A Search for Higgs to Hadronic Taus Produced in Association with W Boson

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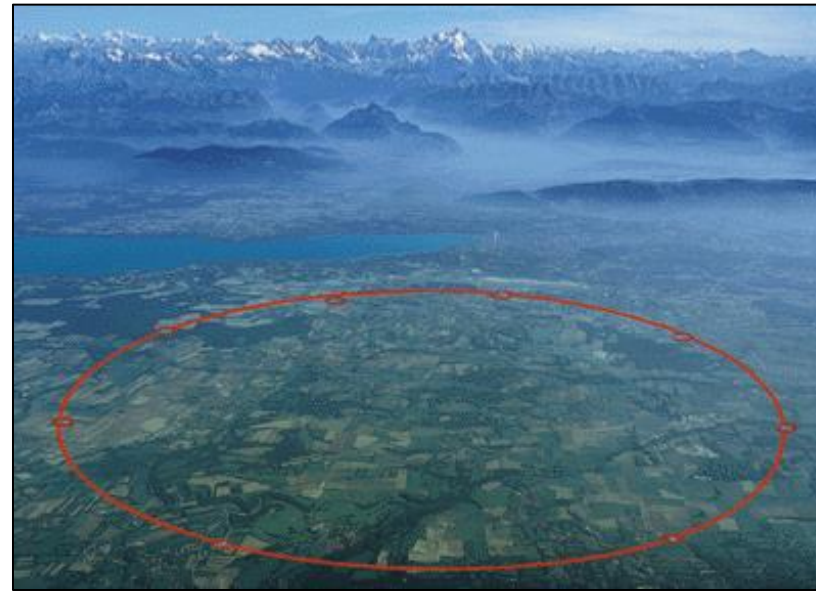
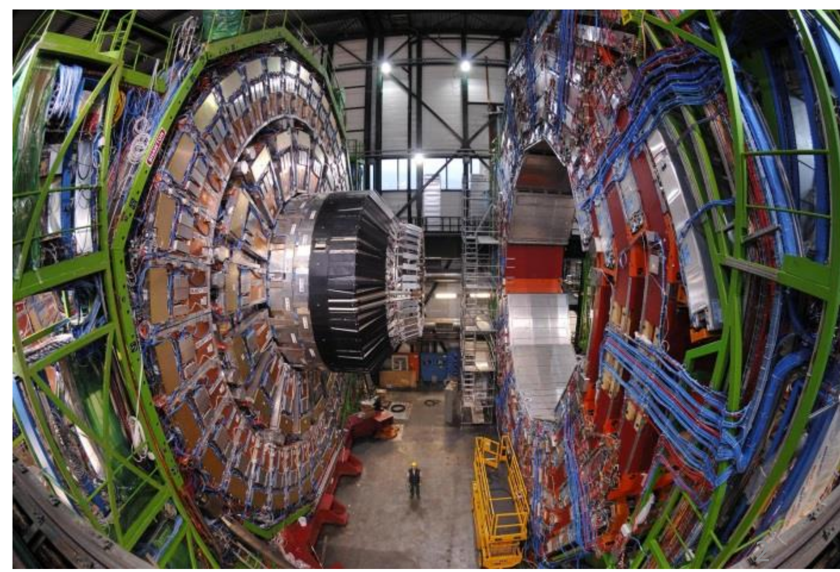
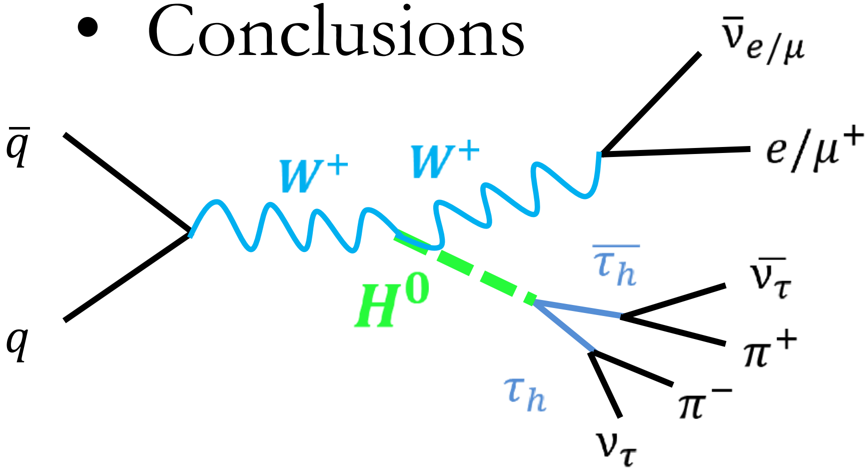
Talk Outline

- Standard Model and Higgs Boson
- Searching for Higgs
- Compact Muon Solenoid Experiment (CMS)
- Analysis Details
- Results
- Conclusions







The Standard Model

- The standard model of particle physics is a physical theory which describes fundamental particles and their interactions
  - SU(3)×SU(2)×U(1) gauge theory
  - 6 quarks
  - 6 leptons
  - 4 gauge bosons
- Huge success in explaining many experimental results
- There are/were still problems
  - Does not incorporate gravity
  - Cannot explain neutrino mass
  - No dark matter or energy candidate
  - Needed Higgs boson (or something like it)

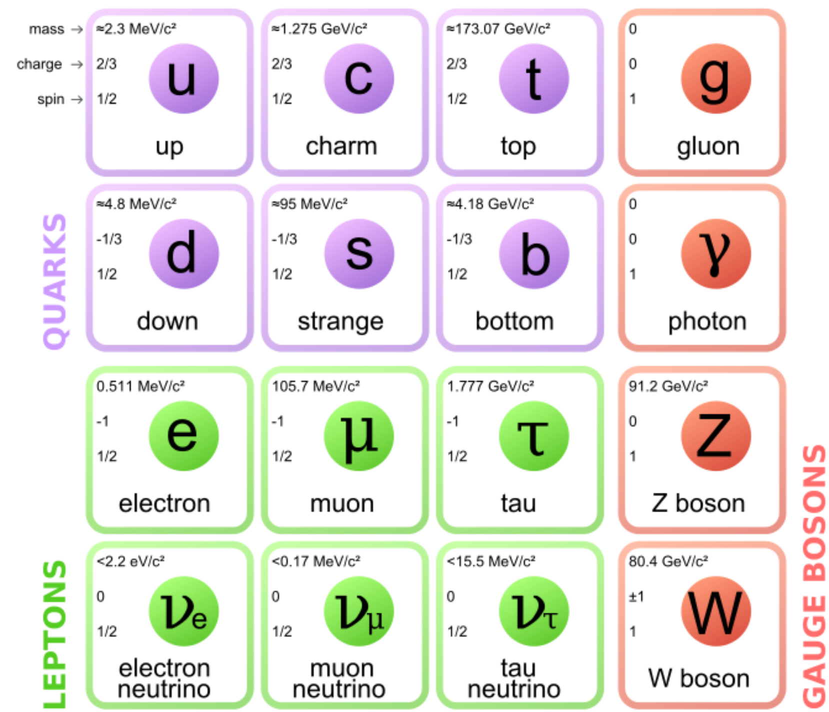
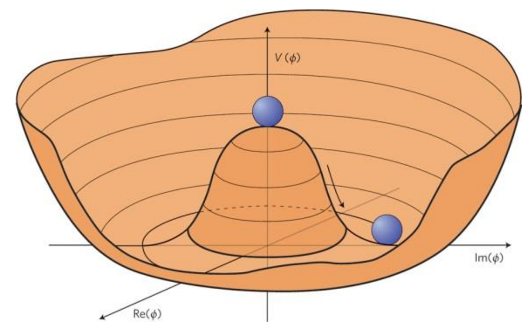


Image courtesy of http://en.wikipedia.org/wiki/Standard_Model

The Higgs

- In 1962, a mechanism to give particles mass was proposed by Peter Warren Anderson in the context of superconductivity
- In 1964, the relativistic theory was proposed by three independent groups
  - Brout and Englert
  - Guralnik, Hagen and Kibble
  - Higgs

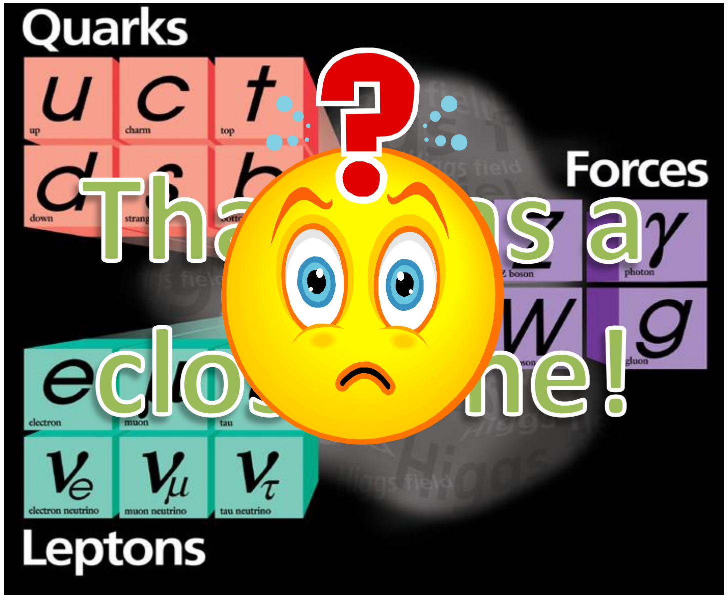


- Introduces a scalar field with a *mexican hat* potential (non-zero VEV!) to the SM Lagrangian
  - Gives rise to particle masses at low enough temperatures via spontaneous symmetry breaking: **Higgs Mechanism**
  - Requires a new particle: **Higgs Boson**
    - Its mass is a free parameter in the SM

Image courtesy of http://www.nature.com/nphys/journal/v7/n1/fig_tab/nphys1874_F1.html

The Search for the Higgs Boson

- As of 2012, there was no experimental evidence of the Higgs Boson
  - Large Electron-Positron Collider (LEP)
    - Excluded M_H under 114.4 GeV/c^2
  - Tevatron
    - Excluded M_H from 147 - 180 GeV/c^2

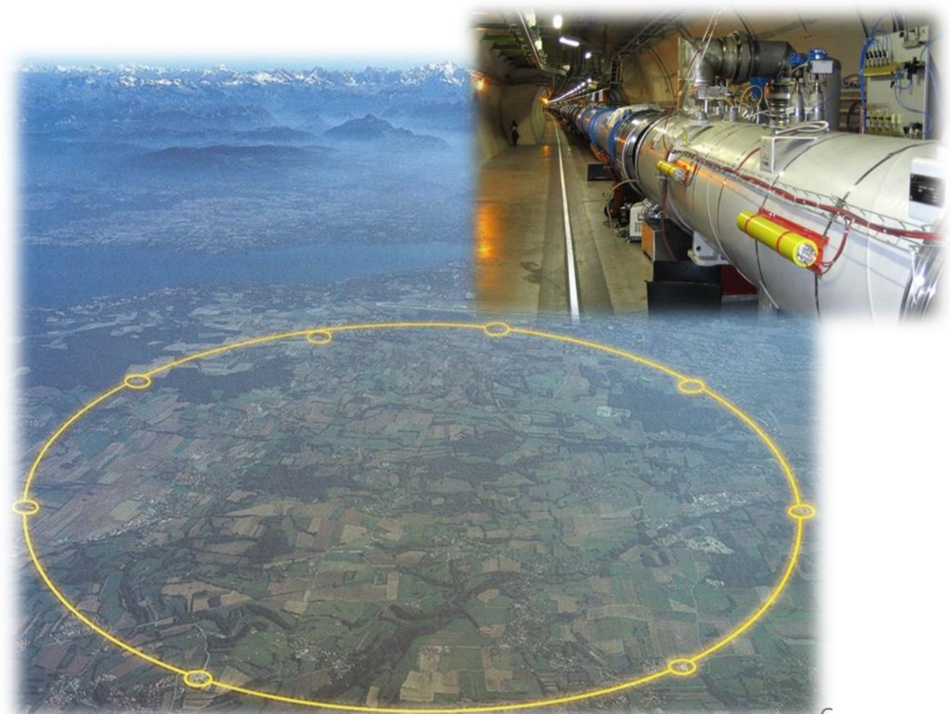


- Announcement of discovery of a Higgs-like particle with mass of 125 GeV/c^2 by the CMS and ATLAS experiments at the LHC on July 4, 2012

Image courtesy of SLAC Infomedia Services

The Large Hadron Collider (LHC)

- To search for a particle like Higgs, one option is to try and produce them in high energy collisions
- The LHC is one such machine which can do just that
  - Collides proton bunches at enormous rates and energies to produce new particles

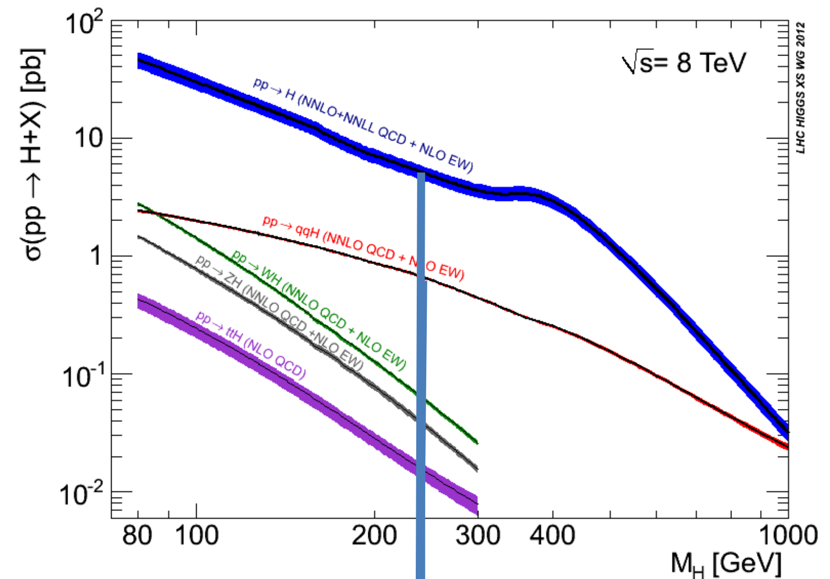


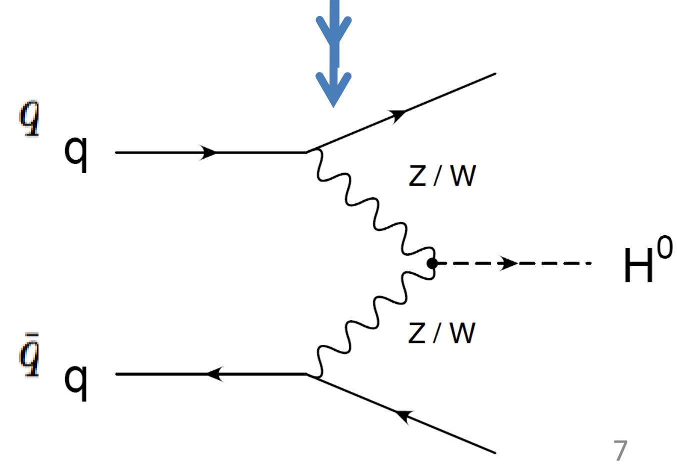
- Near Geneva, Switzerland on the Swiss-French border
- 27 km circumference
- 175 m underground
- Designed for 14 TeV pp collisions
- 7/8TeV collisions in 2011/2012
- 5/19.7fb^{-1} integrated luminosity in 2011/2012

Images courtesy of http://www.darkroastedblend.com/2008/03/time-machine-worlds-biggest-particle.html

Producing Higgs

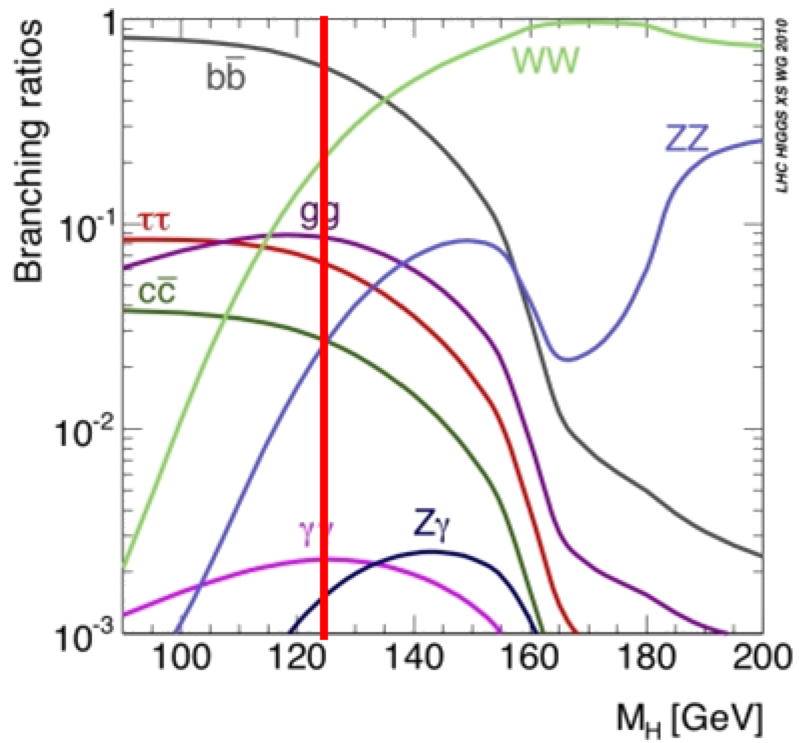
- In a proton collider like LHC, there are several ways for this to happen
  - Gluon-gluon fusion
  - Vector-boson fusion
  - Associated production
    - Particles from W/Z decays provide additional handles
    - Can measure coupling to vector bosons
  - $t\bar{t}$ fusion





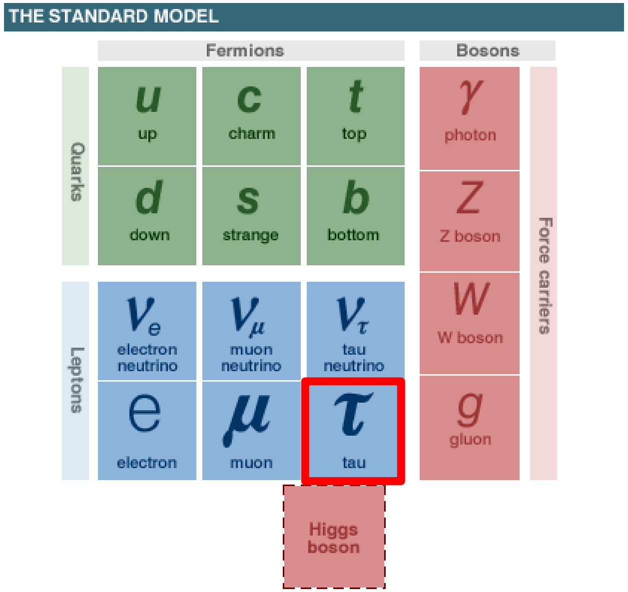
Higgs to Tau Tau

- Producing Higgs is only half of the story
  - Higgs itself quickly decays in many different channels
- At 125 GeV/c^2, the di-tau mode is one of the most important
  - High branching ratio
  - Significantly lower background than **$b\bar{b}$, gg**
- Measuring cross section in as many production modes and decay channels as possible is extremely important



Properties of Taus

- Mass = 1.77 GeV/c^2
- Lifetime = 2.9×10^{-13} seconds
  - Decay length ~ 10^{-4} meters
- Decays to light leptons ~35%
- Decay to hadrons ~65%
  - 1-Prong decays ~85%:
    - $\tau^\pm \to \pi^\pm \nu_\tau$
    - $\tau^\pm \to \pi^\pm \pi^0 \nu_\tau$
  - 3-Prong decays ~15%:
    - $\tau^\pm \to \pi^\pm K_s \to \pi^\pm \pi^\pm \pi^\pm \nu_\tau$
  - 5-Prong and more < 1%
  - These types of decays are **easily faked by jets**



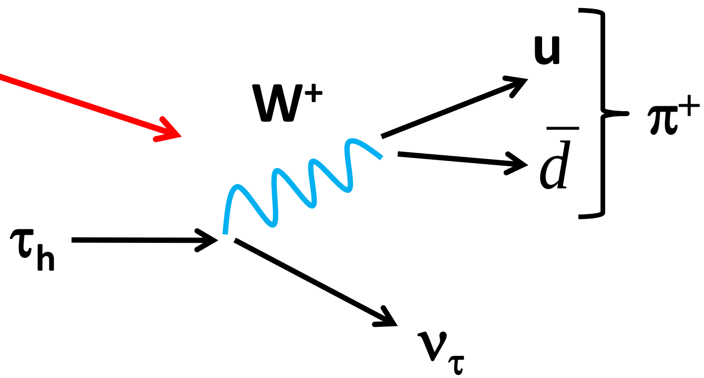
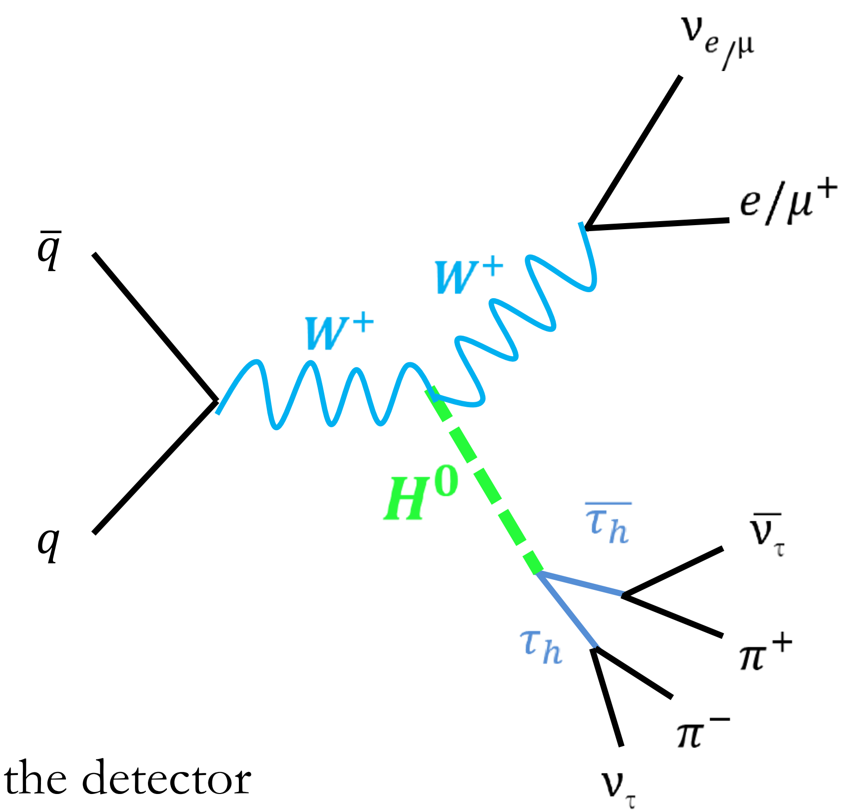


Image of Standard Model courtesy of http://news.bbc.co.uk/2/hi/science/nature/4862112.stm

Our Analysis: WH → $\ell\tau_h\tau_h$

- Putting everything together, we are searching for:
  - Production of **Higgs** in association with **W boson**
  - W to a **light lepton** (e/μ)
    - Separate analyses
  - Higgs to **two hadronic taus**
  - Effective σ ~ **2 fb**
    - $M_H = 125\ \mathrm{GeV}/c^2$
- **Signature:**
  - 1 high p_T light lepton
  - + 2 high p_T hadronic taus
  - + 3 high p_T neutrinos
    - Manifest as energy imbalance in the detector

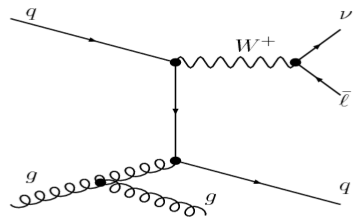
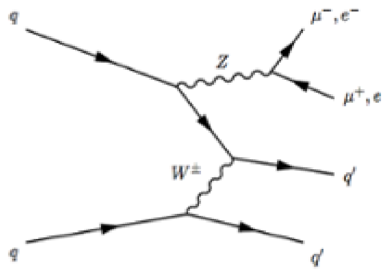
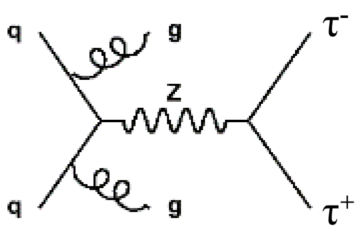
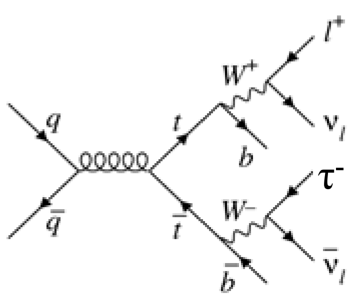


- **Caveat**: There are other processes with signatures similar to ours which are produced at much higher rates: **Backgrounds**

Not so fast?...

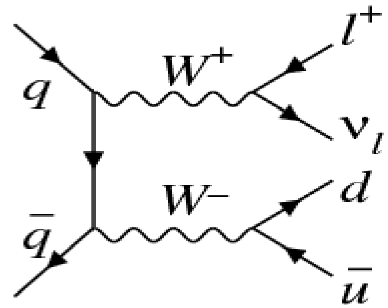
Backgrounds

- *Reducible* backgrounds are those with fake taus

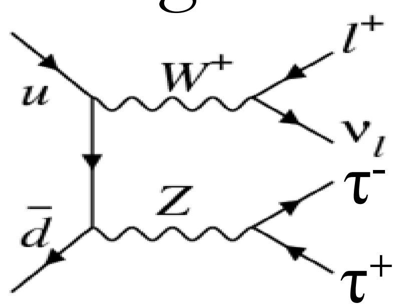
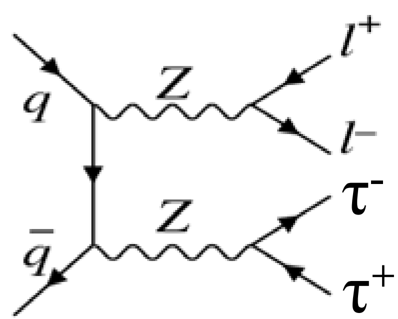
W+N Jets (N = 2,3,4…)		Lepton from W decay. Both taus faked by jets σ ~ 300 pb
Z → ee/μμ + N Jets (N = 1,2,3 …)		Lepton from one leg of Z decay. One tau faked by additional lepton (opposite sign to lepton), one tau faked by recoil jet (same sign to lepton) σ ~ 1000 pb
Z → ττ + N Jets (N = 1,2,3 …)		Lepton from one leptonic decay of one tau. One real hadronic tau (opposite sign to lepton), one tau faked by recoil jet (same sign to lepton) σ ~ 500 pb
$t\bar{t}$		Lepton from W decay. Multiple ways to get the taus (1 tau + 1 jet, 2 jets). σ ~ 20 pb

Backgrounds

- *Reducible* backgrounds continued…

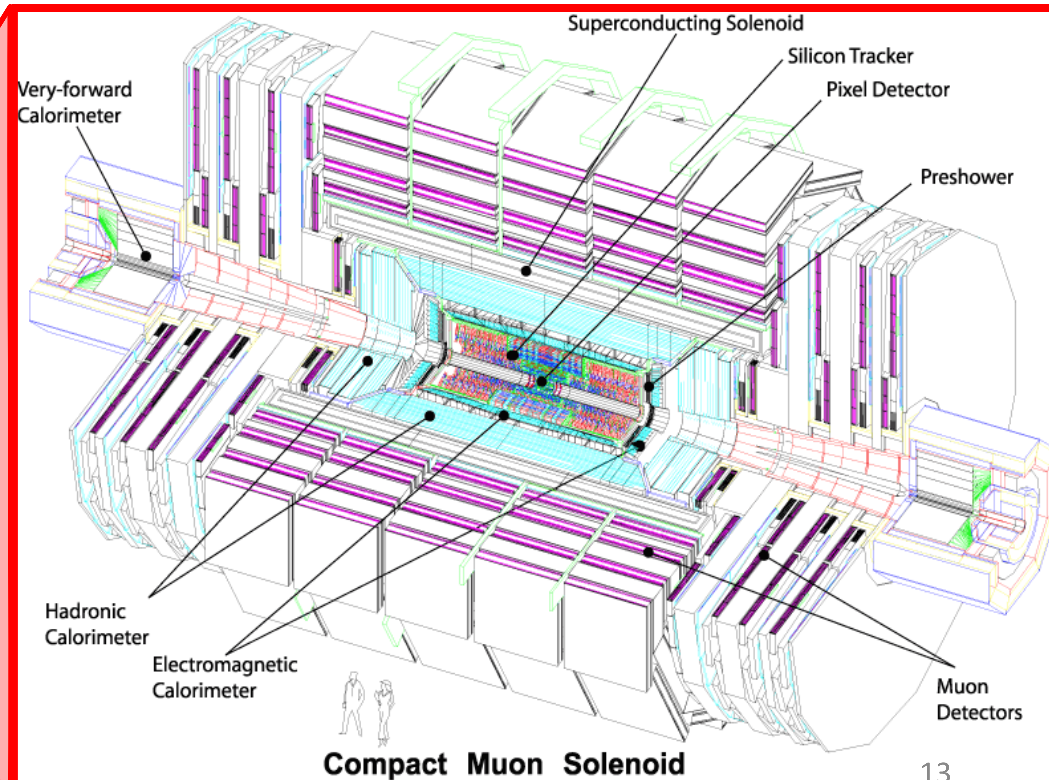
WW		Lepton from W decay. One or both tau candidates come from jets σ ~ 10 pb

- *Irreducible* backgrounds are those with real taus

WZ		Final states identical to our signal. **Very hard background to reduce** σ ~ 50 fb
ZZ		Lepton from one Z decaying to di-leptons. Two hadronic taus from of Z decaying to di-taus. σ ~ 20 fb

The Compact Muon Solenoid (CMS)

- To looks for final states like this, we use massive detectors surrounding the proton interaction point
- CMS is one such detector
  - One of two flagship experiments along the ring of the LHC



CMS Layout

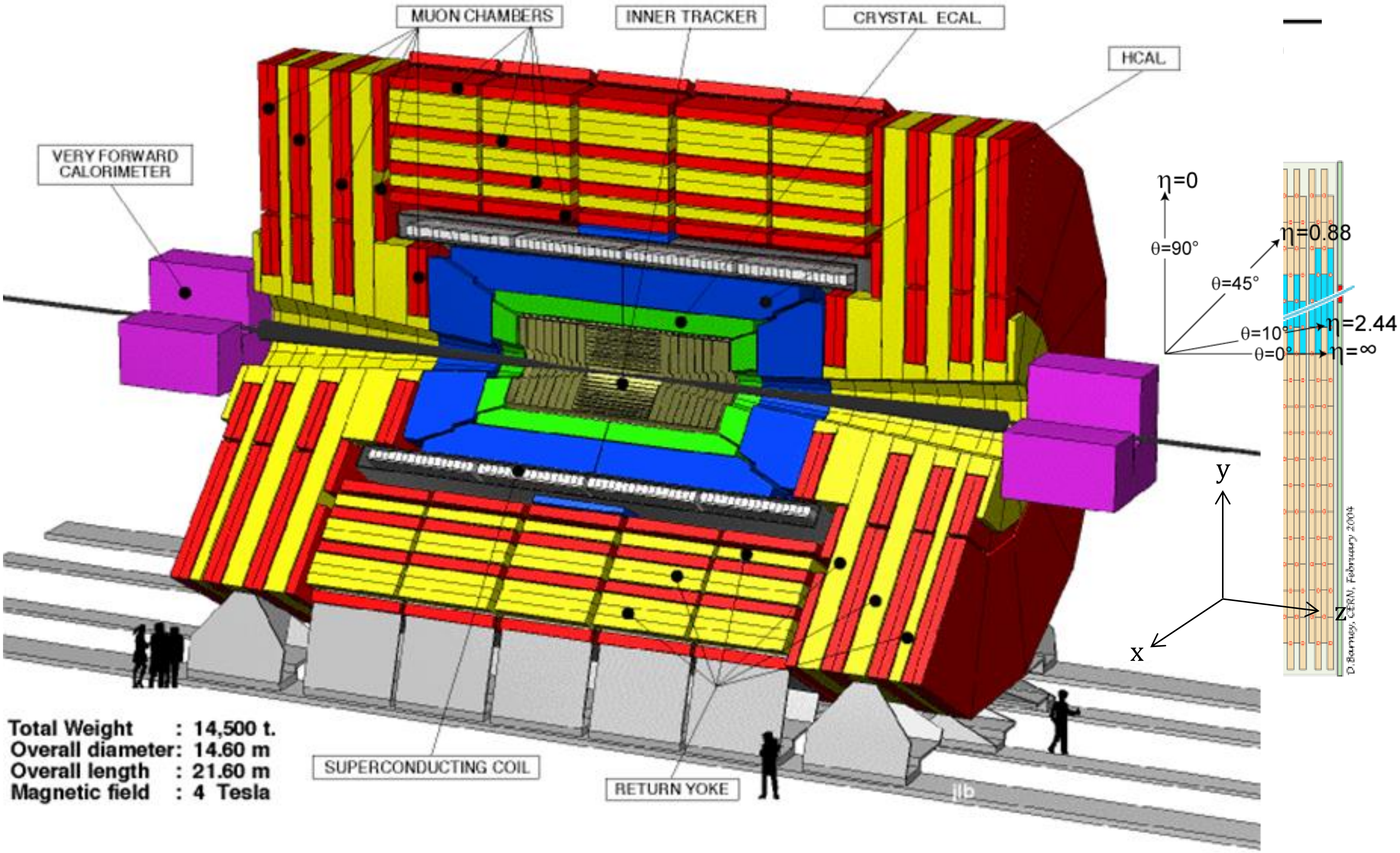
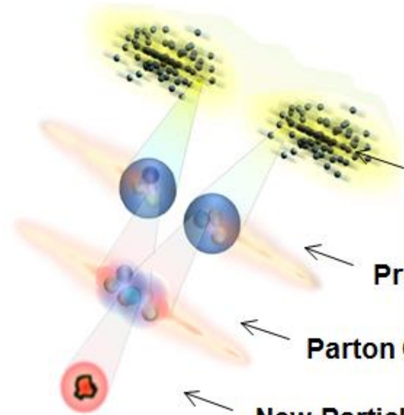


Image courtesy of http://hepwww.rl.ac.uk/OpenDays98/Detectors/cms-main.htm

Triggering

- It is impossible to record all data that comes from every collision in the LHC
  - Proton interactions happen around GHz rates, while new physics is happening at Hz to μHz rates



- We instead try to quickly identify and *trigger* only on interesting signatures and only record events interesting for analysis
  - Done in multiple steps (fastest first): Hardware → Software
  - Understanding the trigger efficiency is very important
- Examples:
  - **High p_T muons**, electrons, taus
  - High energy imbalance in the detector (high p_T ν's, SUSY?)
  - Di-particle signatures: di-tau, di-electron, **e+tau**, etc.
  - Many more…

Image courtesy of Alexei Safonov

Taus in CMS

- Hadronic taus (mostly) decay to 1 or 3 charged pions, accompanied by varying numbers of π^0s
- Tau reconstruction in CMS is done by the "Hadrons Plus Strips" algorithm
  - Combines particle flow charged hadrons with photons found in strips of psuedorapidity (η)
- An important property of tau reconstruction is *isolation*
  - Measure of how collimated the energy of the reconstructed particle is
    - Jets faking taus tend to be 'wider' than hadrons from decaying taus

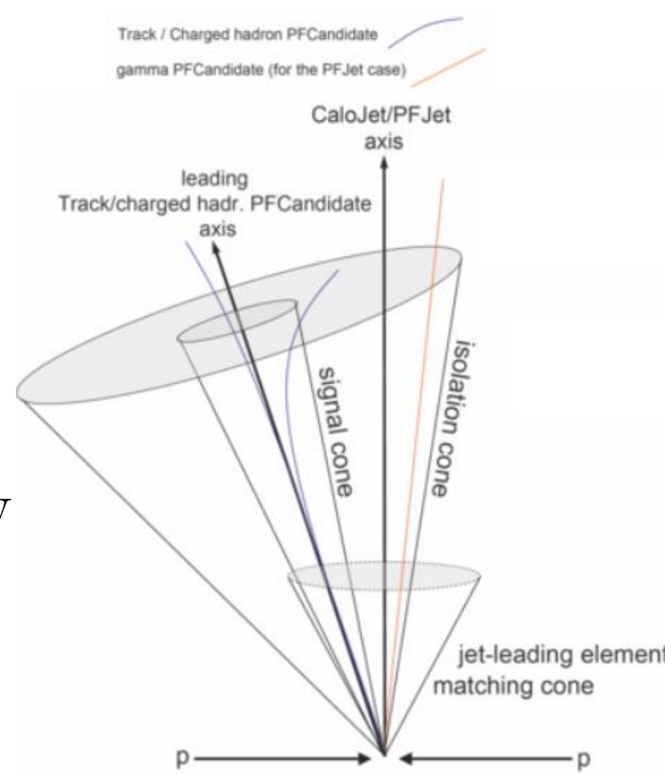


Image courtesy of https://twiki.cern.ch/twiki/bin/view/CMSPublic/SWGuidePFTauID#Creation

Analysis overview

- Used the data collected in by the CMS experiment 2011 (5 fb^{-1}) and 2012 (19.7 fb^{-1})
  - Single muon dataset used for the muon channel
  - Tau + X dataset used for the electron channel
- Topological selections to get to trigger plateaus and reduce background
  - Includes an multivariate analysis against di-tau fakes → details later
- Irreducible background prediction from events generated by Monte Carlo simulation techniques
- Reducible backgrounds estimated with a data driven method
- Statistical interpretation of results taken from the visible di-tau mass shape with the CLs method

Selection Overview

Trigger

- Single muon – Muon channel
- Electron + tau – Electron channel

Leptons

- $p_T > 24$ GeV/c
- $|\eta| < 2.1$
- Tight muon ID – Muon channel
- Loose electron ID – Electron Channel
- Relative isolation < 0.1
- Near primary vertex

Taus

- $p_T > 25$ (20) GeV/c for lead (sublead)
- $|\eta| < 2.1$
- Loose (medium) isolation for OS (SS) to μ – Muon channel
- Medium isolation for both – Electron channel
- Tight muon rejection
- Loose electron rejection
- Near primary vertex

Additional Cuts and Vetoes

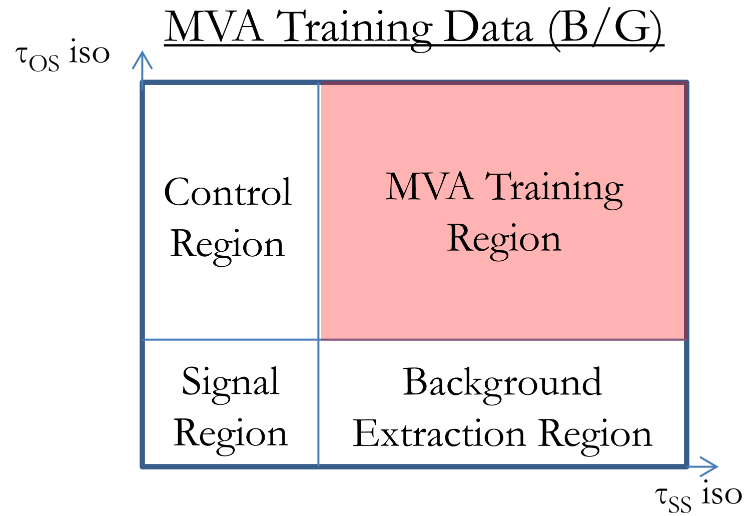
- All objects well separated in ΔR ($\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$)
- Opposite sign taus
- Tight B-jet veto
- Tight electron rejection for OS tau to electron – Electron channel

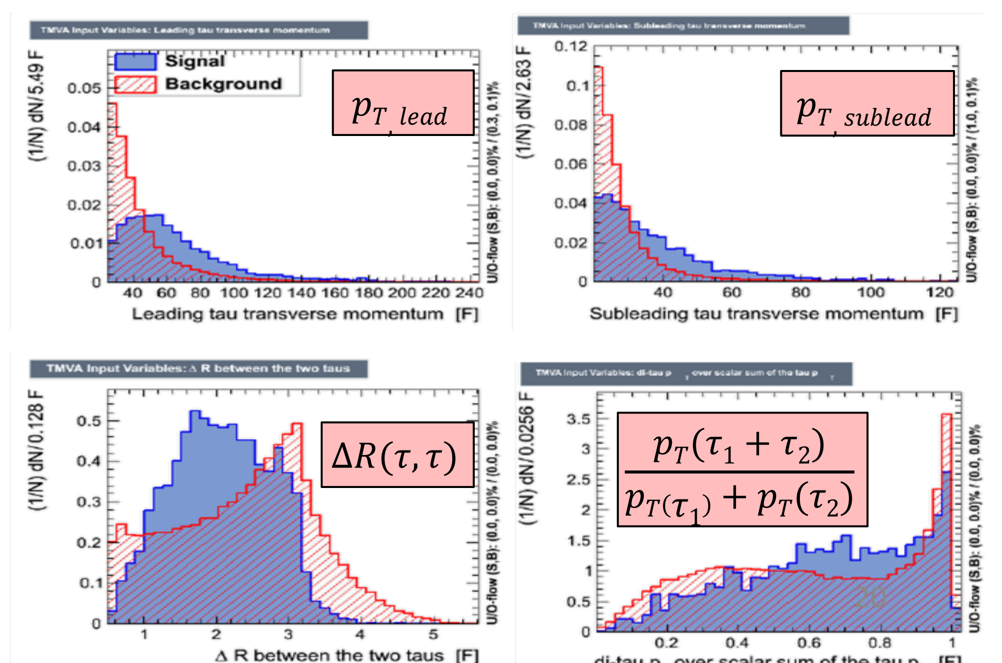
MVA Against Fakes: W+Jets

- After selections, W+Jets is the dominant background for this analysis
  - Recoil jets misidentified as our two taus
- There still may be some unused kinematics which could help to discriminate against fake taus
  - $p_T(\tau_1)$
  - $p_T(\tau_2)$
  - $p_T(\tau_1+\tau_2)/[p_T(\tau_1) + p_T(\tau_2)]$
  - $\Delta R(\tau_1, \tau_2)$
  - Missing Transverse Energy (MET)
- Want to maximize our effectiveness using these variables: **M**ulti**v**ariate **A**nalysis (MVA)
  - Use a **B**oosted **D**ecision **T**ree (BDT) to deal with events with fake taus

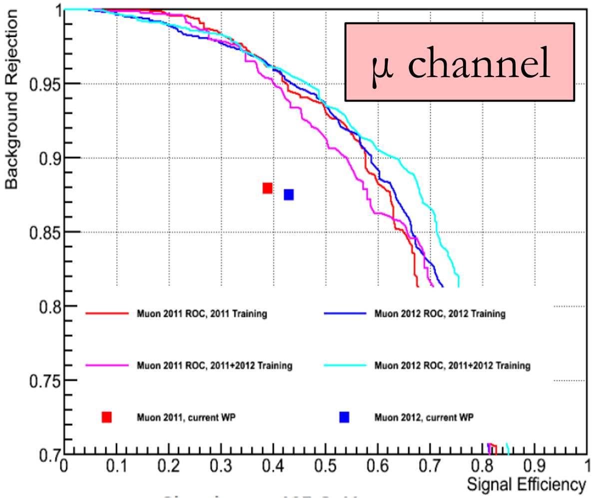
MVA Against Fakes: Training

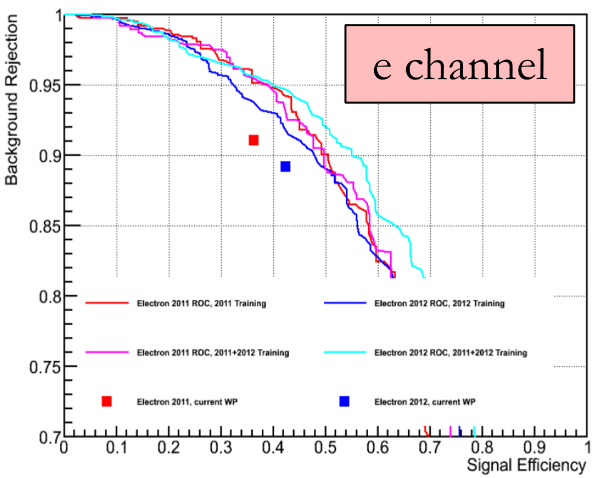
- **Background**: Data passing all cuts but having both taus anti-isolated
  - Dominated by W+Jets
  - Muon selections only
- **Signal:** MC events from sample different than that used in the analysis
  - $M_H = 110 – 145\ \text{GeV}/c^2$



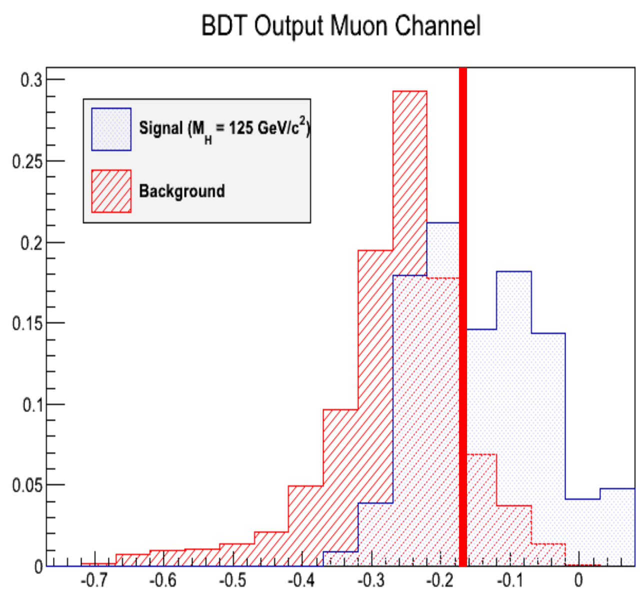


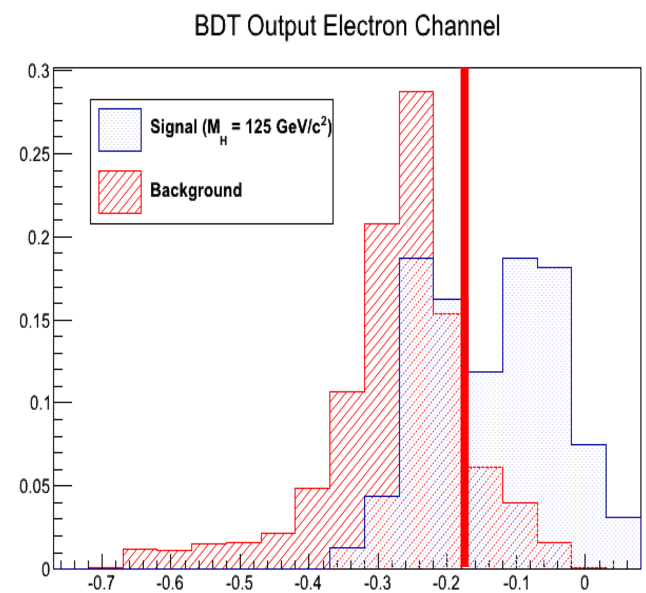
MVA Against Fakes: Performance





- Combined 7 TeV + 8 TeV training gives best performance
- Cut at -0.170 based on optimization of expected limit





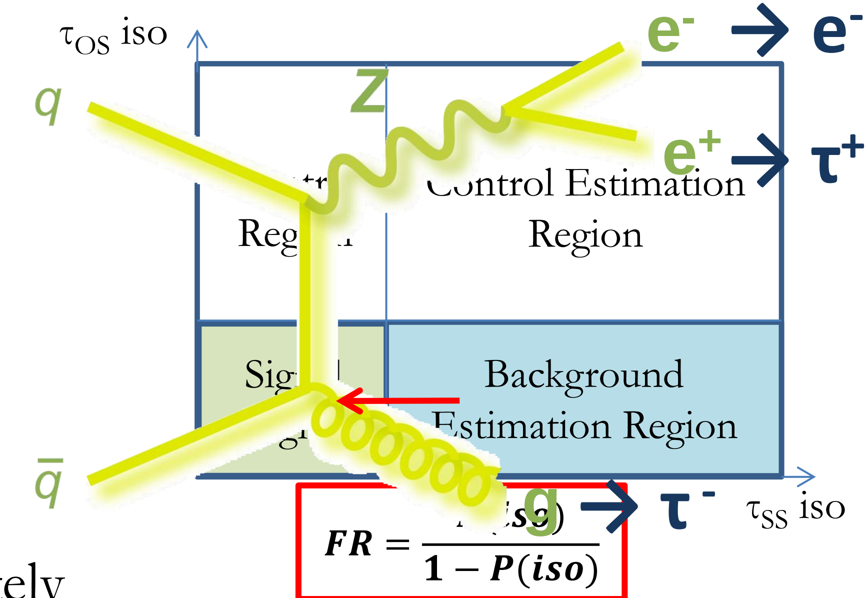
Data Driven Background Estimation
Reducible Backgrounds

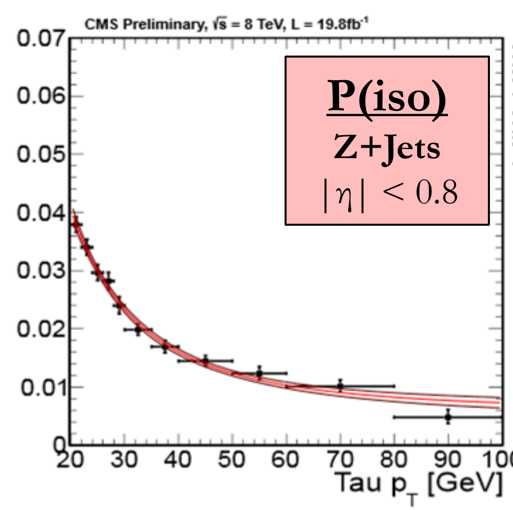
- Simulation of jets is not known to be reliable
- Very low MC statistics in signal region for backgrounds with fake taus
  - Less than 5 events left after cuts → means large uncertainty (relative error ~ $\sqrt{n}/n$)
- Use data-driven background estimation
  - Use real data to extrapolate from region of high statistics and dominated by background into the signal region
  - Can use tau isolation to accomplish this

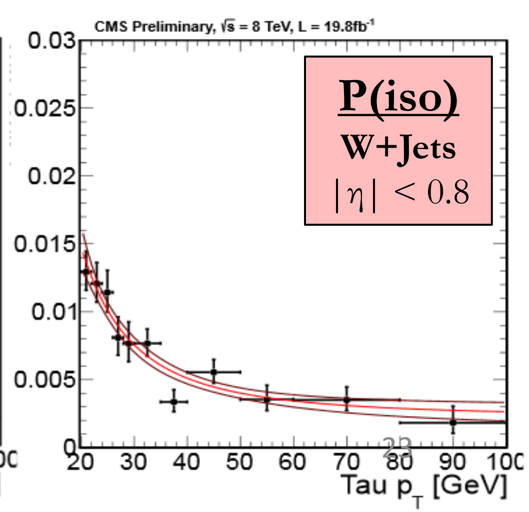
Reducible Background Estimation

Fake Rate Method

- Tau SS to lepton always fake in reducible backgrounds
  - Apply a Fake Rate to a side-band with SS tau anti-isolated
  - FR = P(isolated) / P(not isolated)
- FR different for W's and Z's
  - Measure W and Z Fake Rate separately
  - Total FR = 0.6 FR_W + 0.4 FR_Z
- FR a function of both "tau" (really a jet) p_T and η
  - Measure as function of p_T in three regions of η



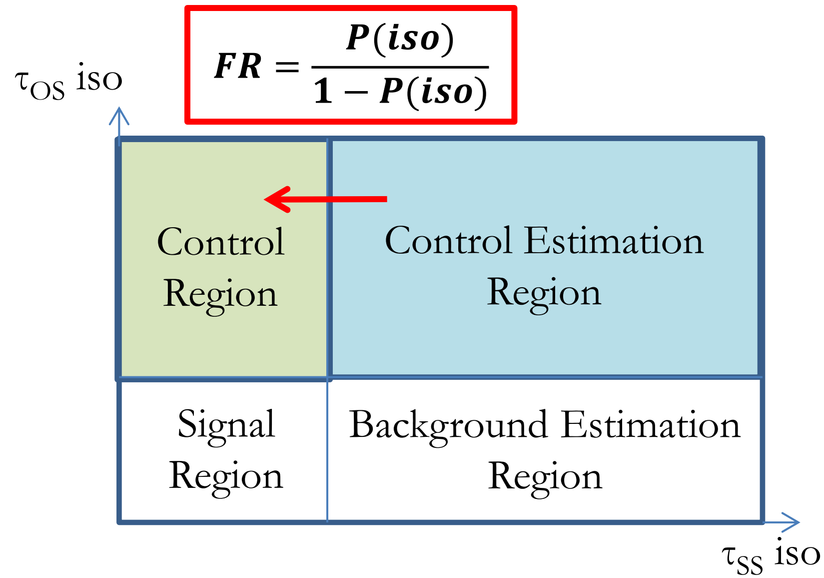




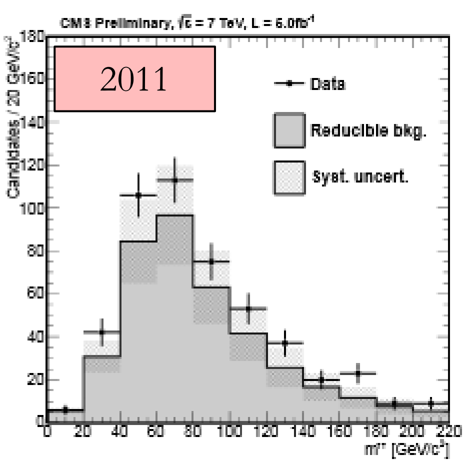
Background Estimation
Control Region

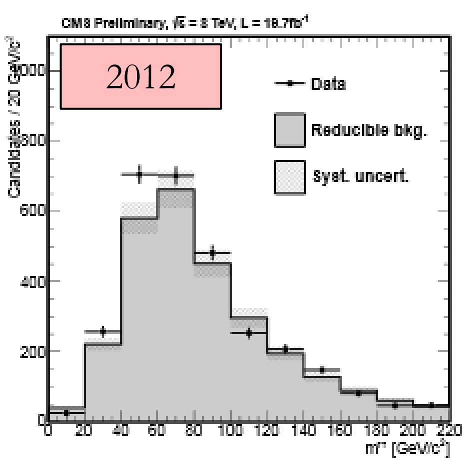
- We need to test the reliability of the fake rate estimation in a control region
- Apply the fake rate to the same sign tau in a double anti-isolated region

$$FR = \frac{P(iso)}{1 - P(iso)}$$

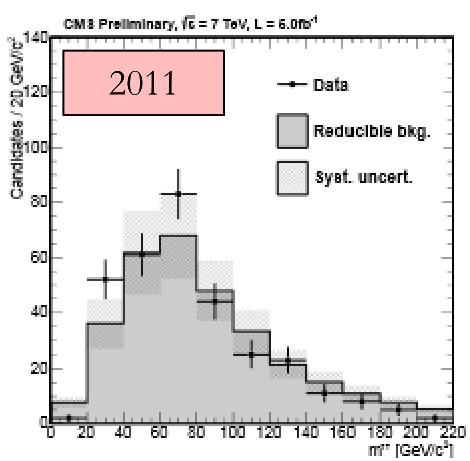


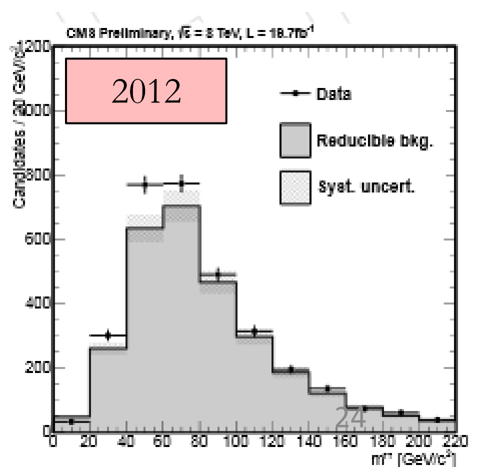
Muon Channel





Electron Channel





Systematics

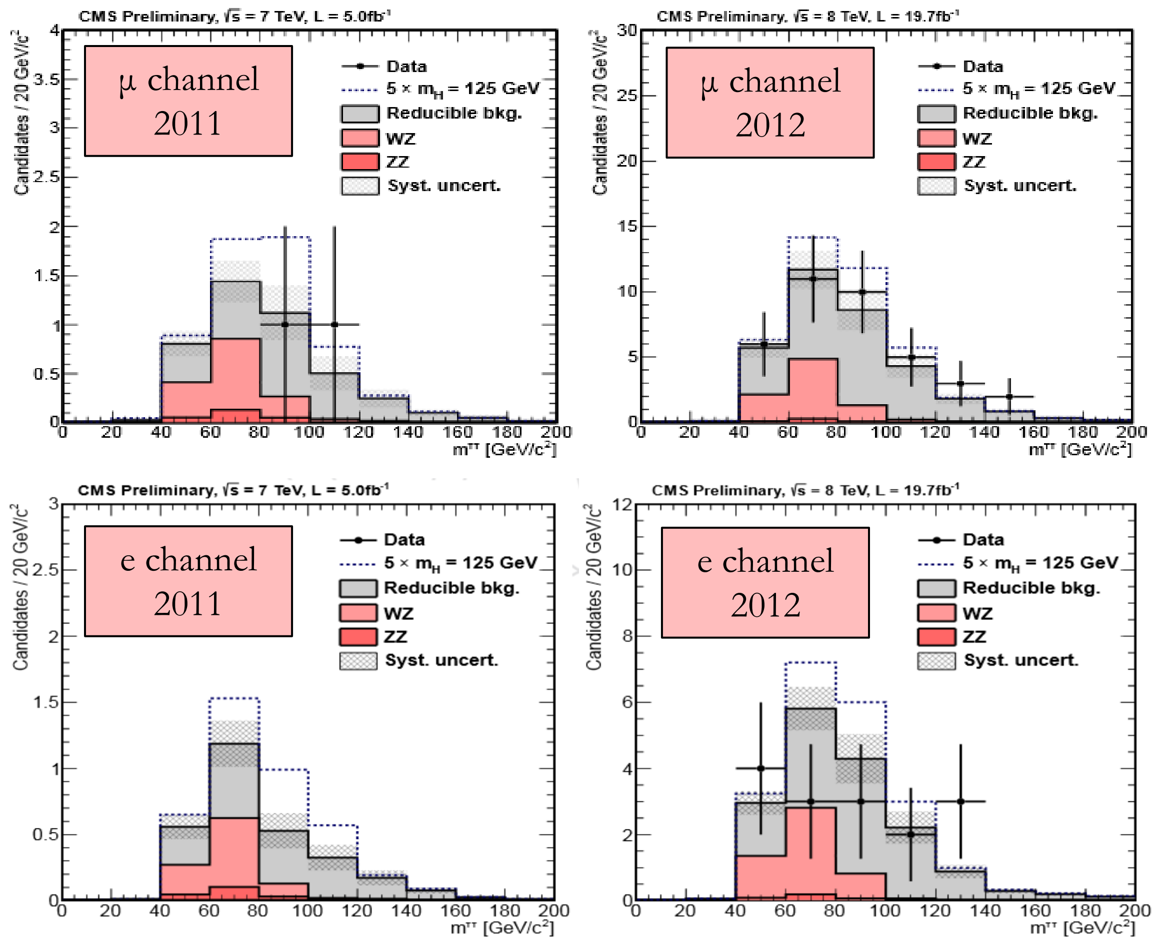
- These uncertainties were taken into account as nuisance parameters in the final fit of the di-tau mass

Systematic Uncertainty	Affected Sample	Value
Luminosity	Simulation	2.2% (2011) or 2.6% (2012)
Parton Distribution Functions	Simulation	3.3% - 4.0%
QCD Scale	Simulation	0.4% - 4.0%
Trigger Efficiency	Simulation	1% (μ), 2%(e)
Electron ID Efficiency	Simulation	2.9%
Muon ID Efficiency	Simulation	1.4%
Tau ID Efficiency	Simulation	12%
Tau Energy Scale	Simulation	Shape-altering
$E_{\mathrm{T}}^{\mathrm{miss}}$ Energy Scale	Simulation	Shape-altering
Additional Electron Veto	Simulation	3.8%
Additional Muon Veto	Simulation	0.7%
Fake Rate Normalization	Fake Background Estimate	15%
Fake Rate Fit	Fake Background Estimate	Shape-altering

Yields and Di-tau Shape

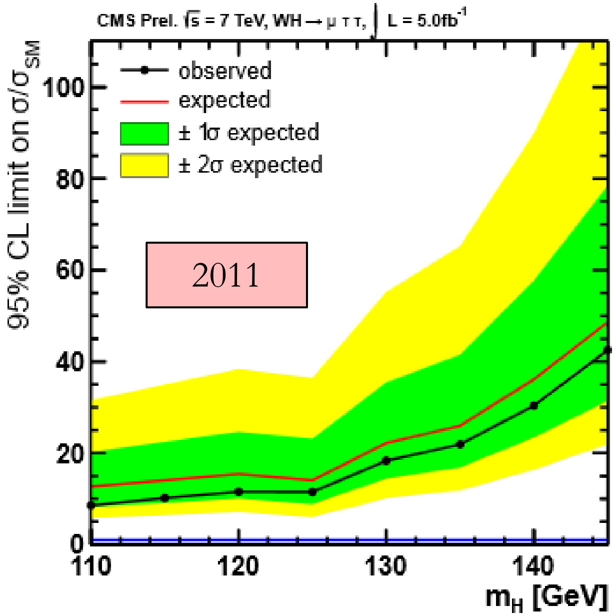
$\mu\tau_h\tau_h$	2011	2012
Signal (mH=125)	0.36 ± 0.04	1.57 ± 0.08
Reducible Bkg.	2.73 ± 0.18	25.23 ± 0.60
WZ	1.37 ± 0.08	8.33 ± 0.32
ZZ	0.25 ± 0.01	0.60 ± 0.02
Background	4.33 ± 0.19	34.10 ± 0.68
Data	2	38

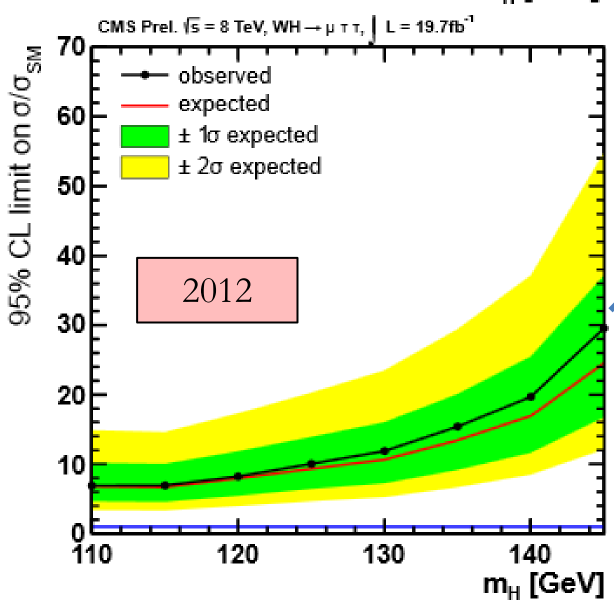
$e\tau_h\tau_h$	2011	2012
Signal (mH=125)	0.24 ± 0.01	0.88 ± 0.06
Reducible Bkg.	1.84 ± 0.15	11.90 ± 0.40
WZ	0.89 ± 0.07	4.78 ± 0.23
ZZ	0.20 ± 0.01	0.37 ± 0.02
Background	2.92 ± 0.16	17.02 ± 0.47
Data	0	15

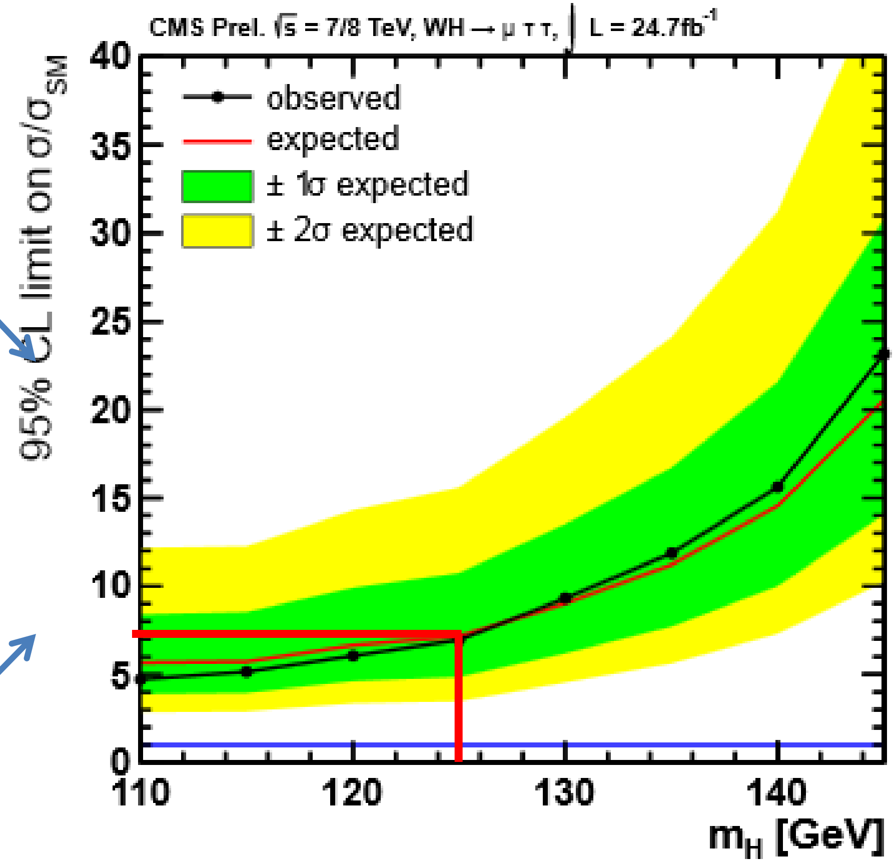


- Results interpreted by a fits to the visible di-tau mass with the CLs method using standard CMS tools

Muon Channel Limits

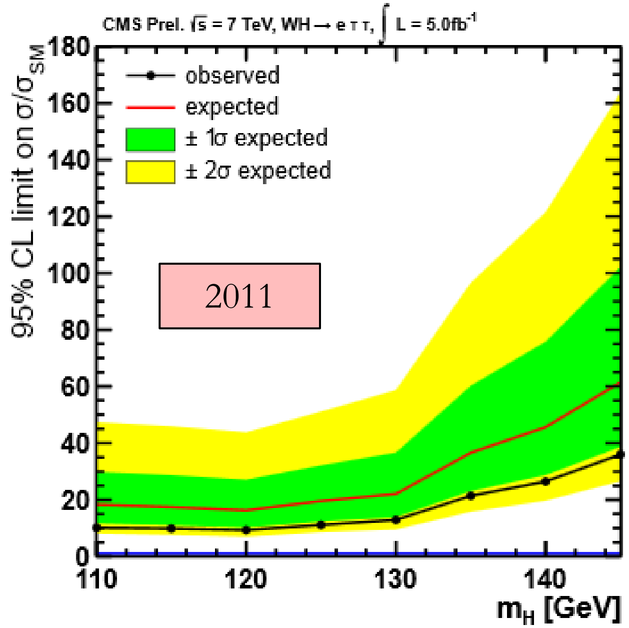


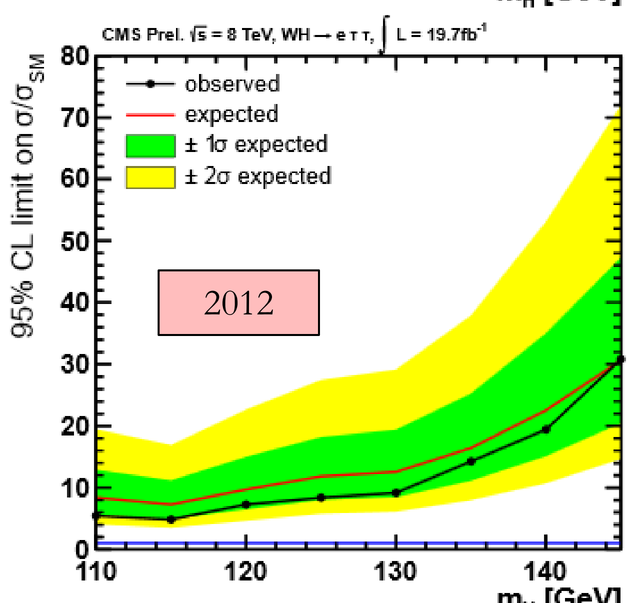


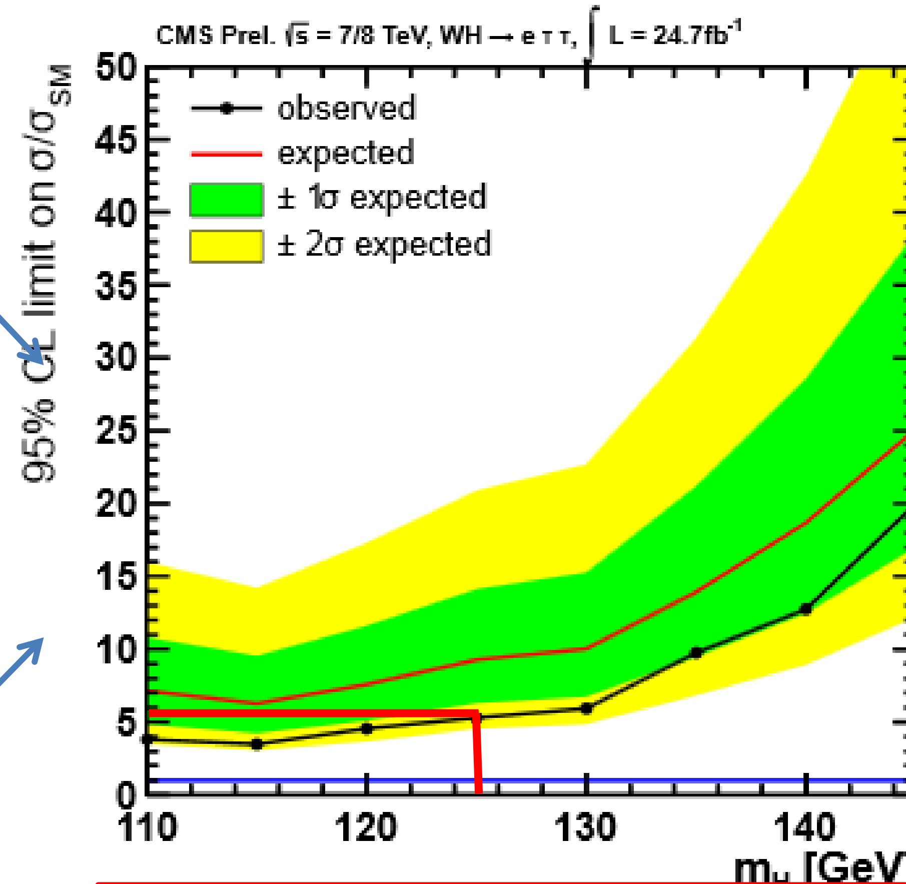


Observed limit of $\sim 7\sigma_{SM}$ for $M_H = 125$ GeV/c^2

Electron Channel Limits

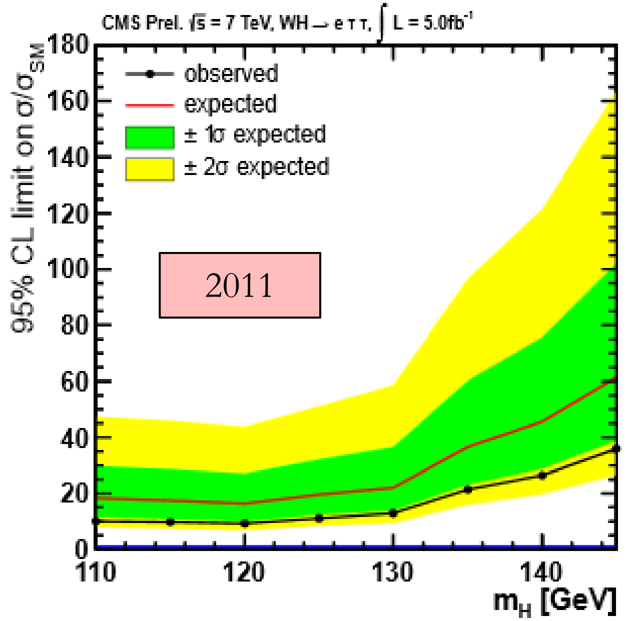


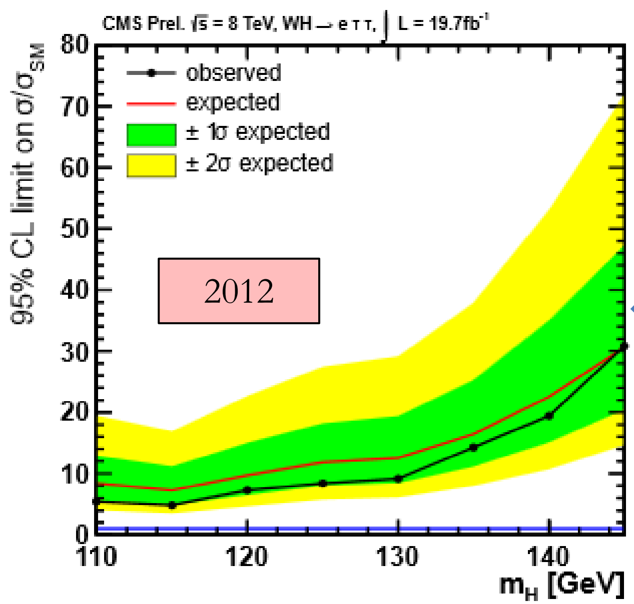


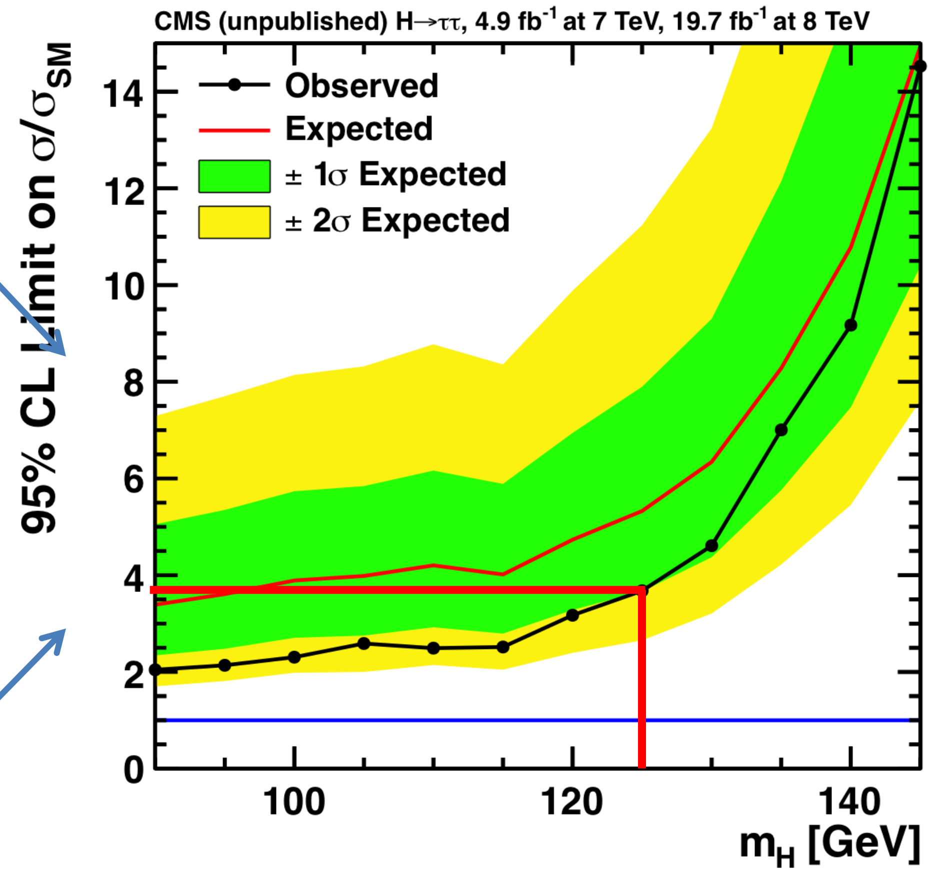


Observed limit of $\sim 6\sigma_{SM}$ for $M_H = 125$ GeV/c^2

Combined Limits



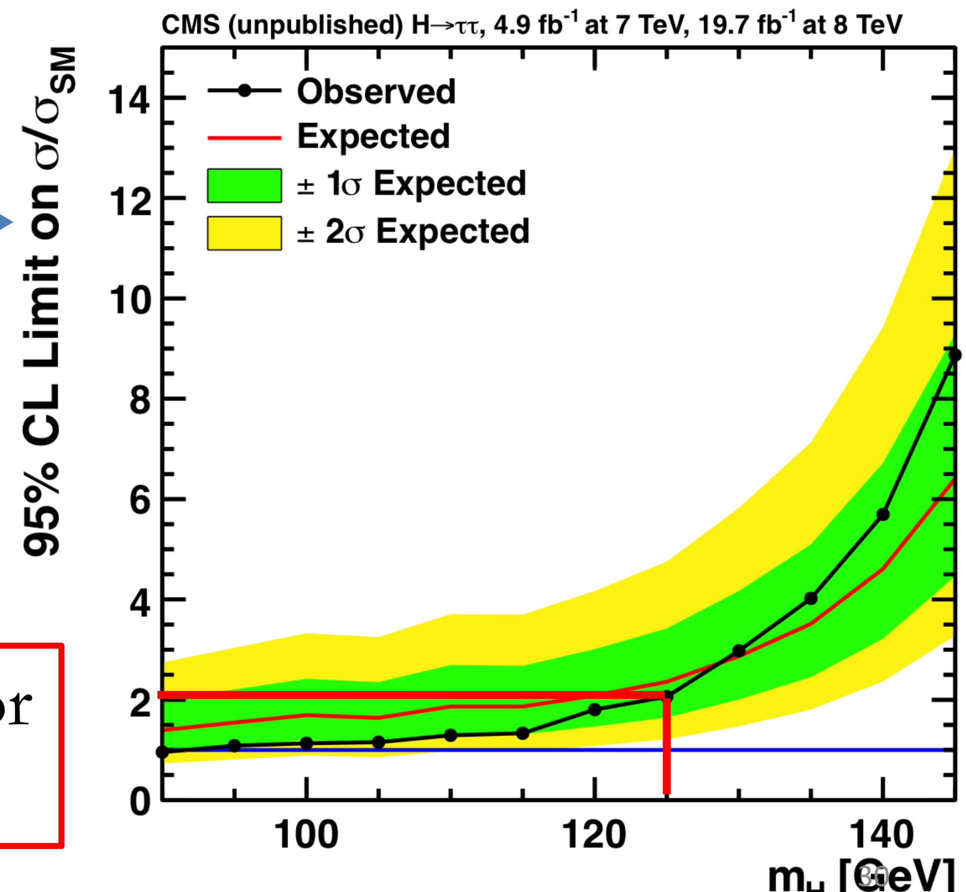




Observed Limit of $\sim 3.5\sigma_{SM}$ for M_H = 125 GeV/c^2

Inclusive VH Production

- This search was done in the in parallel with several VH ($H \to \tau\tau$) searches
  - $WH \to \ell\tau_\ell\tau_h$
  - $ZH \to \ell\ell\tau_h\tau_h$
  - $ZH \to \ell\ell\tau_\ell\tau_h$
  - $ZH \to \ell\ell\tau_\ell\tau_\ell$

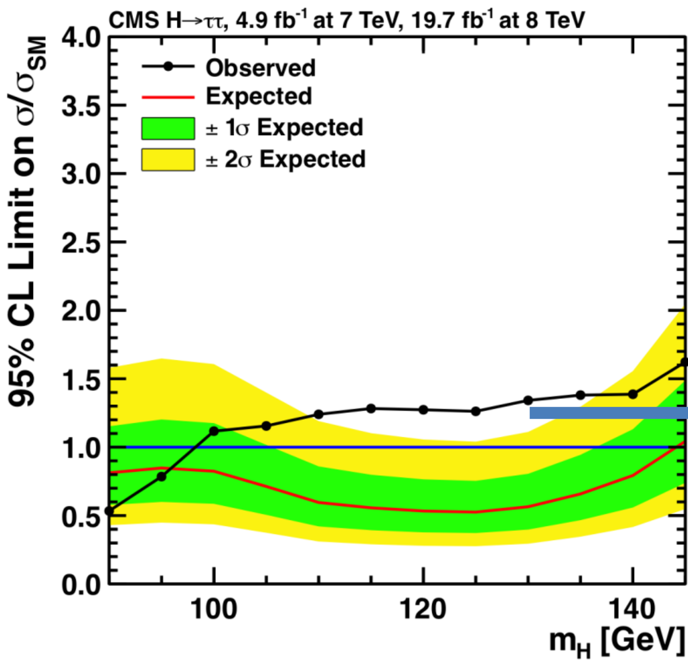


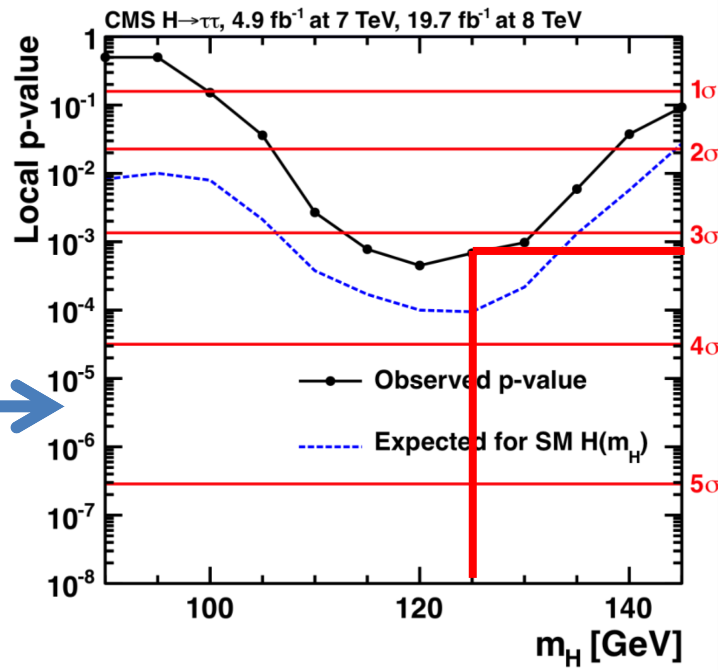
Observed Limit of $\sim 2\sigma_{SM}$ for $M_H = 125\ \mathrm{GeV}/c^2$

Plot from the CMS Public $H \to \tau\tau$ twiki: **https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13004PubTWiki**

Inclusive H→ττ

- The VH searches contributed to the limit in the inclusive H→ττ search





Local p-value corresponds to just above 3σ for M_H = 125 GeV/c^2

Almost there!

Plots from the CMS Public H → ττ twiki: **https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13004PubTWiki**

Conclusions

- Presented a search for WH $\rightarrow \boldsymbol{\ell\tau_h\tau_h}$
  - We exclude cross sections down to $3.5\sigma_{SM}$
- Part of a general associated production search
  - Excludes cross sections down to $2\sigma_{SM}$
- Even more general inclusive H $\rightarrow$ **ττ** search
  - ~3 sigma excess at $M_H = 125$ GeV/c^2 $\rightarrow$ **Almost there!**
- With LHC energy and luminosity upgrades coming in 2015, the sensitivity should be enough to claim discovery of Higgs in the ττ channel!

References

- Public Twikis:
  - Higgs:
    https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
  - Higgs to tau tau:
    https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig13004PubTWiki
- Papers
  - $WH \rightarrow \ell\tau_h\tau_h$
    "Search for the standard model Higgs boson decaying to a pair of hadronically decaying tau leptons produced in association with a W boson"
    arXiv, 2014
  - $H \rightarrow \tau\tau$
    "Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons"
    CMS Analysis Note AN-2014/012

Thank You

The Lagrangian again

- $\mathcal{L} = \overline{E_L}\,\gamma^\mu(i\partial_\mu - g\frac{1}{2}\vec{\tau}\overrightarrow{W}_\mu)E_L + \overline{e_R}\gamma^\mu(i\partial_\mu - g\frac{1}{2}W'_\mu)e_R + \overline{\nu_R}\gamma^\mu(i\partial_\mu - g\frac{1}{2}W'_\mu)\nu_R$
  - An interesting thing is that you can use W (couples to left-handed fermions only) and W' (couples to right handed fermions only) to build a physical photon and the Z-boson
  - And re-write (sorry about different notations)
    $$\mathcal{L}_{\mathrm{EW}} = \sum_\psi \bar{\psi}\gamma^\mu\left(i\partial_\mu - g'\frac{1}{2}Y_{\mathrm{W}}B_\mu - g\frac{1}{2}\vec{\tau}_{\mathrm{L}}\vec{W}_\mu\right)\psi$$
    - Subscript L means Pauli matrices act only on left-handed fields
  - Then Z=aB+bW_3 and γ=cB+dW_3(you need to pick parameters to preserve unitarity)
  - This is a step towards electroweak unification!
    - Physical bosons are a mixture of true EM and Weak interaction bosons

Fermion Masses

- Forget for now about gauge boson masses
- Let's see if there is a way to make fermion masses not zero without adding a mass term explicitly
- Say we add a new scalar field ϕ: and allow it to couple to fermions:

$$\Delta\mathcal{L}_e = -\lambda_e \overline{E}_L \cdot \phi\, e_R + \mathrm{h.c.}$$

- What if this field can have a non-zero VEV v?

$$\Delta\mathcal{L}_e = -\frac{1}{\sqrt{2}}\lambda_e v\, \bar{e}_L e_R + \mathrm{h.c.} + \cdots$$

- Then you effectively "generate " fermion mass to be

$$m_e = \frac{1}{\sqrt{2}}\lambda_e v.$$

Higgs Potential

- Write a lagrangian for the new scalar field as follows:

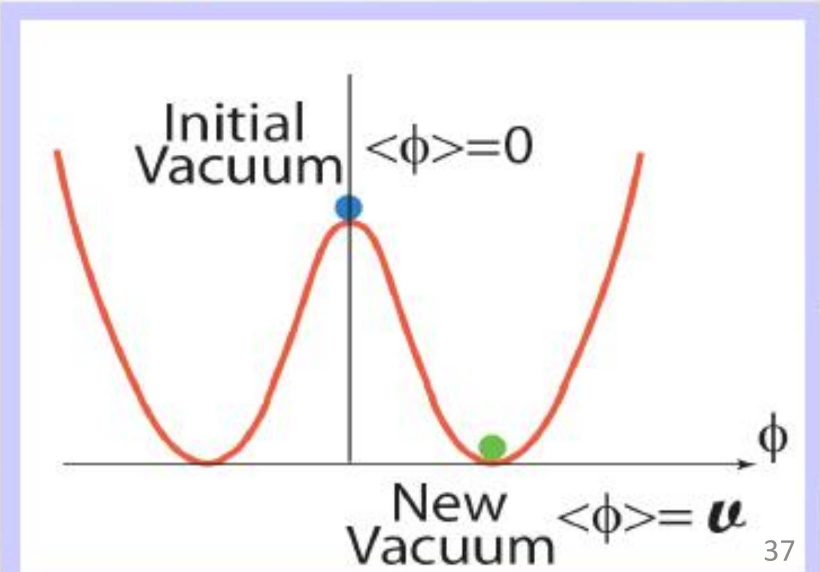
$$\mathcal{L} = \left|D_\mu \phi\right|^2 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2.$$

  - Let's say this new field has VEV of v, expand:

$$\phi(x) = U(x) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

  - The minimum of potential energy occurs at

$$v = \left(\frac{\mu^2}{\lambda}\right)^{1/2}.$$



Higgs Boson

- Now expand the lagrangian around v:

$$\mathcal{L} = \left|D_\mu \phi\right|^2 + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2.$$

  - You will get the following:

$$\mathcal{L}_V = -\mu^2 h^2 - \lambda v h^3 - \frac{1}{4}\lambda h^4$$
$$= -\frac{1}{2} m_h^2 h^2 - \sqrt{\frac{\lambda}{2}}\, m_h h^3 - \frac{1}{4}\lambda h^4.$$

  - The first term is the new boson's mass!
  - It can be expressed as:

$$m_h = \sqrt{2}\mu^2 = \sqrt{\frac{\lambda}{2}}\, v.$$

  - If you re-write above lagrangian (remember you use covariant derivative, which includes W and Z in it

$$\mathcal{L}_K = \frac{1}{2}(\partial_\mu h)^2 + \left[m_W^2 W^{\mu +} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right] \cdot \left(1 + \frac{h}{v}\right)^2,$$

  - This new field can generate W and Z masses

Weak Mixing Angle

- Gauge bosons responsible for electromagnetism and weak interaction turned out to be mixed together
  - W^3 was the third Pauli matrix and B was the one coupling to right-handed fermions

$$Z_\mu = \cos\theta_W \; W^3_\mu \; - \; \sin\theta_W \; B_\mu$$
$$A_\mu = \sin\theta_W \; W^3_\mu \; + \; \cos\theta_W \; B_\mu$$

$$\tan\theta_W = \frac{g_1}{g_2}$$

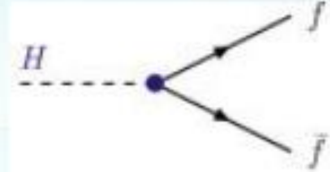
  - Where θ is the weak mixing angle (W stands for Weinberg)

$$M_W = \frac{v}{2}\, g_2 \qquad M_\gamma = 0\ , \qquad M_Z = \frac{v}{2}\sqrt{g_1^2 + g_2^2}$$

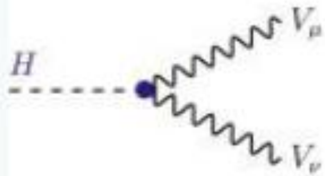
- Can be measured experimentally:
  - From $\frac{M_W}{M_Z} = \cos\theta_W$ M(W)~80 GeV, M*Z)~91 GeV

Higgs Couplings

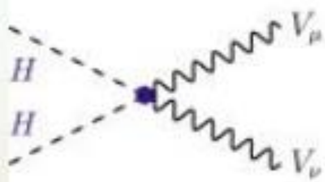
- Higgs couples to fermion proportional to their mass
  - It's VEV "creates" the mass
- Also couples to gauge bosons
  - Its VEV part creates their mass
- And to itself



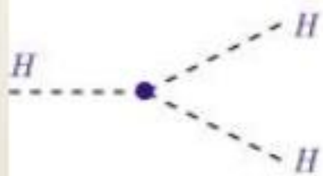
$$g_{Hff} = m_f/v = (\sqrt{2}G_\mu)^{1/2} m_f \qquad \times (-i)$$



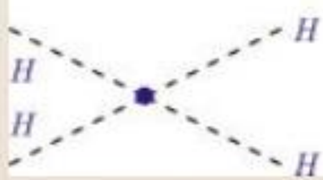
$$g_{HVV} = 2M_V^2/v = 2(\sqrt{2}G_\mu)^{1/2} M_V^2 \qquad \times (ig_{\mu\nu})$$



$$g_{HHVV} = 2M_V^2/v^2 = 2\sqrt{2}G_\mu M_V^2 \qquad \times (ig_{\mu\nu})$$



$$g_{HHH} = 3M_H^2/v = 3(\sqrt{2}G_\mu)^{1/2} M_H^2 \qquad \times (-i)$$



$$g_{HHHH} = 3M_H^2/v^2 = 3\sqrt{2}G_\mu M_H^2 \qquad \times (-i)$$

Samples and Triggers

Process	MC generator	$\sigma_{(N)NLO}$ 7 TeV	8 TeV	Comments and sample name
Higgs boson $H \to \tau\tau$				
WH_ZH_TTH_HToTauTau	PYTHIA	[5.4-28] fb	[6.7-34] fb	m_H = 110-140 GeV/c^2
WH_ZH_TTH_HToWW	PYTHIA	[1.8-5.2] fb	[2.1-6.3] fb	m_H = 110-140 GeV/c^2
Di-bosons				
$WW \to 2l2\nu$	Madgraph	4.88 pb	5.995 pb	WWJetsTo2L2Nu
$WZ \to 3l\nu$	Madgraph	0.868 pb	1.057 pb	WZJetsTo3LNu
$ZZ \to 4l$	PYTHIA	0.106 pb	0.130 pb	ZZTo4L
WW (inclusive)	PYTHIA		54.8 pb	
WZ (inclusive)	PYTHIA		33.21 pb	
ZZ (inclusive)	PYTHIA		17.654 pb	
$t\bar{t}$				
$t\bar{t} \to l^+l^-\nu\bar{\nu}b\bar{b}$	POWHEG	17.32 pb	23.64 pb	TTTo2L2Nu2B
$t\bar{t}Z$	MADGRAPH	0.139 pb	0.208 pb	TTZJets
Z/W + jets ($q = d, u, s, c, b$)				
W + jets (inclusive)	MadGraph	31314 pb	36257.2 pb	WJetsToLNu
W + 1 jet	MadGraph	5050 pb	6440 pb	
W + 2 jets	MadGraph	1618 pb	2087 pb	
W + 3 jets	MadGraph	342.9 pb	619.0 pb	
W + 4 jets	MadGraph	194.6 pb	255.2 pb	
Z + jets, $m_{ll} > 50$	MadGraph	3048 pb	3503.7 pb	DYJetsToLL*M-50

Dataset	Run Range
$\sqrt{s} = 7$ TeV	
/%/Run2011A-May10ReReco-v1/AOD	160431-163869
/%/Run2011A-PromptReco-v4/AOD	165088-167913
/%/Run2011A-05Aug2011-v1/AOD	170826-172619
/%/Run2011A-03Oct2011-v1/AOD	172620-173692
/%/Run2011B-PromptReco-v1/AOD	175860-180252
$\sqrt{s} = 8$ TeV	
/%/Run2012A-13Jul2012-v1/AOD	190450 - 193680
/%/Run2012A-06Aug2012recover-v1/AOD	190782,190895,190906,190945,190949
/%/Run2012B-13Jul2012-v1/AOD	193752 - 196531
/%/Run2012C-24Aug2012-v1/AOD	198022 - 198523
/%/Run2012C-PromptReco-v2/AOD	198941 - 203002
/%/Run2012D-PromptReco-v1/AOD	203894 - 208686

Triggers

HLT path
$e\tau\tau$ channel
HLT_Ele15_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_LooseIsoPFTau15 HLT_Ele15_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_LooseIsoPFTau20 HLT_Ele15_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_TightIsoPFTau20 HLT_Ele20_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_MediumIsoPFTau20
$\mu\tau\tau$ channel
HLT_IsoMu24 HLT_IsoMu24_eta2p1

Table 3: HLT paths used for the 2011 data.

HLT path
$e\tau\tau$ channel
HLT_Ele20_CaloIdVT_CaloIsoRhoT_TrkIdT_TrkIsoT_LooseIsoPFTau20 HLT_Ele22_eta2p1_WP90Rho_LooseIsoPFTau20
$\mu\tau\tau$ channel
HLT_IsoMu24_eta2p1

Table 4: HLT paths used for the 2012 data.

Boundary Conditions

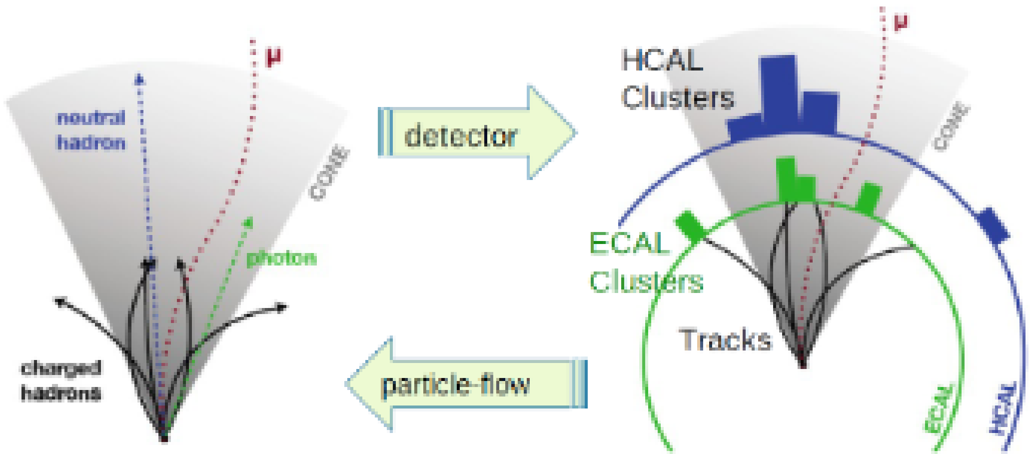
- On the input:
  - Bunch Crossing rate: 40 MHz
  - Interactions rate: 1-10 GHz (depends on how many overlapping events)
  - Data rate: hundreds of Terrabits per second
- On the output:
  - Need to write events on disk so that one can analyze the data
  - With some reasonable assumptions on how much you can spend, the likely writing rate is 100-300 crossings per second (100-300 Hz)
    - Multiply by 1 MB event size to get some Gigabits per second

What ‘s in between” ?
The trigger!

Tau identification

Tau identification is a complicated problem which requires sophisticated algorithms and reconstruction of the tau decay mode.

Hadron Plus Strips (HPS)
is the currently used algorithm for hadronic tau decay reconstruction at CMS.



- HPS algorithm uses Particle Flow method.
- Particle Flow algorithm reconstructs a list of particles produced in the collision.

Slide courtesy of http://epiphany.ifj.edu.pl/epiphany.2013/pres/day3_3_Boniecki_Tau_identification_and_reconstruction_at_CMS.pdf

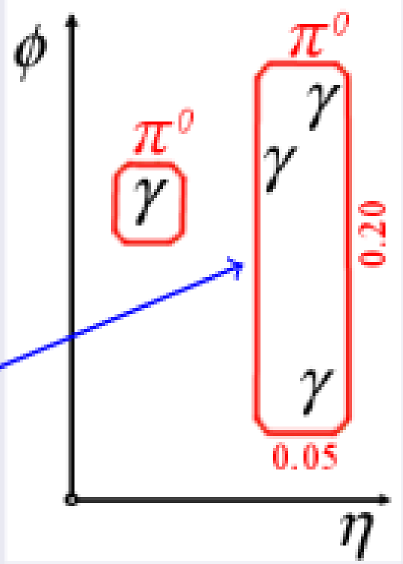
Hadron Plus Strips Algorithm

Hadron Plus Strips algorithm uses PFJet as a starting point.

- Charged hadrons are reconstructed with Particle Flow algorithm.
- π^0's are reconstructed in ECAL as objects called strips.

Strips

- $\pi^0 \rightarrow \gamma\gamma$
- Photon conversions in the tracker material.
- Electron tracks bending in magnetic field - broadening of the signal in the azimuthal direction.
- A strip of 0.05 in η and 0.20 in ϕ is built.
- Mass required to be consistent with π^0.



Slide courtesy of http://epiphany.ifj.edu.pl/epiphany.2013/pres/day3_3_Boniecki_Tau_identification_and_reconstruction_at_CMS.pdf

Hadron Plus Strips Algorithm

Decay mode reconstruction

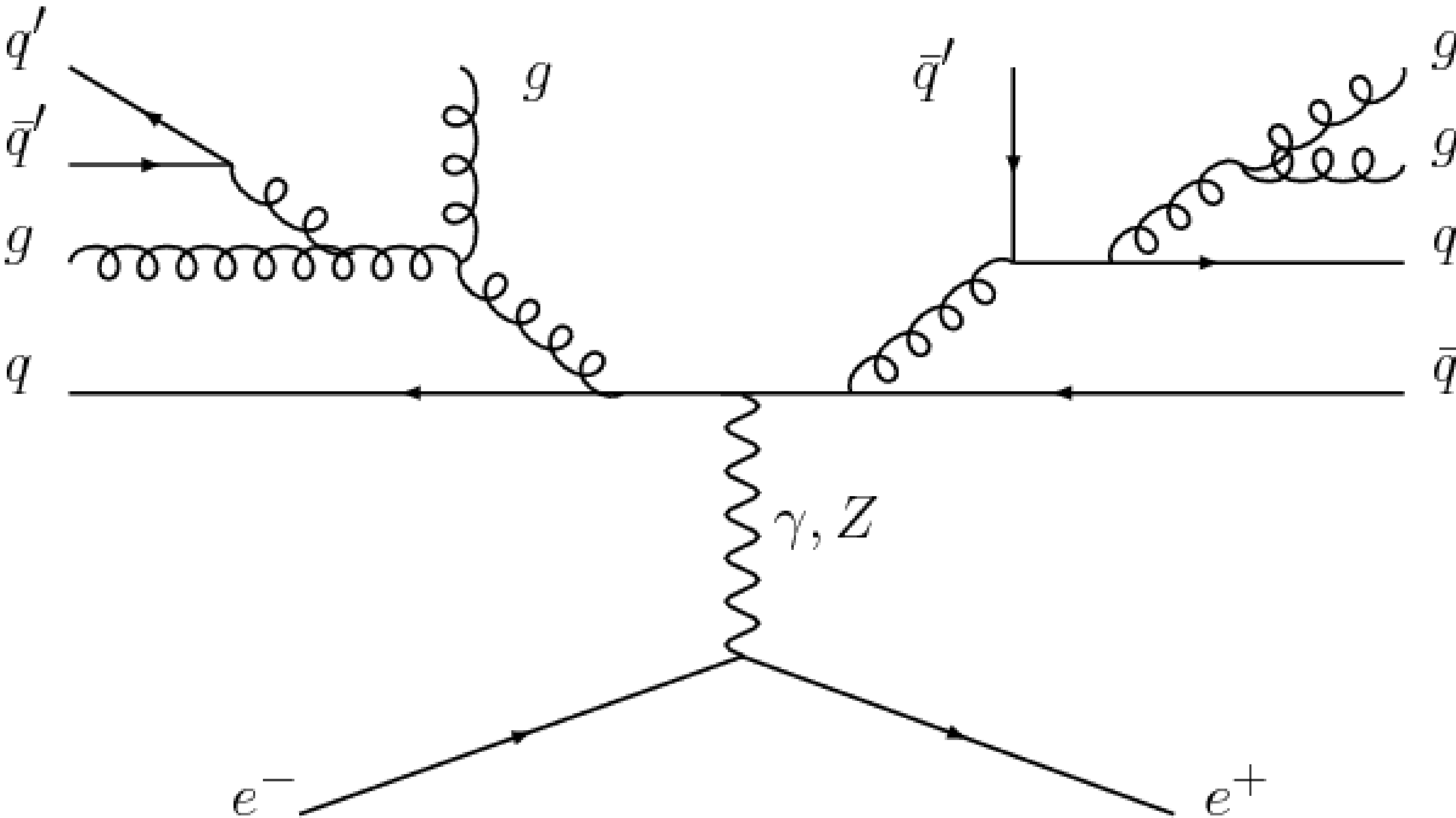
HPS objects	tau decay mode
1 hadron	$\tau^- \rightarrow h^- \nu_\tau$ $\tau^- \rightarrow h^- \pi^0 \nu_\tau$, with low energy π^0
1 hadron + 1 strip	$\tau^- \rightarrow h^- \pi^0 \nu_\tau$, with both photons inside one strip
1 hadron + 2 strips	$\tau^- \rightarrow h^- \pi^0 \nu_\tau$, with photons well separated
3 hadron	$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$, same secondary vertex

Hadronic tau reconstruction

- Shrinking Cone - size $\Delta R = (2.8\ \text{GeV}/c)/p_T^\tau$ has to contain all the reconstructed hadrons and strips.
- $\vec{p}^\tau$ is required to match the direction of the input PFJet.
- Decay must be compatible with a corresponding resonance (ρ or a_1) hypothesis.

Slide courtesy of http://epiphany.ifj.edu.pl/epiphany.2013/pres/day3_3_Boniecki_Tau_identification_and_reconstruction_at_CMS.pdf

Jets vs Taus



Muon ID

Plain-text description	Technical description	Comments
The candidate is reconstructed as a Global Muon	`recoMu.isGlobalMuon()`	
Particle-Flow muon id	`recoMu.isPFMuon()`	Reference measurements for Tight Muon version without this cut will be provided as well
χ^2/ndof of the global-muon track fit < 10	`recoMu.globalTrack()->normalizedChi2() < 10.`	To suppress hadronic punch-through and muons from decays in flight (see CMS AN 2008/098). This cut might need to be re-tuned due to the change to fully segment based global fit in 50X releases and later.
At least one muon chamber hit included in the global-muon track fit	`recoMu.globalTrack()->hitPattern().numberOfValidMuonHits() > 0`	To suppress hadronic punch-through and muons from decays in flight.
Muon segments in at least two muon stations This implies that the muon is also an arbitrated tracker muon, see SWGuideTrackerMuons	`recoMu.numberOfMatchedStations() > 1`	To suppress punch-through and accidental track-to-segment matches. Also makes selection consistent with the logic of the muon trigger, which requires segments in at least two muon stations to obtain a meaningful estimate of the muon p_T.
Its tracker track has transverse impact parameter d_{xy} < 2 mm w.r.t. the primary vertex	`fabs(recoMu.muonBestTrack()->dxy(vertex->position())) < 0.2` Or `dB() < 0.2` on `pat::Muon` [1]	To suppress cosmic muons and further suppress muons from decays in flight (see CMS AN 2008/098). The 2 mm cut preserves efficiency for muons from decays of b and c hadrons. It is a loose cut and can be tightened further with minimal loss of efficiency for prompt muons if background from cosmic muons is an issue. Another way to obtain a better cosmic-ray suppression is to complement the d_{xy} cut with a cut on the opening angle α or use a dedicated cosmic-id algorithm (see Section 7.1 of MUO-10-004). innerTrack() is also supported for dxy cut, as the performance of the two is very close.
The longitudinal distance of the tracker track wrt. the primary vertex is d_z < 5 mm	`fabs(recoMu.muonBestTrack()->dz(vertex->position())) < 0.5`	Loose cut to further suppress cosmic muons, muons from decays in flight and tracks from PU. innerTrack() is also supported for dz cut, as the performance of the two is very close.
Number of pixel hits > 0	`recoMu.innerTrack()->hitPattern().numberOfValidPixelHits() > 0`	To further suppress muons from decays in flight.
Cut on number of tracker layers with hits >5	`track()->hitPattern().trackerLayersWithMeasurement() > 5`	To guarantee a good p_T measurement, for which some minimal number of measurement points in the tracker is needed. Also suppresses muons from decays in flight.

Tau ID

ByLooseElectronRejection	yes	electron pion MVA discriminator < 0.6
ByMediumElectronRejection	yes	electron pion MVA discriminator < -0.1 and not 1.4442 < $\lvert\eta\rvert$ < 1.566
ByTightElectronRejection	yes	electron pion MVA discriminator < -0.1 and not 1.4442 < $\lvert\eta\rvert$ < 1.566 and Brem pattern cuts (see AN-10-387)
ByMVA3Loose/Medium/Tight /VTightElectronRejection	yes	anti-electron MVA discriminator with improved training (see talk)
ByMVA3VTightElectronRejection	yes	anti-electron MVA discriminator with improved training (same efficiency as "HCP 2012 working point" (see talk)
ByLooseMuonRejection	yes	Tau Lead Track not matched to chamber hits
ByMediumMuonRejection	yes	Tau Lead Track not matched to global/tracker muon
ByTightMuonRejection	yes	Tau Lead Track not matched to global/tracker muon and large enough energy deposit in ECAL + HCAL
ByLooseMuonRejection2	yes	Same as AgainstMuonLoose
ByMediumMuonRejection2	yes	Loose2 && no DT, CSC or RPC Hits in last 2 Stations
ByTightMuonRejection2	yes	Medium2 && large enough energy deposit in ECAL + HCAL in 1 prong + 0 strip decay mode (Σ(ECAL+HCAL) > 0.2 * p_T)
ByDecayModeFinding	yes	You will always want to use this (see AN-10-82)
ByVLooseIsolation	yes	isolation cone of 0.3 , no PF Charged Candidates with pT > 1.5 GeV/c and no PF Gamma candidates with ET > 2.0 GeV
ByVLooseCombinedIsolationDBSumPtCorr	yes	isolation cone of 0.3 , Delta Beta corrected sum pT of PF charged and PF gamma isolation candidates (pT > 0.5 GeV) less than 3 GeV

Tau ID

ByLooseCombinedIsolationDBSumPtCorr	yes	isolation cone of 0.5 , Delta Beta corrected sum pT of PF charged and PF gamma isolation candidates (pT > 0.5 GeV) less than 2 GeV
ByMediumCombinedIsolationDBSumPtCorr	yes	isolation cone of 0.5 , Delta Beta corrected sum pT of PF charged and PF gamma isolation candidates (pT > 0.5 GeV) less than 1 GeV
ByTightCombinedIsolationDBSumPtCorr	yes	isolation cone of 0.5 , Delta Beta corrected sum pT of PF charged and PF gamma isolation candidates (pT > 0.5 GeV) less than 0.8 GeV
ByLooseCombinedIsolationDBSumPtCorr3Hits	yes	same as ByLooseCombinedIsolationDBSumPtCorr but requiring 3 hits (instead of 8) on track of isolation candidates
ByMediumCombinedIsolationDBSumPtCorr3Hits	yes	same as ByMediumCombinedIsolationDBSumPtCorr but requiring 3 hits (instead of 8) on track of isolation candidates
ByTightCombinedIsolationDBSumPtCorr3Hits	yes	same as ByTightCombinedIsolationDBSumPtCorr but requiring 3 hits (instead of 8) on track of isolation candidates
ByLooseIsolationMVA	yes	BDT based selection using isolation in rings around tau direction and shower shape variables
ByMediumIsolationMVA	yes	BDT based selection using isolation in rings around tau direction and shower shape variables
ByTightIsolationMVA	yes	BDT based selection using isolation in rings around tau direction and shower shape variables
ByIsolationMVAraw	no	output of BDT based selection using isolation in rings around tau direction and shower shape variables
ByLooseIsolationMVA2	yes	same as ByLooseIsolationMVA with new training and improved performance
ByMediumIsolationMVA2	yes	same as ByMediumIsolationMVA with new training and improved performance
ByTightIsolationMVA2	yes	same as ByTightIsolationMVA with new training and improved performance
ByIsolationMVA2raw	no	output of "MVA2" BDT discriminator

Muon Channel Selections

Trigger

- Single muon trigger

Topological

- $\Delta R(\mu,\tau_{OS}) > 0.5$
- $\Delta R(\mu,\tau_{SS}) > 0.5$
- $\Delta R(\tau_{SS},\tau_{OS}) > 0.5$
- Opposite sign taus

Additional Vetoes

- Tight B-jet veto
  - Combined Secondary Vertex (CVS)
- $M_T(\mu,MET) > 30$
  - Removes overlap with main $H\rightarrow\tau\tau$ search
- Extra lepton veto
  - Removes overlap with $ZH\rightarrow\tau\tau$ search

Muons

- $p_T > 24$ GeV/c
- $|\eta| < 2.1$
- Tight muon ID
- Relative isolation < 0.1
- $\Delta Z(\mu,PV) < 0.2$ cm
- $\Delta XY(\mu,PV) < 0.045$ cm

Taus (x2)

- $p_T > 25$ (20) GeV/c for lead (sublead) τ
- $|\eta| < 2.1$
- Decay mode > 0
- Loose (medium) isolation for OS (SS) to μ
- Tight muon rejection
- Loose electron rejection
- $\Delta Z(\tau,PV) < 0.2$ cm

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2},$$

$$M_T(v_1,v_2) = \sqrt{(v_1.ET + v_2.ET)^2 - (v_1.px + v_2.px)^2 - (v_1.py + v_2.py)^2}$$

Electron Channel Selections

Trigger

- Electron + tau trigger
- OS Tau is a trigger tau

Topological

- $\Delta R(e,\tau_{OS}) > 0.5$
- $\Delta R(e,\tau_{SS}) > 0.5$
- $\Delta R(\tau_{SS},\tau_{OS}) > 0.5$
- Opposite sign taus

Additional Vetoes

- Tight B-jet veto
  - Combined Secondary Vertex (CVS)
- $M_T(e,MET) > 30$
  - Removes overlap with main $H\rightarrow\tau\tau$ search
- Extra lepton veto
  - Removes overlap with $ZH\rightarrow\tau\tau$ search

Electrons

- $p_T > 24$ GeV/c
- $|\eta| < 2.1$
- Loose electron ID
- Relative isolation < 0.1
- $\Delta Z(e,PV) < 0.2$ cm
- $\Delta XY(e,PV) < 0.045$ cm

Taus (x2)

- $p_T > 25$ (20) GeV/c for lead (sublead) τ
- $|\eta| < 2.1$
- Decay mode > 0
- Medium isolation
- Tight muon rejection
- Loose (tight) electron rejection for SS (OS) to e
- $\Delta Z(\tau,PV) < 0.2$ cm

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2},$$

$$M_T(v_1, v_2) = \sqrt{(v_1.ET + v_2.ET)^2 - (v_1.px + v_2.px)^2 - (v_1.py + v_2.py)^2}$$

Efficiencies muons

	Signal (MH = 125)	WZ -> 3LNu	ZZ -> 4L	W+2Jets	TTBar	DY->mumu	DY->tautau
Trigger Bit	43.2604 +- 0.485443%	61.8255 +- 0.0463604%	58.8243 +- 0.0300679%	51.1481 +- 0.0160098%	33.1181 +- 0.0282311%	49.3574 +- 0.00833299%	13.9299 +- 0.0146391%
Muon Pt > 24	99.1567 +- 0.136227%	99.6867 +- 0.00678247%	99.643 +- 0.00475088%	99.6257 +- 0.00273463%	99.667 +- 0.00600493%	99.6253 +- 0.00144941%	98.631 +- 0.0131628%
Muon Eta < 2.1	99.9105 +- 0.0447427%	99.9577 +- 0.00249827%	99.9467 +- 0.00184184%	99.9986 +- 0.000170815%	99.9957 +- 0.000680751%	99.946 +- 0.000552118%	99.9935 +- 0.000919893%
Muon ID Tight	98.0511 +- 0.206901%	98.5738 +- 0.0144155%	98.8549 +- 0.00849245%	97.8083 +- 0.00656917%	97.7975 +- 0.0153238%	98.9855 +- 0.00238247%	97.8998 +- 0.0163555%
Muon Rel Iso < 0.1	92.1864 +- 0.405667%	95.3867 +- 0.0256883%	96.0899 +- 0.0155614%	91.7358 +- 0.0124915%	88.8073 +- 0.0332866%	95.9044 +- 0.00473605%	91.2347 +- 0.0326002%
Muon XY Vertex < 0.045	100 +- 0%	99.9956 +- 0.000831863%	99.9946 +- 0.000599919%	99.9969 +- 0.000261647%	99.9946 +- 0.000823057%	99.9993 +- 6.32956e-05%	99.978 +- 0.00178975%
Muon Z Vertex < 0.2	100 +- 0%	99.9962 +- 0.000770191%	99.9973 +- 0.000424235%	99.9952 +- 0.000327451%	99.997 +- 0.000614936%	99.9942 +- 0.000186587%	99.9633 +- 0.00231243%
Tau 1 Pt > 25	85.4027 +- 0.55584%	99.5414 +- 0.00847203%	99.4364 +- 0.00613138%	98.8947 +- 0.00495246%	99.8459 +- 0.0043955%	98.6291 +- 0.0028375%	95.8256 +- 0.0241458%
Tau 1 Eta < 2.1	95.502 +- 0.353067%	99.7444 +- 0.00634523%	99.7331 +- 0.00423737%	99.4154 +- 0.00363132%	99.8827 +- 0.00383795%	99.5976 +- 0.00155556%	98.4618 +- 0.0151775%
Tau 1 Decay Mode > 0	93.6797 +- 0.424157%	99.1686 +- 0.0114259%	99.1651 +- 0.00748341%	98.2794 +- 0.00621225%	99.4094 +- 0.00859639%	98.9086 +- 0.00255809%	96.9666 +- 0.0213161%
Tau 1 Isolation	70.3536 +- 0.822513%	88.1268 +- 0.0408755%	91.2092 +- 0.0233862%	74.8123 +- 0.0209185%	68.2951 +- 0.0523608%	89.7827 +- 0.00749814%	82.6724 +- 0.0477713%
Tau 1 Mu Reject Tight	97.9714 +- 0.302703%	29.3331 +- 0.0612856%	35.3029 +- 0.0413289%	1.32381 +- 0.00636768%	13.5649 +- 0.0466237%	0.300411 +- 0.00142987%	21.1682 +- 0.0567061%
Tau 1 Ele Reject Loose	99.7176 +- 0.115107%	45.3659 +- 0.123734%	47.9749 +- 0.0727134%	99.3458 +- 0.0390372%	47.3376 +- 0.184586%	97.8322 +- 0.0694198%	88.5601 +- 0.0960344%
Tau 1 Z Vertex < 0.2	99.9056 +- 0.0667082%	98.4273 +- 0.0459097%	98.5252 +- 0.0253299%	97.7625 +- 0.0718525%	98.3023 +- 0.0694153%	90.7163 +- 0.139861%	99.6351 +- 0.0193319%
Tau 2 Pt > 20	63.675 +- 1.04527%	84.3471 +- 0.135146%	92.7007 +- 0.0550684%	89.0249 +- 0.153585%	97.013 +- 0.0922564%	89.4436 +- 0.155483%	98.9178 +- 0.0332328%
Tau 2 Eta < 2.1	91.6914 +- 0.751767%	98.8372 +- 0.0434163%	99.0476 +- 0.0213556%	99.7559 +- 0.0256956%	99.7639 +- 0.026707%	99.2729 +- 0.0454552%	99.8686 +- 0.0116995%
Tau 2 Decay Mode > 0	88.2686 +- 0.915311%	97.6835 +- 0.0612777%	97.4238 +- 0.035001%	98.2411 +- 0.0685375%	98.6283 +- 0.0640749%	97.9902 +- 0.0753579%	96.8586 +- 0.0563698%
Tau 2 Isolation	51.3291 +- 1.51323%	76.9582 +- 0.17356%	83.9806 +- 0.0820987%	76.5455 +- 0.22289%	66.2123 +- 0.262366%	81.3024 +- 0.211502%	80.8673 +- 0.129159%
Tau 2 Mu Reject Tight	95.8929 +- 0.838627%	25.0315 +- 0.203526%	36.7702 +- 0.117772%	0.216904 +- 0.0279718%	1.29653 +- 0.0771163%	0.148395 +- 0.0231582%	0.237327 +- 0.0177673%
Tau 2 Ele Reject Loose	100 +- 0%	35.679 +- 0.449859%	33.8898 +- 0.190658%	100 +- 0%	64.8746 +- 2.85789%	100 +- 0%	91.0112 +- 2.14382%
Tau 2 Z Vertex < 0.2	99.6276 +- 0.262864%	97.998 +- 0.220204%	97.8217 +- 0.101001%	88.3333 +- 4.14438%	90.0552 +- 2.2244%	80.4878 +- 6.18908%	89.5062 +- 2.40789%
dR(mu,tau1) > 0.5	100 +- 0%	99.9243 +- 0.043667%	99.9804 +- 0.00978713%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%
dR(tau1,tau2) > 0.5	100 +- 0%	99.9748 +- 0.0252366%	99.9755 +- 0.0109442%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%
dR(mu,tau2) > 0.5	99.4393 +- 0.322839%	99.798 +- 0.0713347%	99.7895 +- 0.0320727%	100 +- 0%	100 +- 0%	96.9697 +- 2.98404%	100 +- 0%
Opposite Sign Taus	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%
B Veto Tight	88.5338 +- 1.38136%	97.7738 +- 0.234653%	97.4486 +- 0.11045%	96.2264 +- 2.6175%	25.7669 +- 3.42559%	100 +- 0%	97.2414 +- 1.36015%
Mt(e,MET) > 30	86.1996 +- 1.58924%	87.1151 +- 0.538905%	75.1322 +- 0.306712%	88.2353 +- 4.51156%	83.3333 +- 5.75055%	65.625 +- 8.39617%	30.4965 +- 3.8772%
Primary Vertex Cut	98.5222 +- 0.598848%	99.406 +- 0.132427%	99.4036 +- 0.0630331%	100 +- 0%	100 +- 0%	100 +- 0%	97.6744 +- 2.29838%
Electron Veto	99.25 +- 0.431386%	71.0188 +- 0.784182%	71.0106 +- 0.372535%	100 +- 0%	82.8571 +- 6.37049%	100 +- 0%	97.619 +- 2.35244%
Extra Muon Veto	84.6348 +- 1.80988%	96.9289 +- 0.353882%	30.0864 +- 0.446879%	100 +- 0%	93.1034 +- 4.70544%	33.3333 +- 10.2869%	100 +- 0%
MVA Against Fakes > -0.17	56.25 +- 2.70633%	38.7153 +- 1.01479%	36.5415 +- 0.855415%	6.66667 +- 3.71849%	29.6296 +- 8.78772%	14.2857 +- 13.226%	7.31707 +- 4.06702%

Efficiencies electrons

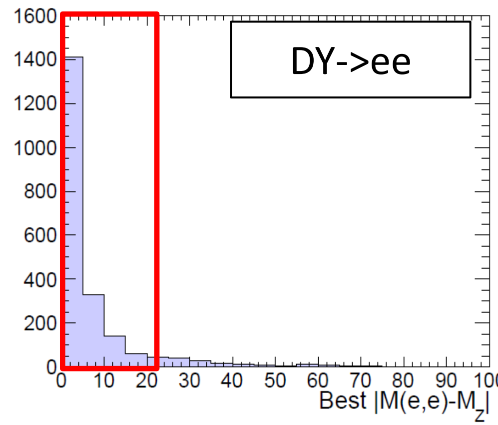
	Signal (MH = 125)	WZ -> 3LNu	ZZ -> 4L	W+2Jets	TTBar	DY->ee	DY->tautau
Trigger Bit	58.659 +- 0.719608%	36.8766 +- 0.0406828%	38.9921 +- 0.026449%	10.9763 +- 0.00723517%	13.7444 +- 0.0147762%	28.1056 +- 0.00760393%	2.21218 +- 0.0034137%
SS Tau not Trigger Tau	62.9778 +- 0.921288%	81.4052 +- 0.054024%	90.7953 +- 0.0251059%	31.181 +- 0.0323624%	47.6897 +- 0.0578162%	87.2922 +- 0.0106272%	69.9356 +- 0.0715547%
Electron Pt > 24	97.2832 +- 0.390861%	91.7995 +- 0.042226%	93.2708 +- 0.0228331%	87.3066 +- 0.0416494%	87.9412 +- 0.0545858%	96.8699 +- 0.00594677%	84.5487 +- 0.0674451%
Electron Eta < 2.1	99.7623 +- 0.118694%	98.7443 +- 0.0178864%	98.7676 +- 0.0104115%	99.5961 +- 0.00849273%	99.699 +- 0.00979133%	99.3648 +- 0.0027567%	99.6738 +- 0.0115711%
Electron MVA ID loose	96.7838 +- 0.430574%	95.9978 +- 0.0316842%	96.5265 +- 0.0173874%	93.7251 +- 0.0325374%	93.915 +- 0.0427944%	96.6793 +- 0.00623703%	90.7216 +- 0.0589741%
Electron Rel Iso < 0.1	95.8154 +- 0.496728%	97.1685 +- 0.0273657%	97.3032 +- 0.0156563%	96.5517 +- 0.0252876%	94.9631 +- 0.0403999%	97.4111 +- 0.00562204%	95.4597 +- 0.0444288%
Electron XY Vertex	99.7431 +- 0.128287%	99.6832 +- 0.00940549%	99.7125 +- 0.00524633%	99.709 +- 0.00759761%	99.7517 +- 0.00943385%	99.6773 +- 0.00203427%	99.6584 +- 0.0127445%
Electron Z Vertex	99.678 +- 0.143752%	99.8499 +- 0.00648876%	99.8846 +- 0.0033319%	99.0611 +- 0.0136217%	99.9337 +- 0.00488466%	99.6247 +- 0.00219686%	98.9501 +- 0.0223009%
Tau 1 Pt > 25	96.5762 +- 0.46217%	99.8258 +- 0.00699578%	99.7842 +- 0.0045561%	99.1564 +- 0.0129797%	99.7812 +- 0.00887107%	99.6164 +- 0.00222512%	98.0377 +- 0.0305087%
Tau 1 Eta < 2.1	98.3278 +- 0.33164%	99.8886 +- 0.00559994%	99.8697 +- 0.00354565%	99.6019 +- 0.00897411%	99.8378 +- 0.00764856%	99.8214 +- 0.00152262%	99.3298 +- 0.0181249%
Tau 1 Decay Mode > 0	97.8912 +- 0.374744%	99.3494 +- 0.0135061%	99.266 +- 0.00839522%	98.5968 +- 0.0167965%	99.2666 +- 0.0162309%	99.1006 +- 0.00340783%	97.9734 +- 0.0314078%
Tau 1 Isolation medium	71.369 +- 1.19163%	88.5253 +- 0.0537188%	90.4093 +- 0.029067%	73.1571 +- 0.0637298%	71.3279 +- 0.0863406%	88.8659 +- 0.0114058%	84.5871 +- 0.0813099%
Tau 1 Mu Reject tight	98.0526 +- 0.431195%	93.6175 +- 0.0437887%	93.8899 +- 0.0248654%	99.9443 +- 0.00396693%	93.285 +- 0.056579%	99.9684 +- 0.000684167%	97.9851 +- 0.0344039%
Tau 1 Ele Reject loose	93.8431 +- 0.757474%	8.33925 +- 0.0511877%	9.97222 +- 0.0321024%	4.57908 +- 0.0351563%	6.81655 +- 0.0589891%	0.707723 +- 0.00322493%	34.2437 +- 0.117375%
Tau 1 Z Vertex	100 +- 0%	99.5191 +- 0.0443547%	99.528 +- 0.023253%	98.3445 +- 0.100288%	99.1963 +- 0.0800429%	95.644 +- 0.0933411%	99.9035 +- 0.0131232%
Tau 2 Pt > 20	74.1799 +- 1.42366%	97.2079 +- 0.105879%	97.4972 +- 0.0531244%	98.9824 +- 0.0795414%	99.1088 +- 0.0845925%	98.2508 +- 0.0612992%	99.0807 +- 0.0403597%
Tau 2 Eta < 2.1	95.5777 +- 0.7765%	99.0567 +- 0.0630092%	99.153 +- 0.0315631%	99.4098 +- 0.0610176%	99.436 +- 0.0677116%	99.0542 +- 0.0456601%	99.3466 +- 0.0342305%
Tau 2 Decay Mode > 0	89.403 +- 1.18913%	97.006 +- 0.111617%	96.7243 +- 0.0615682%	97.0124 +- 0.136021%	97.8708 +- 0.130888%	96.8929 +- 0.0822413%	95.7321 +- 0.0861588%
Tau 2 Isolation medium	54.2571 +- 2.03553%	74.1366 +- 0.291179%	77.5193 +- 0.146818%	76.0018 +- 0.346435%	66.2579 +- 0.433351%	78.2717 +- 0.19858%	81.3437 +- 0.169711%
Tau 2 Mu Reject tight	97.8462 +- 0.805263%	96.642 +- 0.139126%	96.6205 +- 0.0721812%	99.9567 +- 0.0193557%	98.39 +- 0.141713%	99.9911 +- 0.00513071%	99.9277 +- 0.0129859%
Tau 2 Ele Reject loose	83.6478 +- 2.07397%	10.3314 +- 0.239113%	13.2956 +- 0.137976%	0.259853 +- 0.0473807%	0.721557 +- 0.0960735%	0.183682 +- 0.0233062%	0.280184 +- 0.0255413%
Tau 2 Z Vertex	99.6241 +- 0.375233%	99.1637 +- 0.222579%	99.5777 +- 0.0722721%	90 +- 5.47723%	89.2857 +- 4.13313%	91.9355 +- 3.45808%	91.6667 +- 2.52304%
dR(e,tau1) > 0.5	100 +- 0%	99.6988 +- 0.1345%	99.9376 +- 0.0278829%	92.5926 +- 5.0401%	94 +- 3.35857%	98.2456 +- 1.73893%	92.7273 +- 2.47603%
dR(tau1,tau2) > 0.5	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%
dR(e,tau2) > 0.5	100 +- 0%	98.6103 +- 0.287758%	99.326 +- 0.0914087%	68 +- 9.32952%	80.8511 +- 5.7394%	87.5 +- 4.41942%	67.6471 +- 4.63214%
Opposite Sign Taus	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%
B Veto = Tight	86.4151 +- 2.10475%	96.875 +- 0.430696%	96.5444 +- 0.204751%	100 +- 0%	21.0526 +- 6.61348%	100 +- 0%	94.2029 +- 2.81328%
Ele Rejection Tau OS = tight	85.5895 +- 2.32077%	86.3378 +- 0.863765%	90.108 +- 0.34061%	100 +- 0%	100 +- 0%	28.5714 +- 6.45363%	86.1538 +- 4.28396%
Mt(e,MET) > 30	84.6939 +- 2.57176%	89.6703 +- 0.823761%	81.2509 +- 0.469091%	88.2353 +- 7.81425%	87.5 +- 11.6927%	50 +- 13.3631%	33.9286 +- 6.32697%
Primary Vertex Cut	98.7952 +- 0.846788%	99.1013 +- 0.269746%	99.36 +- 0.106325%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%
Extra Electron Veto	100 +- 0%	97.7741 +- 0.423578%	36.5003 +- 0.643972%	100 +- 0%	100 +- 0%	57.1429 +- 18.7044%	100 +- 0%
Muon Veto	97.561 +- 1.20455%	99.747 +- 0.145857%	97.9412 +- 0.314396%	100 +- 0%	100 +- 0%	100 +- 0%	100 +- 0%
MVA Against Fakes > -0.17	59.375 +- 3.88274%	42.4345 +- 1.43697%	37.9379 +- 1.08556%	6.66667 +- 6.44061%	28.5714 +- 17.0747%	0 +- 0%	15.7895 +- 8.36547%

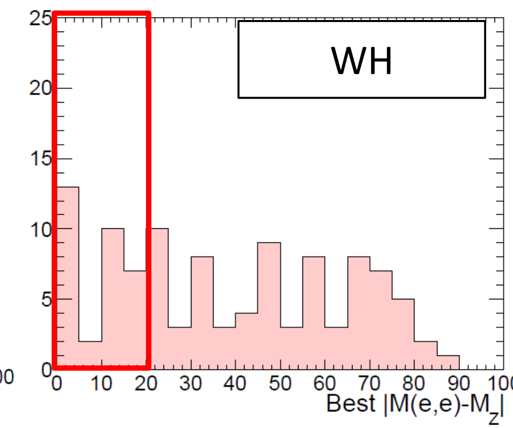
Improvements in the electron channel:
Goal and strategy

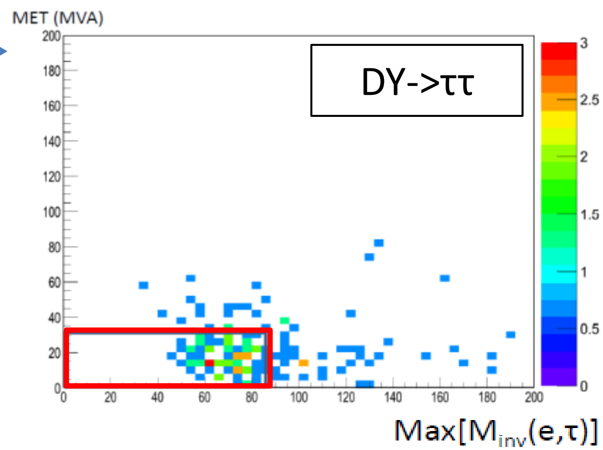
- Currently, high rates of W+Jets and DY+Jets require tight thresholds

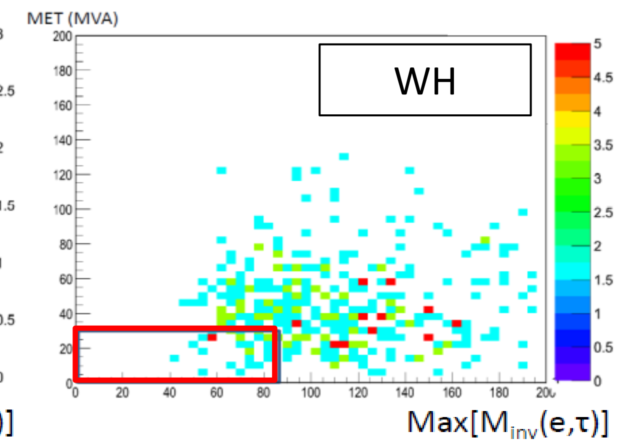
- **Electron ID (MVA)**
- **Z->ee veto [$M(e_{gsf},e_{gsf})$]**
- **τ p_T thresholds**
- **τ electron rejections**
- **MVA MET**
- **Z->ττ veto [M_T(e,MET)]**
- **τ isolations**

- Dedicated vetoes should allow us to loosen these cuts
- **DY->ee Veto (5 steps):**
  - M_{inv} between reco objects
  - EM fraction of τ's
  - dR between τ candidate and closest electron
  - Tighter electron rejection on τ's
- **DY->ττ (1 step):**
  - $M_{inv}(e,\tau_1)$, $M_{inv}(e,\tau_2)$
  - MET
- **W+Jets (1 step):**
  - "track isolation"
  - M_T(e,MET)









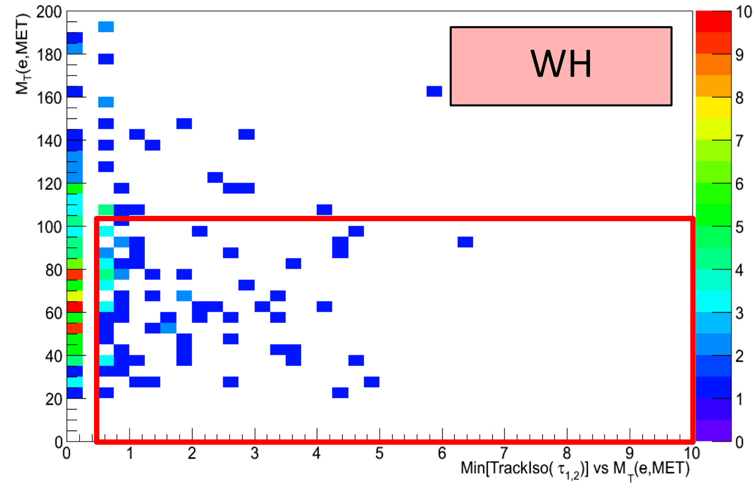
“Track Isolation” + M_T(e,MET) for W+Jets Suppression

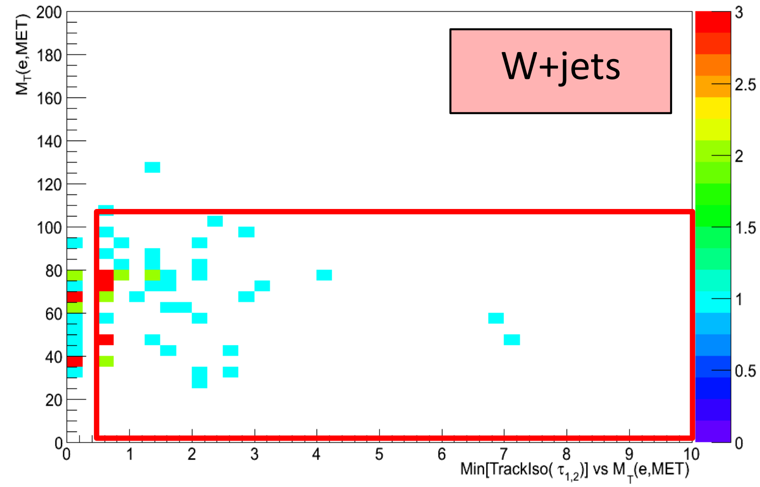
- **W+Jets Veto:**

$$TrackIso(\tau_1) > A \;\&\&\; TrackIso(\tau_2) > A \;\&\&\; M_T(e, MET) < B$$

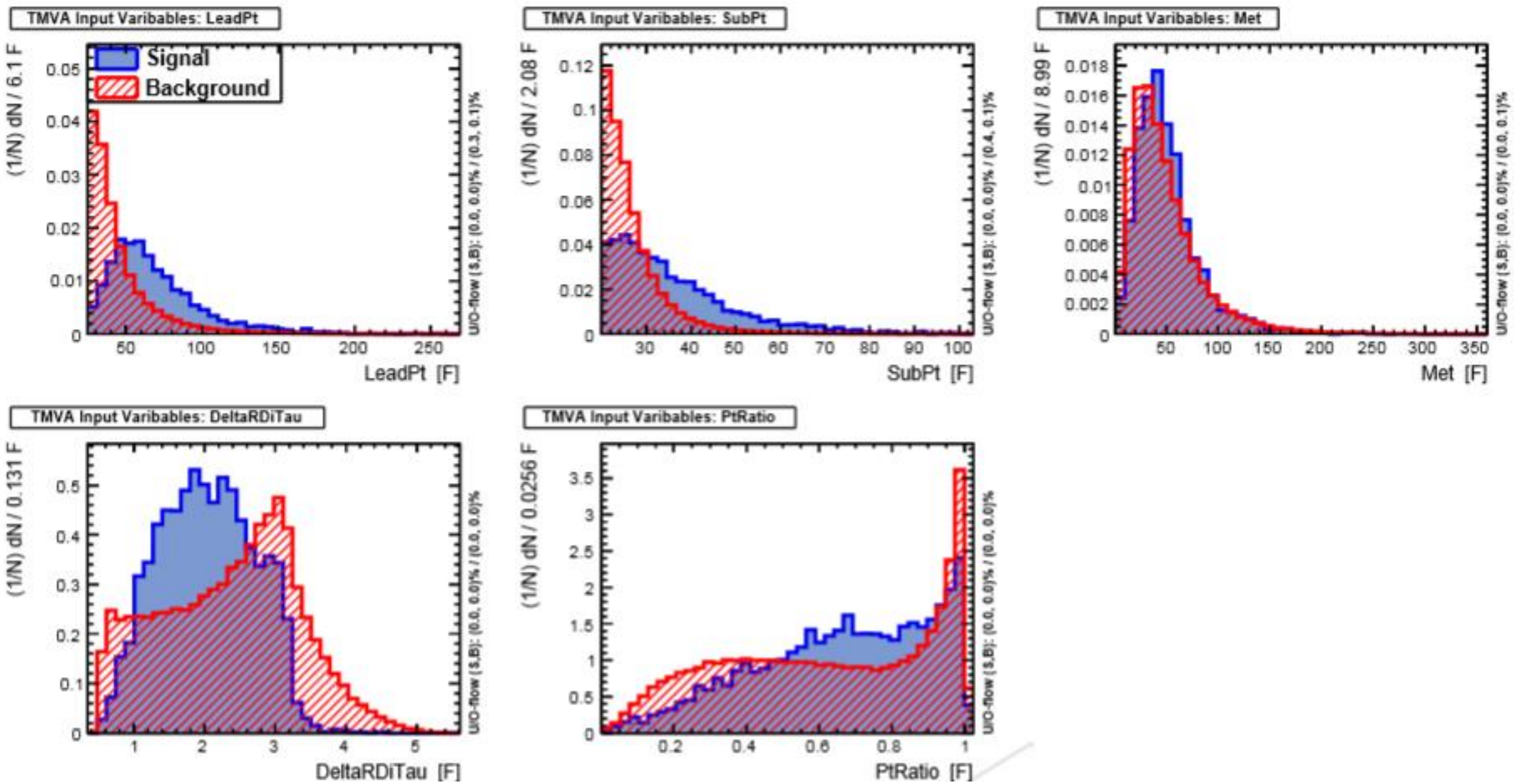
  – “Track isolation” of both τ’s is larger than some value
    - **“Track isolation”** is defined as the p_T sum of all charged hadrons with p_T > 0.5 GeV/c within an isolation cone around the τ of dR = 1.0
    - Applied **on top of standard tau isolations**

  – AND M_T(e,MET) relatively small
    - True M_T(e,MET) for W+2 jets can be no bigger than the W mass

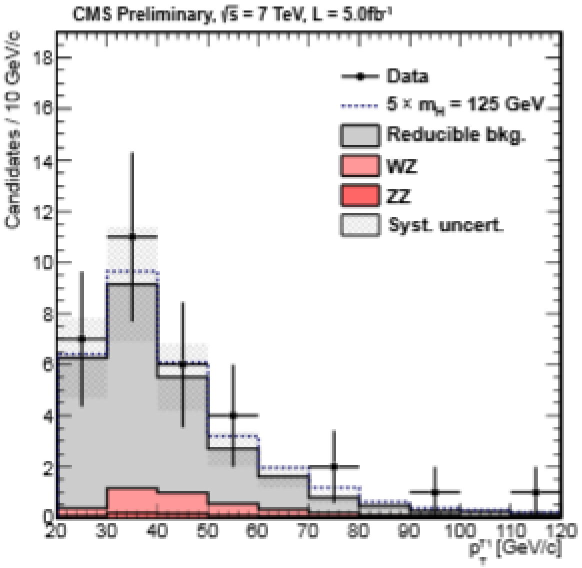


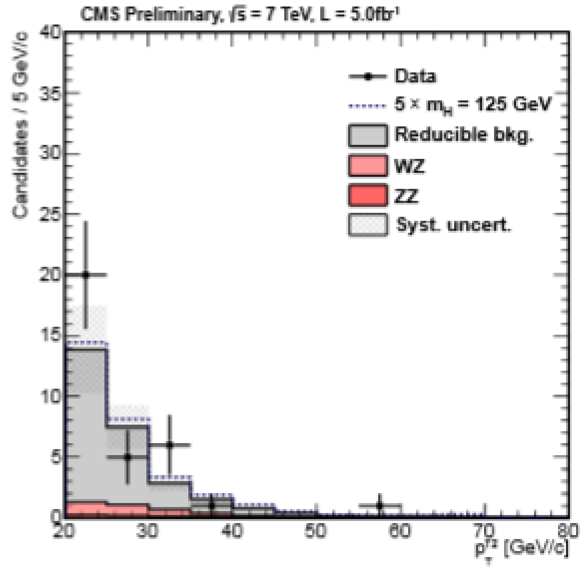


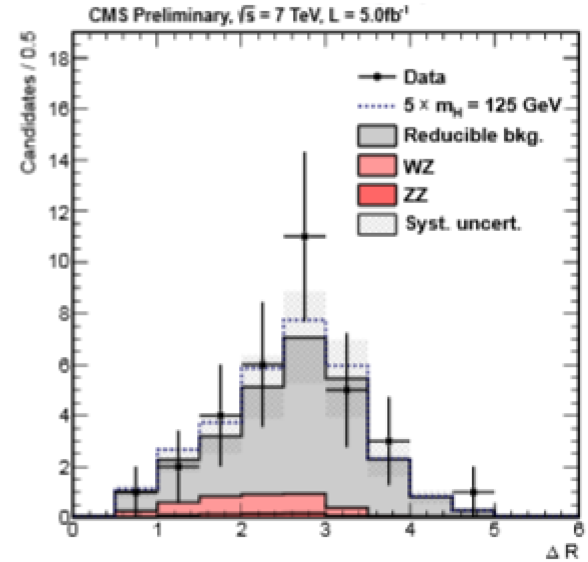
MVA Variable Plots

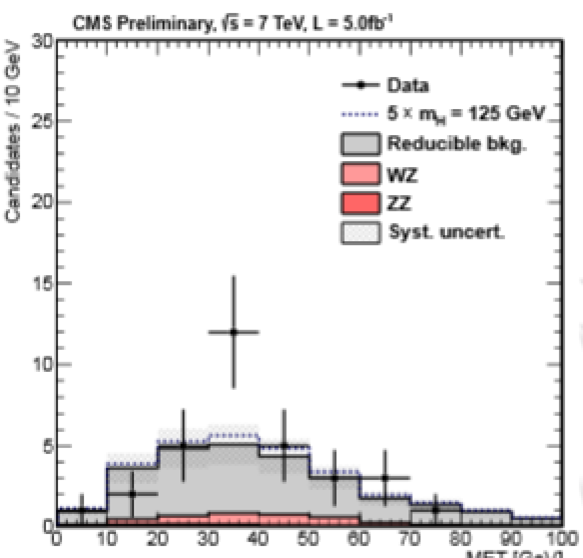


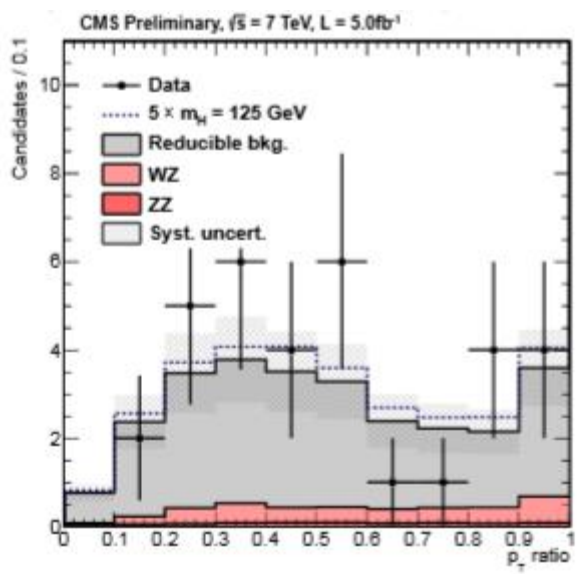
MVA Control plots: Muons 2011



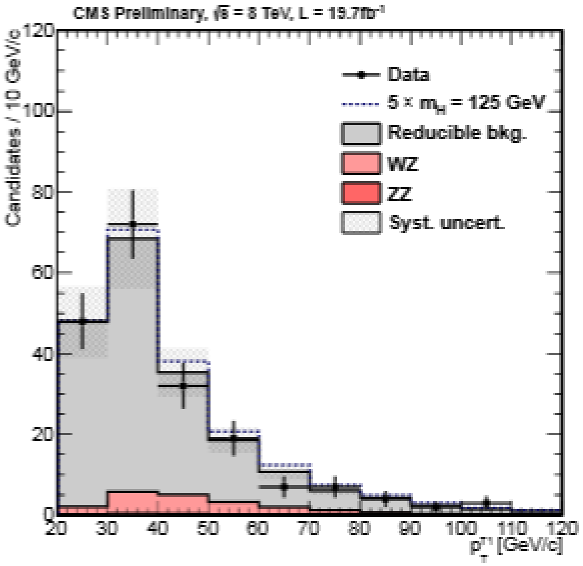


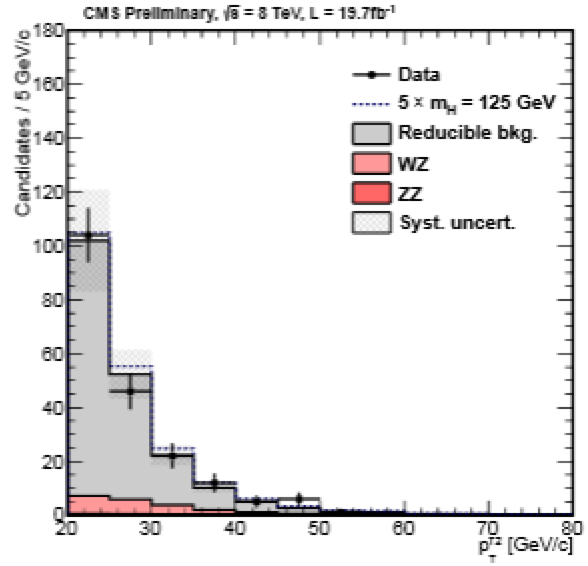


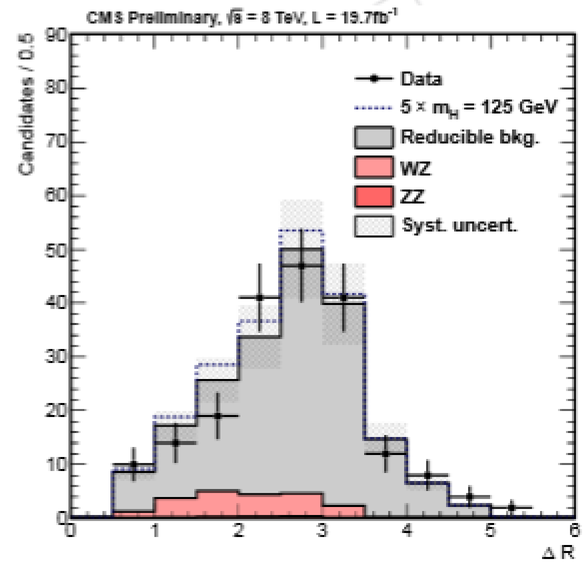


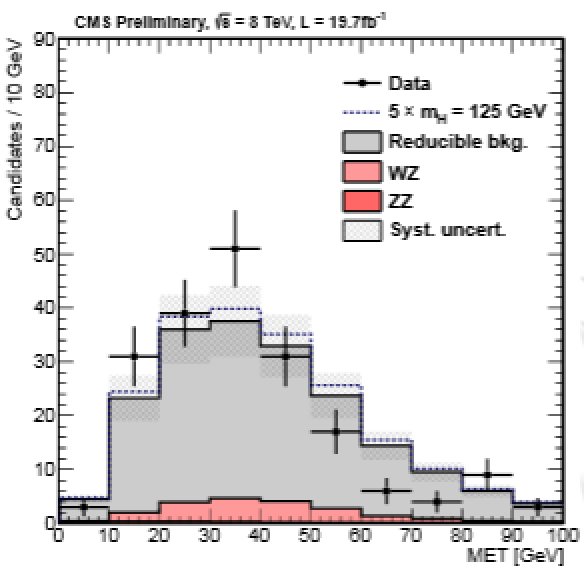


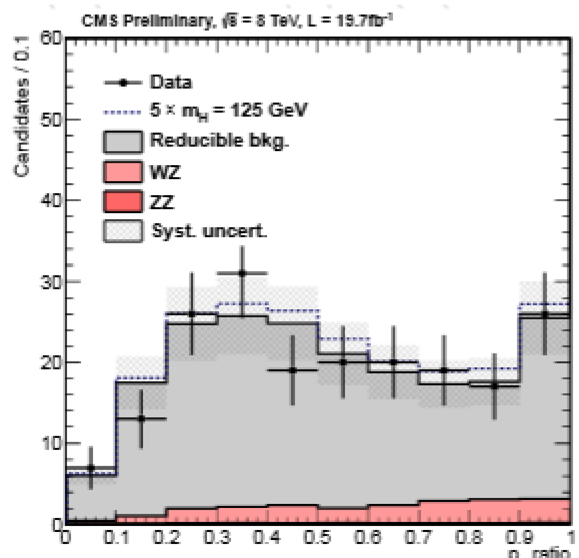
MVA Control plots: Muons 2012



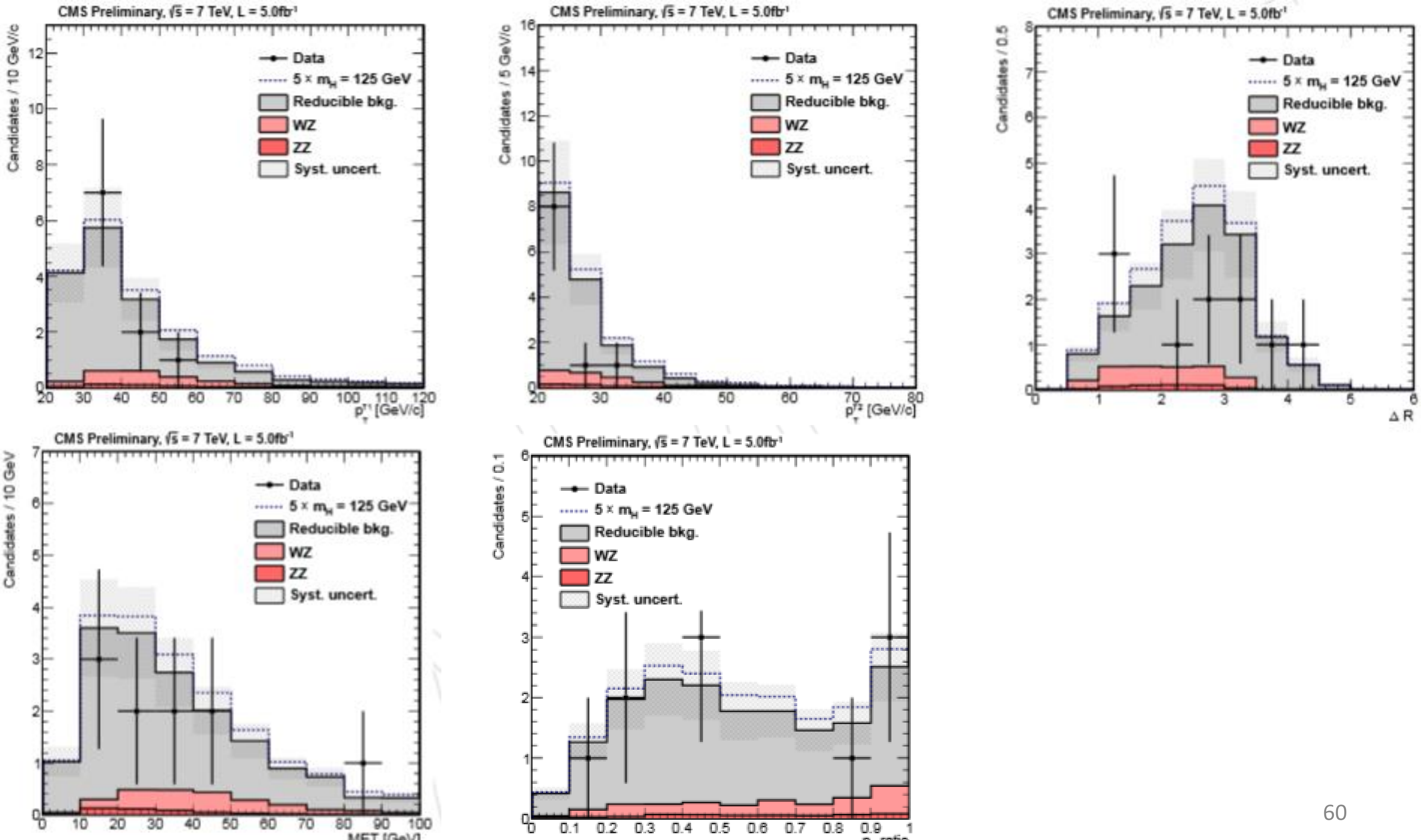




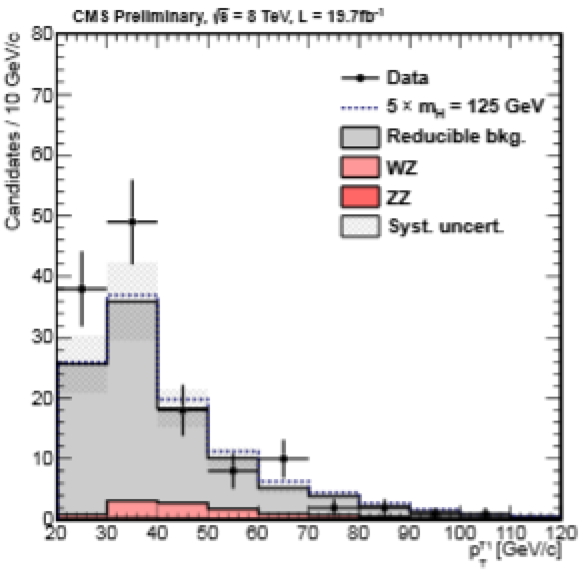


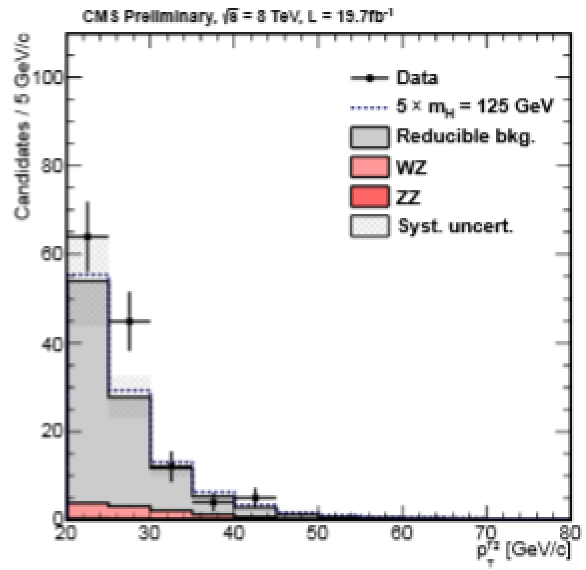


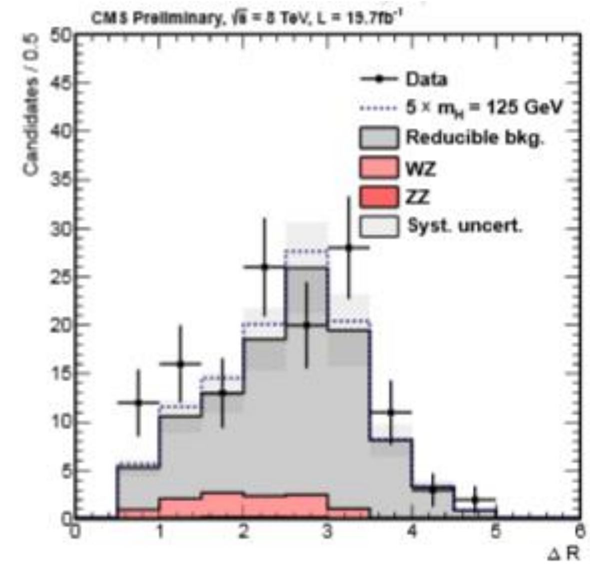
MVA Control plots: Electrons 2011

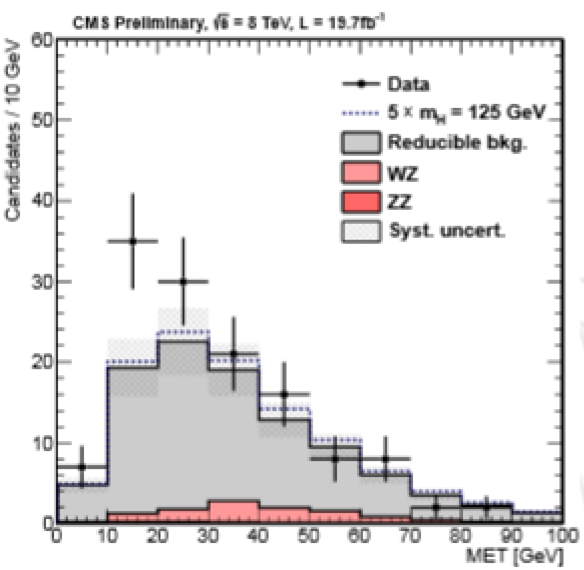


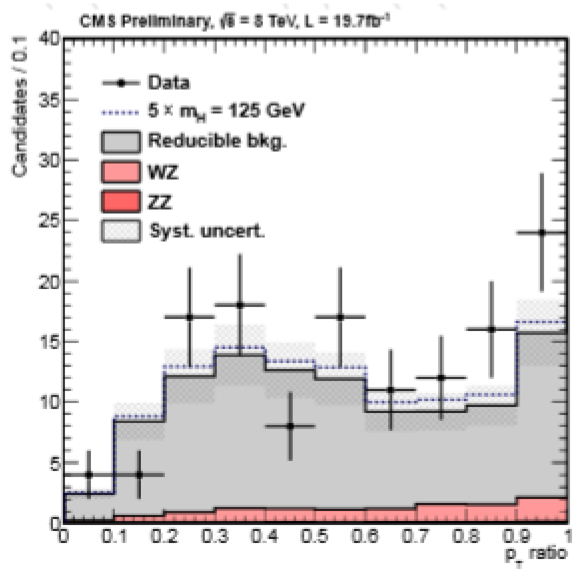
MVA Control plots: Electrons 2012



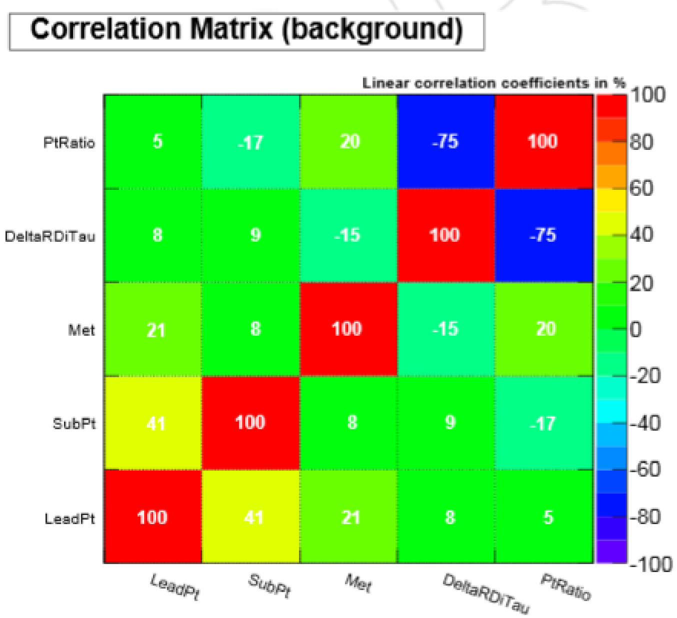


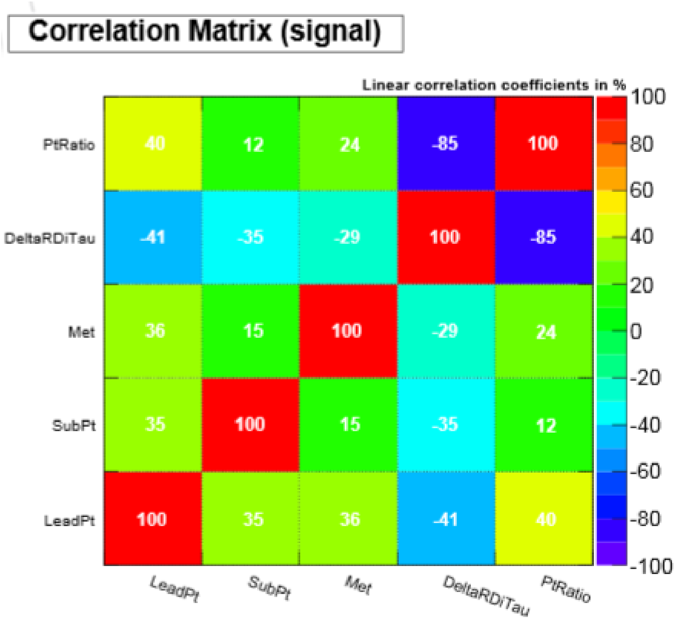


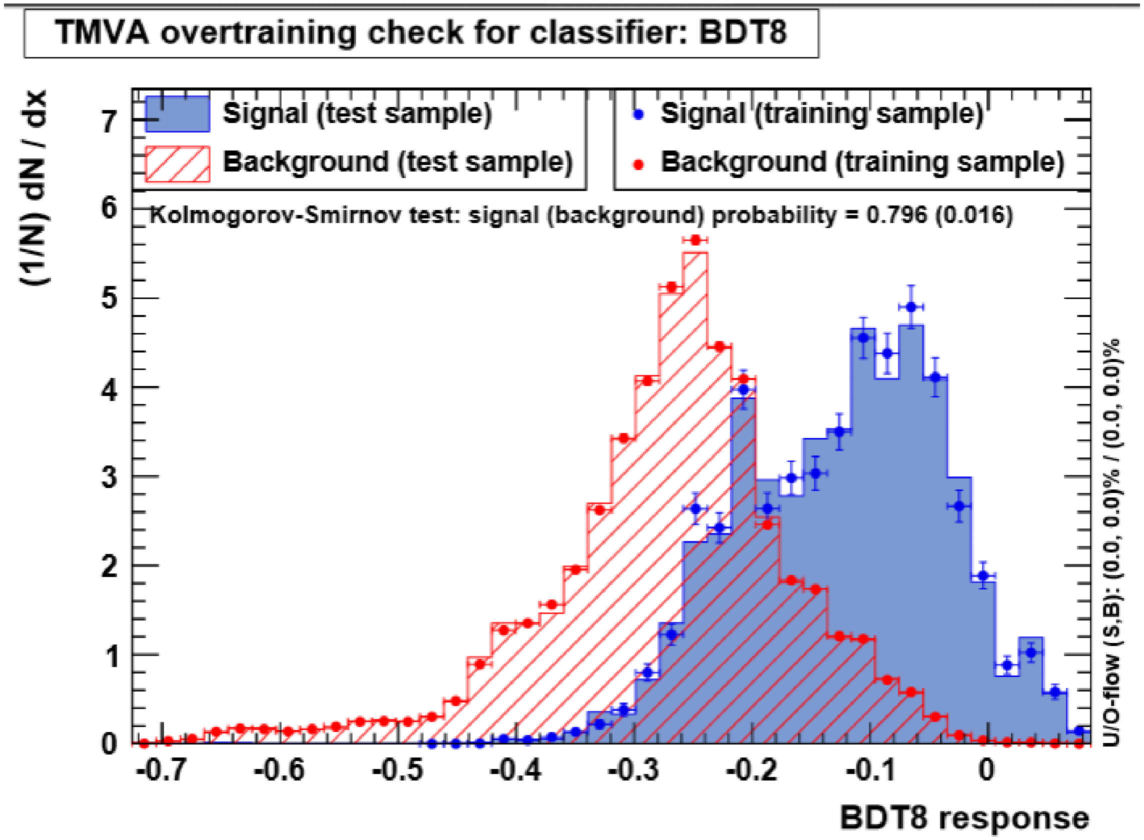




Overtraining Check







- *NNodesMax* set to 8 to minimize overtraining

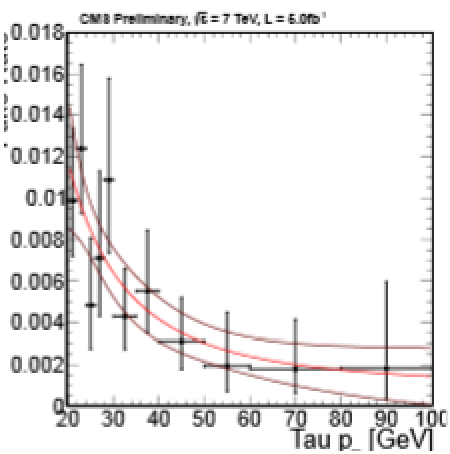
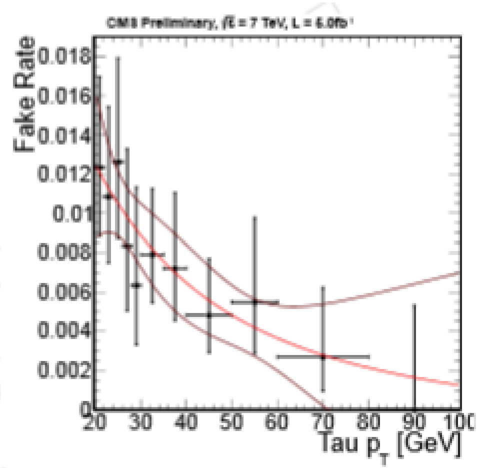
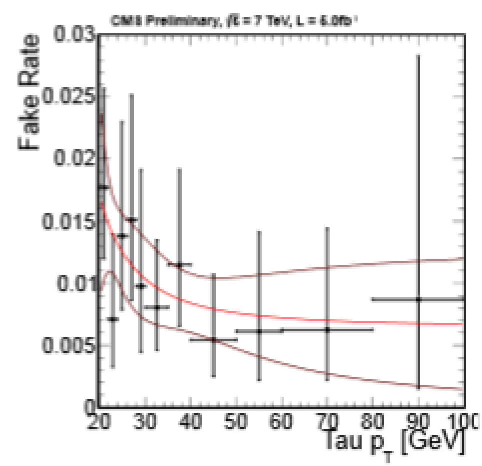
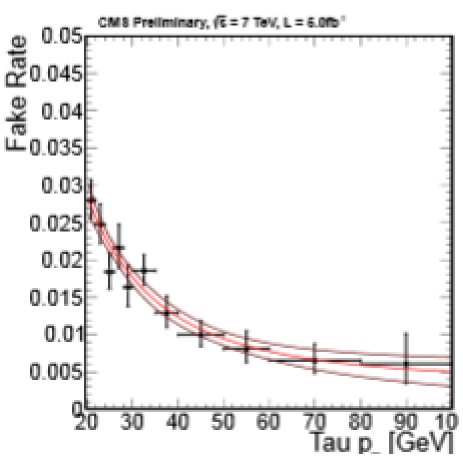
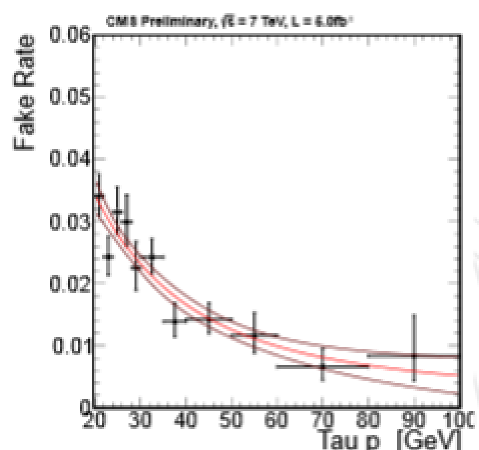
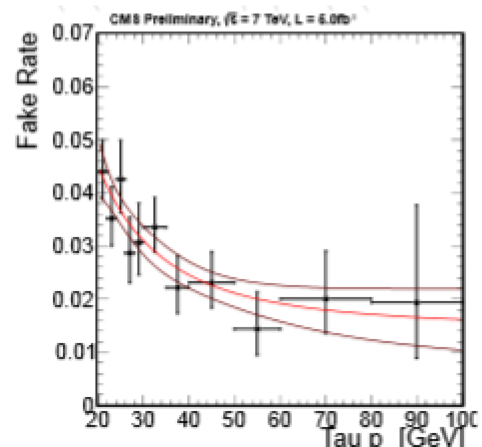
W+Jets FR Measurement

- Events must pass either the single electron, the electron+m_T trigger or the single muon trigger
- Require either an electron with $p_T > 27\,\text{GeV}/c$ and $|\eta| < 2.5$ or a muon with $p_T > 24\,\text{GeV}/c$ and $|\eta| < 2.1$
- If an electron was selected, the electron must pass the tight working point of the MVA identification
- In a muon was selected, the muon must pass the tight Particle Flow identification
- The Combined PF Relative Isolation, $\Delta\beta$ corrected, less than 0.1
- The longitudinal impact parameter of the lepton track with respect to the primary vertex must be less than 0.2 cm.
- $m_T > 40\,\text{GeV}$
- Two tau candidates are required, both with the same charge as the electron
- Events are rejected if they contain another muon or electron with $p_T > 15\,\text{GeV}/c$
- Events are rejected if they contain a jet with $p_T > 20\,\text{GeV}/c$ and $|\eta| < 2.4$ passing loose CSV b–tagging working point.

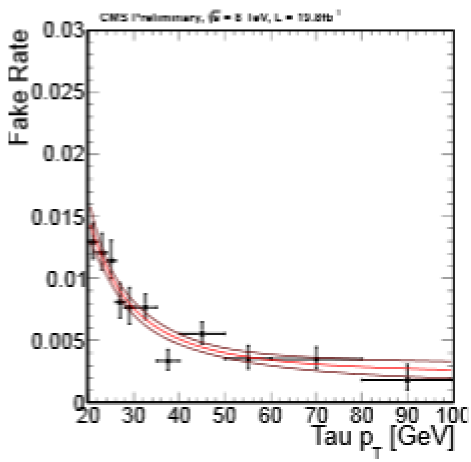
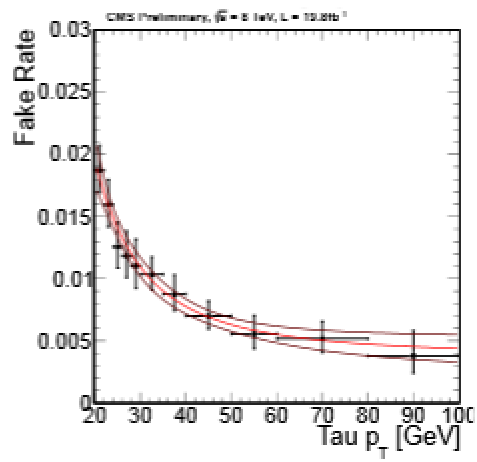
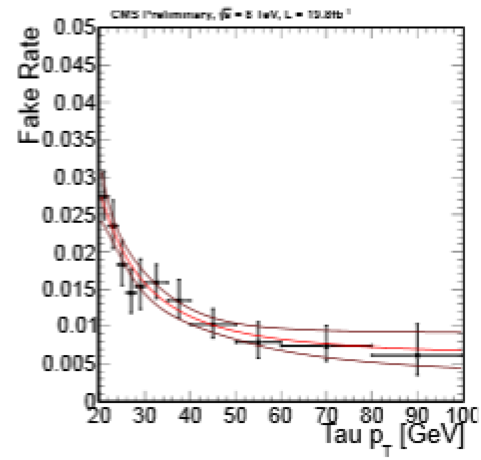
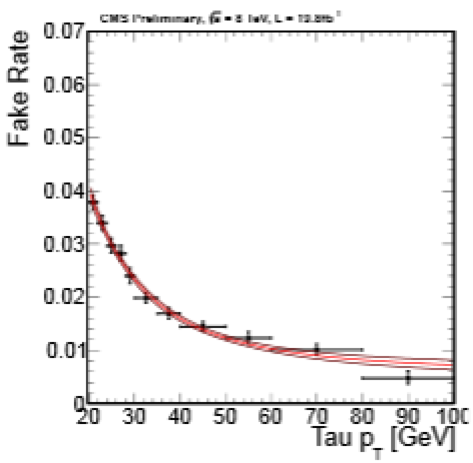
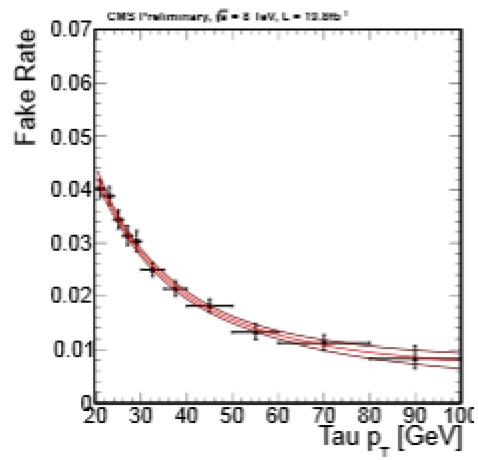
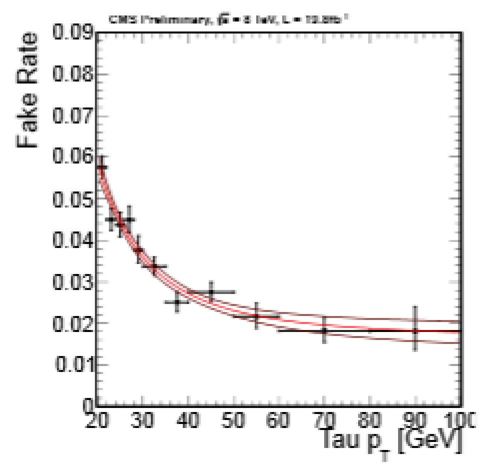
DY+Jets FR Measurement

- Two oppositely charged muons with $p_T \geq 20(10)$ GeV/c for the leading (sub-leading) muon, and $|\eta| \leq 2.1$ for both muons.
- Both muons are required to pass the "tight" Particle Flow identification.
- Both muons must have combined PF Relative Isolation, $\Delta\beta$ corrected, less than 0.10
- $|M_{\mu\mu} - M_Z| < 10\,\text{GeV}$
- The longitudinal impact parameters of the two muon tracks with respect to the primary vertex are less than 0.2 cm.
- At least one tau candidate
- Events are rejected if they contain another electron or muon with $p_T > 15\,\text{GeV}/c$
- Events are rejected if they contain a jet with $p_T > 20\,\text{GeV}/c$ and $|\eta| < 2.4$ passing loose CSV b–tagging working point.

2011 Fake Rates Muons

|η| < 0.8	**0.8 < |η| < 1.6**	**|η| > 1.6**	
			W+Jets
			Z+Jets

2012 Fake Rates Muons

|η| < 0.8	0.8 < |η| < 1.6	|η| > 1.6	
			W+Jets
			Z+Jets

2011 Fake Rates Electrons

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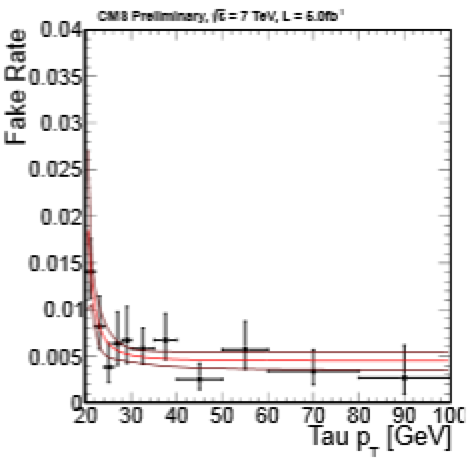
<td>
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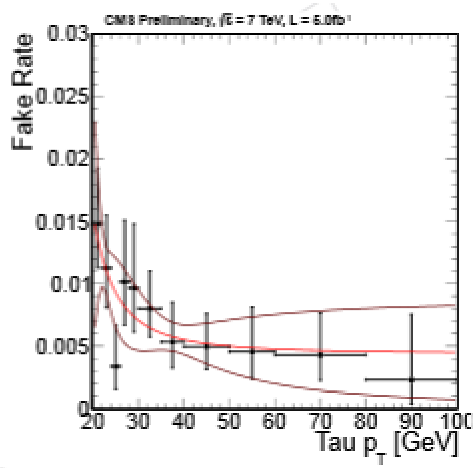
<td>
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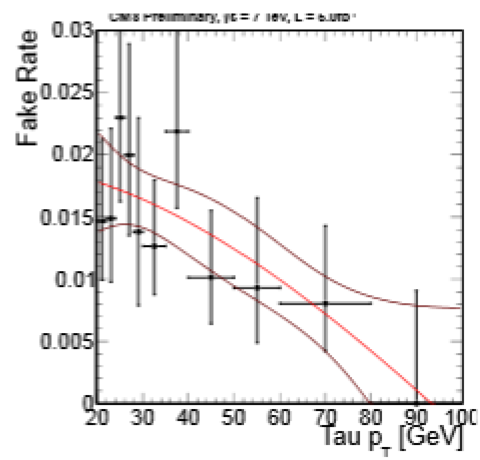
<td>
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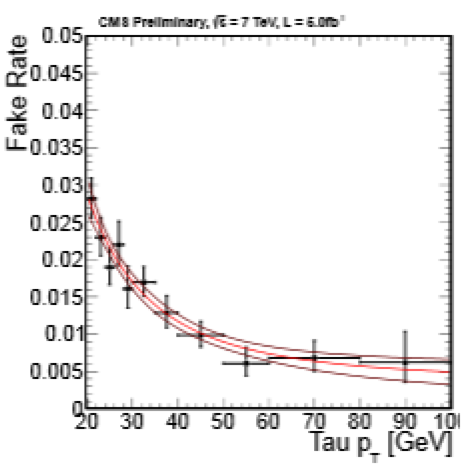
<td>
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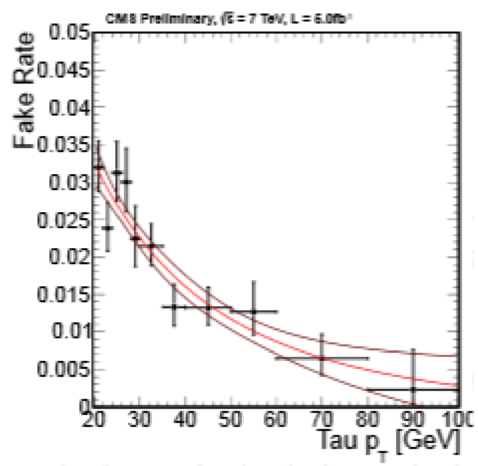
<td>
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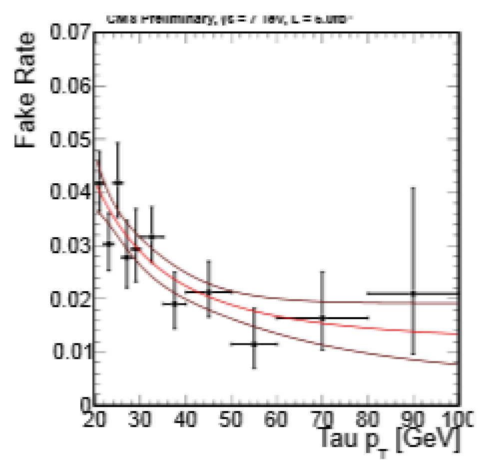
<td>
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2012 Fake Rates Electrons

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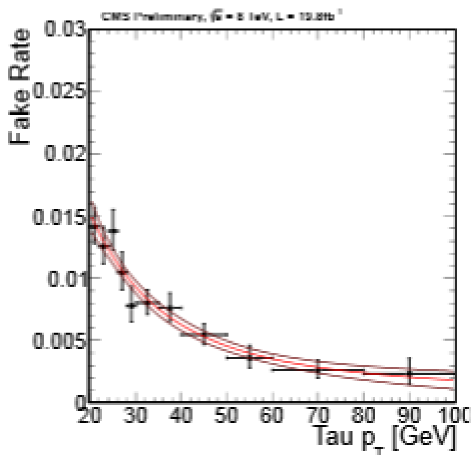
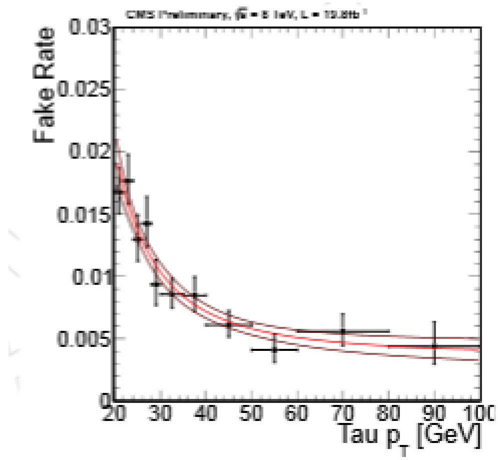
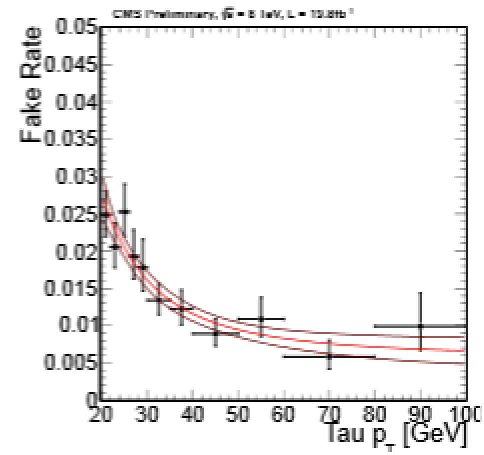
<tr><td>
</td><td>
</td><td>
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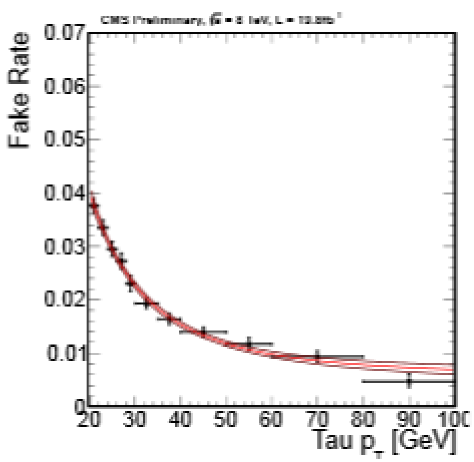
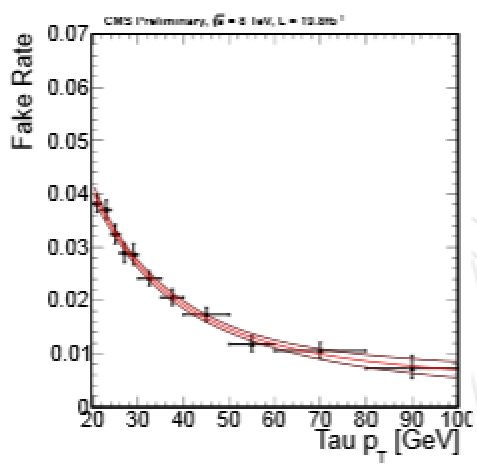
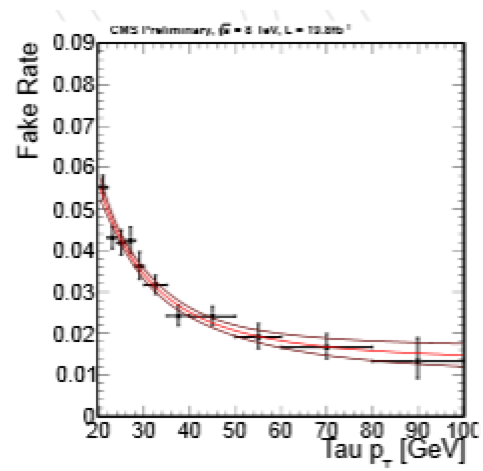
<tr><td>
</td><td>
</td><td>
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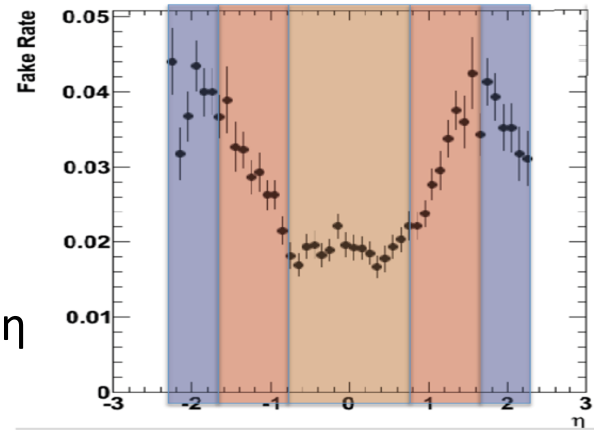
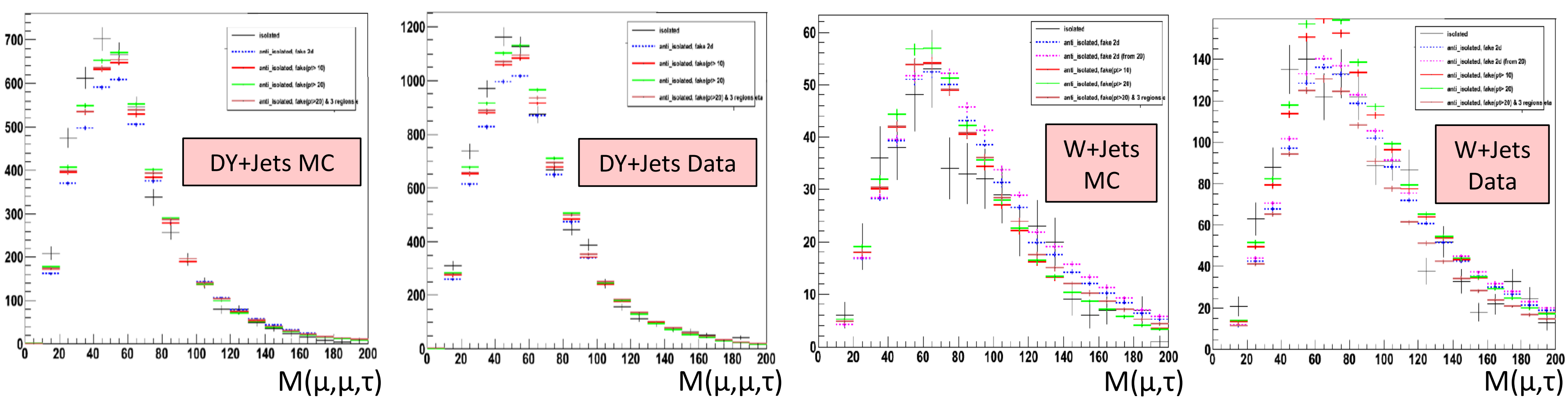
Fake Rate Improvements

- **Goal:** reduce systematics on background estimate (currently 20%) with better fake rate prediction
  - Want to describe fake rate in 2D (p_T vs. η)
    - Fit fake rate as a function of p_T in three η regions
    - Parameterize parameters of *FR(p_T)* as a function of η

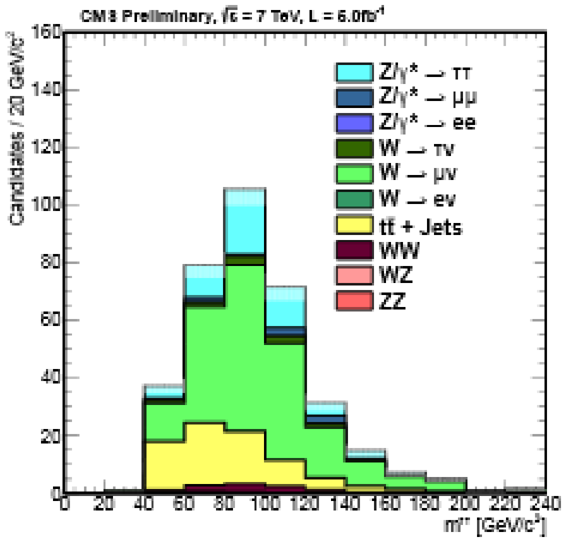


- **1st order method validation**
  - Use fake rate to extrapolate a kinematic distribution from the anti-isolated to isolated region in the same data that was used for the measurement

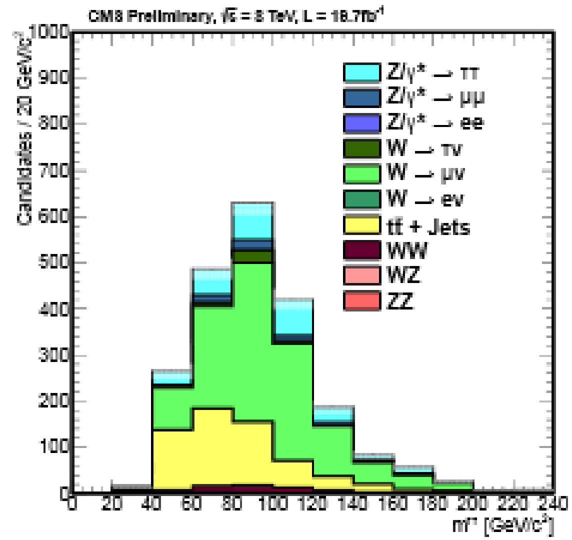


Isolated taus
Estimation with FR(p_T>10)
Estimation with FR(p_T>20)
Estimation with FR(p_T) in 3 η regions
Estimation with FR(p_T,η)

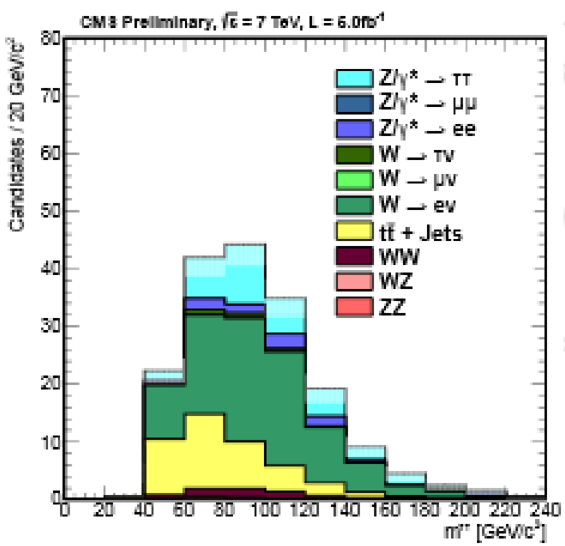
Fake rate background composition



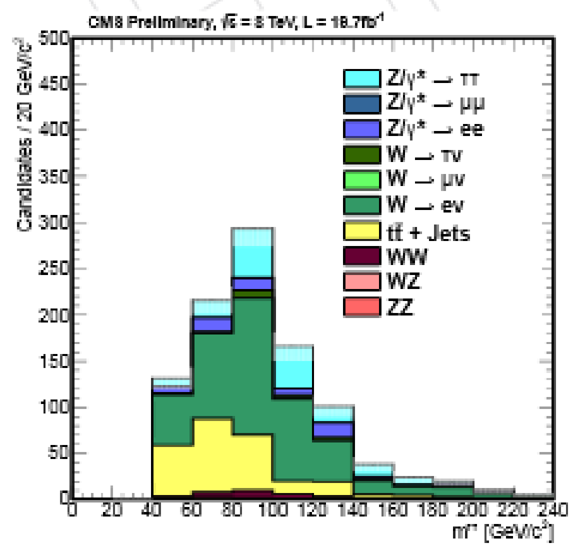
(a) 2011 data/MC comparison ($\mu\tau_h\tau_h$ final state).



(b) 2012 data/MC comparison ($\mu\tau_h\tau_h$ final state).



(c) 2011 data/MC comparison ($e\tau_h\tau_h$ final state).



(d) 2012 data/MC comparison ($e\tau_h\tau_h$ final state).

Systematics Details

- **Luminosity**: We consider a 2.2% (2.6%) uncertainty for 2011 (2012) [16, 17].
- **Theory Uncertainties**: We account a 3.4%, 4.0% and 3.3% error due to the imprecise knowledge of the proton PDF for signal, WZ and ZZ, respectively. These values were obtained as the maximal deviation from the central value while comparing different PDF with respect to the default one. Another 0.4%, 4.0% and 2.3% are accounted for the QCD scale in these processes.
- **Electron ID and Trigger Efficiency**: Electron trigger, identification and reconstruction efficiencies are measured with the "tag and probe" method. The total uncertainty accounted for this source is 2.0% [18].
- **Muon ID and Trigger Efficiency**: We assign a total systematic systematic uncertainty on muon trigger and ID efficiency of 2% [18].
- **Tau Trigger Efficiency**: The sample of events used in this search are collected with either the inclusive muon trigger or the $e + \tau_h$ trigger, depending on the channel. The trigger efficiency is measured with the Tag and Probe method on Drell-Yan events [18]. The total uncertainty arising is 3% for the tau trigger leg in the electron channel.
- **Tau ID Efficiency**: The tau identification systematic uncertainty measured in [19] is 6%. In a conservative approach, considering that the two selected taus are correlated, the total systematic uncertainty due to tau identification is 12%.

Systematics Details

- **Additional Lepton Veto**: For the additional lepton veto cut, a systematic uncertainty comes from the ID uncertainties on the additional lepton. This is obtained by propagating the electron and muon ID uncertainties to the event yield due to those cuts, multiplied by the cut inefficiencies. We find a value of 0.7% (3.8%) for the muon (electron) veto.
- ***b*-Tagging Efficiency**: We found this uncertainty to be negligible in our topology.
- **Electron and Muon Energy Scale**: Both uncertainties are found to be negligible.
- **Tau Energy Scale**: The 3% uncertainty on the tau scale measured by the tau POG is propagated to the final histogram used for computing the upper limit on Higgs $\sigma \times$ BR and treated as a shape uncertainty.
- **Jet Energy Scale**: Following JetMET POG prescription the JES prescriptions were propagated to the signal acceptance uncertainty which is found to be 1%
- E_T^{miss}: A 10% uncertainty on the MET is propagated to the final histogram and is treated as shape uncertainty.

Systematics Details

- **Fake Rate**: The uncertainties from the fits of the Fake Rate function as described in Section 6.3 are propagated to the event yield as a shape-altering uncertainty. This contribution is on the order of 5-10% for 8 TeV data and 10-20% for 7 TeV data.

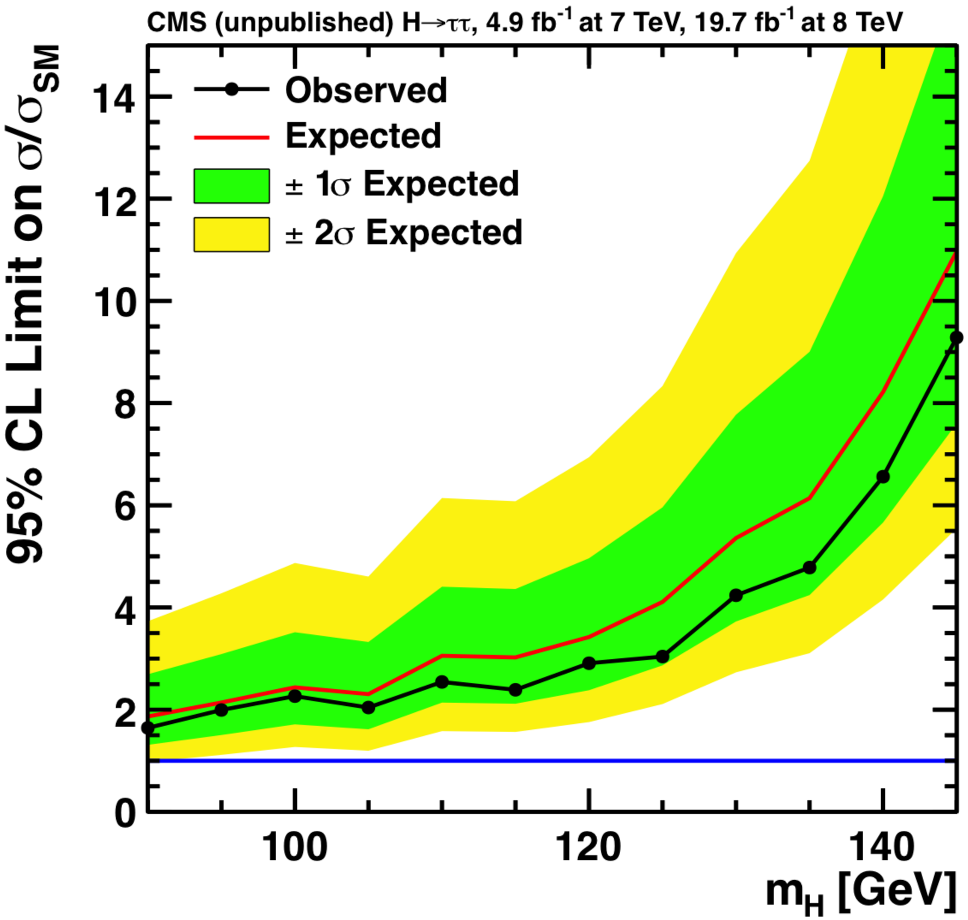
  As a second component, a 15% uncertainty on the normalization of the background estimated with the Fake Rate method is assumed. There are two contributions to this normalization uncertainty. The first is the limited knowledge of the composition of the background (we only have the expectation from simulation shown in Fig. 12), including the fact that we do not know how much the Fake Rates in QCD and $t\bar{t}$ events deviate from the Fake Rates measured in W+Jets and Z+Jets events. We attribute 10% uncertainty for this, covering the range from $W = 0.5 \times W_{\mathrm{W}} + 0.5 \times W_{\mathrm{Z}}$ to $W = 0.7 \times W_{\mathrm{W}} + 0.3 \times W_{\mathrm{Z}}$.

  The second contribution comes from the observed agreement in a control region. In this control region we invert the isolation of the tau which is opposite sign to the light lepton. We use the single electron trigger instead of the electron+tau trigger, because otherwise we would have a remaining trigger-level isolation requirement on the opposite sign tau. The agreement is shown in Fig. 13 after all cuts except the final cut on the MVA output. This region is largely dominated by W+Jets and QCD events, so the Fake Rate used for the background estimation is taken only from the measurement W+Jets-like events. The grey bands correspond to the shape altering systematic uncertainty. Another 10% uncertainty is attributed for any disagreement in this control region.

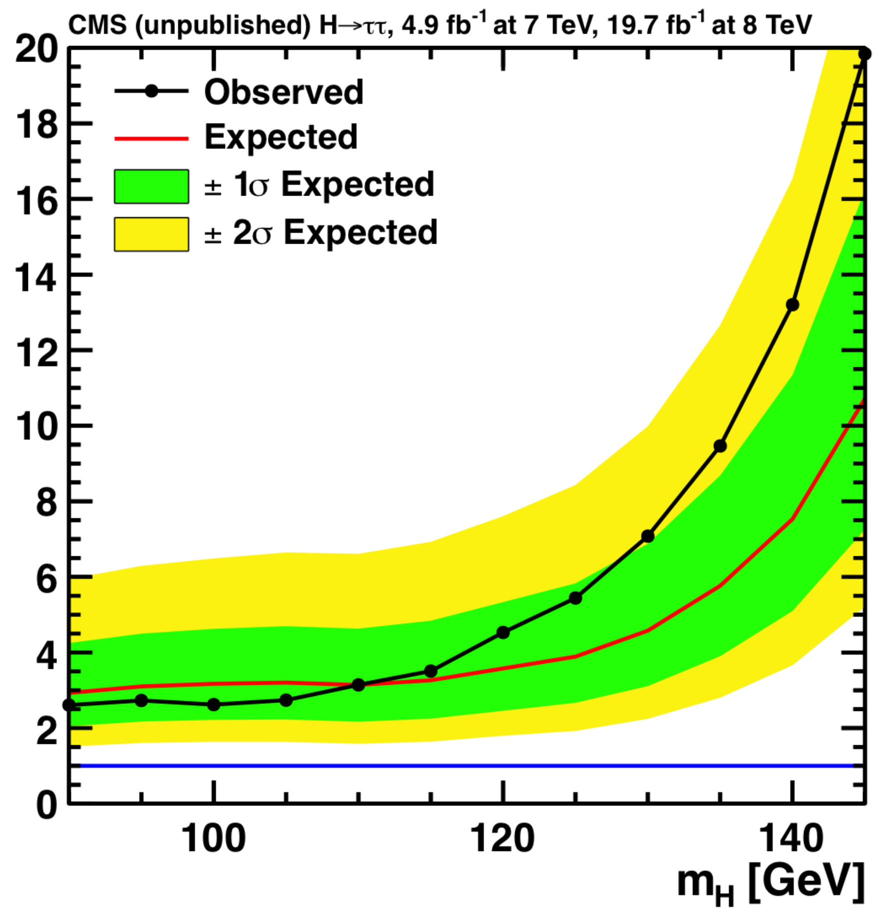
  The uncertainty on the Fake Rate is uncorrelated between the two channels and the two data taking periods.

VH Limits

L + Ltau$_h$



LL + tautau



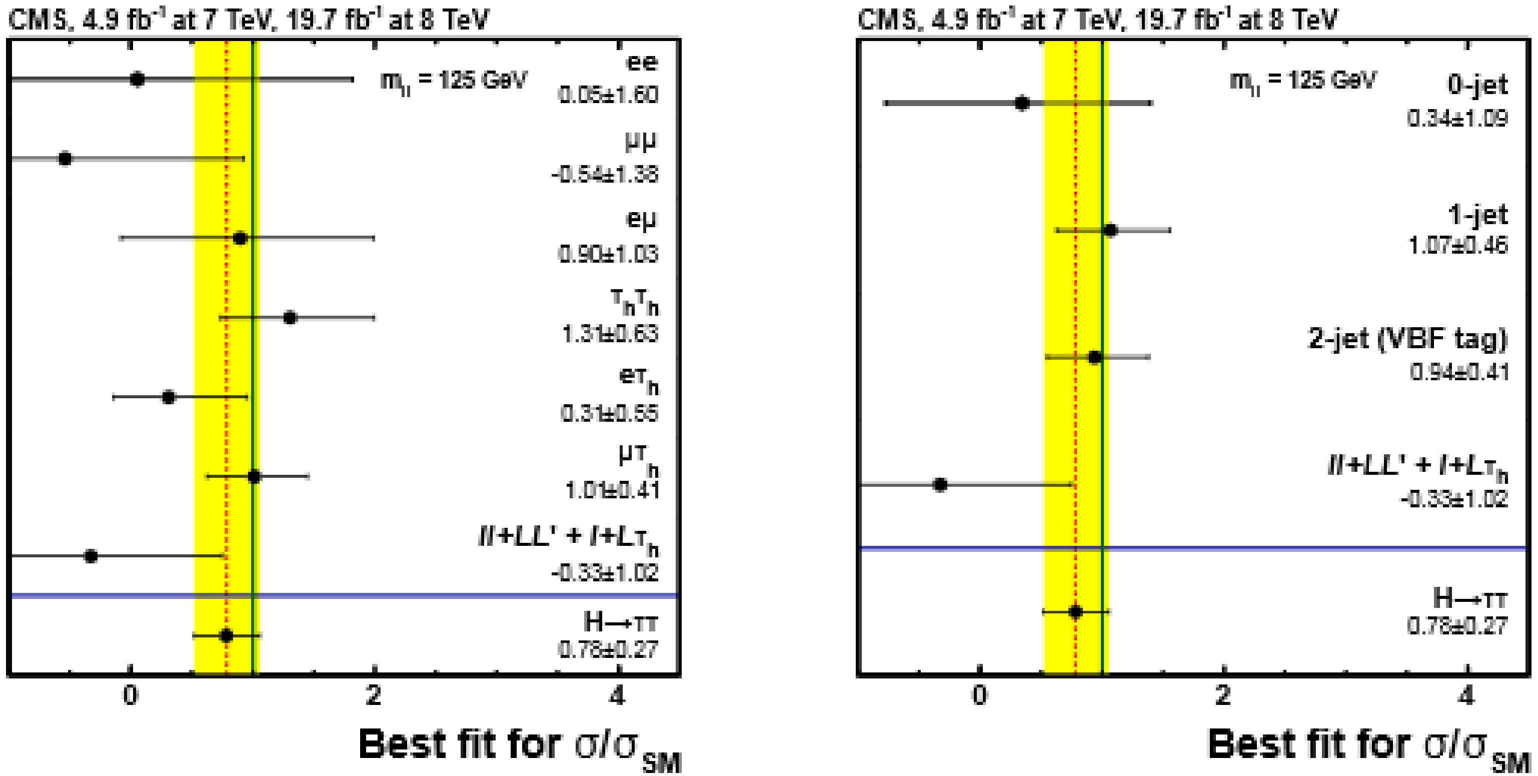
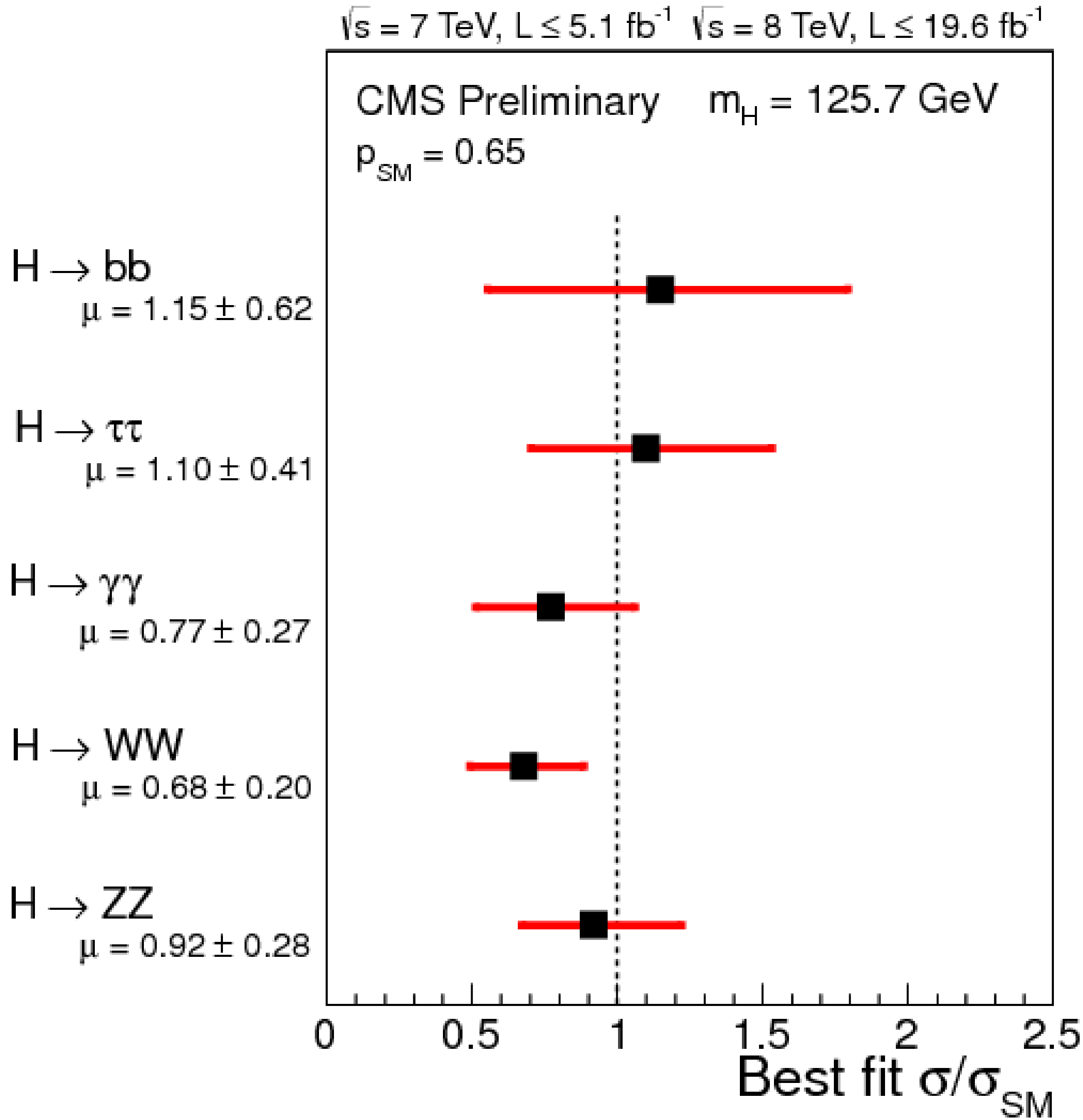
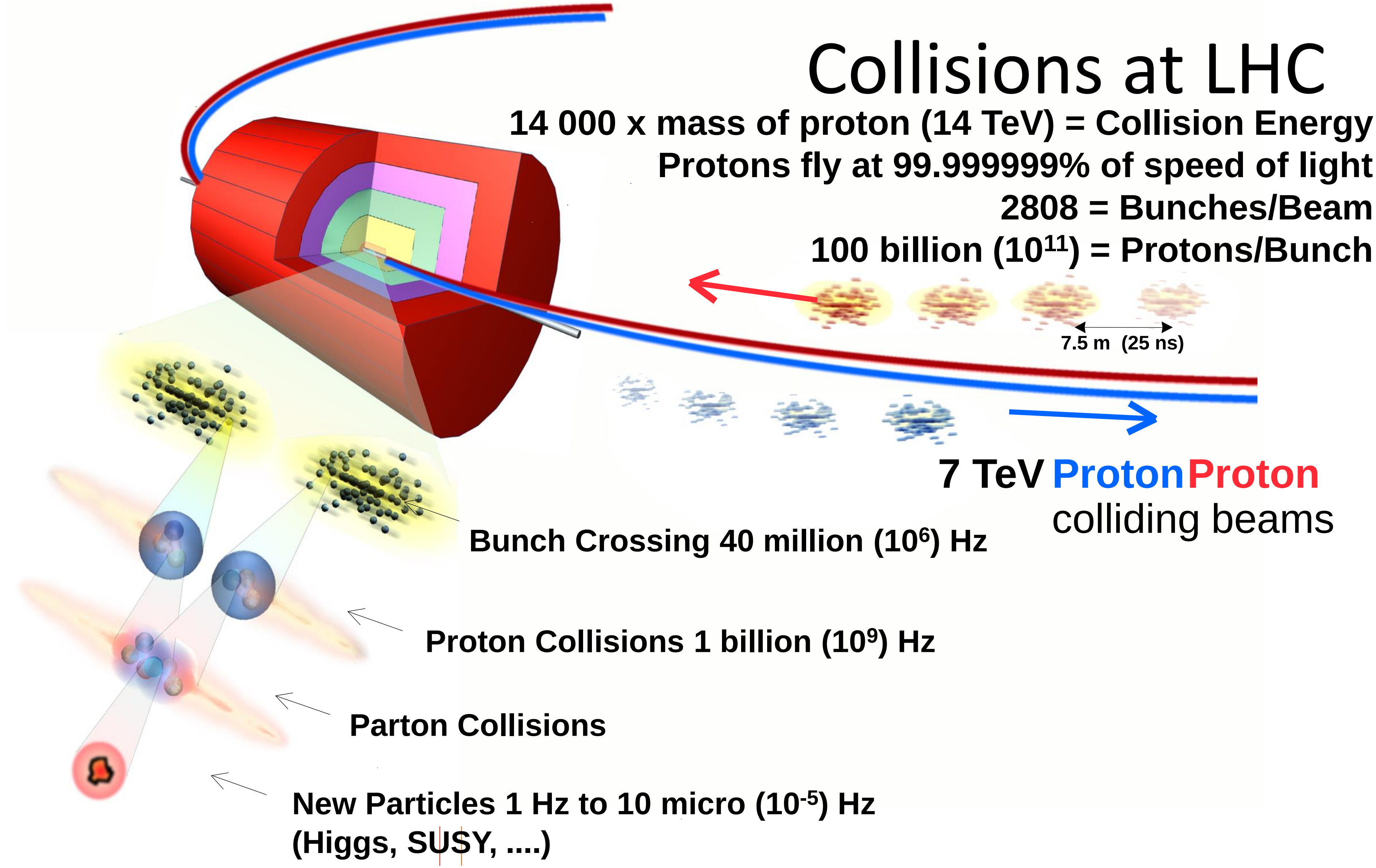


Figure 15: Best-fit signal strength values, for independent channels (left) and categories (right), for $m_{\mathrm{H}} = 125\,\mathrm{GeV}$. The combined value for the $\mathrm{H} \to \tau\tau$ analysis in both plots corresponds to $\hat{\mu} = 0.78 \pm 0.27$, obtained in the global fit combining all categories of all channels. The dashed line corresponds to the best-fit μ value. The contribution from the $\mathrm{pp} \to \mathrm{H}(125\,\mathrm{GeV}) \to \mathrm{WW}$ process is treated as background normalized to the SM expectation.



Plot from CMS Higgs Public twiki: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

Collisions at LHC



Courtesy of Alexei Safonov

Higgs Doge-on
Much Mass. Very Boson. Such Coupling. Wow