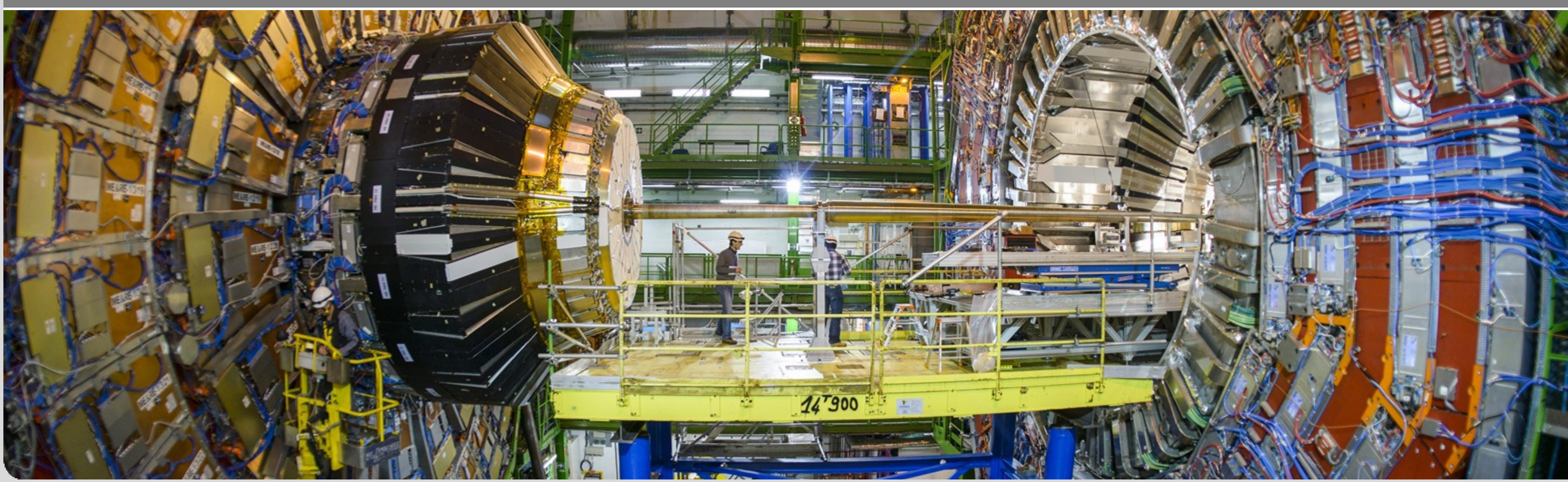
Karlsruhe Institute of Technology

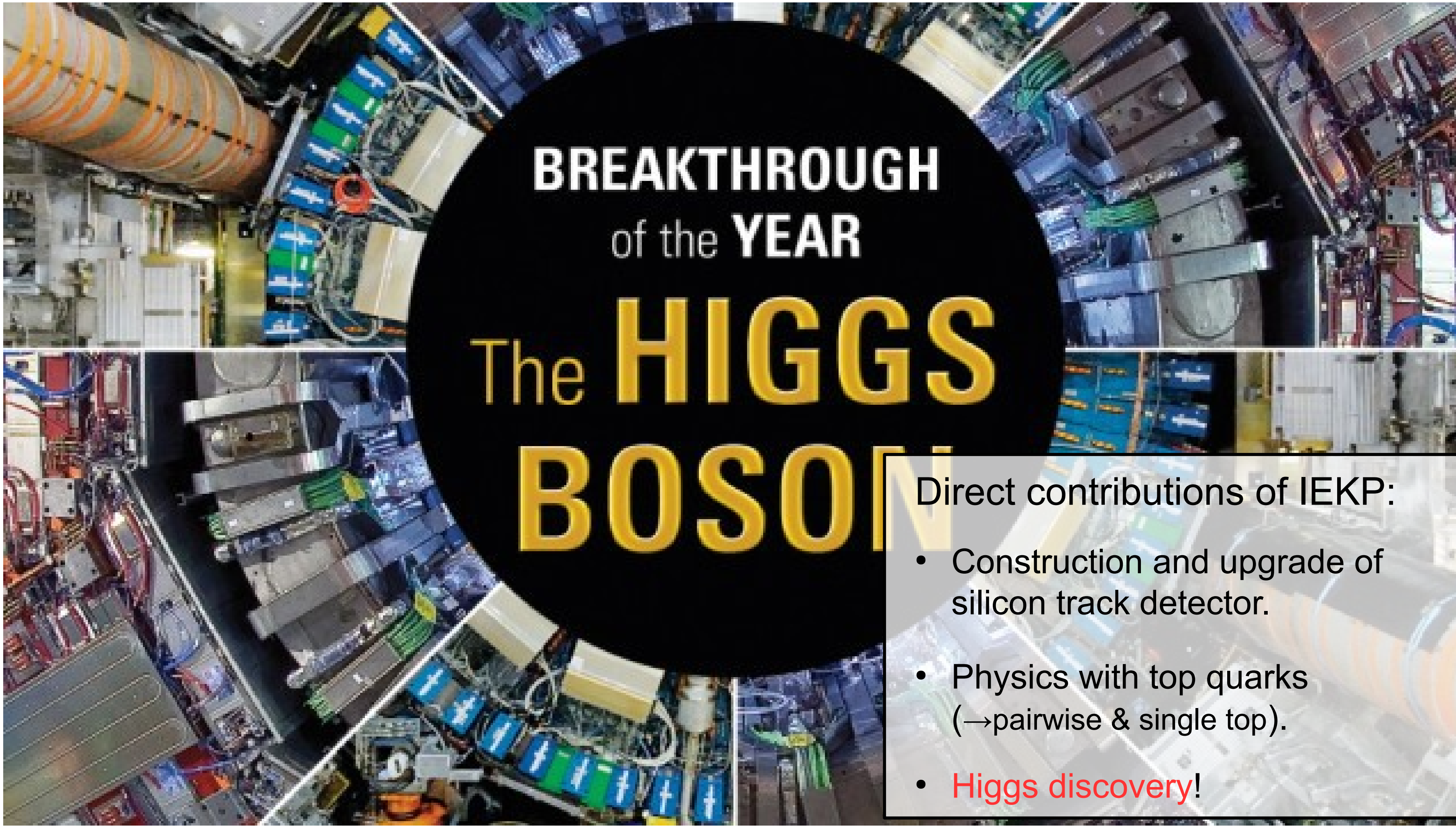
Discovery of the Higgs Boson at the LHC

Roger Wolf, Andrew Gilbert

30. June 2016

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY

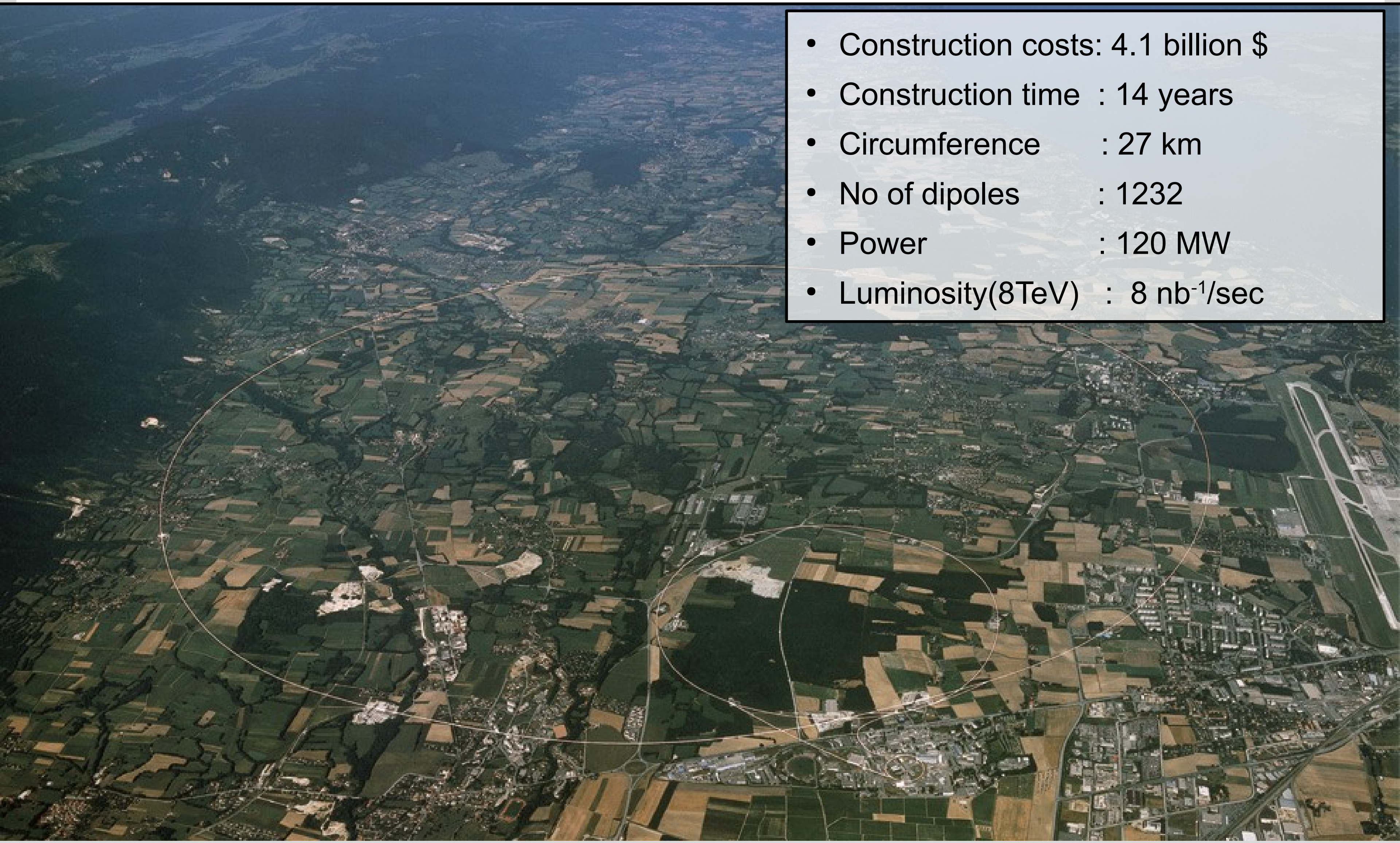




Direct contributions of IEKP:

- Construction and upgrade of silicon track detector.
- Physics with top quarks (→pairwise & single top).
- Higgs discovery!

The Large Hadron Collider



- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb^{-1}/sec

The Large Hadron Collider

Energy radiated off per rotation cycle:

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

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

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

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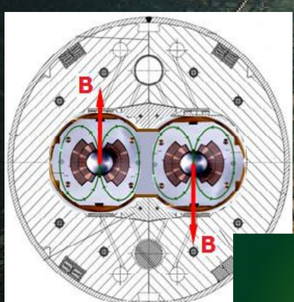
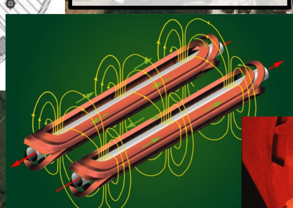
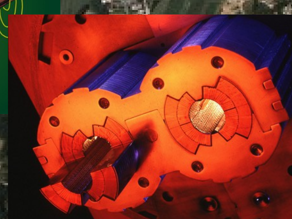


- 8.3 T
- 11.8 kA
- 160 cyc





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

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The Large Hadron Collider

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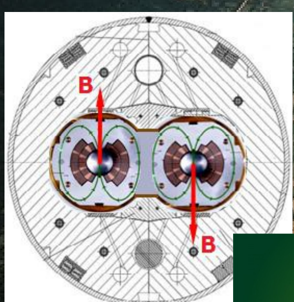

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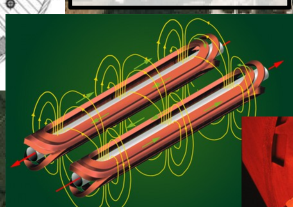

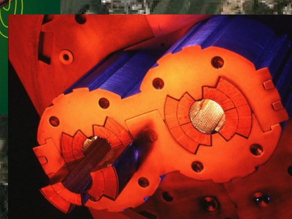

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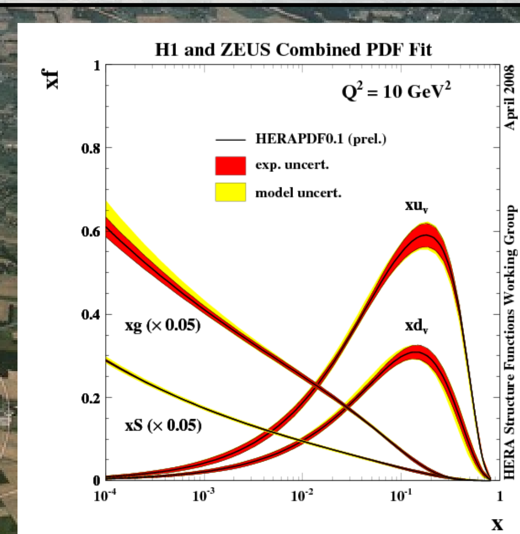

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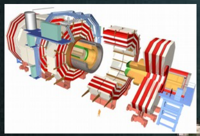

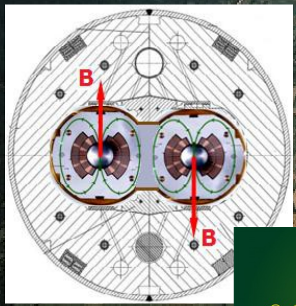

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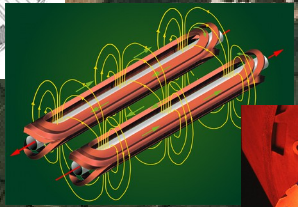

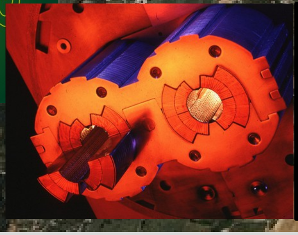

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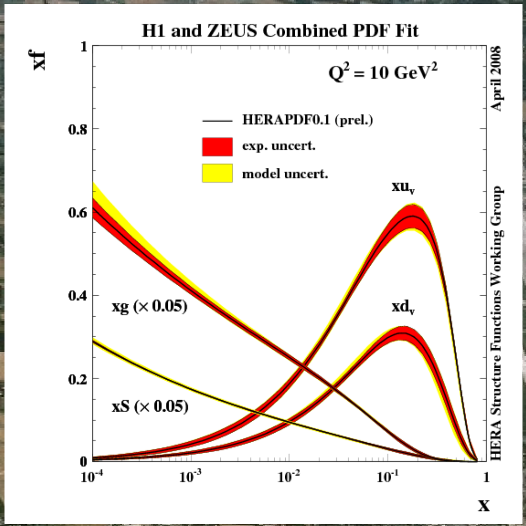
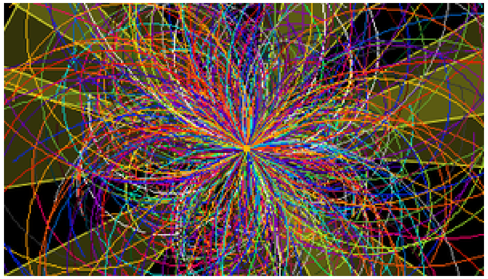
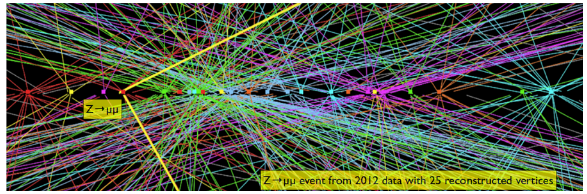
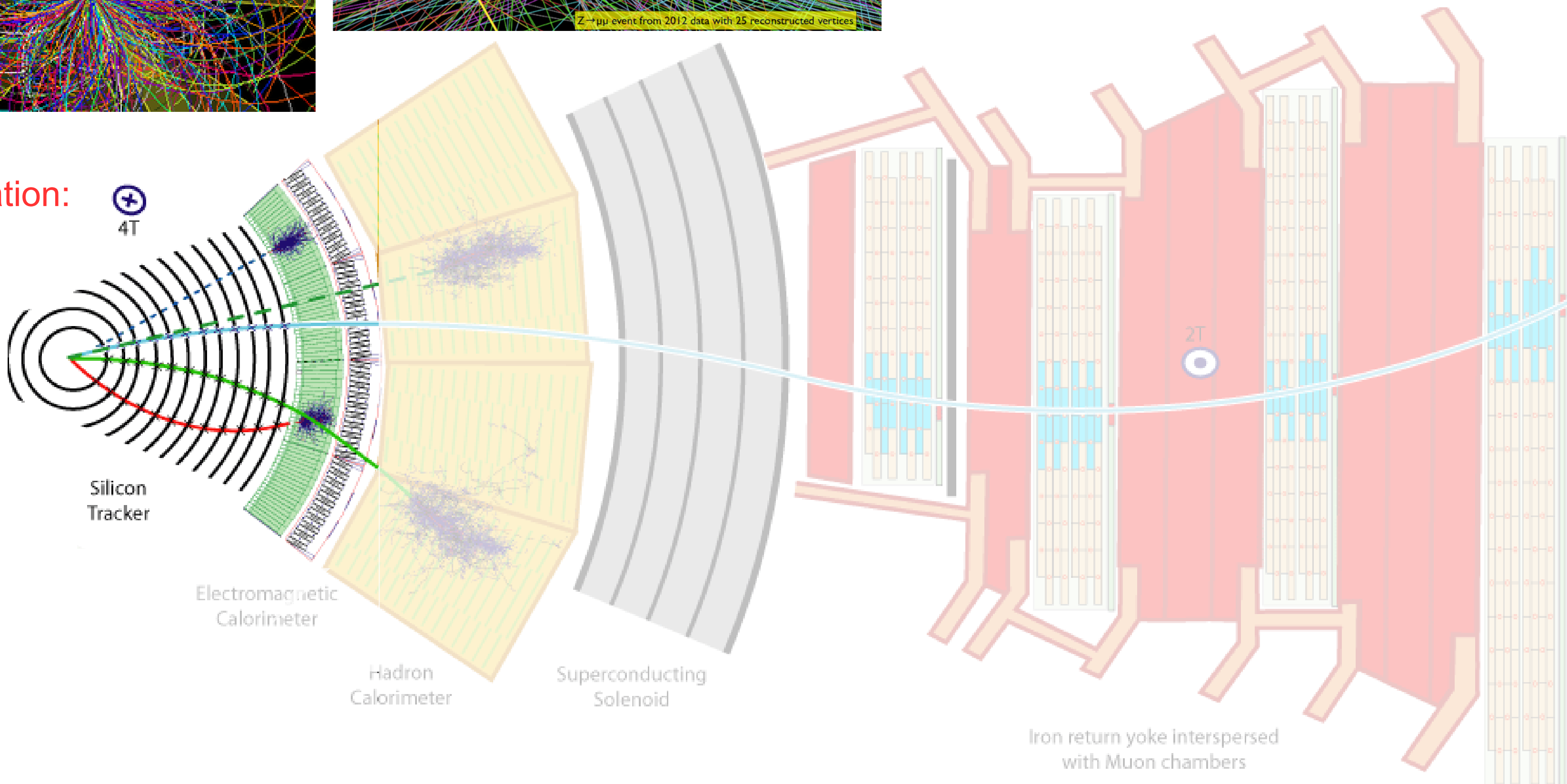


Key demands on Experiments





Vertex identification:



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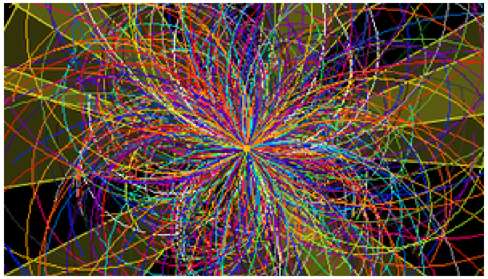

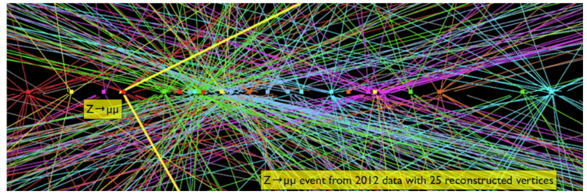

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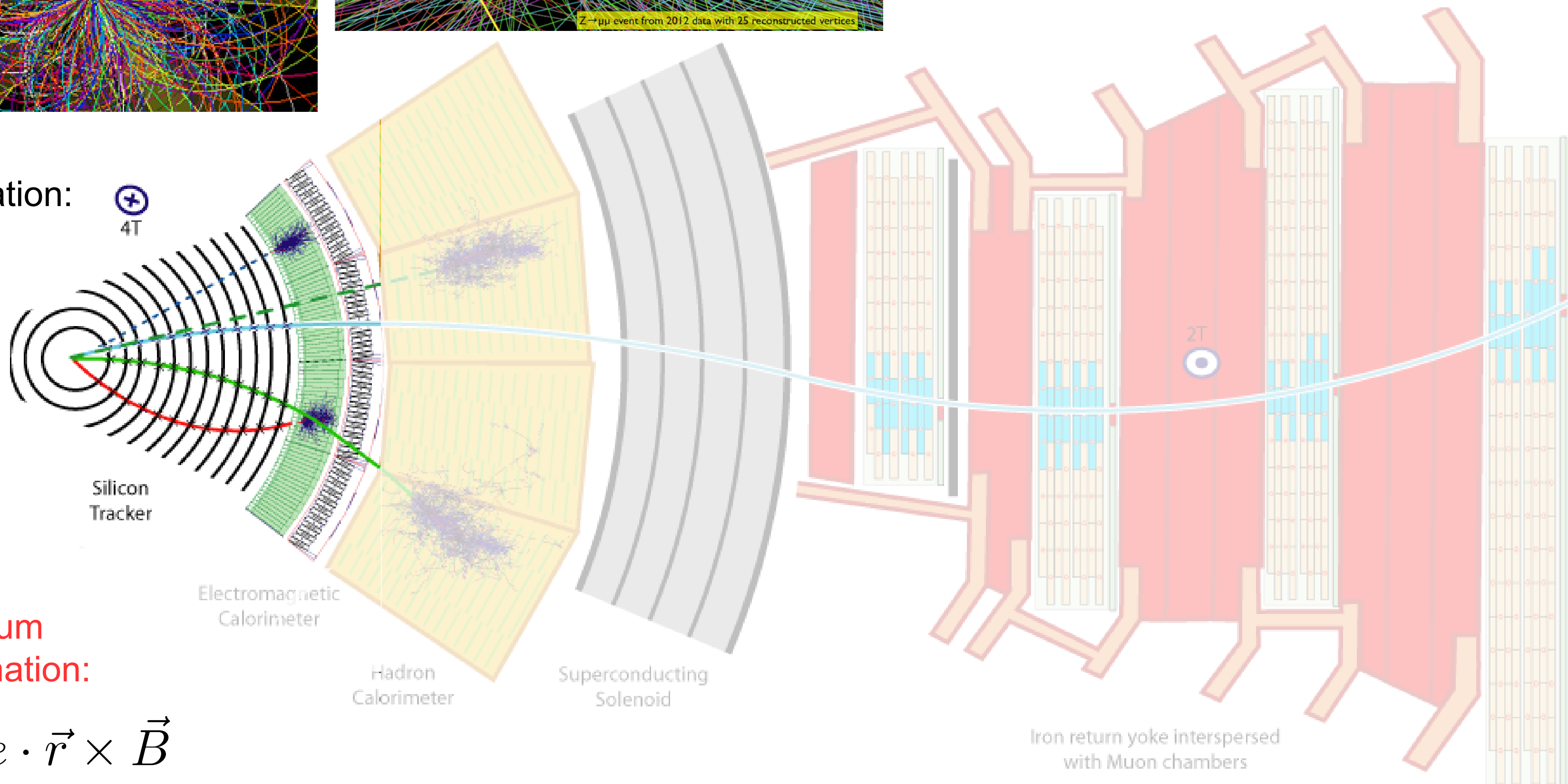

Momentum determination:

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

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

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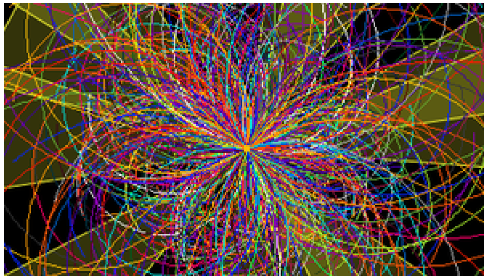

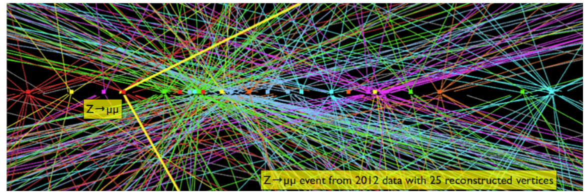

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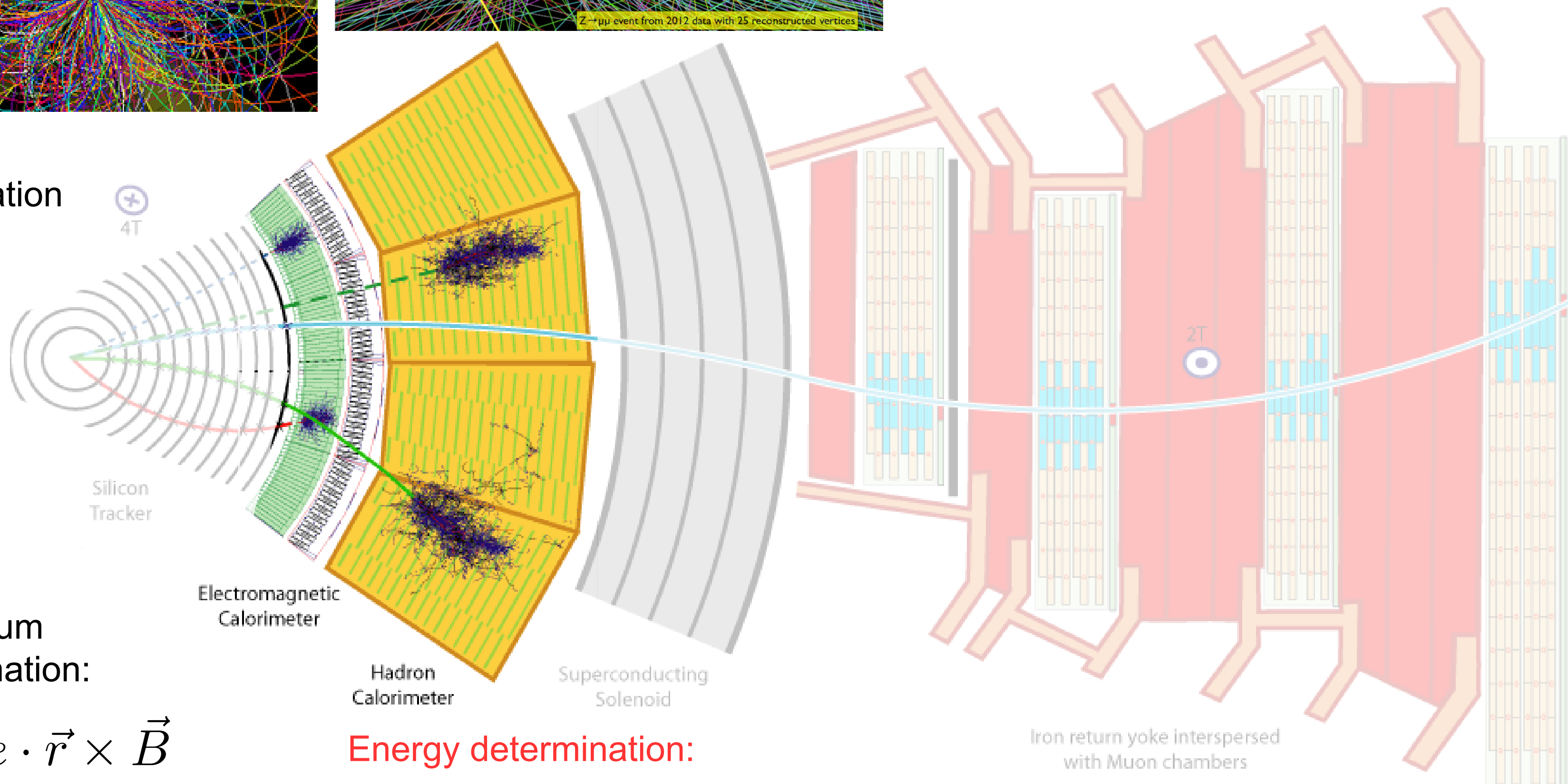

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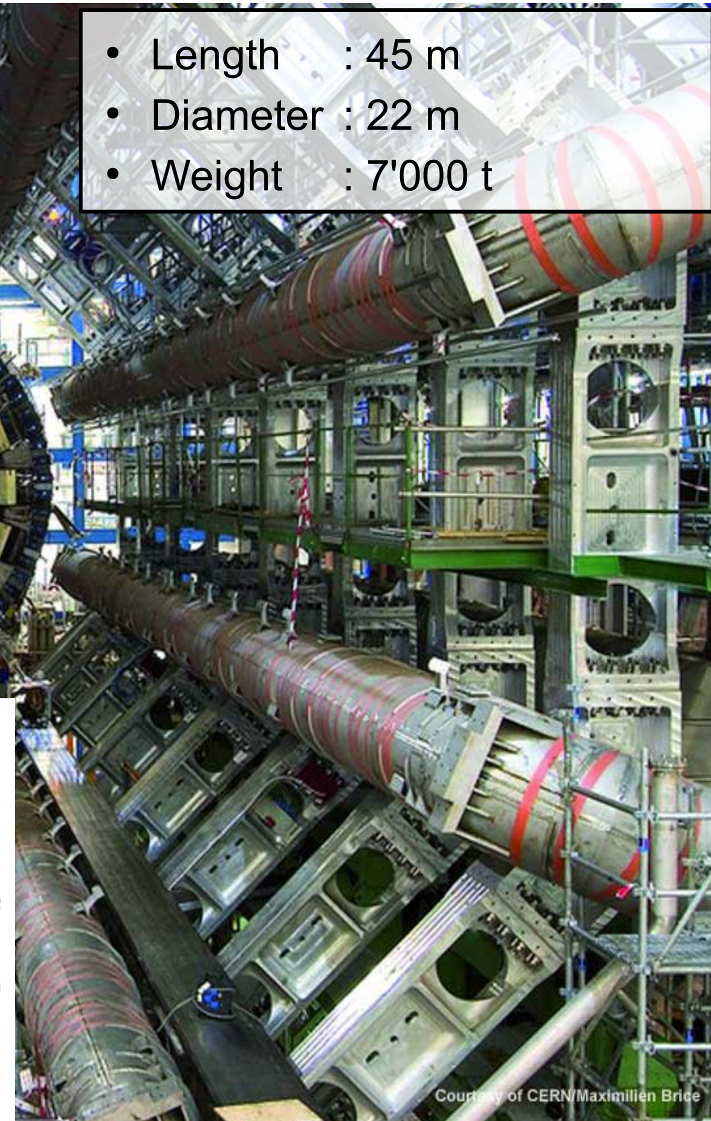
Energy determination:

- Energy resolution
- Stopping power

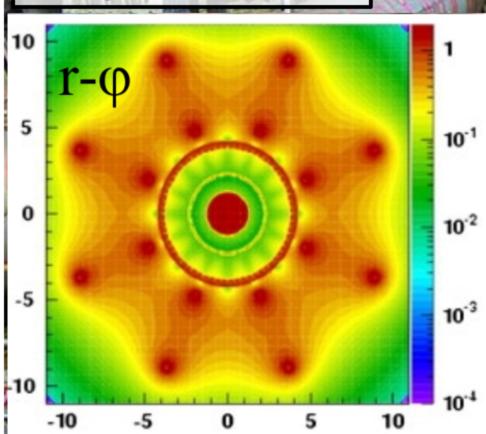
The Large Scale Solution (ATLAS)

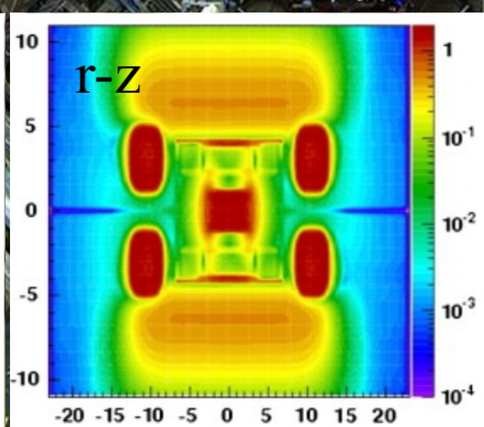


- Magnet field (solenoid): 2.6 T (inside calorimeter)
- Magnet field (toroid): ~4 T (outside calorimeter)
- Tracker: Si/multi-wire chambers
- ECAL/HCAL: LAr (varying granularity)

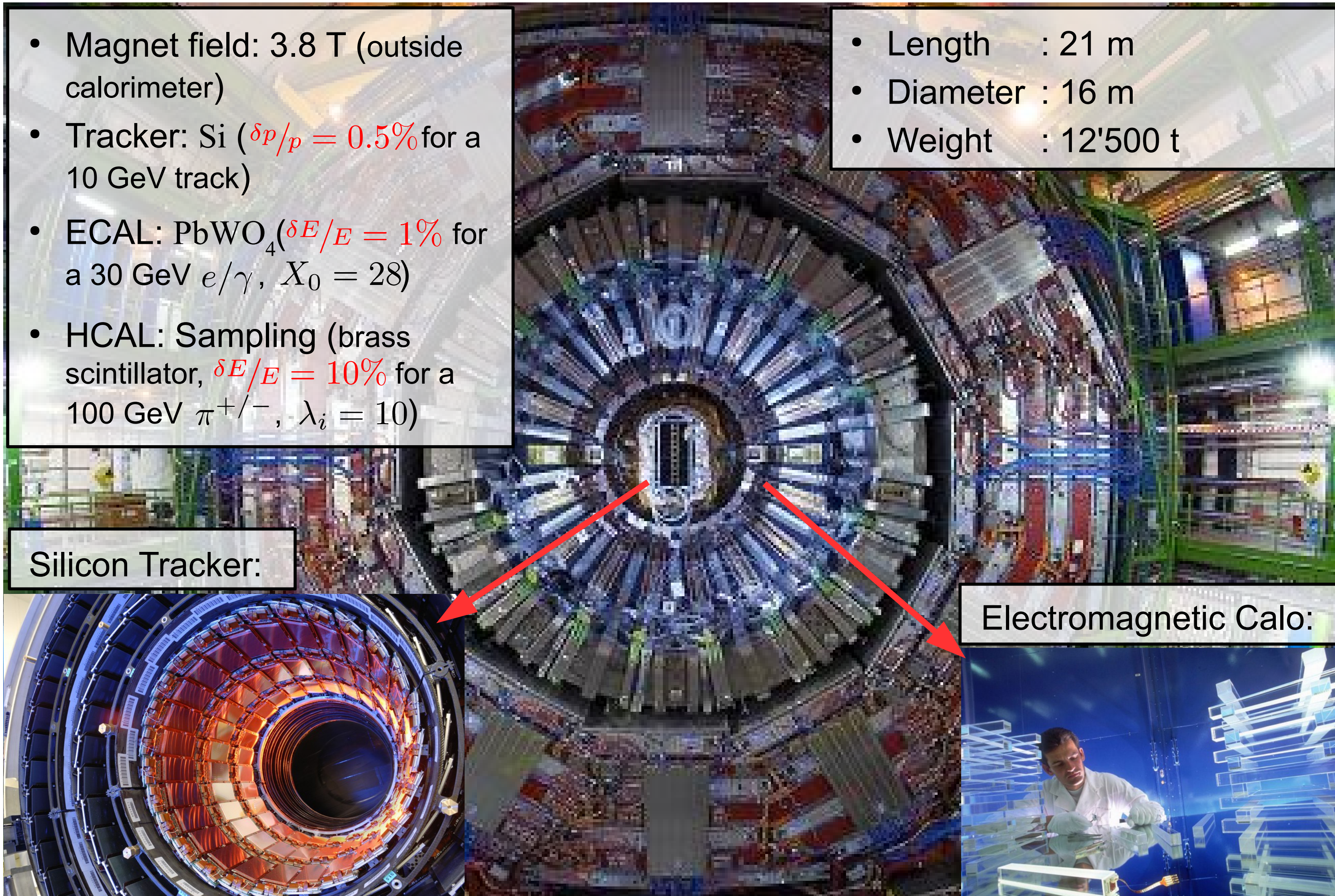
- Length : 45 m
- Diameter : 22 m
- Weight : 7'000 t

Magnet Field:





The Compact Solution (CMS)



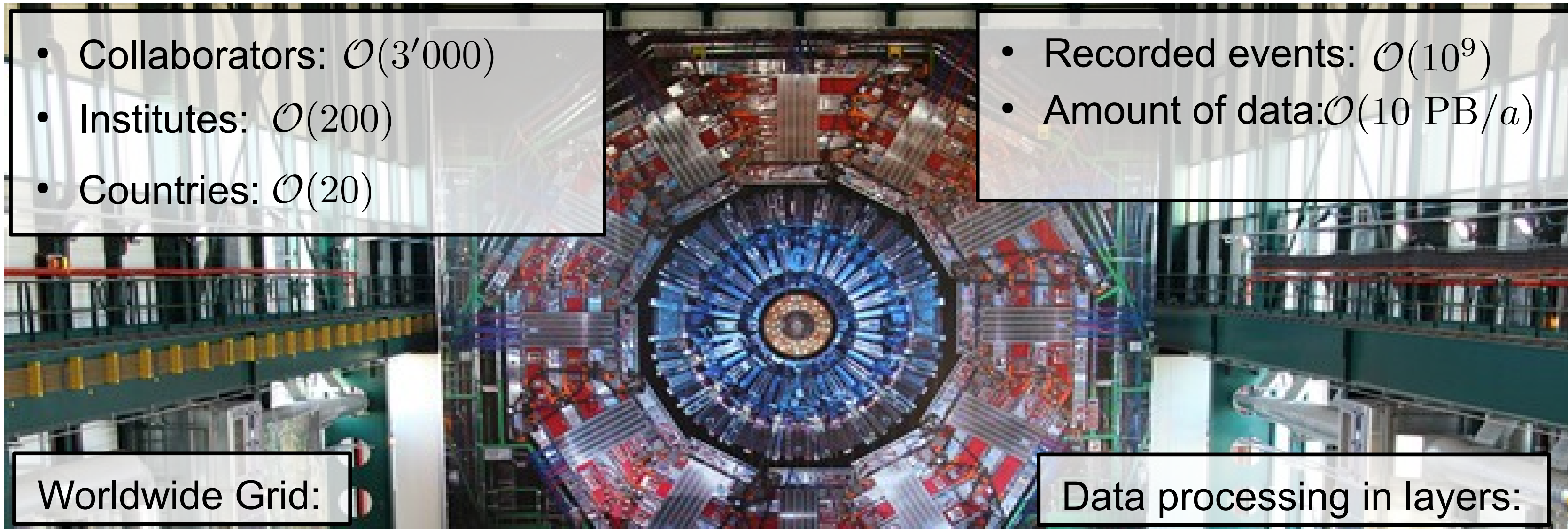
- Magnet field: 3.8 T (outside calorimeter)
- Tracker: Si ($\delta p/p = 0.5\%$ for a 10 GeV track)
- ECAL: $PbWO_4$ ($\delta E/E = 1\%$ for a 30 GeV e/γ, $X_0 = 28$)
- HCAL: Sampling (brass scintillator, $\delta E/E = 10\%$ for a 100 GeV $\pi^{+/-}$, $\lambda_i = 10$)

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

Silicon Tracker:

Electromagnetic Calo:

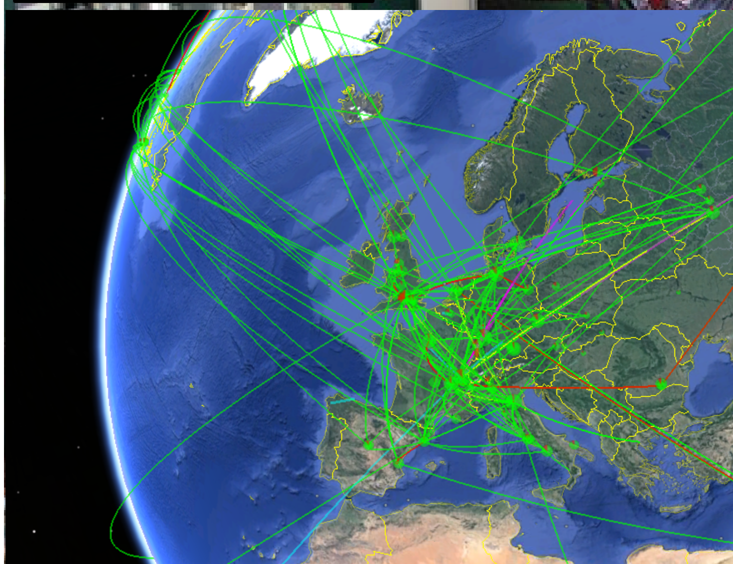
Worldwide Distribution of Data



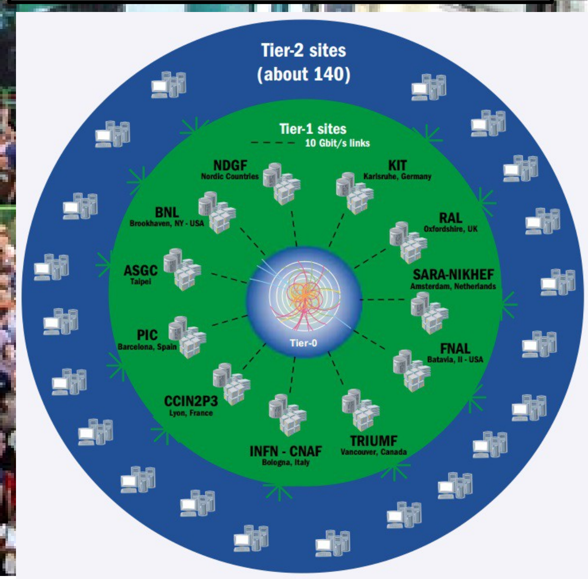
- Collaborators: $\mathcal{O}(3'000)$
- Institutes: $\mathcal{O}(200)$
- Countries: $\mathcal{O}(20)$

- Recorded events: $\mathcal{O}(10^9)$
- Amount of data: $\mathcal{O}(10\ \mathrm{PB}/a)$

Worldwide Grid:



Data processing in layers:

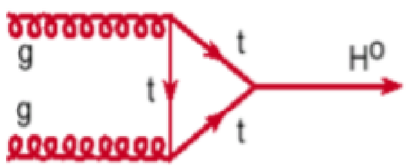


Wanted: Higgs Boson (Dead or Alive)

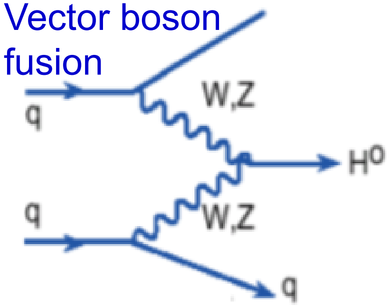
If m_H is given all properties of the (SM) Higgs boson are known:

Production (in proton (anti-)proton collisions)

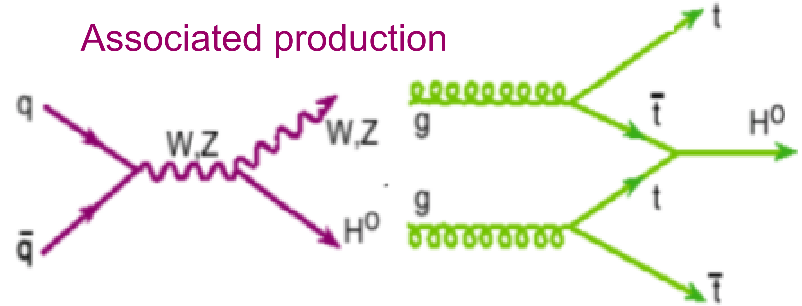
Gluon fusion

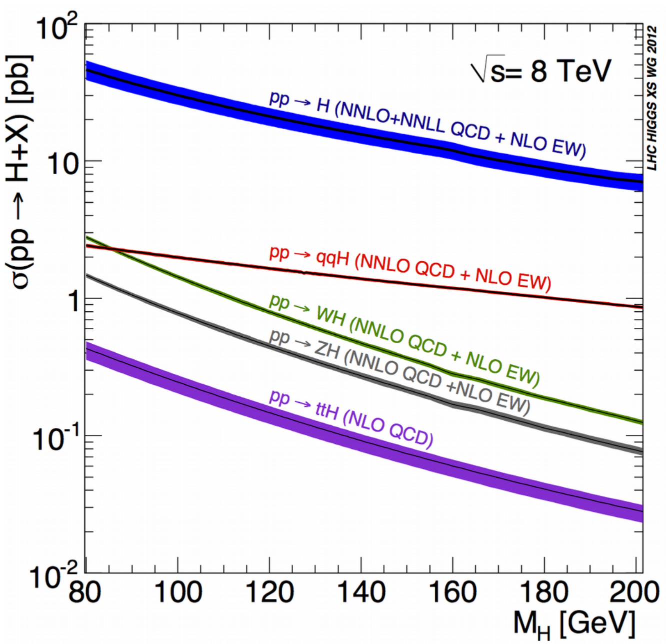


Vector boson fusion



Associated production





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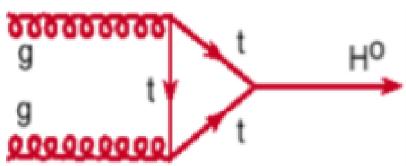

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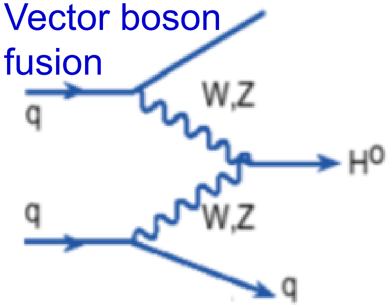

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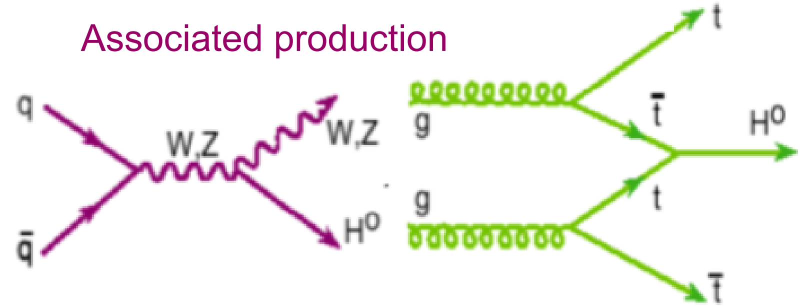
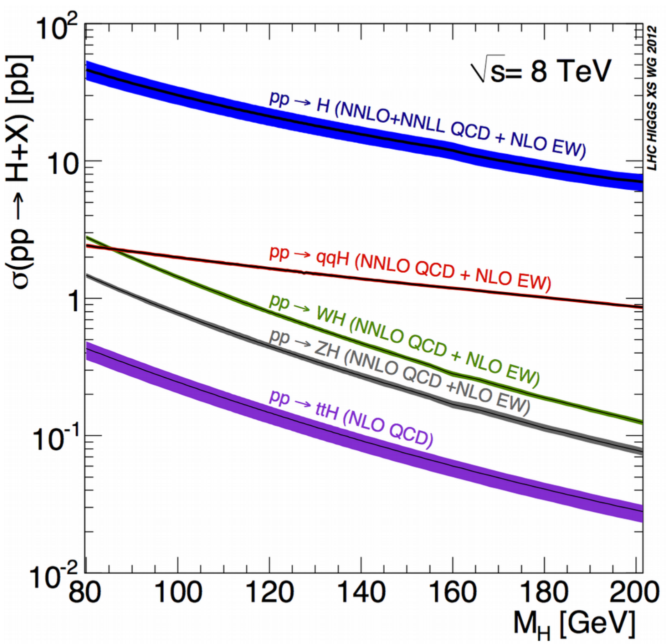
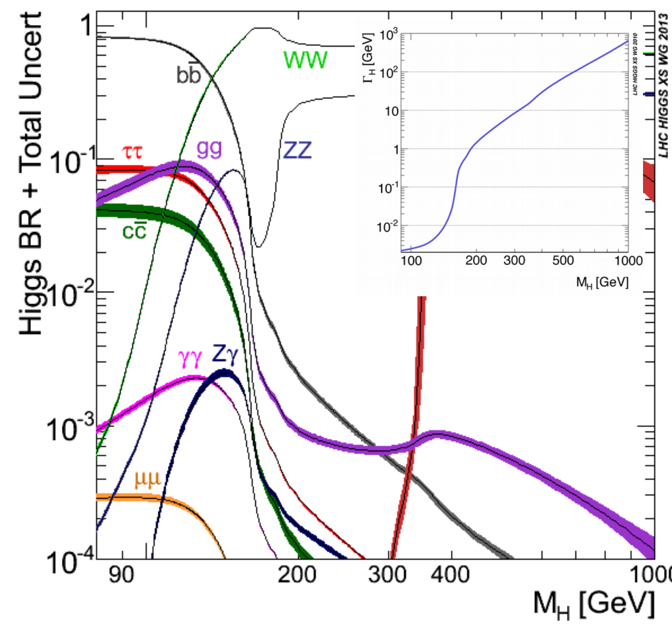




Decay



A Long Road of Theory Developments

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$gg \to H$
- 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 WZ ZZ
- NLO(α_s)
- Precision 10%

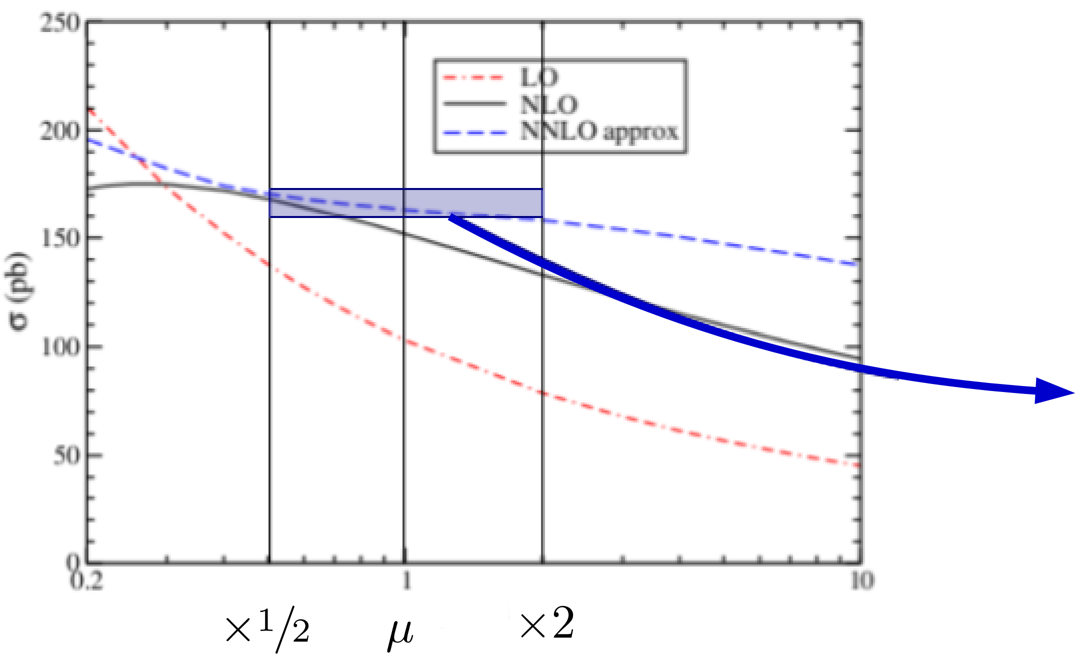
Example: Top Quark Pair Production

		uncertainty	
$\sigma_{t\bar{t}}$ [pb]	order in α_s	scale (μ)	pdf
158	NLO	$^{+23}_{-24}$	
160	NLO	$^{+20}_{-21}$	$^{+5}_{-4}$
164	NNLO(approx)	$^{+5}_{-9}$	$^{+4}_{-5}$
163	NNLO(approx)	$^{+7}_{-5}$	$^{+9}_{-9}$

Kleiss/Stirling '88.

Moch/Uwer '09.

Kidonakis '10.



Scale uncertainty
(NNLO approx) $\lesssim 5\%$

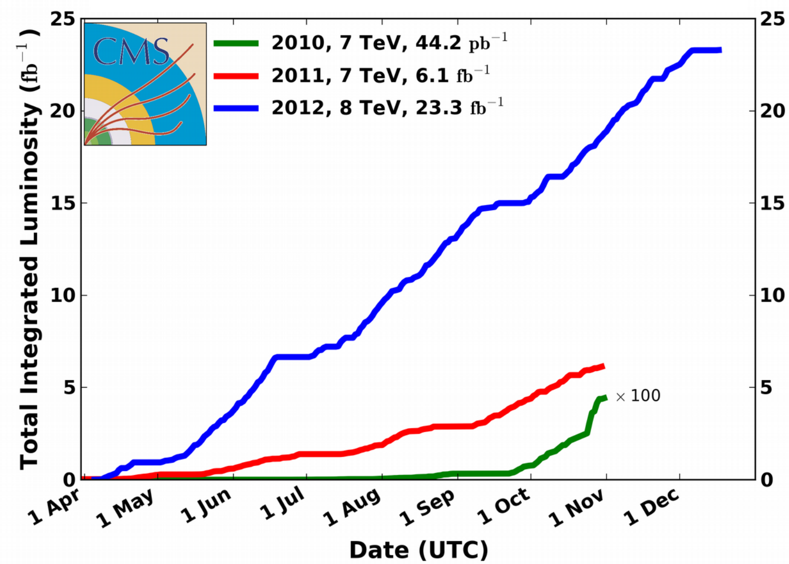
LHC History

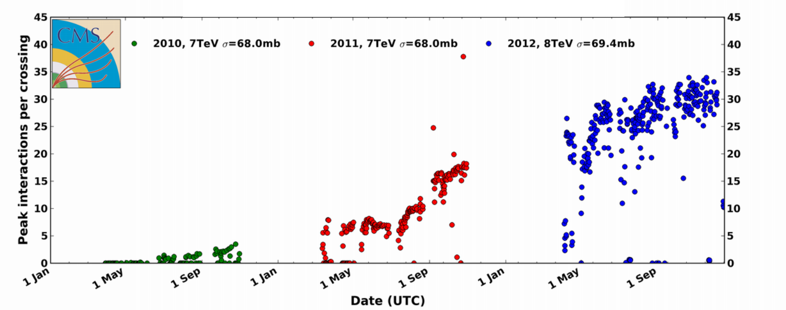
Start 10. September 2008:

Incident 19. September 2008:

- Quench in 100 dipoles.
- Set free 6t of He.
- 53 damaged superconducting magnets.

Restart 20. November 2009:





LHC History (measured in physics measurements)

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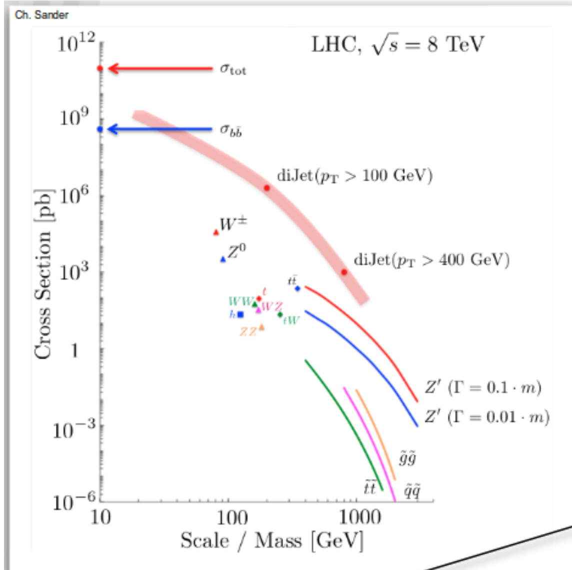
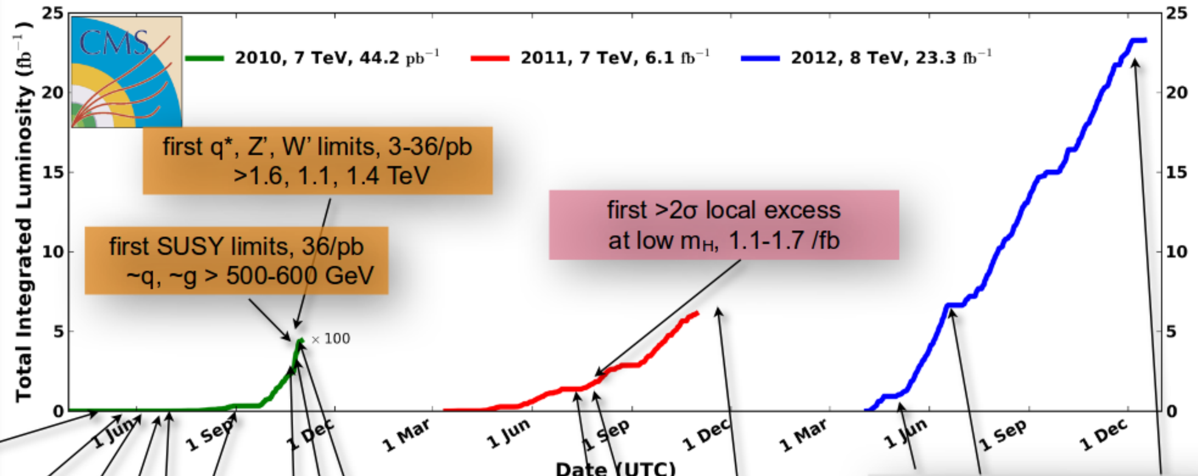




first q*, Z', W' limits, 3-36/pb >1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb ~q, ~g > 500-600 GeV

first >2σ local excess at low m_H, 1.1-1.7 /fb

first MinBias / UE studies, particle multiplicities

first incl. b x-section, 8/nb δ ~ 15 %

first incl. jet x-section, PF jets 60/nb δ ~ 20-30%

first incl. W/Z x-sections, 200/nb δ ~ 4-6%, +11% lumi

first incl. J/Ψ x-section, 100/nb δ ~ 20%

first top xsec, 3/pb δ ~ 40%

first single top xsec, t-chan., 36/pb δ ~ 36%

first m_{top}, 36/pb Δ ~ 6.5 GeV

first WW xsec, 36/pb δ ~ 40% first limit on HWW

first ZZ xsec, 1.1 /fb δ ~ 40%

going more differential, e.g. Z/W + j,b,c

first significant limit on $B_s \rightarrow \mu\mu$, BR<1.9x10⁻⁸

first particle discovered by CMS: Ξ_b

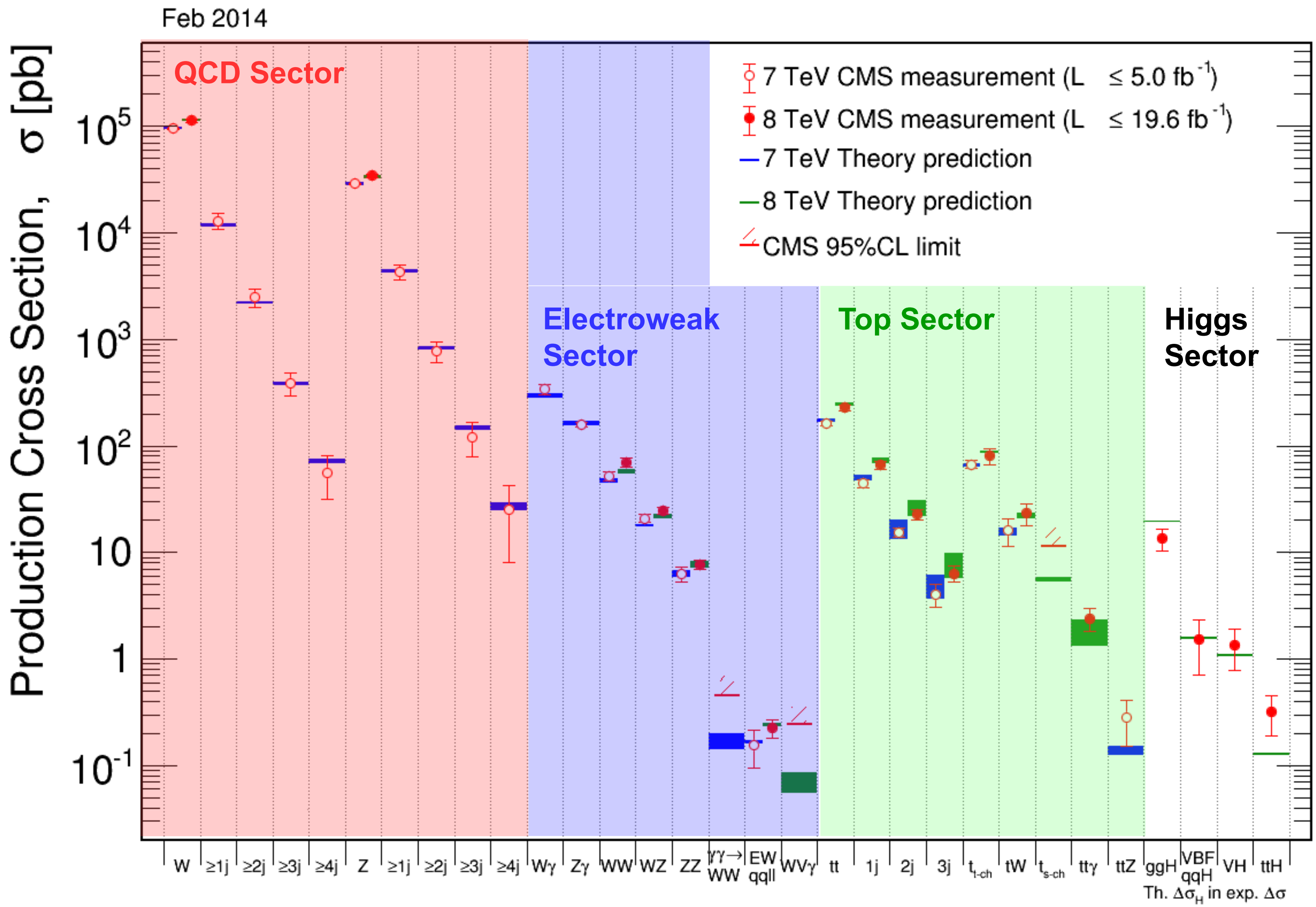
BSM searches continue, limits pushed

repeating the program at 8 TeV

a new boson is announced, 5 /fb

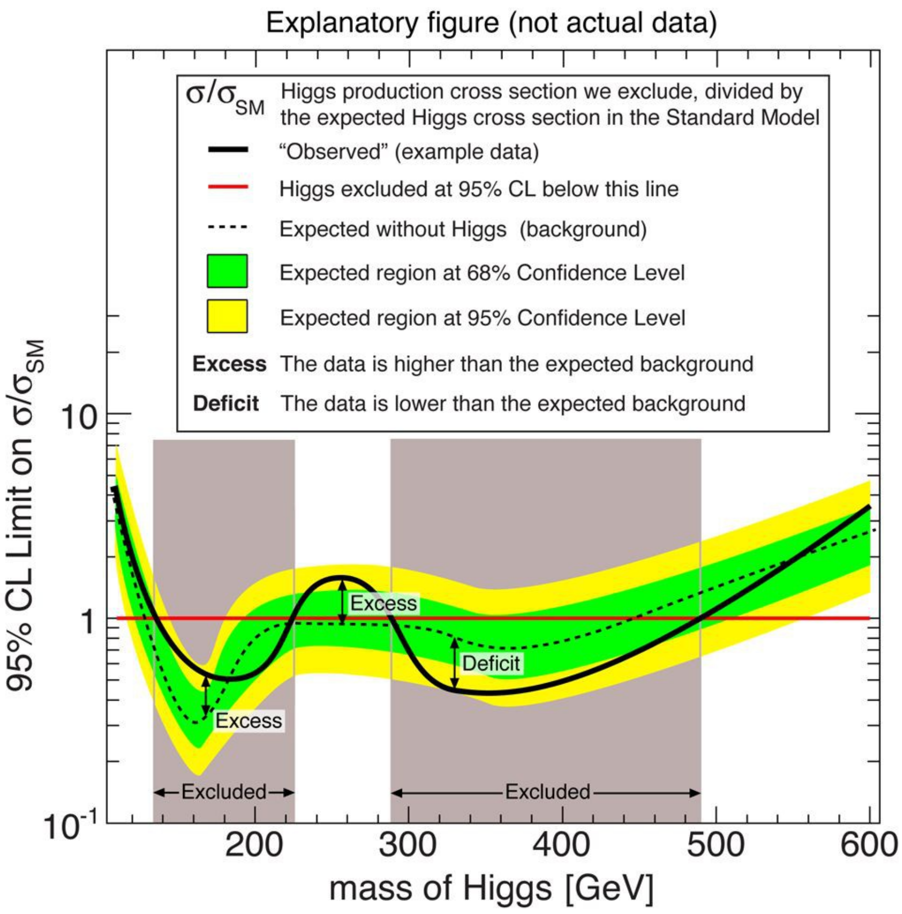
first spin parity analysis of the boson, 17 /fb

First SM Measurements 2010-2012

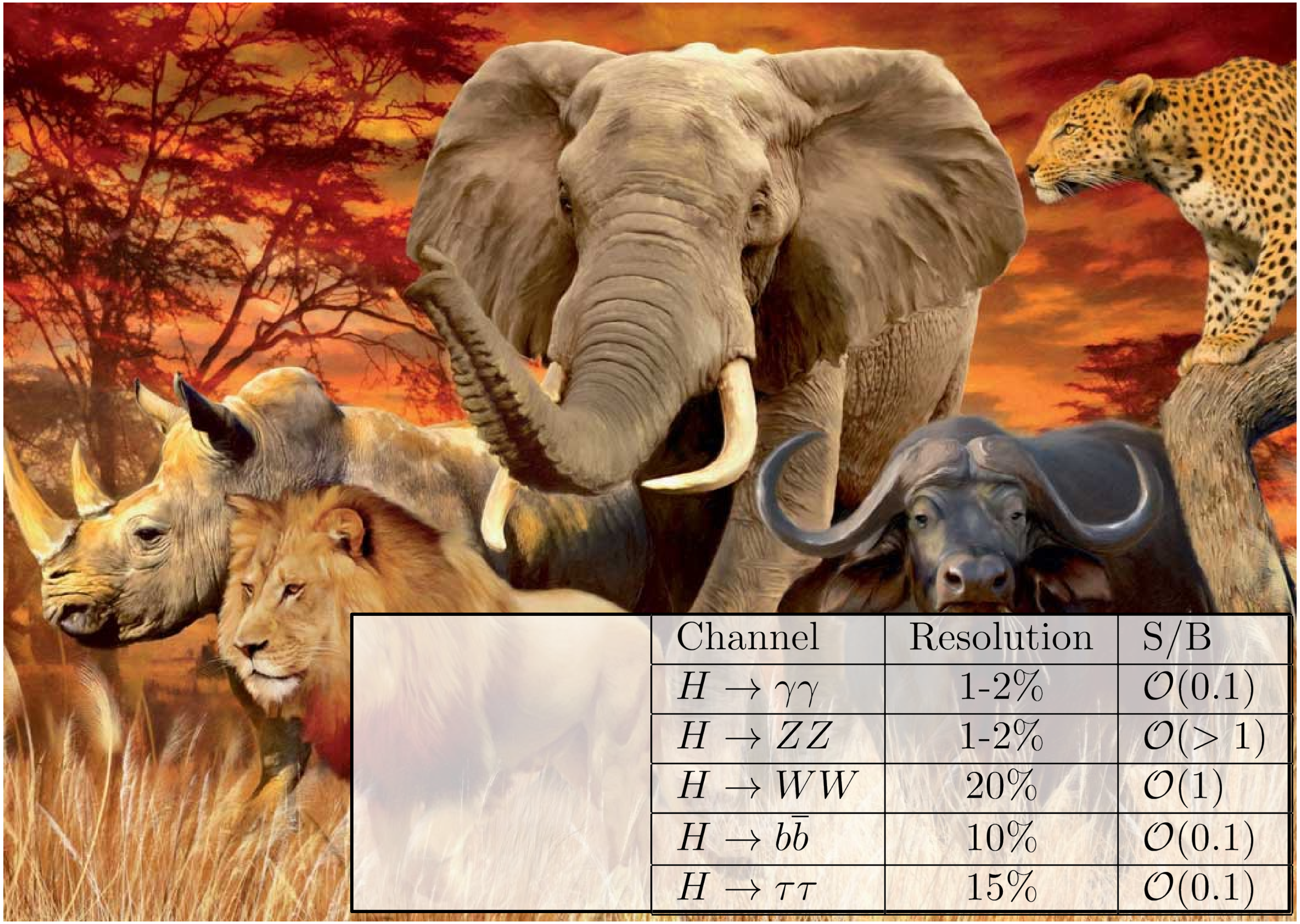


Search for the Higgs Boson 2011-2012

* for us finding the Higgs it was
48 years = 1,513,728,000 sec



Most Important Decay Channels



Channel	Resolution	S/B
$H \to \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
$H \to ZZ$	1-2%	$\mathcal{O}(> 1)$
$H \to WW$	20%	$\mathcal{O}(1)$
$H \to b\bar{b}$	10%	$\mathcal{O}(0.1)$
$H \to \tau\tau$	15%	$\mathcal{O}(0.1)$

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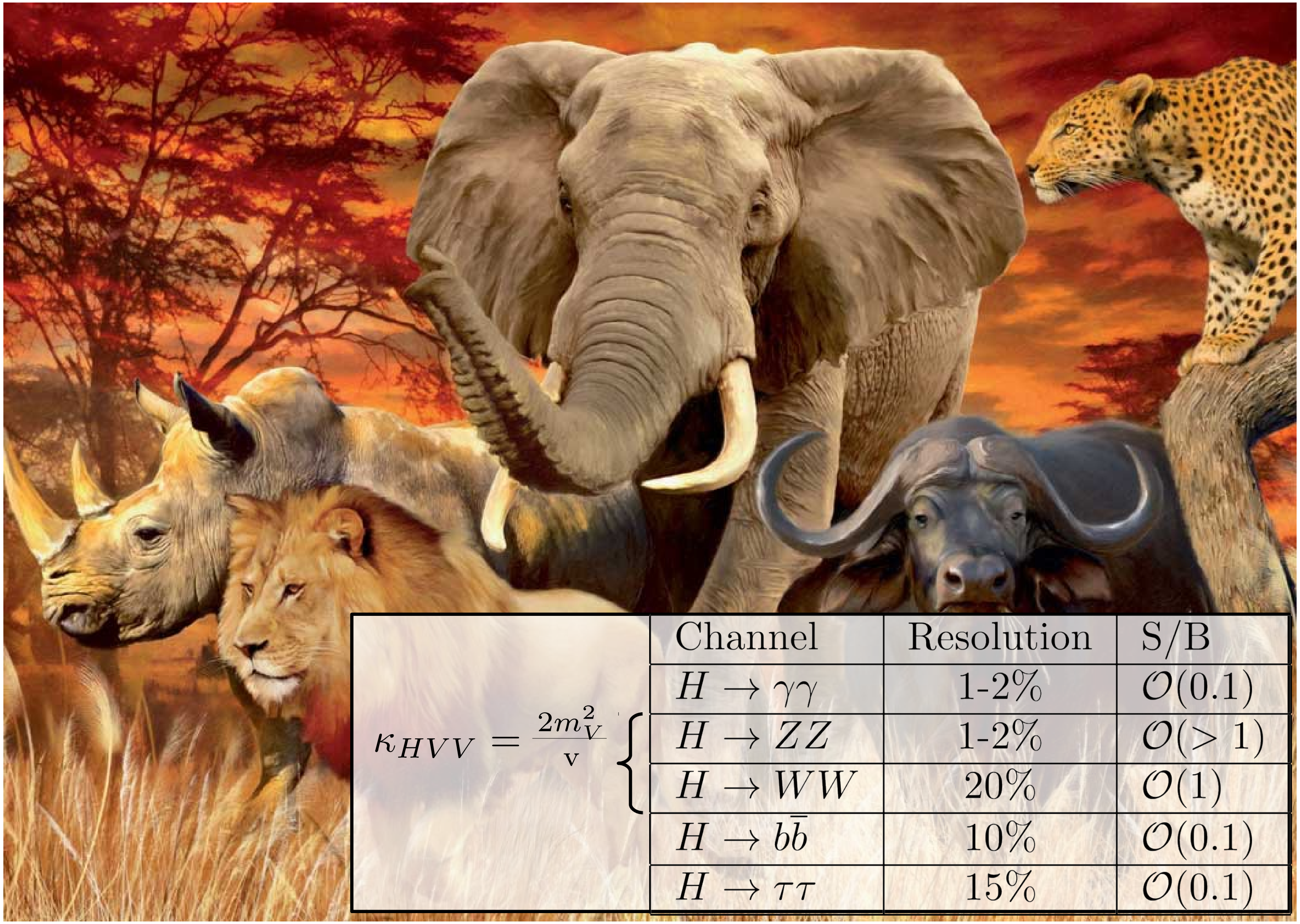

$$\kappa_{HVV} = \frac{2m_V^2}{\mathrm{v}}$$

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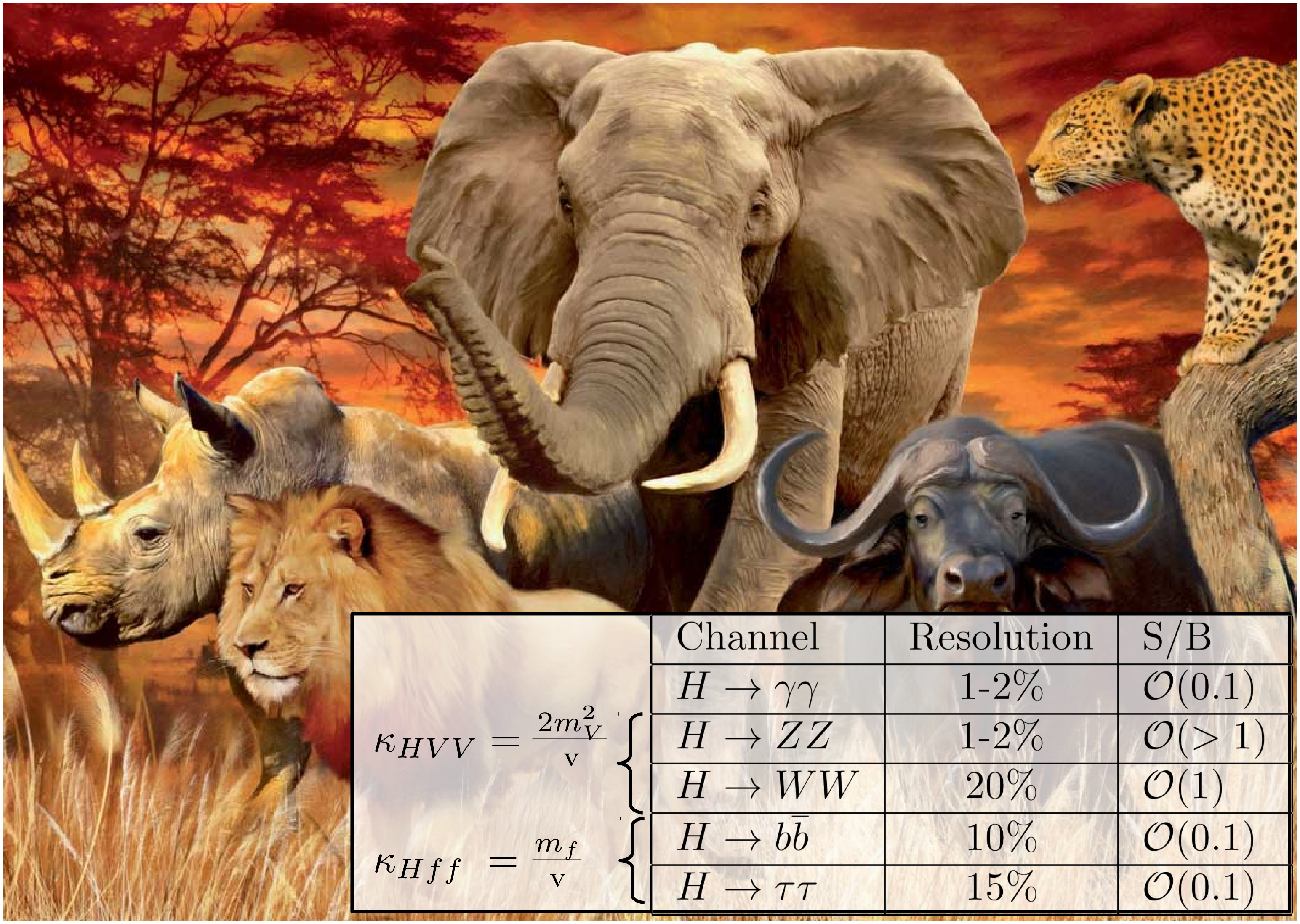
$H \to WW$	20%	$\mathcal{O}(1)$
$H \to b\bar{b}$	10%	$\mathcal{O}(0.1)$
$H \to \tau\tau$	15%	$\mathcal{O}(0.1)$

Most Important Decay Channels



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

Pre-Discovery – February 2012

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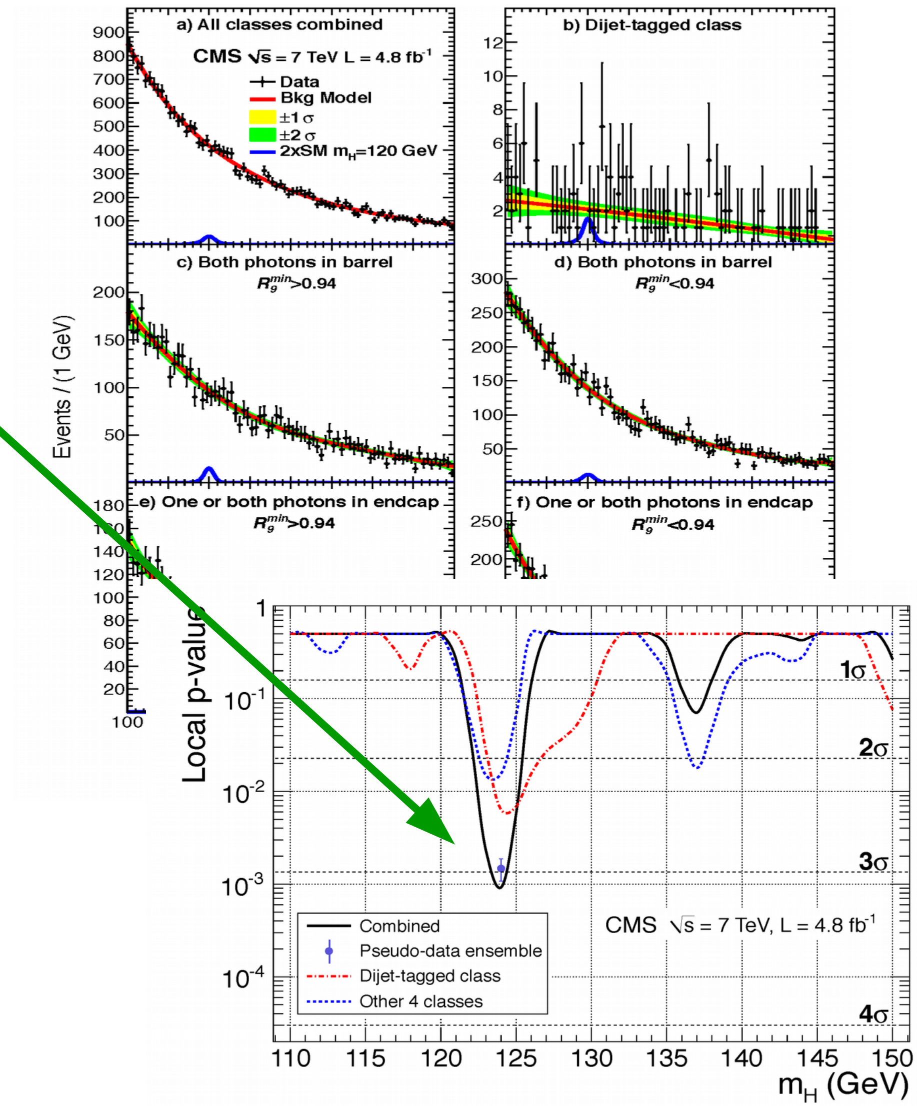
- Analysis of full 2011 dataset ~ 5 fb^{-1}
- Hints start to appear...
- **H→γγ:**
  - **3.1σ** local significance at $m_{\gamma\gamma}$=124 GeV
- This is high, but must be careful!
  - Searching a wide mass range – background fluctuations can appear anywhere: **Look-elsewhere effect**
- **“global” significance only 1.8σ**
- One of the reasons we demand **5σ** for discovery...



Discovery of a new particle 4th July 2012

Discovery of a new particle 4th July 2012

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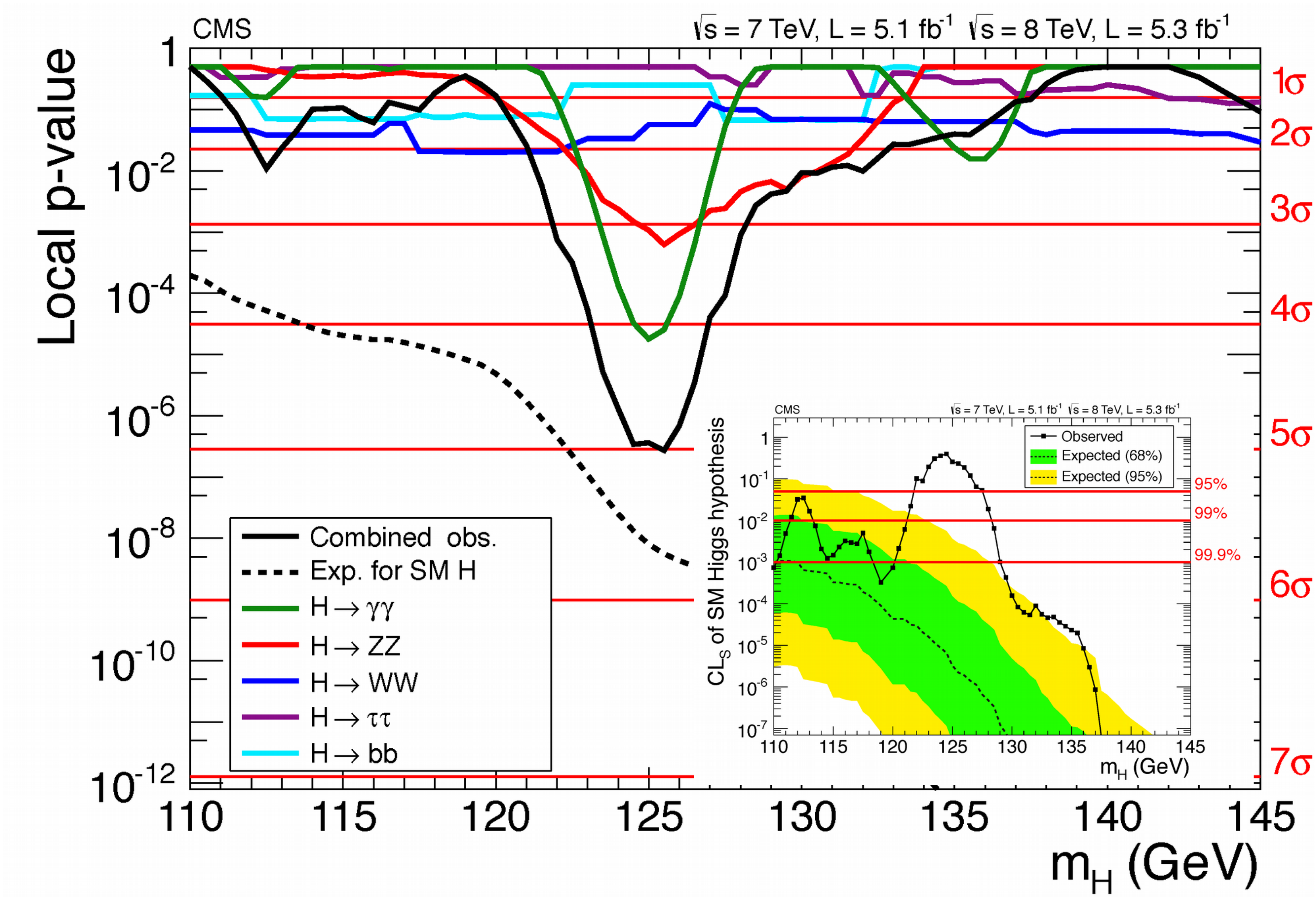
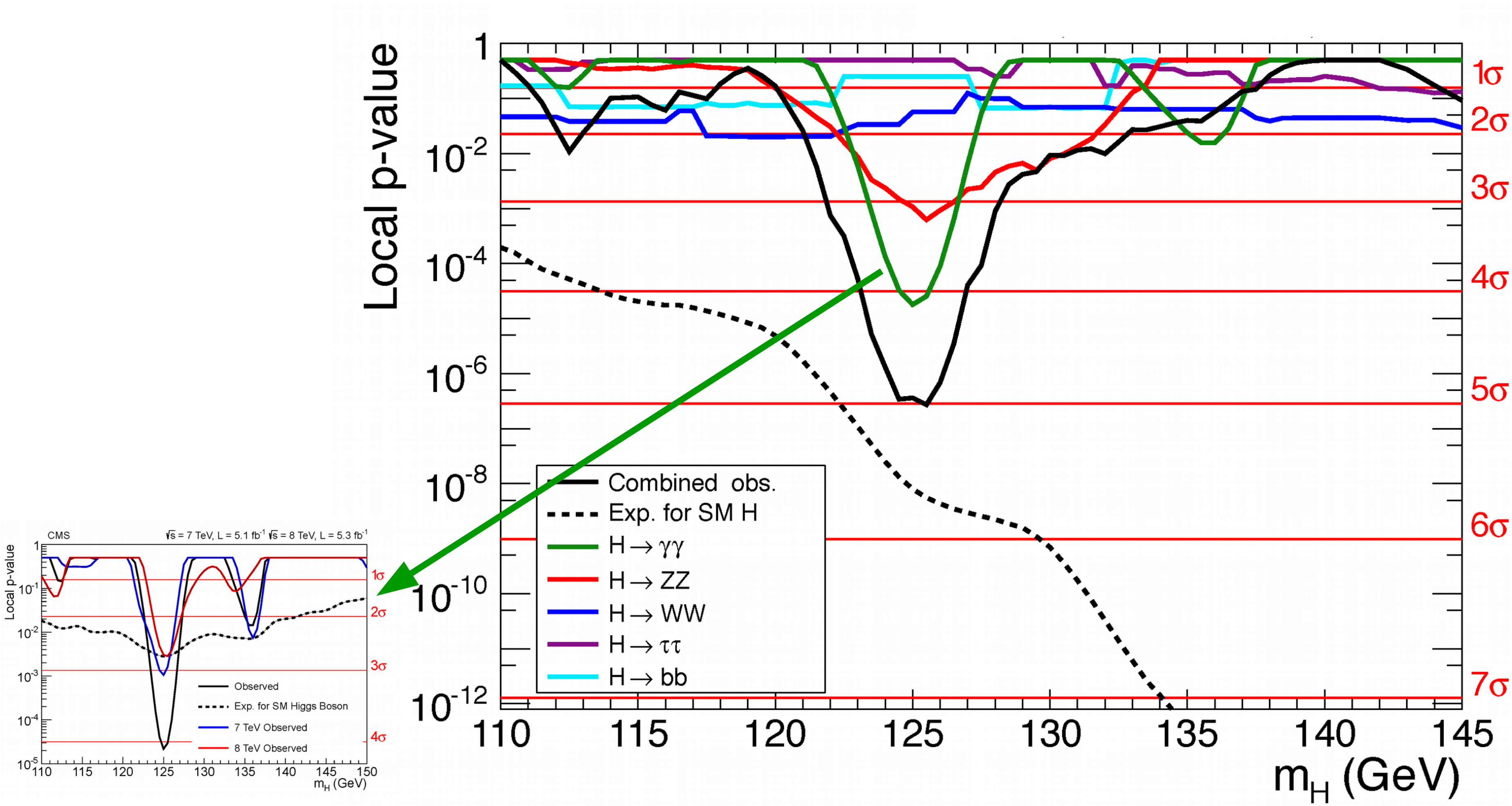
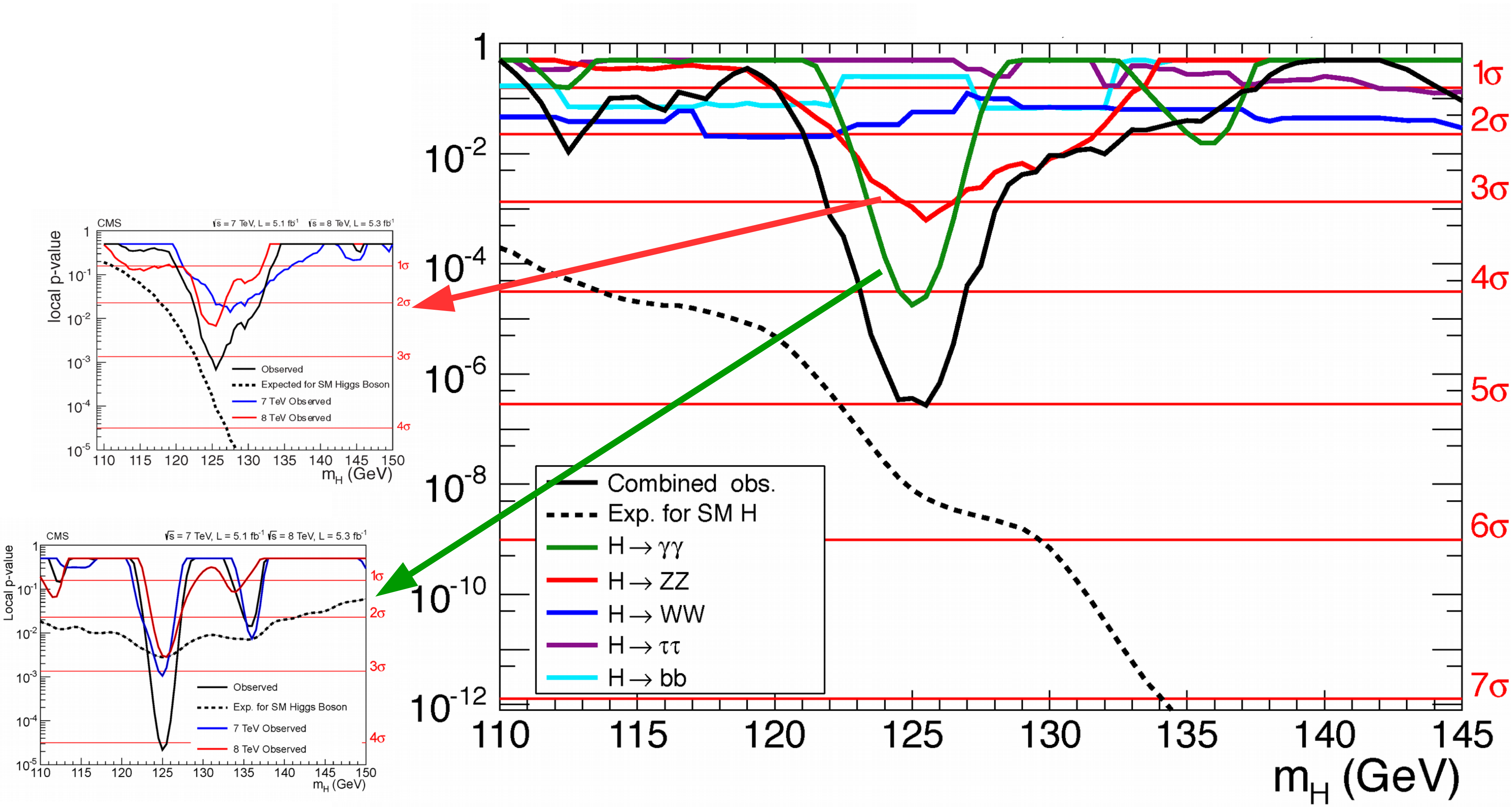
- Scratching magic 5σ boundary.
- Discovery driven by $H \to \gamma\gamma$ and $H \to ZZ$ (high resolution channels).
- Broad moderate excesses for $H \to WW$ and $H \to bb$.
- No signal seen in $H \to \tau\tau$.



Discovery of a new particle 4th July 2012



Discovery of a new particle 4th July 2012



Discovery of a new particle 4th July 2012

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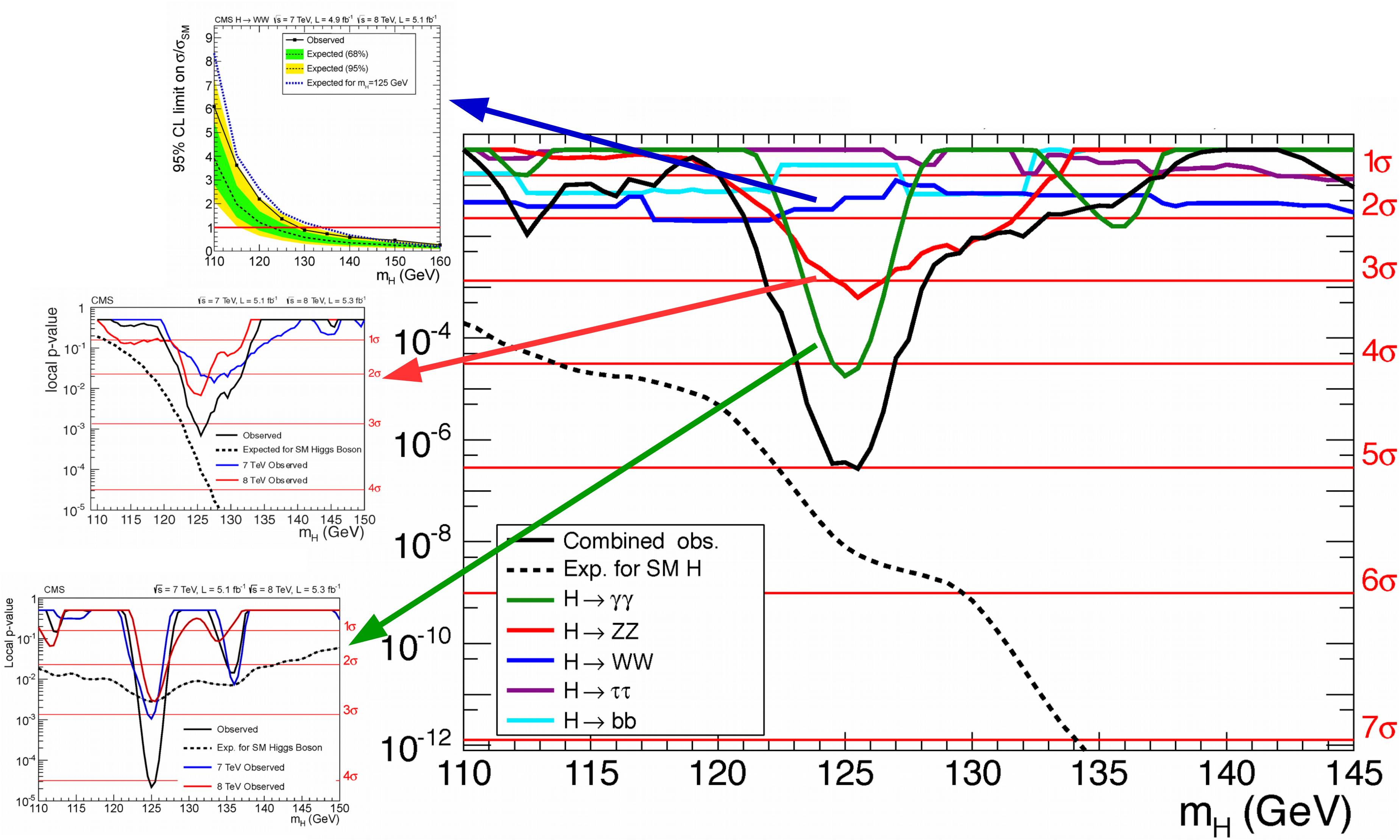
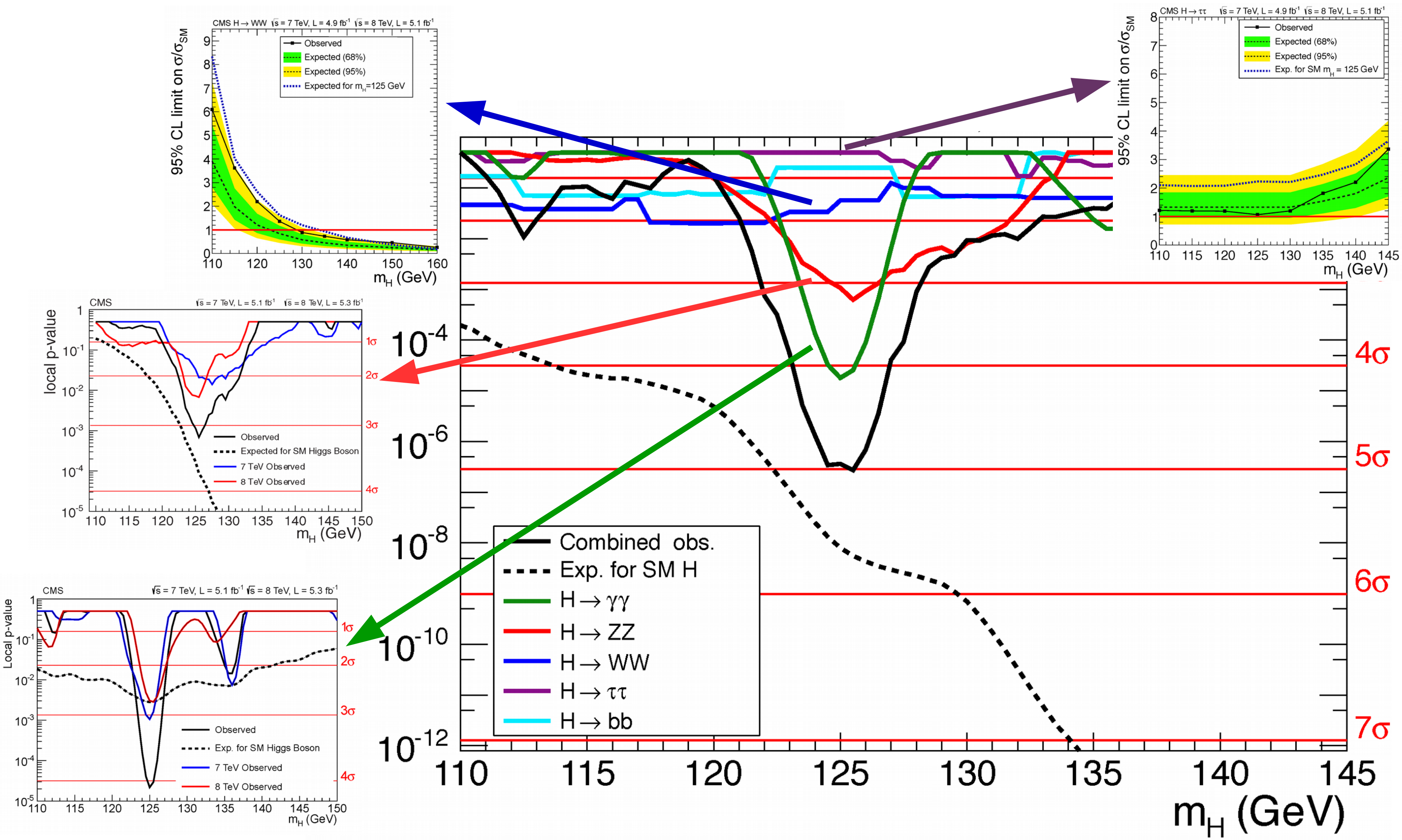
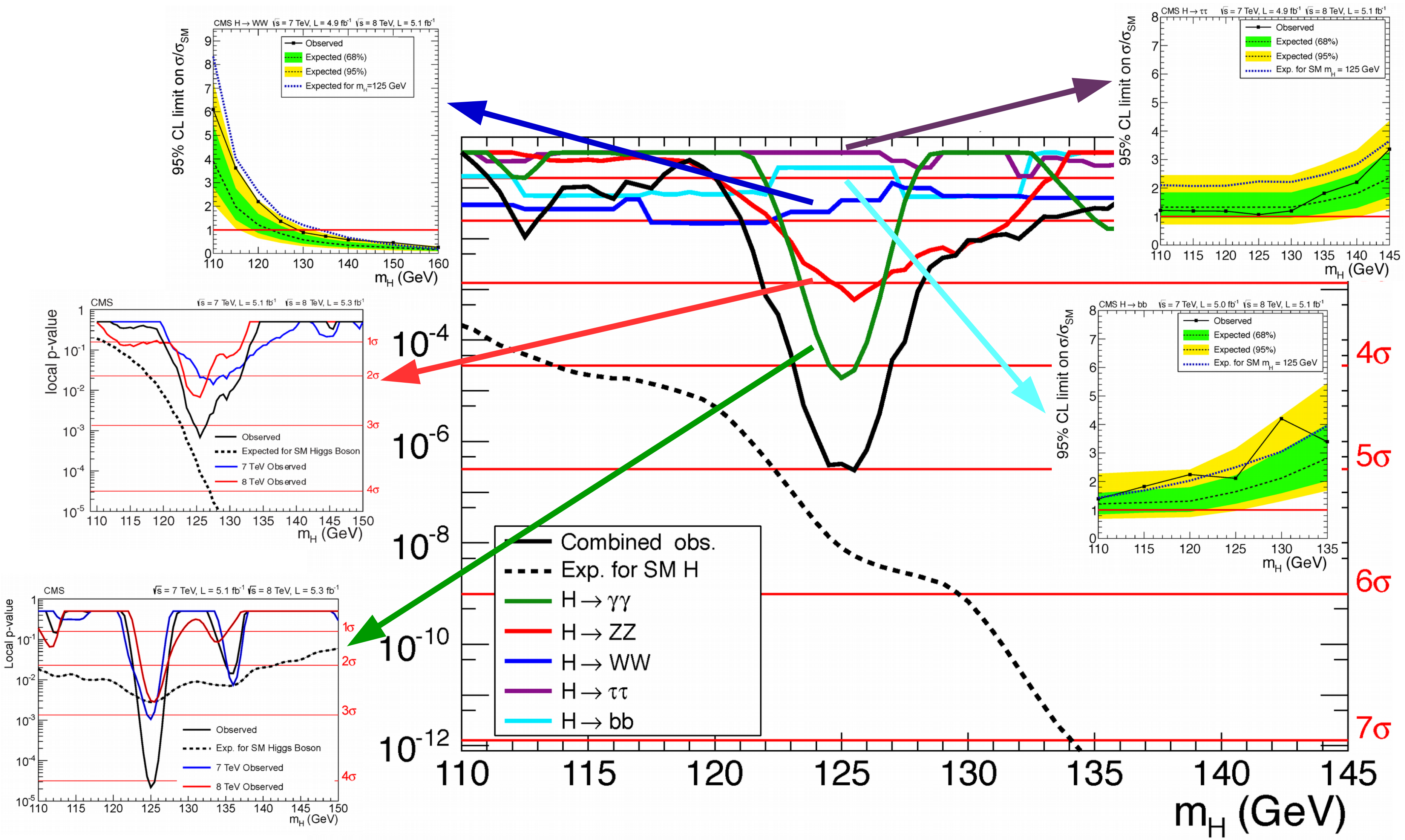


Discovery of a new particle 4th July 2012



Discovery of a new particle 4th July 2012



What Happened Since Then?

- Briefly discuss each channel and its peculiarities.
- Go through all five decay channels and discuss what happened to them since 4th July 2012?
- Make 2 pit-stops:

Status July 2012:		
• ICHEP summer conference (Sydney) • Discovery (with $\mathcal{L} \approx 10\ fb^{-1}$ @ $7\ \mathrm{TeV}$ & $8\ \mathrm{TeV}$ equal share).		

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Status July 2012:	Status March 2013:	
• ICHEP summer conference (Sydney)	• Moriond spring conference (La Thuille)	
• Discovery (with $\mathcal{L} \approx 10\ fb^{-1}$ @ $7\ \mathrm{TeV}$ & $8\ \mathrm{TeV}$ equal share).	• Preliminary results based on full dataset (w/ $\mathcal{L} \approx 25\ fb^{-1}$).	

What Happened Since Then?

- Briefly discuss each channel and its peculiarities.
- Go through all five decay channels and discuss what happened to them since 4th July 2012?
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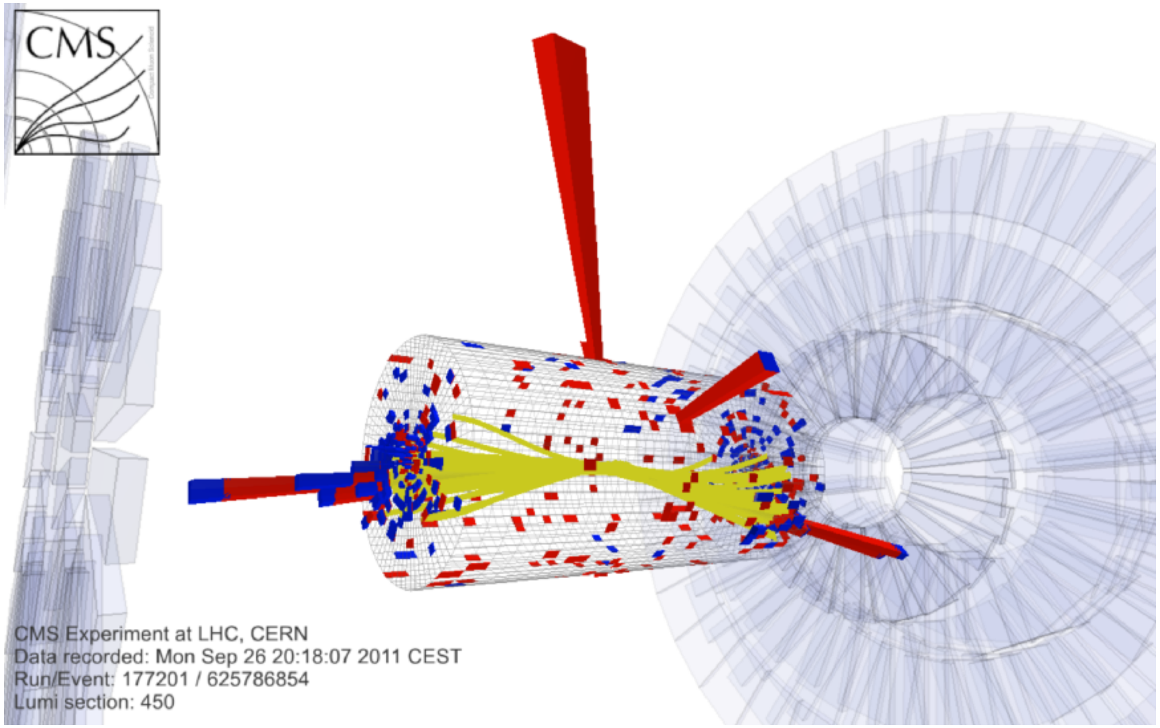
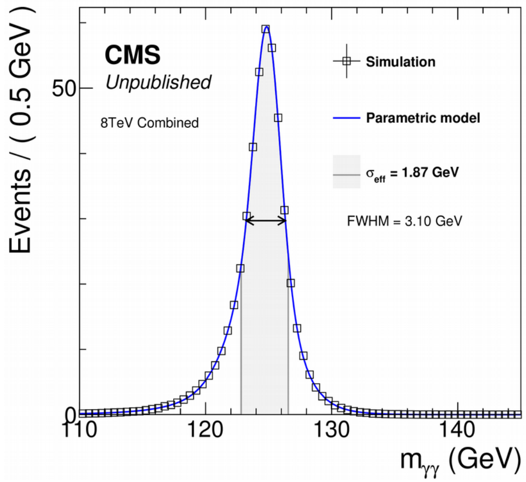
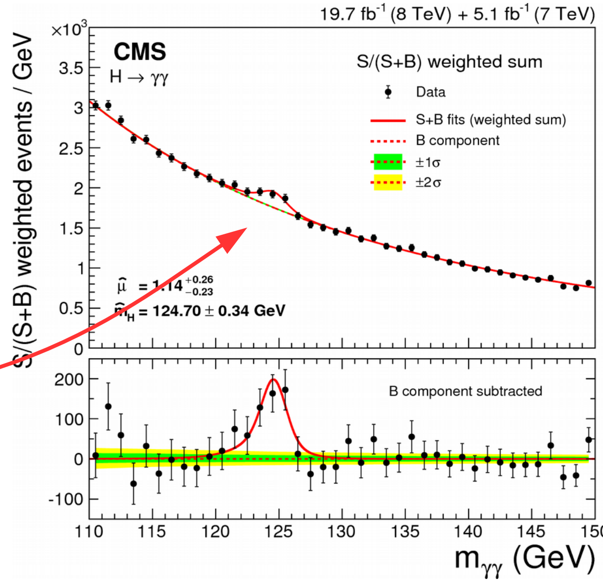
Status July 2012:	Status March 2013:	Status Summer 2014:
• ICHEP summer conference (Sydney)	• Moriond spring conference (La Thuille)	
• Discovery (with $\mathcal{L} \approx 10\ fb^{-1}$ @ $7\ \mathrm{TeV}$ & $8\ \mathrm{TeV}$ equal share).	• Preliminary results based on full dataset (w/ $\mathcal{L} \approx 25\ fb^{-1}$).	• Final publications based on full dataset (w/ $\mathcal{L} \approx 25\ fb^{-1}$). • Final calibrations, alignment, more channels included, more sophisticated analysis methods applied.

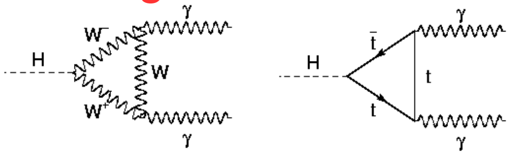
$H \to \gamma\gamma$ Decay Channel







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



$H \to \gamma\gamma$ Decay Channel

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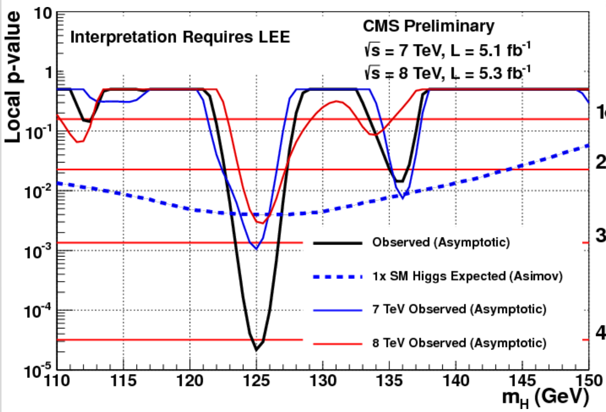
Status **July 2012**:

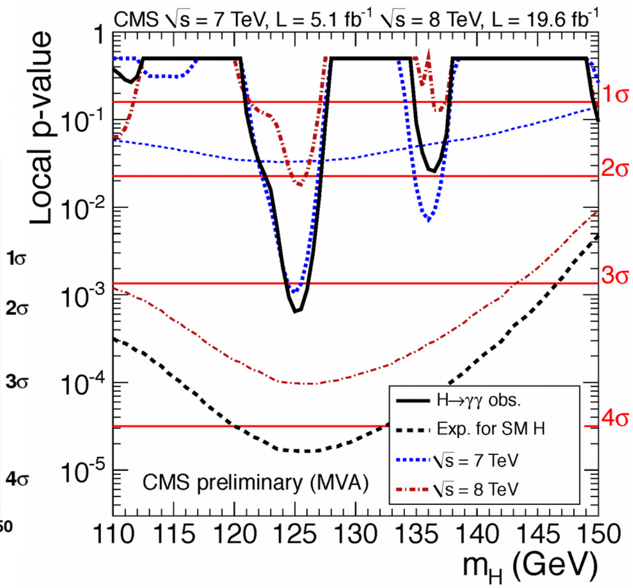


$\mu = 1.6 \pm 0.4$

$\sigma = 4.1(\mathrm{obs}) \;\; 2.8(\mathrm{exp})$

@ $m_H \approx 125$ GeV

Status **March 2013**:

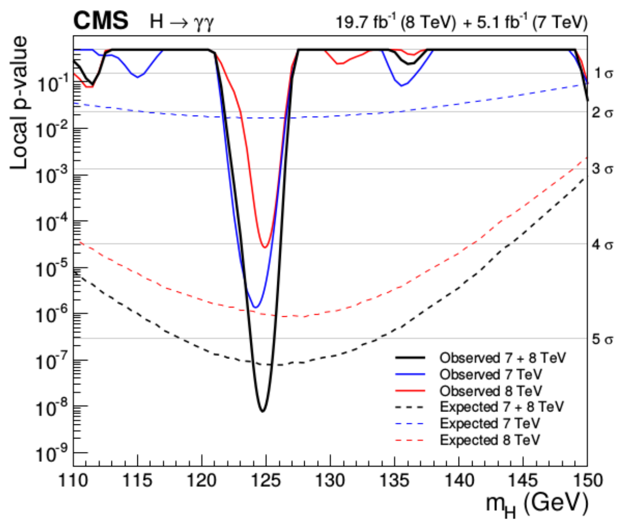


$\mu = 0.8 \pm 0.2$

$\sigma = 3.2(\mathrm{obs}) \;\; 4.2(\mathrm{exp})$

Status **Summer 2014**:

(after complete re-analysis)



$\mu = 1.1 \pm 0.2$

$\sigma = 5.7(\mathrm{obs}) \;\; 5.2(\mathrm{exp})$

$H \to ZZ$ Decay Channel

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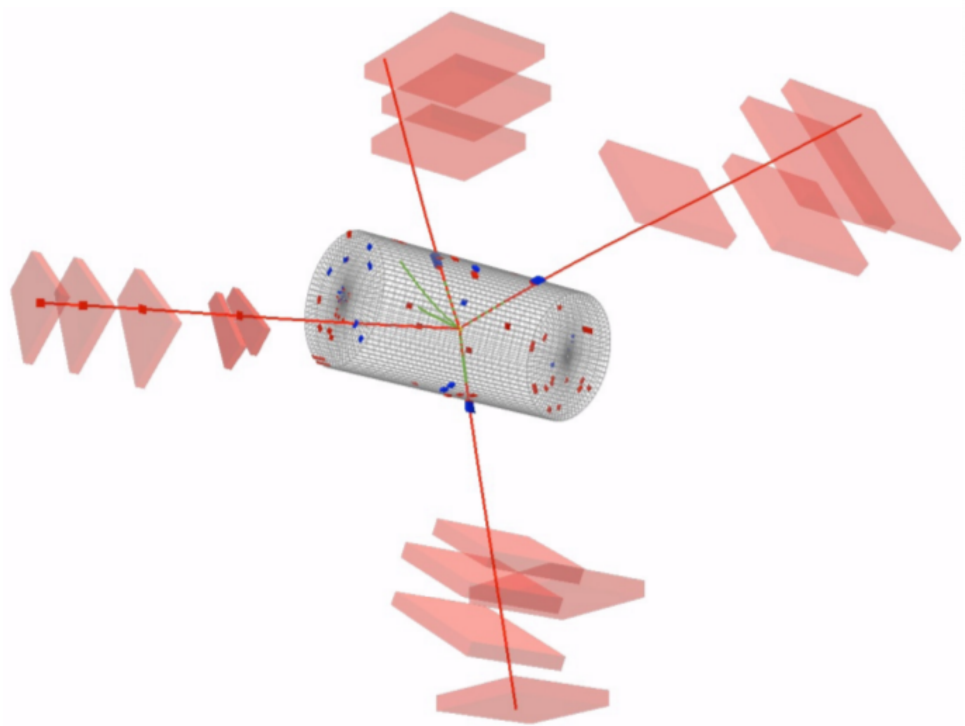
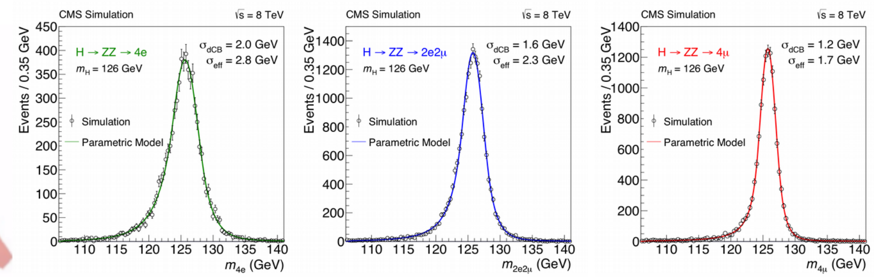
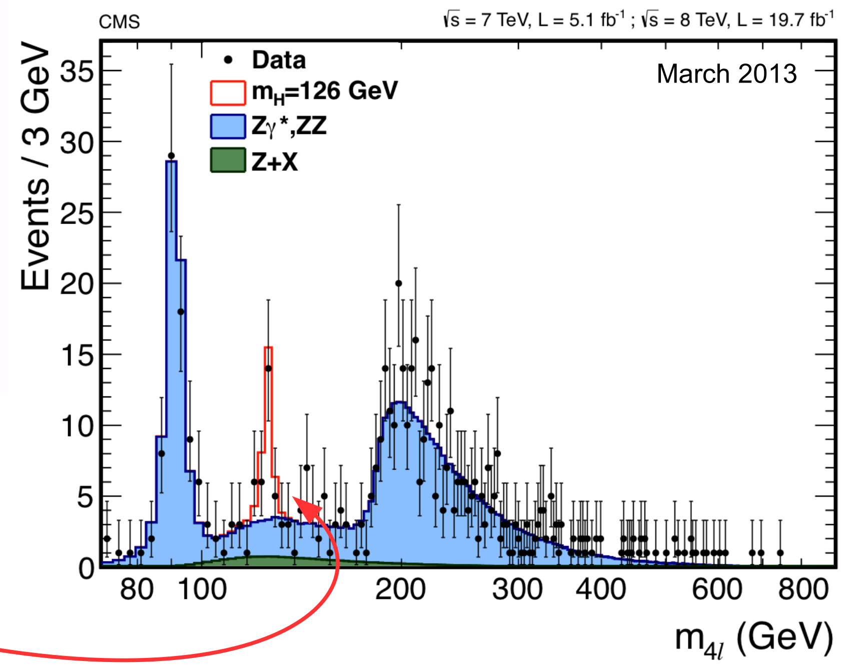




Summer 2014



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

$H \to ZZ$ Decay Channel

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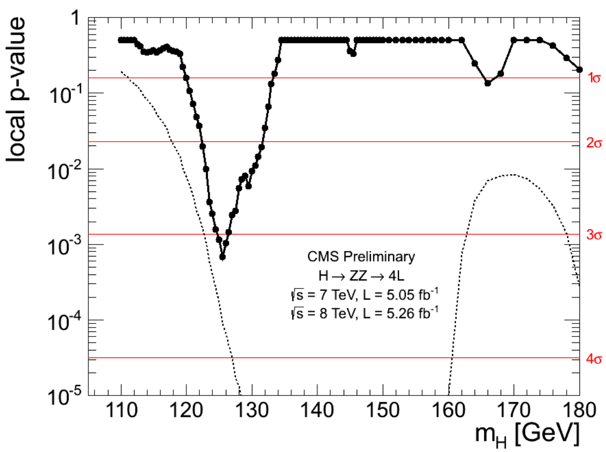
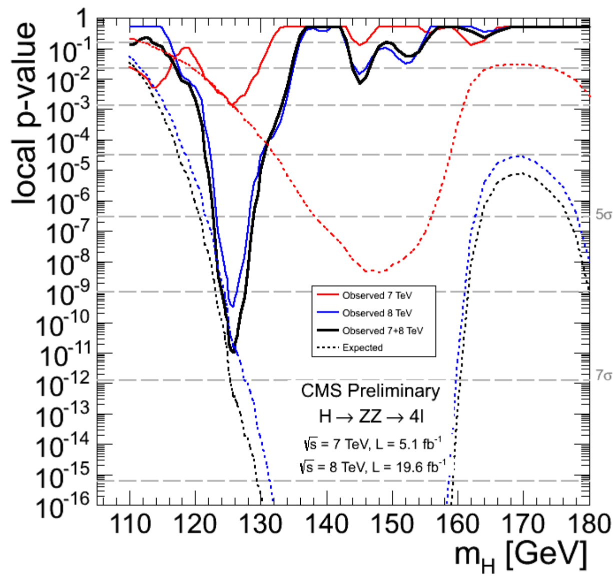
Status **July 2012**:



$$\mu = 0.7\pm^{0.4}_{0.3}$$
$$\sigma = 3.2(\mathrm{obs})\ \ 3.8(\mathrm{exp})$$

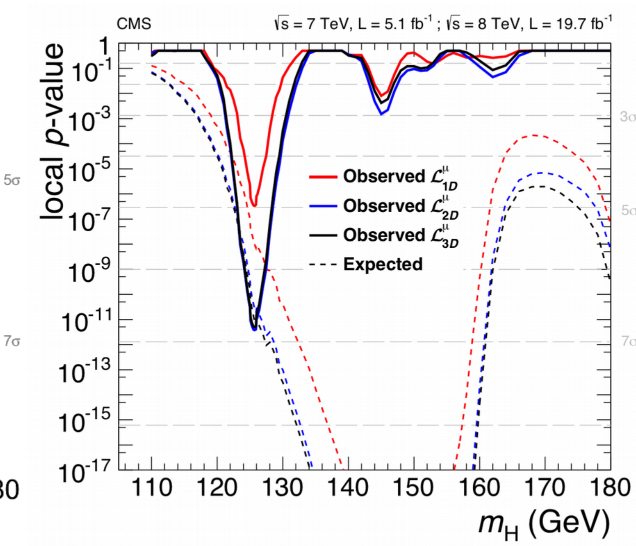
@ $m_H \approx 125$ GeV

Status **March 2013**:



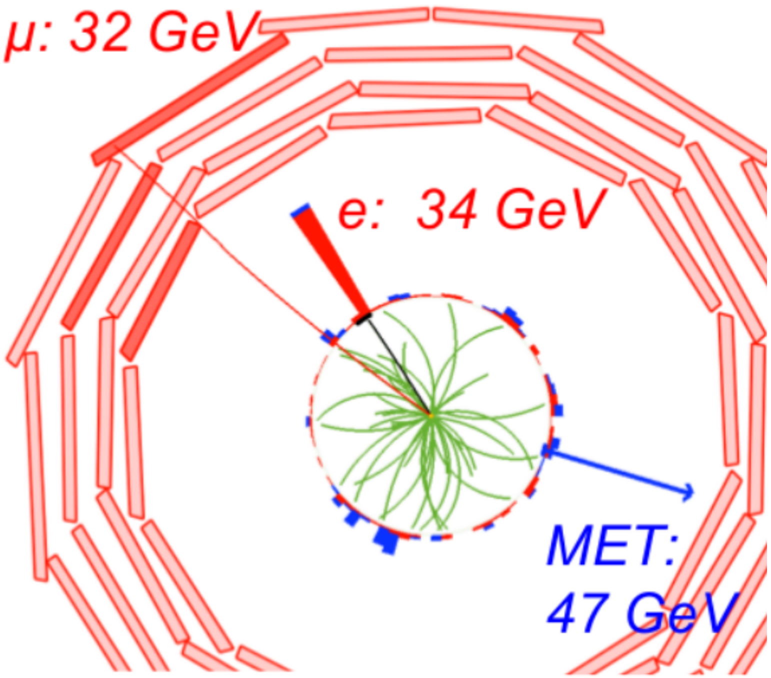
$$\mu = 0.9\pm^{0.3}_{0.2}$$
$$\sigma = 6.7(\mathrm{obs})\ \ 7.2(\mathrm{exp})$$

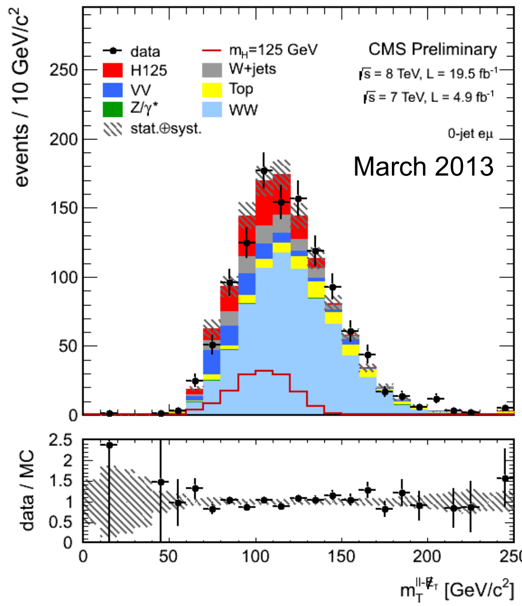
Status **Summer 2014**:

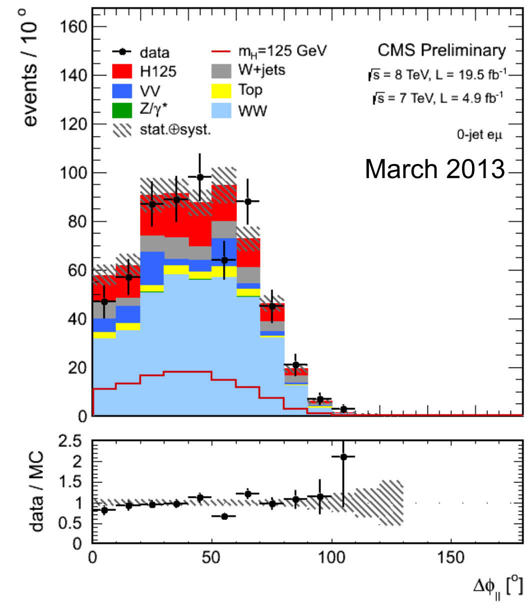


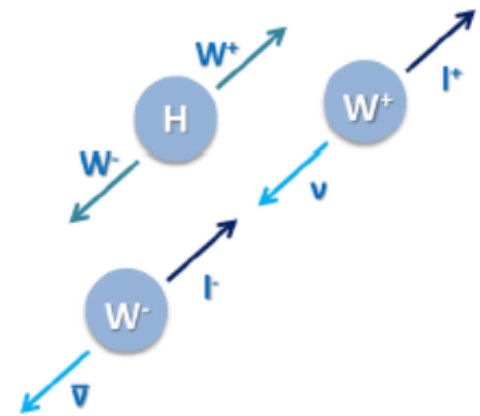
$$\mu = 0.9\pm^{0.3}_{0.2}$$
$$\sigma = 6.8(\mathrm{obs})\ \ 6.7(\mathrm{exp})$$

$H \to WW$ 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)

$H \to WW$ Decay Channel

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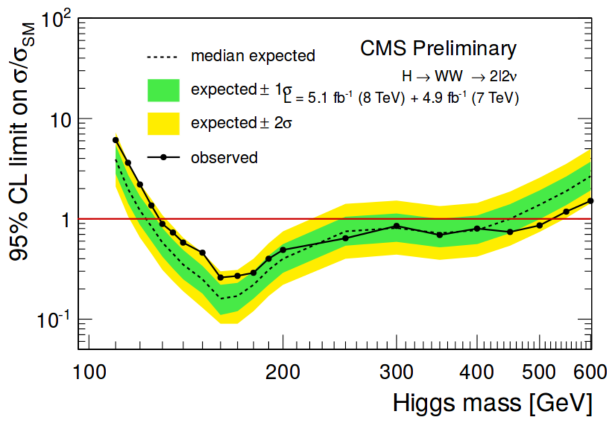
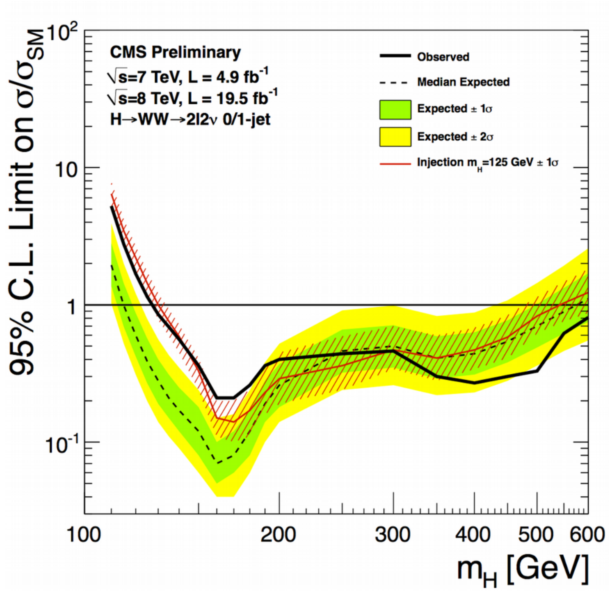
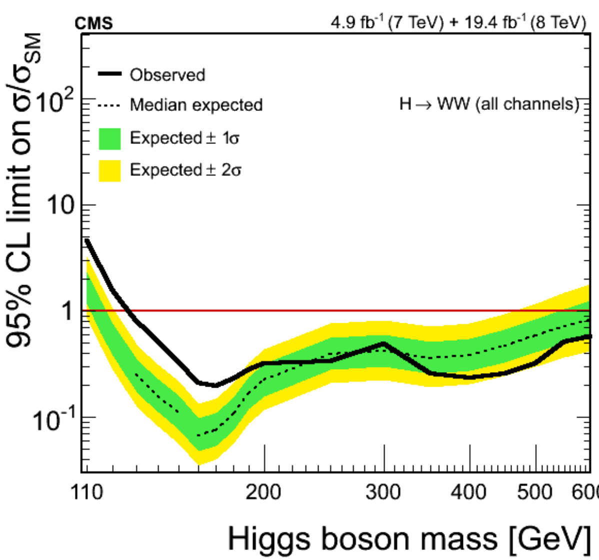
Status **July 2012**:



Status **March 2013**:



Status **Summer 2014**:



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

$\sigma = 1.6(\text{obs}) \;\; 2.4(\text{exp})$

$\mu = 0.8 \pm 0.2$

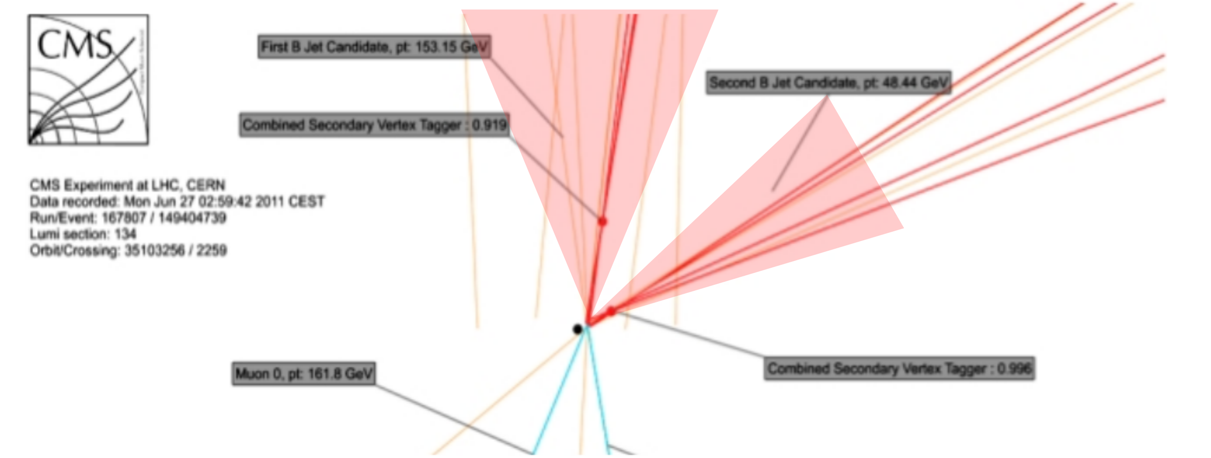
$\sigma = 4.0(\text{obs}) \;\; 5.1(\text{exp})$

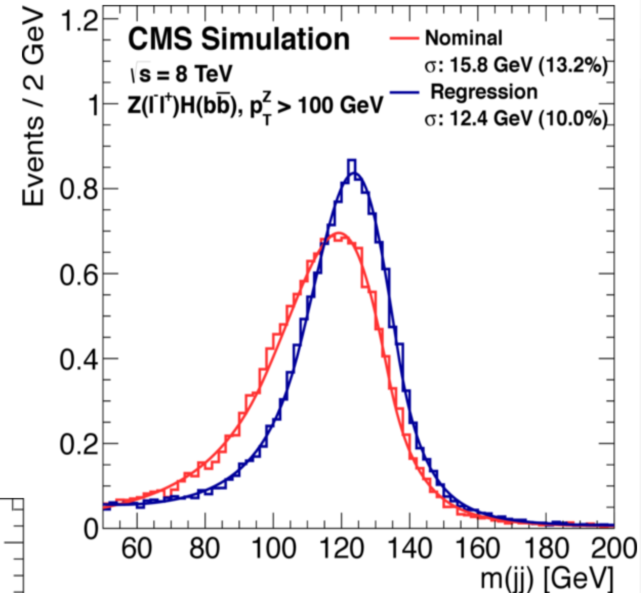
$\mu = 0.8 \pm 0.2$

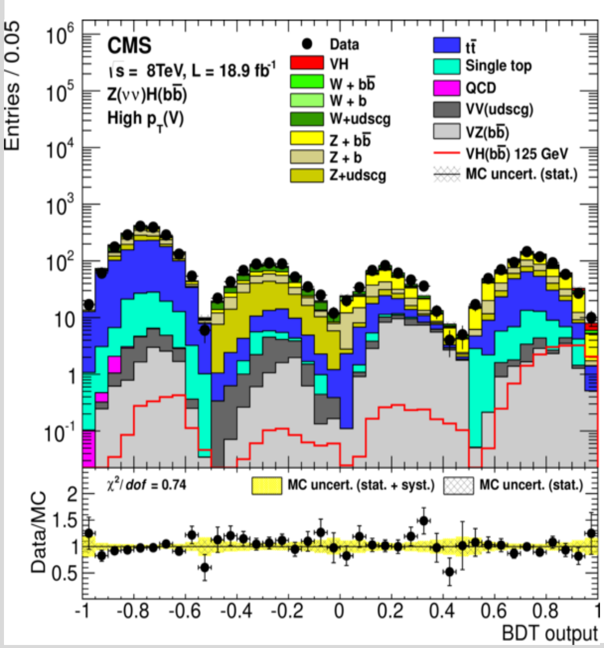
$\sigma = 4.0(\text{obs}) \;\; 5.2(\text{exp})$

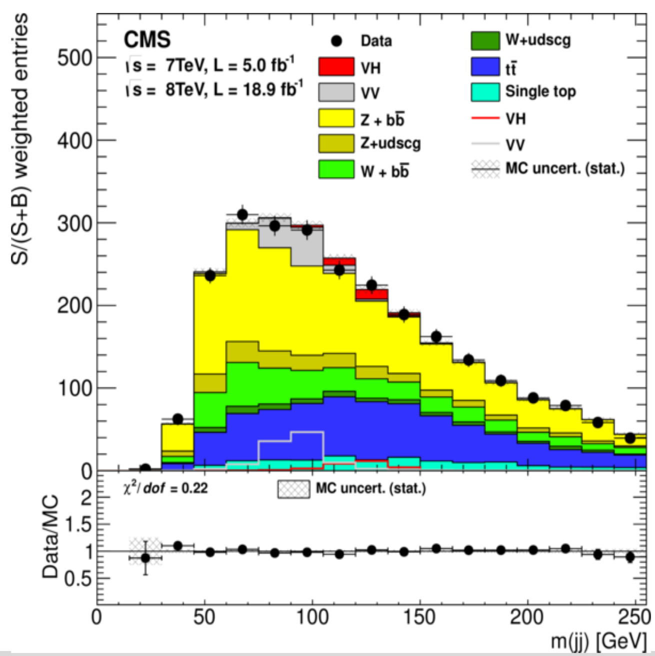
@ $m_H \approx 125$ GeV

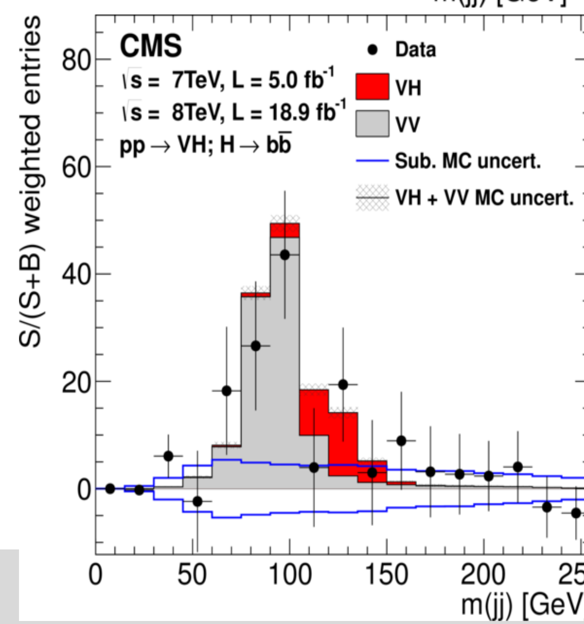
$H \to bb$ Decay Channel





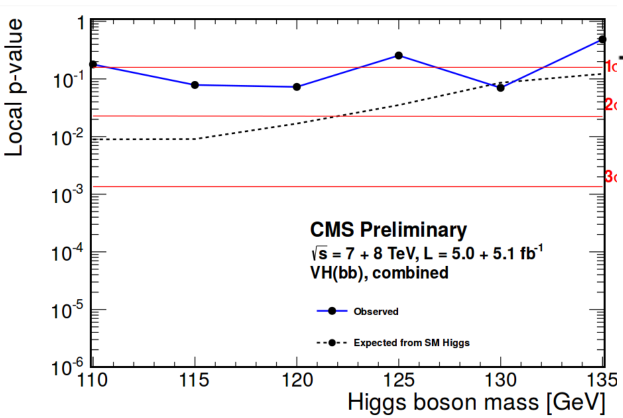




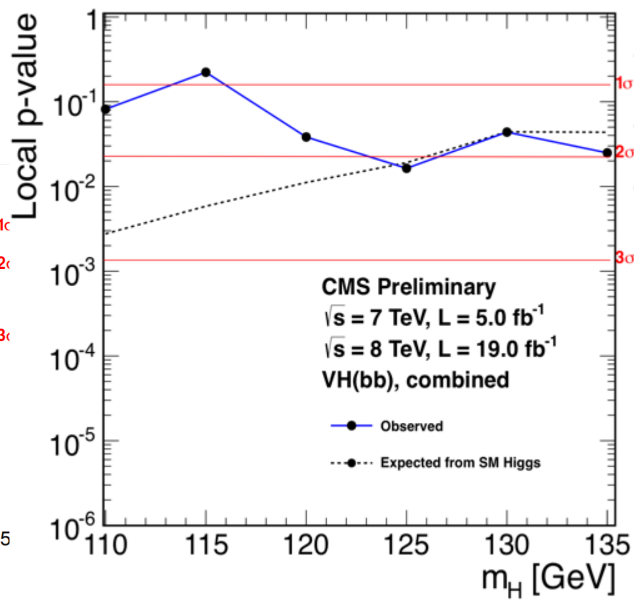


$H \to bb$ Decay Channel

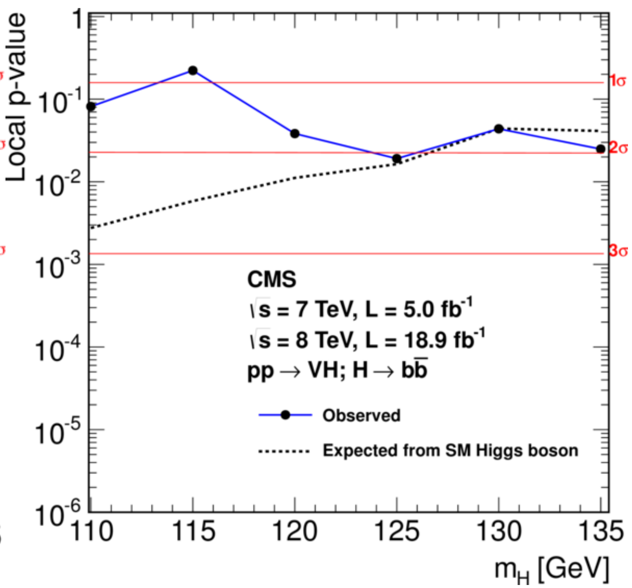
Status **July 2012**:



Status **March 2013**:



Status **Summer 2014**:



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

$\sigma = 0.7(\text{obs}) \;\; 1.9(\text{exp})$

$\mu = 1.0 \pm 0.5$

$\sigma = 2.1(\text{obs}) \;\; 2.1(\text{exp})$

$\mu = 1.0 \pm 0.5$

$\sigma = 2.1(\text{obs}) \;\; 2.1(\text{exp})$

@ $m_H \approx 125$ GeV

$H \to \tau\tau$ Decay Channel

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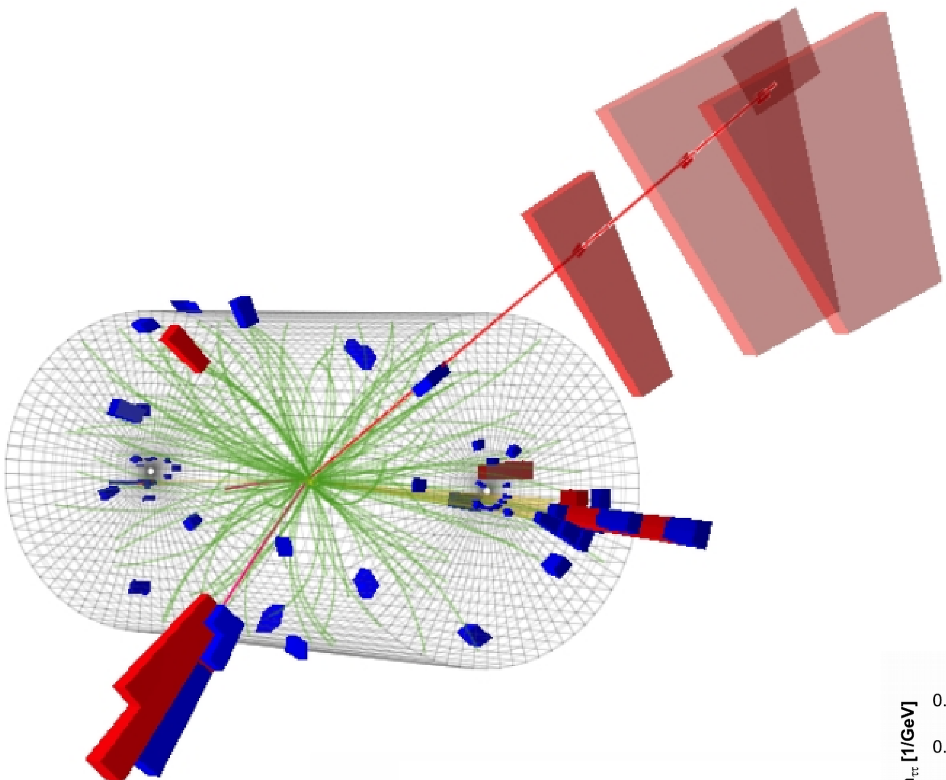
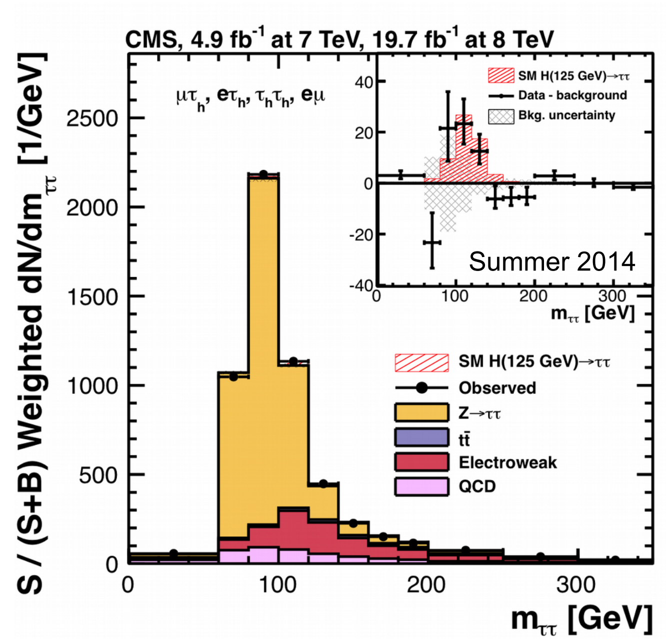
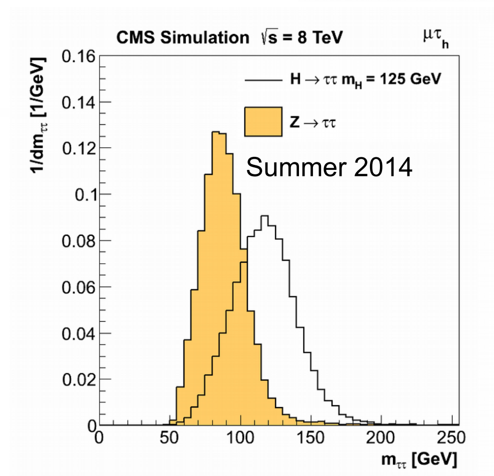
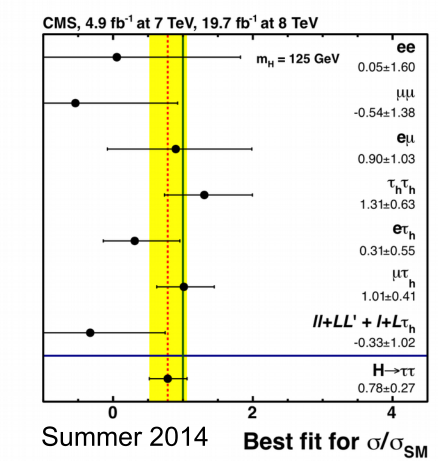




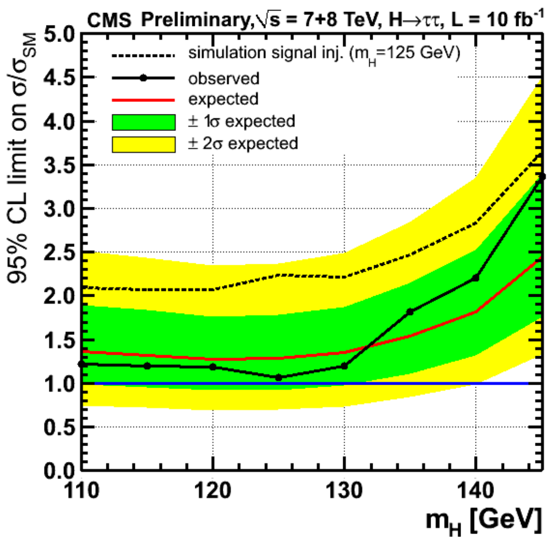
- $m_{\tau\tau}$ as main discriminating variable.
- Separation between irreducible $Z \to \tau\tau$ background and $H \to \tau\tau$ signal.





$H \rightarrow \tau\tau$ Decay Channel

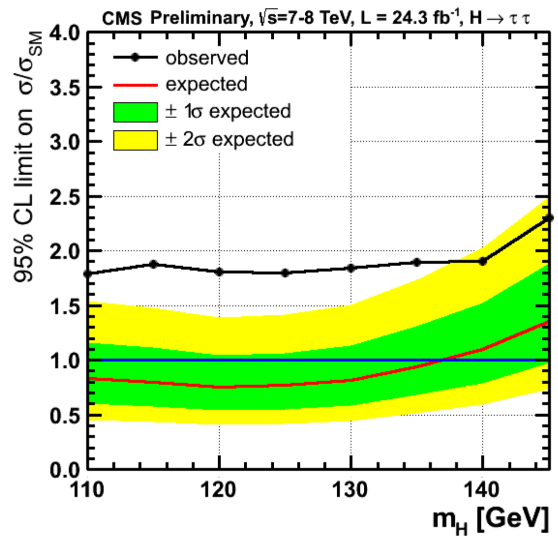
Status **July 2012**:



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

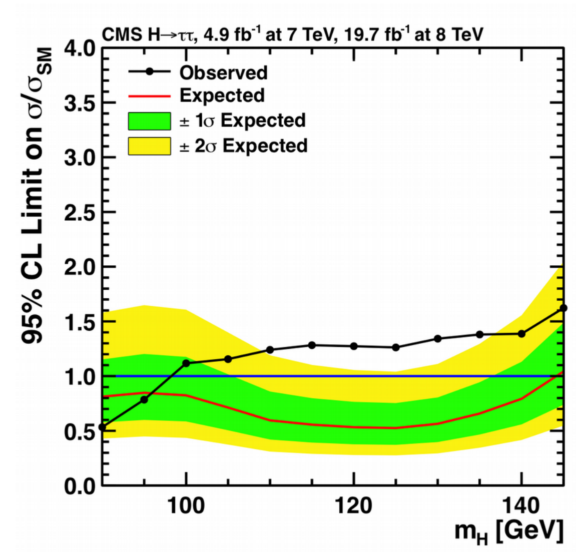
$@\, m_H \approx 125$ GeV

Status **March 2013**:



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

Status **Summer 2014**:

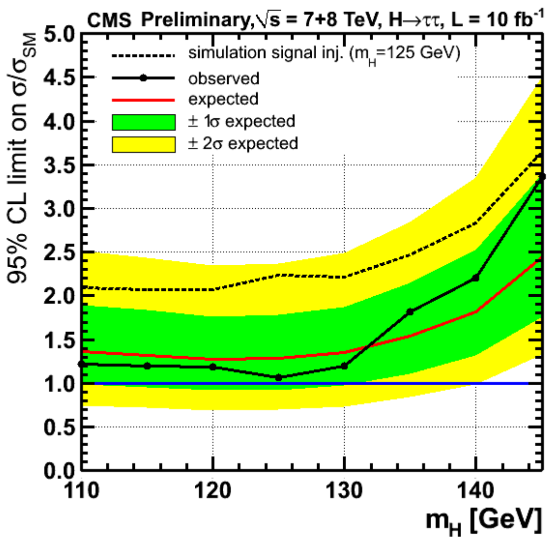


$$\mu = 0.8 \pm 0.3$$
$$\sigma = 3.2(\text{obs}) \quad 3.7(\text{exp})$$

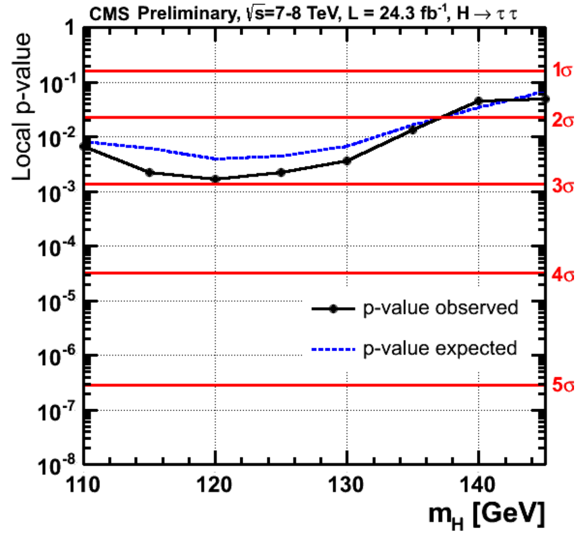
Treating contributions from $H \rightarrow WW$ as background.

$H \to \tau\tau$ Decay Channel

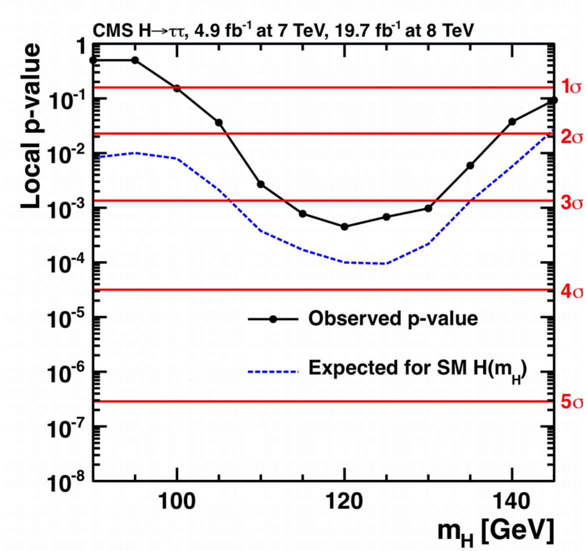
Status **July 2012**:



Status **March 2013**:



Status **Summer 2014**:



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

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

$@\ m_H \approx 125\ \text{GeV}$

$\mu = 1.1 \pm 0.4$

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

Treating contributions from as background.

$\mu = 0.8 \pm 0.3$

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

$H \to \tau\tau$ Decay Channel

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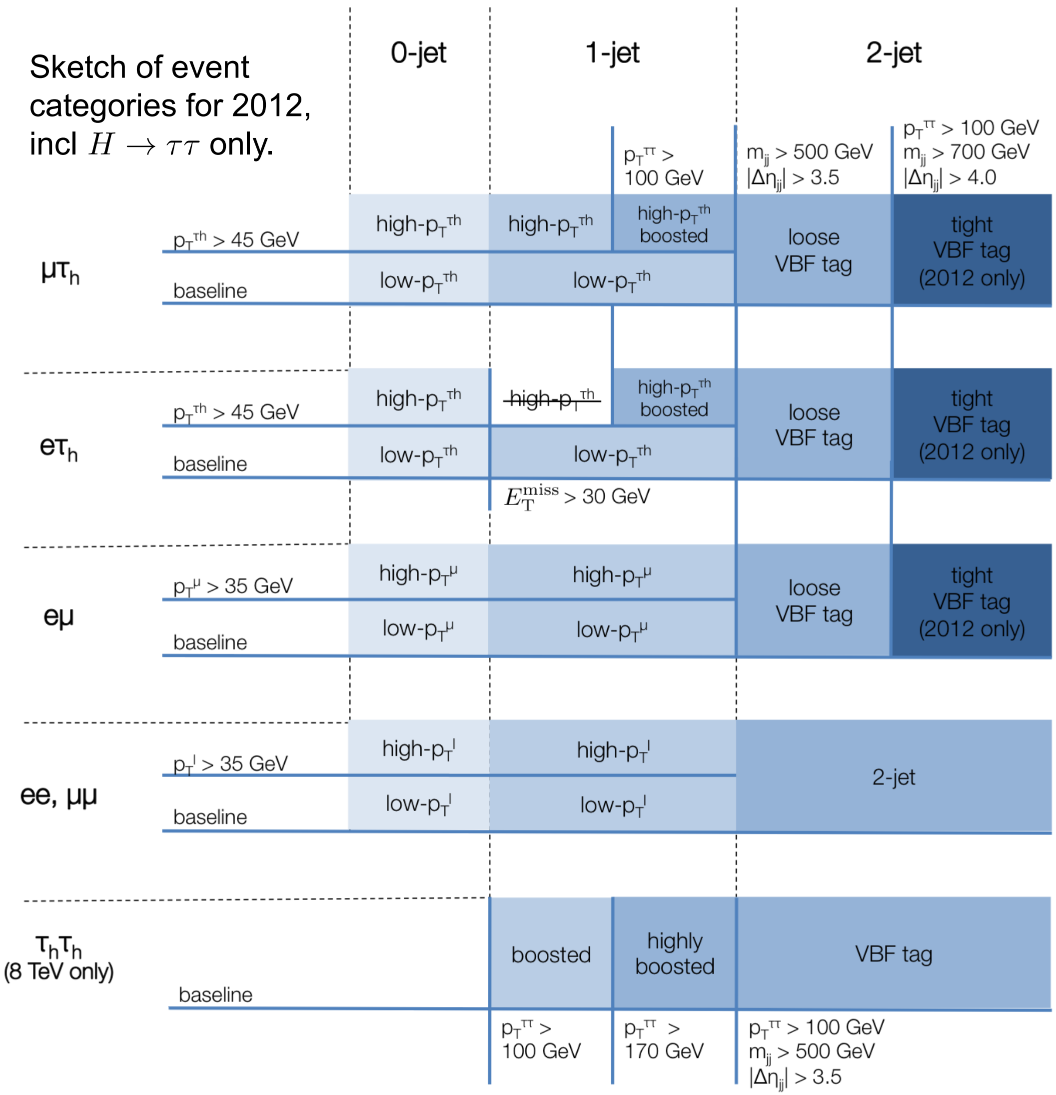
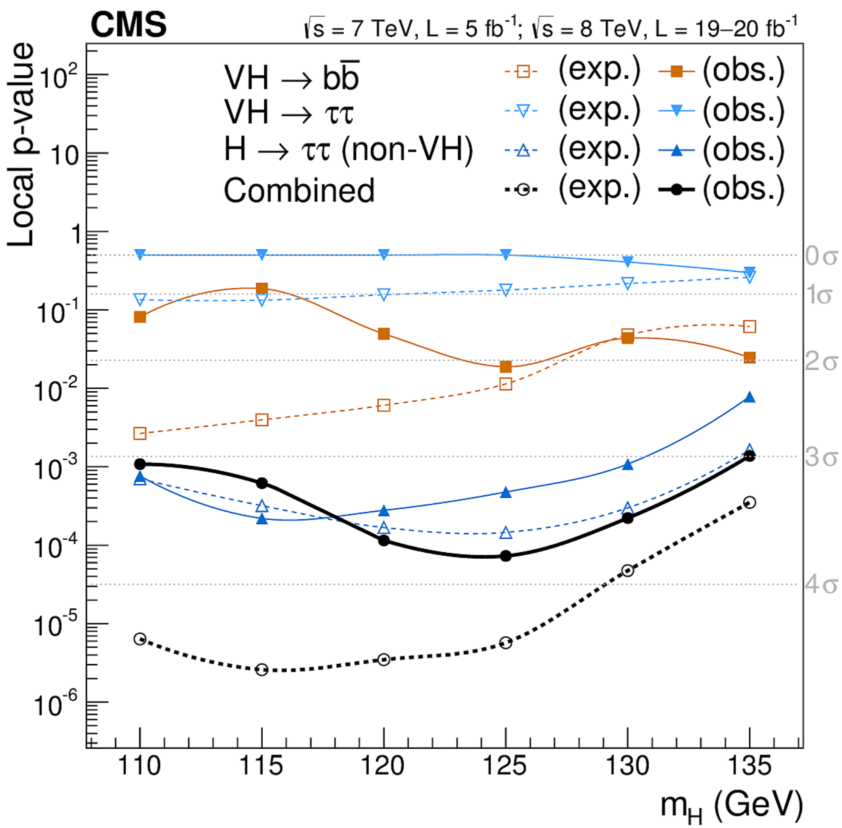
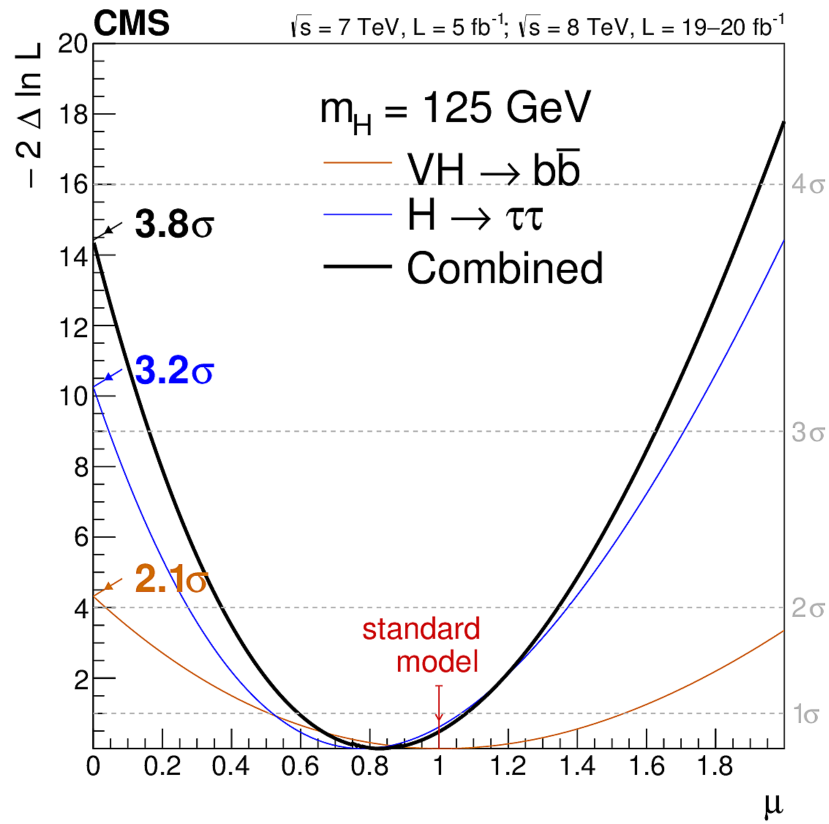


- Nearly 100 exclusive event categories.
- 6 inclusive decay channels.
- Exclusive decay channels for production in association with Z, W bosons.
- On 7 TeV and 8 TeV dataset.

Combination of $H \to \tau\tau$ & $H \to bb$





$\mu = 0.8 \pm 0.2$

$\sigma = 3.8(\mathrm{obs})\ \ 4.4(\mathrm{exp})$

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

@ $m_H \approx 125$ GeV

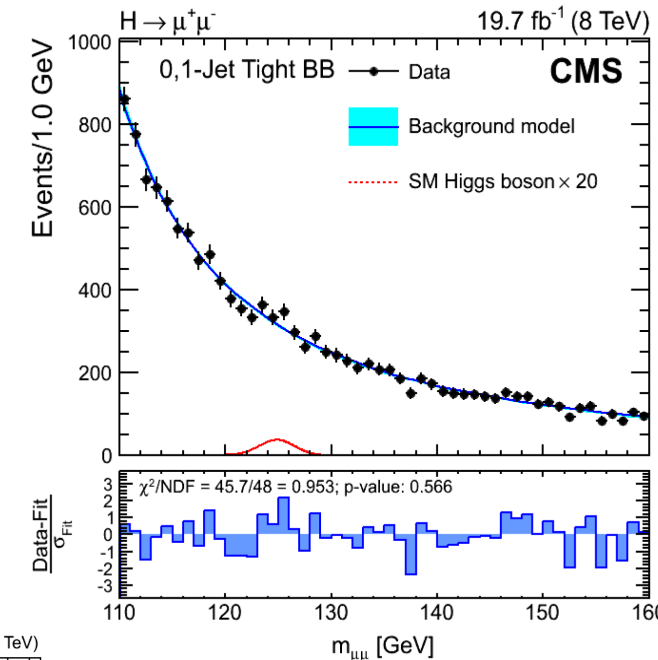
H→μμ and H→ee

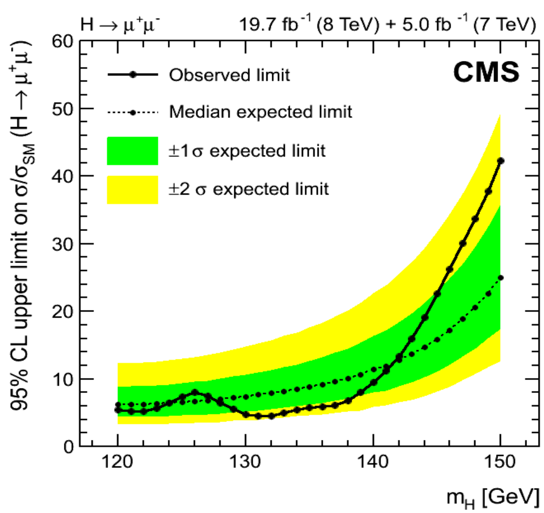
- BR (H→μμ): 2.2 x10-4
- BR (H→ee): 5 x 10-9

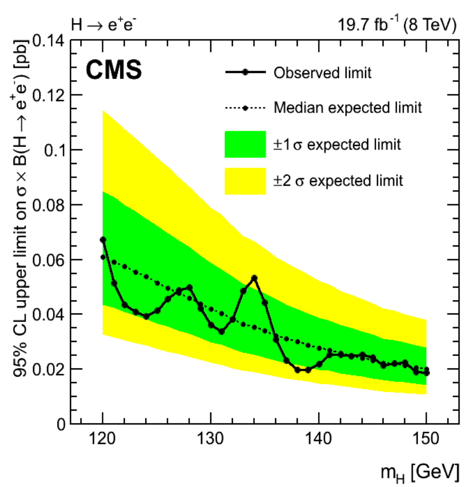
- Looking for a small bump on a falling background

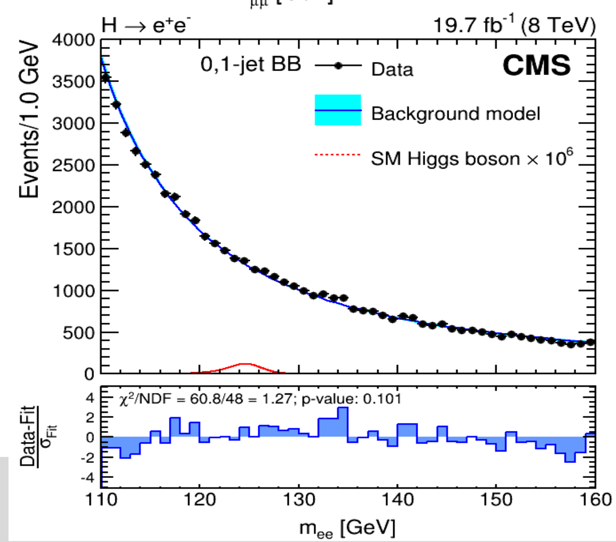
- Set Limits:
  - BR (H→μμ) < 0.0016
  - BR (H→ee) < 0.0019

- **Evidence for non-flavour-universality in Higgs to lepton coupling**









ttH Production

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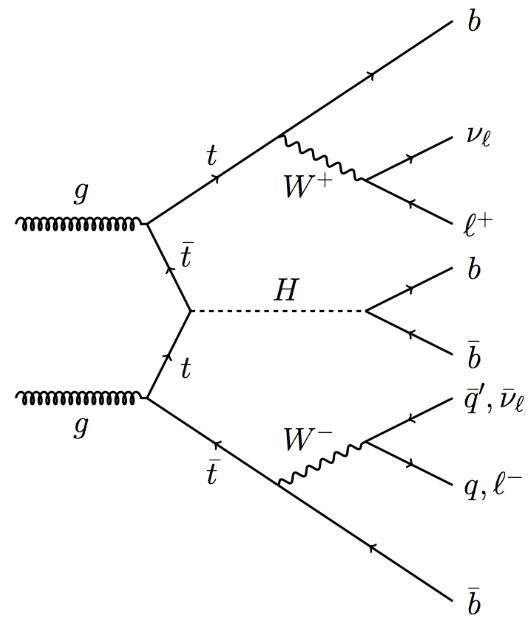
- Want to measure top quark Yukawa coupling directly...
  - Indirect measurement from loops
  - m_t (173 GeV) > m_H: no H→tt decay
  - Leaves associated-top production

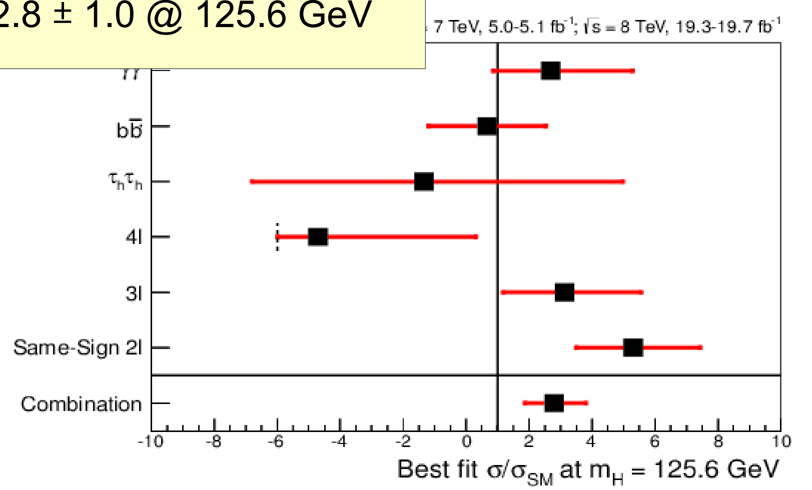
- **Small cross section:** 130 fb (ggH is ~19 pb)

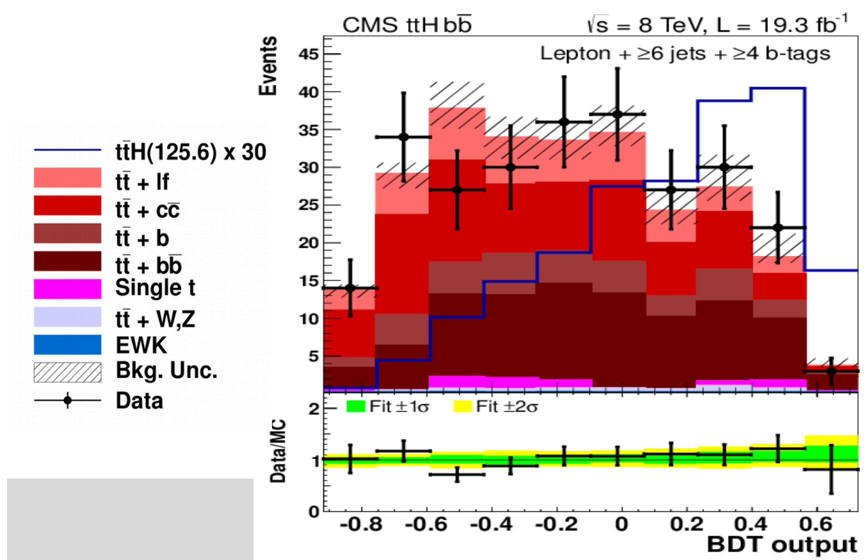
- Complicated analysis with many channels:
  - **Production** 2x t→bW$^{+/-}$→(bl$^{+/-}$ν or bjj)
    X **Decay** H→γγ, H→bb, H→WW, H→ZZ, H→ττ

- Use a multi-variate approach to separate signal



μ = 2.8 ± 1.0 @ 125.6 GeV





Mapping out the Discovery

	significance		
channel	expected	observed	$\mu = {}^{\sigma}/_{\sigma_{\rm SM}}$
$H \to \gamma\gamma$	5.2	5.7	1.1 ± 0.2
$H \to ZZ$	6.7	5.7	0.9 ± 0.3
$H \to WW$	5.2	4.0	0.8 ± 0.2
$H \to bb$	2.1	2.1	1.0 ± 0.5
$H \to \tau\tau$ (1)	3.7	3.2	0.8 ± 0.3
$H \to bb, \tau\tau$ (1)	4.4	3.8	0.8 ± 0.2

@ $m_H \approx 125$ GeV

(1) Treating contributions from $H \to WW$ as background.

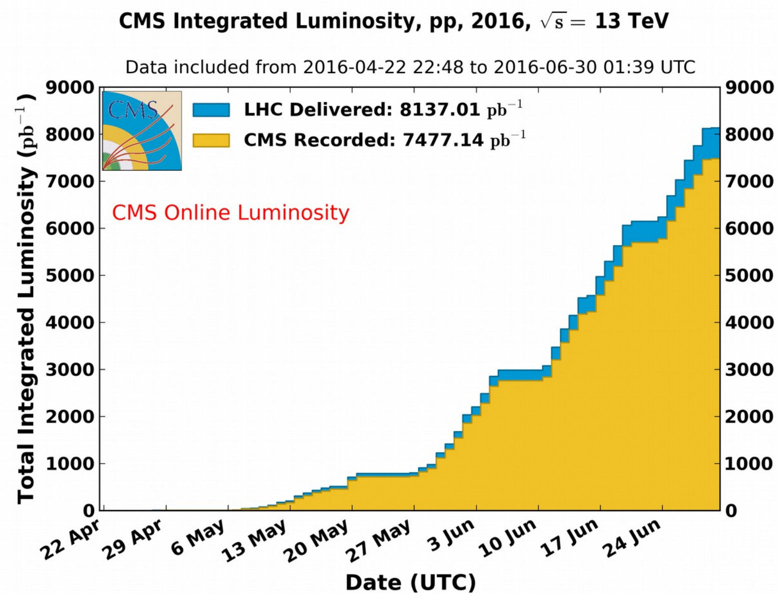
- Clear evidence in all but one of the main decay channels.
- Observation in the high resolution channels ($H \to \gamma\gamma$ & $H \to ZZ$).
- Clear evidence for coupling to fermions ($H \to \tau\tau$).
- No striking surprises in loops ($H \to \gamma\gamma$).

Long Shutdown 1

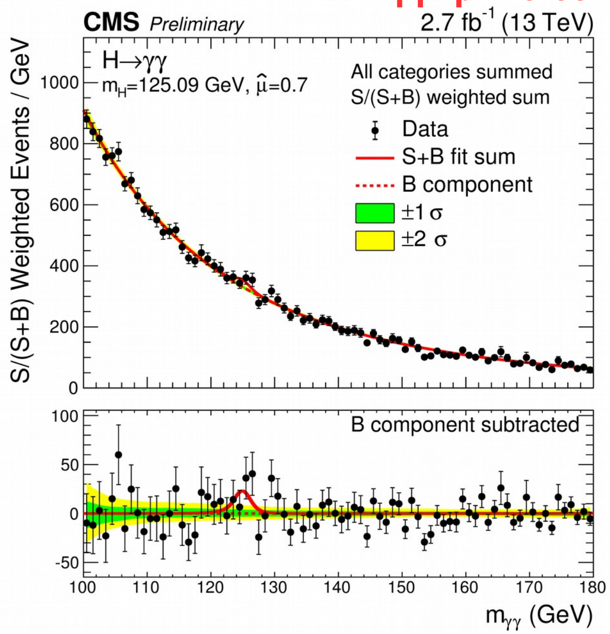
- Main task of reinforcing and protecting magnet interconnects to enable beam energy up to 14 TeV

LHC Run 2

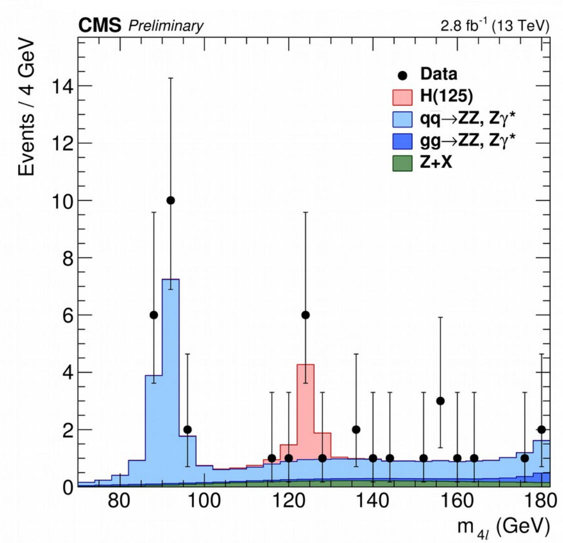
- Collisions restarted this year on 20th May at new record-setting 13 TeV energy
- 8.1 fb^{-1} delivered so far and counting
- Process of re-discovering the Higgs has begun!

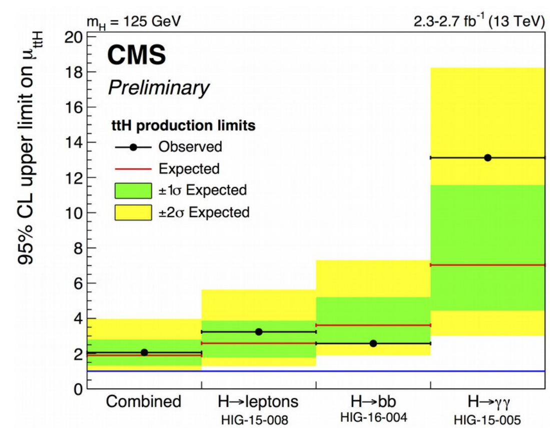


H→γγ: $\mu = 0.69^{+0.47}_{-0.42}$



H→ZZ: $\mu = 0.86^{+0.57}_{-0.43}$





Tomorrow

- We have a clear discovery of a new particle at $m_H = 125\ \mathrm{GeV}$.
- Tomorrow morning we will investigate the properties of this particle:
  - Exact mass?
  - Decay width?
  - Spin and parity?
  - **Compatibility of couplings with SM?**
- Remaining questions:
  - Is this **A** Higgs bosons?
  - Is this **THE** Higgs bosons?
  - Is there **MORE THAN ONE** Higgs bosons?

Backup