Standard Model Higgs search in $H \rightarrow ZZ \rightarrow l^+l^-\tau^+\tau^-$ decay channel with CMS experiment @ $\sqrt{s}$ = 7 and 8 TeV

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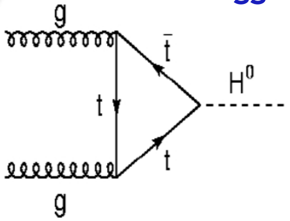
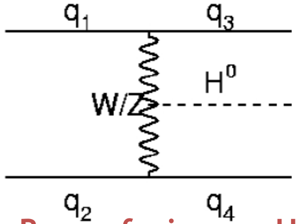
Outline

- SM Higgs X-sections and branching ratios
- H→ZZ→llττ analysis in a nutshell
- e, μ and τ identification and isolation, and 4-lepton final state overlap removal
- Background estimation
- Results (5.05 fb^{-1} @ 7 TeV + 5.26 fb^{-1} @ 8TeV)
- Conclusions

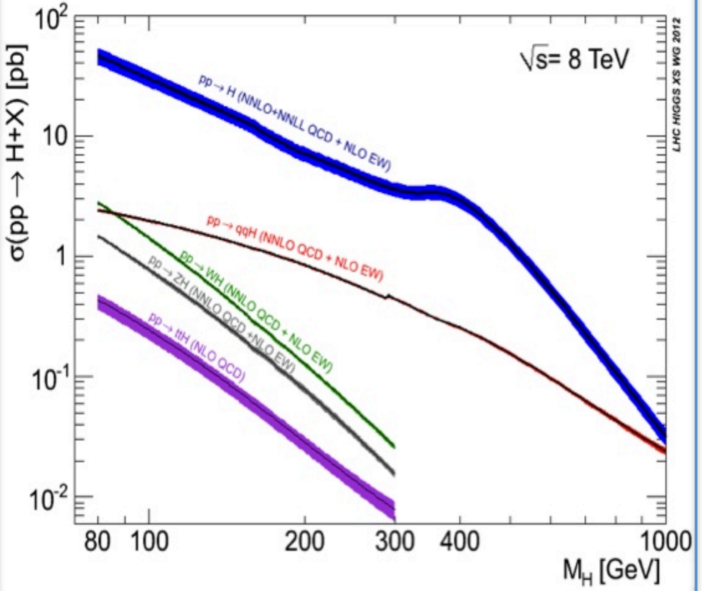
SM Higgs: X-sections and Branching Ratios

Gluon fusion: gg→H

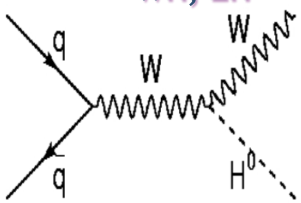


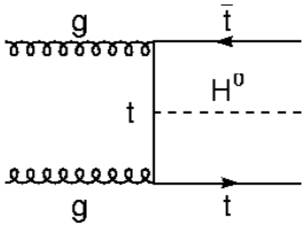


Vector Boson fusion: qqH



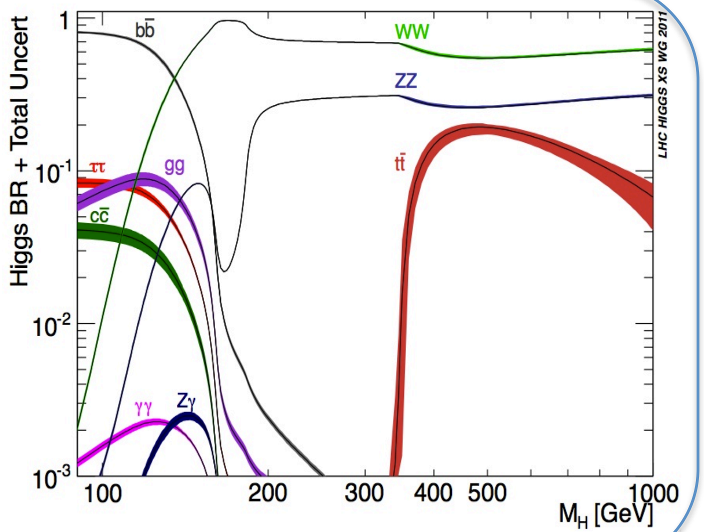
Associated production: WH, ZH





Associated production with heavy quarks: ttH

- m_H < 130 GeV:
  H→bbbar dominant; BR = 60-90%
  $H\to\tau^+\tau^-$, ccbar, gg; BR = Few %
  H→γγ, Zγ; BR < 10^{-3}
- m_H > 130 GeV:
  H→WW*, ZZ* dominant up to $2m_W$
  H→WW, ZZ; BR = (66%, 33%)
  H→ttbar for higher m_H; BR < 20%



√s = 8 TeV

	σ (pp→H) (pb)	BR (H→ZZ*)	σ (pp→H→ZZ*→4l) (fb)
H150	15.56	8.25E-02	13.23
H200	8.21	2.55E-01	21.26
H250	5.48	2.97E-01	16.50
H300	4.10	3.07E-01	12.75

	BR	σ (fb)
$2l\tau_{had}\tau_{had}$	4.88E-04	4.01
$2l\tau_{lep}\tau_{had}$	5.25E-04	4.31
$2l\tau_{lep}\tau_{lep}$	1.53E-04	1.26
$\mu\mu\mu\mu$	2.88E-04	2.37
$ee\mu\mu$	5.75E-04	4.72
$eeee$	2.88E-04	2.37

H→ZZ→llττ analysis in a nutshell

- Signature:
  - Both Z are on mass shell, and $190 < m_H < 600$ GeV/c^2
  - Leading Z:
    - $\mu^+\mu^-$
    - e^+e^-
  - Sub-leading Z→$\tau^+\tau^-$:
    - $\tau_h\tau_h$
    - $\tau_\mu\tau_h$
    - $\tau_e\tau_h$
    - $\tau_e\tau_\mu$
  - 8 final states

    $\mu\mu\tau_h\tau_h$, $\mu\mu\tau_\mu\tau_h$, $\mu\mu\tau_e\tau_h$, $ee\tau_h\tau_h$, $ee\tau_e\tau_h$, $ee\tau_\mu\tau_h$, $\mu\mu\tau_\mu\tau_e$, $ee\tau_\mu\tau_e$
- Backgrounds:
  - ZZ (Measured from simulation)
  - WZ and Z associated with jets (Measured from data using Fake Rate method)
- Selection Strategy:
  - Leading Z selection
  - Leptons identification and isolation
  - Phase space requirements
  - τ discriminators against e's and μ's
  - τ isolation
- Control from data:
  - Leptons (e, μ, τ) related efficiencies
  - Background estimation

- Lepton identification and isolation:
  - Tight Particle Flow (PF) μ selection for μ's
  - MVA electron Id for e's
  - Relative PF Isolation using "ρ with effective area($\pi\Delta R^2$)" correction for pile up, for both e's and μ's

$$\Delta R = \sqrt{(\eta_{lepton} - \eta_{isol.particle})^2 + (\phi_{lepton} - \phi_{isol.particle})^2}$$

$$I_{rel}^{PF}(\rho) = \frac{\sum \left(p_T^{charged} + max(E_T^{\gamma} + E_T^{neutral} - \rho.A_{eff}, 0.0)\right)}{p_T^l}$$

- Hadron Plus Strip (HPS) τ:
  - Combined isolation with $\Delta\beta$ correction for pile up

$$I^{PF}(\Delta\beta) = \sum \left(p_T^{charged} + max(E_T^{\gamma} + E_T^{neutral} - 0.0729 \times E_T^{PU}, 0.0)\right)$$

- Veto for 4 lepton overlap removal
  - Rejection of the event if an additional loose e, μ or τ is found

Event selection

- Leading $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$:
  - $P_T > 20$ and 10 GeV respectively for leading and sub-leading leptons
  - $|\eta| < 2.4$ and 2.5 for μ's and e's respectively
  - Relative PF Isolation < 0.25
  - $60 < m_{Z1} < 120$ GeV/c^2
- Sub-leading $Z \rightarrow \tau_l \tau_h$:
  - $P_T > 10$ and 20 GeV respectively for τ_l and τ_h
  - $|\eta| < 2.4$ and 2.5 for τ_μ and τ_e respectively and 2.3 for τ_h
  - Relative PF Isolation < 0.15 and 0.10 for τ_μ and τ_e
  - HPS medium isolation with $\Delta\beta$ correction
  - $30 < m_{Z2} < 90$ GeV/c^2
- Sub-leading $Z \rightarrow \tau_h \tau_h$:
  - $P_T > 20$ GeV for both τ_h
  - $|\eta| < 2.3$ for both τ_h
  - HPS tight isolation with $\Delta\beta$ correction
  - $30 < m_{Z2} < 90$ GeV/c^2
- Sub-leading $Z \rightarrow \tau_l \tau_l$:
  - $P_T > 10$ GeV for both τ_l
  - $|\eta| < 2.4$ and 2.5 for τ_μ and τ_e
  - Relative PF Isolation < 0.25 for both τ_μ and τ_e
  - $0 < m_{Z2} < 90$ GeV/c^2

Reducible backgrounds estimation

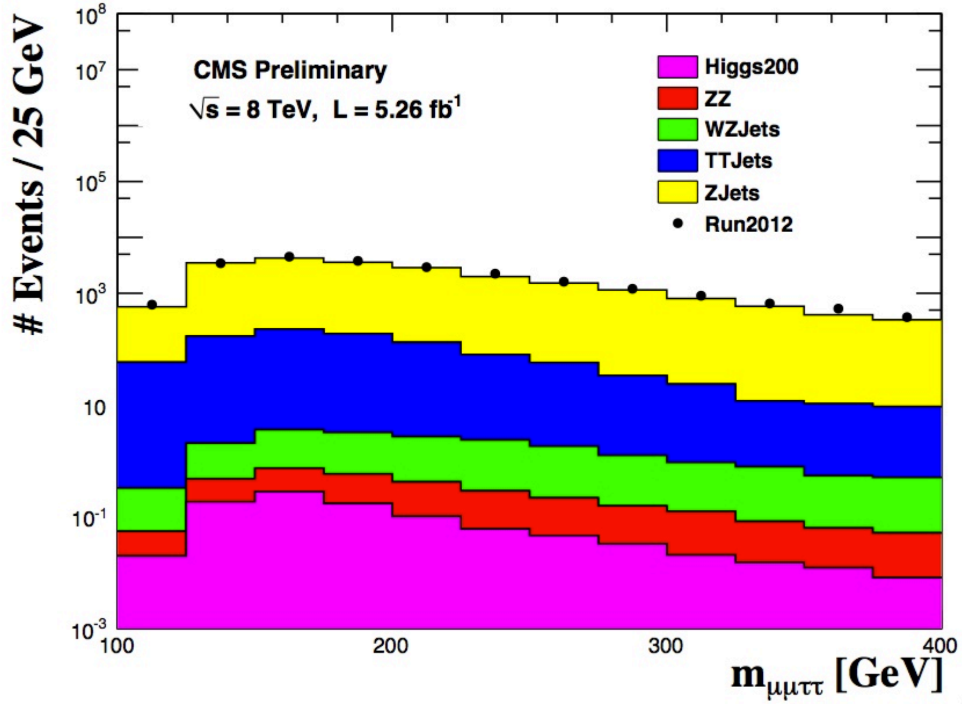
Jet to τ FR: using $\mu\mu\tau\tau$ and $ee\tau\tau$

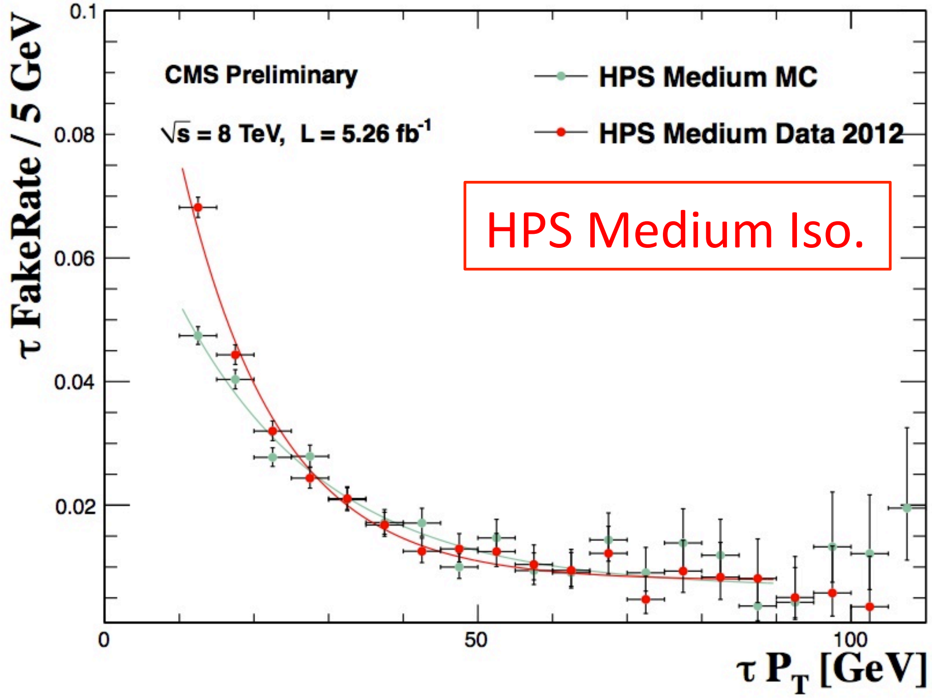
- Definition of control region:
- Same leading Z selection (as for baseline analysis)
- Sub-leading Z Selection:
  - Same charge for both τ's
  - No mass window
  - τ pT > 10 GeV and $|\eta|<2.3$
  - Decay mode, loose e and μ discrimination
  - No isolation requirement for τ
- Fake Rate (FR) = No. of jets passing τ isolation / Total jets
- FR has been measured for both HPS medium and tight Isolation.

Control region and Jet to τ FR measurement

√s=8TeV
5.26 fb-1

$\mu\mu\tau_h\tau_h$





- Fit with the function:

$$F(p_T(\tau)) = C_0 + C_1 e^{C_2 p_T(\tau)}$$

Jet to e and μ FR measurements

Using μμμτ and eeμτ for μ's
Using eeeτ and μμeτ for e's

- Definition of control region:
- Same leading Z selection (as for baseline analysis)
- Sub-leading Z Selection:
  - Same charge for e(μ) and τ
  - No mass window
  - No isolation requirement for τ and e(μ)
  - e(μ) identification and acceptance requirements
  - For WZ+Jets rejection
    - m_T (jet, PFMET) < 30 GeV and MET < 20 GeV
- FR = No. of jet passing e(μ) isolation / Total jets

FR application to signal region

- We consider two categories for background events in the signal region *(Ns)* with OS leptons from sub-leading Z:
  - Category 0: one Z + two fakeable objects
  - Category 1: one Z + one real lepton + one fakeable object

$$N_B^{Tot} = N_0.F_1.F_2 + (N_{1a} - N_0.F_2).F_1 + (N_{1b} - N_0.F_1).F_2 = N_{1a}.F_1 + N_{1b}.F_2 - N_0.F_1.F_2$$

- As an example: total estimation for μμeτ final state @ 8TeV

▪Category 0: both e and τ are anti-isolated	▪Category 1a: e is anti-Isolated and τ is isolated	▪Category 1b: e is Isolated and τ is anti-isolated
▪# Events = 198	▪# Events = 5	▪# Events = 18
▪Total estimation = 0.6	▪Total estimation = 0.88	▪Total estimation = 0.4
$N_B = \frac{N_S F_1 F_2}{1 - F_1 F_2}$	$N_B = \frac{N_S F1}{1 - F1}$	$N_B = \frac{N_S F2}{1 - F2}$

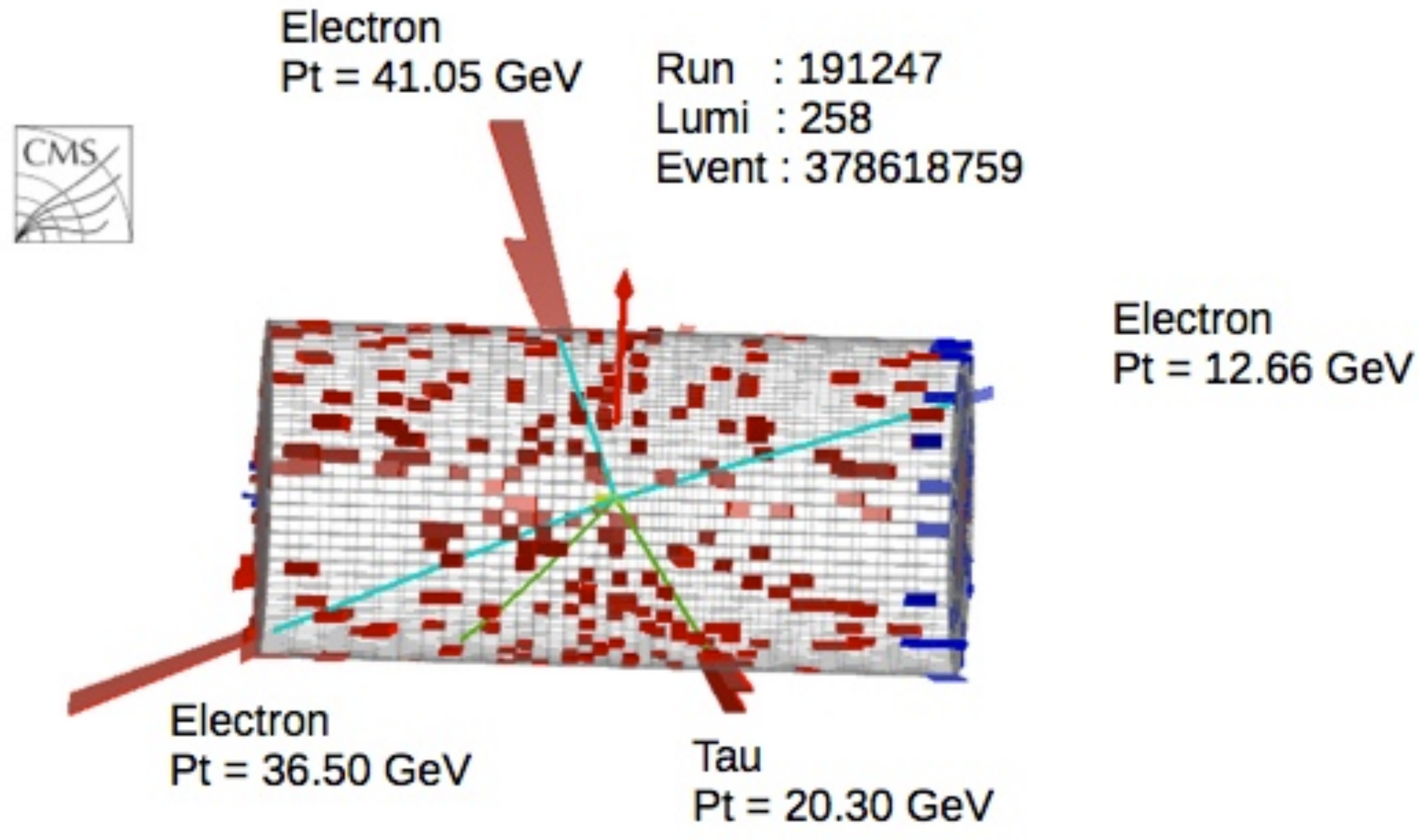
Total background = (0.88 + 0.4) – 0.6 = 0.68

Final results

5.05 fb^{-1} @ $\sqrt{s}$=7TeV + 5.26 fb^{-1} @ $\sqrt{s}$=8TeV

Decay channel	N_{ZZ}^{est}	Other backgrounds	Total backgrounds	m_H 200 ± 15 GeV	Observed
$\mu\mu\tau_h\tau_h$	1.47 ± 0.02	2.00 ± 0.30	3.47 ± 0.30	0.36 ± 0.01	2
$ee\tau_h\tau_h$	1.38 ± 0.02	1.62 ± 0.29	3.00 ± 0.29	0.33 ± 0.01	2
$ee\tau_e\tau_h$	1.58 ± 0.02	1.20 ± 0.36	2.78 ± 0.36	0.38 ± 0.01	8
$\mu\mu\tau_e\tau_h$	1.50 ± 0.02	1.25 ± 0.47	2.75 ± 0.47	0.39 ± 0.01	1
$\mu\mu\tau_\mu\tau_h$	1.96 ± 0.03	0.69 ± 0.17	2.65 ± 0.17	0.49 ± 0.01	0
$ee\tau_\mu\tau_h$	1.77 ± 0.02	0.82 ± 0.18	2.59 ± 0.18	0.45 ± 0.01	2
$ee\tau_e\tau_\mu$	1.14 ± 0.02	0.84 ± 0.41	1.98 ± 0.41	0.28 ± 0.01	2
$\mu\mu\tau_\mu\tau_e$	1.25 ± 0.02	0.47 ± 0.26	1.72 ± 0.26	0.33 ± 0.01	3
TOTAL	12.07 ± 0.06	8.89 ± 0.91	20.96 ± 0.91	3.01 ± 0.03	20

Event display



- $ee\tau_e\tau_h$ event in data @ $\sqrt{s}$ = 8TeV (Invariant mass = 200.4 GeV)

Systematic uncertainties

Systematics uncertainties common to all channels

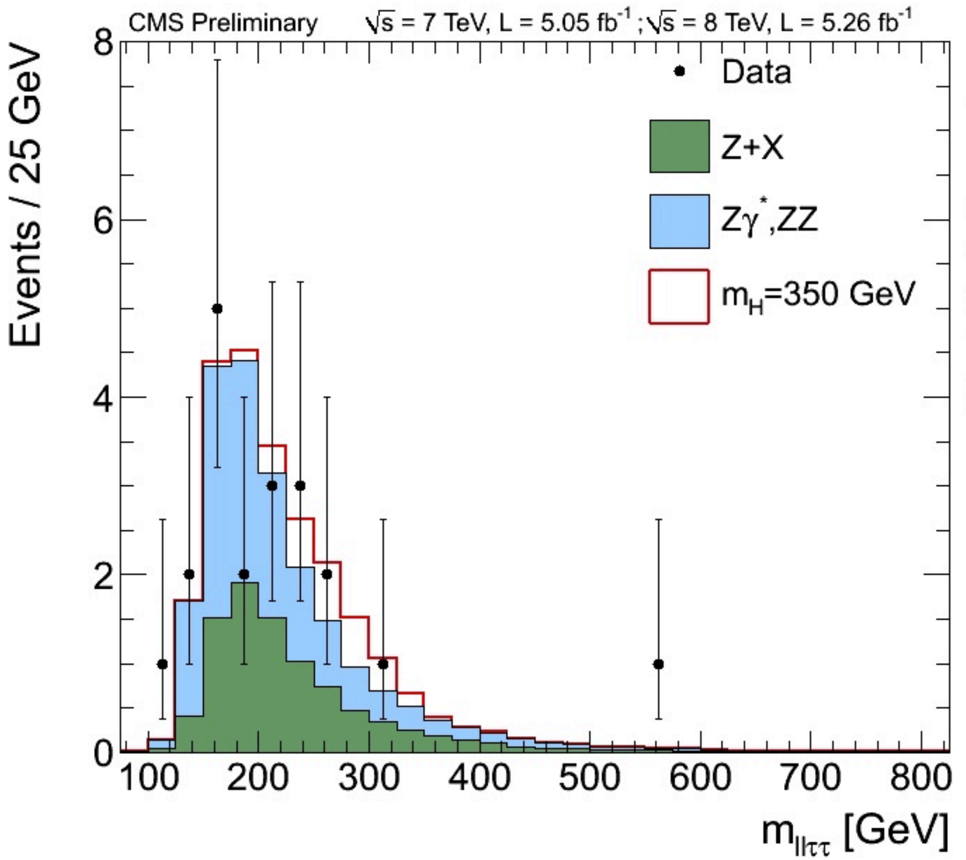
Source	Uncertainty
Luminosity measurements 2011	2.2%
Luminosity measurements 2012	5.0%
Trigger efficiency	1.5%

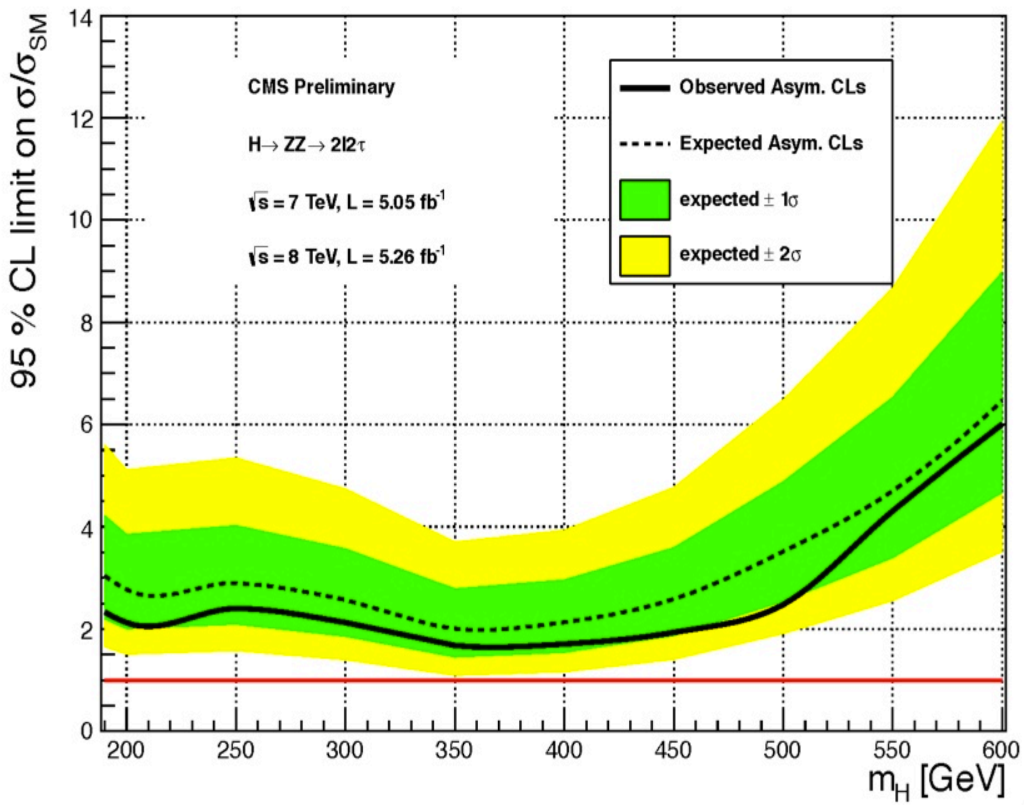
Channel specific systematic uncertainties

Channel	μ ID/Iso	e ID/Iso	τ_h ID/Iso	τ_{ES}
$\mu\mu\tau_h\tau_h$	1.01/1.01	-	1.1	1.04
$ee\tau_h\tau_h$	-	1.02/1.01	1.1	1.04
$ee\tau_e\tau_h$	-	1.04/1.02	1.06	1.03
$\mu\mu\tau_e\tau_h$	1.01/1.01	1.02/1.01	1.06	1.03
$\mu\mu\tau_\mu\tau_h$	1.02/1.02	-	1.06	1.03
$ee\tau_\mu\tau_h$	1.01/1.01	1.02/1.01	1.06	1.03
$ee\tau_e\tau_\mu$	1.01/1.01	1.04/1.02	-	-
$\mu\mu\tau_\mu\tau_e$	1.02/1.02	1.02/1.01	-	-

2l2τ mass spectrum and limits @ 95% CL

5.05 fb^{-1} @ √s=7TeV + 5.26 fb^{-1} @ √s=8TeV





- Observed limit is ~2 to 6 times the SM expectation in the range of 190 < m_H < 600 GeV

Conclusions

- $H \rightarrow ZZ \rightarrow ll\tau\tau$ analysis has been presented for (5.05 fb^{-1} @ 7 TeV + 5.26 fb^{-1} @ 8TeV) data
- No evidence found for a significant deviation from expected backgrounds
- Limit has been set @ 95 % CL for the mass range of $190 < m_H < 600$ GeV/c^2
  - ~2 to 6 times the Standard Model expectation

Back Up

Data Samples and Triggers

- Fully certified data has been processed
  - ✓ 2011(5.05 fb^{-1}) and 2012(5.26 fb^{-1})

Runs	Dataset	Primary dataset	Year
160431-173692	Run2011A-16Jan2012-v1	DoubleMu / DoubleElectron	2011
175832-180252	Run2011B-16Jan2012-v1	DoubleMu / DoubleElectron	2011
190450-193686	Run2012A-PromptReco-v1	DoubleMu / DoubleElectron	2012
193752-197044	Run2012B-PromptReco-v1	DoubleMu / DoubleElectron	2012
190782-190949	Run2012A-23May2012-v2_May23ReReco	DoubleMu /DoubleElectron	2012

- Triggers used:

HLT path	Run range	Year
$\mu\mu$ channels		
HLT_DoubleMu7	160431-163869	2011
HLT_Mu13_Mu8	165088-178380	2011
HLT_Mu17_Mu8	178420-180252	2011
HLT_Mu17_Mu8	190450-190949	2012
HLT_Mu17_TkMu8	190450-190949	2012
ee channels		
HLT_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_Ele8_CaloIdL_CaloIsoVL_TrkIdVL_TrkIsoVL	160432-180252	2011
HLT_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_Ele8_CaloIdL_CaloIsoVL_TrkIdVL_TrkIsoVL	190450-197044	2012
HLT_Ele17_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL_Ele8_CaloIdT_TrkIdVL_CaloIsoVL_TrkIsoVL	190450-197044	2012

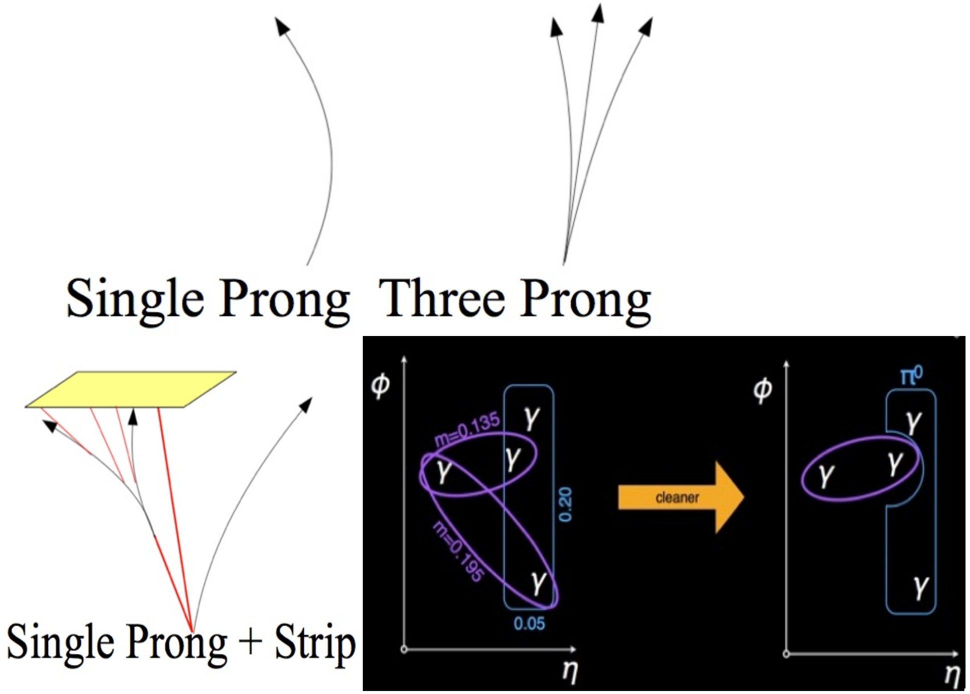
Simulation Samples

Process	MC generator	$\sigma_{(N)NLO}$ 7 TeV	$\sigma_{(N)NLO}$ 8 TeV	Comments and sample name
Higgs boson $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$				
$gg \to \mathrm{H}$	POWHEG	[1-20] fb	[1.2-25] fb	$m_{\mathrm{H}} = 110\text{-}1000\,\mathrm{GeV}/c^2$
$VV \to \mathrm{H}$	POWHEG	[0.2-2] fb	[0.3-25] fb	$m_{\mathrm{H}} = 110\text{-}1000\,\mathrm{GeV}/c^2$
ZZ continuum				
$q\bar{q} \to \mathrm{ZZ} \to 4e(4\mu, 4\tau)$	POWHEG	15.34 fb	76.91 fb	ZZTo4e(4mu,4tau)
$q\bar{q} \to \mathrm{ZZ} \to 2e2\mu$	POWHEG	30.68 fb	176.7 fb	ZZTo2e2mu
$q\bar{q} \to \mathrm{ZZ} \to 2e(2\mu)2\tau$	POWHEG	30.68 fb	176.7 fb	ZZTo2e(2mu)2tau
$gg \to \mathrm{ZZ} \to 2\ell 2\ell'$	gg2ZZ	3.48 fb	4.47 fb	GluGluToZZTo2L2L
$gg \to \mathrm{ZZ} \to 4\ell$	gg2ZZ	1.74 fb	2.24 fb	GluGluToZZTo4L
Other di-bosons				
$\mathrm{WW} \to 2\ell 2\nu$	Madgraph	4.88 pb	5.995 pb	WWTo2L2Nu
$\mathrm{WZ} \to 3\ell\nu$	Madgraph	0.868 pb	1.057 pb	WZTo3LNu
$t\bar{t}$ **and single** t				
$t\bar{t} \to \ell^+\ell^-\nu\bar{\nu}b\bar{b}$	POWHEG	17.32 pb	23.64 pb	TTTo2L2Nu2B
t (s-channel)	POWHEG	3.19 pb	3.89 pb	T_TuneXX_s-channel
$\bar{t}$ (s-channel)	POWHEG	1.44 pb	1.76 pb	Tbar_TuneXX_s-channel
t (t-channel)	POWHEG	41.92 pb	55.53 pb	T_TuneXX_t-channel
$\bar{t}$ (t-channel)	POWHEG	22.65 pb	30.00 pb	Tbar_TuneXX_t-channel
t (tW-channel)	POWHEG	7.87 pb	11.77 pb	T_TuneXX_tW-channel-DR
$\bar{t}$ (tW-channel)	POWHEG	7.87 pb	11.77 pb	Tbar_TuneXX_tW-channel-DR
Z/W + jets ($q = d, u, s, c, b$)				
W + jets	MadGraph	31314 pb	36257.2 pb	WJetsToLNu
Z + jets	MadGraph	3048 pb	3503.7 pb	DYJetsToLL
QCD inclusive multi-jets, binned p_T^{min}				
$b, c \to e + X$	PYTHIA			QCD_Pt-XXtoYY_BCtoE
EM-enriched	PYTHIA			QCD_Pt-XXtoYY_EMEnriched
MU-enriched	PYTHIA			QCD_Pt-XXtoYY_MuPt5Enriched

HPS τ algorithm

- HPS algorithm uses PF jet ($\Delta R=0.5$) and reconstruct τ decays inside jet
  - ✓ Selection of highest P_T track
  - ✓ Reconstruction of π^0 from electromagnetic particle clusters in ECAL strips
  - ✓ Associated distances for $\eta = 0.05$ & for $\Phi = 0.2$ radians
- Important aspects:
  - ✓ Strips with $E_T > 1$ GeV are considered
  - ✓ A mass constraint of (strip mass matches to π^0 mass + hadron mass) = $\rho(770)$ is applied
  - ✓ Isolation is calculated as energy sum of particles in $\Delta R=0.5$ cone
  - ✓ For PU $\Delta\beta$ correction, energy sum of particles in $\Delta R=0.8$ cone is used

Decay Mode	Branching ratio(%)
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$	17.4
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$	17.9
$\tau^- \rightarrow h^- \nu_\tau$	11.6
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	26.0
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	10.8
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	9.8
$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$	4.8
other	1.7



HPS τ Isolation and discriminators against e's and μ's

- In Isolation cone of ΔR=0.5
  - All charged particles and neutral particles with P_T > 0.5 GeV are considered
    - HPS Tight Isolation: Iso. < 0.8 GeV
    - HPS Medum Isolation: Iso. < 1 GeV
    - HPS Loose Isolation: Iso. < 2 GeV
- μ discriminator:
  - μ Loose: Leading track should not have μ chamber hits
  - μ Medium: Leading track should not match with global/ tracker μ track
  - μ Tight: μ Medium + μ should not have large energy deposits in ECAL and HCAL
- e Discrimination – Based on PF e-π MVA (ξ):
  - e Loose: $\xi < 0.6$
  - e Medium: $\xi < -0.1$ and not $1.4442 < |\eta| < 1.566$
  - e Tight: $\xi < -0.1$ and not $1.4442 < |\eta| < 1.566$ and Brem pattern cuts

τ Performance