Heavy Neutral Particle Decays to Tau Pairs at $\sqrt{s}$ = 7 TeV with CMS at the Large Hadron Collider

Michail Bachtis

University of Wisconsin-Madison

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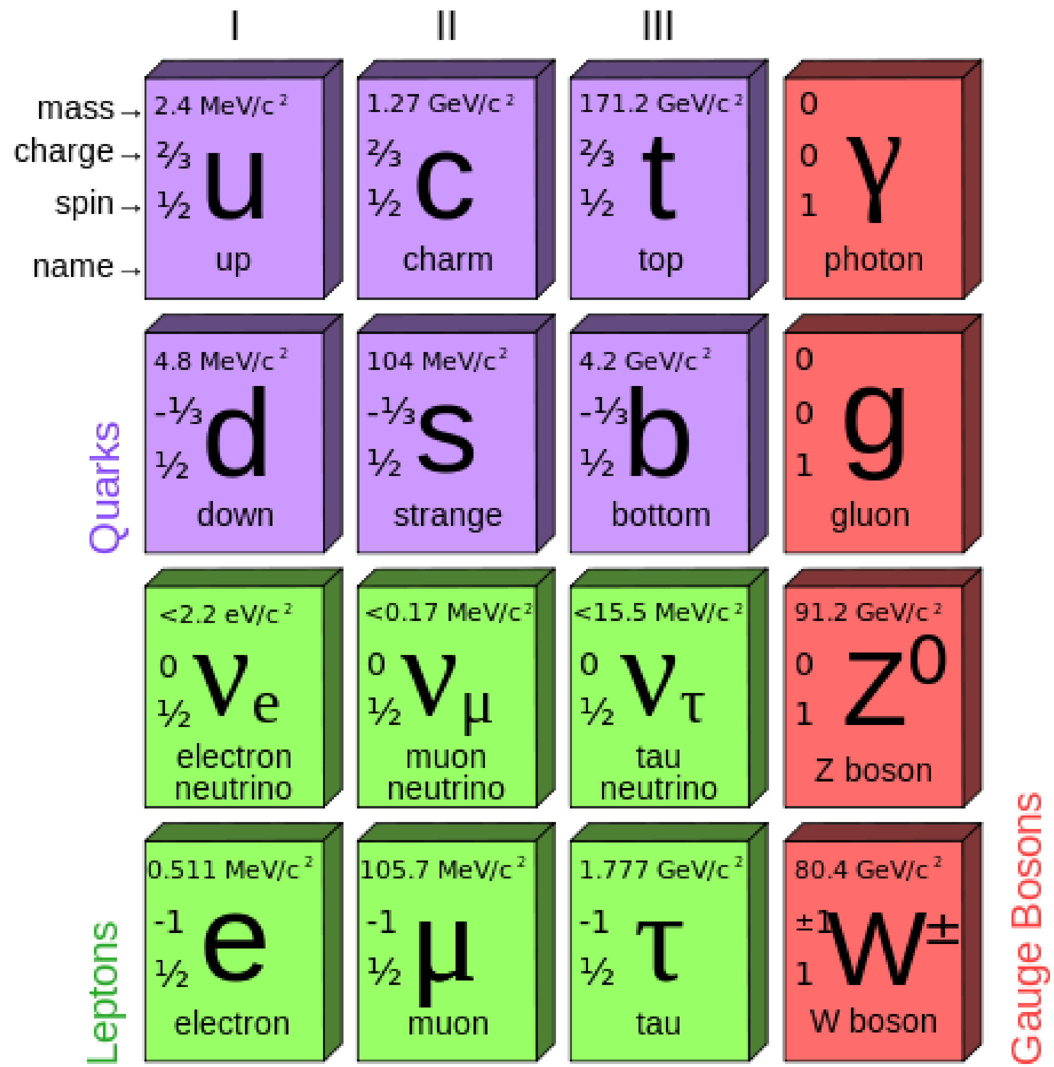
The Standard Model of Particle Physics

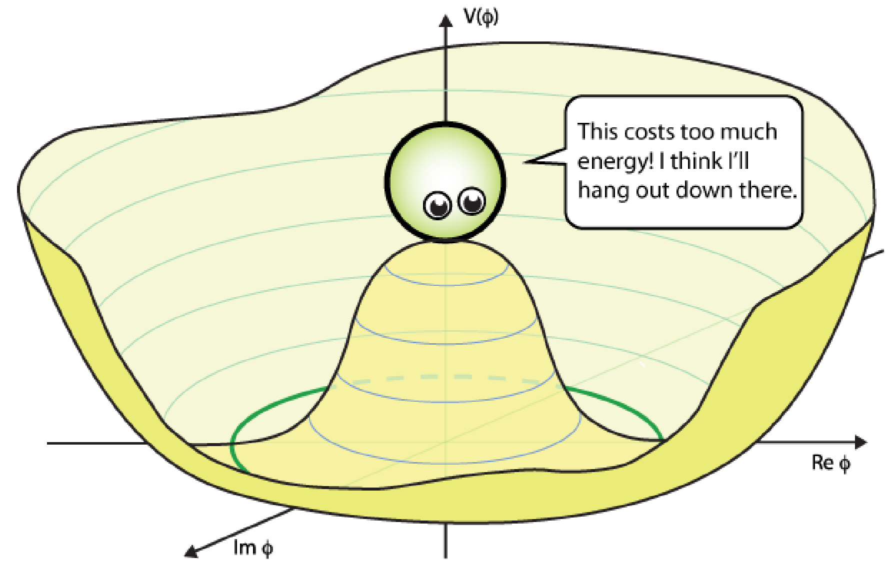
- Three generations of matter
  - 6 quarks
  - 6 leptons
    - 3 charged (e,μ,τ)
    - 3 neutrinos (ν_e,ν_μ,ν_τ)
  - Neutrinos supposed to be massless in the SM
    - Recent experiments show they have very small masses
- Force carriers
  - Photon ↔ EM force
    - massless
  - 8 gluons ↔ strong force
    - massless
  - $W^{\pm}$,Z ↔ weak force
    - Very massive



Formulated as a quantum field theory under $SU(3)xSU(2)_LxU(1)$ gauge symmetries unifying EM and weak interactions

The Higgs Mechanism

- In $SU(2)_L$ x U(1) symmetry
  - Gauge bosons massless
  - Fermions as well
- Gauge bosons acquire mass by breaking the SU(2) x U(1) symmetry
  - Adding a complex scalar field doublet
  - Three degrees of freedom give mass to the gauge bosons
    - Become Longitudinal polarization of W/Z fields
  - Fourth degree of freedom corresponds to a new scalar particle, the Higgs boson
- Fermions acquire masses via couplings to the Higgs
- Higgs boson not discovered yet



$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2\Phi^2 - \lambda\Phi^4$$

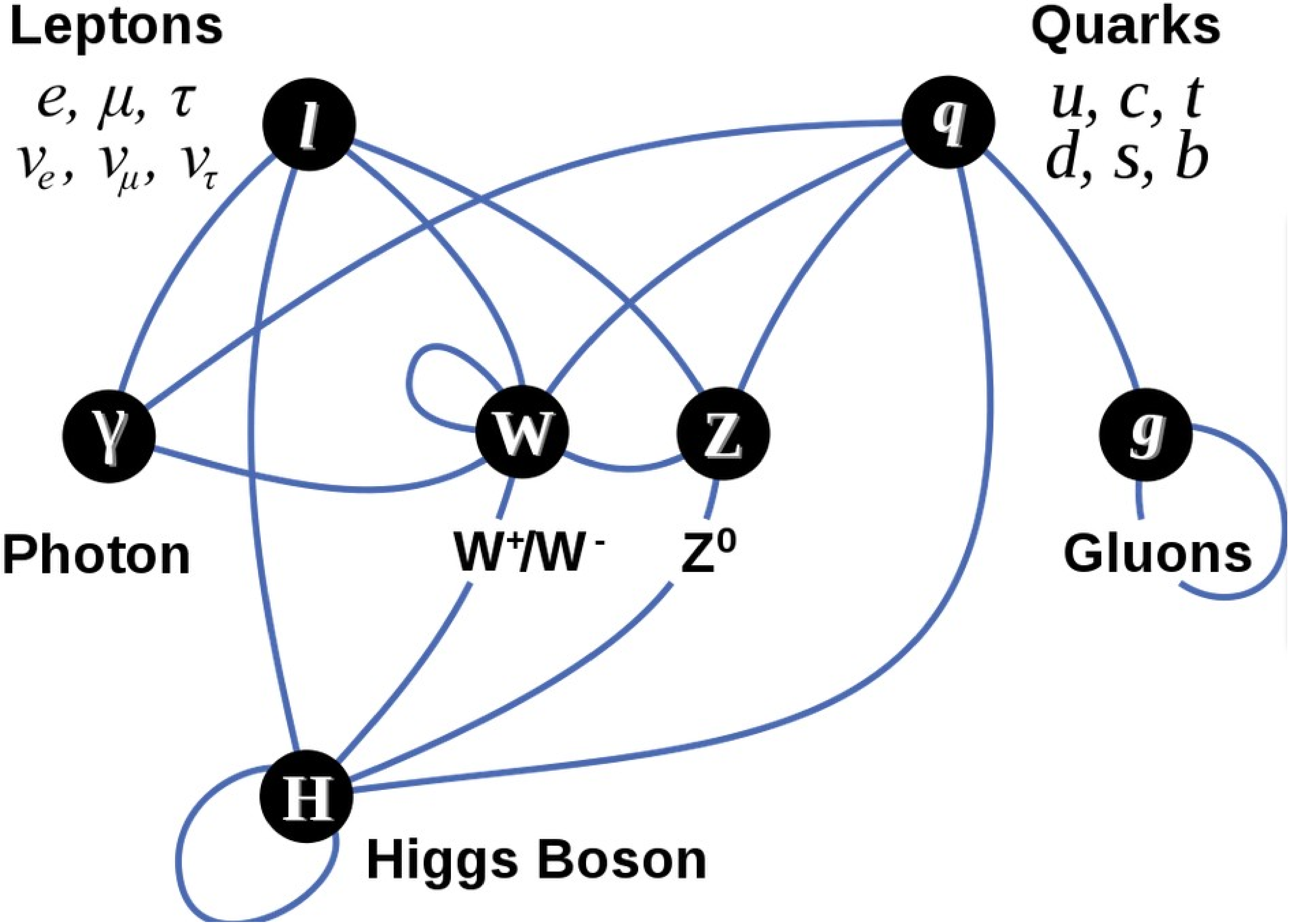
For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

Translating the field to the new minimum gives:

$$M_W = \frac{gv}{2},\ M_Z = \frac{M_W}{\cos\theta_W},\ M_H = \sqrt{-2\mu^2}$$

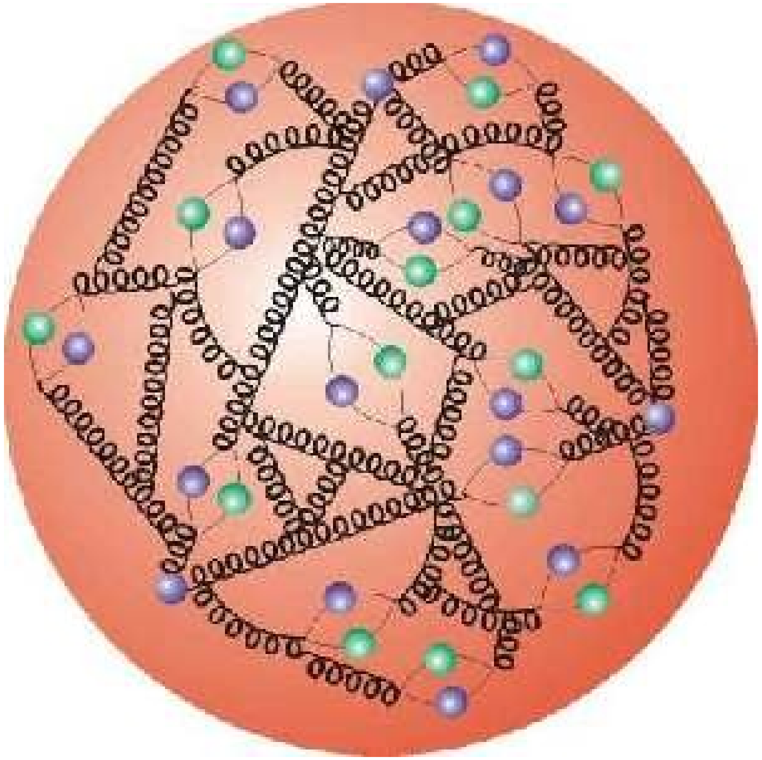
$$g^2 = \frac{8M_W^2 G_F}{\sqrt{2}}$$

Particle Interactions in the SM



The Structure of the Proton

- In proton collisions
  - Partons (quarks and gluons) are pulled from the proton and interact
- Quarks in the proton not free
  - Exchanging colored gluons
  - Virtual particles- off their mass shell
  - Two types
    - Valence (u,d)
    - Sea(u,d,c,s) : produced by strong interactions in the proton
- Gluons
  - Carry ~50% of the proton momentum
- Parton Distribution Functions
  - Probability of a parton to be pulled out of the proton with momentum fraction x : f(x)
  - Measured with experimental data

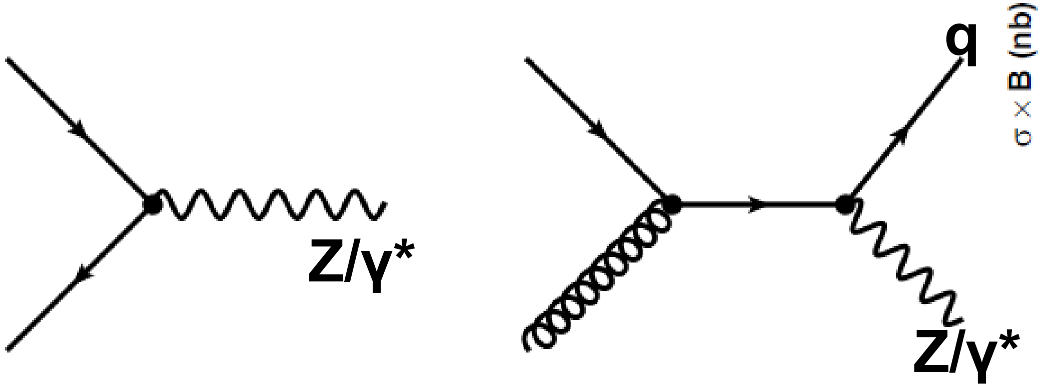


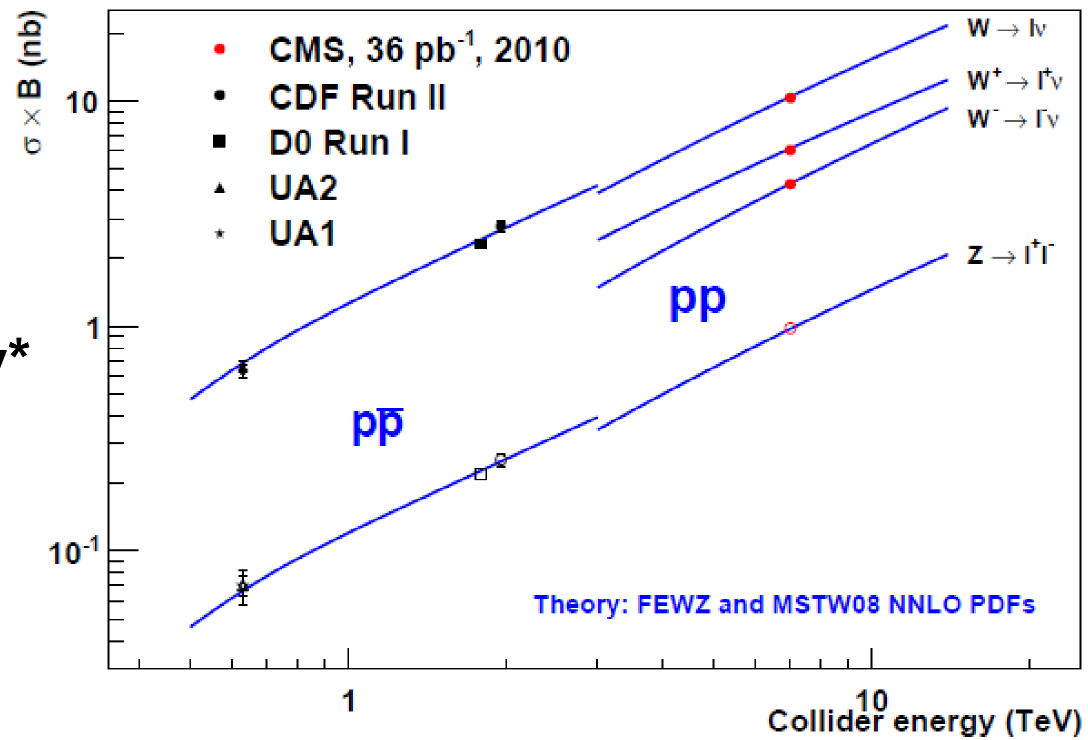
- In 7 TeV proton collisions
  - Two partons with momentum fraction x,y will give an effective center of mass of the interaction

$$\sqrt{s} = \sqrt{xyS} = 7\sqrt{xy}\ \text{TeV}$$

  - Hadron colliders versatile for discovery

Z Production in the LHC



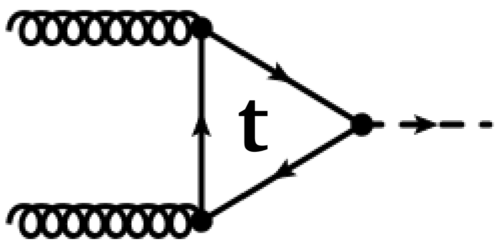


- Production via the Drell-Yan process
- Leading order
  - Quark annihilation
  - Z has no transverse momentum
- At higher orders
  - Jets in the final states
  - Z has transverse momentum
    - Produced in association with jets

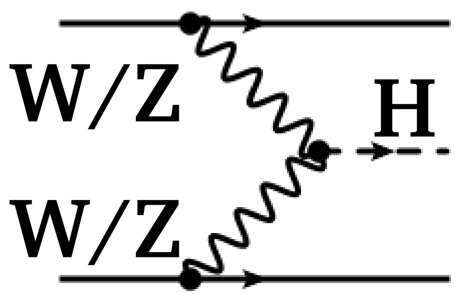
- CMS and ATLAS measured Z production
  - in di-muon and di-electron final states
- This thesis:
  - Measurement of cross section in di-tau final state
    - Test of lepton universality and benchmark for Higgs search

Higgs Phenomenology in the LHC

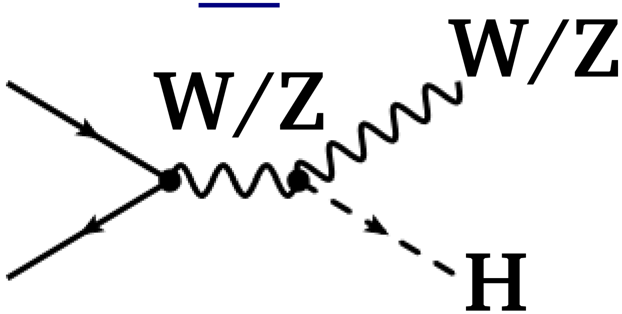
Gluon Fusion



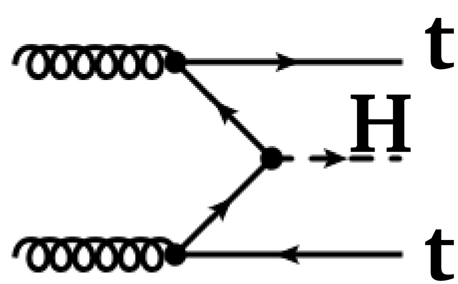
VBF

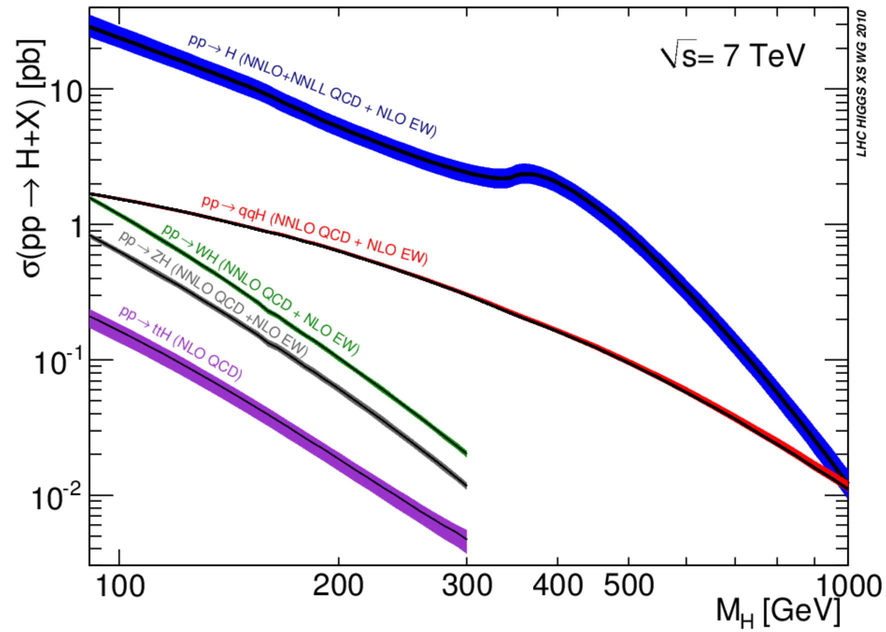


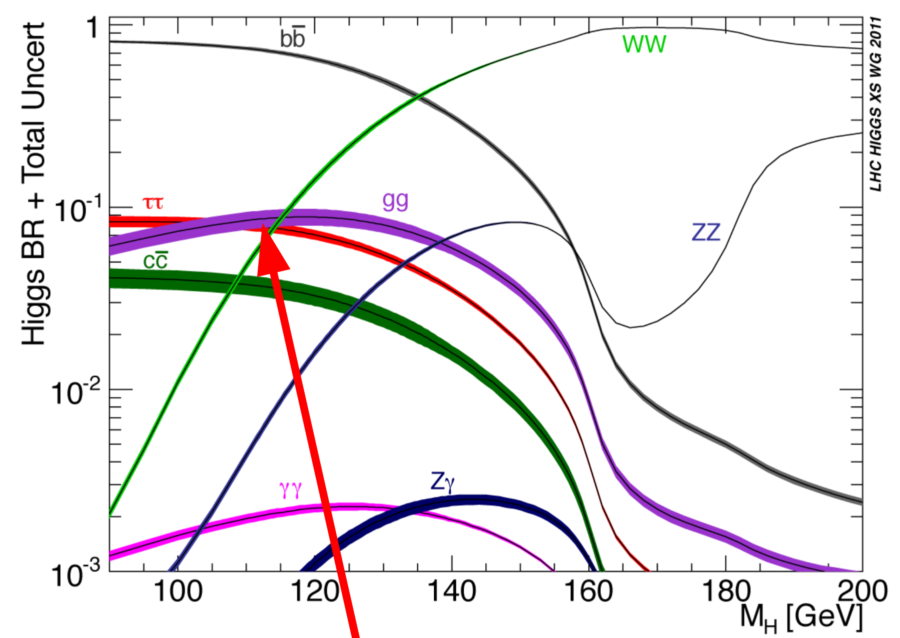
VH



ttH





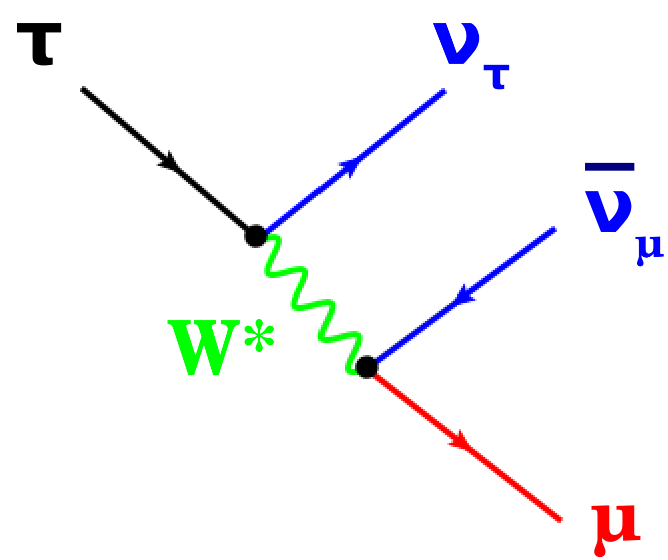


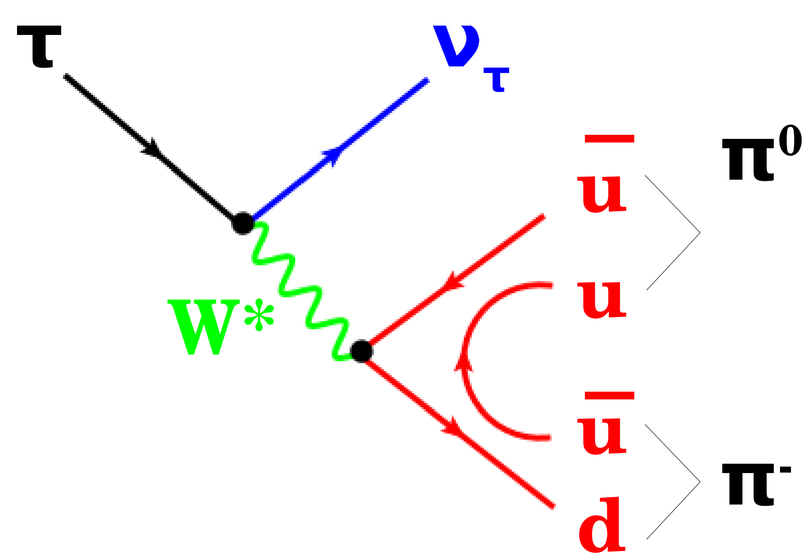
- Gluon fusion
  - Dominant production mechanism
- Vector Boson Fusion
  - Second dominant mechanism
  - Distinct forward jet signature
- Associated Production(with W/Z or tt)
  - Low rates

At low mass significant branching ratio to tau leptons

The Tau Lepton

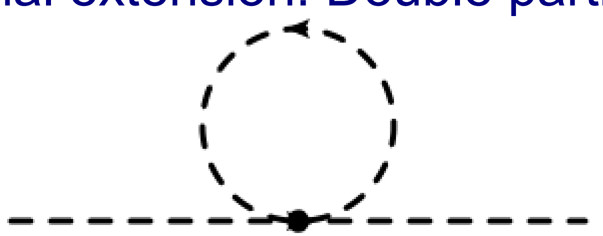
- Heaviest lepton
  - Mass = 1.78 GeV
- Decays via the weak interactions
  - To electrons/muons + 2 neutrinos (35%)
  - To hadrons + 1 neutrino(65%)
    - Single π^+/K^+
    - $\rho \rightarrow \pi^+\pi^0$
    - $\alpha_1 \rightarrow \pi^+\pi^-\pi^+$, $\pi^+\pi^0\pi^0$
- Identification of hadronic tau decays
  - Important since tau is a tool to search for the Higgs
  - Experimentally challenging
- Novel algorithm implemented in this thesis to identify hadronic decays of taus

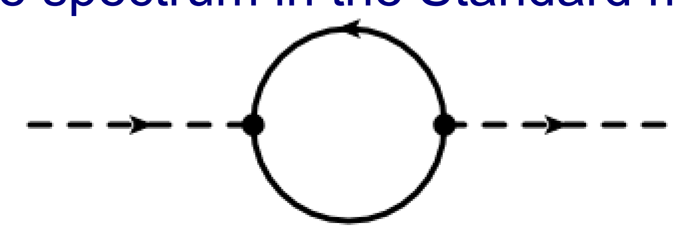




Beyond the SM: Supersymmetry

- SM: a theory of almost everything
  - Problems arise when SM is seen as part of a larger theory (e.g @ Plank scale) → hierarchy problem
  - Corrections to the Higgs mass become quadratically divergent in high scale Λ
    - For Higgs mass to be low excessive fine tuning is needed
- Supersymmetry(SUSY) solves this problem
  - By introducing a new symmetry between fermions and bosons
  - For each particle there is a super-partner with spin differing by ½
    - Divergences cancel by construction!
    - Minimal extension: Double particle spectrum in the Standard model → MSSM

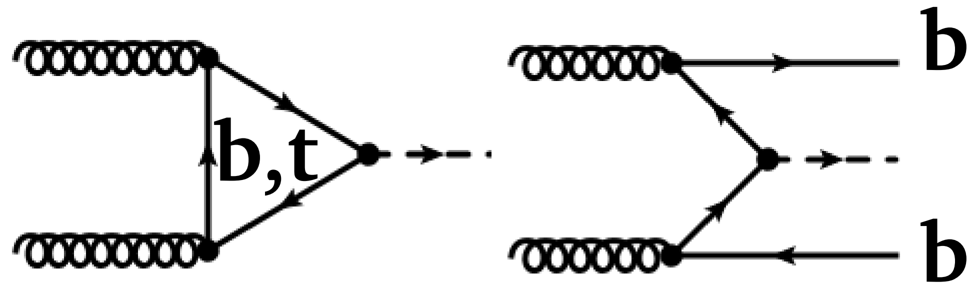


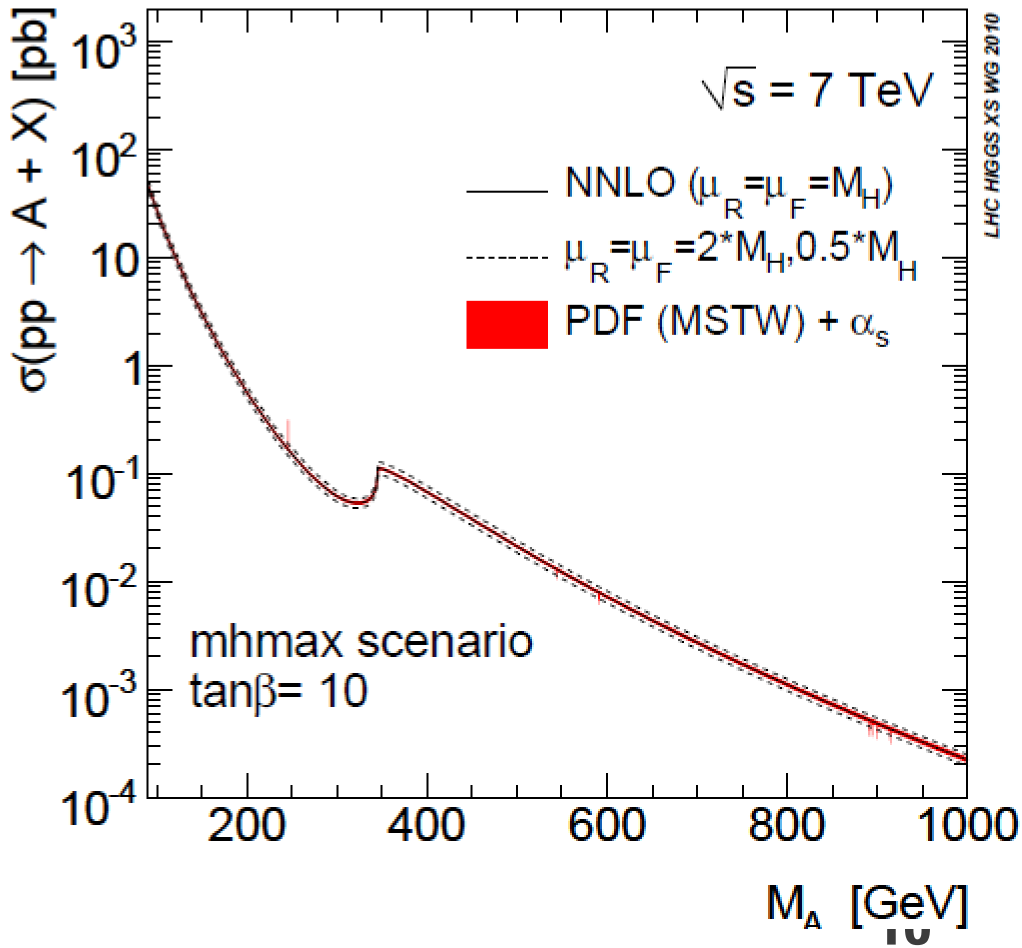


$$\lambda \int^{\Lambda} \frac{d^4 k}{k^2 - m_h^2} \approx \lambda \Lambda^2 \qquad -g^2 \int^{\Lambda} \frac{d^4 k}{\not{k}\not{k}} \approx -g^2 \Lambda^2$$

The Higgs sector in the MSSM

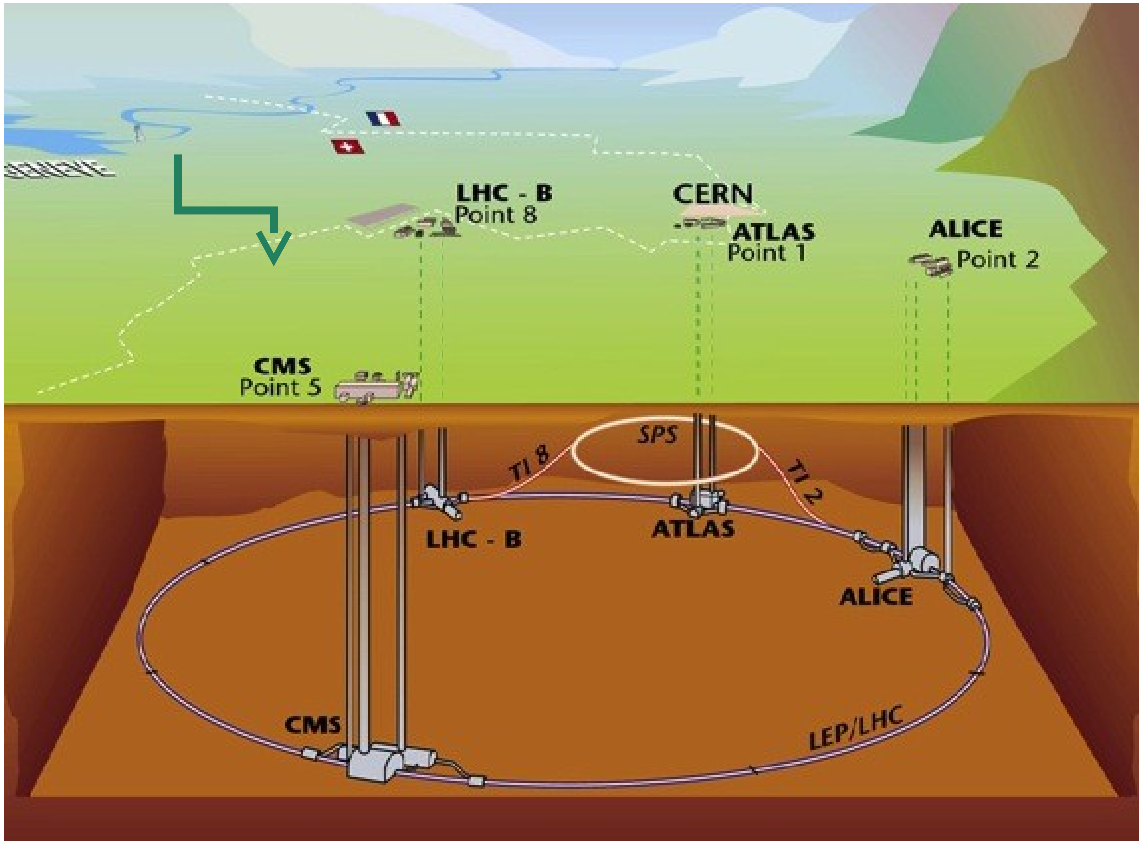
- Two Higgs doublets
  - 5 physical Higgs bosons ($h, H, A, H^{\pm}$)
- Production mechanisms
  - Gluon fusion (b,t loop)
  - Associated production with b-quarks
    - Identifying b quarks in the final state enhances sensitivity
- At tree level
  - 2 parameters: M_A , $\tan\beta$
  - $M_h < M_Z$
  - Loop corrections from SUSY particles
    - M_h <133 GeV
    - Fixed in benchmark scenarios(mh^{max})
- At large $\tan\beta$
  - Cross section Enhanced
  - $BR(\Phi \to \tau\tau) \sim 15\%$





The Large Hadron Collider

- 7 TeV proton proton (or heavy ion) collider
- Center of Mass energy = 7 TeV
- 27km circumference , 100m underground



- Four large detectors
  - ATLAS+ CMS
    - General purpose mainly proton physics
  - ALICE
    - Heavy Ion experiment
  - LHCb
    - Forward detector for b physics

LHC Operation

The number of events for a given process is given by:

$$N = \sigma \int dt \mathcal{L}$$

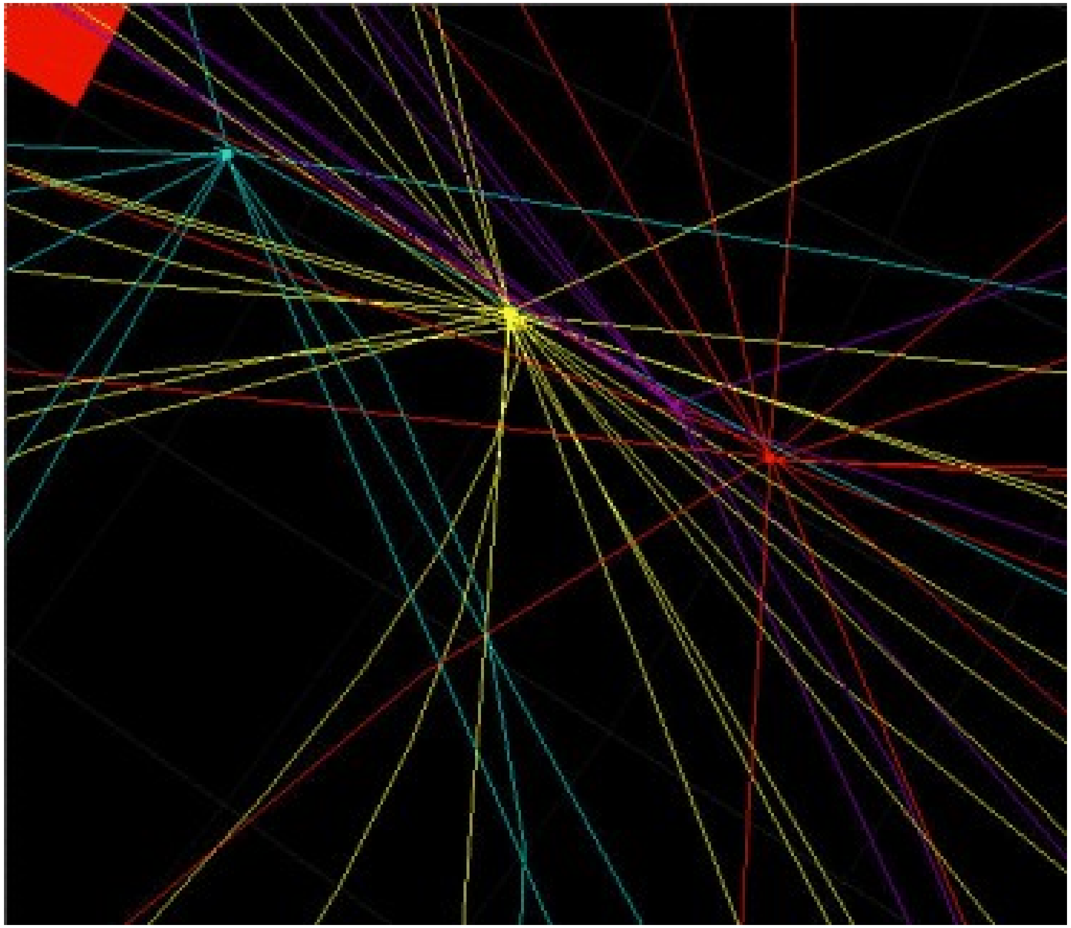
- σ: the cross section of the process
  - Expresses the probability of the interaction
  - Measured in units of area-effective area of the interaction
- L :The instantaneous luminosity of the collider
  - Particle Flux / time
  - Units of 1/(area x time)
- Integrated Luminosity :
  - Instantaneous luminosity integrated over time

	Design	2011 run
Beam Energy	7 TeV	3.5 TeV
Bunches/Beam	2835	1380
Rev Frequency	25ns	50ns
Peak Luminosity	$10^{34}cm^{-2}s^{-1}$	$3x10^{33} cm^{-2}s^{-1}$
Integrated Luminosity		5.2 fb^{-1}
SM Higgs bosons produced		~100,000

- Goal : maximize luminosity
  - Increase particles per bunch
  - Maximize the number of bunches and revolution frequency
  - Decrease the bunch area

The challenge of pileup

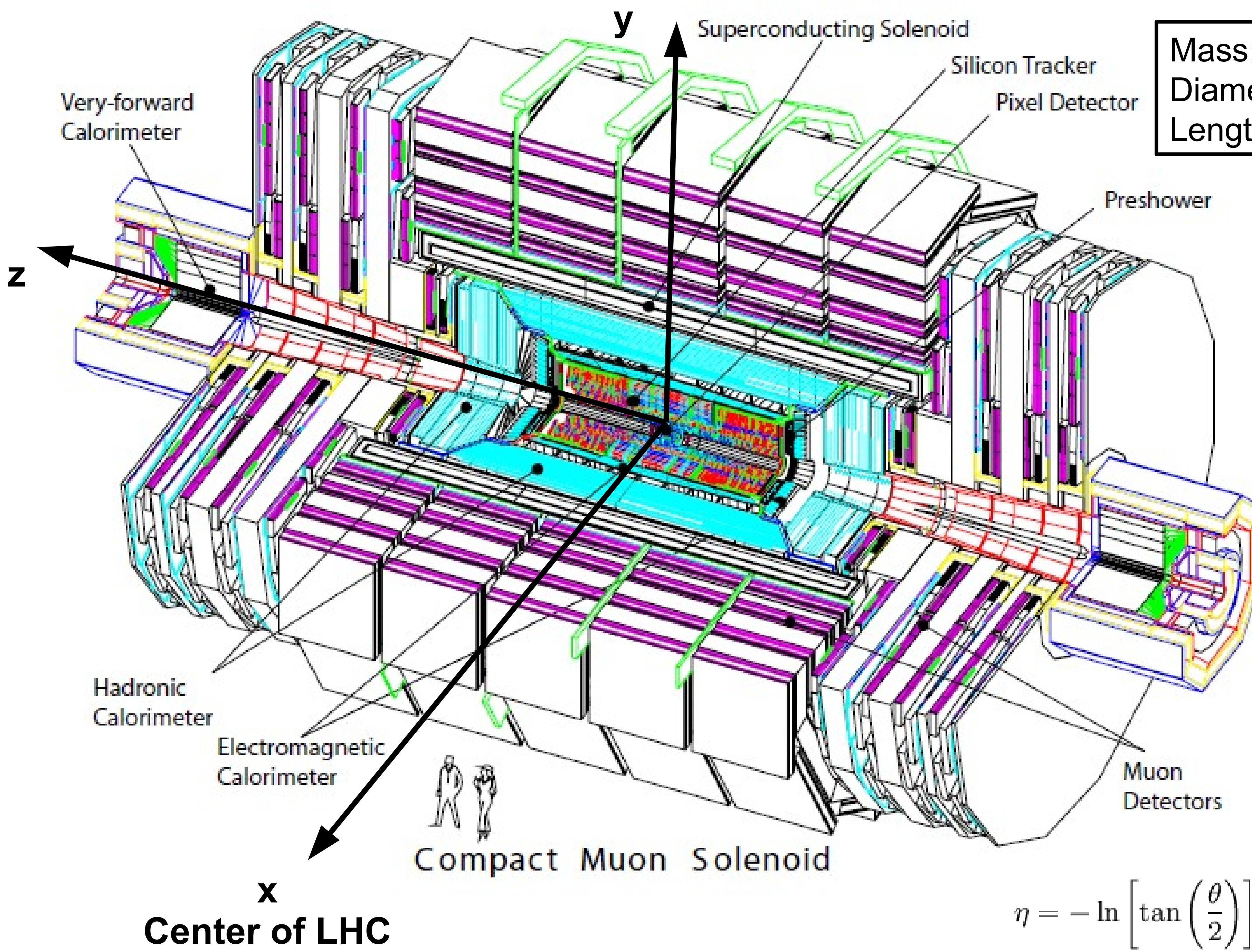
- At high luminosity several pairs of protons can interact
  - Producing multiple interactions in the detector
  - Event of interest overlayed with other events
- Special techniques are needed to maintain high performance of particle identification



Mean number of interactions/crossing

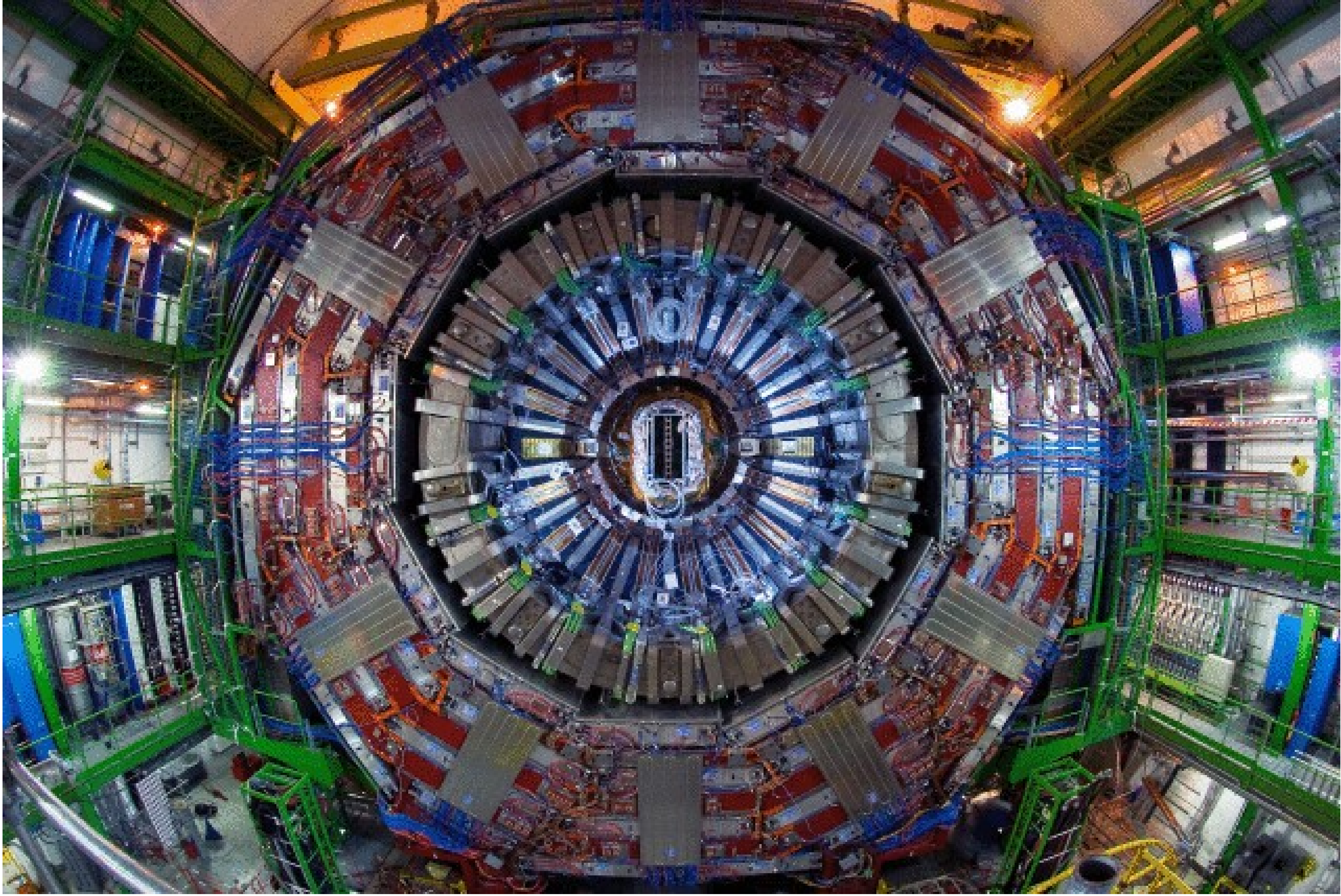
$$\mu = \frac{\mathcal{L}\sigma_T}{R_B f_B}$$

The Compact Muon Solenoid



Mass: 12,500T
Diameter: 15.0m
Length: 21.5m

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



Magnet

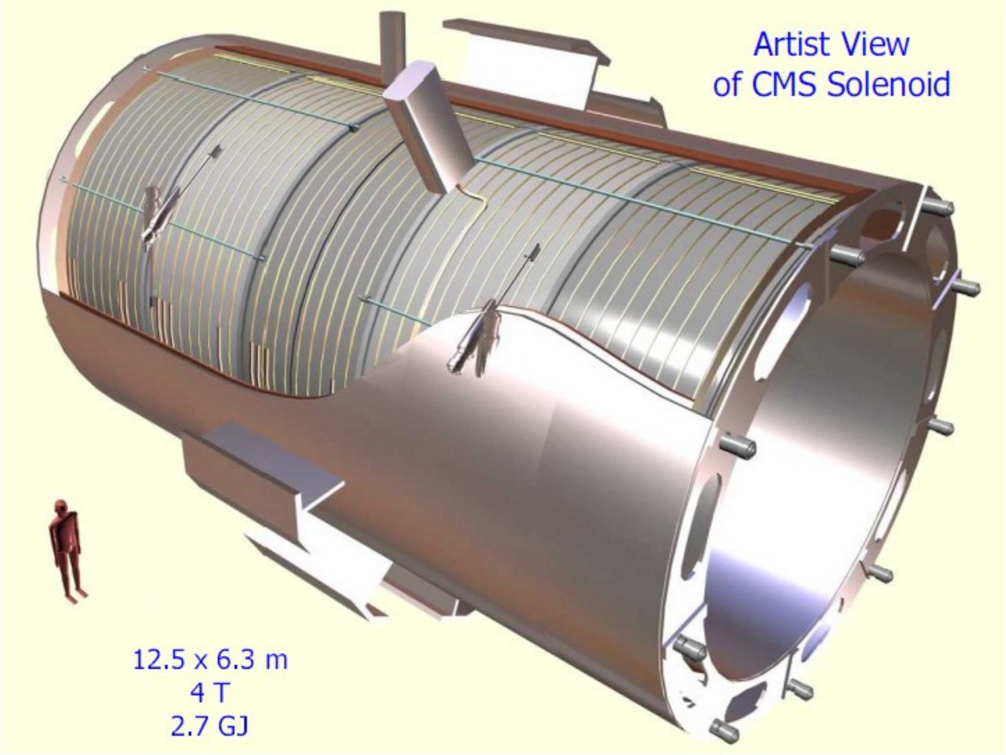
- Large solenoid magnet provides bending power for momentum measurement
- Sagitta of a particle trajectory

$$s = \frac{L^2}{8r} = \frac{qBL^2}{8p}$$

- Momentum resolution

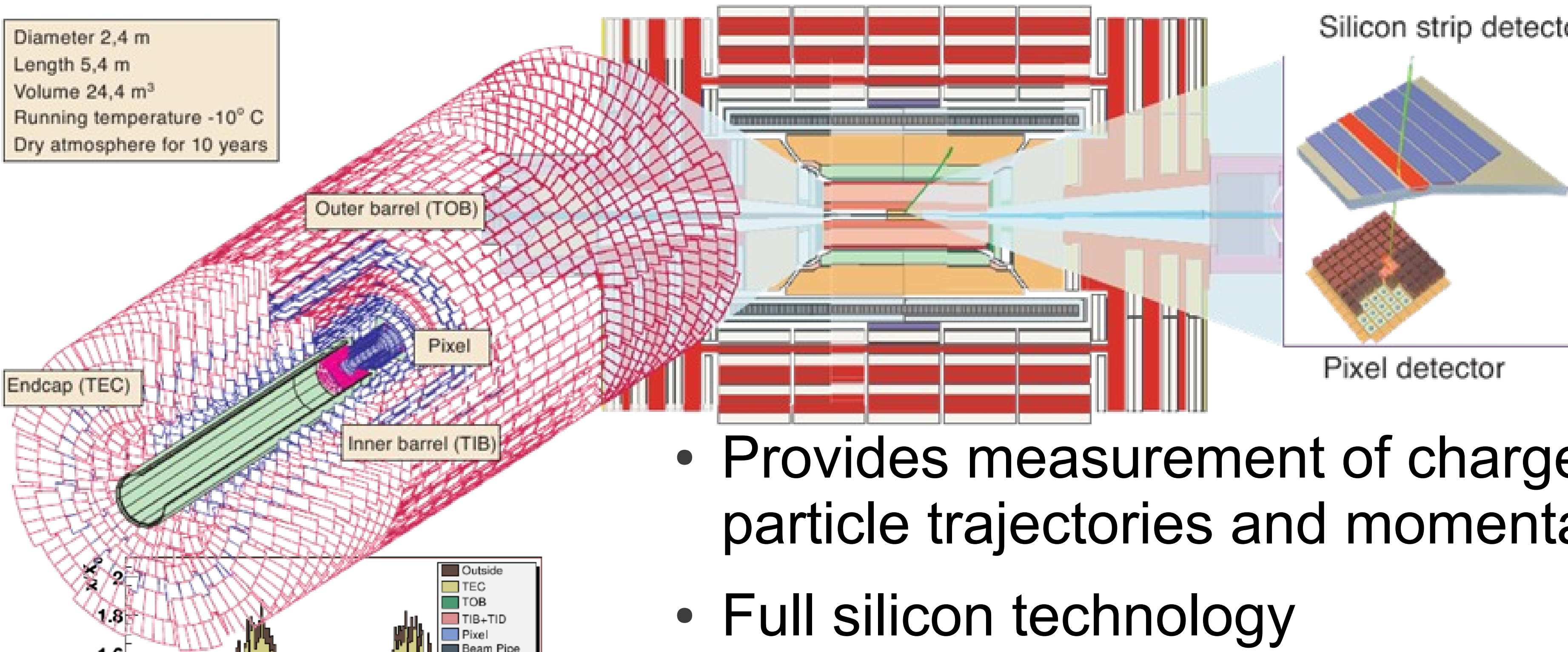
$$\frac{dp}{p} \approx \frac{p}{BL^2}$$

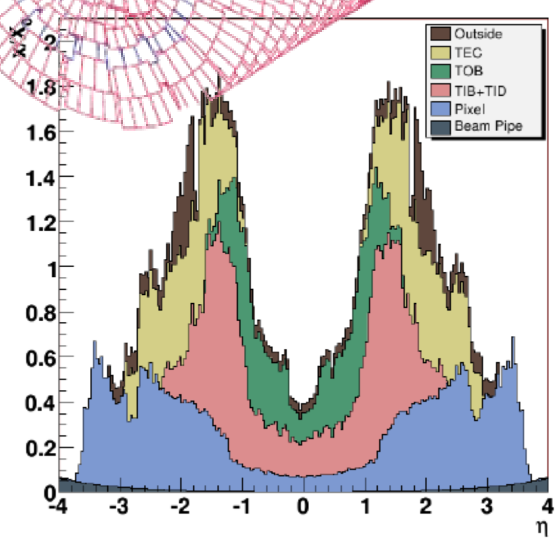
- Optimal momentum resolution for large tracking path and large magnetic field
  - 3.8T magnet in CMS
  - 6.3 meter diameter



- 4 layer winding
- Magnet flux returned by 10000 ton iron yoke

Tracker



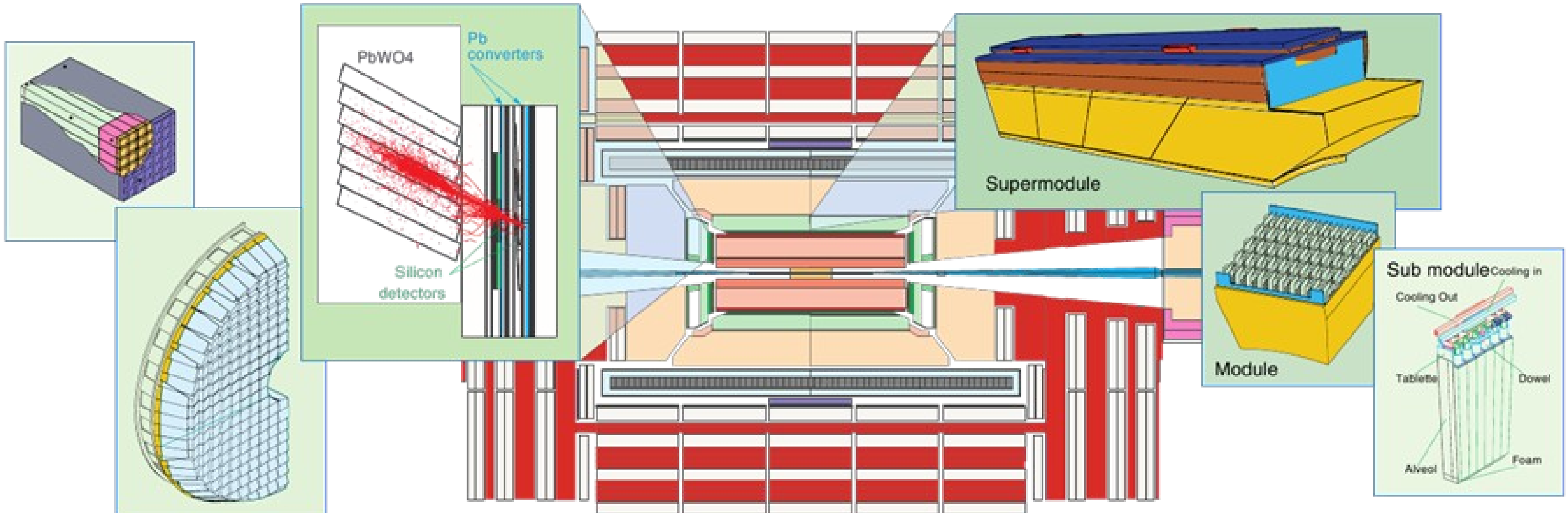


- Provides measurement of charged particle trajectories and momenta
- Full silicon technology
  - Pixel detector near interaction point
    - Highest occupancy
  - Silicon strip outside
    - (barrel and endcap) covering η<2.5
- **Resolution**

$$\frac{dp_T}{p_T} = \left(\frac{p_T}{\mathrm{TeV}} 15\%\right) \oplus 0.5\%$$

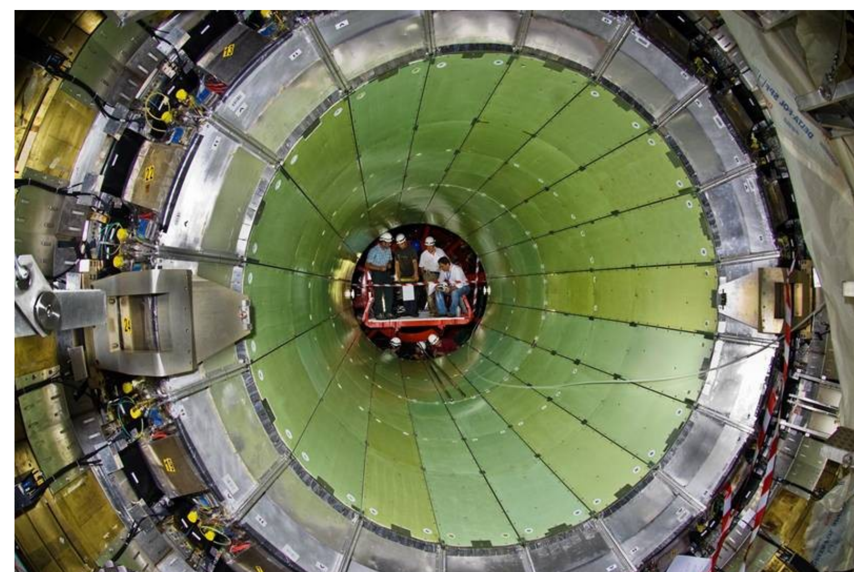
- Large size + full silicon technology result in large material budget

Electromagnetic Calorimeter

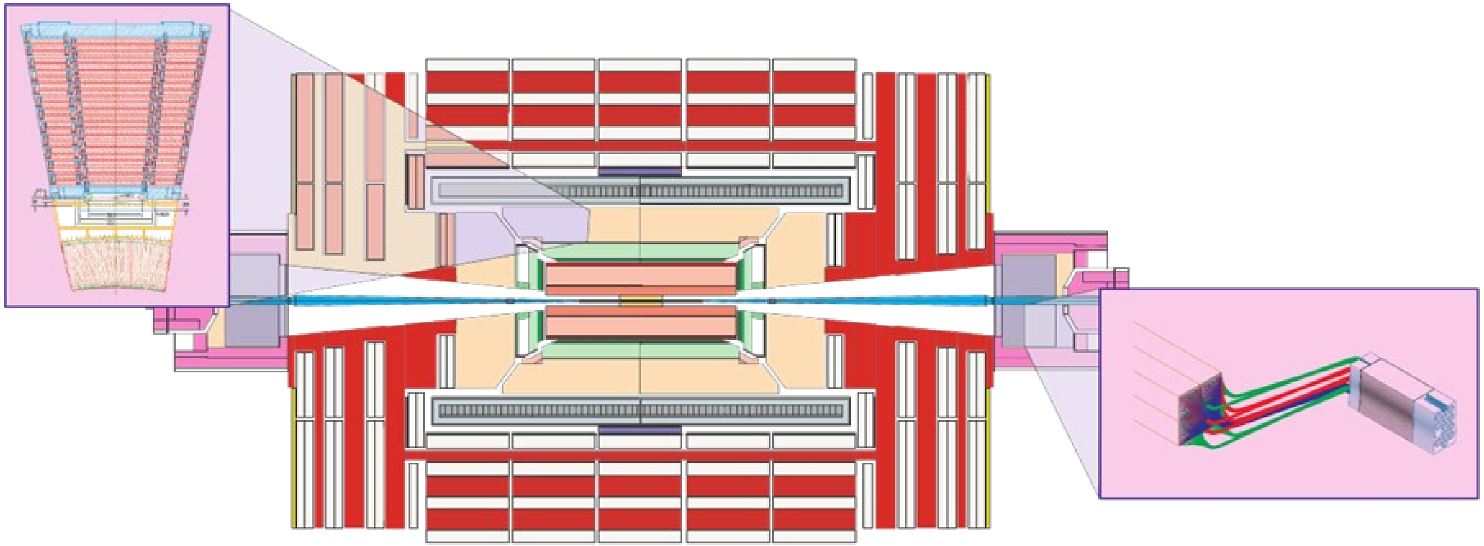


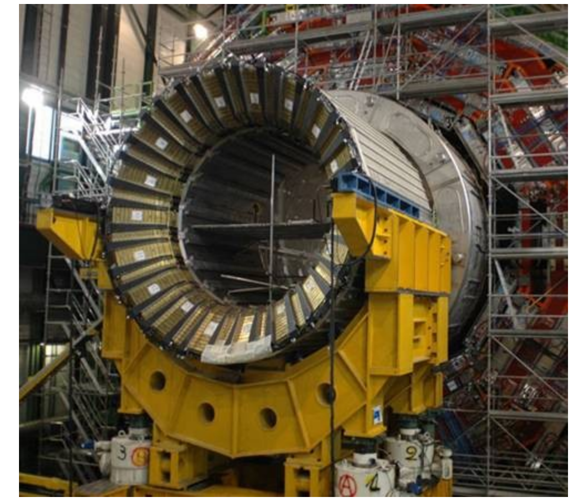
- Crystal Technology
  - Lead Tungstate Crystals(~76000)
    - Radiation Length of 8.9 mm
      - 26 radiation lengths/crystal
    - Moliere radius of 22mm
      - Transverse shower profile within 2x2
    - 80% of the light emitted within 25 ns
- Fine segmentation for position resolution
- Covering up to η<3
- **Resolution:**

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.30\%)^2$$



Hadron Calorimeter





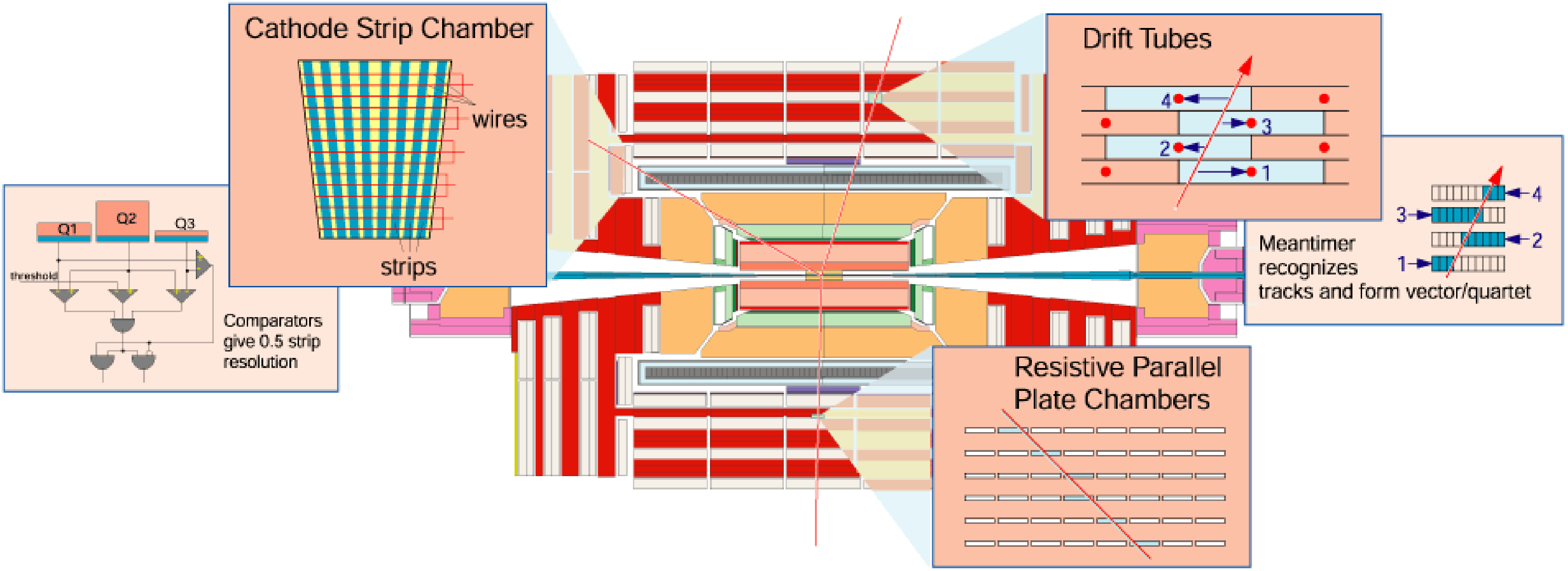
- Barrel and endcap (η<3)
  - Sampling Calorimeter
  - Brass and scintillator plates
    - Light transmitted via fibers to photodetectors
- Resolution

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{90\%}{\sqrt{E}}\right)^2 + (4.5\%)^2$$

- Forward region(3<η<5)
  - Cherenkov based
  - Using quartz fibers within steel plates
    - Light collected by photo multipliers
- Resolution

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{172\%}{\sqrt{E}}\right)^2 + (9\%)^2$$

Muon System



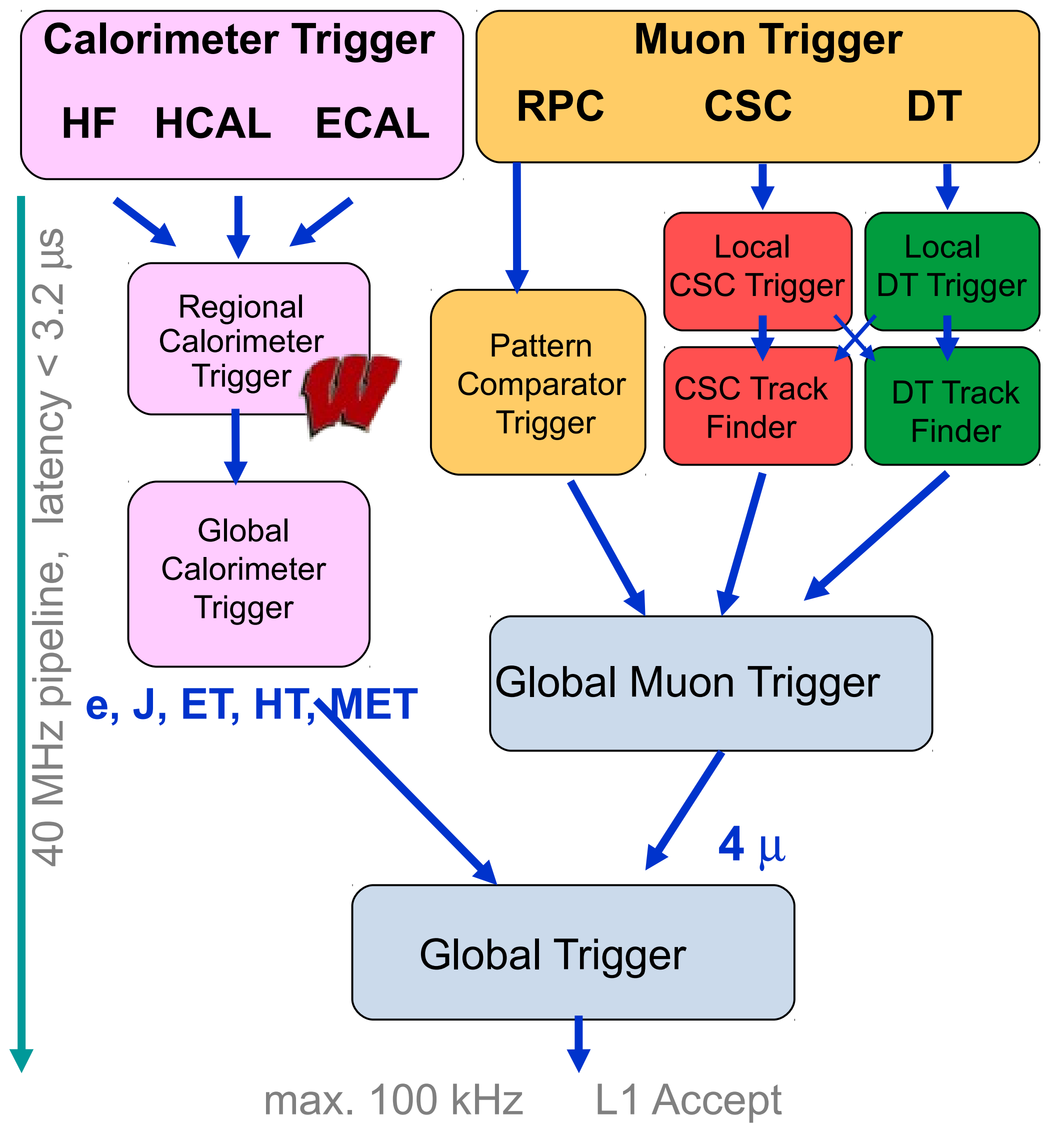
- Provides muon identification and Trigger

- Drift Tube chambers(η<1.2)
  - Tubes filled with gas
  - Anode wire @ 1.8 kV
  - Muon interacts via ionization
  - Slow and precise
- Resistive Plate Chambers(η<1.6)
  - Consists of two gaps filled with gas between readout strips
  - Very fast-Extensive monitoring needed

- Cathode strip chambers(0.9<η<2.4)
  - Consist of a set of wires
    - Running Azimuthially
  - And cathode strips
    - Run lengthwise in constant Δφ
  - Provide fast, precise measurement of both coordinates

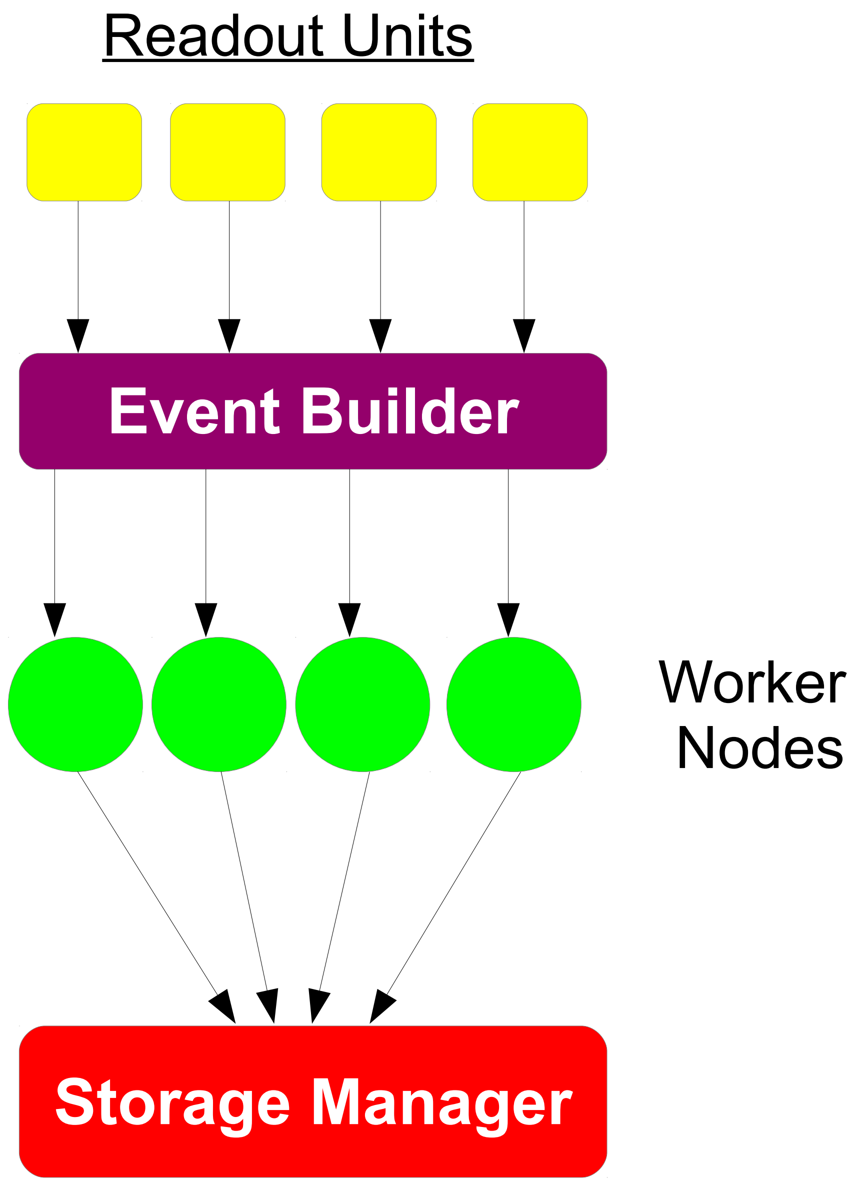
L1 Trigger

- At design conditions LHC provides collisions at 40MHz
  - Average event size 0.5-1 MB
  - Rate must be reduced before storing
- L1 Trigger
  - Made of custom electronics (ASICs + FPGAs)
  - Uses information from calorimeters and muon detectors
  - Implements basic particle ID in firmware and LUTs
  - Forwards all objects to the Global Trigger
  - Global Trigger produces decision if the event is stored
- Output rate ~100kHz



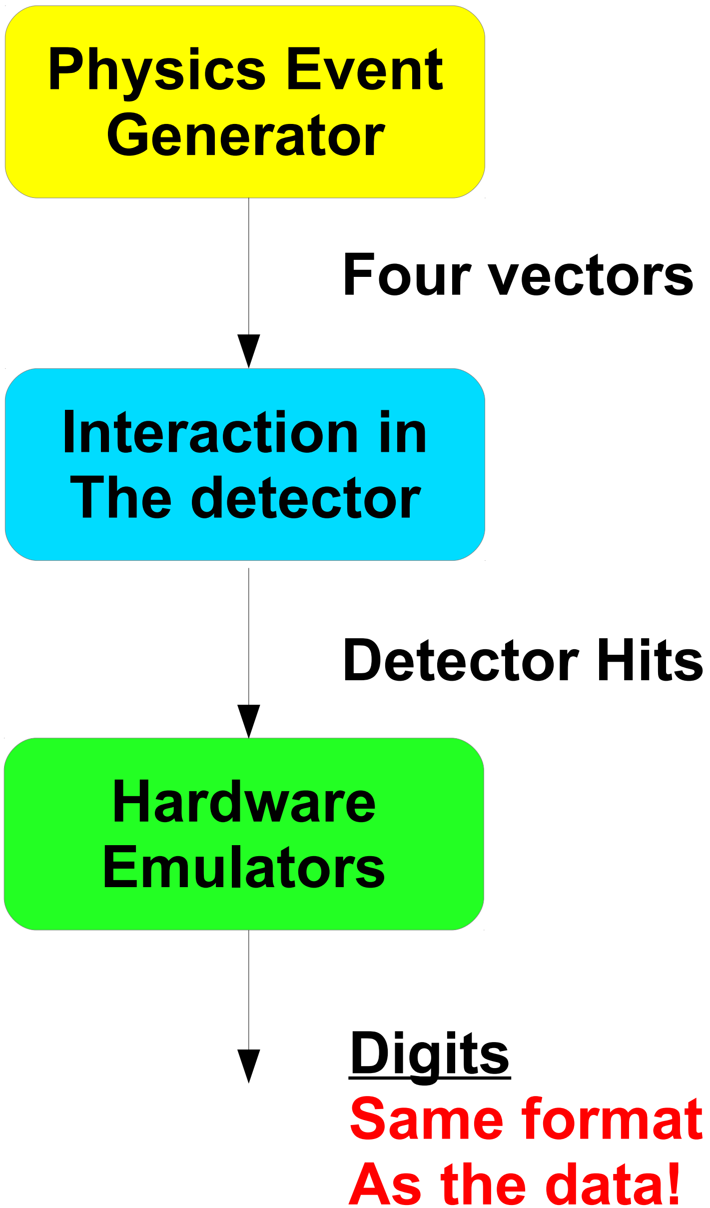
High Level Trigger

- Processes events selected by L1
- Implements more complex algorithms
  - Written in C++, running in commercial processor farm(Scientific Linux)
    - Each working node processes one event
    - Events that pass are stored
  - Algorithms similar or identical to offline reconstruction
- Trigger path implementation optimized for speed
  - Simpler algorithms run first
  - If event passes , complex algorithms run after
- Event rate reduced to ~300 Hz



Event Simulation

- HEP experiments
  - Large and complicated
- Precise simulation
  - Essential for experiment design and validation of experimental techniques
  - Performed using Monte Carlo Methods
- Modular design of simulation
  - Physics Event Generators
  - Simulation of Particles through the detector
  - Hardware emulation



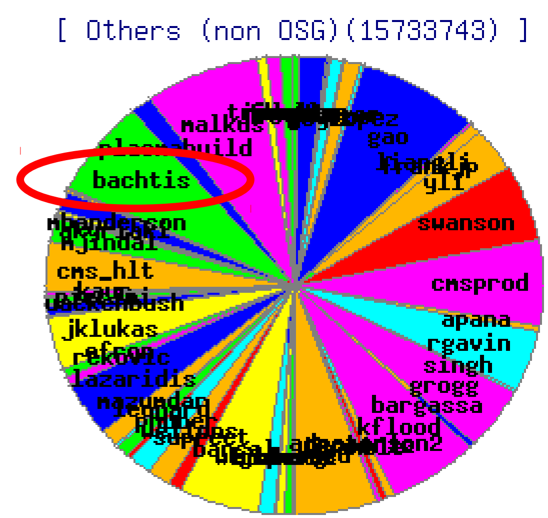
Event Reconstruction+Analysis

Event Reconstruction

- Processes RAW data and creates physics objects
  - Electrons , Muon, Taus , Jets etc
- Runs Centrally in the stored datasets
  - Users usually access the reconstructed data for analysis
- Implemented in CMS SoftWare (CMSSW)
  - Framework for reconstruction and data analysis
    - Implemented in C++/Python
  - Any new reconstruction algorithm is implemented and integrated in CMSSW

Data Analysis

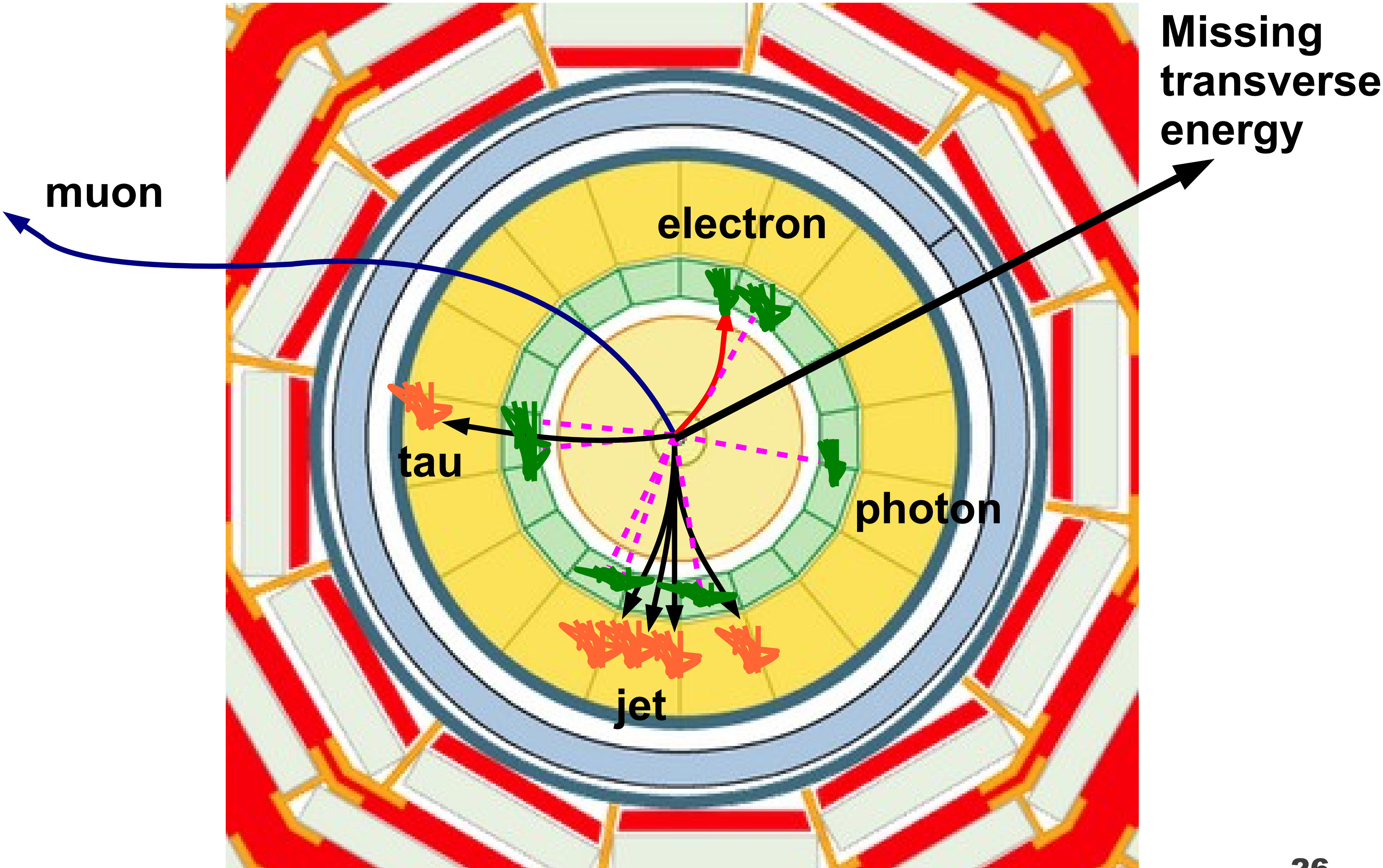
- Custom User code to analyze specific final states
- Implemented in CMSSW
- Running on datasets using the GRID
  - The presented analysis was exclusively processed at Wisconsin T2 /Condor



Analysis Strategy

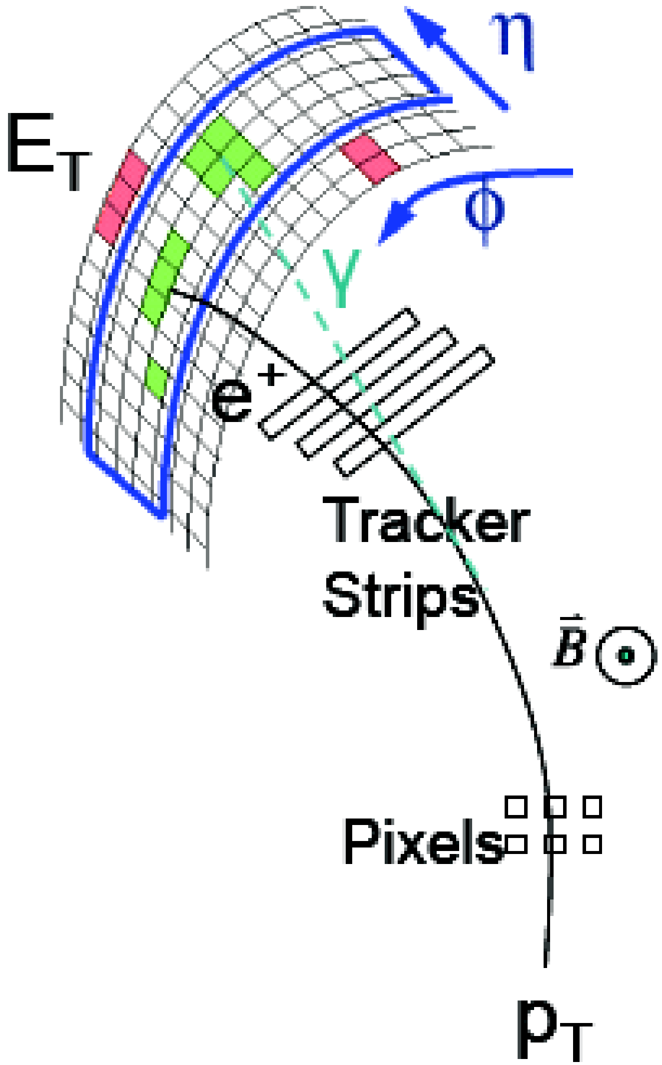
- Select events in the following $\tau\tau$ final states
  - $\tau\tau \rightarrow \mu\tau\ 3\nu$
    - Branching ratio ~23%. Clean final state
  - $\tau\tau \rightarrow e\tau\ 3\nu$
    - Branching ratio ~23%. High background from $Z \rightarrow ee$
    - Electrons have very similar detector signature with taus
  - $\tau\tau \rightarrow e\mu\ 3\nu$
    - Branching ratio ~6%. Almost background free
- Measure Z production cross section
  - Establish performance of tau ID and experimental techniques on data
- Use the sample to search for SM and MSSM Higgs bosons

Principles of Particle Identification



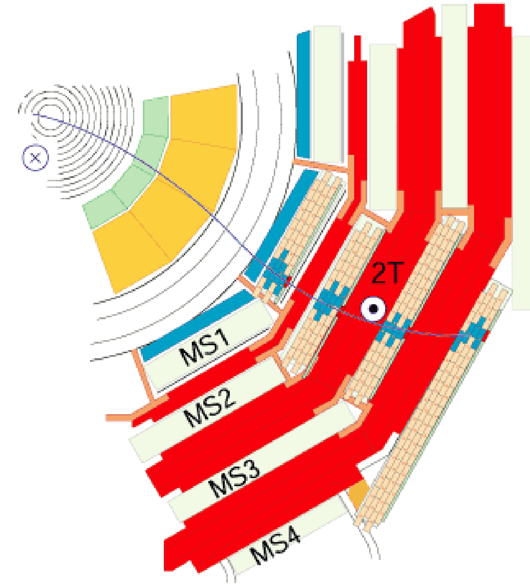
Electron Identification

- Requires a track matched to an electromagnetic deposit
  - Electromagnetic deposit formed as a supercluster
    - Cluster of clusters growing in the bending direction
    - To account for material effects
  - Supercluster must have low hadronic activity
    - H/E<0.05
- Additional rejection of photon conversions

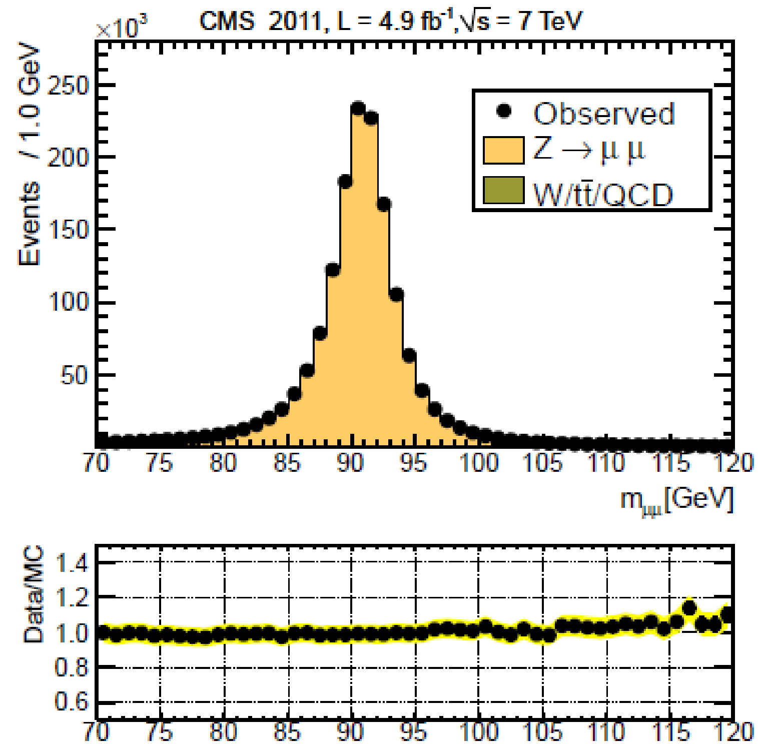


Muon Identification

- Three types of muon reconstruction
  - Standalone muon
    - Track reconstructed in muon system
  - Tracker muon
    - Tracker track extrapolated to match hits in muon system
  - Global Muon
    - Muon track reconstructed both in tracker and muon system
- Requirements
  - Muon identified as tracker and global muon
  - At least one pixel hit,muon hit
  - At least 10 tracker hits
  - At least two segment matches
  - $\chi 2/NDOF<10$



Validation with Z → μμ



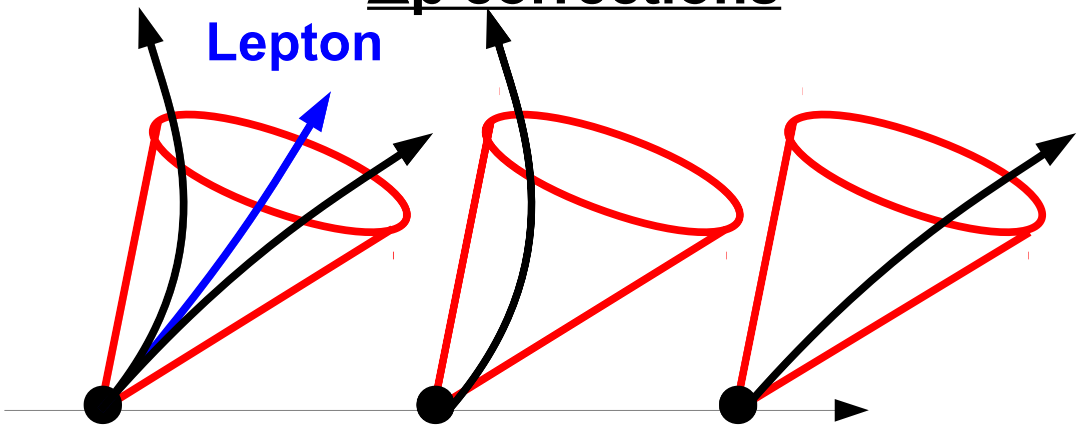
The Particle Flow Algorithm

- Uses information from all sub-detectors
  - Combines tracks with calorimeter deposits
  - Provides unique event description
    - PF candidates (muons, electrons, charged hadrons, neutral hadrons, photons)
- PF candidates can be used to form higher level objects
  - Jets , Taus, missing transverse energy, isolation deposits
- PF provides the most precise measurement of the particle energy
  - Charged Hadrons are measured dominantly by the tracker
  - Electrons and photons are measured dominantly by the ECAL
  - Neutral Hadrons are measured with the calorimeters

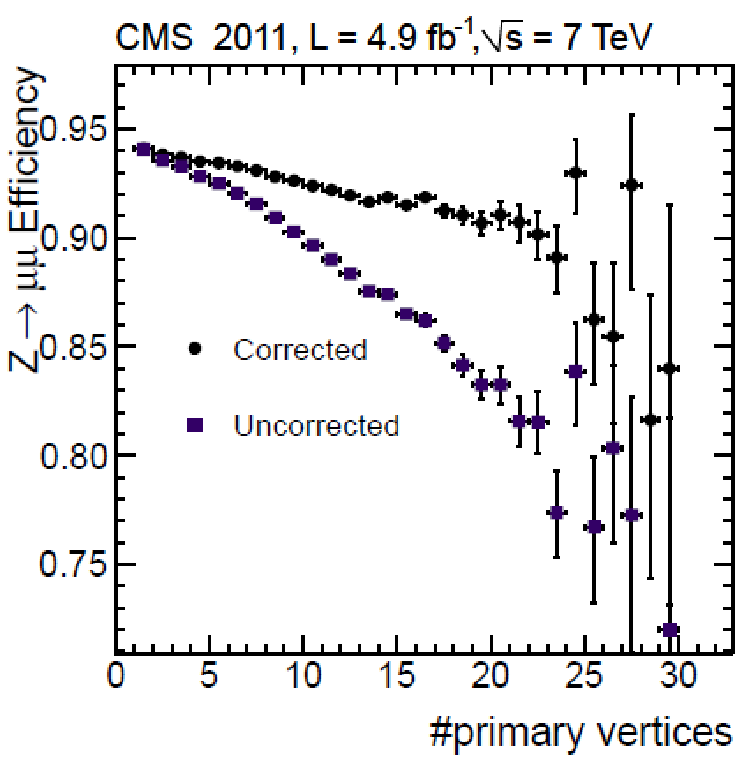
Lepton isolation

- Leptons from tau decays are isolated in the detector
- Leptons from QCD processes are inside jets
- Isolation:
  - Very important discriminator against QCD background
  - Using PF candidates in a cone of ΔR=0.4
  - Defined as sum of the candidate Pt divided by the lepton Pt(relative)
- Corrected for PU effects
  - Charged particles coming from primary vertex
  - Neutral particle deposit corrected by Δβ corrections

Δβ corrections



Predict neutral fraction in original cone via charged fraction from PU



Jet and missing E_T reconstruction

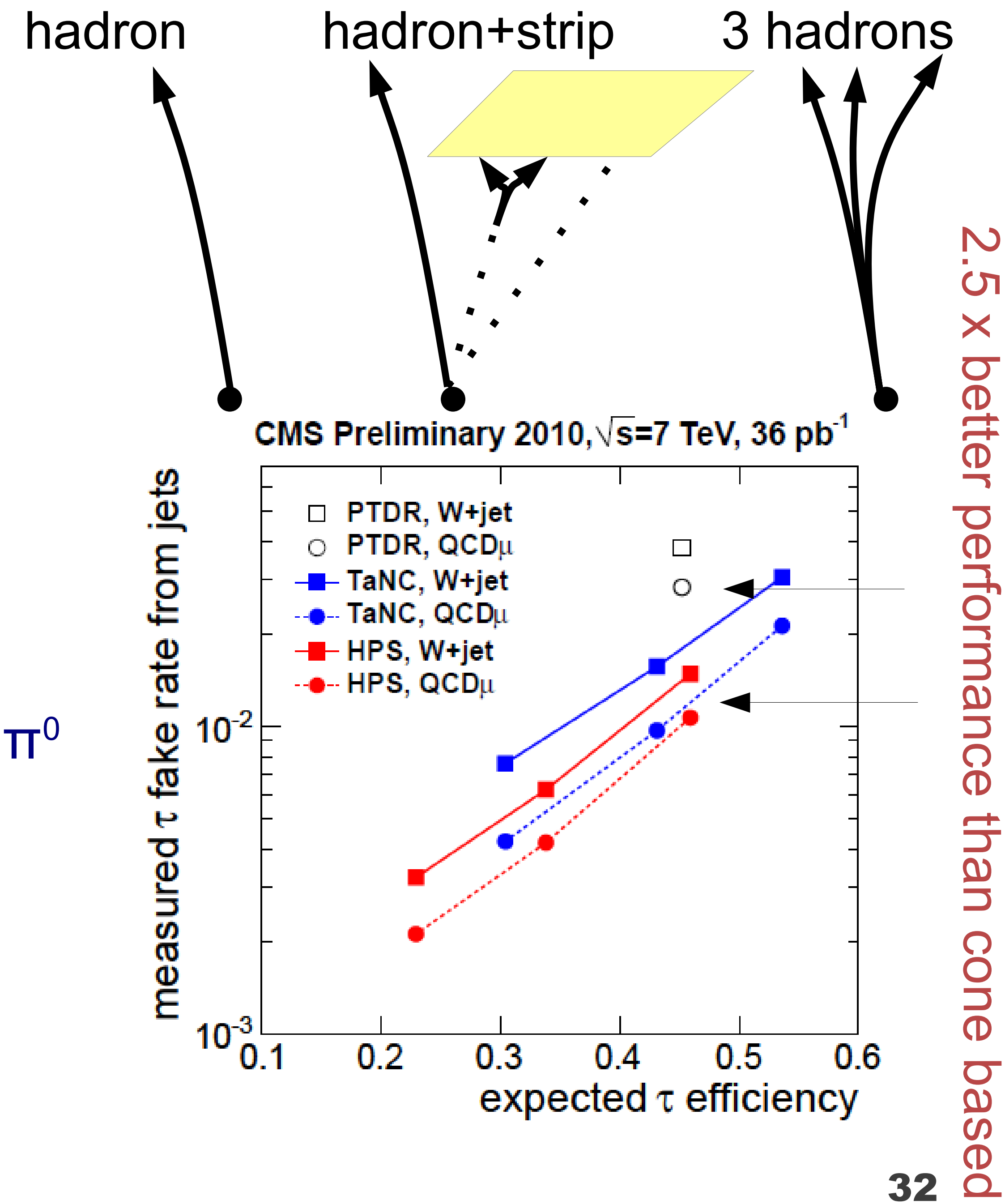
- Jets
  - Particle clusters created using PF candidates
  - Using the anti-kt algorithm
- Full set of energy corrections is applied
  - L1 FastJet:
    - Removes energy coming from PU
  - L2Relative
    - Equalizes the jet response within the detector
  - L3Absolute
    - Equalizes the jet response in different Pt
  - Residual corrections
    - Applied on data to account residual differences with the simulation

- b-jet identification
  - Jets originating by b quarks
    - Several B hadrons
    - Have long lifetime
    - Exploit the displacement of the tracks from the vertex
- Missing transverse energy
  - Neutrinos cannot be detected
  - The overall invisible energy is estimated in the transverse direction
    - Balancing visible products
    - Using Particle Flow

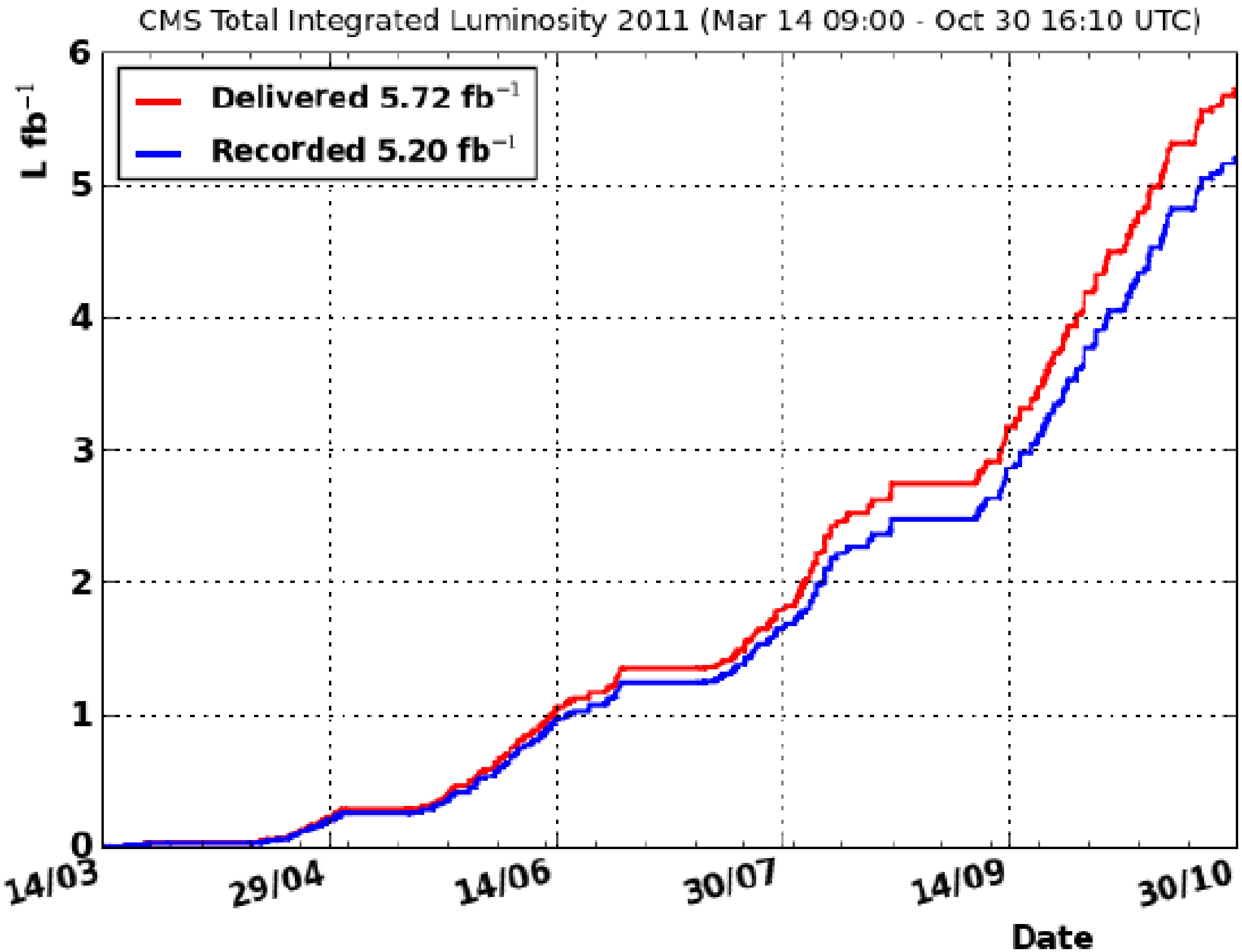
$$E_T^{\text{miss}} = \sum_i \vec{E}_T$$

Hadronic Tau Identification

- Traditional Tau ID
  - Cone based
  - Requires Narrow jet
- The HPS Algorithm
  - Reconstructs the individual decay modes
    - One charged hadron
    - One charged hadron+ 1 π^0
    - Three charged hadrons
- Reconstruction of π^0s
  - Challenging due to material effects
  - Introduce an EM strip



Data sample



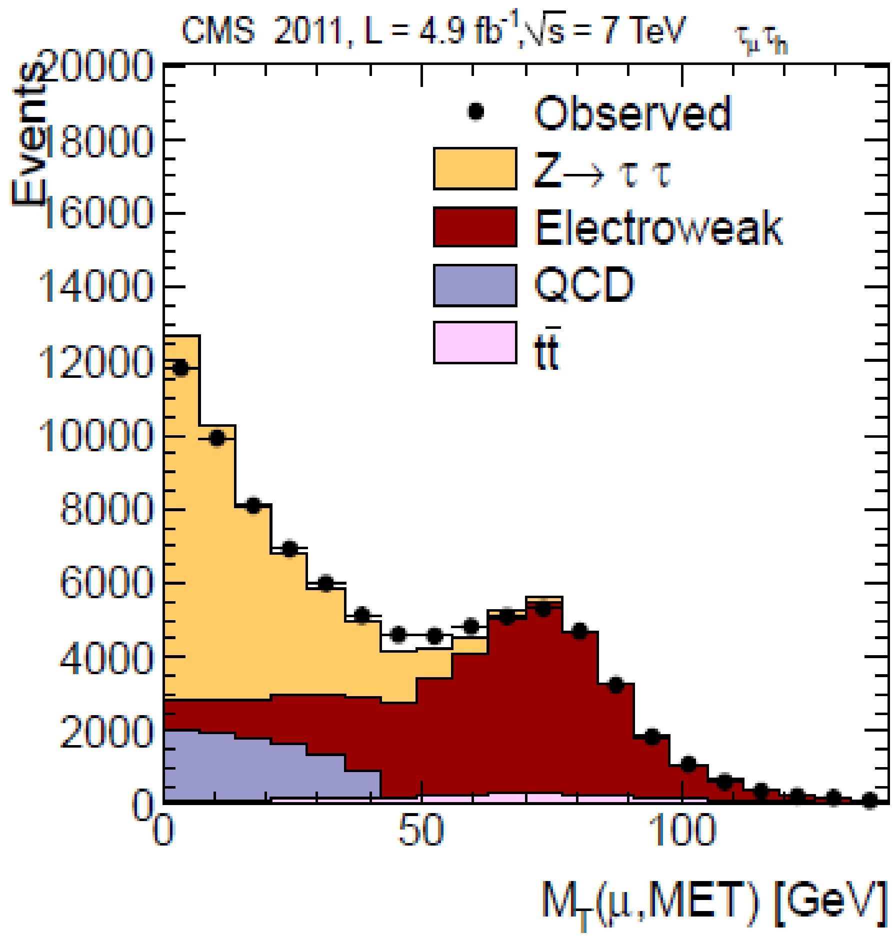
- After data certification, 4.9fb^{-1} of data were used for analysis

Selection of tau pairs

- Muon+Tau
  - muon+tau trigger
  - muon Pt>17 GeV, η<2.1
  - tau Pt>20 GeV, η<2.3
- Electron+Tau
  - electron+tau trigger
  - electron Pt>20 GeV, η<2.1
  - tau Pt>20 GeV, η<2.3
- Electron+Muon
  - electron+muon trigger(17/8)
  - Leading Lepton Pt>20
  - Sub-leading Lepton Pt>10
  - Muon η<2.1 ,Electron η<2.3
- All final states
  - Opposite charge
  - Veto on Z/γ* → μμ/ee

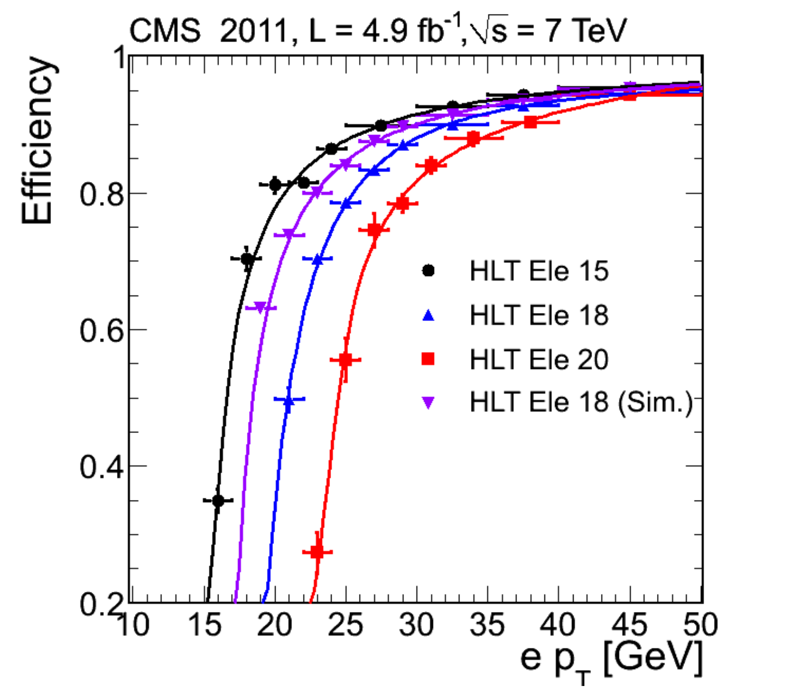
Veto W+jets events using
The transverse mass

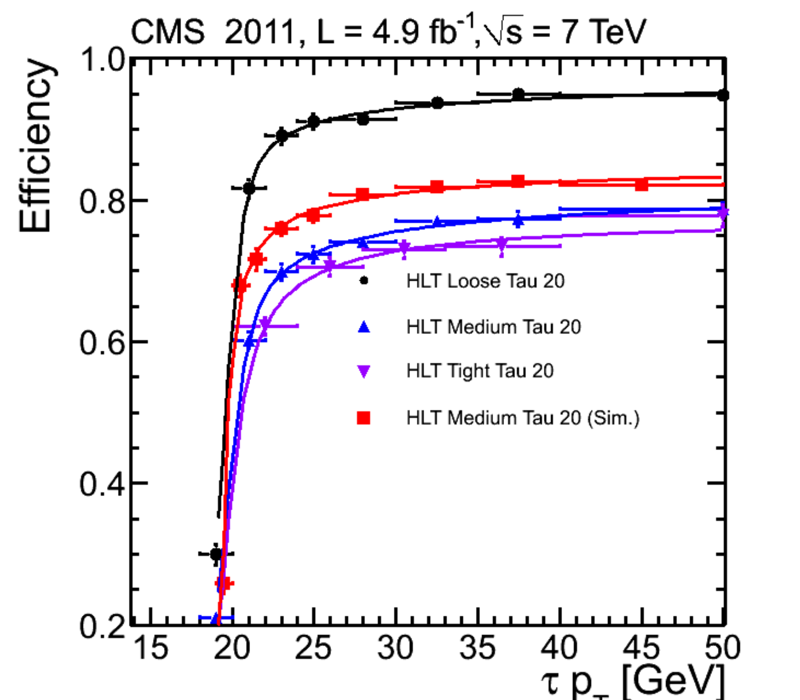
$$M_T = \sqrt{2 P_T E_T^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$



Corrections to the Simulation

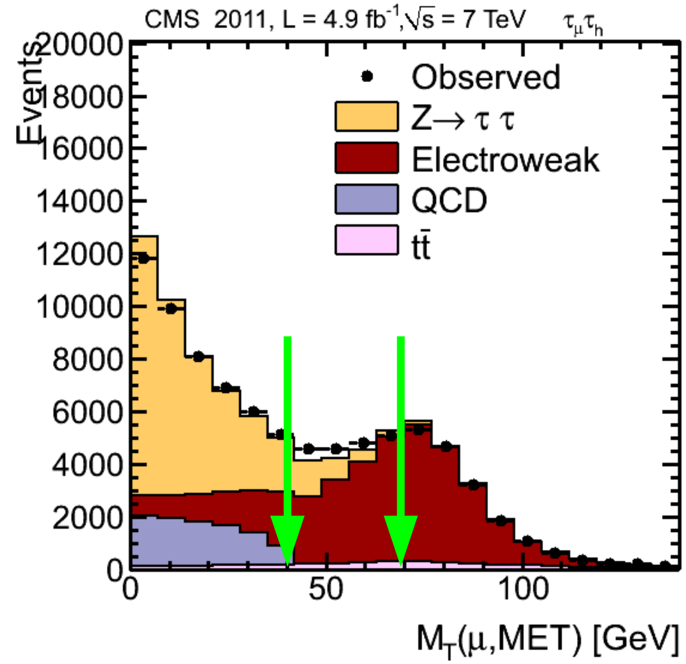
- Light Lepton Trigger /ID
  - Using Z → μμ/ee events
- Tau ID
  - Independent measurement of Z → ττ events (uncertainty. 6%)
- Tau Trigger
  - With Z → ττ that fire lepton triggers
- Missing Transverse Energy
  - Calibrated with Z → μμ data





Background Estimation

- In e/μ+τ final states
  - W extrapolated from high MT region
  - QCD estimated from SS events
    - After subtracting W and Electroweak/tt backgrounds

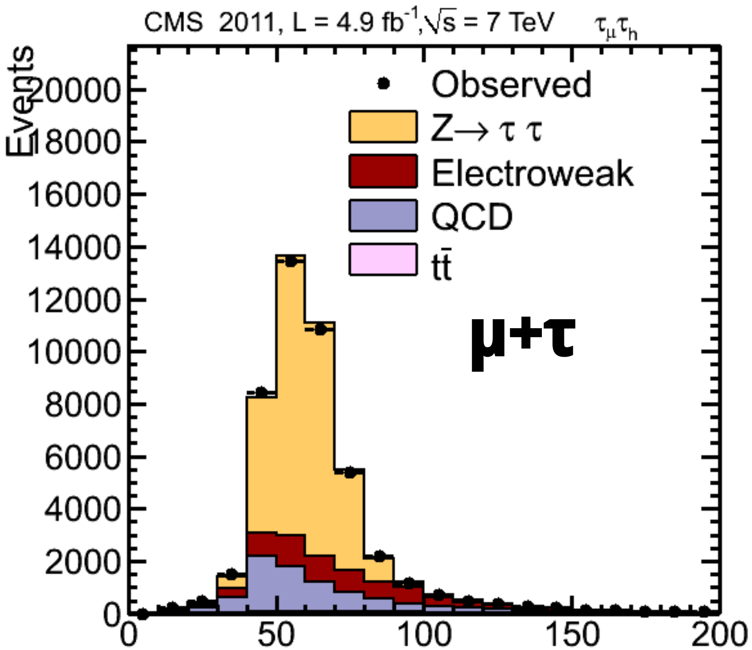


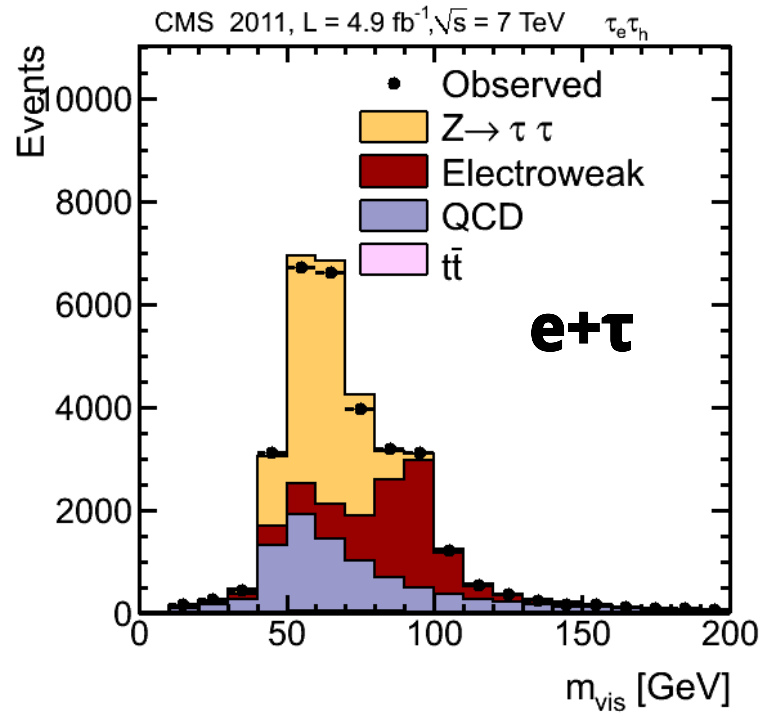
- In e+μ final state
  - Measuring an extrapolation ratio from non-isolated to isolated leptons in SS region
  - Apply it in OS region

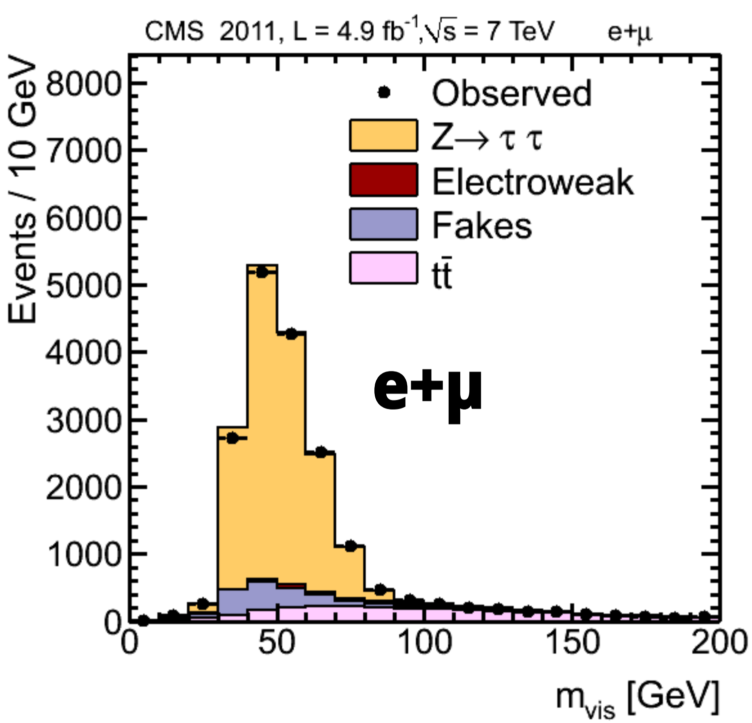
B OS Both Legs Anti-Isolated	**C** SS Both Legs Anti-Isolated
A OS Both Legs Isolated	**D** SS Both Legs Isolated

	μ+τ	e+τ	e+μ
Exp	46364±2292	31467±1709	18530±797
Obs	46244	30679	18316

Results after full selection







- Good agreement with simulation
  - Within background uncertainties
  - In all final states
- No first sign of new physics
  - Not expected to show up on those distributions

Cross section calculation

Data

Background

$$\sigma = \frac{N - N_b}{\mathcal{BR} \cdot A \cdot \epsilon \cdot L},$$

Luminosity

Branching Ratio
(ττ → final state)

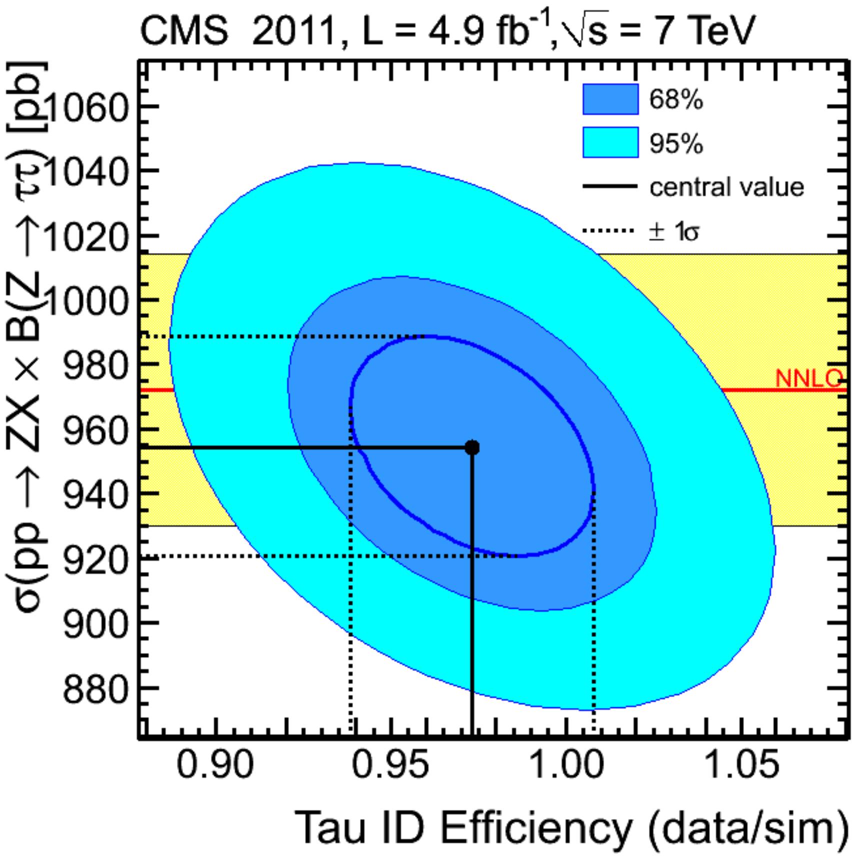
Acceptance x efficiency
=(A xε) from MC x corr.factors

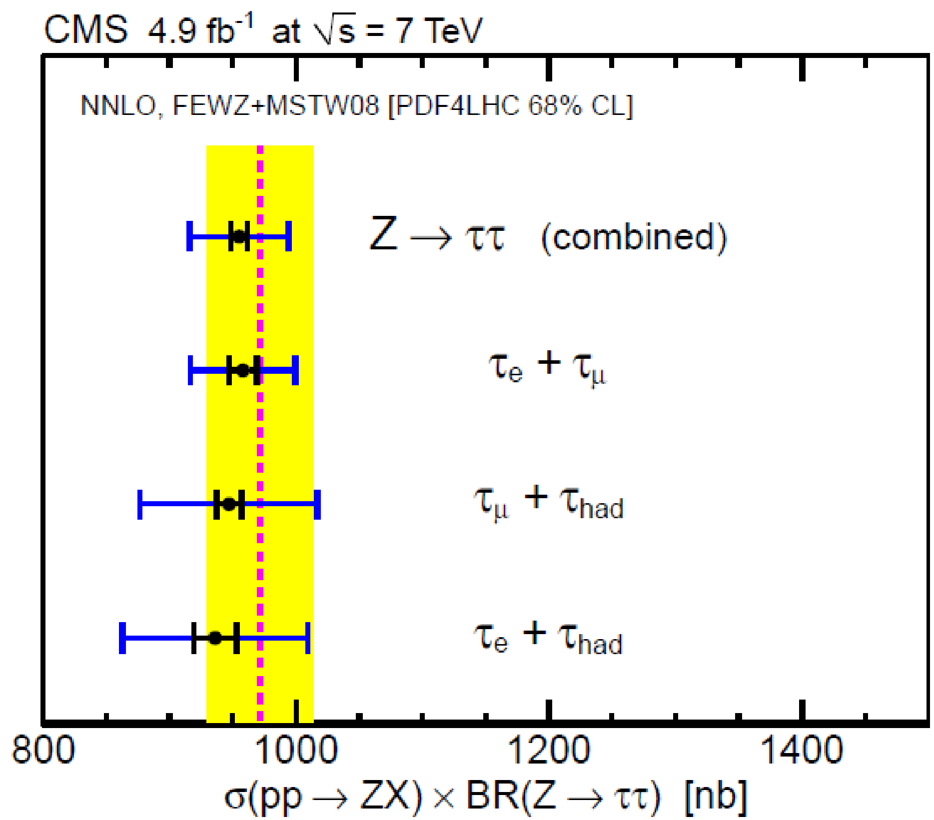
$$\bar{A} = A \times \epsilon_{MC} \times \prod_i \rho_i$$

Systematic uncertainties

Source	μ+τ	e+τ	e+μ
Muon ID/Trigger	1%	-	2%
Electron ID/Trigger	-	1%	2%
Tau ID	6%	6%	-
Tau Trigger	3.3%	3.3%	-
Tau energy Scale	3%	3%	-
Topological Requirements	0.5%	0.5%	-
Luminosity	2.2%	2.2%	2.2%
P.D.Fs	2%	2%	2%
NNLO effects	0.5%	0.5%	0.5%

Cross section results

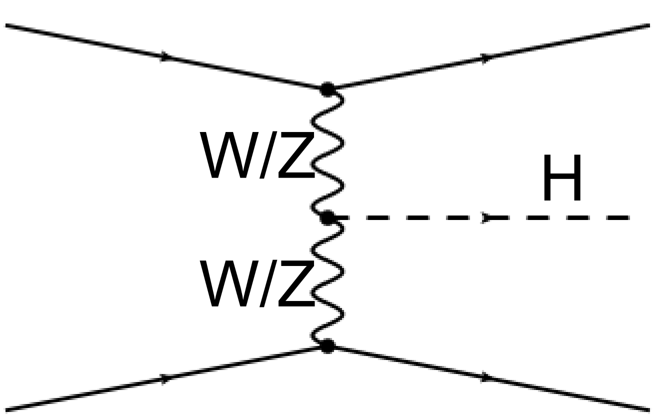


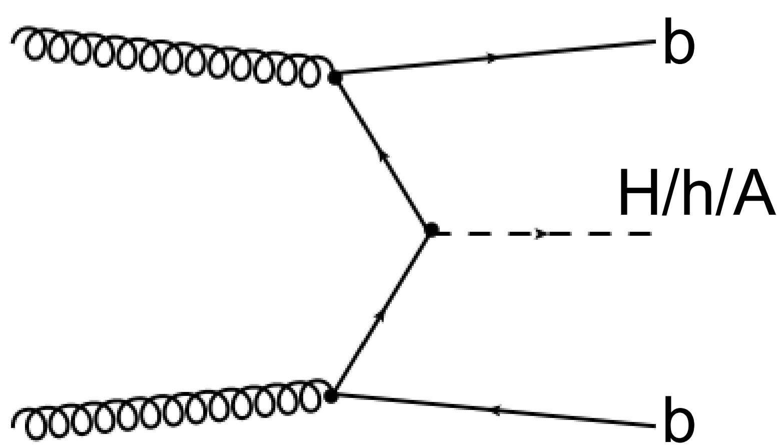


- Shape fit performed on all final states
- All channels in agreement with theoretical prediction
- Combined fit constrains the tau ID to 3%
- Combined cross section:
  - σ= 955 ± 7 (stat) ± 33 (syst) ± 20 (lumi) pb

Search for Higgs bosons

- $Z \to \tau\tau$ cross section doesn't show any excess of events
  - Higgs production overwhelmed by Z background
  - Higgs signal would not be visible in the visible mass distributions
- Better sensitivity can be achieved in specific final states
  - Vector boson fusion for the SM Higgs
  - Associated Production with b-quarks for the MSSM Higgs

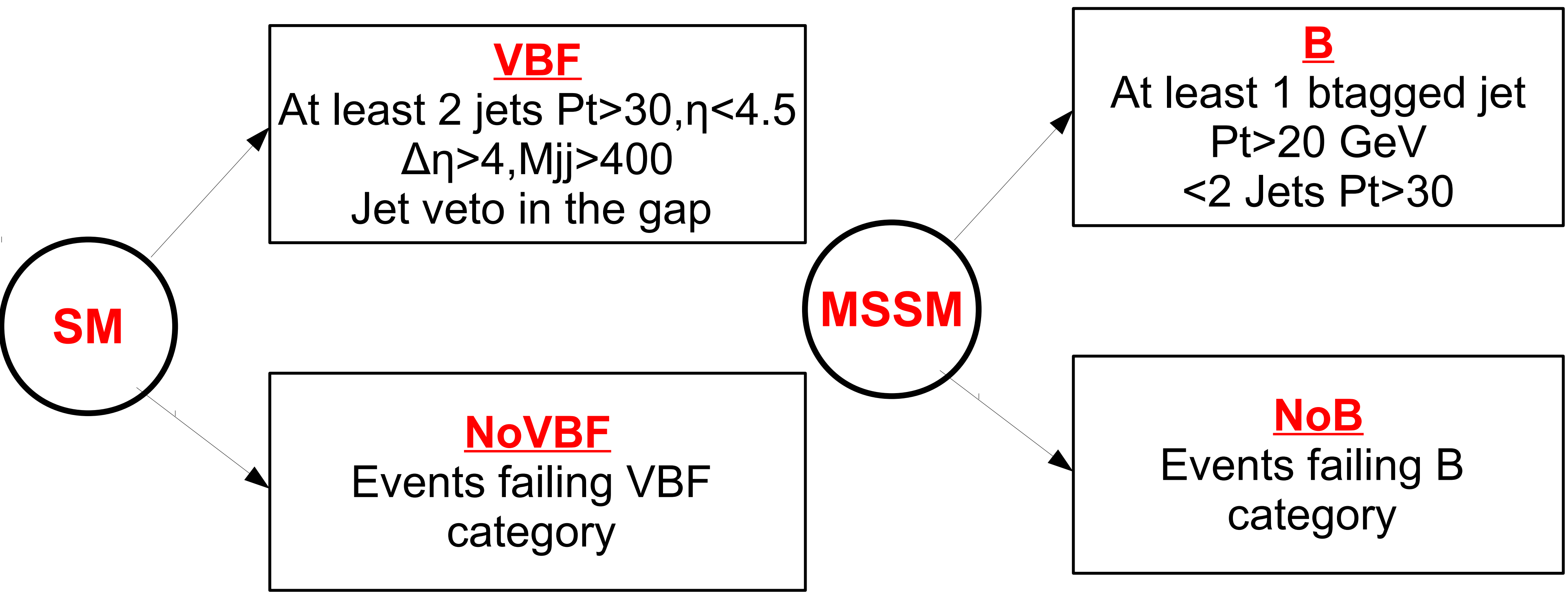




- Distinct VBF forward jet signature and presence of b-tagged jets suppress $Z \to \tau\tau$ background

Event Categorization

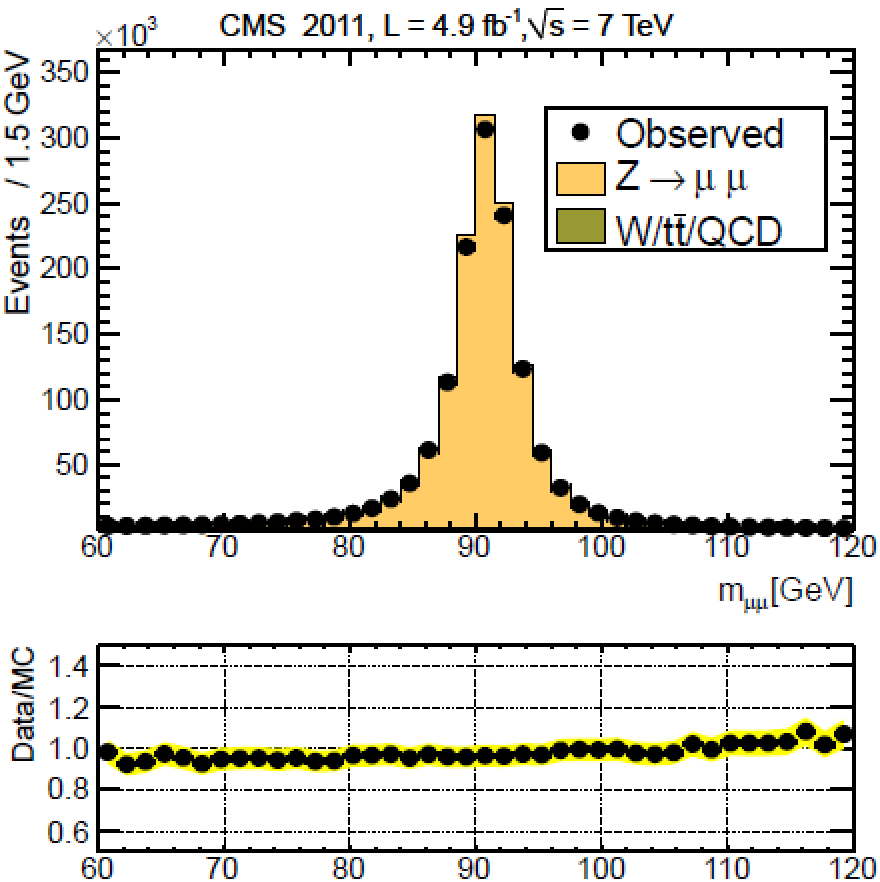
- Separate events into event classes with different expected sensitivity
  - Combine different categories as separate final states
  - All the events are used in the search



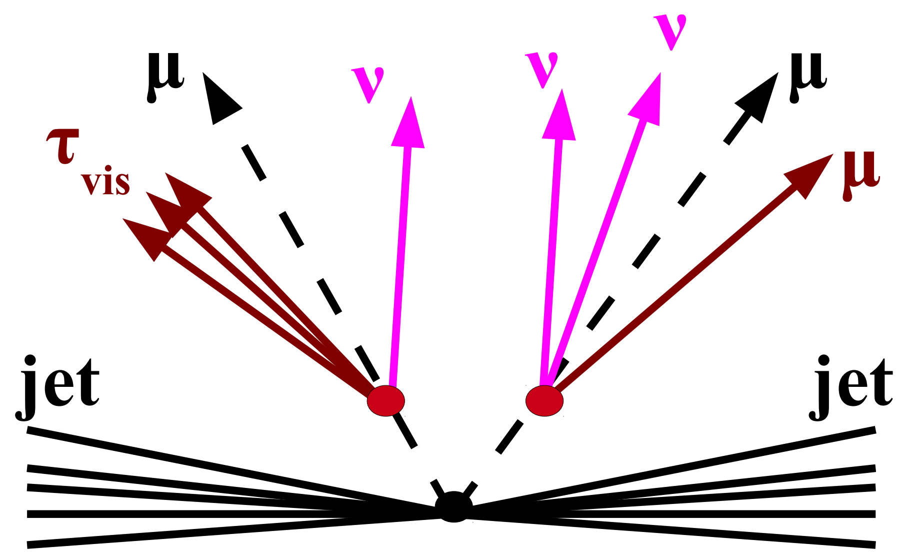
$Z \rightarrow \tau\tau$ Background Estimation

Z normalization

- Scaled based on the number of $Z \rightarrow \mu\mu$ observed events
- MC scaling factor = 0.99 +-0.03

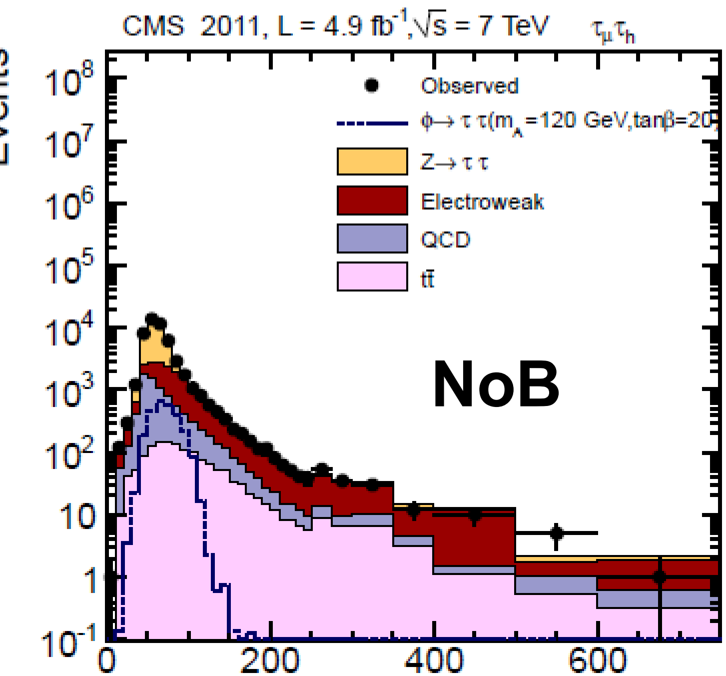


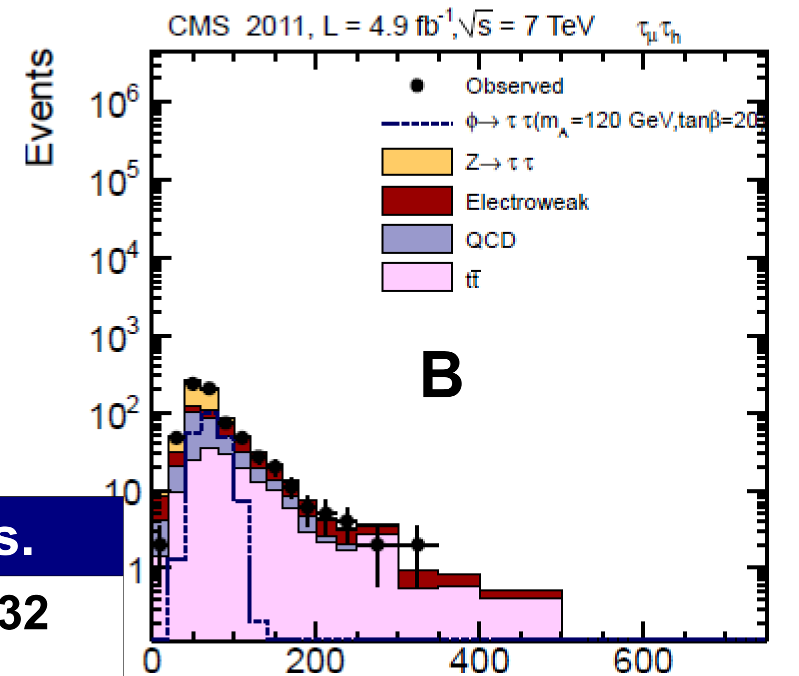
Embedding Technique



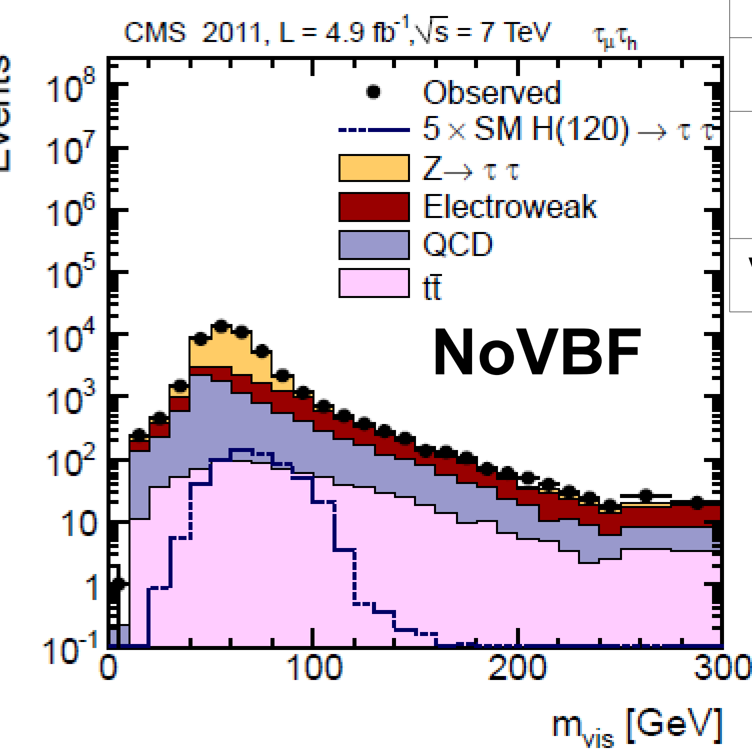
- Reconstruct $Z \rightarrow \mu\mu$ events in data
- Replace μ with decay the event
- Mix the simulated tau pair event with the initial events without the muon
- PU/UE and jets from data!

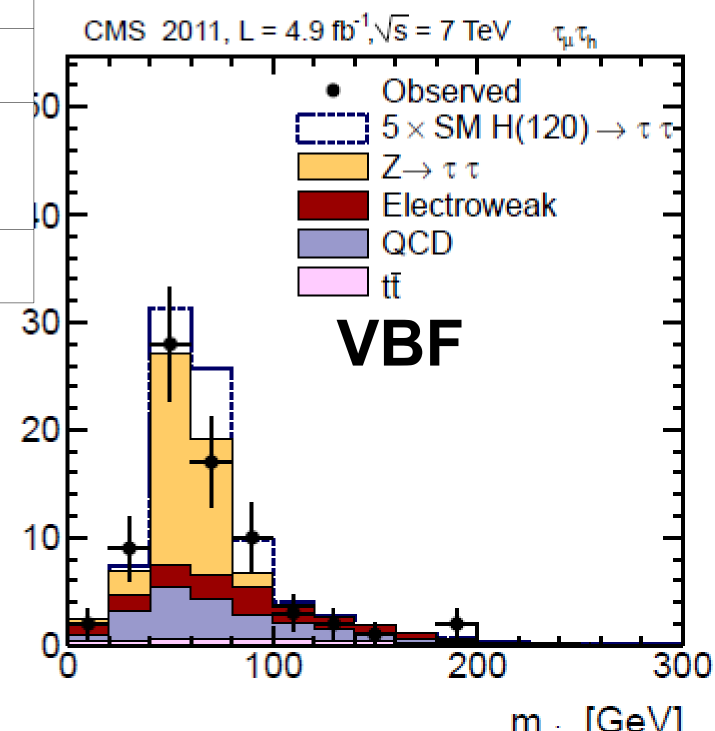
Muon+Tau



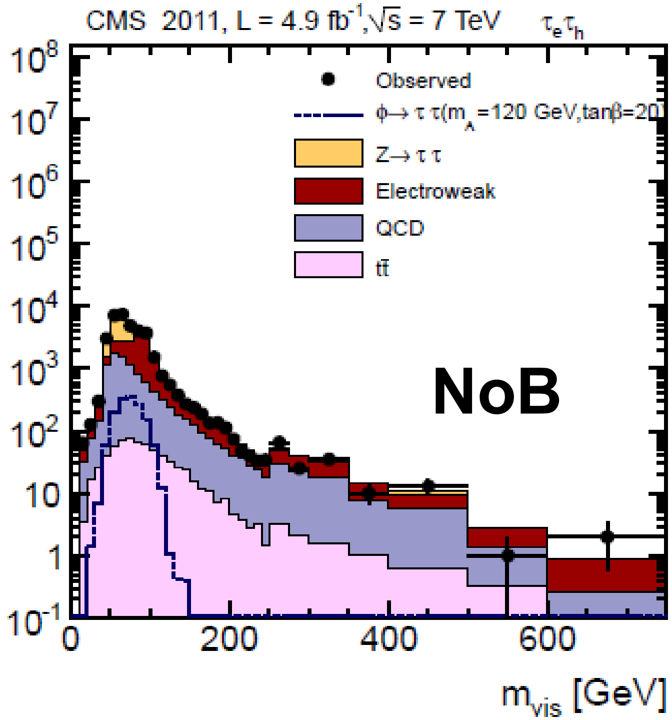


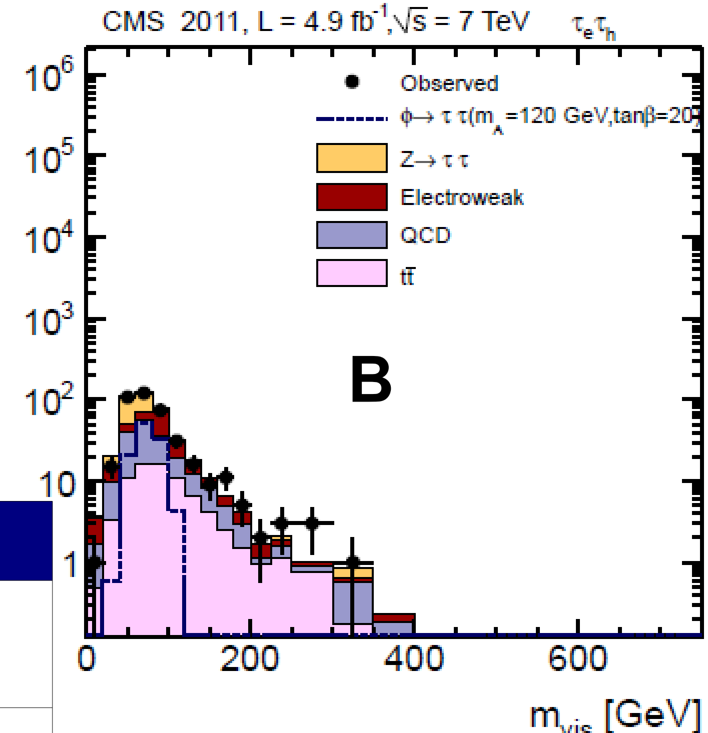
	Exp.	Obs.
NoB	50565± 2603	50532
B	730±42	681
NVBF	46311 ± 2493	46389
VBF	73±7	74



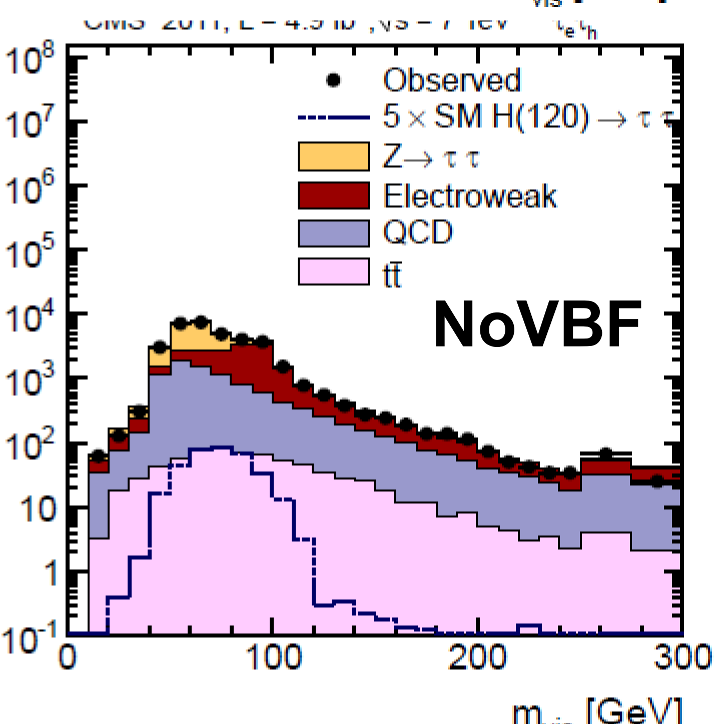


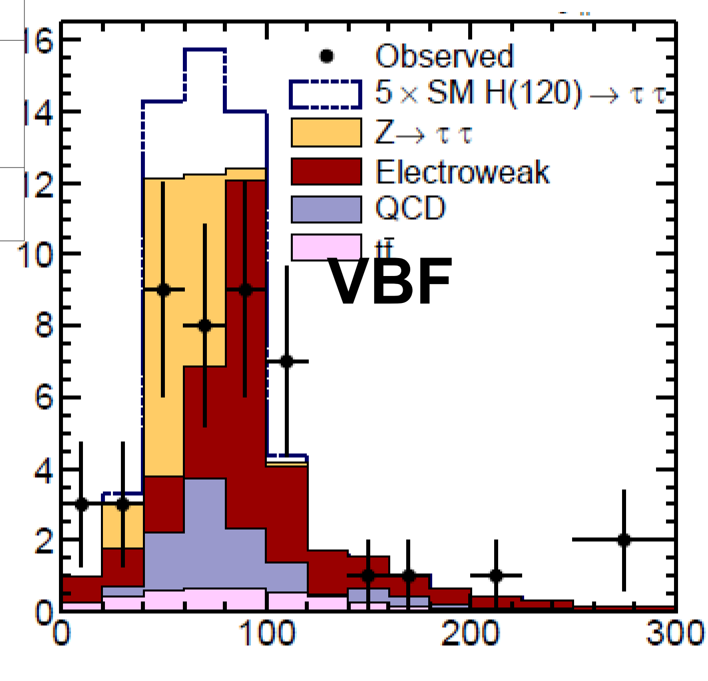
Electron+Tau



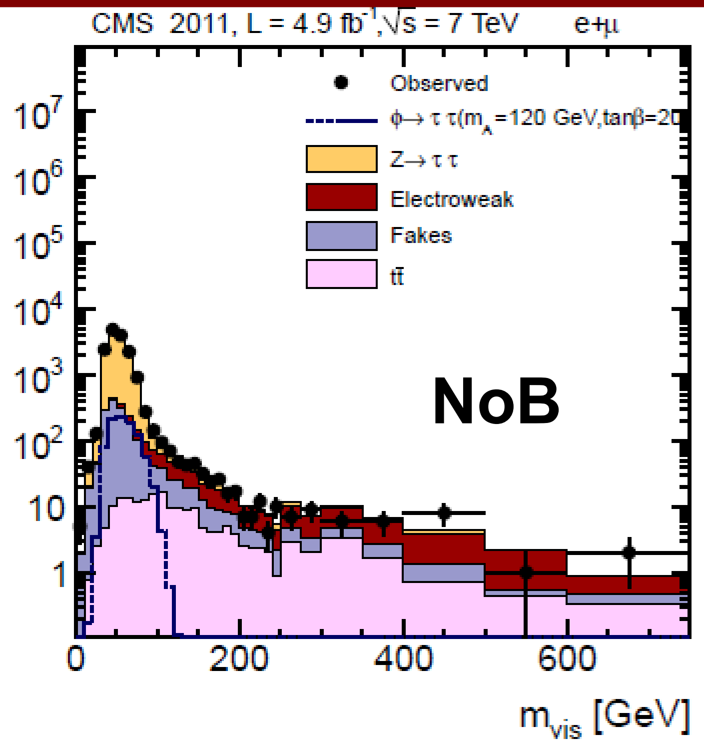


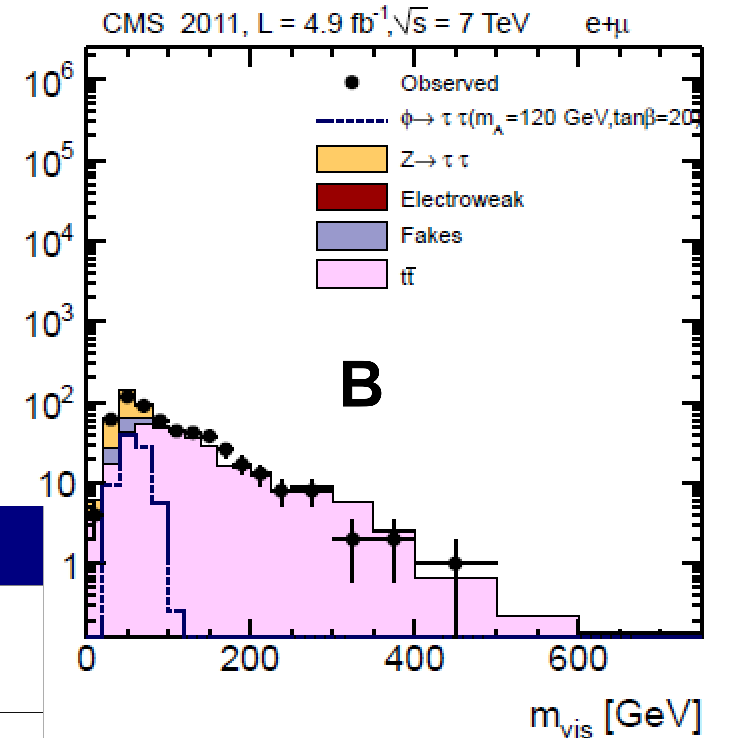
	Exp.	Obs.
NoB	35939± 1829	35189
B	415±28	398
NVBF	36221 ± 1842	35479
VBF	51±6	44



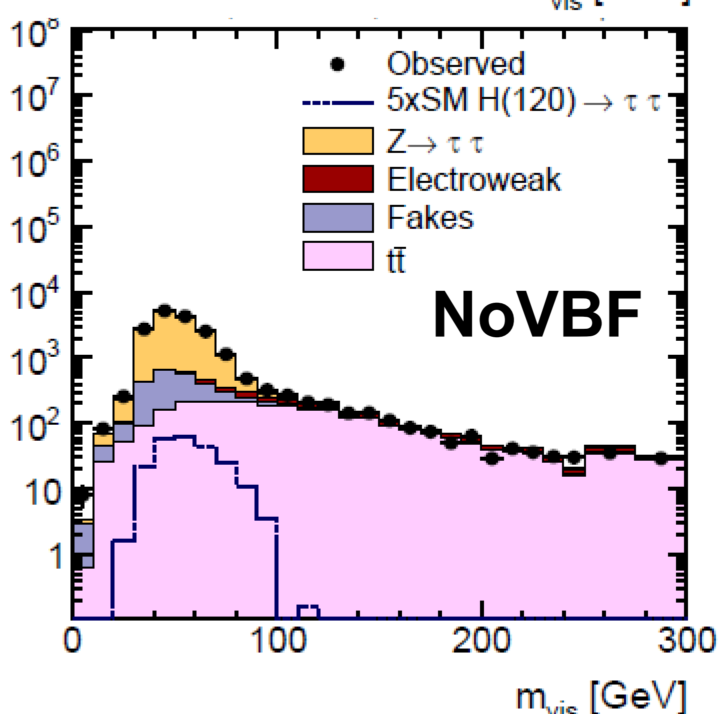


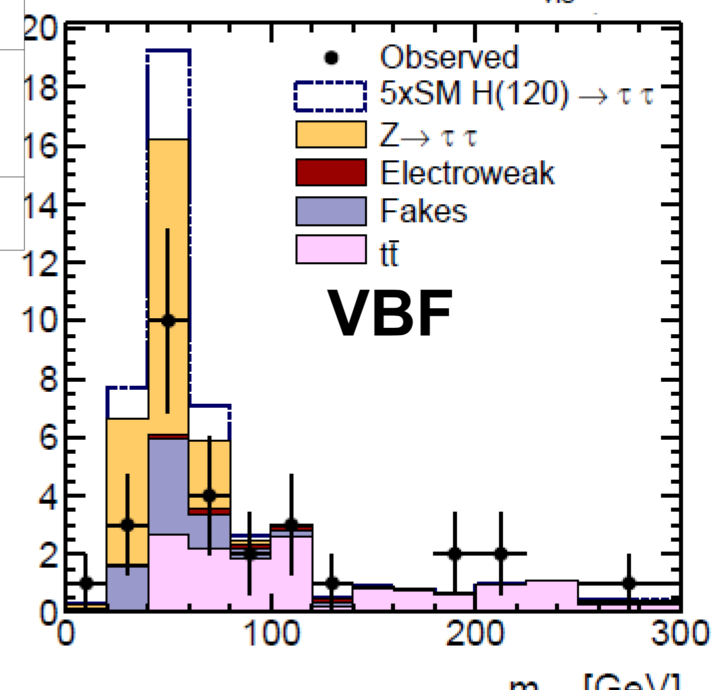
Electron+Muon





	Exp.	Obs.
NoB	18797± 798	18092
B	564±49	519
NVBF	18646 ± 659	18521
VBF	40±3	29

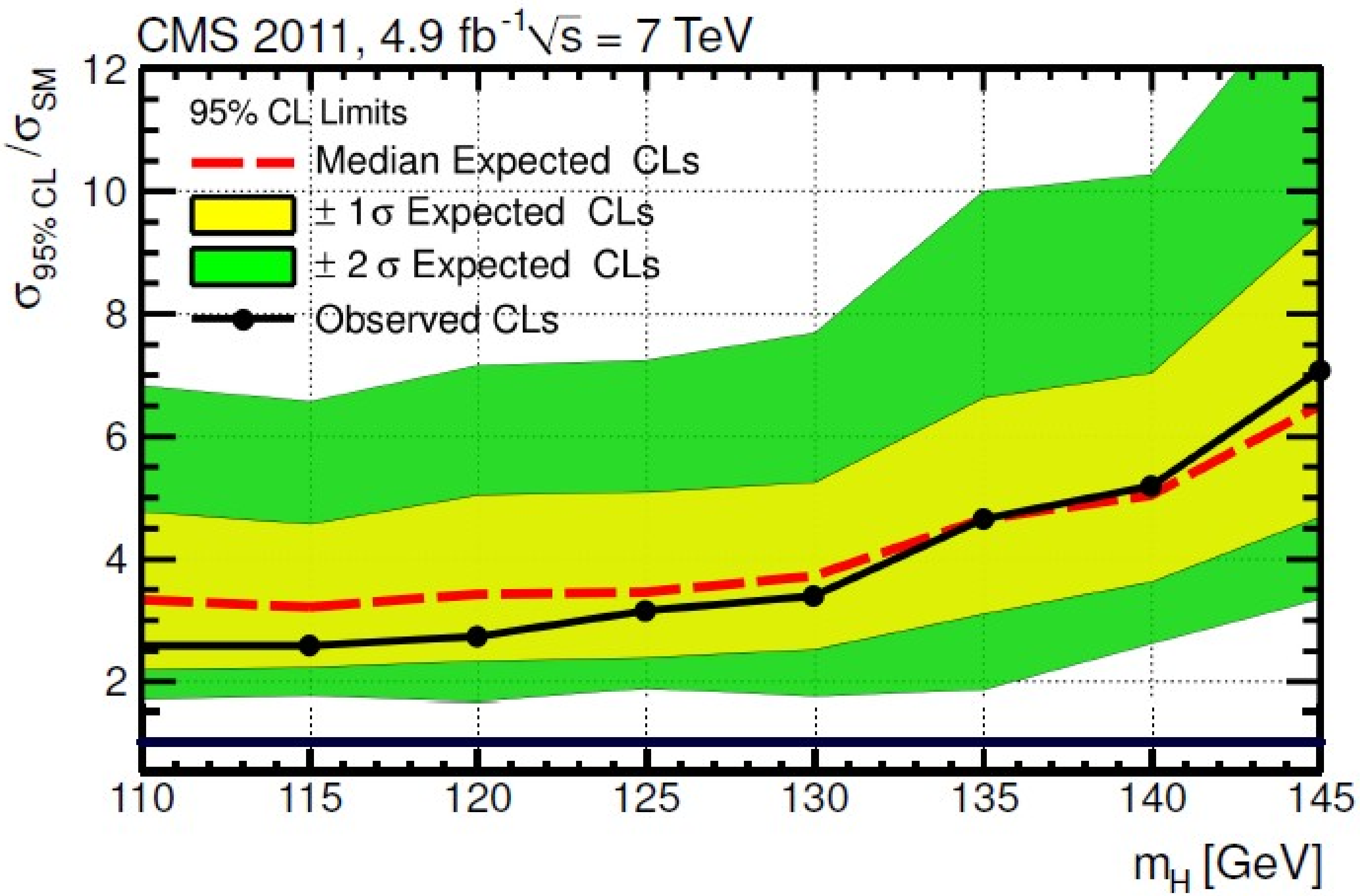




Statistical Analysis

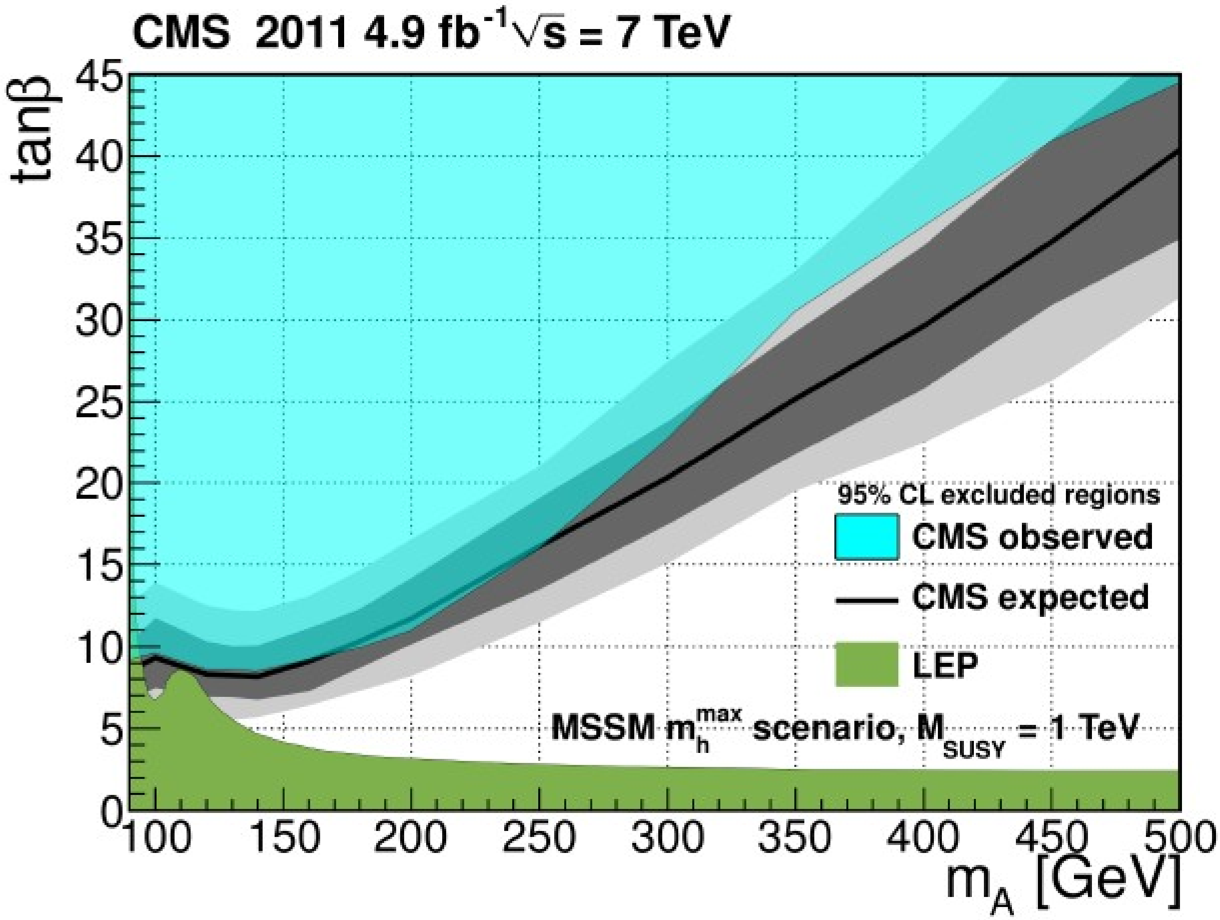
- No significant excess is observed in any final states in the SM or the MSSM Higgs searc
- 95% CL Upper limits are set
  - In the SM Higgs production cross section
  - In the MSSM parameter space (m_A,tanβ)
- Using modified frequentist approach (CLs)

Upper Limits on SM Higgs



- Expected To exclude ~3.5xSM at M_H between 110-130 GeV
- Observed exclusion 2.56 x SM at M_H=115 GeV
- Need more data to derive conclusions

Upper Limits in the MSSM



- Excluding tanβ <8 at low MA
  - Observed in agreement with expected at low MA
  - Small excess of events at high mass
    - Local significance = 1.5 standard deviations at M_A=350 tanβ=20

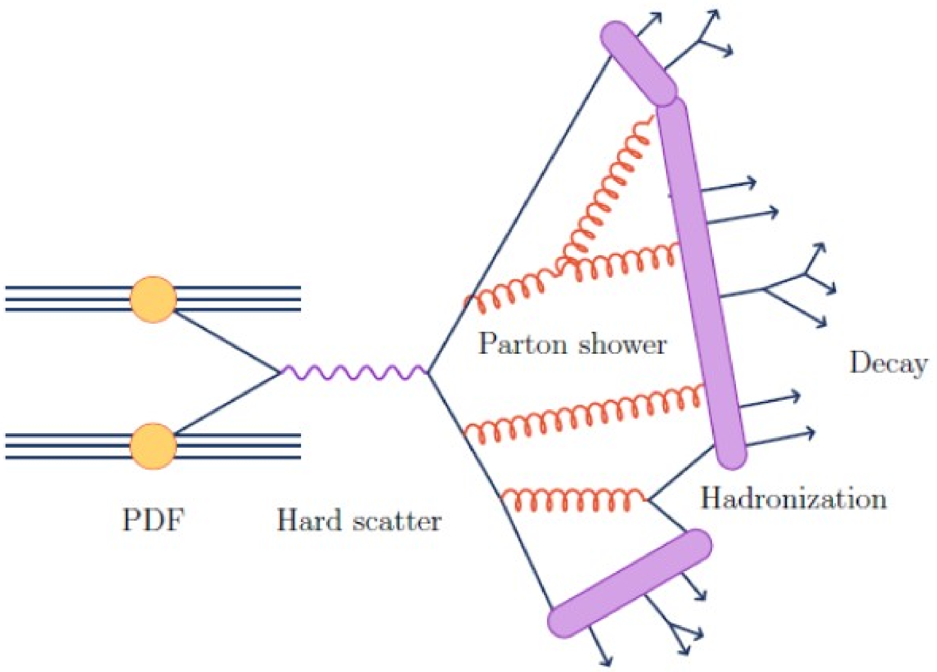
Conclusions

- A complete study of the di-tau final state was performed using ~5 fb-1 of data collected with CMS in 2011
- Novel Tau identification and lepton isolation techniques were proposed and implemented
- The $Z \rightarrow \tau\tau$ cross section was measured in the full dataset in agreement with the theoretical prediction
- A search for SM and MSSM Higgs bosons was presented
  - No significant deviation from the background only hypothesis observed
  - Stringent new bounds are set to the SM Higgs production and MSSM parameter space
- More data in 2012 will shed light about the existence of the Higgs boson

Backup

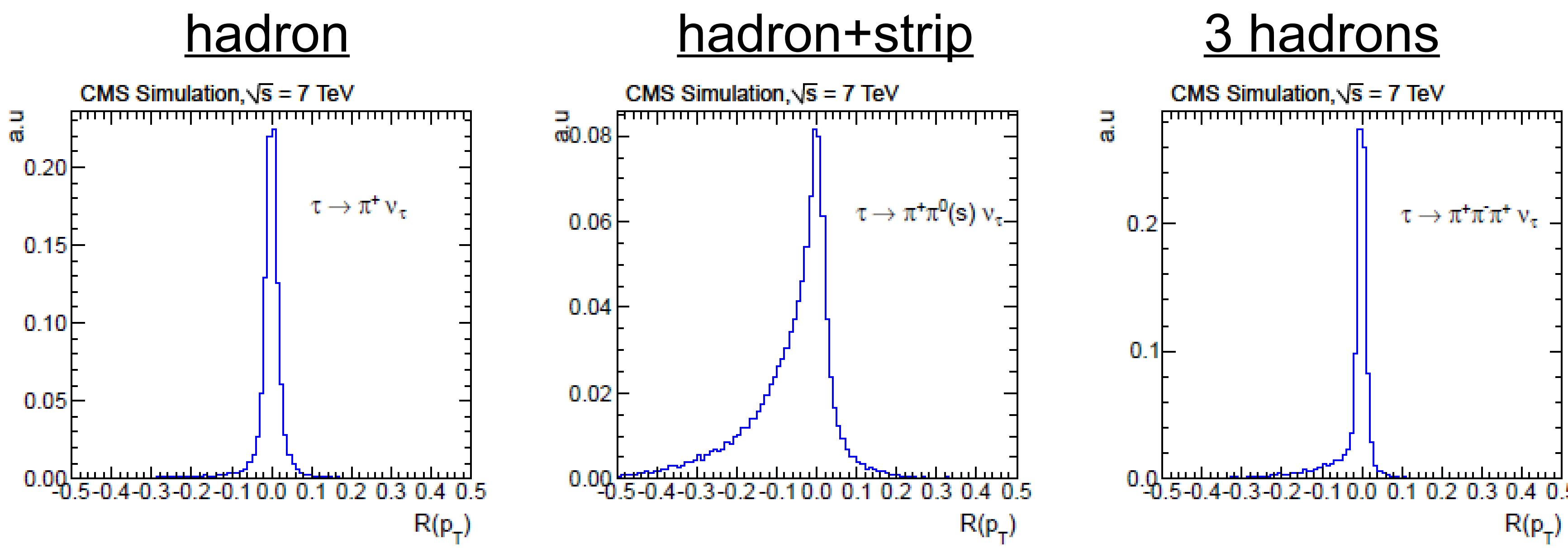
Event Simulation packages

- Physics Generators
  - PYTHIA
    - General purpose leading order(LO) generator
    - Includes hadronization and parton shower
  - POWHEG
    - Improvement to PYTHIA
    - NLO calculation
  - MADGRAPH
    - Tree level generator
    - Ideal for processes witrh multiple objects (e.g Z+jets)
  - TAUOLA
    - Simulation of the tau decay



- Particles Interaction in the detector
  - GEANT4
  - Using precise detector description

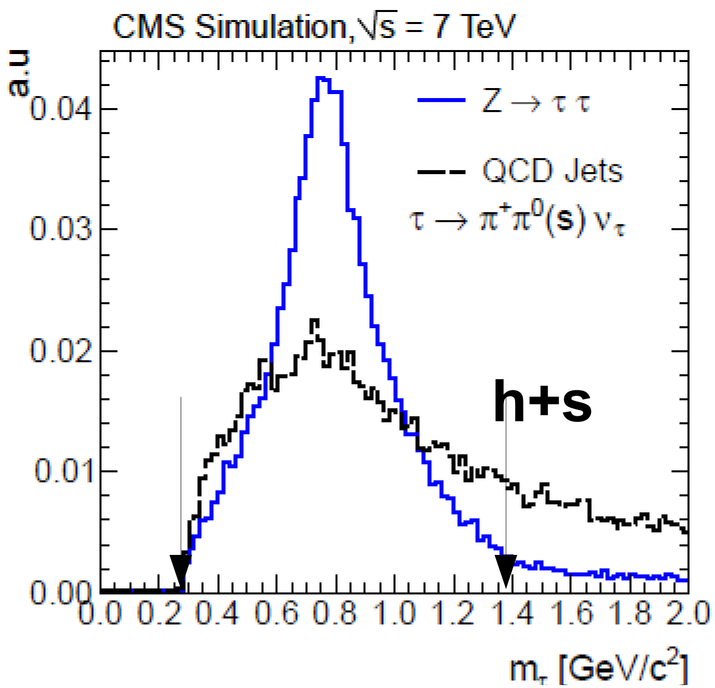
Tranvserse momentum resolution

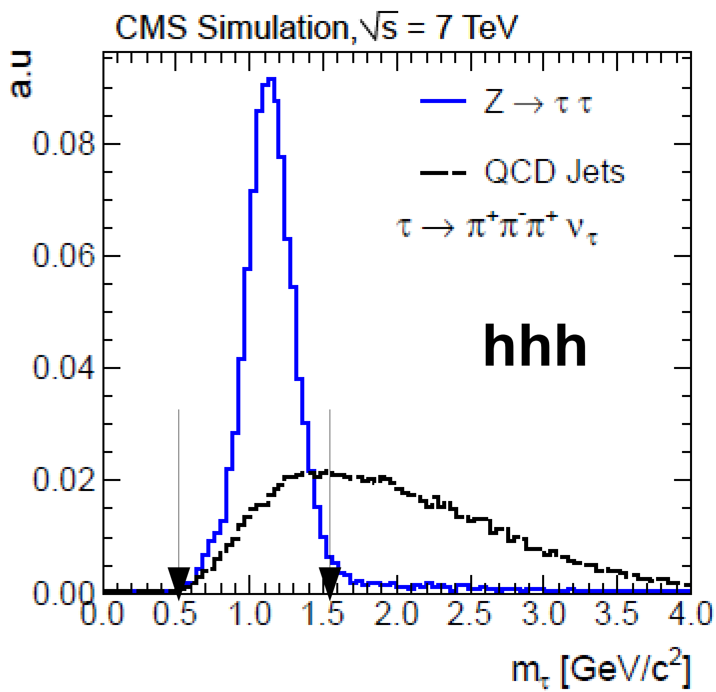


- One and three prong ecay modes dominated by the tracker
  - Excellent resolution
- Hadron+strip decay mode dominated by energy loss
  - Material effects , mis-identification of neutral pions

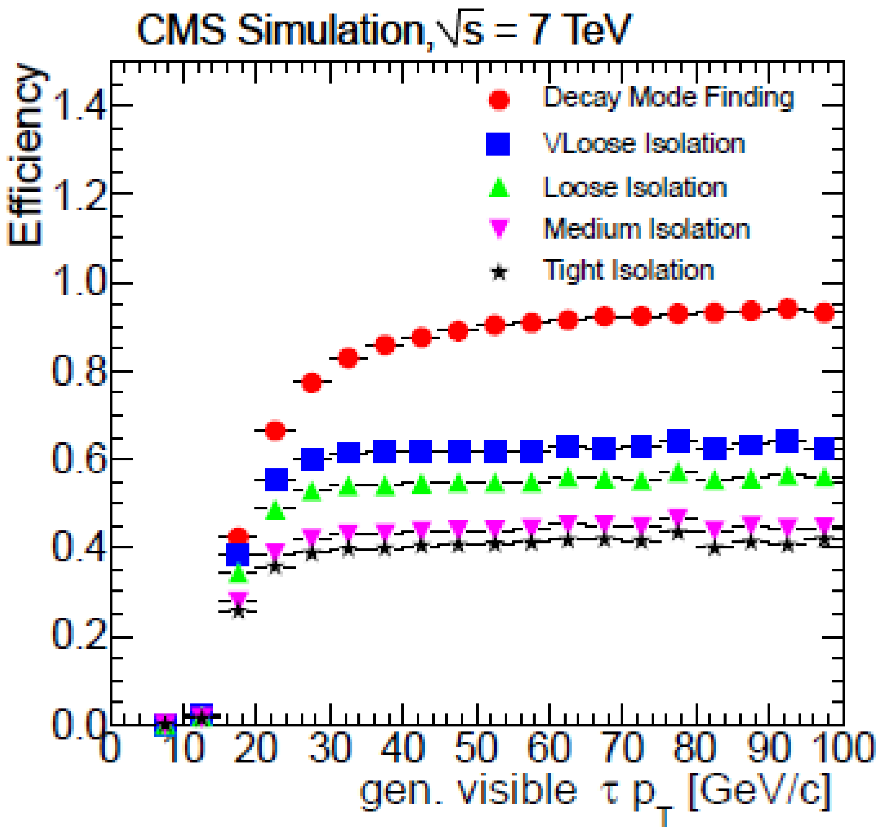
The Hadrons+Strips (HPS) Algorithm

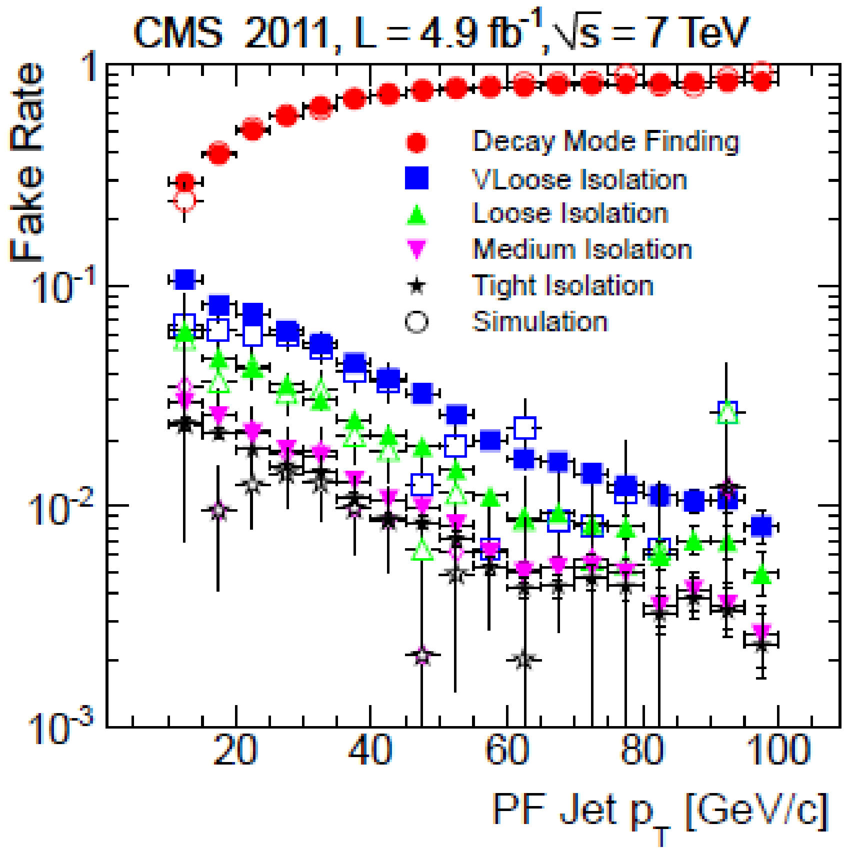
- Start from a jet
- Build combinatorially tau decay modes using PF candidates
  - One charged hadron
  - Three charged hadrons
  - One hadron+ strip
    - Strip is introduced to account for material effects
      - As in electrons
- Apply mass requirements on the decay mode
- Apply isolation on a solid cone of 0.5
  - After subtracting tau constituents





HPS Efficiency and fake rate



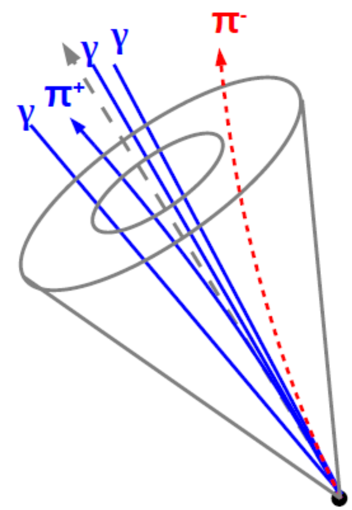


- Efficiency calculated on simulation
- Fake rate calculated on data
  - +compared to simulation
- HPS Algorithm achieves an efficiency of 50-60% for a fake rate <= 1%

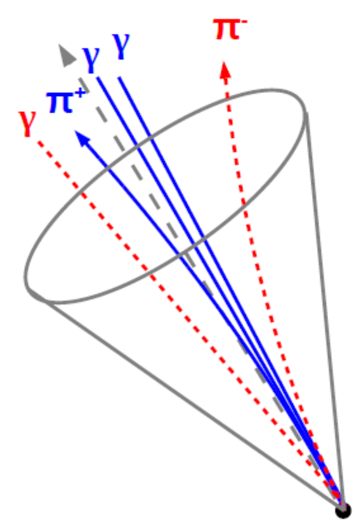
Hadronic Tau identification

- Traditional Tau ID method in hadron colliders
  - Start from a jet
  - Create a narrow signal cone and isolation annulus
  - Assume signal cone constituents = tau
  - Apply Isolation
- Caveats
  - Energy measurement not precise
  - Sensitive to PU
  - Not using additional decay mode info
- Solution:
  - Propose Decay Mode Tau ID

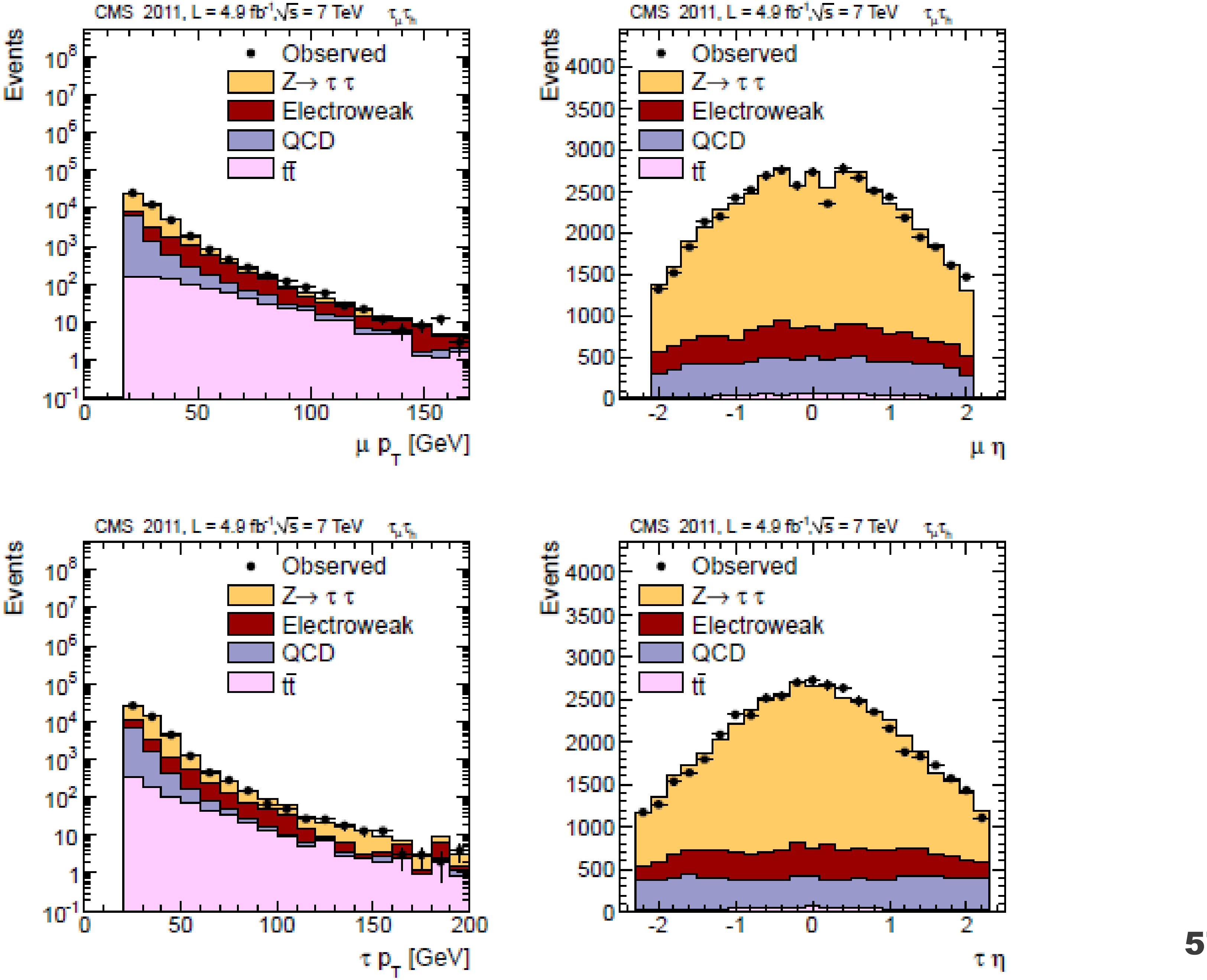
Cone based



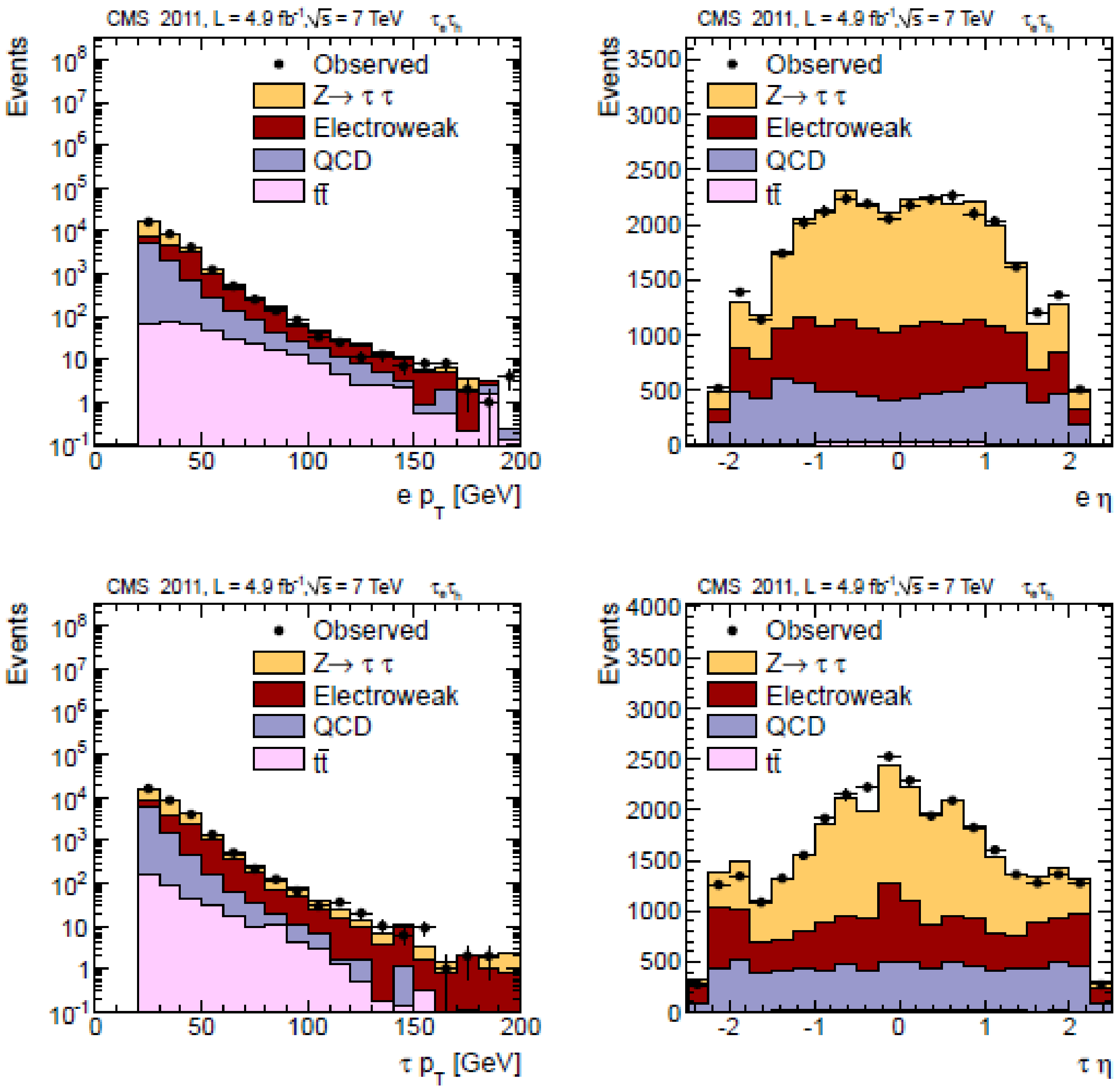
Decay mode based



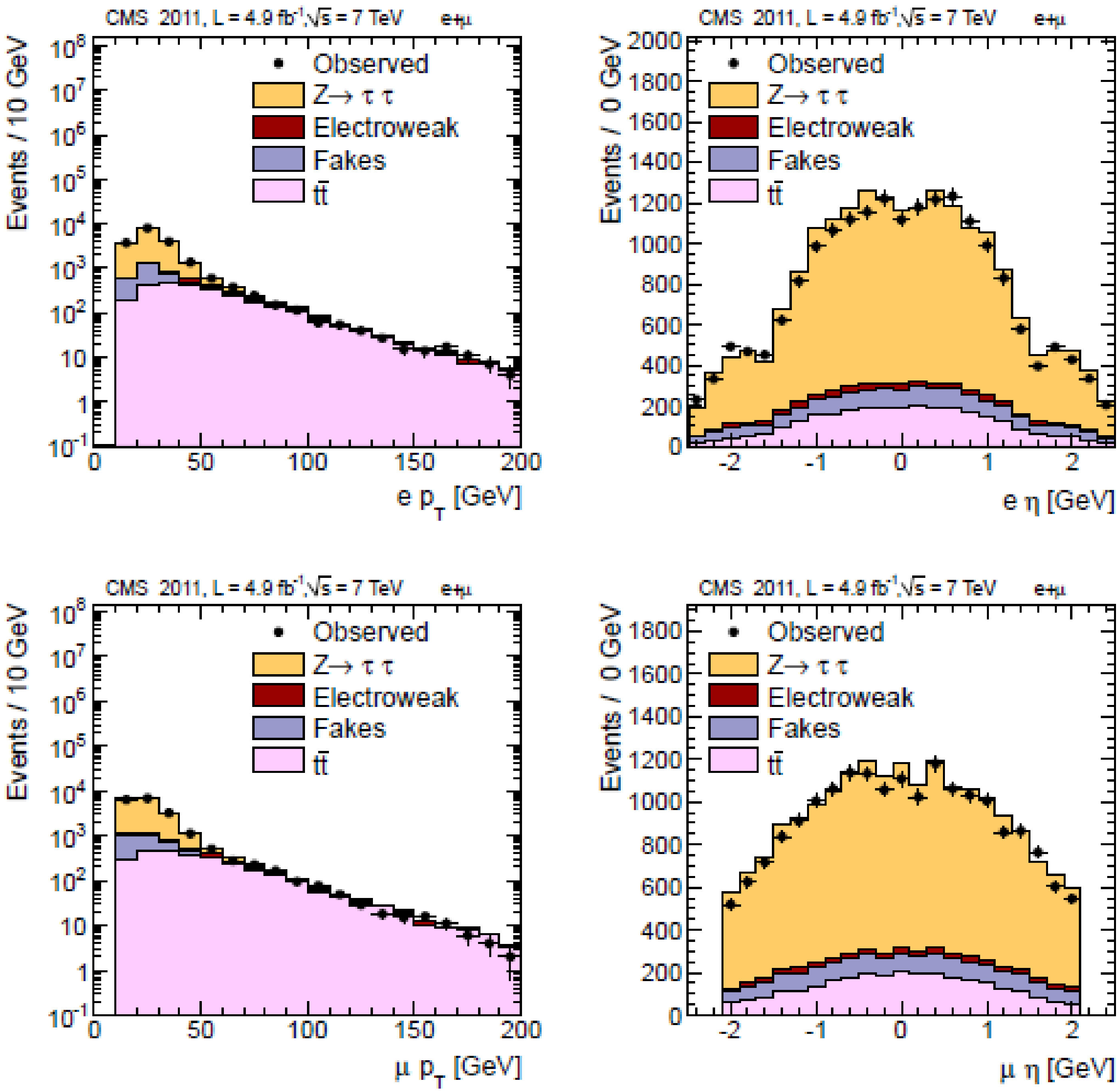
Muon+Tau


CMS 2011, L = 4.9 fb⁻¹, √s = 7 TeV τμτh
Observed
Z→ τ τ
Electroweak
QCD
tt̄
Events
μ pT [GeV]
μ η
τ pT [GeV]
τ η

Electron+Tau

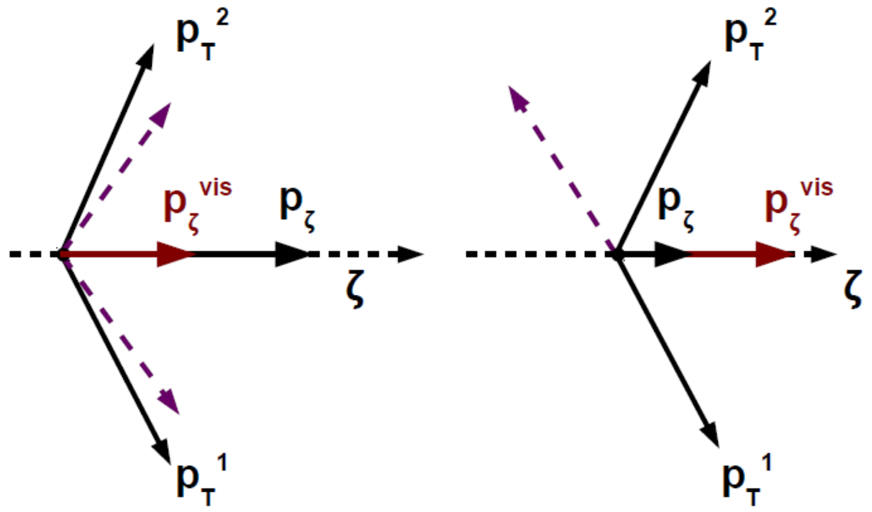


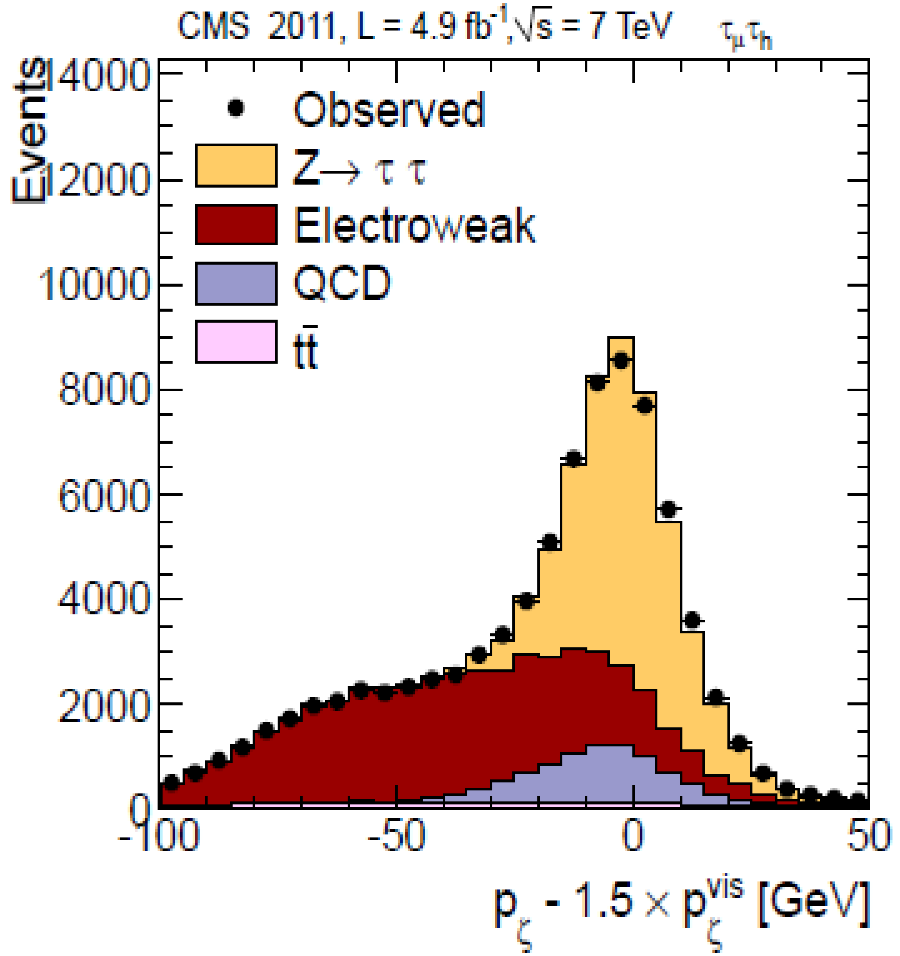
Electron+Muon



Alternative W/tt rejection

- Exploit the fact that the tau decay products are boosted
  - Neutrinos near visible products
  - Form ζ variables(used in CDF)





- Require
  - P_ζ -1.25 $P_{\zeta,vis}$>-25 GeV (e/μ)

Background Estimation (e+μ)

- TTBar: Dominant + ~Irreducible
  - Estimated by MC using CMS measurement
- QCD: ABCD method (isolation vs charge)
- Non QCD fakes(small) MC +40% uncertainty

	e+μ
Exp	18530+-797
Obs	18316

B
OS
Both Legs
Anti-Isolated

C
SS
Both Legs
Anti-Isolated

A
OS
Both Legs
Isolated

D
SS
Both Legs
Isolated

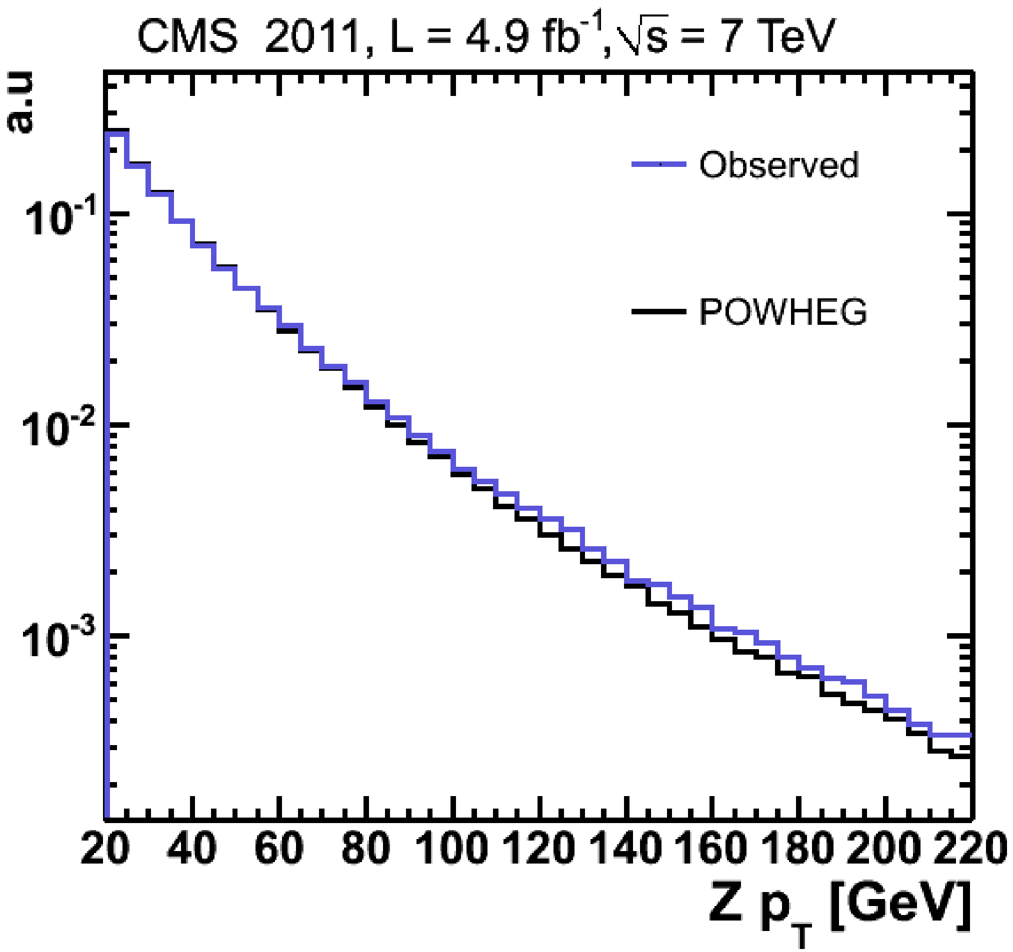
Acceptance Modeling

- Acceptance is calculated with visible products using POWHEG+TAUOLA
- We don't calculate acceptance in Mass window
  - No way to restrict the reconstructed Z to a Z mass window due to invisible products
- To compare with Z $\rightarrow$ ll results:
  - We estimate the cross section at M>20 GeV
    - However more than 97% of the events with M>50
  - Then we extrapolate the measurement to M>50 GeV mass window using theoretical predictions

Final State	Acceptance (%)
$\mu + \tau_h$	5.889 ± 0.011
$e + \tau_h$	4.524 ± 0.009
$e + \mu$	8.084 ± 0.011

Theoretical systematics

- Effect of PDFs in acceptance : 2%
- FSR:negligible
- ISR+NNLO effects + higher order weak corrections
  - Those affect the Z Pt
  - We compare Z pt in POWHEG and μμ data
  - We reweigh the POWHEG spectrum to match data
  - Assigning the full difference in acceptance as systematic
    - <0.5%



Likelihood definition

Applying a shape fit with backgrounds and systematic uncertainties floating around the estimated values

The likelihood is: $\mathcal{L} = \mathcal{L}_{\text{shape}} \times \mathcal{L}_{\text{bkg}} \times \mathcal{L}_{\text{syst}}$

$\mathcal{L}_{\text{bkg}} \times \mathcal{L}_{\text{syst}}$: product of constraints

The shape part is a stack of all visible mass distributions multiplied by their normalizations

Signal **Backgrounds**

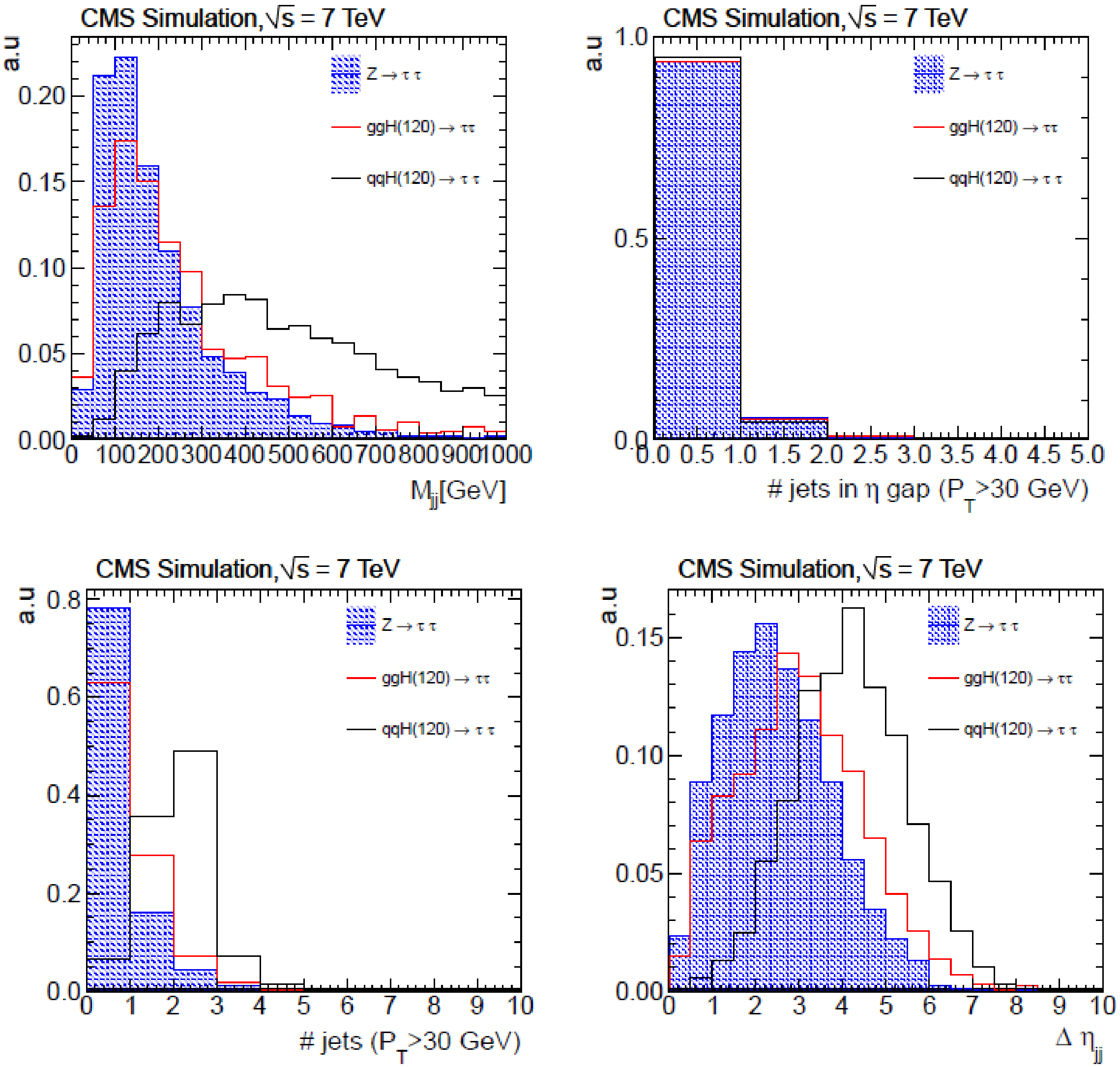
$$\mathcal{L}_{\text{shape}} = N_{Z\to\tau\tau}(n_j) f_{Z\to\tau\tau}(m_{\text{vis}}, n_j) + \sum N_i(n_j) f_i(m_{\text{vis}}, n_j)$$

Finally the signal coefficient is modified so that we can extract the cross section

$$N_{Z\to\tau\tau}(n_j) = \sigma \bar{A}(n_j) L,$$

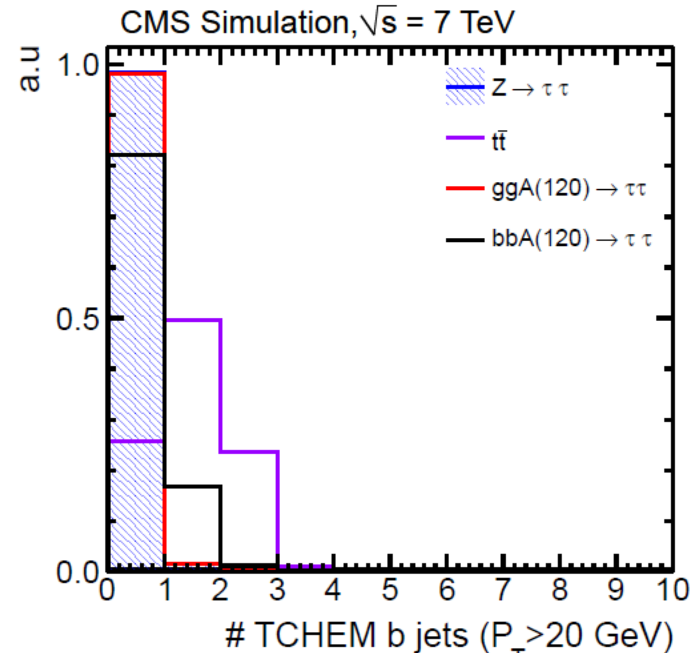
VBF kinematics

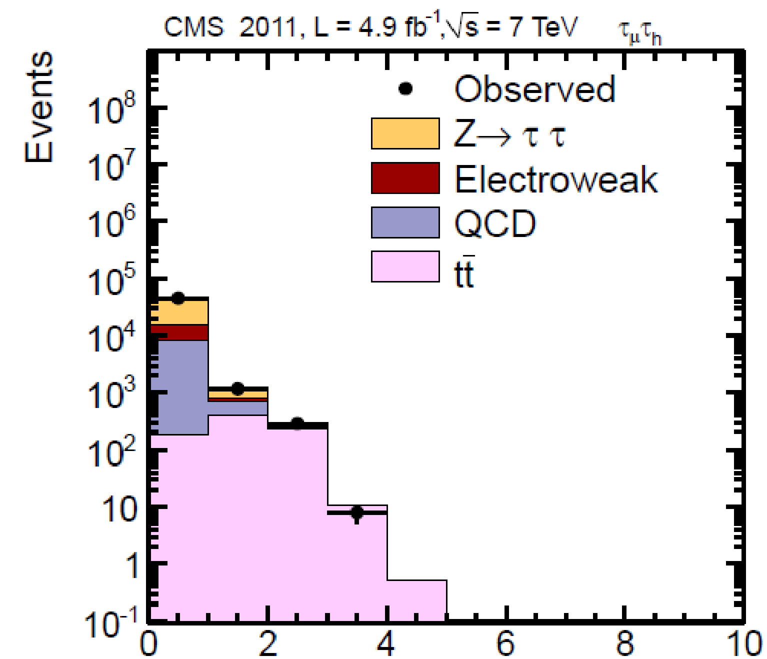
- Most of the VBF events have 2 jets within η<4.5 and Pt>30
- The mass of the two jets is much higher than Z background
- The jets appear in high η difference



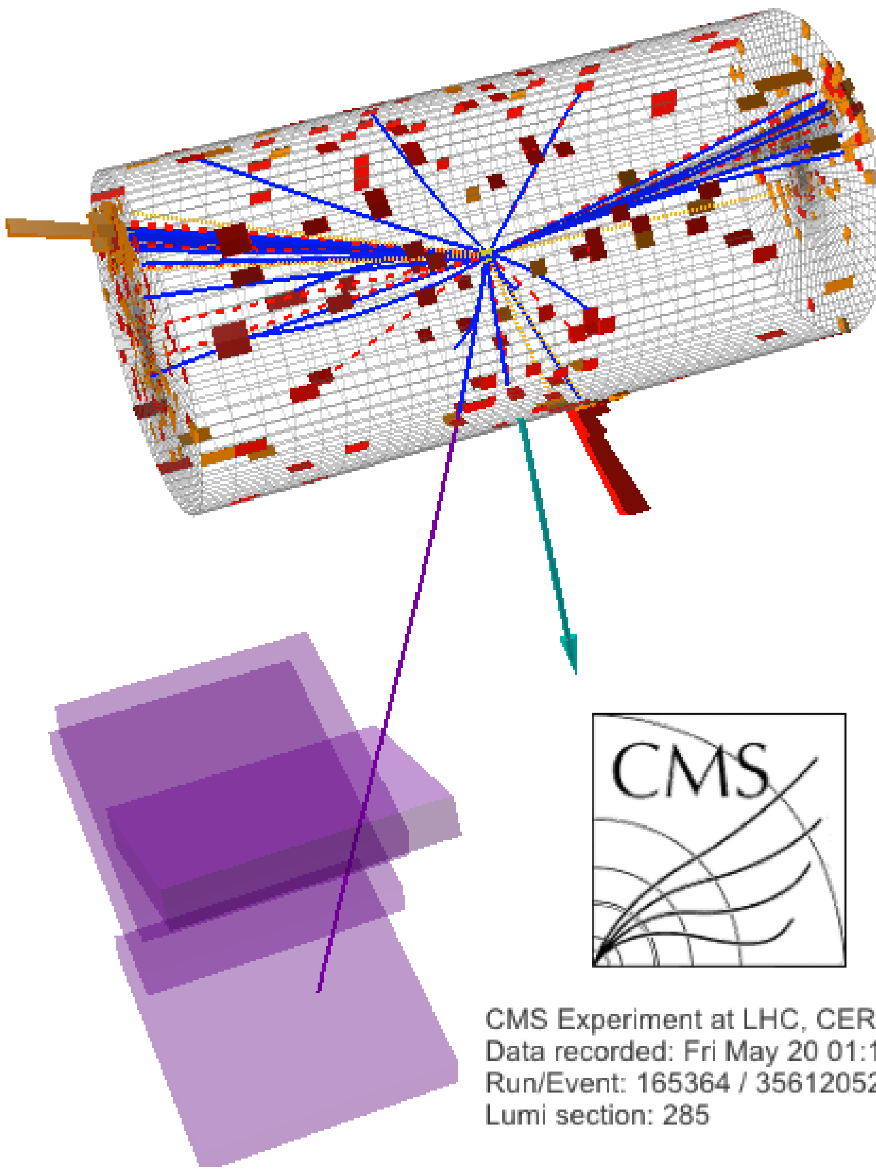
MSSM Higgs search categorization

- Split the data into two categories
- MSSM-VBF:
  - Require onje b-tagged jet>20 GeV
  - To reduce ttbar require less than two jets with Pt>20
- MSSM-NoVBF:
  - All events failing B selection
- Signal has mostly one b-jet tagged
- Good agreement with simulation





VBF candidate event



CMS Experiment at LHC, CERN
Data recorded: Fri May 20 01:10:36 2011 CEST
Run/Event: 165364 / 356120525
Lumi section: 285