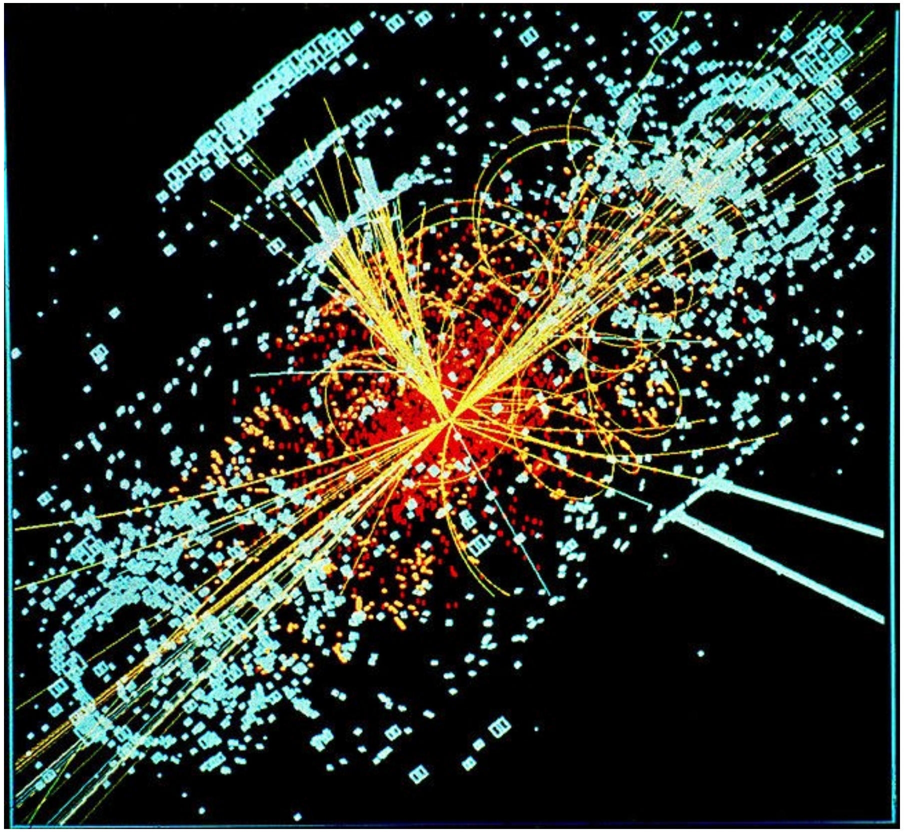
Search for a Lepton Flavor Violating Higgs Boson Using the Compact Muon Solenoid Detector at the Large Hadron Collider



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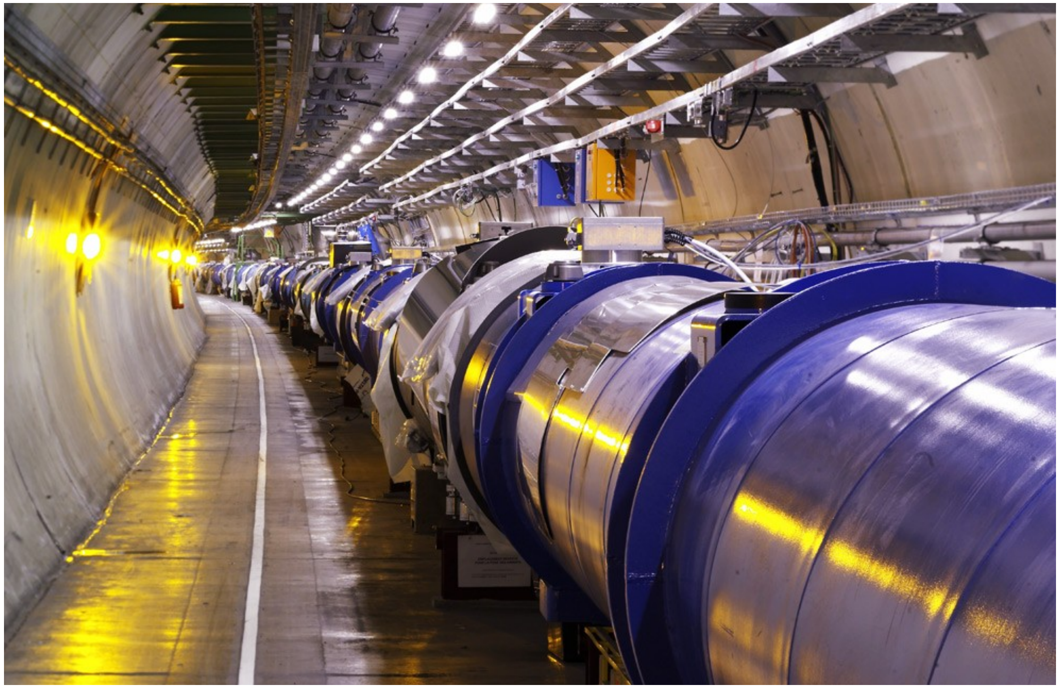
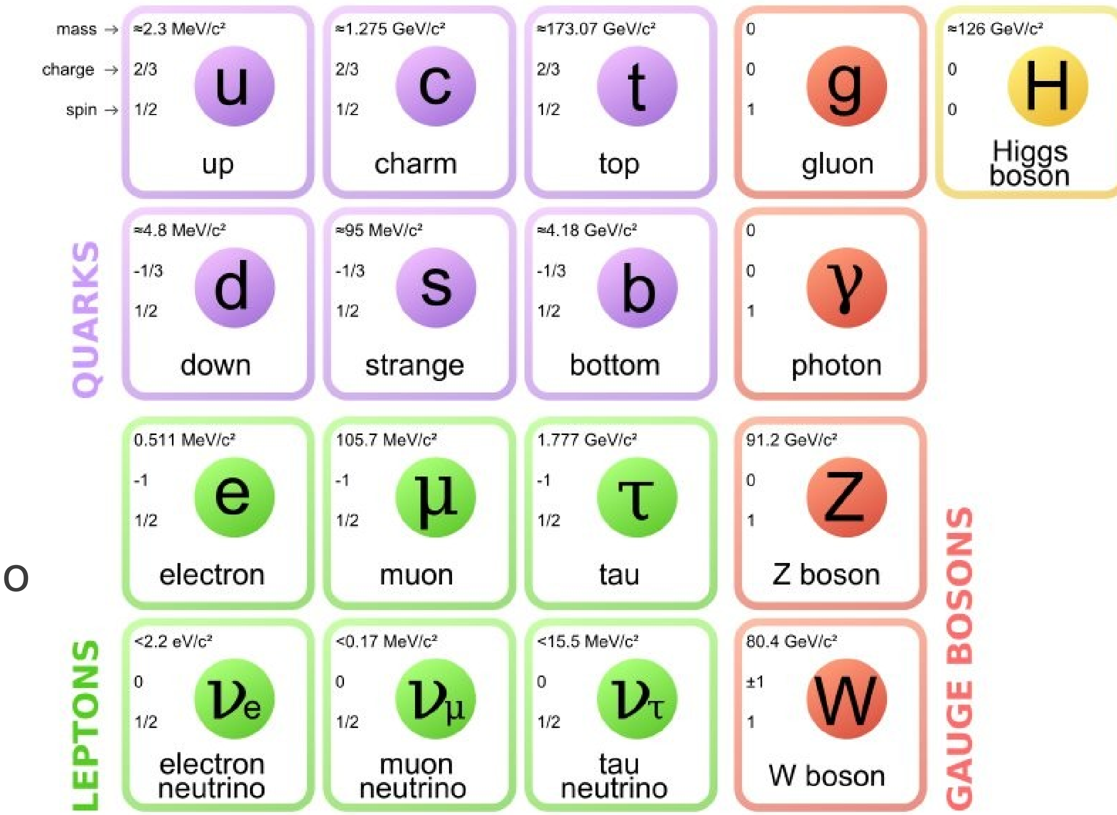
Outline

- Theoretical Background
  - Standard Model
  - Higgs Boson
  - Lepton Flavor Violation
  - Signal and Backgrounds
- Experimental Background
  - Large Hadron Collider (LHC)
  - Compact Muon Solenoid (CMS)
- Analysis
  - Monte Carlo Generation
  - Selections
  - Results
  - Outlook

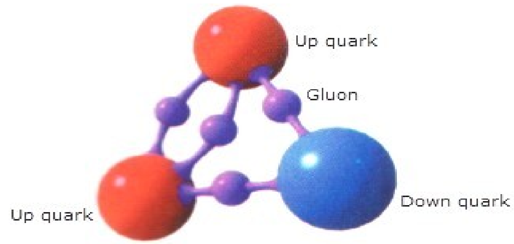


Standard Model (Particles)

- Theoretical framework that describes particle interactions
- Quarks
  - Six quarks in three generations
  - Quarks form hadrons (ex: proton, neutron)
- Leptons
  - Three generations
  - Each charged lepton has a neutrino partner
- Gauge Bosons
  - Force carriers
- Higgs Boson
  - Responsible for masses of quarks, leptons, and massive gauge bosons

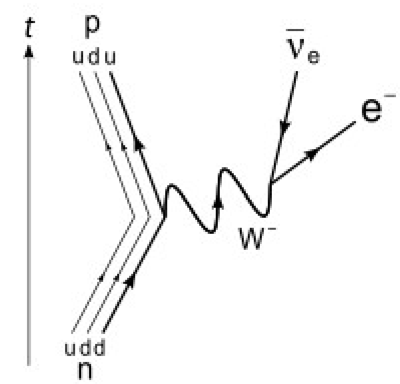


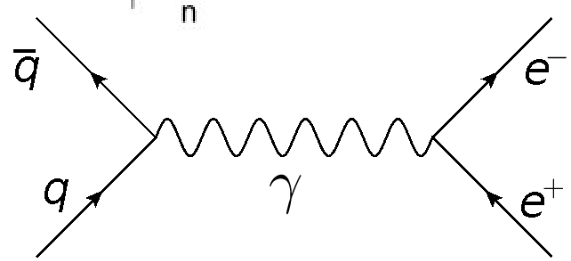
Standard Model (Forces)



Gluons holding quarks together to form a proton
(diagram from *Scientific American*)

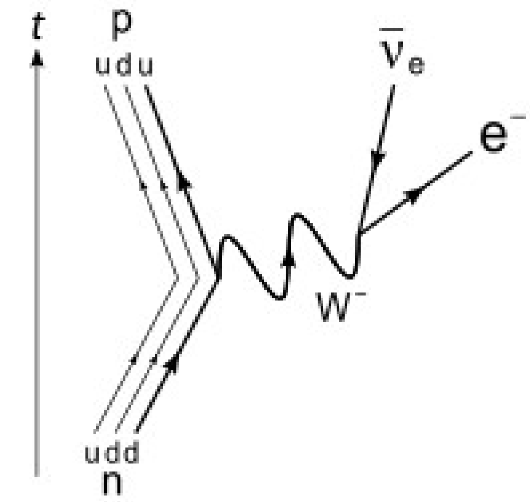
- Strong Nuclear Force
  - Mediated by gluon
  - Binds quarks within hadrons
- Weak Nuclear Force
  - Mediated by W and Z bosons
  - Responsible for beta decay of the neutron
- Electromagnetic Force
  - Mediated by photon





Massive Gauge Bosons

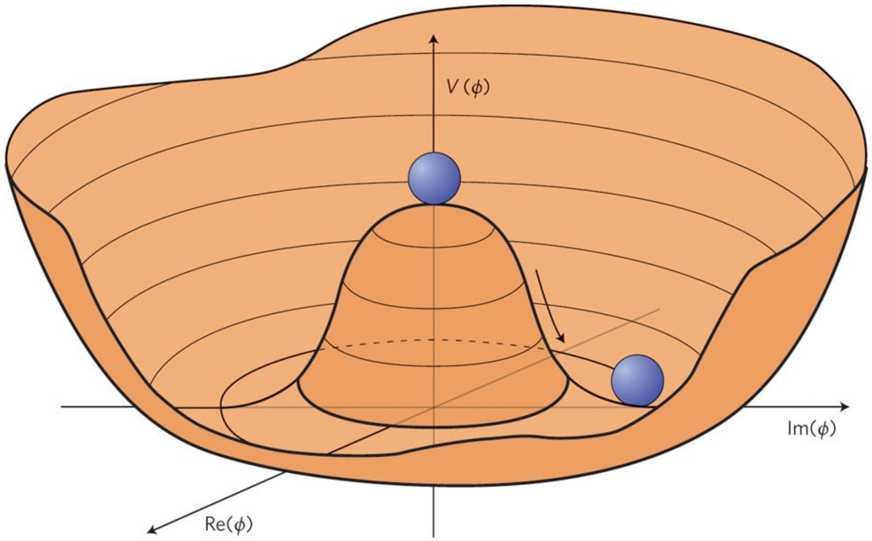
- Weak interaction has very short range
  - 10^{-17} m
- Requires massive mediators
  - W and Z bosons



- Weak interaction and electromagnetic interaction can be combined into Electroweak Lagrangian
  - Contains triplet of weak isospin currents with SU(2) symmetry and single hypercharge current with U(1) symmetry
  - W and Z mass terms of the form $M^2 W^\mu W_\mu$ are not SU(2) X U(1) gauge invariant

Standard Model Higgs Boson (Theory)

- Higgs Mechanism
  - Higgs field produces spontaneous symmetry breaking of Lagrangian in weak isospin x hypercharge space
  - Gauge transformation generates mass terms in Lagrangian for quarks, leptons, and massive bosons
  - SM Higgs has no charge, no spin, and is its own antiparticle

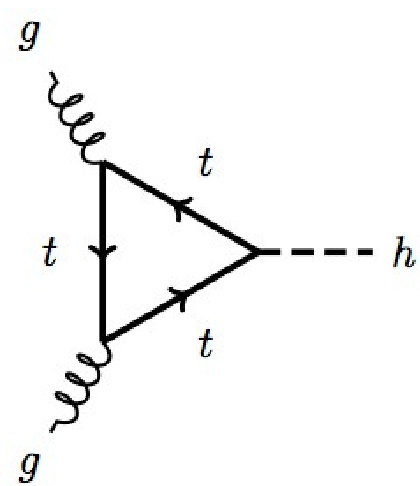


- Discovery
  - Discovery of Higgs Boson with a mass of 125-126 GeV announced on July 4th 2012

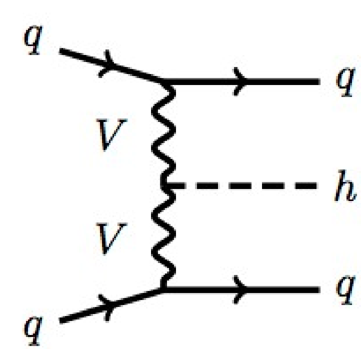
SM Higgs Boson (Major Production Mechanisms)

- Gluon Gluon fusion
  - Dominant at LHC
  - Higgs couples to virtual top quarks in loop
  - More than 10 times more likely than any other production mechanism
- Vector boson fusion
  - Second largest at LHC
  - Quarks in proton exchange virtual W or Z Boson
  - Higgs couples to virtual bosons

Gluon Gluon Fusion



Vector Boson Fusion



SM Cross Sections at MH = 125 GeV and $\sqrt{s}$ = 8 TeV

σ = 19.27 pb

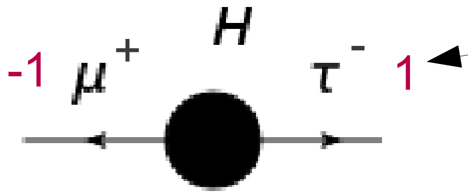
σ = 1.578 pb

Source: Handbook of LHC Higgs Cross Sections: 3. Higgs Properties

Lepton Flavor Violation

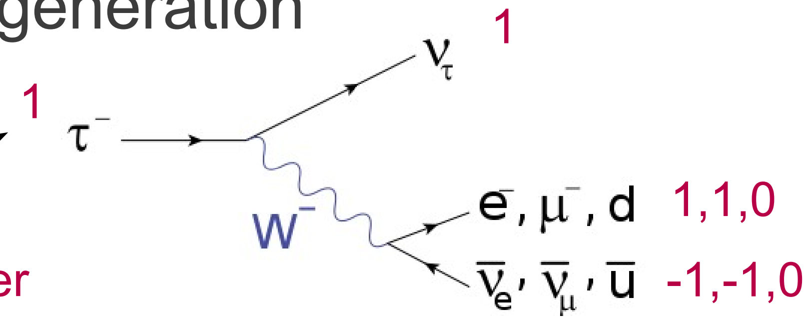
- Lepton Number
  - 3 generations of leptons
  - Lepton number defined for each generation
    - #(leptons) - #(anti leptons)
  - Conserved in SM

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$



Lepton Number

Lepton # Violated

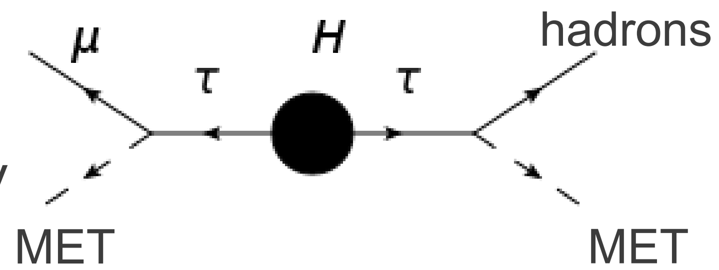


Lepton # conserved

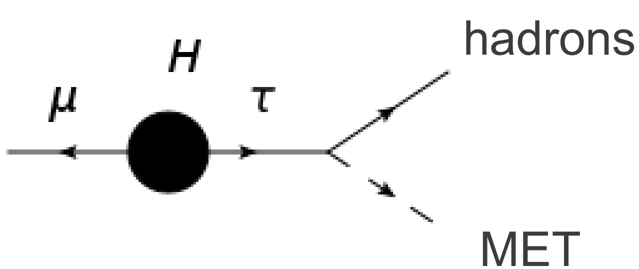
- Lepton flavor violating Higgs
  - Some beyond the standard model (BSM) theories predict flavor violating Higgs boson
  - Search for Higgs decaying directly to a tau and a muon

Lepton Flavor Violating Higgs Decay

- SM process: $H \rightarrow \tau_\mu \tau_h$
  - τ_h denotes a tau decaying hadronically (hadrons and a tau neutrino)
  - τ_μ denotes a tau decaying to a muon (with a tau neutrino and an antimuon neutrino)
  - MET denotes missing energy
    - Neutrinos are not detected by CMS
  - $H \rightarrow \tau\tau$ Branching Ratio (BR) of 6.3 % at M_H = 125 GeV
- Similar BSM LFV process: $H \rightarrow \mu\tau_h$
  - No previous direct experimental searches
  - BR up to 13%
    - Based on analysis of ATLAS $H \rightarrow \tau\tau$ data by Harnik, Kopp, Zupan
  - Larger visible mass than SM process
  - Search Higgs Mass range of 125-126 GeV
  - Assume SM production modes



SM Process

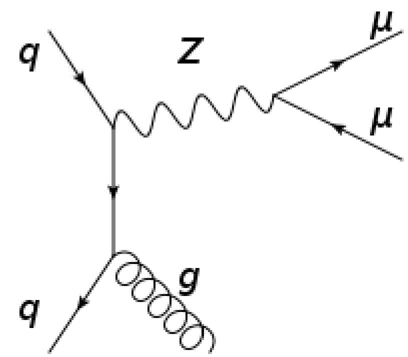


BSM Process

Important Backgrounds

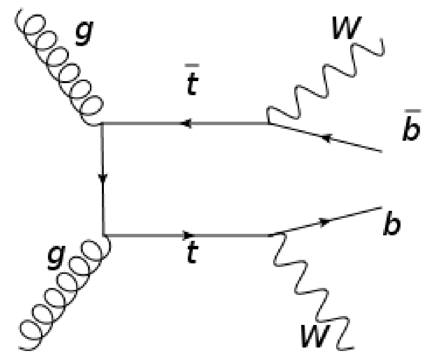
- Z+jets

  σ = 3500 pb



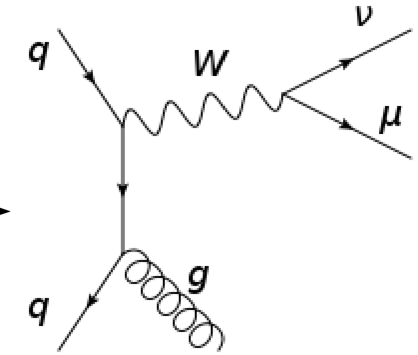
- ttbar

  σ = 130 pb



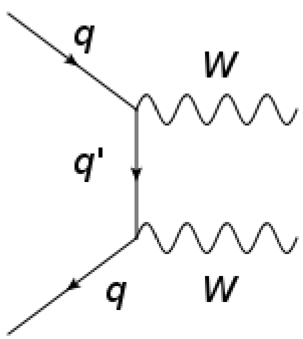
- W+jets

  σ = 38000 pb



- WW

  σ = 5.8 pb



W decays hadronically or leptonically

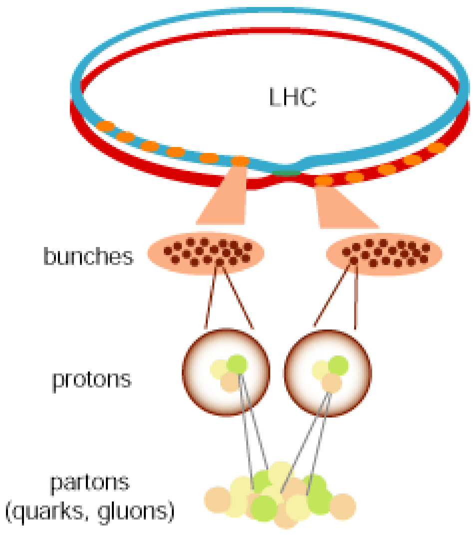
Large Hadron Collider

- 14 TeV Center of Mass proton/proton collider
  - Currently operating at 8 TeV
- 27 km circumference
- Four experiments
  - CMS, ATLAS: General purpose high energy physics detector
  - LHCb: High energy B physics
  - ALICE: High energy heavy ion physics

LHC Collisions

- Acceleration Process
  - Electric field strips Hydrogen atoms of electrons
  - Linear accelerator accelerates protons to 50 MeV
  - Synchrotrons accelerate protons to 450 GeV
  - Protons then go to main LHC beam, accelerated to 4 TeV
- Protons are guided by superconducting magnets cooled by liquid helium
  - Dipoles accelerate protons
  - Quadrupoles focus protons along horizontal and vertical planes
- RF system creates bunches of protons
  - 25 ns design bunch spacing

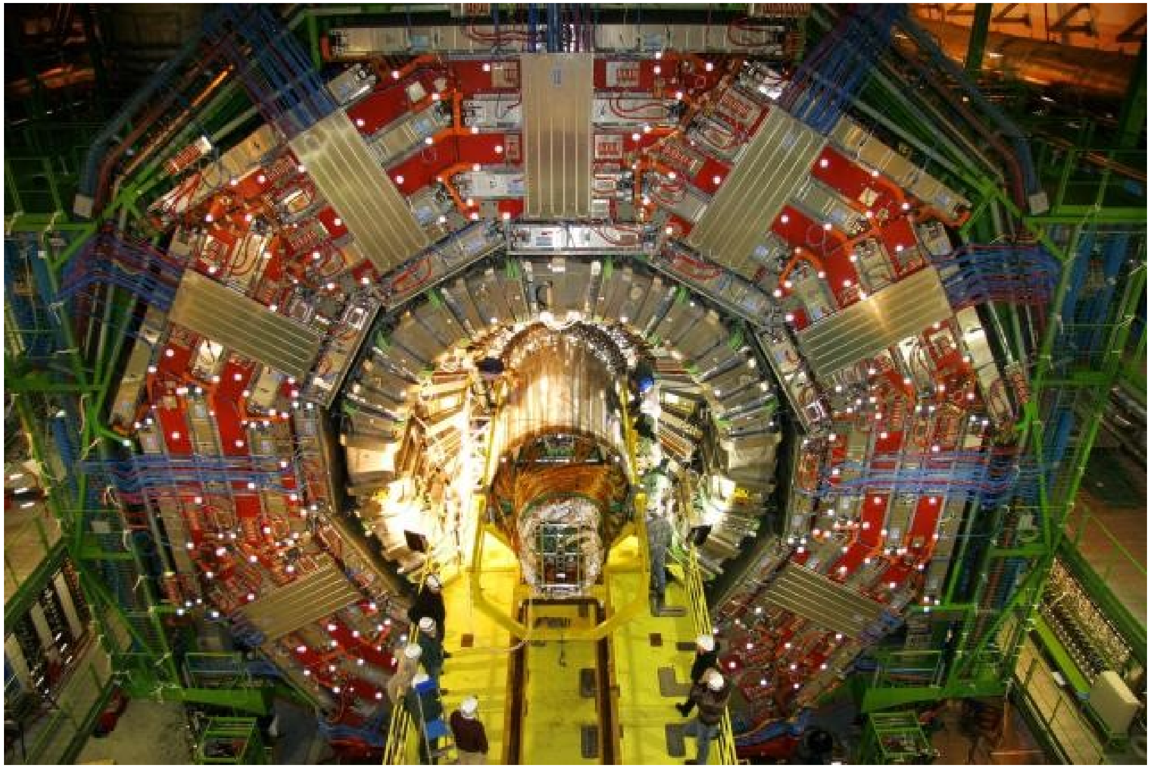
$$\mathcal{L} = \frac{\#Interactions}{Effective\ Flux}$$



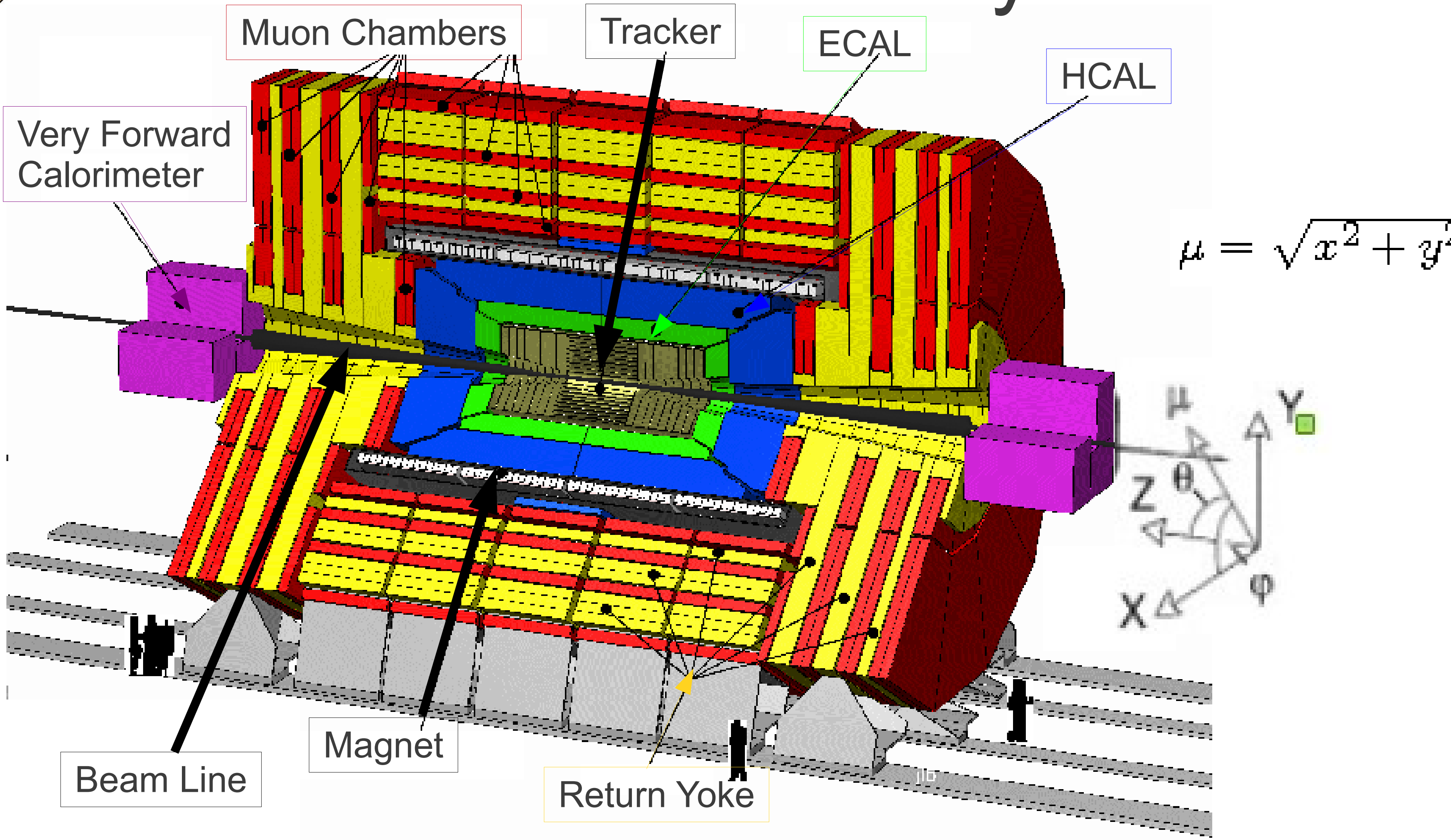
	Design	2010	2011	2012	Upgrade (2015-2018)
Beam Energy (TeV)	7	3.5	3.5	4	6-7
Bunches/Beam	2835	368	1380	1380	2835
Protons/Bunch(1e11)	1.15	1.3	1.5	1.5	1.2
Peak Luminosity(1e32cm^{-2}s^{-1})	100	2	30	60	100
Integrated Luminosity (fb^{-1})	100/year	.036	6	19.71	50/year

Compact Muon Solenoid (CMS)

- General background
  - Located 100 meters underground in Cessy, France
  - One of two general physics detectors at the LHC
  - Size
    - 21 meters long
    - 15 meters wide
    - 12500 tons
- Physics Goals
  - Study Higgs Boson
  - Search for BSM (Beyond the Standard Model) physics



CMS Geometry



Pseudorapidity (η) is a Lorentz invariant quantity that describes the position of a particle relative to the beam axis.

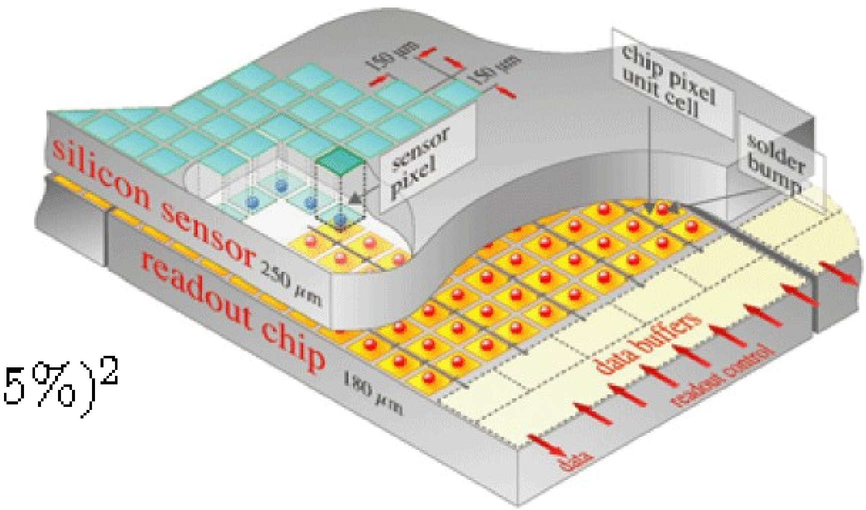
$\eta = -\ln[\tan(\theta/2)]$

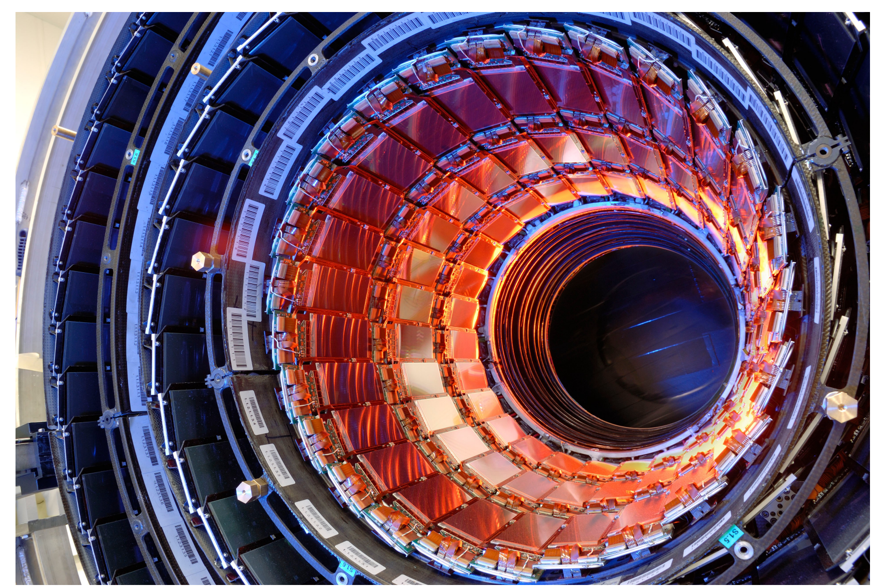
θ = angle relative to z axis

Transverse mass (M_T) and momentum (P_T) correspond to the mass and momentum of a particle perpendicular to the beam axis

CMS Tracker

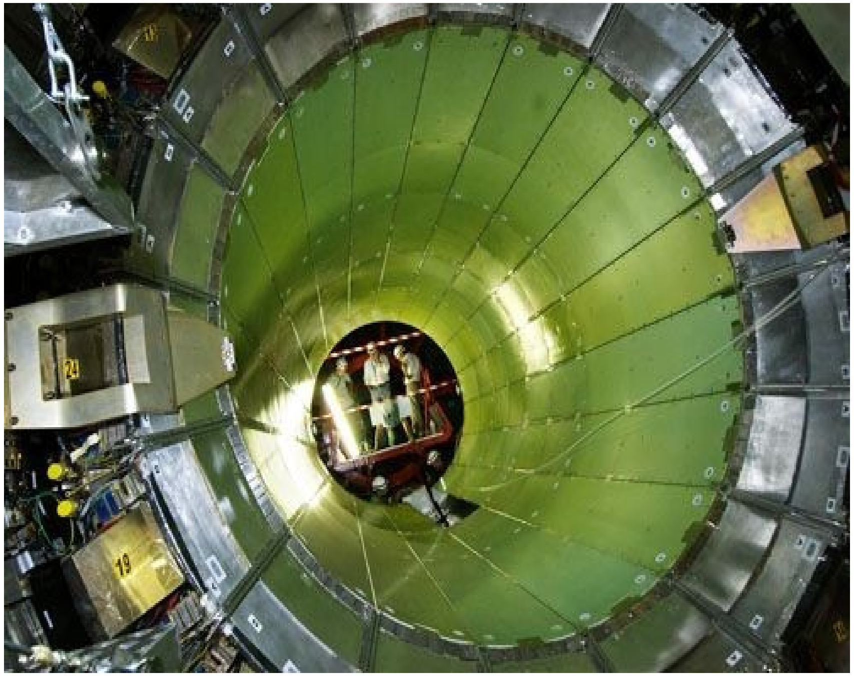
- Measures P_T and charge of muons, electrons, and hadrons, using 3.8 T magnetic field
  - P_T determined by examining tracker hits to reconstruct the radius of curvature
- Extends to $|\eta| < 2.5$
- Resolution: $(\frac{\delta pT}{pT})^2 = (15pT(TeV)\%)^2 + (0.5\%)^2$
- Inner silicon pixel detector
  - High granularity
  - Pixels are 100 X 150 μm
  - Cylindrical layers at 4, 7, and 11 cm from beam
  - High flux (10 million particles per square cm per second)
- Outer silicon strip detector
  - 10 cylindrical layers with 4 endcaps
  - Extends 130 cm from beam
  - Lower flux than pixel detector (3e5 particles per square cm per second)
    - Allows cell size up to 25 cm X 180 μm



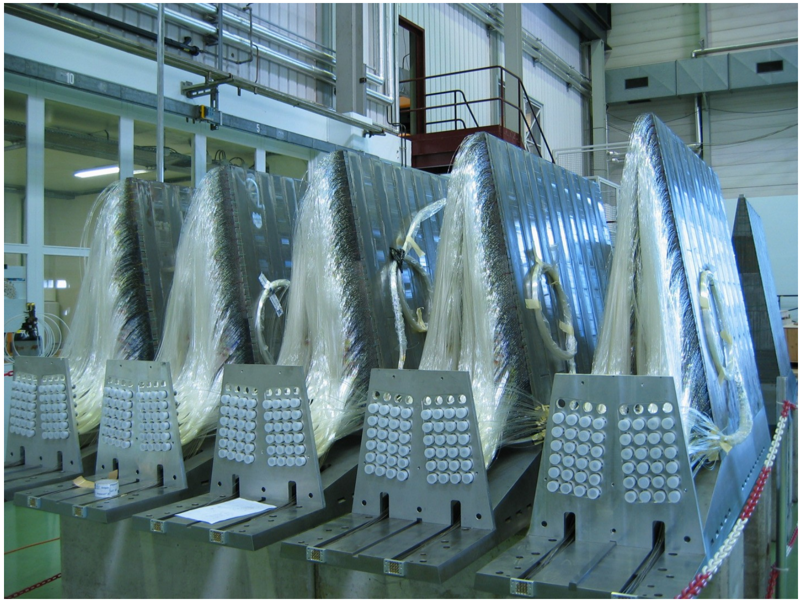


CMS Electromagnetic Calorimeter

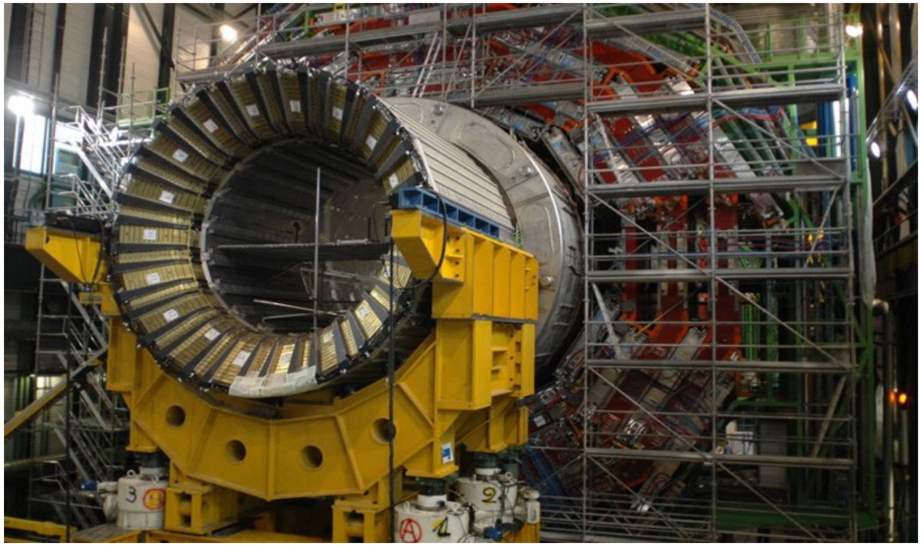
- Measures energy deposited by electrons and photons
- Composed of lead tungstate scintillating crystals
  - Crystals have high density (8.28 g/cm^3) and short radiation length (0.89 cm)
    - Allows fine granularity
  - 61,200 crystals in the barrel
  - 7324 crystals in each of the two endcaps
  - Emitted light detected by photodetectors
- 80% of light emitted in 25 ns
  - Same order as LHC design bunch crossing time
- Energy resolution: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2$



CMS Hadronic Calorimeter

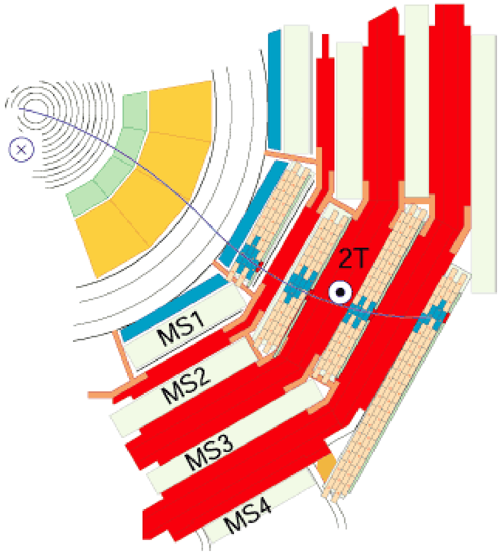


- Measures energy deposited by hadrons
- Barrel and Endcaps
  - Barrel (HB): $|\eta| < 1.3$
  - Endcaps (HE): $1.3 < |\eta| < 3.0$
  - Wedges of brass absorber and plastic scintillator
  - Wavelength shifting fibers bring scintillation light to electronics
  - Energy resolution: $(\frac{\sigma}{E})^2 = (\frac{115\%}{\sqrt{E}})^2 + (5.5\%)^2$
- Forward Calorimeter (HF)
  - $3.0 < |\eta| < 5.0$
  - Very high flux region
  - Quartz scintillating fibers
  - Steel shielding for electronics
  - Energy resolution: $(\frac{\sigma}{E})^2 = (\frac{280\%}{\sqrt{E}})^2 + (11\%)^2$

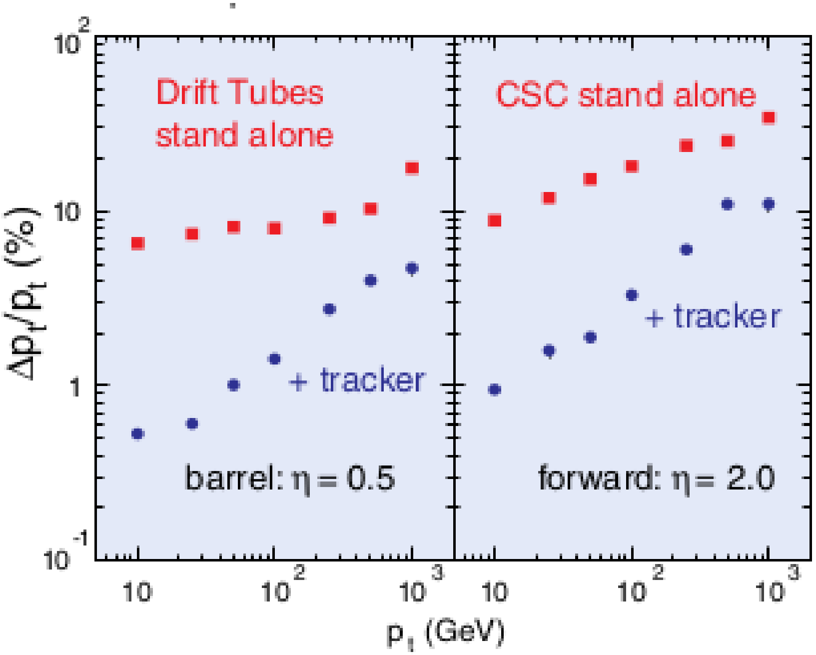


CMS Muon Chamber

- Muons are highly penetrating particles that are very important for new physics
  - Not stopped by Calorimeters
    - Need muon system
- Trajectory is bent by 2T magnetic field in return yoke

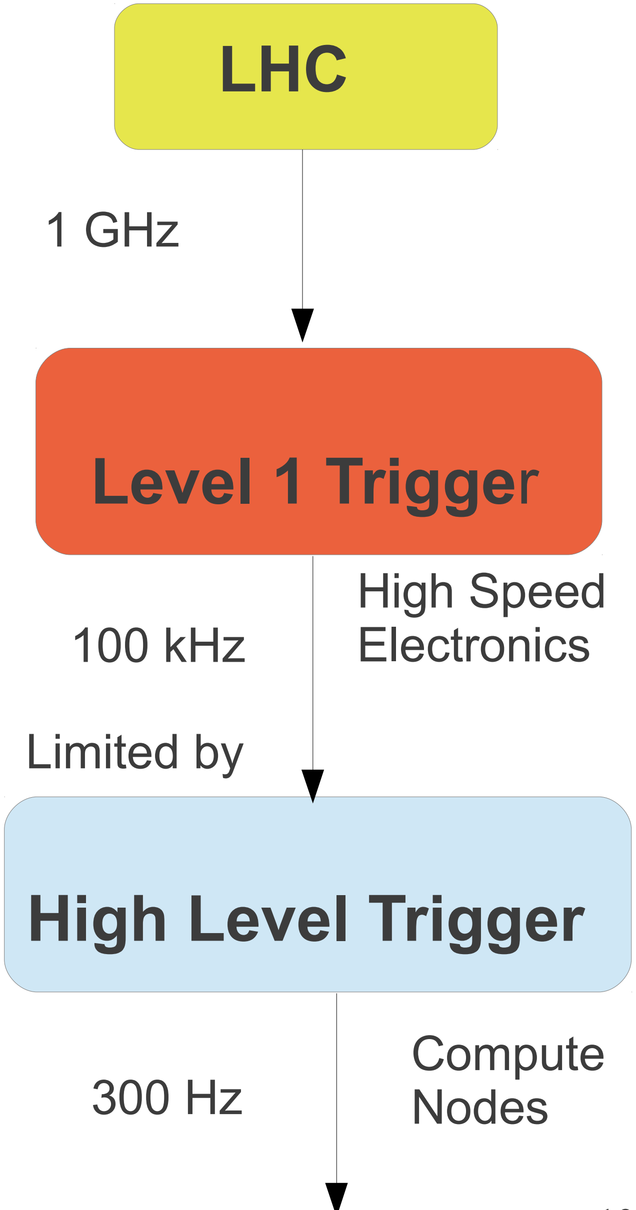


- 4 muon stations interspersed with iron yoke
  - 610 resistive plate chambers
    - Redundant trigger system, provides time coordinate
  - 250 drift tubes track the muons in the barrel
    - Barrel covers $|\eta| < 1.2$ region
  - 500 cathode strip chambers (CSC) track the muons in the endcaps
    - Endcaps cover up to $|\eta| < 2.4$
  - Drift tubes and CSCs provide position of muon
    - Both use cathode strips and anode wires
    - Muons ionize gas, electrons drift to anode wires



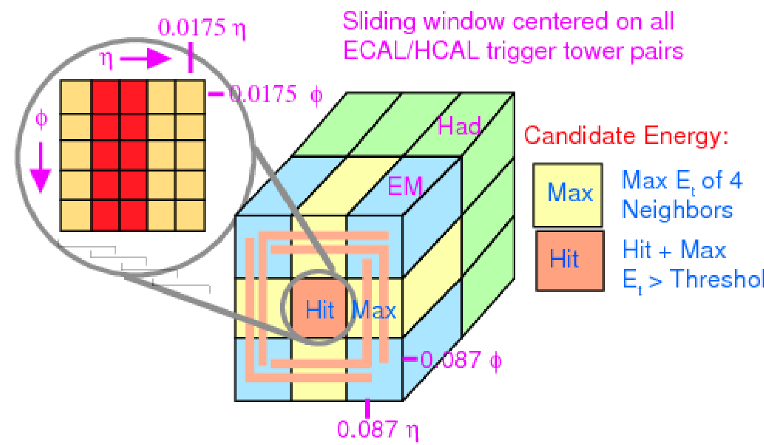
CMS Trigger System

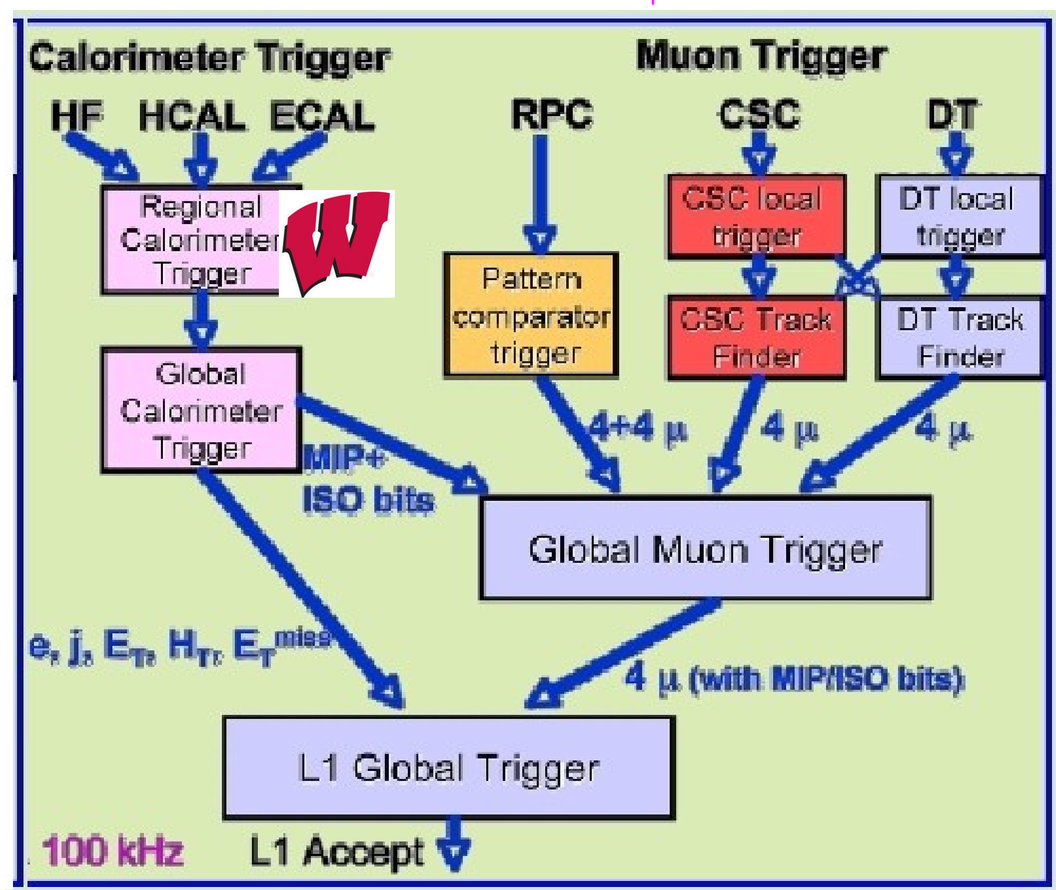
- Impossible to store all data produced via LHC collisions
- Trigger system must reduce rate from 1 GHz (LHC collisions) to 300 Hz (maximum output rate)
- Level 1 Trigger
  - High speed electronics
  - Basic selection and rejection
  - Rate limited by readout electronics
    - Tracker has 7 μs readout time, 8 event buffer
- High Level Trigger
  - Compute nodes
    - 20,000 cores
  - Defines object filters for physics analysis



CMS Level 1 Trigger

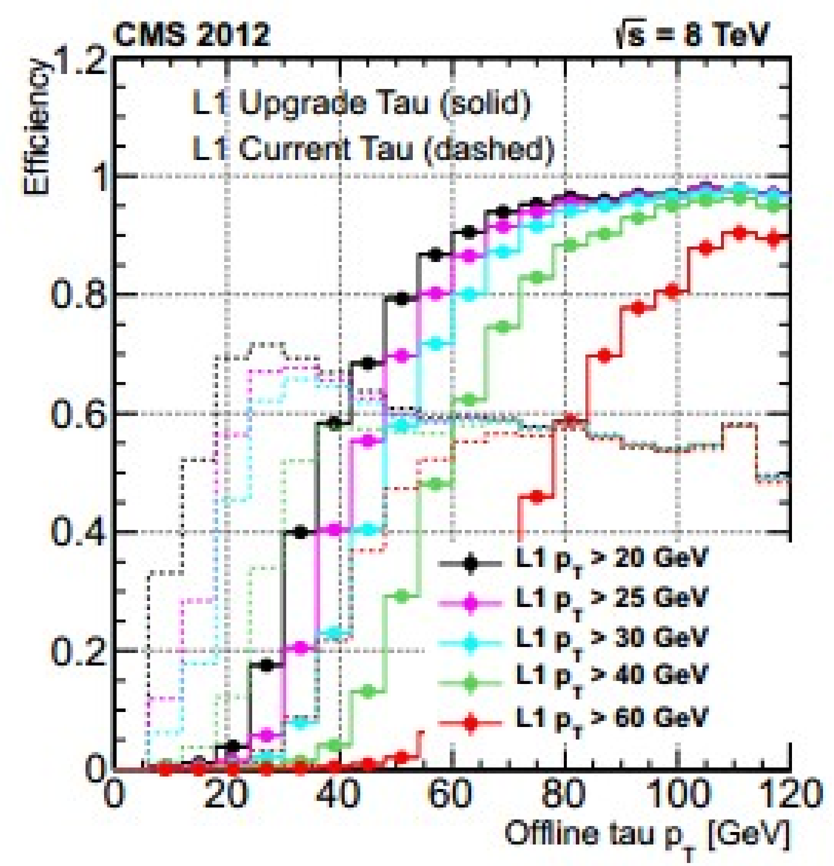
- Level 1 Trigger must analyze every bunch crossing
- Global trigger uses hardware algorithms to accept or reject each event it receives
- Calorimeter triggers sum energy over η/φ regions
  - 5X5 crystal block = trigger tower
- Regional Calorimeter Trigger (RCT)
  - Identify e/γ candidates
  - Sums transverse energy (E_T) in regions
- Global Calorimeter Trigger (GCT)
  - Jet identification
- Muon trigger system (RPC,DT,CSC)
  - Records energy and track geometry of muons
  - Global Muon Trigger combines information to determine well identified muon candidates





CMS Level 1 Trigger Upgrade

- Long Shutdown 1 (LS1) from 2013-2015
- Increase beam energy to 6-7 TeV
- Decrease bunch spacing from 50 ns to 25 ns
- Need to improve tau identification efficiency because taus couple strongly to Higgs boson
  - ID taus as taus, not as jets
- Example: change tau identification from 12X12 trigger towers to 2X1 ECAL+HCAL towers
  - Increases plateau efficiency from 0.3 to 0.7
  - Overall L1 Trigger rate remains below 100 kHz with upgrade algorithms



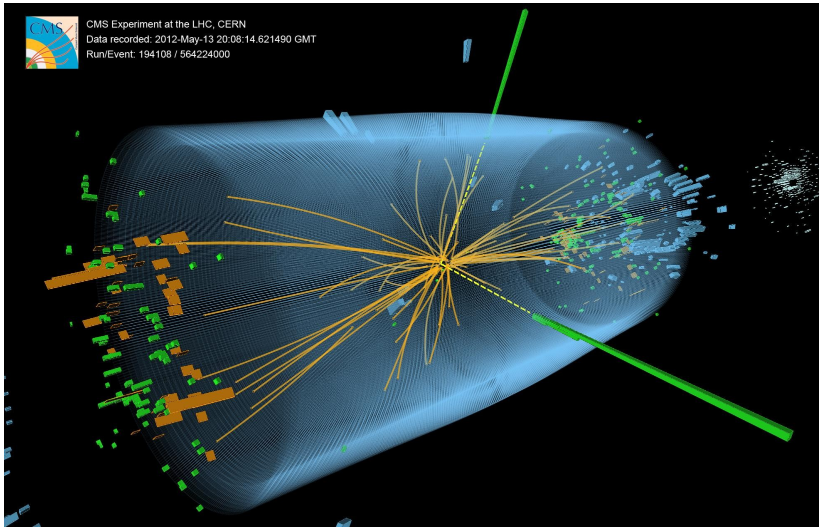
Source: Level-1 Trigger Upgrade Technical Design Report

CMS High Level Trigger

- Processes events from L1 trigger
- Uses offline software algorithms to define filters for physics analysis
- Accepts events at up to 100kHz, outputs events at up to 300 Hz
  - Large reduction in rate
- Example: HLT filter used for this analysis:
  - Requires isolated, well constructed muon with $P_T > 30$ GeV
  - The terms “isolated” and “well constructed” will be defined in future slides

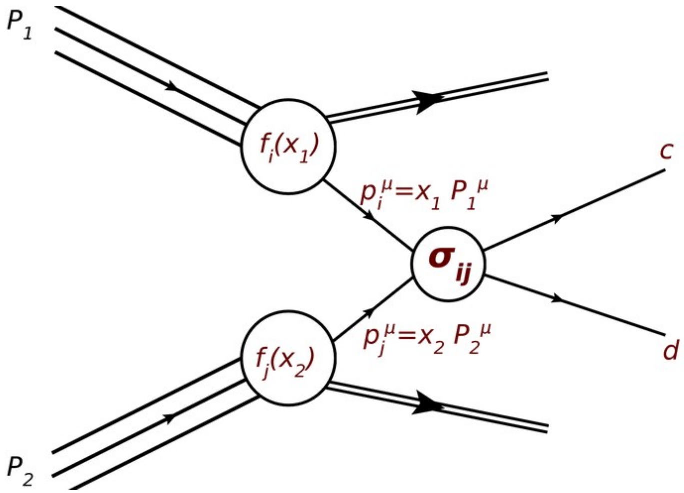
Analysis Summary

- Simulation techniques
  - Monte Carlo (MC) techniques used to simulate signal and background
- Object Identification and Reconstruction
  - Muons
  - Jets
  - Taus
- Initial Data/Monte Carlo Comparison
- Analysis Selections
- Results and Future Plans

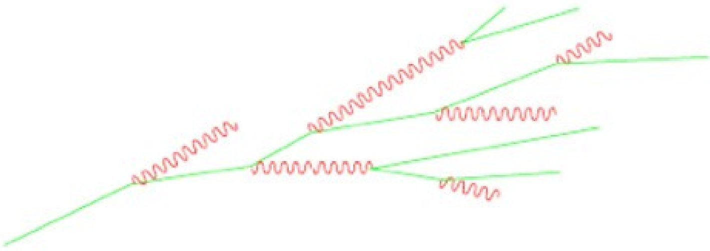


Monte Carlo Generators

- Madgraph
  - Matrix element MC generator
  - Partonic interactions
- Pythia
  - Quarks allowed to radiate gluons
  - Hadronization, showering
- Tauola
  - Simulates Tau decay
  - Used in conjunction with Pythia
  - Takes into account tau polarization and spin



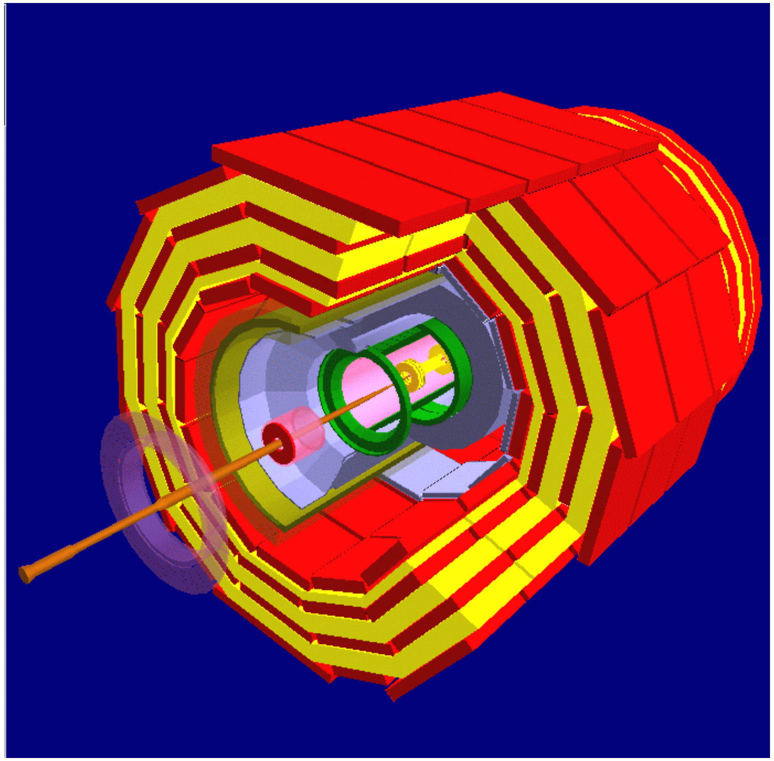
Parton Parton Scattering



Hadronic Shower

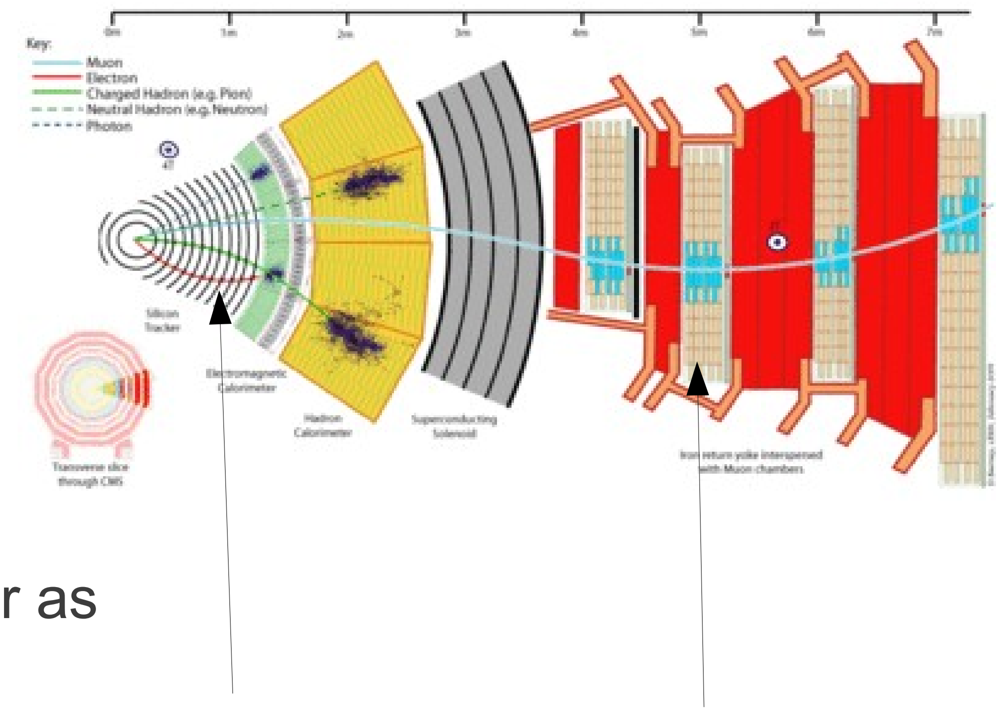
Monte Carlo Workflow

- Generate samples with Madgraph + Tauola and Pythia
  - Partonic level to hadronization and tau decay
- Use GEANT to simulate detector interactions
  - Software for simulating passage of particles through matter
  - Currently responsible for most of signal simulation
    - New signal monte carlo studies are ongoing
- Use CMSSW software to reconstruct MC events to be compatible with CMS analysis framework
- Scale MC samples to 19.71 fb^{-1} of data
  - 8 TeV dataset used in this analysis



Muon Reconstruction

- Standalone Muons
  - Offline reconstructed track segments in muon chambers
- Global Muons
  - Match standalone muons to tracks silicon tracker
  - Fit and reconstruct path
- Tracker Muons
  - ID low PT muons that don't register as standalone muons
  - Reconstruct track with P > 2.5 GeV, P_T > 0.5 GeV matched with hit in muon chamber



Silicon Tracker

Muon Chambers

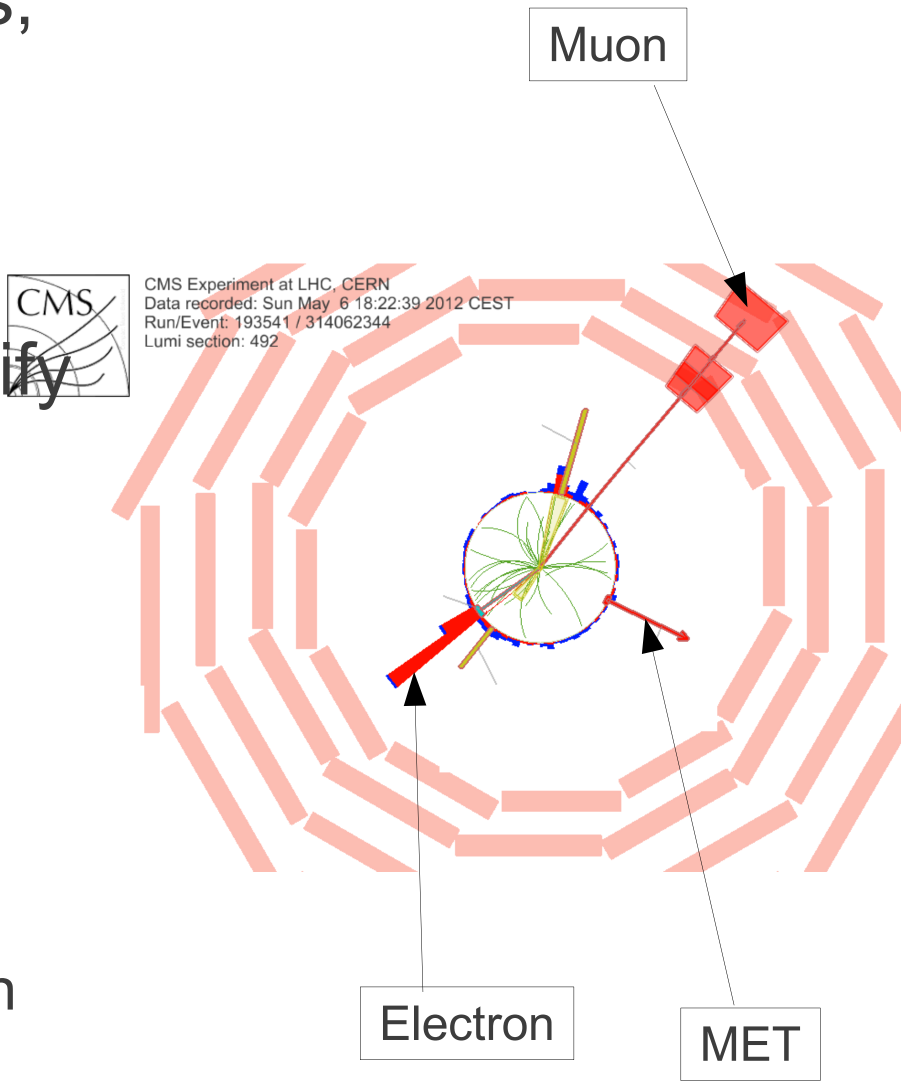
Muon Isolation

- Muon from LFV Higgs decay should be isolated
- Define isolation cone around muon
  - $\Delta R = \sqrt{\phi^2 + \eta^2}$ < 0.4
- Relative Isolation Definition
  - Tracker isolation: sum of PT of tracks in isolation cone
  - ECAL isolation: sum of ECAL energy deposited in isolation cone
  - HCAL isolation: sum of HCAL energy deposited in isolation cone

$$Iso_{Rel} = \frac{Iso_{HCAL} + Iso_{ECAL} + Iso_{Tracker}}{\mu P_T} < 0.12$$

Particle Flow Objects

- Reconstruct hadrons, photons, muons, and electrons
  - Used to identify jets, taus, and missing E_T (MET)
- Particle Flow Algorithms identify objects
  - Identify calorimeter clusters and tracker hits
  - Reconstruct path and identify particles
- Example:
  - Electron will have a curved path in tracker and will leave an energy deposit in ECAL



Jet Identification

- Particle flow jets
  - Reconstruct jets from energy deposited by particle flow objects
- Define distance measures d_{ij} and d_{iB}
  - d_{ij} = distance between particles i and j
  - d_{iB} = distance between particle i and beam
  - If $d_{ij} < d_{iB}$ then combine particles i and j
  - If $d_{ij} > d_{iB}$ then call particle i a jet
- Use Anti-kt jet algorithm (p = -1) with R = 0.5
- Anti-kt algorithm keeps jet cone well defined
  - Cone unaffected by soft radiation
  - Hard events within cone are combined based on energy and position
  - Collinear and infrared safe
- Find cones by identifying clusters of HCAL depositions

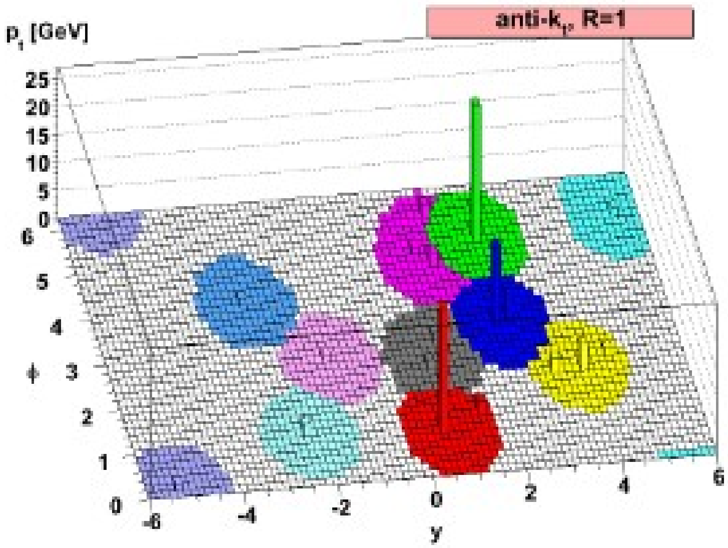
$$d_{ij} = min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

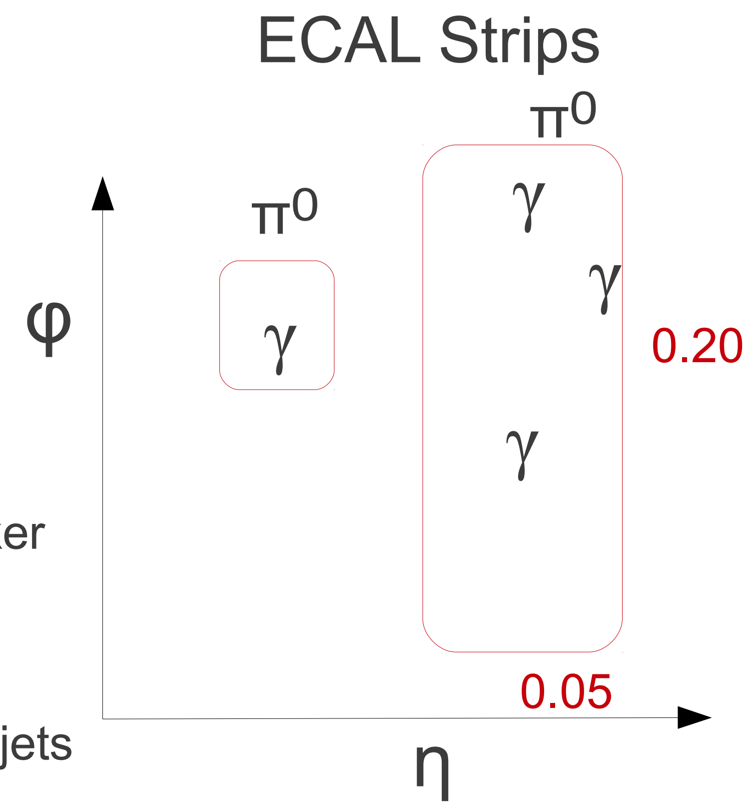
$$k_t = \text{transverse momentum}$$

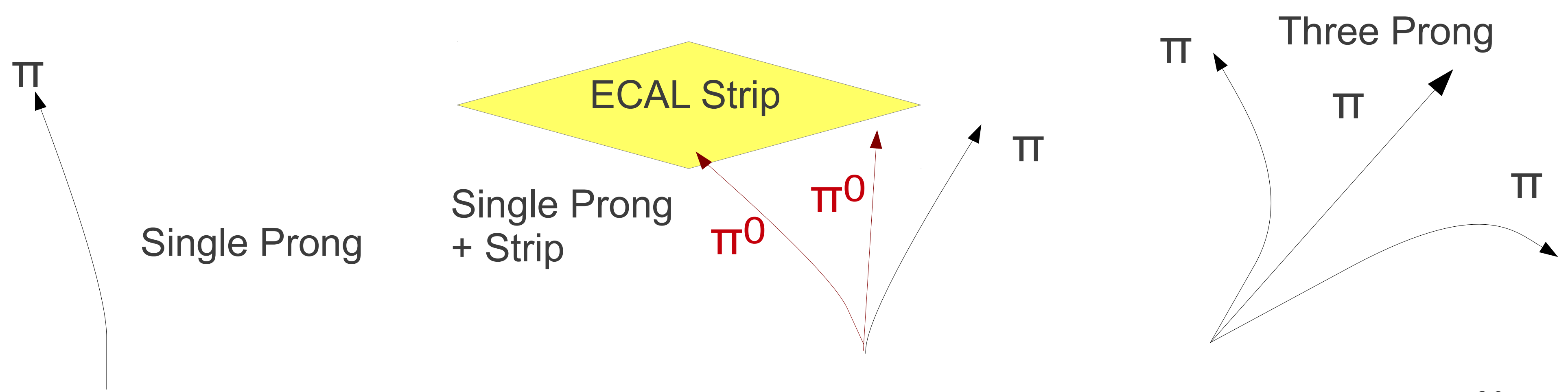
$$y = \frac{1}{2}ln\frac{E+p}{E-p} = \text{rapidity}$$



Tau Reconstruction

- Use hadronic tau decays for identification
  - 64% branching ratio
- Three primary decay modes
  - Single prong (π)
  - Single prong plus strip (π and π^0 or $\pi^0\pi^0$)
  - Three prong (π π π)
- Hadron Plus Strips (HPS) algorithm
  - Photons from π^0 decay may convert to electrons in tracker
    - Trajectory of electrons is bent by magnetic field
    - Use "strips" in ECAL to reconstruct π^0 candidates
  - π^0 candidates matched to tau signatures in particle flow jets
  - π candidates matched to HCAL depositions





Preselection Strategy

- Apply loose "preselection" cuts before applying full analysis cuts
- Allows data/MC comparison
  - More statistics than signal region
  - Allows testing of analysis strategies before implementation in signal region
- "Blind" portion of preselection region
  - Hide data events where the signal is non-negligible to prevent biased selection

- Require well reconstructed Muon
  - $P_T > 30$ GeV
  - $|\eta| < 2.1$
- Require well reconstructed Tau
  - $P_T > 25$ GeV
  - $|\eta| < 2.3$
- Eliminate events irrelevant to signal
  - Require Muon and Tau to have opposite sign
- Separate events into 0, 1, and 2 jet channels
  - 0 and 1 jet events correspond to gluon gluon fusion
  - 2 jet events correspond to VBF

$H\to\mu\tau_h$ 0 Jet Preselection

Data approximately matches MC models

Z→ττ: (embedded data samples for shape, DY + (1,2,3,4) jet samples for normalization

Z+jets (other): Monte Carlo used for shape and normalization

W+jets: data driven (high Mt (tau,MET) sideband)

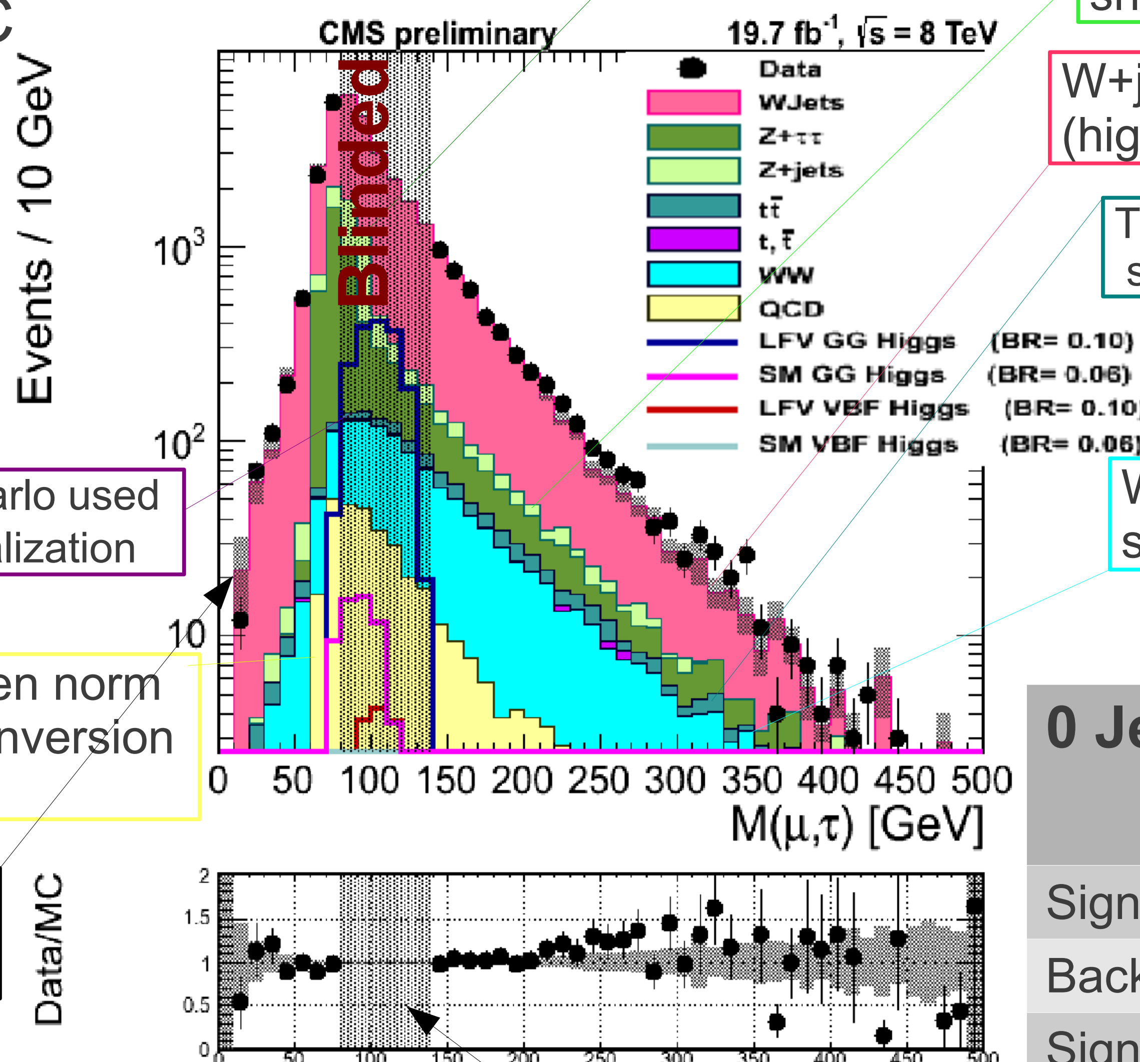
TT+Jets: Monte Carlo used for shape and normalization

WW: Monte Carlo used for shape and normalizaiton

Single top: Monte Carlo used for shape and normalization

QCD: Data driven norm Muon isolation inversion (shape)

MC statistical uncertainty



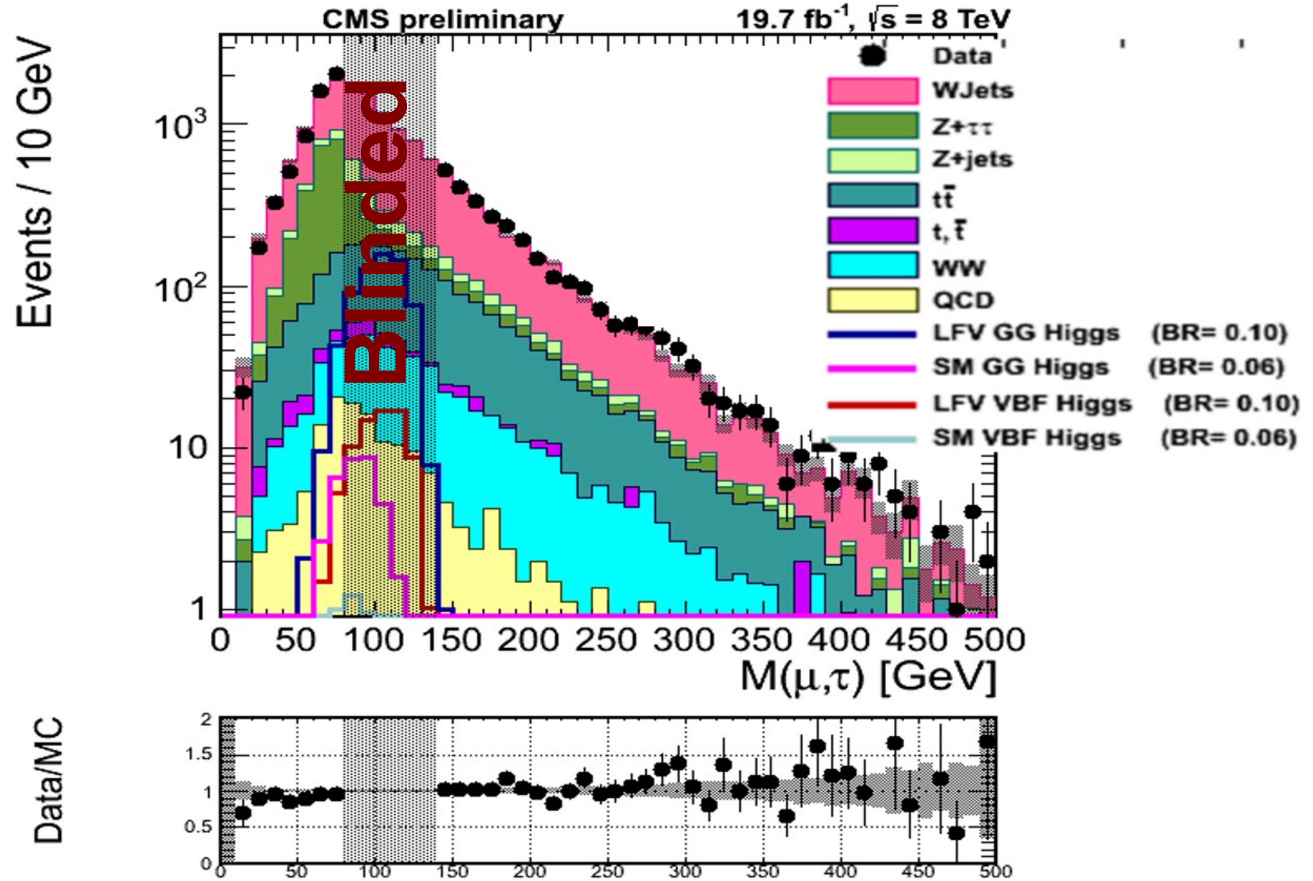
blinded

0 Jet	Events: (80-140 GeV)
Signal:	1700
Background:	26000
Signal/Background	0.07

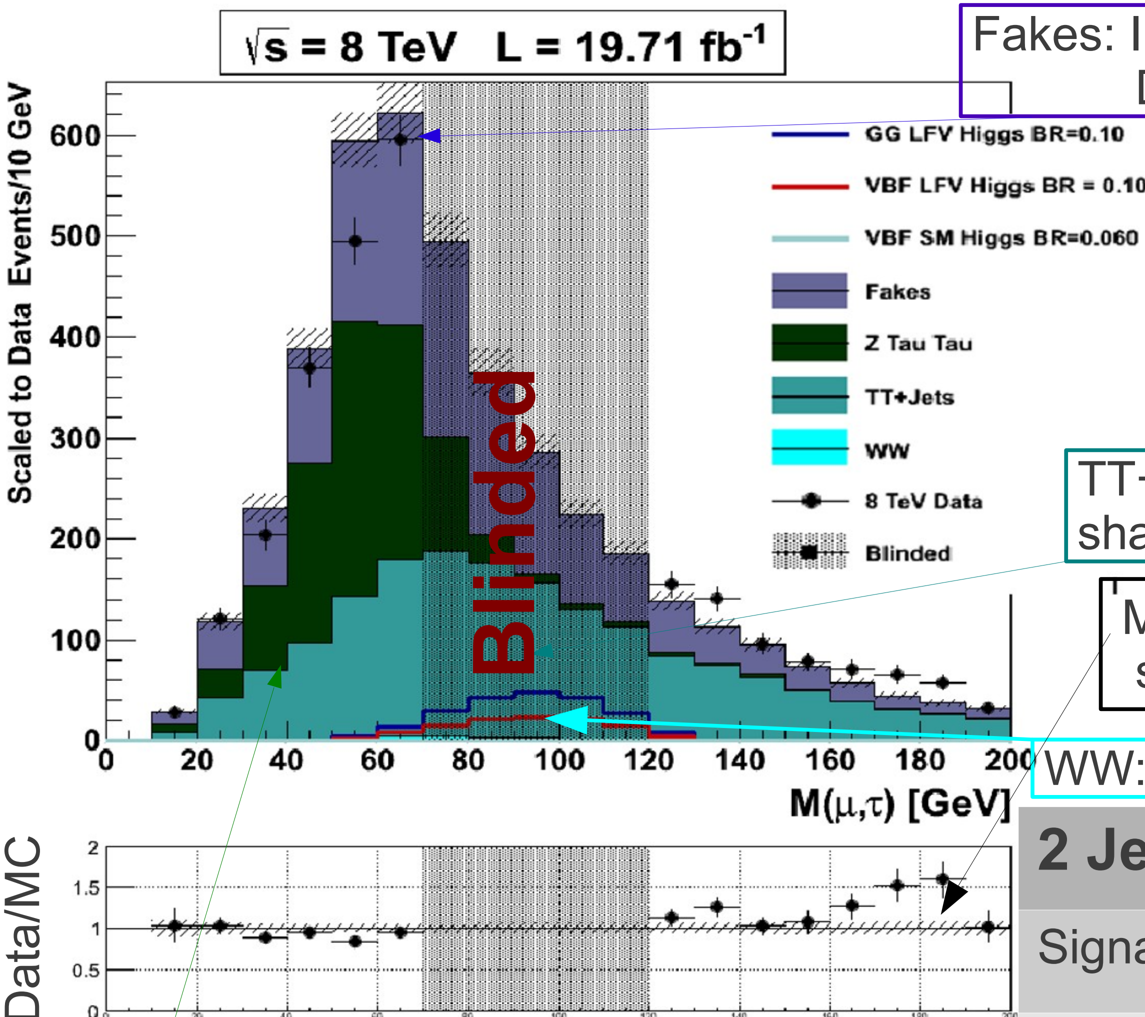
$H \rightarrow \mu\tau_h$ 1 Jet Backgrounds

- Backgrounds are determined in the same way as the 0 jet backgrounds
- Data approximately matches MC models within statistical uncertainty

1 Jet	Events: (80-140 GeV)
Signal:	820
Background:	13000
Signal/Background	0.07



$H \to \mu\tau_h$ VBF (2 Jet) Backgrounds



Fakes: Includes QCD, W+jets
Determined by Fake Rate Method

Data/MC agreement suggests that systematic uncertainties should be increased. Studies are ongoing.

TT+Jets: Normalization and shape from Monte Carlo

MC and Fake rate statistical uncertainty

WW: Normalization and Shape from Monte Carlo

$Z^- \to \tau\tau$: (embedded data samples for shape, DY + (1,2,3,4) jet samples for normalization

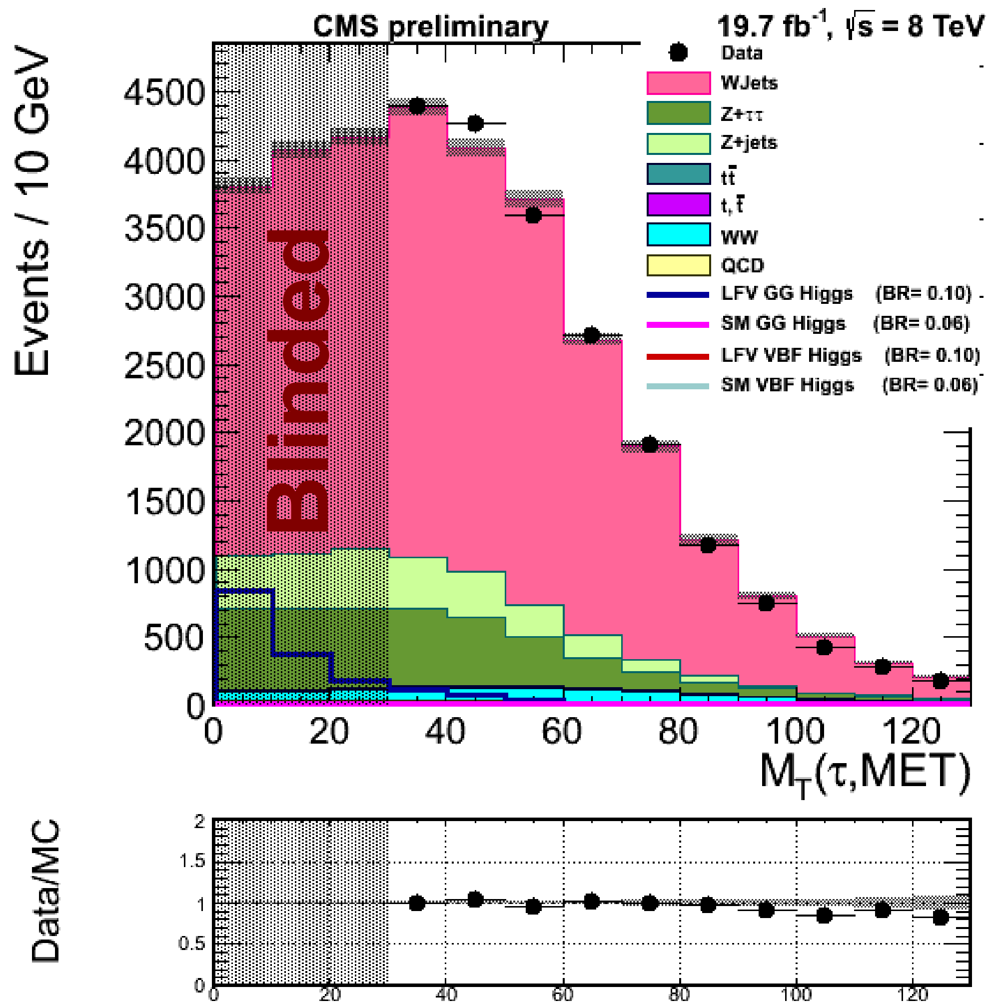
2 Jet	Events: (70-120 GeV)
Signal:	290
Background:	1600
Signal/Background	0.19

W+Jets and QCD Estimation Techniques

- Get W+jets shape from Monte Carlo
- Compute the appropriate normalization factor by scaling W+jets in region dominated by W+jets
  - $M_T(\tau, MET) > 70$ GeV
  - Require (W+jets events) = (data events - other background events)
  - Scale factor of 0.8 for 0 Jet
  - Scale factor of 1.0 for 1 Jet

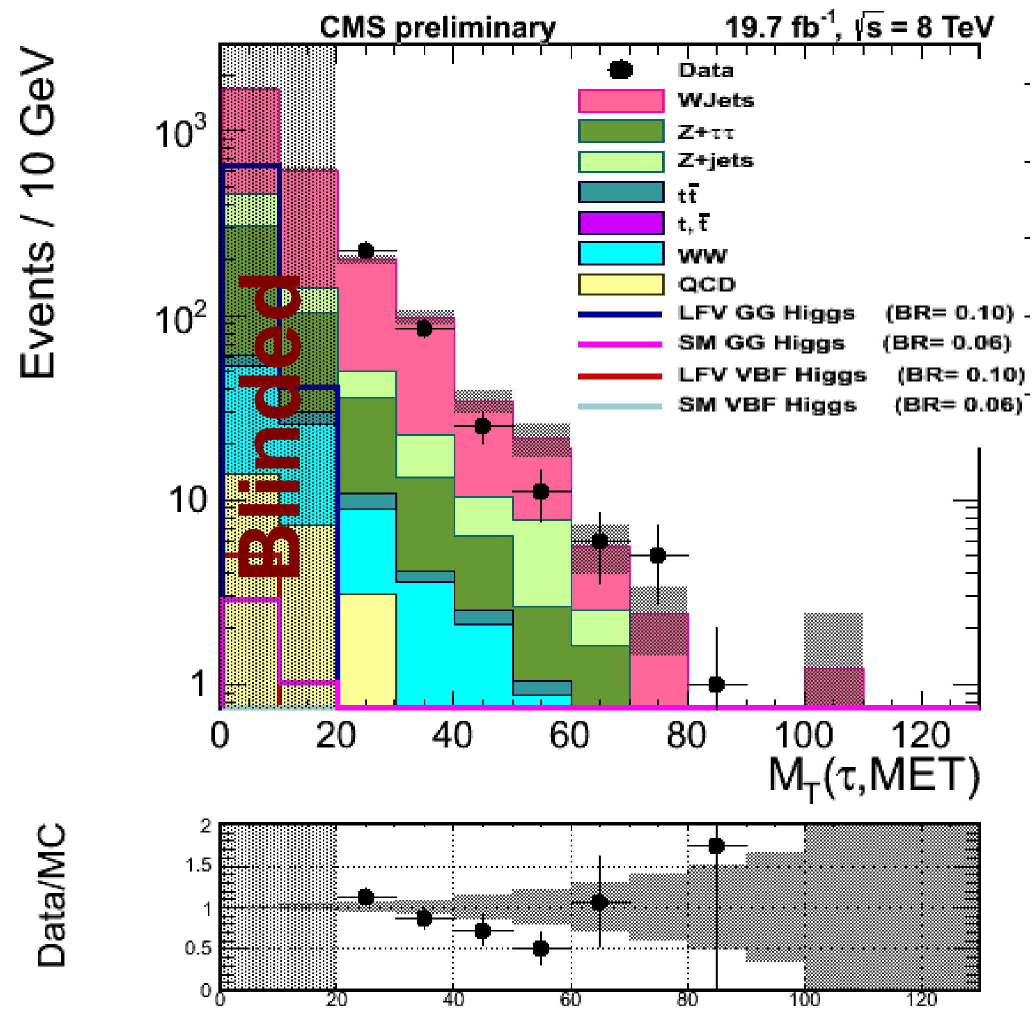
- Determine QCD shape by inverting muon isolation in the data sample
  - Invert isolation to enter rich realm of QCD statistics
  - Compute normalization factor by requiring QCD to agree with data in same sign region
    - Same sign: muon and tau have same sign
    - High QCD statistics in this region

W+Jets Estimation Results



0 Jets, Preselection

Scaled for $M_T(\tau,MET)$ > 70 GeV



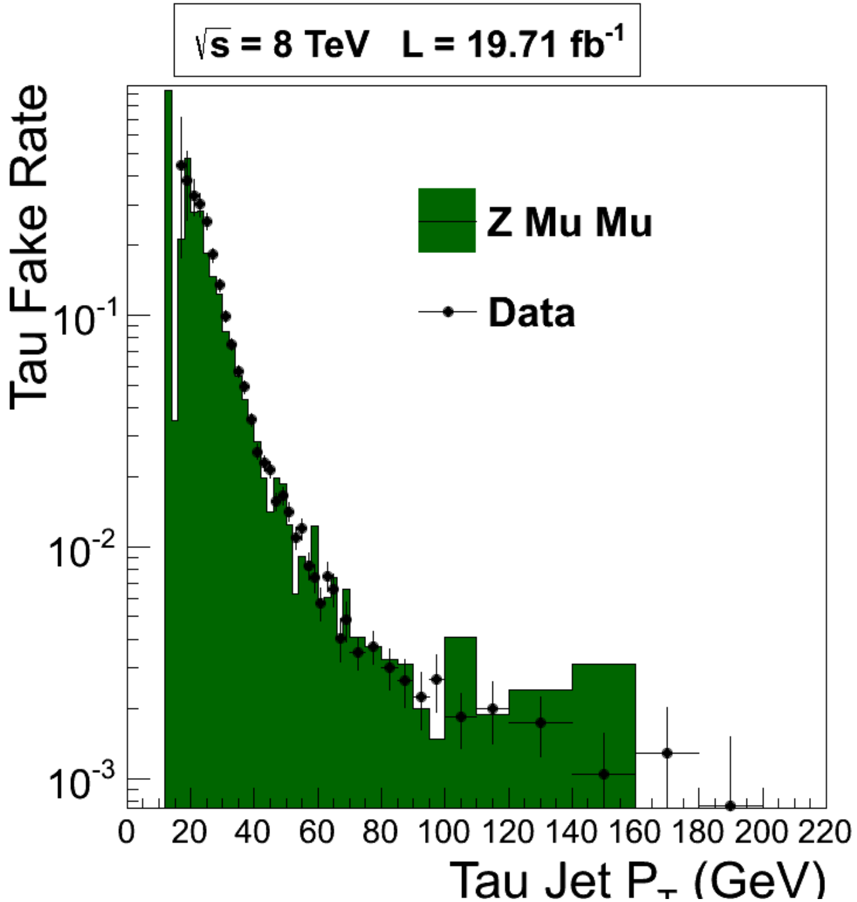
0 Jets, Signal region

No $M_T(\tau,MET)$ < 10 cut

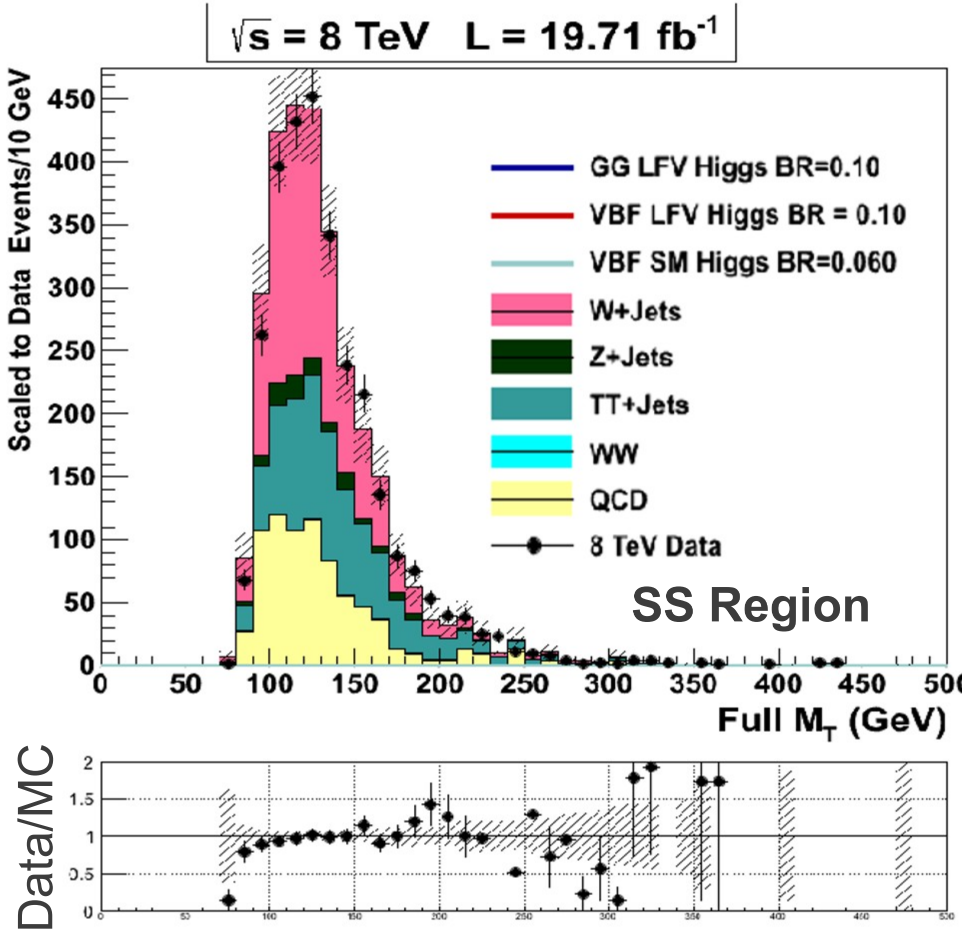
Check scaling close to signal region

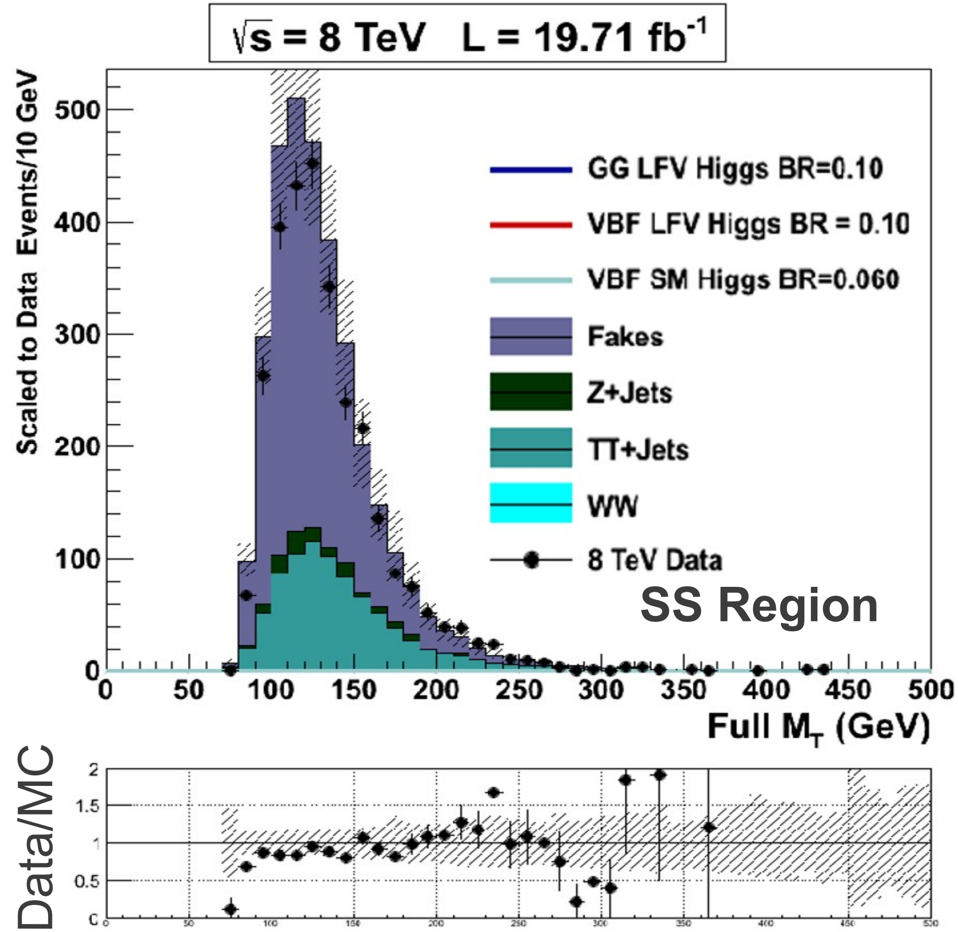
$H \to \mu\tau_h$ VBF Fakes Estimation

- The fake rate method is a way of improving W+jets and QCD background estimation in the 2 jet channel
- Select events with two muons and a tau
  - fake tau rich region
- Estimate tau fake rate (fTau) by computing the fraction of events that are identified as taus but are not isolated
- Invert tau isolation in data sample to enter rich region of tau fakes
- Weight events by a factor of fTau/(1-fTau)
  - Gives shape and yield of "fake" tau events
  - This group of events is dominated by W+jets and QCD



VBF Fake Rate Validation





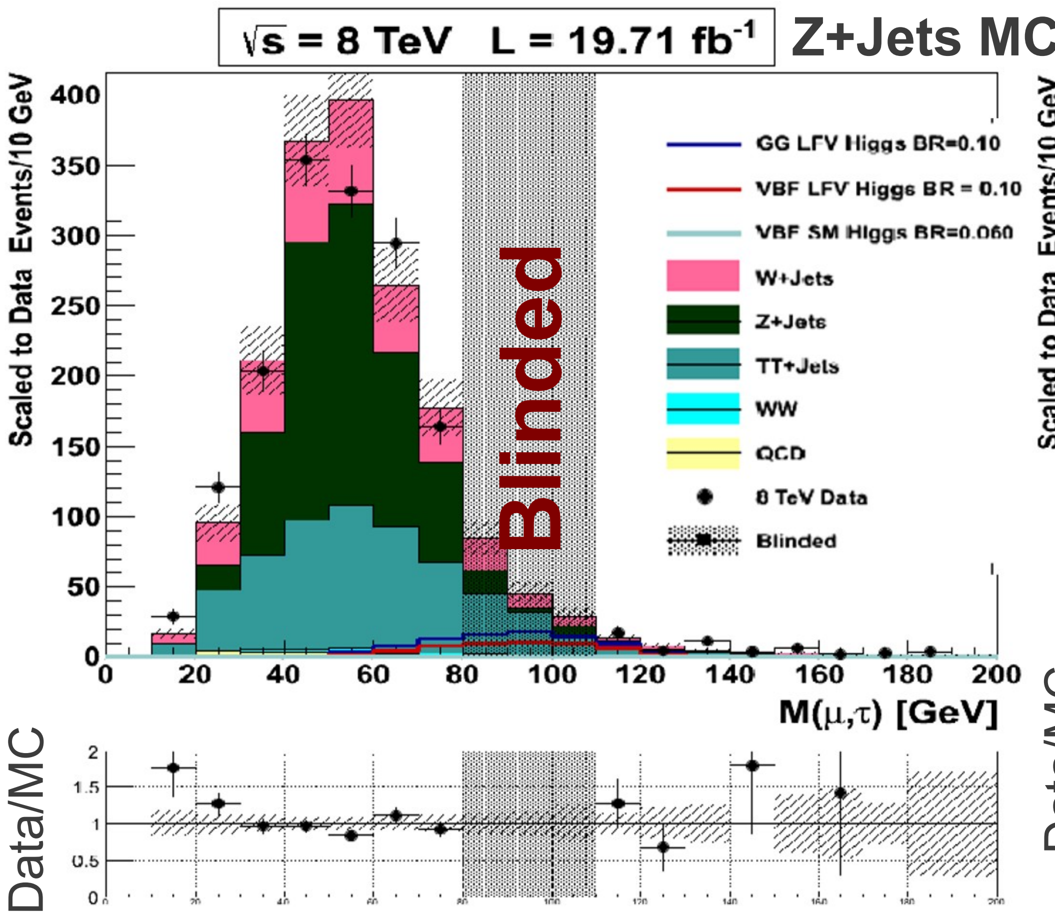
- Compare W+jets Monte Carlo and data driven QCD to fake rate method in fakes control region
  - Preselection cuts
  - Muon and tau have same sign
  - $M_T(\mu,MET) > 70$ GeV
- Data/MC agreement within uncertainties

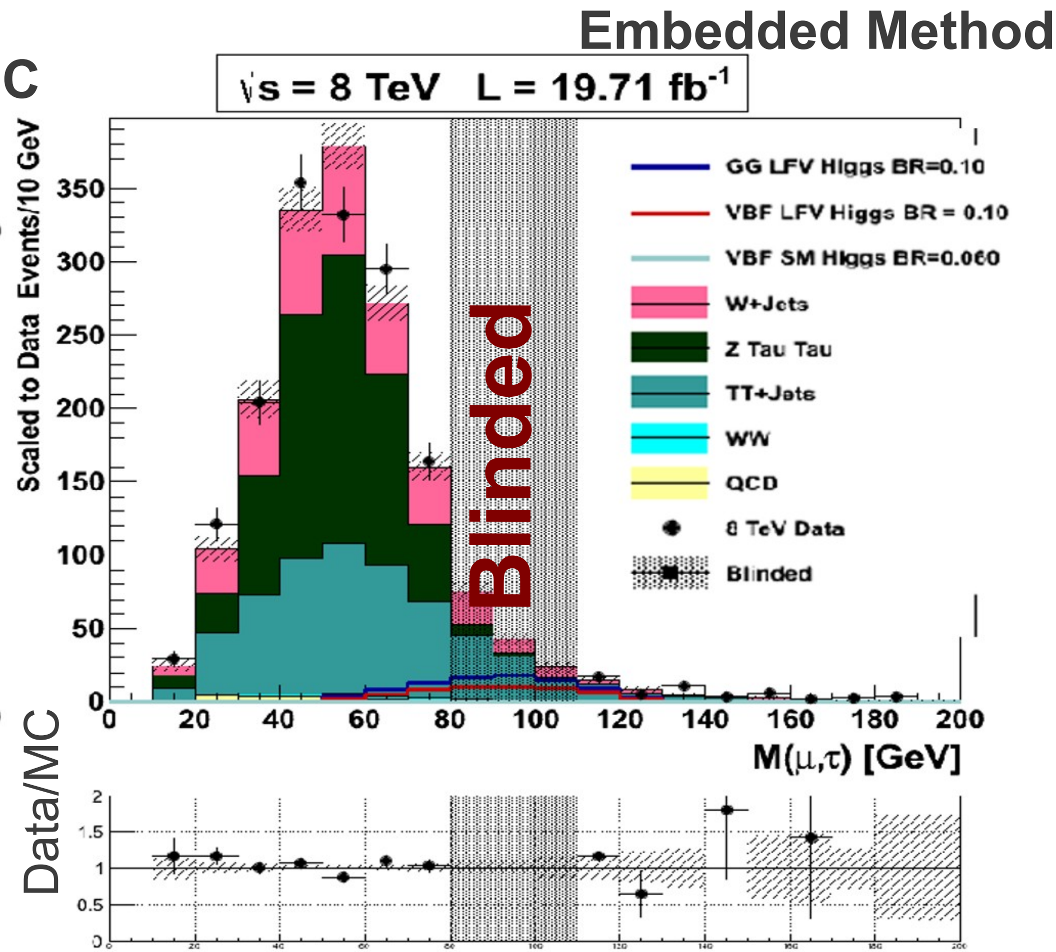
Calculate uncertainty in fake rate by shifting fake rate up and down by error bars from data (previous slide).

Z→ττ Estimation

- Low Z+jets MC statistics
  - Estimate shape from Z→ττ embedded samples
  - Normalization from Drell Yan + (1,2,3,4) Jet MC
    - Drell Yan: quark/anti-quark annihilation that produces Z boson
- Z+jets(other) negligible in VBF channel

- Examine method in VBF Z→ττ control region
  - Preselection Cuts
  - ΔR(μ,τ) < 2.0

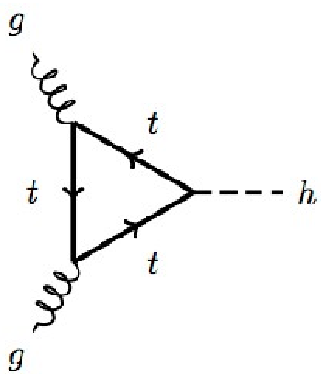




$H \rightarrow \mu\tau_h$ Signal Region Cuts: Gluon Gluon Fusion (GGF)

- Selection optimized in 0 Jet GGF category by varying cuts to maximize $\frac{signal}{\sqrt{background}}$

Ongoing Work

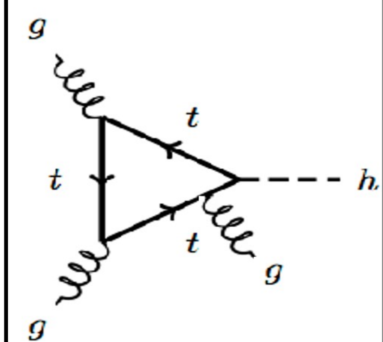


0-Jet Category:

- Preselection
- 0 Jets (p_T > 30 GeV)
- $p_T(\mu) > 40$ GeV
- $p_T(\tau) > 25$ GeV
- $\Delta\Phi(\mu,MET) > 2.5$
- $\Delta\Phi(\tau,MET) < 0.3$
- $M_T(\tau,MET) < 10$ GeV

1-Jet Category:

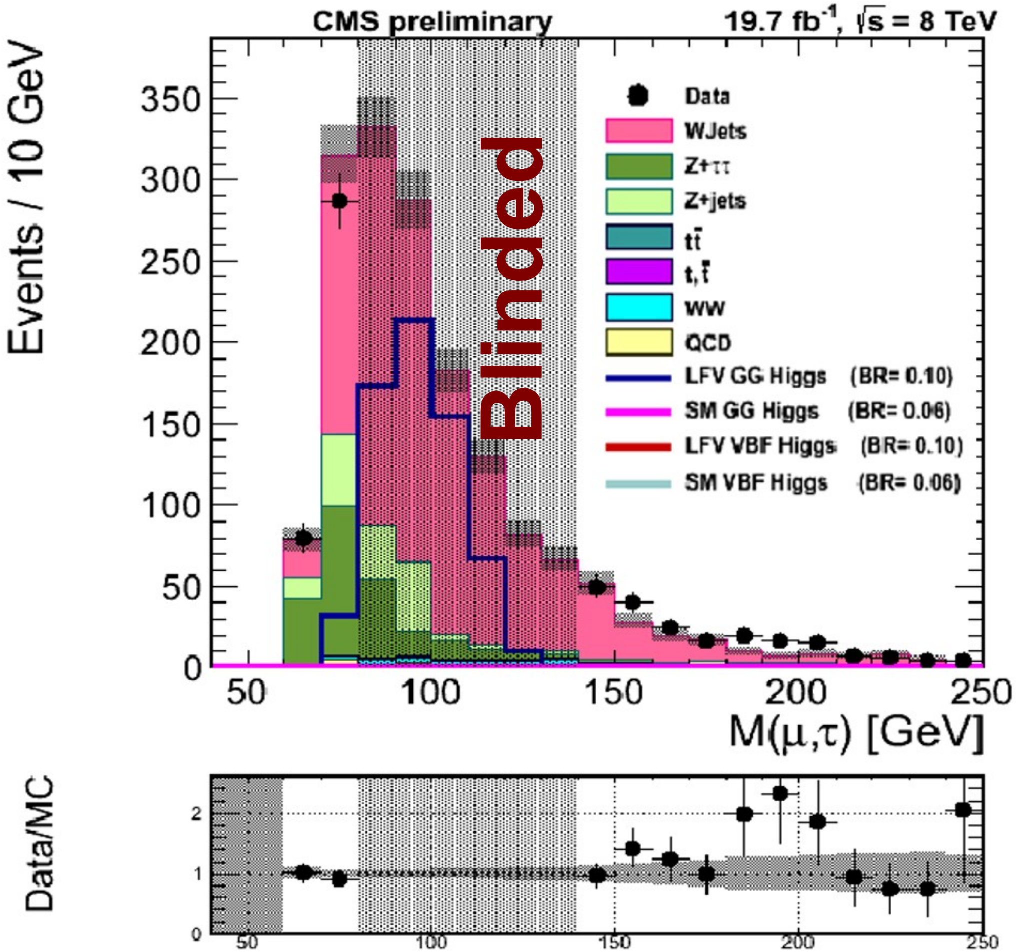
- Preselection
- 1 Jet (p_T > 30 GeV)
- $p_T(\mu) > 40$ GeV
- $\Delta\Phi(\tau,MET) < 0.3$
- $p_T(\tau) > 25$ GeV
- $M_T(\tau,MET) < 10$ GeV

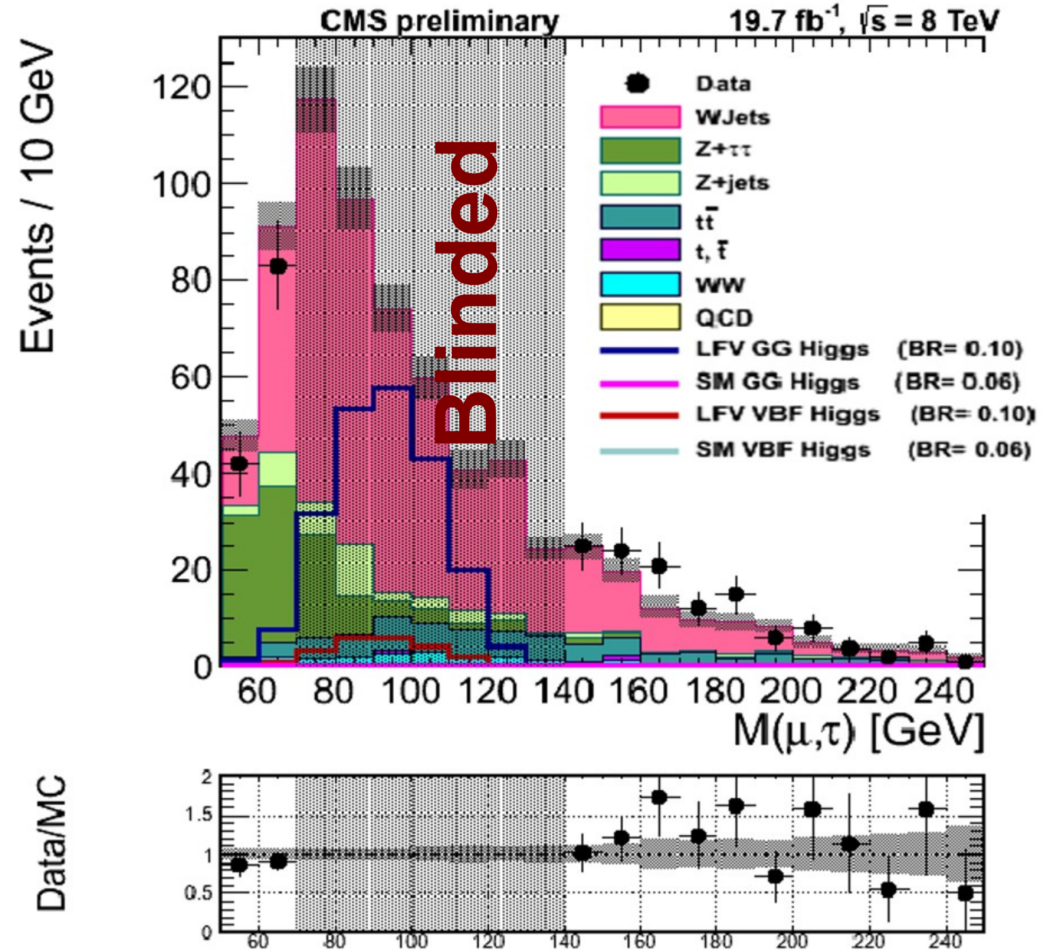


Sensitive to GGF

LFV Higgs process has low $M_T(\tau,MET)$ and $\Delta\Phi(\tau,MET)$ because the emitted tau and neutrino are roughly collinear

Signal Region: $H\to\mu\tau_h$ 0 and 1 Jet Channels





0 Jets	Events: (80-140 GeV)
Signal	620
Background	1100
Signal/Background	0.55

1 Jet	Events: (70-140 GeV)
Signal	290
Background	890
Signal/Background	0.33

S/B increase by factor of 7.9 from preselection

S/B increase by factor of 4.7 from preselection

$H \rightarrow \mu\tau_h$ Signal Region Cuts: Vector Boson Fusion (VBF)

- Selection optimized by varying cuts to maximize $\frac{signal}{\sqrt{background}}$

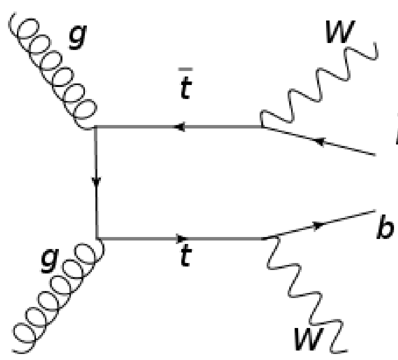
2-Jet Category:

Preselection
2 Jets ($p_T > 30$ GeV)
Mjj > 600 GeV
$|\Delta\eta(jj)| > 3.5$
$p_T(\mu) > 45$ GeV
$p_T(\tau) > 45$ GeV
$M_T(\tau,MET) < 30$ GeV
Central jet veto (30 GeV)

Sensitive to VBF

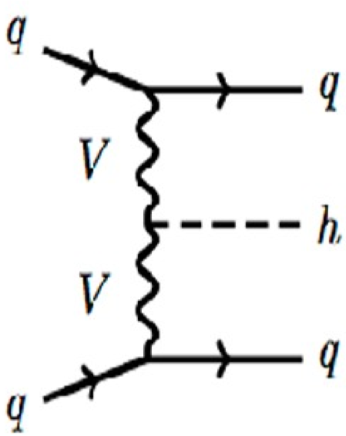
Central jet veto reduces ttbar and QCD

ttbar backgroud



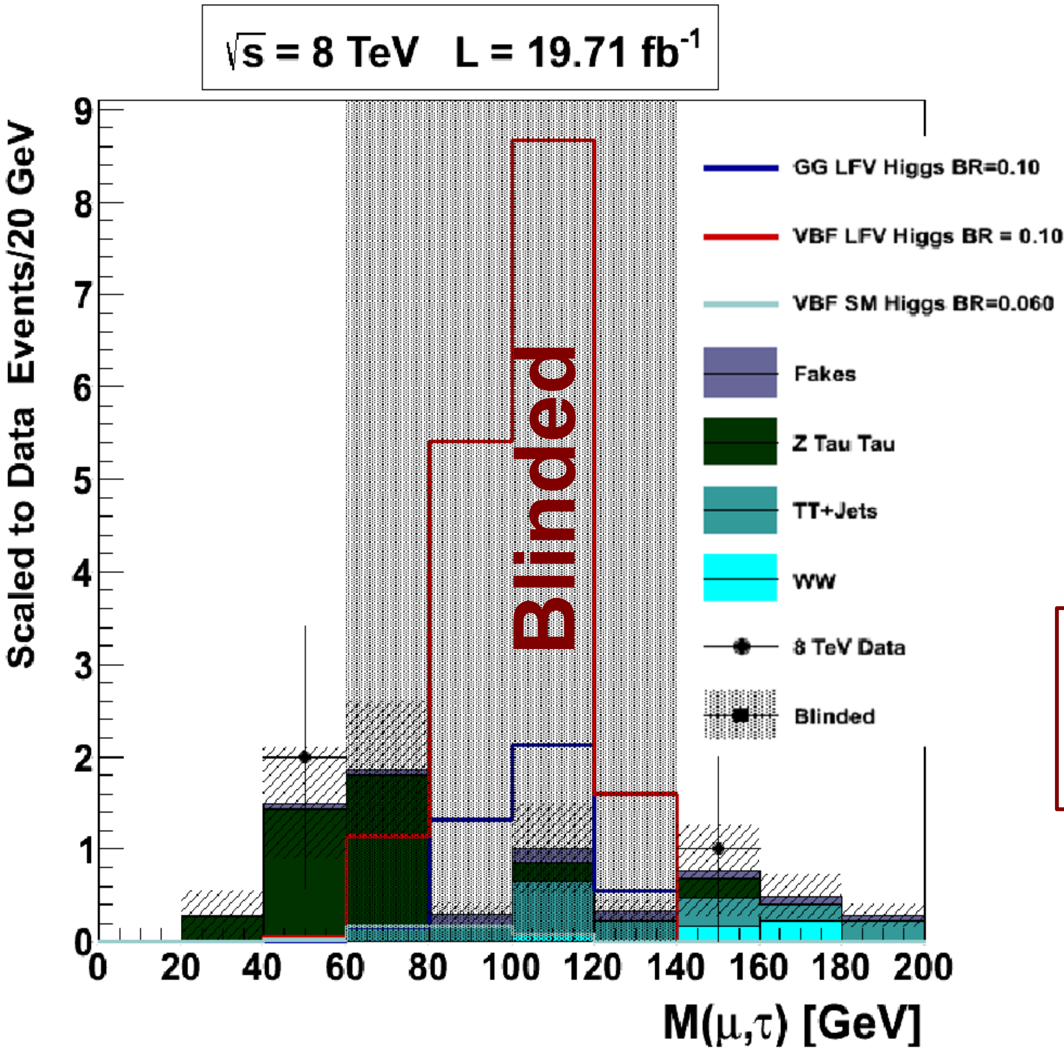
Heavy t quark may radiate gluons which produce hadronic showers (central jets)

VBF jets have pronounced separation in η



Central jet veto eliminates jets with $P_T > 30$ GeV that are not either of the 2 leading jets

Signal Region: $H \rightarrow \tau_h \mu$ 2 Jet Channel



2 Jets	Events: (60-140 GeV)
Signal	21
Background	3.9
Signal/Background	5.4

Recall: S/B = 0.19 for Preselection Cuts

Improvement by factor of 28

Systematic Uncertainties

Source	Uncertainty
Common (Signal+Background)	
Luminosity	2.6%
Trigger	1-3%
Muon Trigger/ID/Isolation	2%
Tau ID/Isolation	6%

Backgrounds	
$Z \rightarrow \tau\tau$ Embedding	3%
WJets/QCD	20%
Tau Fakes	30%
WW+Jets (MC NLO)	15%
TTBar+Jets	10%
SingleTop	10%
SM Higgs	10 %
Signal Uncertainties – 10%	

- Small luminosity and trigger uncertainties are standard CMS values
- Object ID and Isolation uncertainties are from the respective particle object groups
- Tau fake uncertainty
  - Shift fake yield up and down by uncertainty on $Z \rightarrow \mu\mu$ data
  - $(Yield_{up} – Yield)/Yield = (Yield-Yield_{down})/Yield = 30\%$
- MC Backgrounds: estimate of 10-15% uncertainty on MC
- Systematic uncertainties used for the expected limit calculations

Sensitivity to Exclusion Limits

All numbers given are expected limits on branching ratio (BR) ($H\rightarrow\tau_h\mu$)

95% Confidence Level (Blinded Analysis)

	0 Jets	**1 Jet**	**2 Jets**	**All**
$\tau_{had}\mu$	BR: 1.69 +/- 0.86%	BR: 2.50 +/- 1.29% (not optimized)	BR: 2.12 +/- 1.08%	BR: 1.12 +/- 0.57 %

Expected Limit: Limit that can be established after unblinding if signal is not detected

Definition of 95% confidence level limit:

$$\text{Probability}[BR(H\rightarrow\mu\tau_h) < 1.12\%] \geq 95\%$$

These limits are computed using the standard confidence level estimation procedure for CMS and ATLAS

Future Plans

- Pre-upgrade analysis goals
  - Repeat limits with new signal MC
    - Pileup and tau decay with tauola
  - Add jet energy scale and tau systematics
  - Unblind analysis and compute BR($H \to \mu\tau$)
    - Will verify or put new constraints on BSM theories
- Planned LHC upgrade for 2015
  - Beam energy of 6-7 TeV
  - Gluon gluon Higgs production cross section will increase to 50 pb (at 14 TeV)
    - Increase by factor of 2.6
  - VBF cross section will increase to 4.2 pb (at 14 TeV)
    - Increase by factor of 2.7
  - Cross sections of major backgrounds expected to increase by factor of 2
  - Expected limit will improve by about a factor of 3
  - Expect 50 fb^{-1} of new data in first year of upgrade to use for my thesis

Conclusions

- This analysis is currently sensitive to an expected limit of 1.12% +/- 0.57% for BR($H \rightarrow \mu\tau$)
  - Improved sensitivity to come with LHC upgrade
- This analysis is well equipped to search for the BSM $H \rightarrow \mu\tau_h$ process
- This is the first analysis to make a direct search for a Lepton Flavor violating Higgs boson