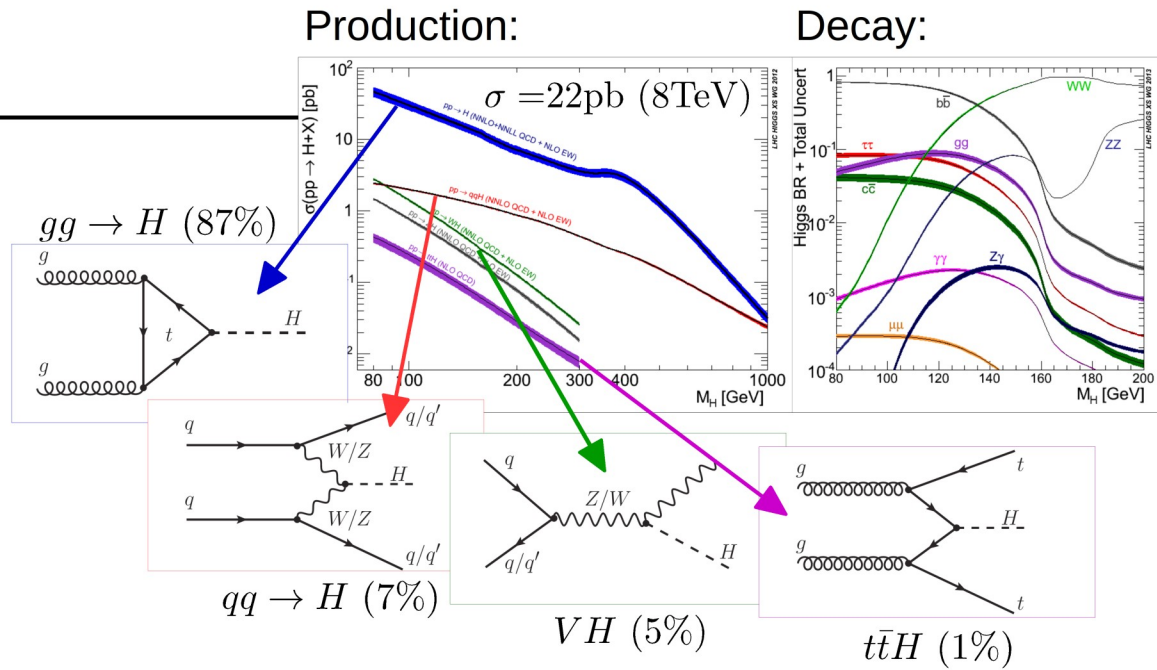


# The challenge



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

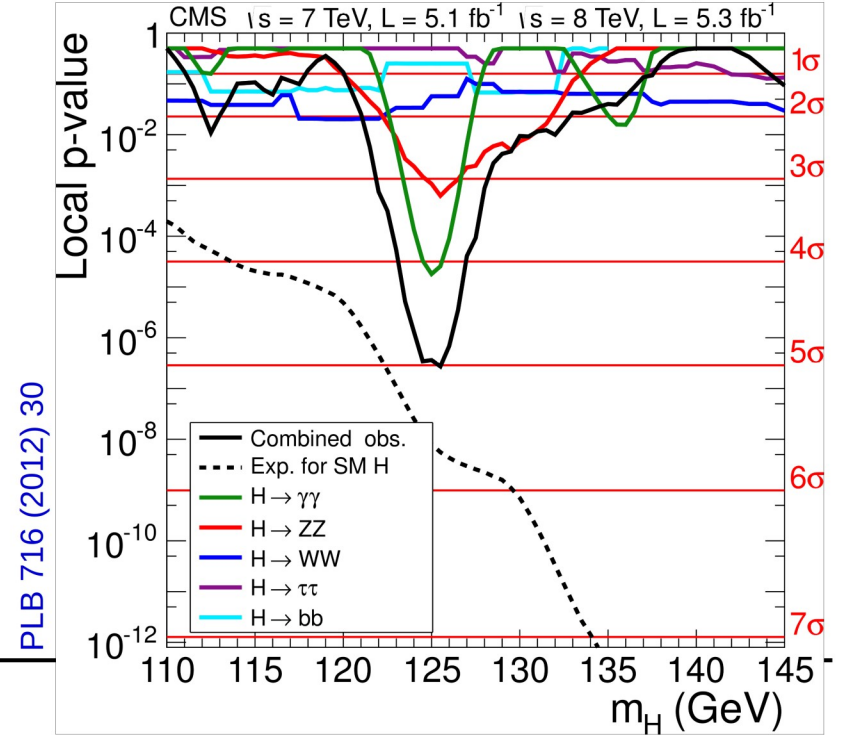
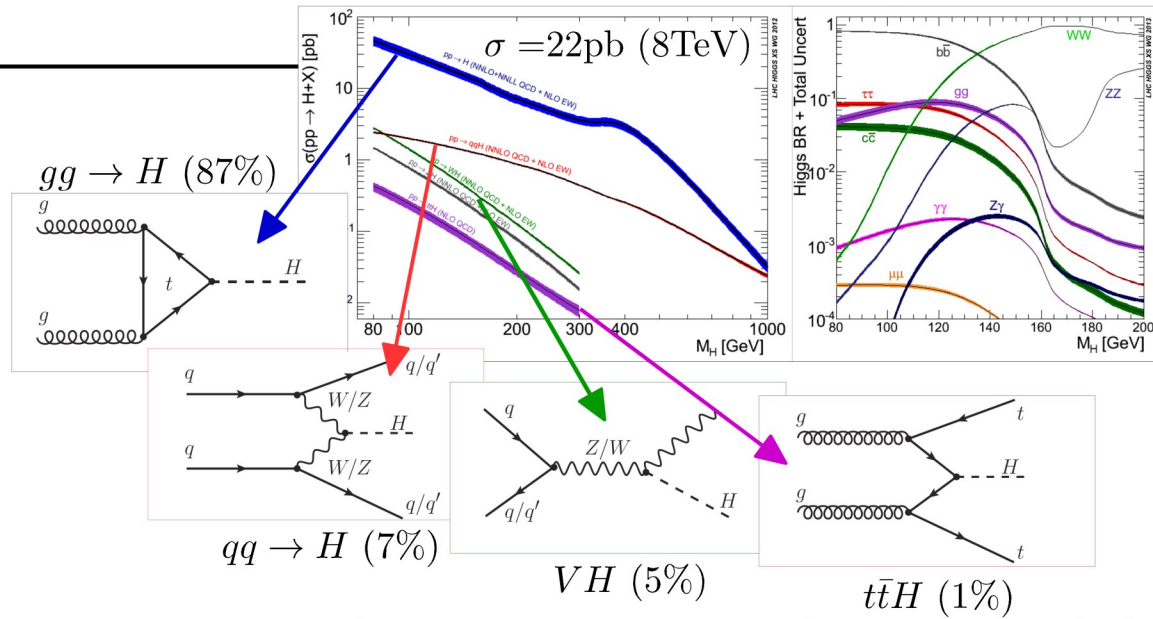
# The discovery...



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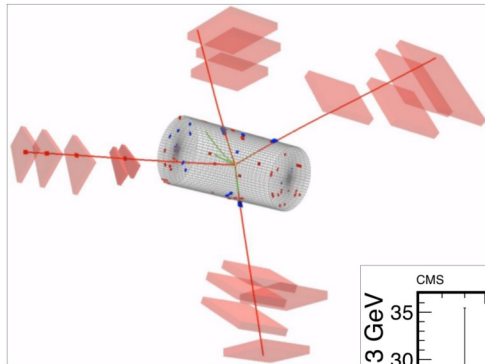
Production:

Decay:

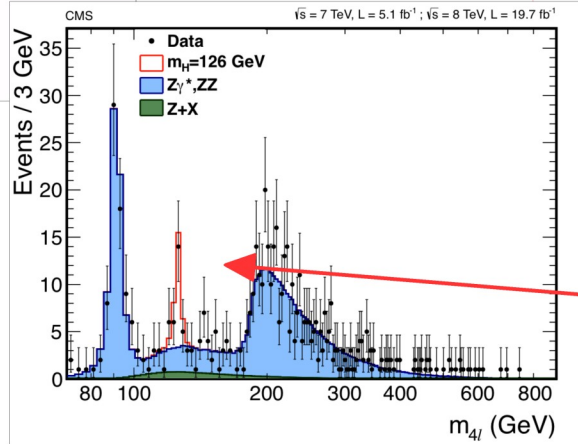


PLB 716 (2012) 30

# The discovery...

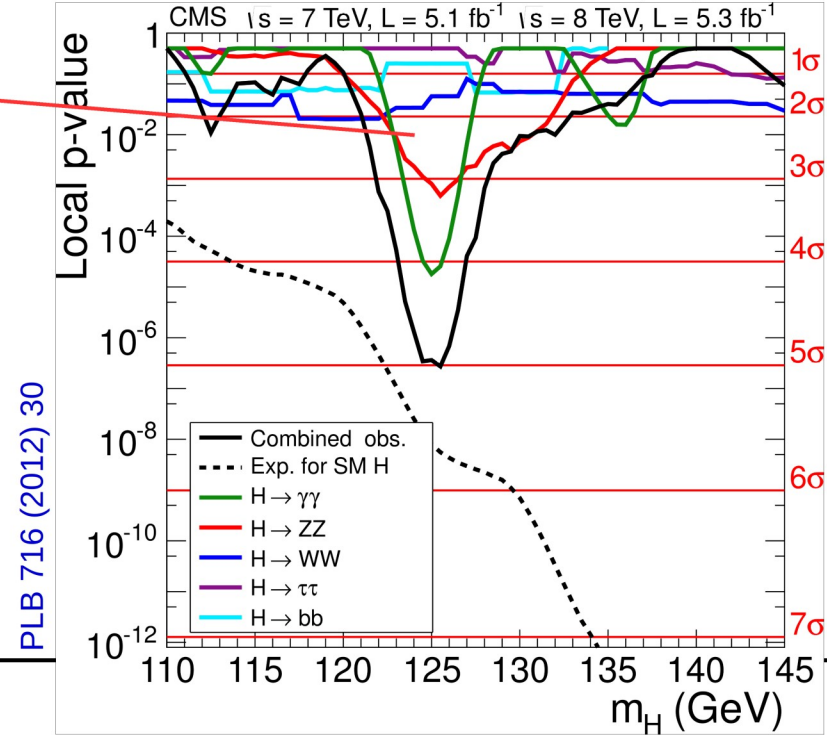
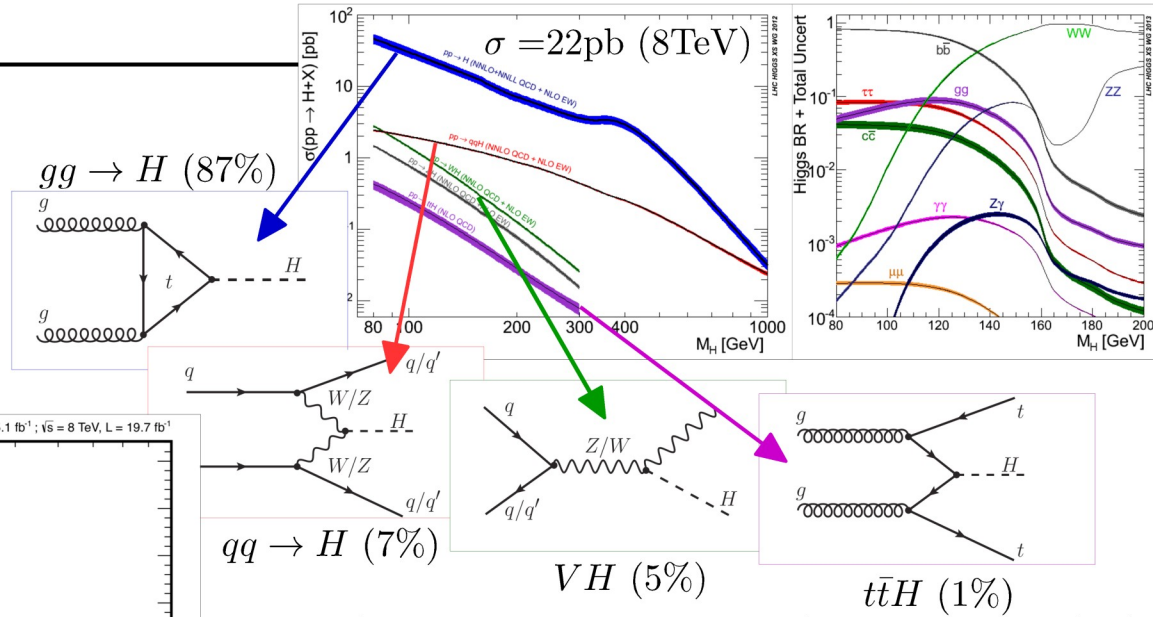


$$H \rightarrow ZZ \rightarrow 4\ell$$



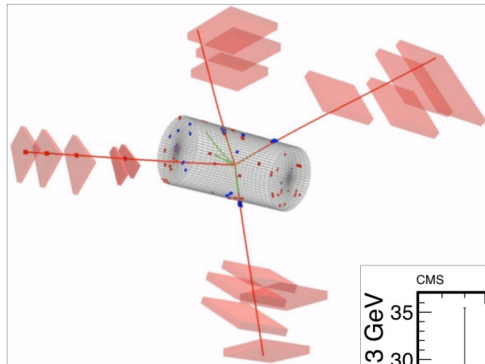
Production:

Decay:

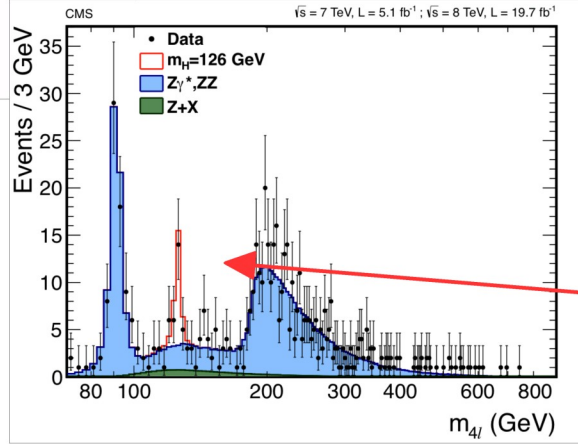


PLB 716 (2012) 30

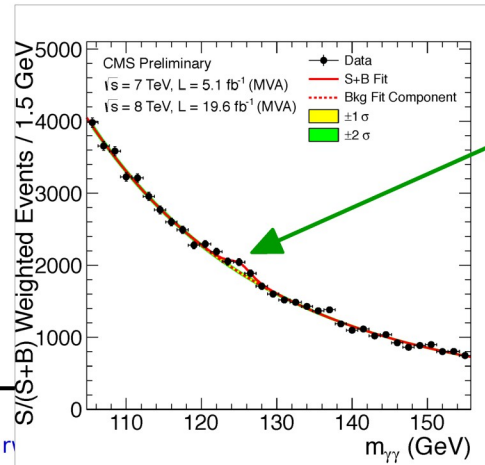
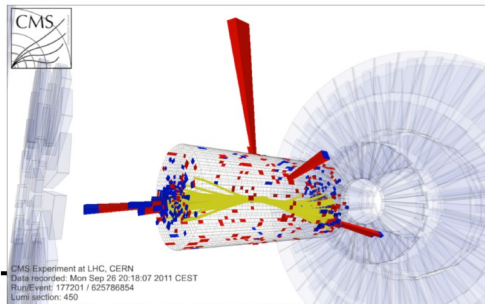
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$$H \rightarrow ZZ \rightarrow 4\ell$$



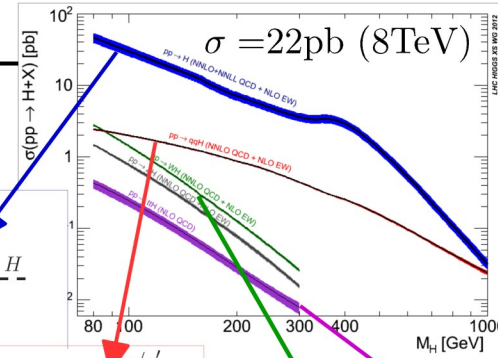
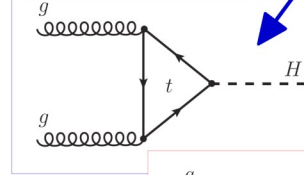
$$H \rightarrow \gamma\gamma$$



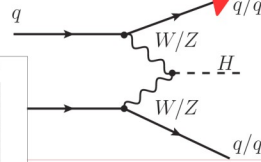
Production:

Decay:

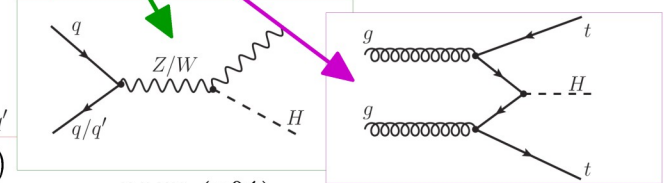
$$gg \rightarrow H \text{ (87\%)}$$



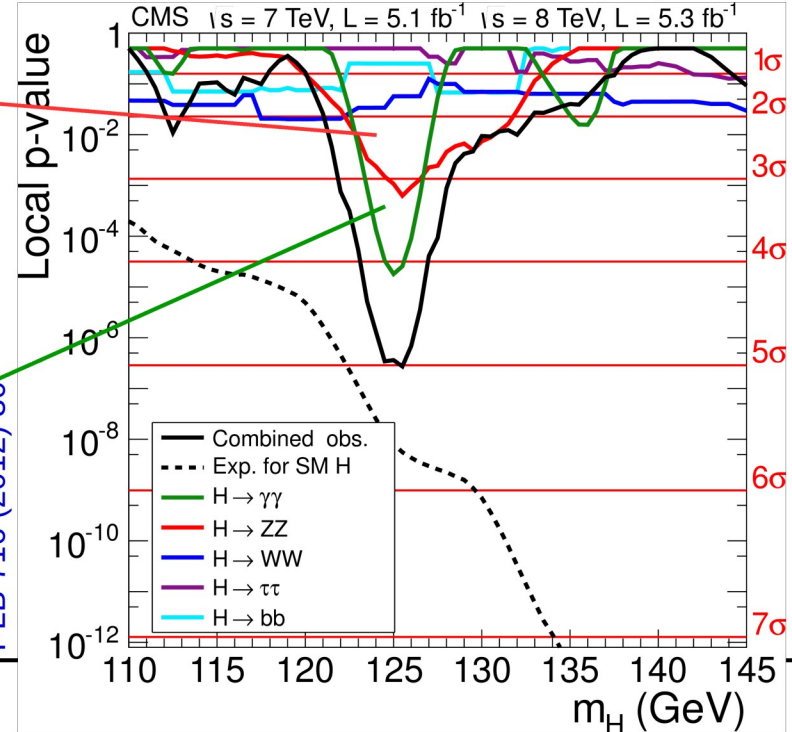
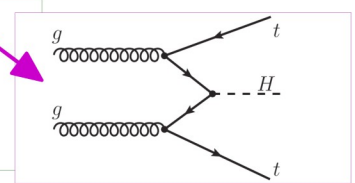
$$qq \rightarrow H \text{ (7\%)}$$



$$VH \text{ (5\%)}$$



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

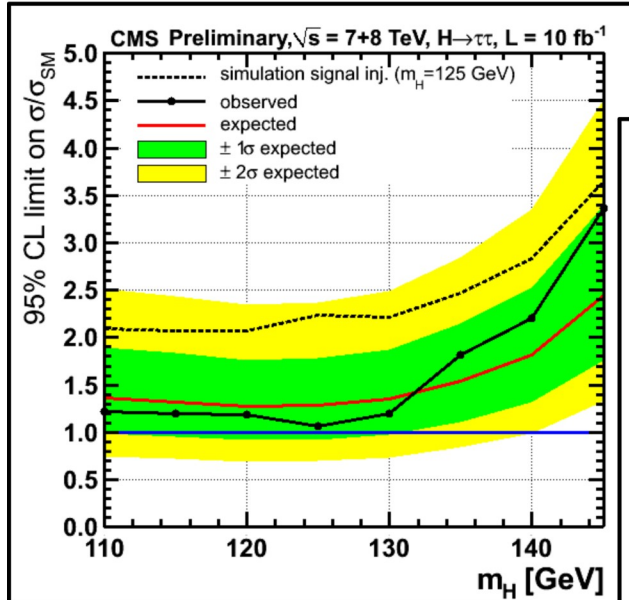


PLB 716 (2012) 30



# Intermezzo: evolution of the $H \rightarrow \tau\tau$ signal

July 2012:

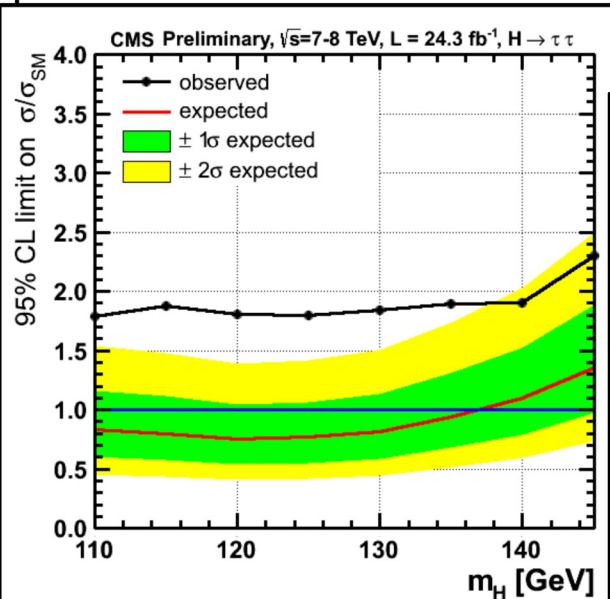


$\mu = \text{N.A.}$

$\sigma = 0(\text{obs}) \quad 1.4(\text{exp})$

@  $m_H \approx 125$  GeV

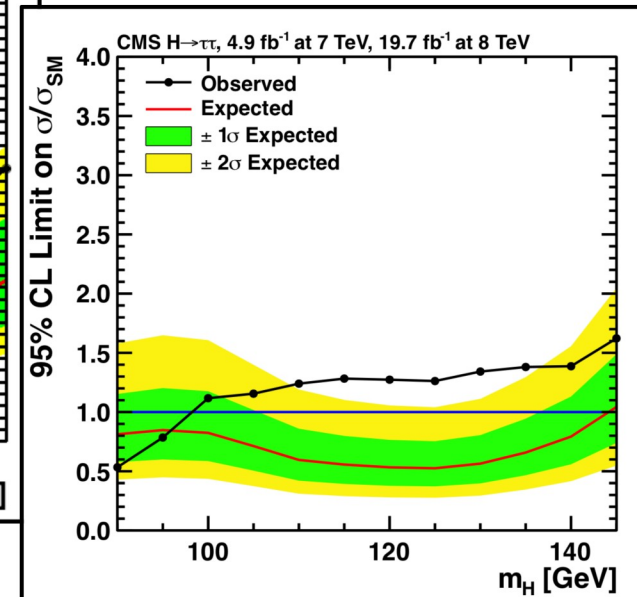
March 2013:



$\mu = 1.1 \pm 0.4$

$\sigma = 2.9(\text{obs}) \quad 2.6(\text{exp})$

Summer 2014:

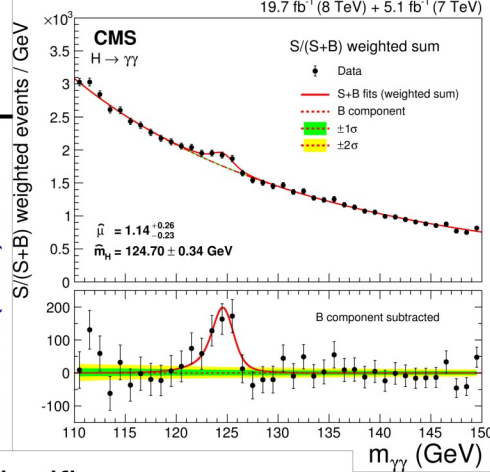


$\mu = 0.8 \pm 0.3$

$\sigma = 3.2(\text{obs}) \quad 3.7(\text{exp})$

# ... and beyond (a.k.a. Run-1 legacy)

EPJ C 74 (2014) 3076



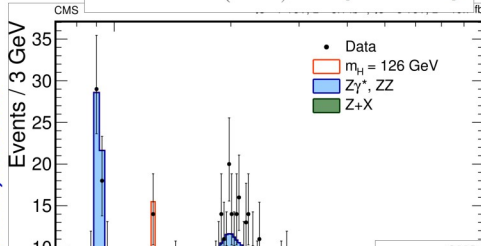
Significance:  
 $S = 5.7(5.2)\sigma$  (CMS)  
 $S = 5.2(4.6)\sigma$  (ATLAS)

“untagged”

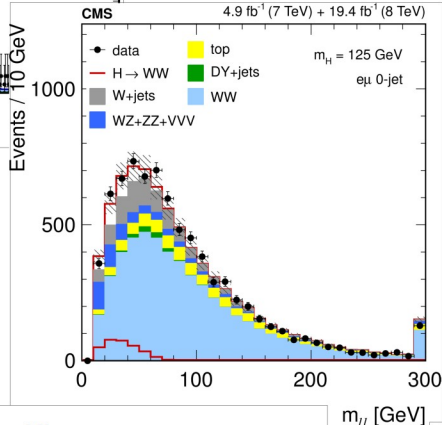
Decay / Prod	$gg \rightarrow H$	$qq \rightarrow H$	$VH$	$t\bar{t}H$
$H \rightarrow \gamma\gamma$	✓ 87%	✓ 7%	✓ 5%	✓ 1%
$H \rightarrow ZZ$	✓	✓	✓	✓
$H \rightarrow WW$	✓	✓	✓	✓
$H \rightarrow \tau\tau$	✓	✓	✓	✓
$H \rightarrow b\bar{b}$		✓	✓	✓
$H \rightarrow \mu\mu$	✓	✓		

Part of discovery   
  After LHC run-1   
  Not covered

PRD 89 (2014) 092007

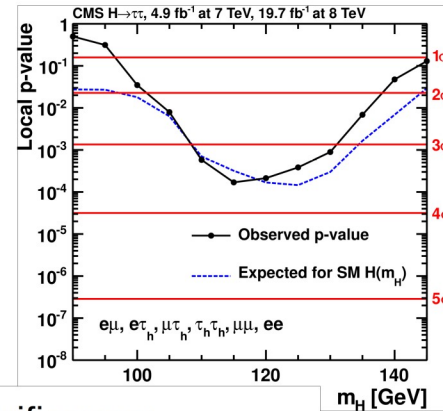


Significance:  
 $S = 6.8(6.7)\sigma$  (CMS)  
 $S = 8.1(6.2)\sigma$  (ATLAS)



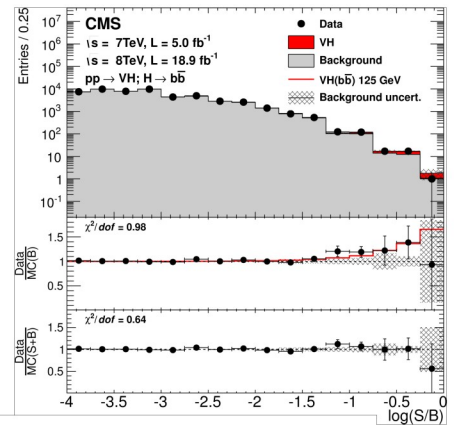
Significance:  
 $S = 4.3(5.8)\sigma$  (CMS)  
 $S = 6.1(5.8)\sigma$  (ATLAS)

JHEP 01 (2014) 096



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

JHEP 05 (2014) 104



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

# $H \rightarrow \mu\mu$ decay

+14 further exclusive categories

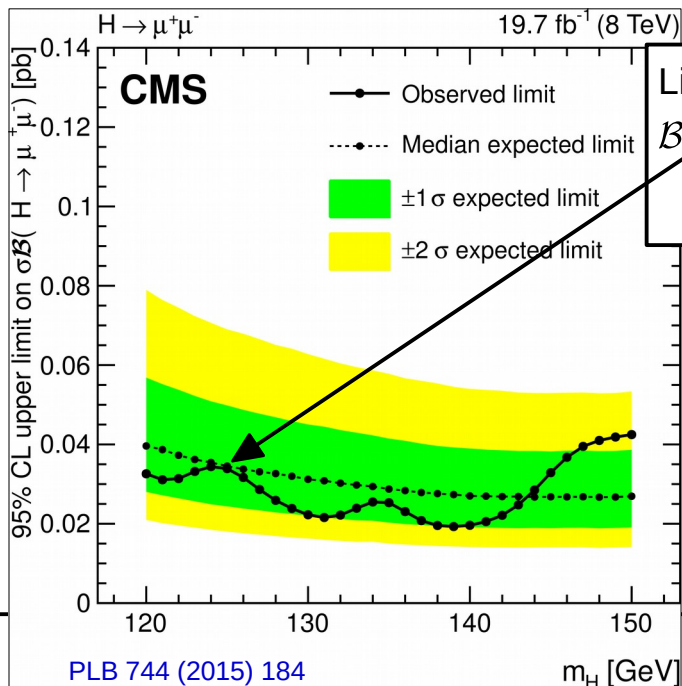
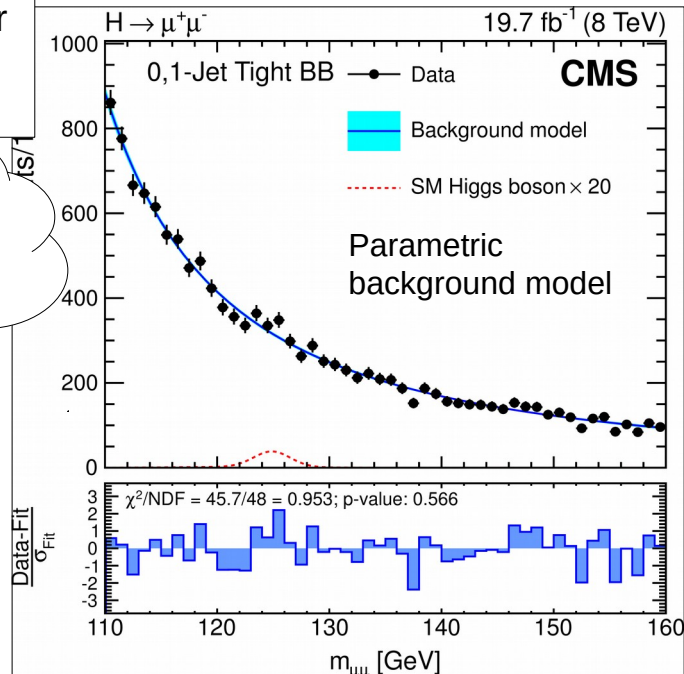
- Clear signature, high mass resolution, small  $\mathcal{BR}$  ( $\rightarrow$  similar to  $H \rightarrow \gamma\gamma$ ):

- SM expectation:

$$\mathcal{BR}(H \rightarrow \tau\tau) = 6.30 \pm 0.36 \%$$

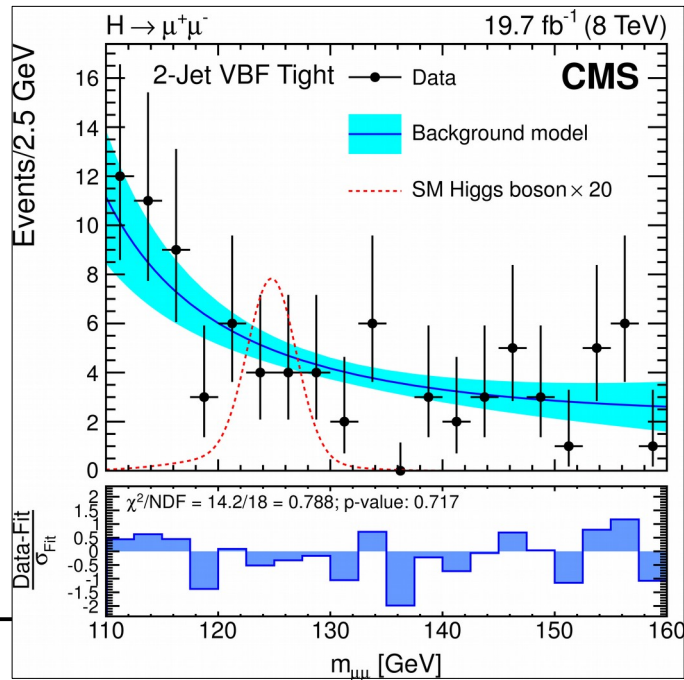
$$\mathcal{BR}(H \rightarrow \mu\mu) = ???$$

$m_\mu = 106 \text{ MeV}$   
 $m_\tau = 1777 \text{ MeV}$



Limit (95% CL):  
 $\mathcal{BR}(H \rightarrow \mu\mu) \leq 0.16\%$   
 $(7.4 (6.5) \times SM)^{(*)}$

(\*) on 7+8TeV





# $H \rightarrow \mu\mu$ decay

+14 further exclusive categories

- Clear signature, high mass resolution
- small  $\mathcal{BR}$  ( $\rightarrow$  similar to  $H \rightarrow \gamma\gamma$ ):

$$= \left(\frac{m_\mu}{m_\tau}\right)^2 \cdot \mathcal{BR}(H \rightarrow \tau\tau)$$

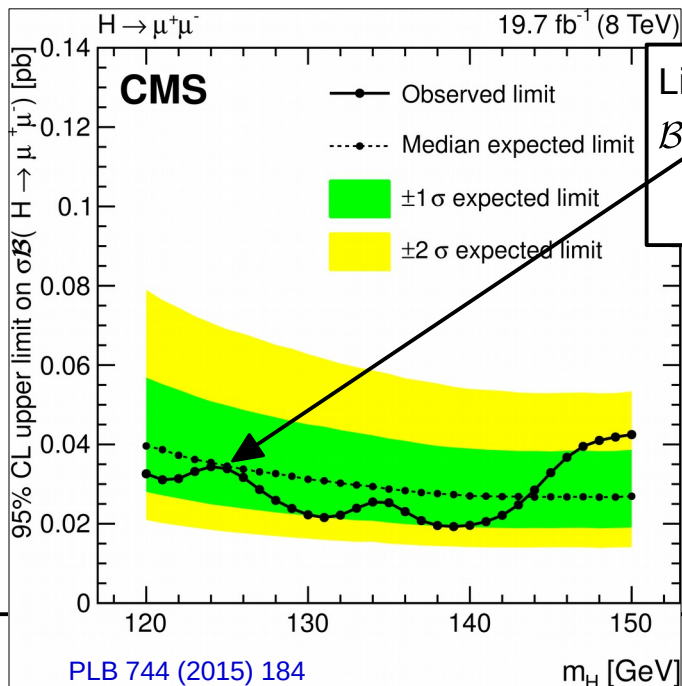
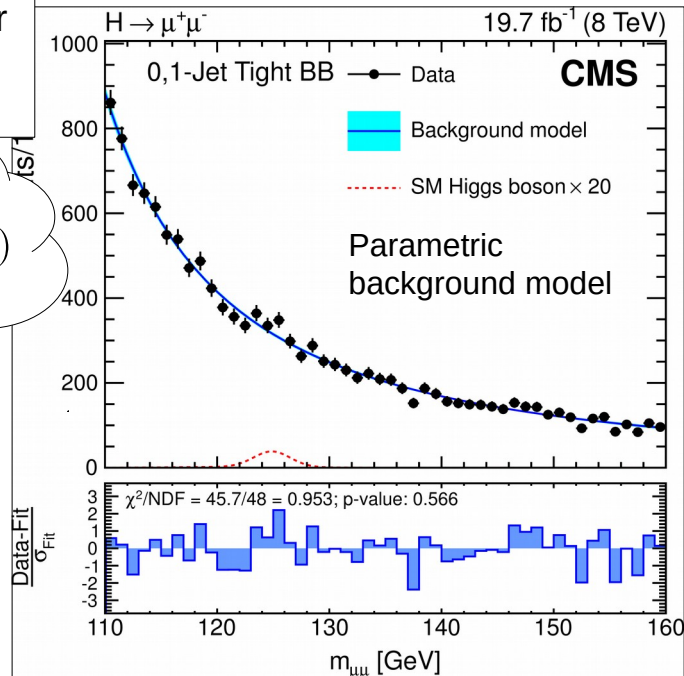
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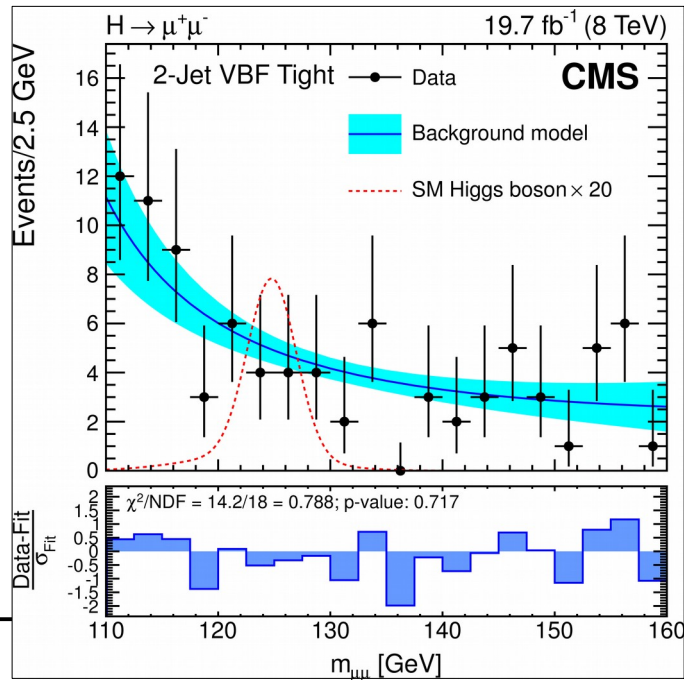
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$$\mathcal{BR}(H \rightarrow \mu\mu) = ???$$



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 $(7.4 (6.5) \times SM)^{(*)}$

(\*) on 7+8TeV



# $H \rightarrow \mu\mu$ decay

+14 further exclusive categories

- Clear signature, high mass resolution, small  $\mathcal{BR}$  ( $\rightarrow$  similar to  $H \rightarrow \gamma\gamma$ ):
- SM expectation:
- Non-universal coupling to leptons!

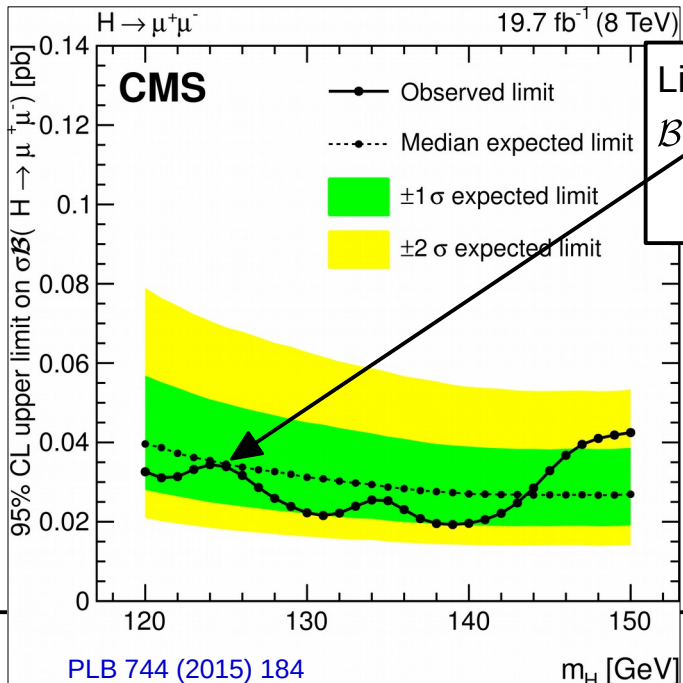
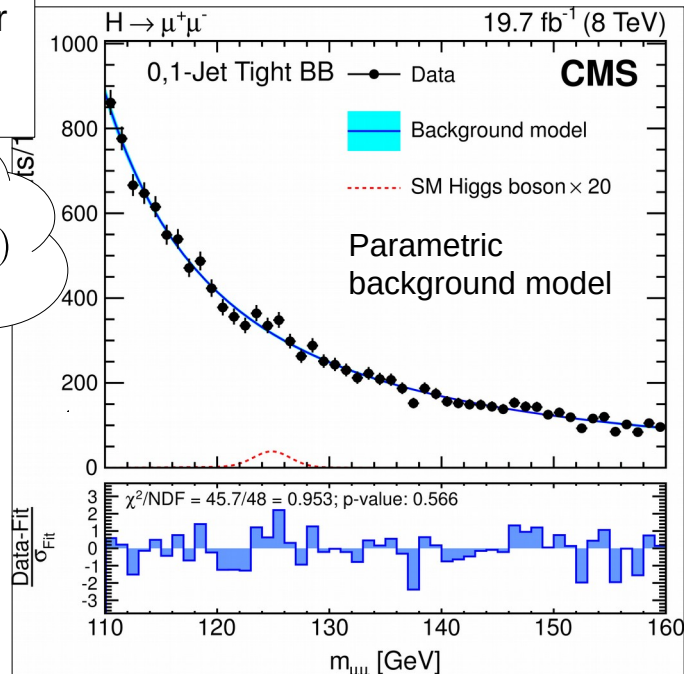
$$= \left(\frac{m_\mu}{m_\tau}\right)^2 \cdot \mathcal{BR}(H \rightarrow \tau\tau)$$

$$m_\mu = 106 \text{ MeV}$$

$$m_\tau = 1777 \text{ MeV}$$

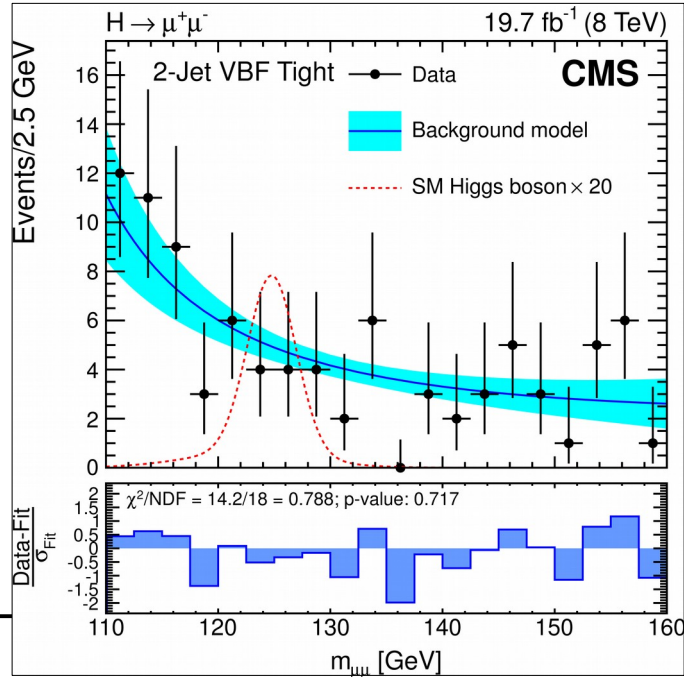
$$\mathcal{BR}(H \rightarrow \tau\tau) = 6.30 \pm 0.36 \%$$

$$\mathcal{BR}(H \rightarrow \mu\mu) = 0.022 \pm 0.001\%$$



Limit (95% CL):  
 $\mathcal{BR}(H \rightarrow \mu\mu) \leq 0.16\%$   
 $(7.4 (6.5) \times SM)^{(*)}$

(\*) on 7+8TeV





Spin & CP?

Single particle?

Decay width?

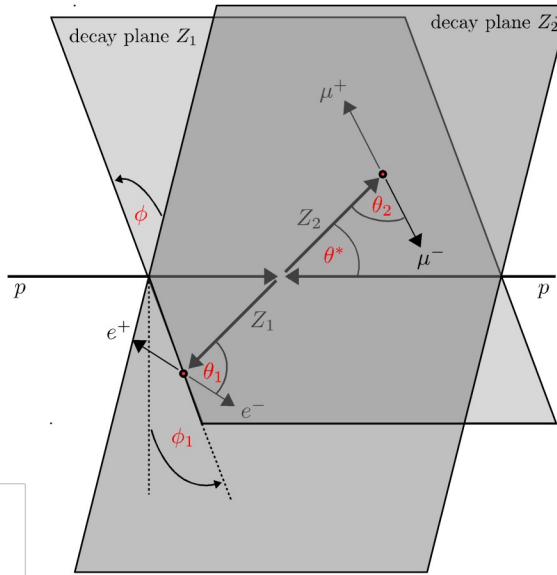
Mass?

Coupling structure?



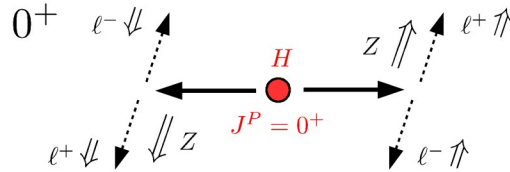
# Spin & CP

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

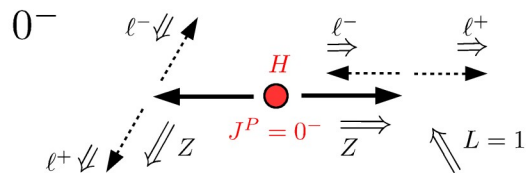


$$P(Y_L^m(\theta, \varphi)) = (-1)^L \cdot Y_L^m(\theta, \varphi)$$

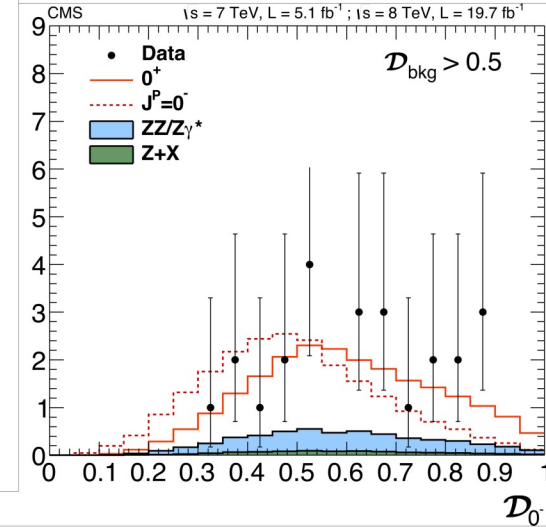
$$P(4\ell) = (-1)^L (-1)^2 (+1)^2 = (-1)^L$$



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

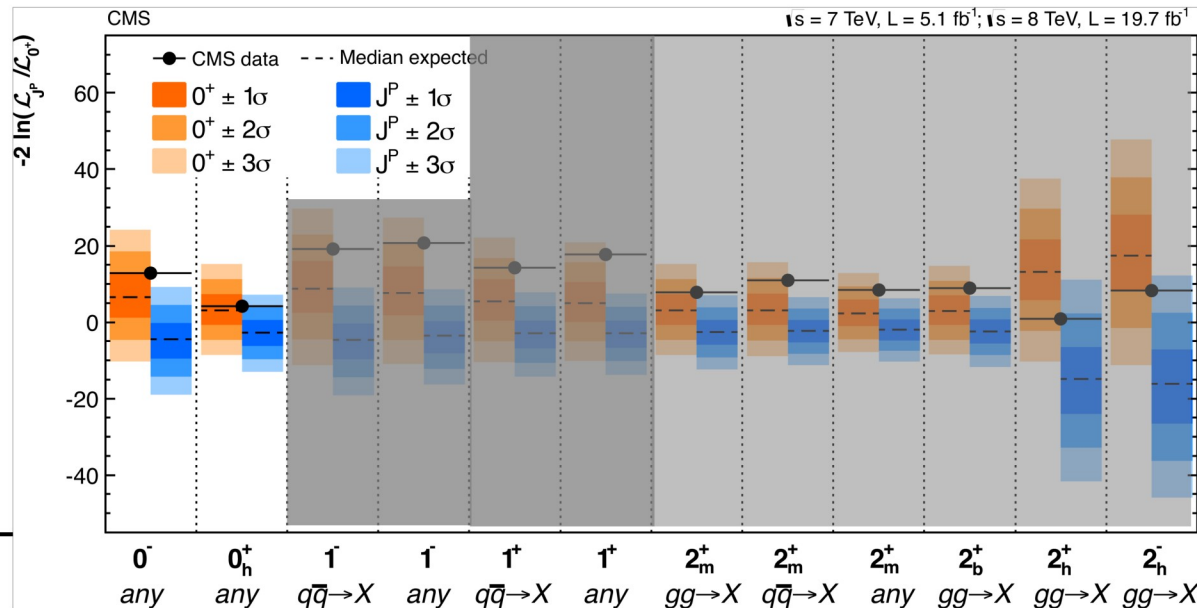


$$|1, \pm 1\rangle = \sqrt{\frac{1}{2}}|1, \pm 1\rangle \otimes |1, 0\rangle - \sqrt{\frac{1}{2}}|1, 0\rangle \otimes |1, \pm 1\rangle$$



PRD 89 (2014) 092007

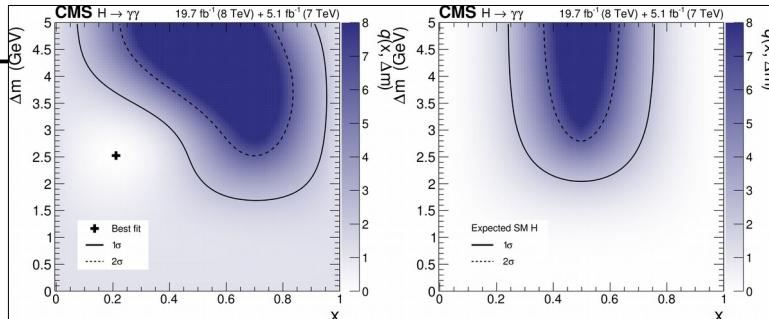
## Test of pure spin hypotheses (based on $\mathcal{O}(50)$ evts):



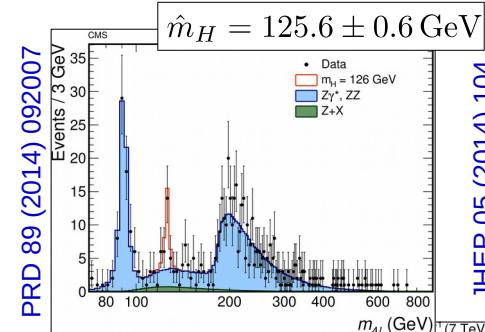
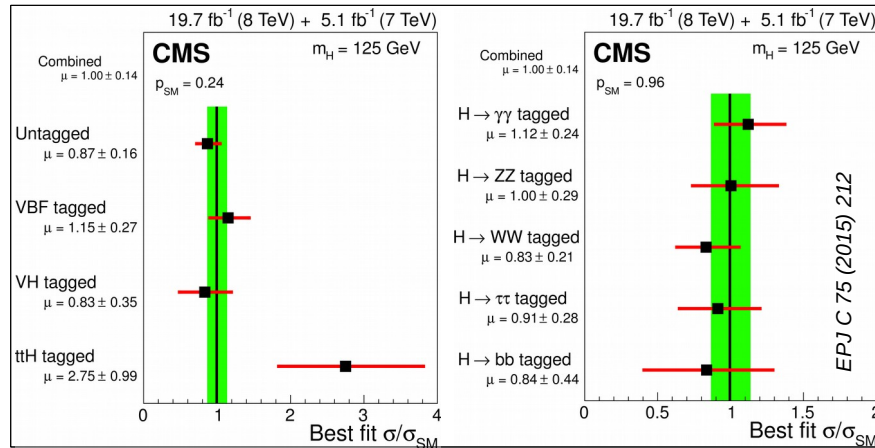
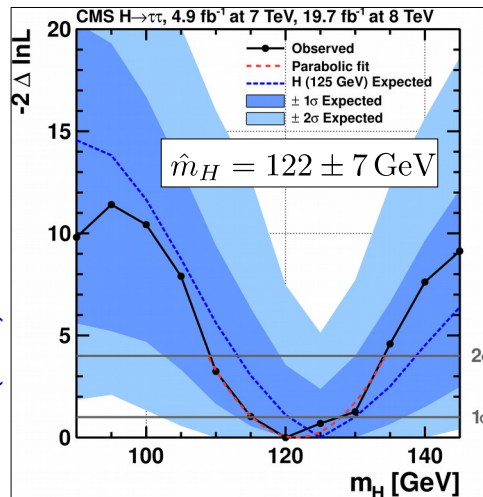
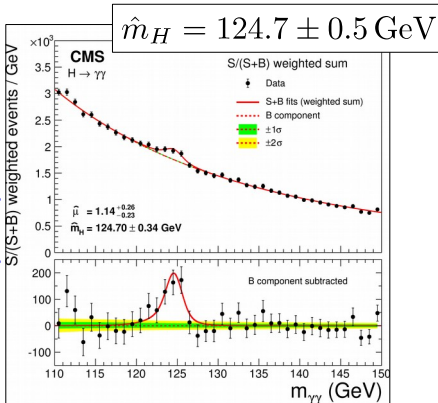


# Compatibility

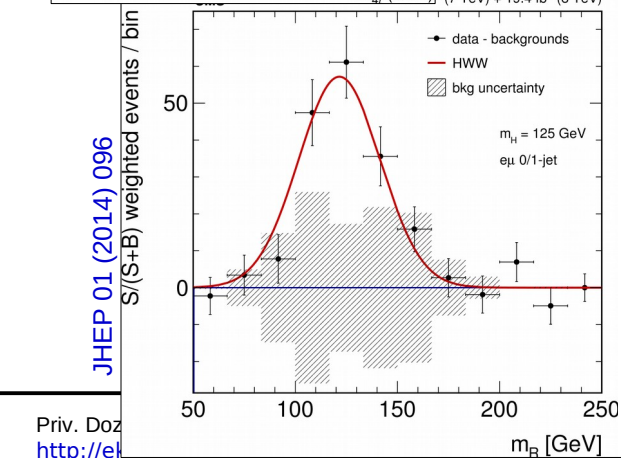
EPJ C 74 (2014) 3076



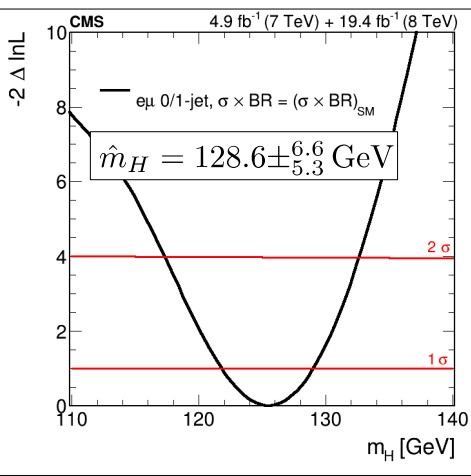
Coupling across production modes or decay channels:



JHEP 05 (2014) 104



JHEP 01 (2014) 096



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).

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

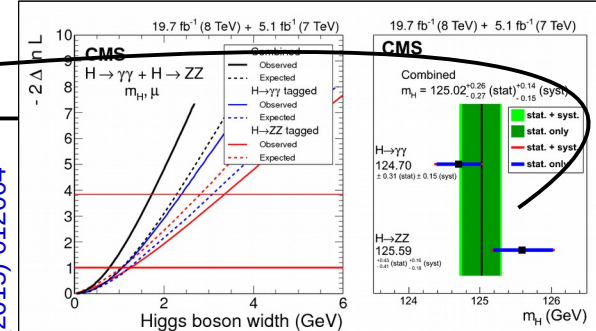
$$p\text{-value} = 84\%$$

# Mass & decay width

- From high resolution channels:

$$H \rightarrow \gamma\gamma \quad \& \quad H \rightarrow ZZ \rightarrow 4\ell$$

compatible within 1.6 $\sigma$ .

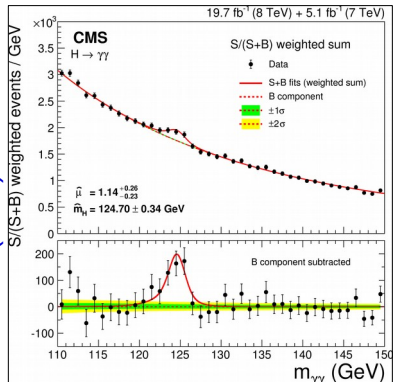


PRD 92 (2015) 012004

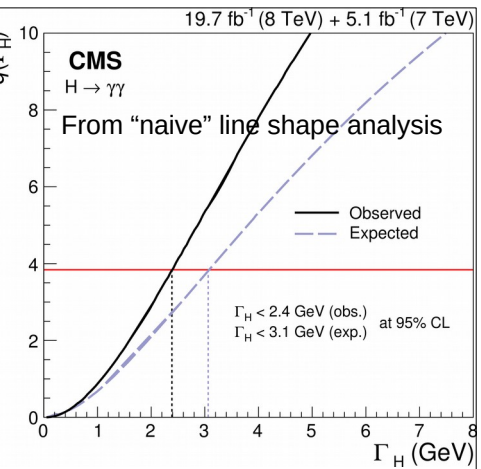
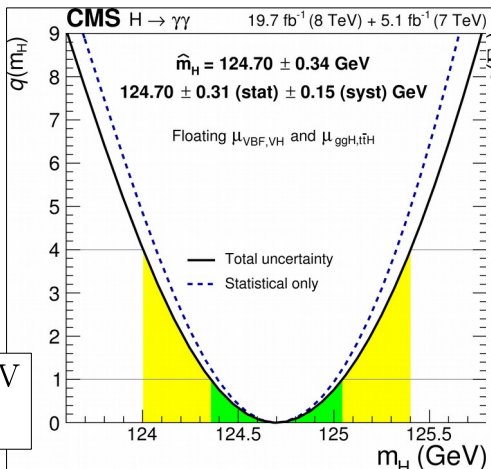
$\hat{m}_H = 125.02 \pm 0.26$  (stat.)  $\pm 0.14$  (syst.) GeV  
 $\Gamma_H < 1.7$  (2.3) GeV (95% CL)

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

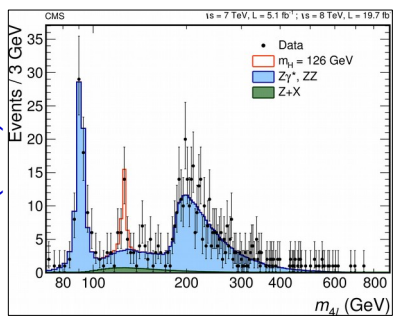
EPJ C 74 (2014) 3076



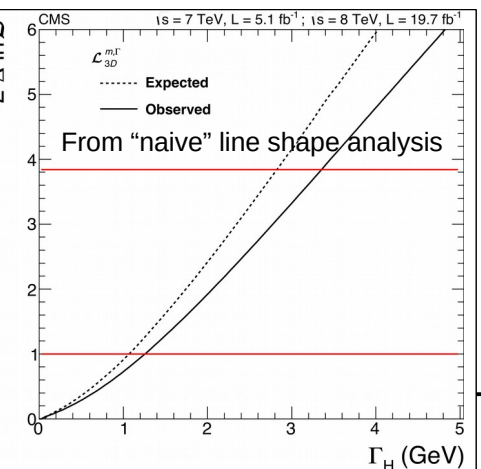
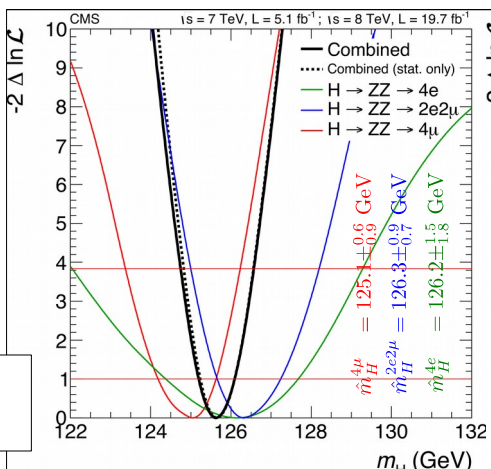
$\hat{m}_H = 124.7 \pm 0.5$  (stat.)  $\pm 0.15$  (syst.) GeV  
 $\Gamma_H < 2.4$  (3.1) GeV (95% CL)



PRD 89 (2014) 092007



$\hat{m}_H = 125.6 \pm 0.5$  (stat.)  $\pm 0.1$  (syst.) GeV  
 $\Gamma_H < 3.4$  (2.8) GeV (95% CL)



# Mass & decay width (offshell)

- Proposed by K. Melnikov, pioneered by CMS:

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

$$\frac{d\sigma(gg \rightarrow ZZ \rightarrow 4\ell)}{dm_{4\ell}^2} \propto \frac{\kappa_g^2 \kappa_Z^2}{(m_{4\ell}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

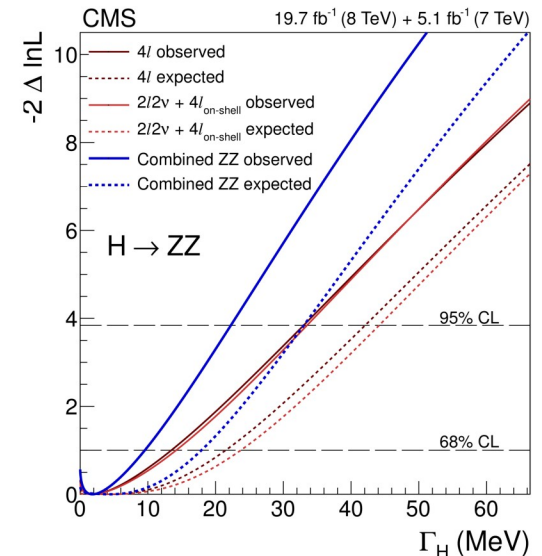
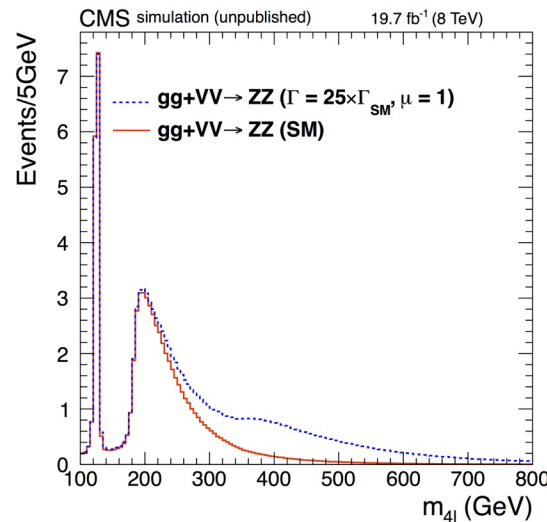
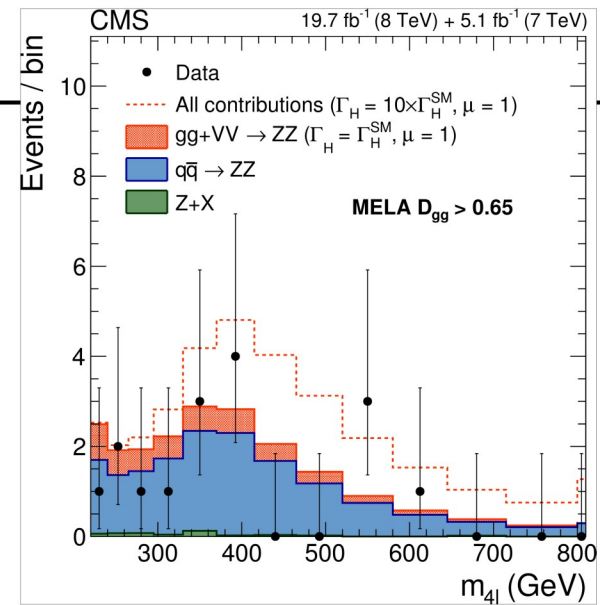
$$\propto \frac{\kappa_g^2 \kappa_Z^2}{m_H \Gamma_H} \Big|_{m_{4\ell} \approx m_H}$$

$$\propto \frac{\kappa_g^2 \kappa_Z^2}{m_{4\ell}^4} \Big|_{m_{4\ell} \gg m_H}$$

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









# Coupling structure

- ATLAS+CMS LHC run-1 combination:

• Event categories : 574

• Nuisance parameters: 4268

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

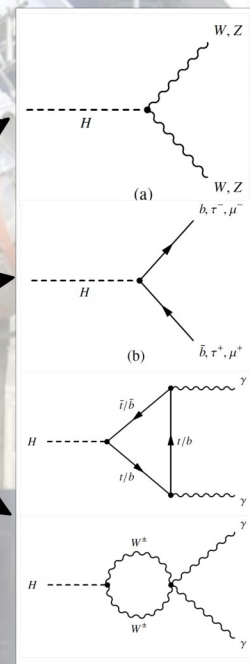
CMS-PAS-HIG-15-002

Considered production modes:

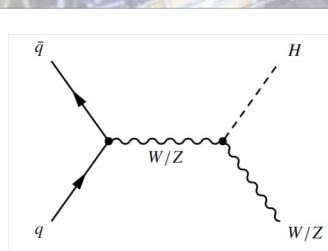
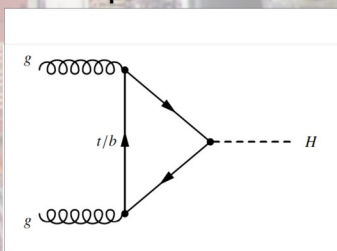
Production process	Cross section [pb]		Order of calculation
	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	
ggF	$15.0 \pm 1.6$	$19.2 \pm 2.0$	NNLO(QCD)+NLO(EW)
VBF	$1.22 \pm 0.03$	$1.58 \pm 0.04$	NLO(QCD+EW)+~NNLO(QCD)
WH	$0.577 \pm 0.016$	$0.703 \pm 0.018$	NNLO(QCD)+NLO(EW)
ZH	$0.334 \pm 0.013$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

Considered decay channels:

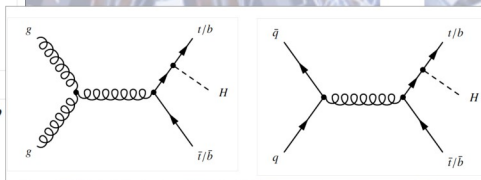
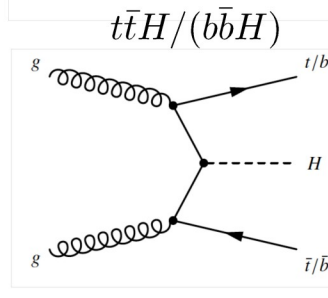
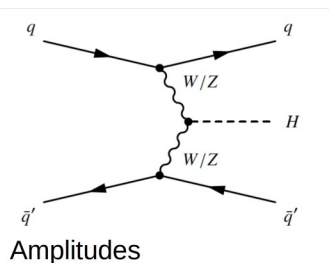
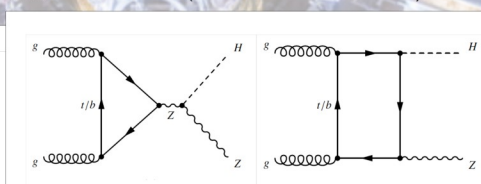
Decay channel	Branching ratio [%]
$H \rightarrow bb$	$57.5 \pm 1.9$
$H \rightarrow WW$	$21.6 \pm 0.9$
$H \rightarrow gg$	$8.56 \pm 0.86$
$H \rightarrow \tau\tau$	$6.30 \pm 0.36$
$H \rightarrow cc$	$2.90 \pm 0.35$
$H \rightarrow ZZ$	$2.67 \pm 0.11$
$H \rightarrow \gamma\gamma$	$0.228 \pm 0.011$
$H \rightarrow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



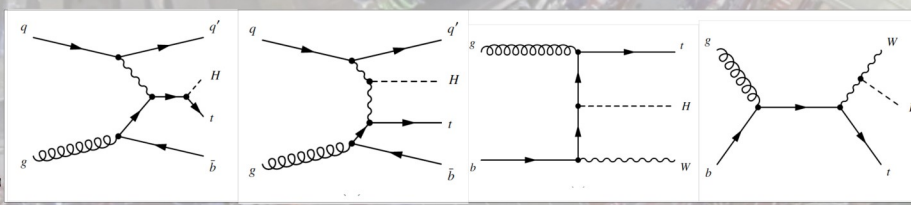
Main production modes:



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



$tqH + tHW$





# The $\kappa$ model

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

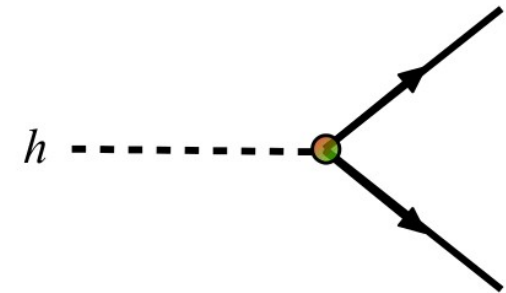
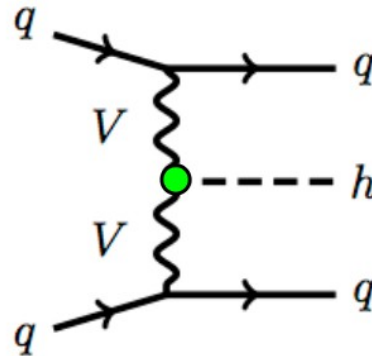
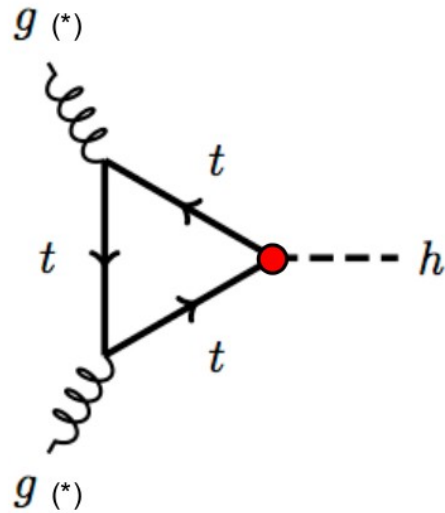
Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(qq/qg \rightarrow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

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

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

# Coupling estimates

- Determine couplings from production mode & decay channel:



●  $f$  :  $\kappa_{Hff} = \frac{m_f}{v}$

●  $V$  :  $\kappa_{HVV} = \frac{2m_V^2}{v}$

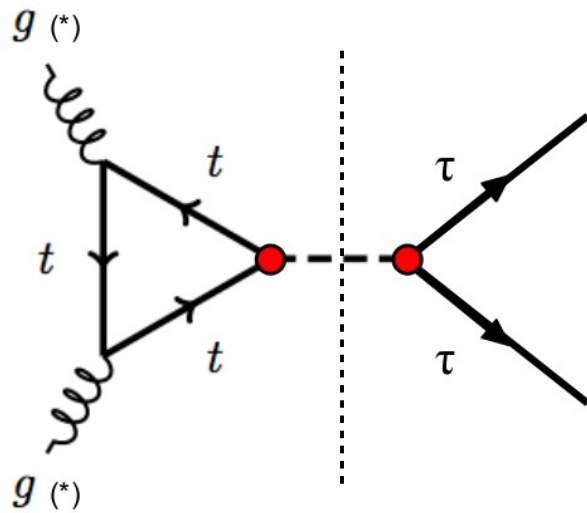
- Coupling to gluon can be  $f$  or effective (\*).
- Coupling to  $\gamma$  can be effective or a mixture of  $f + V$ .

- Direct measurement not possible, since  $\kappa_i$  appear in nominator and denominator of BR:

$$\text{BR}_i = \frac{\kappa_i}{\Gamma_h} = \frac{\kappa_i}{\sum_j \kappa_j}$$

# Narrow width approximation

- Assume  $\Gamma_H \ll m_H$ , which is well justified by  $\Gamma_H = 4.04 \text{ MeV}$  and  $m_H = 125 \text{ GeV}$ .
- Propagator:  $\frac{1}{(q^2 - m^2 + m^2\Gamma^2)} \rightarrow \frac{\pi}{m\Gamma} \delta(q^2 - m^2)$  for  $\Gamma \rightarrow 0$ .



- i.e. put propagating particle on shell.

- Calculate cross section as  $\sigma \times \text{BR}$ .

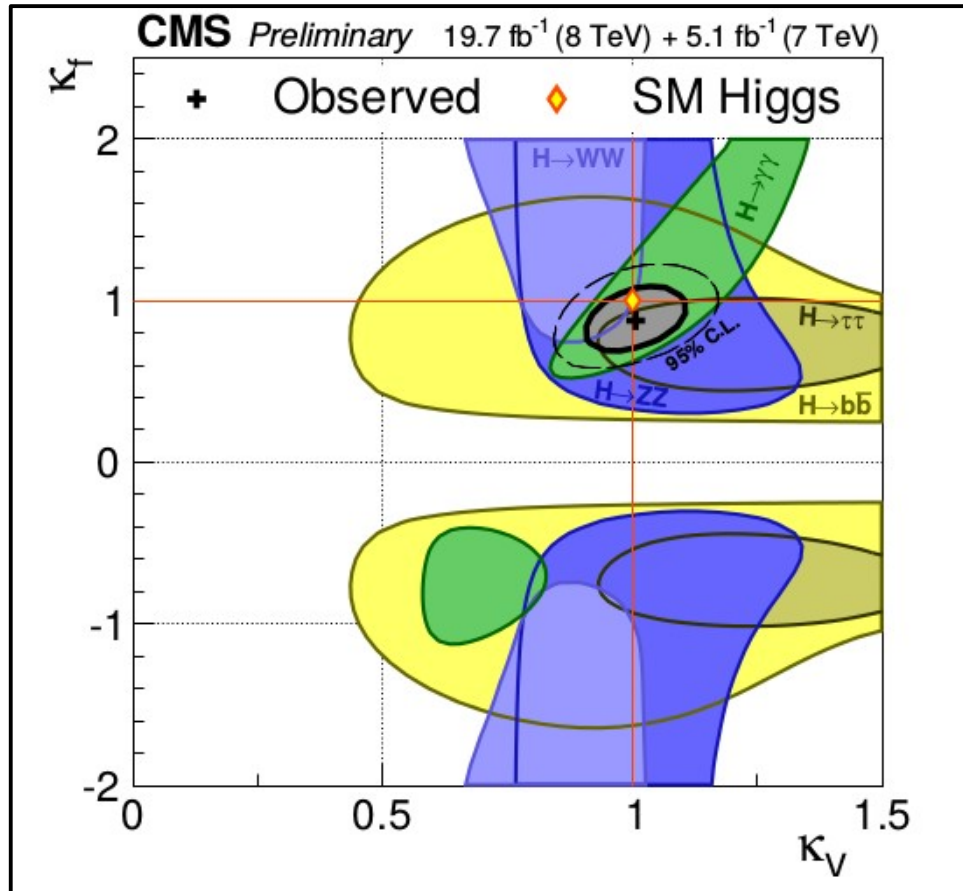
- $\text{BR}_X = \frac{\Gamma_X}{\Gamma_H}$ ,  $\Gamma_H = \sum_i \Gamma_i$ .

- Example to the left:

$$\sigma \propto (\kappa_t \kappa_\tau)^2 \propto (\kappa_u \kappa_d)^2 \propto (\kappa_q \kappa_f)^2 \propto (\kappa_g \kappa_f)^2$$

- For each production mode and decay channel collect  $\kappa_i$  and express  $\Gamma_H$  as sum of individual  $\kappa_i$ .

# Example: vector boson vs. fermion coupling



- Cross section  $H \rightarrow VV$ :  

$$\sigma \propto (\kappa_f \kappa_V)^2 + (\kappa_V \kappa_V)^2$$

$\downarrow$   
 $gg \rightarrow H$

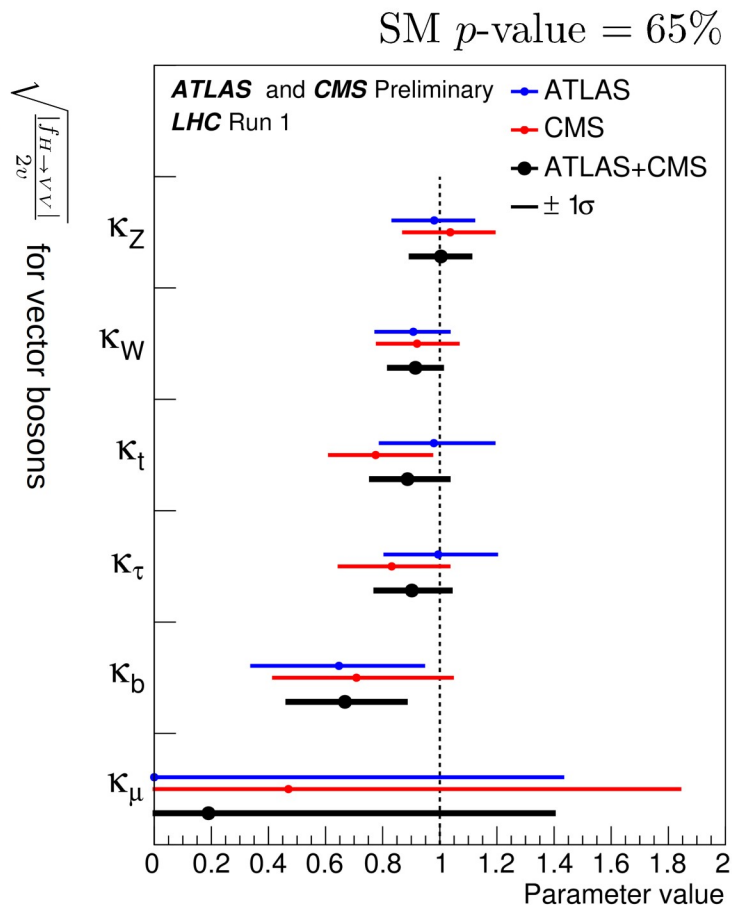
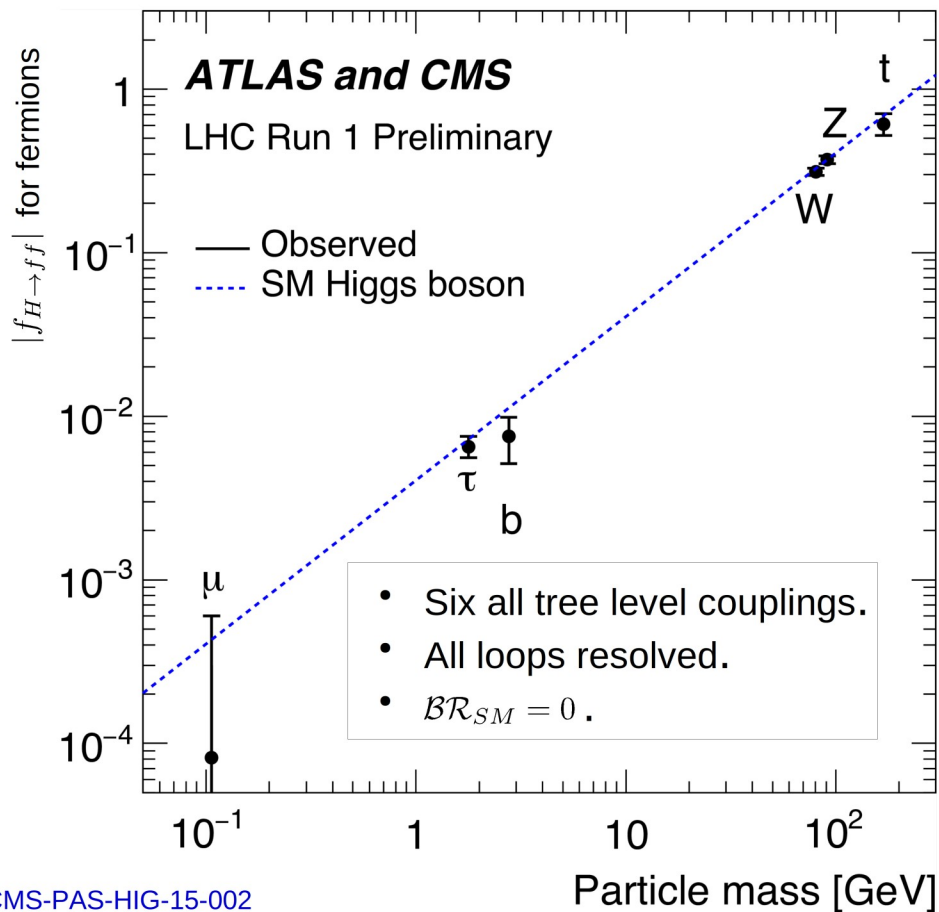
$\downarrow$   
 $qq \rightarrow qqH$
- Cross section  $H \rightarrow ff$ :  

$$\sigma \propto (\kappa_f \kappa_f)^2 + (\kappa_V \kappa_f)^2$$
- Cross section  $H \rightarrow \gamma\gamma$ :  

$$\sigma \propto (\kappa_f^2 - \kappa_f \kappa_V)^2 + (\kappa_V \kappa_f - \kappa_V^2)^2$$
- $H \rightarrow \gamma\gamma$  resolves sign ambiguities due to interference term.



# “Money plot”



CMS-PAS-HIG-15-002

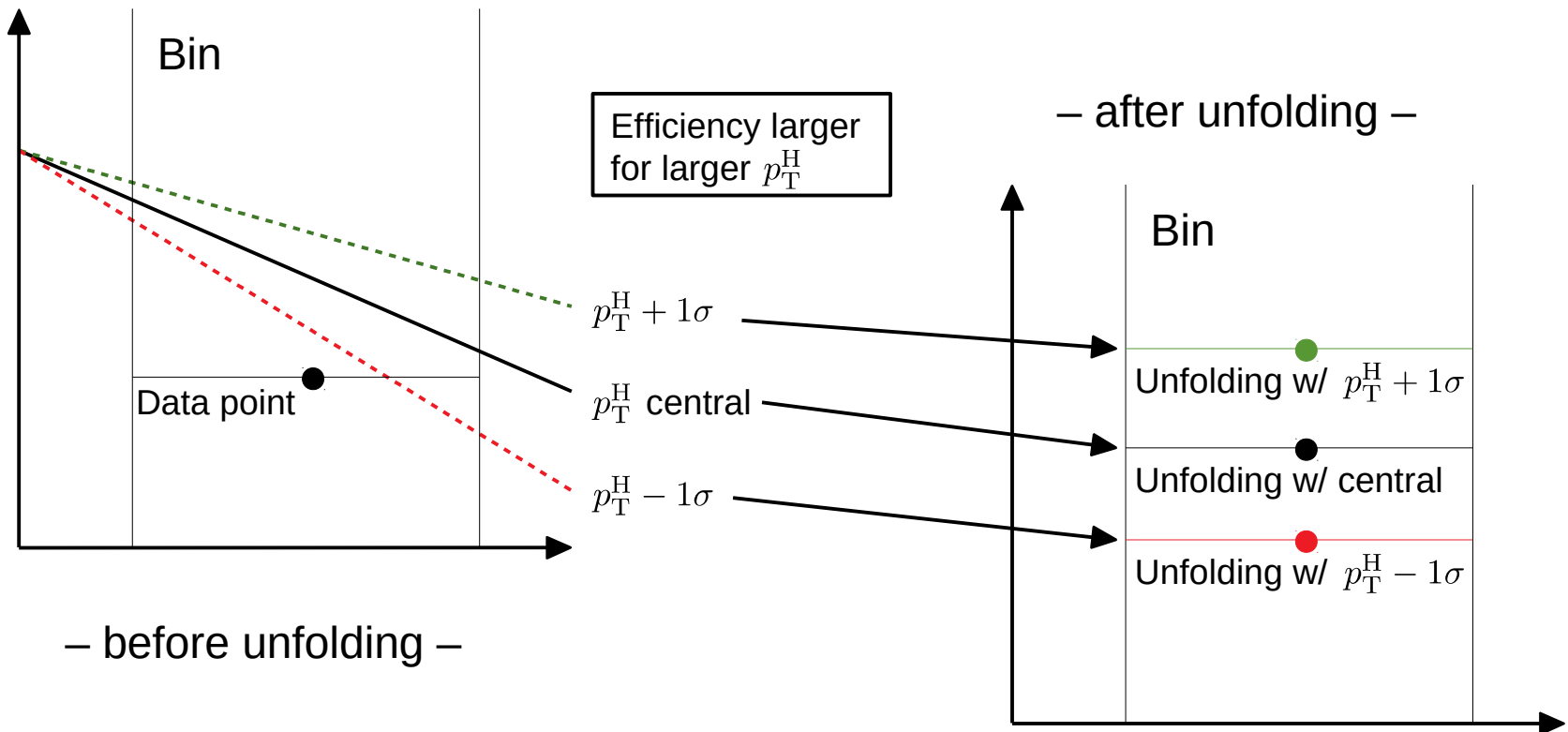
$$|f_{H \rightarrow ff}^{\text{obs}}| = \kappa_f \cdot |f_{H \rightarrow ff}^{\text{SM}}| = \kappa_f \cdot \frac{m_f}{v} \quad f = \mu, \tau, b, t$$

$$\sqrt{\frac{|f_{H \rightarrow VV}^{\text{obs}}|}{2v}} = \sqrt{\kappa_V} \cdot \sqrt{\frac{|f_{H \rightarrow VV}^{\text{SM}}|}{2v}} = \sqrt{\kappa_V} \cdot \frac{m_V}{v} \quad V = W, Z$$

Within measurement accuracy  
unique scaling as expected within  
the SM.

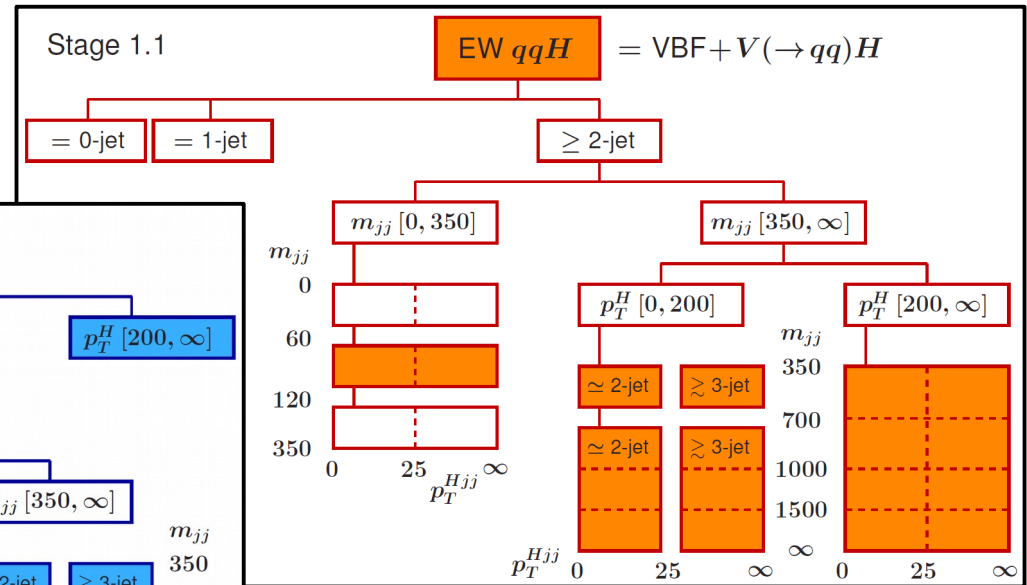
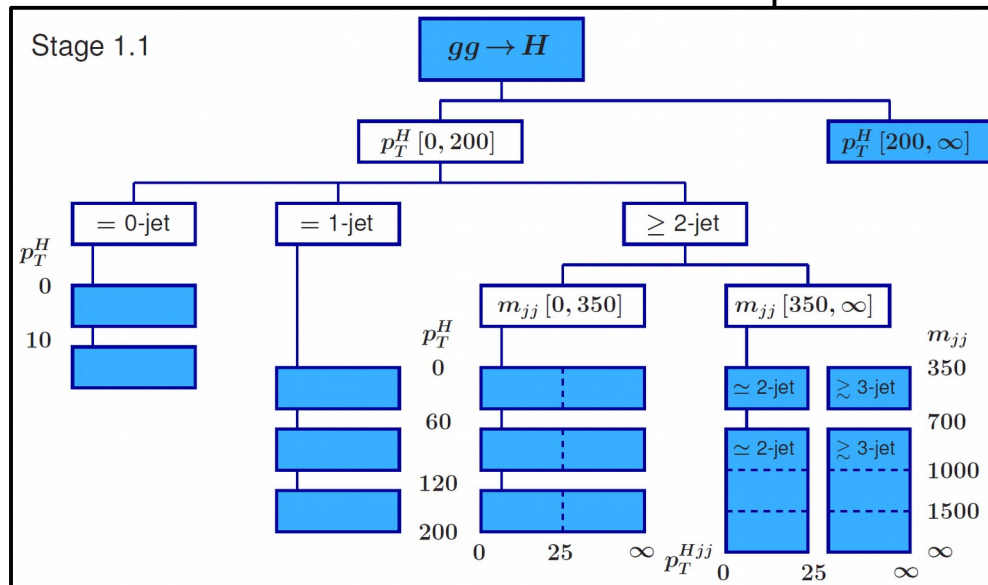
# Simplified template cross section (STXS)

- Define common phasespace regions based on pseudo-observable objects and quantities:
  - Convention facilitates combination of final states and across experiments.
  - Kinematic bins help to reduce influence of theory uncertainties (e.g. in  $p_T^H$  or  $N_{\text{Jet}}$ ) on measurement.



# Simplified template cross section (STXS)

- Defined for analysis of LHC Run-2 data by LHC HXSWG:





# Template vs. fiducial cross section

---

## Simplified template cross section (STXS):

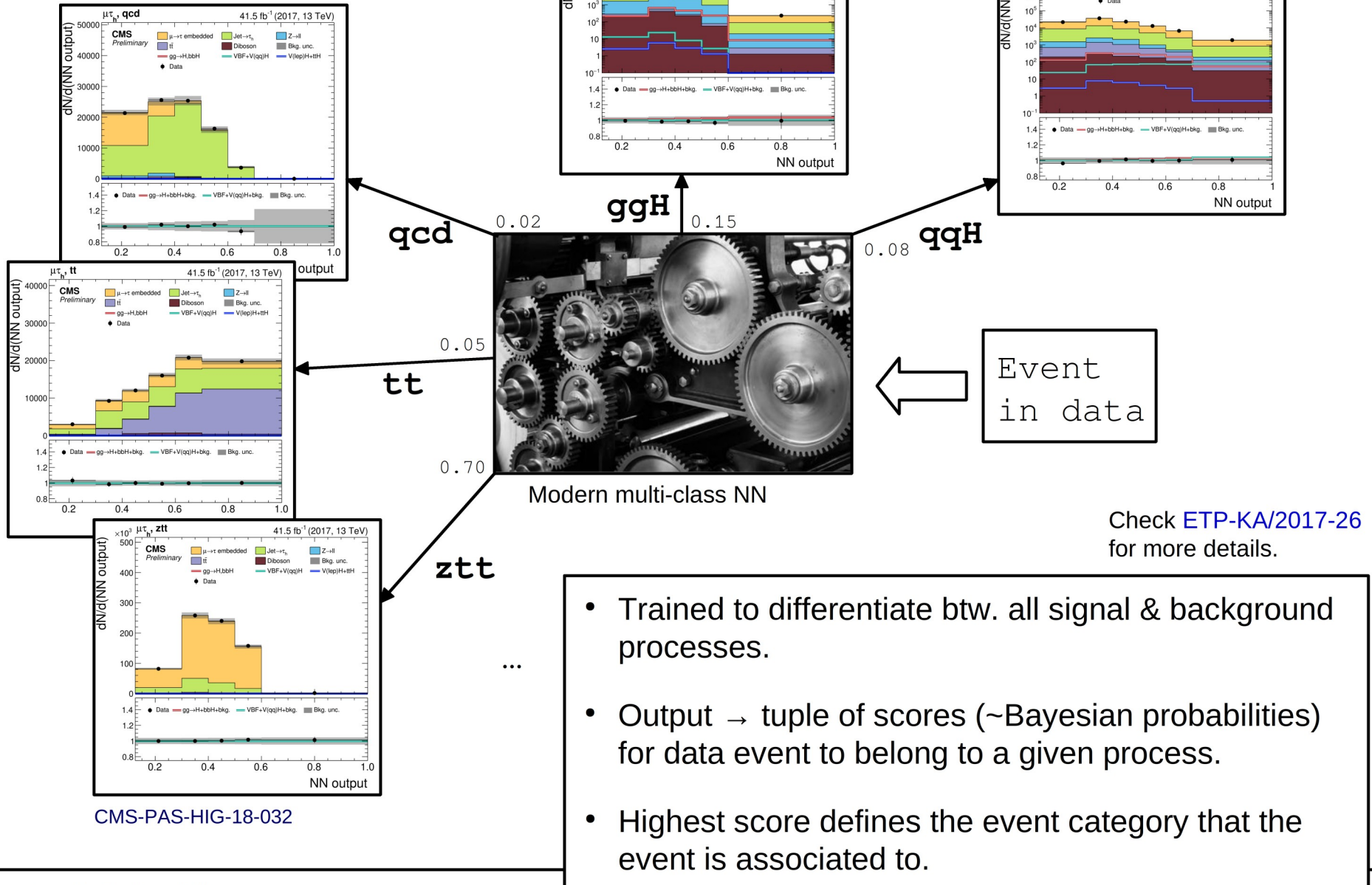
- E.g. Higgs production in VBF & gluon fusion.



## Fiducial cross section:

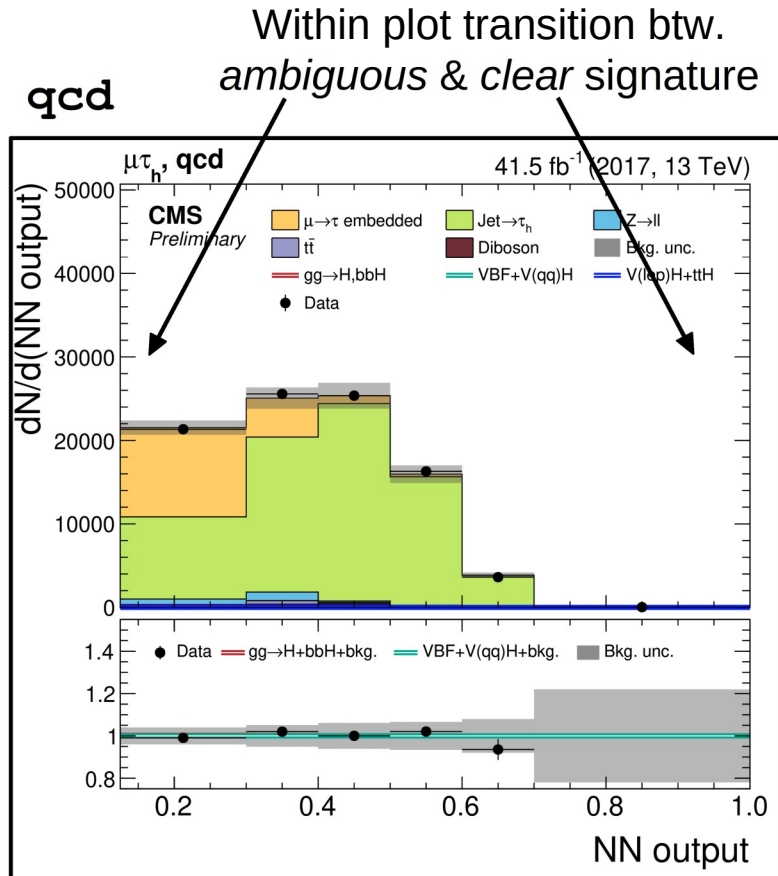
- Obey detector acceptance and stick to measurable quantities.
- E.g. Higgs production in association w/ two jets w/  $m_{jj} > 350$  GeV.

# Event classification

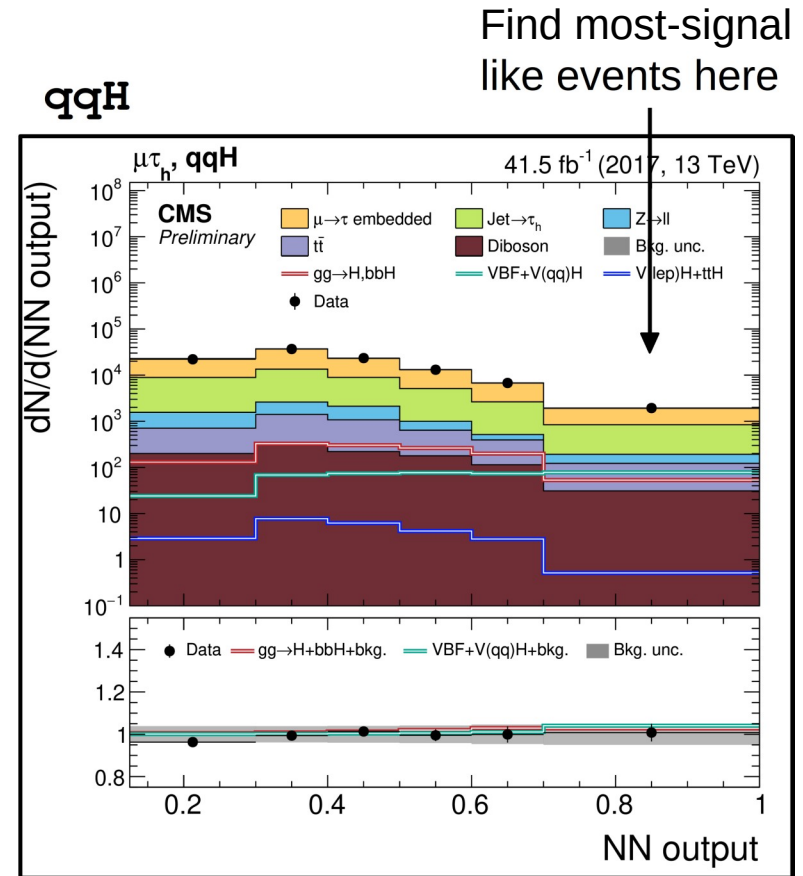


# Signal extraction

- Signal derived from maximum likelihood fit to NN output of each event category.
- Pure background categories help to constrain backgrounds in signal categories.



CMS-PAS-HIG-18-032



# NN inputs

- Use one NN for each final state and separated btw. 2016 & 2017 (→ 8 NNs):

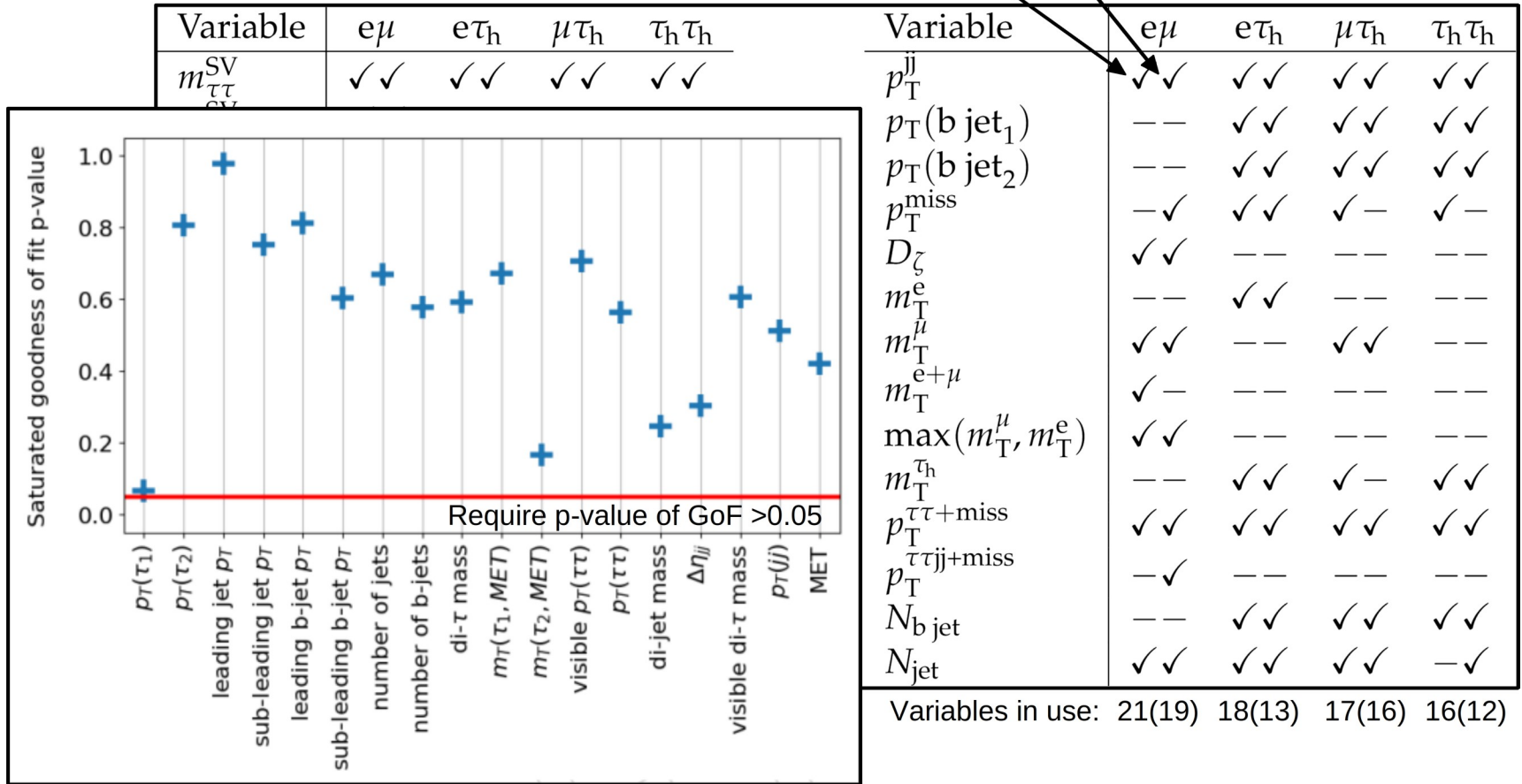
Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$m_{\tau\tau}^{SV}$	✓✓	✓✓	✓✓	✓✓	$p_T^{jj}$	✓✓	✓✓	✓✓	✓✓
$m_{T\tau\tau}^{SV}$	✓✓	---	---	---	$p_T(\text{b jet}_1)$	---	✓✓	✓✓	✓✓
$p_{T\tau\tau}^{SV}$	✓✓	---	---	---	$p_T(\text{b jet}_2)$	---	✓✓	✓✓	✓✓
$m_{vis}$	✓-	✓-	✓-	✓✓	$p_T^{miss}$	-✓	✓✓	✓-	✓-
$p_T^{vis}$	✓✓	✓✓	✓-	✓-	$D_\zeta$	✓✓	---	---	---
$p_T^{\tau_1}$	---	---	✓-	✓✓	$m_T^e$	---	✓✓	---	---
$p_T^{\tau_2}$	✓-	✓✓	✓✓	✓-	$m_T^\mu$	✓✓	---	✓✓	---
$\Delta R^{e\mu}$	✓✓	---	---	---	$m_T^{e+\mu}$	✓-	---	---	---
$p_T(\text{jet}_1)$	✓✓	✓✓	✓✓	✓-	$\max(m_T^\mu, m_T^e)$	✓✓	---	---	---
$\eta(\text{jet}_1)$	✓-	---	---	---	$m_T^{\tau_h}$	---	✓✓	✓-	✓✓
$p_T(\text{jet}_2)$	✓✓	✓✓	✓✓	✓✓	$p_T^{\tau\tau+miss}$	✓✓	✓✓	✓✓	✓✓
$\eta(\text{jet}_2)$	✓-	---	---	---	$p_T^{\tau\tau jj+miss}$	-✓	---	---	---
$m_{jj}$	✓✓	✓✓	✓✓	✓✓	$N_{b\text{ jet}}$	---	✓✓	✓✓	✓✓
$\Delta\eta_{jj}$	✓✓	✓✓	✓✓	✓✓	$N_{\text{jet}}$	✓✓	✓✓	✓✓	-✓

Variables in use: 21(19) 18(13) 17(16) 16(12)



# NN inputs

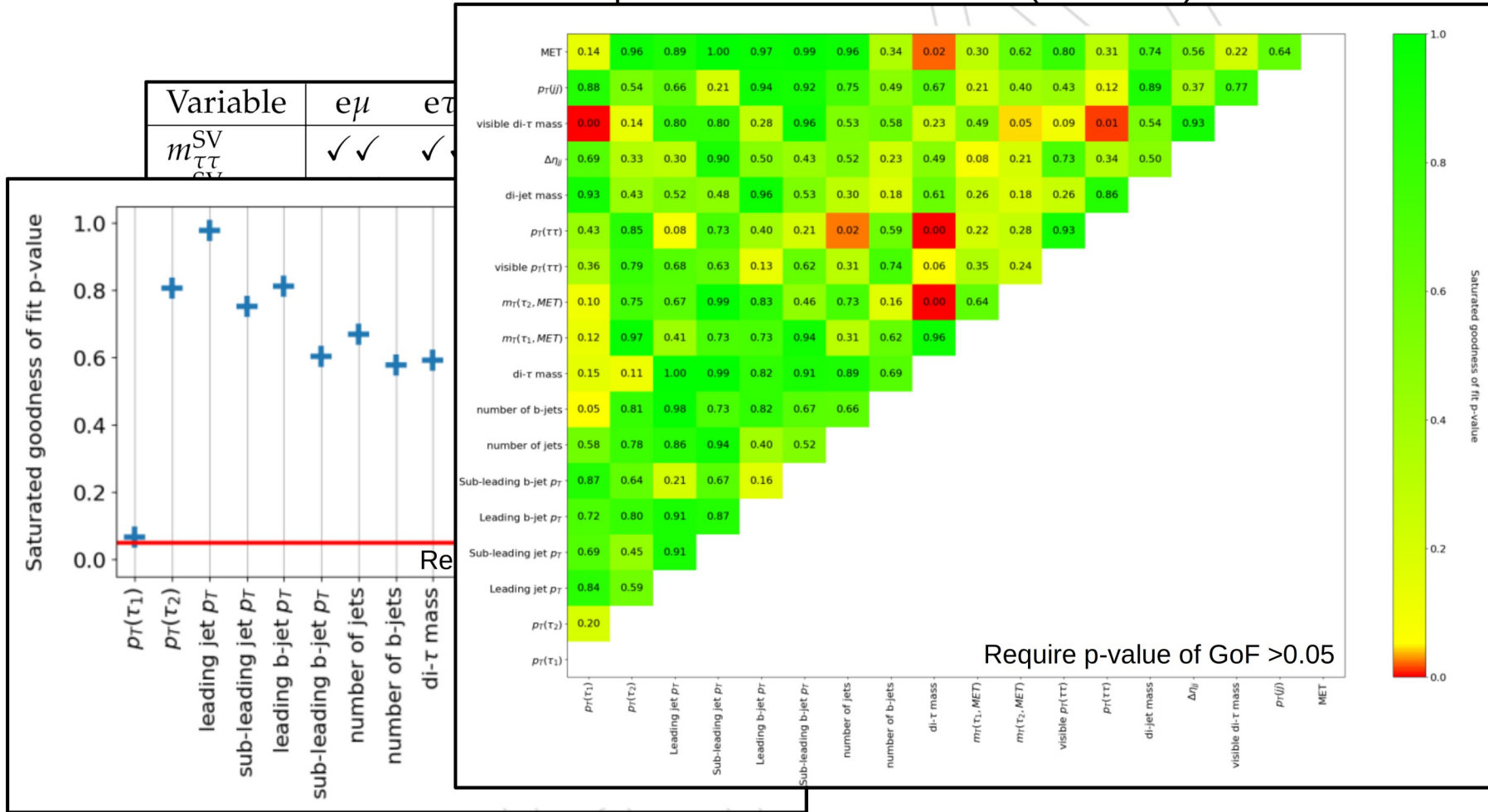
- Use one NN for each final state and separated btw. 2016 & 2017 (→ 8 NNs):



Making sure that input variables are well described by our model exploiting goodness-of-fit (GoF) test in 1d...

# NN inputs

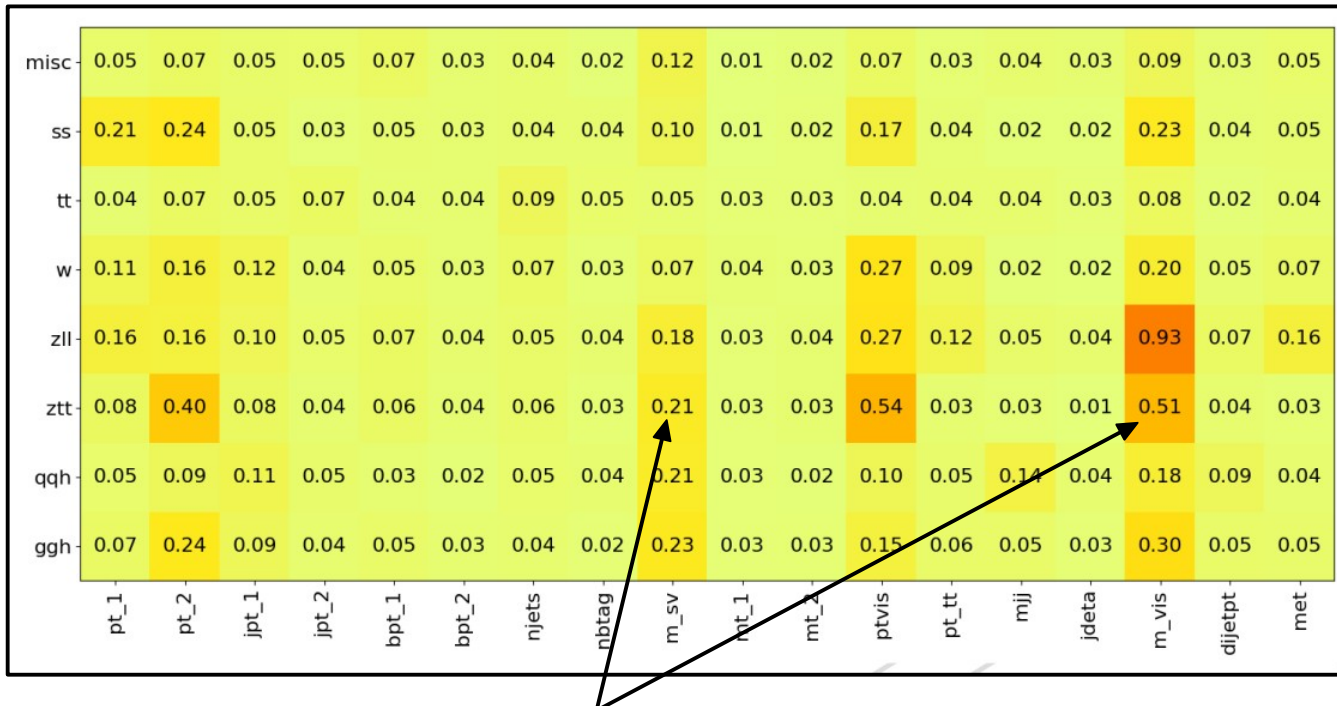
- Use one NN for each final state and separated btw. 2016 & 2017 ( $\rightarrow$  8 NNs):



Making sure that input variables are well described by our model exploiting goodness-of-fit (GoF) test in 1d... & 2d.

# “Unboxing” the NN

- Decipher what the NN is doing using a Taylor expansion of the full NN output function. Impact analysis like on LEP likelihood, but here on NN output function.



Note that all values >0 are allowed.

Relative size of number indicates how sensitive the NN output is on the given input.

# “Unboxing” the NN

- Decipher what the NN is doing using a Taylor expansion of the full NN output function. Impact analysis like on LEP likelihood, but here on NN output function.

misc	0.05	0.07	0.05	0.05	0.07	0.03	0.04	0.02	0.12	0.01	0.02	0.07	0.03	0.04	0.03	0.09	0.03	0.05					
ss	0.21	0.24																					
tt	0.04	0.07																					
w	0.11	0.16																					
zll	0.16	0.16																					
ztt	0.08	0.40																					
qqh	0.05	0.09																					
ggh	0.07	0.24																					
	pt_1	pt_2																					
	ggh	qqh	ztt	zll	w	tt	ss	misc															
m_vis	m_vis	1.50	m_vis	m_vis	0.44	pt_2	pt_vis	1.14	m_vis	m_vis	7.58	m_vis	m_vis	0.83	m_vis	m_vis	0.16	m_vis	m_vis	0.56	m_vis	m_vis	0.23
pt_vis	m_vis	0.58	m_vis	m_vis	0.39	pt_vis	pt_vis	1.06	m_vis	m_vis	1.29	pt_2	pt_vis	0.43	m_vis	m_vis	0.11	pt_2	pt_vis	0.42	m_vis	m_vis	0.22
pt_vis	pt_vis	0.50	m_vis	m_vis	0.39	pt_vis	m_vis	0.90	pt_vis	m_vis	1.28	pt_vis	pt_vis	0.42	njets	0.09	pt_2	m_vis	0.34	m_vis	m_vis	0.20	
pt_2	m_vis	0.48	m_vis	pt_vis	0.26	m_vis	pt_vis	0.85	m_vis	met	1.01	pt_vis	m_vis	0.41	pt_2	m_vis	0.08	pt_vis	m_vis	0.34	m_vis	pt_vis	0.14
pt_2	pt_vis	0.48	m_vis	m_vis	0.21	pt_1	pt_vis	0.67	m_vis	0.89	pt_2	m_vis	0.29	jpt_1	jpt_1	0.08	pt_1	pt_vis	0.33	m_vis	0.13		
m_vis	m_vis	0.45	m_vis	dijetpt	0.20	pt_2	m_vis	0.63	pt_tt	m_vis	0.88	pt_vis	0.28	pt_2	0.08	pt_vis	pt_vis	0.32	pt_2	pt_vis	0.12		
m_vis	pt_vis	0.33	pt_vis	dijetpt	0.18	pt_2	m_vis	0.62	pt_1	m_vis	0.87	pt_1	pt_vis	0.27	pt_vis	m_vis	0.08	pt_1	pt_2	0.28	pt_vis	m_vis	0.11
pt_1	pt_vis	0.31	m_vis	m_vis	0.17	m_vis	m_vis	0.60	pt_2	m_vis	0.73	m_vis	m_vis	0.26	m_vis	m_vis	0.07	pt_1	m_vis	0.26	pt_vis	m_vis	0.11
m_vis	0.29	pt_2	m_vis	0.16	pt_vis	0.57	m_vis	dijetpt	0.72	jpt_1	pt_vis	0.25	jpt_2	0.07	m_vis	pt_vis	0.25	pt_2	pt_2	0.24	pt_1	pt_vis	0.09
pt_1	m_vis	0.29	pt_vis	m_vis	0.16	m_vis	m_vis	0.55	jpt_1	pt_vis	0.63	m_vis	pt_vis	0.22	jpt_1	0.07	pt_2	pt_2	0.23	pt_2	pt_1	pt_vis	0.09
m_vis	met	0.26	pt_vis	pt_vis	0.16	m_vis	m_vis	0.52	pt_vis	pt_vis	0.62	pt_vis	pt_tt	0.21	m_vis	m_vis	0.06	pt_2	pt_2	0.21	pt_1	pt_vis	0.09
m_vis	m_vis	0.24	m_vis	dijetpt	0.15	pt_2	pt_2	0.52	pt_1	pt_vis	0.49	m_vis	0.20	pt_2	pt_2	0.06	m_vis	0.21	jpt_1	pt_vis	0.09		
pt_tt	m_vis	0.24	m_vis	m_vis	0.15	m_vis	m_vis	0.45	mjj	m_vis	0.49	pt_tt	m_vis	0.18	m_vis	pt_vis	0.06	pt_1	0.21	m_vis	0.09		
jpt_1	pt_vis	0.23	dijetpt	dijetpt	0.14	pt_2	0.40	pt_2	pt_vis	0.47	pt_2	0.18	pt_2	0.18	pt_2	0.06	m_vis	m_vis	0.20	pt_vis	0.08		
jpt_1	m_vis	0.23	jpt_1	dijetpt	0.13	jpt_1	pt_vis	0.32	mt_2	m_vis	0.39	pt_2	pt_2	0.17	jpt_1	pt_2	0.06	pt_1	pt_1	0.19	m_vis	dijetpt	0.08
pt_2	pt_2	0.22	pt_2	pt_vis	0.13	pt_1	pt_2	0.31	m_vis	pt_vis	0.36	m_vis	met	0.17	pt_vis	pt_vis	0.06	pt_2	m_vis	0.18	pt_1	m_vis	0.07
pt_vis	pt_tt	0.20	pt_1	m_vis	0.12	pt_vis	dijetpt	0.29	pt_1	pt_2	0.33	jpt_1	m_vis	0.16	jpt_1	m_vis	0.05	jpt_1	pt_vis	0.15	jpt_1	m_vis	0.07
m_vis	dijetpt	0.19	jpt_1	jpt_1	0.12	jpt_1	m_vis	0.27	bpt_1	m_vis	0.32	pt_1	pt_2	0.16	pt_1	pt_2	0.05	m_vis	m_vis	0.13	jpt_1	m_vis	0.07
pt_2	m_vis	0.18	jpt_1	m_vis	0.12	pt_vis	pt_tt	0.27	pt_vis	0.30	pt_2	m_vis	0.14	pt_1	m_vis	0.05	pt_vis	met	0.12	bpt_1	0.07		
pt_vis	dijetpt	0.18	pt_1	m_vis	0.12	nbttag	pt_vis	0.26	bpt_2	m_vis	0.30	njets	pt_vis	0.13	pt_1	pt_vis	0.05	pt_1	met	0.12	pt_2	pt_2	0.07
pt_1	pt_2	0.17	jpt_1	0.11	bpt_1	pt_vis	0.25	pt_vis	pt_tt	0.30	pt_2	pt_tt	0.13	pt_2	jpt_1	0.05	m_vis	met	0.12	jpt_1	jpt_1	0.07	
pt_vis	met	0.16	jpt_1	m_vis	0.11	pt_1	pt_1	0.25	pt_1	pt_1	0.29	pt_vis	dijetpt	0.13	pt_2	m_vis	0.05	jpt_1	m_vis	0.11	pt_1	pt_2	0.06
pt_1	m_vis	0.15	pt_tt	m_vis	0.11	njets	pt_vis	0.24	m_vis	m_vis	0.29	m_vis	dijetpt	0.13	pt_tt	m_vis	0.05	pt_vis	pt_tt	0.11	pt_vis	dijetpt	0.06
pt_vis	0.15	pt_vis	0.11	m_vis	0.23	pt_vis	met	0.28	jpt_1	jpt_1	0.13	nbttag	0.05	pt_tt	m_vis	0.11	jpt_1	0.06					
jpt_1	m_vis	0.15	mjj	m_vis	0.10	pt_1	m_vis	0.23	jpt_2	m_vis	0.28	pt_2	jpt_1	0.12	m_vis	0.04	pt_2	jpt_1	0.11	m_vis	pt_tt	0.06	
mjj	m_vis	0.14	pt_2	0.10	m_vis	dijetpt	0.22	jpt_1	pt_vis	0.27	pt_1	pt_1	0.12	jpt_1	m_vis	0.04	pt_vis	dijetpt	0.11	m_vis	met	0.06	
bpt_1	pt_vis	0.14	pt_2	m_vis	0.09	pt_2	pt_tt	0.19	nbttag	m_vis	0.26	bpt_1	pt_vis	0.12	pt_vis	0.04	bpt_1	pt_vis	0.10	met	0.06		
pt_1	pt_1	0.14	dijetpt	0.09	bpt_2	pt_vis	0.18	pt_vis	dijetpt	0.26	pt_tt	0.12	jpt_1	dijetpt	0.04	jpt_1	m_vis	0.10	m_vis	dijetpt	0.06		
njets	m_vis	0.13	m_vis	pt_tt	0.09	pt_2	jpt_1	0.18	pt_2	0.25	pt_1	0.12	m_vis	dijetpt	0.04	njets	pt_vis	0.10	pt_vis	pt_tt	0.06		
njets	pt_vis	0.13	m_vis	mjj	0.09	m_vis	pt_tt	0.17	pt_1	m_vis	0.23	jpt_1	0.12	pt_tt	0.04	m_vis	0.10	jpt_2	m_vis	0.06			
pt_2	jpt_1	0.13	pt_1	pt_vis	0.09	pt_2	bpt_1	0.17	pt_2	m_vis	0.23	jpt_1	m_vis	0.12	pt_2	njets	0.04	m_vis	dijetpt	0.10	bpt_2	m_vis	0.05
bpt_1	m_vis	0.12	mjj	0.08	pt_tt	m_vis	0.16	m_vis	dijetpt	0.21	nbttag	pt_vis	0.11	pt_2	pt_tt	0.04	pt_1	jpt_1	0.09	pt_1	pt_1	0.05	
jpt_1	jpt_1	0.12	pt_2	0.08	jpt_1	m_vis	0.16	m_vis	met	0.19	m_vis	0.11	pt_vis	dijetpt	0.04	nbttag	pt_vis	0.09	pt_tt	pt_vis	0.05		
m_vis	dijetpt	0.11	m_vis	met	0.08	pt_2	njets	0.15	pt_1	m_vis	0.19	pt_1	m_vis	0.11	pt_1	pt_1	0.04	pt_2	pt_tt	0.09	pt_vis	met	0.05
pt_2	pt_tt	0.11	pt_tt	0.08	jpt_1	jpt_1	0.15	pt_1	met	0.18	jpt_2	pt_vis	0.10	bpt_1	0.04	pt_2	dijetpt	0.08	pt_2	jpt_1	0.05		
mt_2	m_vis	0.11	jpt_2	dijetpt	0.08	pt_1	nbttag	0.15	njets	pt_vis	0.17	pt_1	jpt_1	0.10	njets	m_vis	0.04	pt_2	njets	0.08	njets	pt_vis	0.05
jpt_2	m_vis	0.11	bpt_2	m_vis	0.08	pt_2	met	0.15	pt_2	jpt_1	0.17	pt_1	met	0.09	jpt_1	hjets	0.04	pt_1	pt_tt	0.08	bpt_1	pt_vis	0.05
nbttag	pt_vis	0.11	jpt_1	mjj	0.08	pt_1	dijetpt	0.14	nbttag	pt_vis	0.17	pt_2	met	0.09	pt_1	m_vis	0.04	pt_2	met	0.08	jpt_2	0.05	
jpt_2	pt_vis	0.10	jpt_2	m_vis	0.08	m_vis	met	0.14	jpt_2	pt_vis	0.17	njets	m_vis	0.09	pt_1	0.04	jpt_2	pt_vis	0.08	m_vis	met	0.05	
bpt_2	m_vis	0.10	pt_1	jpt_2	0.07	m_vis	met	0.13	jpt_1	pt_vis	0.16	mjj	m_vis	0.09	mjj	0.04	pt_2	bpt_1	0.08	jpt_1	jpt_2	0.05	
jdeta	m_vis	0.10	mjj	dijetpt	0.07	pt_2	dijetpt	0.13	mt_1	m_vis	0.16	bpt_1	m_vis	0.09	bpt_2	0.04	pt_1	dijetpt	0.08	jpt_1	dijetpt	0.05	
m_vis	met	0.10	m_vis	jdeta	0.07	pt_1	met	0.13	jpt_1	m_vis	0.16	jpt_1	dijetpt	0.08	pt_1	jpt_1	0.04	njets	m_vis	0.08	jpt_2	m_vis	0.05
jpt_1	0.09	jpt_2	m_vis	0.07	pt_1	jpt_1	0.13	pt_1	jpt_1	0.15	pt_2	njets	0.08	met	0.04	pt_1	nbttag	0.08	0.04	pt_1	njets	0.05	
m_vis	pt_tt	0.09	pt_2	jpt_1	0.07	bpt_1	m_vis	0.12	pt_1	pt_1	0.14	pt_2	pt_vis	0.08	jpt_2	m_vis	0.08	jpt_2	jpt_2				
pt_2	dijetpt	0.09	njets	m_vis	0.07	m_vis	dijetpt	0.12	jpt_1	jpt_1	0.14	jpt_2	m_vis	0.08	pt_1	met	0.08	pt_1	met				
nbttag	m_vis	0.09	jdeta	m_vis	0.07	bpt_2	m_vis	0.12	pt_2	pt_tt	0.14	m_vis	0.08	pt_1	met	0.08	pt_2	pt_2	pt_2				
pt_2	njets	0.09	jpt_1	njets	0.07	njets	m_vis	0.12	met	0.14	pt_2	dijetpt	0.08	pt_2	dijetpt	0.08	pt_2	pt_2	pt_2				
pt_1	jpt_1	0.09	njets	pt_vis	0.07	jpt_2	pt_vis	0.12	pt_2	met	0.13	jpt_1	njets	0.08	jpt_2	njets							

Also this can be done in 2d.  
And that way one can learn a lot about the NN task and how it is solved.



# How well can the NN do?

- Confusion matrix tells how well the NN can identify each individual process:
- In this representation: all columns normalized to unity.
- 72% of all **qqH** events can be identified as such.
- Assess success of NN by comparison to random association (prob.  $1/8=12.5\%$ ).

*CMS Simulation Preliminary*

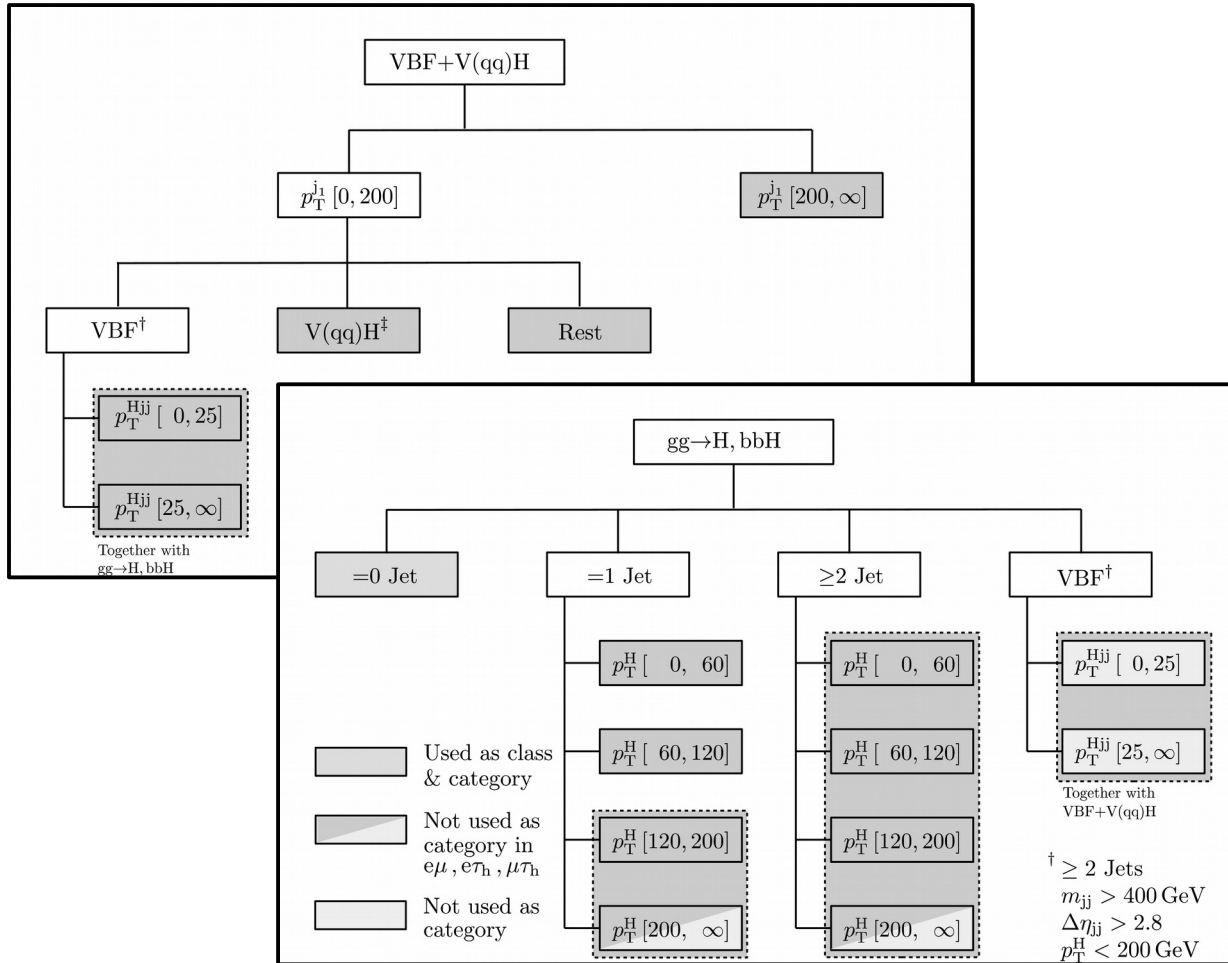
$\mu\tau_h$  (2017)

NN predicted event class	True event class							
	ggH	qqH	ztt	qcd	tt	misc	zll	wj
ggH	0.27	0.08	0.08	0.07	0.01	0.05	0.11	0.08
qqH	0.21	0.72	0.07	0.06	0.06	0.12	0.05	0.06
ztt	0.23	0.06	0.63	0.26	0.01	0.09	0.14	0.18
qcd	0.02	0.01	0.02	0.17	0.02	0.06	0.04	0.13
tt	0.01	0.04	0.01	0.06	0.75	0.23	0.01	0.02
misc	0.02	0.04	0.06	0.07	0.14	0.28	0.02	0.09
zll	0.17	0.03	0.08	0.13	0.00	0.04	0.53	0.14
wj	0.07	0.02	0.06	0.19	0.02	0.13	0.10	0.31

CMS-PAS-HIG-18-032

# STXS classification

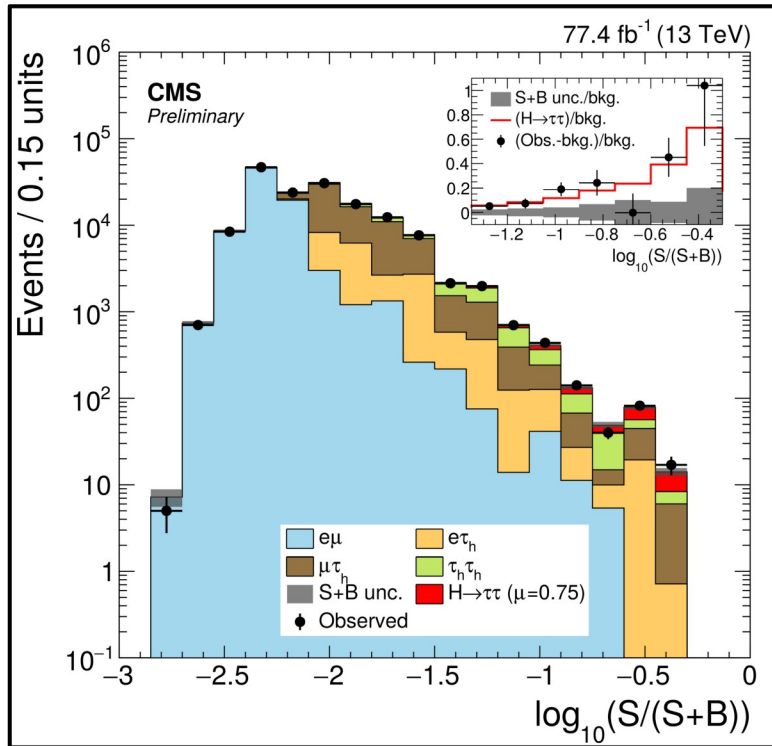
- After classification of  $ggH$  and  $qqH$  events are split into STXS bins, based on selection requirements on theory-related quantities after reconstruction:



CMS-PAS-HIG-18-032

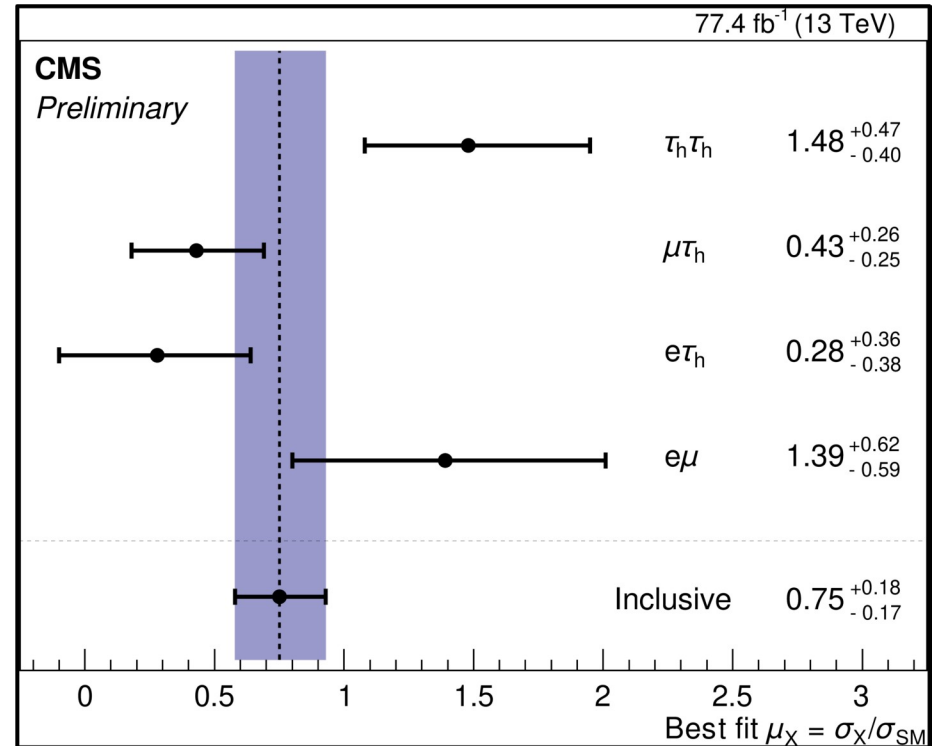
# Results (inclusive)

Inclusive signal (sorted by  $\log(S/(S+B))$ )



CMS-PAS-HIG-18-032

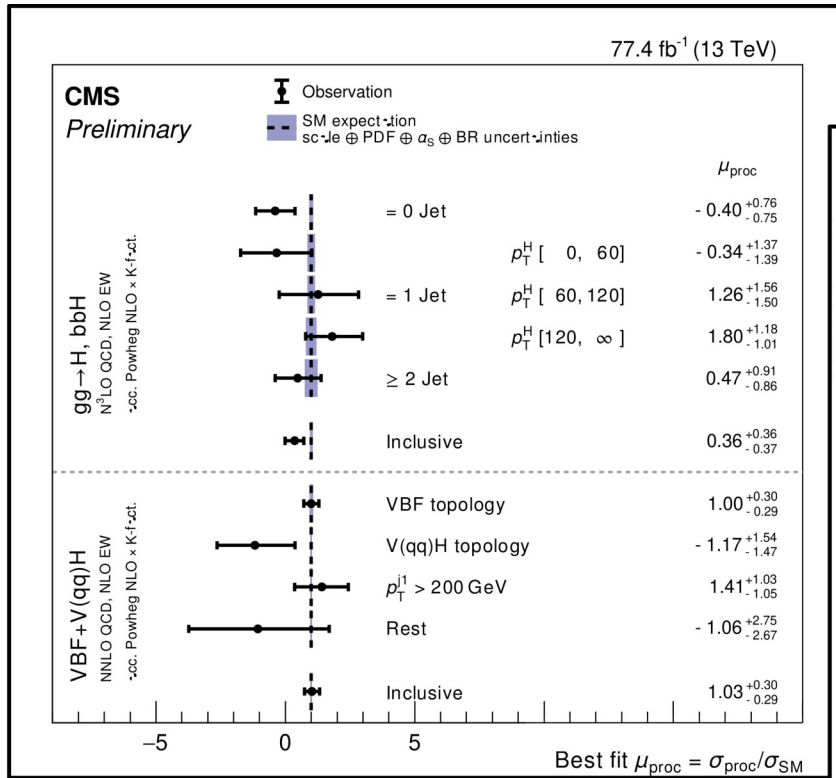
Signal strength: (top) split by final state and (bottom) inclusive



- Clear signal seen, though a bit on the low side, compared to other Higgs decay modes.

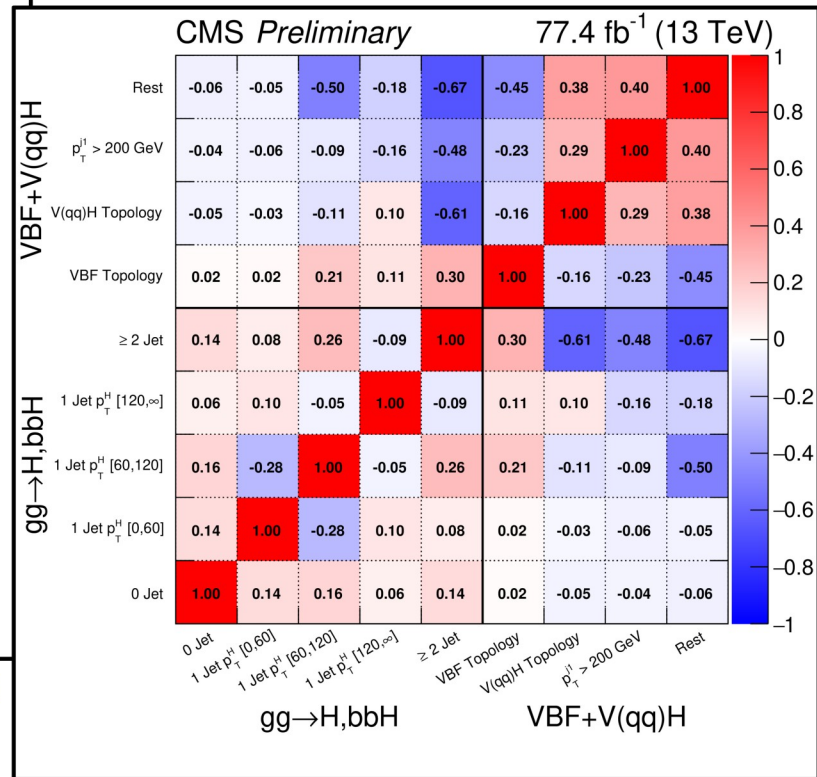
# Results (STXS)

- More differential measurement in 9 predefined STXS bins:



STXS bins

CMS-PAS-HIG-18-032



Correlation matrix

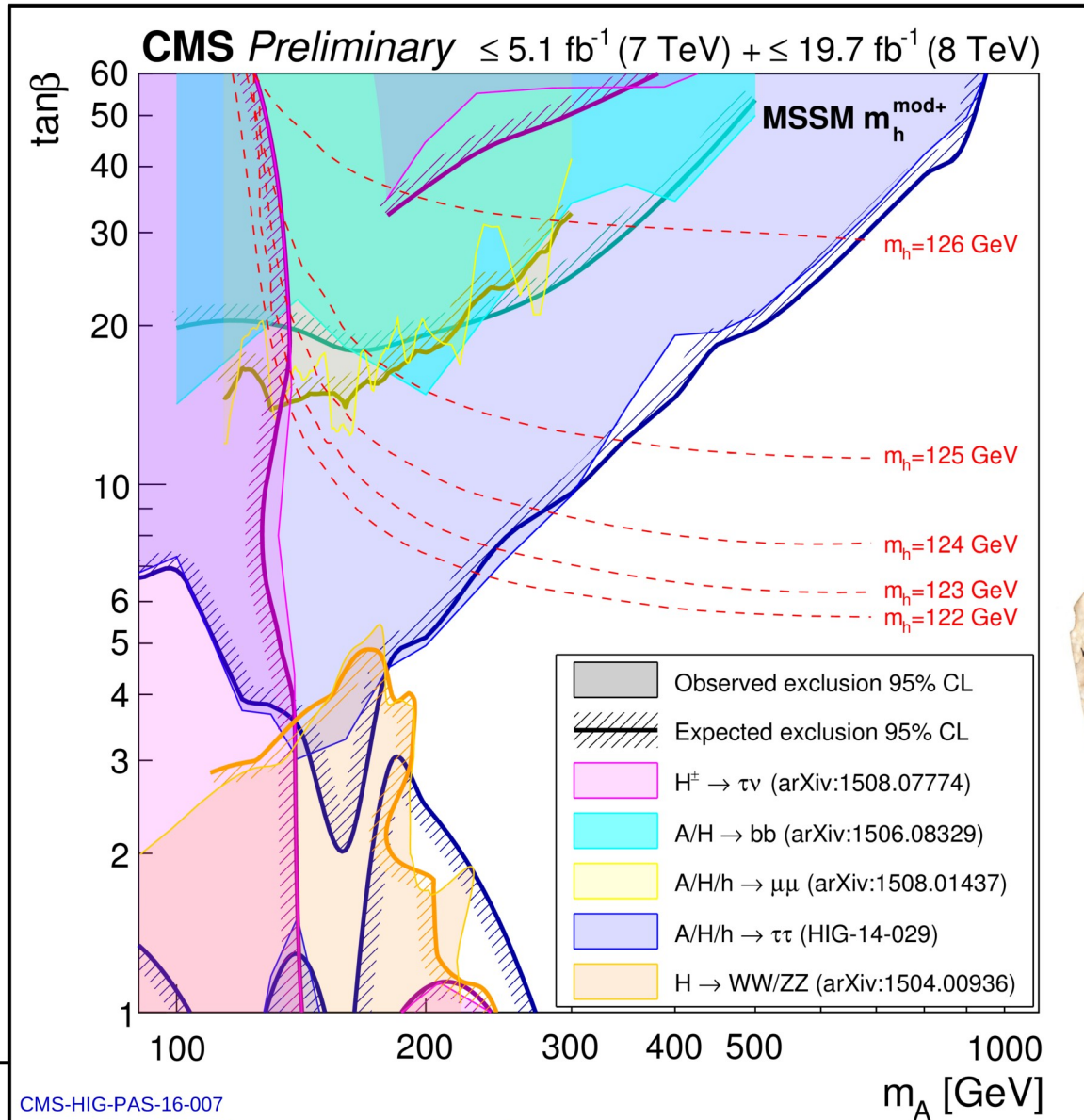


# Summary

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- Higgs boson fully established. Properties unique and so far as expected by SM.
- Higgs mechanism indeed realized in nature! Last missing piece → self-coupling.
- THE Higgs boson or just A Higgs Boson?
- Look for deviations in coupling structure → prime measurement.
- Differential taking kinematic properties of production and decay into account → STXS.
- Quantify deviations via generic effective field operator expansion → EFT.
- Look for more Higgs bosons in a more complex Higgs sector → prime searches.

# Landkarte der „Neuen Welt“



Mary Rose (Flagschiff der englischen Marine 1511 – 1545)

