Search for a heavy Higgs in $H \to ZZ \to 2\ell 2\nu$ decay channel.

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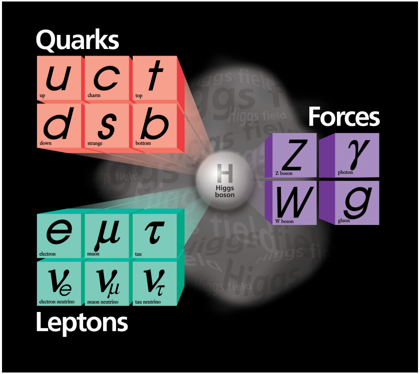
Standard Model

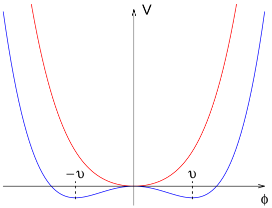
- Standard Model describes all fundamental interactions in particle colliders.
- The theory proved to be very precise and reliable.
- In 1964/1965 the Higgs mechanism was introduced to explain masses of the weak gauge bosons.
- A new particle, the Higgs boson, was predicted and searched for since then, without any success.



Source: http://www.fnal.gov/pub/presspass/press_releases/2013/Higgs-Boson-20130314.html

In 2012 ATLAS and CMS announced discovery of a new spin 0 boson at 126 GeV. All properties of this particle are consistent with the SM Higgs boson.

Why we need Higgs?



$$V(\phi) = \frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4$$

- Gauge invariant theories should have massless gauge bosons (as in QED or QCD).
- On the other hand, weak gauge bosons ($W^{\pm}$ and Z) are heavy.
- In the simple case of a scalar field ϕ in particular type of potential, we obtain minimum at $\phi \neq 0$ and we observe spontaneous symmetry breaking, where boson of the field ϕ "gains" mass.
- In SM electroweak interactions, described by $SU(2)_L \times U(1)_Y$ gauge theory, are coupled to the doublet of scalar fields ϕ in similar potential and as a result weak bosons "gain" mass in addition to generating a new Higgs boson.

Why search for a Higgs at high mass?

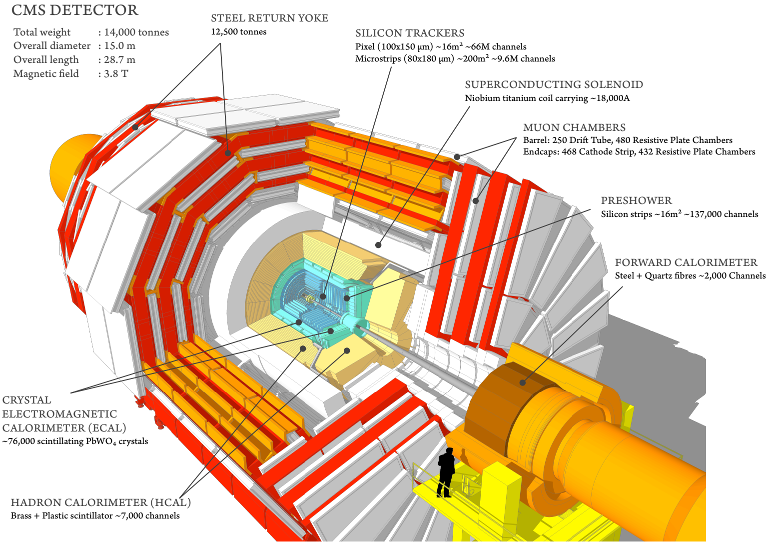
Do we need to search for a Higgs after July 4th, 2012?

Many Beyond the Standard Model (BSM) theories extend the simple Higgs sector of the SM and lead to more complicated particle spectrum. Very often one of the new particles has properties very similar to the SM Higgs.

Thus a lot of questions needs to be answered:

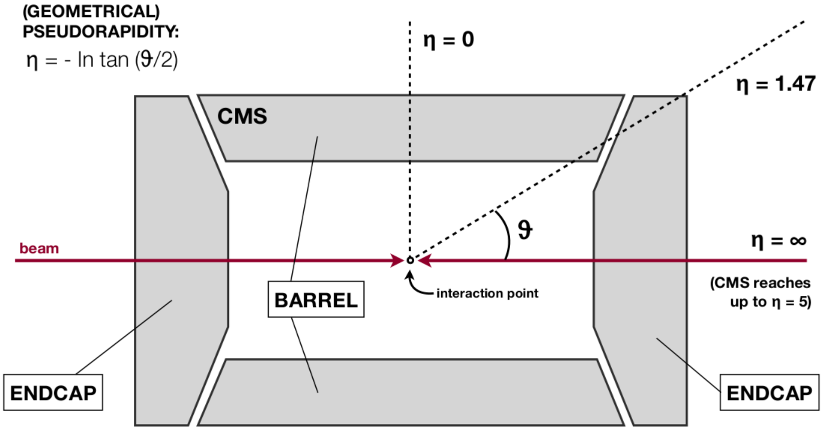
- Is the new discovered boson the long sought SM Higgs?
- How is the cross section for VV scattering affected by the newly observed particle?
- Does vector boson scattering conserves unitarity?
- **Are there any other Higgs bosons?**

CMS Detector Overview

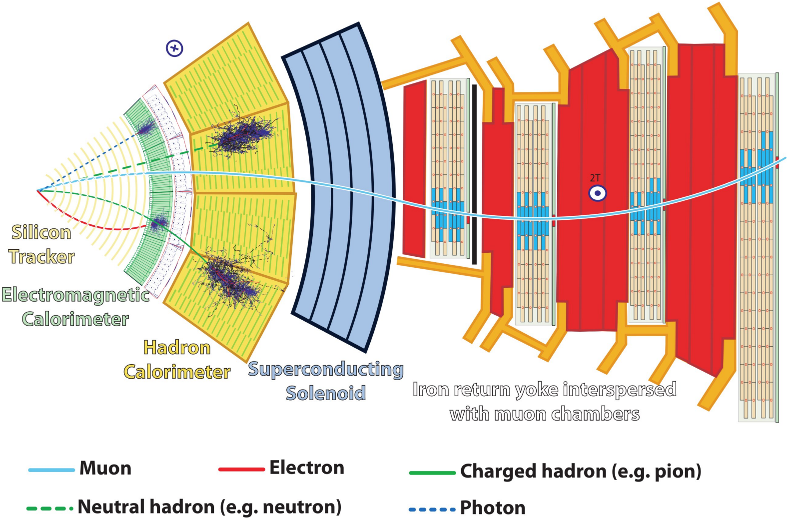


Source: http://cms.web.cern.ch/news/cms-detector-design

CMS Detector Geometry

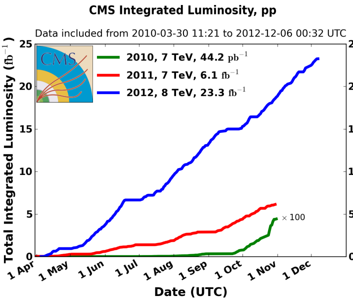


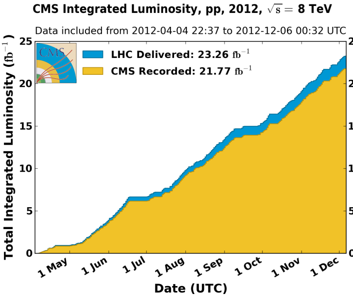
Particle Reconstruction



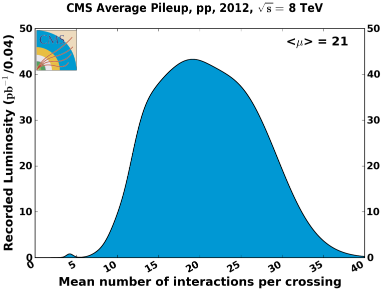
Source: https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/ShowDocument?docid=5581

Status of CMS





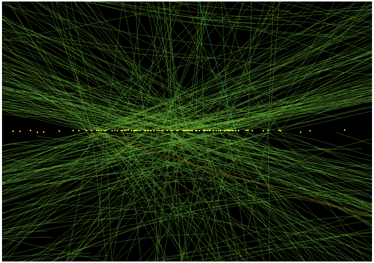
- CMS has done extremely well during Run I (2010-2012).
- Data-taking efficiency was very high ($\sim$ 95%)
- Main challenge of the 2012 was how to deal with pileup.

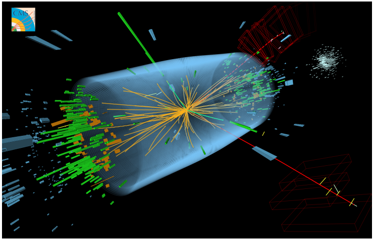


Source: https://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults

High Pile-Up and Particle Flow

- **Pile-Up:** Due to excellent performance of the tracking system, CMS is able to perform well with multiple simultaneous scattering events.
- **Particle Flow (PF):** Reconstruction algorithm which tries to reconstruct individually each particle in the event, prior to the jet clustering, based on information from all relevant sub-detectors. Improves jet energy and E_T^{miss} resolution.





Source: http://cms.web.cern.ch/

Motivation and Features

- **Motivation:**
  - High branching ratio.
  - The most sensitive analysis at high mass region (400–1000 GeV).
- **Features:**
  - Clean signature, given by two high p_T, isolated leptons of the same flavor with di-lepton mass close to Z peak and large E_T^{miss}.
  - No possibility of reconstructing Higgs mass.
- **Challenges:**
  - Huge backgrounds (mainly Z+jets with cross section 5 orders of magnitude larger than that of the signal) require precise method of estimation.
  - Pileup adversely affects the E_T^{miss} and jet resolution and isolation variables.

Data and Triggers

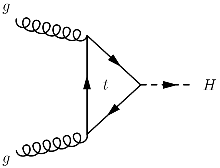
- Results are based on $19.6fb^{-1}$ of 2012 data at $\sqrt{s} = 8$ TeV
- **Analysis:** double electron, double muon, single muon
- **Background Control:** electron–muon, single photon
- **Efficiency Measurements:** double electron, single muon

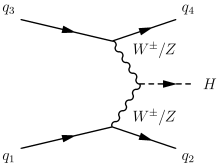
Trigger Type	Kinematic requirements	Additional requirements	Purpose
double electron	$p_T > 17$ GeV, $p_T > 8$ GeV	identification and isolation on both legs	signal selection
double muon	$p_T > 17$ GeV, $p_T > 8$ GeV		signal selection
single muon	$p_T > 24$ GeV, $\|\eta\| < 2.1$		signal selection, efficiency measurements
electron – ECAL supercluster	$p_T(e) > 32$ GeV, $p_T(SC) > 17$ GeV	identification and isolation for an electron, invariant mass of the system $m_{eSC} > 50$ GeV	efficiency measurements
single photon	$p_T > 22$ GeV, $\|\eta\| < 1.479$	identification and isolation	Z+jets control sample
single photon	$p_T > 36$ GeV, $\|\eta\| < 1.479$	identification and isolation	Z+jets control sample
single photon	$p_T > 50$ GeV, $\|\eta\| < 1.479$	identification and isolation	Z+jets control sample
single photon	$p_T > 75$ GeV, $\|\eta\| < 1.479$	identification and isolation	Z+jets control sample
single photon	$p_T > 90$ GeV, $\|\eta\| < 1.479$	identification and isolation	Z+jets control sample
electron – muon	$p_T(e) > 17$ GeV, $p_T(\mu) > 8$ GeV	identification and isolation for an electron	non-resonant control sample
electron – muon	$p_T(e) > 8$ GeV, $p_T(\mu) > 17$ GeV	identification and isolation for an electron	non-resonant control sample

MC Samples — Backgrounds

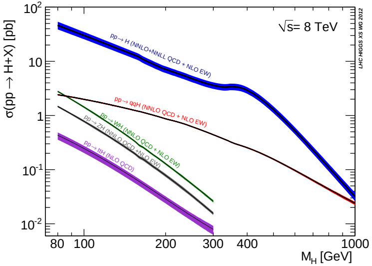
Process	Generator	$\sigma \cdot k$ (pb)	$\int L(fb^{-1})$
$W \to \ell\nu$	MADGRAPH	36257	0.6
$Z \to \ell\ell$	MADGRAPH	3533	8.6
$t\bar{t}$	MADGRAPH	22.89	423
$\bar{t}$ (tW-channel)	POWHEG	11.2	39
t (tW-channel)	POWHEG	11.2	45
$\bar{t}$ (t-channel)	POWHEG	30.7	74
t (t-channel)	POWHEG	56.4	168
$\bar{t}$ (s-channel)	POWHEG	1.76	81
t (s-channel)	POWHEG	3.89	69
WZ	MADGRAPH	$1.057\ ^{+5.3\%}_{-4.1\%}$	2871
WW	MADGRAPH	$5.995\ ^{+4.1\%}_{-2.8\%}$	241
ZZ	MADGRAPH	$0.320\ ^{+4.7\%}_{-3.0\%}$	2471
$W\gamma$	MADGRAPH	461.6	10.37
$Z\gamma$	MADGRAPH	123.9	12.03

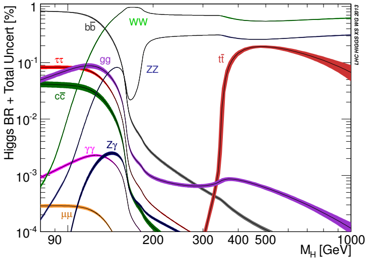
- Two main production mechanisms are gluon-gluon fusion and vector boson fusion.





- Signal samples are simulated with POWHEG include Complex Pole Scheme.
- Signal cross sections, branching ratios and corresponding uncertainties provided by LHC Higgs Cross Section Working Group.



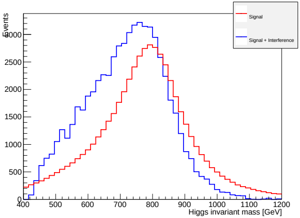


Source: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

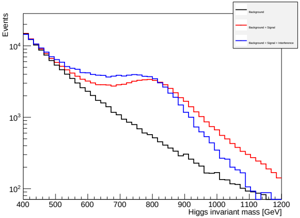
Interference effects

- We include the effects of the interference between the signal and $gg \to VV$ background production.
- The interference increases the cross section by a factor of $R \approx 1.07$ for $m_H = 600$ GeV, and the effect grows with mass to value of $R \approx 1.93$ for $m_H = 1$ TeV
- The generated line-shape of the signal is also re-weighted to match the one obtained from MCFM.

Interference effects for $m_H = 800$ GeV



BKG Subtracted



With BKG

Beyond Standard Model searches

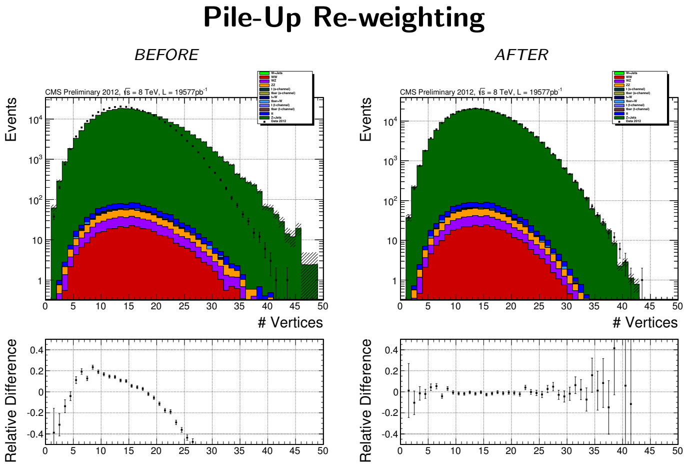
In addition to search for the SM-like Higgs we are interested in re-interpreting our results in the context of the search for an electroweak singlet scalar which could mix with the recently discovered Higgs candidate.

- Such a particle could exist if the Higgs-like particle at the 126 GeV is not fully responsible for unitarization of scattering amplitudes.
- Unitarity imposes constraints on couplings of the 126 GeV Higgs-like state (C) and the second scalar particle (C'): $C^2 + C'^2 = 1$.
- The observables of interest in the search for the new boson are then given by

$$\sigma' = C'^2 \sigma_{SM},$$
$$\Gamma' = \frac{C'^2}{1 - BR_{new}} \Gamma_{SM},$$
$$\mu' = C'^2 (1 - BR_{new}),$$

where BR_{new} is branching ratio of the new boson into "new" final states.

- Distribution of a number of interactions in Monte Carlo samples is re-weighted to match the observed pile-up conditions in data.



Lepton Selection

We follow standard recommendations from the CMS Physics Object Groups (POG) for identification and isolation selection.

Electrons

- $p_T > 20 GeV$, $|\eta| < 2.5$
- Veto on electrons in the transition region $(1.4442 < |\eta| < 1.566)$
- Medium WP for electron ID and PF isolation (< 0.15) with effective area correction.
- For third lepton veto: $p_T > 10 GeV$, $|\eta| < 2.5$ and Veto WP for ID and Isolation

Muons

- $p_T > 20 GeV$, $|\eta| < 2.4$
- Tight Muon ID
- Loose PF based combined relative isolation (< 0.2) with $\Delta\beta$ correction.
- For third lepton veto: $p_T > 10 GeV$, $|\eta| < 2.4$ with Loose Muon ID and Loose PF isolation.
- Soft muons: non-isolated muons passing Soft Muon ID with $p_T > 3 GeV$.

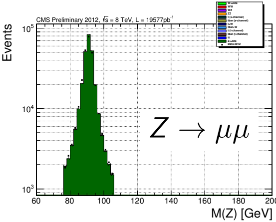
- **Jets:**
  - Reconstructed with anti-k_T algorithm with the cone size of $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.5$ using PF particles.
  - Kinematic selection: $p_T > 30 GeV$ and $|\eta| < 5.0$
  - We apply Loose Jet identification selection and 3 levels of corrections: L1FastJet, L2 and L3.
  - For each jet the transverse momentum is smeared using the data/MC scale factors for the jet energy resolution as measured in 2011 data

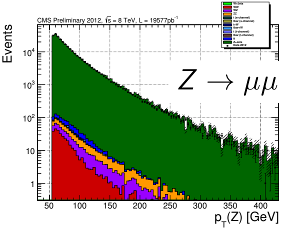
$$p_T \rightarrow \max\left[0, p_T^{gen} + \mathcal{G}_{aus}(\bar{c}, \sigma_c) \cdot (p_T - p_T^{gen})\right].$$

- **Missing Transverse Energy:**
  - $\vec{E}_T^{\mathrm{miss}} = -\sum_{i=1}^{N_{PF}} \vec{p}_{\mathrm{T,i}}$
  - One of the most powerful variables in the analysis.
  - Sensitive to mis-reconstruction of the jets, detector noise and beam gas interactions.

Z Candidates selection and extra leptons veto

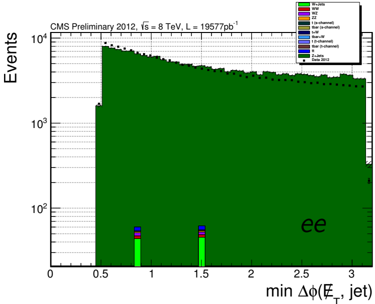
- **Z candidates selection:** Two leptons of the same flavor with their invariant mass in range $|m(ll) - m_Z| < 15$ GeV, where $m_Z = 91.1876$ GeV. Removes non-resonant backgrounds.
- We additionally require $\mathbf{p_T(Z) > 55GeV}$ in order to have decent statistics of photon events used for Z+jets estimation and to employ some properties of the boosted Z's from high mass Higgs decays.
- **Third lepton veto:** Events with a more than 2 leptons passing loose selection are rejected to suppress WZ background.
- **Soft muons veto:** Veto events with soft muons. This requirement was adopted to additionally suppress the $t\bar{t}$ background.

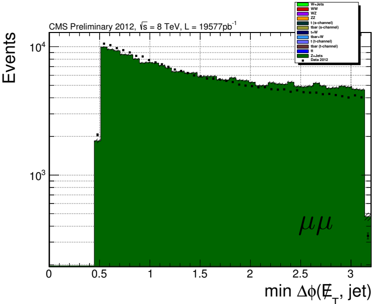




Anti-b-tagging and $\Delta\phi$ requirement

- Top production is the second biggest background in this analysis.
- To reduce this background, events with any *b*-tagged jet are rejected.
  - $p_T > 30\,GeV$ and $|\eta| < 2.4$
  - Jet Probability discriminator was used — for each jet the confidence level is calculated that measures how consistent are tracks in a given jet with originating from the primary vertex
- If a jet is found close to the E_T^{miss} vector ($\mathbf{min}\,\boldsymbol{\Delta\phi}(\mathbf{jet}, \vec{\mathbf{E}}_{\mathbf{T}}^{\mathbf{miss}}) < \mathbf{0.5}$) the event is rejected in order to reduce the instrumental background originating from jet mis-measurements.

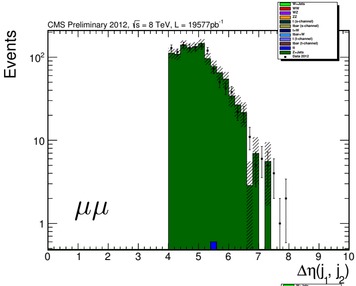


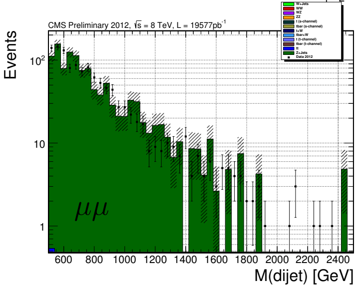


We categorize all events based on the number of jets ($p_T > 30 GeV$) in the event into 3 bins: 0-jet, $\geq$1-jet and VBF.

An event is **VBF tagged** if it has:

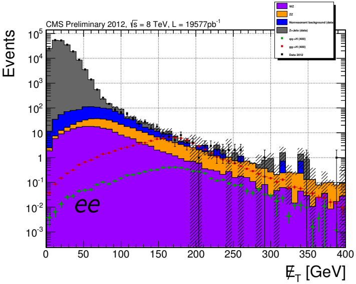
- 2 non-b-tagged jets with $p_T > 30 GeV$,
- rapidity gap $\Delta\eta_{jj} > 4.0$,
- di-jet mass $M_{jj} > 500 GeV$,
- central di-lepton (between two tag jets),
- no other jets ($p_T > 30 GeV$) in central region,
- no third lepton.





- E_T^{miss} variable is very powerful in further reducing all the backgrounds
- Especially important for the instrumental background (Z+jets), reducing it by few orders of magnitude.
- For the 0-jet and $\geq$1-jet categories, E_T^{miss} selection is mass dependent.
- In the VBF category we require mass independent $E_T^{miss} > 70$ GeV, which guarantees a very high $S/\sqrt{S+B}$ with $B \sim 0$

$m(H)$ [GeV]	MET [GeV]
250	90
300	100
350	100
$\geq$400	110



Shape-based vs Cut-based analysis

- We perform two analyses in the search.
- In the shape-based analysis we use the shape of the transverse mass distribution to set limits on the Higgs production.
- In the cut-based analysis we count events after applying mass dependent selection on the transverse mass of the Higgs candidate.
- Counting experiment is very simple and robust, but . . .
- . . . the analysis of the shapes is much more sensitive to the signal and yields better results.

Final Selection — Transverse Mass of the Higgs, M_T

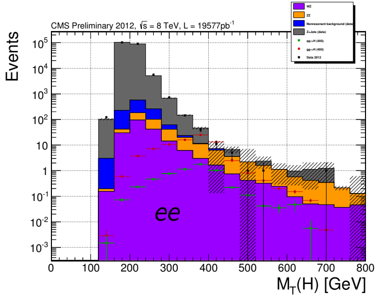
- We define transverse mass of the Higgs candidate as

$$M_T{}^2 = \left(\sqrt{P_T^2(Z) + M_{\ell\ell}^2} + \sqrt{E_T^{miss\,2} + M_{\ell\ell}^2}\right)^2 - \left(\vec{P}_T(Z) + \vec{E}_T^{miss}\right)^2$$

Counting experiment:

- Thresholds on the min M_T and max M_T help to improve sensitivity.
- The selection is optimized as a function of Higgs mass.
- We don't apply these requirements in the VBF category.

$M(H)$ $[GeV]$	min M_T $[GeV]$	max M_T $[GeV]$
250	180	270
300	280	320
350	330	370
400	350	450
450	400	500
500	400	600
550	450	∞
$>$600	500	∞



Backgrounds Estimation

In this analysis backgrounds are estimated as follows:

- Z+jets (mostly instrumental background with fake missing energy) is estimated from data using γ+jets events.
- Non-resonant backgrounds (Top/WW/W+jets, have real E_T^{miss}) are estimated from data using $e\mu$ sample.
- Irreducible electroweak ZZ background and fully leptonic WZ decays are estimated from Monte Carlo simulation.

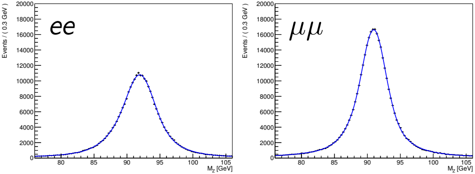
- Z+jets is not well modeled in simulation, because E_T^{miss} in those events originates from mis-reconstruction of the jets.
- We use **data** to estimate this instrumental background as an alternative to obtaining yields from MC.
- Z+jets and γ+jets events are produced through the same physics processes.
- Both processes have similar kinematics and the detector response.
- γ+jets events have much larger statistics.
- We estimate yields of the Z+jets by using a sample of photons.

Photon Sample Selection

- Only events with single isolated photon are selected.
- We apply standard identification and isolation requirements for the γ's.
- $p_T(\gamma) > 55$ GeV
- Photon can't be converted.
- γ is isolated from jets ($\Delta R > 0.4$).
- In the event there should be no extra leptons or b-jets.

In order to produce the template of Z+jets from γ+jets events, we perform following steps.

- p_T distribution of γ's is re-weighted to be identical to that of Z's.
- Vertex multiplicity distribution in γ sample is re-weighted to match shape in Z+jets events.
- Each photon is assigned a mass by sampling Z line shape in data.
- The procedure is done separately for each category.
- Final normalization is obtained for each category using events with $E_T^{miss} < 50$ GeV.



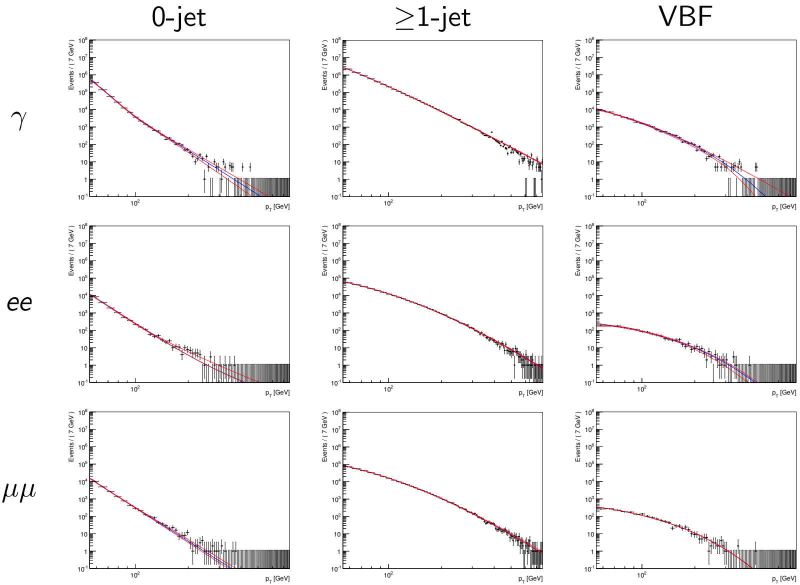
γ+jets p_T Re-weighting I

- The p_T distributions are fitted with the function

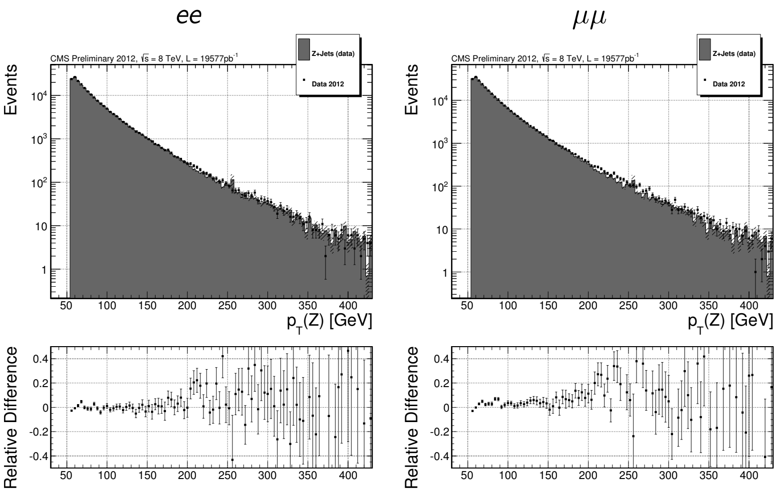
$$f(p_T) = N\left[\left(1 + \frac{p_T}{a}\right)^{-b} + c \cdot \left(1 + \frac{p_T}{c}\right)^{-e}\right]$$

- Fits are performed separately for each channel and category.
- The systematic uncertainty of the re-weighting due to statistical uncertainty of the fits is estimated by using bootstrapping method:
    - We generate given p_T distribution multiple times (100) by drawing with replacement from the original distribution.
    - Each of the generated distributions is fitted with the same function.
    - The spread of the fits determines the uncertainty bands.
    - Final effect on the yields is estimated by using upper and lower variations of the fits to recalculate the weights and propagating them through the whole method.
    - Obtained uncertainties are between 3% for the most populated category to $\sim$25% for categories with the lowest statistics.

γ+jets p_T Re-weighting II



γ+jets p_T Re-weighting III

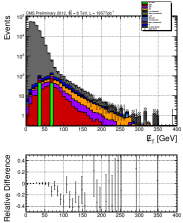


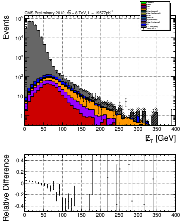
EWK contamination of γ+jets sample

- The method over-predicts contribution of the instrumental background.
- The single photon sample is contaminated with EWK events ($W\gamma$, $Z\gamma$, W+jets) with real E_T^{miss}.
- We apply p_T weights as calculated for the photon sample to the simulation the EWK processes and we subtract it from our estimation.
- We assign 100% systematic error on the subtracted component.

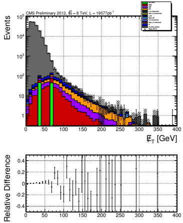
ee	$\mu\mu$

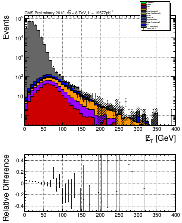
Before subtraction





After subtraction





Non-resonant backgrounds estimation I

- Estimation of non-resonant backgrounds is performed with the standard technique, using $e\mu$ events passing the full analysis selection ($N_{e\mu}^{SIG}$).
- Using sidebands ($55 < m_{\ell\ell} < 70$ and $110 < m_{\ell\ell} < 200$ GeV) of the Z peak a scale factor α is determined from ratio of $ee/\mu\mu$ and $e\mu$ events passing $E_T^{miss} > 70$ GeV and requiring at least one b-tagged jet.

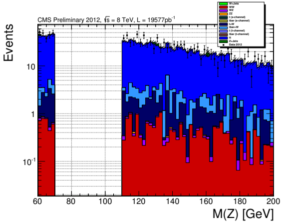
$$\alpha_e = \frac{N_{ee}^{SB}}{N_{e\mu}^{SB}}; \quad \alpha_\mu = \frac{N_{\mu\mu}^{SB}}{N_{e\mu}^{SB}}$$

- Predicted number of background events is given then as

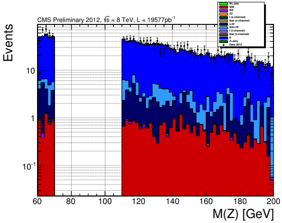
$$N_{ee}^{SIG} = \alpha_e \cdot N_{e\mu}^{SIG}; \quad N_{\mu\mu}^{SIG} = \alpha_\mu \cdot N_{e\mu}^{SIG}$$

	Data	Simulation
α_e	0.48 ± 0.02	0.45 ± 0.02
α_μ	0.58 ± 0.02	0.54 ± 0.02

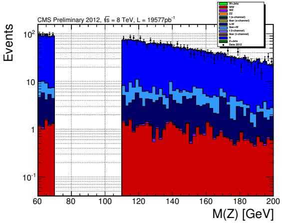
- Systematic uncertainty of the α_ℓ factor can be estimated by changing the definition of the side bands region.
- Tests have shown that variations are within 25%.
- The presented method for estimating contribution from non-resonant backgrounds suffers greatly from small statistics of $e\mu$ events after final selection ($N^{SIG}_{e\mu}$). Statistical error for higher masses is close to 100%.



ee

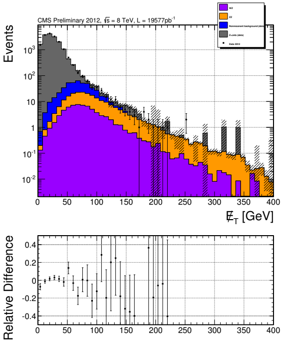


$\mu\mu$

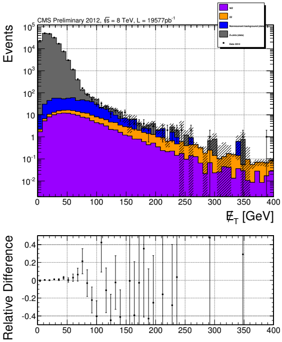


$e\mu$

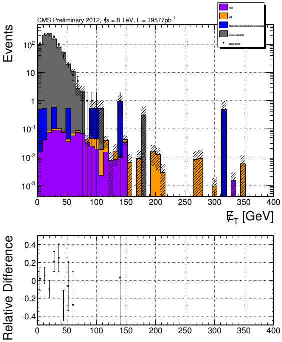
0-jet



≥1-jet

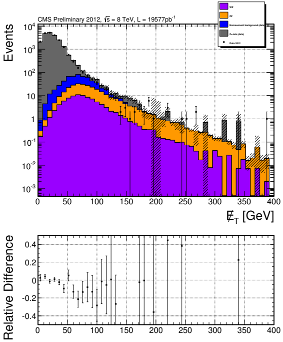


VBF

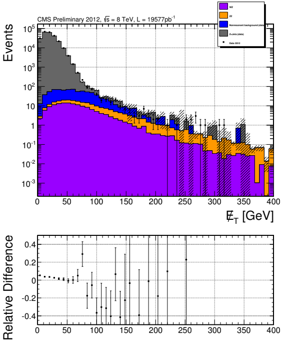


Control Plots — E_T^{miss} $(\mu\mu)$

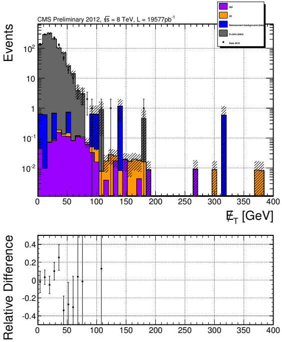
0-jet



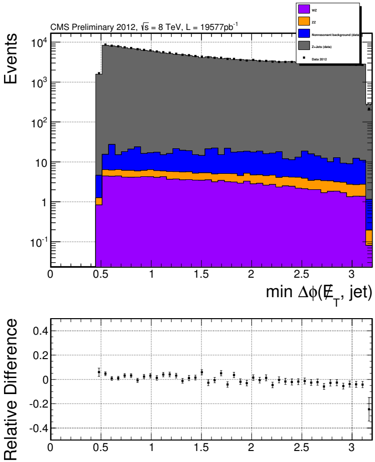
≥1-jet



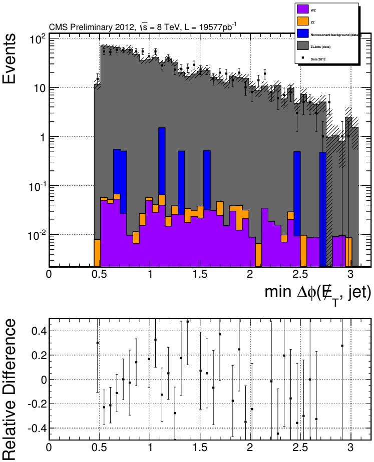
VBF



≥1-jet

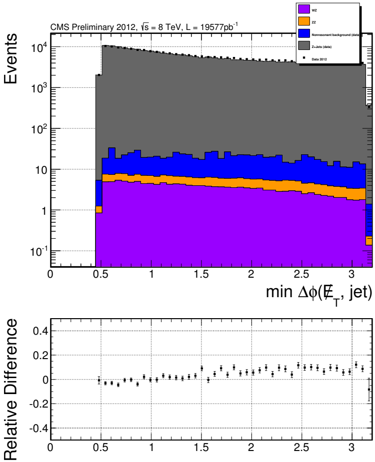

CMS Preliminary 2012, √s = 8 TeV, L = 19577pb-1
Events
min Δφ(E̸T, jet)
Relative Difference

VBF

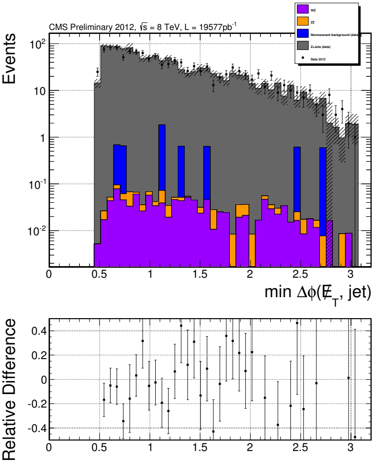

CMS Preliminary 2012, √s = 8 TeV, L = 19577pb-1
Events
min Δφ(E̸T, jet)
Relative Difference

Control Plots — min $\Delta\phi(E_T^{miss}, jet)$ $(\mu\mu)$

$\geq$1-jet

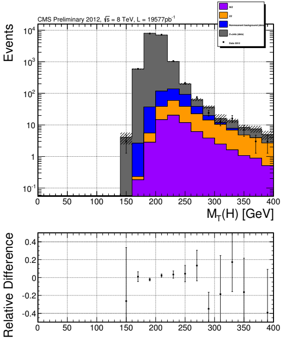


VBF

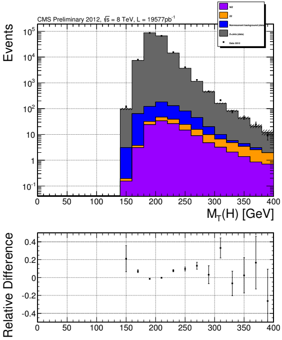


Control Plots — M_T (ee)

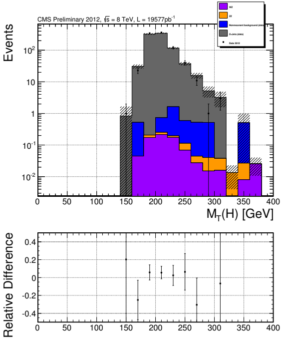
0-jet



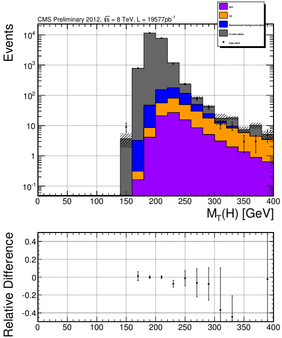
$\geq$1-jet



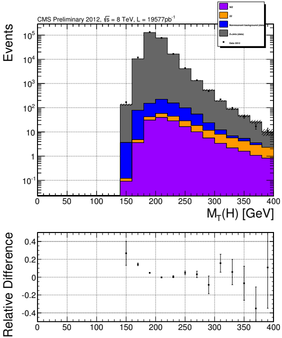
VBF



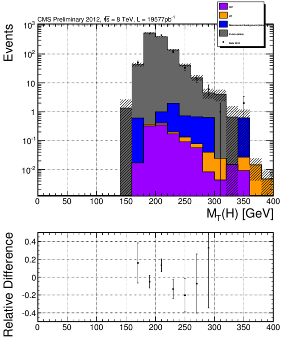
0-jet



≥1-jet



VBF



Experimental Systematic Uncertainties

- **Lepton momentum scale:** Nominal energy of the leptons is shifted by momentum scale uncertainty (1% for muons, 2% for electrons in EB, and 5% for electrons in EE) up and down and propagated to the E_T^{miss} variable.
- **Jet energy scale and resolution:** We vary the jet energy scale and resolution separately by $\pm 1\sigma$ and effects are propagated through the whole analysis.
- **Unclustered component of E_T^{miss}:** We subtract from the $\vec{E}_T^{miss}$ momenta of the leptons and all of the jets with $p_T > 10$ GeV. We vary residual recoil by $\pm 10\%$ and propagate results through the analysis.
- **Pileup effects:** The expected shapes of the number of interactions distribution in data are calculated for variations of the minimum bias cross section (70$\pm$3.5 mb) and used for pileup re-weighting.

Theoretical Systematic Uncertainties

- We use the QCD scale and PDF uncertainties recommended by the LHC Higgs Cross Section Working Group for the signal cross sections.
- We evaluate systematic uncertainty in the theoretical definition of exclusive production of the Higgs boson in association with 0 and $\geq$1 jets via the gluon-gluon fusion process.
- The cross sections and theoretical uncertainties for $ZZ \to 2\ell 2\nu$ and $W^{\pm}Z \to 3\ell\nu$ were calculated using MCFM with LHAPDF PDFs according to PDF4LHC recommendations.

Process	ΔPDF	$\Delta\alpha_S$	Systematic Uncertainty
$ZZ \to e^+e^- + 3(\nu\bar{\nu})$	3.12%	6.69%	9.8%
$W^+Z \to (\mu^+ + \nu) + (e^- + e^+)$	2.68%	7.67%	10.3%
$W^-Z \to (\mu^- + \nu) + (e^- + e^+)$	4.55%	6.90%	11.5%

Systematic Uncertainties Summary

Source	Uncertainty [%]	Type
Luminosity	3	rate
Trigger	2	rate
Lepton ID+Isolation	2	rate
Lepton momentum scale	1–2	shape
Jet energy scale/resolution	1	shape
PU effects, MET	1–3	shape
b-veto	1	rate
Non-resonant background estimation from data	25	rate
Z+jets estimation from data	0–50	shape
PDF, gluon-gluon initial state	6–11	rate
PDF, quark-quark initial state	3.3–7.6	rate
QCD scale, gluon-gluon initial state (ggH)	7.6–11	rate
QCD scale, quark-quark initial state (VBF)	0.2–2	rate
QCD scale, quark-quark initial state ($qqVV$)	5.8–8.5	rate
VV interference	2–15	rate+shape
Simulation statistics	1–2	shape

Final Yields — $8\,TeV$, $19.6 fb^{-1}$, Counting Experiment

Selection for $m_H = 400$ GeV

Category	0-jet (ee)	0-jet ($\mu\mu$)	$\geq$1-jet (ee)	$\geq$1-jet ($\mu\mu$)	VBF (ee)	VBF ($\mu\mu$)
Total Bkg	13$\pm$13$\pm$7.3	16$\pm$15$\pm$8.6	10$\pm$4.2$\pm$1.9	12$\pm$4.7$\pm$2.3	3.5$\pm$0.65$\pm$1.2	4.5$\pm$0.8$\pm$1.6
ZZ	10$\pm$0.53	12$\pm$0.56	5.6$\pm$0.46	6.8$\pm$0.48	0.17$\pm$0.19	0.18$\pm$0.2
WZ	2.6$\pm$0.38	3.1$\pm$0.39	3$\pm$0.39	3.3$\pm$0.4	0.12$\pm$0.17	0.1$\pm$0.17
Non-resonant	0$\pm$0$\pm$0	0$\pm$0$\pm$0	1.4$\pm$0.36$\pm$0.91	1.8$\pm$0.44$\pm$1	2.4$\pm$0.6$\pm$1	2.9$\pm$0.73$\pm$1.1
Z+jets	0$\pm$13$\pm$7	0$\pm$15$\pm$8.2	0.046$\pm$4.2$\pm$1.5	0.54$\pm$4.7$\pm$1.7	0.78$\pm$0.25$\pm$0.77	1.3$\pm$0.31$\pm$0.96
$gg \to H(400)$	21$\pm$0.46	25$\pm$0.49	20$\pm$0.46	23$\pm$0.48	0.74$\pm$0.2	0.84$\pm$0.21
$qq \to H(400)$	0.35$\pm$0.15	0.44$\pm$0.16	1.9$\pm$0.23	2.4$\pm$0.24	1.5$\pm$0.22	1.9$\pm$0.23
Data	15$\pm$2	17$\pm$2	10$\pm$1.8	15$\pm$2	3$\pm$1.3	3$\pm$1.3

Selection for $m_H = 800$ GeV

Category	0-jet (ee)	0-jet ($\mu\mu$)	$\geq$1-jet (ee)	$\geq$1-jet ($\mu\mu$)	VBF (ee)	VBF ($\mu\mu$)
Total Backgrounds	4.5$\pm$1.8$\pm$1.8	5$\pm$1.6$\pm$1.6	2.8$\pm$2.5$\pm$7.5	2.9$\pm$3.1$\pm$8.6	3.5$\pm$0.65$\pm$1.2	4.5$\pm$0.8$\pm$1.6
ZZ	2.5$\pm$0.37	3$\pm$0.39	2.2$\pm$0.36	2.4$\pm$0.37	0.17$\pm$0.19	0.18$\pm$0.2
WZ	0.45$\pm$0.25	0.57$\pm$0.26	0.63$\pm$0.27	0.52$\pm$0.26	0.12$\pm$0.17	0.1$\pm$0.17
Non-resonant	0$\pm$0$\pm$0	0$\pm$0$\pm$0	0$\pm$0$\pm$0	0$\pm$0$\pm$0	2.4$\pm$0.6$\pm$1	2.9$\pm$0.73$\pm$1.1
Z+jets	1.5$\pm$1.8$\pm$1.5	1.4$\pm$1.6$\pm$1.4	0$\pm$2.5$\pm$7.4	0$\pm$3.1$\pm$8.6	0.78$\pm$0.25$\pm$0.77	1.3$\pm$0.31$\pm$0.96
$gg \to H(800)$	1.1$\pm$0.11	1.3$\pm$0.11	2$\pm$0.13	2.4$\pm$0.14	0.056$\pm$0.052	0.07$\pm$0.055
$qq \to H(800)$	0.096$\pm$0.089	0.11$\pm$0.088	0.57$\pm$0.13	0.76$\pm$0.15	0.3$\pm$0.11	0.36$\pm$0.12
Data	1$\pm$1	6$\pm$1.6	2$\pm$1.2	5$\pm$1.5	3$\pm$1.3	3$\pm$1.3

Results: Combined Categories Exclusion Limit

We extract 95% C.L. limits on the signal strength $\mu = \sigma/\sigma_{th}$ using CLs method.

Shape-based analysis:

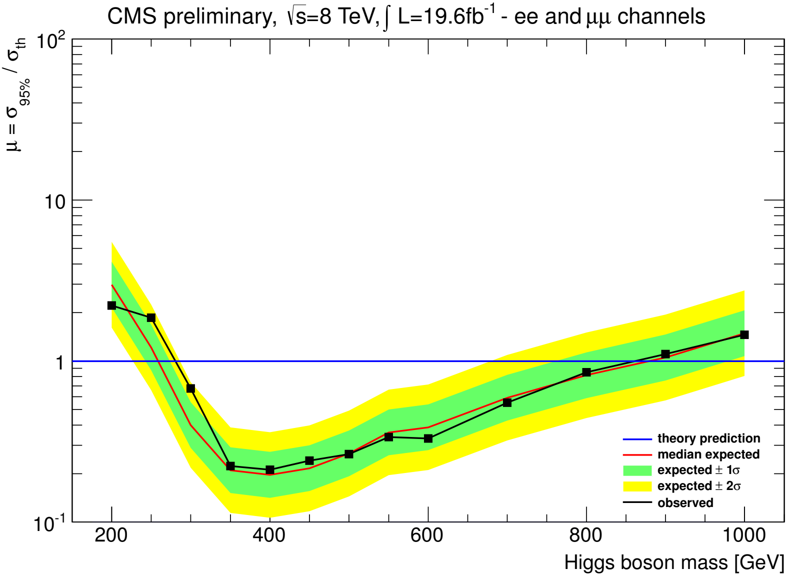
- Expected exclusion limits: 264–879 GeV.
- Observed exclusion limits: 287–859 GeV.

Cut-based analysis:

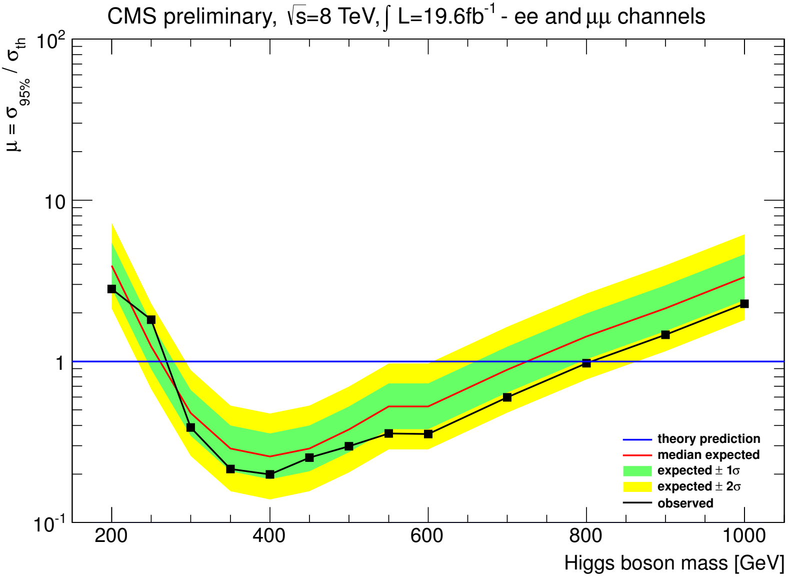
- Expected exclusion limits: 266–722 GeV.
- Observed exclusion limits: 279–806 GeV.

We also compute limits on the signal strength for the electroweak singlet model for various values of the parameter C'.

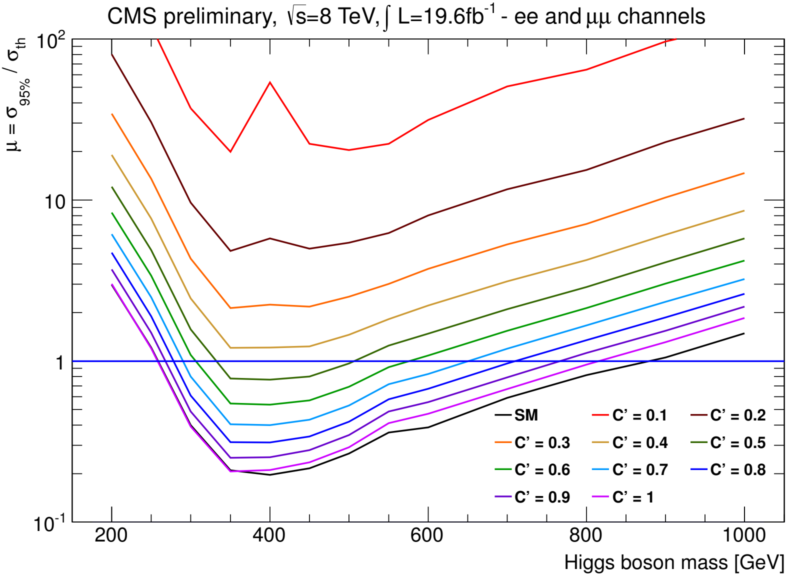
Results: Shape-based Analysis Exclusion Limit



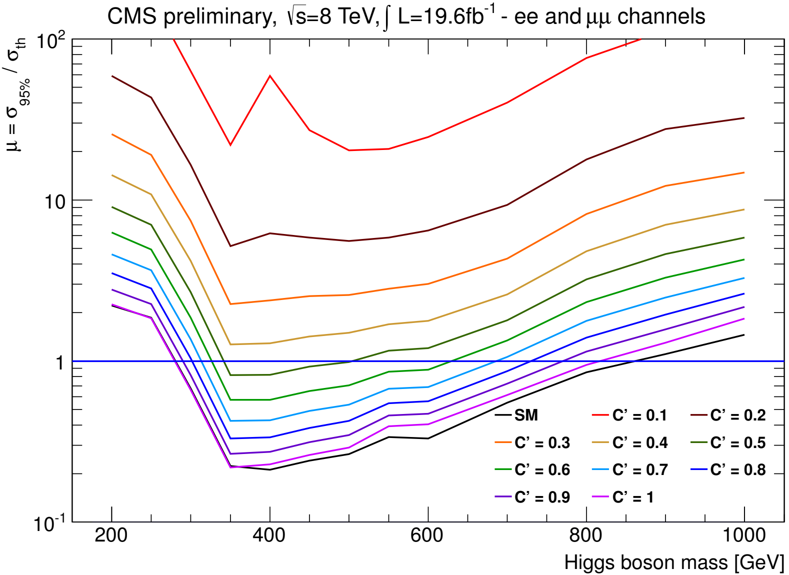
Results: Cut-based Analysis Exclusion Limit



Results: BSM Model, Expected Limit

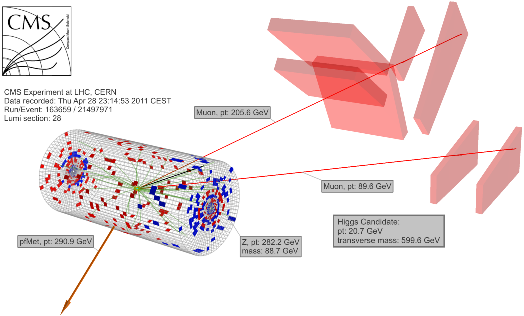


Results: BSM Model, Observed Limit



Summary

- I have presented a search for a heavy Higgs in decay channel $H \to ZZ \to 2l2\nu$.
- Overview of the physics objects selection, event selection, background estimation methods and main systematic uncertainties were shown.
- We don't observe any excess of events above the SM predictions and we compute exclusion limits for the SM-like Higgs and narrow resonance Higgs partner scenarios.



THANK YOU