Search for Higgs Boson Decays to Two W Bosons in the Fully Leptonic Final State at $\sqrt{s}$ = 7 TeV

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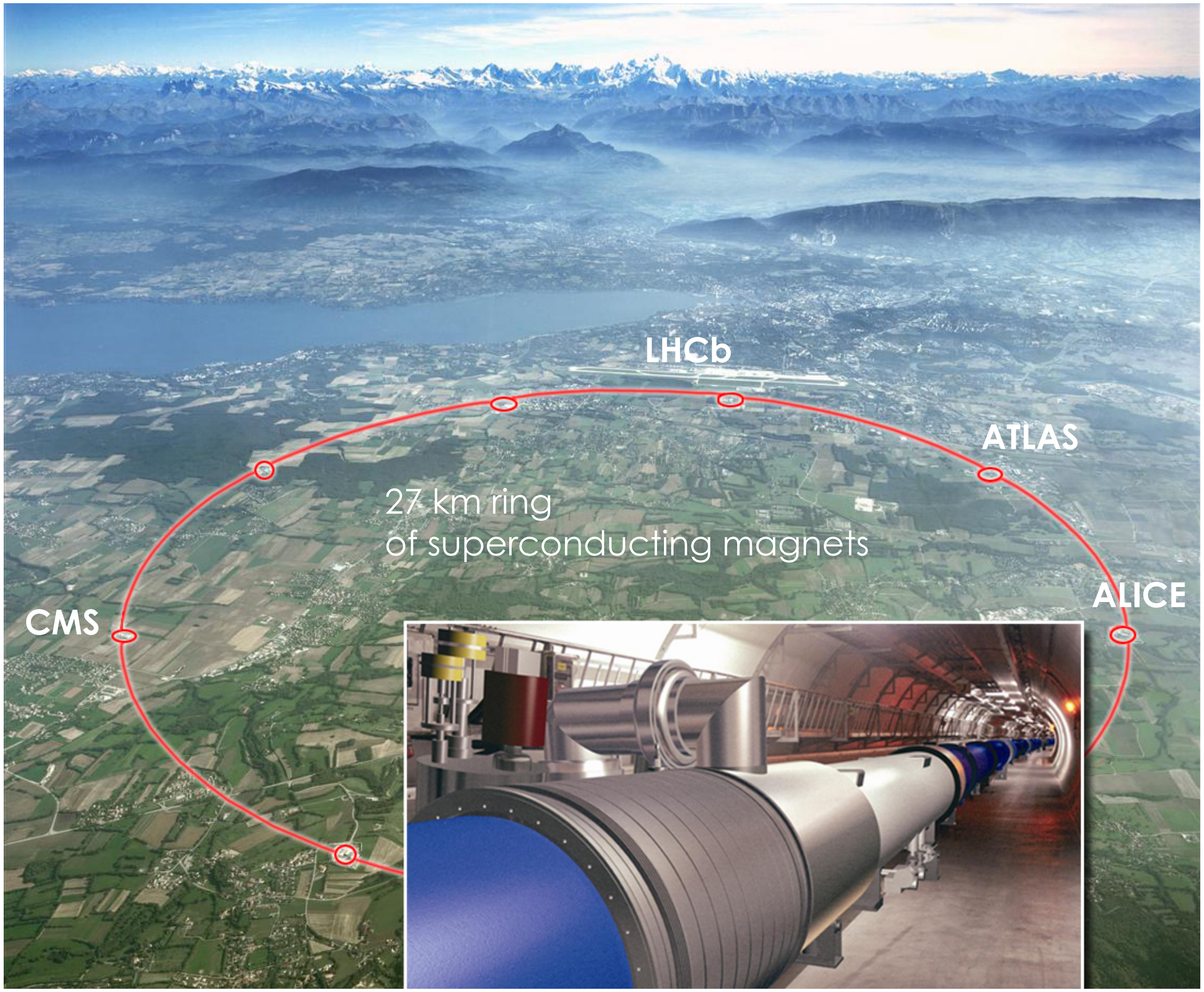
Outline

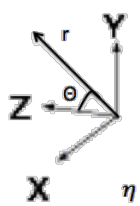
- ✦ The CMS experiment
- ✦ Motivation for a Higgs boson search
- ✦ Signature and Main Backgrounds
- ✦ Standard Model W^+W^- cross section measurement
- ✦ Limits on Anomalous Triple Gauge Couplings WWZ and WWγ
- ✦ Search for $H \to WW \to 2\ell 2\nu$
- ✦ Sensitivity and limits for $\sigma_H \times BR(H \to WW \to 2\ell 2\nu)$ in the SM and in a 4^{th} fermions generation scenario
- ✦ Conclusion

The LHC proton-proton collider at center of mass energy of 7TeV



The CMS detector

Total weight: 12500t
Overall diameter: 15m
Overall length: 21.6m
Magnetic field: 3.8T

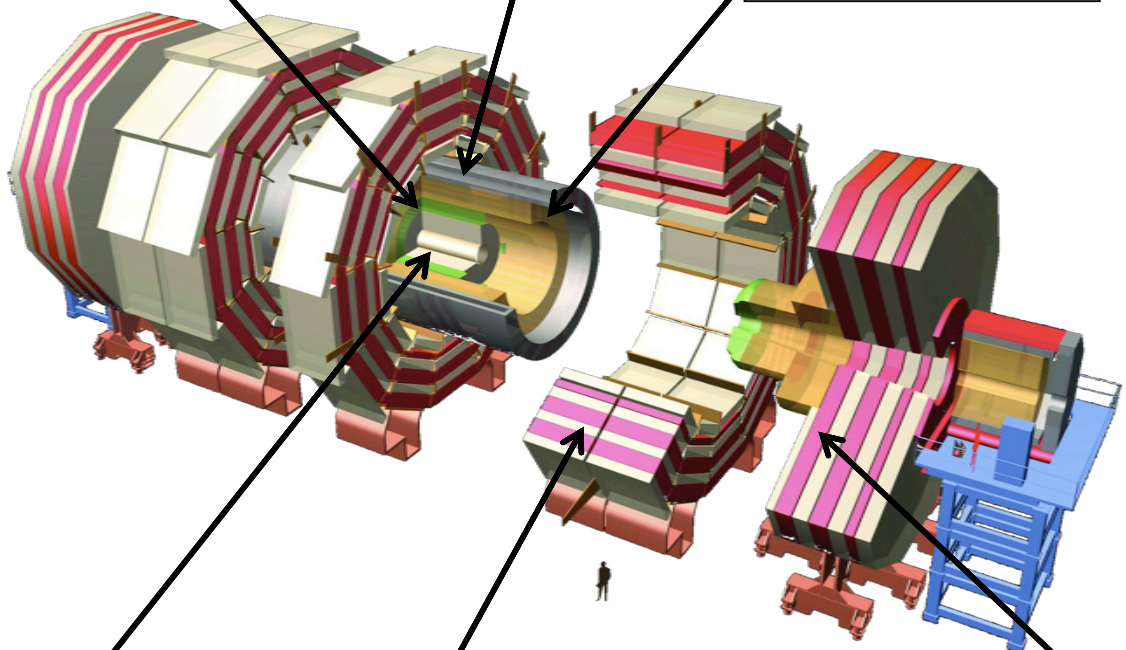


$\eta = -\ln[\tan(\theta/2)]$

ECAL
Scintillating
$PbW0_4$ crystals

Superconducting
coil

HCAL
Plastic scintillator
tiles and copper
absorber plates



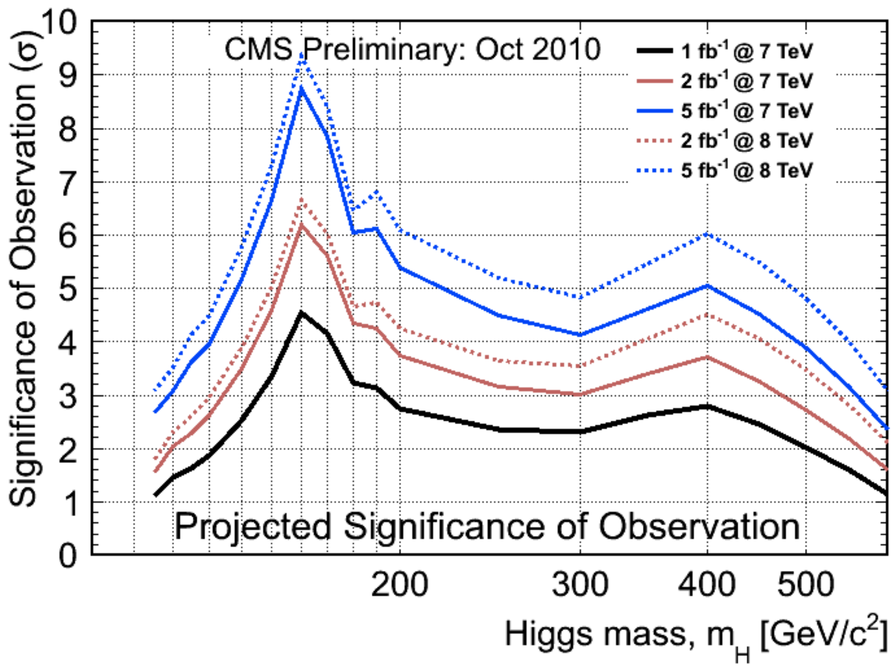
Tracker
Silicon microstrips
Pixels

Muon barrel
Drift Tube chambers
Resistive Plate Chambers

Muon endcaps
Cathode Strip Chambers
Resistive Plate Chambers

Large B-field for muon system (via iron return yoke)

Discovering the Standard Model

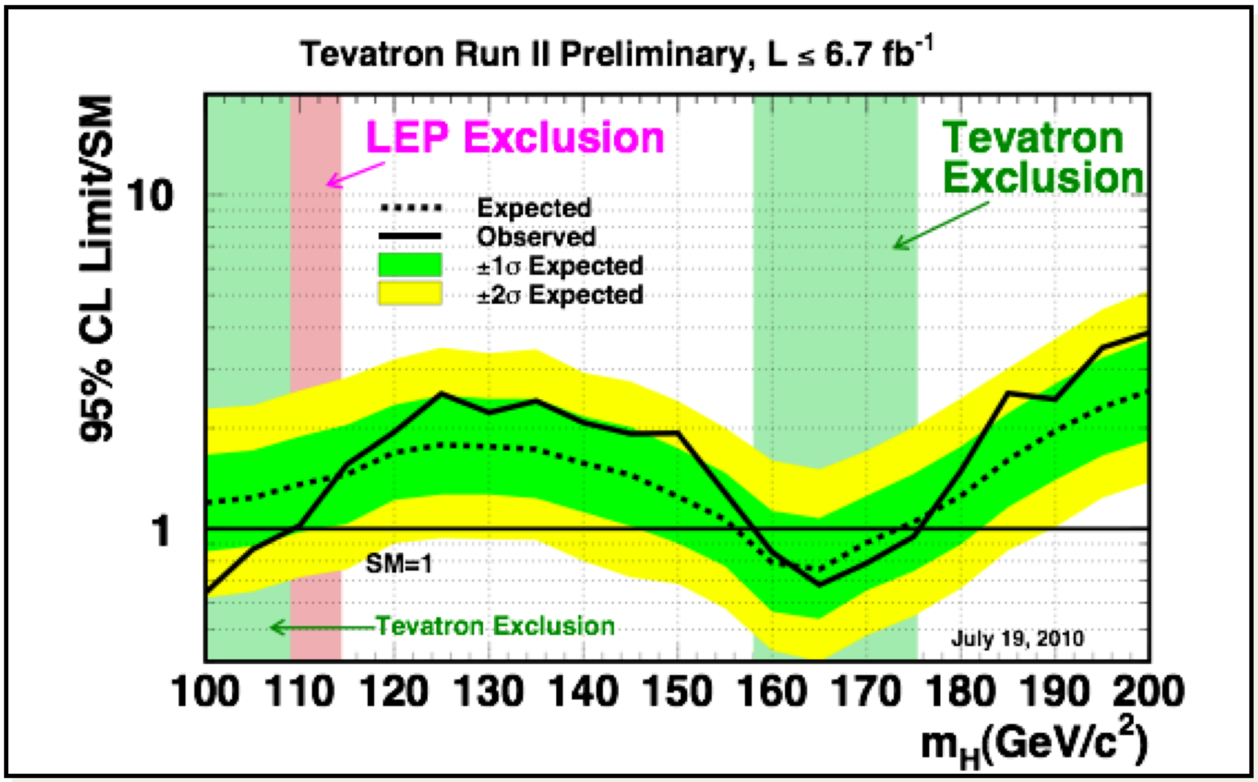


SM describes the majority of High Energy Physics data

Origin of masses is described by the spontaneous breaking of EWK symmetry caused by a scalar field: Higgs.

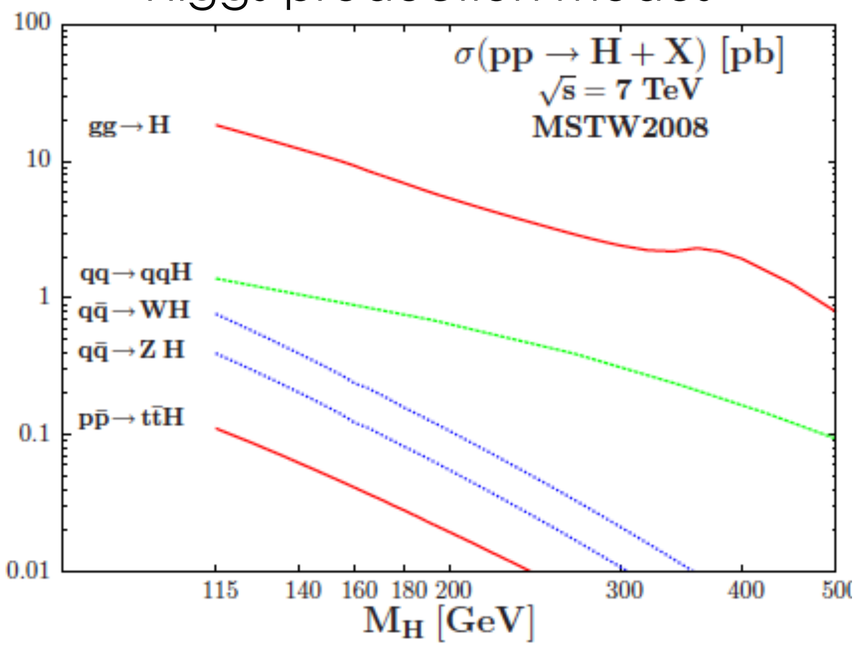
With 1 fb^{-1} at 7 TeV "ATLAS + CMS" projected 3σ sensitivity for $135 < m_H < 475$ GeV/c^2

Higgs exclusion ranges

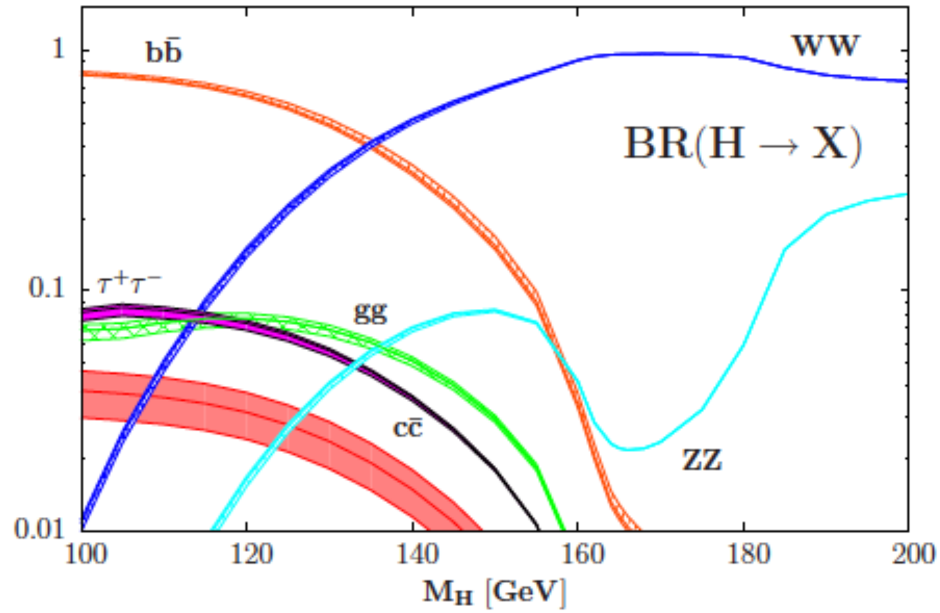


The SM Higgs at LHC at 7TeV

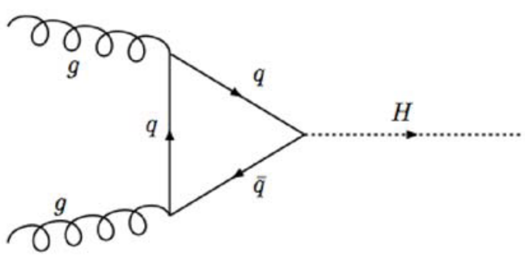
Higgs production modes



Higgs decay modes



Dominant production:
gluon-gluon fusion

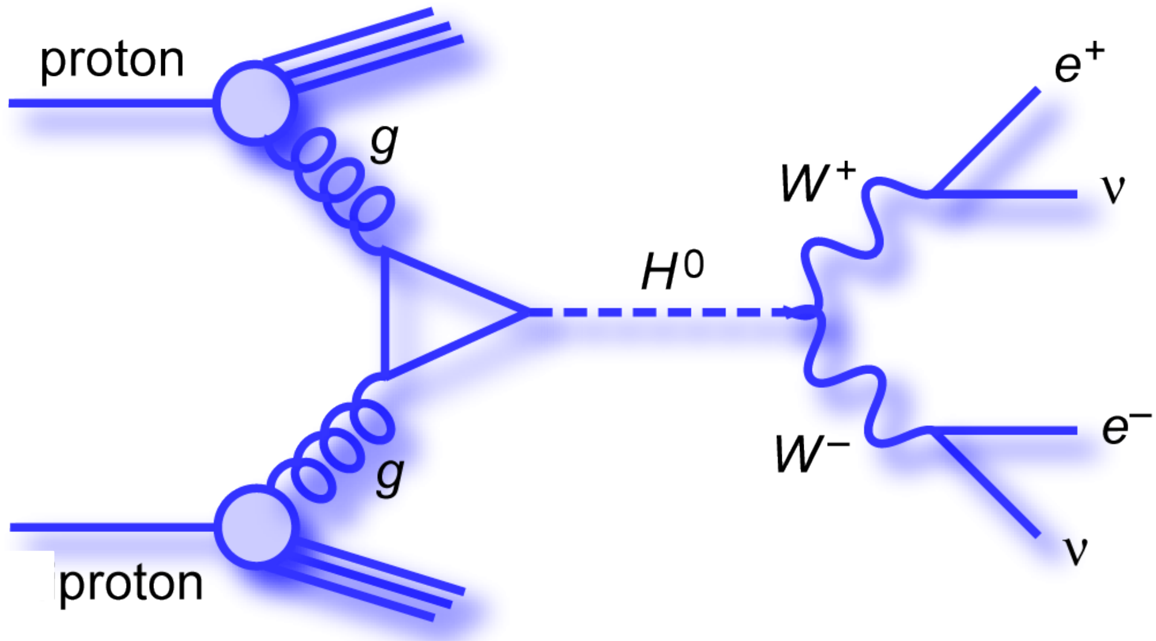


Dominant decay mode at high mass:

H → WW, ZZ

J. Baglio and A. Djouadi arXiv:1012.0530

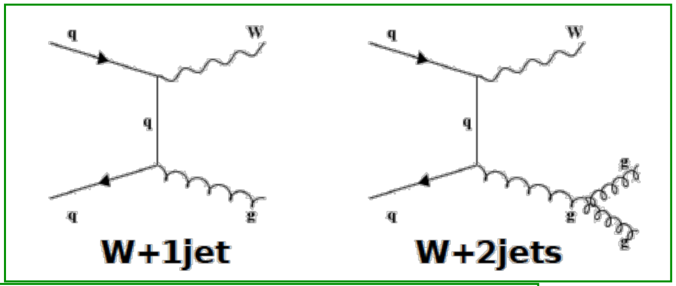
The Higgs to W^+W^- Signature



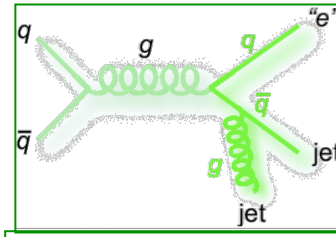
- BR(gg→H)≈1 for $2M_W \le m_H \le 2M_Z$
- 2 isolated leptons
- Significant MET
- No jet activity

The Higgs to W^+W^- Backgrounds

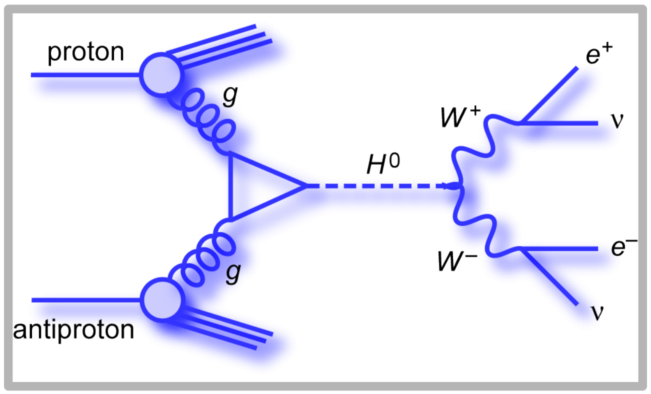
Instrumental contributions



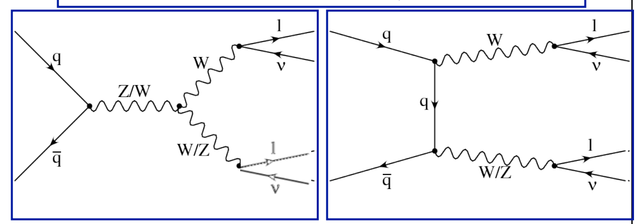
W+jets with fake leptons

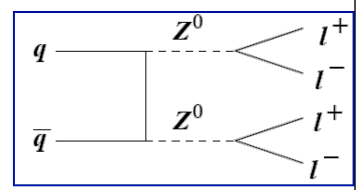


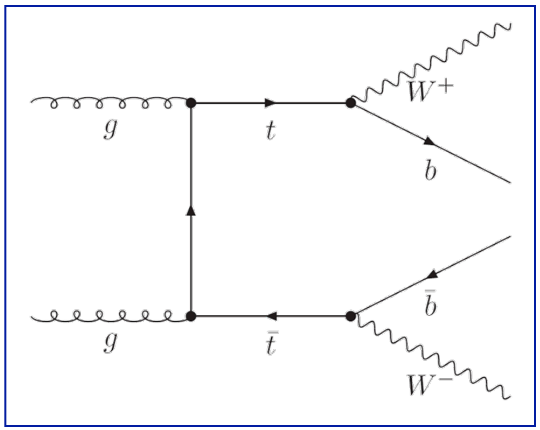
QCD multijet production with fake leptons



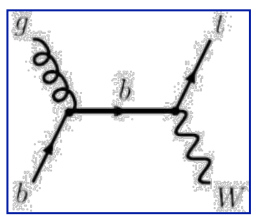
diboson WW, Wγ, WZ, ZZ



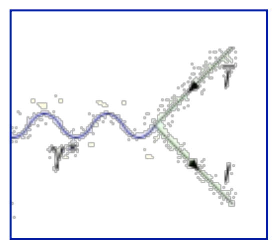




ttbar production



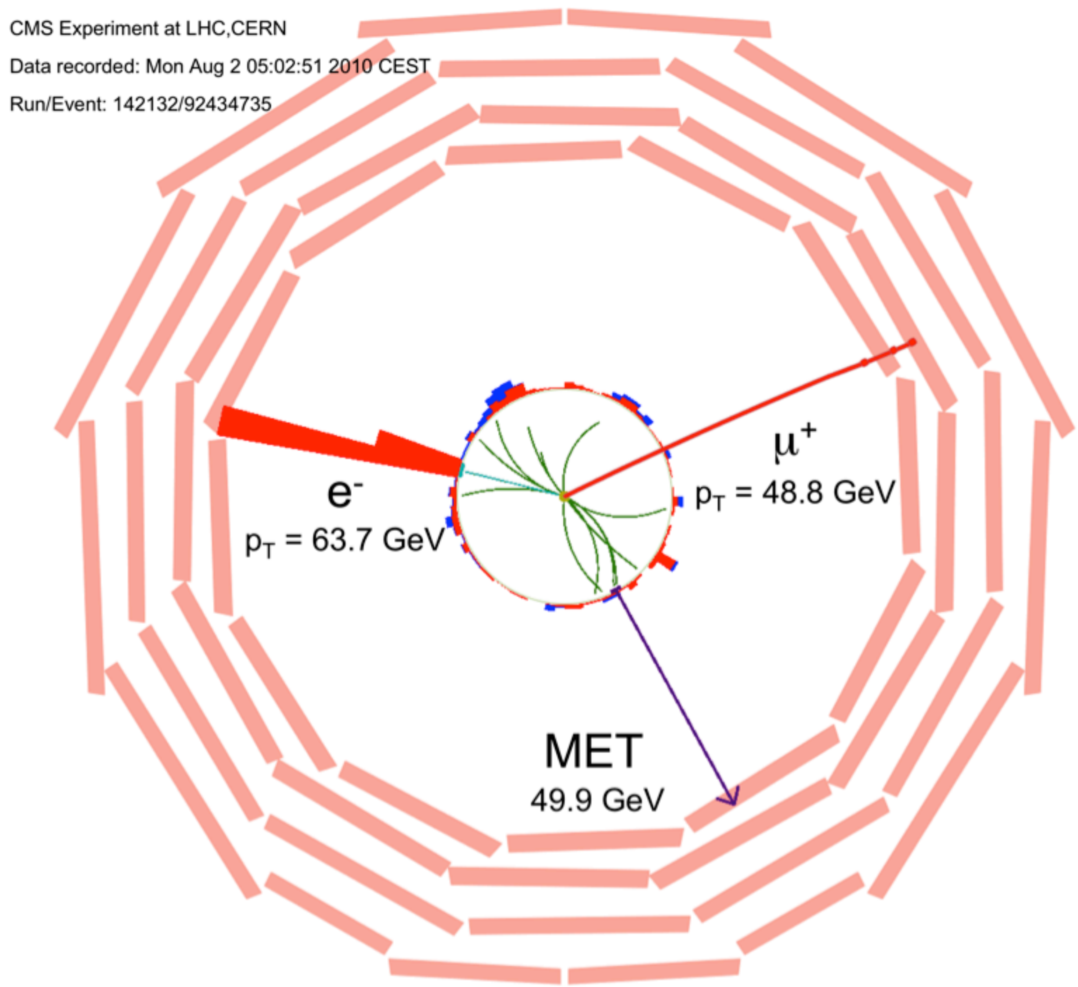
Single Top tW



Drell-Yan with mismeasured MET

Standard Model W^+W^- Cross Section Measurement

CMS W^+W^- candidate



W^+W^- Event Selection

- 2 opposite sign isolated leptons (e, μ) with p_T>20GeV/c
- Reject low mass resonances m_{ll} > 12 GeV/c^2
- Significant amount of MET to reject Drell-Yan and QCD
- Reject events consistent with Z mass
- Jet veto to reject Top background
- Top veto to further reject Top background
- Reject WZ and ZZ: Veto events with more than 2 well identified isolated leptons

➔ See backup for details

Expected yields after W^+W^- selection

MC statistical uncertainty

final state	data	$qq \to WW$	$gg \to WW$	other bkgs.	WZ	ZZ
$\mu\mu$	1	2.18 ± 0.02	0.12 ± 0.01	0.42 ± 0.07	0.06 ± 0.01	0.05 ± 0.01
ee	2	1.47 ± 0.01	0.09 ± 0.01	0.75 ± 0.19	0.04 ± 0.01	0.04 ± 0.01
$e\mu$	10	6.63 ± 0.04	0.28 ± 0.01	1.54 ± 0.26	0.13 ± 0.01	0.01 ± 0.01
all	13	10.28 ± 0.05	0.48 ± 0.01	2.71 ± 0.33	0.23 ± 0.01	0.10 ± 0.01

final state	$t\bar{t}$	tW	$t(\text{t}-chan)/t(\text{s}-chan)$	$DY \to \ell\ell$	W + jets
$\mu\mu$	0.13 ± 0.02	0.06 ± 0.01	0.00 ± 0.00	0.12 ± 0.06	0.00 ± 0.00
ee	0.10 ± 0.02	0.04 ± 0.01	0.00 ± 0.00	0.09 ± 0.05	0.44 ± 0.18
$e\mu$	0.25 ± 0.03	0.19 ± 0.01	0.01 ± 0.01	0.15 ± 0.07	0.80 ± 0.24
all	0.48 ± 0.05	0.29 ± 0.02	0.01 ± 0.01	0.36 ± 0.10	1.24 ± 0.30

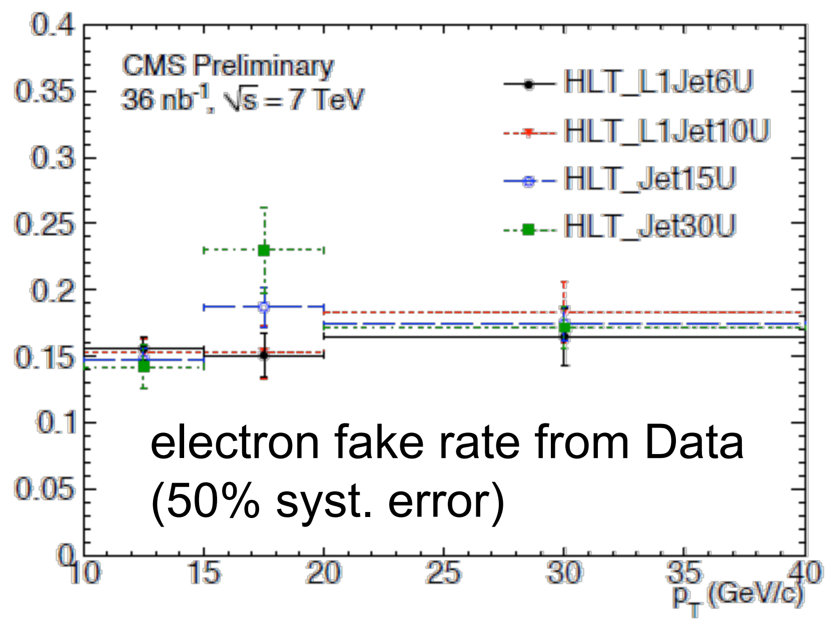
integrated luminosity of 36 pb^{-1}

13 events selected, good agreement with expectations

W+jets and QCD Background Estimations using Data driven technique: Fake rate method

Fake Lepton Background Method

- Define loose lepton-like objects (relax some ID and Isolation cuts)
- Efficiency for fake objects to pass analysis (tight) lepton selection = fake rate (FR)
- FR measured in jet-triggered data (fake enriched data)
- Apply to data events where one (both) leptons pass loose, but fail tight lepton selection:
  1) W+Jets: 1 tight plus 1 fake lepton
  2) QCD: 2 fake leptons



Drell-Yan Background Estimation using Data driven technique: Z mass window

Z/γ* Background Estimate

Off-peak Z/γ* contribution

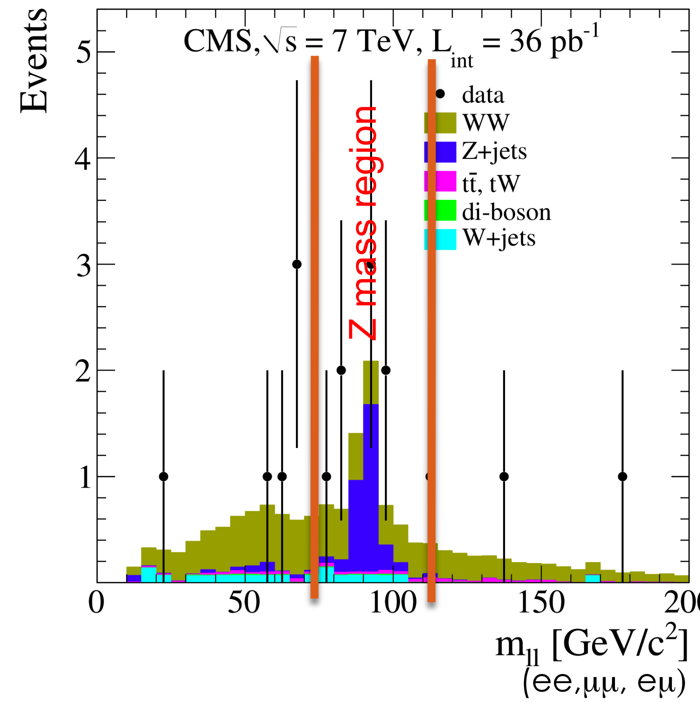
$$N^{\ell\ell,\text{data}}_{\text{out}} = R^{\ell\ell}_{\text{out/in}}(N^{\ell\ell}_{\text{in}} - 0.5N^{e\mu}_{\text{in}}k_{\ell\ell})$$

from DY simulation

correct for non-DY contribution from eμ sample

$$k_{ee} = \sqrt{\frac{N^{ee}_{\text{in}}}{N^{\mu\mu}_{\text{in}}}} \quad \text{and} \quad k_{\mu\mu} = \sqrt{\frac{N^{\mu\mu}_{\text{in}}}{N^{ee}_{\text{in}}}}$$

Relative detection efficiencies of electrons and muons



- Ratio of yield outside to inside Z mass window from DY MC
- Extrapolate Z/γ* background to outside the Z mass window
- Systematics reflects dependence on MET cut

Total Background: Summary

Process	Events
W+jets + QCD	$1.70 \pm 0.40 \pm 0.70$
$t\bar{t}$ + tW	$0.77 \pm 0.05 \pm 0.77$
$W\gamma$	$0.31 \pm 0.04 \pm 0.05$
$Z + WZ + ZZ \rightarrow e^+e^- / \mu^+\mu^-$	$0.20 \pm 0.20 \pm 0.30$
$WZ + ZZ$, leptons not from the same boson	$0.22 \pm 0.01 \pm 0.04$
$Z/\gamma^* \rightarrow \tau^+\tau^-$	$0.09 \pm 0.05 \pm 0.09$
Total	$3.29 \pm 0.45 \pm 1.09$

Wγ suppressed by photon conversion veto (see backup slides)

Efficiencies

- Lepton Selection Efficiency
- Jet Veto Efficiency
- Trigger Efficiency

Lepton Selection Efficiency

- Tag and probe method applied on selected $Z \to \ell\ell$ events in MC and Data
- Lepton Selection Efficiency Scale factors: Overall weak pT and η dependence
- Lepton Selection efficiency in W^+W^- data is extracted from W^+W^- MC and corrected by data to simulation scale factor:

Electron
- Barrel : 0.969 ± 0.019
- Endcap : 0.992 ± 0.026

Muon
consistent with 1.00 (±0.01)

Jet Veto Efficiency

- Jet veto p_T cut of 25GeV/c
- W^+W^- MC jet veto efficiency corrected by scale factor derived from $Z \to \ell\ell$

$$\epsilon_{\mathrm{WW}}^{\mathrm{data}} = \epsilon_{\mathrm{WW}}^{\mathrm{MC}} \times \frac{\epsilon_{\mathrm{Z}}^{\mathrm{data}}}{\epsilon_{\mathrm{Z}}^{\mathrm{MC}}}$$

Experimental uncertainty from Z data sample

= 79.3 ± 0.3%

= 62.1 ± 0.2%

= 101.5 ± 0.4%

5.5% uncertainty

Theoretical uncertainty from higher order corrections
Estimate by varying renormalization and factorization scale

Single Lepton Trigger Efficiency

- Measured for leptons passing identification and isolation in a Z control sample
- Probe is matched to the relevant HLT trigger object candidate within a cone of $\Delta R < 0.1$.

- Trigger Efficiency
  - Single Electron Trigger Efficiency : 97%
  - Single Muon Trigger Efficiency : 89%
- Event Trigger Efficiency = $1 - (1 - \varepsilon_1)(1 - \varepsilon_2)$
  - ee : 99.9%
  - eμ : 99.7%
  - μμ : 98.7%
  - Systematic Uncertainty : 1.5%

W^+W^- Cross Section Measurement

$$DY/WZ/ZZ \to ee/\mu\mu \quad W + jets$$
$$QCD \quad t\bar{t} \quad tW \quad Z/\gamma^* \to \tau\tau$$
$$WZ/ZZ \text{ (leptons not from same boson)} \quad W\gamma$$

total number of events passing the selection

$$\sigma = \frac{N^{\text{pass}} - N^{\text{bkgr}}}{A \times BR(W \to \ell\nu)^2 \times \epsilon \times \int L dt}$$

acceptance

efficiency (for signal falling within the acceptance): trigger, lepton identification, jet veto…

total integrated luminosity

WW Cross Section Measurement Results

We consider both $qq \to W^+W^-$ and $gg \to W^+W^-$ processes as signal with average efficiency of 6.34 ± 0.46 (%)

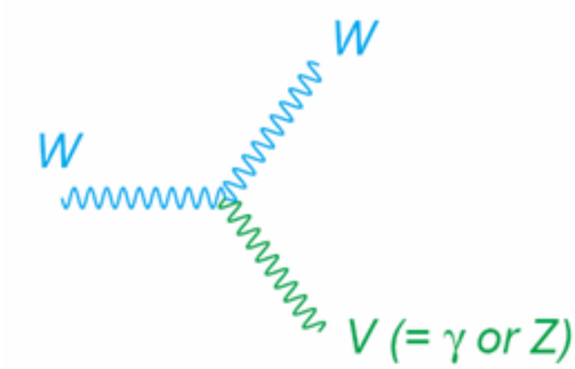
$$\sigma_{WW \to 2\ell 2\nu} = 4.3 \pm 1.6(\mathrm{stat.}) \pm 0.6(\mathrm{syst.}) \pm 0.5(\mathrm{lumi.})\mathrm{pb}$$

$$\sigma_{WW} = 41.1 \pm 15.3(\mathrm{stat.}) \pm 5.8(\mathrm{syst.}) \pm 4.5(\mathrm{lumi.})\mathrm{pb}$$

Limits on WWγ and WWZ Anomalous Triple Gauge Couplings

Self-interaction Couplings

- Self-interaction between gauge bosons



- $pp \to W^+W^-$ governed by WWZ and WWγ couplings

- Any deviation in measured values from the SM predictions would be indications of new physics

(aTGCs = Anomalous Triple Gauge Couplings)

WWZ and WWγ Interaction Lagrangian

$$\frac{\mathcal{L}}{g_{WWV}} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^\dagger_{\delta\nu} W^\mu_\nu V^{\nu\delta}$$

EWK coupling (g_{WWV})

W- boson ($W^\dagger_{\mu\nu}$)

Z or γ (V^ν)

$W^{\mu\nu}$: $\partial_\mu W_\nu - \partial_\nu W_\mu$

Standard Model: $\lambda_Z = \lambda_\gamma = 0$ and $g_1^Z = \kappa_Z = \kappa_\gamma = 1$

With non-Standard Model couplings, the interaction diverges at high energies (scaling is necessary):

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1 + \hat{s}/\Lambda^2)^2}$$

α_0: Low energy approximation of the couplings

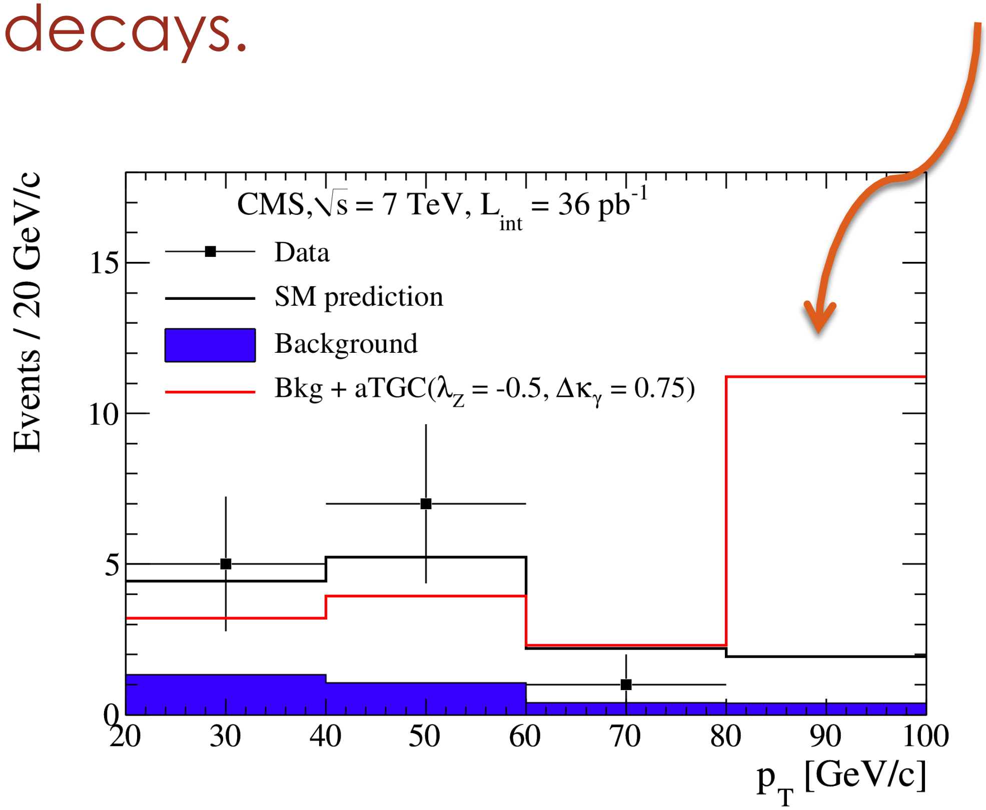
$\hat{s}$: Square of the WW invariant mass

Λ: Form factor scale (Λ=2TeV)

Leading Lepton p_T

Anomalous coupling gives enhancement of W^+W^- cross section at large $\hat{S}$.

Excess of events with high momentum leptons from W decays.



Compare the leading lepton p_T spectrum in data to the signal-plus-background hypothesis

Anomalous couplings and Likelihood Formalism

- Derive limits on aTGCs by fitting to leading lepton pT

- Reduction after parametrization: $\Delta\kappa_\gamma = \kappa_\gamma - 1$, $\lambda = \lambda_\gamma = \lambda_Z$ and $\Delta g_1^Z = g_1^Z - 1$

- W^+W^- aTGC signal samples modeled using SHERPA/Pythia

- Samples obtained by varying 2 parameters freely and fixing the third one to SM value

- Construct a Likelihood function assuming Gaussian errors (reflected in nuisance parameters).

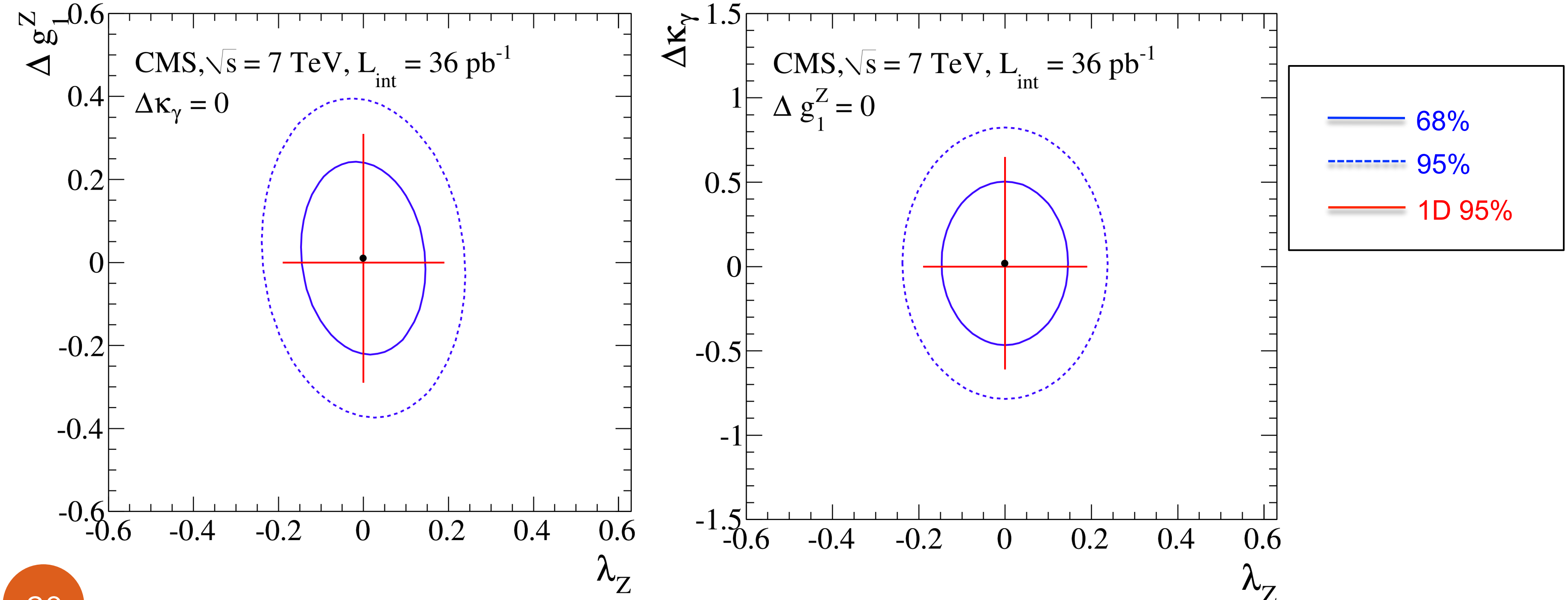
- Determine aTGCs by minimizing –log L with respect to all parameters.

- Calculate 95% confidence intervals on the measured aTGCs

CMS Limits on anomalous Triple Gauge Couplings

	λ_Z	Δg_1^Z	$\Delta\kappa_\gamma$
Unbinned fit	$[-0.19, 0.19]$	$[-0.29, 0.31]$	$[-0.61, 0.65]$
Binned fit	$[-0.23, 0.23]$	$[-0.33, 0.40]$	$[-0.75, 0.72]$

By comparison, CDF limits are:
λ=[-0.14,0.15] , Δg_1^Z=[-0.22,0.30]
$\Delta\kappa_\gamma$=[-0.57, 0.65]
PRL 104.201801 (2010)



Search for Higgs boson in the W^+W^- decay mode

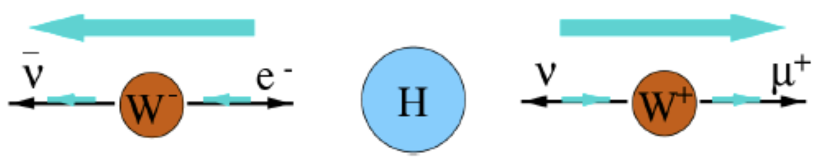
Strategy for Higgs Search

- After full W^+W^- selection is applied
- Discriminate against the remaining background, specially diboson W^+W^- continuum
- One of the discriminators is the opening angle between leptons $\Delta\phi_{ll}$
- The final step is a Higgs mass dependent event selection (two approaches)
  - cut-based approach
  - multivariate analysis

Diboson W+W- continuum discrimination

Standard Model Higgs has spin zero

Angular momentum conservation:
Ws must be anti-correlated



W$^-$ decays to a left-handed charged lepton and a right-handed neutrino
l$^-$ tends to point away from the W$^-$ spin

Opening angle $\Delta\phi_{\ell\ell}$ between leptons from Higgs to WW is on average *smaller* than in continuum WW production

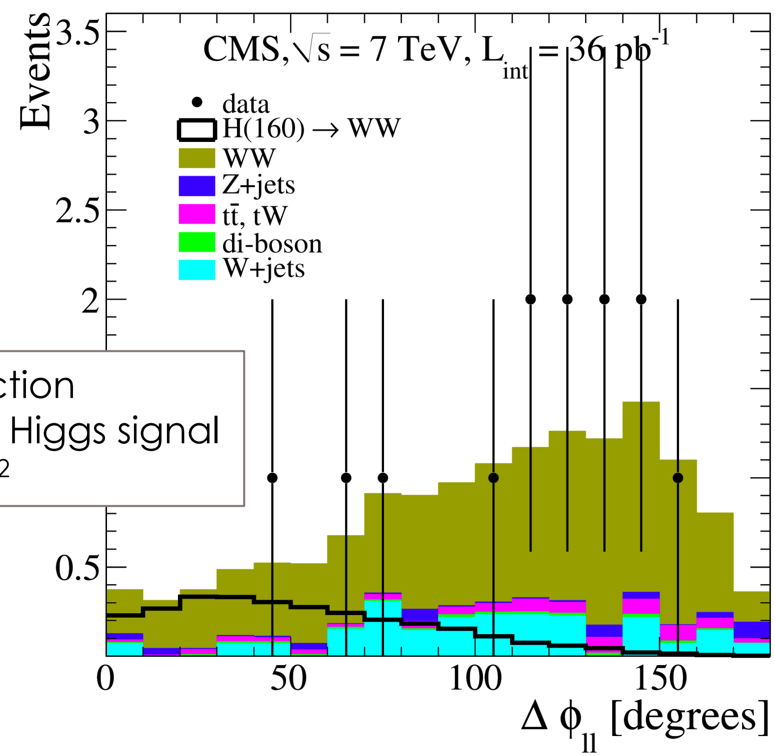
Cut based approach to enhance sensitivity to Higgs signal

Discriminant variables: $p_T^{\ell,\max}, p_T^{\ell,\min}, m_{\ell\ell}, \Delta\phi_{\ell\ell}$

m_H (GeV/c^2)	$p_T^{\ell,\max}$ (GeV/c) >	$p_T^{\ell,\min}$ (GeV/c) >	$m_{\ell\ell}$ (GeV/c^2) <
130	25	20	45
160	30	25	50
200	40	25	90
210	44	25	110
400	90	25	300

m_H (GeV/c^2)	$\Delta\phi_{\ell\ell}$ (degree) <
130	60
160	60
200	100
210	110
400	175

After W^+W^- selection
Standard Model Higgs signal
m_H = 160 GeV/c^2



Multivariate approach to enhance sensitivity to Higgs signal

- Boosted Decision Tree (BDT) technique for each m_H hypothesis
- Sophisticated multiple cut technique
- Salvage signal which would be lost and Remove background that would pass
- Designed to maximize the signal and background separation

$$p_T^{\ell,\max}, p_T^{\ell,\min}, m_{\ell\ell}, \Delta\phi_{\ell\ell}$$

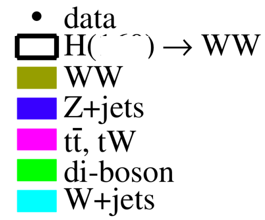
$$\text{projected MET}, \Delta R_{\ell\ell}, \text{dilepton type}$$

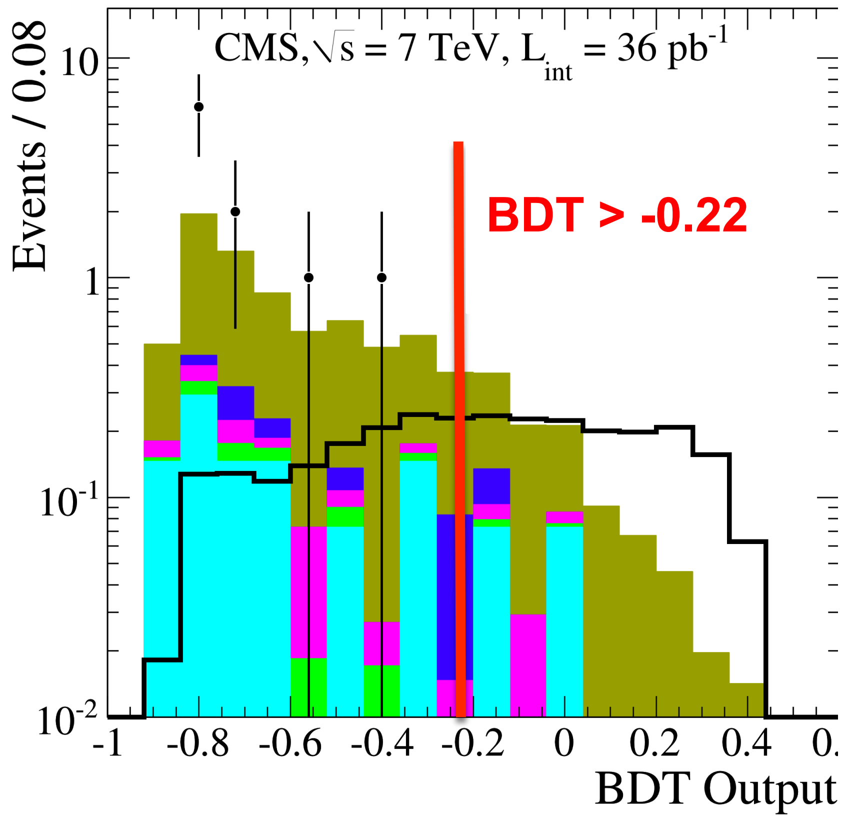
$$\Delta\phi(\ell, \text{MET}), M_T^{\ell_1,\text{MET}}, M_T^{\ell_2,\text{MET}}$$

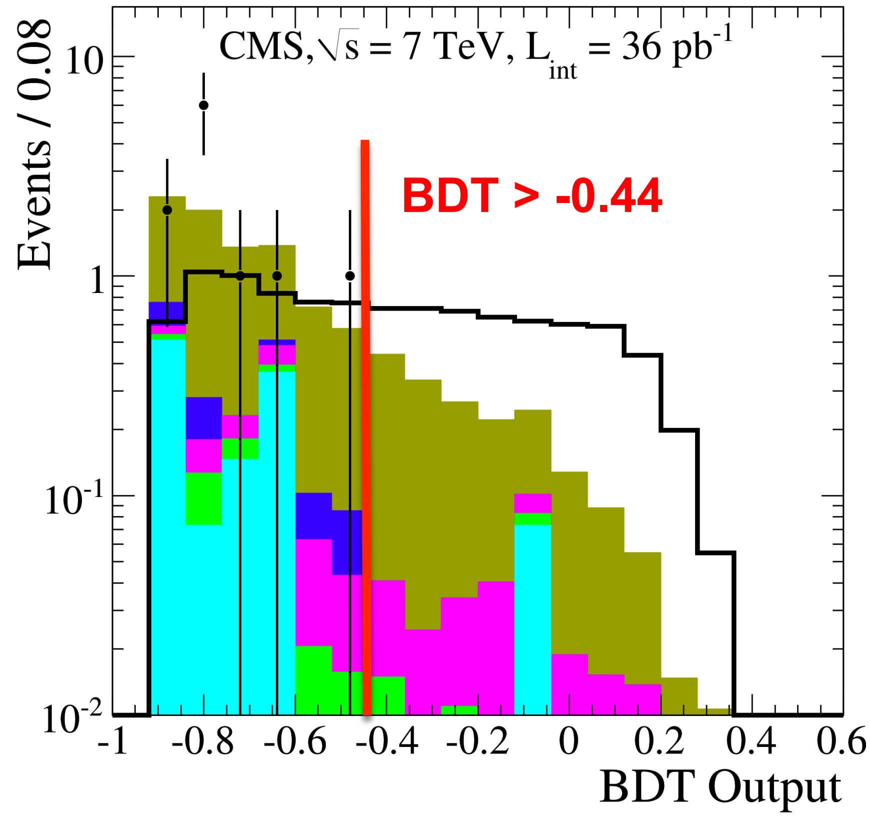
Boosted Decision Tree Output

BDT output is used as a simple cut

= decision tree score







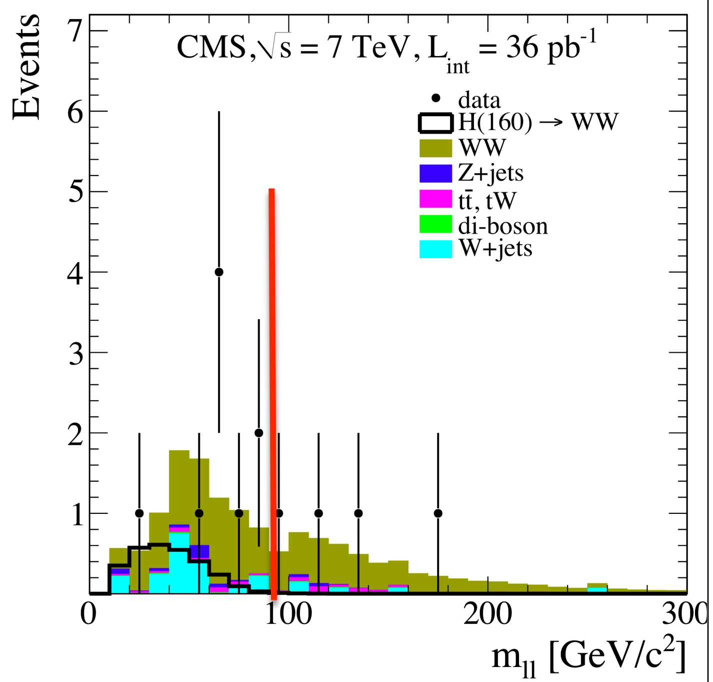
Higgs (m_H=160) event yield is normalized to SM expectation

Higgs (m_H=200) event yield normalized to 4^{th} family lepton scenario

W^+W^- background estimate

$qq \to W^+W^-$ Data driven method

- Apply the WW selection
- Obtain a signal-free region, dominated by WW:
  - m_H<200 GeV/c² m_{ll}>100GeV/c²
  - m_H>200 GeV/c² m_{ll}<100GeV/c²
- Measure WW background in control region
- Extrapolate WW background in the signal region (depending on the Higgs mass hypothesis) using simulation



$gg \to W^+W^-$ From MC

Higgs to W^+W^- Yields

1 event surviving low-mass H selections (or MVA cut)

m_H (GeV/c^2)	data	SM $H \to W^+W^-$	SM with 4th gen. $H \to W^+W^-$	all bkg.	$qq \to W^+W^-$	$gg \to W^+W^-$	all non-W^+W^-
cut-based approach							
130	1	0.30 ± 0.01	1.73 ± 0.04	1.67 ± 0.10	1.12 ± 0.01	0.10 ± 0.01	0.45 ± 0.10
160	0	1.23 ± 0.02	10.35 ± 0.16	0.91 ± 0.05	0.63 ± 0.01	0.07 ± 0.01	0.21 ± 0.05
200	0	0.47 ± 0.01	3.94 ± 0.07	1.47 ± 0.09	1.13 ± 0.01	0.12 ± 0.01	0.23 ± 0.09
210	0	0.34 ± 0.01	2.81 ± 0.07	1.49 ± 0.05	1.09 ± 0.01	0.10 ± 0.01	0.30 ± 0.05
400	0	0.19 ± 0.01	0.84 ± 0.01	1.06 ± 0.03	0.79 ± 0.01	0.04 ± 0.01	0.23 ± 0.03
multivariate approach							
130	1	0.34 ± 0.01	1.98 ± 0.04	1.32 ± 0.18	0.75 ± 0.01	0.04 ± 0.00	0.53 ± 0.18
160	0	1.47 ± 0.02	12.31 ± 0.17	0.92 ± 0.10	0.63 ± 0.01	0.06 ± 0.00	0.22 ± 0.10
200	0	0.57 ± 0.01	4.76 ± 0.07	1.47 ± 0.07	1.07 ± 0.01	0.13 ± 0.00	0.27 ± 0.07
210	0	0.42 ± 0.01	3.47 ± 0.07	1.44 ± 0.07	1.03 ± 0.01	0.12 ± 0.00	0.29 ± 0.07
400	0	0.20 ± 0.01	0.90 ± 0.01	1.09 ± 0.07	0.75 ± 0.01	0.04 ± 0.00	0.30 ± 0.07

statistical uncertainties from the simulations

Background from fake leptons, Top, Drell-Yan and WZ/ZZ/Wγ are measured with same techniques as shown in previous slides (WW production cross section)

BDT give better discriminating power

Dominant Uncertainties

The uncertainty on the $H \rightarrow W^+W^-$ signal yield is ~14%
(After Higgs boson p_T distribution reweighted in POWHEG to match NNLO+NNLL prediction)

The uncertainties on the background estimations in the $H \rightarrow W^+W^-$ signal regions are ~40%, dominated by statistical uncertainties in the data control regions

- Luminosity 11%
- Jet veto efficiency uncertainty: 6.9%
- PDF uncertainty on signal efficiency: 3%
- μ_R and μ_F scales effect on acceptance: 2%

Interpretation of Results

- No excess compatible with Higgs signal production is observed in the current data sample

- We compute 95% Confidence Level Upper Limits on:

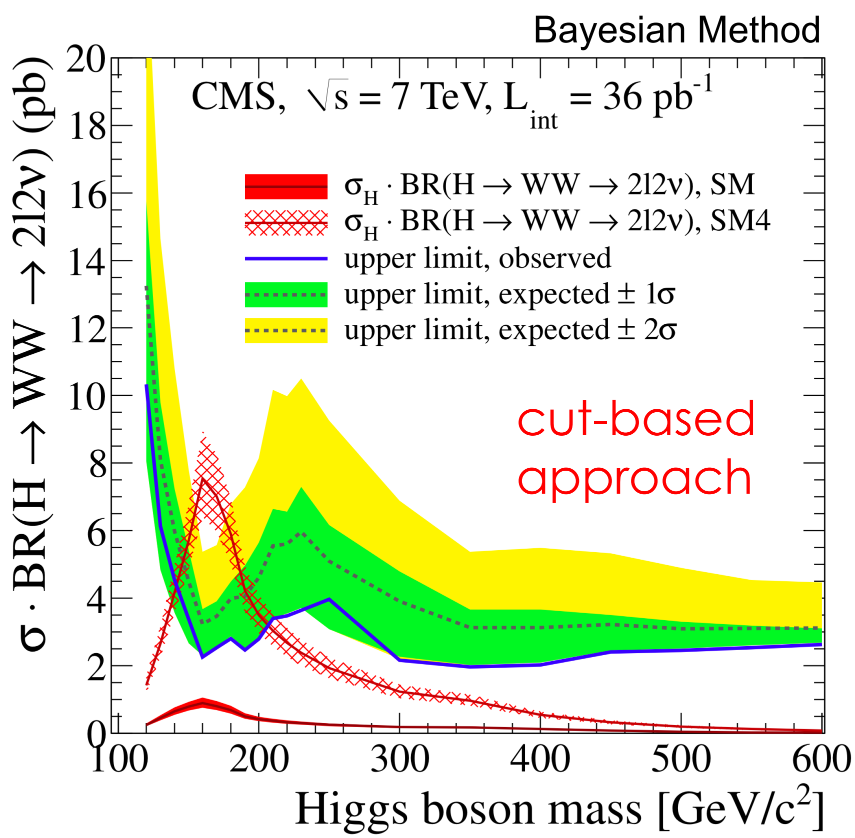
$$\sigma_H \cdot BR(H \rightarrow WW \rightarrow 2l2\nu)$$

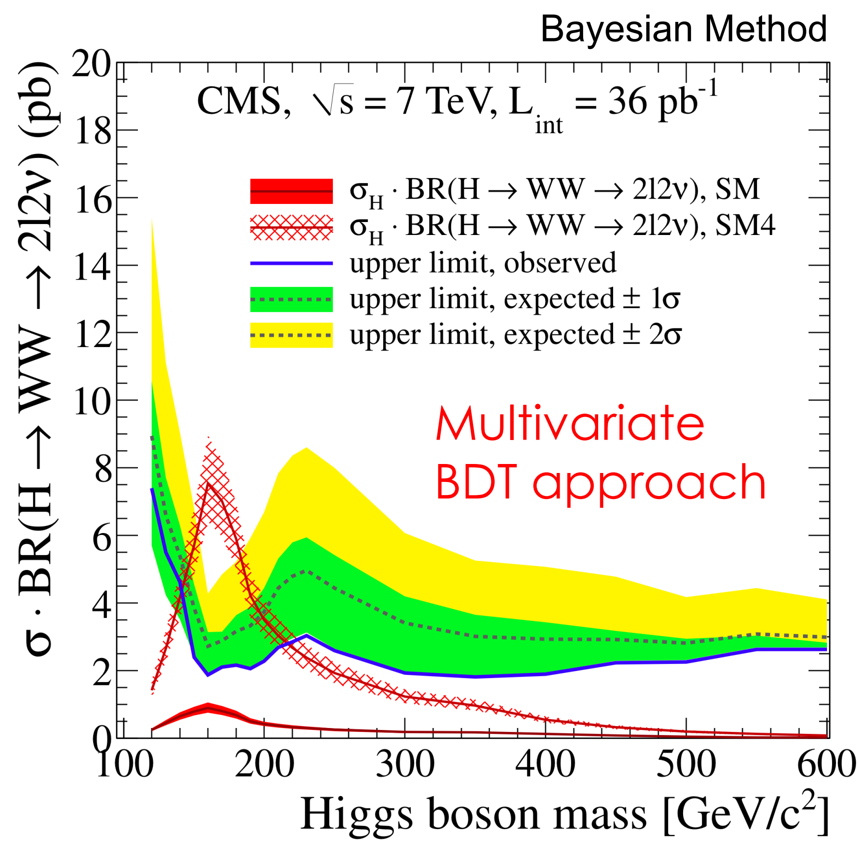
- Two statistical methods*: Bayesian & CLs hybrid Frequentist Bayesian approaches: first is shown (identical results)

- Limits in the 4th generation of (heavy) leptons

* PHYSTAT-LHC workshop *LHC Statistics for Pedestrians* http://cdsweb.cern.ch/record/1099994/

CMS Exclusion Limits





The observed limits have no sensitivity to the SM Higgs boson

But in the context of SM with a four fermion generation, CMS excludes a Higgs boson with m_H=[144-207]GeV/c^2 at 95% CL
(Tevatron excludes m_H = [131-204] GeV/c^2 with ~10fb^{-1})

Conclusion

First measurement of pp → W+W- production cross section at 7 TeV

Derived limits on the anomalous triple gauge couplings (comparable in sensitivity to Tevatron)

First search of H → W+W- is done in 35 pb^{-1}

No excess above backgrounds observed in data

In context of SM with a four fermion generation, CMS excludes a Higgs boson with m_H=[144-207]GeV/c^2 at 95% CL

- Tevatron limits are m_H = [131-204] GeV/c^2 (see http://arxiv.org/abs/1012.1483v1)

Starting to be competitive with the world limits

Stay tuned on H → WW in 2011!

Backup Slides

W^+W^- event Selection

- Single lepton triggers
- Muon selection
  - Found by Global and Tracker Muon algorithms
  - $N_{muon\ hits} \geq 1$ and $N_{matches\ to\ muon\ segments} \geq 2$
  - N_{hits}(strips)>10 and N_{hits}(Pixels)≥1
  - p_T>20 GeV/c and $|\eta|<2.4$
  - Combined Relative Isolation < 15%
  - Impact parameter: $|d_0(PV)|<0.02$cm and $|d_z(PV)|<1$cm
  - Global fit χ^2/ndof < 10
  - Relative p_T resolution is better than 10%

$$\mathrm{RelIso} = \frac{\sum_{\Delta R<0.3}^{\mathrm{tracks}} p_T + \sum_{\Delta R<0.3}^{\mathrm{ECAL}} E_T + \sum_{\Delta R<0.3}^{\mathrm{HCAL}} E_T}{p_T(\mathrm{electron})}$$

- Electron selection
  - p_T>20 GeV/c and $|\eta|<2.5$
  - EleID based on shower shape and track cluster matching
  - Combined Relative isolation < 10%
  - Impact parameter: $|d_0(PV)|<0.02$cm and $|d_z(PV)|<1$cm
  - Photon conversion veto

W^+W^- event Selection

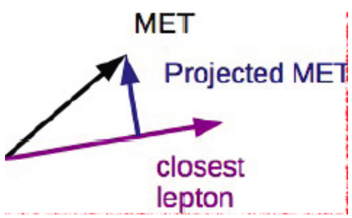
- Z veto to further reject Drell-Yan: reject ee and μμ events which have dilepton mass within 15 GeV from Z mass.

- Missing E_T > 20GeV

To reject background events where there is no natural source of missing energy, like in Drell-Yan and QCD

- *Projected* Missing E_T

To reject $Z \to \ell\ell$ events with a small opening angle between MET and one of the leptons



$$\Delta\phi_{\rm min} = \min(\Delta\phi(\ell_1, {\rm E}_T^{\rm miss}), \Delta\phi(\ell_2, {\rm E}_T^{\rm miss}))$$

$$\text{projected } {\rm E}_T^{\rm miss} = \begin{cases} {\rm E}_T^{\rm miss} & \text{if } \Delta\phi_{\rm min} > \pi/2 \\ {\rm E}_T^{\rm miss}\sin(\Delta\phi_{\rm min}) & \text{if } \Delta\phi_{\rm min} < \pi/2 \end{cases}$$

Improves rejection against events with mis-reconstructed MET

ee/μμ: $^{\rm projected}$MET > 35 GeV

eμ: $^{\rm projected}$MET > 20 GeV

W^+W^- event Selection

* Jet veto for Top contamination rejection

Veto events with jets $|\eta|<5$ and $p_T>25GeV/c$
Jets are reconstructed using particle flow algorithm. The anti-kT clustering algorithm with R = 0.5 is used.
Jets are required to be separated from the selected leptons by at least $\Delta R > 0.3$

* Extra lepton veto for diboson processes rejection

Events with a third lepton passing ID and isolation are rejected

W^+W^- event Selection

* Top tagging veto for further Top contamination rejection
  - soft-muon tagging
    - p_T>3GeV/c
    - Tracker muon
    - Pass TMLastStationAndTight muon ID requirements
    - Number of valid inner tracker hits > 10
    - Impact parameter $|d_0(PV)|<0.02$cm
    - Muon with p_T>20GeV/c have to be non-isolated with Combined Relative Isolation > 10%
  - b-jet tagging: any jet that pass the Track Counting High Efficiency tagger with a discriminator > 2.1