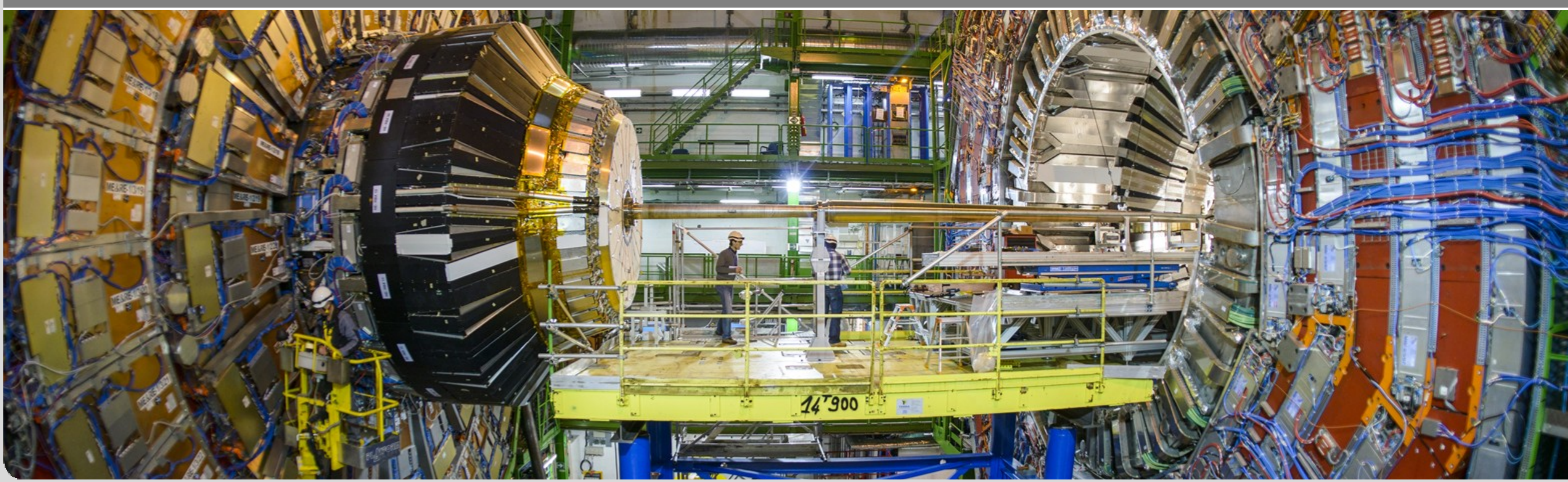
Karlsruhe Institute of Technology

LHC Searches for the Higgs Bosons and potential Higgs Singlet Extensions of the SM

Roger Wolf

10. December 2015

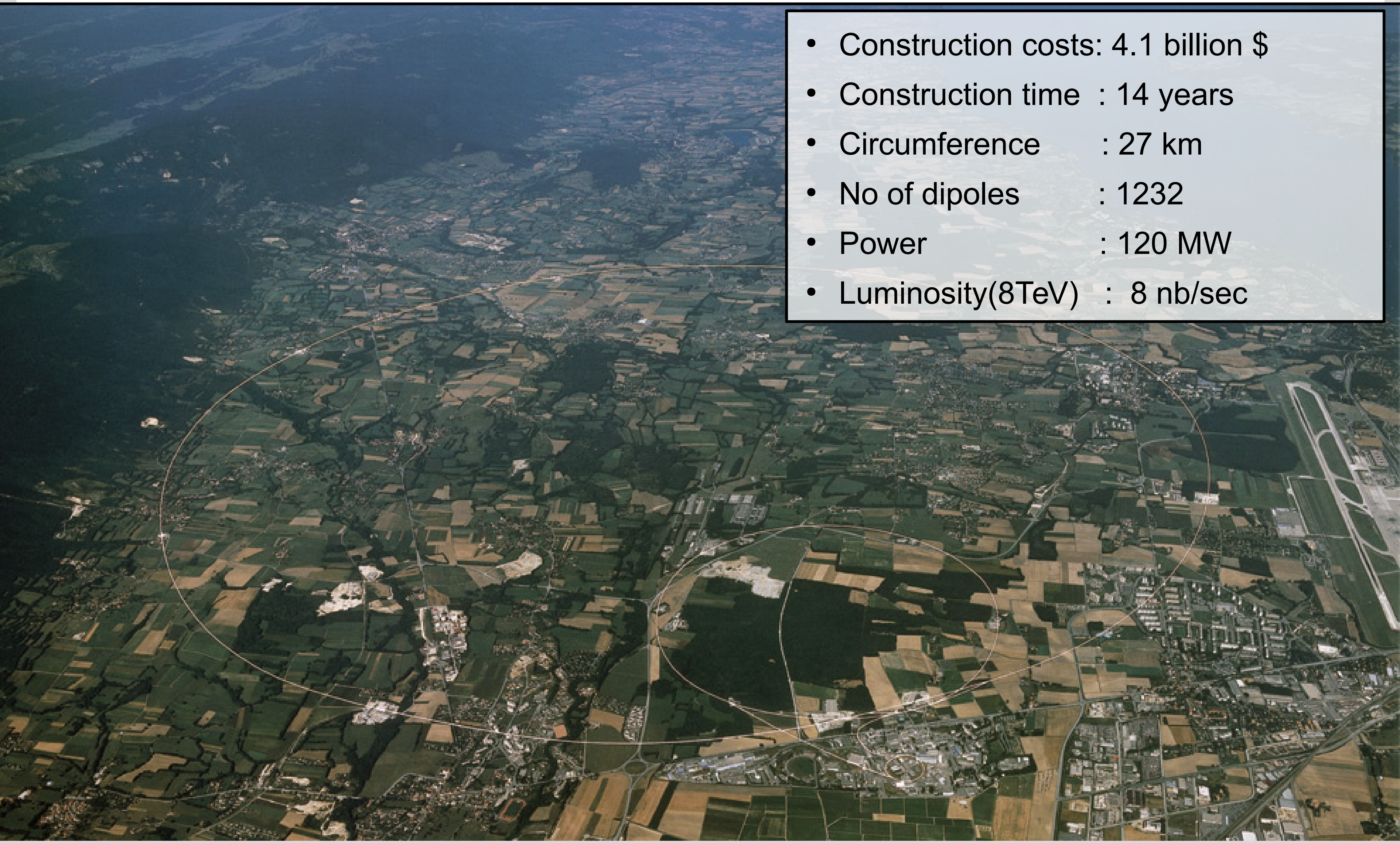
INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



The Large Hadron Collider

Karlsruhe Institute of Technology

- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb/sec



The Large Hadron Collider

Energy radiated off per rotation cycle:

$$P = \frac{e^2}{6\pi\epsilon_0 c}|\vec{\beta}|^2\gamma^4 = \frac{e^2 c}{6\pi\epsilon_0\rho^2}\gamma^4 = \frac{e^4}{6\pi\epsilon_0\rho^2}\frac{E^2B^2}{m^4}$$

$$P(p|_{m_p=1\ \mathrm{GeV}}) = 280\ \mu\mathrm{W}$$

$$P(e|_{m_e=0.511\ \mathrm{MeV}}) = 450\ \mathrm{kW}$$

- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb/sec

The Large Hadron Collider

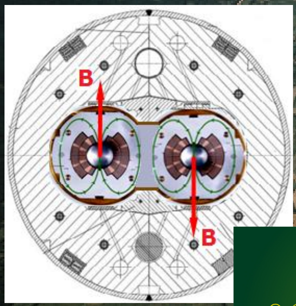
Energy radiated off per rotation cycle:

$$P = \frac{e^2}{6\pi\epsilon_0 c}|\vec{\beta}|^2\gamma^4 = \frac{e^2 c}{6\pi\epsilon_0\rho^2}\gamma^4 = \frac{e^4}{6\pi\epsilon_0\rho^2}\frac{E^2B^2}{m^4}$$

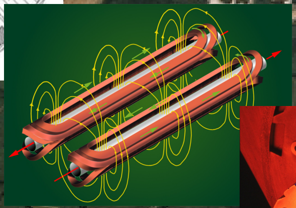
$$P(p|_{m_p=1\ \mathrm{GeV}}) = 280\ \mu\mathrm{W}$$

$$P(e|_{m_e=0.511\ \mathrm{MeV}}) = 450\ \mathrm{kW}$$

- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb/sec



- 8.3 T
- 11.8 kA
- 160 cyc



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

The Large Hadron Collider

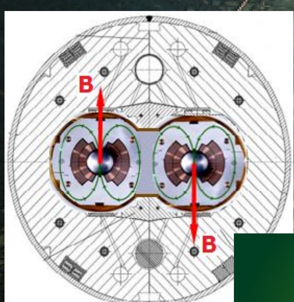
Energy radiated off per rotation cycle:

$$P = \frac{e^2}{6\pi\epsilon_0 c}|\vec{\beta}|^2\gamma^4 = \frac{e^2 c}{6\pi\epsilon_0\rho^2}\gamma^4 = \frac{e^4}{6\pi\epsilon_0\rho^2}\frac{E^2B^2}{m^4}$$

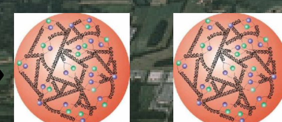
$$P(p|_{m_p=1\ \mathrm{GeV}}) = 280\ \mu\mathrm{W}$$

$$P(e|_{m_e=0.511\ \mathrm{MeV}}) = 450\ \mathrm{kW}$$

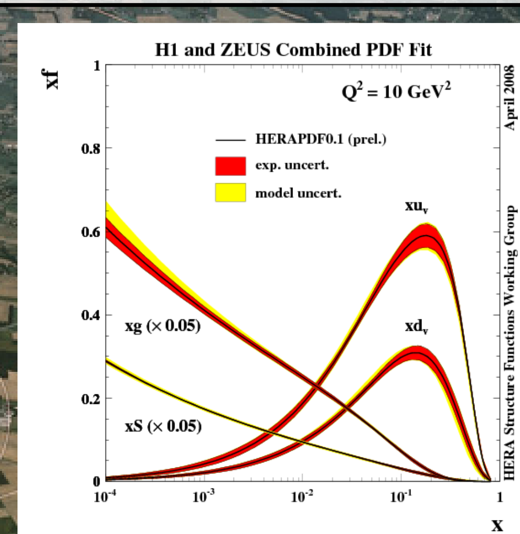
- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb/sec



- 8.3 T
- 11.8 kA
- 160 cyc



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



The Large Hadron Collider

Karlsruhe Institute of Technology

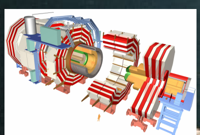
Energy radiated off per rotation cycle:

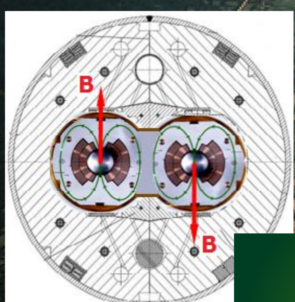
$$P = \frac{e^2}{6\pi\epsilon_0 c}|\vec{\beta}|^2\gamma^4 = \frac{e^2 c}{6\pi\epsilon_0\rho^2}\gamma^4 = \frac{e^4}{6\pi\epsilon_0\rho^2}\frac{E^2B^2}{m^4}$$

$$P(p|_{m_p=1\ \mathrm{GeV}}) = 280\ \mu\mathrm{W}$$

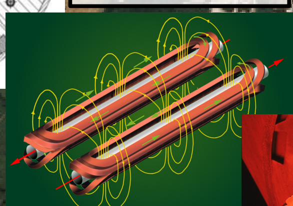
$$P(e|_{m_e=0.511\ \mathrm{MeV}}) = 450\ \mathrm{kW}$$

- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb/sec

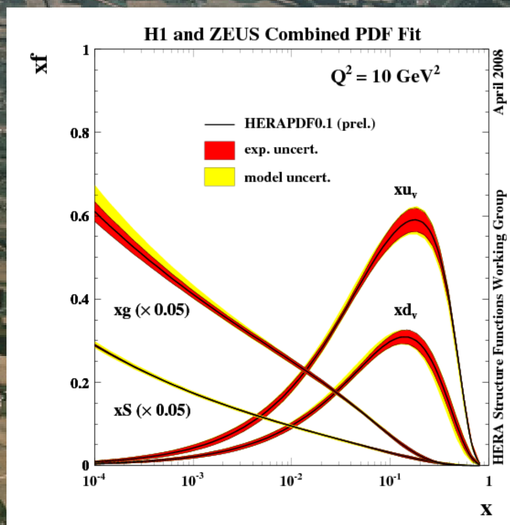


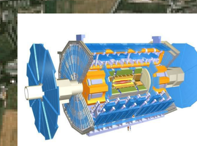


- 8.3 T
- 11.8 kA
- 160 cyc

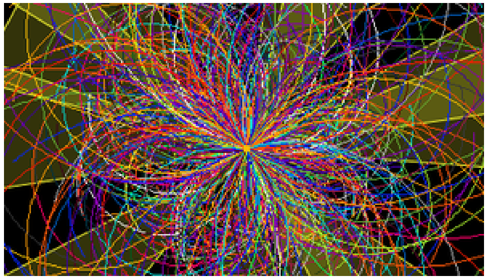


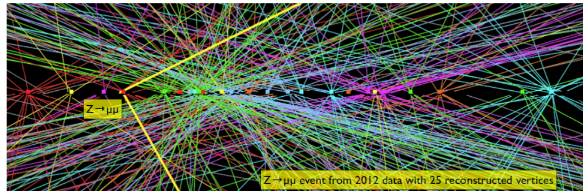
- Energy density 500 kJ/m
- Tension 200'000 t/m



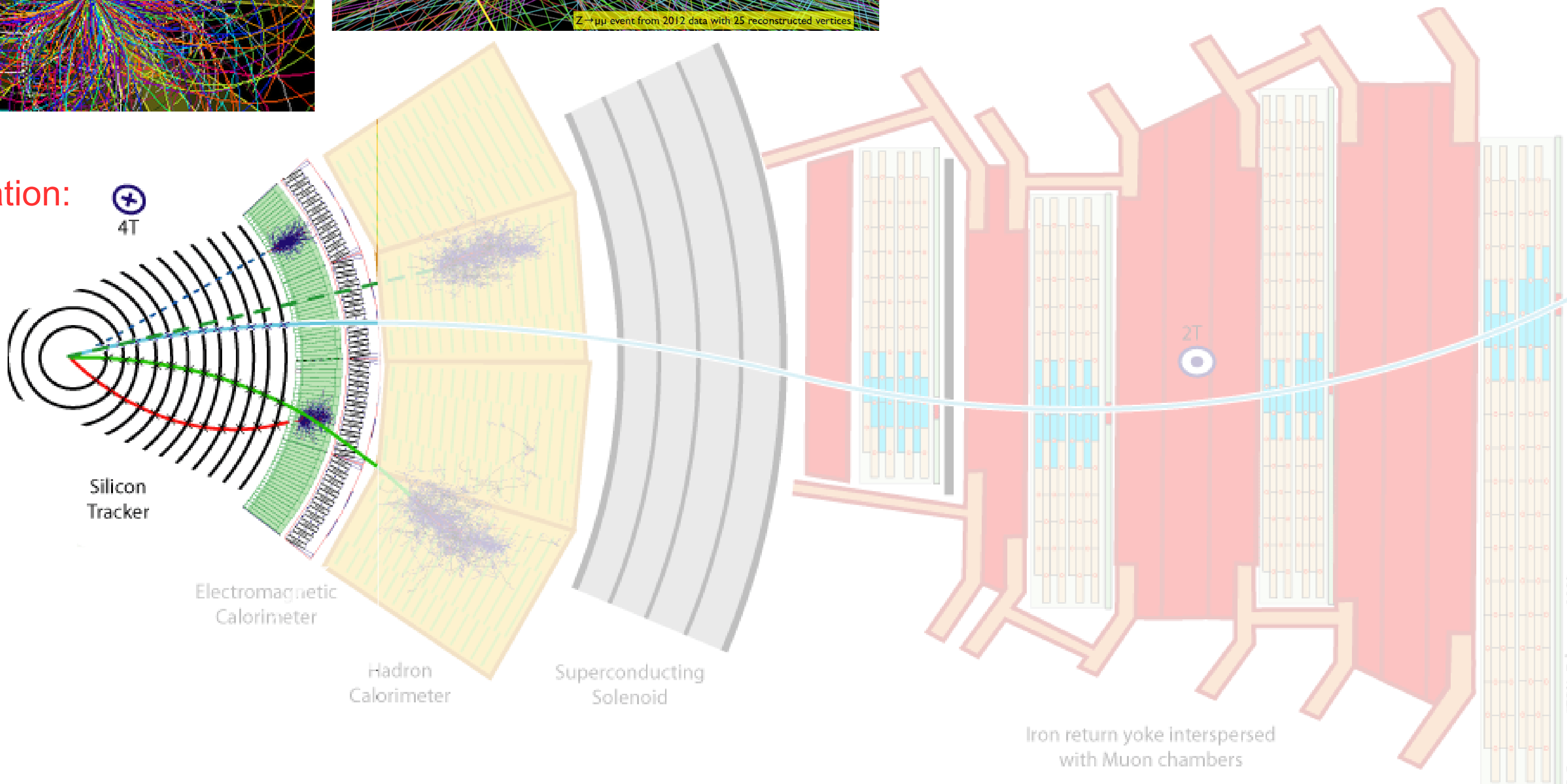


Key demands on Experiments

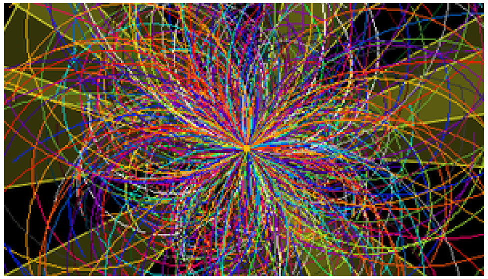


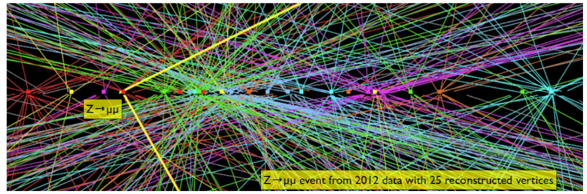


Vertex identification:

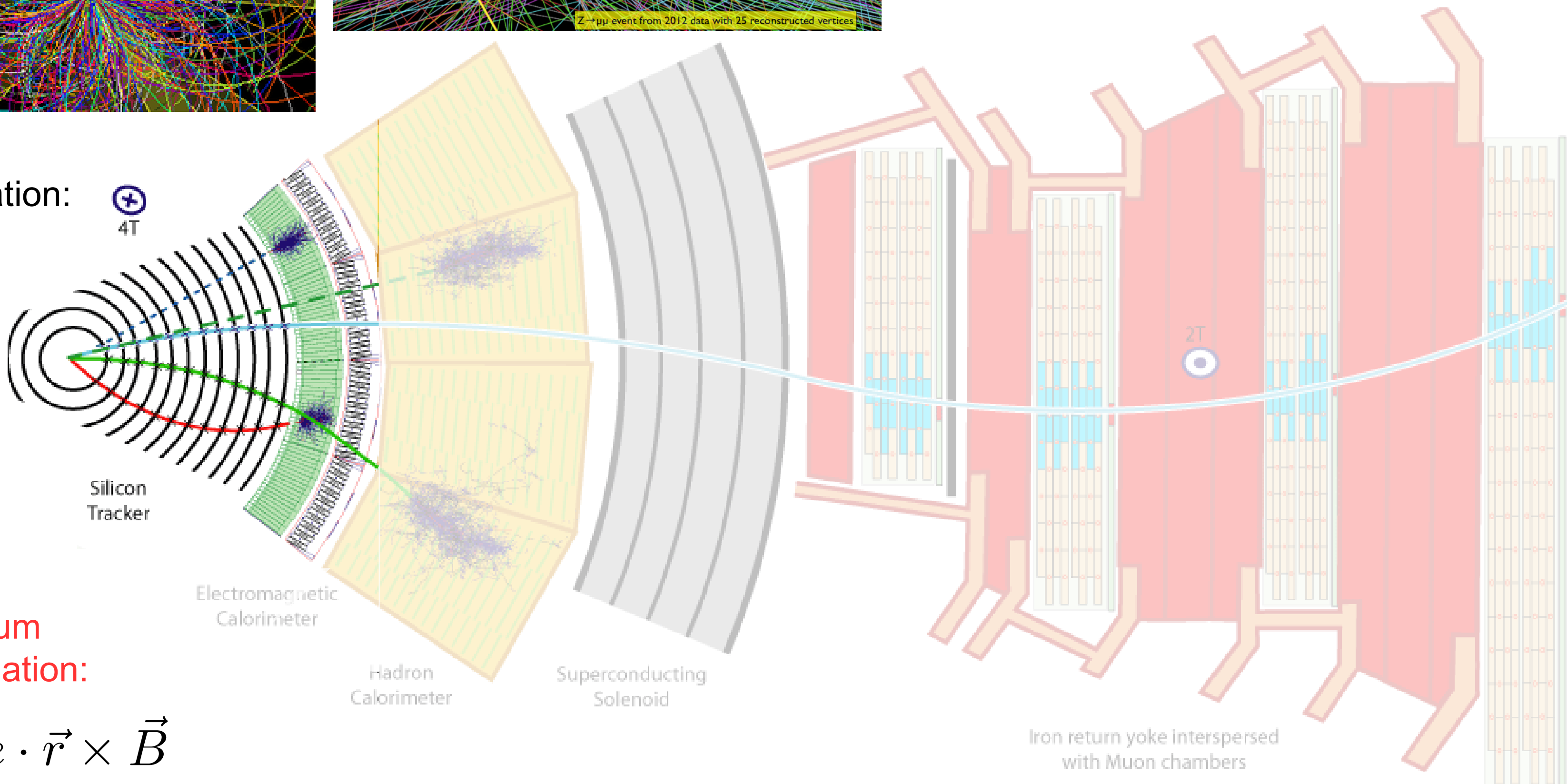


Key demands on Experiments





Vertex identification:

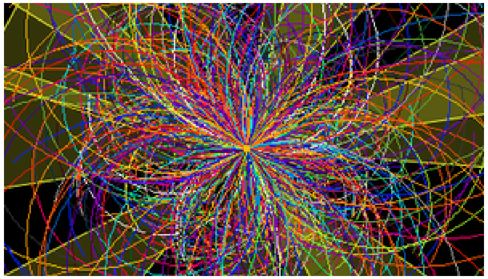


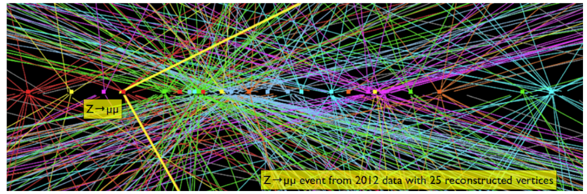
Momentum determination:

$$\vec{p} = e \cdot \vec{r} \times \vec{B}$$

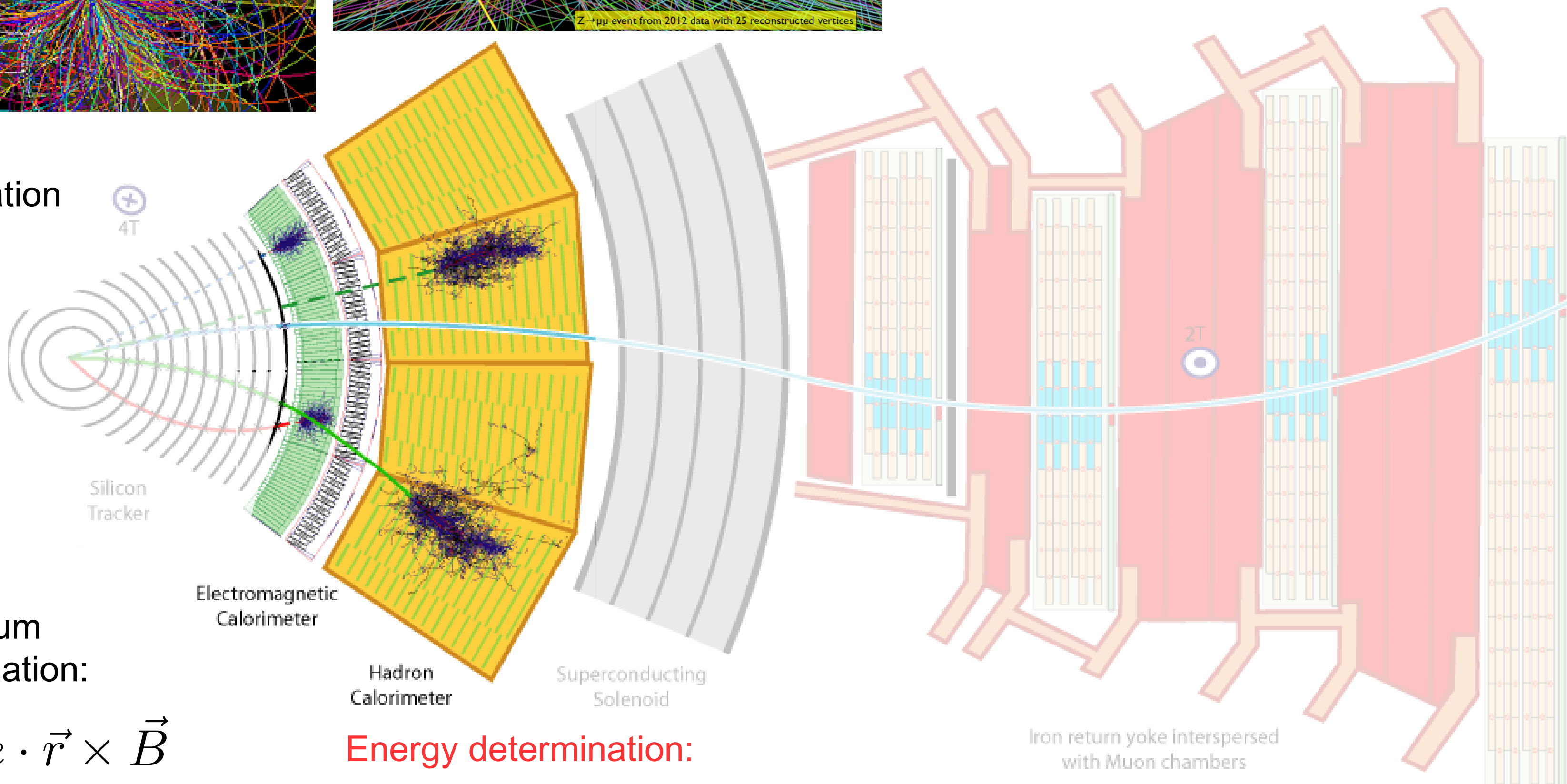
$$\frac{\delta p}{p} = \frac{\delta B}{erB} \oplus \frac{\delta r}{erB}$$

Key demands on Experiments





Vertex identification



Momentum determination:

$$\vec{p} = e \cdot \vec{r} \times \vec{B}$$

$$\frac{\delta p}{p} = \frac{\delta B}{erB} \oplus \frac{\delta r}{erB}$$

Energy determination:

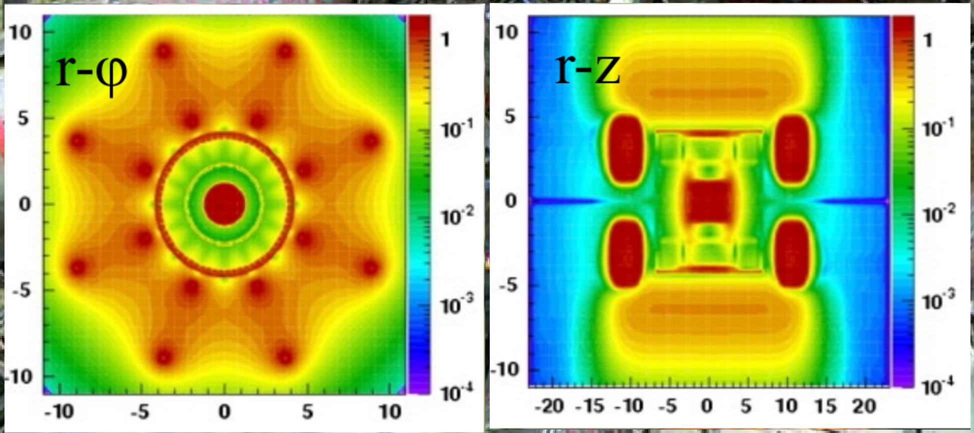
- Energy resolution
- Stopping power

The Large Scale Solution (ATLAS)

- Magnet field (solenoid): 2.6 T (inside calorimeter)
- Magnet field (toroid): ~4 T (outside calorimeter)
- Tracker: Si/multi-wire chambers
- ECAL/HCAL: LAr (varying granularity)

- Length : 45 m
- Diameter : 22 m
- Weight : 7'000 t

Magnet Field:

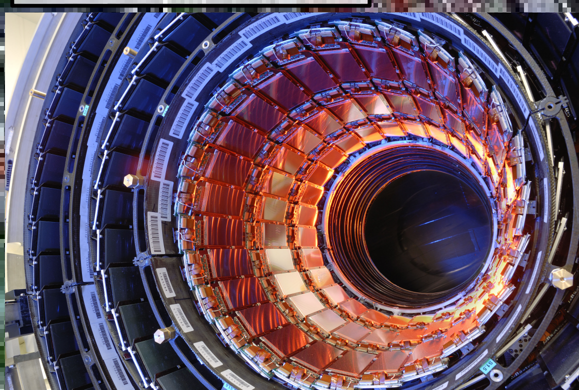


The Compact Solution (CMS)

- Magnet field: 3.8 T (outside calorimeter)
- 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, $X_0 = 28$)
- HCAL: Sampling (brass scintillator, $\delta E / E = 10\%$ for a 100 GeV $\pi^{+/-}$, $\lambda_i = 10$)

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

Silicon Tracker:

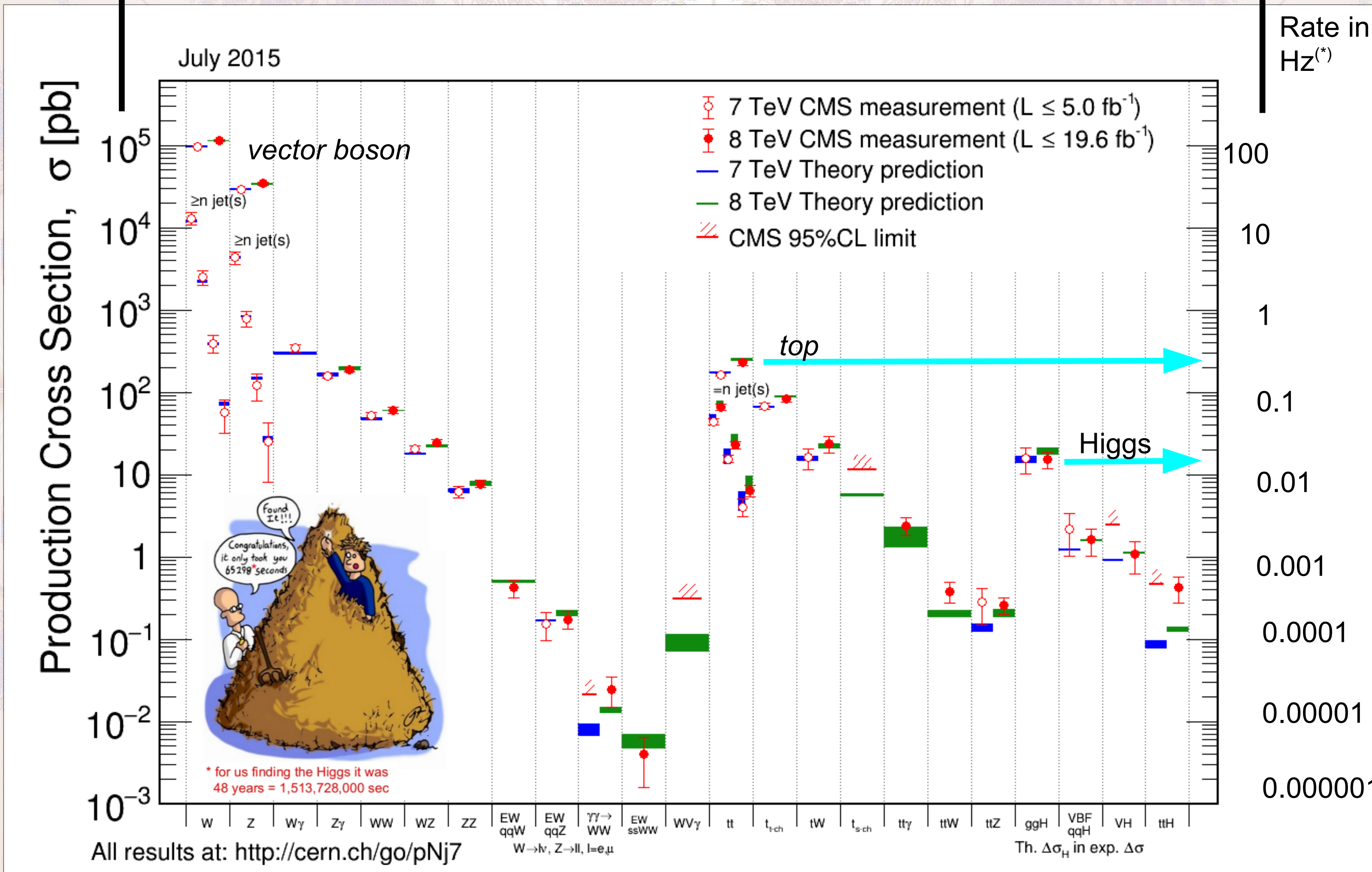


Electromagnetic Calo:

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

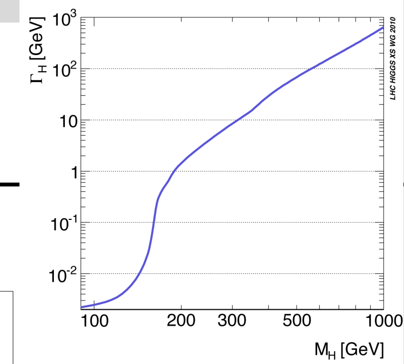
10^8

The challenge



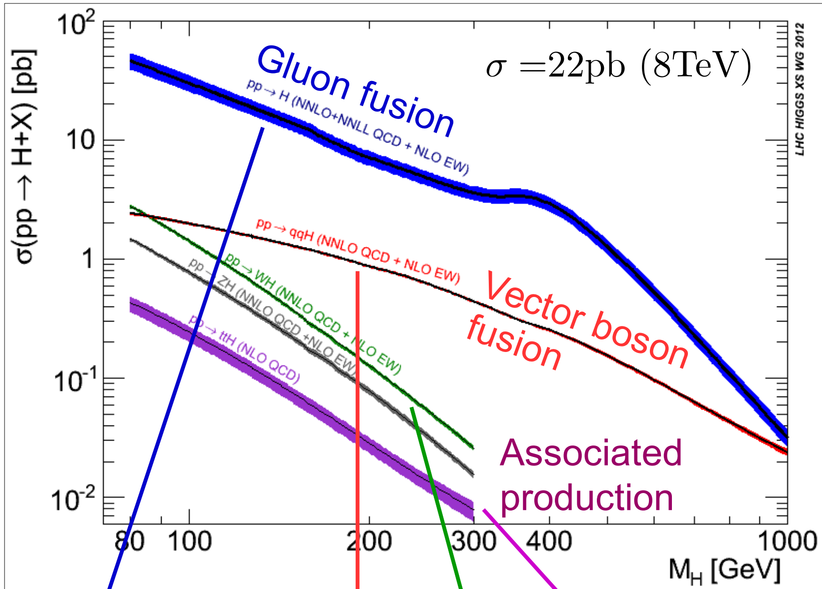
(*) for $\dot{\mathcal{L}} = 1\,\mathrm{nb}^{-1}s^{-1}$.

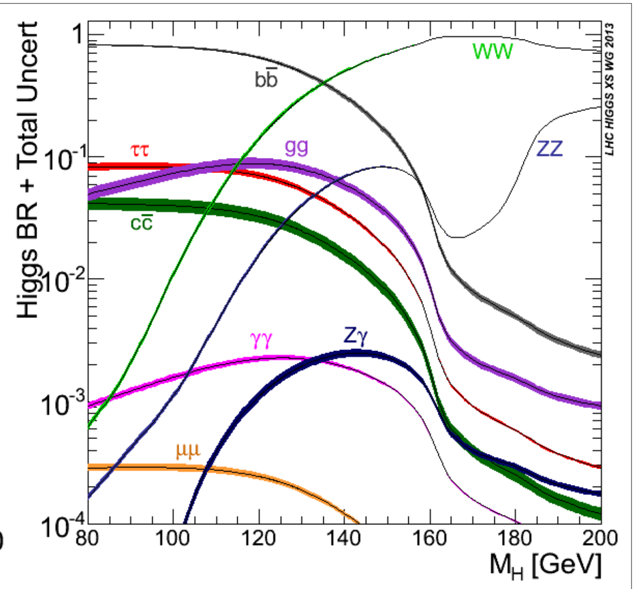
Wanted: Higgs Boson (Dead or Alive)

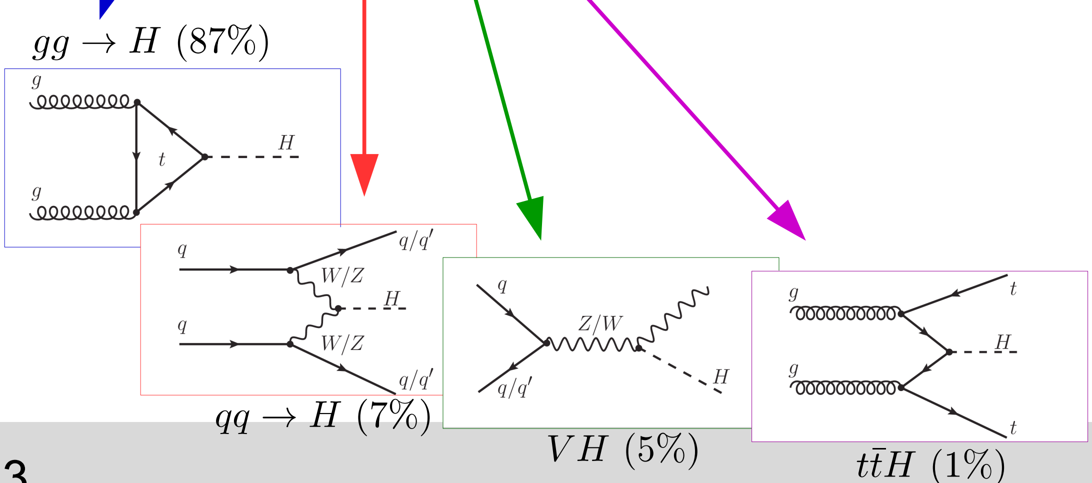


Production:

Decay:







A Long Road of Theory Developments

$gg \to H$
- NNLO+NNLL(α_s)
- NLO(α)
- Precision 15%

$qq \to qqH$
- NNLO(α_s)
- NLO(α)
- Precision 3%

$qq \to VH$
- NNLO(α_s)
- NLO(α)
- Precision 4%

tt production
- NNLO+NNLL(α_s)
- Precision 4%

Single top production
- NNLO(α_s)
- Precision 4%

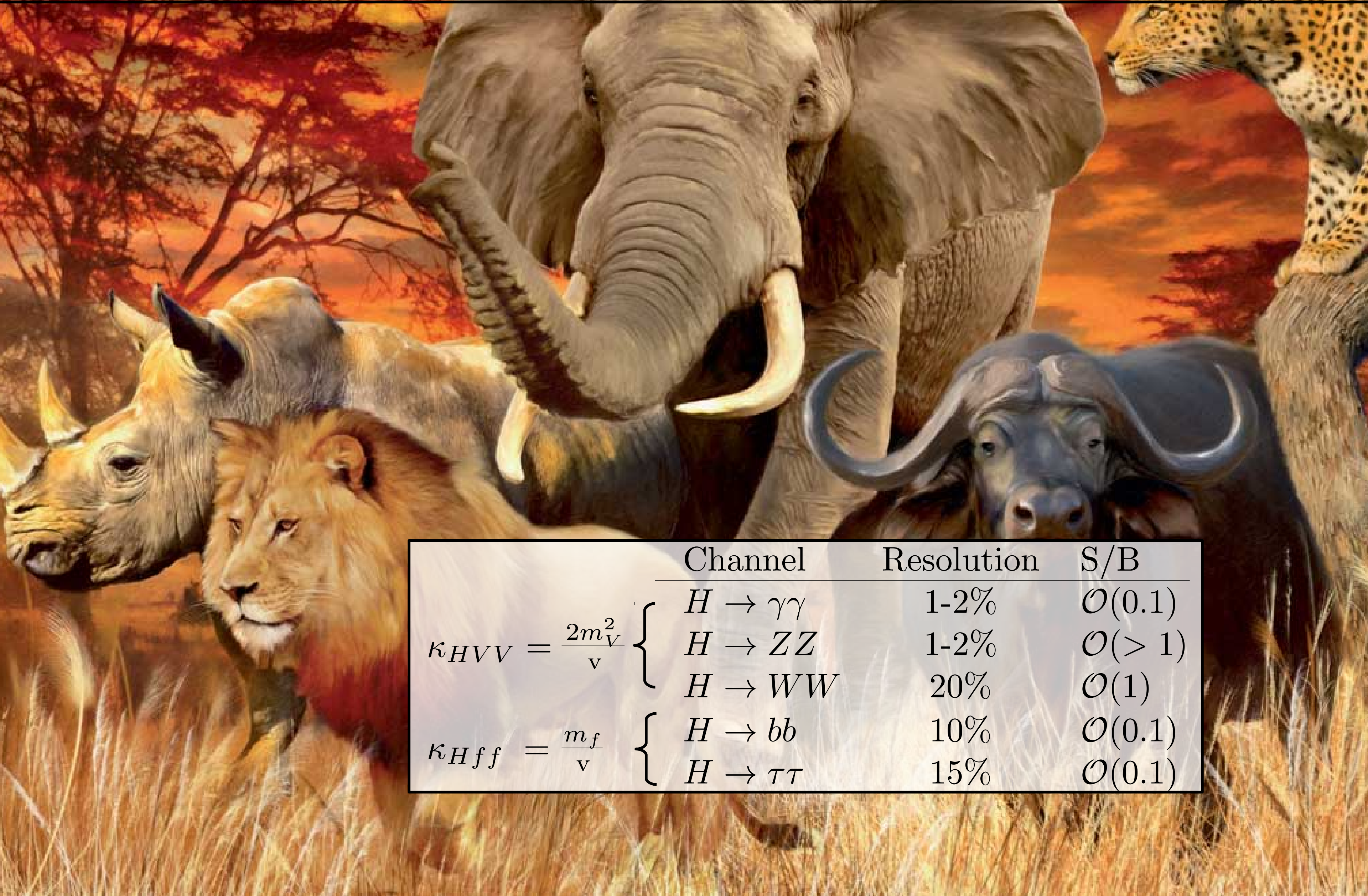
How this precsion was obtained:

W + additional jets
- NNLO(α_s)
- Precision 5%

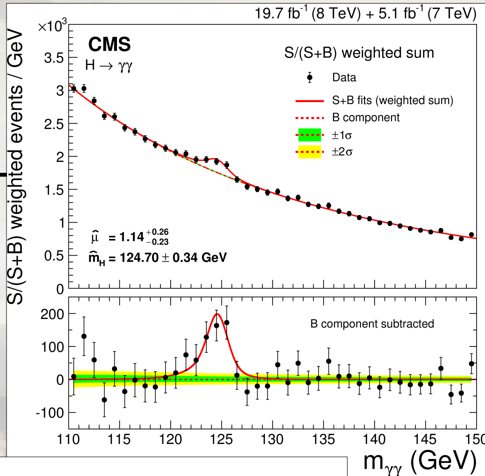
Z + additional jets
- NNLO(α_s)
- Precision 5%

$WW \quad WZ \quad ZZ$
- NLO(α_s)
- Precision 10%

Most Important Decay Channels



	Channel	Resolution	S/B
$\kappa_{HVV} = \frac{2m_V^2}{v}$	$H \to \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
	$H \to ZZ$	1-2%	$\mathcal{O}(> 1)$
	$H \to WW$	20%	$\mathcal{O}(1)$
$\kappa_{Hff} = \frac{m_f}{v}$	$H \to bb$	10%	$\mathcal{O}(0.1)$
	$H \to \tau\tau$	15%	$\mathcal{O}(0.1)$

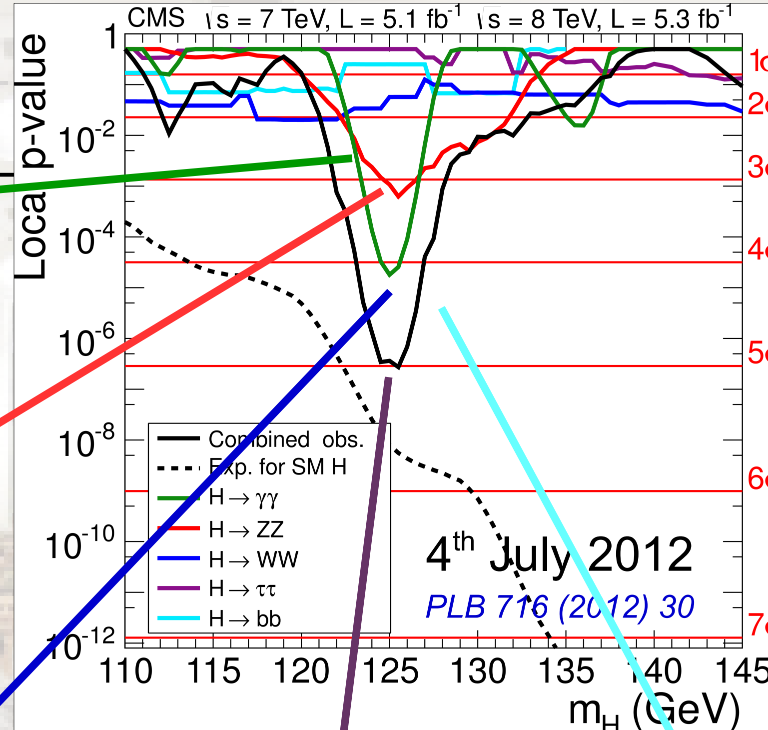


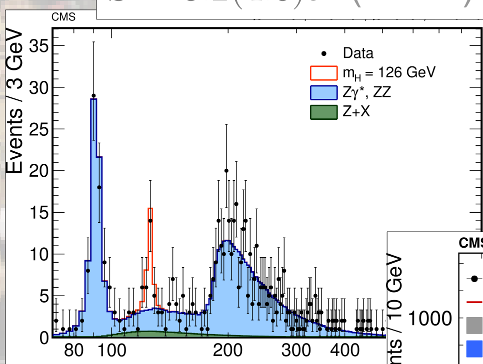
EPJ C 74 (2014) 3076

Significance:

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

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



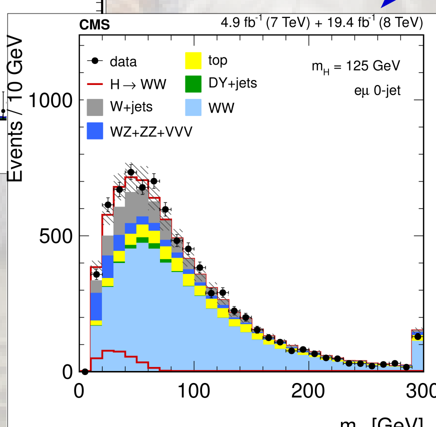


PRD 89 (2014) 092007

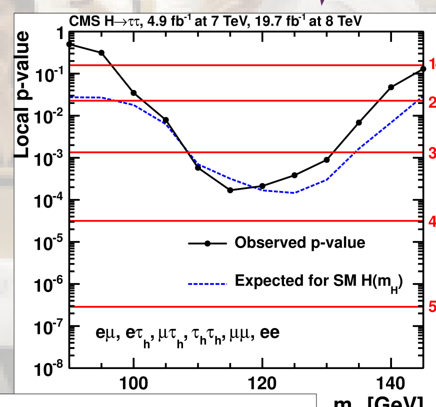
Significance:

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

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



JHEP 01 (2014) 096

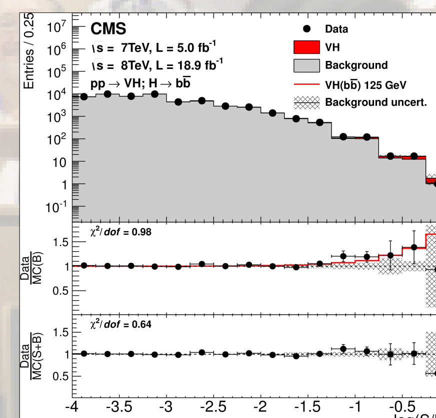


JHEP 05 (2014) 104

Significance:

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

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



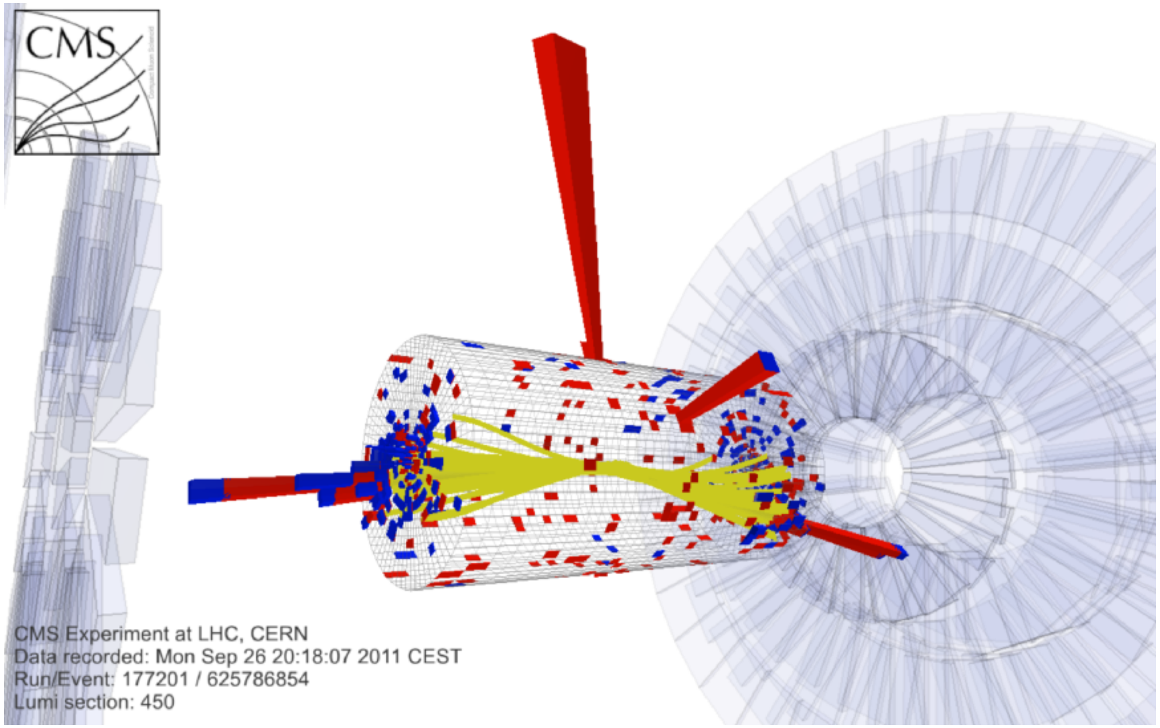
PRD 89 (2013) 012003

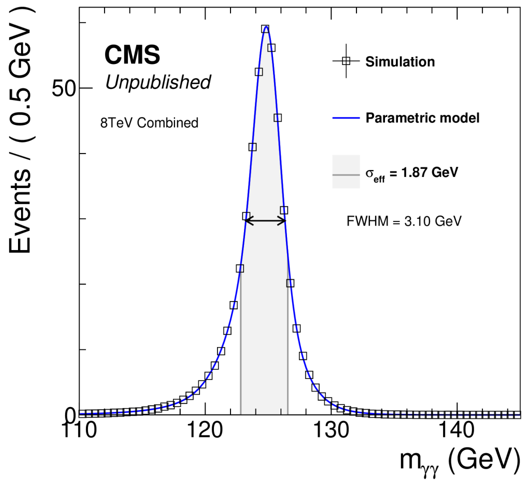
Significance:

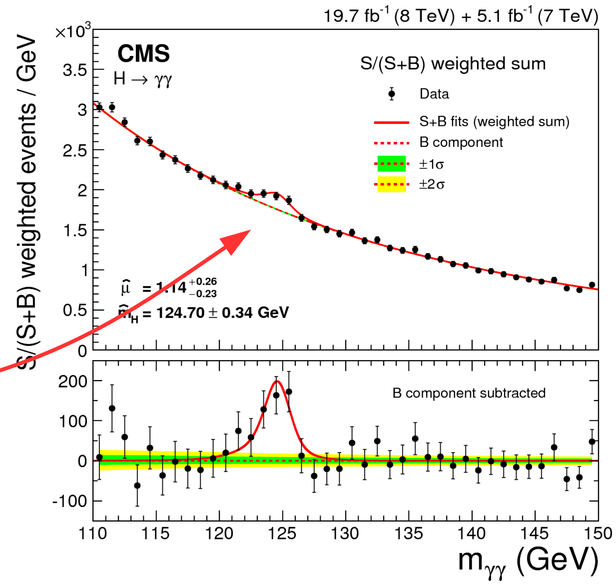
$S = 2.1(2.5)\sigma$ (CMS)

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

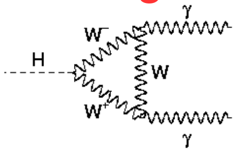
$H \to \gamma\gamma$ Decay Channel

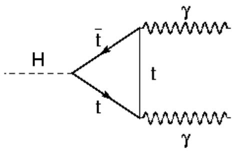






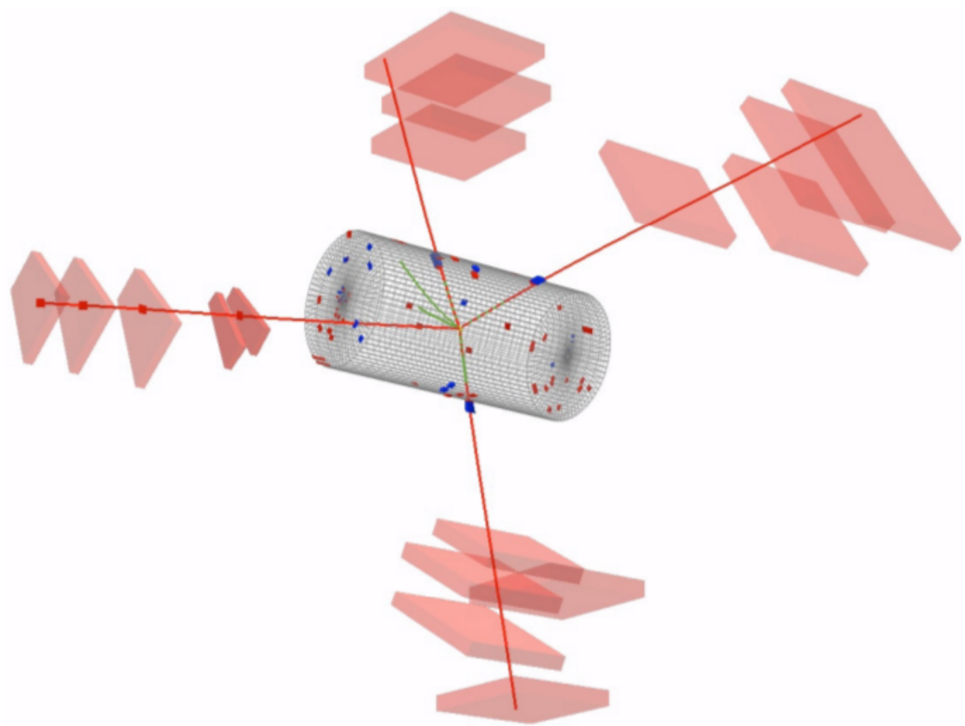
- High mass resolution ($\mathcal{O}(1\text{-}2\%)$). Simple reconstruction and event selection.
- Tiny signal on huge background.
- Decay via loops:

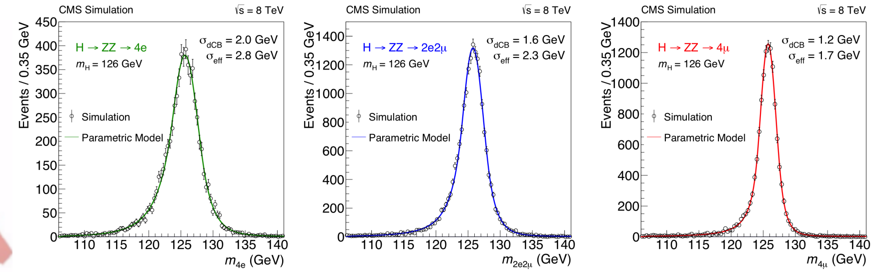




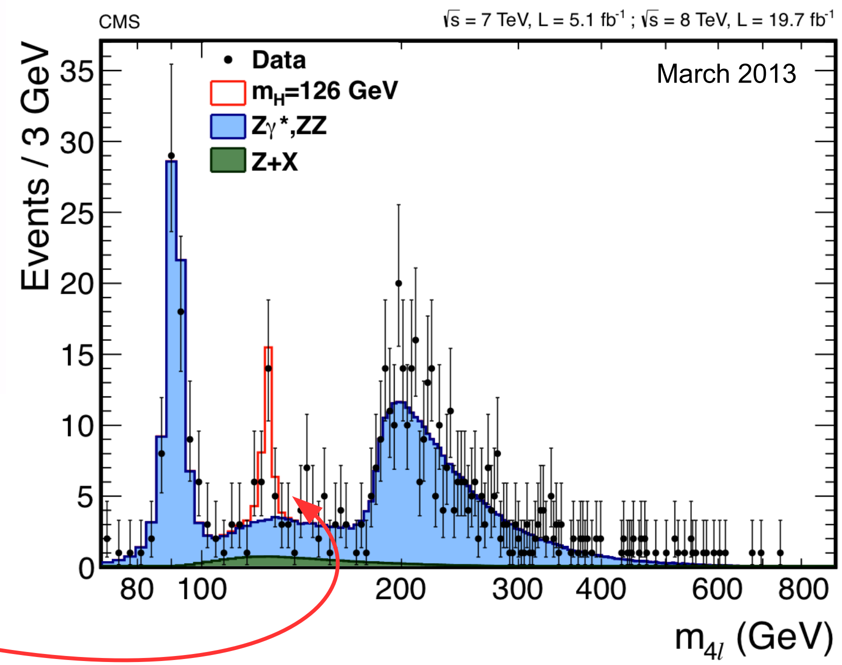
$H \rightarrow ZZ$ Decay Channel

Karlsruhe Institute of Technology



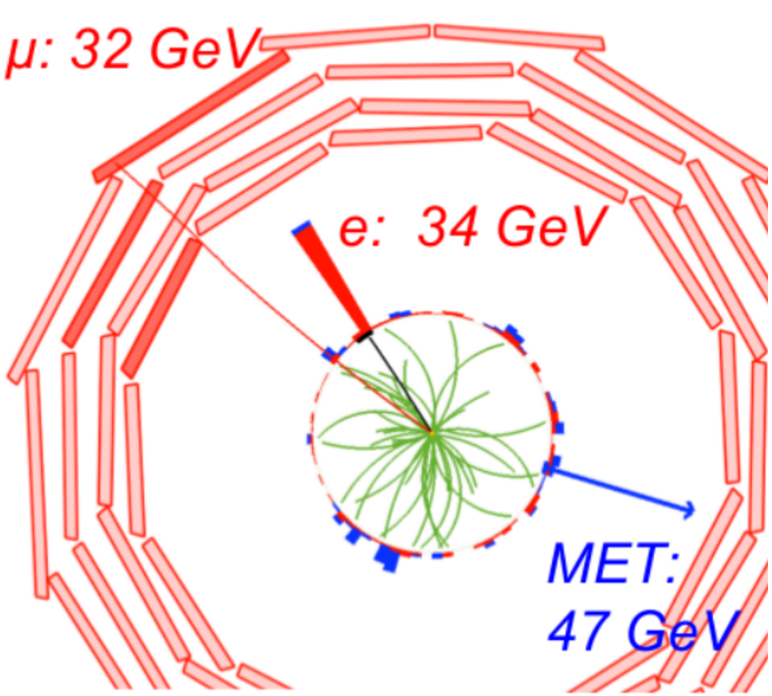


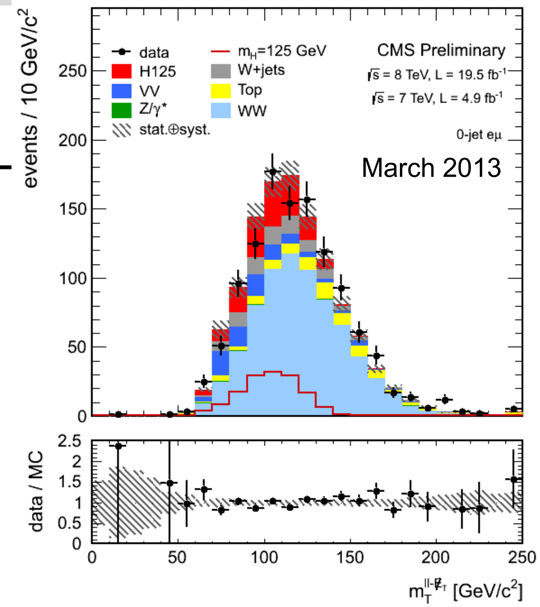
Summer 2014

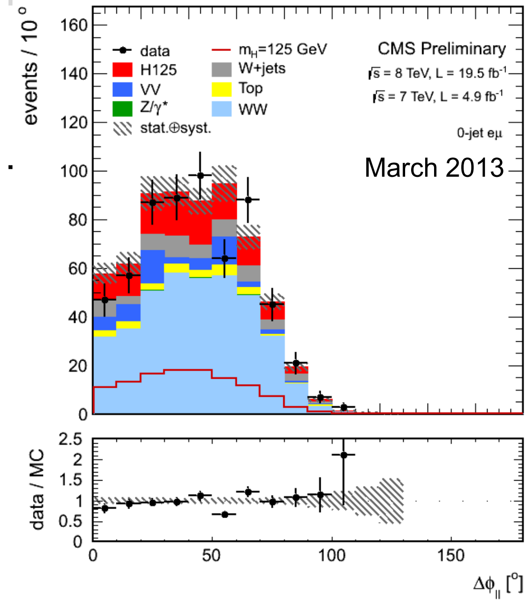


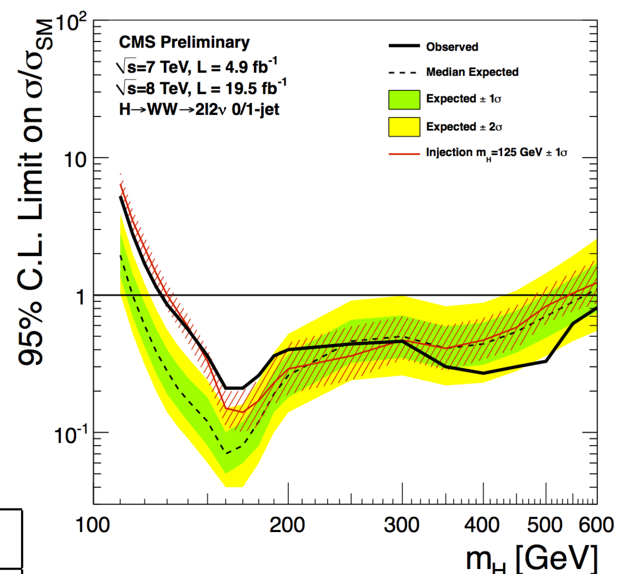
- High mass resolution ($\mathcal{O}(1\text{-}2\%)$). Simple reconstruction and event selection.
- Obvious signal on small background.
- Most important search channels: 4μ $2\mu 2e$ $4e$

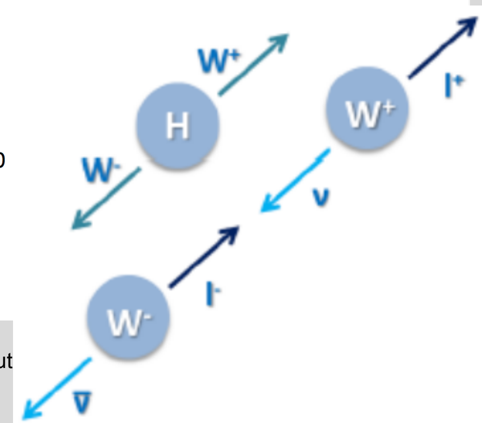
$H \to WW$ Decay Channel







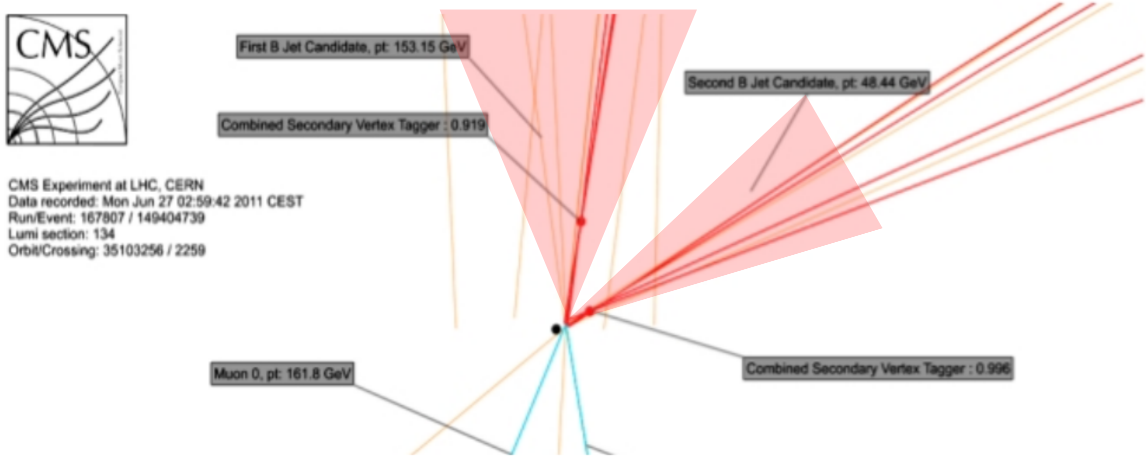


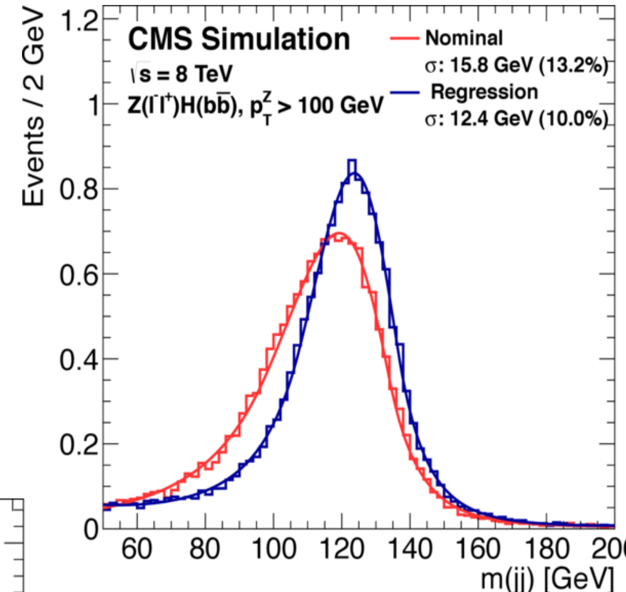


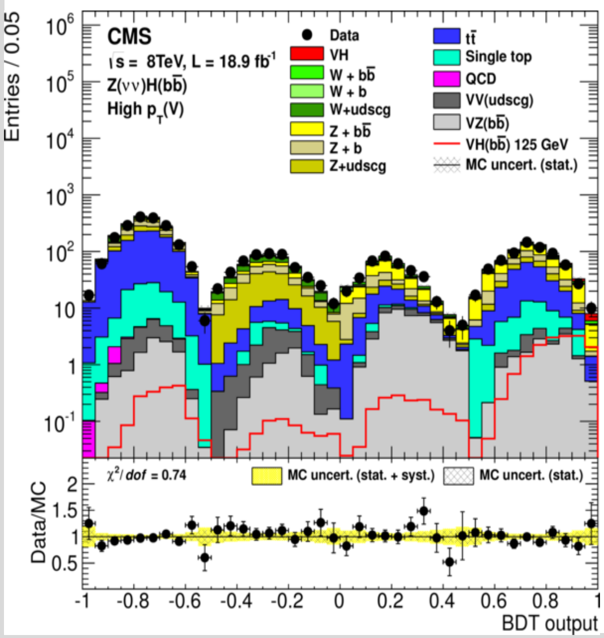
- High discovery potential, but bad mass resolution.

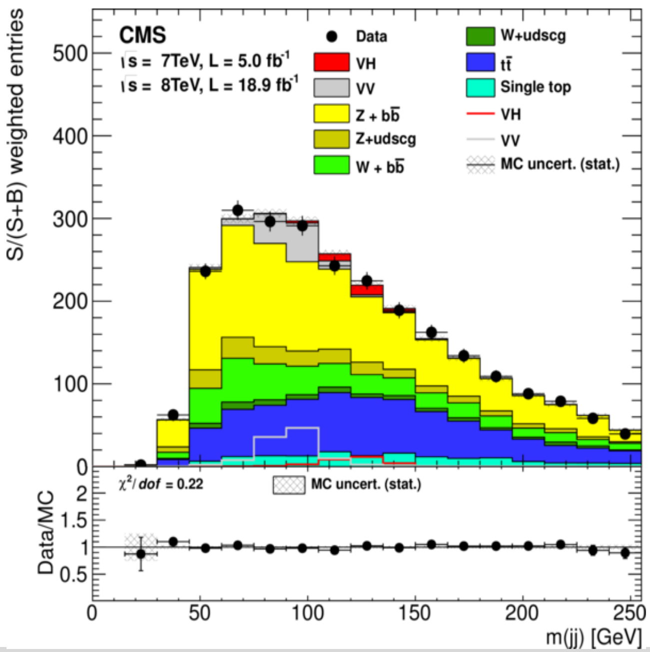
ff	0-jet	1-jet	2-jet(VBF)
ff'	0-jet	1-jet	2-jet(VBF)

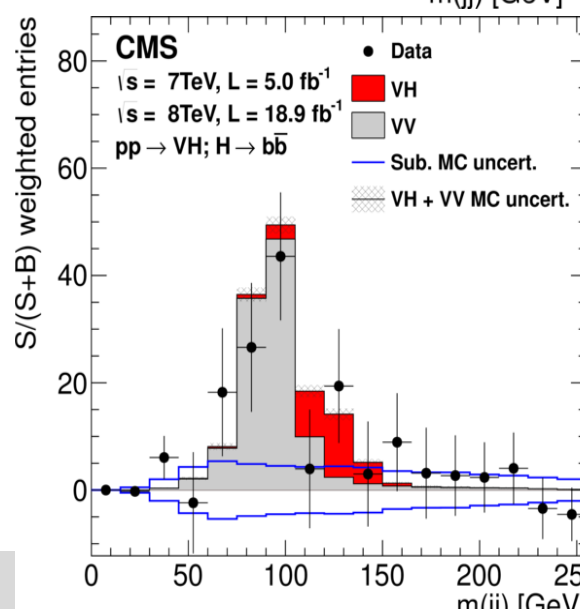
$H \to bb$ Decay Channel







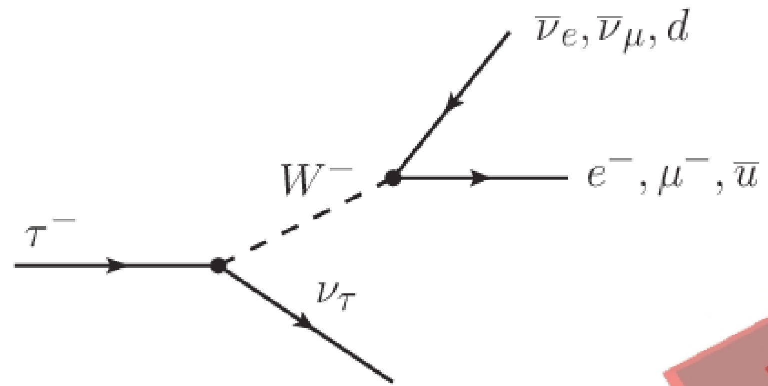




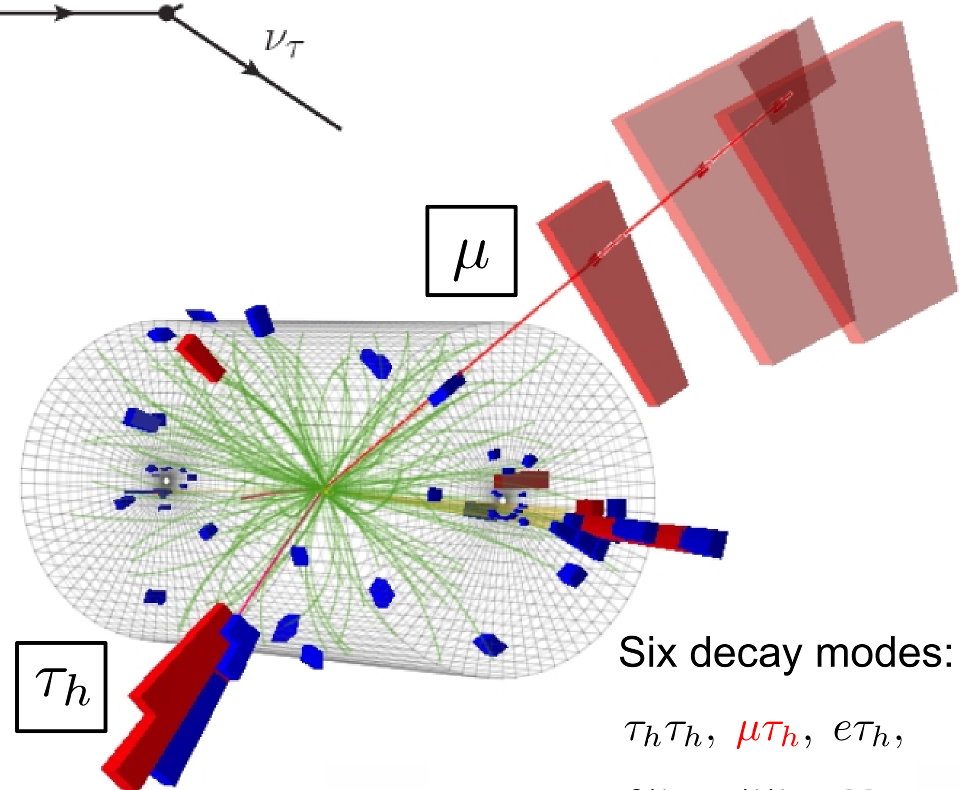
$H \to \tau\tau$ Decay Channel

Decay Mode	BR
$\tau \to e\nu_e\nu_\tau$	17.83%
$\tau \to \mu\nu_\mu\nu_\tau$	17.41%
$\tau \to$1-prong ν_τ	37.10%
$\tau \to$3-prong ν_τ	15.20%

$> 50\%$ of all decay modes.



- Search for 2 isolated high p_T leptons (e , μ , τ_h).
- Reduce obvious backgrounds (use on $\not{E}_T$) & reconstruct $m_{\tau\tau}$.
- Exploit characteristics of production mode to increase sensitivity.



Six decay modes:

$\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$,
$e\mu$, $\mu\mu$, ee

Institute of Experimental Particle Physics (IEKP)

$H \to \mu\mu$ decay channel

15 exclusive categories

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

- SM expectation:

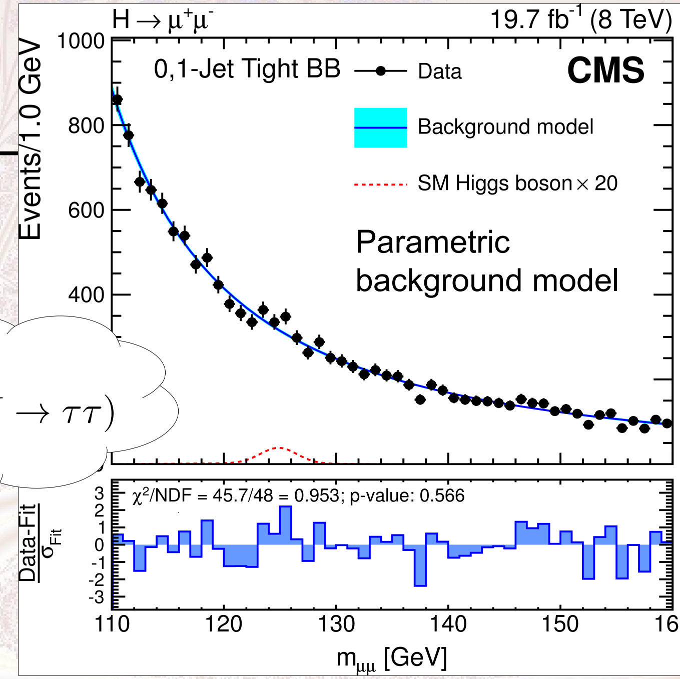
$$\mathcal{BR}(H \to \tau\tau) = 6.30 \pm 0.36\ \%$$

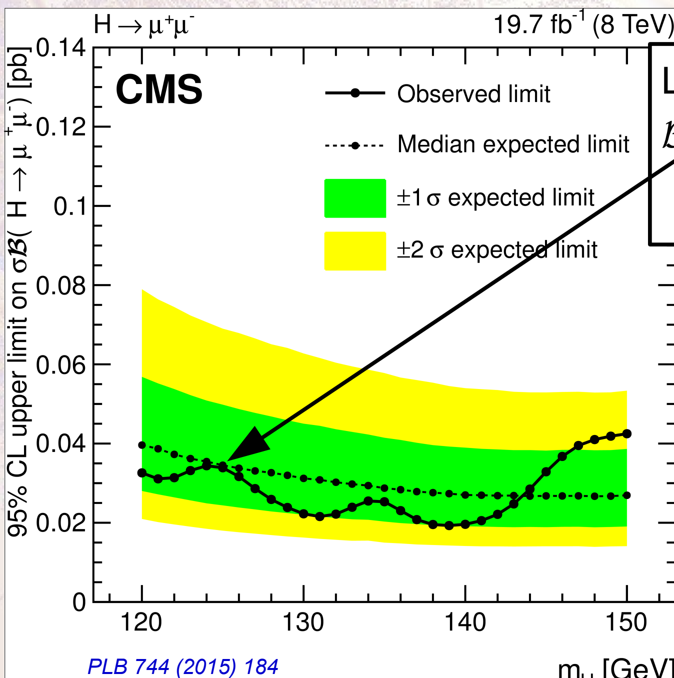
$$\mathcal{BR}(H \to \mu\mu) = 0.022 \pm 0.001\%$$

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

$$\left(\frac{106}{1777}\right)$$

- Non-universal coupling to leptons!



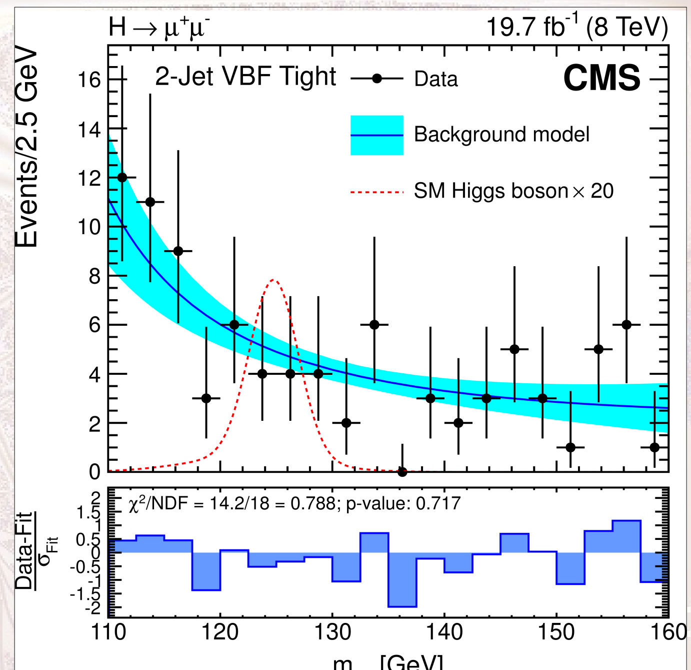


Limit (95% CL):

$$\mathcal{BR}(H \to \mu\mu) \leq 0.16\%$$

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

(*) on 7+8TeV



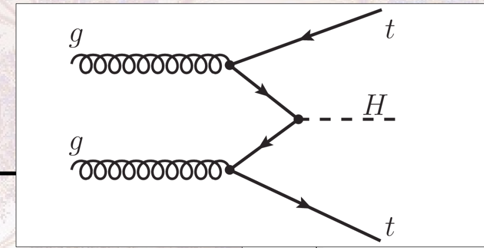
$t\bar{t}H$ Production (1% of total production!)

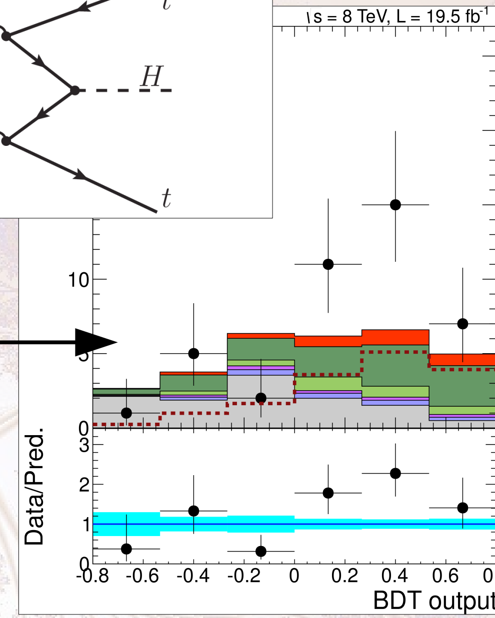
- Complex multi-channel analysis on its own:

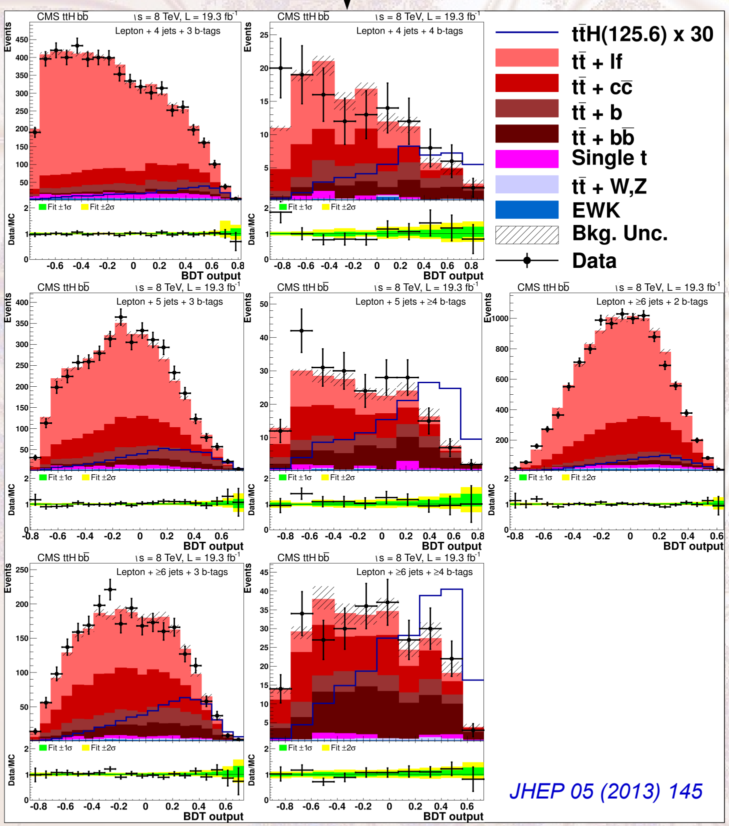
	$H \to$ hadrons			$H \to \gamma\gamma$		$H \to$ leptons		
	$\ell +$ jets	2ℓ	hadronic τ	leptonic	hadronic	$\ell^{\pm}\ell^{\pm}$	3ℓ	4ℓ
H decay	$b\bar{b}$		$\tau\tau/WW$	$\gamma\gamma$		$\tau\tau/WW$		ZZ
$t\bar{t}$ decay	$\ell\nu jj$	$\ell\nu\ell\nu$	$\ell\nu jj$	$\ell\nu\ell\nu/jj$	$jjjj$	$\ell\nu jj$		$\ell\nu\ell\nu$

JHEP 09 (2014) 087

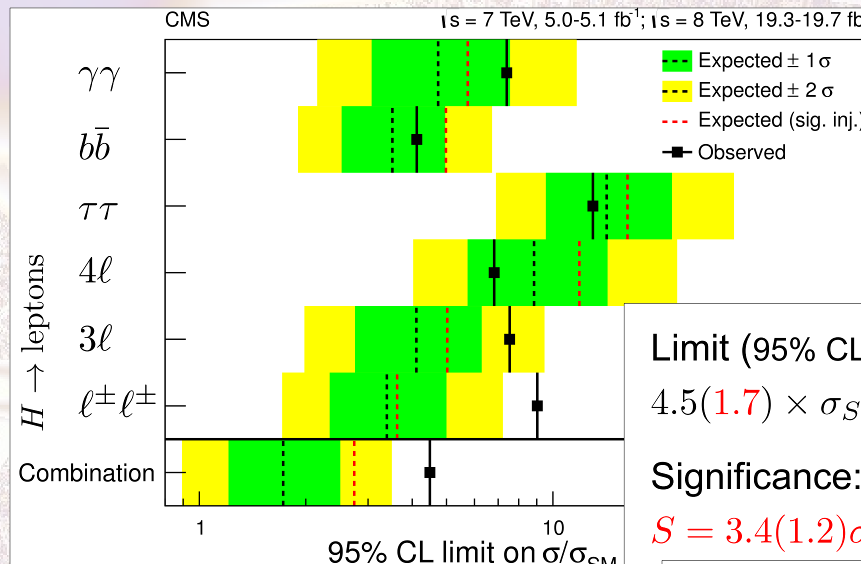
23 event categories on the 8TeV dataset







JHEP 05 (2013) 145



Limit (95% CL):

$4.5(1.7) \times \sigma_{SM}$

Significance:

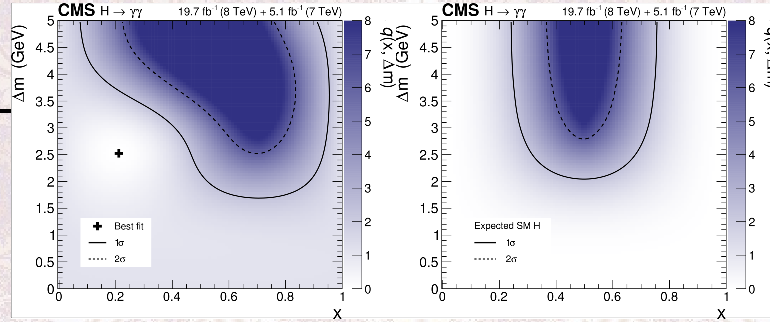
$S = 3.4(1.2)\sigma$

($2.1\ \sigma$ above SM)

Compatibility

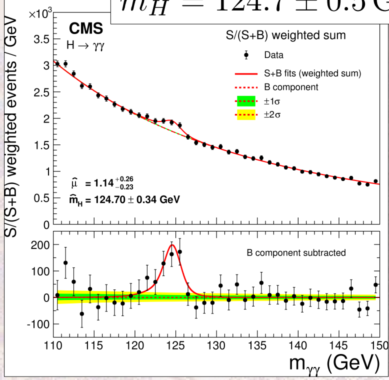
Second close-by resonance in $H \to \gamma\gamma$?

EPJ C 74 (2014) 3076



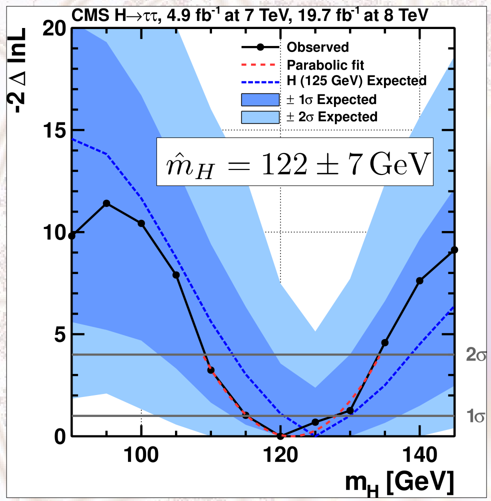
EPJ C 74 (2014) 3076

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



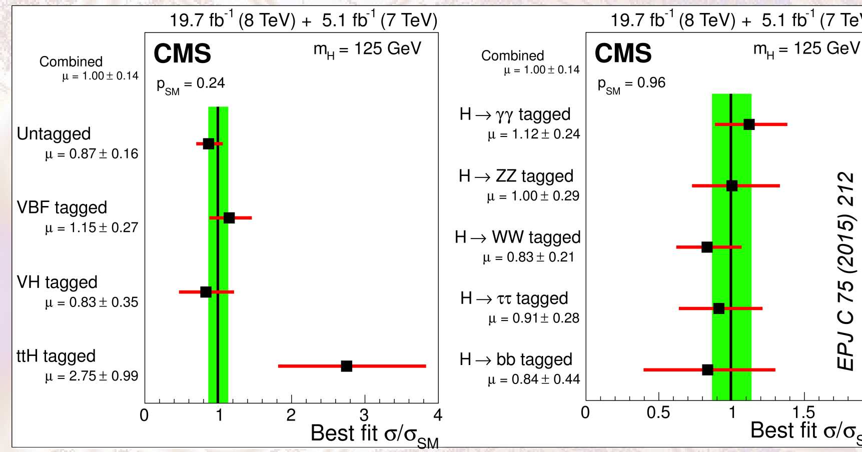
JHEP 05 (2014) 104

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



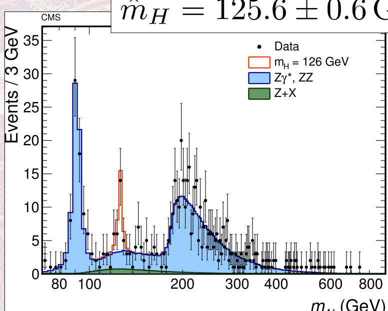
Coupling across production modes or decay channels:

EPJ C 75 (2015) 212

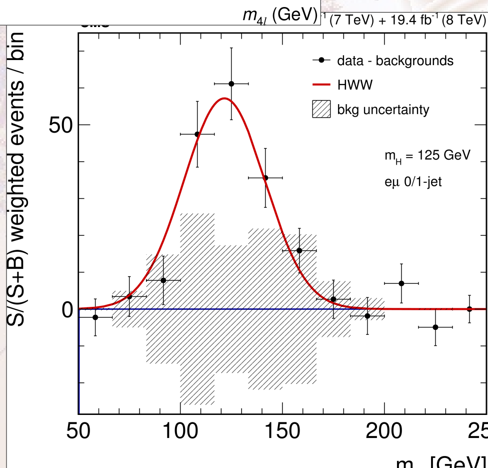


PRD 89 (2014) 092007

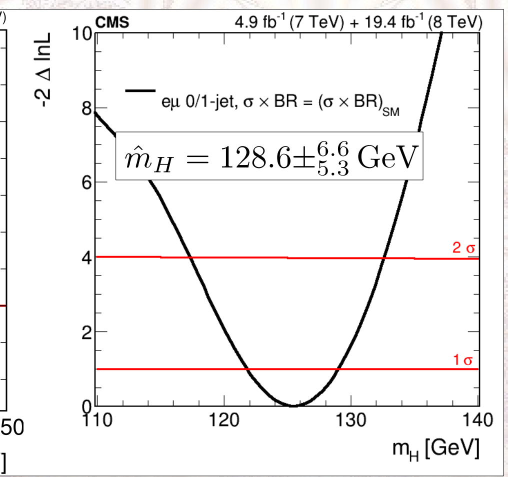
$\hat{m}_H = 125.6 \pm 0.6\,\mathrm{GeV}$



JHEP 01 (2014) 096



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



EPJ C 75 (2015) 212

Overall coupling consistency:

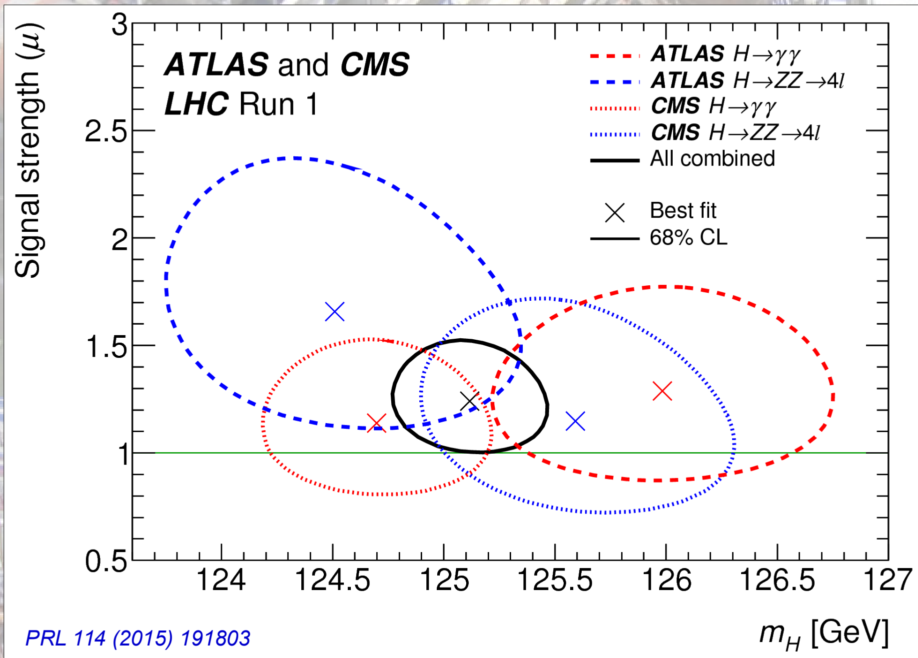
- Event categories : 227
- Nuisance parameters: $\mathcal{O}(2500)$
- 16 MB binary file of stat. model (~145 MB in human readable form).

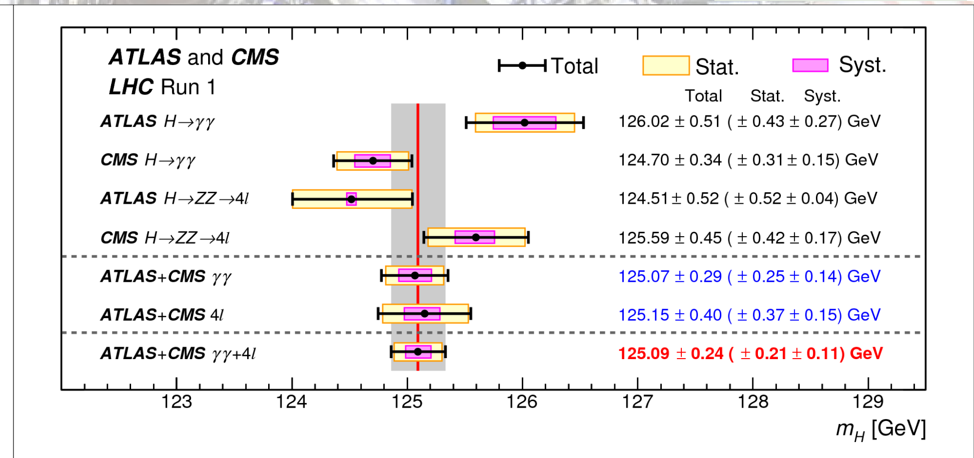
$\mu = \sigma/\sigma_{SM} = 1.00 \pm 0.14$

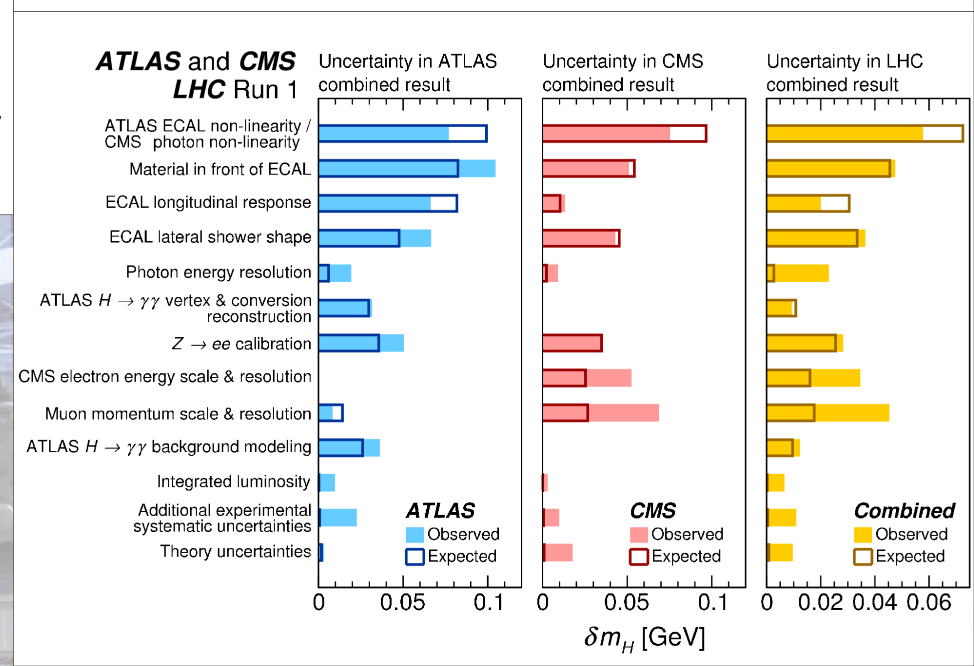
p-value $= 84\%$

Mass

- ATLAS+CMS LHC run-1 combination:







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

Coupling structure

CMS-PAS-HIG-15-002

- Event categories : 574
- Nuisance parameters: 4268

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

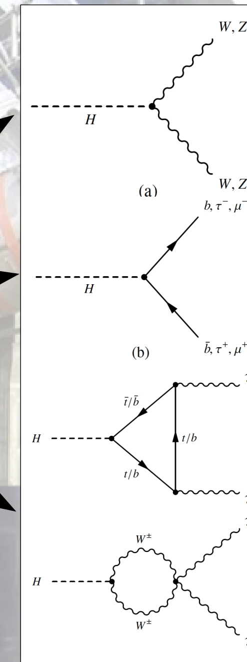
- ATLAS+CMS LHC run-1 combination:

Considered production modes:

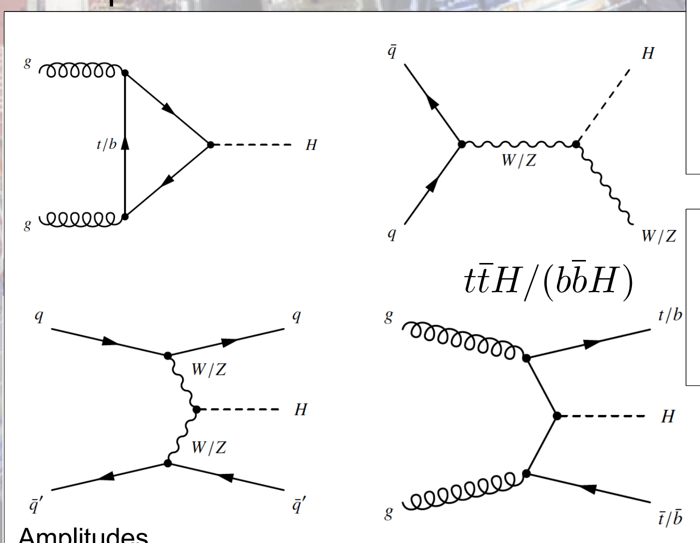
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)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

Considered decay channels:

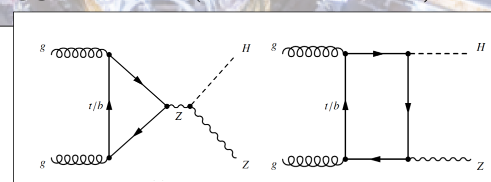
Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

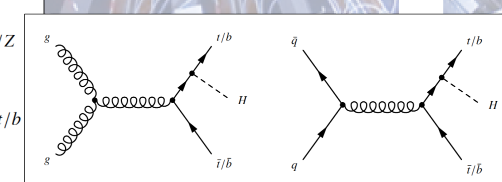


Main production modes:

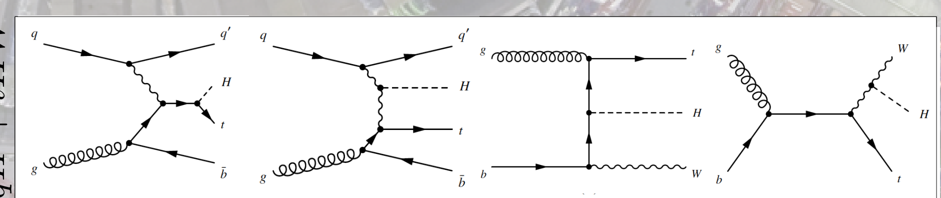


$gg \to ZH$ (10% to $ZHbb$)

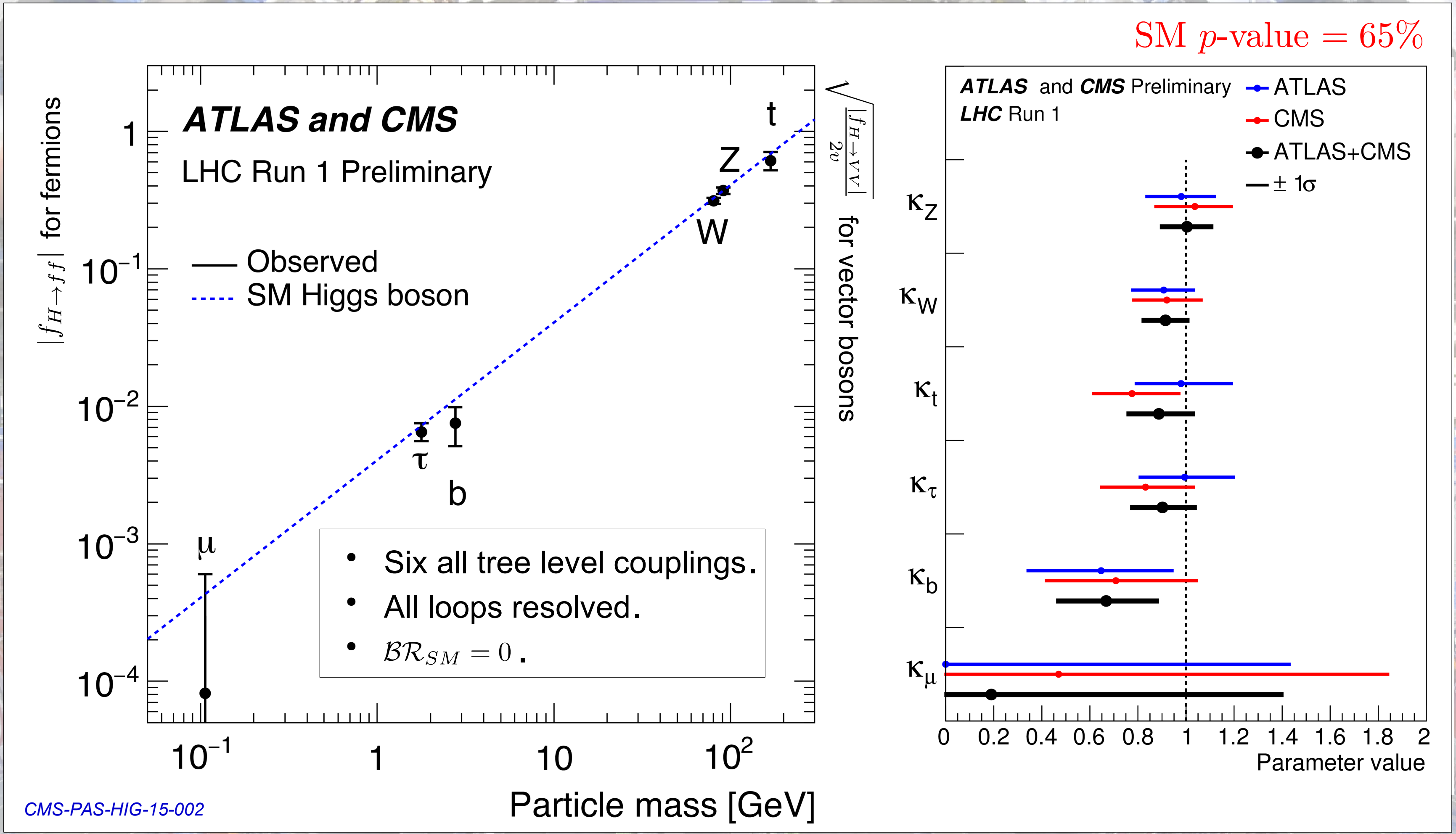




$tqH + tHW$



“Money plot”



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

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

Within measurement accuracy unique scaling as expected within the SM.

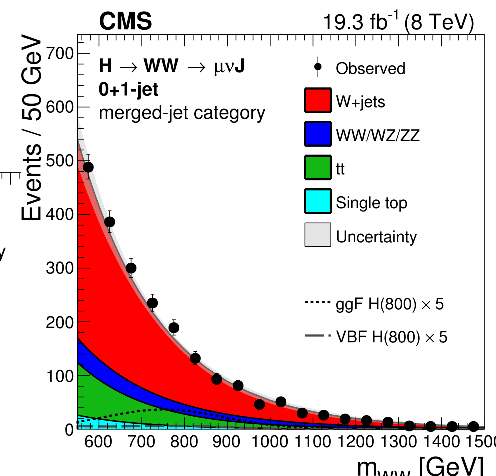
High mass Higgs boson search in WW and ZZ

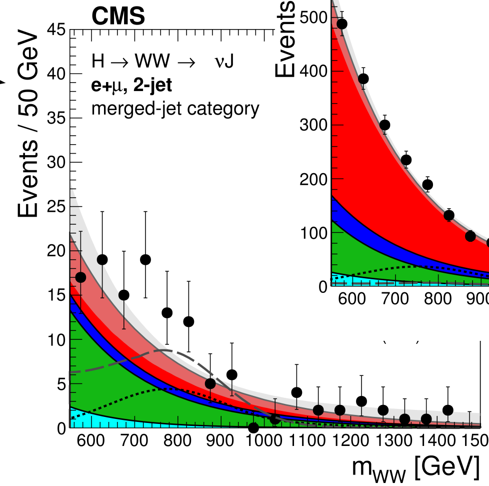
- Search in mass range of $m_H = 145 \dots 1000$ GeV.
- Combination of several channels in WW and ZZ (55 channels/categories).

H decay mode	H production	Exclusive final states	No. of channels	m_H range [GeV]	m_H resolution
$WW \to \ell\nu\ell\nu$	untagged	$((ee, \mu\mu), e\mu) + (0 \text{ or } 1 \text{ jets})$	4	145–1000 [a,b]	20%
	VBF tag	$((ee, \mu\mu), e\mu) + (jj)_{VBF}$	2	145–1000 [a,b]	20%
$WW \to \ell\nu qq$	untagged	$(e\nu, \mu\nu) + (jj)_W$	2	180–600	5–15%
	untagged	$(e\nu, \mu\nu) + (J)_W + (0{+}1\text{-jets})$	2	600–1000 [b]	5–15%
	VBF tag	$(e\nu, \mu\nu) + (J)_W + (jj)_{VBF}$	1	600–1000 [b]	5–15%
$ZZ \to 2\ell 2\ell'$	untagged	$4e, 4\mu, 2e2\mu$	3	145–1000	1–2%
	VBF tag	$(4e, 4\mu, 2e2\mu) + (jj)_{VBF}$	3	145–1000	1–2%
	untagged	$(ee, \mu\mu) + (\tau_h\tau_h, \tau_e\tau_h, \tau_\mu\tau_h, \tau_e\tau_\mu)$	8	200–1000	10–15%
$ZZ \to 2\ell 2\nu$	untagged	$(ee, \mu\mu) + (0 \text{ or } \geq 1 \text{ jets})$	4	200–1000	7%
	VBF tag	$(ee, \mu\mu) + (jj)_{VBF}$	2	200–1000	7%
$ZZ \to 2\ell 2q$	untagged	$(ee, \mu\mu) + (jj)_Z^{0,1,2\,b\text{ tags}}$	6	230–1000 [c]	3%
	untagged	$(ee, \mu\mu) + (J)_Z^{0,1,2\,b\text{ tags}}$	6	230–1000 [c]	3%
	VBF tag	$(ee, \mu\mu) + (jj)_Z^{0,1,2\,b\text{ tags}} + (jj)_{VBF}$	6	230–1000 [c]	3%
	VBF tag	$(ee, \mu\mu) + (J)_Z^{0,1,2\,b\text{ tags}} + (jj)_{VBF}$	6	230–1000 [c]	3%

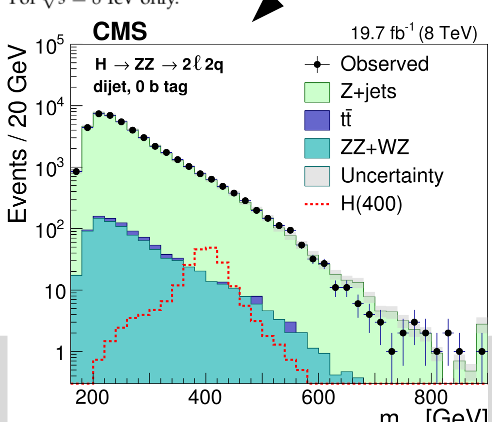
[a] EW singlet model interpretation starts at 200 GeV to avoid cont
[b] 600-1000 GeV for $\sqrt{s} = 8$ TeV only.
[c] For $\sqrt{s} = 8$ TeV only.

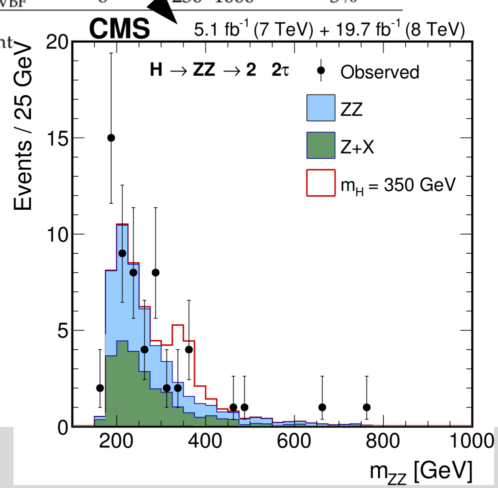
Merged jet event categories in WW:



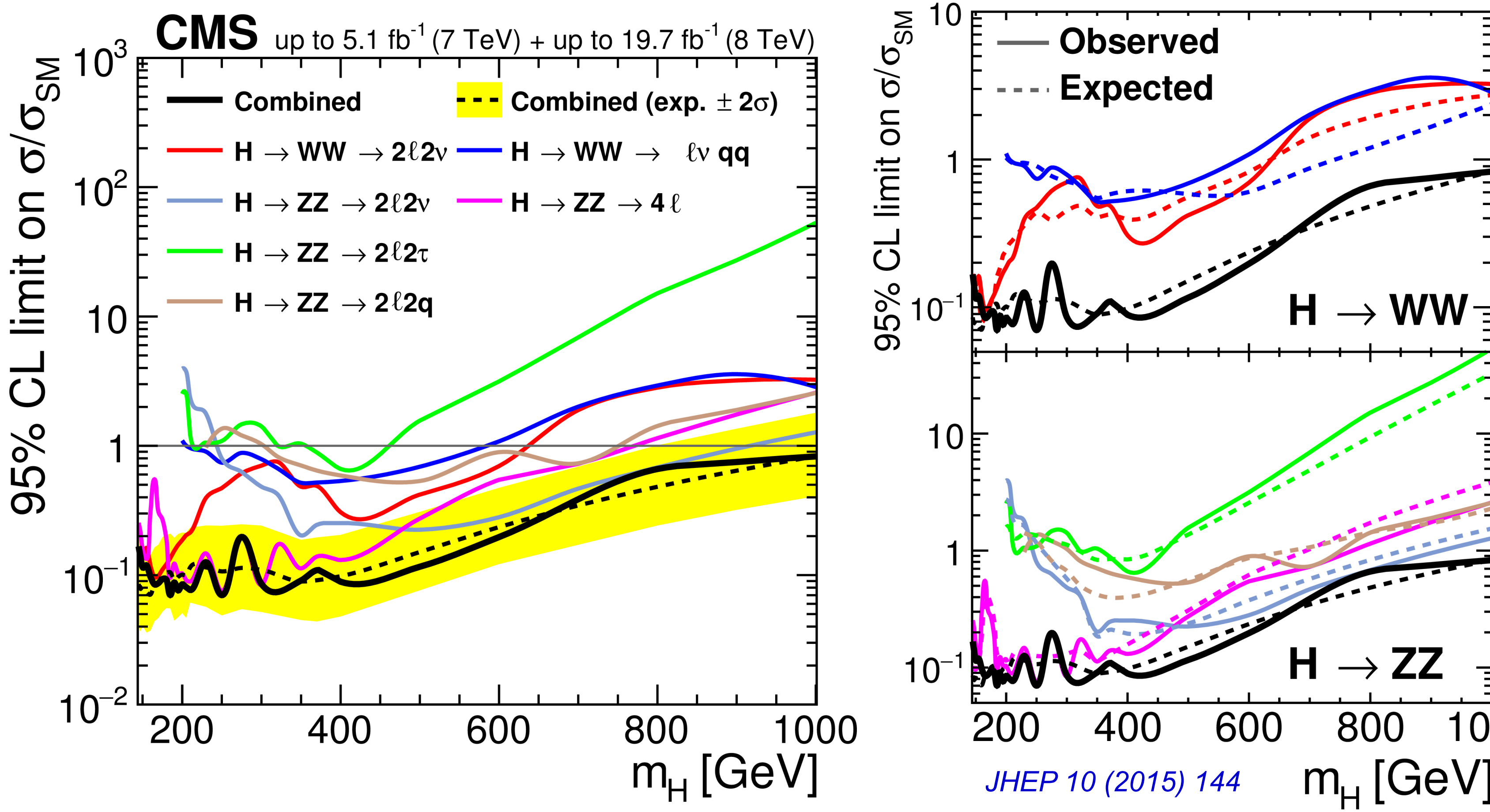


JHEP 10 (2015) 144





Additional SM-like Higgs boson?

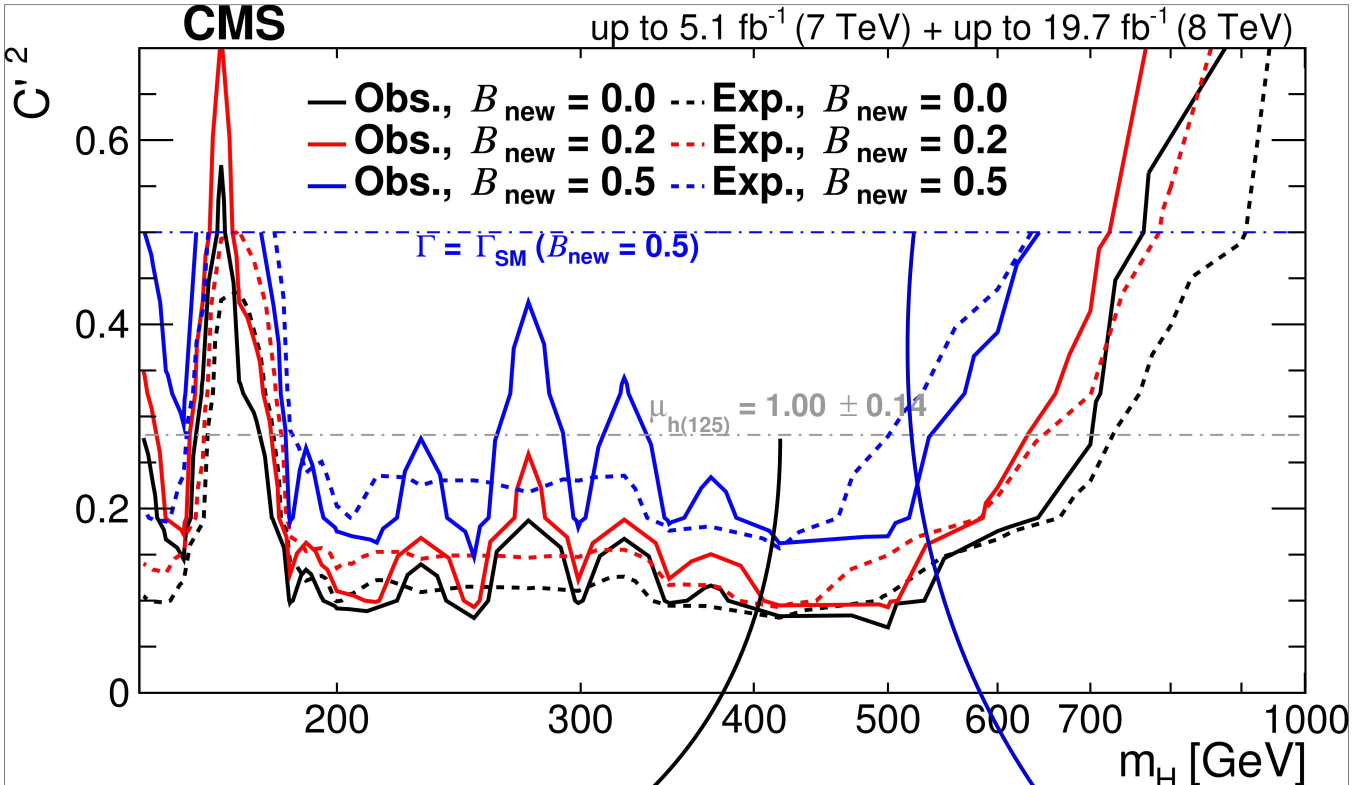


JHEP 10 (2015) 144

- Additional Higgs boson with same production cross section and BR as expected for the SM (for given mass value).

EWK singlet admixtures?

Additional heavy Higgs (H) that mixes with $h(125)$.



JHEP 10 (2015) 144

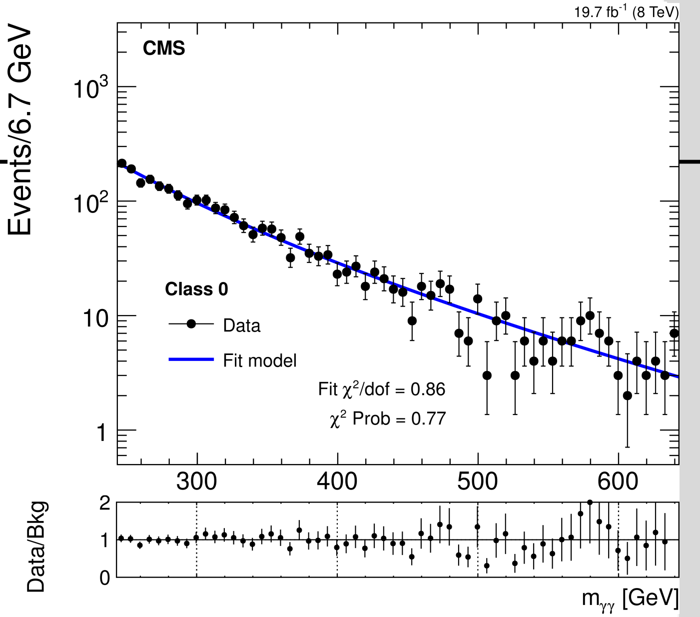
- Unitarity constraint:
  C : coupling to h
  C': coupling to H
  $C'^2 + C^2 = 1$
  → couplings of h reduced by coupling to H.
- Allow additional $\mathcal{BR}$ for non-SM H decays:
  $\mu' = C'^2(1 - \mathcal{BR}_{new})$
  $\Gamma' = \frac{\Gamma_{SM}}{(1-\mathcal{BR}_{new})}$

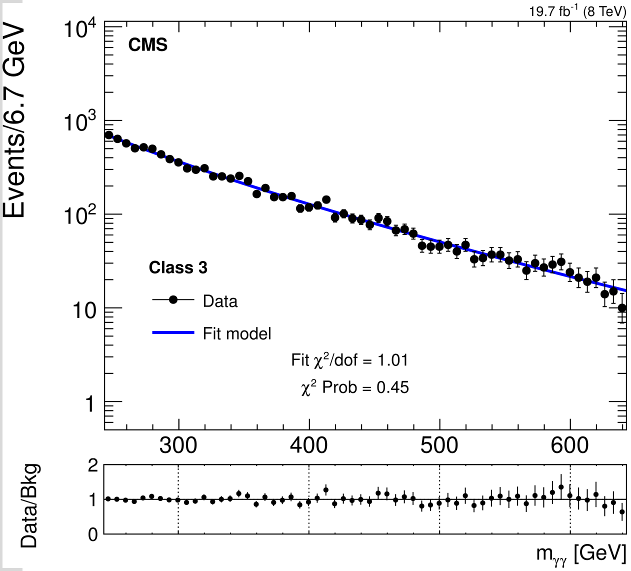
Unitarity bound for:
$\mu_{h(125)} = 1 \pm 0.14$
$-2\sigma \sim C'^2\big|_{B_{new}=0} \leq 0.28$

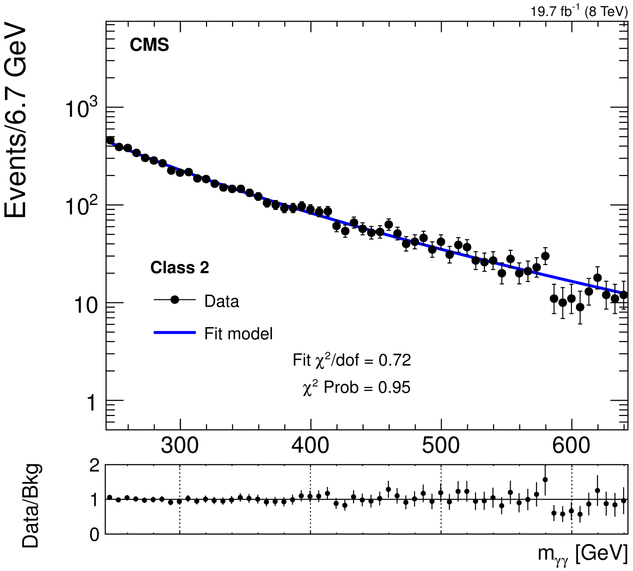
Boundary for main assumption of analysis:
$\Gamma' \leq \Gamma_{SM}$ (based on CMS limit on $\mathcal{BR}_{BSM} \lesssim 0.5 (95\% CL)$ from couplings)

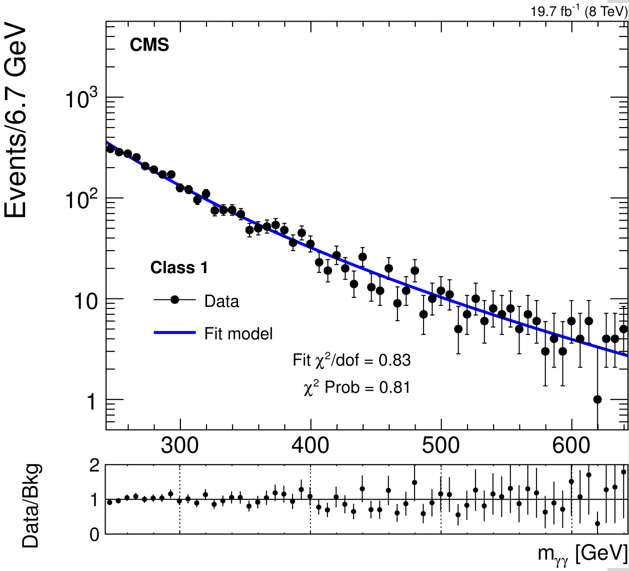
High mass Higgs boson search in $\gamma\gamma$

- Search in mass range of $m_H = 150 \ldots 850$ GeV .
- Combination of four sub-categories.
- Analysis strategy same as for SM Higgs search.





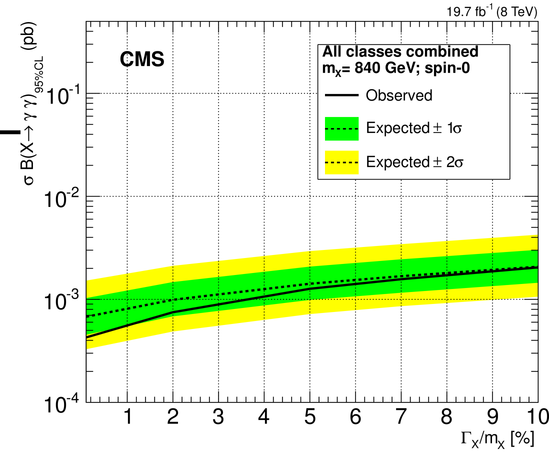


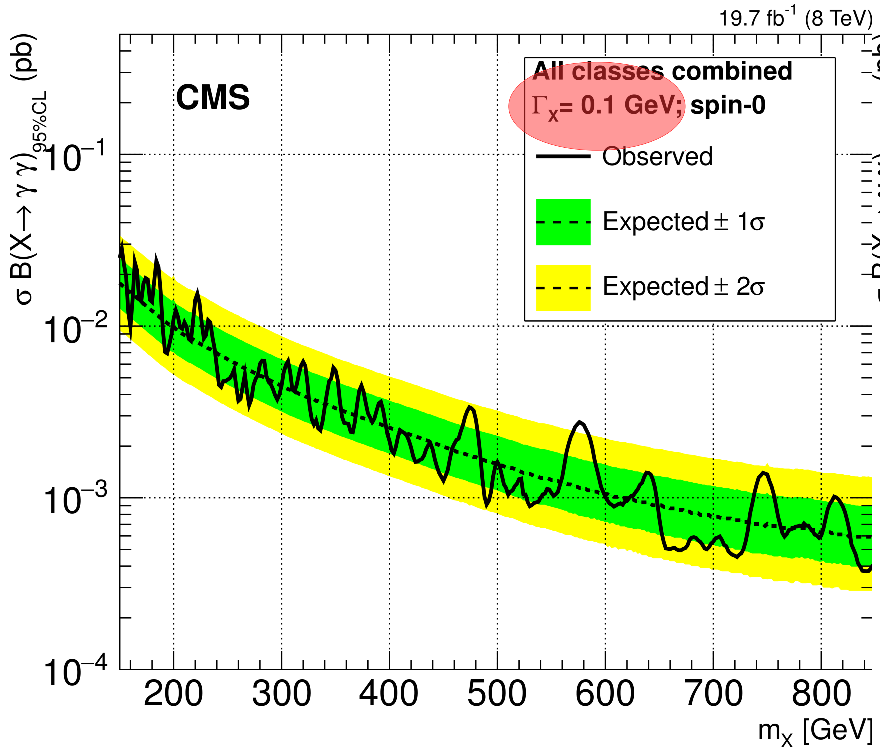


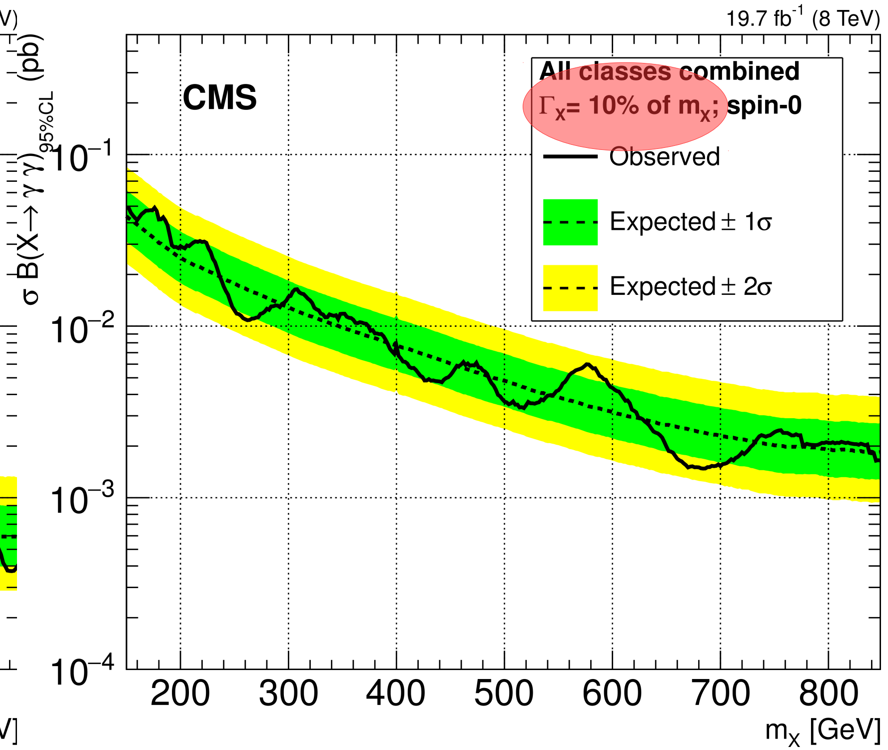
PLB 750 (2015) 494

High mass Higgs boson search in $\gamma\gamma$

- Search in mass range of $m_H = 150 \ldots 850$ GeV .
- Combination of four sub-categories.
- Analysis strategy same as for SM Higgs search.







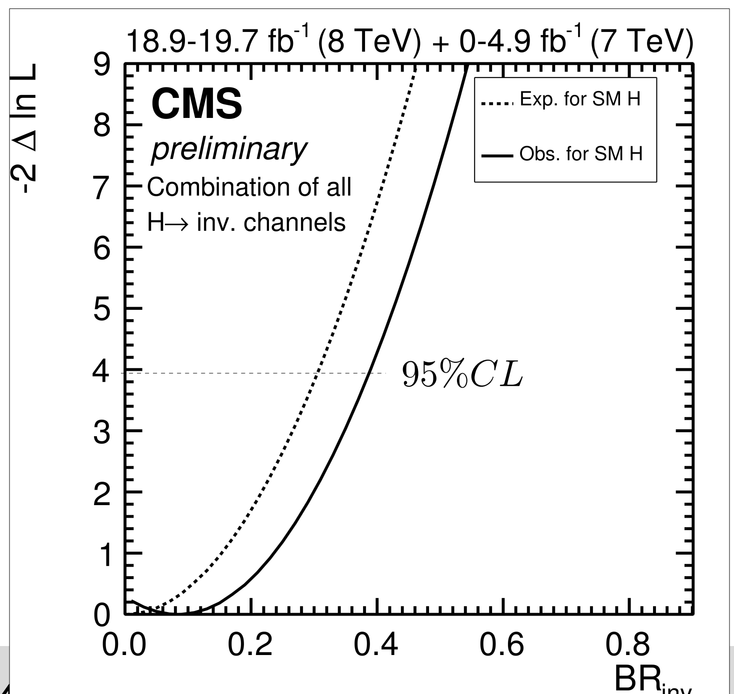
PLB 750 (2015) 494

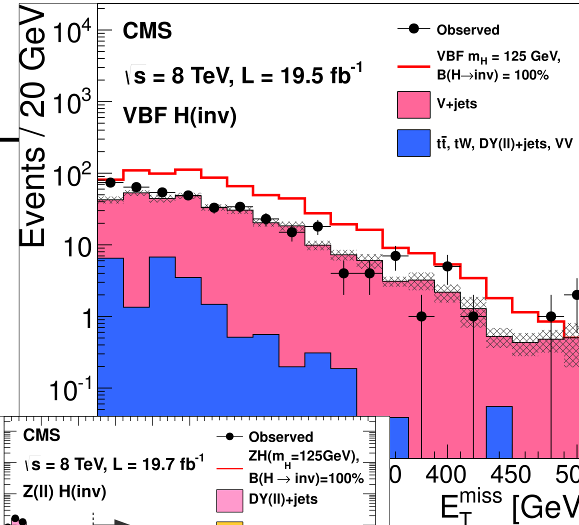
Backup

Searches for $H \to \text{inv.}$

Channel	Observed (expected) upper limits on $\frac{\sigma}{\sigma_{SM}} \cdot \mathcal{BR}(H \to \text{inv.})$
VBF-tagged	0.57 (0.40)
VH-tagged	0.60 (0.69)
ggH-tagged	0.67 (0.71)
Combined	0.36 (0.30)

CMS-PAS-HIG-15-012





EPJC 74 (2014) 2980