Search for the SM Higgs Boson in $H \rightarrow ZZ \rightarrow l^+l^-\tau^+\tau^-$ Decay Channel with the CMS Experiment @ $\sqrt{s}$ = 7 and 8 TeV

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Outline

- Motivations
- H→ZZ→llττ analysis in a nutshell
- e, μ and τ identification and isolation
- Background estimation
- Results (5.1 fb^{-1} @ 7 TeV + 12.2 fb^{-1} @ 8TeV)
- Conclusions

Motivations

- Discovery of SM Higgs boson would shed light on the electroweak spontaneous symmetry breaking
- It complements the SM Higgs search in $H \rightarrow ZZ^* \rightarrow 4l$ ($l = e, \mu$) channel, the '*golden channel*' at CMS experiment
- Reasonable cross-section and branching ratios
- Strong signal and backgrounds separation power because of leptons in the final states
- Either discover or exclude!

$H \rightarrow ZZ \rightarrow ll\tau\tau$ Analysis in a Nutshell

- Signature:
  - Both Z are on mass shell: $190 < m_H < 1000$ GeV
  - Leading Z (Z1): $\mu^+\mu^-$ or e^+e^-
  - Sub-Leading Z (Z2): $\tau^+\tau^-$
  - 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:
  - Irreducible: ZZ (estimated from MC)
  - Reducible: WZ and Z associated with additional jets (estimated from data)
- Selection strategy:
  - Trigger requirement
  - Leading Z selection
  - Leptons Identification and isolation
  - Phase space requirements
  - τ discrimination against e's and μ's
  - τ isolation
- Control from data:
  - Leptons (e, μ, τ) related efficiency
  - Reducible background estimation

Event Reconstruction

- Leptons identification:
  - μ's: Particle-Flow Id
  - e's: Multivariate Analysis based Id
- Lepton isolation (both μ's and e's):
  - Relative combined PF isolation (ρ correction with effective area)

$$I_{rel}^{PF}(\rho) = \frac{\left(\sum p_T^{charged} + max(0, \sum E_T^{\gamma} + \sum E_T^{neutral} - \rho \times A_{eff})\right)}{P_T^l}$$

- Hadron Plus Strips (HPS) τ's:
  - Combined isolation with $\Delta\beta$ correction

$$I^{PF}(\Delta\beta) = \sum \left(p_T^{charged} + max(0, E_T^{\gamma} + E_T^{neutral} - f^{\Delta\beta} \times E_T^{PU})\right)$$

- Removal of overlap with 4l (l = e, μ) analysis:
  - Rejection of the event if additional loose e, μ or τ is found

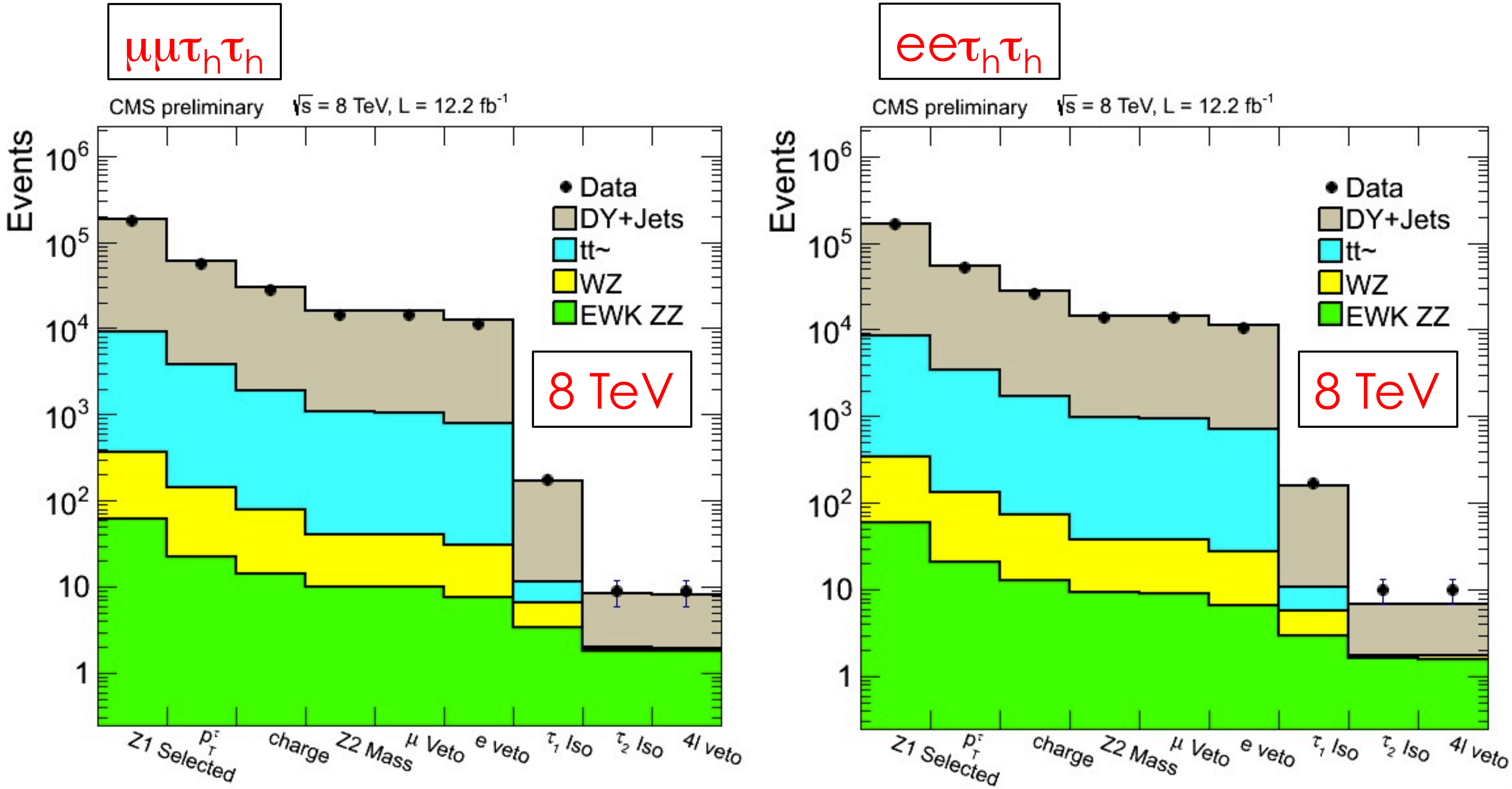
Event Selection

- Leading Z ($\rightarrow \mu^+\mu^-$ or e^+e^-) Selection:
  - p_T > 20 and 10 GeV for leading and sub-leading leptons respectively
  - Relative combined PF isolation < 0.25
  - $60 < m_{Z1} < 120$ GeV

- e: $|\eta| < 2.5$
- μ: $|\eta| < 2.4$
- τ_h: $|\eta| < 2.3$

- Sub-leading Z ($\rightarrow \tau^+\tau^-$) Selection:
  - Fully hadronic ($Z \rightarrow \tau_h^+\tau_h^-$):
    - p_T > 20 GeV for both the τ_h's
    - Tight combined isolation with $\Delta\beta$ correction
    - $30 < m_{Z2} < 90$ GeV
  - Semi leptonic ($Z \rightarrow \tau_l^+\tau_h^-$ or $\tau_l^-\tau_h^+$):
    - p_T > 20 and 10 GeV for τ_h and lepton respectively
    - Medium combined isolation with $\Delta\beta$ correction
    - Relative combined PF isolation < 0.15(0.1) for μ(e)
    - $30 < m_{Z2} < 90$ GeV
  - Fully leptonic ($Z \rightarrow \tau_l^+\tau_l^-$):
    - p_T > 10 GeV for both μ and e
    - Relative combined PF isolation < 0.25 for both μ and e
    - $0 < m_{Z2} < 90$ GeV

Cut Flow Data to MC Comparison



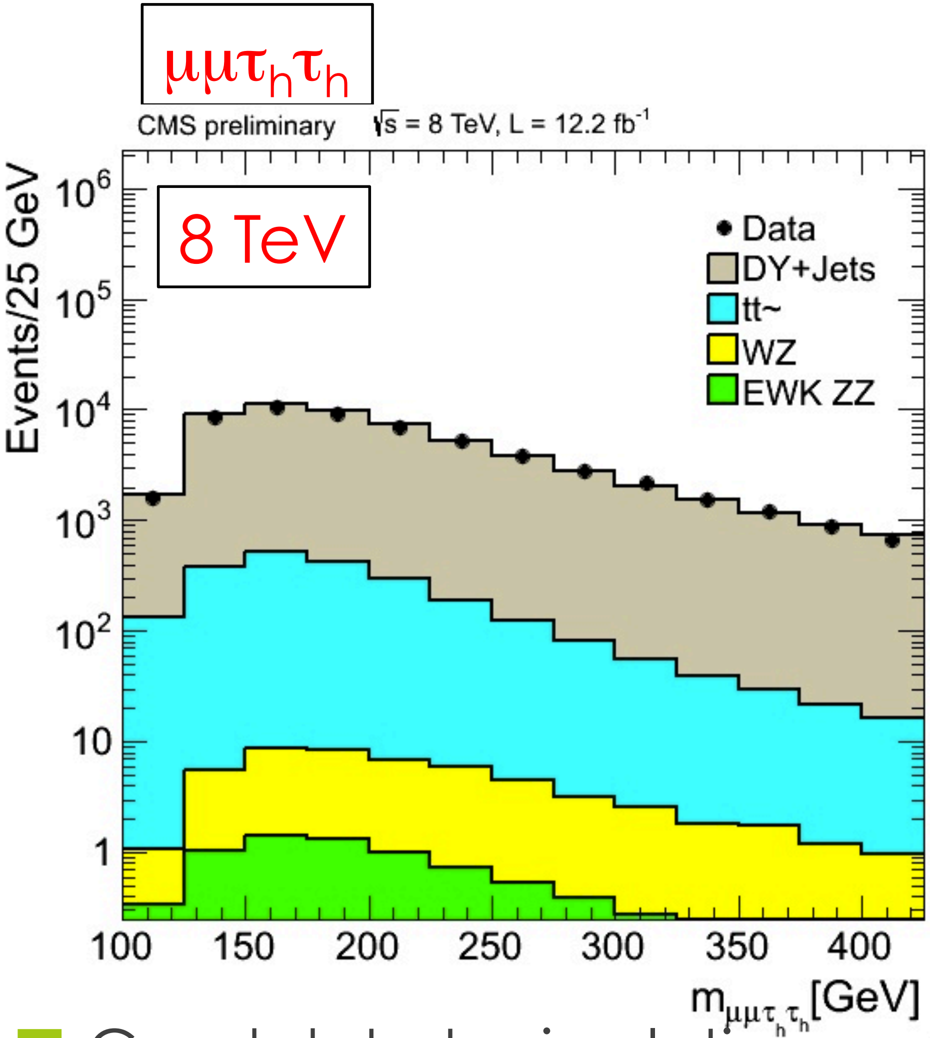
- Good data to simulation agreement is observed at each selection step

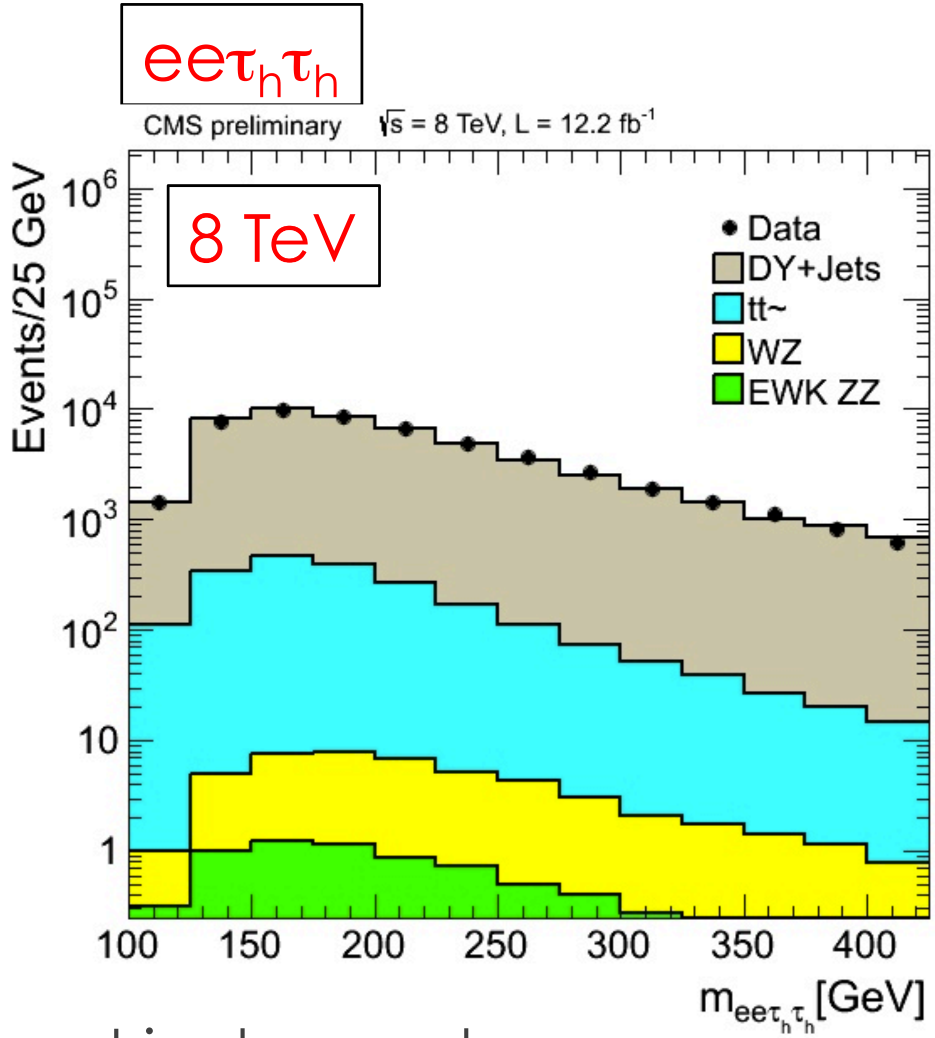
Reducible Bkg. Estimation (step I)

- Measurement of Jet → τ_h, e, μ FR In the control region defined as:
  - Leading Z: as per base-line selection
  - Sub-leading Z:
    - Same charge for the two objects
    - No mass window
    - No isolation requirement for both objects
    - FR = No. of jets passing isolation / Total no. of jets

- Measured for:
  - both τ_h working points (Tight and Medium)
  - Tight(<0.15) and Medium(<0.25) working points for μ's
  - Tight(<0.10) and Medium(<0.25) working points for e's

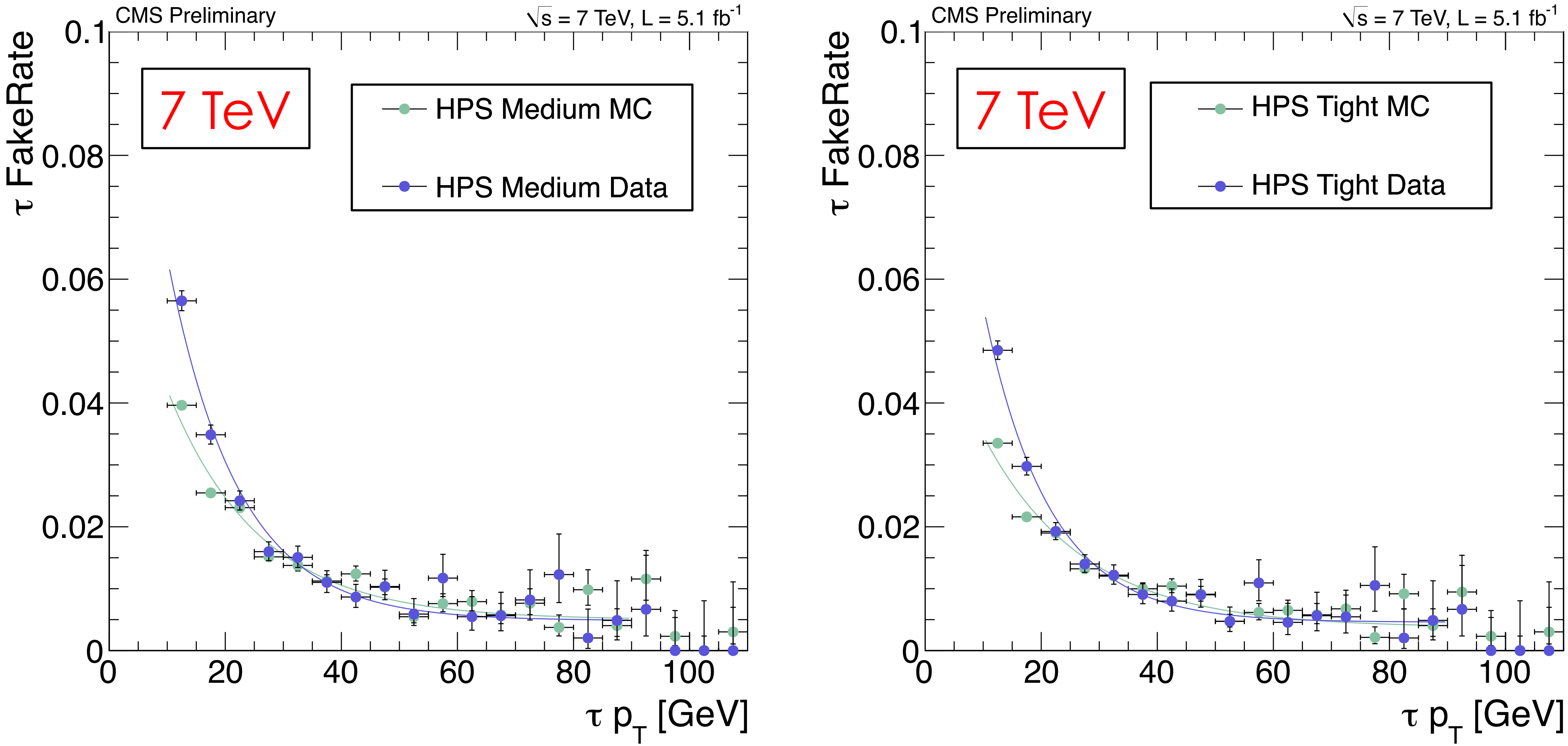
Control Regions (Jet → τ_h FR)





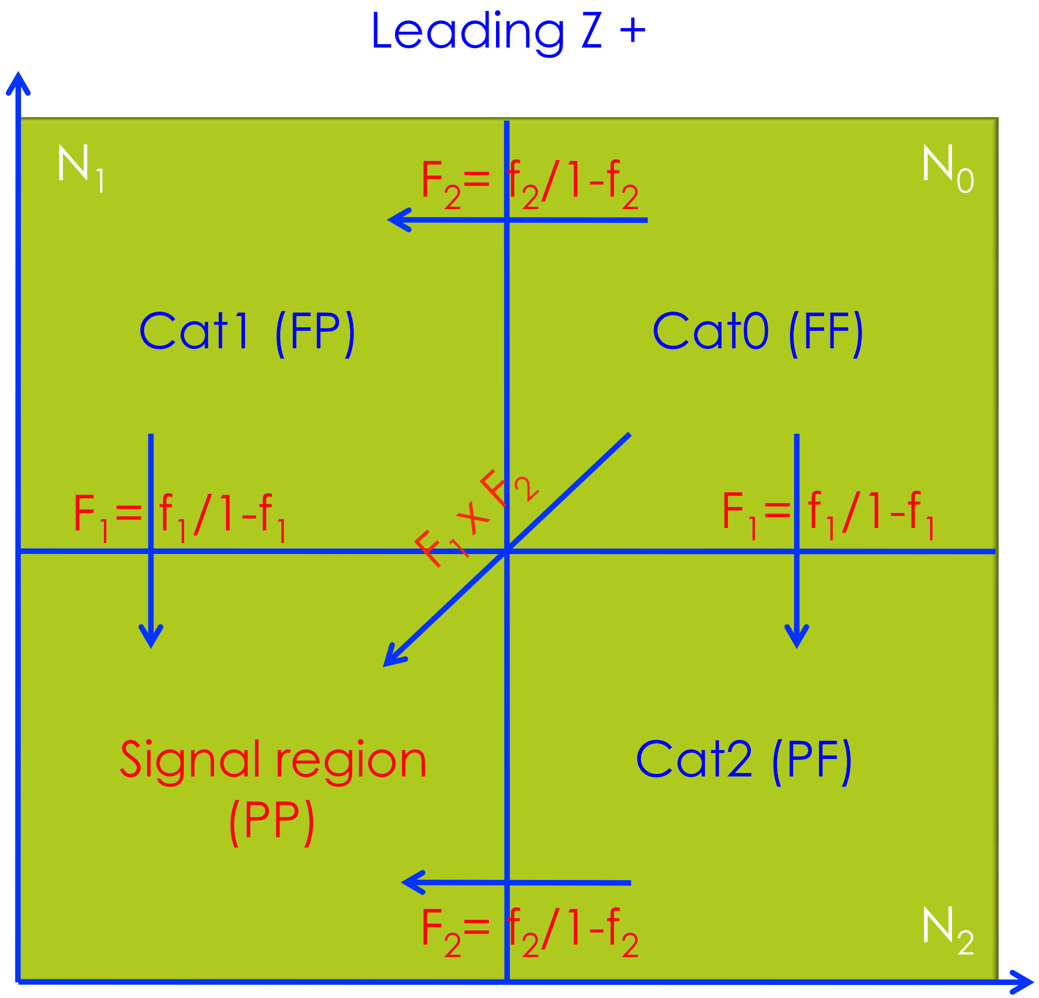
- Good data to simulation agreement is observed
- Z+jets is the dominant contribution

FR Measurements (Jet → τ_h FR)



Reducible Bkg. Estimation (step II)

- By applying the measured FR in the region defined as:
  - Leading Z: as per base-line selection
  - Sub-leading Z:
    - Opposite charge for the two objects
    - No isolation check for the two objects
- Categorization of the region:
  - Cat0: Leading Z + two fakeable objects (O_1 and O_2)
    - Both O_1 and O_2 are required to be anti-isolated
  - Cat1: Leading Z + one real object (O_2) + one fakeable object (O_1)
    - O_2 is isolated and O_1 is anti-isolated
  - Cat2: Leading Z + one real object (O_1) + one fakeable object (O_2)
    - O_1 is isolated and O_2 is anti-isolated



- Final estimation: $N_{tot}^{est} = N_0 \times F_1 \times F_2 + (N_1 - N_0 \times F_2) \times F_1 + (N_2 - N_0 \times F_1) \times F_2 = N_1 \times F_1 + N_2 \times F_2 - N_0 \times F_1 \times F_2$

Final Results

5.1 fb^{-1} @ $\sqrt{s}$ = 7 TeV + 12.2 fb^{-1} @ $\sqrt{s}$ = 8 TeV

Decay channel	N_{ZZ}^{est}	Other backgrounds	Total background	m_H 200 GeV	Observed
2012					
$\mu\mu\tau_h\tau_h$	2.40 ± 0.04	4.23 ± 0.41	6.63 ± 0.41	0.66 ± 0.02	9
$ee\tau_h\tau_h$	2.21 ± 0.04	4.65 ± 0.46	6.86 ± 0.46	0.56 ± 0.02	10
$ee\tau_e\tau_h$	2.48 ± 0.04	4.00 ± 0.95	6.48 ± 0.95	0.72 ± 0.02	11
$\mu\mu\tau_e\tau_h$	2.42 ± 0.04	2.18 ± 0.62	4.60 ± 0.62	0.72 ± 0.02	0
$\mu\mu\tau_\mu\tau_h$	3.06 ± 0.04	1.15 ± 0.36	4.21 ± 0.36	0.92 ± 0.02	2
$ee\tau_\mu\tau_h$	2.67 ± 0.04	1.48 ± 0.40	4.15 ± 0.40	0.81 ± 0.02	4
$ee\tau_e\tau_\mu$	1.70 ± 0.04	1.87 ± 0.95	3.57 ± 0.95	0.57 ± 0.02	3
$\mu\mu\tau_\mu\tau_e$	2.06 ± 0.04	0.84 ± 0.78	2.90 ± 0.78	0.60 ± 0.02	6
TOTAL	18.97 ± 0.09	20.39 ± 3.35	39.36 ± 3.35	5.56 ± 0.06	45

- Total events in data: 45
- Total bkg. expected: 39.4

Systematic Uncertainties

Systematics uncertainties common to all channels

Source	Uncertainty
Luminosity measurements 2011	2.2%
Luminosity measurements 2012	4.4%
Trigger efficiency	1.5%

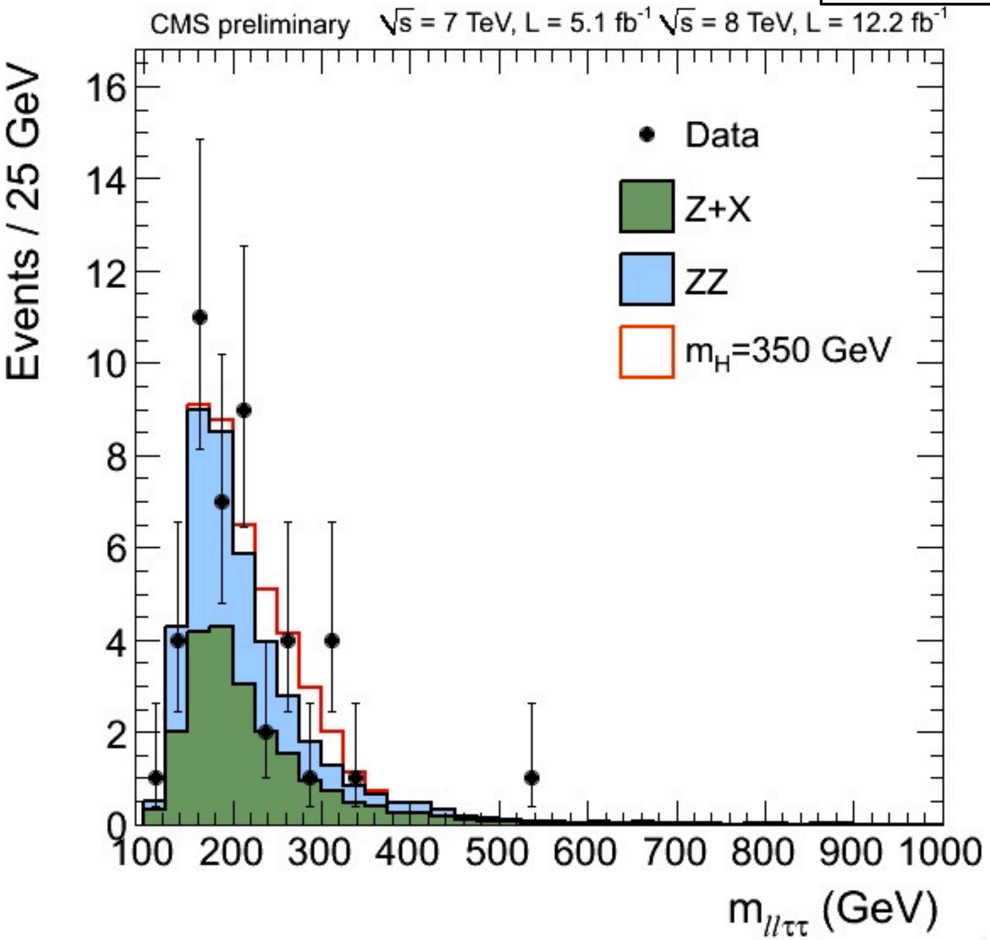
Channel specific systematic uncertainties

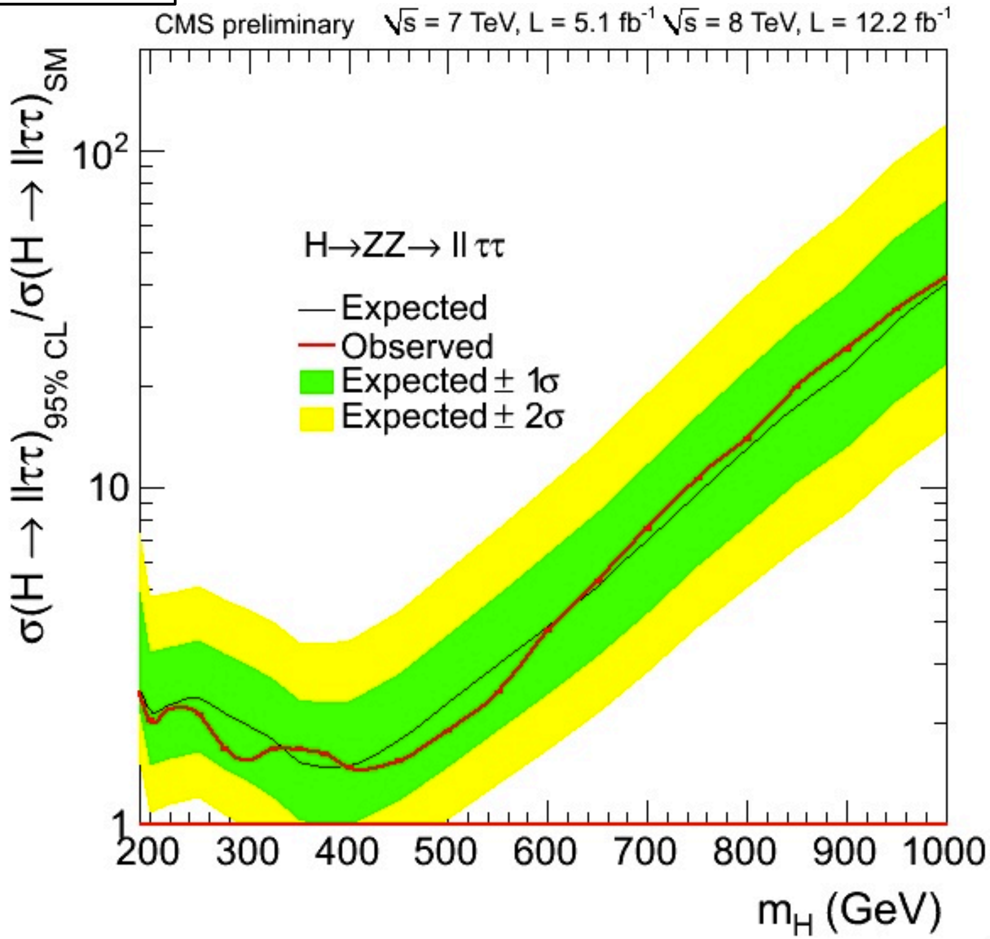
Channel	μ ID/Iso	e ID/Iso	τ_h ID/Iso	τ_{ES}
$\mu\mu\tau_h\tau_h$	1.01/1.01	-	1.1	1.04
$ee\tau_h\tau_h$	-	1.02/1.01	1.1	1.04
$ee\tau_e\tau_h$	-	1.04/1.02	1.06	1.03
$\mu\mu\tau_e\tau_h$	1.01/1.01	1.02/1.01	1.06	1.03
$\mu\mu\tau_\mu\tau_h$	1.02/1.02	-	1.06	1.03
$ee\tau_\mu\tau_h$	1.01/1.01	1.02/1.01	1.06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

- 30% Uncertainty on the reducible background estimation
  - Comes from fit uncertainty and data to MC mismatch in control regions

llττ Invariant Mass and Exclusion Upper Limits

7 + 8 TeV





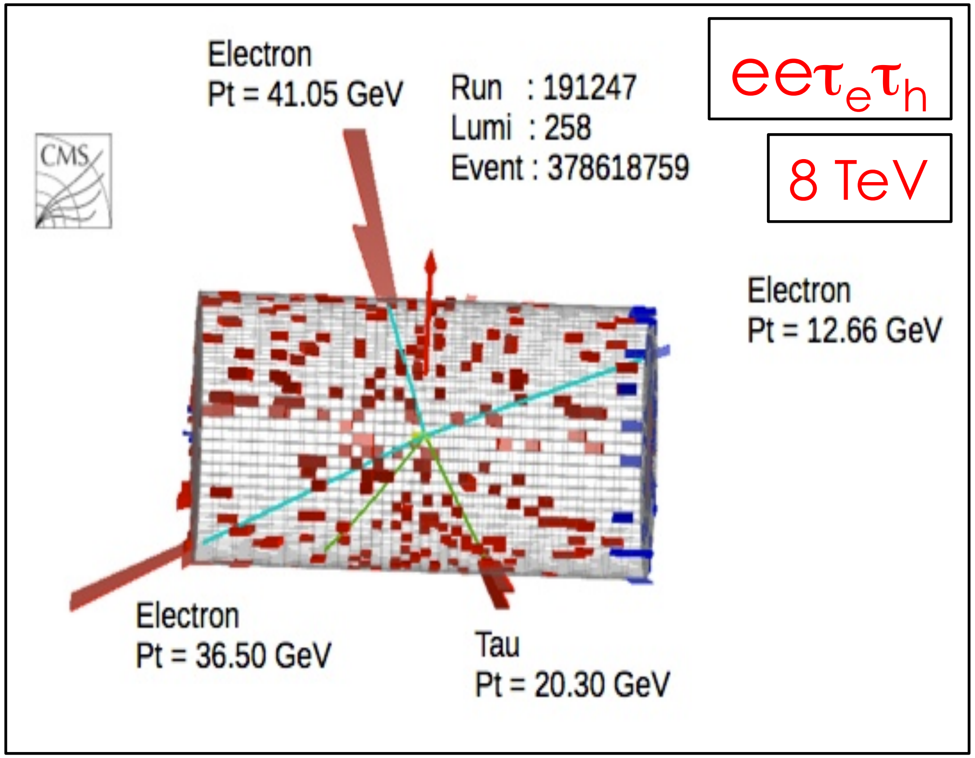
- No access of events is observed as compare to expected bkg.
- Observed limit is ~2 to 4 times the SM expectation in the range of $190 < m_H < 600$ GeV

Conclusions

- $H \rightarrow ZZ \rightarrow ll\tau\tau$ analysis has been performed for (5.1 fb^{-1} @ 7 TeV + 12.2 fb^{-1} @ 8TeV) data

- No evidence found for a significant deviation from the expected backgrounds

- Limit has been set @ 95 % CL for the mass range of 190 < m_H < 1000 GeV
  - Observed limit is ~2 to 4 times the SM expectation for 190 < m_H < 600 GeV

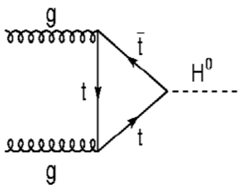


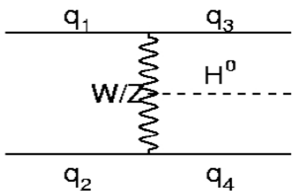
Thanks...☺

Back up

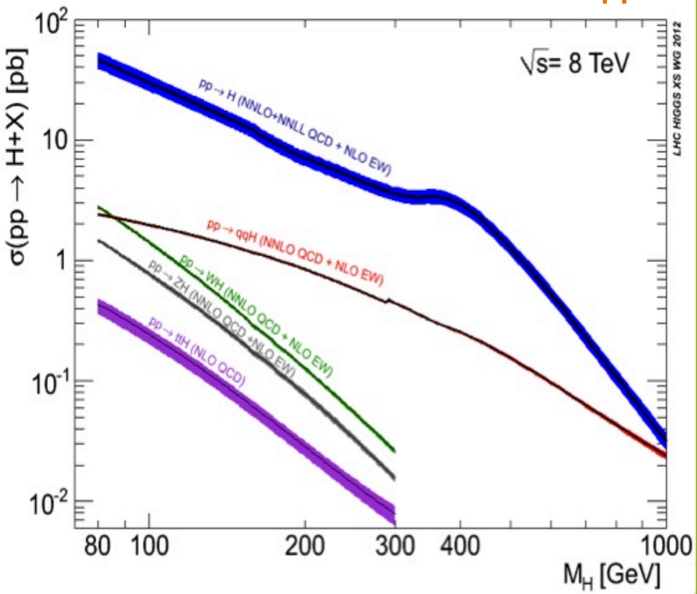
SM Higgs @ LHC

Gluon fusion: gg→H

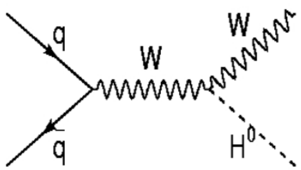


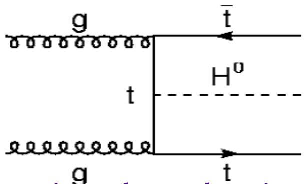


Vector Boson fusion: qqH



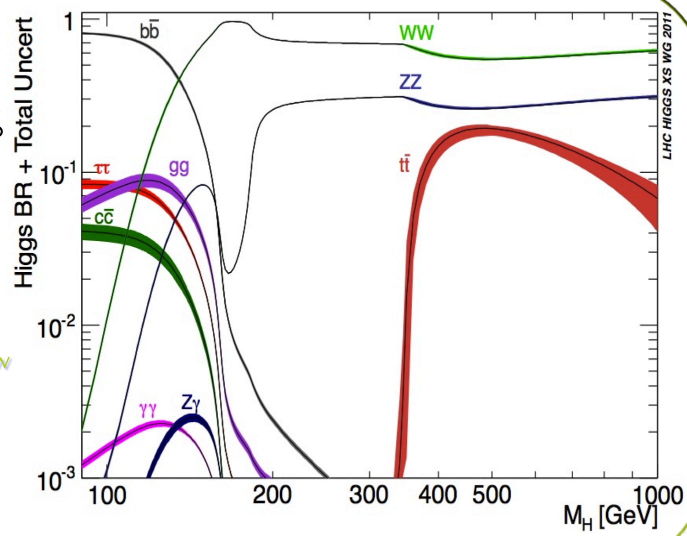
Associated production: WH, ZH





Associated production with heavy quarks: ttH

- m_H < 130 GeV:
  H→bbbar dominant; BR = 60-90%
  H→$\tau^+\tau^-$, ccbar, gg; BR = Few %
  H→$\gamma\gamma$, 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%



Data Samples and Triggers

Dataset	Primary dataset	Year
Run2011A-16Jan2012-v1	DoubleMu / DoubleElectron	2011
Run2011B-16Jan2012-v1	DoubleMu / DoubleElectron	2011
Run2012A-13Jul2012-v1	DoubleMu / DoubleElectron	2012
Run2012B-13Jul2012-v1	DoubleMu / DoubleElectron	2012
Run2012C-PromptReco-v2	DoubleMu / DoubleElectron	2012
Run2012C-PromptReco-v1	DoubleMu / DoubleElectron	2012

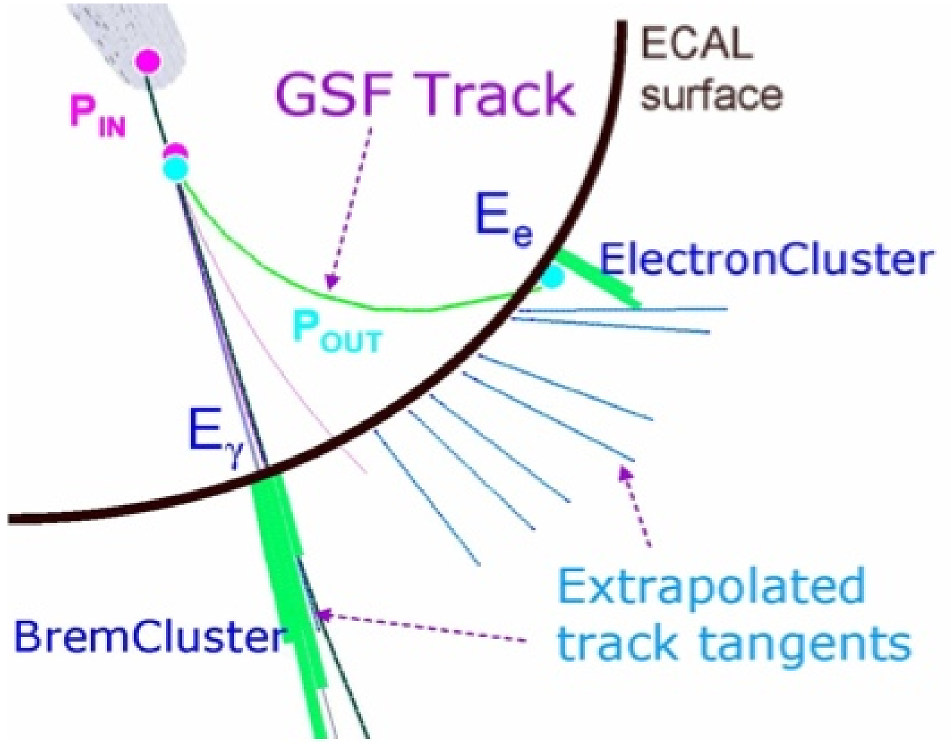
HLT path	Run range	Year
μμ channels		
HLT_DoubleMu7	160431-163869	2011
HLT_Mu13_Mu8	165088-178380	2011
HLT_Mu17_Mu8	178420-180252	2011
HLT_Mu17_Mu8	190450-203002	2012
HLT_Mu17_TkMu8	190450-203002	2012
ee channels		
HLT_Ele17_CaloIdT_CaloIsoVL_TrkIdVL_TrkIsoVL_ Ele8_CaloIdL_CaloIsoVL_TrkIdVL_TrkIsoVL	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	190450-203002	2012

MC Samples

Process	MC generator	$\sigma_{(N)NLO}$ 7 TeV	$\sigma_{(N)NLO}$ 8 TeV	Comments and sample name
Higgs boson $H \to ZZ \to 4\ell$				
$gg \to H$	POWHEG	[1-20] fb	[1.2-25] fb	$m_H = 110\text{-}1000\,GeV/c^2$
$VV \to H$	POWHEG	[0.2-2] fb	[0.3-25] fb	$m_H = 110\text{-}1000\,GeV/c^2$
ZZ continuum				
$q\bar{q} \to ZZ \to 4e(4\mu,4\tau)$	POWHEG	15.34 fb	76.91 fb	ZZTo4e(4mu,4tau)
$q\bar{q} \to ZZ \to 2e2\mu$	POWHEG	30.68 fb	176.7 fb	ZZTo2e2mu
$q\bar{q} \to ZZ \to 2e(2\mu)2\tau$	POWHEG	30.68 fb	176.7 fb	ZZTo2e(2mu)2tau
$gg \to ZZ \to 2\ell2\ell'$	gg2ZZ	9.74 fb	12.03 fb	GluGluToZZTo2L2L
$gg \to ZZ \to 4\ell$	gg2ZZ	3.85 fb	4.80 fb	GluGluToZZTo4L
Other di-bosons				
$WW \to 2\ell2\nu$	Madgraph	4.88 pb	5.995 pb	WWTo2L2Nu
$WZ \to 3\ell\nu$	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

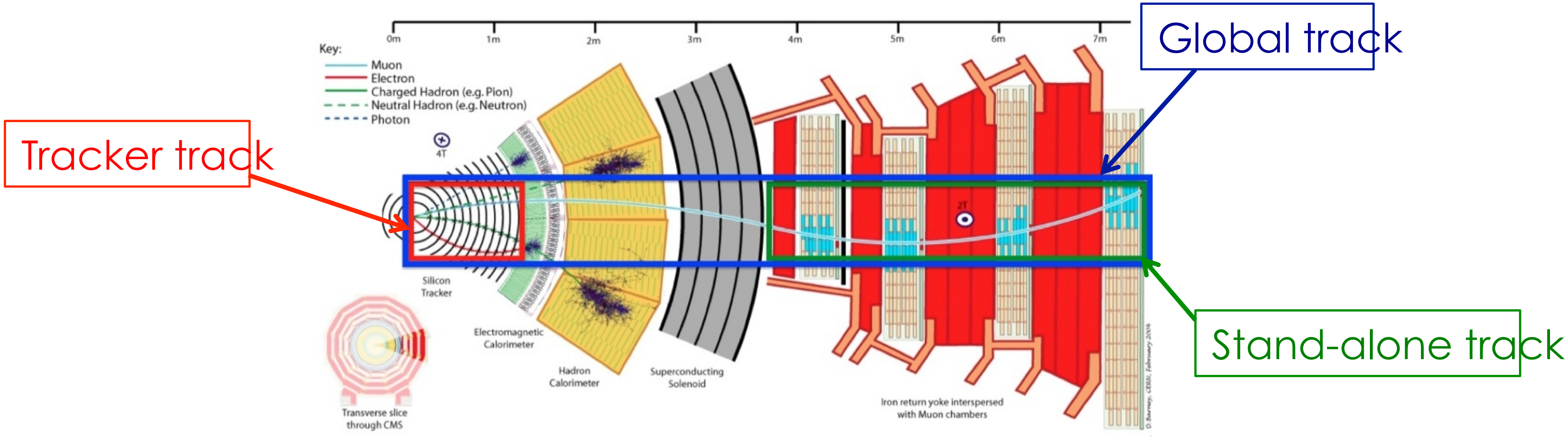
e reconstruction

- ECAL driven seeding:
  - Starts from super-cluster: energy collected in ϕ due to bramsstrahlung (ET > 4GeV)
  - GSF fit to cope with change in curvature: leads to hit collection upto ECAL
- Tracker driven seeding:
  - Starts from very first hit in tracker and estimate the brem-cluster
  - Do the same for all hits
  - It increases the efficiency at low p_T
- Energy correction:
- A weighted combination of E and p from ECAL and Tracker information
- ECAL information obtained by technique, such as in $H \rightarrow \gamma\gamma$



μ reconstruction

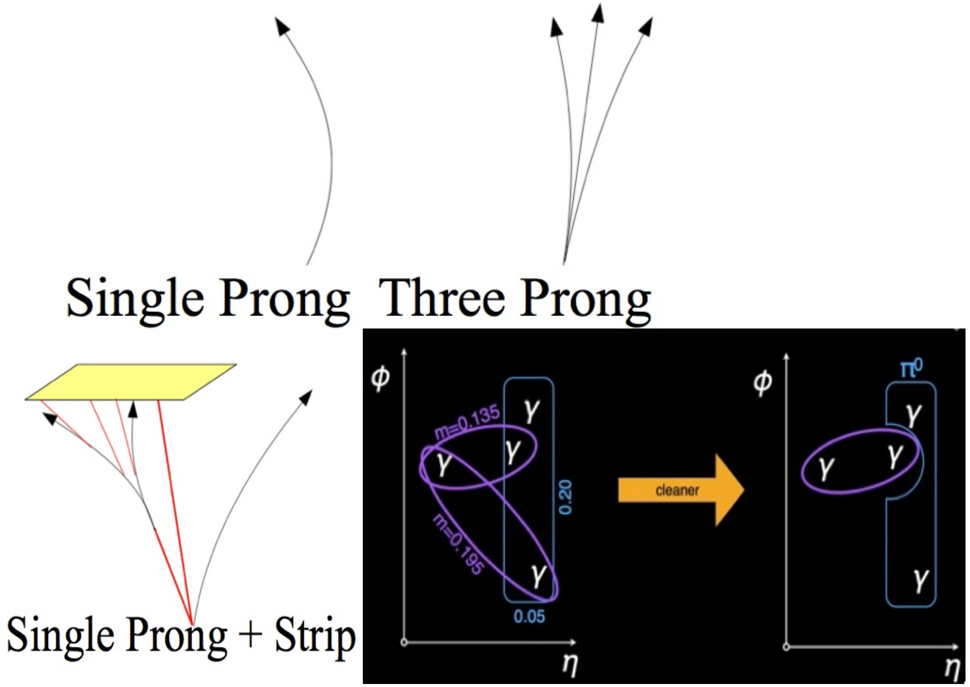
- Built tracker track (in tracker) and stand-alone track (in muon system)
- Global μ (Outside-in): a tracker track find out by comparing the track parameters at a common surface.
  - A global track is then fit with tracker hits from tarcker track and stand-alone track
- Tracker μ (inside-out): it starts with all the possible tracker tracks with p_T > 0.5 GeV and if we find a μ segment we declare it the tracker μ.



HPS τ_h 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 ΔR=0.5 cone
  - ✓ For PU $\Delta\beta$ correction, energy sum of particles in ΔR=0.8 cone is used

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



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

- In Isolation cone of $\Delta R = 0.5$
  - All charged particles and neutral particles with $P_T > 0.5$ GeV are considered
    - HPS Tight Isolation: Iso. < 0.8 GeV
    - HPS Medium 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 DiscrimHiggs Hunting Workshop, July 18–20, 2012ination – 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

ZZ Estimation

- Estimated from simulation

Decay channel	N_{ZZ}^{est} (2011)	N_{ZZ}^{est} (2012)
	7 TeV	8 TeV
$\mu\mu\tau_h\tau_h$	0.68 ± 0.02	1.72 ± 0.03
$ee\tau_h\tau_h$	0.63 ± 0.02	1.58 ± 0.03
$ee\tau_e\tau_h$	0.71 ± 0.02	1.77 ± 0.03
$\mu\mu\tau_e\tau_h$	0.68 ± 0.02	1.74 ± 0.03
$\mu\mu\tau_\mu\tau_h$	0.92 ± 0.02	2.14 ± 0.03
$ee\tau_\mu\tau_h$	0.82 ± 0.02	1.85 ± 0.03
$ee\tau_e\tau_\mu$	0.53 ± 0.02	1.17 ± 0.03
$\mu\mu\tau_\mu\tau_e$	0.59 ± 0.02	1.47 ± 0.03
TOTAL	5.55 ± 0.05	13.42 ± 0.07