Higgs boson discovery & properties

Roger Wolf

17. July 2019

Historical context

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1962: Spontaneous symmetry breaking in super conductivity.

1964: Higgs mechanism in particle physics.

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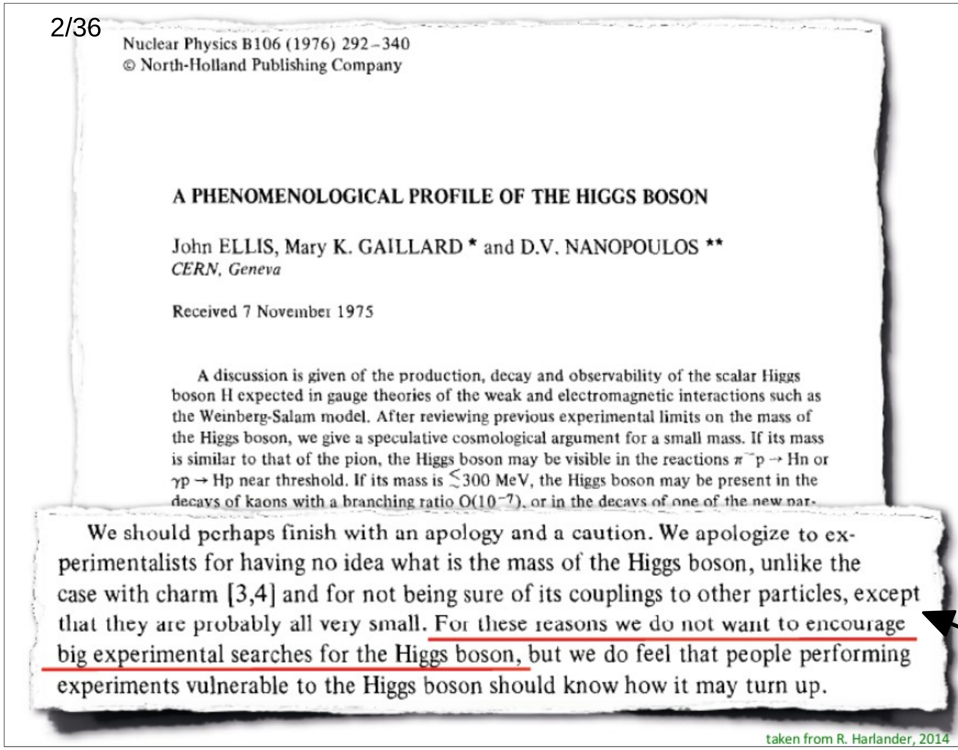

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A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

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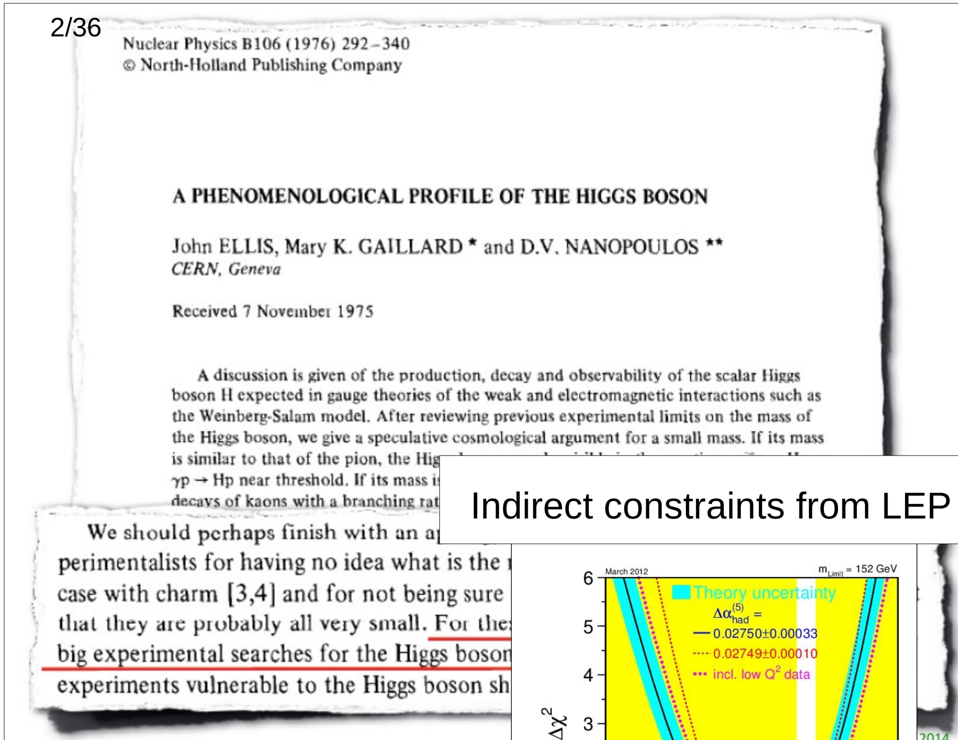
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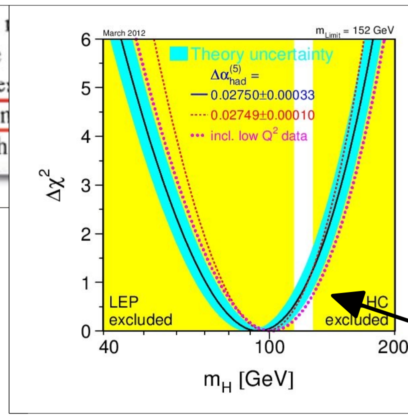
Indirect constraints from LEP



$$m_H = 98 \pm^{25}_{21} \;\; \text{GeV}$$

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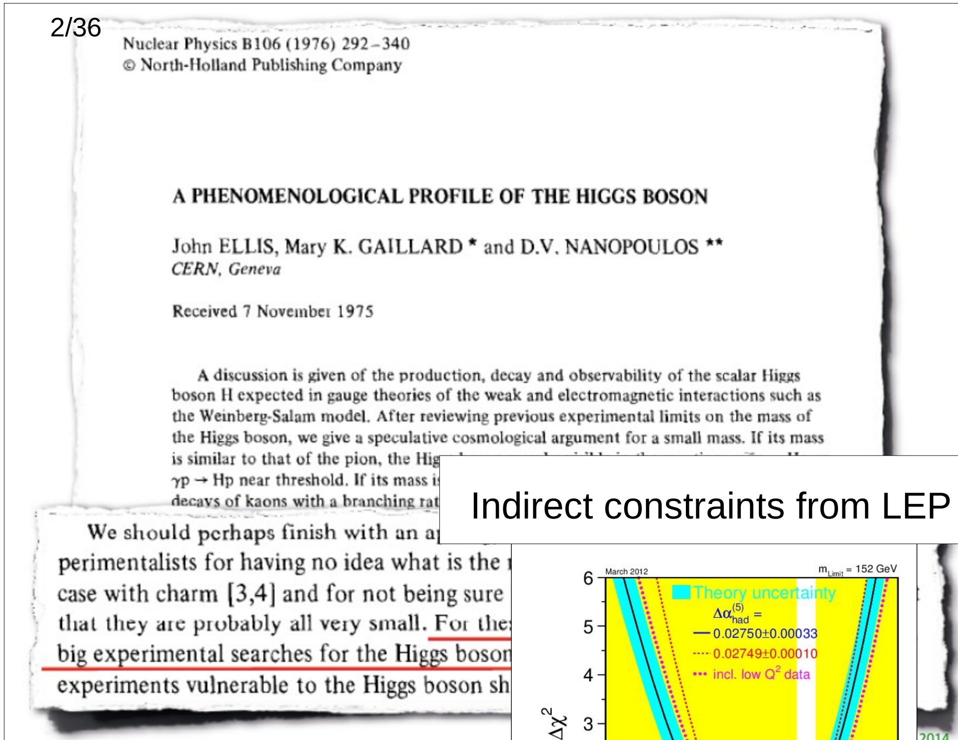
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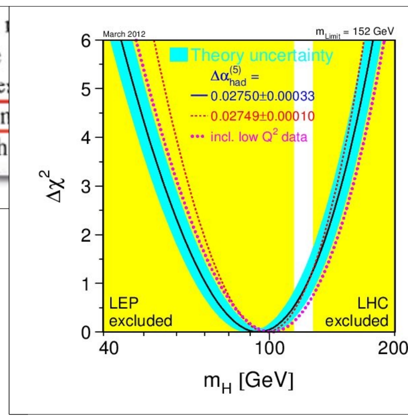

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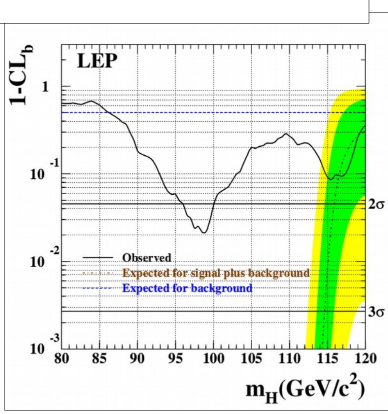
Final word from LEP



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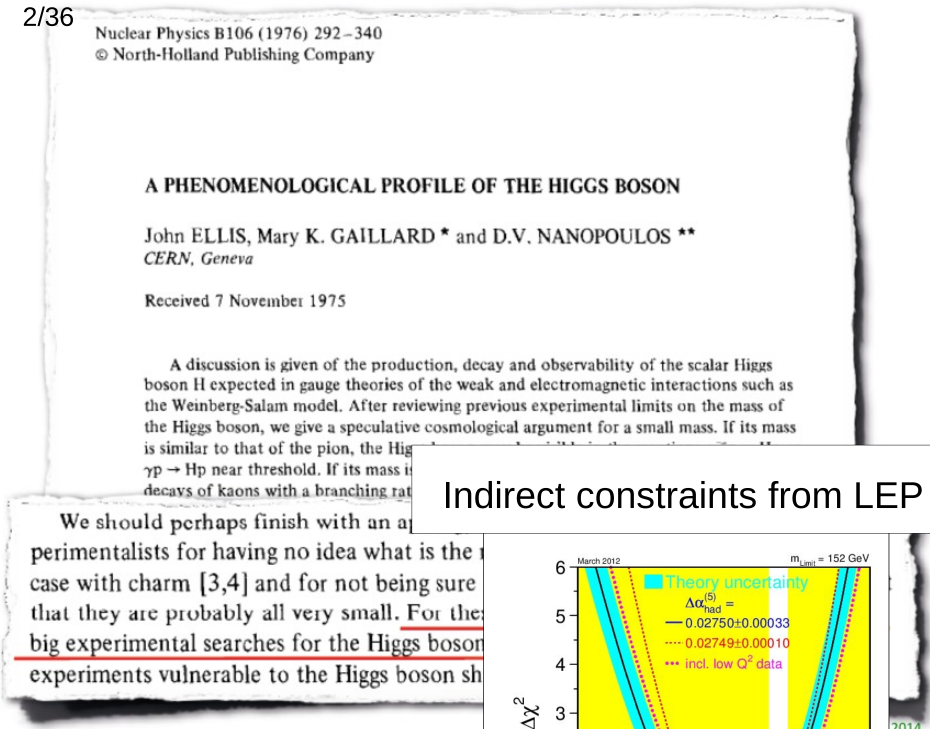
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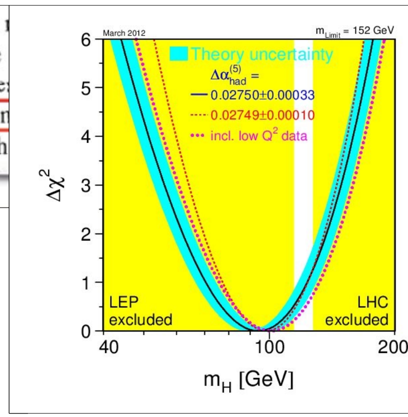

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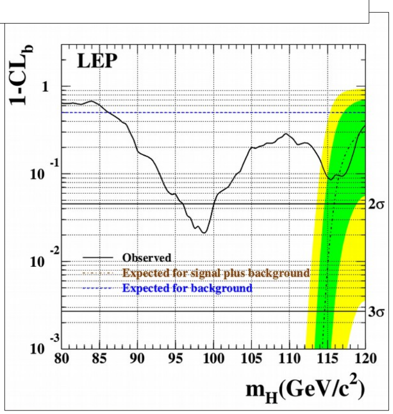
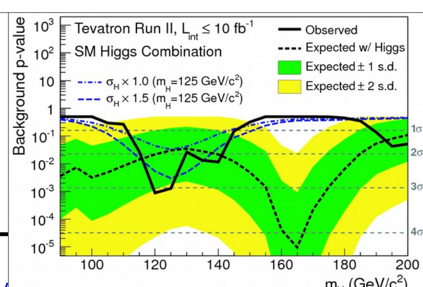


Final word from Tevatron



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Direct Higgs boson searches today …

Direct Higgs boson searches @ LEP

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

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

Direct Higgs boson searches @ LEP

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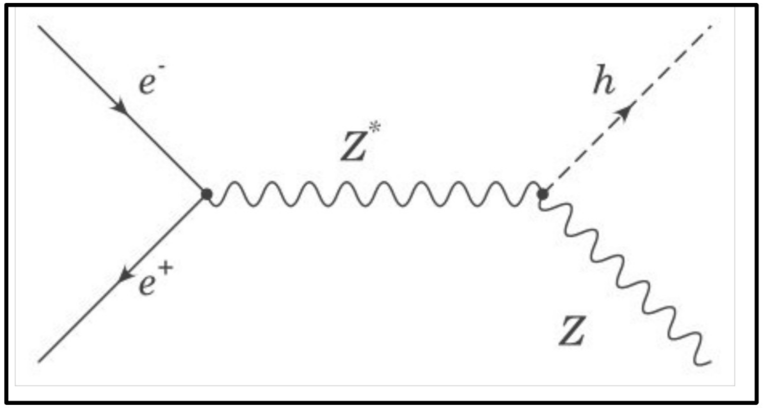
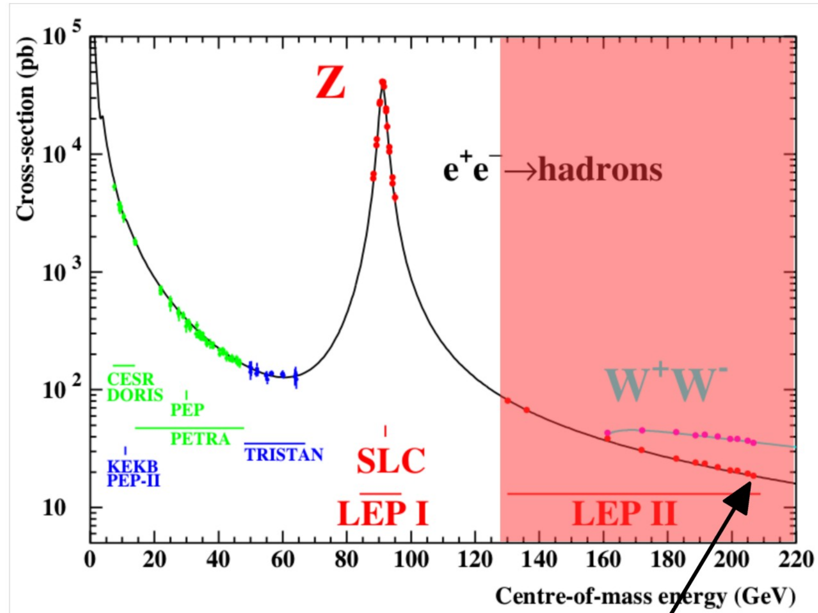


Integrated luminosities in pb^{-1}					
	ALEPH	DELPHI	L3	OPAL	LEP
$\sqrt{s} \geq 189$ GeV	629	608	627	596	2461
$\sqrt{s} \geq 206$ GeV	130	138	139	129	536



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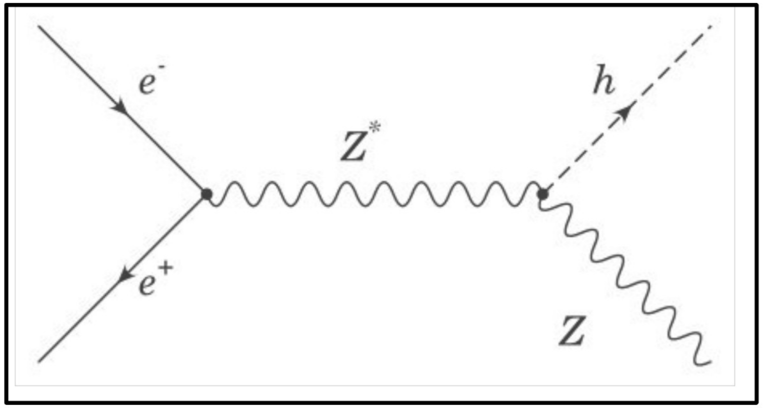
Year	1996		1997	1998	1999				2000	
E_{CM} nominal [GeV]	161	172	183	189	192	196	200	202	205	207

What was the maximal reach on m_H at LEP?

Direct Higgs boson searches @ LEP

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



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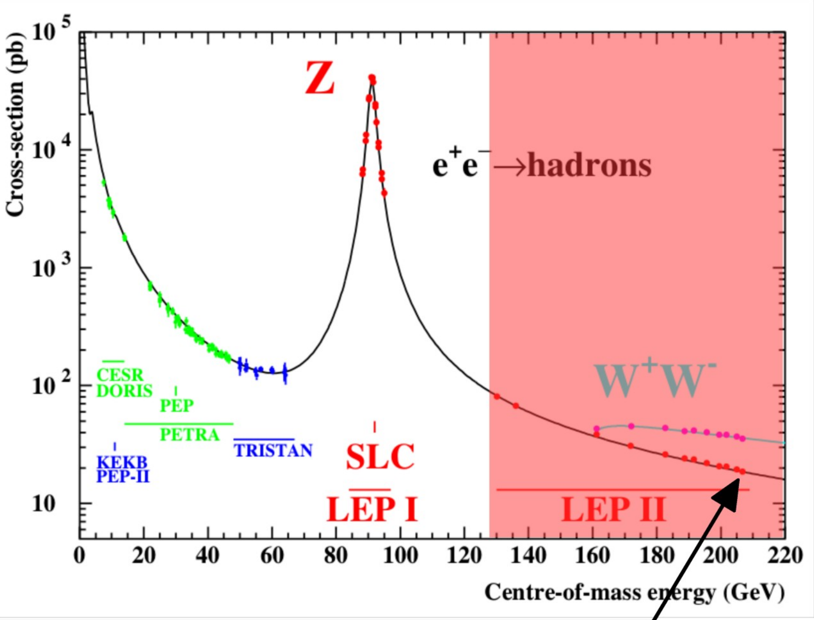

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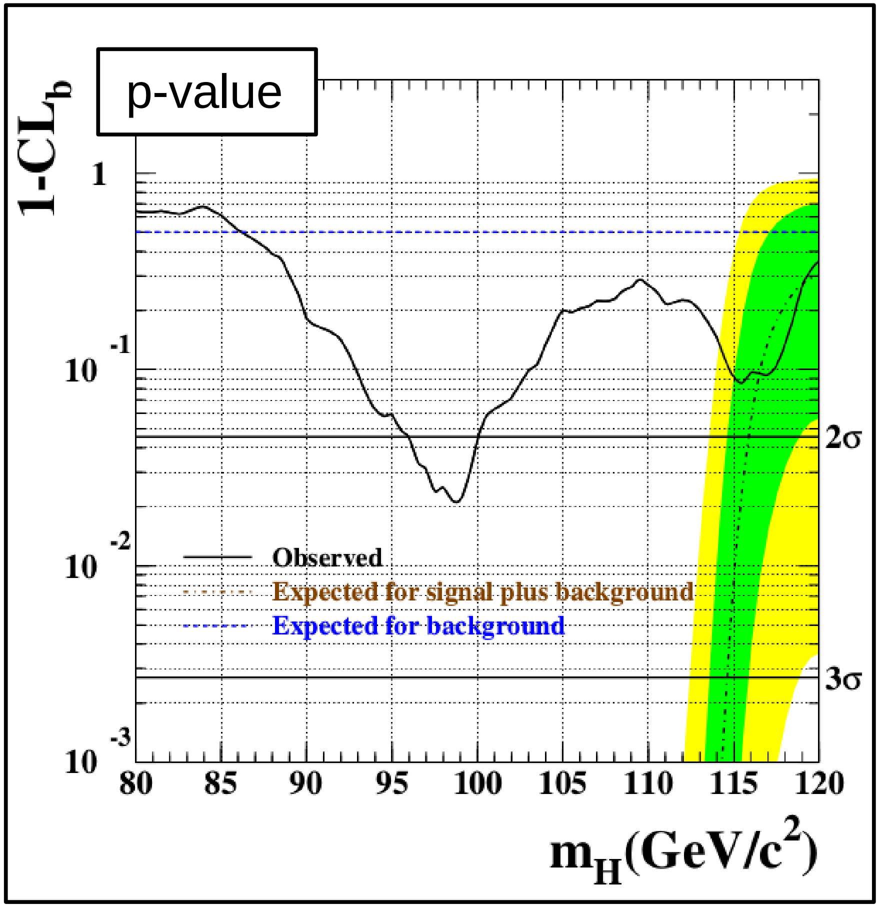
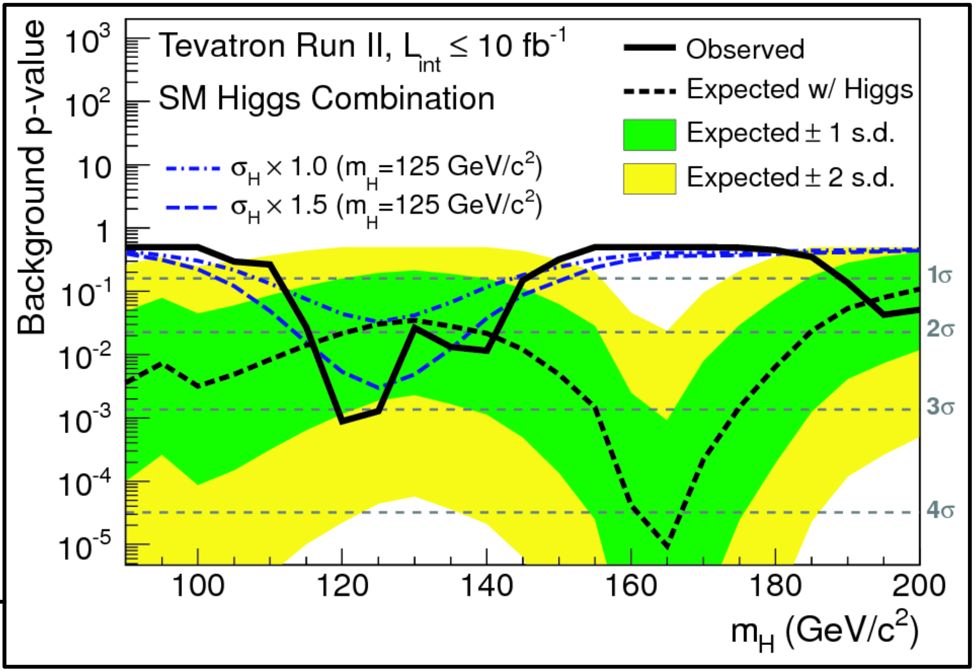
What was the maximal reach on m_H at LEP? $m_H \approx 117$ GeV

LEP result (2000)

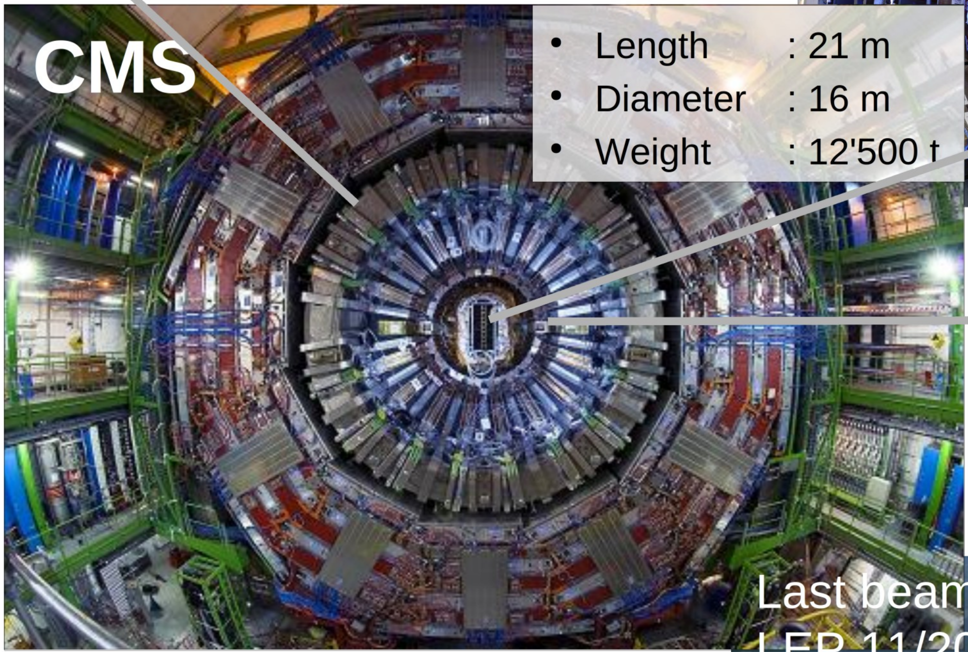


Tevatron result (2012)



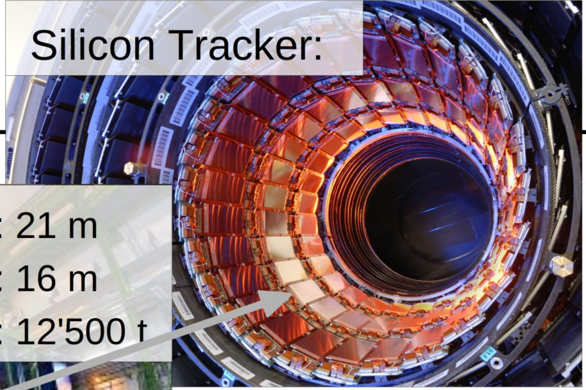
The LHC

3.8T superconducting solenoid magnet:



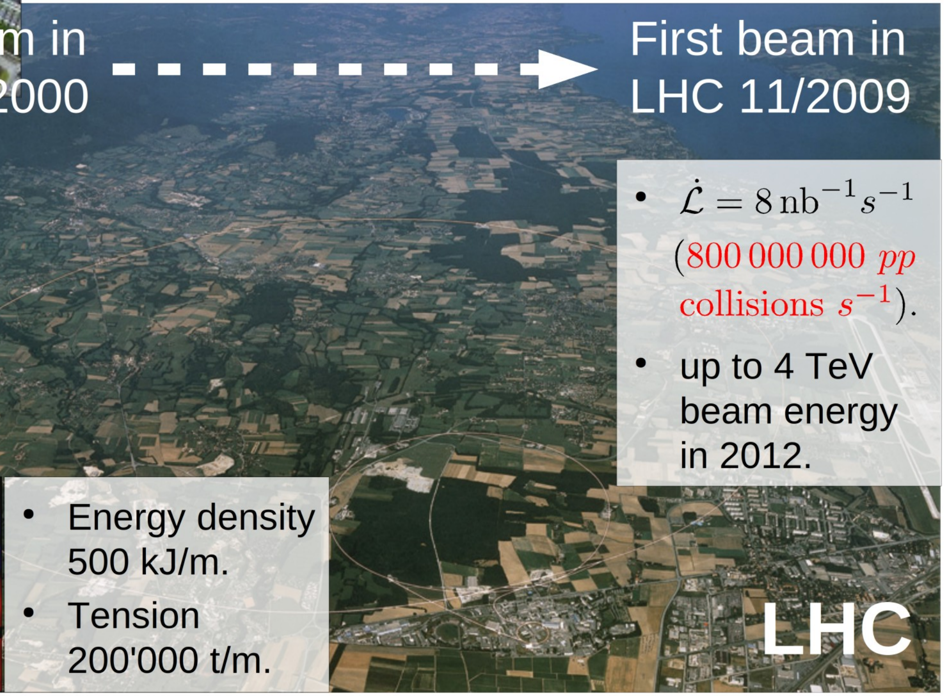
- Length : 21 m
- Diameter : 16 m
- Weight : 12'500 t

Silicon Tracker:



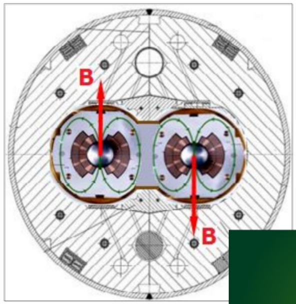
- Tracker: Si ($\delta p/p = 0.5\%$ for a 10 GeV track).
- ECAL: $PbWO_4$ ($\delta E/E = 1\%$ for a 30 GeV e/γ).

Electromagnetic Calo:

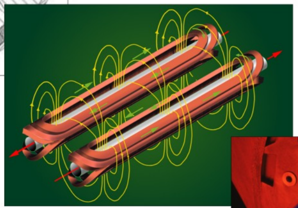


Last beam in LEP 11/2000 → First beam in LHC 11/2009

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



- 8.3 T
- 11.8 kA
- 160 cyc

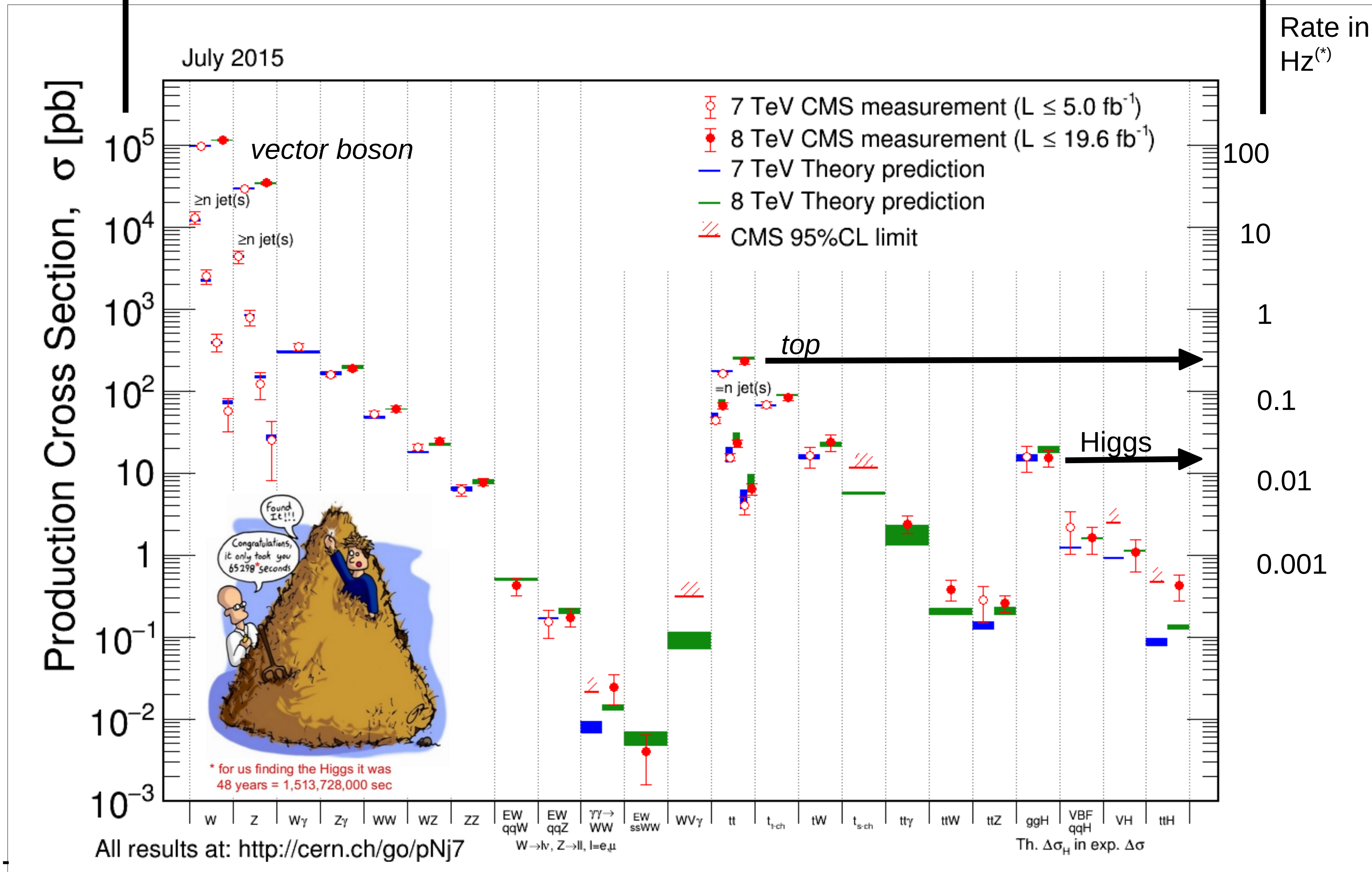


- Energy density 500 kJ/m.
- Tension 200'000 t/m.

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

The challenge

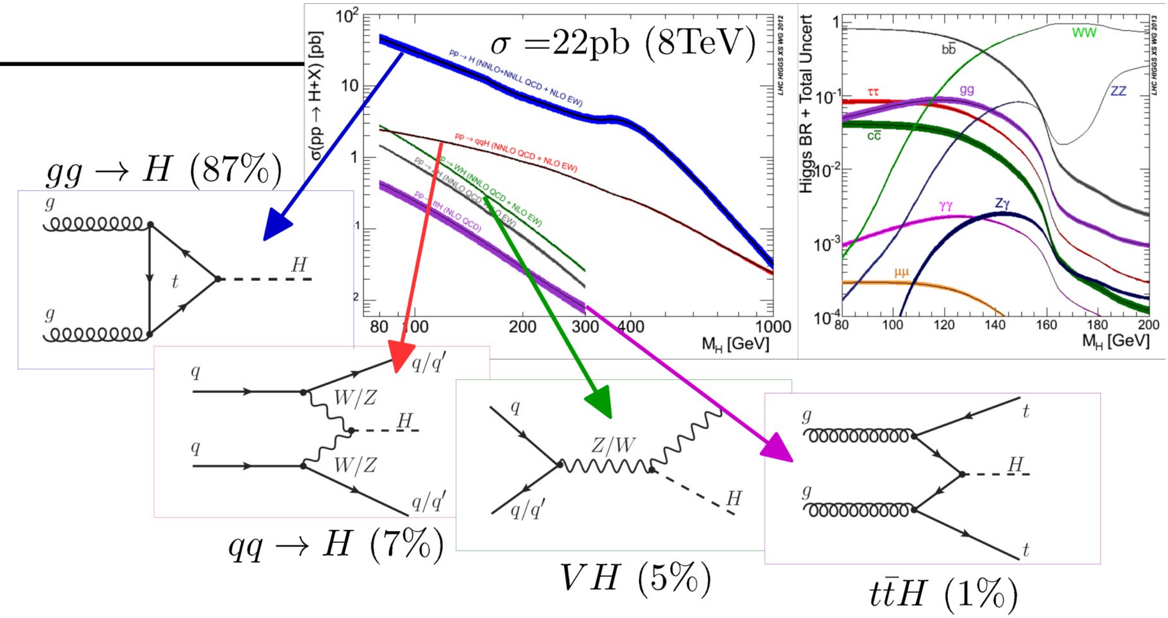
Rate in Hz(*)



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

The discovery…

Production: Decay:



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http://ekpwww.physik.uni-karlsruhe.de/~rwolf/

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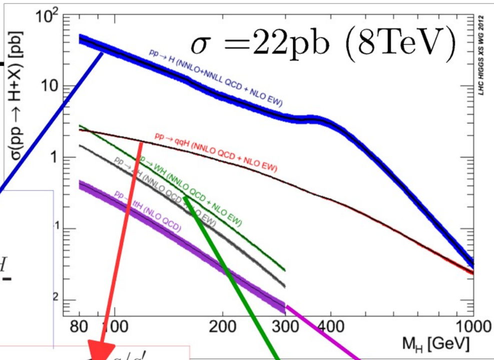

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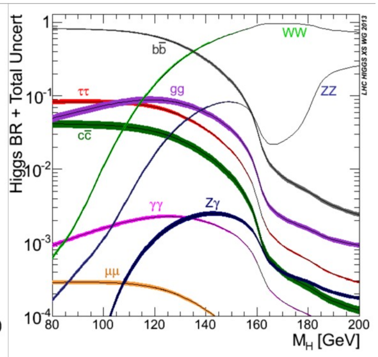
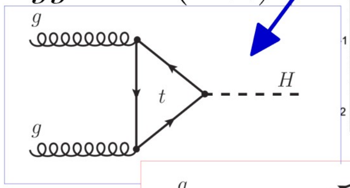
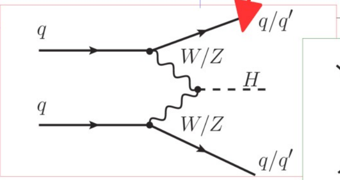
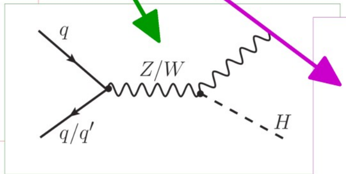


$gg \to H$ (87%)

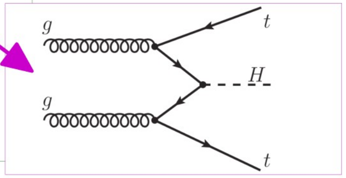




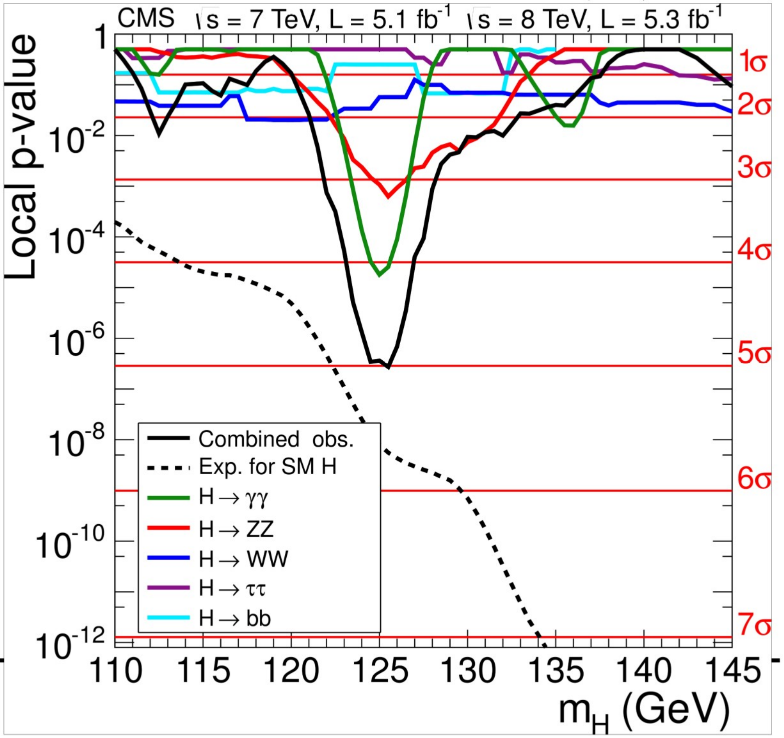
$qq \to H$ (7%)



VH (5%)



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



PLB 716 (2012) 30

The discovery...

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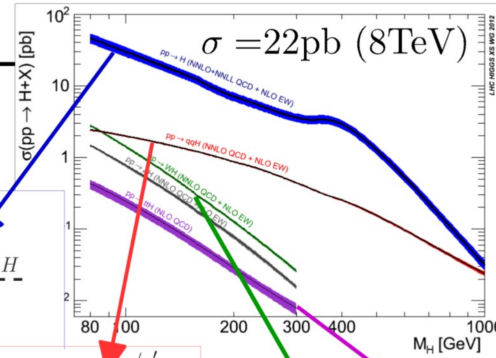

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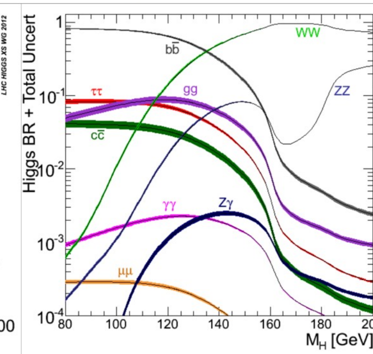

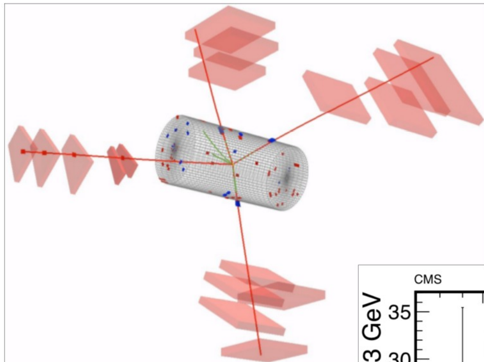

$H \to ZZ \to 4\ell$

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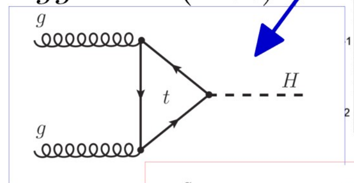

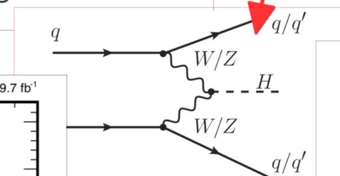

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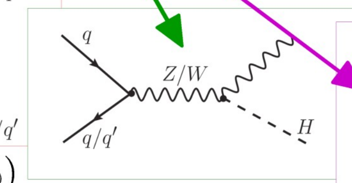

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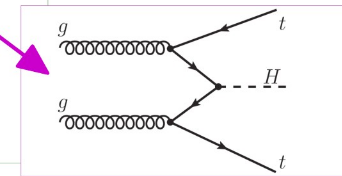
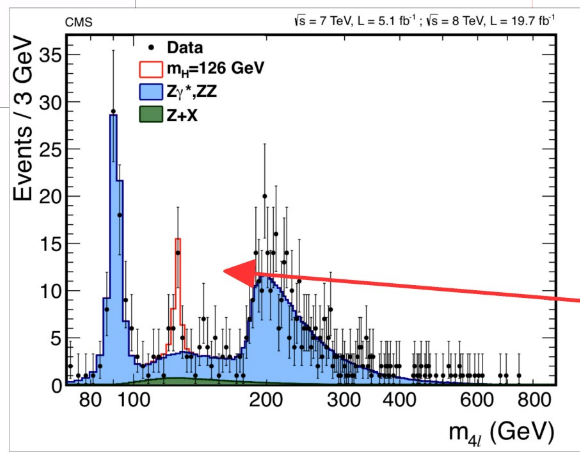


$t\bar{t}H$ (1%)



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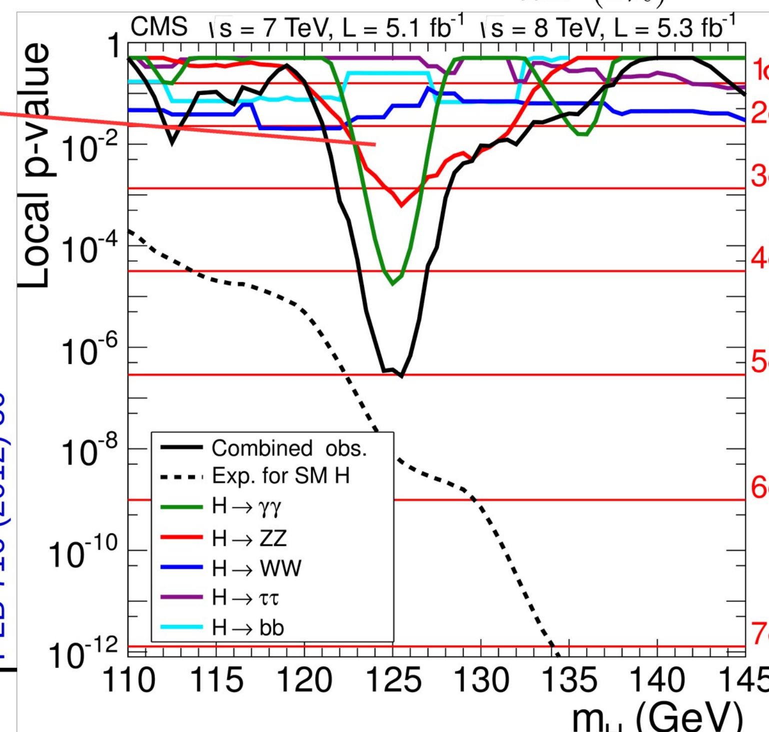

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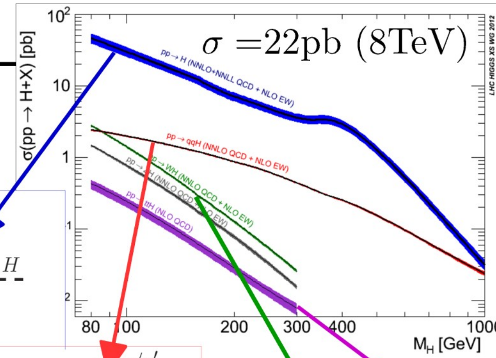
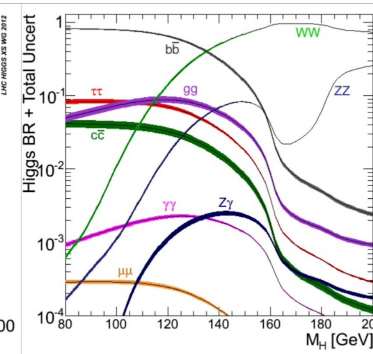


Decay:



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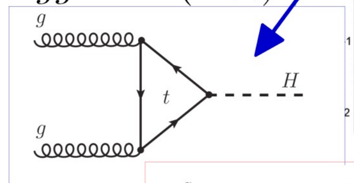

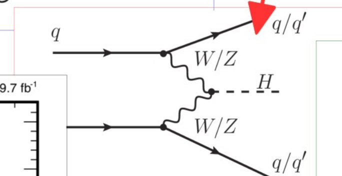

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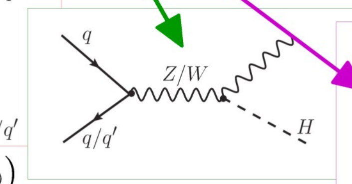

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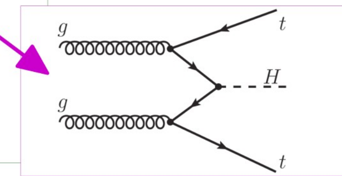

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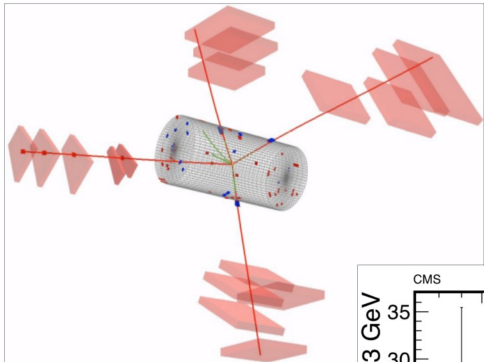

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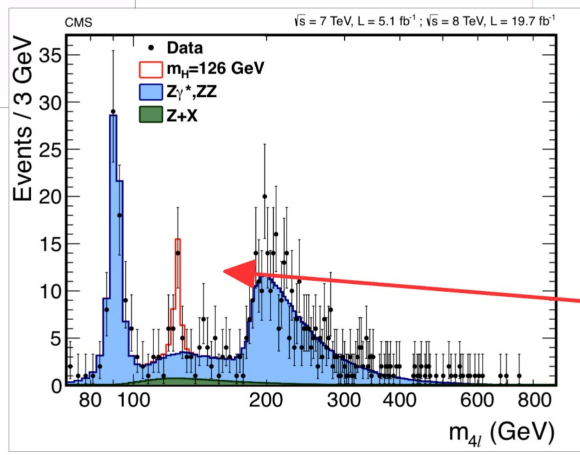

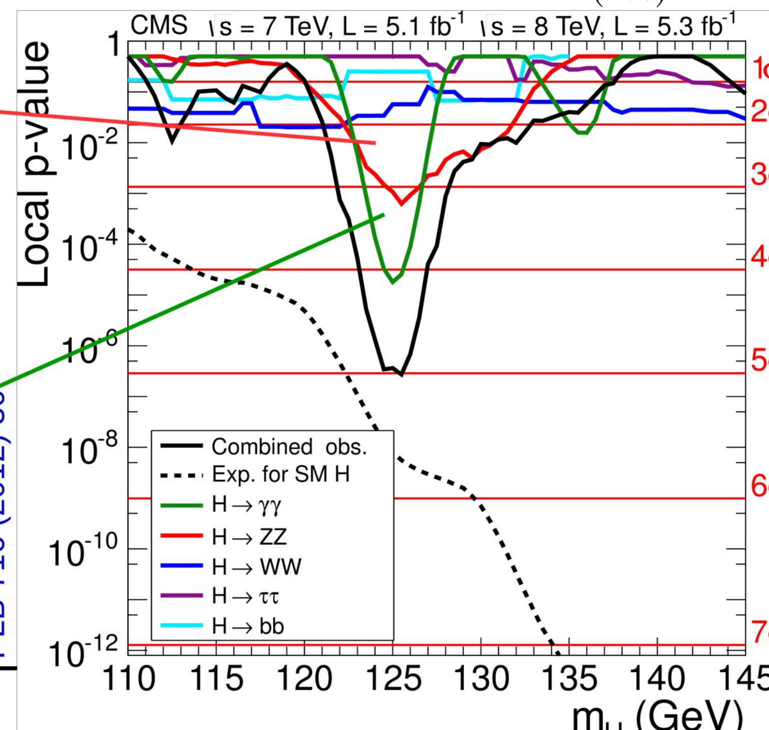

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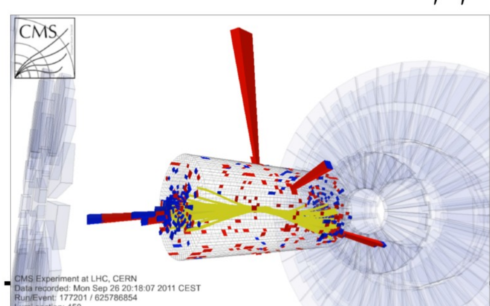
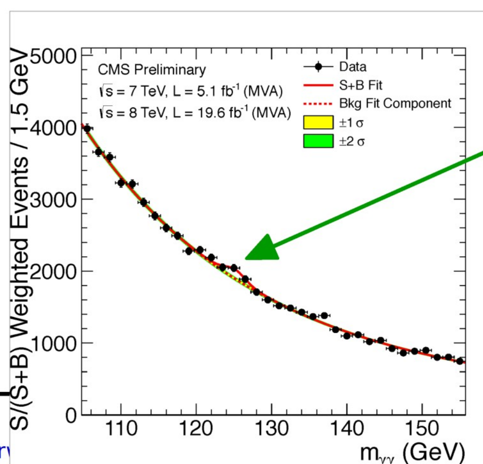
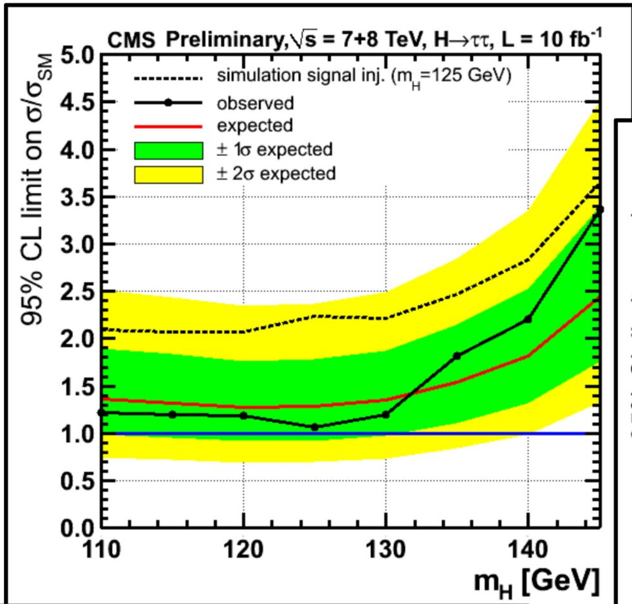
$H \to \gamma\gamma$





Intermezzo: evolution of the $H \to \tau\tau$ signal

July 2012:

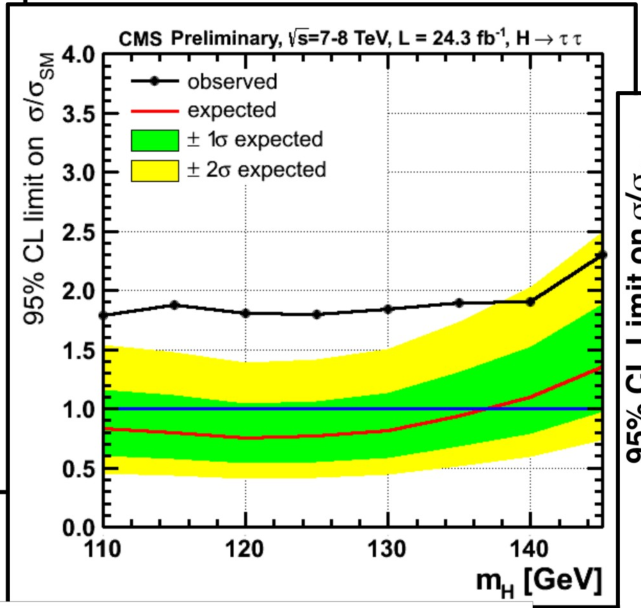


$$\mu = \mathrm{N.A.}$$

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

$@\ m_H \approx 125$ GeV

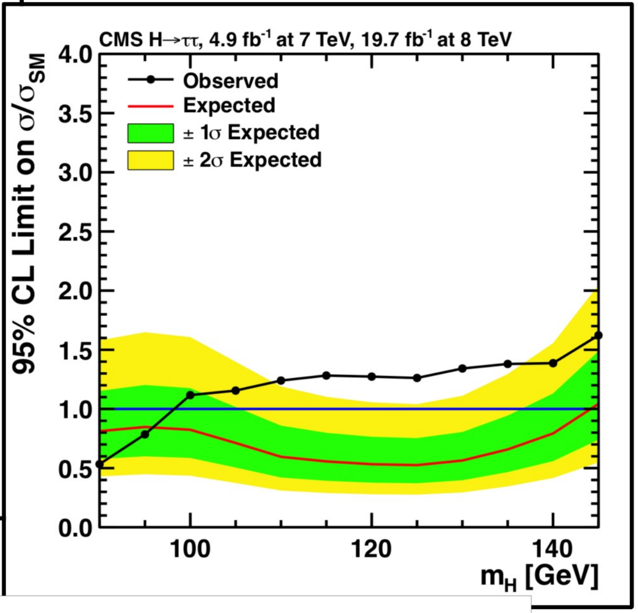
March 2013:



$$\mu = 1.1 \pm 0.4$$

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

Summer 2014:



$$\mu = 0.8 \pm 0.3$$

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

… and beyond (a.k.a. Run-1 legacy)

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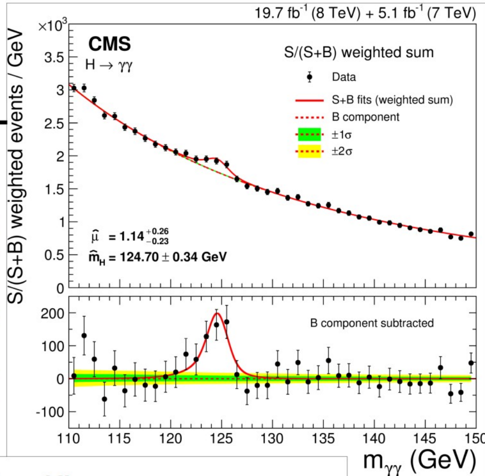
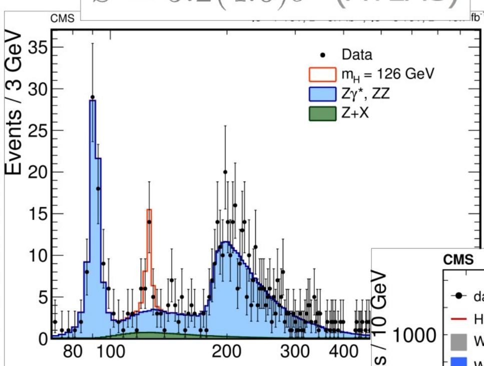


Significance:

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

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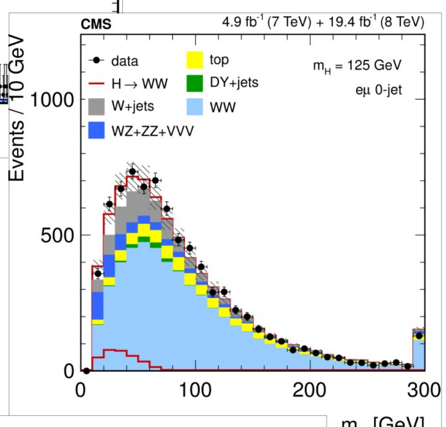

Significance:

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

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

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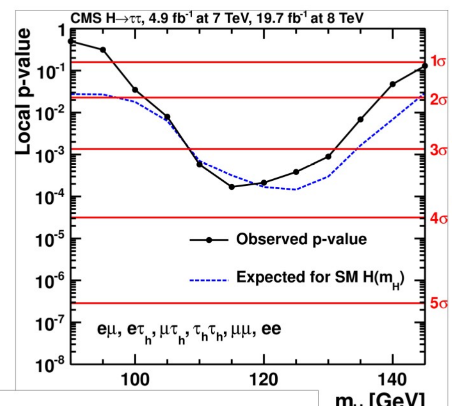
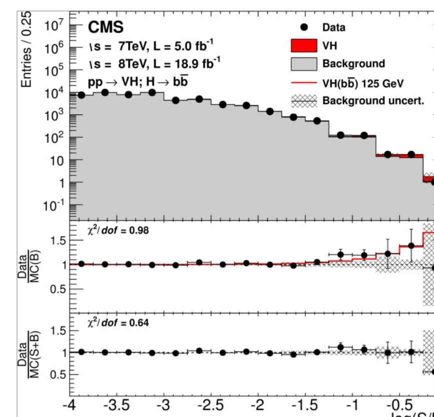


Significance:

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

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



Significance:

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

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

"untagged"

Decay / Prod	$gg \to H$	$qq \to H$	VH	$t\bar{t}H$
$H \to \gamma\gamma$	✓ (Part of discovery) 87%	✓ (Part of discovery) 7%	✓ (After LHC run-1) 5%	✓ (After LHC run-1) 1%
$H \to ZZ$	✓ (Part of discovery)	✓ (After LHC run-1)	✓ (After LHC run-1)	✓ (After LHC run-1)
$H \to WW$	✓ (Part of discovery)	✓ (Part of discovery)	✓ (After LHC run-1)	✓ (After LHC run-1)
$H \to \tau\tau$	✓ (Part of discovery)	✓ (After LHC run-1)	✓ (After LHC run-1)	✓ (After LHC run-1)
$H \to b\bar{b}$	(Not covered)	✓ (After LHC run-1)	✓ (Part of discovery)	✓ (After LHC run-1)
$H \to \mu\mu$	✓ (After LHC run-1)	✓ (After LHC run-1)	(Not covered)	(Not covered)

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

$H \to \mu\mu$ decay

+14 further exclusive categories

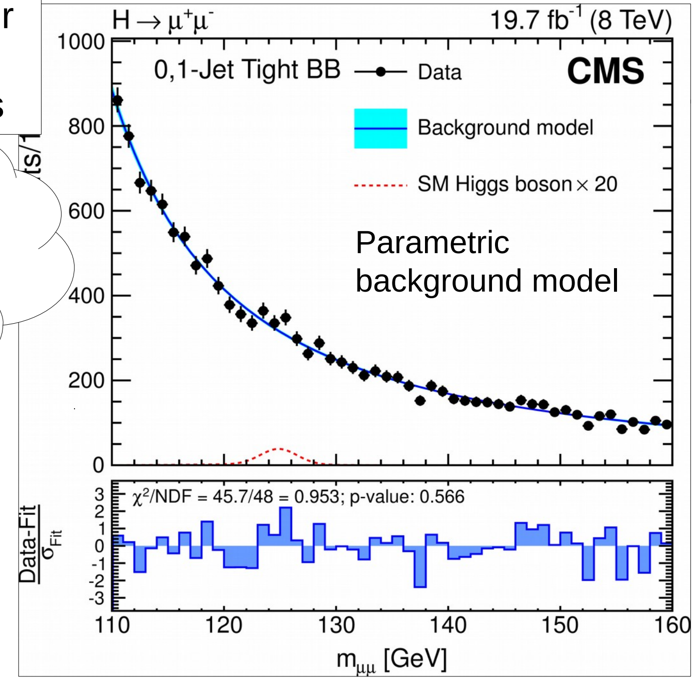
- Clear signature, high mass resolution, small $\mathcal{BR}$ ($\rightarrow$ similar to $H \to \gamma\gamma$):

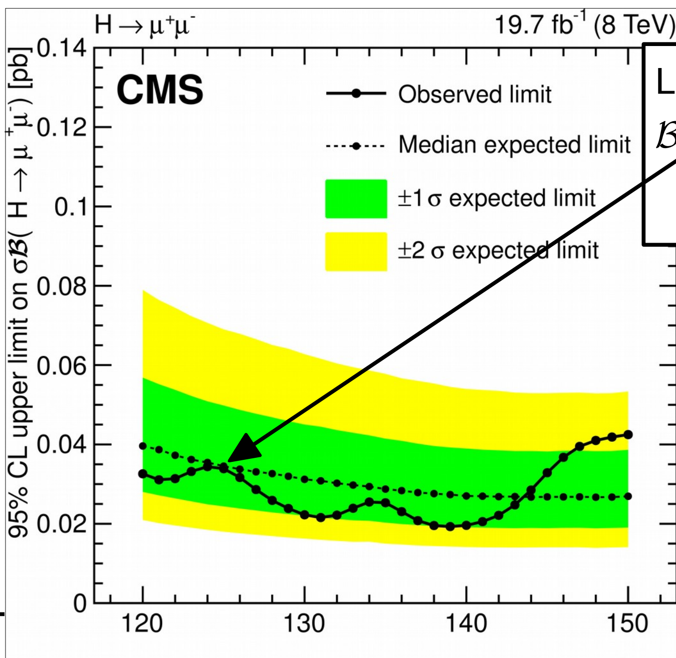
$m_\mu = 106\,\mathrm{MeV}$
$m_\tau = 1777\,\mathrm{MeV}$

- SM expectation:

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

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





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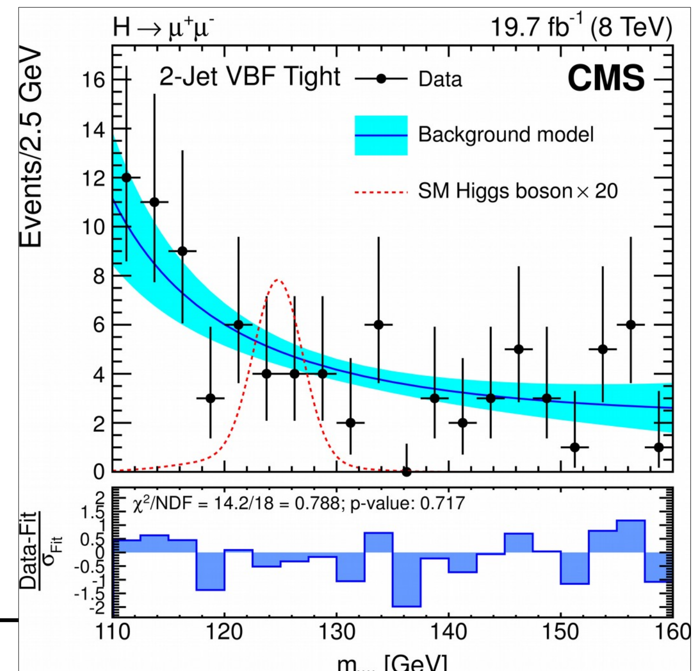
Limit (95% CL):
$\mathcal{BR}(H \to \mu\mu) \leq 0.16\%$
$\left(7.4\,(6.5) \times SM\right)^{(*)}$

(*) on 7+8TeV



$H \to \mu\mu$ decay

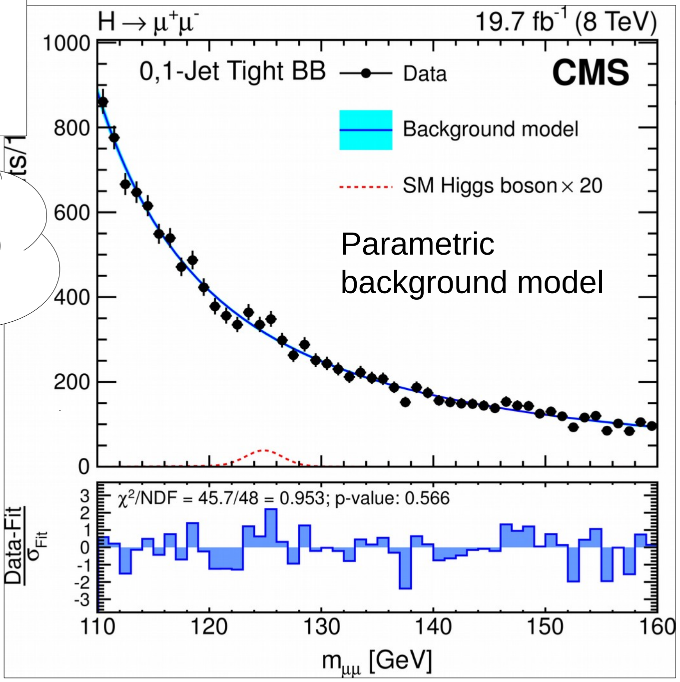
+14 further exclusive categories

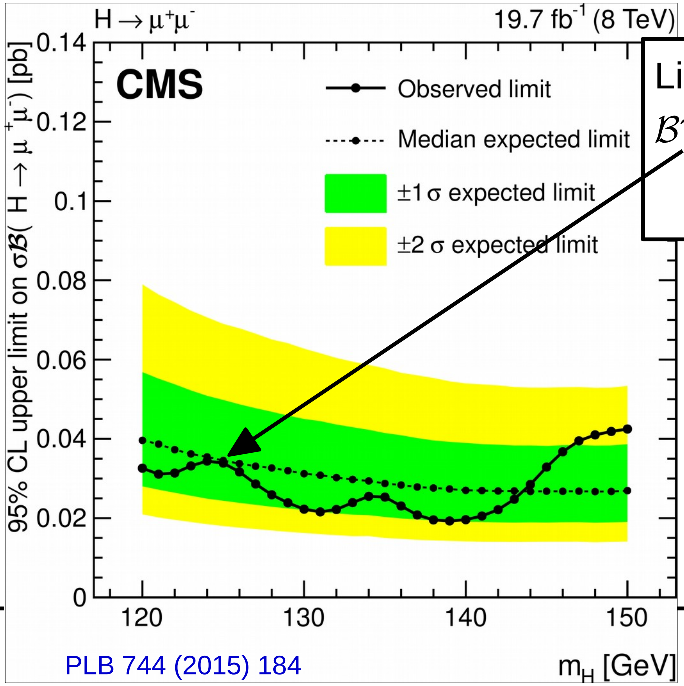
- Clear signature, high mass resolution, small $\mathcal{BR}$ (→ similar to $H \to \gamma\gamma$):

$$= \left(\frac{m_\mu}{m_\tau}\right)^2 \cdot \mathcal{BR}(H \to \tau\tau)$$
$$m_\mu = 106\,\mathrm{MeV}$$
$$m_\tau = 1777\,\mathrm{MeV}$$

- SM expectation:

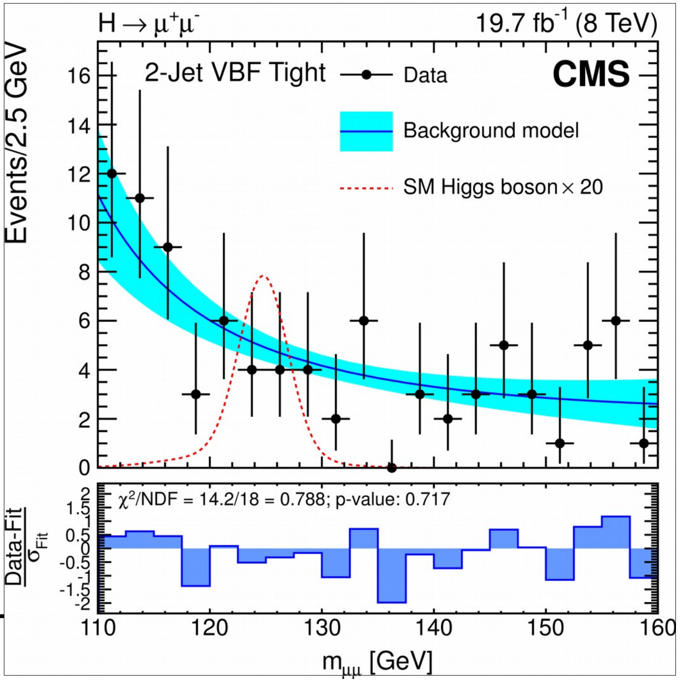
$$\mathcal{BR}(H \to \tau\tau) = 6.30 \pm 0.36\ \%$$
$$\mathcal{BR}(H \to \mu\mu) = ???$$





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

(*) on 7+8TeV



$H \to \mu\mu$ decay

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

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

$$m_\mu = 106\,\mathrm{MeV}$$

$$m_\tau = 1777\,\mathrm{MeV}$$

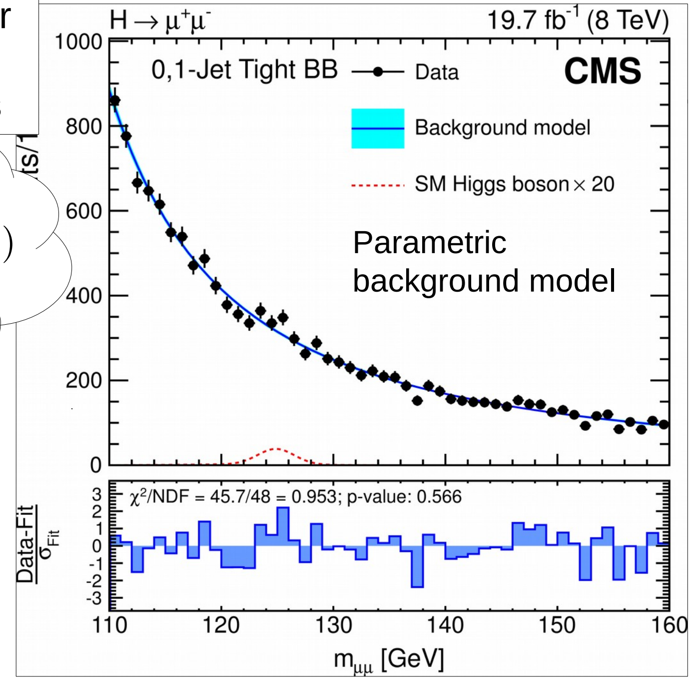
- SM expectation:

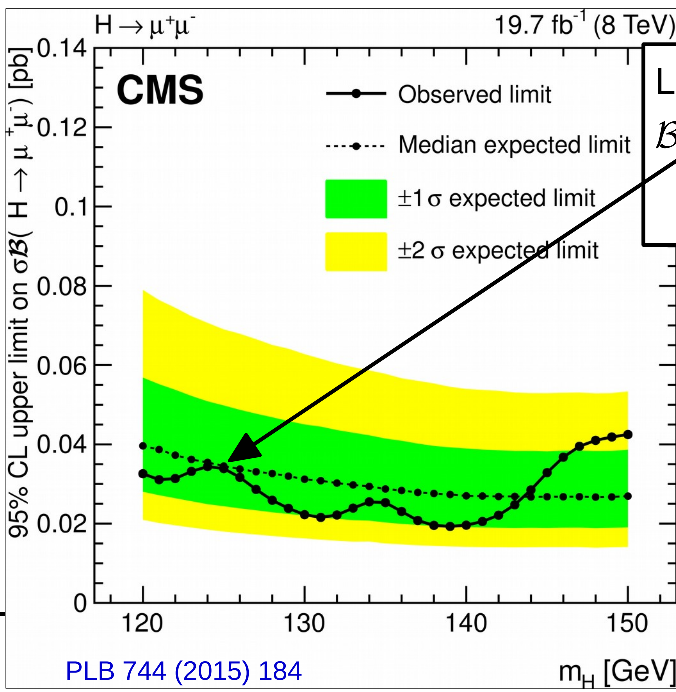
$$\mathcal{BR}(H \to \tau\tau) = 6.30 \pm 0.36\ \%$$

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

- Non-universal coupling to leptons!

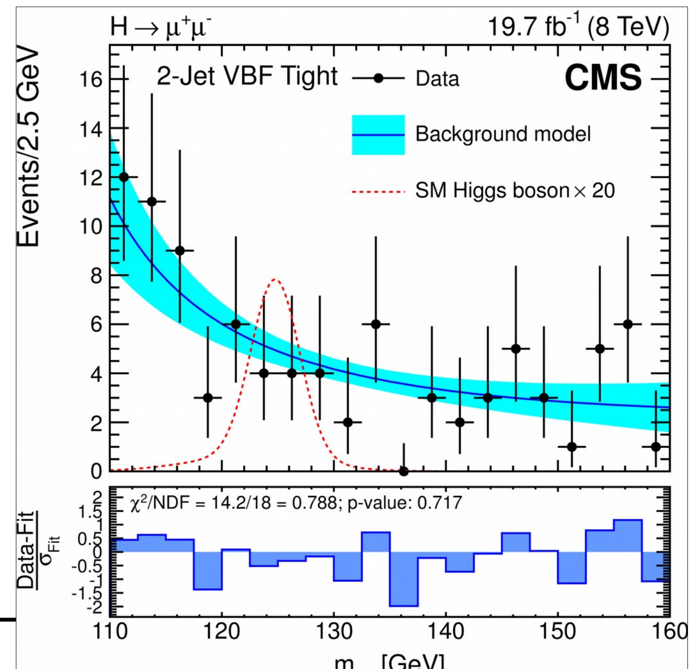
+14 further exclusive categories





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

(*) on 7+8TeV



Spin & CP?

Single particle?

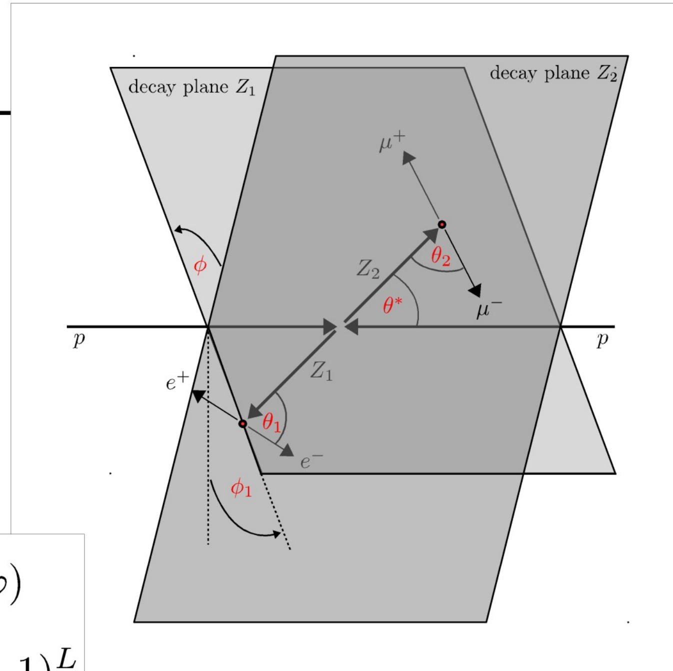
Decay width?

Mass?

Coupling
structure?

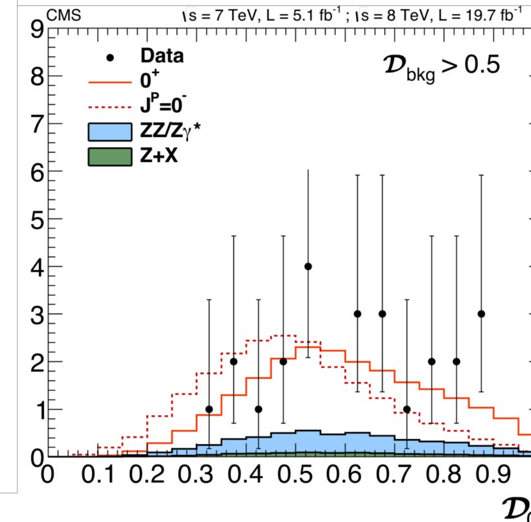
Spin & CP

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



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

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



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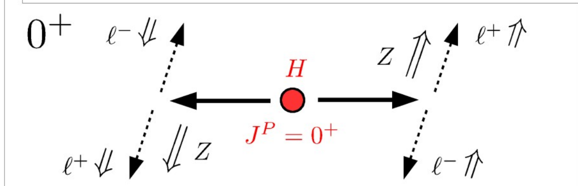
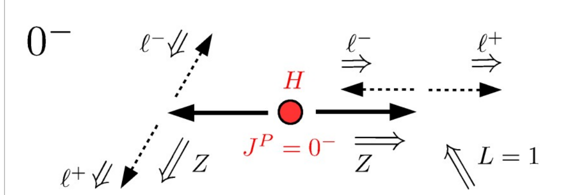
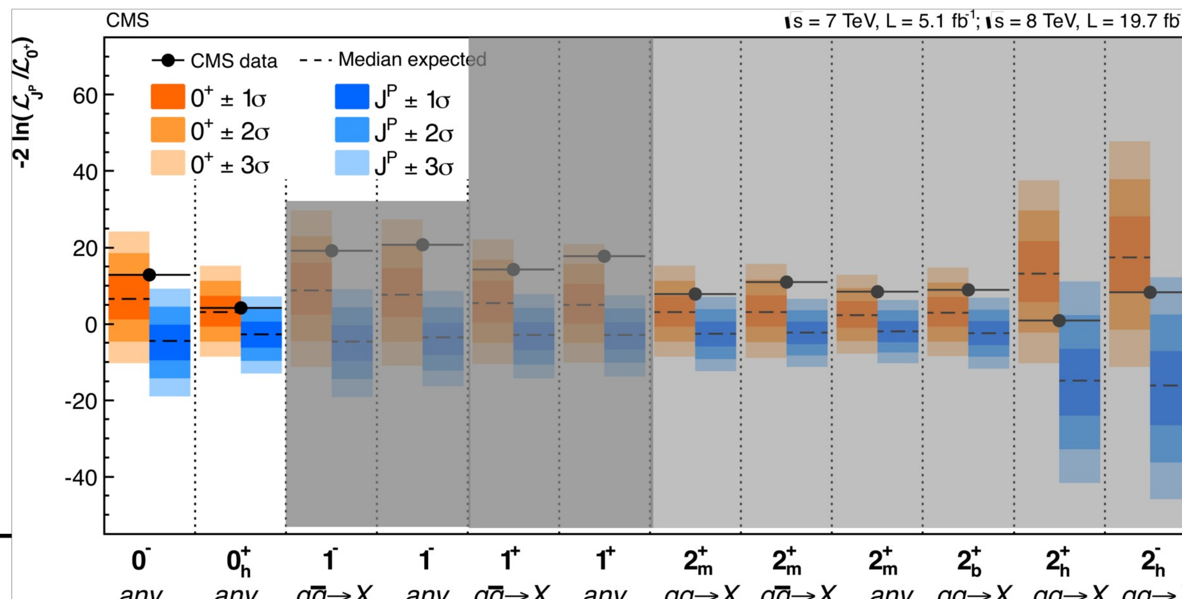


$$|0,0\rangle = \sqrt{\tfrac{1}{3}}|1,\ \ 1\rangle \otimes |1,-1\rangle - \sqrt{\tfrac{1}{3}}|1,0\rangle \otimes |1,0\rangle + \sqrt{\tfrac{1}{3}}|1,-1\rangle \otimes |1,\ \ 1\rangle$$



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

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



Compatibility

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

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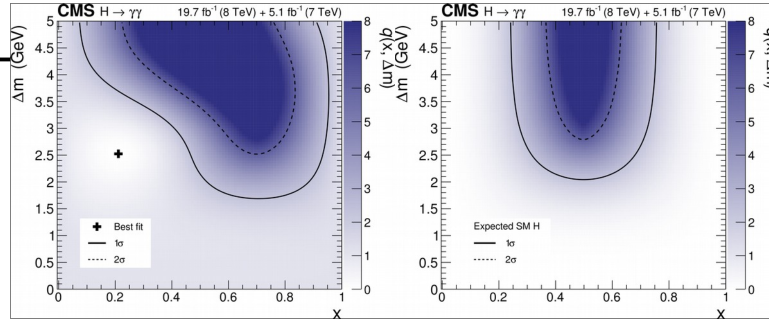

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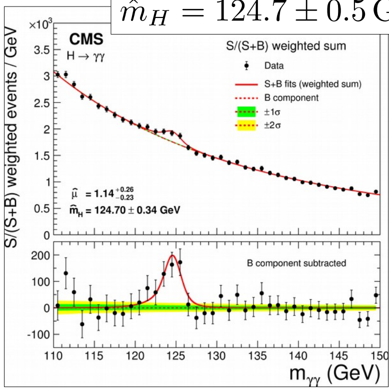
$\hat{m}_H = 124.7 \pm 0.5\,\mathrm{GeV}$



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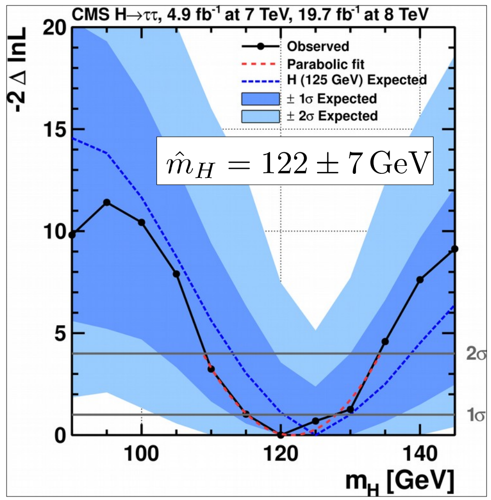
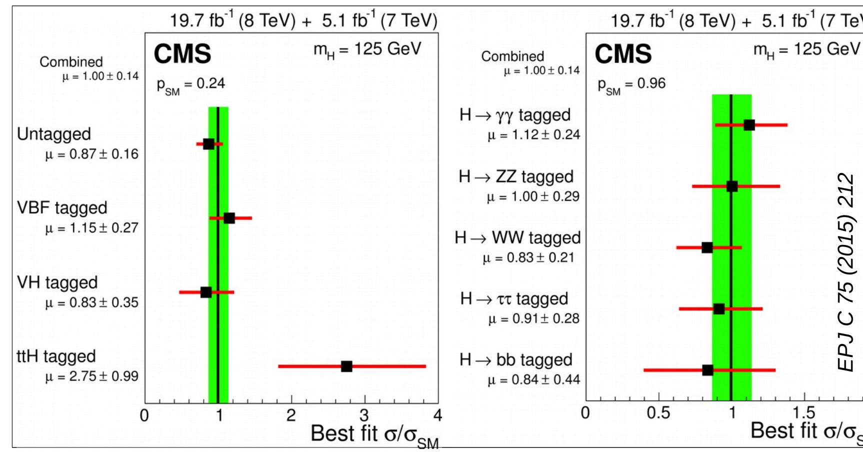
$\hat{m}_H = 122 \pm 7\,\mathrm{GeV}$



Coupling across production modes or decay channels:



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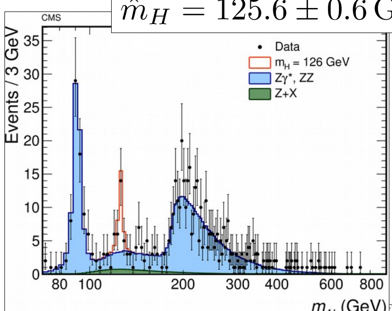
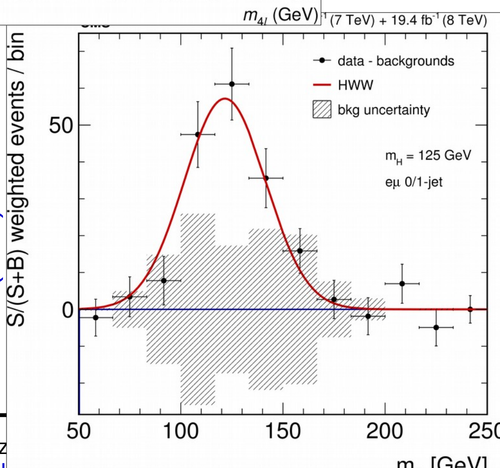
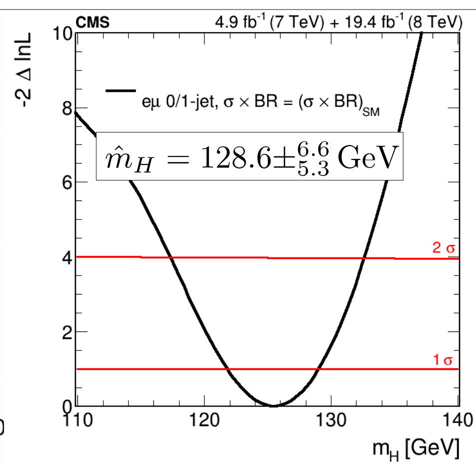
$\hat{m}_H = 125.6 \pm 0.6\,\mathrm{GeV}$



JHEP 01 (2014) 096

$\hat{m}_H = 128.6^{+6.6}_{-5.3}\,\mathrm{GeV}$





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Overall coupling consistency:

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

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

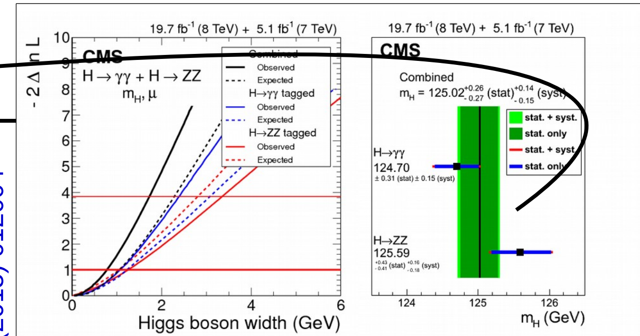
$p\text{-value} = 84\%$

Mass & decay width

compatible within 1.6σ.

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

PRD 92 (2015) 012004



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

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

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

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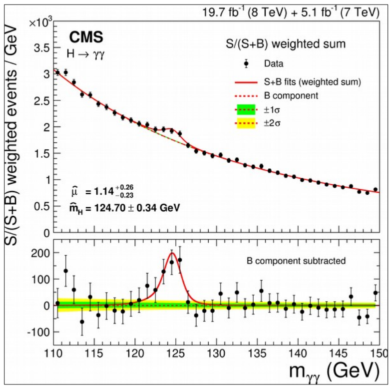
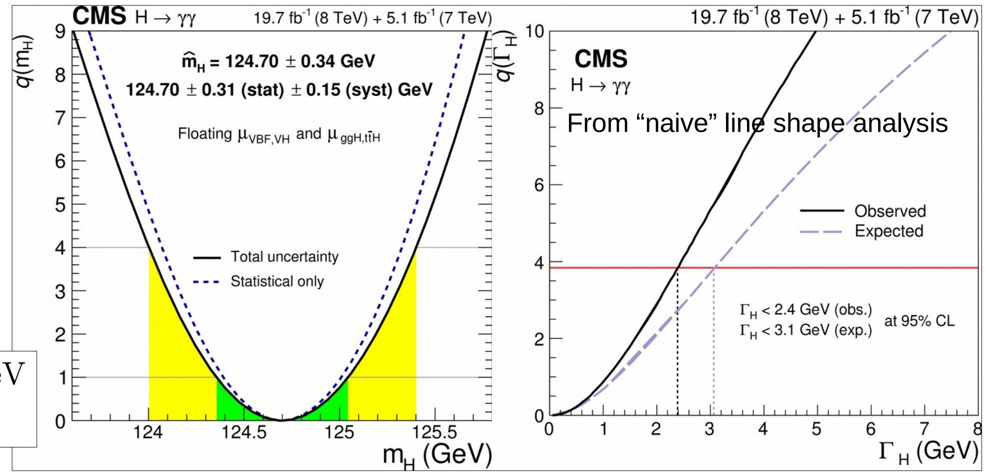


$$\hat{m}_H = 124.7 \pm^{0.5}_{0.31} \text{ (stat.)} \pm 0.15 \text{(syst.) GeV}$$

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



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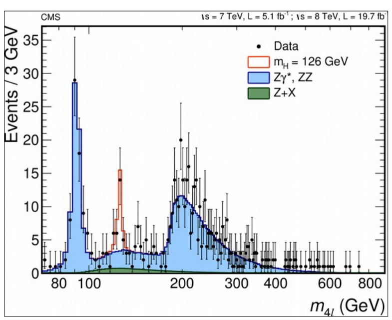
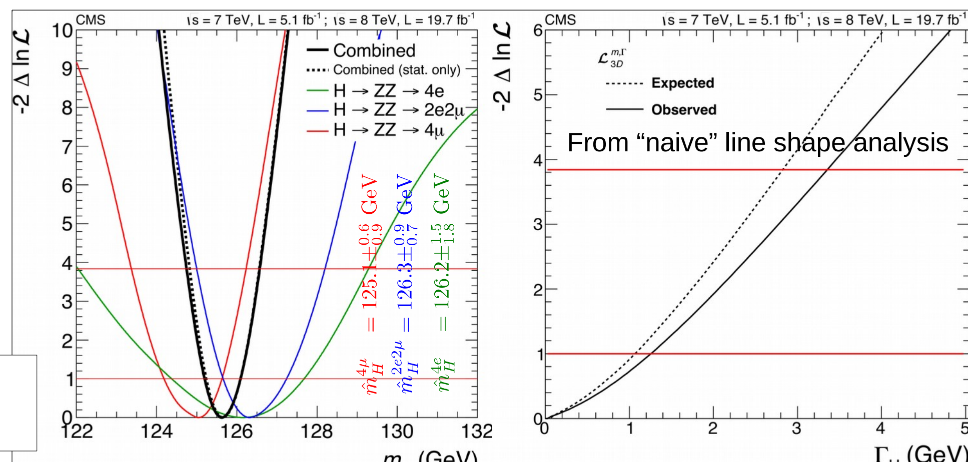


$$\hat{m}_H = 125.6 \pm^{0.5}_{0.4} \text{ (stat.)} \pm 0.1 \text{(syst.) GeV}$$

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



Mass & decay width (offshell)

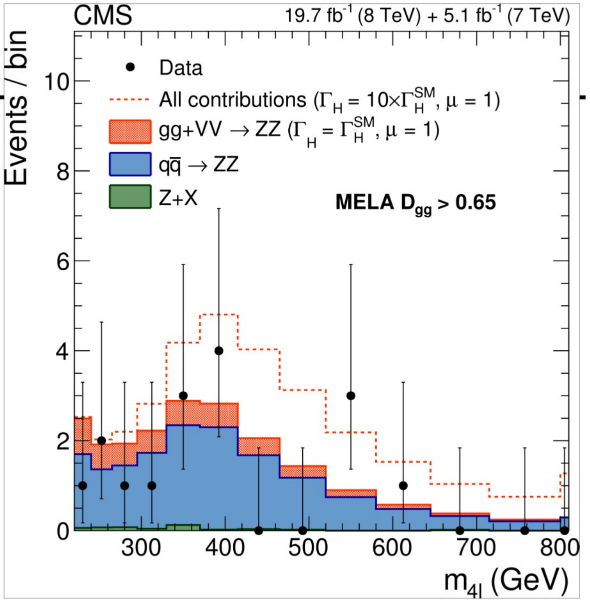
- Proposed by K. Melnikov, pioneered by CMS:

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

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

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

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



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

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

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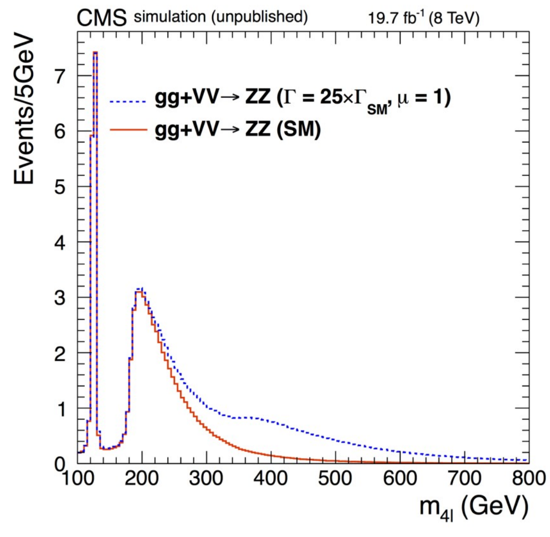
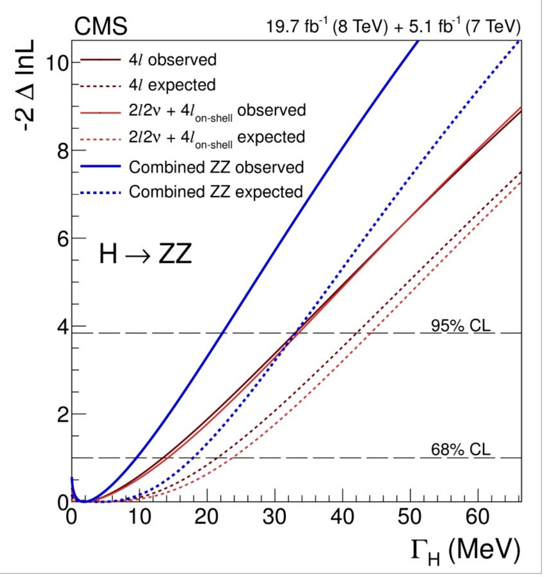
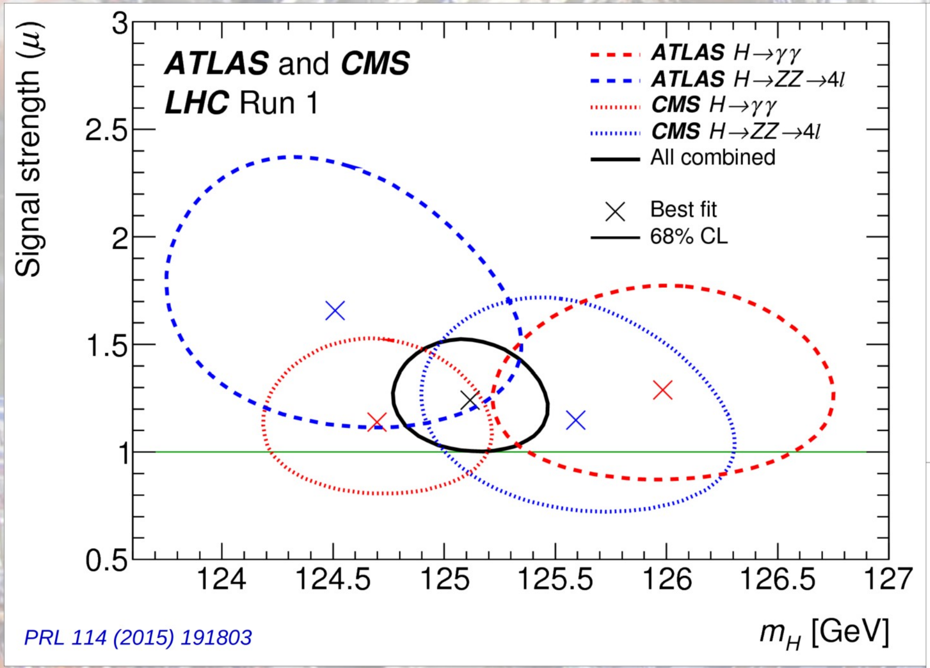


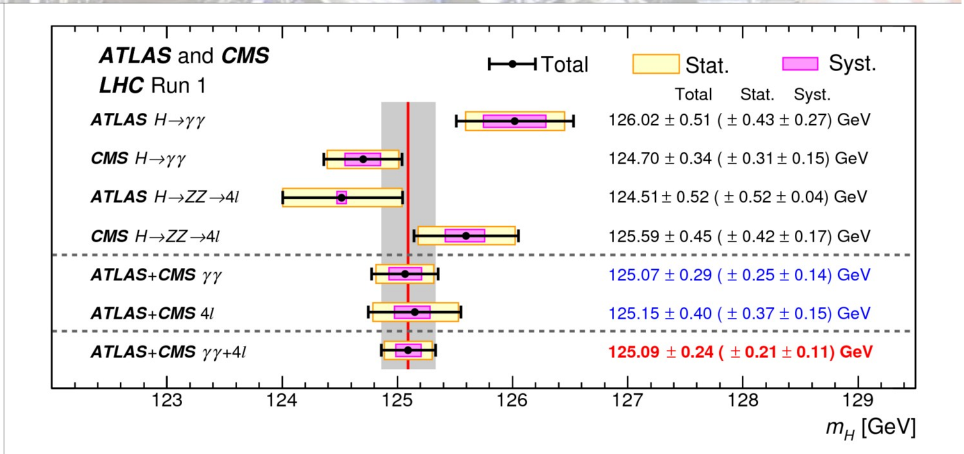


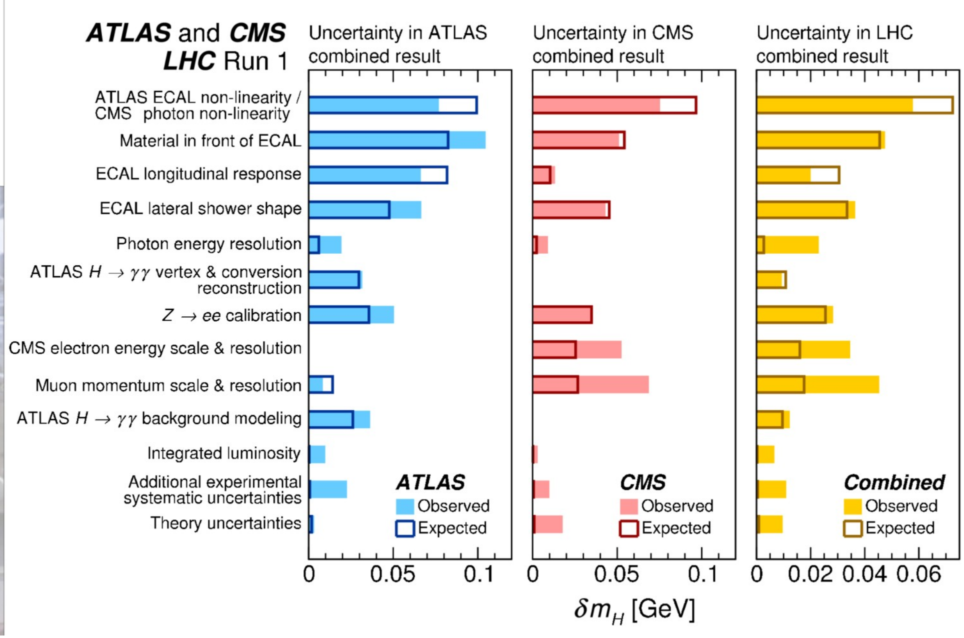
Priv. Doz. Dr. Roger Wolf
http://ekpwww.physik.uni-karlsruhe.de/~rwolf/

Mass

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







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

Coupling structure

- Event categories : 574
- Nuisance parameters: 4268

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

- ATLAS+CMS LHC run-1 combination:

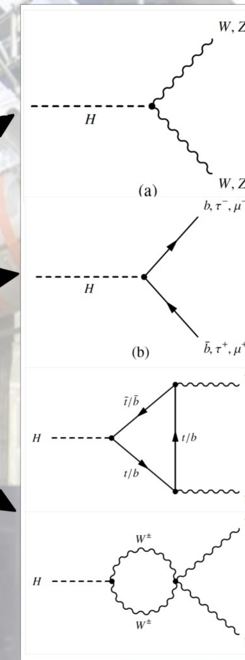
CMS-PAS-HIG-15-002

Considered production modes:

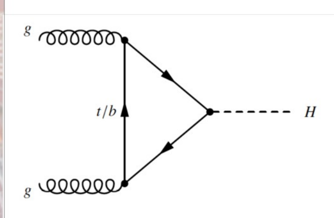
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	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	

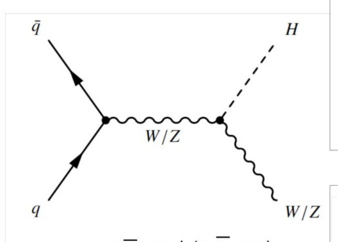
Considered decay channels:

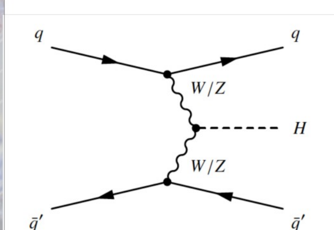
Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001



Main production modes:

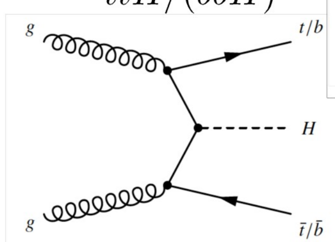




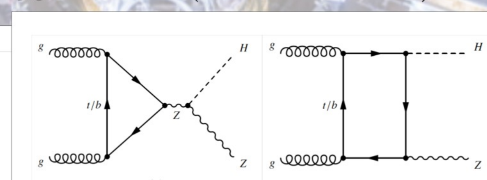


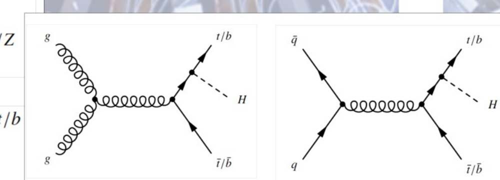
Amplitudes

$t\bar{t}H/(b\bar{b}H)$

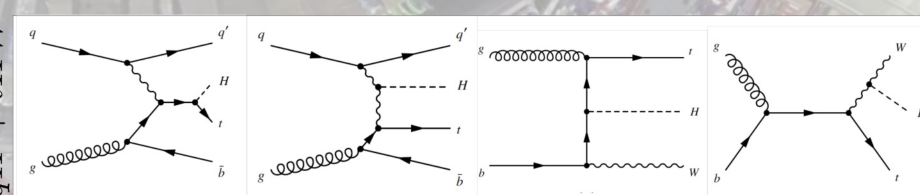


$gg \to ZH$ (10% to $ZHbb$)





$tqH + tHW$



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.

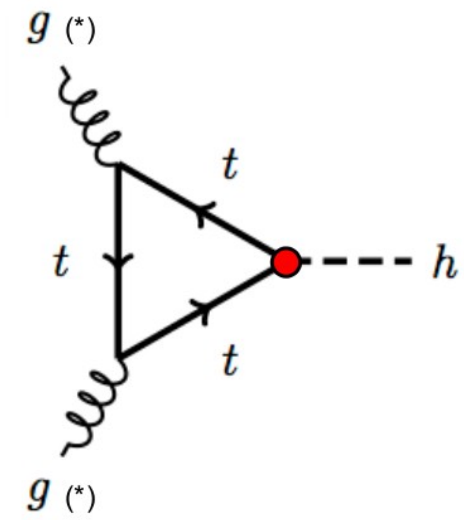
Production	Loops	Interference	Multiplicative factor	
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim$	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim$	$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim$	κ_W^2
$\sigma(qq/qg \to ZH)$	–	–	$\sim$	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 $\mathrm{BR}_{\mathrm{BSM}} = 0$				
Γ_H	✓	–	$\kappa_H^2 \sim$	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

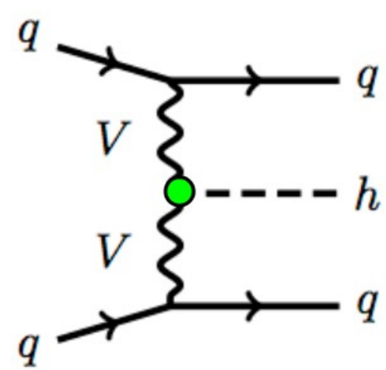
$\approx (1.26\kappa_W - 0.26\kappa_t)^2$

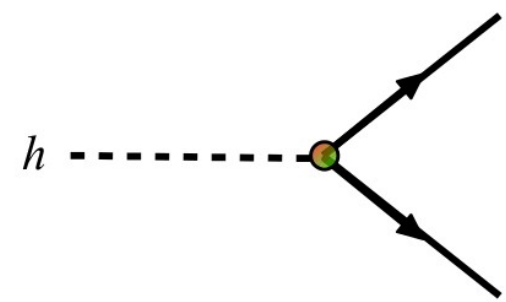
Non measurable couplings tied to measurable ones: $\kappa_c = \kappa_t$, $\kappa_\mu = \kappa_\tau$, $\kappa_s = \kappa_b$.

Coupling estimates

- Determine couplings from production mode & decay channel:







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

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

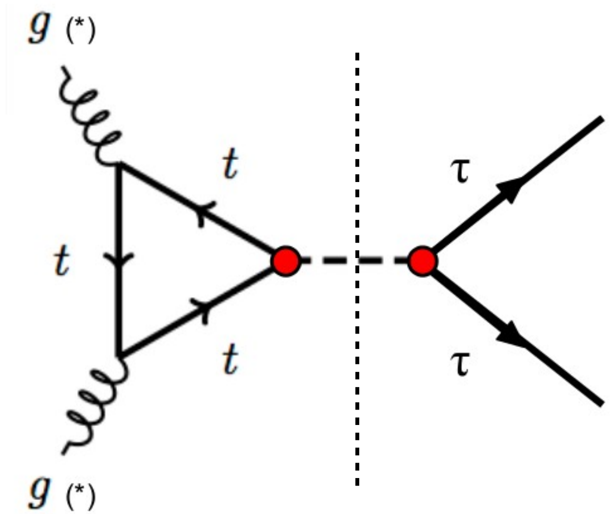
- Coupling to gluon can be f or effective (*).
- Coupling to γ can be effective or a mixture of $f + V$.

- Direct measurement not possible, since κ_i appear in nominator and denominator of BR:

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

Narrow width approximation

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

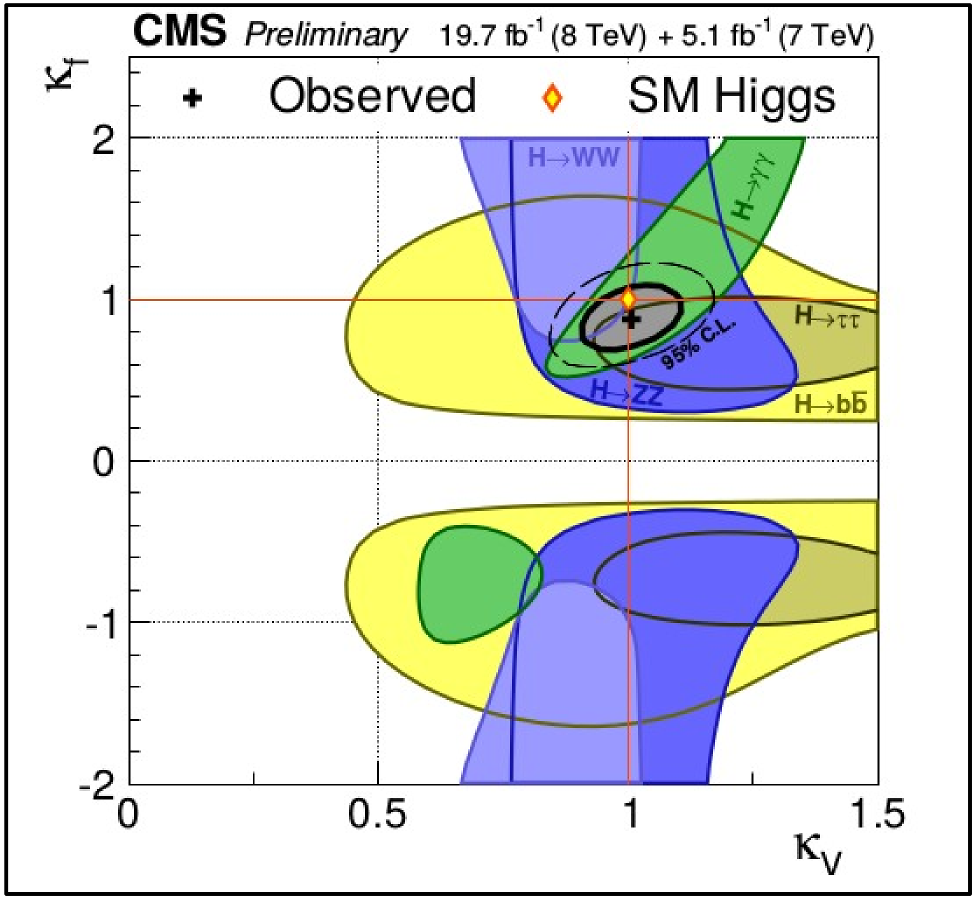


- i.e. put propagating particle on shell.
- Calculate cross section as $\sigma \times \mathrm{BR}$.
- $\mathrm{BR}_X = \frac{\Gamma_X}{\Gamma_H}$, $\Gamma_H = \sum_i \Gamma_i$.
- Example to the left:

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

- For each production mode and decay channel collect κ_i and express Γ_H as sum of individual κ_i .

Example: vector boson vs. fermion coupling



- Cross section $H \rightarrow VV$:

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

$$gg \rightarrow H \qquad qq \rightarrow qqH$$

- Cross section $H \rightarrow ff$:

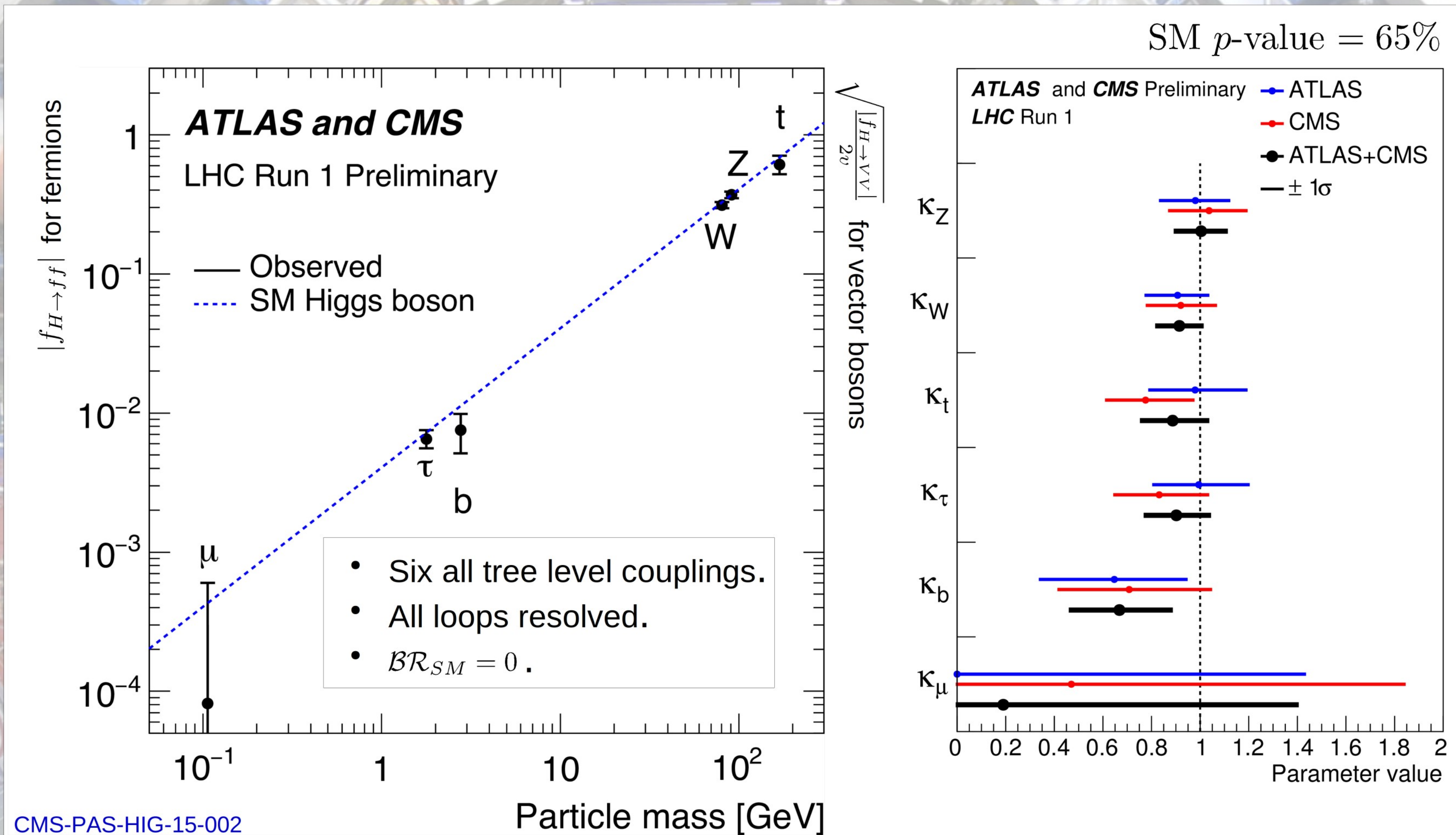
$$\sigma \propto (\kappa_f \kappa_f)^2 + (\kappa_V \kappa_f)^2$$

- 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”



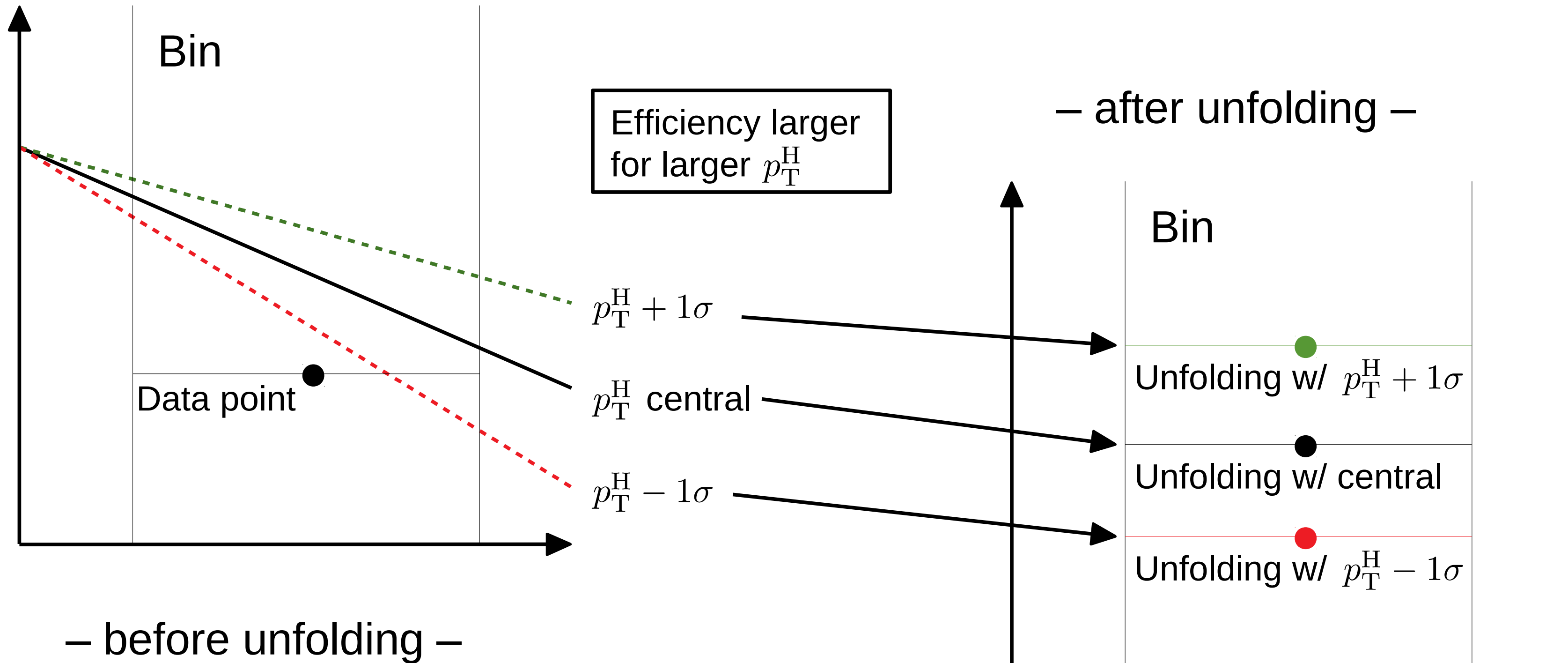
$$|f^{\rm obs}_{H\to ff}| = \kappa_f \cdot |f^{\rm SM}_{H\to ff}| = \kappa_f \cdot \frac{m_f}{v} \qquad f = \mu, \tau, b, t$$

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

Within measurement accuracy unique scaling as expected within the SM.

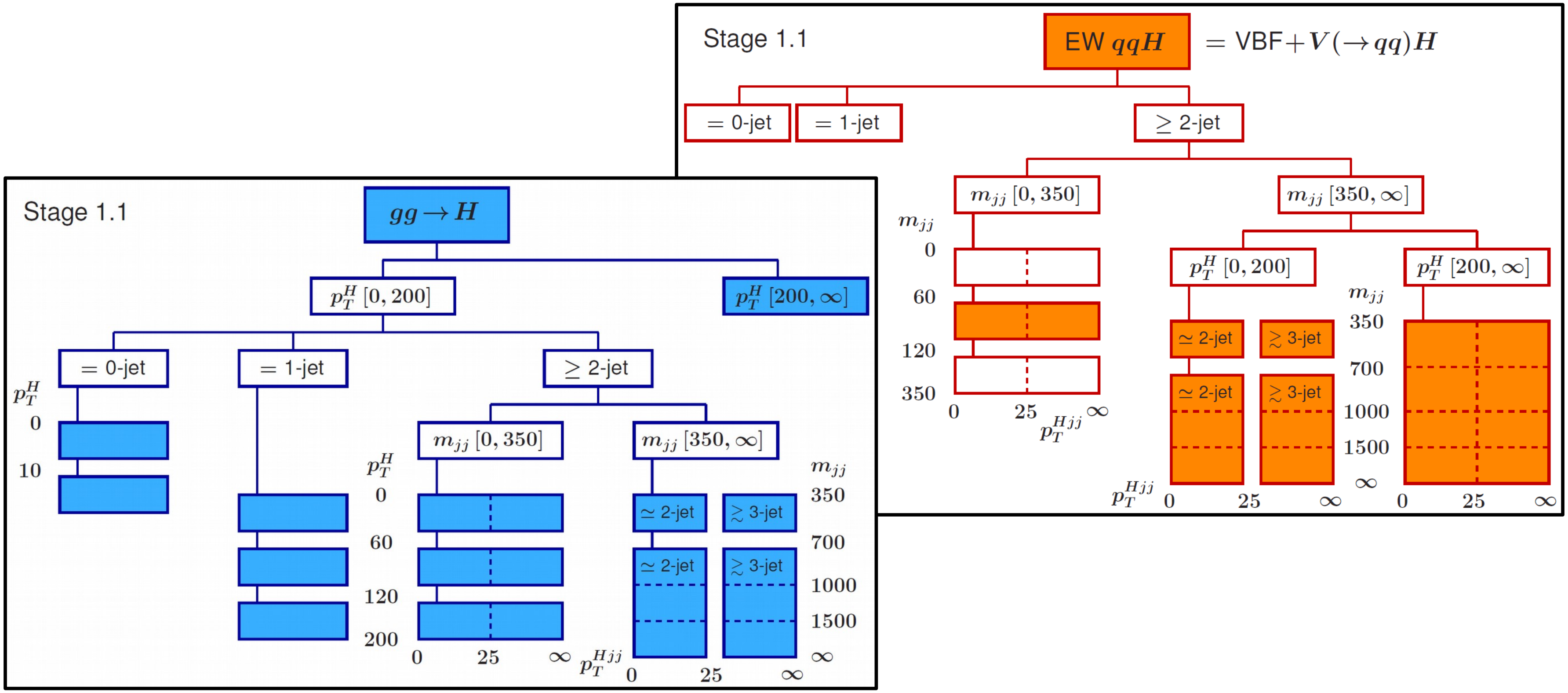
Simplified template cross section (STXS)

- 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 $p_{\mathrm{T}}^{\mathrm{H}}$ or N_{Jet}) on measurement.



Simplified template cross section (STXS)

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



Template vs. fiducial cross section

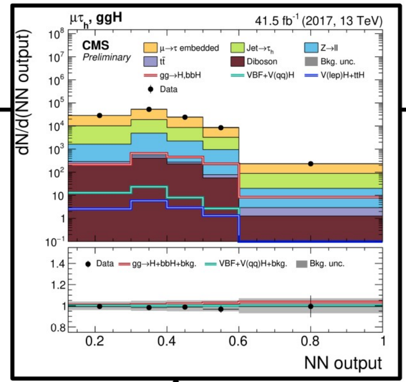
Simplified template cross section (STXS):

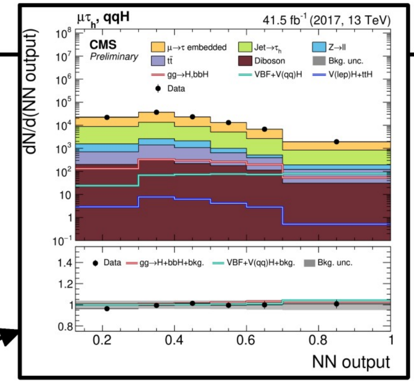
- E.g. Higgs production in VBF & gluon fusion.

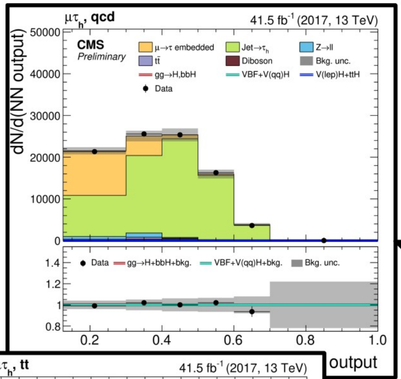
Fiducial cross section:

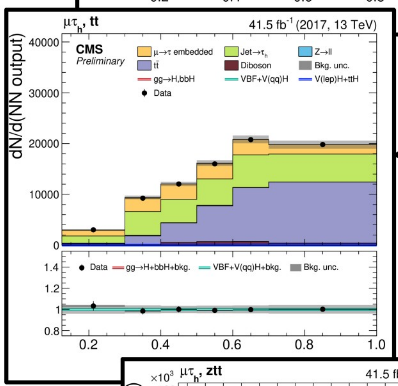
- Obey detector acceptance and stick to measurable quantities.
- E.g. Higgs production in association w/ two jets w/ $m_{\mathrm{jj}} > 350\ \mathrm{GeV}$.

Event classification



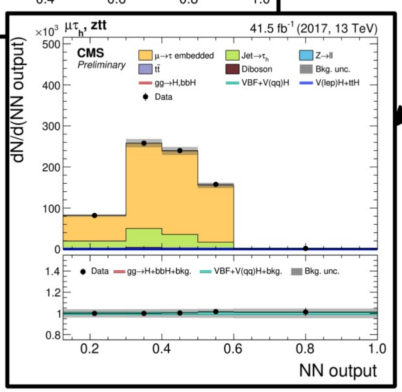






Modern multi-class NN

Event in data



...

CMS-PAS-HIG-18-032

Check ETP-KA/2017-26 for more details.

- Trained to differentiate btw. all signal & background processes.
- Output → tuple of scores (~Bayesian probabilities) for data event to belong to a given process.
- Highest score defines the event category that the event is associated to.

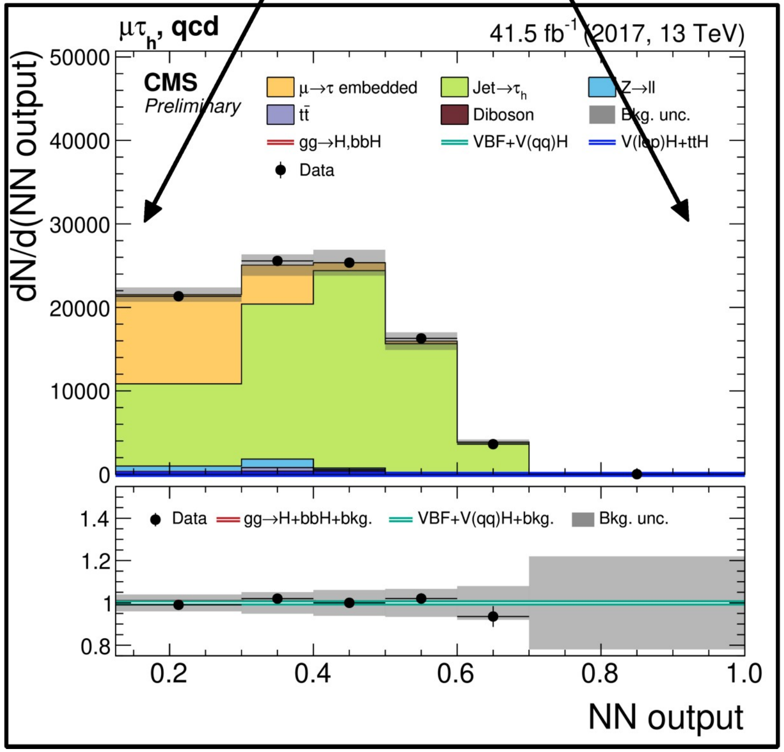
Signal extraction

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

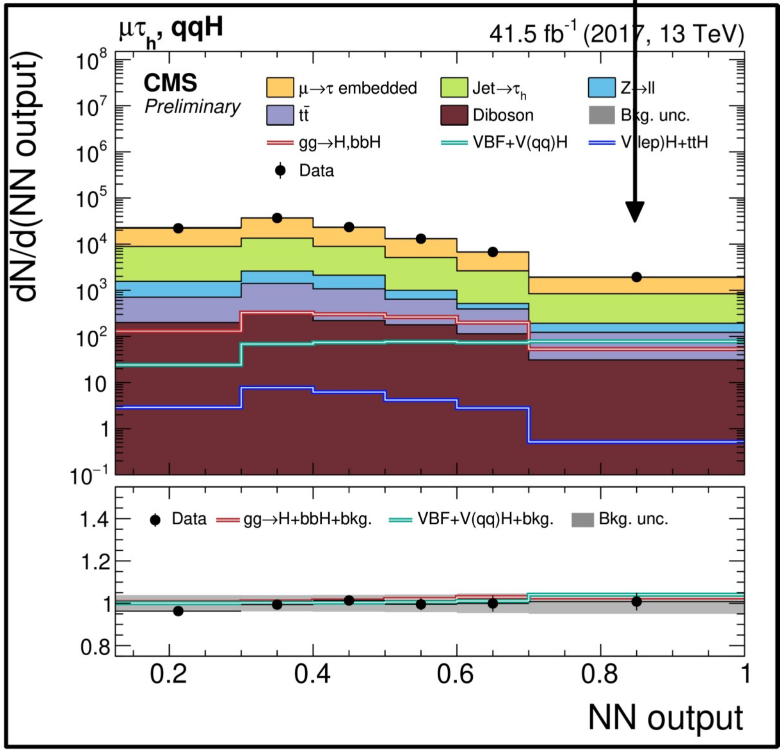
Within plot transition btw. *ambiguous* & *clear* signature

Find most-signal like events here

qcd



qqH



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NN inputs

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

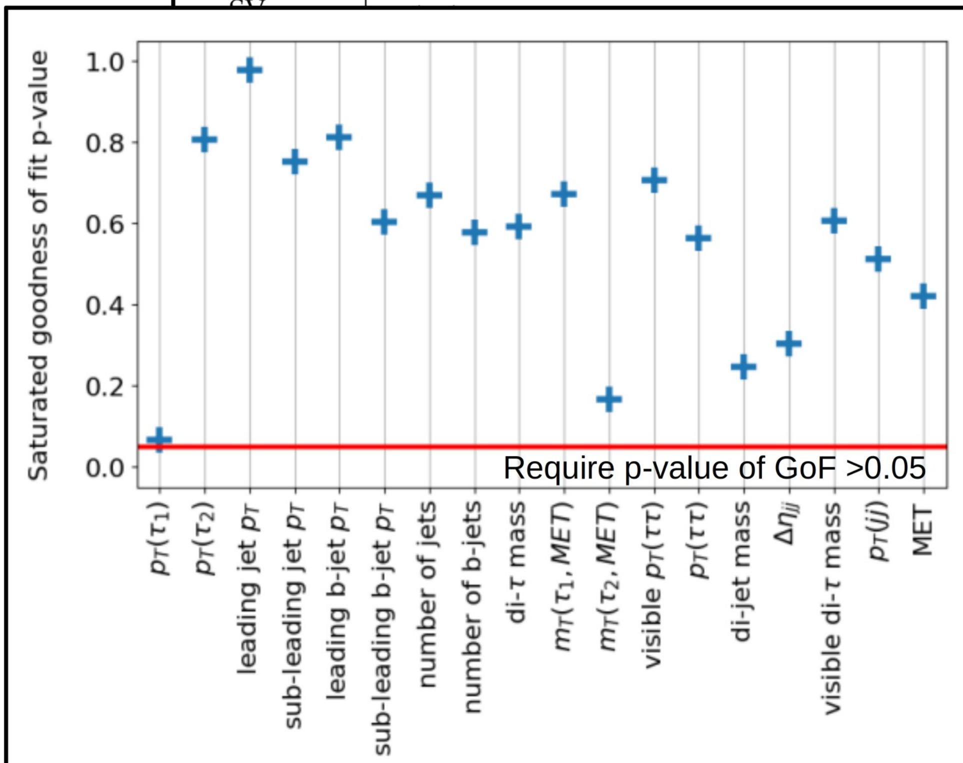
Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$m_{\tau\tau}^{SV}$	✓✓	✓✓	✓✓	✓✓	p_T^{jj}	✓✓	✓✓	✓✓	✓✓
$m_{T\tau\tau}^{SV}$	✓✓	——	——	——	$p_T(\text{b jet}_1)$	——	✓✓	✓✓	✓✓
$p_{T\tau\tau}^{SV}$	✓✓	——	——	——	$p_T(\text{b jet}_2)$	——	✓✓	✓✓	✓✓
m_{vis}	✓—	✓—	✓—	✓✓	p_T^{miss}	—✓	✓✓	✓—	✓—
p_T^{vis}	✓✓	✓✓	✓—	✓—	D_ζ	✓✓	——	——	——
$p_T^{\tau_1}$	——	——	✓—	✓✓	m_T^{e}	——	✓✓	——	——
$p_T^{\tau_2}$	✓—	✓✓	✓✓	✓—	m_T^{μ}	✓✓	——	✓✓	——
$\Delta R^{e\mu}$	✓✓	——	——	——	$m_T^{e+\mu}$	✓—	——	——	——
$p_T(\text{jet}_1)$	✓✓	✓✓	✓✓	✓—	$\max(m_T^{\mu}, m_T^{e})$	✓✓	——	——	——
$\eta\ (\text{jet}_1)$	✓—	——	——	——	$m_T^{\tau_h}$	——	✓✓	✓—	✓✓
$p_T(\text{jet}_2)$	✓✓	✓✓	✓✓	✓✓	$p_T^{\tau\tau+\text{miss}}$	✓✓	✓✓	✓✓	✓✓
$\eta\ (\text{jet}_2)$	✓—	——	——	——	$p_T^{\tau\tau jj+\text{miss}}$	—✓	——	——	——
m_{jj}	✓✓	✓✓	✓✓	✓✓	$N_{\text{b jet}}$	——	✓✓	✓✓	✓✓
$\Delta\eta_{jj}$	✓✓	✓✓	✓✓	✓✓	N_{jet}	✓✓	✓✓	✓✓	—✓
					Variables in use:	21(19)	18(13)	17(16)	16(12)

NN inputs

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

Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$m_{\tau\tau}^{SV}$	✓✓	✓✓	✓✓	✓✓

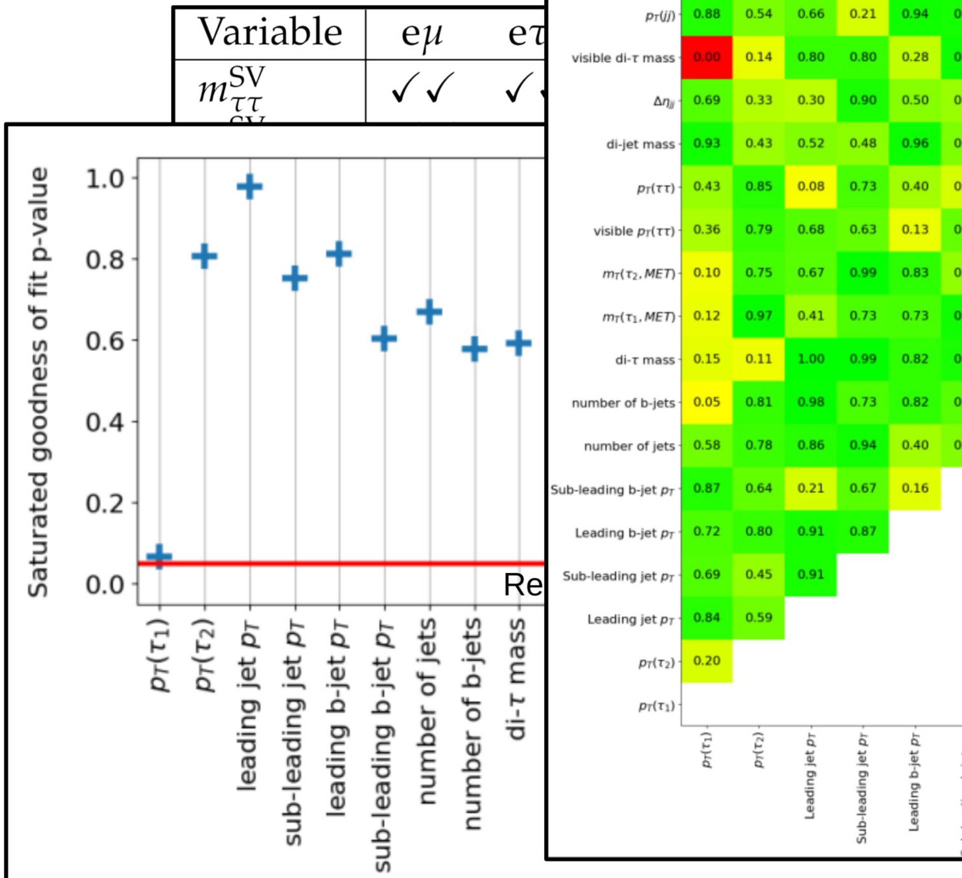
Variable	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
p_T^{jj}	✓✓	✓✓	✓✓	✓✓
$p_T(\text{b jet}_1)$	−−	✓✓	✓✓	✓✓
$p_T(\text{b jet}_2)$	−−	✓✓	✓✓	✓✓
p_T^{miss}	−✓	✓✓	✓−	✓−
D_ζ	✓✓	−−	−−	−−
m_T^e	−−	✓✓	−−	−−
m_T^μ	✓✓	−−	✓✓	−−
$m_T^{e+\mu}$	✓−	−−	−−	−−
$\max(m_T^\mu, m_T^e)$	✓✓	−−	−−	−−
$m_T^{\tau_h}$	−−	✓✓	✓−	✓✓
$p_T^{\tau\tau+miss}$	✓✓	✓✓	✓✓	✓✓
$p_T^{\tau\tau jj+miss}$	−✓	−−	−−	−−
$N_{\text{b jet}}$	−−	✓✓	✓✓	✓✓
N_{jet}	✓✓	✓✓	✓✓	−✓
Variables in use:	21(19)	18(13)	17(16)	16(12)

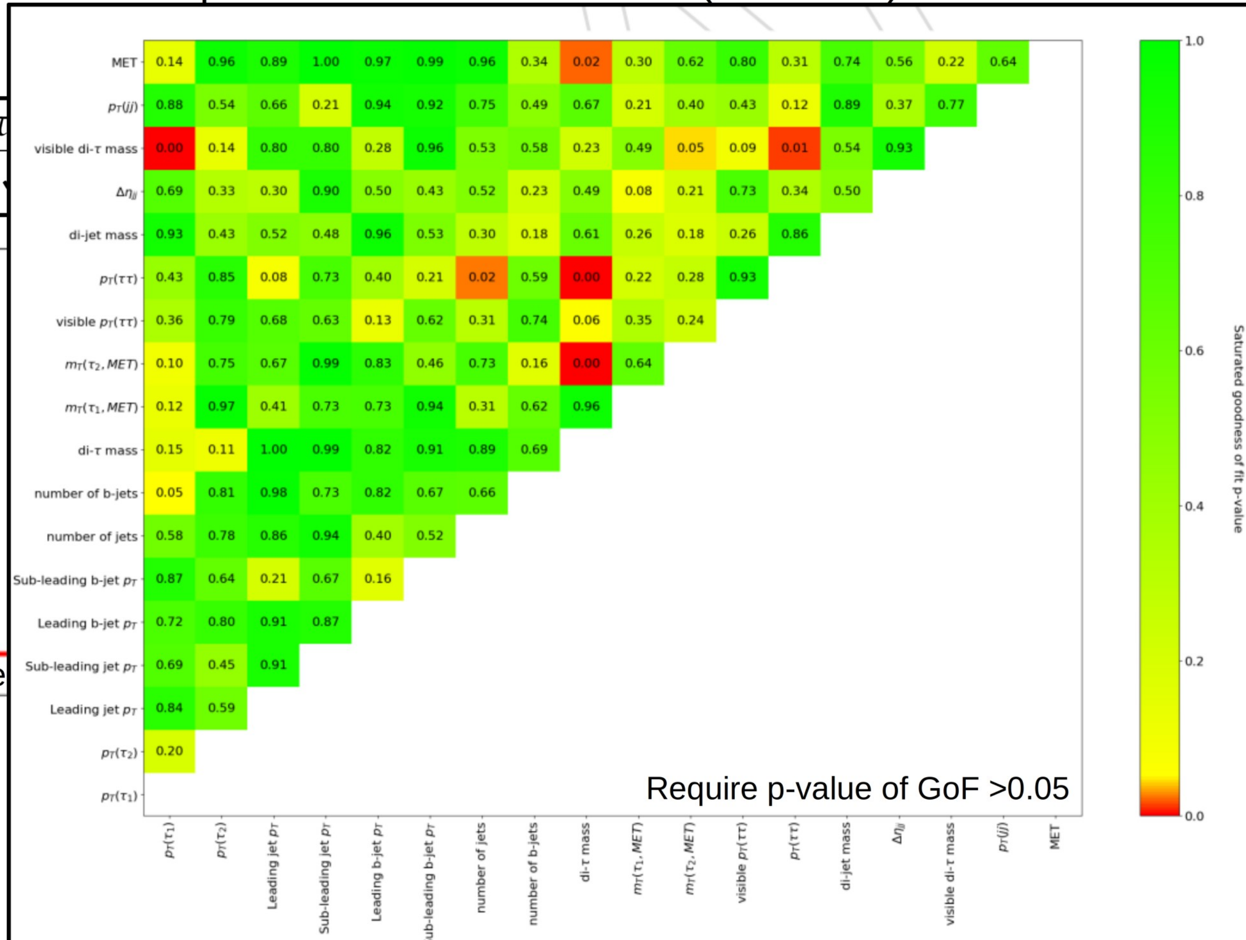


Making sure that input variables are well described by our model exploiting goodness-of-fit (GoF) test in 1d…

NN inputs

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

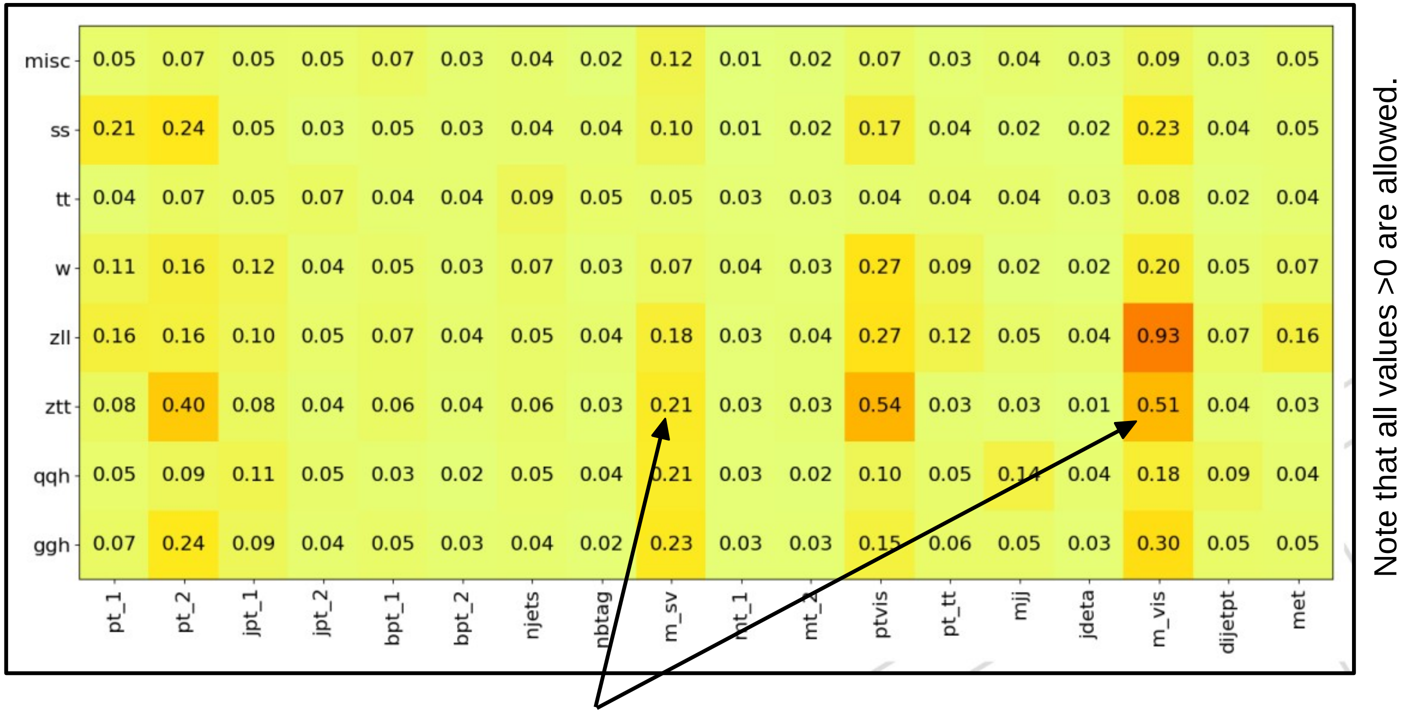




Making sure that input variables are well described by our model exploiting goodness-of-fit (GoF) test in 1d… & 2d.

“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.



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

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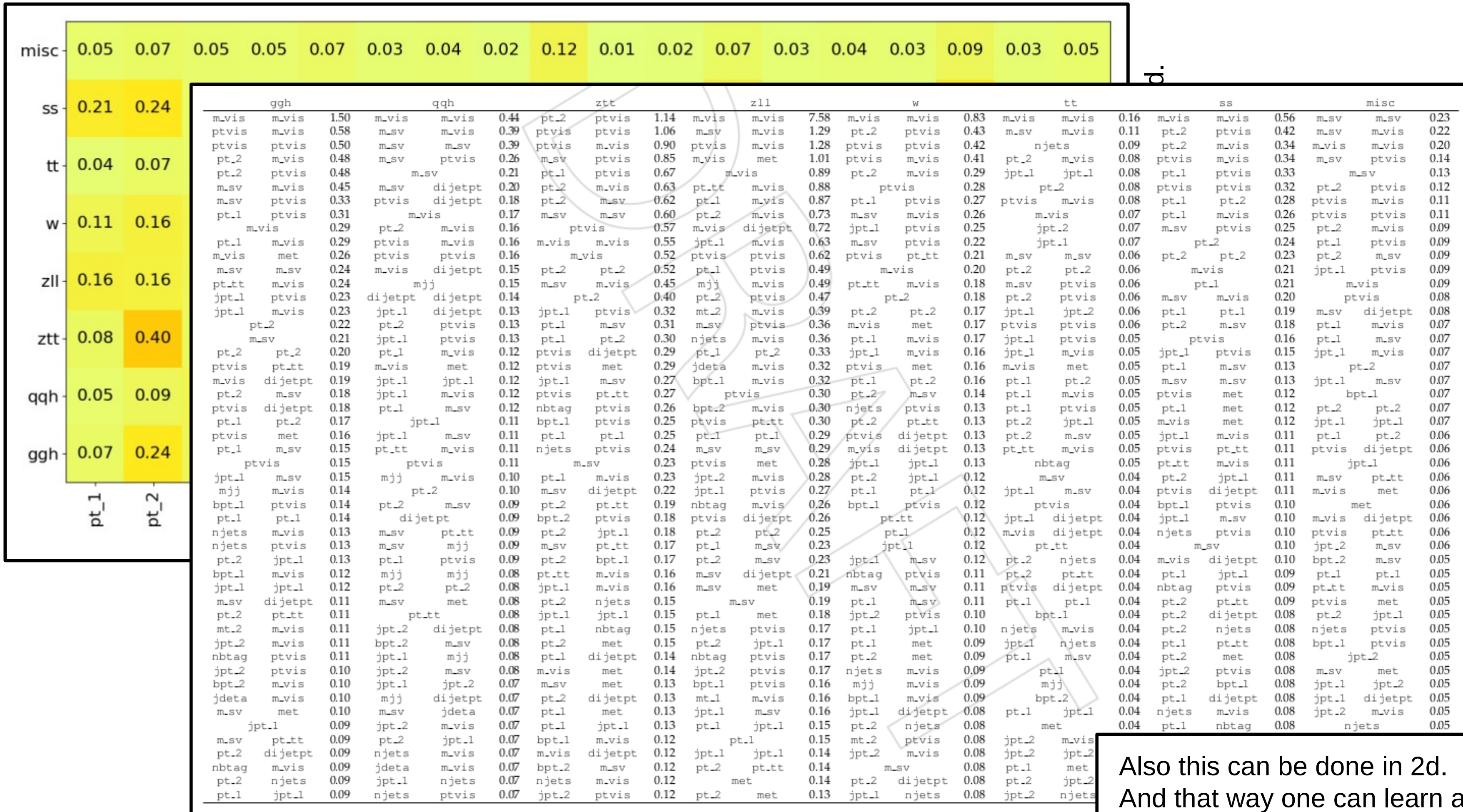
"Unboxing" the NN

- 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.

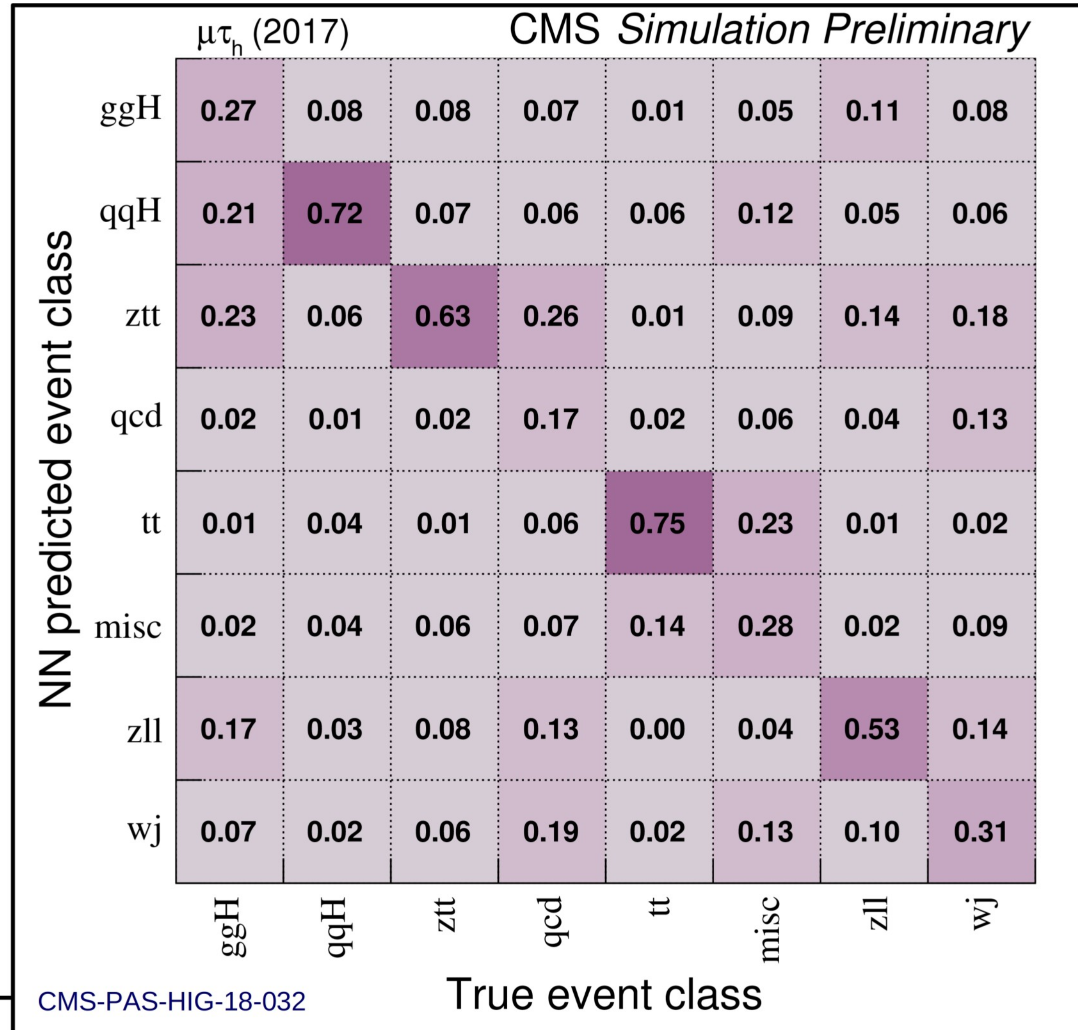


Also this can be done in 2d. And that way one can learn a lot about the NN task and how it is solved.

How well can the NN do?

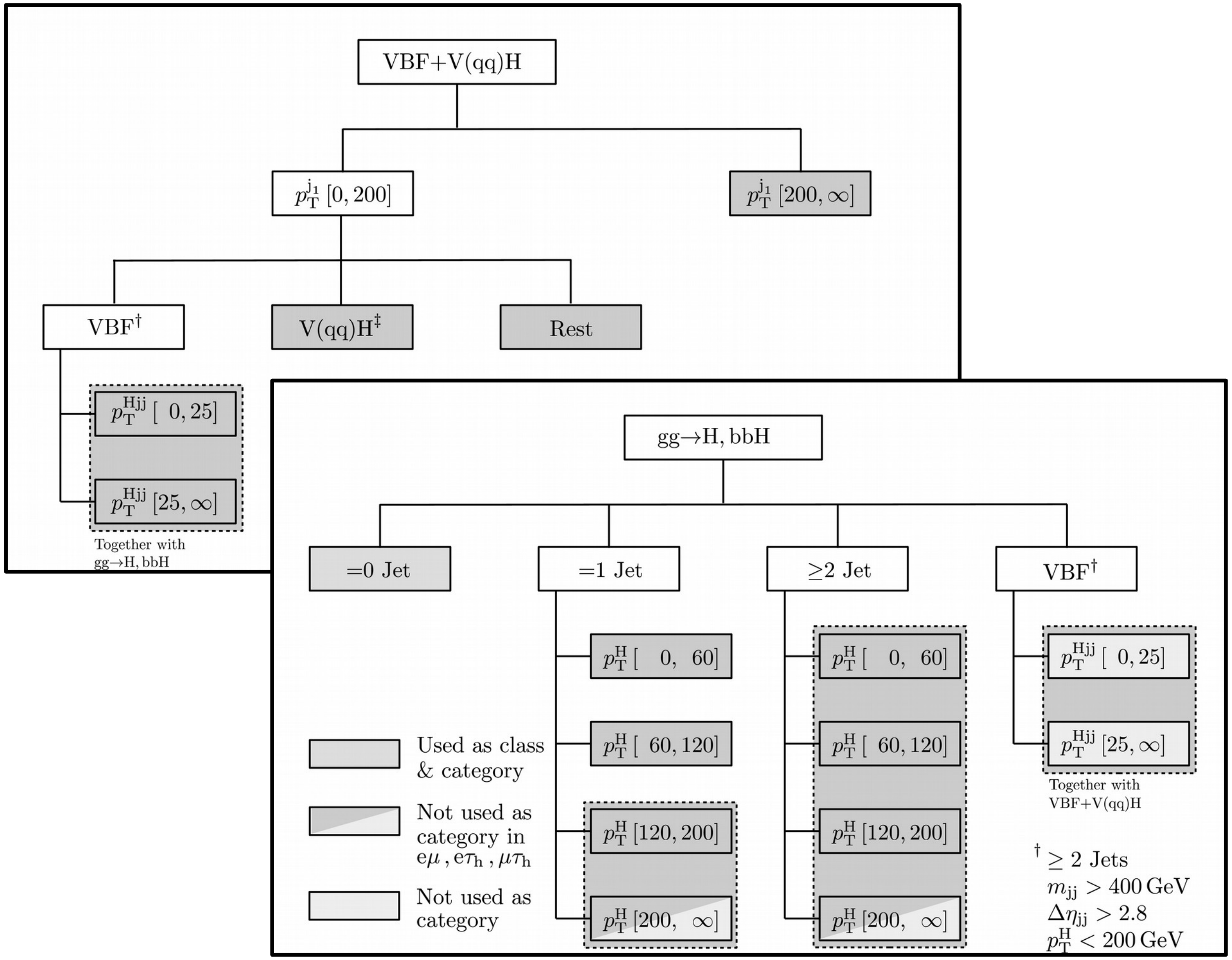
- Confusion matrix tells how well the NN can identify each individual process:

- 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%).



STXS classification

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



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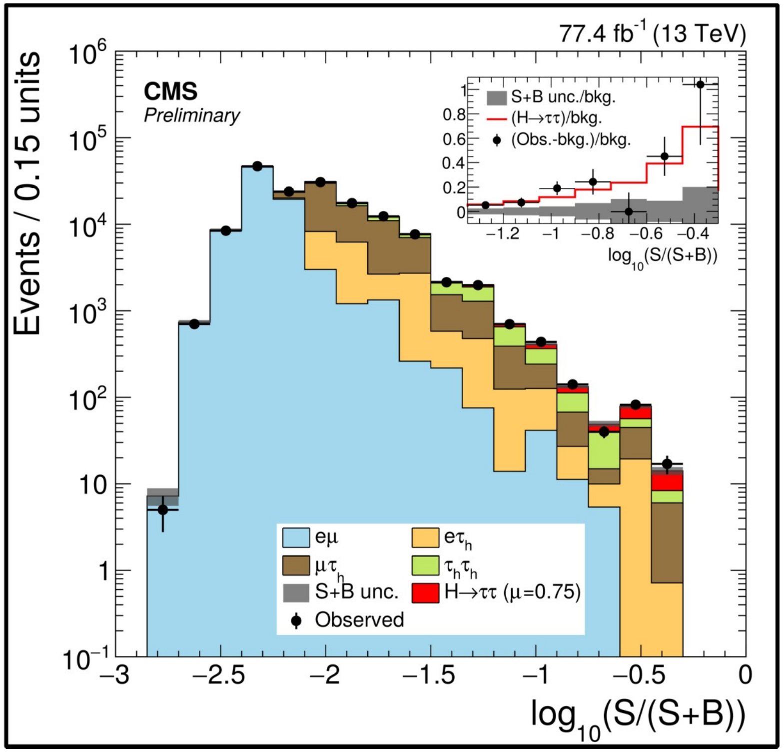
Results (inclusive)

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



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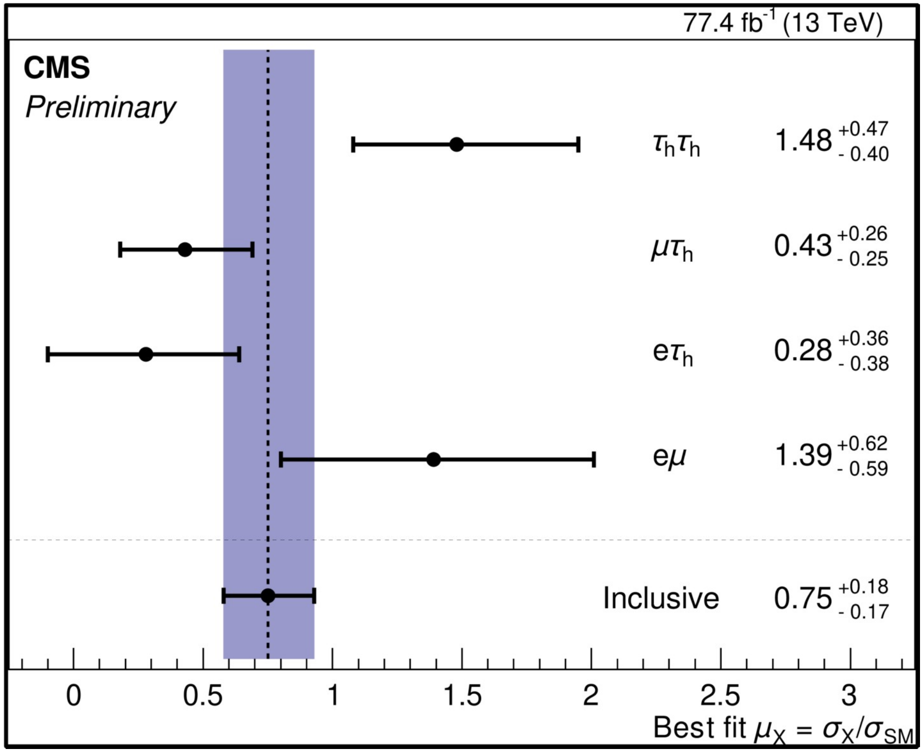
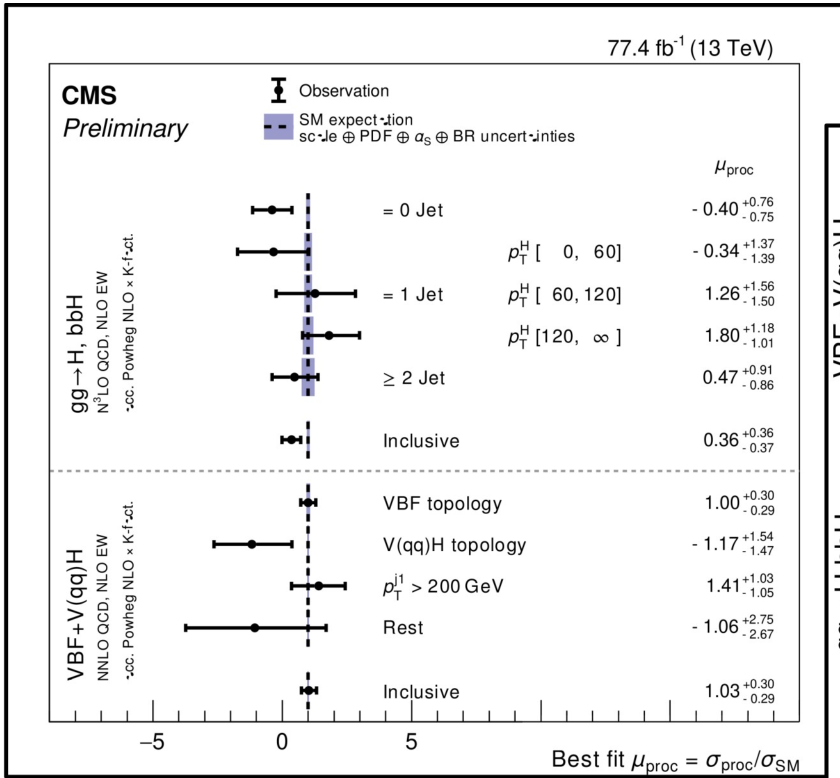
Signal strength: (top) split by final state and (bottom) inclusive



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

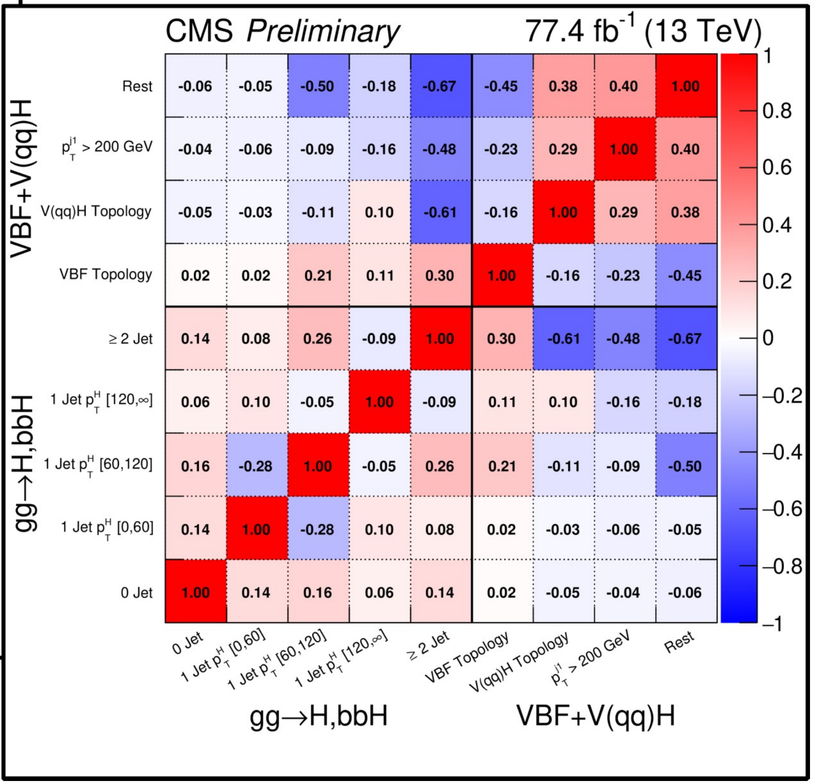
Results (STXS)

- More differential measurement in 9 predefined STXS bins:



STXS bins

CMS-PAS-HIG-18-032



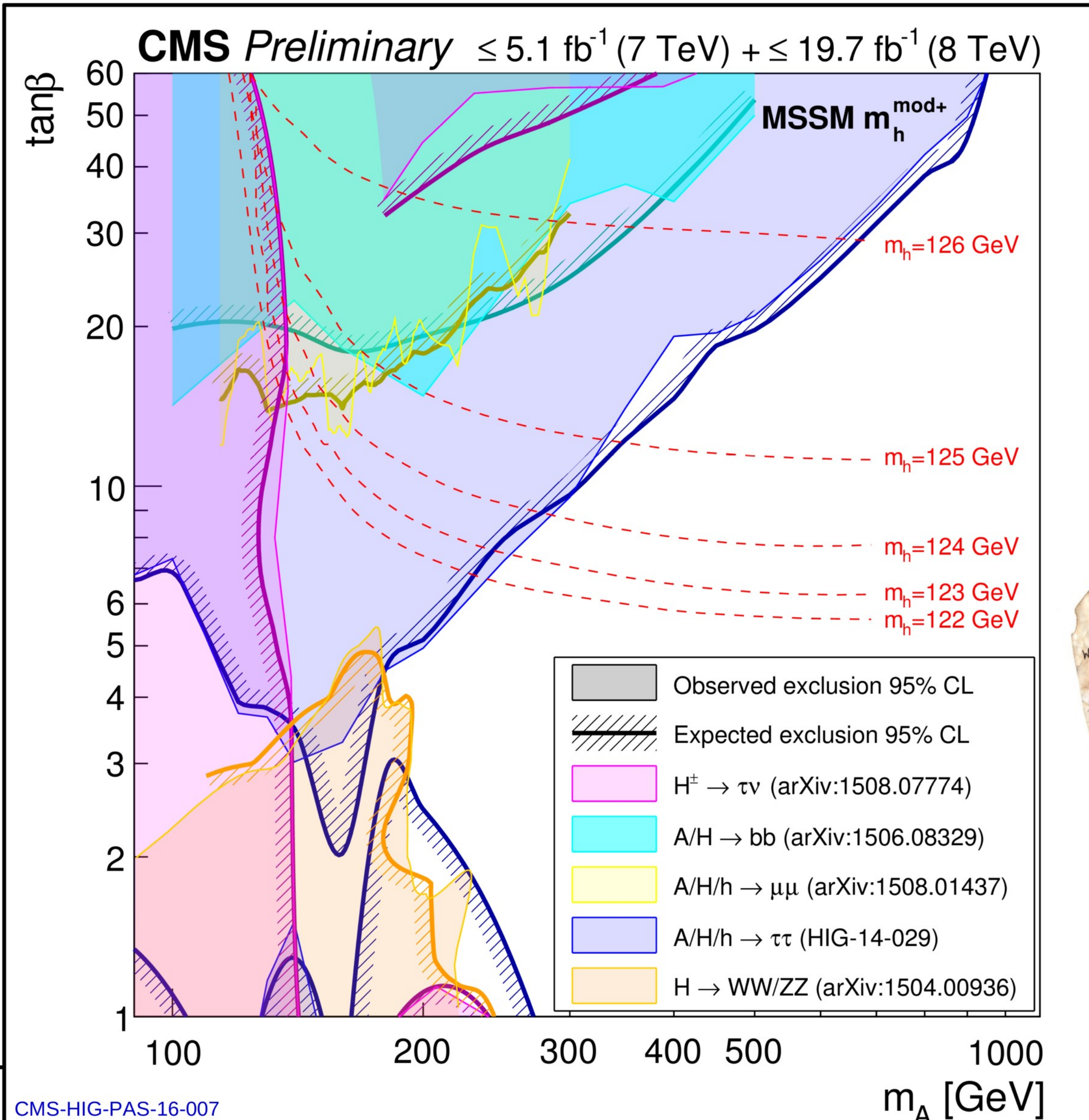
	0 Jet	1 Jet p_T^H [0,60]	1 Jet p_T^H [60,120]	1 Jet p_T^H [120,∞]	≥ 2 Jet	VBF Topology	V(qq)H Topology	p_T^{j1} > 200 GeV	Rest
Rest	-0.06	-0.05	-0.50	-0.18	-0.67	-0.45	0.38	0.40	1.00
p_T^{j1} > 200 GeV	-0.04	-0.06	-0.09	-0.16	-0.48	-0.23	0.29	1.00	0.40
V(qq)H Topology	-0.05	-0.03	-0.11	0.10	-0.61	-0.16	1.00	0.29	0.38
VBF Topology	0.02	0.02	0.21	0.11	0.30	1.00	-0.16	-0.23	-0.45
≥ 2 Jet	0.14	0.08	0.26	-0.09	1.00	0.30	-0.61	-0.48	-0.67
1 Jet p_T^H [120,∞]	0.06	0.10	-0.05	1.00	-0.09	0.11	0.10	-0.16	-0.18
1 Jet p_T^H [60,120]	0.16	-0.28	1.00	-0.05	0.26	0.21	-0.11	-0.09	-0.50
1 Jet p_T^H [0,60]	0.14	1.00	-0.28	0.10	0.08	0.02	-0.03	-0.06	-0.05
0 Jet	1.00	0.14	0.16	0.06	0.14	0.02	-0.05	-0.04	-0.06

Correlation matrix

Summary

- 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“



CMS-HIG-PAS-16-007

Mary Rose (Flagschiff der englischen Marine 1511 – 1545)