Spin and Parity of the Higgs Boson Near $m_H = 126$ GeV/c^2 in the $H \rightarrow ZZ \rightarrow 4\ell$ Channel and a Search for a Doubly Charged Higgs with the CMS Detector at the LHC

PhD Thesis Defense

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Compact Muon Solenoid
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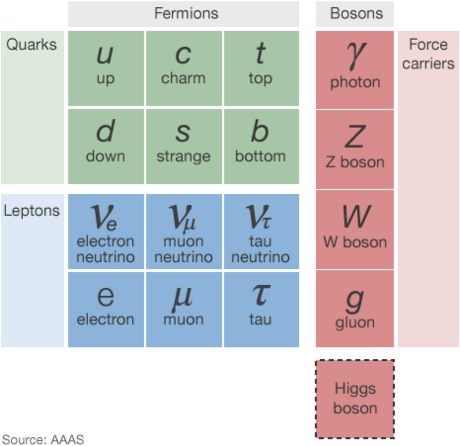
The Standard Model

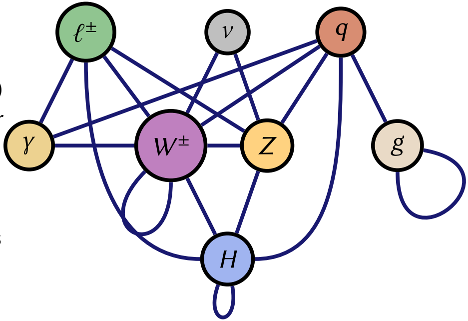
- **Matter Particles**
  - Quarks: u, d, c, s, t, b
  - Leptons: e, μ, τ, ν_e, ν_μ, ν_τ
- **Force Carriers**
  - Electromagnetism: γ
  - Weak: Z and $W^\pm$ (massive)
  - Strong: g
- **Higgs Boson**
  - $m_H = 125.09 \pm 0.24$ GeV
  - Spin-0 scalar particle
- **Missing Pieces**
  - Dark Matter and Dark Energy
  - Gravity



Source: AAAS

Particle Interactions

- **Strong Force**
  - Carried by gluons
  - Binds quarks into mesons and baryons (e.g. protons and neutrons)
  - Keeps atomic nuclei bound together
- **Electromagnetic Force**
  - Carried by photons
  - Binds electrons into atomic orbitals
  - Binds atoms into molecules
- **Weak Force**
  - Carried by Z and W bosons
  - Responsible for radioactive decay
- Dynamics are described by the *Standard Model*, which is a quantum field theory that obeys $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry



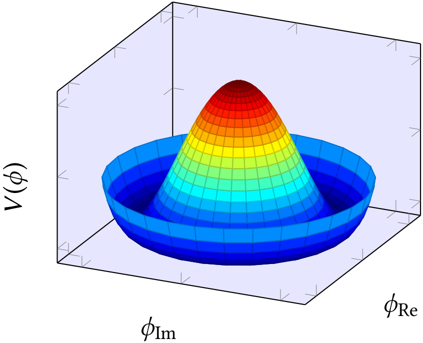
The Higgs Mechanism

- $SU(2)_L \times U(1)_Y$ symmetry requires massless gauge bosons
- Photon is massless, $W^{\pm}$ and Z are not – broken symmetry
- The Brout-Englert-Higgs Mechanism provides a means for spontaneous symmetry breaking
- Add a complex $SU(2)_L$ scalar doublet, which obeys the following potential

$$V(\phi) = \mu^2 \phi^\dagger \phi + \frac{1}{2}\lambda^2 \left(\phi^\dagger \phi\right)^2$$

- Spontaneous symmetry breaking occurs when $\mu^2 < 0$, and the vacuum expecation value (VEV) is no longer zero

$$v/\sqrt{2} = \mu/\lambda$$



- Predicts a neutral, spin-0 boson with mass $M_H = -\lambda v$
- Photon remains massless, Z and $W^{\pm}$ acquire mass

$$M_W = \frac{1}{2} g v \quad M_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v$$

Yukawa Couplings

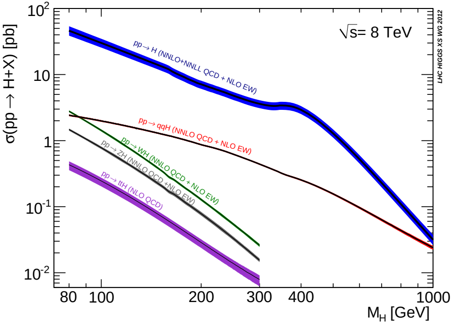
- The Higgs can also couple to fermions
- For electrons, this would be

$$\mathcal{L} = -\frac{Y_e}{\sqrt{2}}(v + H)(\bar{e}_L e_R + \bar{e}_R e_L)$$

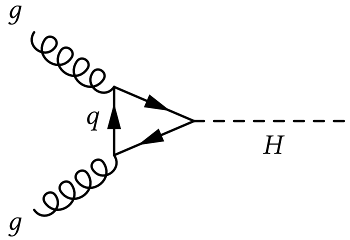
- This coupling gives the electrons their mass
- The heavier the particle, the stronger the coupling
- Right and left-handed varieties of a particle are required for this to work
- Only left-handed neutrinos have been observed in nature – cannot aquire mass in this way
- Higgs can only couple directly to massive particles – photons and gluons are massless

Higgs Production

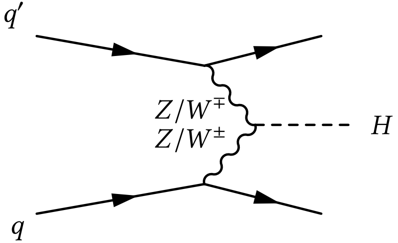
- Gluon fusion is the dominant Higgs production mode in proton collisions
- Vector boson fusion is second dominant



Gluon Fusion

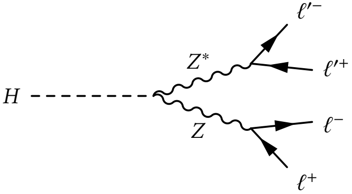


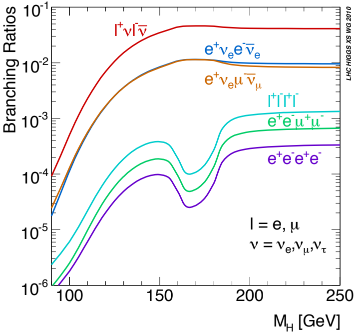
Vector Boson Fusion



$H \rightarrow ZZ \rightarrow 4\ell$

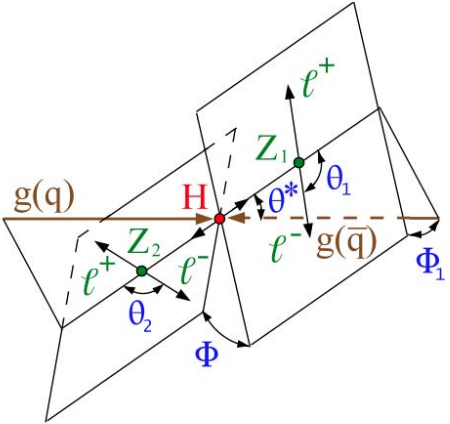
- A Higgs boson may decay directly to two Z bosons
- The Z's may decay to two charged leptons
- Called the "golden channel", specifically when the leptons are muons and electrons – has a very clean signature in the detector
- The event can be fully reconstructed (no missing transverse energy or jets)
- Very well suited for precision studies





Spin and Parity of the Higgs Boson

- The Standard Model Higgs boson is predicted to be a spin-0, pure-scalar particle
- The spin-parity configuration of the Higgs is manifest in the kinematics of the four leptons
- *Inferring the nature of the boson at 125-126 GeV*, arXiv:arXiv:1301.5404 [hep-ph]
- Assuming the Higgs is not spin-1, use of the angles $\theta_{1,2}$ and ϕ, can distinguish between the pure-scalar, pseudoscalar, and spin-2 hypotheses



Neutrino Masses

- Neutrinos have very small mass, $m_{\nu_e} < 2\,\text{eV}$
- Only left-handed neutrinos are known to exist: cannot acquire mass through SM Higgs mechanism
- Neutrino masses have not been measured individually, but the square of the mass differences has been measured
- *Normal mass hierarchy*: $m_1 < m_2 < m_3$
- *Inverted mass hierarchy*: $m_3 < m_1 < m_2$

Neutrino Oscillations

- A single neutrino can change flavor
- Neutrinos propagate through space in one of three mass eigenstates: $(\nu_1,\ \nu_2,\ \nu_3)$
- They can be observed in any of the three flavor eigenstates $(\nu_e,\ \nu_\mu,\ \nu_\tau)$
- Neutrino oscillations are brought about by mixing between these eigenstates
- Mixing described by the unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- *Tri-bi-maximal mixing*: predicts that ν_2 is maximally mixed among all three flavor eigenstates, and ν_3 is maximally mixed between ν_μ and ν_τ

$$\begin{array}{c} \\ \nu_e \\ \nu_\mu \\ \nu_\tau \end{array} \begin{array}{c} \begin{array}{ccc} \nu_1 & \nu_2 & \nu_3 \end{array} \\ \begin{pmatrix} 2/3 & 1/3 & 0 \\ 1/6 & 1/3 & 1/2 \\ 1/6 & 1/3 & 1/2 \end{pmatrix} \end{array}$$

Doubly Charged Higgs

- In the Standard Model, neutrinos are massless, but it is well established experimentally that they do have mass
- One model that can accommodate neutrino masses is a Higgs triplet
- This extends the SM particle spectrum with three scalars: Φ, Φ^{+}, and Φ^{++}
- The triplet couples to lepton doublet via

$$\mathcal{L} = i\ell^{c}_{Li}\tau_2 Y^{ij}_{\Phi}(\tau \cdot \Phi)\ell_{Lj} + h.c.$$

- The neutrino mass matrix is directly related to the Yukawa couplings

$$(m_{\nu})_{ij} = 2(Y_{\Phi})_{ij}v_{\Phi}$$

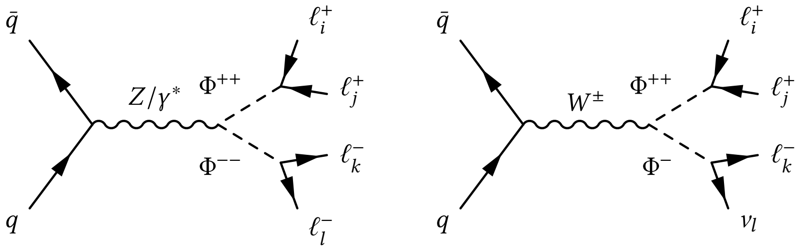
- Discovery of the doubly charged component of this triplet could allow us to measure neutrino masses with a collider experiment
- The doubly charged Higgs decays to same-sign leptons, which do not necessarily have to be same-flavor
- There are no individual SM particles that decay in this fashion

Doubly Charged Higgs Phenomenology

- The width of the doubly charged Higgs to charged leptons is

$$\Gamma\left(\Phi^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}\right) = \begin{cases} \frac{1}{8\pi}\left|(Y_\Phi)_{ij}\right|^2 m_{\Phi^{\pm\pm}} & i = j \\ \frac{1}{4\pi}\left|(Y_\Phi)_{ij}\right|^2 m_{\Phi^{\pm\pm}} & i \neq j \end{cases}$$

- Measuring the branching fractions gives us information about the Yukawa couplings, and thus, neutrino masses
- Doubly charged Higgs can be produced through pair-production or associated production



Non-LHC Spin-Parity

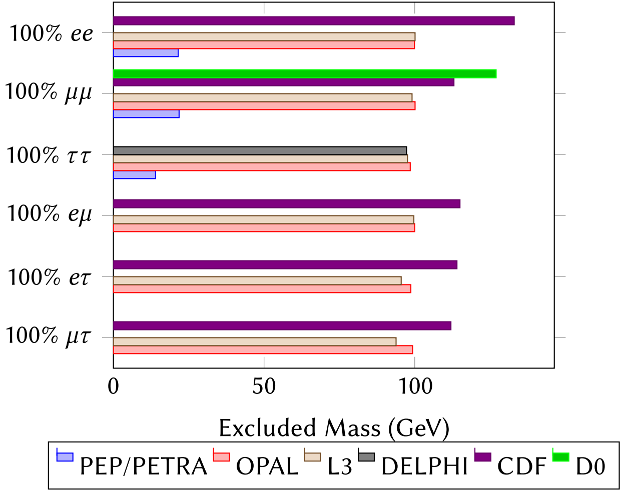
- The most extensive spin-parity measurements are performed by CMS and ATLAS
- Tevatron performed a measurement for the associated production of a Higgs decaying to $b\bar{b}$

$$WH \rightarrow \ell\nu b\bar{b} \quad ZH \rightarrow \ell^+\ell^- b\bar{b} \quad WH + ZH \rightarrow \not{E}_T b\bar{b}$$

- **CDF, D0 Collaboration**, "Tevatron Constraints on Models of the Higgs Boson with Exotic Spin and Parity Using Decays to Bottom-Antibottom Quark Pairs", `arXiv:1502.00967 [hep-ex]`
- Relies on the differences in kinematics of Higgs associated production for different spin-parity configurations
- Exclude 0^- with 5.0σ significance
- Exclude 2^+ with 4.9σ significance

Prior Searches for a Doubly Charged Higgs

- Excluded mass hypotheses of a doubly charged Higgs
- 90% CL for PEP/PETRA, and 95% for others



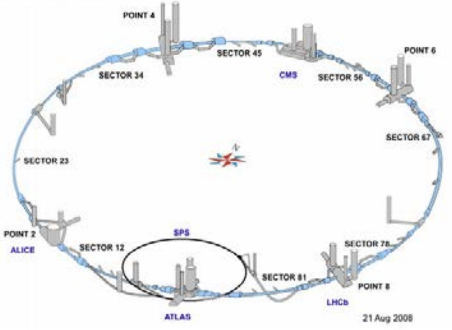
Large Hadron Collider

- Proton synchrotron
- 26.7 km in circumference, $\sim$ 100 m underground
- Center-of-mass energy

2010-2011	$\sqrt{s} = 7\,\text{TeV}$
2012	$\sqrt{s} = 8\,\text{TeV}$

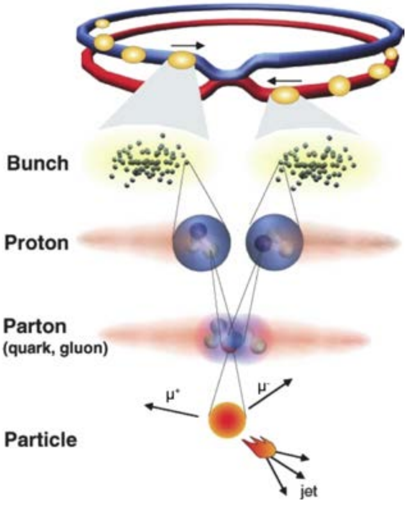
- Long Shutdown 1 – ended in June, now running at $\sqrt{s} = 13\,\text{TeV}$
- Four experiments

CMS	general purpose
ATLAS	general purpose
ALICE	heavy-ion experiment
LHCb	*b*-physics experiment



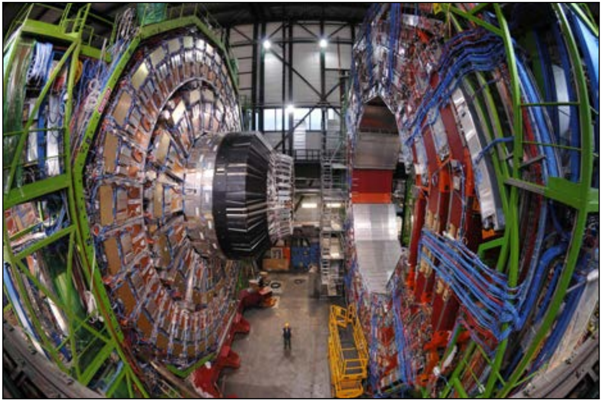
Proton-Proton Collisions

- Proton bunches cross at a rate of 40 MHz
- $\sim$ 20 *pp* collisions per bunch crossing at design specs.
- LHC ran at $\sqrt{s} = 8\,\text{TeV}$ during 2012
- 1380 bunches per ring with 16×10^{10} protons per bunch
- Instantaneous luminosity $\mathcal{L} = 77 \times 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$
- LHC delivered an integrated luminosity of $\mathcal{L}_{int} = \int \mathcal{L}\, dt = 23.3\,\text{fb}^{-1}$
- CMS recorded $19.7\,\text{fb}^{-1}$
- Event rate: $N = \sigma \cdot \mathcal{L}_{int}$
- Cross section, σ, is an “effective area” for a particular interaction



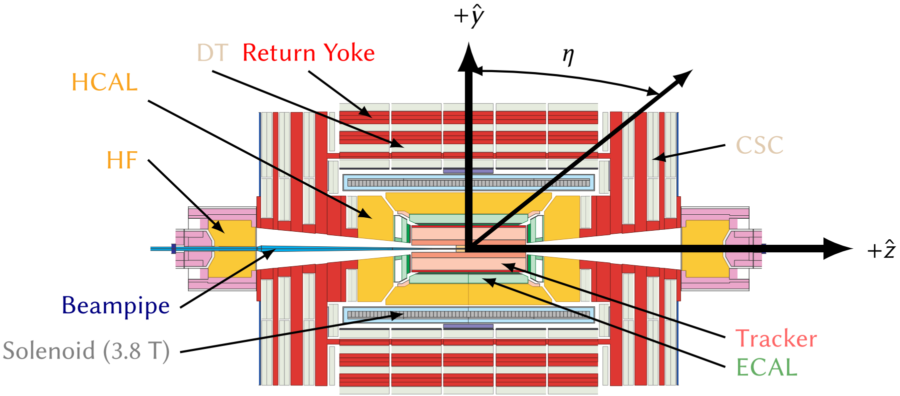
Compact Muon Solenoid

- Located at Point 5 along the LHC ring in Cessy, France
- Primary goal of CMS was to search for the Higgs boson – *discovered in 2012*
- Current goals
  - Measurement of Higgs properties
  - Searches for physics beyond the Standard Model



- Mass: 14 000 metric tons
- 15.0 m in diameter, and 28.7 m long
- Features a 3.8 T superconducting solenoid with a 6 m bore

Sub-Detectors and Geometry

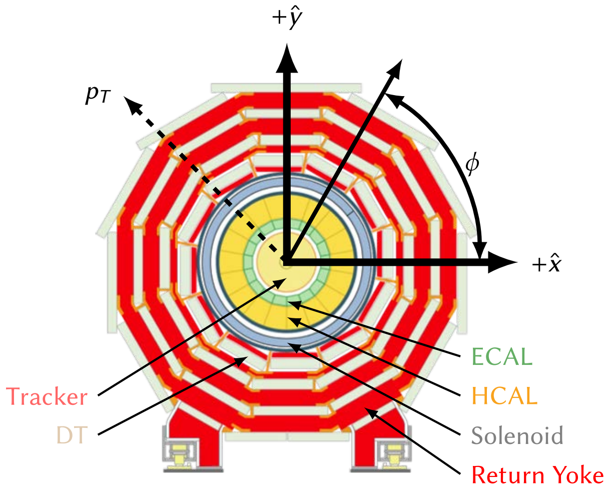


- Pseudorapidity ($\eta = -\ln \tan(\theta/2)$) – polar angle of a particle's trajectory (Lorentz invariant)
- Occupancy in $d\eta$ is constant across the detector

Sub-Detectors and Geometry

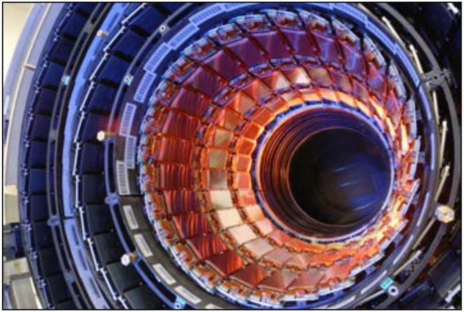
- ϕ – azimuthal angle of a particle's trajectory
- p_T – transverse momentum

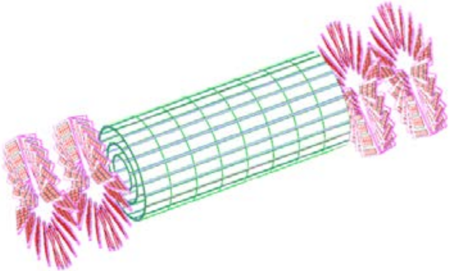
$$p_x = p_T \cos\phi$$
$$p_y = p_T \sin\phi$$
$$p_z = p_T \sinh\eta$$



Tracker

- 3.8 T magnetic field bends the paths of charged particles
- Tracker records the paths of charged particles and their momenta
- Resolution: $dp_T/p_T = (p_T(\text{TeV}) \cdot 15\%) \oplus 0.5\%$
- **Pixel Detector**
  - 60 million pixels cover 1 m^2
  - Three barrel layers ($r = 4.4,\ 7.3,\ 10.2$ cm)
  - Two endcap disks
  - Pixel size of $100 \times 150\ \mu m^2$
- **Strip Detector**
  - 15 148 silicon strip modules
  - Tracker inner barrel: $20 < r < 55$ cm
  - Minimum cell size: 10 cm × 80 µm
  - Tracker outer barrel: $55 < r < 120$ cm
  - Maximum cell size: 25 cm × 180 µm
  - 3 inner and 9 outer endcap disks

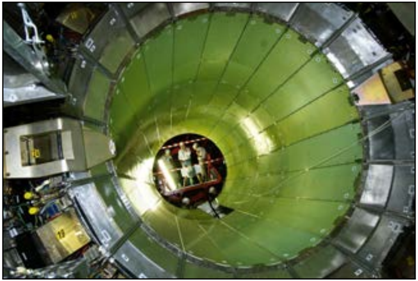


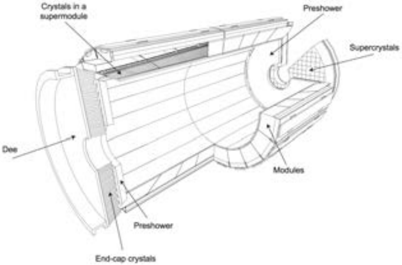


Electromagnetic Calorimeter

- Designed to measure the energy of particles interacting via EM (mostly photons and electrons)
- Composed of lead-tungstate ($PbWO_4$) crystals
  - B: 61 200, EC: 7324
  - Molière radius: 2.2 cm
  - Radiation length: 0.89 cm
- Each crystal is 230 mm long (25.8 radiation lengths)
- Crystals are 26 mm wide
- Resolution

$$\left(\frac{\sigma(E)}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2$$





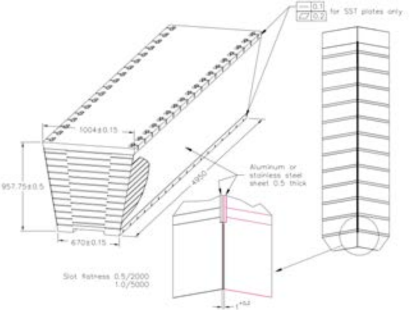
Hadronic Calorimeter

- Measures the energy of particles that interact via the strong force
- Sampling calorimeter
- Alternating layers of brass absorber and scintillator tiles
- Quartz and steel used in the endcaps
- 5.82 to 16 interaction lengths
- Barrel Resolution

$$\left(\frac{\sigma(E)}{E}\right)^2 = \left(\frac{90\%}{\sqrt{E}}\right)^2 + (4.5\%)^2$$

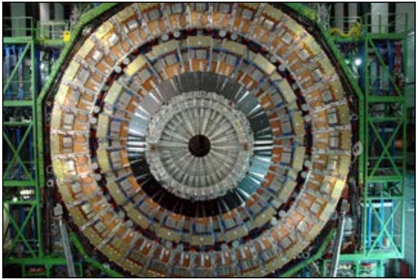
- Endcap Resolution

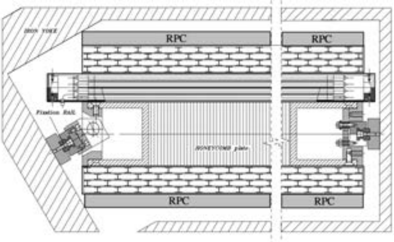
$$\left(\frac{\sigma(E)}{E}\right)^2 = \left(\frac{172\%}{\sqrt{E}}\right)^2 + (9.0\%)^2$$



Muon System

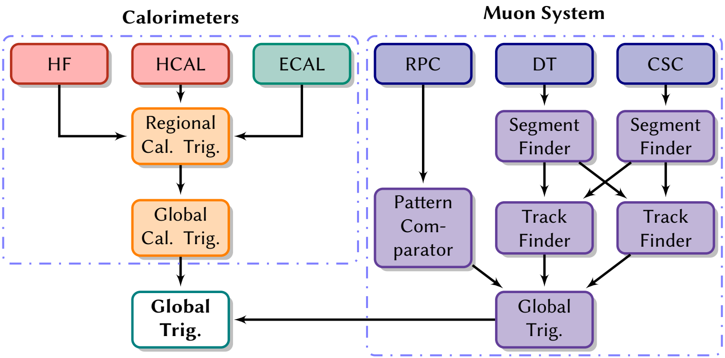
- Used for muon identification, momentum measurement, and triggering
- Located outside of the solenoid (2 T field in this region)
- **Drift Tubes**
  - Used in the barrel ($|\eta| < 1.2$)
  - Interleaved with iron return yoke
  - Good position resolution, slower timing
- **Cathode Strip Chambers**
  - Used in the endcaps ($0.9 < |\eta| < 2.4$)
  - Fast and precise position resolution
  - Suitable for high-radiation, variable *B*-field environment
- **Resistive Plate Chambers**
  - Used in barrel and endcaps
  - Fast timing, and weaker position resolution





Level-1 Trigger

- *pp* collisions occur at 40 MHz – 0.5-1 MB per event
- Must reduce the data rate while retaining events of interest
- Hardware-based trigger system is used to make fast keep/reject decisions
- Maximum data output of about 100 kHz



High-Level Trigger

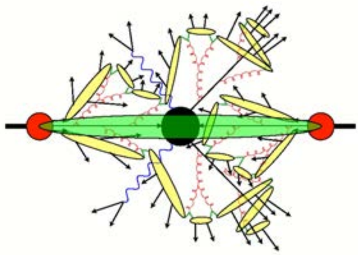
- Designed to further reduce the data-rate
- It accepts the 100 kHz input from the L1 Trigger
- It uses software-based triggers that run on the order of 10k commercial computing nodes
- Able to utilize more sophisticated algorithms for analyzing and selecting events, including use of tracker data
- HLT categorizes events into reconstruction “paths”, based on combinations of leptons, isolation, p_T thresholds, etc.
- **High-Level Trigger Paths Used**
  - Two-electron
  - Three-electron
  - Two-muon
  - Muon-electron

Monte Carlo Samples

- **Spin-Parity Signals**
  - Production modeled with Powheg, decays with JHUGen 2
  - SM Higgs and alternate spin-parity hypotheses
  - 0^+, 0^-, 0_h^+, $2_m^+(gg)$, $2_m^+(q\bar{q})$
  - $m_H = 126\,\text{GeV}$
- **Doubly Charged Higgs Signal**
  - Pythia 6.4
  - $q\bar{q} \rightarrow \Phi^{++}\Phi^{--} \rightarrow 4\ell$
  - $m_{\Phi^{++}} = 110$ to $700\,\text{GeV}$
- **Backgrounds**
  - $q\bar{q} \rightarrow ZZ \rightarrow 4\ell$: Powheg
  - $gg \rightarrow ZZ \rightarrow 4\ell$: gg2ZZ
  - $Z + X$: Pythia 6.4 (Spin-Parity)
  - MadGraph 4/Powheg used for minor backgrounds in Doubly Charged Higgs analysis

Monte Carlo Generators

- MadGraph 4/MadEvent
  - Fixed-order matrix element generator
  - Simulates multi-parton processes
- Powheg
  - NLO w/ parton shower event generator
- Pythia 6.4
  - Leading-order event generator
  - Showering and hadronization generator (SHG)
  - Also used for underlying event
- gg2ZZ
  - Dedicated NLO $gg \to ZZ$ generator
- JHUGen 2
  - Provides full spin and polarization correlations of final state particles from the decay of a given resonnance
  - Used for handling the decays of different spin-parity hypotheses for the Higgs
- Geant4
  - Simulates passage of radiation through matter

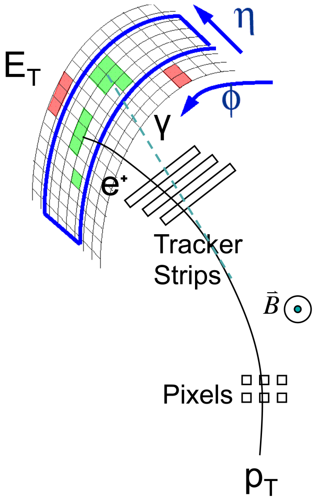


Monte Carlo Simulation Chain

1. MadGraph 4/Powheg/gg2ZZ/Pythia 6.4
   - Simulate the parton-parton hard scattering event
2. JHUGen 2
   - Simulate the decay of a Higgs to leptons, taking into account spin and polarization correlations
3. Pythia 6.4
   - Simulate the underlying event – interactions between other partons in the proton-proton collision
   - Showering and hadronization – form jets from final state quarks and gluons
4. Geant4
   - Simulate the detector response
5. CMSSW
   - Perform CMS reconstruction algorithms for forming particle candiates

Electron Reconstruction

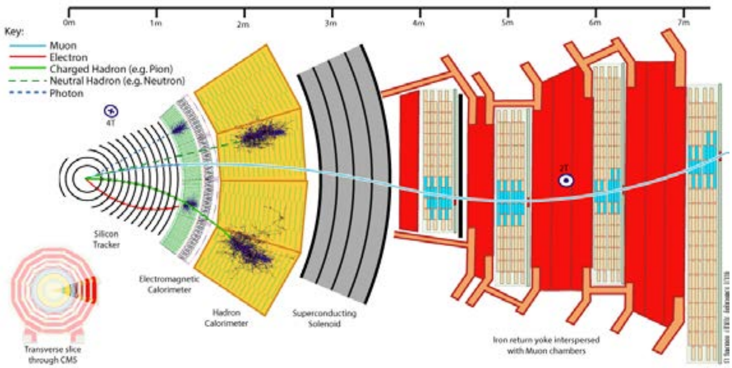
- Electron are reconstructed from ECAL and track information
- ECAL-driven seeding
- Optimized for higher p_T electrons, coming from Z or W decays
- Supercluster – group of one or more clusters of energy deposits in ECAL
- Form ECAL superclusters with $E_T > 4$ GeV
- Superclusters are narrow in η, but extend in ϕ to capture bremsstrahlung radiation from the electron due to the B-field
- Superclusters are matched to track seeds (pair or triplets of hits)
- The track is fit using a Gaussian Sum Filter, which accounts for energy loss due to bremsstrahlung



Muon Reconstruction

- Muons are reconstructed using primarily tracker and muon system information
- Tracker Muons
  - Starts with tracks from the inner tracker
  - Tracks are extrapolated out to the muon system, accounting for curvature due to the magnetic field, expected energy loss, and multiple Coulomb scattering
  - Tracks that align with at least one track segment from DT or CSC are identified as *tracker muons*
- Global Muons
  - Starts with tracks in the muon system
  - A matching tracker track is found by propagating the muon track and tracker track to a common surface
  - Once track pairs are found, they are merged together
  - These are identified as *global muons*

Particle Flow



- Combines information from all CMS sub-detectors to produce particle candidates
- It produces exclusive collections of charged/neutral hadrons, photons, muons, and electrons
- These can be used to produce higher-level observables – used for isolation

Lepton Isolation

- Isolation refers to the amount of energy deposits surrounding a lepton
- Powerful variable for discriminating against fake lepton signatures commonly found in jets
- Sum the energies of particles within $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.4$ of the lepton
- We use particles identified using particle-flow to compute the isolation sum
  - Charged hadrons (ch), Neutral hadrons (nh), photons (γ)
- Isolation is computed in the following way

$$I_{rel}^{pf} = \frac{1}{p_T^{(e)}} \left[\sum p_T^{(ch)} + \max\left(\sum p_T^{(nh)} + \sum p_T^{(\gamma)} - C,\ 0.0 \right) \right]$$

- Pile-up Correction C
  - Two ways to compute the correction
  - $C = A_{eff} \cdot \rho$, where ρ is the average energy density due to pile-up, and A_{eff} is the effective area covered by the lepton candidate
  - $C = \Delta\beta$, where $\Delta\beta = \frac{1}{3} \sum p_T^{ch,\,PU}$

Electron Selection

- **Fiducial Selection**
  - Ensure that the electrons are within the fiducial range of the detector
  - Doubly Charged Higgs: $|\eta| < 2.5$, $p_T > 15$ GeV
  - Spin-Parity: $|\eta| < 2.5$, $p_T > 7$ GeV
- **Impact Parameters**
  - Ensure that the electrons used in the analysis come from from the primary vertex
  - Transverse impact parameter: $d_{xy} < 0.5\,\text{cm}$
  - Longitudinal impact parameter: $d_z < 1.0\,\text{cm}$
- **Isolation**
  - $I_{rel}^{pf} < 0.4$
  - Uses ρ corrections for PU
- **Identification**
  - Require 1 or fewer missing tracker hits to reject converted photons
  - A multivariate technique is used to improve the purity of selected electrons
  - The technique combines observables sensitive to bremsstrahlung, geometrical and momentum matching between electron track and calorimeter clusters, and shower shape

Muon Selection

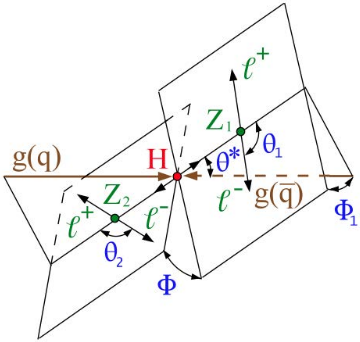
- **Fiducial Selection**
  - For both analyses: $|\eta| < 2.4$, $p_T > 5$ GeV
- **Impact Parameters**
  - Transverse impact parameter: $d_{xy} < 0.5\,\text{cm}$
  - Longitudinal impact parameter: $d_z < 1.0\,\text{cm}$
- **Isolation**
  - $I^{pf}_{rel} < 0.4$
  - Spin-Parity: uses ρ corrections
  - Doubly-Charged Higgs: uses $\Delta\beta$ corrections
- **Identification**
  - Muon identified as a tracker and global muon
  - At least 10 tracker hits, and one pixel hit
  - Track must match at least two muon stations
  - $\chi^2/d.o.f. < 10$ for the track fit

Final State Radiation Recovery

- Zs decaying to leptons can be accompanied by final state radiation
- This procedure improves the 4ℓ invariant mass resolution, and is used only in the spin-parity analysis
- We include FSR photons to more fully recover the energy from the Z decays
- Uses photons identified with particle-flow, and photons from ECAL energy clusters associated with particle-flow muons
- Preselection
  - $p_T > 2.0$ GeV and $|\eta| < 2.4$
- Isolation
  - Computed using a cone of $\Delta R < 0.3$, a threshold of 0.2 GeV on charged hadrons, and 0.5 GeV on neutral hadrons and photons
  - $I_{rel} = \left[I_{charged} + I_{neutral} + I_{photons}\right] / p_T$
- For each photon considering its closest lepton,
  - If $\Delta R(\gamma, \ell) < 0.07$, accept the photon if $p_T > 2.0$ GeV
  - If $\Delta R(\gamma, \ell) < 0.5$, accept the photon if $p_T > 4$ GeV and $I_{rel} < 1.0$

Spin and Parity of the Higgs Boson

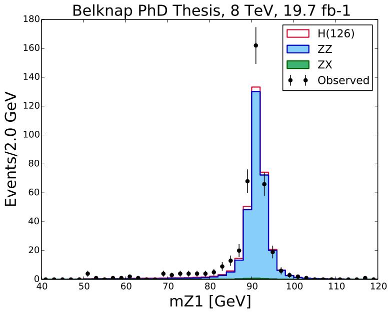
- Select 4ℓ events around the Higgs resonance near 126 GeV
- Consider only electrons and muons in the final state: $4e$, $2e2\mu$, and 4μ
- Test the Standard Model pure-scalar hypothesis against four other spin-parity configurations
- *Inferring the nature of the boson at 125-126 GeV*, arXiv:arXiv:1301.5404 [hep-ph]
- Use three kinematic angles to discriminate between hypotheses: $\theta_{1,2}$ and ϕ

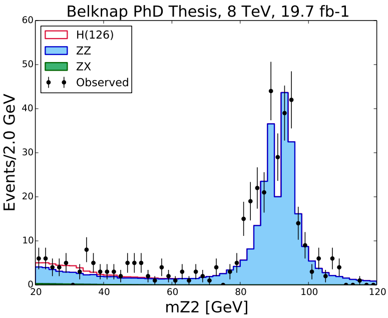


0^-	Any	Pseudoscalar
0_h^+	Any	Non-SM scalar with higher-dimension operators
$2_m^+(gg)$	$gg \rightarrow X$	Graviton-like with minimal couplings
$2_m^+(q\bar{q})$	$q\bar{q} \rightarrow X$	Graviton-like with minimal couplings

Building a 4ℓ Candidate

- Require that at least four leptons pass initial selections
- For all opposite-sign same-flavor leptons, choose the pair with an invariant mass closest to the nominal Z mass – label as Z_1
- From the remaining leptons, choose the pair the pair of opposite-sign, same-flavor leptons with the highest scalar p_T sum – label as Z_2



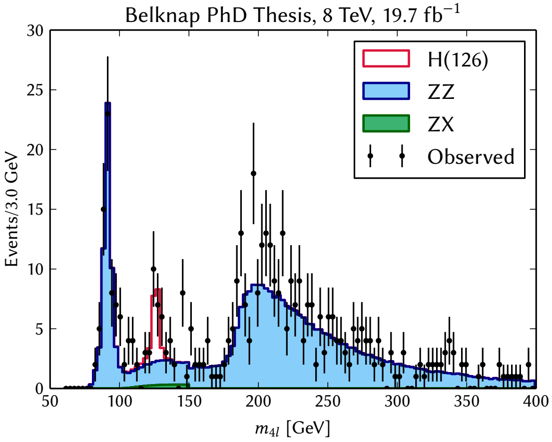


Final State Radiation

- For all pre-selected leptons, and pre-selected photons, assign a photon to the lepton it is closest to (by ΔR)
- Build the 4ℓ candidate
- For the photons assigned to the leptons of a Z candidate, select a photon if its 4-momenta brings the Z's mass closer to nominal, and $4 < m(\ell\ell\gamma) < 100$ GeV
- If more than one photon passes, select the one with the highest p_T provided it is greater than 4 GeV
- Otherwise, choose the lepton with the smallest ΔR to its lepton
- No more than one photon may be assigned to a Z candidate

Final Selection

- Require $40 < m_{Z_1} < 120$ GeV and $12 < m_{Z_2} < 120$ GeV
- Apply isolation requirement to leptons $I^{pf}_{ref} < 0.4$
  - Ensure any FSR photons are not included in a lepton's isolation sum
- Trigger threshold: $p_T^{leading} > 20$ GeV and $p_T^{sub-leading} > 10$ GeV
- Require that all opposite-sign leptons have $m(\ell^+\ell^-) > 4$ GeV for QCD suppression



Yields

	4μ	$4e$	$2e2\mu$
$H(126)$	4.5 ± 0.5	2.5 ± 0.4	6.2 ± 0.8
$q\bar{q} \rightarrow ZZ$	2.1 ± 0.1	0.9 ± 0.1	2.7 ± 0.2
$gg \rightarrow ZZ$	0.04 ± 0.01	0.02 ± 0.01	0.05 ± 0.01
$Z + X$	0.2 ± 0.2	0.3 ± 0.3	0.4 ± 0.4
Total	6.8 ± 0.6	3.7 ± 0.5	9.3 ± 0.9
Observed	7	4	10

- Monte Carlo and data yields within a mass window of

$$121.5 < m_{4\ell} < 130.5\,\text{GeV}$$

- Source of systematic uncertainties discussed on next slide

Included Systematic Uncertainties

		Signal	ZZ	$gg \to ZZ$	$Z+X$
Luminosity Norm.	4.4%	•	•	•	
μ Efficiency	4.3% (4μ), 1.5% ($2e2\mu$)	•	•	•	
e Efficiency	10.0% ($4e$), 2.4% ($2e2\mu$)	•	•	•	
Z+Jets Norm.					100%
gg PDF		7.2%		7.1%	
$q\bar{q}$ PDF			3.42%		
HZZ4L Acceptance PDF		2%			
QCD Scale $gg \to H$		7.5%			
QCD Scale $gg \to VV$				24.35%	
QCD Scale $q\bar{q} \to VV$			2.85%		
Higgs BR		2%			

- ZX is normalized directly to the expected reducible background yields – conservatively use 100% error
- PDF errors from uncertainties in PDF plus strong coupling, α_s
- QCD uncertainties are derived from moving normalization and factorization scales up/down by x2

Statistical Analysis Strategy

- Compute a log-likelihood ratio test statistic to separate the different hypotheses

$$q = -2 \ln \left[\frac{\mathcal{L}_{J^P}}{\mathcal{L}_{SM}} \right]$$

- Compute the likelihood functions from the p.d.f.

$$f(P_2(\cos\theta_1),\ P_2(\cos\theta_2),\ \cos(2\phi))$$

- Create the p.d.f.s as $8 \times 8 \times 8$ histograms from signal + background Monte Carlo
- This is done in a mass window surrounding the Higgs resonance

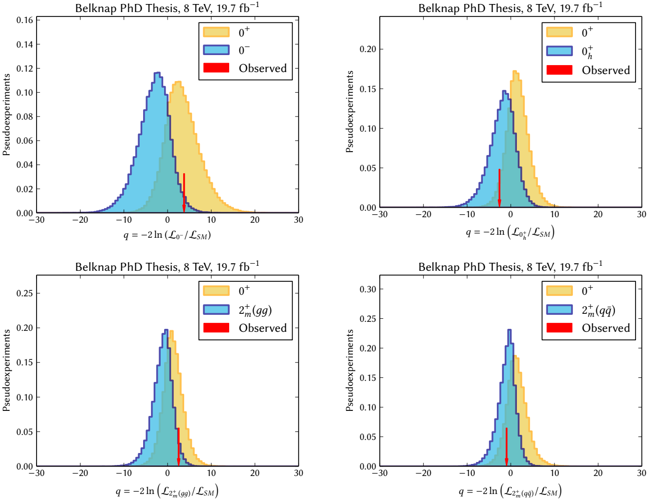
$$121.5 < m(4\ell) < 130.5\,\text{GeV}$$

- Run 50,000 simulated MC events from the templates to find the expected distributions of q for SM and J^P hypotheses

Spin-Parity Results

0^+ | 0_h^+

$2_m^+(gg)$ | $2_m^+(q\bar{q})$



The values of q are shown for the standard model and the alternate hypothesis, and the arrow indicates the observed value

Spin-Parity Results

J^P	J^P Production	Expected	Obs. 0^+	Obs. J^P	CL_s
0^-	Any	1.83σ	-0.17σ	$+2.04\sigma$	4.8%
0_h^+	Any	1.33σ	$+1.73\sigma$	-0.30σ	65%
2_m^+	$gg \to X$	1.11σ	-0.62σ	$+1.77\sigma$	14%
2_m^+	$q\bar{q} \to X$	1.10σ	$+1.08\sigma$	-0.11σ	63%

- Effect of systematics (on 0^-)
  - $Z + jets$ normalization: 0.152%
  - Lepton systematics: 0.117%
  - $q\bar{q}$ PDF: 0.094%
- Expected separation is computed for a value of q such that $P(SM < q) = P(J^P > q)$
- The observed values are given for $P(SM < Obs)$ and $P(J^P > Obs)$
- $CL_s = P(J^P > Obs)/P(SM > Obs))$
- Pseudoscalar hypothesis excluded at 95% CL
- Results are consistent with Standard Model expectations

Previously Published CMS Results

- **CMS Collaboration**, "Measurement of the properties of a Higgs boson in the four-lepton final state", 2013, arXiv:1312.5353 [hep-ex]
- CMS results reflect ($5.1\,\mathrm{fb}^{-1}$) 7 TeV and ($19.7\,\mathrm{fb}^{-1}$) 8 TeV datasets
- CMS uses all five kinematic angles, $m(4\ell)$ shape, and $m_{Z_{1,2}}$ shapes for discrimination

J^P	J^P Production	Expected	Obs. 0^+	Obs. J^P	$\mathrm{CL_s}$
0^-	Any	2.4σ	-0.9σ	$+3.6\sigma$	0.09%
0_h^+	Any	1.7σ	-0.0σ	$+1.8\sigma$	7.1%
2_m^+	$gg \to X$	1.7σ	-0.8σ	$+2.6\sigma$	1.9%
2_m^+	$q\bar{q} \to X$	1.6σ	-1.6σ	$+3.6\sigma$	0.03%

Comparison

Thesis Results

J^P	J^P Production	Expected	Obs. 0^+	Obs. J^P	CL_s
0^-	Any	1.83σ	-0.17σ	$+2.04\sigma$	4.8%
0_h^+	Any	1.33σ	$+1.73\sigma$	-0.30σ	65%
2_m^+	$gg \to X$	1.11σ	-0.62σ	$+1.77\sigma$	14%
2_m^+	$q\bar{q} \to X$	1.10σ	$+1.08\sigma$	-0.11σ	63%

CMS Published Results

J^P	J^P Production	Expected	Obs. 0^+	Obs. J^P	CL_s
0^-	Any	2.4σ	-0.9σ	$+3.6\sigma$	0.09%
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2_m^+	$q\bar{q} \to X$	1.6σ	-1.6σ	$+3.6\sigma$	0.03%

Doubly Charged Higgs Strategy

- The doubly charged Higgs is a member of a Higgs triplet (Φ^0, Φ^+, Φ^{++})
- The mass, VEV, and branching ratios are not set by the model
- We search for different trial configurations of the branching ratios
- Additionally, we scan over different hypothesized masses of the doubly charged Higgs (130 to 700 GeV)
- The search is performed by computing an upper limit on the signal strength for the different BR/mass hypotheses
- CMS has performed a search for the doubly charged Higgs using ($4.63\,\mathrm{fb}^{-1}$) 7 TeV data – this analysis is a continuation utilizing ($19.7\,\mathrm{fb}^{-1}$) 8 TeV data
- Focus will be on the pair-production mode with a four-lepton final state

Branching Ratios

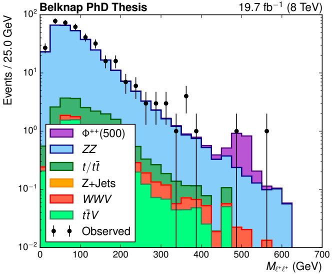
- We examine cases where we assume the Φ^{++} decays 100% to ee, $e\mu$, and $\mu\mu$
- We also consider four benchmark points that target different neutrino mass hierarchies
  - BP1 Tri-bi-maximal neutrino mixing is assumed, no CP violation, normal neutrino mass hierarchy, and a vanishing lowest neutrino mass ($m_1 < m_2 < m_3$)
  - BP2 Same as BP1, but with an inverted neutrino mass hierarchy ($m_3 < m_1 < m_2$)
  - BP3 Same as BP1, but the lightest neutrino mass is assumed to be 0.2 eV (consistent with cosmological limits for degenerate or nearly degenerate neutrino masses)
  - BP4 All BRs are assumed to be equal
- These are the same benchmark points used in the 7 TeV CMS analysis
- 8 TeV analysis does not include τ channels

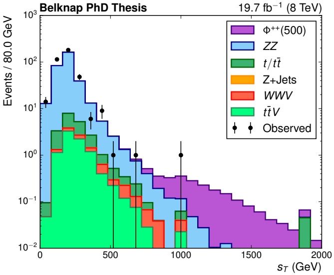
Φ^{++} Branching Ratios

Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

4ℓ Selections

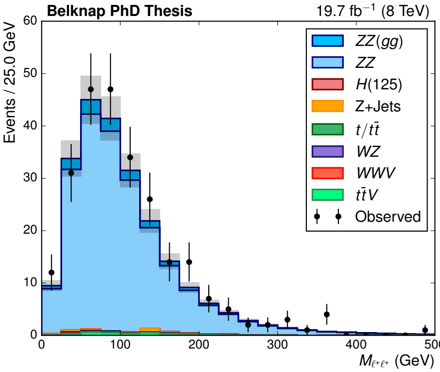
- **Preselection**
  - $p_T^{leading} > 20.0$ and $p_T^{subleading} > 10.0$ GeV
  - $I_{rel}^{pf} < 0.4$ for all leptons
  - For all lepton pairs $m(\ell\ell) > 12.0$ for QCD suppression
- **Build the 4ℓ event**
  - Form ++ and −− lepton pairs: in case of degeneracy, select the combination where $|m(\ell^+\ell^+) - m(\ell^-\ell^-)|$ is minimized
- **Final Selection**
  - $s_T = \sum p_T > (0.6 \cdot M_{\Phi^{++}} + 130\,\text{GeV})$
  - $0.9 \cdot M_{\Phi^{++}} < M_{\ell^+\ell^+} < 1.1 \cdot M_{\Phi^{++}}$
  - $0.9 \cdot M_{\Phi^{++}} < M_{\ell^-\ell^-} < 1.1 \cdot M_{\Phi^{++}}$

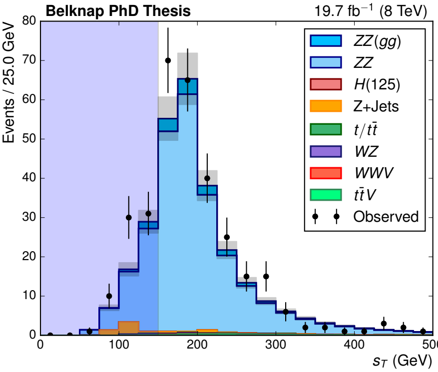




ZZ Background Control Region

- Start with 4ℓ selections (except final selection)
  - Z-tag: require at least one opposite-sign same-flavor pair where $|m(\ell\ell) - M_Z| < 20.0$
  - $s_T > 150$ GeV
- Shaded error bands shown for 10% uncertainty





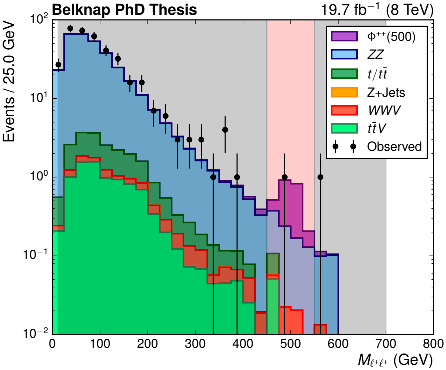
Data-Driven Background Estimation

- Backgrounds are estimated with a sideband method
- The sidebands are defined as follows:
  - 4ℓ Excludes the signal region: $[0.9 \cdot M_\Phi;\ 1.1 \cdot M_\Phi]$ for both M_Φ^{++} and M_Φ^{--}
- Define the ratio of background MC events in the signal region to the sidebands

$$\alpha = N_{SR}/N_{SB}$$

- The background rate in the signal region is given as

$$B_{BGSR} = \alpha \left(1 + N_{SB}^{Data}\right)$$



- with relative error

$$\frac{1}{\sqrt{1 + N_{SB}^{Data}}}$$

Systematics

- Signal cross section: 15%
- Luminosity: 2.6%
- Ratio used in sideband method: 10%
- Lepton systematics:

Leptons in Final State	Muon Systematic	Electron Systematic
4μ	1.0%	-
$4e$	-	6.6%
$2e + 2\mu$	0.5%	3.2%
$3e + 1\mu$	0.2%	4.7%
$1e + 3\mu$	0.7%	1.6%

Excluded Masses

- If the 95% upper limit on the signal strengths drops below 1 for a given mass point, we exclude it
- We exclude masses up to the values shown in the table below
- Expected values are computed assuming a background-only hypothesis

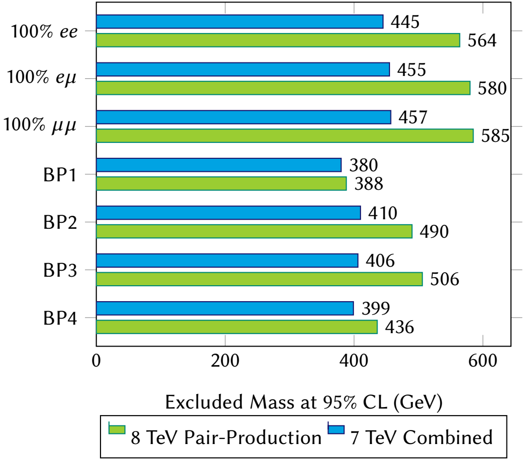
Benchmark Point	Expected (GeV)	Observed (GeV)
100% ee	564	564
100% $e\mu$	580	580
100% $\mu\mu$	585	585
BP1	388	388
BP2	490	490
BP3	506	506
BP4	436	436

Previous CMS Results

- CMS performed the search utilizing pair-production and associated production channels
- **CMS Collaboration**, "A search for a doubly-charged Higgs boson in *pp* collisions at $\sqrt{s} = 7\,\text{TeV}$", arXiv:1207.2666 [hep-ex]
- Used $4.63\,\text{fb}^{-1}$ of 7 TeV *pp* collision data
- Included τ final states
- Shown below are the observed excluded masses at 95% CL

Benchmark Point	Combined	Pair-Production
100% ee	445	387
100% $e\mu$	455	389
100% $e\tau$	352	300
100% $\mu\mu$	457	391
100% $\mu\tau$	369	313
100% $\tau\tau$	198	165
BP1	380	326
BP2	410	361
BP3	406	350
BP4	399	353

Comparison



- 7 TeV dataset of 4.63 fb^{-1}
- 8 TeV dataset of 19.7 fb^{-1}
- Increasing the data significantly extends the reach to higher mass values
- 7 TeV – excludes 380 to 457 GeV
- 8 TeV – excludes 388 to 585 GeV

Conclusions

- Two analyses were presented
  - Spin-parity measurement of the Higgs boson in the 4ℓ final state
  - Search for a doubly charged Higgs
- Both utilize $19.7\,\text{fb}^{-1}$ of $8\,\text{TeV}$ pp collision data collected by CMS
- **Spin-Parity**
  - $H \to ZZ \to 4\ell$ very well suited for property measurements
  - Tested SM 0^+ hypothesis against 0^-, 0^+_h, $2^+_m(gg)$, and $2^+_m(q\bar{q})$ hypotheses
  - Results consistent with SM, excluded 0^- at 95% CL
  - More powerful measurement techniques are possible with more data
  - Ideally, estimate the parameters of an effective Higgs Lagrangian from data
- **Doubly Charged Higgs**
  - Considered pair-production with a 4ℓ final state ($\ell = e, \mu$)
  - Considered cases where Φ^{++} decays 100% to ee, $e\mu$, $\mu\mu$, and four alternate BR configurations
  - Excluded masses 564 to 585 for the 100% BR cases at 95% CL
  - Excluded masses 388 to 506 for the benchmark points at 95% CL
  - Significant increase in sensitivity to higher masses with an increase in $\sqrt{s}$ and data
  - LHC Run II is at $\sqrt{s} = 13\,\text{TeV}$, $\sim 100\,\text{fb}^{-1}$ expected