Search for the Higgs boson candidate with the CMS Experiment at the LHC

Detailed look at $H \rightarrow ZZ^{(*)}$ decay and general status as of Moriond 2013

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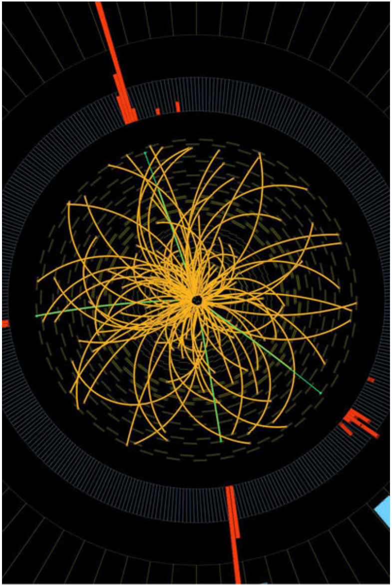
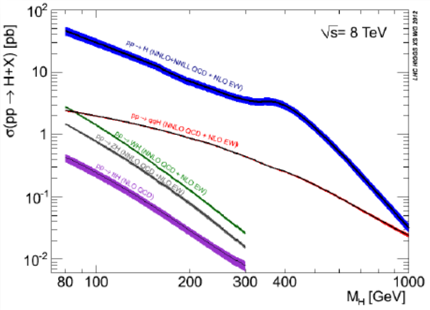
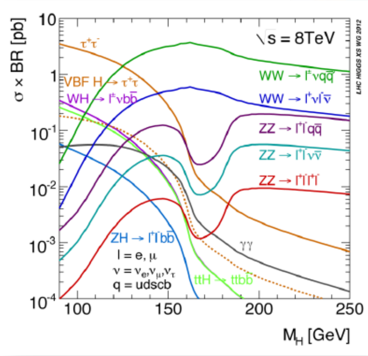


Outline

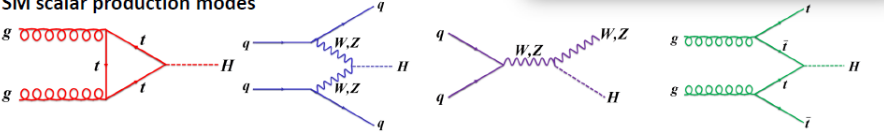
- SM Higgs Boson
- Ingredients:
  - Large Hadron Collider
  - CMS Collaboration
  - Compact Muon Solenoid
- $H \to ZZ^{(*)}$
  - Analysis
  - Mass and Couplings
  - Spin and Parity
- Moriond 2013 Status

Higgs production and decays



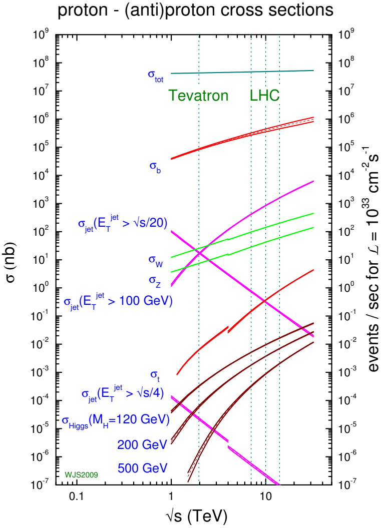


SM scalar production modes



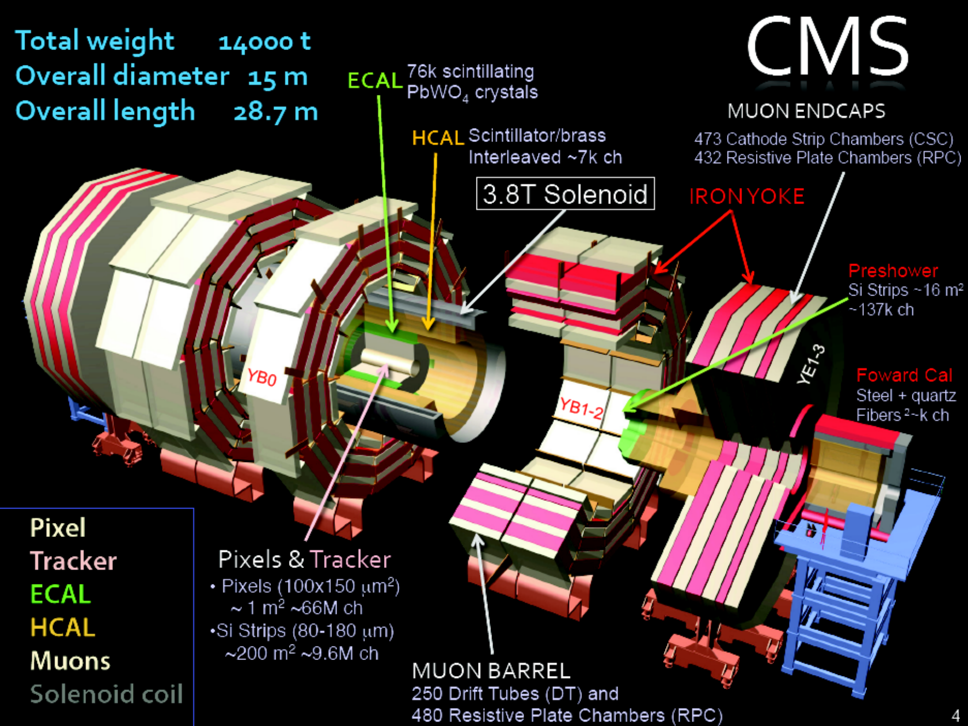
gluon fusion | vector boson fusion | W/Z-associated production | *tt*-associated production

Large Hadron Collider

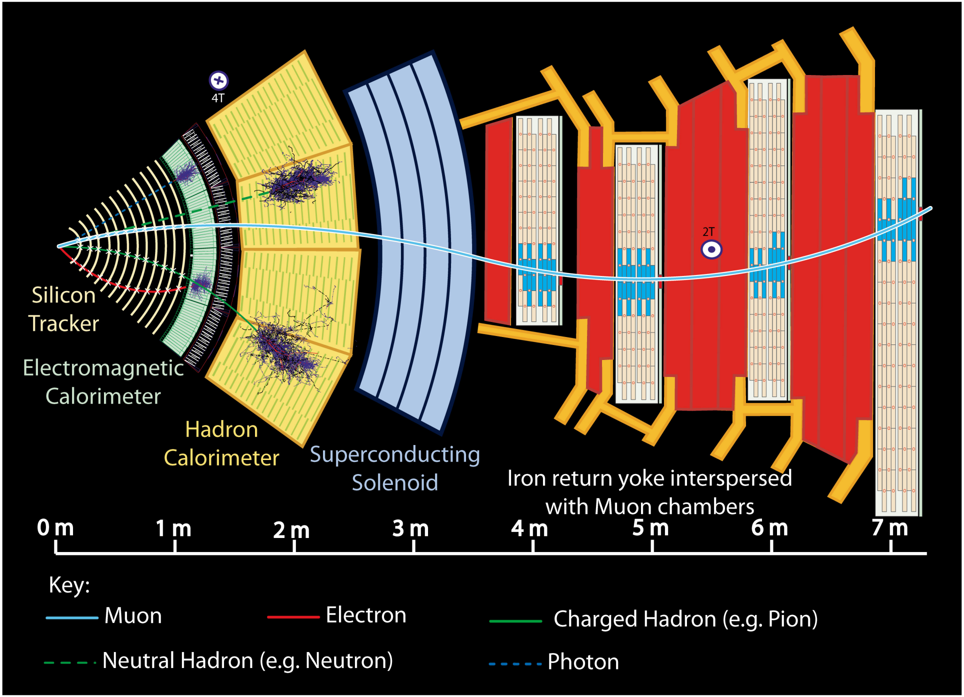


CMS Collaboration

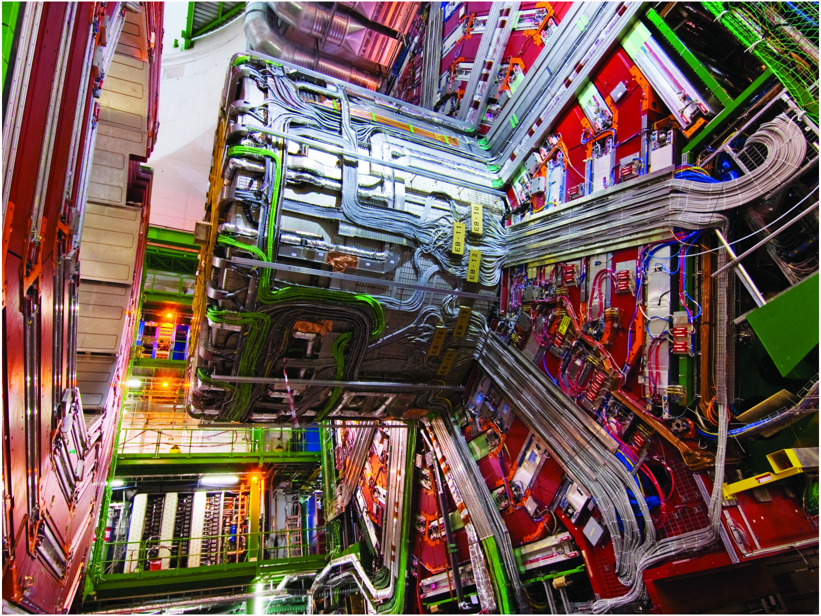
a Huge amount of work done by many, many people ($\sim$ 3000)



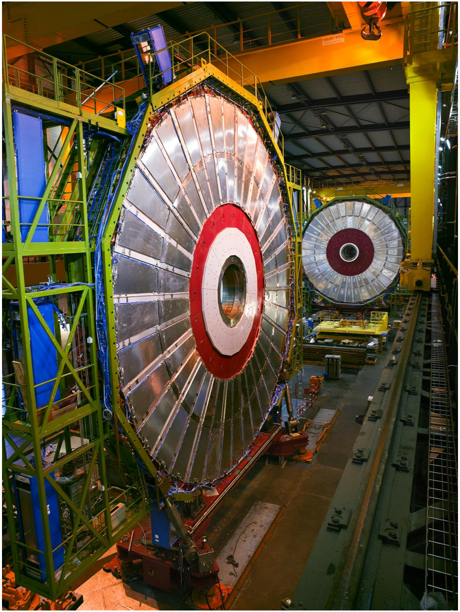
CMS
Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
ECAL 76k scintillating PbWO4 crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
IRON YOKE
Preshower
Si Strips ~16 m²
~137k ch
YE1-3
Foward Cal
Steel + quartz
Fibers ²~k ch
YB0
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²)
~ 1 m² ~66M ch
•Si Strips (80-180 μm)
~200 m² ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

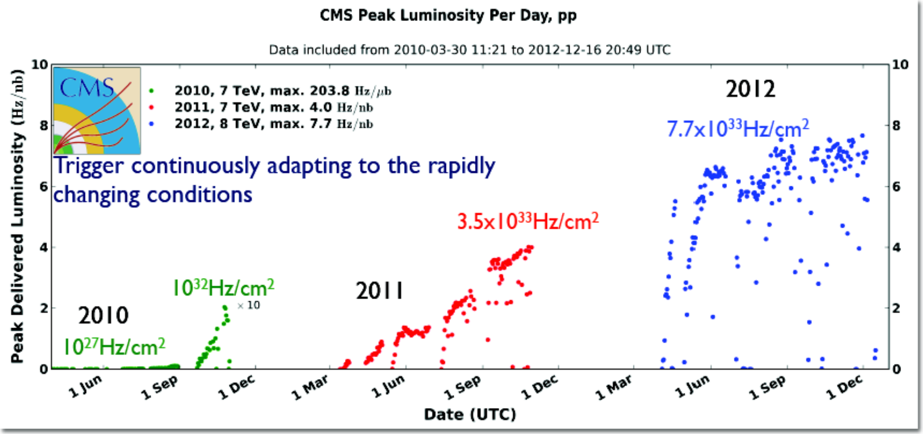
Readout Cables – Cooling – Gas – HV – LV



Resistive Plate Chambers



CMS instantaneous luminosity

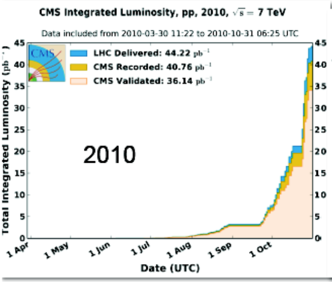


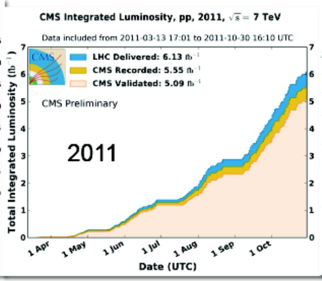
In 2010: luminosity increased by 5 orders of magnitude

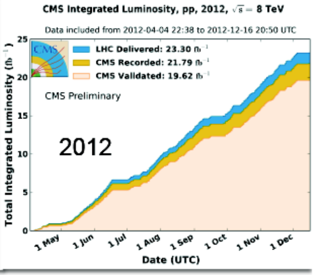
In 2011: instantaneous luminosity reached 40% of the nominal LHC luminosity

In 2012: The LHC reached 77% of the nominal luminosity

Data taking efficiency and data validated







Data taking efficiency

- Increased in 2012 due to development of automatic recovery procedures

Data validated

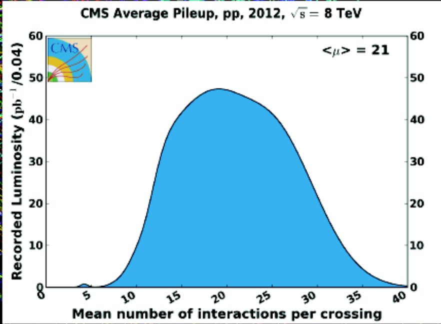
- Very stable over time ~90%

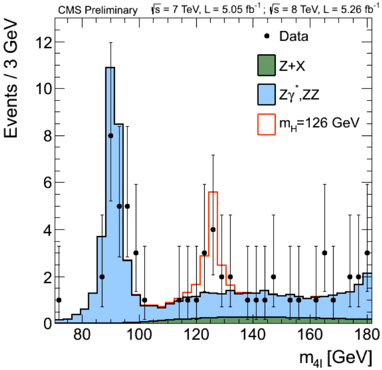
Period	$\sqrt{s}$ [GeV]	Delivered luminosity [fb^{-1}]	Data taking efficiency [%]	Data validated [%]
2010	7	0.044	92.2	88.6
2011	7	6.13	90.5	90.1
2012	8	23.20	93.5	90.0

The challenge in 2012

CMS design value: 25 pile up events at luminosity $10^{34}cm^{-2}s^{-1}$ and 25 ns bunch spacing

Raw ΣE_T~2 TeV
14 jets with E_T>40 GeV
Estimated PU~50




CMS Preliminary
√s = 7 TeV, L = 5.05 fb-1 ; √s = 8 TeV, L = 5.26 fb-1
Data
Z+X
Zγ*,ZZ
mH=126 GeV
Events / 3 GeV
m4l [GeV]
0
2
4
6
8
10
12
80
100
120
140
160
180

$$H \to ZZ^{(*)}$$

Introduction - Event Selection

leptons

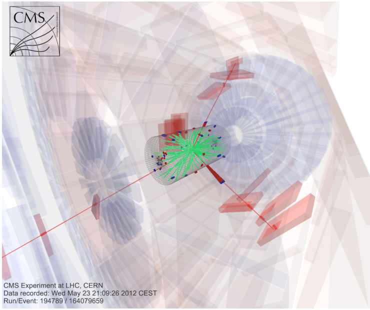
- $p_T(\mu) > 5\,\text{GeV}/c$, $\eta^{\mu} < 2.4$
  $p_T(e) > 7\,\text{GeV}/c$, $\eta^{e} < 2.5$
- $\left|\frac{\sigma_{IP}}{IP}\right| < 4.0$ $\quad I_{rel}^{PF} < 0.4$

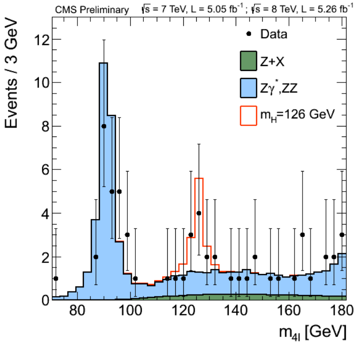
signal

- Narrow resonance $\mathcal{O}(2 - 4\,\text{GeV}/c^2)$

background

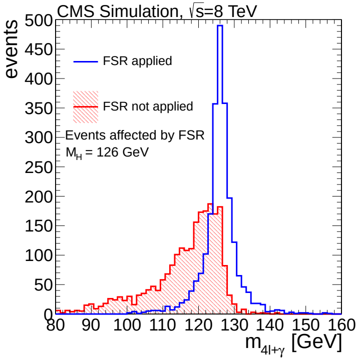
- $Z + X$ (reducible)
  - $Z + \text{jets}$
  - $Z + bb$
  - estimated from data
- ZZ (ireducible)
  - estimated from MC

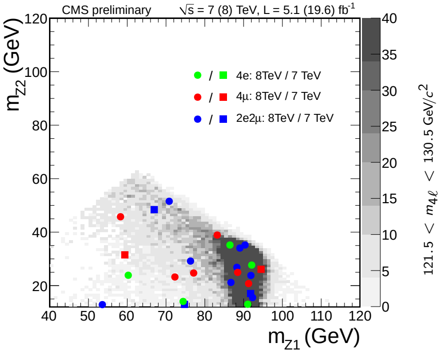




At the time of Discovery

Building 4ℓ candidates





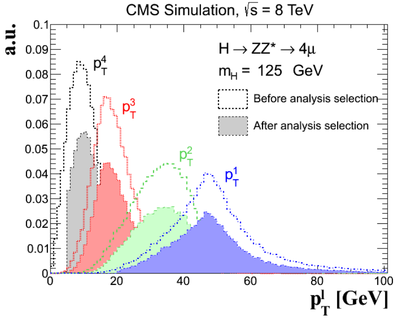
- Z candidates formed from $\ell^+\ell^-$ pair of same flavour
- FSR recovery: $|m_{\ell\ell\gamma} - m_Z| < |m_{\ell\ell} - m_Z|$
- $\exists \ell_a$ with $p_T(\ell_a) > 20\,\mathrm{GeV}/c$
- $\exists \ell_b$ with $p_T(\ell_b) > 10\,\mathrm{GeV}/c$

- $40 < m_{Z_1} < 120\,\mathrm{GeV}/c^2$
- Z_1 closest to PDG mass Z

- $12 < m_{Z_2} < 120\,\mathrm{GeV}/c^2$
- Z_2 with highest p_T

$$m_{4\ell} > 100\,\mathrm{GeV}/c^2\ \&\ \forall \ell : m_{2\ell} > 4\,\mathrm{GeV}/c^2$$

Lepton Selection

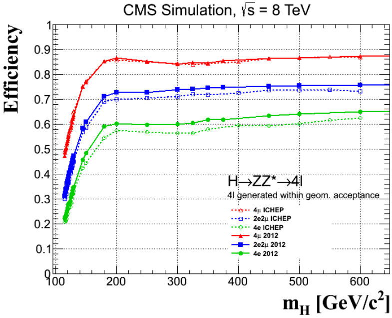


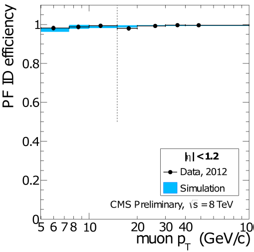
one on-shell $Z \Rightarrow$ hard ℓ
one off-shell $Z \Rightarrow$ soft ℓ:

- 50% below 10 GeV/c

this is a big **Challenge**

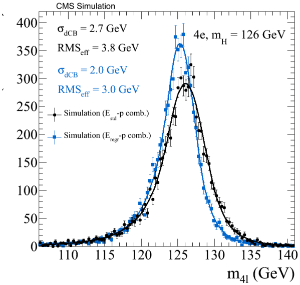
- background rate
- selection efficiency

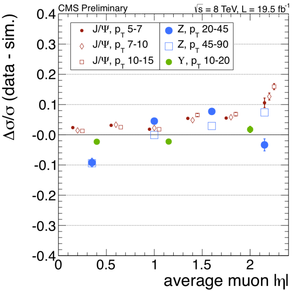


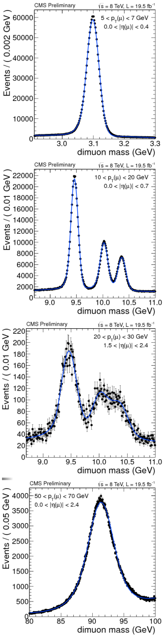


My Work!

Lepton Resolution and Scale

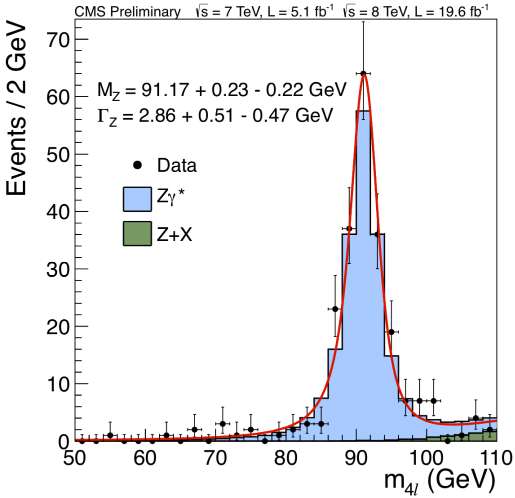


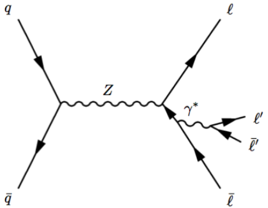




- e :: Momentum Regression in ECAL
  - BDT trained on DY MC leads to 10% improvement
- e :: Momentum Scale: using Z, $J/\Psi \rightarrow ee$
- μ :: Resolution & Scale: improved by correction of Tracker Misalignment ($\langle 1/p_T \rangle$)
- μ :: Validation on J/Ψ, Y and Z decays

Cross Check: Precise Measurement of $Z \to 4\ell$

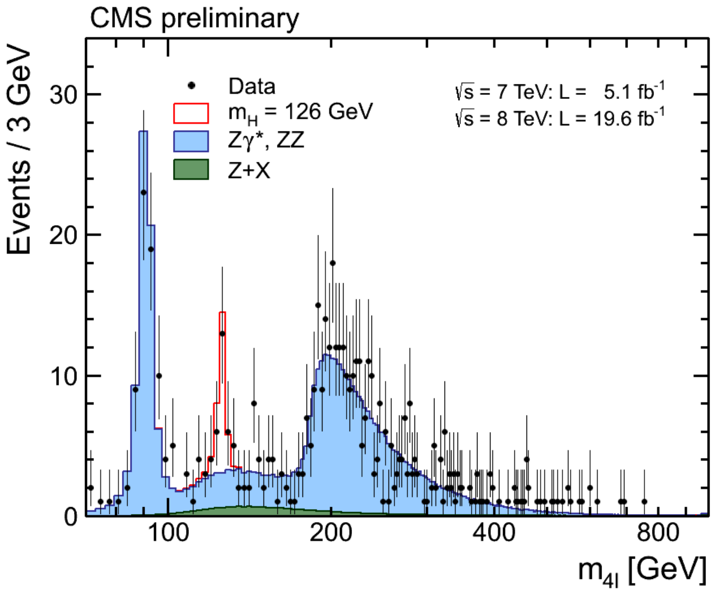




- First observation at CMS
- JHEP 12 (2012) 034
- Same Fit procedure as for $m_{4\ell}$
- Good Data/MC agreement on width

- $M_Z = 91.1876 \pm 0.0021\,\text{GeV}/c^2$
- $\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV}/c^2$ [PDG]

$m_{4\ell}$ distribution

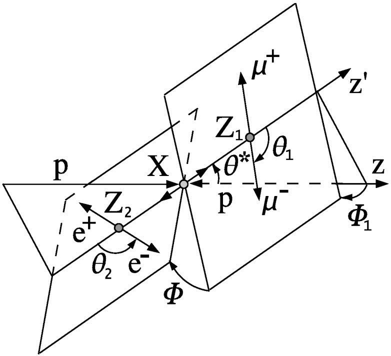


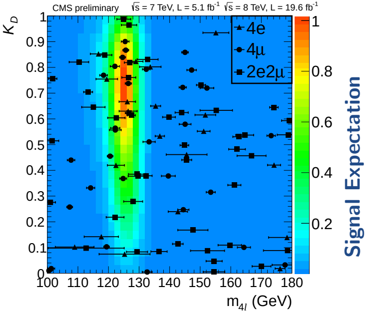
▲ Slow Animation

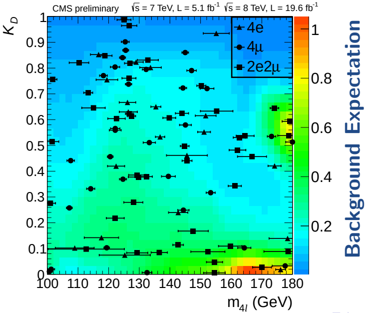
▲ Fast Animation

Animation!

Kinematic Analysis







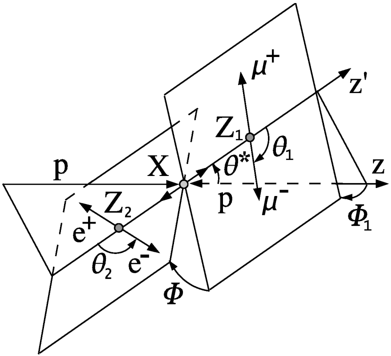
Improve **Signal to Background** discrimination by the use of kinematic information

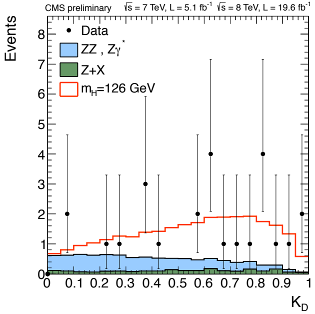
$$K_D = \frac{\mathcal{P}_{\text{sig}}}{\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}}} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

$$\vec{\Omega} = (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$$

arXiv:1208:4018[hep-ph]

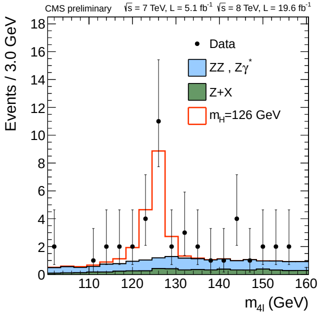
Kinematic Analysis





$(121.5 < m_{4\ell} < 130.5)$

K_D



$K_D > 0.5$

Improve **Signal to Background** discrimination by the use of kinematic information

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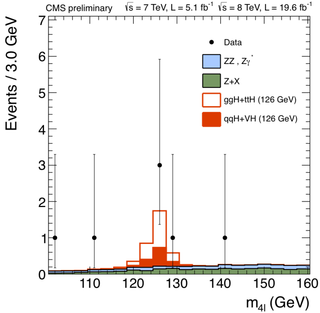
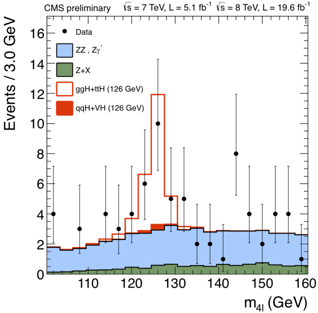
Probing the Production Mechanisms



dijet tagged

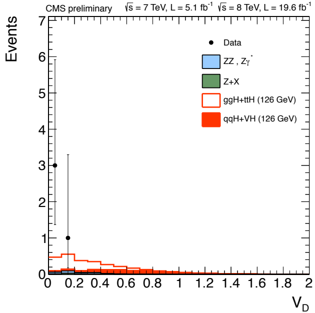


untagged

- $\geq$ 2jets
- Sensitive to *VH* and *qqH*
- measure **Boson** Couplings
- 25% VBF (qqH)
- Discriminant: $V_D(\Delta\eta_{ij}, M_{ij})$

- $<$ 2jets
- Sensitive to *ggH* and *ttH*
- measure **Fermion** Couplings
- 5% VBF (qqH)
- Discriminant: $\frac{p_T(4\ell)}{m_{4\ell}}$

Probing the Production Mechanisms



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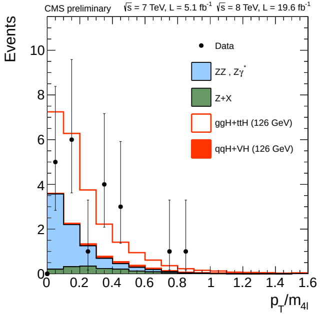

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- $\geq$ 2jets
- Sensitive to VH and qqH
- measure **Boson** Couplings
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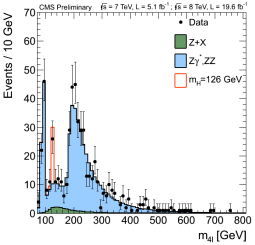
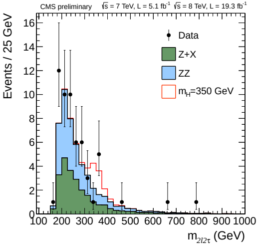
- $<$ 2jets
- Sensitive to ggH and ttH
- measure **Fermion** Couplings
- 5% VBF (qqH)
- Discriminant: $\frac{p_T(4\ell)}{m_{4\ell}}$

Significance: $4\ell + 2\ell 2\tau$

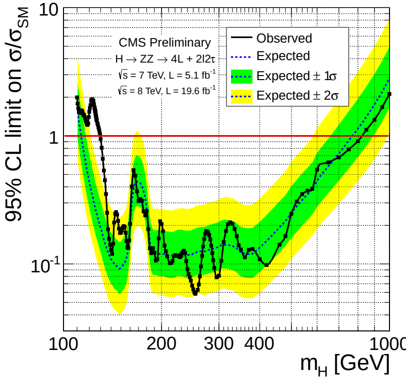


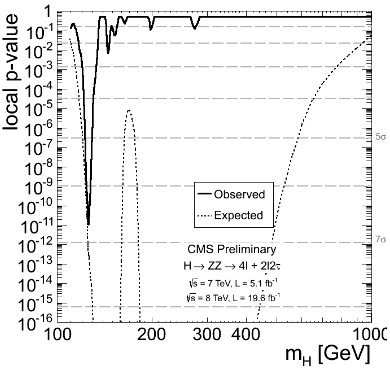


$H \to ZZ \to 2\ell 2\tau$

- no overlap 4ℓ and $2\ell 2\tau$
- $Z_1 \to \ell_a \ell_b \quad Z_2 \to \tau\tau$
- hadronic & leptonic τ
- 8 final states

- 6.7σ (7.2σ expected)
- 130-839 GeV/c^2 excl.





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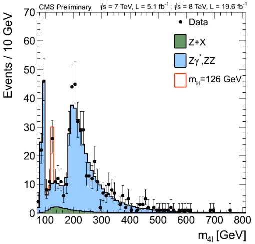

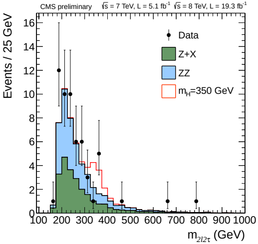

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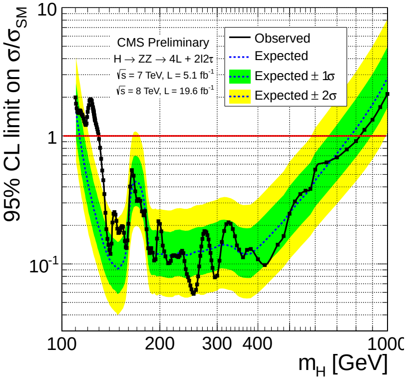
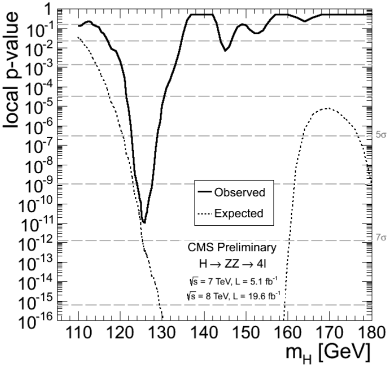
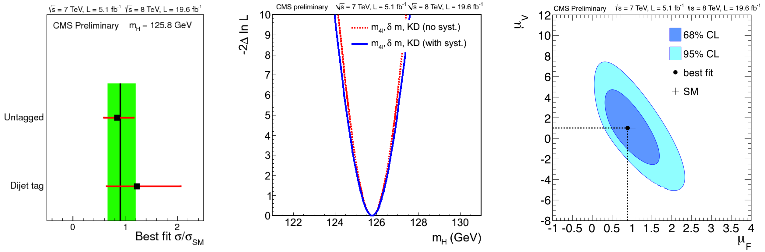


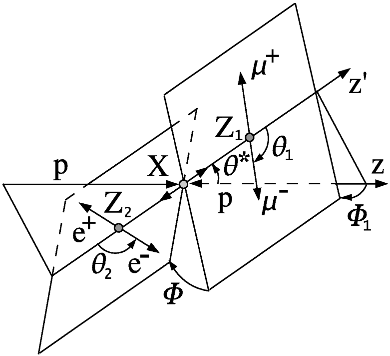


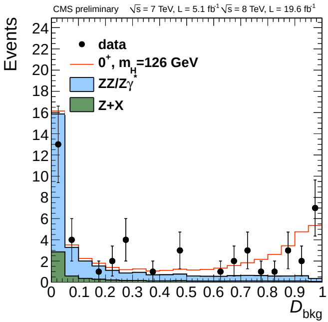
Signal Strength - Mass - Production Mechanisms



- **Signal Strength** (w.r.t. the expectation for a SM Higgs boson): $\mu = 0.91^{+0.30}_{-0.24}$ at 125.8 GeV/c^2
- **Mass Measurement** (3D fit using $m_{4\ell}$, $\sigma(m_{4\ell})$, K_D): $m_H = 125.78 \pm 0.48$ (stat) ± 0.15 (syst) GeV/c^2
- **Production Mechanisms Measurement** (2D fit using μ_V and μ_F at 125.8 GeV/c^2):
  - Bosonic signal strenght modifier (qqH and VH): $\mu_V = 1.0^{+2.4}_{-2.3}$
  - Fermionic signal strength modifier (ggH and ttH): $\mu_F = 0.9^{+0.5}_{-0.4}$

Spin-Parity Measurement





$$\mathcal{D}_{\text{bkg}} = \frac{\mathcal{P}_{\text{sig}}}{\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}}} = K_D$$

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\text{SM}}}{\mathcal{P}_{\text{SM}} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\text{SM}}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

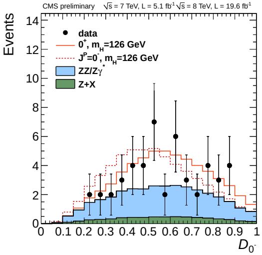
Models

J^P	production	comment
0^-	$gg \to X$	pseudoscalar
0^+_h	$gg \to X$	higher dim operators
$2^+_{m(gg)}$	$gg \to X$	minimal couplings
$2^+_{m(qq)}$	$q\bar{q} \to X$	minimal couplings
1^-	$q\bar{q} \to X$	exotic vector
1^+	$q\bar{q} \to X$	exotic pseudovector

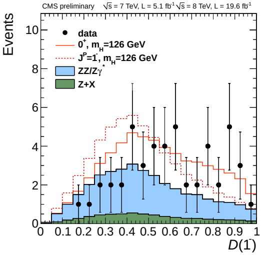
Spin-Parity Distributions

$\mathcal{D}_{J^P}$ for $\mathcal{D}_{\rm bkg} > 0.5$

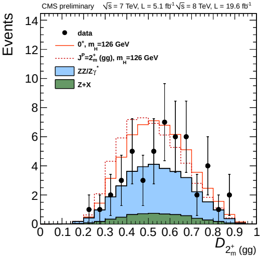
0^- vs 0^+

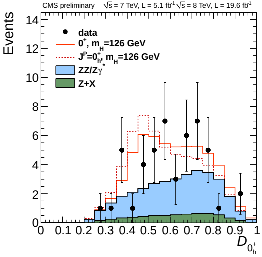


1^- vs 0^+

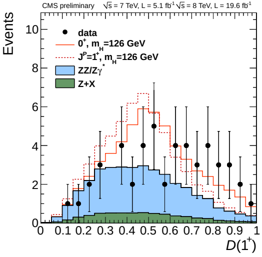


$2^+_{m(gg)}$ vs 0^+

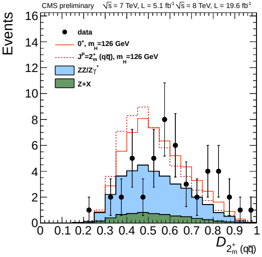




0^+_h vs 0^+



1^+ vs 0^+

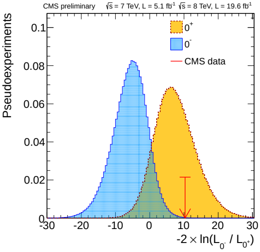


$2^+_{m(qq)}$ vs 0^+

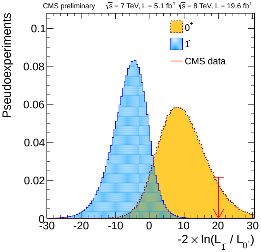
Spin-Parity Separation

$$q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{SM})$$

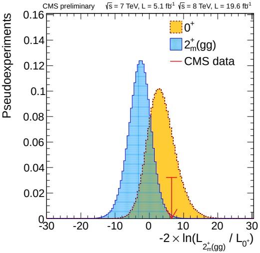
0^- vs 0^+

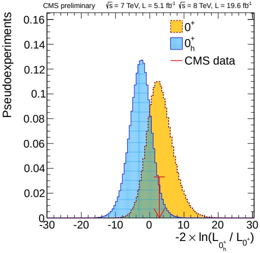


1^- vs 0^+

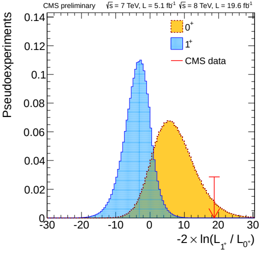


$2^+_{m(gg)}$ vs 0^+

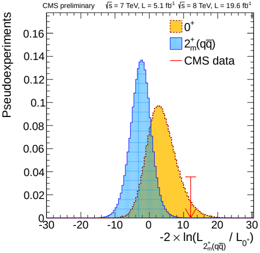




0^+_h vs 0^+



1^+ vs 0^+

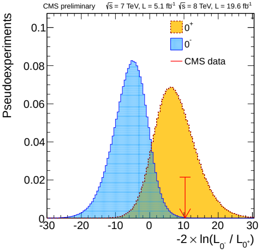


$2^+_{m(qq)}$ vs 0^+

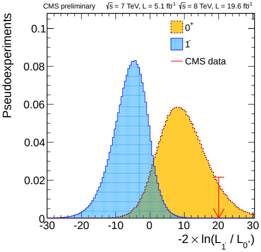
Spin-Parity Separation

$$q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{SM})$$

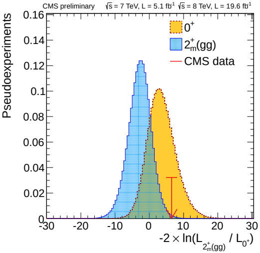
0^-: $3.4\sigma\,(2.4\sigma)$

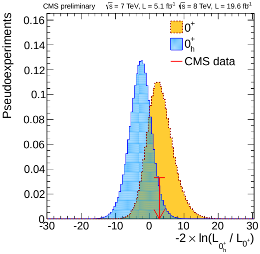


1^- vs 0^+

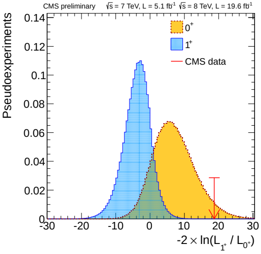


$2^+_{m(gg)}$ vs 0^+

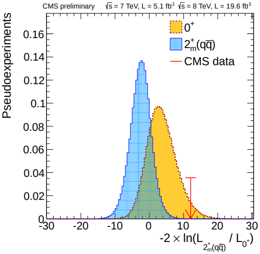




0^+_h vs 0^+



1^+ vs 0^+

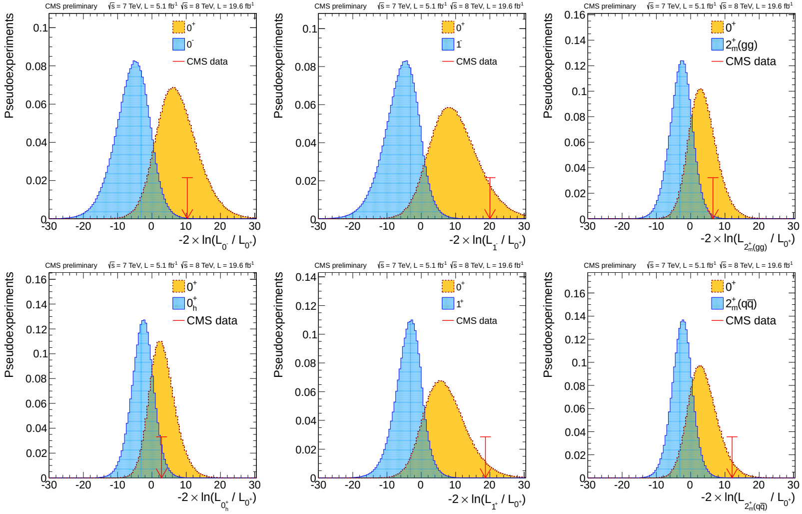


$2^+_{m(qq)}$ vs 0^+

Spin-Parity Separation

$$q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{SM})$$

0^-: 3.4σ(2.4σ) 1^-: > 4.0σ(2.8σ) $2^+_{m(gg)}$ vs 0^+



0^+_h vs 0^+ 1^+ vs 0^+ $2^+_{m(qq)}$ vs 0^+

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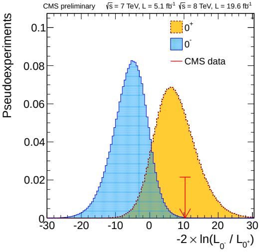
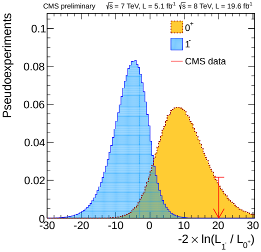
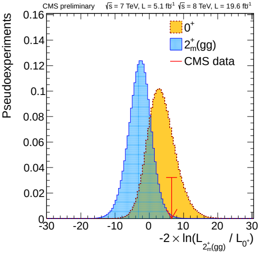
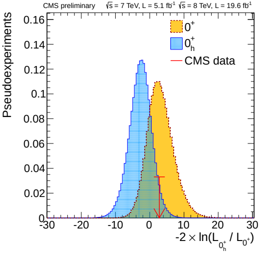
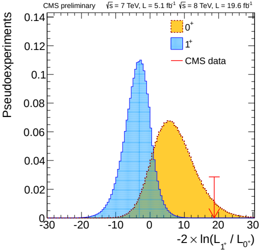
0^-: $3.4\sigma(2.4\sigma)$ | 1^-: $> 4.0\sigma(2.8\sigma)$ | $2^+_{m(gg)}$: $2.8\sigma(1.7\sigma)$

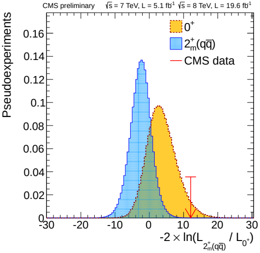










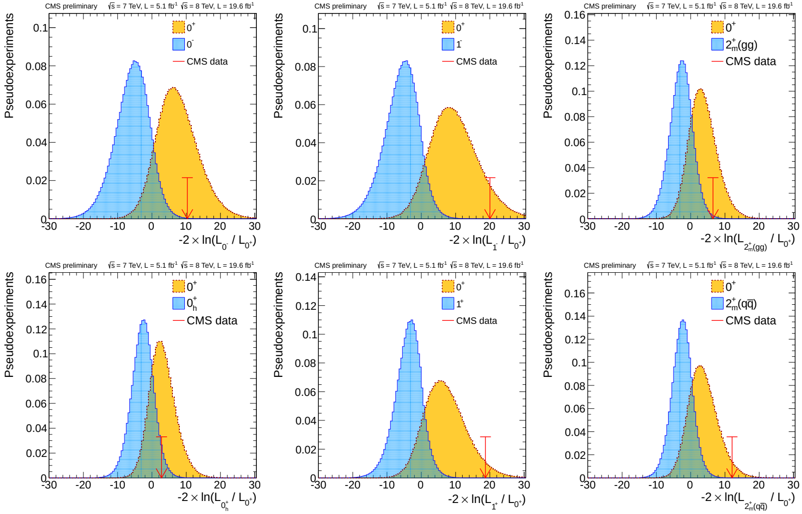


0^+_h vs 0^+ | 1^+ vs 0^+ | $2^+_{m(qq)}$ vs 0^+

Spin-Parity Separation

$$q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{SM})$$

0^-: $3.4\sigma(2.4\sigma)$ 1^-: $> 4.0\sigma(2.8\sigma)$ $2^+_{m(gg)}$: $2.8\sigma(1.7\sigma)$

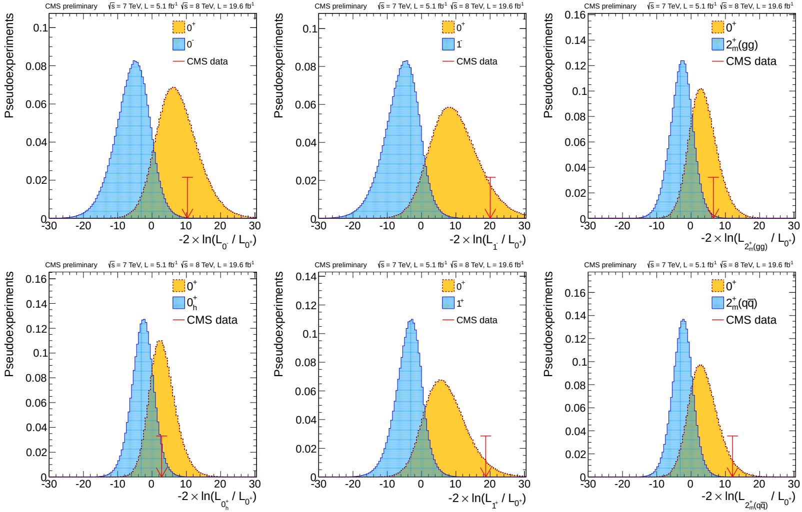


0^+_h: $1.9\sigma(1.6\sigma)$ 1^+ vs 0^+ $2^+_{m(qq)}$ vs 0^+

Spin-Parity Separation

$$q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{SM})$$

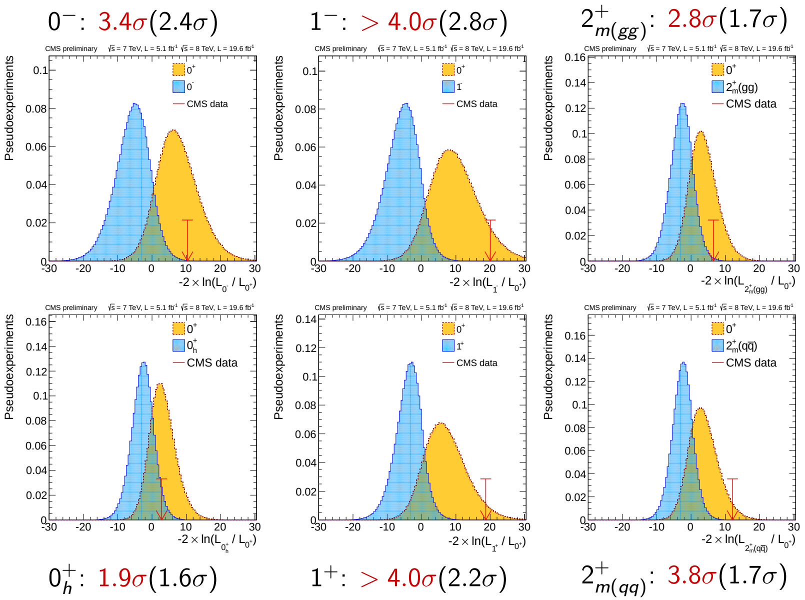
0^-: $3.4\sigma(2.4\sigma)$ 1^-: $>4.0\sigma(2.8\sigma)$ $2^+_{m(gg)}$: $2.8\sigma(1.7\sigma)$

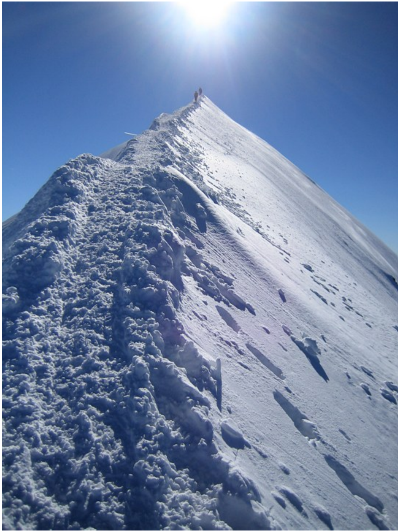


0^+_h: $1.9\sigma(1.6\sigma)$ 1^+: $>4.0\sigma(2.2\sigma)$ $2^+_{m(qq)}$ vs 0^+

Spin-Parity Separation

$q = -2\ln(\mathcal{L}_{J^P}/\mathcal{L}_{SM})$





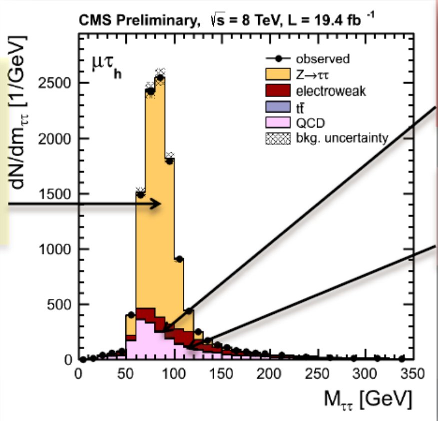
Moriond 2013

- $H \to \tau\tau$
- $G \to gg$

Anatomy of the analysis

$H \rightarrow \tau\tau$

$Z \rightarrow \tau\tau$
Embedding: $Z \rightarrow \mu\mu$ data, replace μ with simulated τ decay
Normalization from $Z \rightarrow \mu\mu$ data



W+jets
Shape from simulation
Normalization from control region

QCD
SS data, corrected for SS/OS ratio

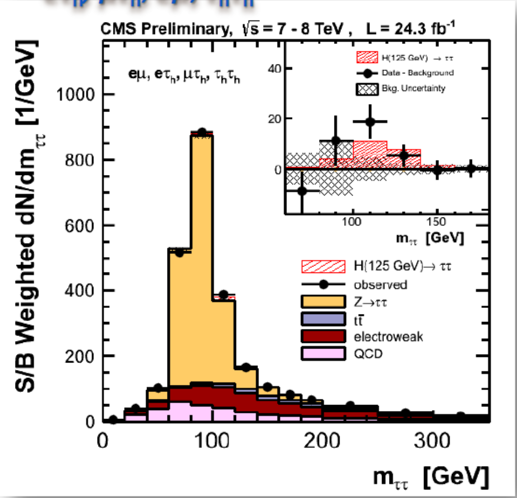
Strategy:

- Select isolated, well-identified **leptons**, τ_h
- Topological cuts (e.g. m_T in $l\tau_h$, $p_T(H)$ in $\tau_h\tau_h$) to suppress backgrounds
- Categorize events based on number of jets, τ p_T
- Template fit to $m_{\tau\tau}$ shape

Combined 1-jet and VBF

$H \to \tau\tau$

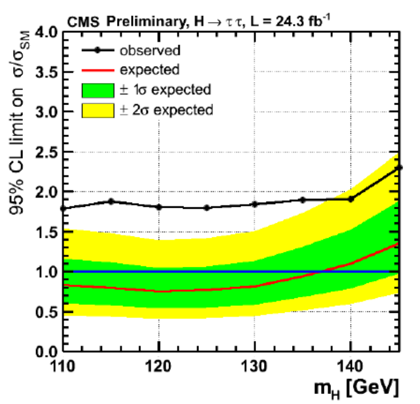
$e\tau_h$, $\mu\tau_h$, $e\mu$, $\tau_h\tau_h$

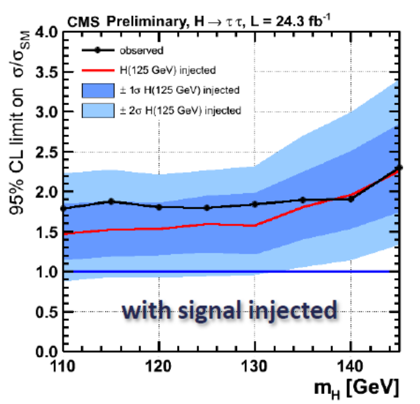


Combined channels and categories, each category in each channel weighted by its S/B

Limits

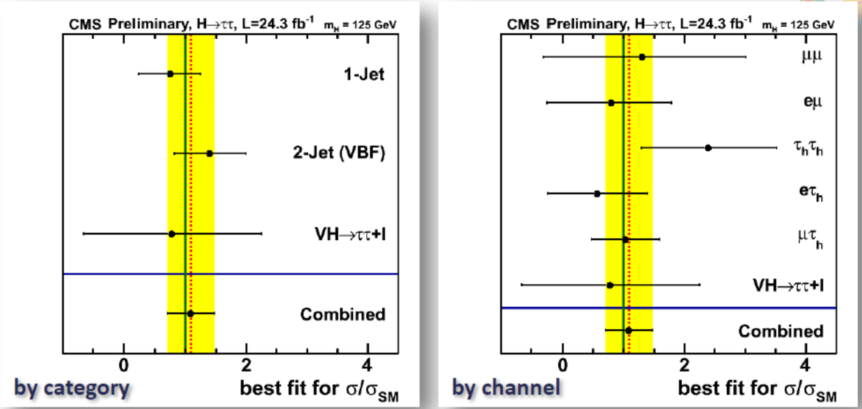
H→ττ





Results consistent with expectation for background + SM scalar at 125 GeV

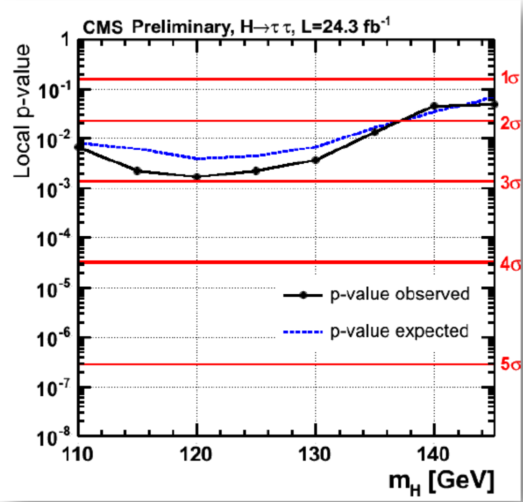
Signal strength



- Consistent picture across channels and categories
- Combined best-fit $\hat{\mu}$ of **1.1±0.4**

$H \rightarrow \tau\tau$

Significance



- Broad excess observed over range of m_H
- Maximum local significance of **2.93σ** at 120 GeV, compatible with presence of 125 GeV SM scalar boson
- Observed (expected) significance of **2.85σ** (**2.62σ**) for m_H = 125 GeV

$H \rightarrow \gamma\gamma$: Analysis strategy

- Events are separated in exclusive categories with different S/B and resolution.

- Special "tagged" categories enriched in VBF and VH signal production.
  - Improve the sensitivity of the analysis for the coupling measurements.

- Background directly estimated from data
  - Fit the $\gamma\gamma$ invariant mass in categories using polynomials (3rd-5th order)

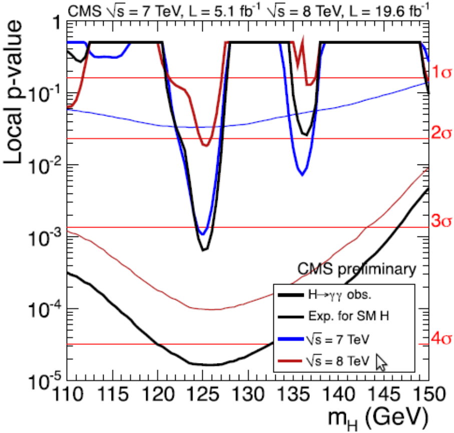
- **Two different analysis**
  - **Cut-based (CiC)**
  - **Multivariate (MVA):** select and categorize events using a BDT
- **Baseline result: MVA approach** (~15% better expected sensitivity)

H→γγ: Results (p-values)

CMS-HIG-13-001

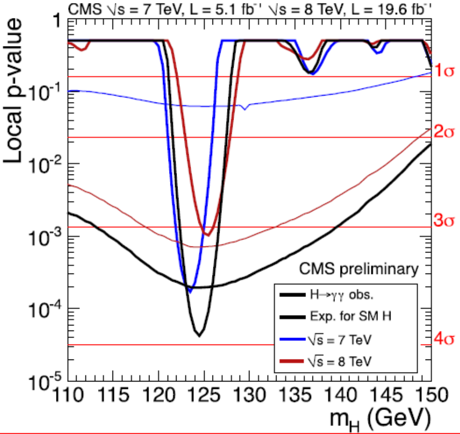
- In the following: results of the two analyses are shown side by side

MVA mass-factorized



Significance @ 125.0 GeV: 3.2 σ (4.2 exp.)

Cut-based



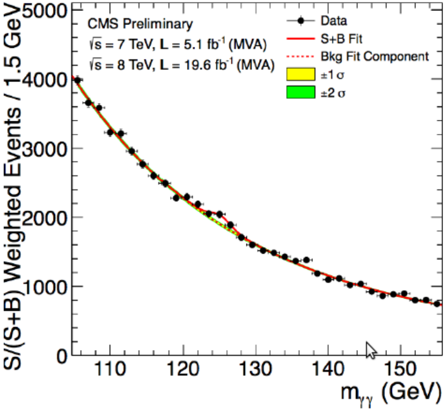
Significance @ 124.5 GeV: 3.9 σ (3.5 exp.)

With additional data and new analysis: significance decreased compared to the published results

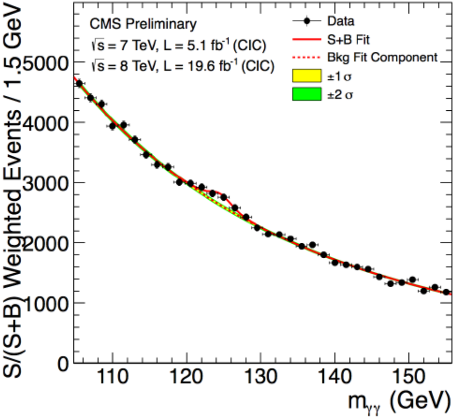
H→γγ: Combined mass plot: 7+8 TeV

CMS-HIG-13-001

MVA mass-factorized



Cut-based



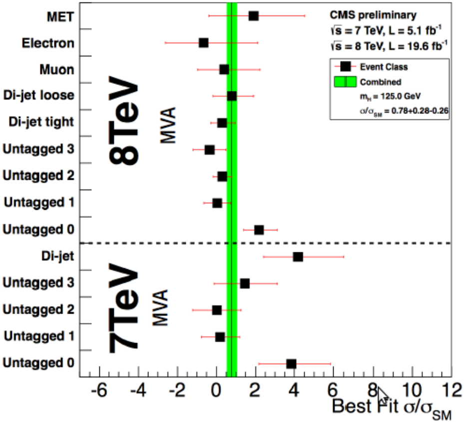
Bump at ~125 GeV consistent with expectations

Each event category is **weighted by its S/(S+B)** only for visualization purpose

H→γγ: Results (channel compatibility)

CMS-HIG-13-001

MVA mass-factorized

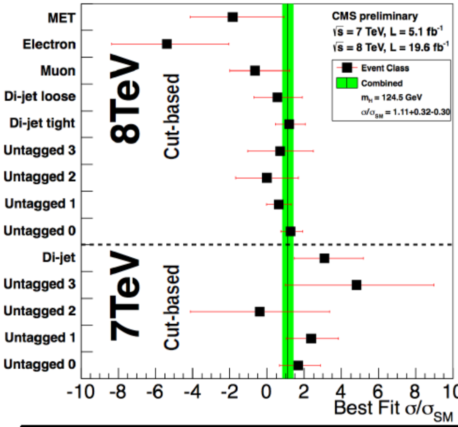


7+8 TeV: σ/σSM @ 125.0 GeV = 0.78 +0.28-0.26

7 TeV: σ/σSM @ 125.0 GeV = 1.69 +0.65-0.59

8 TeV: σ/σSM @ 125.0 GeV = 0.55 +0.29-0.27

Cut-based



7+8 TeV:σ/σSM @ 124.5 GeV = 1.11 +0.32-0.30

7 TeV: σ/σSM @ 124.5 GeV = 2.27 +0.80-0.74

8 TeV: σ/σSM @ 124.5 GeV = 0.93 +0.34-0.32

- Despite the same names, the untagged categories in MVA and Cut-basd are not equivalent

H→γγ: Compatibility among the two analysis   CMS-HIG-13-001

- **Low signal to background ratio a fundamental feature of this channel**
  - Uncertainty on signal strength driven by statistical fluctuations of the background
  - Analysis changes can lead to statistical changes due to fluctuations in selected events
  and their mass

- The correlation coefficient between the MVA and cut-based signal strength measurements
  is found to be **r=0.76** (estimated using jackknife techniques)

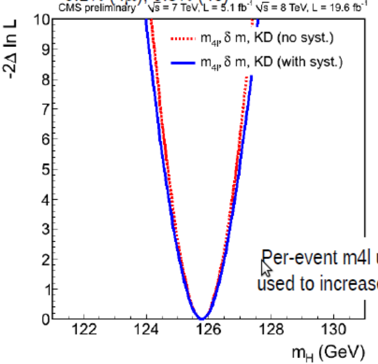
	Signal strength compatibility (including correlation)
MVA vs CiC 7+8 TeV	1.5 σ
MVA vs CiC 8 TeV only	1.8 σ
Updated MVA vs published (5.3/fb 8TeV)	1.6 σ
Updated CiC vs published (5.3/fb 8TeV)	0.5 σ

- Observed changes in results and differences between analyses are all **statistically compatible at less than 2σ**

Mass measurement

H→ZZ→ 4l

- Lepton momentum scale & resolution validated with Z, J/ψ, and ϒ→ll samples.
- m4l uncertainties due to lepton scale: 0.1% (4μ), 0.3% (4e)

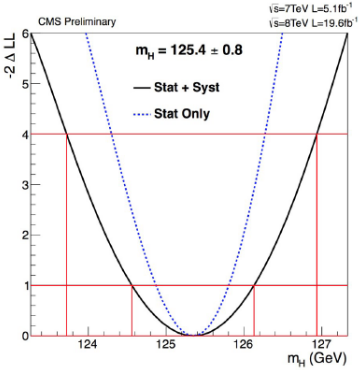


Per-event m4l uncertainty used to increase precision.

mH = 125.8 ± 0.5 (stat.) ± 0.2 (syst.)

H→γγ

- Systematic errors dominated by overall photon energy scale: 0.47%
  (mostly coming from extrapolation from Z→H and e→γ)



mH = 125.4 ± 0.5 (stat.) ± 0.6 (syst.)

Measurements in the two channels are well compatible.

Summary

Conclusions

- The LHC has had a tremendeously succesful 3 years of operation
- The CMS experiment has succesfully analyzed $\sim 25\,\mathrm{pb}^{-1}$ of data
- A new boson has been detected by ATLAS and CMS with spin and parity very consistent with the Standard Model Higgs boson

Thanks to . . .

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- you for all attention

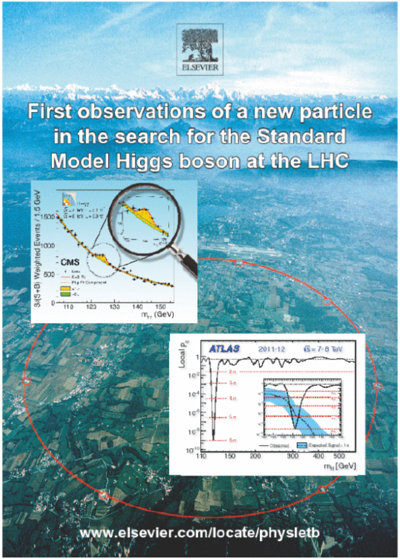
Sources

- CMS Results :: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
- $H \to 4\ell$ :: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13002TWiki
- $H \to \tau\tau$ :: https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13004TWiki

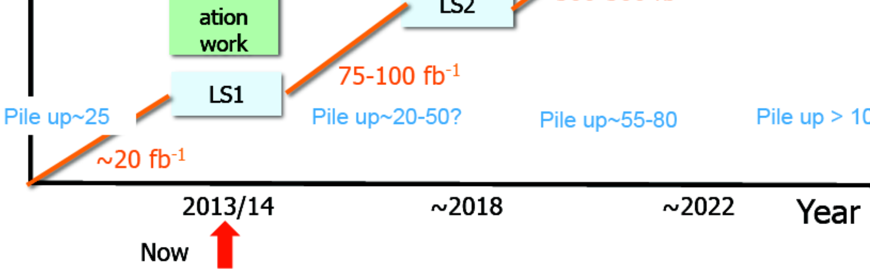
- Moriond EWK :: https://indico.in2p3.fr/conferenceOtherViews.py?view=standard&confId=7411
- Moriond QCD :: http://moriond.in2p3.fr/QCD/2013/MorQCD13Prog.html

Presentations

- M. Chamizo Llatas – Aspen 2013 – The CMS Detector
- V. Dutta – Moriond 2013 – $H \to \tau\tau$
- C. Ochando – Moriond 2013 – $H \to \gamma\gamma$


ELSEVIER
First observations of a new particle in the search for the Standard Model Higgs boson at the LHC
CMS
ATLAS
2011-12
Local p_0
m_H [GeV]
www.elsevier.com/locate/physletb

Appendix

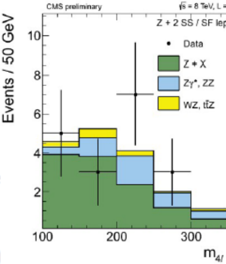

ation
work
LS1
LS2
75-100 fb-1
~20 fb-1
Pile up~25
Pile up~20-50?
Pile up~55-80
Pile up > 10
2013/14
~2018
~2022
Year
Now

LHC Consolidation Works 2013-2014

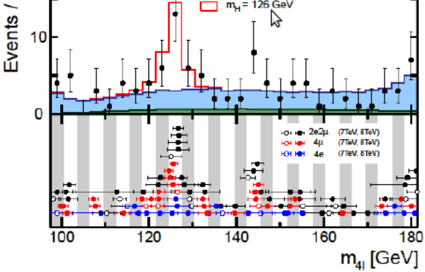
- Z1+ 2 SS SF "loose" leptons
- Extrapolation to signal region:
  - SS/OS factor from MC, cross-checked with data
  - lepton mis-identified probability (corrected for difference in composition of converted photon between CR & sample to extract misID probability)

- **Validation:** samples with relaxed charged and/or flavor requireme

- **Final estimate:** combination of the two methods (yields in control regions & part of the uncertainties un-correlated)



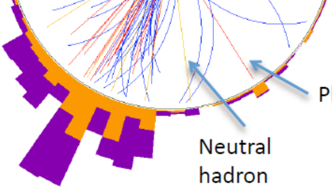
Validation in Z+2SS/SF



110 < m4l < 160 GeV

Channel	4e	4μ	2e2μ	
ZZ background	6.6 ±0.8	13.8 ±1.0	18.1 ±1.3	3
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	4
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	1
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	2
Observed	16	23	32	

List of reconstructed particles: can be used like a list of stable particles from a generator



Also use these particles to reconstruct tau decays, lepton and photon isolation

$$\overrightarrow{\text{MET}} = -\sum_{\text{particles}}$$