A Search for Lepton Flavor Violating Decays of the Higgs Boson and a Measurement of W Boson Production Using the CMS Detector at the LHC

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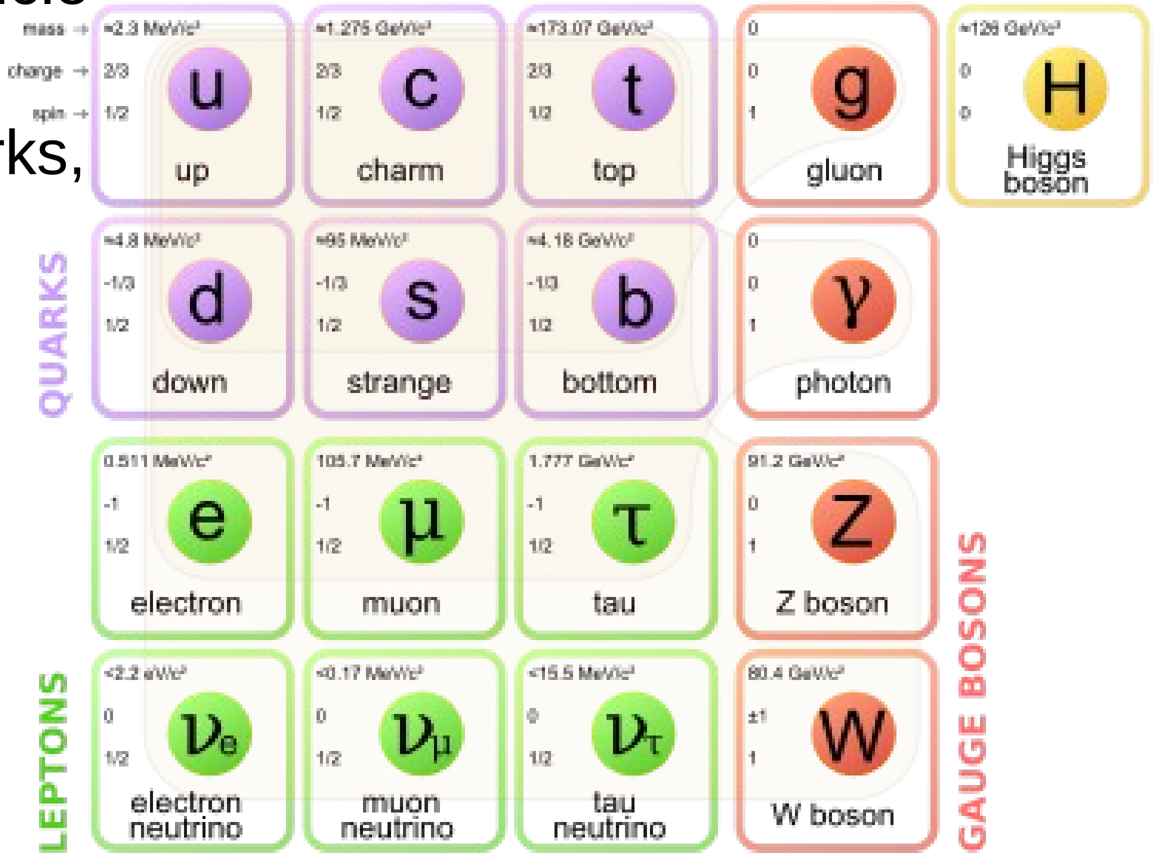
Outline

- Theoretical Background
  - Standard Model
  - Importance of LFV Higgs
  - Importance of W+jets
- Experimental Setup
  - LHC
  - CMS
- Monte Carlo simulation
- Event reconstruction
  - Particle flow objects
- LFV Higgs analysis
- W+Jets analysis
- Conclusions and Outlook

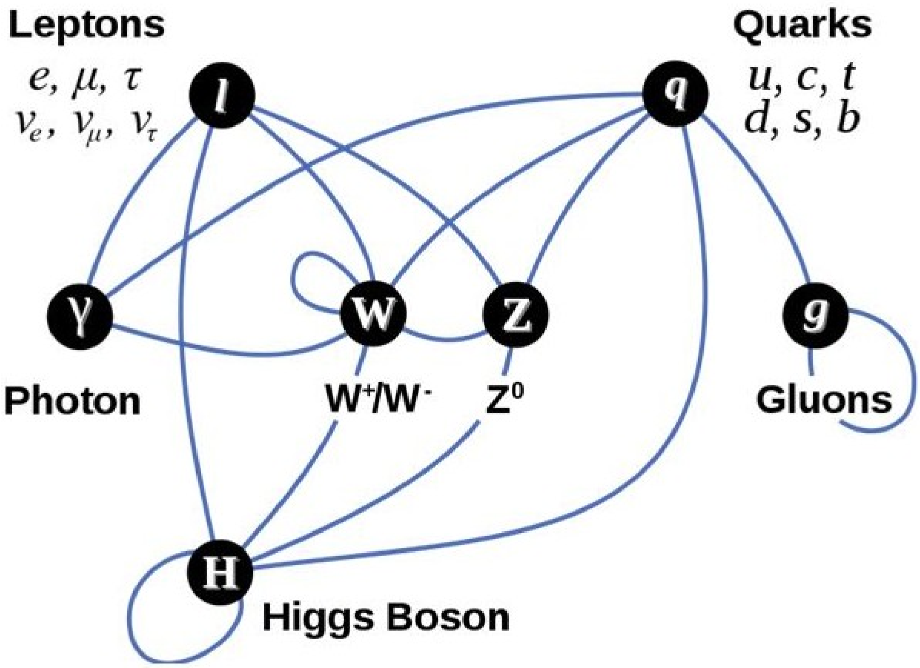
Standard Model (SM)

- Comprehensive theory of particle interactions
- 3 generations (flavors) of quarks, leptons
  - $\begin{pmatrix}u\\d\end{pmatrix}\begin{pmatrix}c\\s\end{pmatrix}\begin{pmatrix}t\\b\end{pmatrix} \quad \begin{pmatrix}e\\\nu_e\end{pmatrix}\begin{pmatrix}\mu\\\nu_\mu\end{pmatrix}\begin{pmatrix}\tau\\\nu_\tau\end{pmatrix}$
  - Form all known matter
- 4 gauge bosons
  - Propagate fundamental forces
  - Strong force: gluon
  - EM force: photon
  - Weak force: W/Z bosons
- Higgs boson
  - generates mass for W/Z, quarks, and charged leptons



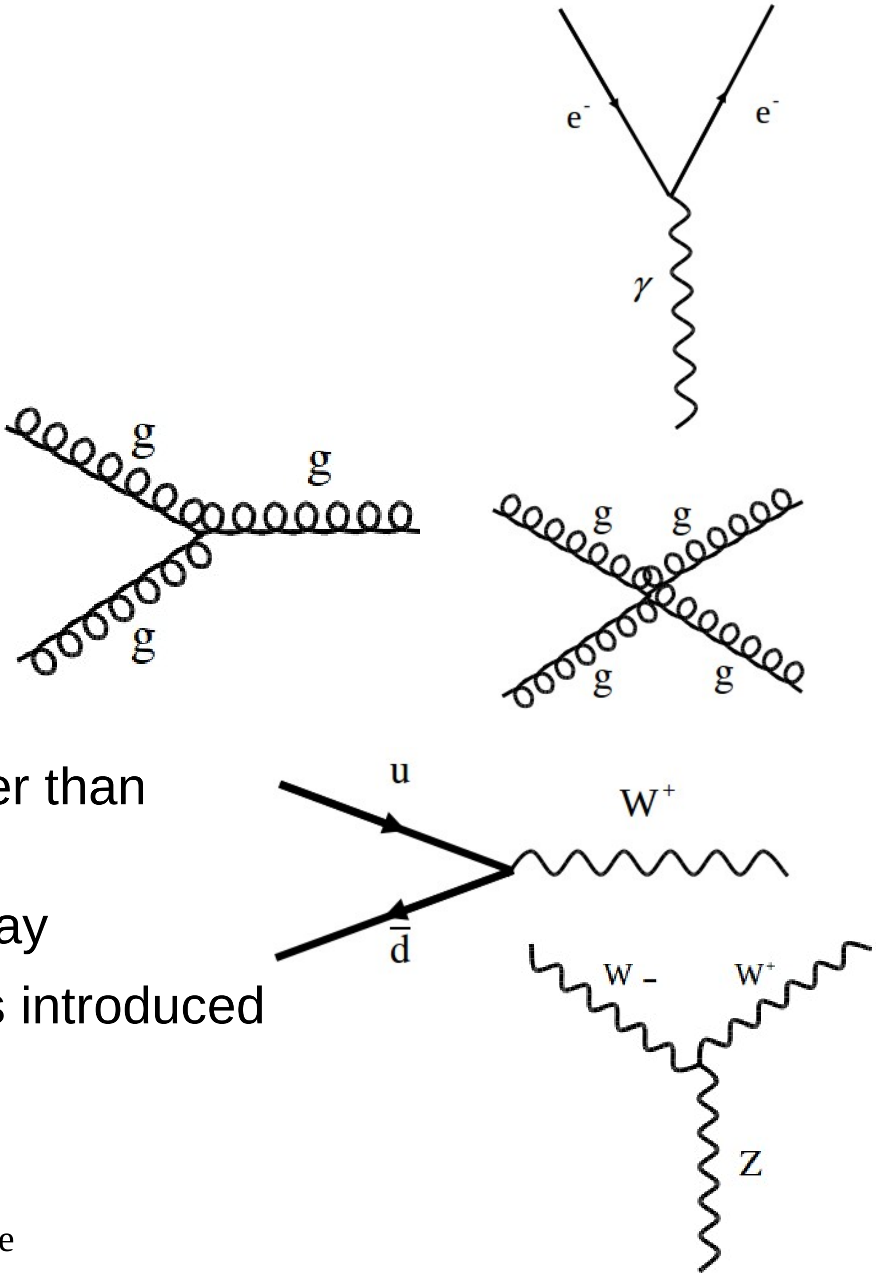
Standard Model Interactions

- Electromagnetic force (photon)
  - Interacts with charged particles
- Weak nuclear force
  - W, Z bosons
  - Responsible for nuclear β decay, tau lepton decay
- Strong nuclear force
  - Gluon mediates interactions between “colored” particles (quarks, gluons)
  - 3 colors/anticolors: red, green,blue
  - Free quarks not found in nature
  - Quarks cluster in “colorless” final states
    - Red/antired, green/antigreen, blue/antiblue, rgb, anti-rgb



Standard Model Gauge Bosons

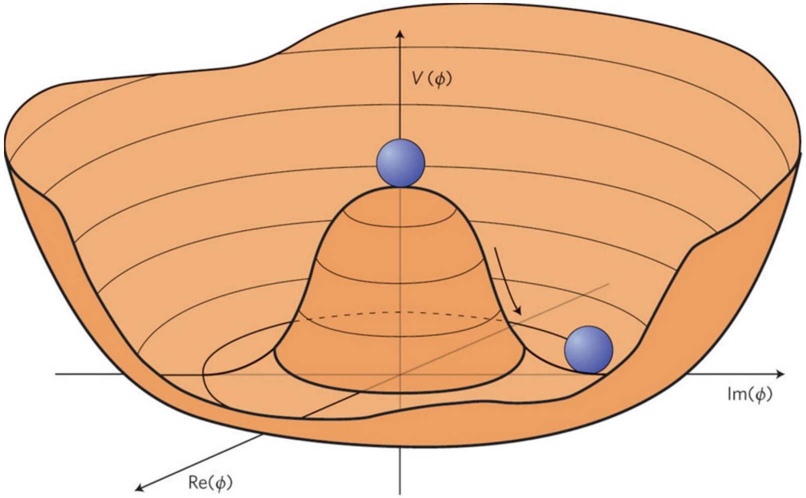
Examples of Feynman Diagrams



- Electromagnetic Force
  - Photon is massless, does not decay
  - Infinite range
- Strong nuclear force
  - Gluon is massless, does not decay
  - Short range: 10^{-15} m
    - Due to gluon-gluon interactions
- Weak nuclear force
  - Short range: 10^{-18} m
  - Self interactions, but 10^{-11} times weaker than strong force
  - W,Z bosons must be massive and decay
  - Not allowed in SM unless Higgs field is introduced

Higgs Field

- W,Z bosons are required to be massless in the SM because of gauge invariance
  - SM must be invariant about rotations and translations in phase space
- Solution: electroweak symmetry breaking
- 2 complex scalar fields in φ: $\left(\frac{\varphi_1}{\varphi_2}\right)$
  - 4 degrees of freedom
- 3 degrees become W+, W-, and Z masses after unitary gauge transformation
- Remaining degree of freedom is Higgs field
  - Higgs field couples with fermions and generates mass terms
- Higgs boson with a mass of 125 GeV discovered on July 4 2012



$$V(\varphi) = \tfrac{1}{2}\mu^2|\varphi|^2 + \tfrac{1}{4}\lambda|\varphi|^4$$

Ground state at:
$|\varphi|_0 = (-\mu^2/\lambda)^{1/2} = v$
$v = 246$ GeV

$$M_H = v(2\lambda)^{1/2}$$

Beyond the Standard Model (BSM)

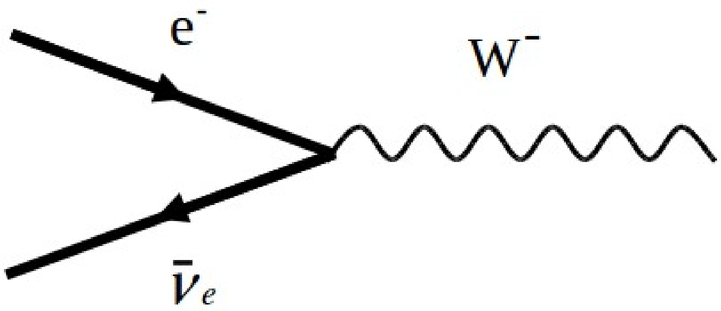
- SM unifies three out of the four forces
  - What about gravity?
- If the SM is applicable up to the scale of the gravitational force (10^{18} GeV), Higgs mass will become extremely large at that energy scale
  - Known as the Hierarchy problem (large difference between weak scale and gravitational scale)
- Why particular values of particle masses and coupling constants between force carriers and particles?
- Analyze couplings of recently discovered Higgs boson to search for a more profound theory

Introduction to Lepton Flavor Violating Higgs

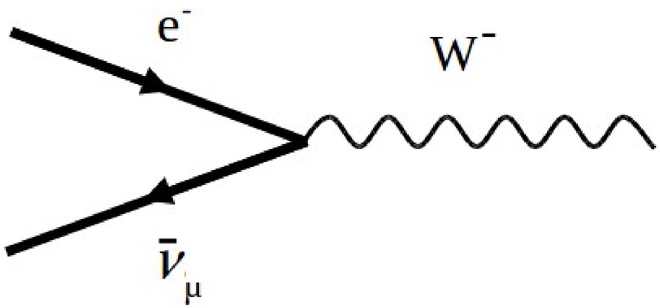
Lepton Flavor Violating (LFV) Higgs

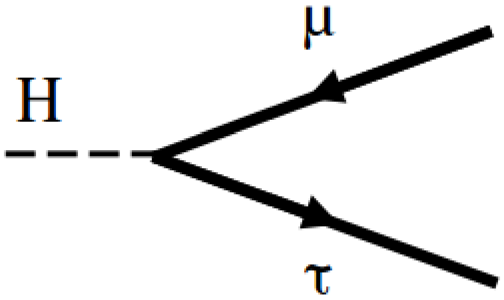
- SM prohibits lepton “flavor” violating couplings
  - Each vertex can include no more than one lepton generation
- Does a flavor mixing exist for leptons, mediated by Higgs couplings?
  - H → ee, H → μμ, H → ττ allowed
  - No fundamental reason why LFV couplings not allowed
- Higgs couplings are mass dependent
  - Look for LFV couplings involving the two heaviest leptons: a muon and a tau

Flavor Conserved



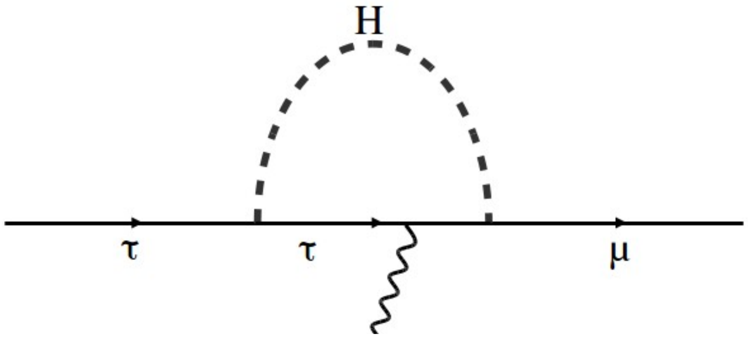
Flavor Violated

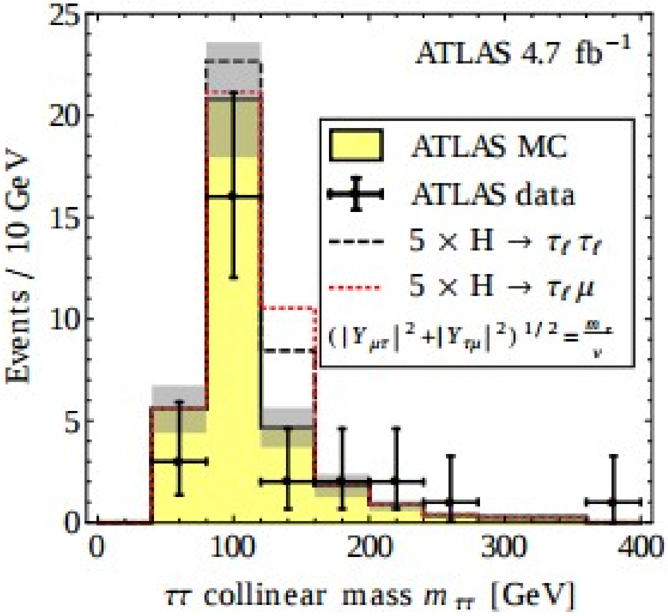




Prior Searches for LFV Higgs Couplings

- No prior direct searches
- Indirect limits have been established from $\tau \to \mu\gamma$
  - $\tau \to \mu\gamma$: $B(H \to \mu\tau) < 24\%$
- Analysis of early ATLAS $H \to \tau\tau$ data[1] by phenomenologists gives limit of $B(H \to \mu\tau) < 13\%$





[1] arXiv:1209.1397

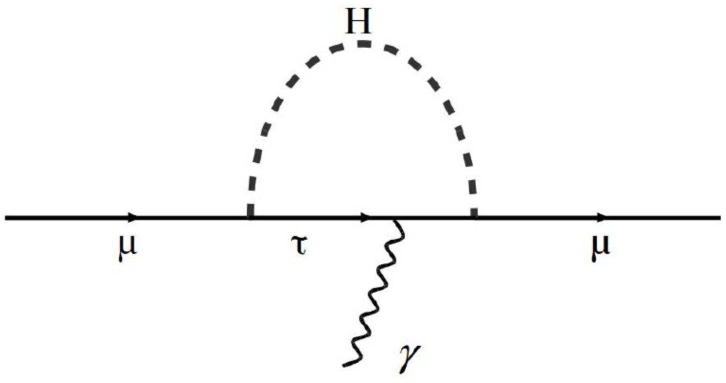
Motivation for BSM Higgs Couplings Hierarchy Problem

- Solution to Hierarchy problem:
  - Supersymmetry: each SM particle has supersymmetric partner
  - Fermions have supersymmetric boson partners, Bosons have supersymmetric fermion partners
    - Fermion and boson loops are opposite sign, prevent increase of Higgs mass
  - Why not LFV couplings at TeV scale as well?

A top quark and its supersymmetric partner interacting with the Higgs

Motivation for LFV Higgs Couplings Muon Dipole Moment

- Magnetic dipole moment (μ): A measure of the torque a current loop experiences in a magnetic field: $\vec{\tau} = \vec{\mu} \times \vec{B}$
  - Intrinsic spin of muons causes them to precess in a magnetic field
- Interactions of muons with virtual particles can affect the magnetic moment
- Currently 3.6σ deviation from SM measured at Brookhaven E821 experiment
  - Could be explained by LFV couplings



LFV contribution to muon dipole moment

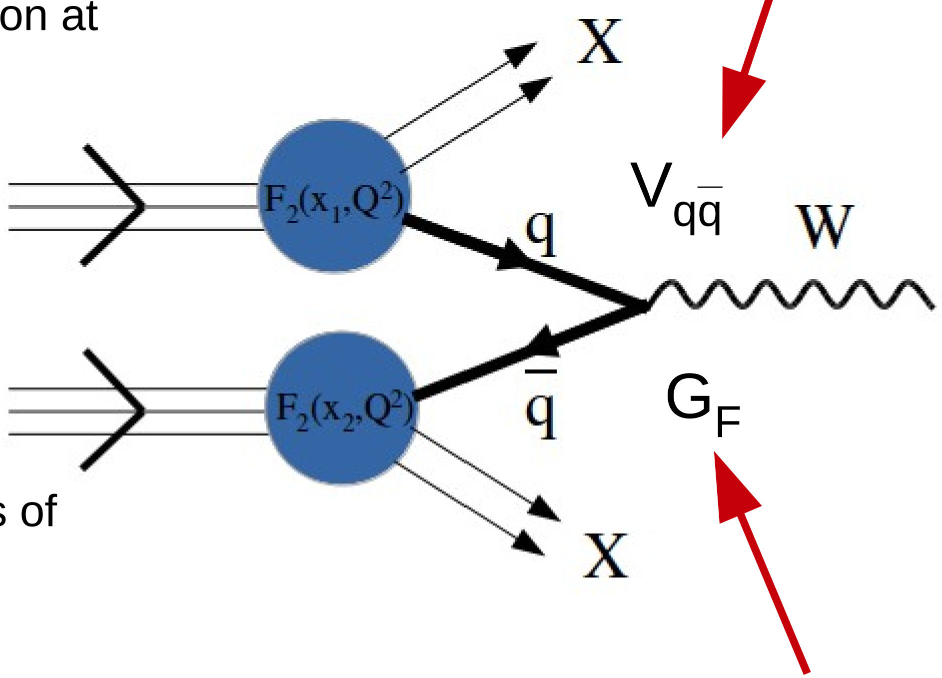
Introduction to W Boson Production in Association with Jets

W+Jets Measurement

- Important to measure Standard Model parameters at new energy scales
  - This is the first measurement of W+Jets production at 13 TeV
- Strong force and weak force both involved in W+Jets production
  - Production of W involves G_F, $V_{q\bar{q}}$
  - Production of jets involves QCD
- $F_2(x,Q^2)$ is a structure function
  - Sum over distribution of quark/gluon constituents of the proton
  - Carry a fraction x of proton's momentum
  - Probed at momentum scale Q^2
- Detect W boson via its decay to a muon and a muon neutrino
- Detect hard scattering products X by identifying jets

Quark mixing matrix element

W Boson production



Fundamental constant of SM that defines weak force strength

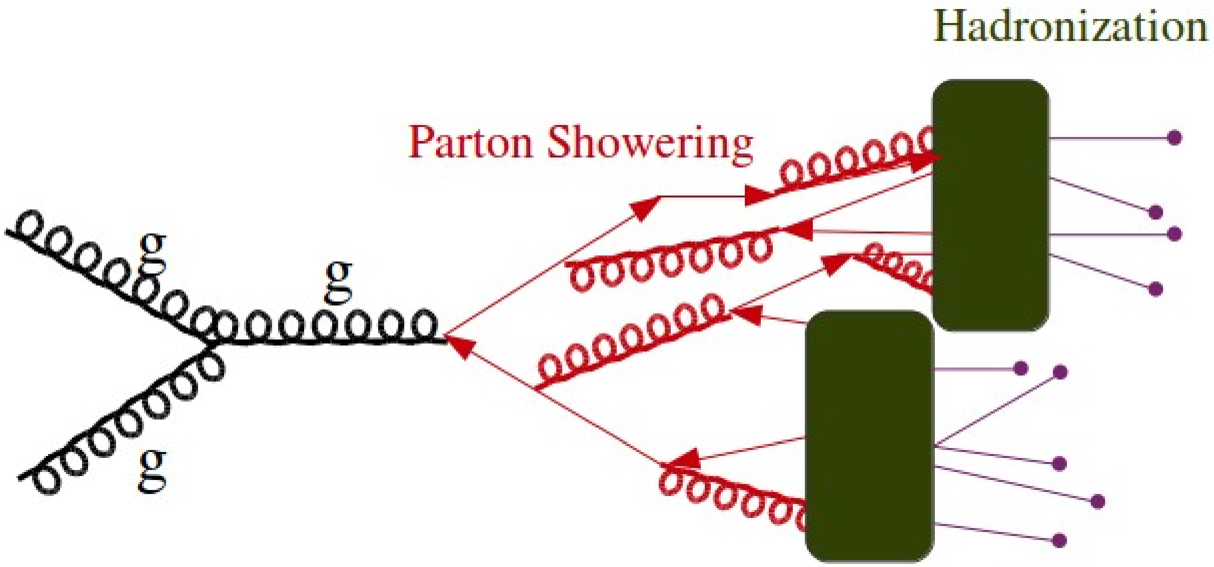
Strong Nuclear Force

- W production is a probe to examine strong interactions
- Strong force describes interactions between quarks and gluons
  - Mediated by the gluon
- Theory of strong force is quantum chromodyamics (QCD)
  - Coupling constant $\alpha_s \sim 1/\ln(Q^2/\Lambda_{QCD})$
  - $\Lambda_{QCD} = 214$ MeV
- At short distances or high momentum transfer (Q^2), coupling constant is small ($\alpha_s << 1$)
  - Perturbative QCD (pQCD) regime
  - Expand α_s perturbatively
    - $\alpha = 1 + \underbrace{A\alpha_s}_{\text{Leading Order (LO)}} + \underbrace{B(\alpha_s)^2}_{\text{NLO}} + \underbrace{C(\alpha_s)^3}_{\text{NNLO}} + \ldots$

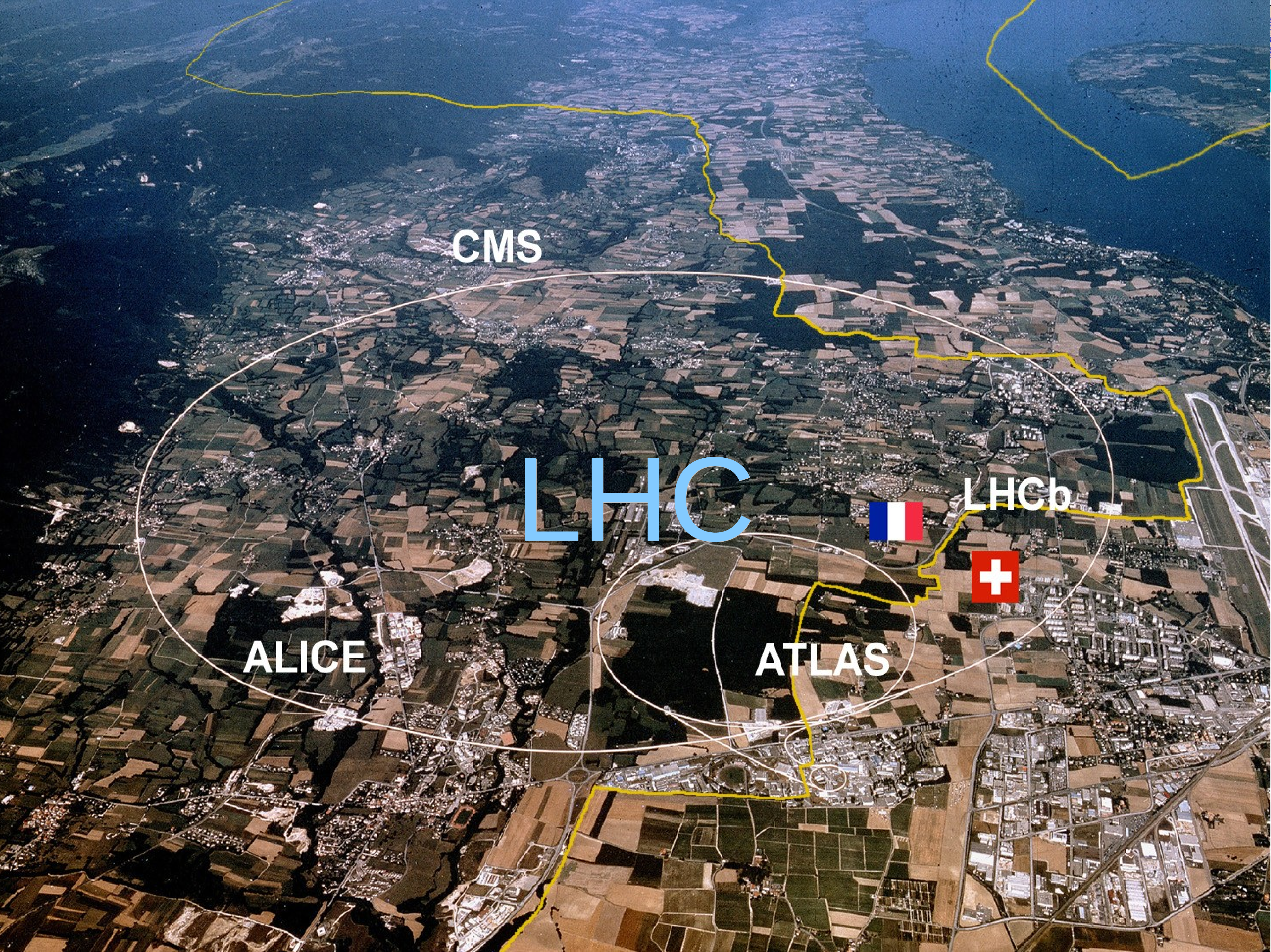
Levine

Jet Formation

- After hard scattering, energetic quarks and gluons will radiate additional quarks and gluons (parton shower)
  - Q^2 too small for pQCD
  - Must model using prior experimental measurements
- Eventually quarks and guons will cluster in colorless states
  - Known as hadronization
- Heavy hadrons will decay
- Jets are collimated streams of hadrons

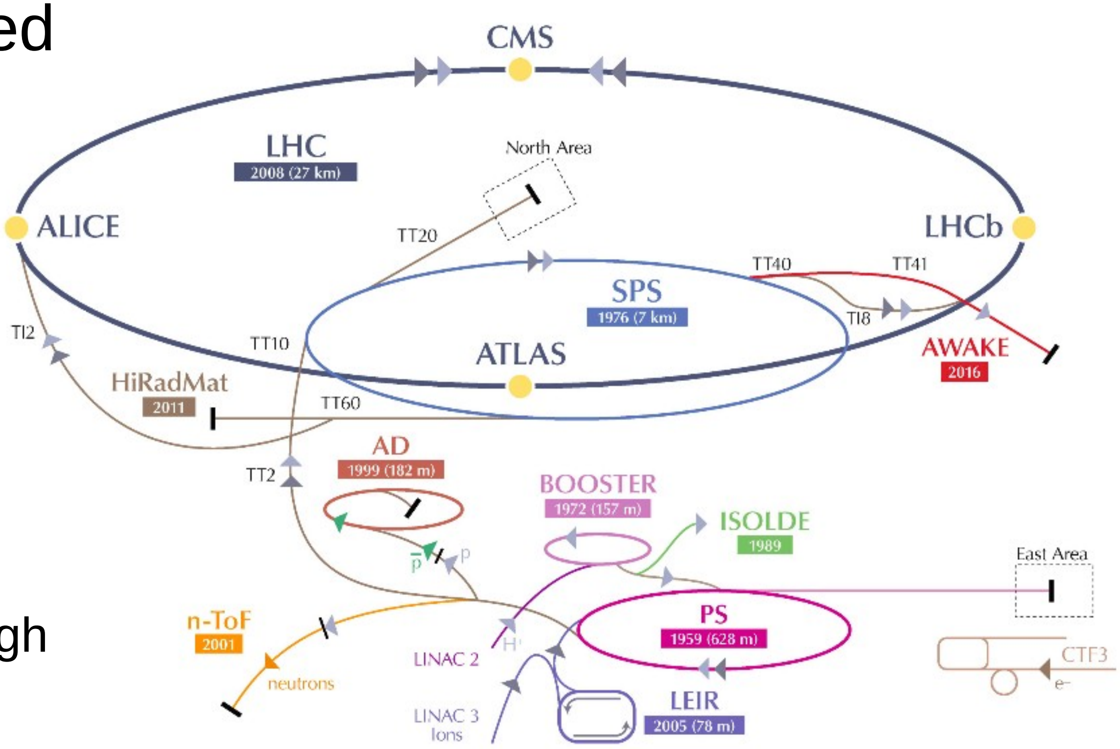


Jet formation from energetic incident gluons


CMS
LHC
LHCb
ALICE
ATLAS

Large Hadron Collider (LHC)

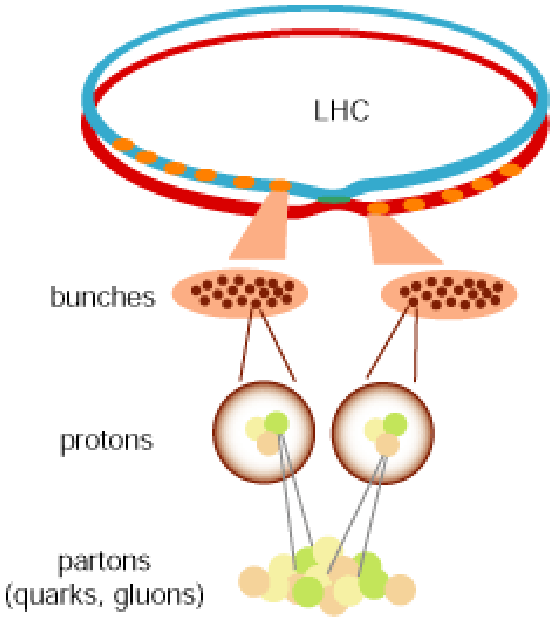
- Proton-Proton collider located near Geneva, Switzerland
  - 27 km circumference
  - Design CM energy of 14 TeV
  - Operated at 8 TeV in 2012
  - Operated at 13 TeV in 2015
- Four experiments
  - CMS, ATLAS: General purpose high energy physics detectors
  - LHCb: High energy B physics
  - ALICE: High 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 move to LHC, accelerated to 4 TeV (6.5 TeV)
- Protons are guided by superconducting magnets cooled by liquid helium to 1.9 K
  - Dipoles bend proton beams in circular path
  - Quadrupoles focus protons along horizontal and vertical planes
- RF system creates bunches of protons
  - 25 ns design bunch spacing
- Multiple proton-proton interactions per bunch crossing
  - Pileup

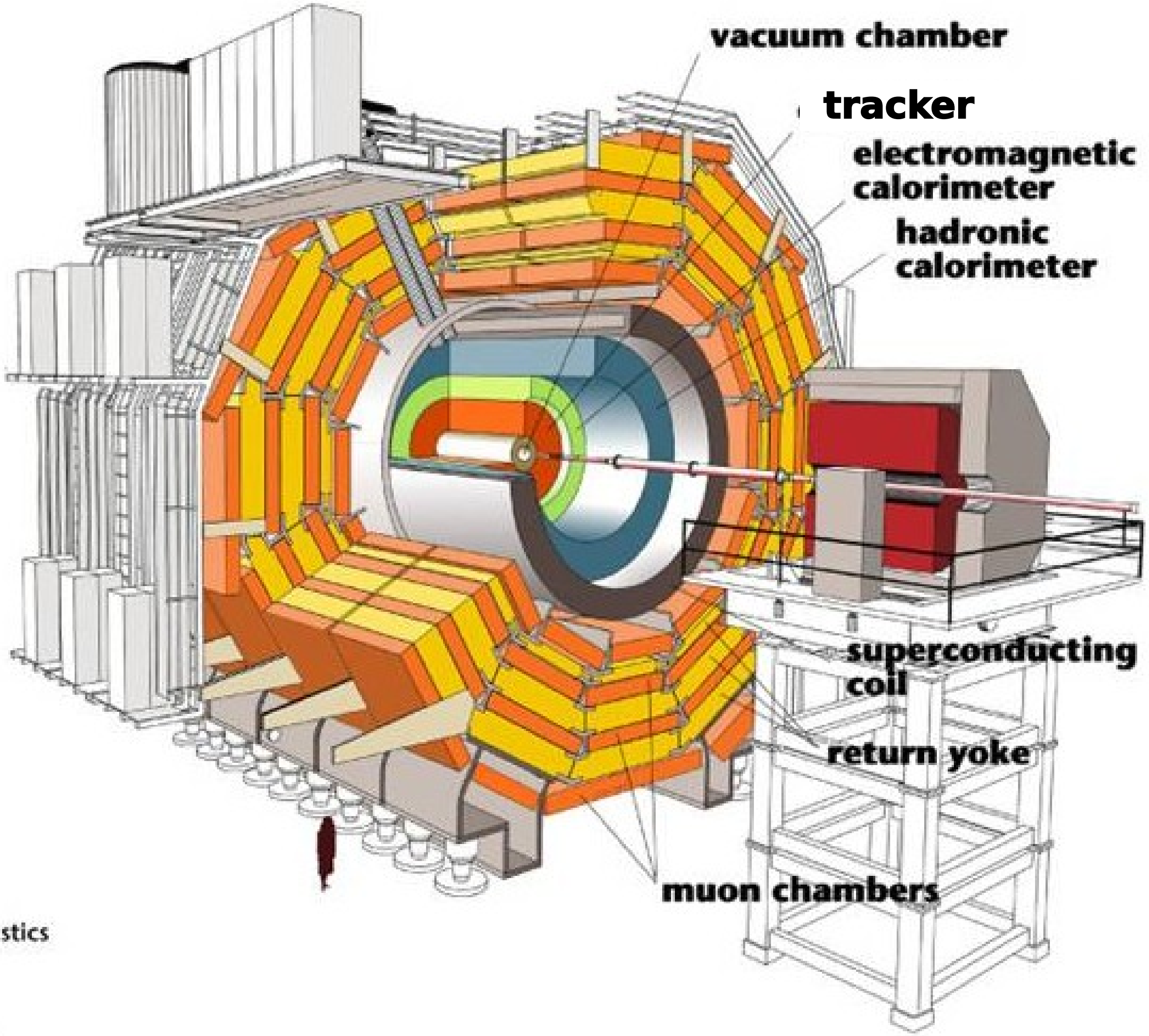
	Design	2012	2015
Beam Energy (TeV)	7	4	6.5
Bunches/Beam	2835	1380	2244
Protons/Bunch(1e11)	1.15	1.5	1.1
Peak Luminosity(1e32$cm^{-2}s^{-1}$)	100	70	53
Pileup	50	21	10
Integrated Luminosity/year	100	19.7	2.3/2.5



Luminosity = Event rate/cross section
∫Luminosity = Events/cross section

CMS

Compact Muon Solenoid Detector

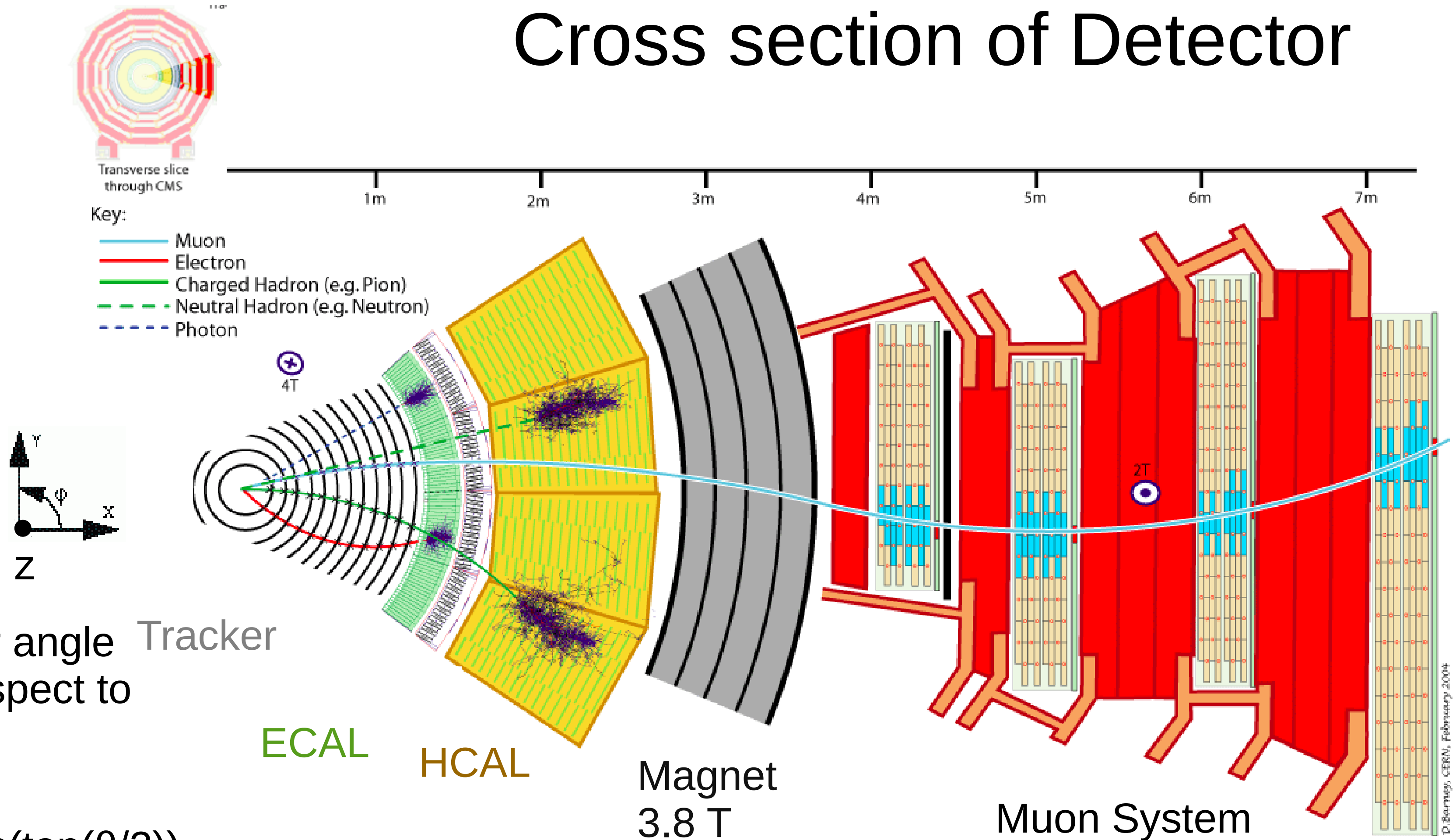


Detector characteristics

Width:	22m
Diameter:	15m
Weight:	14'500t

Compact Muon Solenoid (CMS)

Cross section of Detector



z

Tracker

ECAL

HCAL

Magnet
3.8 T

Muon System

θ: polar angle with respect to z axis

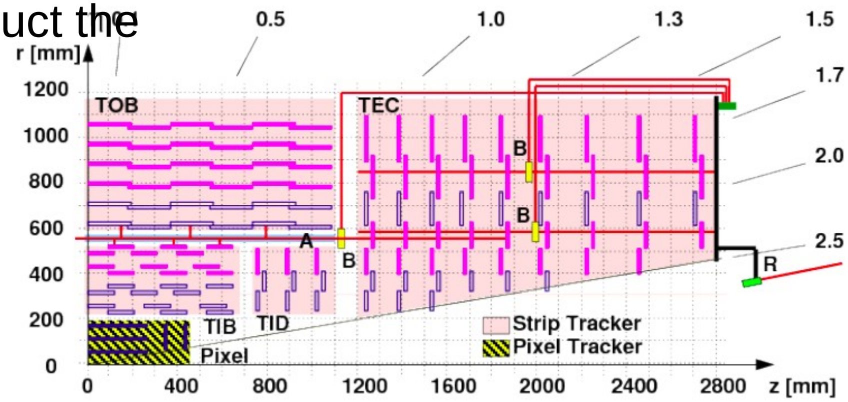
$\eta = -\ln(\tan(\theta/2))$

Pseudorapidity η approximately equal to lorentz invariant rapidity "y" when E >> m
$y = ½ \ln[(E + p_z)/(E - p_z)]$

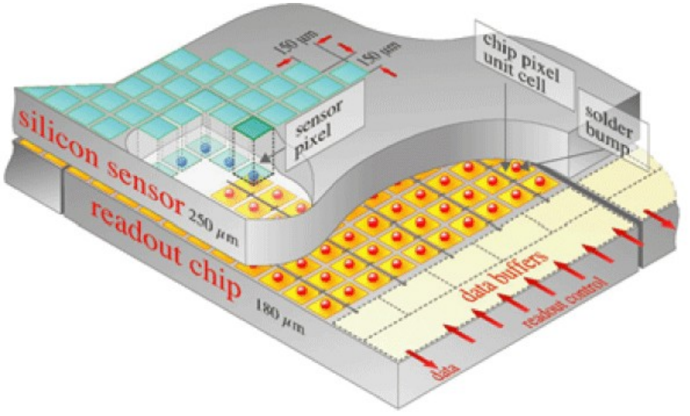
$\Delta R^2 = \Delta\varphi^2 + \Delta\eta^2$

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

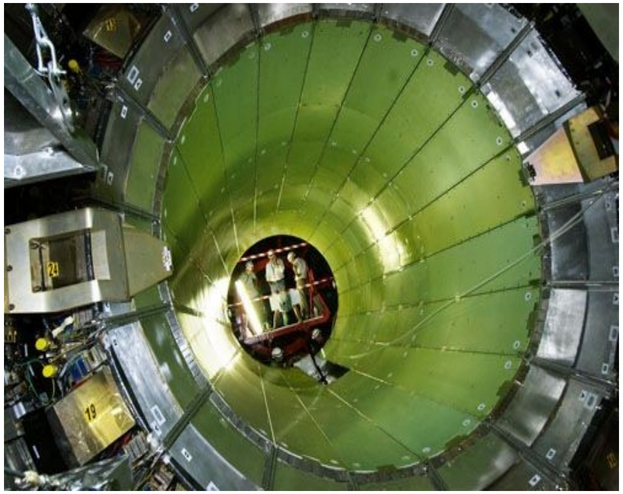


- Extends to $|\eta| < 2.5$
- Resolution: $\left(\frac{\delta p_T}{p_T}\right)^2 = (15 p_T(TeV)\%)^2 + (0.5\%)^2$
- Inner silicon pixel detector
    - 3 Cylindrical layers at 4, 7, and 11 cm from beam
    - Pixels are 100 X 150 μm: high granularity
    - High flux (10 million particles per square cm per second)

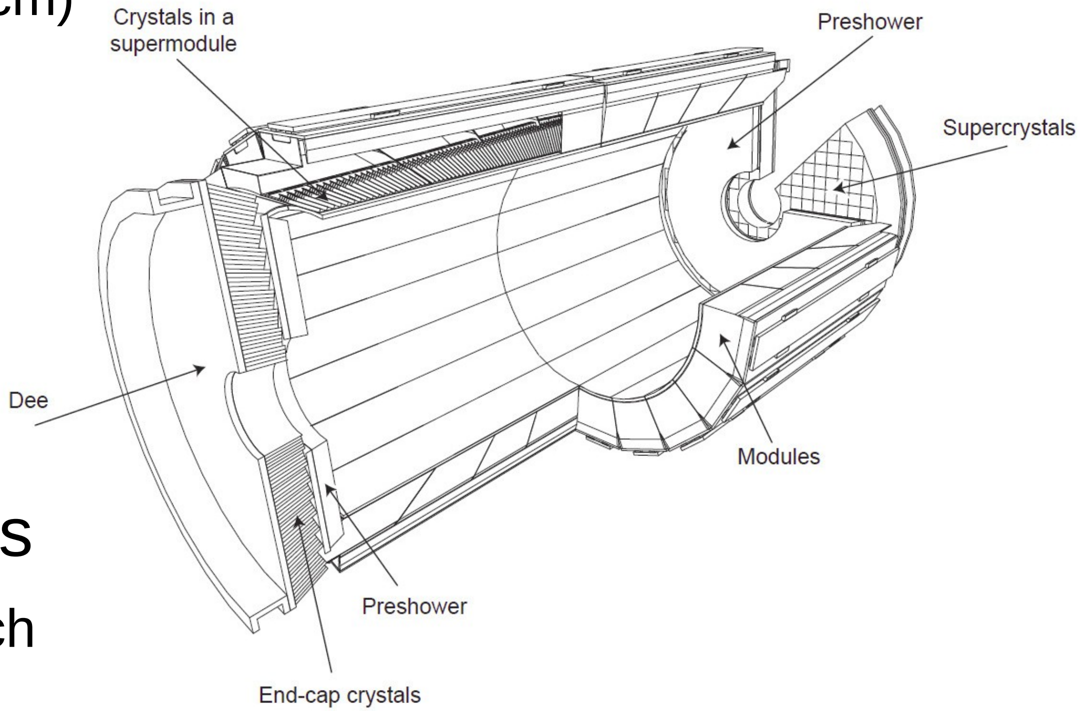


- Outer silicon strip detector
    - 10 cylindrical layers with 4 endcaps, extends 130 cm from beam
    - Lower flux than pixel detector (3e5 particles per square cm per second)
        - Allows cell size up to 25 cm X 180 μm

CMS Electromagnetic Calorimeter (ECAL)

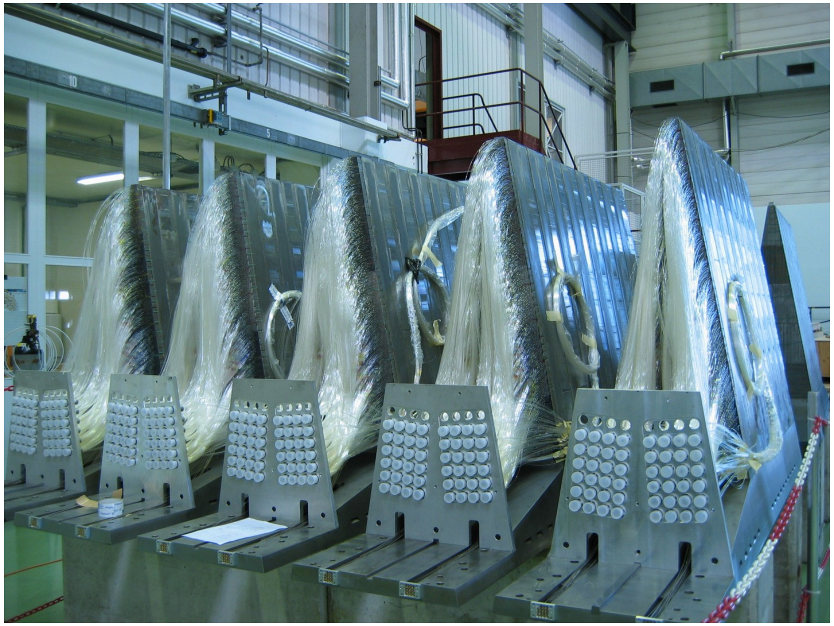


- Measures energy deposited by electrons and photons
- Composed of lead tungstate scintillating crystals
  - Crystals have high density (8.28 g/cm^3) and short radiation length (0.89 cm)
    - Allows fine granularity
  - 61,200 crystals in the barrel
  - 7324 crystals in each of the two endcaps
  - Emitted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



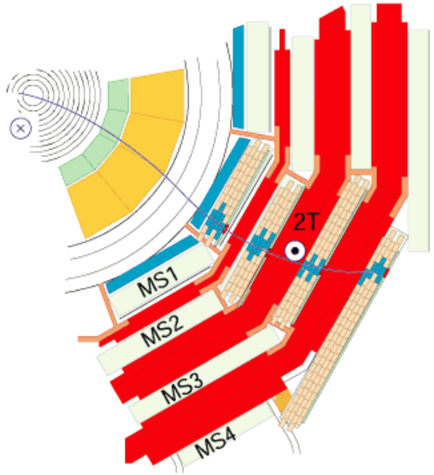
CMS Hadronic Calorimeter (HCAL)

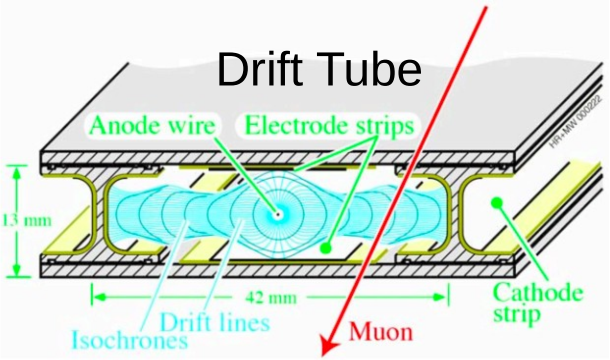
- Measures energy deposited by hadrons
- Barrel and Endcaps
  - Barrel (HB): $|\eta| < 1.3$
  - Endcaps (HE): $1.3 < |\eta| < 3.0$
  - Wedges of brass absorber and plastic scintillator
  - Wavelength shifting fibers bring scintillation light to electronics
  - Energy resolution: $\left(\frac{\sigma}{E}\right)^2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

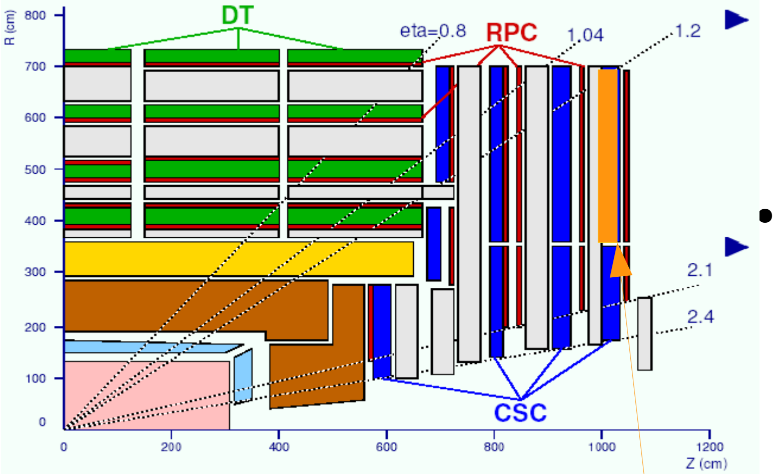


CMS Muon System

- Muons are highly penetrating particles
  - Detected by gas detectors outside solenoid
- Trajectory is bent by 2T magnetic field in return yoke





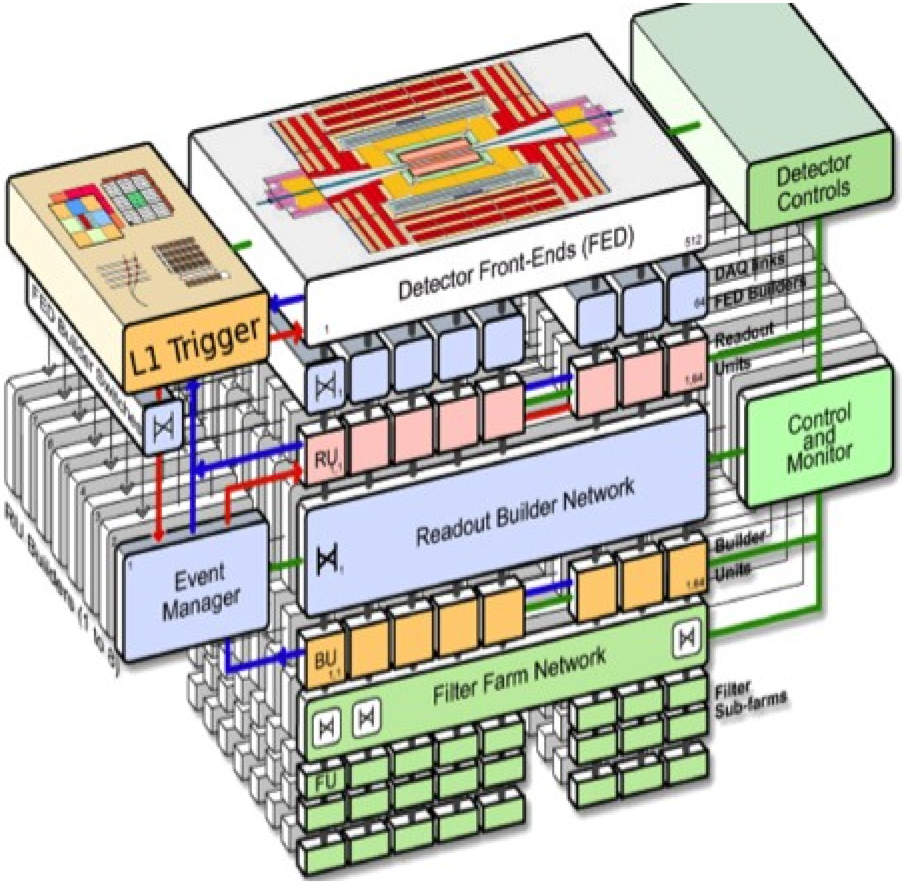


New CSCs in 2015

- 4 muon stations interspersed with iron yoke
- Drift tubes track the muons in the barrel ($|\eta| < 1.2$)
  - Spatial resolution ~ 1mm
- Cathode strip chambers (CSC) track the muons in the endcaps
  - Covers $1.2 < |\eta| < 2.4$
  - Resolution in φ: 0.2 mm
- RPCs provide redundant trigger system in barrel and endcap
  - provides time coordinate (identify track within 1 ns)
  - $|\eta| < 1.6$ (2012) → $|\eta| < 2.1$ (2015)

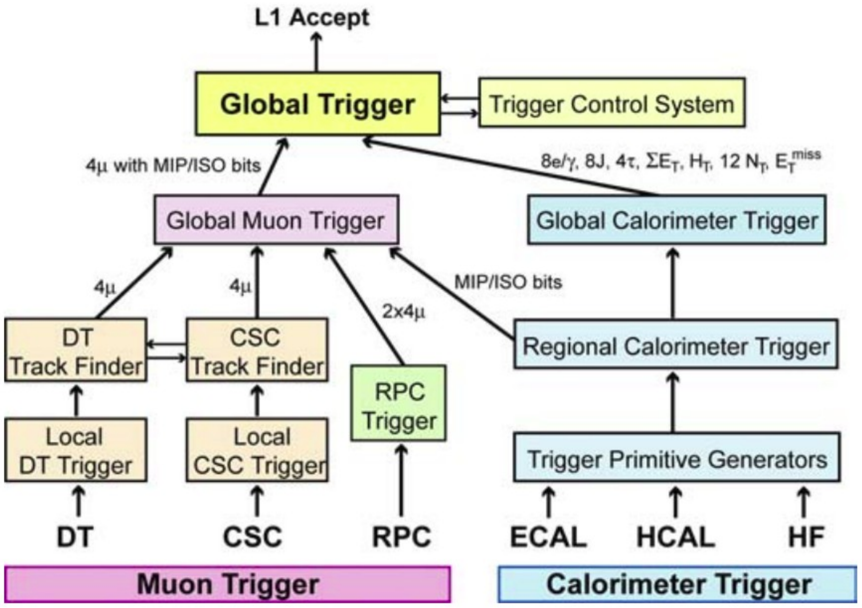
CMS Trigger System

- Impossible to store all data produced via LHC collisions
- Trigger system reads data from detectors at beam crossing rate of 40 MHz
  - Max output rate < 1 kHz
- Level 1 Trigger
  - High speed electronics
  - Basic selection and rejection
  - Rate limited by readout electronics
- High Level Trigger
  - Computing farm
    - 13,000 cores
  - Defines object filters for physics analysis



CMS L1 Trigger

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



L1 Accept

Global Trigger

Trigger Control System

4μ with MIP/ISO bits

8e/γ, 8J, 4τ, ΣE_T, H_T, 12 N_j, E_T^{miss}

Global Muon Trigger

Global Calorimeter Trigger

4μ

4μ

2x4μ

MIP/ISO bits

DT Track Finder

CSC Track Finder

RPC Trigger

Regional Calorimeter Trigger

Local DT Trigger

Local CSC Trigger

Trigger Primitive Generators

DT

CSC

RPC

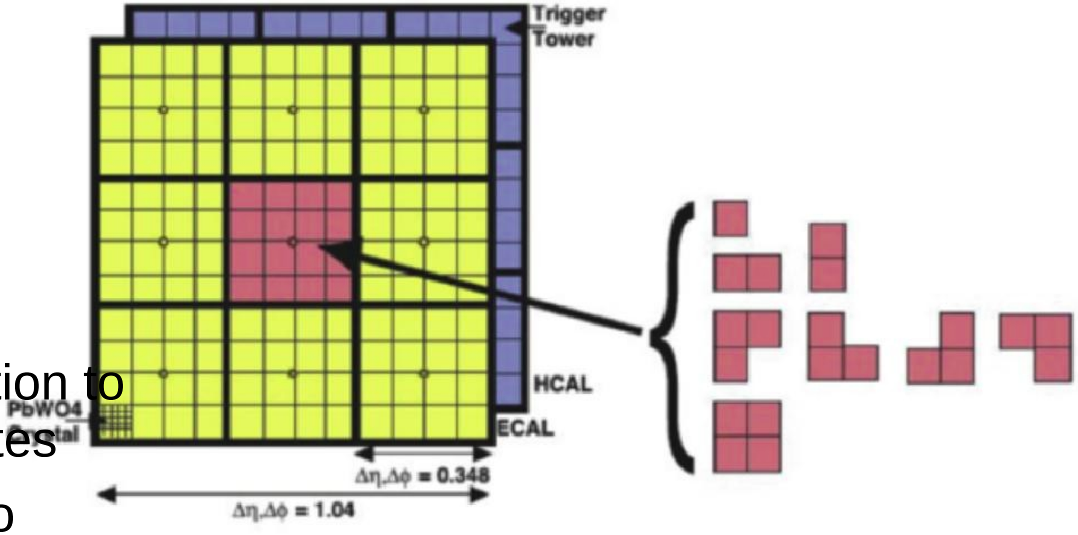
ECAL

HCAL

HF

Muon Trigger

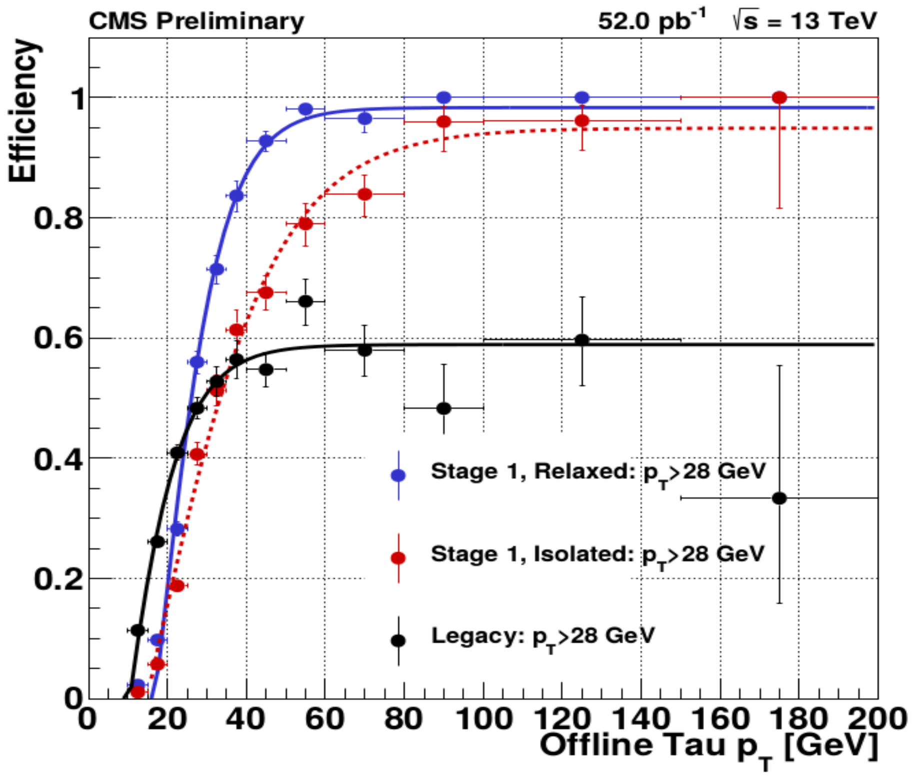
Calorimeter Trigger



CMS L1 Trigger Upgrade

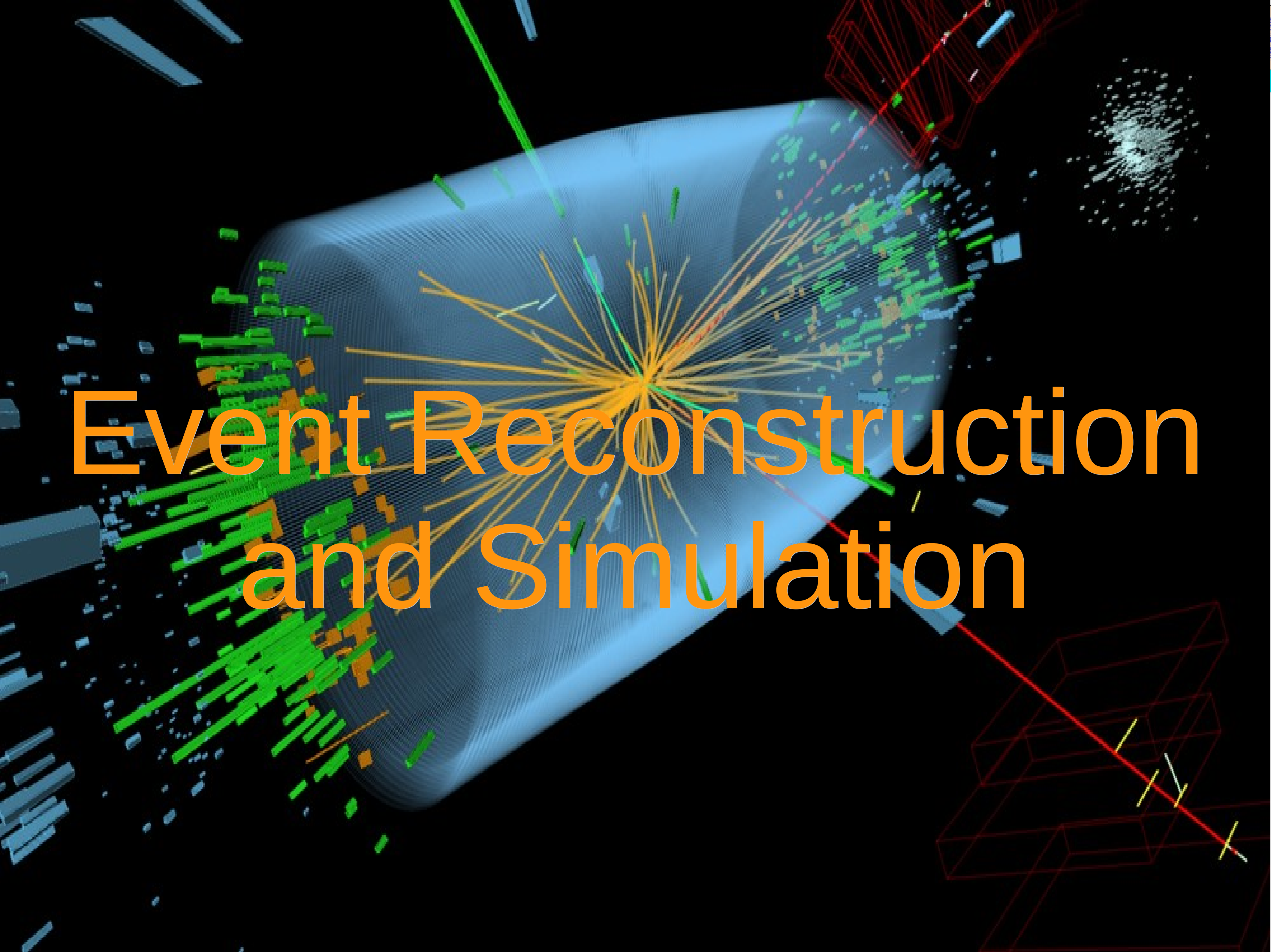
- Long Shutdown 1 (LS1) from 2013-2015
- Increase beam energy from 4 TeV to 6.5 TeV
- Decrease bunch spacing from 50 ns to 25 ns
- Optical links between RCT/ new GCT
  - oRSC developed by UW
- New electronics in new GCT allow improved tau algorithms
- Change tau identification from 12X12 trigger towers to 4X8 dynamic trigger towers
  - Central 4x4+ highest neighbor
  - Overall L1 Trigger rate remains below 100 kHz with upgrade algorithms

Improvement in L1 tau efficiency: 2015 vs 2012



High Level Trigger (HLT)

- Processes events passing L1 trigger
  - Events are reconstructed at full granularity
  - Uses computing farm with 13,000 CPUs
- Uses offline software algorithms to define filters for physics analysis
- Accepts events at up to 100kHz, outputs events at up to 1 kHz
  - Significant reduction in rate

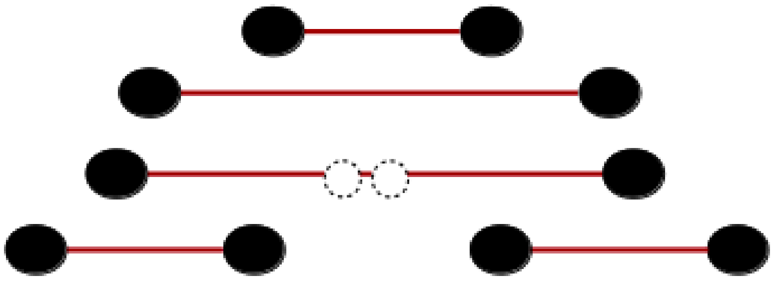


Event Reconstruction and Simulation

Event Simulation

- Need to use simulation to interpret observed data
  - Simulate background processes and signal, compare to events recorded in detector
- Simulate parton showering and hadronization at energies where pQCD is not applicable
  - One solution: Lund string model
- Pass output of physics simulation through detector simulation
  - Convert to same software format as data

Lund String Model



Potential energy increases linearlly as partons move apart

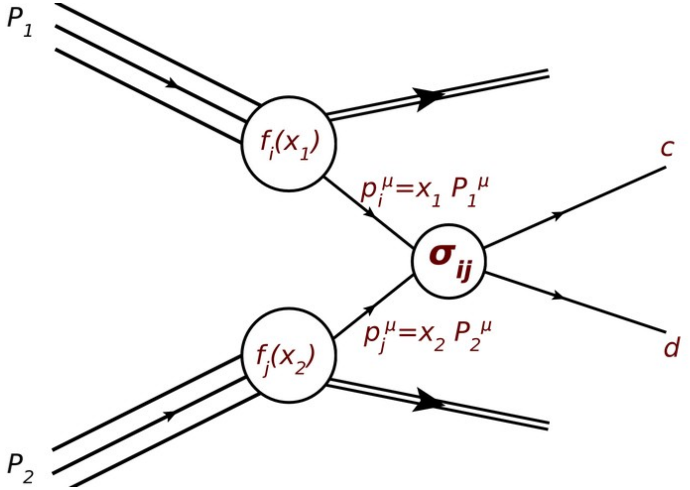
Eventually, potential energy creates a new pair

Parton showering continues until energy cut off is reached

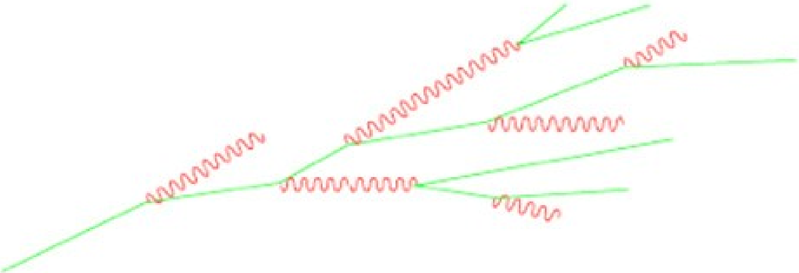
Monte Carlo Generators

- Madgraph
  - Matrix element MC generator
  - Partonic interactions
- Pythia
  - Quarks allowed to radiate gluons
  - Hadronization, showering
  - Only LO at matrix element level,
    - Often interfaced with NLO madgraph
- Tauola
  - Simulates Tau decay
  - Used in conjunction with Pythia
  - Takes into account tau polarization and spin
- GEANT
  - Detector simulation

Parton Parton Scattering

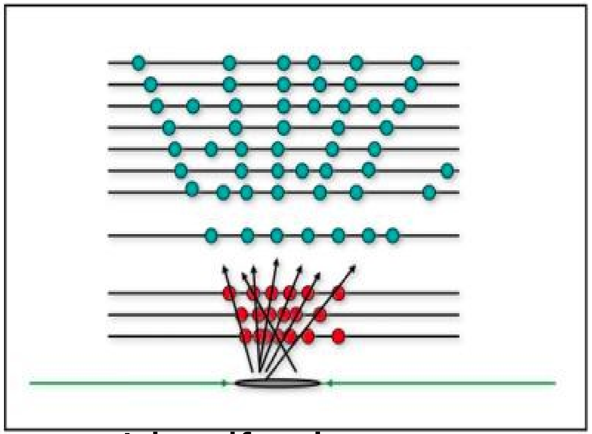


Parton Showering

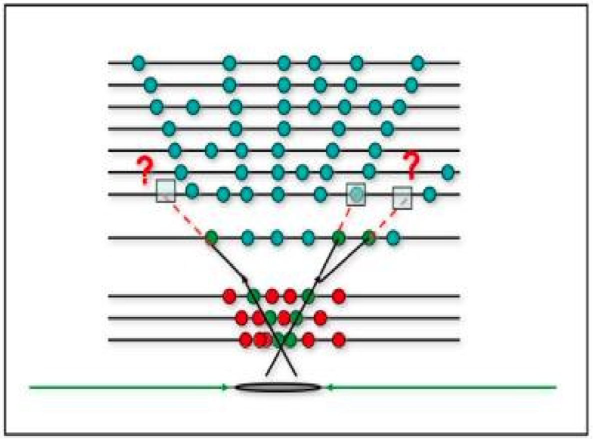


Particle Flow Objects

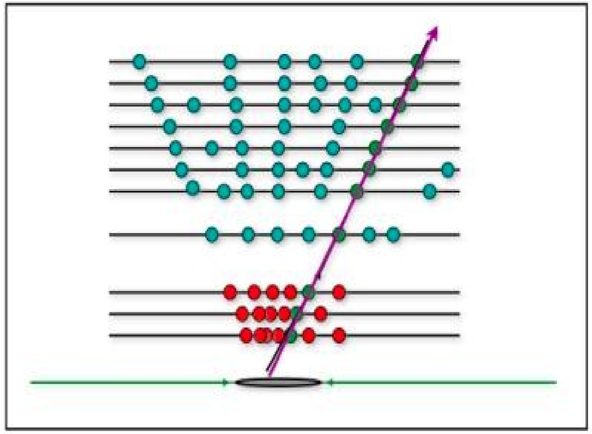
- Reconstruct hadrons, photons, muons, and electrons
  - Used to identify jets, taus, and missing E_T (MET)
- Particle Flow Algorithms identify objects
  - Identify calorimeter clusters and tracker hits
  - Reconstruct path and identify particles
- Tracks reconstructed iteratively and extrapolated to calorimeters



Identify clusters of hits in pixels



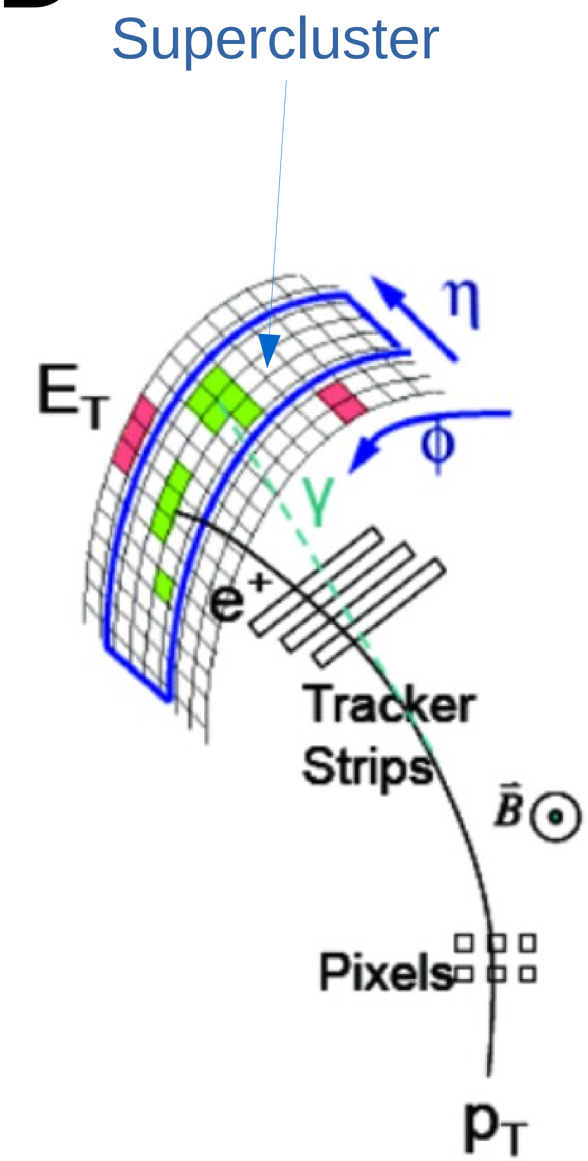
Extrapolate to hits in tracker



Identify best fit for a track

Electron ID

- Track corresponding to energy deposit in ECAL
- Electron radiates photons via Bremstrahlung radiation
  - Photons not bent by B field
  - Electron energy deposit spread out in “supercluster”
  - Require 90% of electron energy deposited in ECAL
- Reject electrons from photon conversion
  - Reject tracks that converge on the same vertex within the tracker material
- 2015: use multivariate analysis (MVA) to require that 90% of electrons are sucessfully identified
  - MVA: input relevant variables, such as electron p_T and shower size, into a function that is “trained” to produce output that relates event to efficiency outcomes

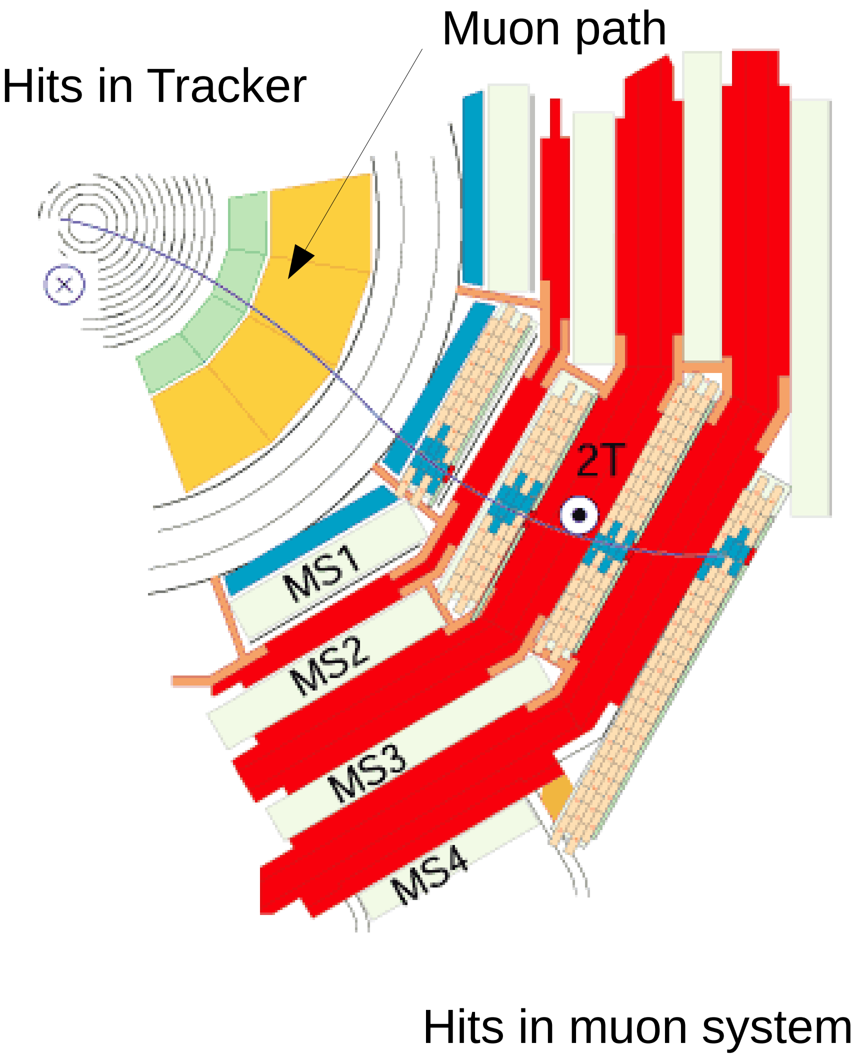


Muon ID

3 Classification schemes

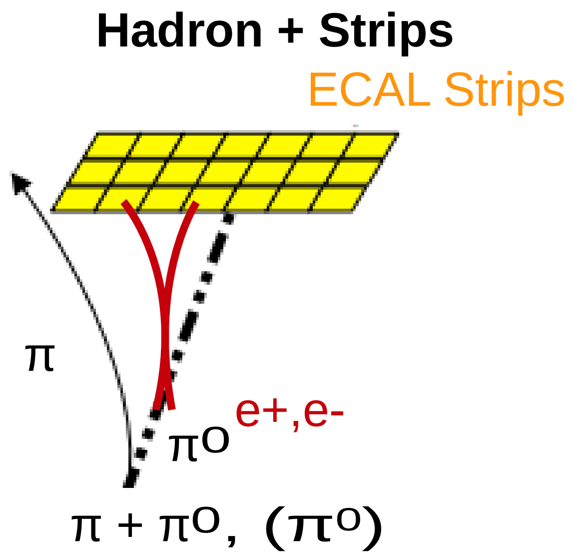
- Standalone muons
  - Offline reconstructed track segments in muon chambers
  - ID high p_T muons that don't have significant curvature in tracker
- Global muons
  - Match standalone muons to tracks in silicon tracker
- Tracker muons
  - ID low p_T muons that don't register as standalone muons
  - Reconstruct track with $P > 2.5$ GeV, $P_T > 0.5$ GeV matched with hit in muon chamber
- Global muons ultimately used in analysis
  - Require good track fit, hits in pixel, silicon strips, and muon stations

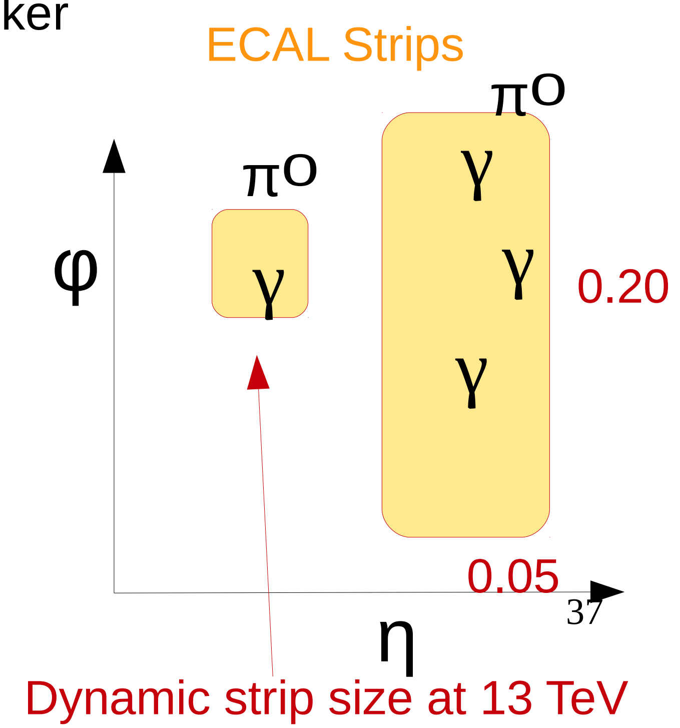
Global Muon



Tau ID

- Only includes hadronic decays of tau (τ_h)
  - Tau decays to electron or muon + neutrino (τ_e, τ_μ) are detected as electrons, muons
- Three primary decay modes (all include tau neutrino)
  - Single prong (π)
  - Single prong plus strip (π and π^0 or $\pi^0\pi^0$)
  - Three prong ($\pi\ \pi\ \pi$)
- 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 candidates matched to HCAL energy deposits
  - 13 TeV: dynamic strip size: can vary from (0.05,0.05) to (0.15,0.30)
- ID efficiency of 60%





Dynamic strip size at 13 TeV

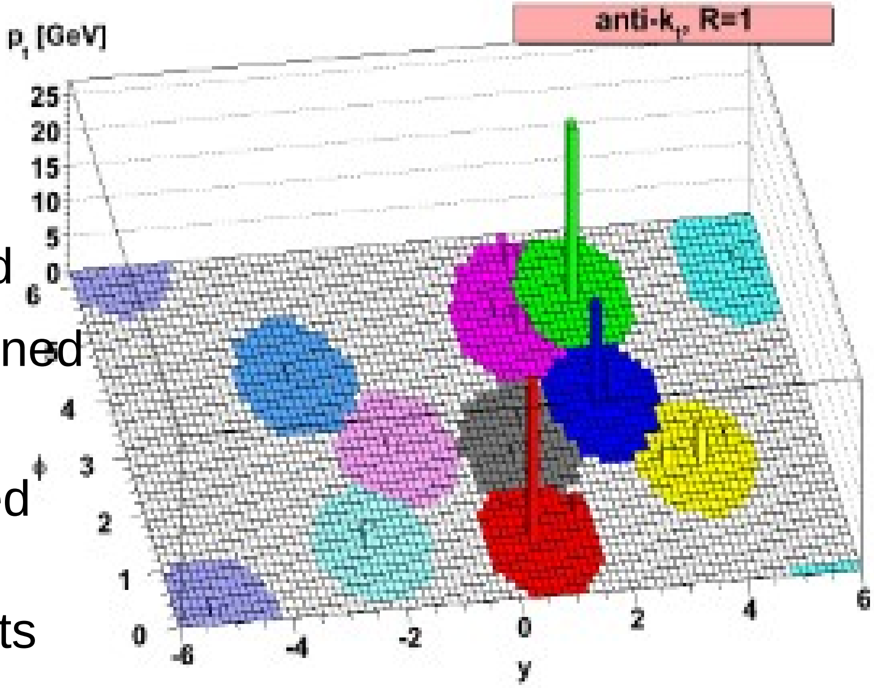
Jet ID

- 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
  - k_t = transverse momentum, y = rapidity
  - 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)
  - d_{ij} defined by higher p_T particle, cone unaffected by soft radiation, anti-kt keeps jet cone well defined
  - Radius R = 0.5 (0.4) for 8 TeV (13 TeV)
  - Hard events within radius R are combined based on energy and position
- Find cones by identifying clusters of HCAL deposits
- B quarks travel 1-2 mm before showering: b-jets originate from secondary vertex

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

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

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



Jet Energy corrections

- Contributions from soft jets that contribute to the underlying event are determined from average pT density per area
  - subtracted using pT and η dependent scale factors
  - Underlying event includes anything not part of the hard scattering process of interest, such as PU, radiation, “soft” elastic scattering between protons.
- Differences in generator level and reconstructed level in MC
  - Corrected using pT and η dependent scale factors
- Residual scale factors from jet pT imbalance in dijet events
- After applying jet energy corrections, take opposite vector sum of transverse momentum of particle flow candidates in the event
- This is the missing transverse energy in the event
  - Due to neutrinos

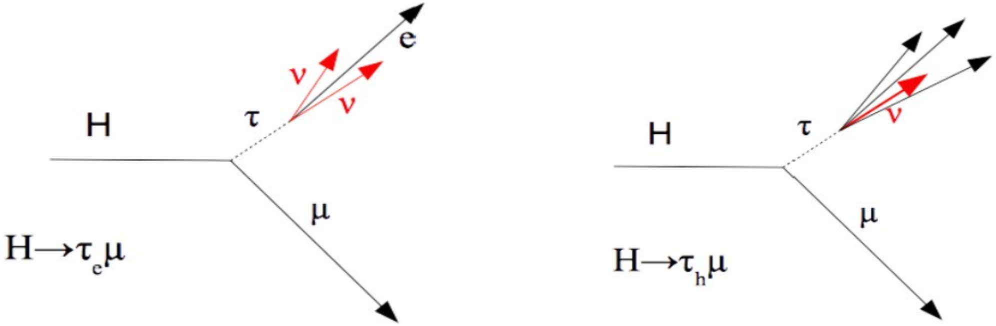
Isolation

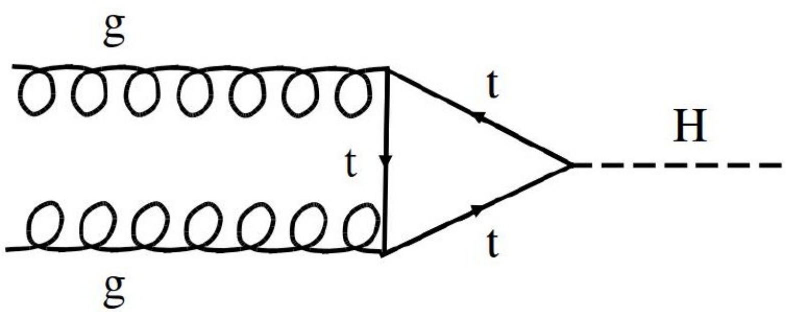
- Need a clean signal for particle flow objects
  - Leptons need to be seperated from large jet energy deposits
- Isolation
  - Sum energy in a cone around lepton of ΔR < 0.4
- Correct for pileup (additional proton-proton collisions in the event)
- $I^{e}_{PF} = \left(\sum^{Ch.had} p_T + max(0, \sum^{N.had.} p_T + \sum^{\gamma} p_T - 0.5 \sum^{PU} p_T \right) / p^{e}_{T}$ electrons and muons, < 0.1 - 0.15
- $I^{\tau}_{PF} = \sum^{Ch.had} p_T + \sum^{N.had.} p_T + \sum^{\gamma} p_T - 0.4576 \sum^{PU} p_T$ Taus, PU independent, < 0.8 GeV

A Search for Lepton Flavor Violating Couplings of the Higgs Boson

LFV Higgs Analysis Overview

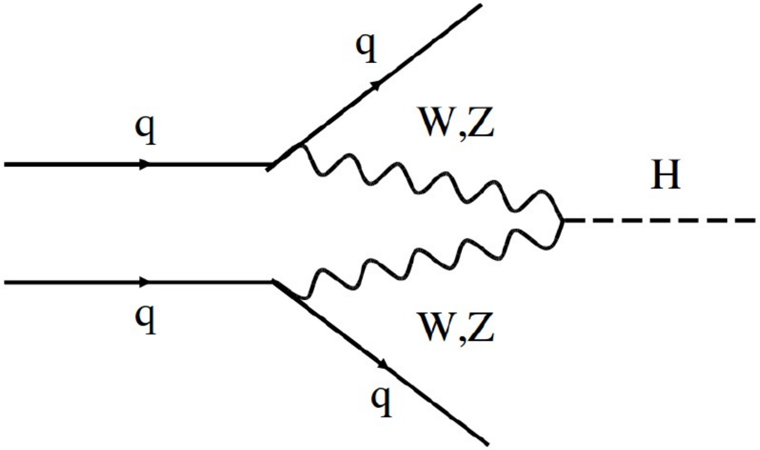
- Search for H → μτ
  - Yukawa couplings
    - Couplings between fermions and Higgs
  - $Y_{\mu\tau}, Y_{\tau\mu} \sim (m_\mu m_\tau)^{1/2}$
  - Heavier leptons make decay channel more promising than H → eτ, μe
- 2 channels
  - Tau may decay hadronically ($H \rightarrow \mu\tau_h$) or leptonically to an electron ($H \rightarrow \mu\tau_e$)
- 3 categories
  - H → μτ in association with 0, 1, or 2 jets
- Search performed using 2012 CMS dataset
  - Center of mass energy: 8 TeV
  - Integrated luminosity: 19.7 fb^{-1}
- Performed again using 2015 CMS dataset
  - Center of mass energy: 13 TeV
  - Integrated luminosity: 2.3 fb^{-1}





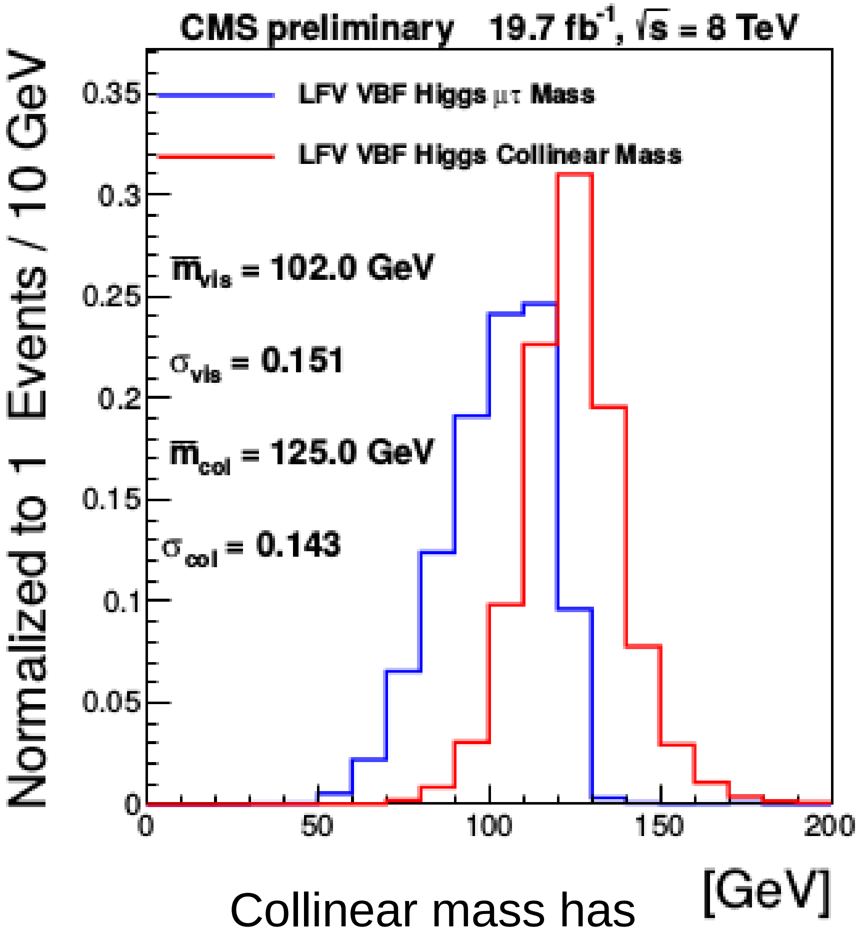
Gluon-Gluon Fusion
Dominates 0,1 Jet

Vector Boson Fusion
Significant presence in 2 Jet



Collinear Mass

- In LFV Higgs analysis, only MET in final state comes from tau decay. Muon has no associated neutrino
- Can estimate mass using the collinear approximation: visible tau decay products and MET are collinear
  - $M_H = \frac{M_{vis}}{\sqrt{x}}$
  - x = fraction of visible tau p_T
  - M_{vis} = mass of visible decay products
    - hadrons+muon



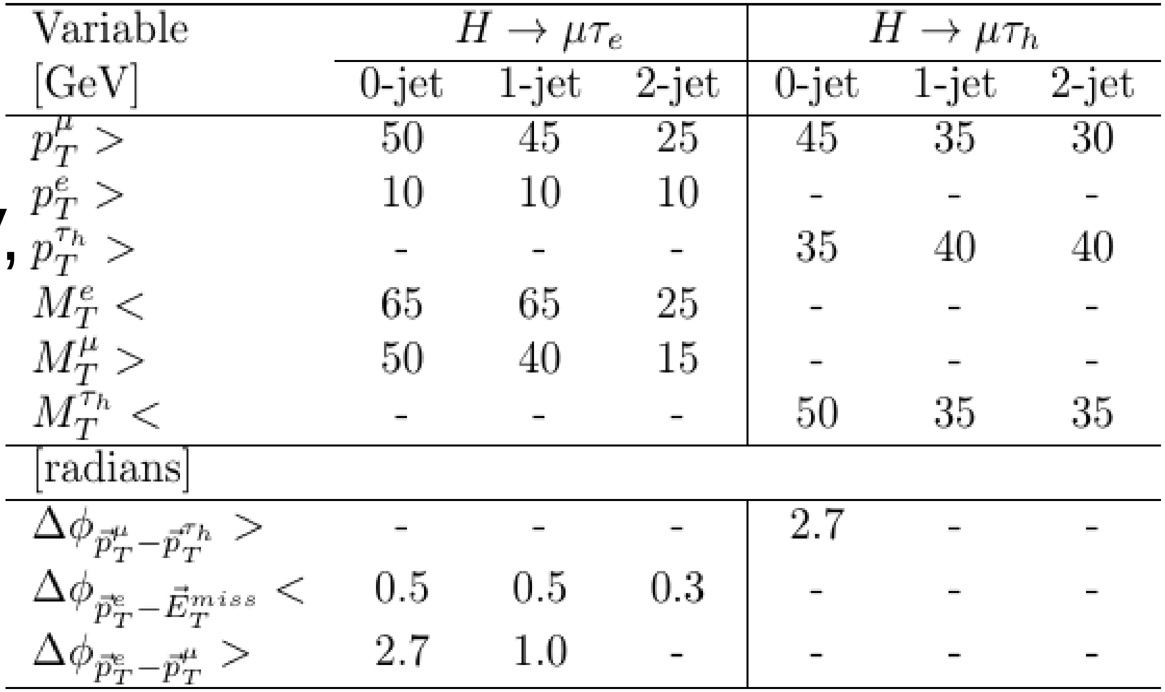
Collinear mass has narrow peak at 125 GeV

[1] arXiv:1401.5041

Signal Region Selections

100 GeV $< M_{coll} <$ 150 GeV

- 2 Jet category:
  - Require $M_{jj} >$ 550 GeV, $\Delta\eta_{jj} > 3.5$
- H → $\mu\tau_e$ channel
  - Veto b-jets: Reduce contribution from pairs of top quarks decaying into W bosons and b quarks



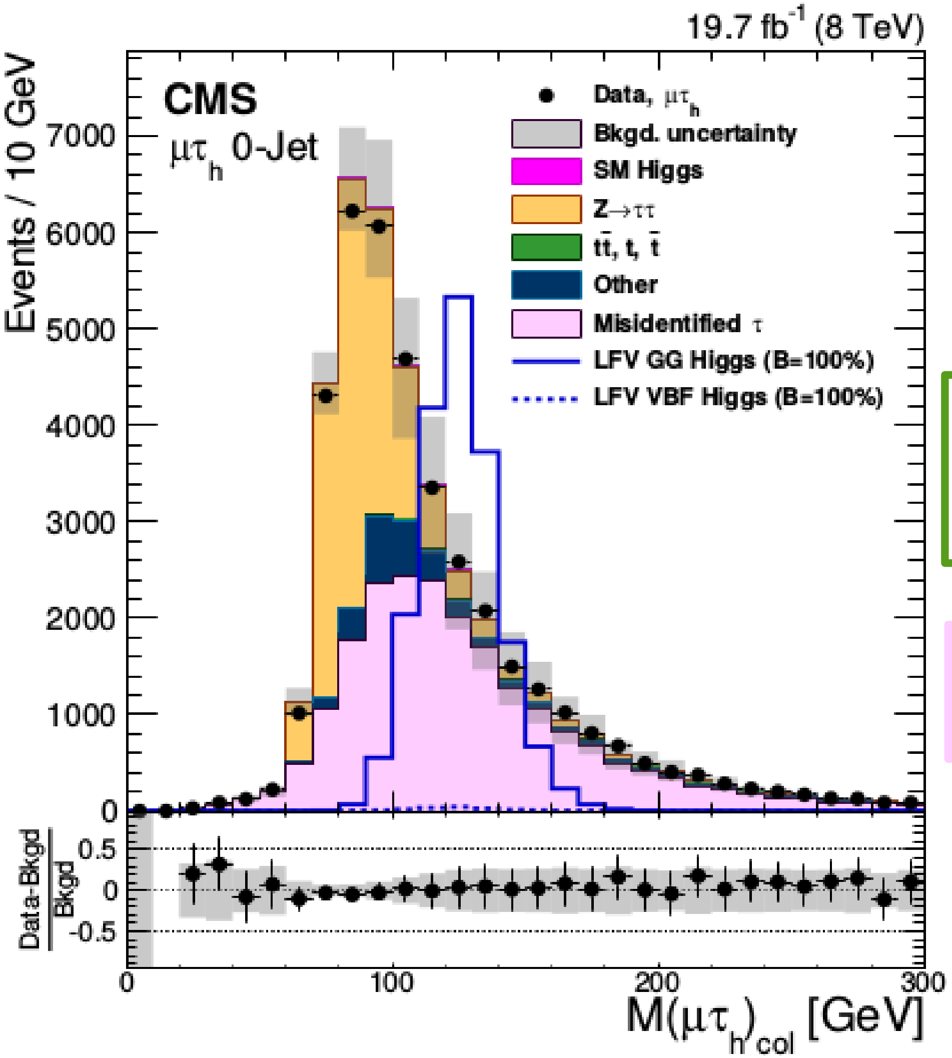
Variable	$H \to \mu\tau_e$			$H \to \mu\tau_h$		
[GeV]	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_T^{\mu} >$	50	45	25	45	35	30
$p_T^{e} >$	10	10	10	-	-	-
$p_T^{\tau_h} >$	-	-	-	35	40	40
$M_T^{e} <$	65	65	25	-	-	-
$M_T^{\mu} >$	50	40	15	-	-	-
$M_T^{\tau_h} <$	-	-	-	50	35	35
[radians]						
$\Delta\phi_{\vec{p}_T^{\mu}-\vec{p}_T^{\tau_h}} >$	-	-	-	2.7	-	-
$\Delta\phi_{\vec{p}_T^{e}-\vec{E}_T^{miss}} <$	0.5	0.5	0.3	-	-	-
$\Delta\phi_{\vec{p}_T^{e}-\vec{p}_T^{\mu}} >$	2.7	1.0	-	-	-	-

LFV Backgrounds

SM Higgs
MC used for shape and normalization

Z→ττ
Embedding method used for shape. Z→μμ data events selected. Muons replaced with taus,
tau decays simulated. Get jets, MET from data.
Normalization from MC
(Not ready for 13 TeV)

Z → ll, Diboson
MC used for shape and normalization

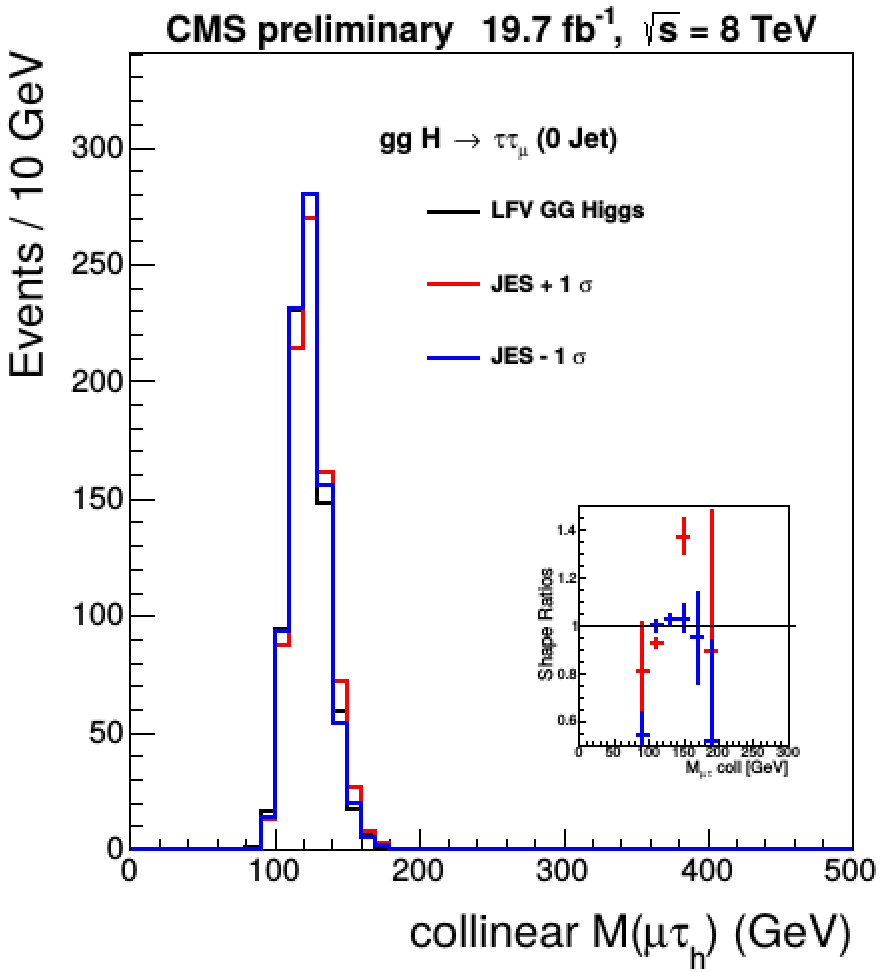


Single top and $t\bar{t}$
MC used for shape and normalization

Misidentified tau
Data driven method

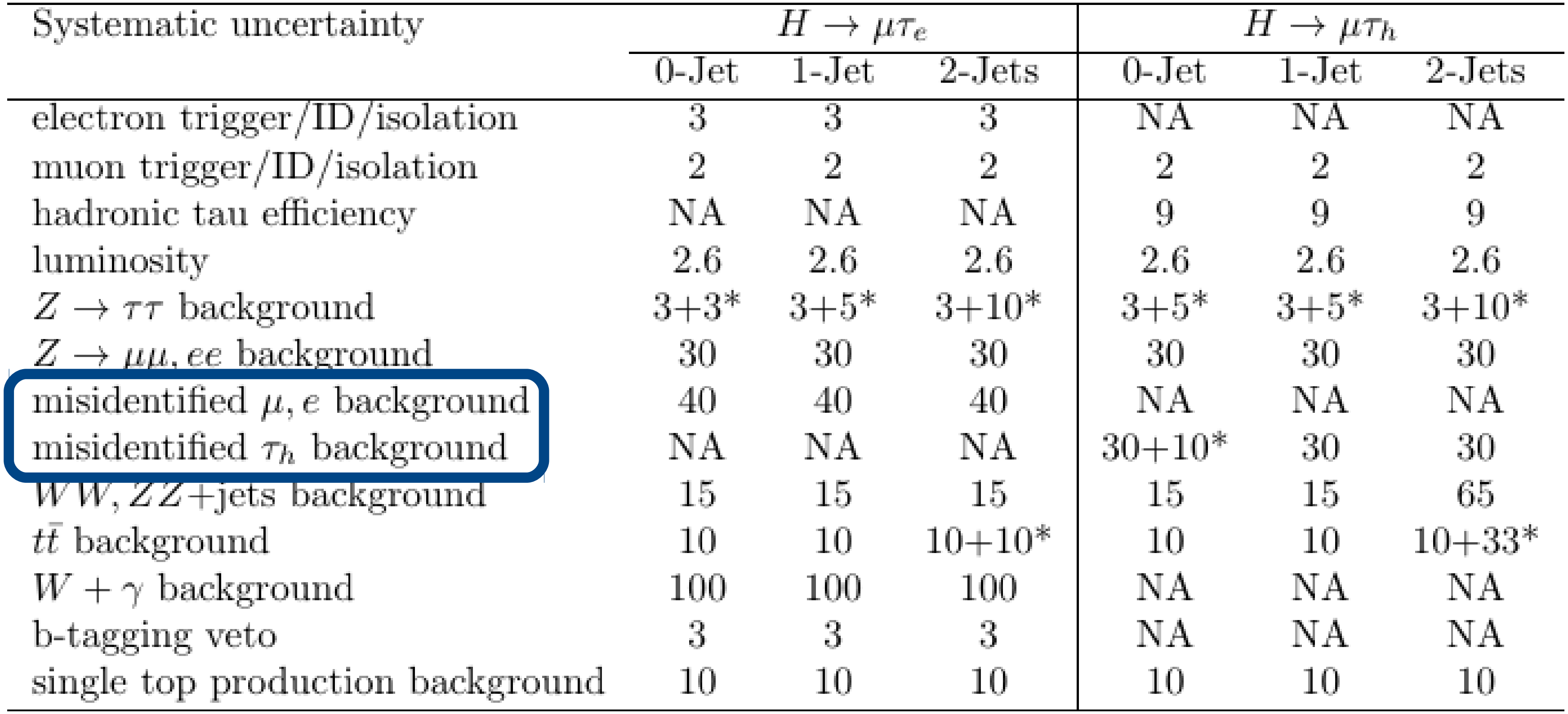
Statistical Methodology

- Perform maximum likelihood fit between signal+background hypothesis and data
- Systematics are nuisances parameters in fit
  - Vary energy scales (tau energy scale, jet energy scale) and fakes by ±σ to determine shape systematics
- After maximum likelihood fit, histograms are referred to as “postfit”
- Calculate limits using CL_s (confidence limit) method
  - CL_s method avoids excluding signal that analysis is not sensitive to
  - Divide signal exclusion limit by background only exclusion limit



Shape differences from shifting jet energy scale (±σ)

Additional Systematics



Systematic uncertainty	$H \rightarrow \mu\tau_e$			$H \rightarrow \mu\tau_h$		
	0-Jet	1-Jet	2-Jets	0-Jet	1-Jet	2-Jets
electron trigger/ID/isolation	3	3	3	NA	NA	NA
muon trigger/ID/isolation	2	2	2	2	2	2
hadronic tau efficiency	NA	NA	NA	9	9	9
luminosity	2.6	2.6	2.6	2.6	2.6	2.6
$Z \rightarrow \tau\tau$ background	3+3*	3+5*	3+10*	3+5*	3+5*	3+10*
$Z \rightarrow \mu\mu, ee$ background	30	30	30	30	30	30
misidentified μ, e background	40	40	40	NA	NA	NA
misidentified τ_h background	NA	NA	NA	30+10*	30	30
WW, ZZ+jets background	15	15	15	15	15	65
$t\bar{t}$ background	10	10	10+10*	10	10	10+33*
$W + \gamma$ background	100	100	100	NA	NA	NA
b-tagging veto	3	3	3	NA	NA	NA
single top production background	10	10	10	10	10	10

Misidentified lepton backgrounds are primary source of systematic uncertainty

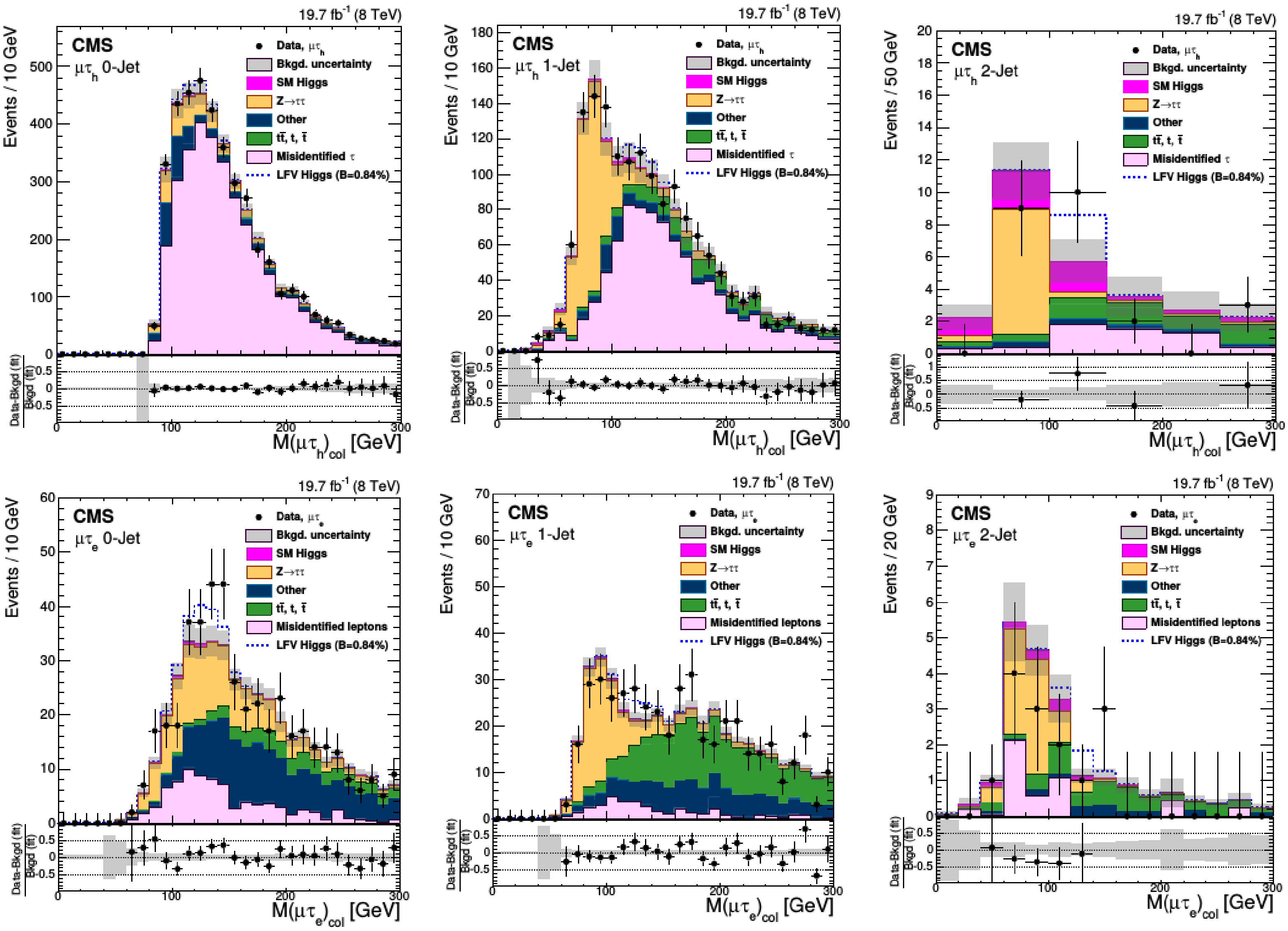
Postfit Results 8 TeV

Best fit: B(H → μτ) = 0.84%

0 Jet **1 Jet** **2 Jet**

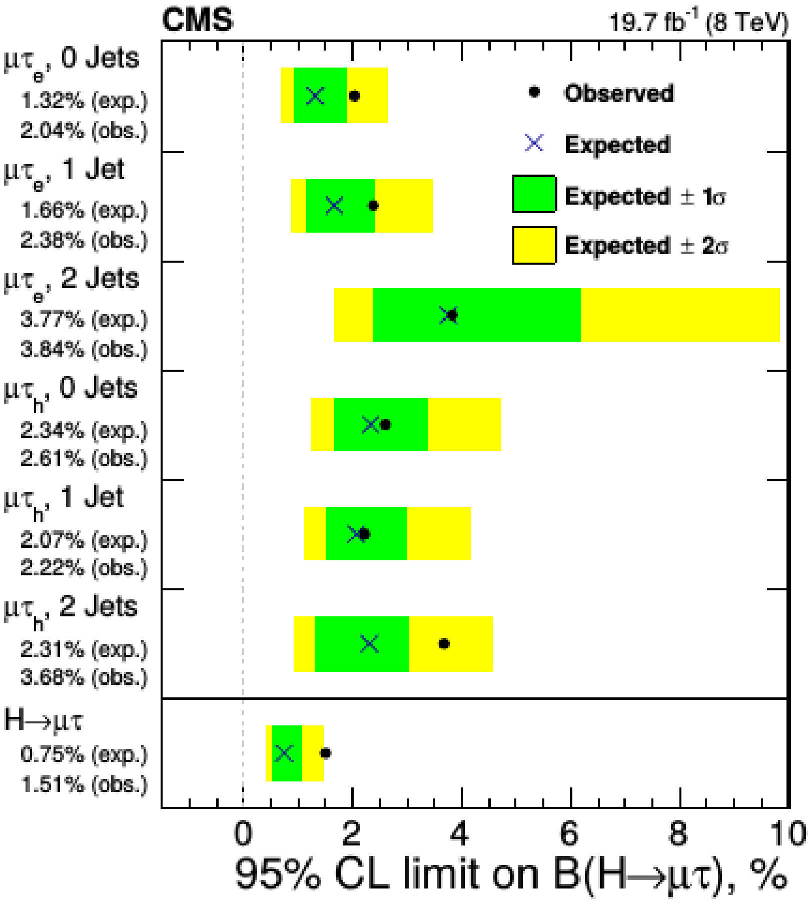
$\mu\tau_h$

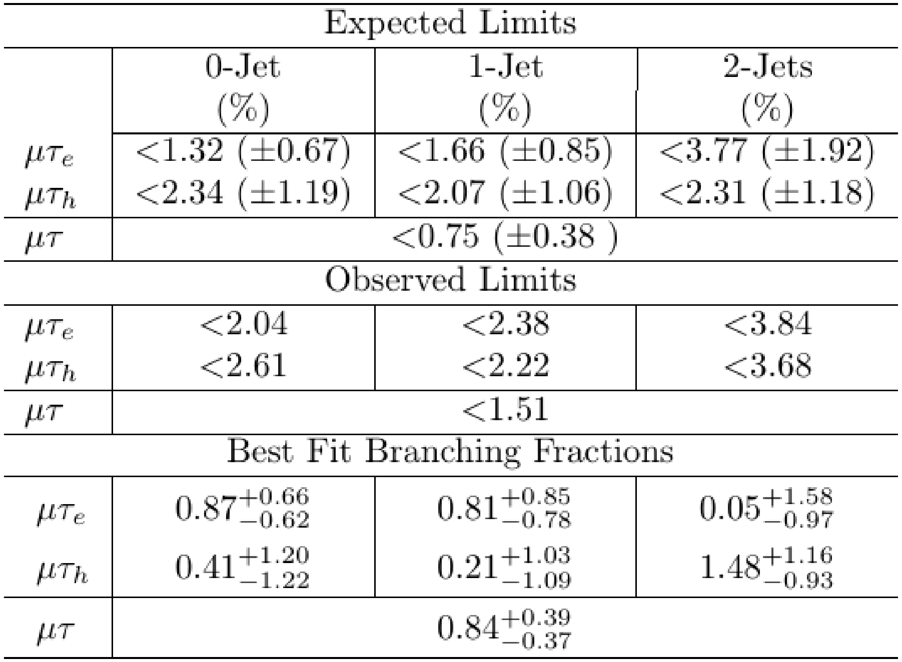
$\mu\tau_e$



CL_s Limits and BR 8 TeV

Best fit: B(H → μτ) = 0.84%
Corresponds to 2.4σ excess





	0-Jet (%)	1-Jet (%)	2-Jets (%)
Expected Limits			
$\mu\tau_e$	$<1.32\ (\pm0.67)$	$<1.66\ (\pm0.85)$	$<3.77\ (\pm1.92)$
$\mu\tau_h$	$<2.34\ (\pm1.19)$	$<2.07\ (\pm1.06)$	$<2.31\ (\pm1.18)$
$\mu\tau$	$<0.75\ (\pm0.38\ )$		
Observed Limits			
$\mu\tau_e$	<2.04	<2.38	<3.84
$\mu\tau_h$	<2.61	<2.22	<3.68
$\mu\tau$	<1.51		
Best Fit Branching Fractions			
$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$	$0.84^{+0.39}_{-0.37}$		

8 TeV → 13 TeV

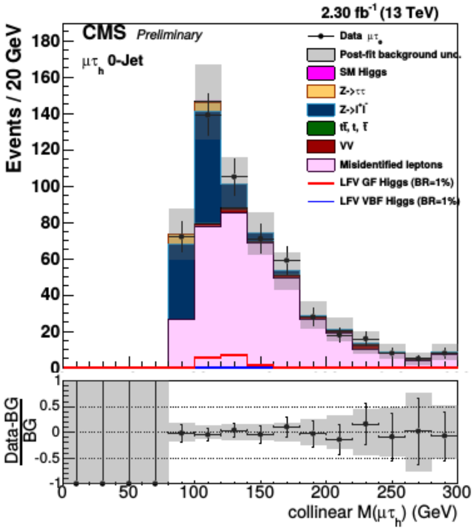
- Redo analysis on 2015 dataset at 13 TeV
  - 2.3 fb^{-1}, significantly fewer statistics than 2012
    - 19.7 fb^{-1} of data gathered in 2012
- Reuse 2012 optimization
- Loosen 2 jet category cuts to increase statistics
  - $M_{jj} > 200$ GeV, $\Delta\eta_{jj} > 2.5$
- Electron p_T increased from 10 GeV to 15 GeV to supress fake background

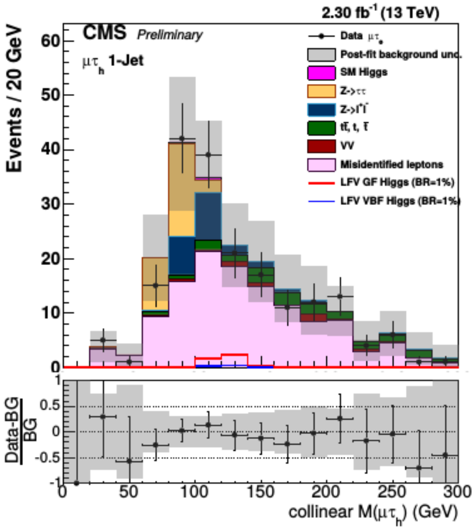
13 TeV Postfit

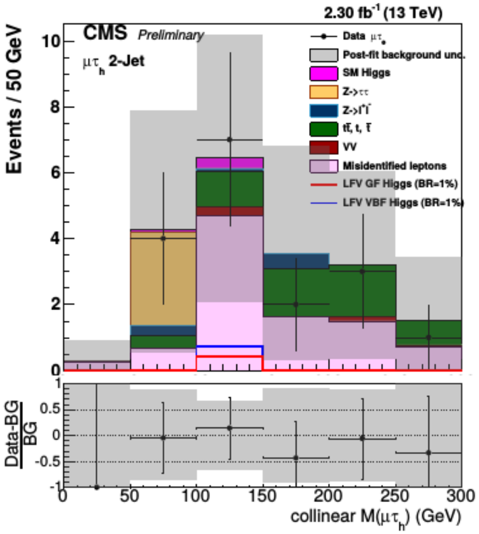
No excess observed

0 Jet **1 Jet** **2 Jet**

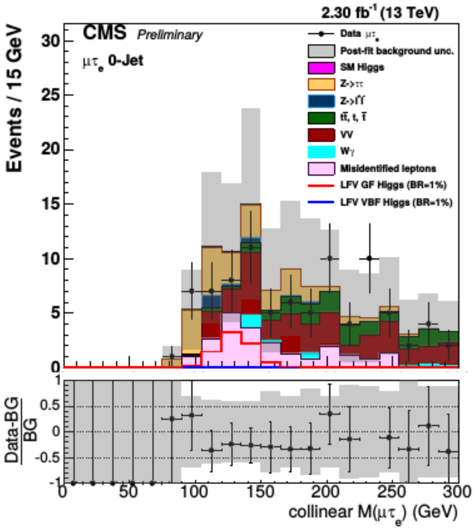
μτ$_h$

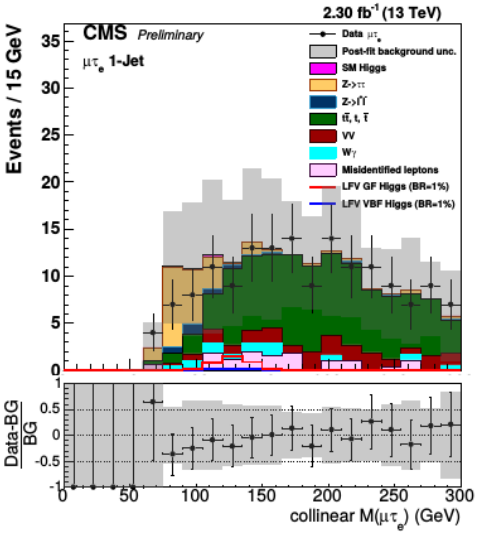


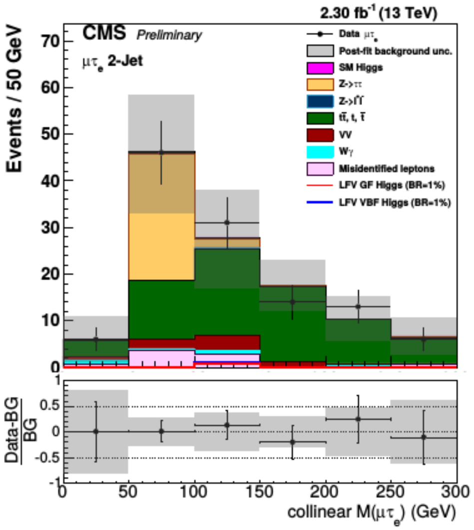




μτ$_e$

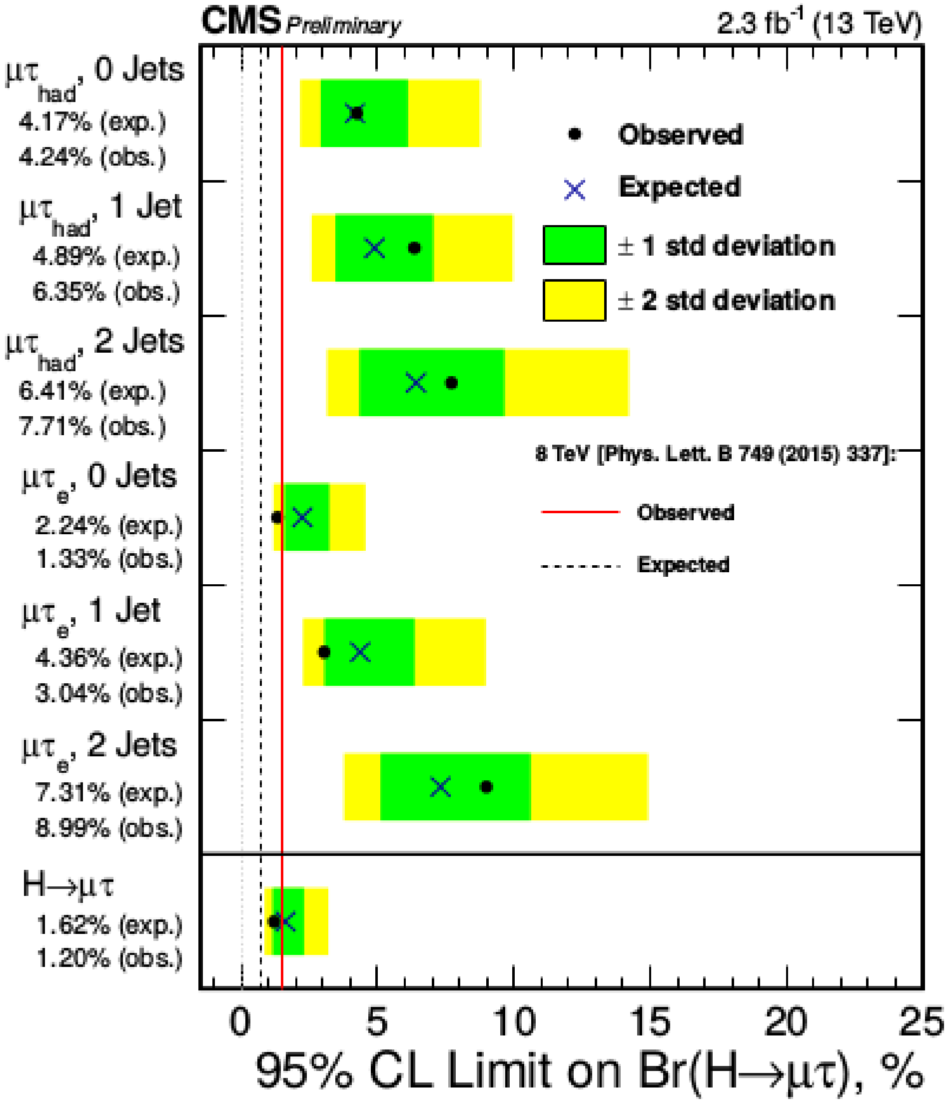






Asymptotic CL_s Limit

- Tighter observed limit than at 8 TeV
  - B (H → μτ) < 1.20%
- Expected limit:
  - B (H → μτ) < 1.62%
  - Need more statistics to probe 8 TeV BR
    - B(H → μτ) = 0.84%

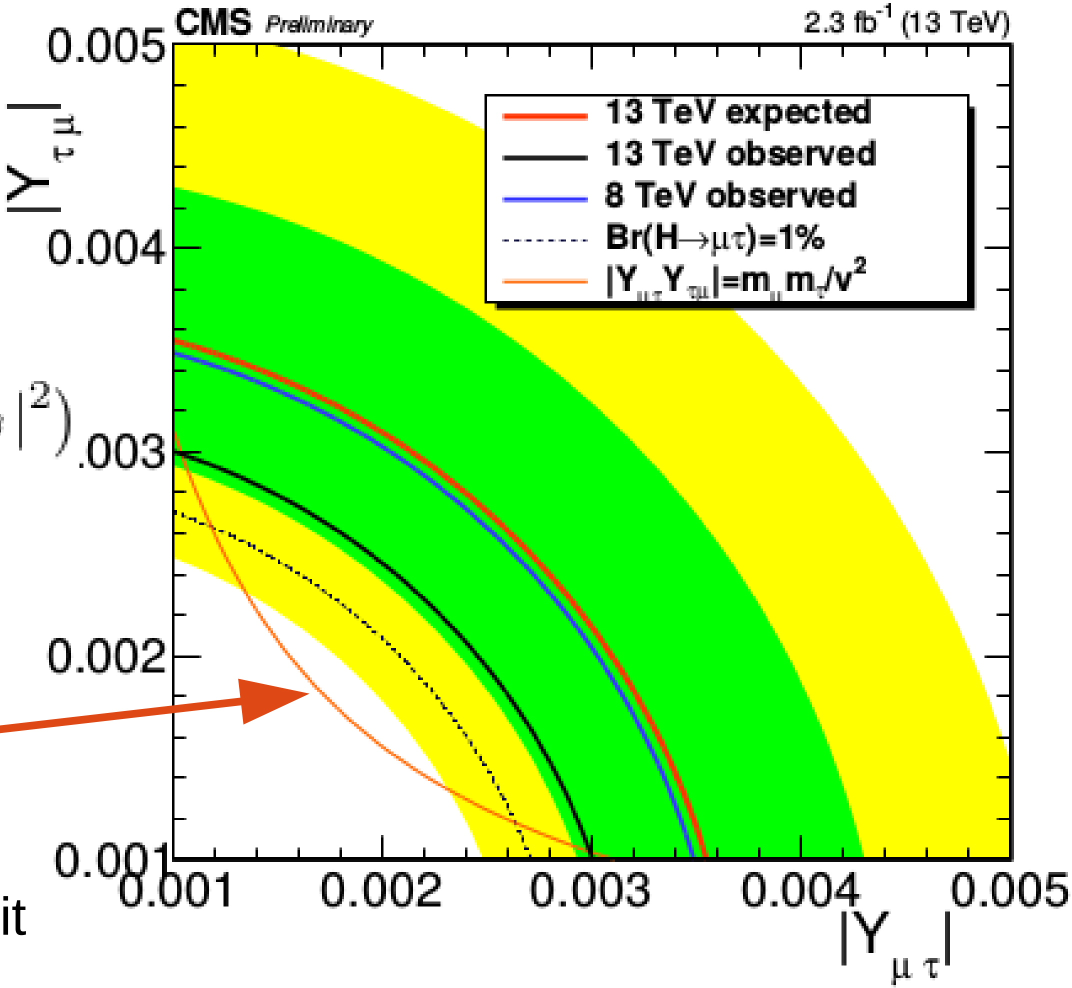


Yukawa Couplings

- Limit of B (H→μτ) can be used to set limits on $Y_{\mu\tau}$, $Y_{\tau\mu}$

$$\Gamma(H \to \ell^\alpha \ell^\beta) = \frac{m_H}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$

$$B(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta)}{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) + \Gamma_{SM}}$$



  - Naturalness limit:
    - $|Y_{\mu\tau}\, Y_{\tau\mu}| < m_\mu m_\tau / v^2$
  - Room to improve observed limit

A Measurement of the Cross Section of W Bosons Produced in Association with Jets

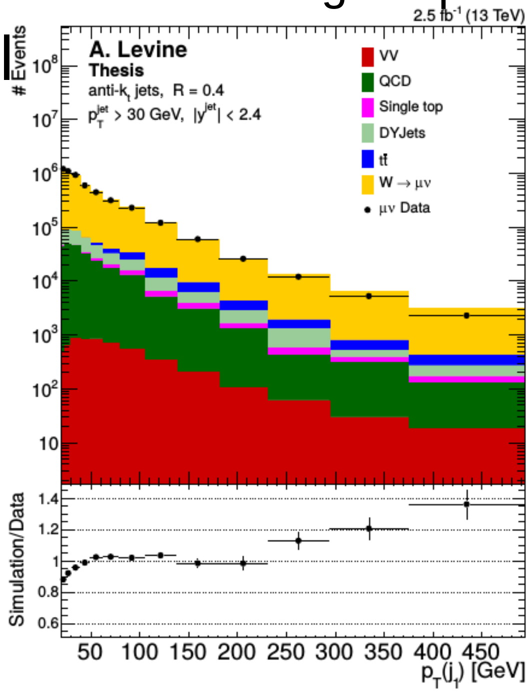
W+Jets Selections

- Measurement performed in W → μν channel
  - CMS ~95-99% efficient for muon reconstruction
- Trigger: Muon with $p_T > 20$ GeV, $|\eta| < 2.4$
- Muon selections
  - $p_T > 25$ GeV
  - $|\eta| < 2.4$
- Jet selections
  - $p_T > 30$ GeV
  - $|y| < 2.4$
  - B-jet veto
- Transverse mass
  - $M_T > 50$ GeV

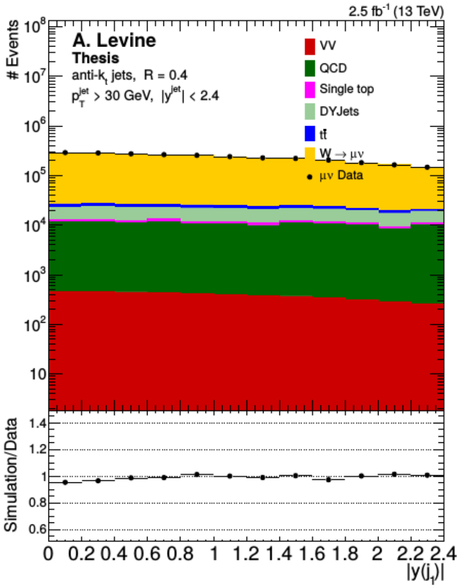
$y = \frac{1}{2} \ln[(E + p_z)/(E - p_z)] \approx \eta$

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

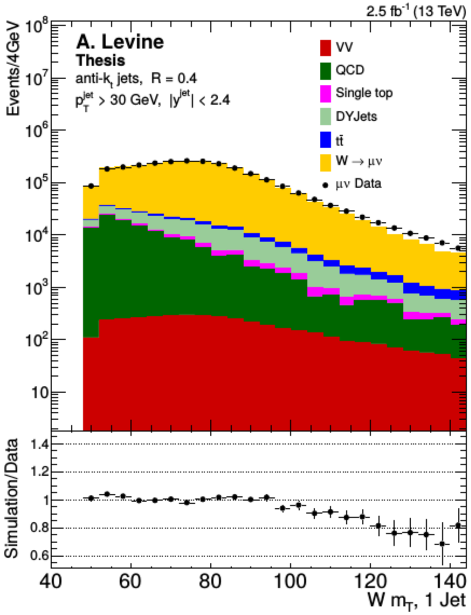
Leading Jet pT



Leading Jet y



mT



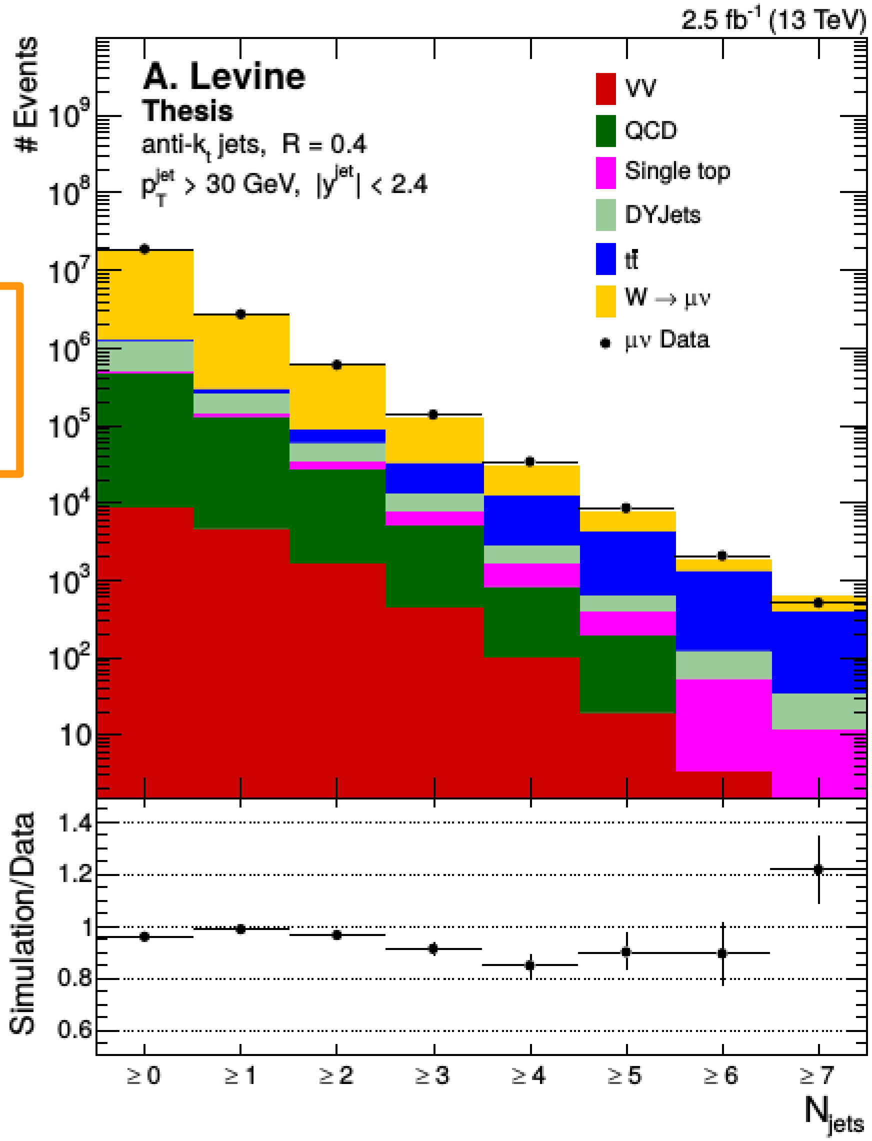
W+jets Backgrounds

Single Top
MC used for shape and normalization

$W\rightarrow\mu\nu$
MC used for shape and Normalization)

$t\bar{t}$
MC used for shape and normalization

Inclusive number of jets distribution



QCD
Data driven iterative method

Drell Yan +Jets
MC used for shape and normalization

Diboson
MC used for shape and normalization

Detector Unfolding

- Use iterative Bayesian method used (d'Agostini)
- Compares bin migrations between generator level and reconstructed level
- Response matrix (R_{ij}): probability to observe a reconstructed event in bin j given a generator level event in bin i: $P(Reco_j|Gen_i)$
- Use Bayes' Theorem to determine smearing matrix S_{ij}: probability a reconstructed event in bin j is due to generator level event in bin i

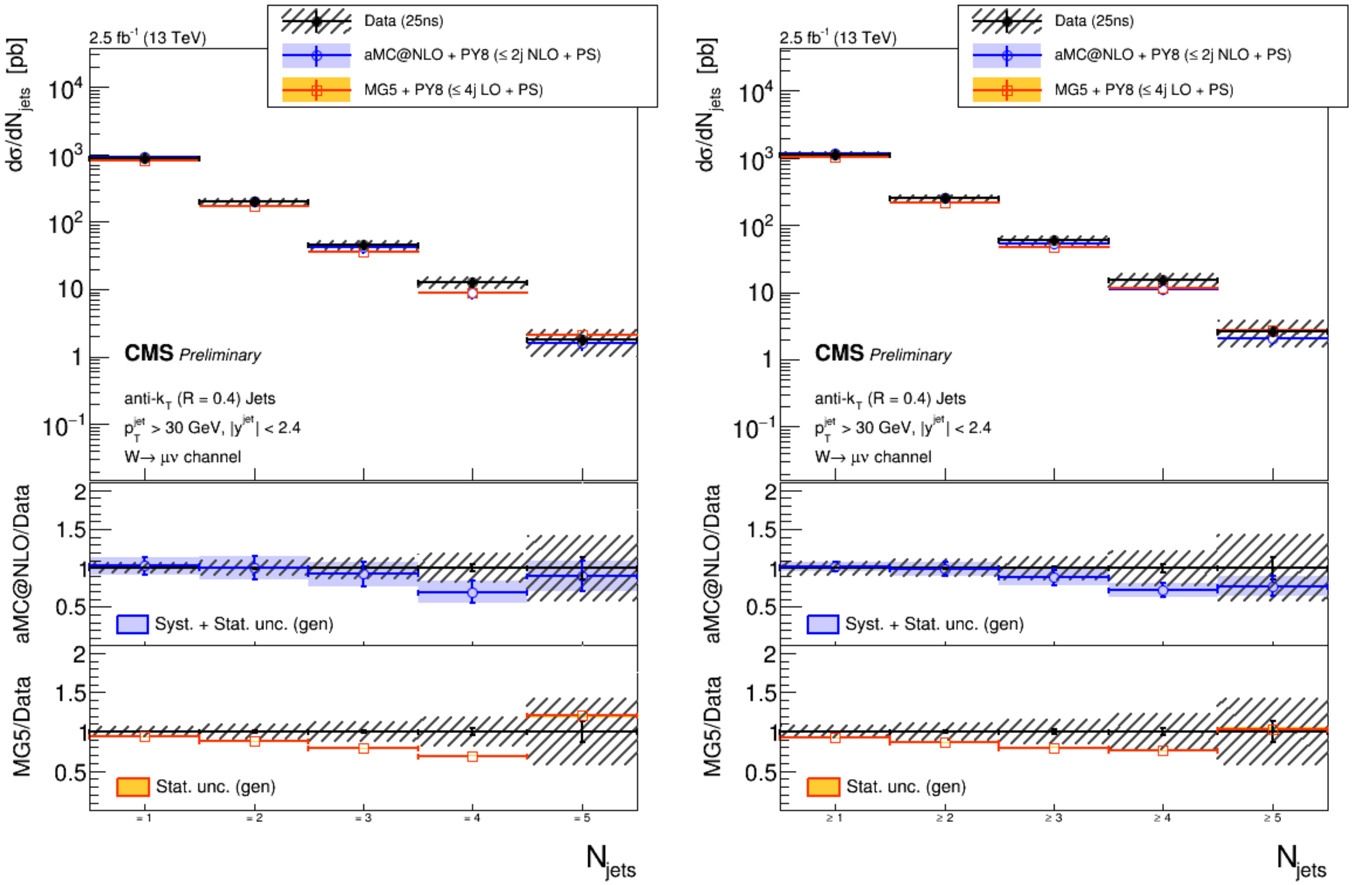
$$P(Gen_i|Reco_j) = \frac{P(Reco_j|Gen_i)P(Gen_i)}{\Sigma_{l=1}^{n_{bins}} P(Reco_j|Gen_l)P(Gen_l)}$$

- The number of true events in bin i is given by, $\hat{n}(i) = \frac{1}{\epsilon_i}\Sigma_{j=1}^{n_{bins}} n_{obs}(j)S_{ij}$ where the efficiency of observing an event in bin i is given by: $\epsilon_i = \Sigma_{j=1}^{n_{bins}} R_{ji}$
- Iterate until number of true events stabilizes

Differential Cross Sections

Cross sections measured up to jet multiplicity of 5

Blue shaded region shows computed theory uncertainty



Exclusive **Inclusive**

Ratio plots show a comparison between data and NLO (blue)/LO(yellow)

Generators agree with data within uncertainties, can use them to estimate backgrounds for studies of new physics

NLO generator gives slightly better agreement than LO generator as jet multiplicity increases

Summary of Results

- Search for lepton flavor violating Higgs couplings
  - The first ever search direct search for lepton flavor violating Higgs couplings has been performed
  - A 2.4σ excess was observed in 19.7 fb^{-1} of 8 TeV data, corresponding to a best fit of $B(H \rightarrow \mu\tau) = 0.84\%$
  - No excess observed in 2.3 fb^{-1} data at 13 TeV
    - Tightest limit set: $B(H \rightarrow \mu\tau) < 1.20\%$
- Measurement of W+Jets cross section in $W \rightarrow \mu\nu$ channel
  - First such measurement at 13 TeV
  - Differential cross sections given as a function of jet multiplicity
    - Inclusive and exclusive, up to a multiplicity of 5
  - General agreement between data and simulation
    - NLO MC has slightly better agreement than LO MC

Outlook

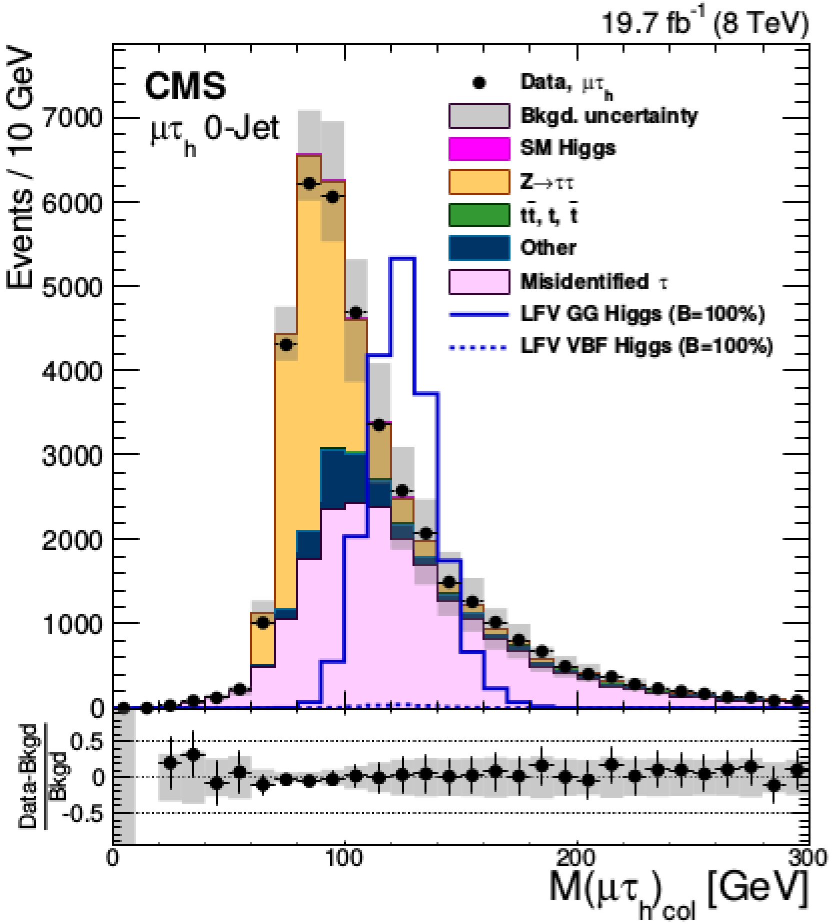
- LFV Higgs search in 2015 didn't have enough data to investigate B(H → μτ) = 0.84%
- LHC currently operating in 2016
- 30-40 fb^{-1} of data expected by the end of the year
  - 2016 results will conclusively investigate 0.84% branching ratio
- NNLO MC samples are in the process of being generated for W+jets
  - Will allow us to determine if small deviations between data and MC are due to a lack of NNLO corrections or if there is a systematic disagreement between theory and experiment

The End

Backup

LFV Preselection

- Select loose preselection
- H → $\mu\tau_e$
  - Muon $p_T > 25$ GeV, $|\eta| < 2.1$
  - Electron $p_T > 10$ GeV, $|\eta| < 2.3$
  - Veto b-jets
    - Reduce contribution from pairs of top quarks decaying into W bosons and b quarks
- H → $\mu\tau_h$
  - Muon $p_T > 30$ GeV, $|\eta| < 2.1$
  - Tau had $p_T > 30$ GeV, $|\eta| < 2.3$



Fake Rate Method Overview

H → $\mu\tau_h$ Channel

- Used to estimate contribution from backgrounds that contain jets faking hadronic taus
  - QCD multijets, W+Jets
  - W+Jets is largest irreducible background
    - Transverse mass $M_T^\ell = \sqrt{2p_T^\ell E_T^{miss}(1 - cos\Delta\phi_{\vec{p}_T^\ell - \vec{E}_T^{miss}})}$
    - LFV Higgs will have high M_T^μ cut because MET and μ will be back to back
    - W+Jets has same kinematic distribution

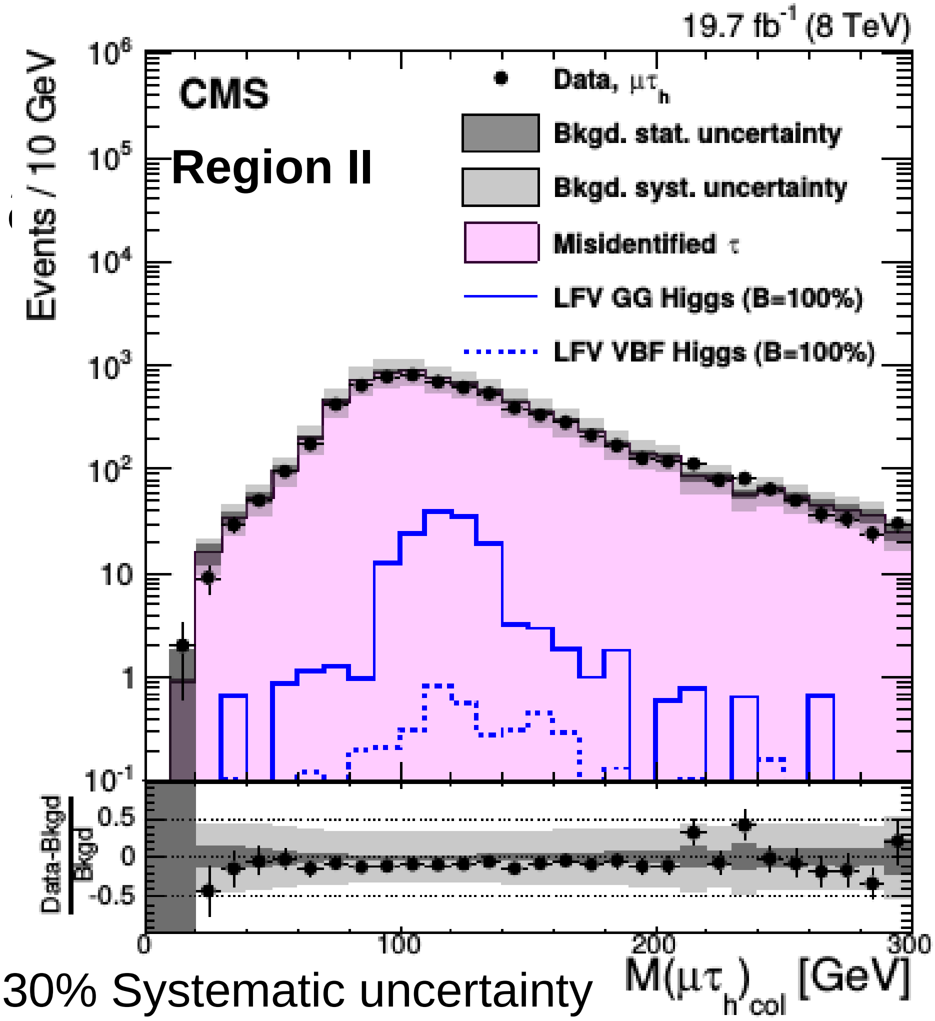
Decay Mode	f_{τ_h}
$\tau \to \pi^\pm$	0.53
$\tau \to \pi^\pm\pi^0(\pi^0)$	0.48
$\tau \to \pi^\pm\pi^\pm\pi^\pm$	0.46

- Data driven method: Select Z → μμ + X sample, where X is identified as a tau
- Calculate fake ratio: $f_\tau = \frac{N_{events}(Z \to \mu\mu + X = (\tau, ID + tight - isolated))}{N_{events}(Z \to \mu\mu + X = (\tau, ID + loose - isolated))}$

Fake Rate Method: Regions H → mutauhad Channel

- Apply scale factor $\frac{f_{\tau_h}}{1-f_{\tau_h}}$ to fakes rich Region III to get yield in Region I (signa region)
- Technique validated in control Region II

Region I OS μτ τ tight iso	**Region II** LS μτ τ tight iso
Region III OS μτ τ loose iso τ not tight iso	**Region IV** LS μτ τ loose iso τ not tight iso

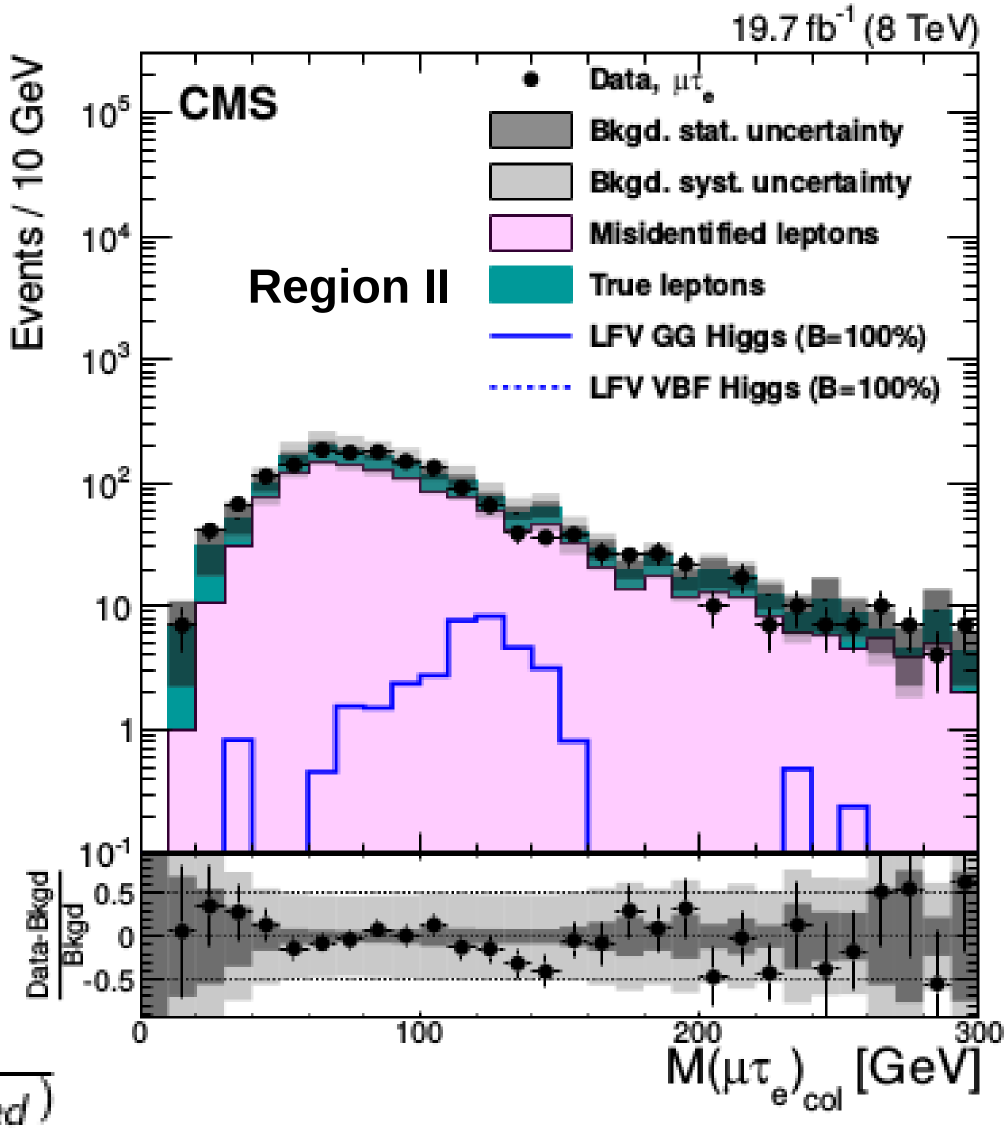


30% Systematic uncertainty

Fake Rate Method Overview H → mutaue Channel

- Include contributions from objects faking electrons or muons
- Analogous to H → mutauhad channel:
  - Select Z → μμ +X sample
- Fake rate = ratio of isolated to non-isolated
  - Non-isolated: invert isolation
- Require non-isolated instead of not-tight

$$f_e = \frac{N_{events}(Z \rightarrow \mu\mu + e_{isolated})}{N_{events}(Z \rightarrow \mu\mu + e_{non-isolated})}$$



40% Systematic uncertainty

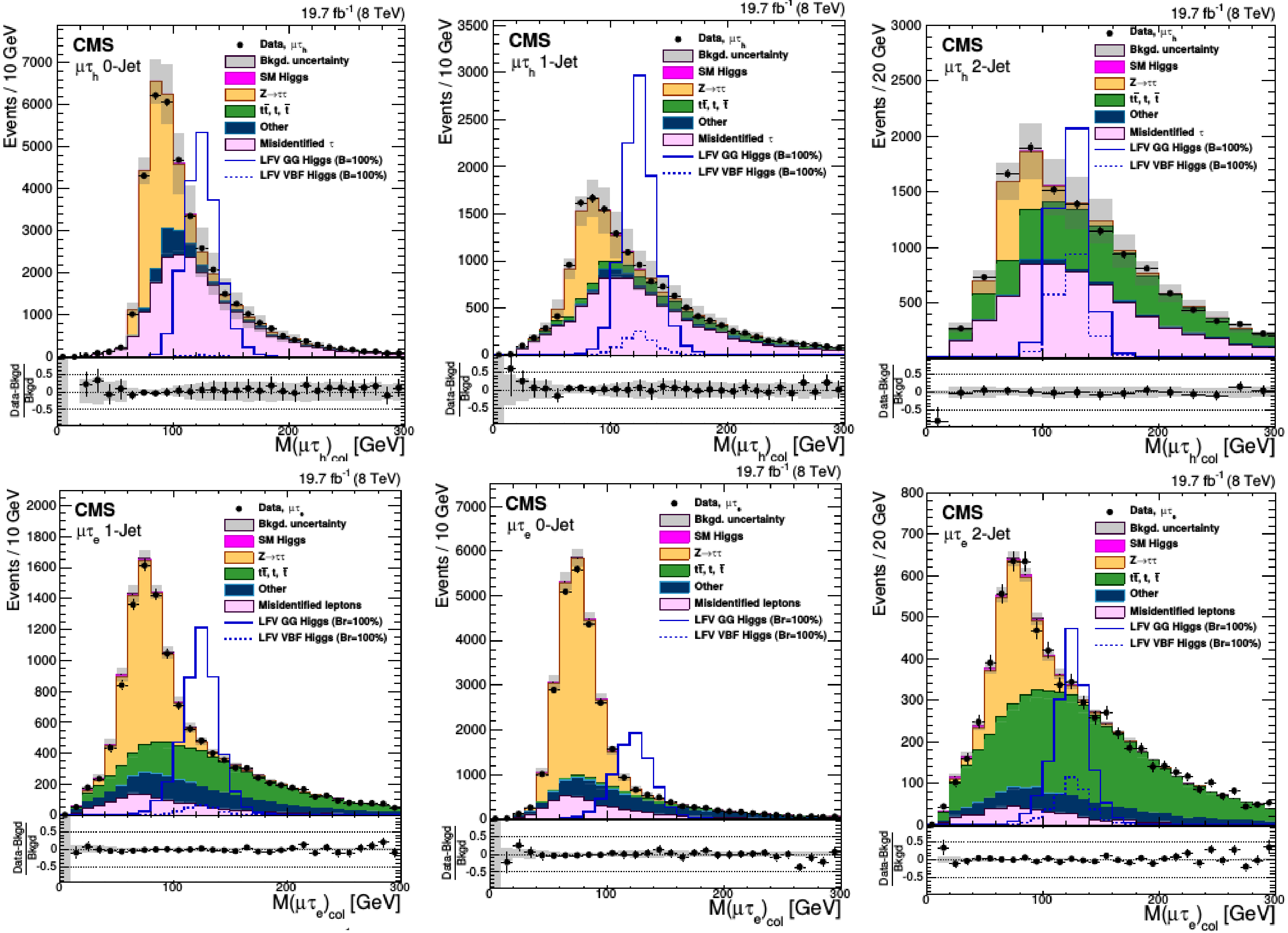
LFV Preselection 8 TeV

Data/MC agreement within uncertainties

0 Jet **1 Jet** **2 Jet**

$\mu\tau_h$

$\mu\tau_e$

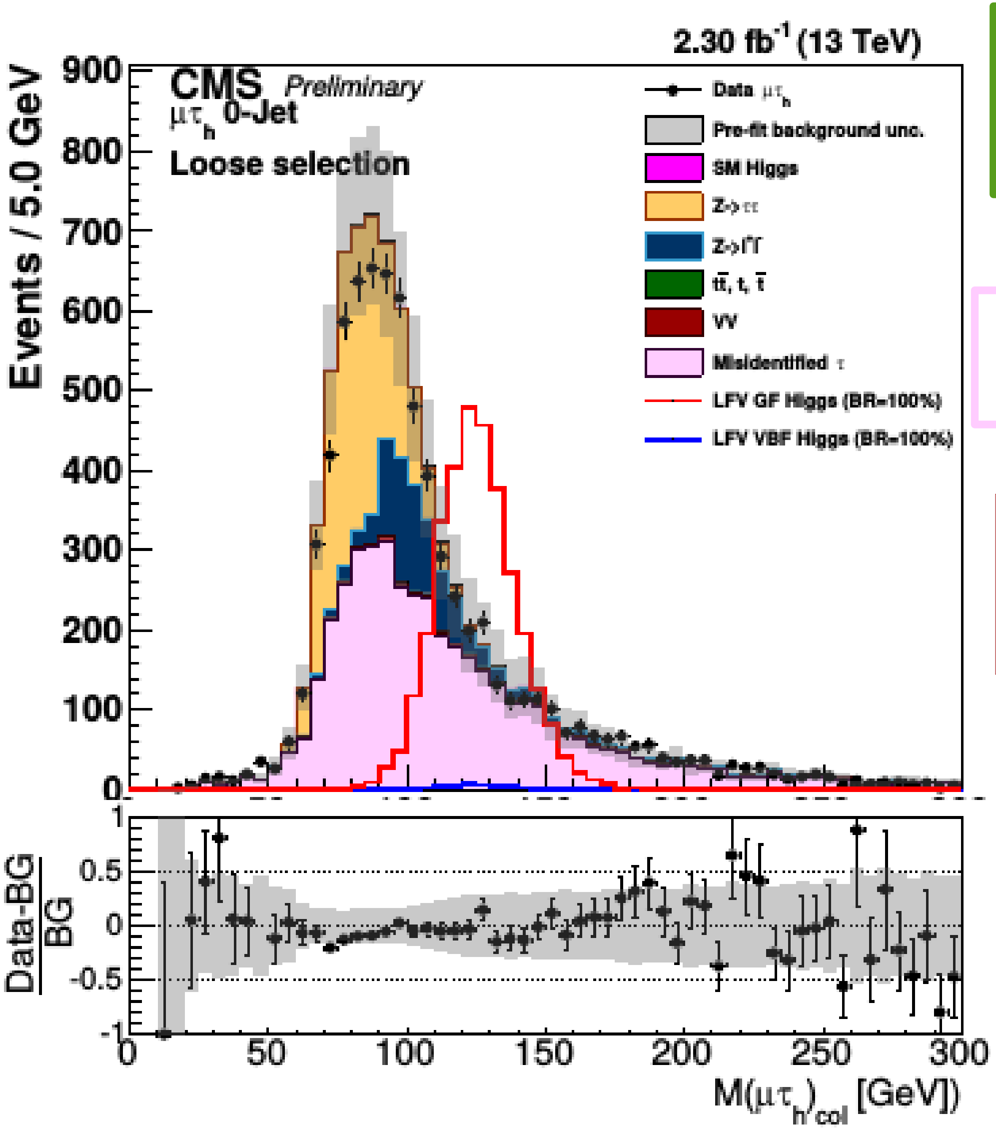


13 TeV Backgrounds

SM Higgs
MC used for shape and normalization

$Z \rightarrow \tau\tau$
MC used for shape and Normalization (Embedded samples not yet available at 13 TeV)

$Z \rightarrow ll$
MC used for shape and normalization



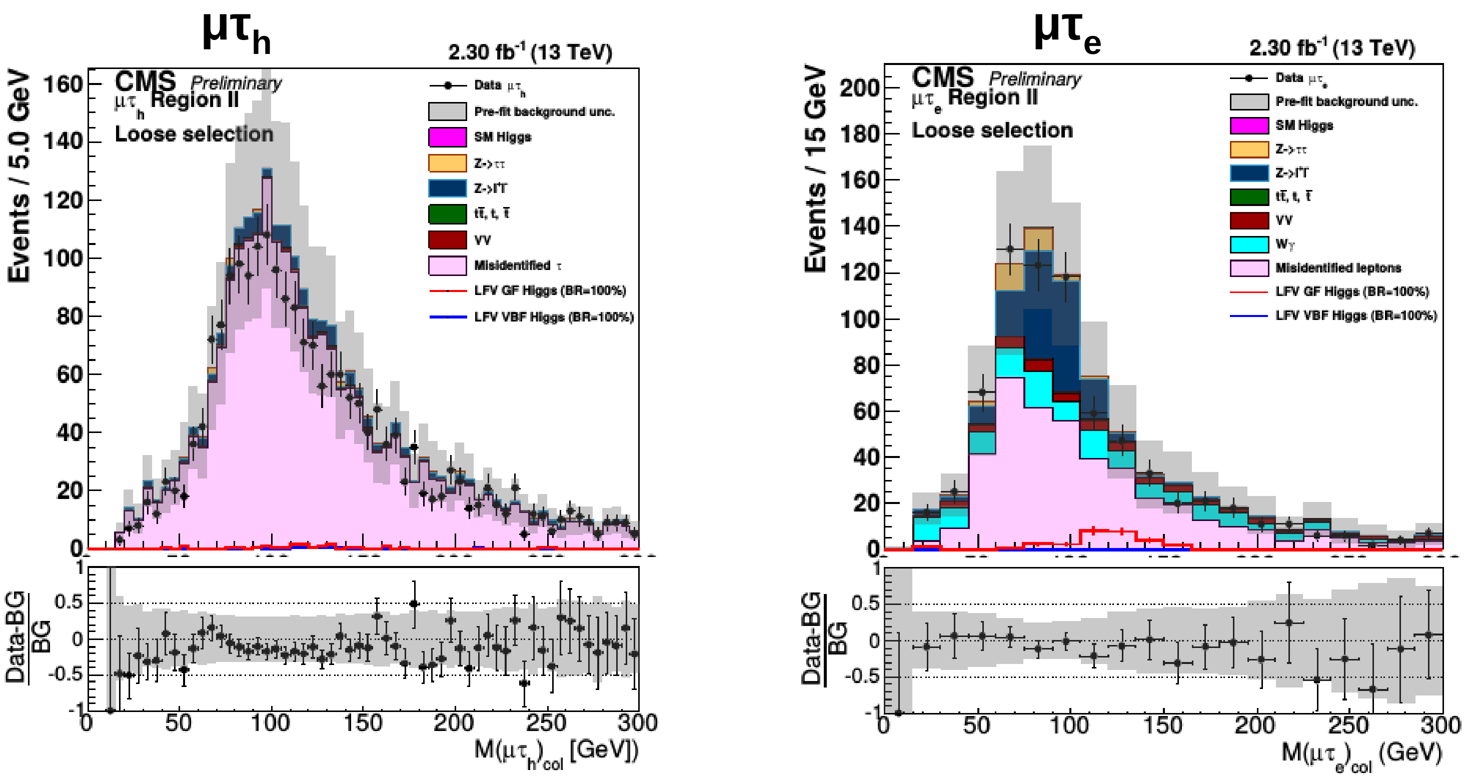
Single top and $t\bar{t}$
MC used for shape and normalization

Misidentified tau
Data driven method

Diboson
MC used for shape and normalization

Fake Rate Control Regions 13 TeV

Agreement between data and misidentified leptons in Region II (like sign control region)



Region I	**Region II**
OS μτ τ tight iso	LS μτ τ tight iso
Region III OS μτ τ loose iso τ not tight iso	**Region IV** LS μτ τ loose iso τ not tight iso

Regions in $\mu\tau_e$ now defined analogously to $\mu\tau_h$ regions

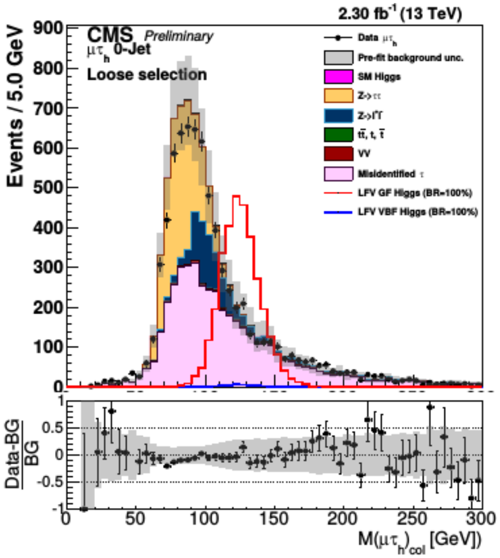
Sideband Regions III, IV require loose, not tight isolation (8 TeV: invert iso)

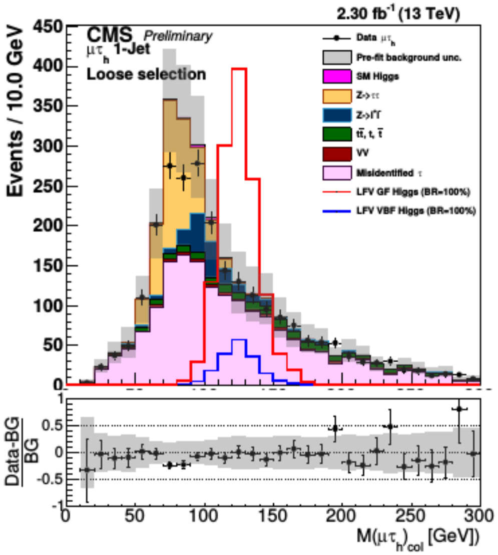
13 TeV After Preselection

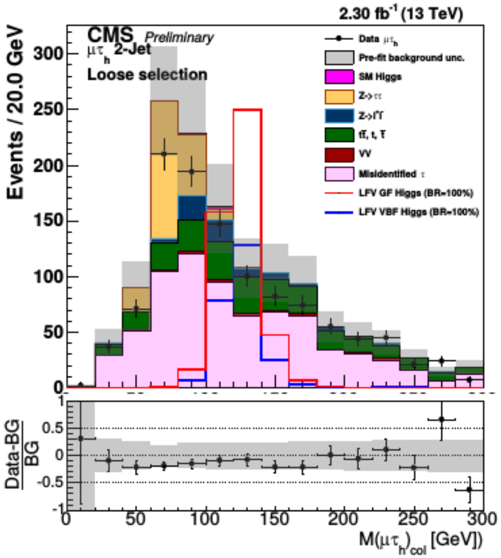
Data/MC agreement within uncertainties

0 Jet **1 Jet** **2 Jet**

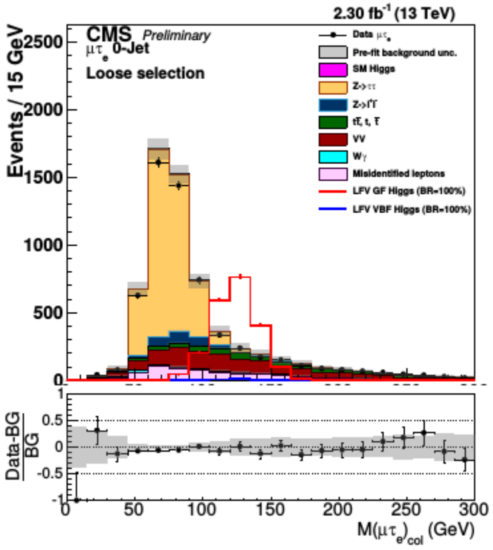
$\mu\tau_h$

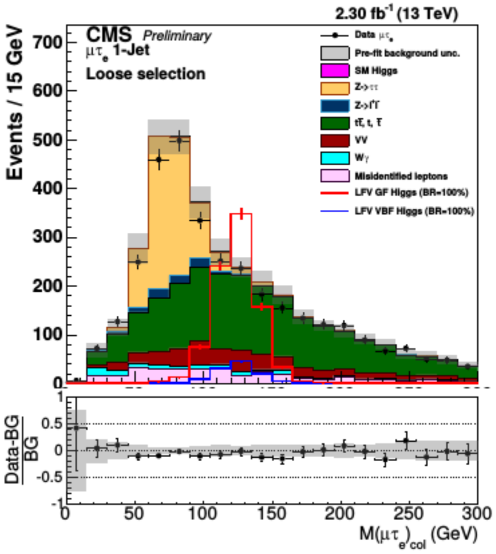


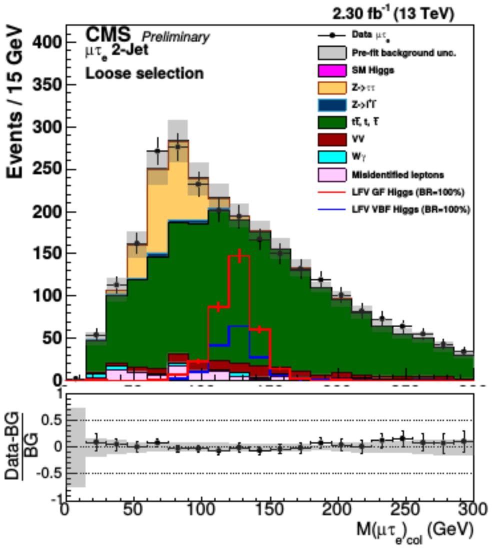




$\mu\tau_e$

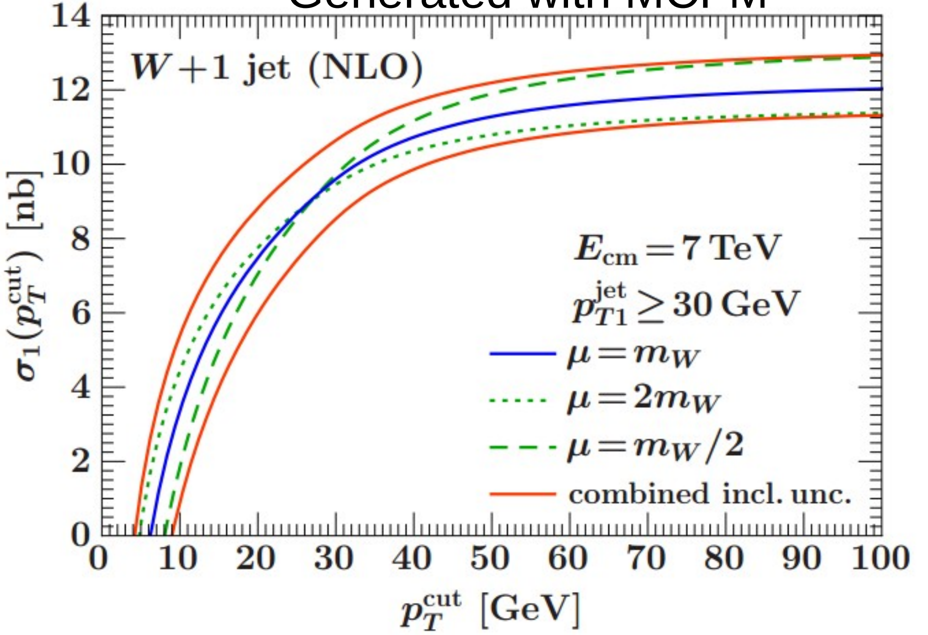






Theoretical Uncertainties

- Theoretical uncertainties must be evaluated for each jet bin
  - Calculate via direct QCD scale variation
  - Vary theoretical scales between half their default value and twice their default value
- Direct scale variation in cross sections of exclusive processes can lead to underestimation of theoretical uncertainties[1]
- Solution: rewrite exclusive cross section as difference of inclusive cross sections



Source: arXiv:1107.2117

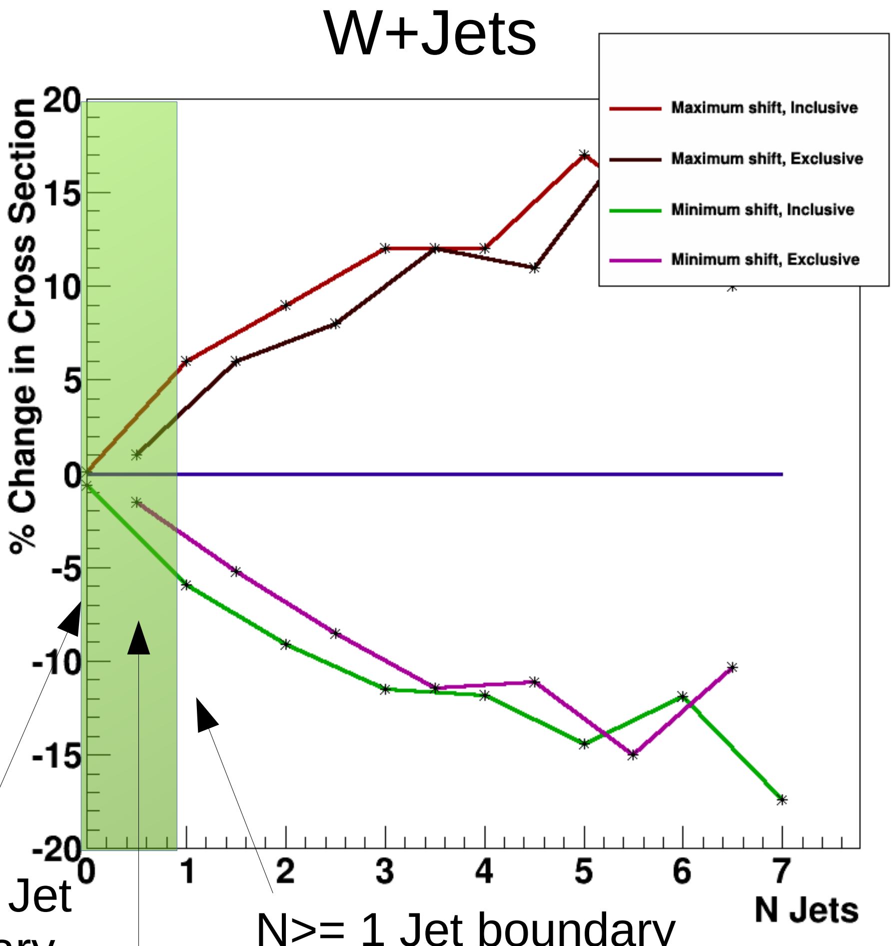
Generated with MCFM

$$\sigma_N = \sigma_{\geq N} - \sigma_{\geq N+1}$$

$$\Delta_N^2 = \Delta_{\geq N}^2 + \Delta_{\geq N+1}^2$$

[1] Source: arXiv:1107.2117

Effect of Scale Variation on Yield



N >= 0 Jet Boundary

N>= 1 Jet boundary

N=0 exclusive jet results

- Used Madgraph aMC@NLO Monte Carlo
- Points at half integer values represent exclusive jet changes in yield from direct scale variation
- Points at integer values represent changes in yield at inclusive jet boundaries
- Exclusive % change from direct scale variation tends to be smaller than inclusive change at one or both of the boundaries
  - Changes at boundaries partially chancel out
- Estimate uncertainties in exclusive jet bins by summing inclusive uncertainties in quadrature